初代星の質量について

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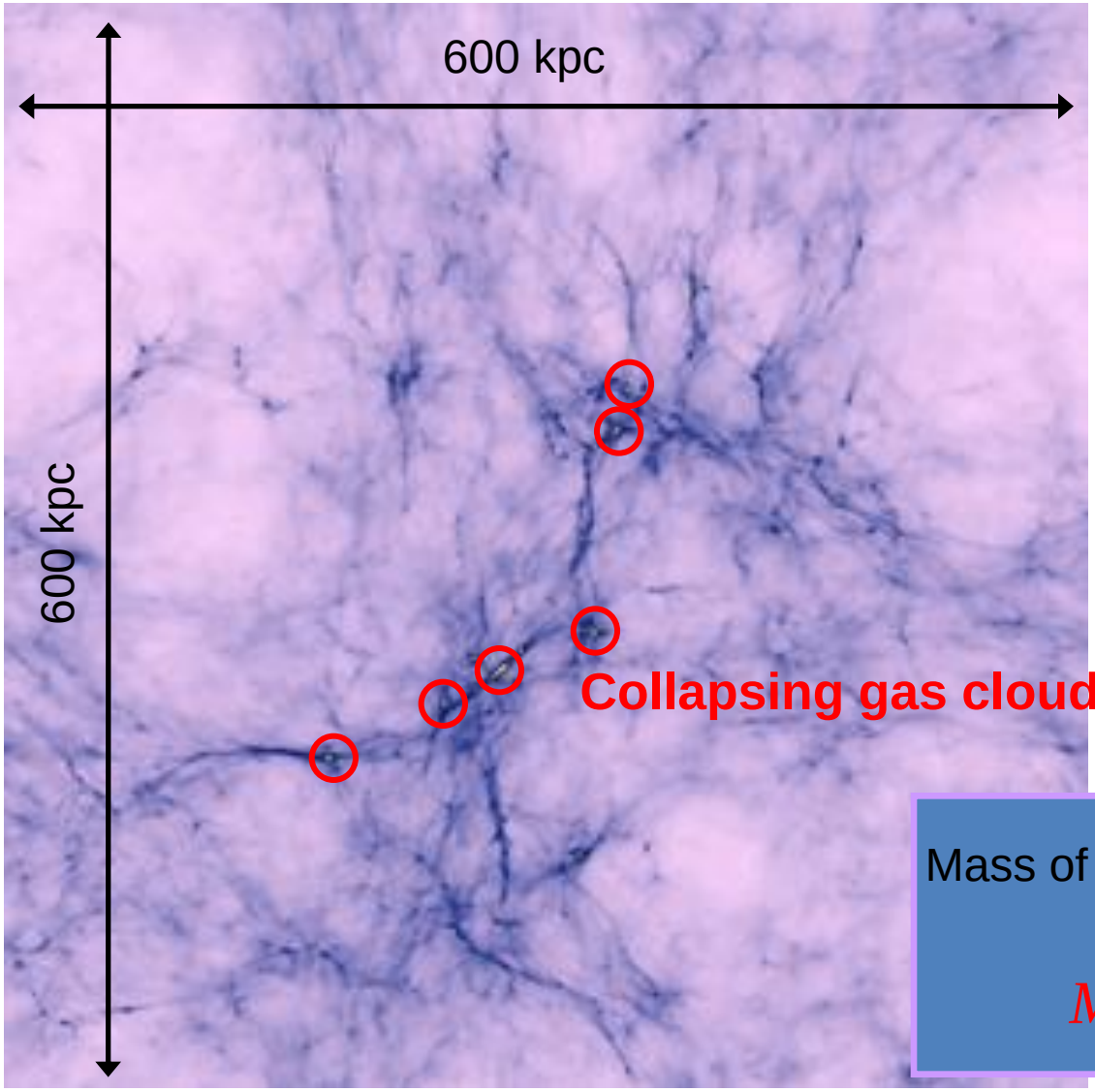
Gas Density field @ z=17

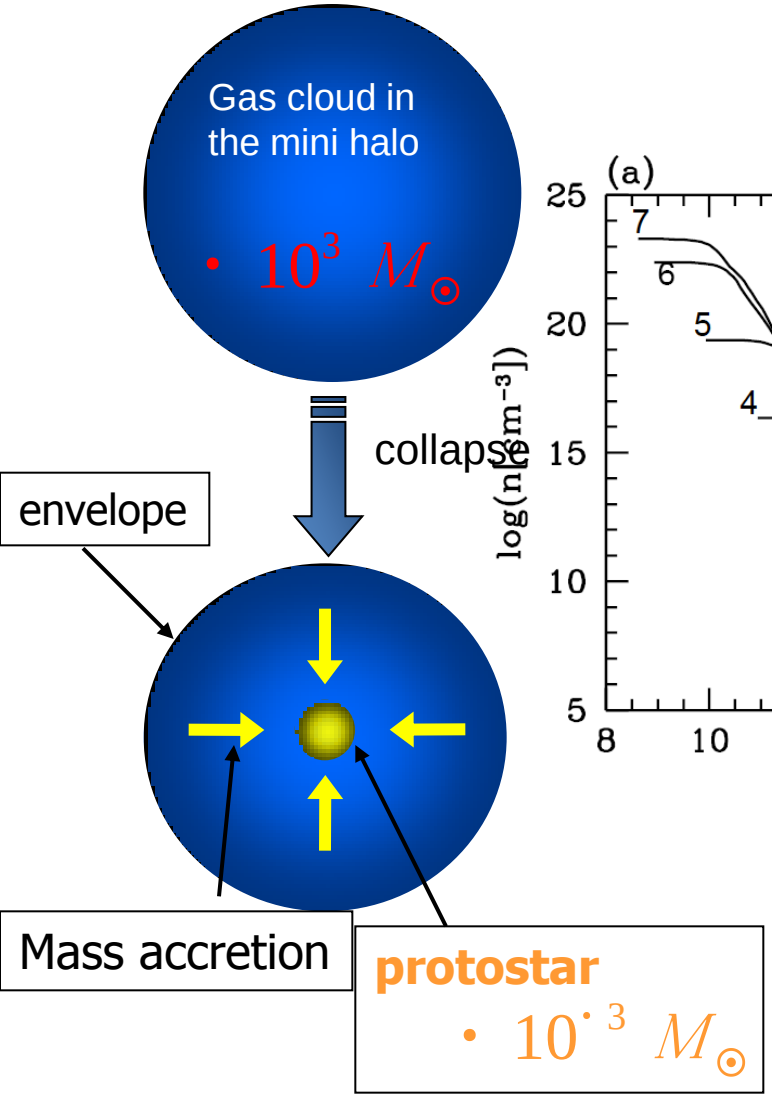


Mass of the gas cloud:

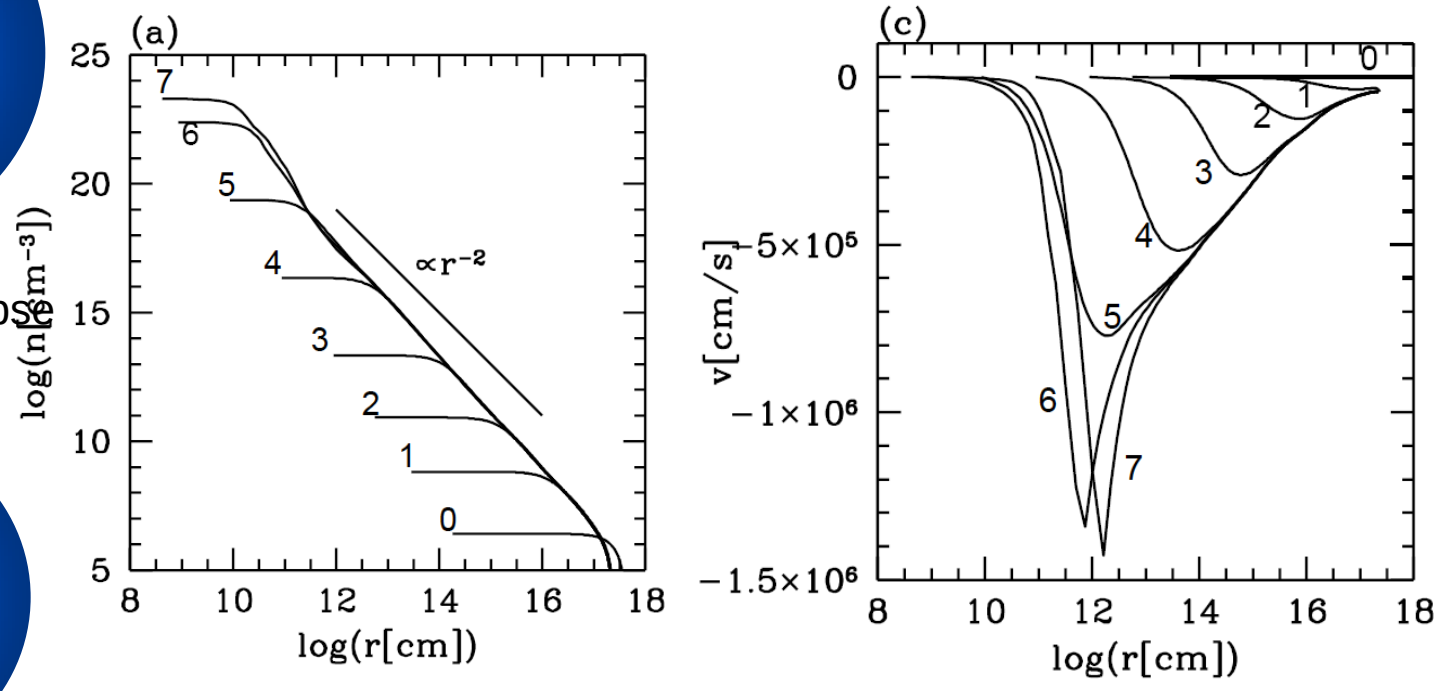
$$M_{\mathrm{frag}} \approx 10^2 - 10^3 M_\odot$$

Yoshida et al. (2003)

Collapse of self gravitating primordial gas



1D simulation



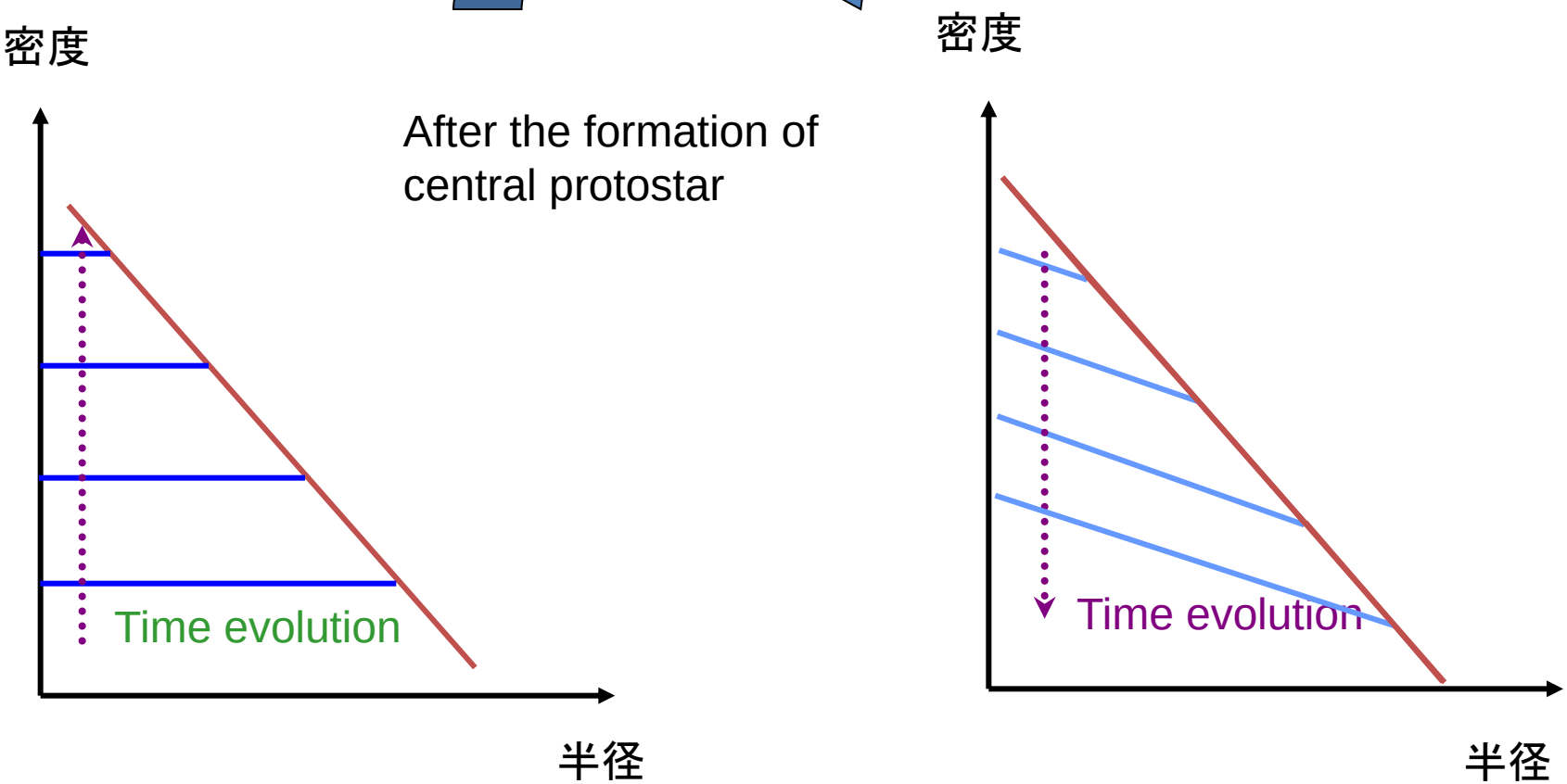
Omukai & Nishi (1998, ApJ, 508, 141)

最終的な星の質量は1000Msunのうちどれほどがprotostarに降着するかで決まる。

Run away phase -> Accretion phase

Run away

accretion



Mass accretion rate

In the accretion phase, matters freely falls onto the protostar.

$$\frac{dM}{dt} \approx 4\pi R_J^2 \rho v_{ff} \approx 4\pi R_J^2 \rho 3 c_S = 4\pi \frac{c_S^2}{4}\left(\sqrt{\frac{\pi}{G\rho}}\right)^2 \rho \cdot 3 c_S \approx 30 \frac{c_S^3}{G}$$

Mass accretion rate determined purely by the temperature of envelope.

Thermal evolution of the Core

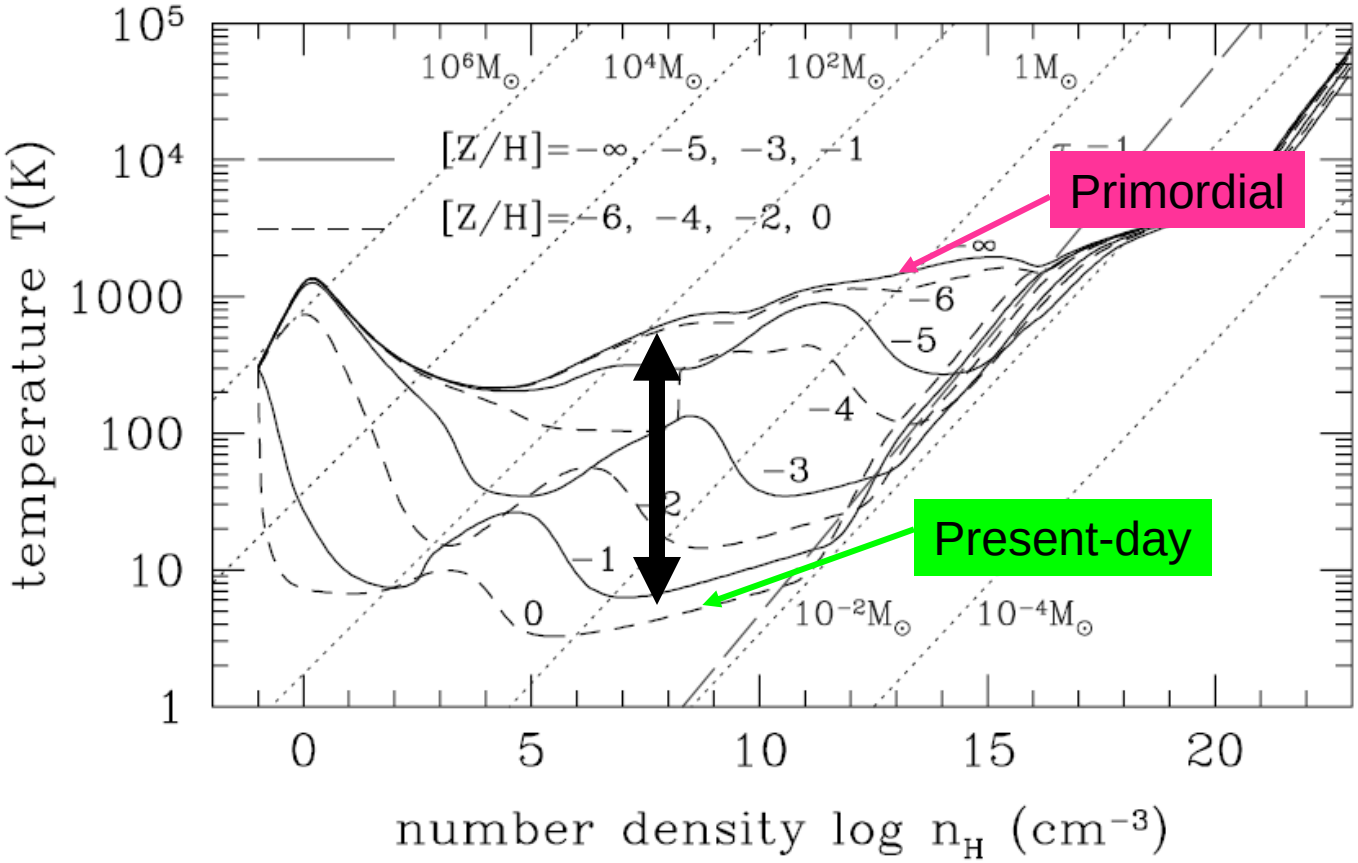


FIG. 1.—Temperature evolution of prestel = 0), −5, −3, and −1 (−6, −4, −2, and 0) are shown by solid (dashed) lines. Only the p stant Jeans mass are indicated by thin dotted lines. The positions at which the central par cated by the thin solid line (eq. [20]). The intersection of the thin solid line with each ev ly thick to the continuum. To the right of this line, the clouds are optically thick and there *or version of this figure.*]

Gas temperature of primordial gas is 100 times higher than local molecular gas clouds

Omukai 2000, Omukai+2005

Final mass

$$\dot{M} \sim 30 \frac{c_s^3}{G}$$ → 1000K, for primordial gas, Very high mass accretion rate（c.f. 10K for interstellar gas)

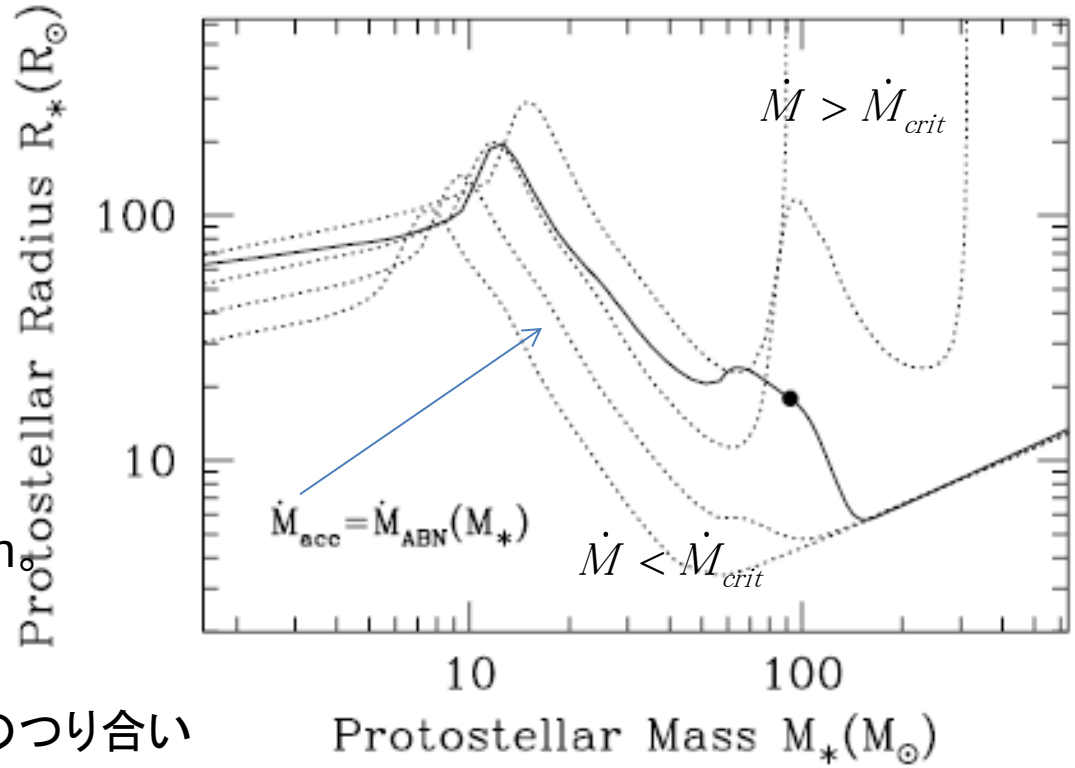
$$\dot{M} \approx 10^{-2} M_{\mathrm{sun}} \mathrm{yr}^{-1}$$ → $$\dot{M} \times 10^5 \mathrm{yr} \approx 10^3 M_{\mathrm{sun}}$$

If the accretion is spherical and is not quenched, POPIII stars are Very Massive.

輻射は(球対称で)降着を止めるか？

$$\dot{M}_{crit} = 4 \times 10^{-3} M_{\odot} yr^{-1}$$

1. 質量降着率が臨界値を超えると、エディントン限界に達して降着できなくなる。
2. 宇宙論的な初期条件の計算から降着率を持ってくると、収縮できる。星の寿命の間、降着できて600Msun



※エディントン限界：重力と放射圧のつり合い

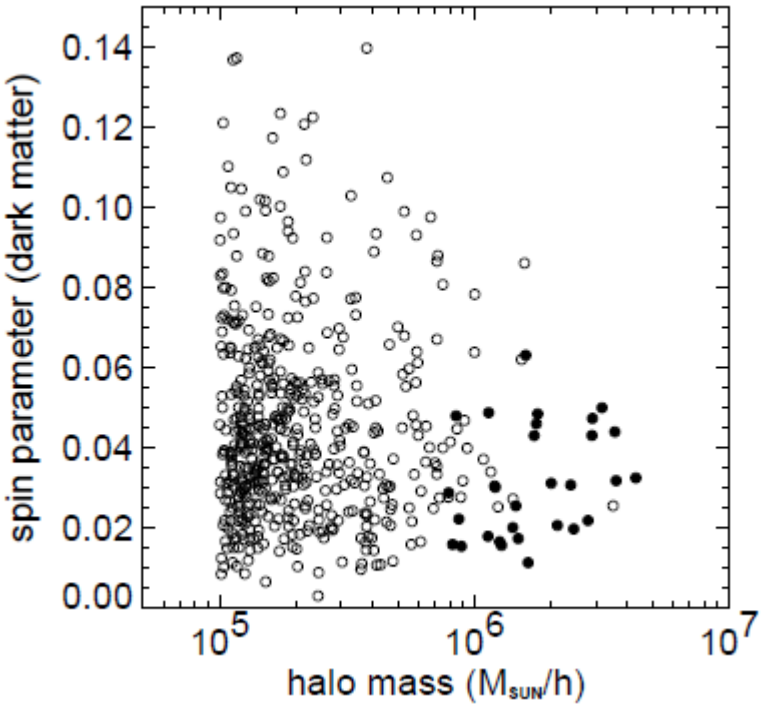
$$\frac{GM\rho}{R^2} = \frac{L}{4\pi R^2 c}\kappa\rho \Rightarrow L_{Edd} = \frac{4\pi GMc}{\kappa}$$

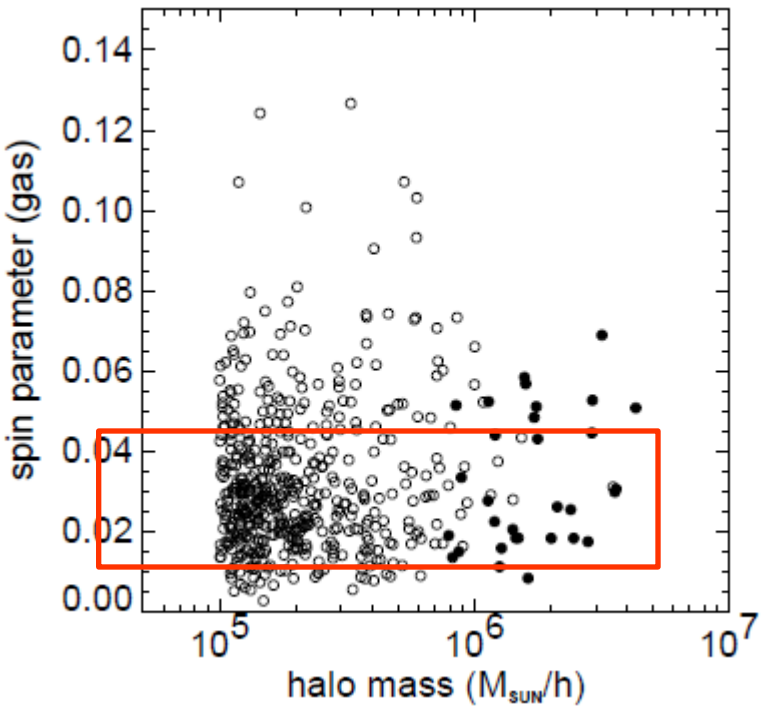
Omukai & Palla 2003

状況によるがあまり降着は止まりそうにない。

Angular momentum of minihalos

$$\lambda = \frac{j}{\sqrt{2} R_{\rm vir} V_{\rm vir}}$$





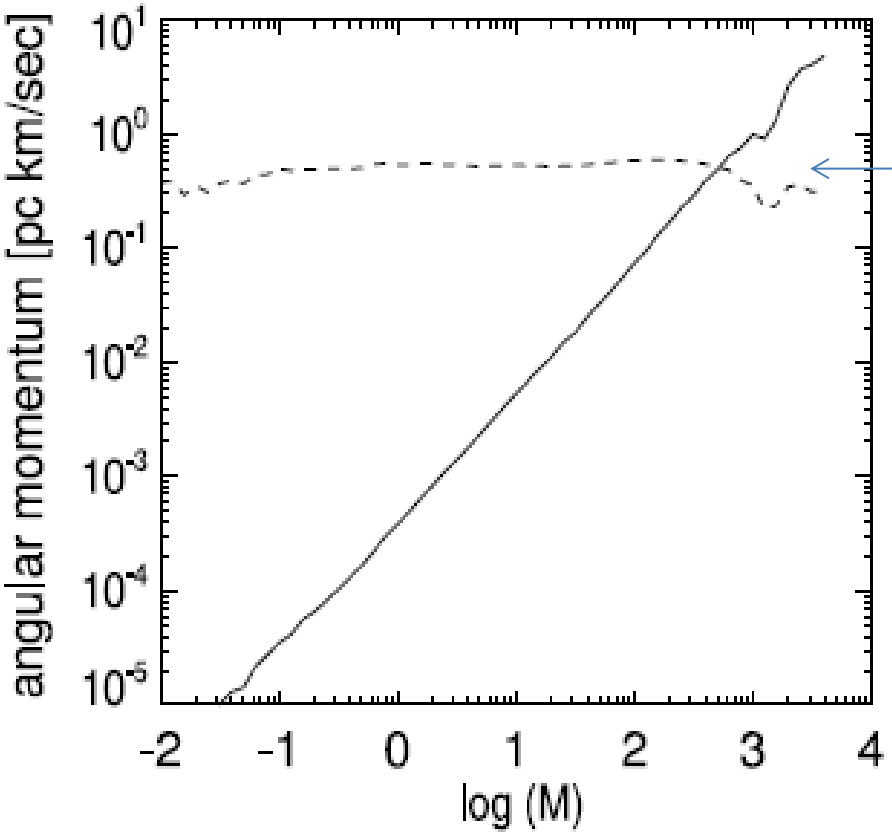
DM

Yoshida et al. 2003

GAS

Specific AM distribution in the core

Yoshida et al. 2006



$$\frac{j}{rV_{Kep}} \approx 0.4 - 0.5$$

Gas cloud is not supported by rotation,
But will be supported in the accretion phase.

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

Formation of rotationally supported disk is inevitable.

Numerical Studies of Accretion Phase

～1000AU・“star cluster”(t>1000yrs)

- Stacy+2009 cosmological・n_{max}=1e12・r_{acc}=50AU
- Clark+2010 turbulent・n_{max}=1e13・r_{acc}=20AU
- Smith+2011 cosmological・ n_{max}=1e15・r_{acc}=20AU
- Hosokawa+2011 cosmological（2D）・Mesh・r_{acc}=10AU + UV
- Hosokawa+2012 cosmological.POP3.2（2D）・Mesh・r_{acc}=10AU + UV
- Stacy+2012 cosmological・n_{max}=1e12・r_{acc}=50AU + UV
- Stacy+2013 cosmological・n_{max}=1e13・r_{acc}=20AU 10 halos
- Susa 2013 BE sphere ・n_{max}=3e13・r_{acc}=30AU + UV
- Hirano+2014 cosmological（2D）・Mesh・r_{acc}=10AU + UV 100 halos ←平野さん講演
- Susa+2014 cosmological ・n_{max}=3e13・r_{acc}=30AU + UV 60 halos ←This talk
- Hosokawa+2014? Cosmological(3D) + UV ←細川さん講演

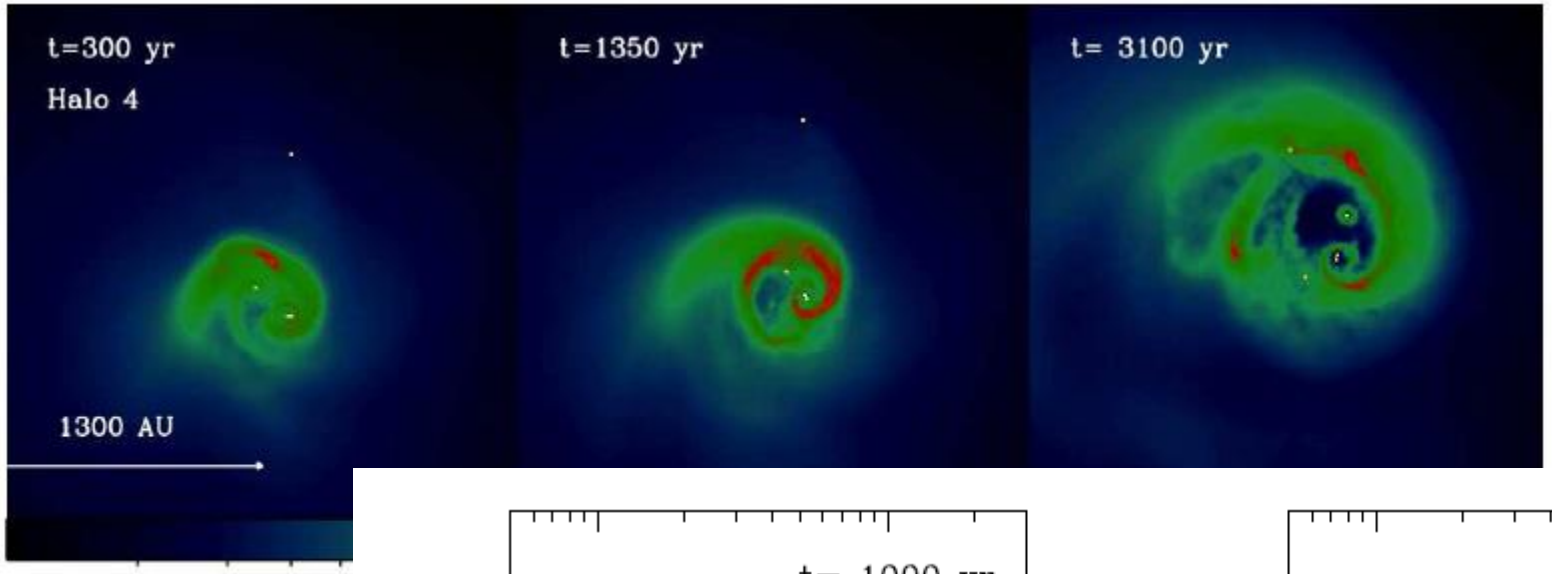
～100AU・”inner disk fragmentation”(t < 1000yrs)

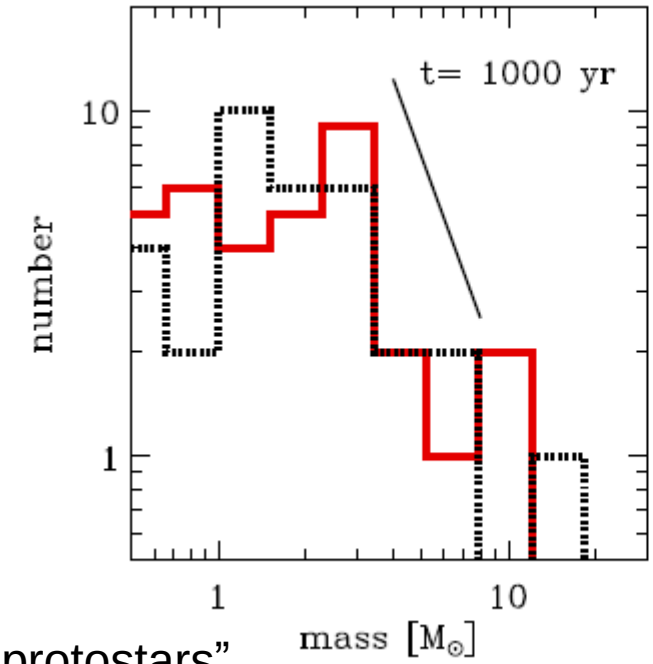
- Clark+2011 cosmological・n_{max}=1e17・r_{acc}=1.5AU
- Greif+2011 cosmological・ n_{max}～1e17 (Arepo)・r_{acc}=0.46AU(=100Rsun)
- Machida+2013 BE sphere・change EOS n_{max}～1e18-1e20 + MHD ←町田さん講演

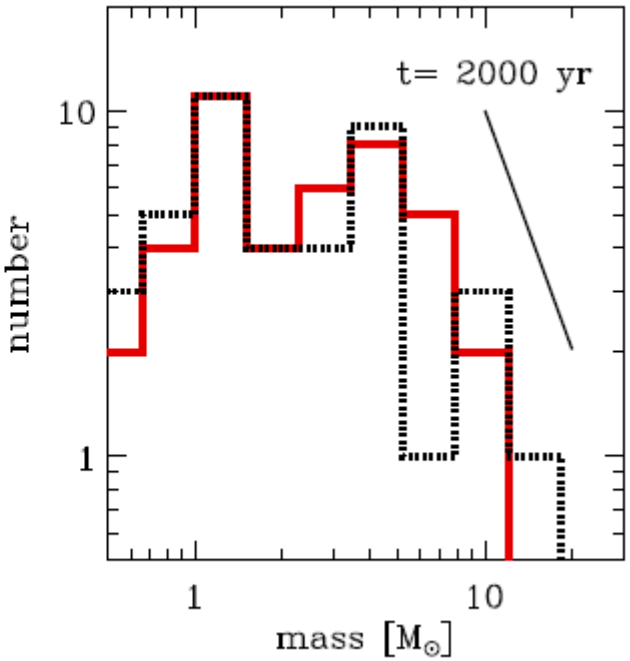
～10AU・”resolve protostellar radius ”(t～10yrs)

- Greif+2012 cosmological・Arepo・No sinks・r_{acc}=0.05Rsun

Smith+2011





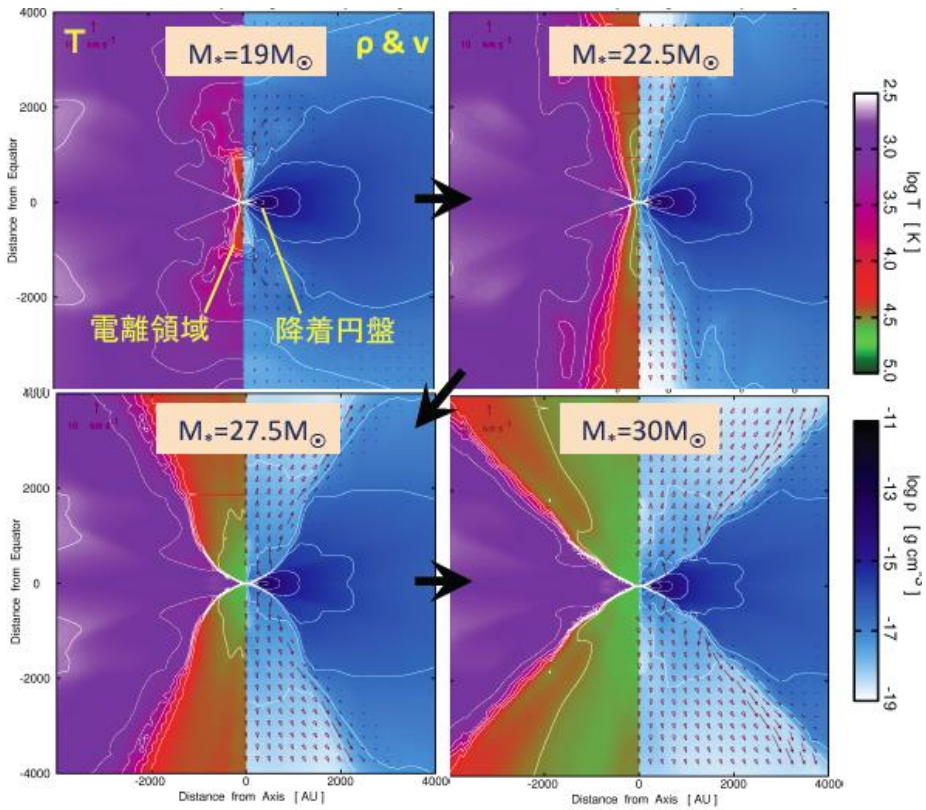


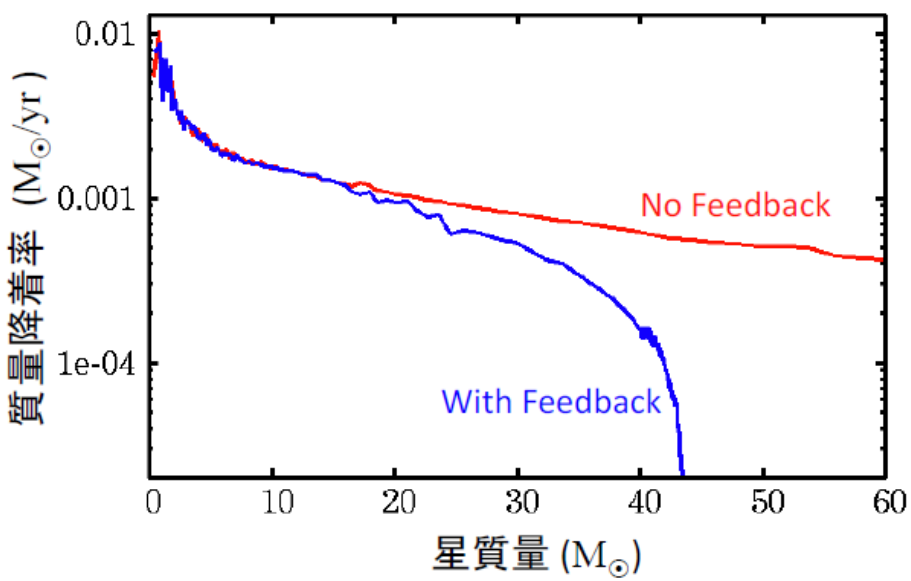
O(10)個の”protostars”

Radiative feedback from the central star (2D)

Long term integration (10^5 yrs) with feedback → Final mass

Hosokawa+ (2011)



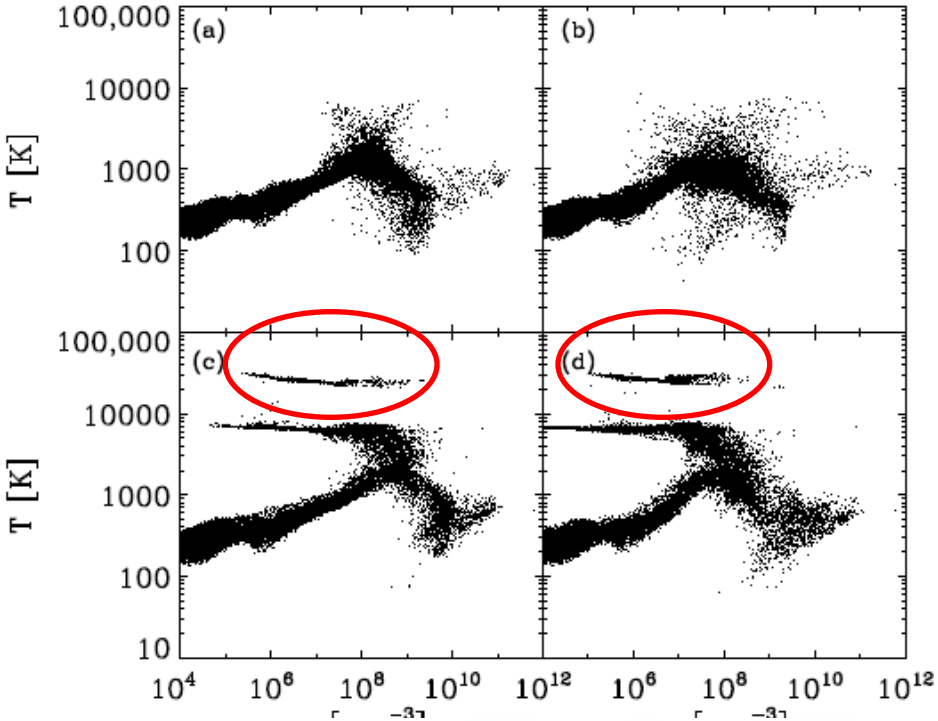


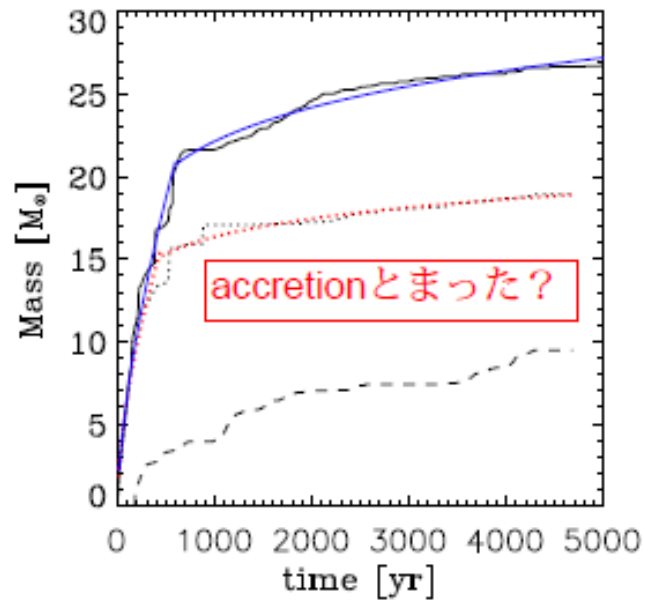
- UV光feedbackの為に大幅に降着率が低下する
- この場合、星質量～45 $M_\odot$で星への降着が止まる。

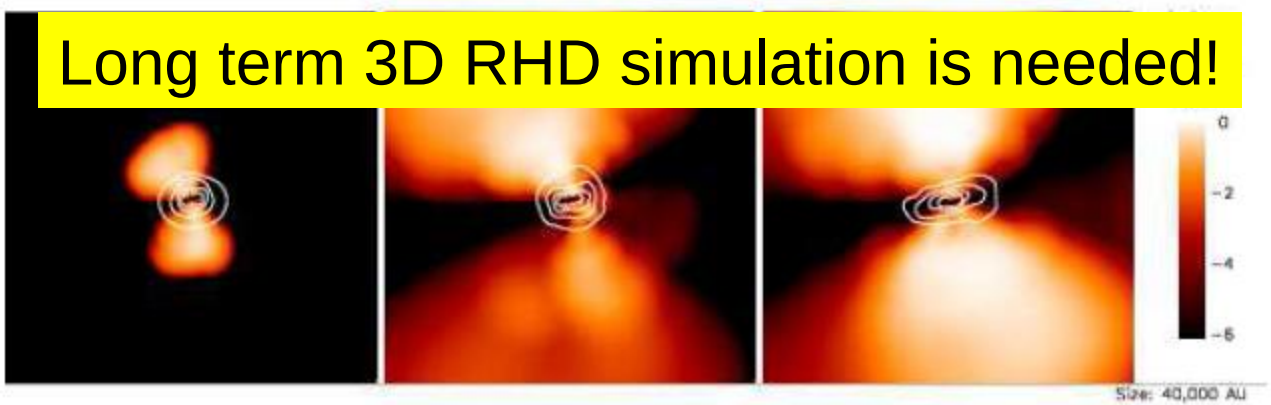
Photoevaporation of accretion disk

courtesy to Hosokawa san

Stacy+2012





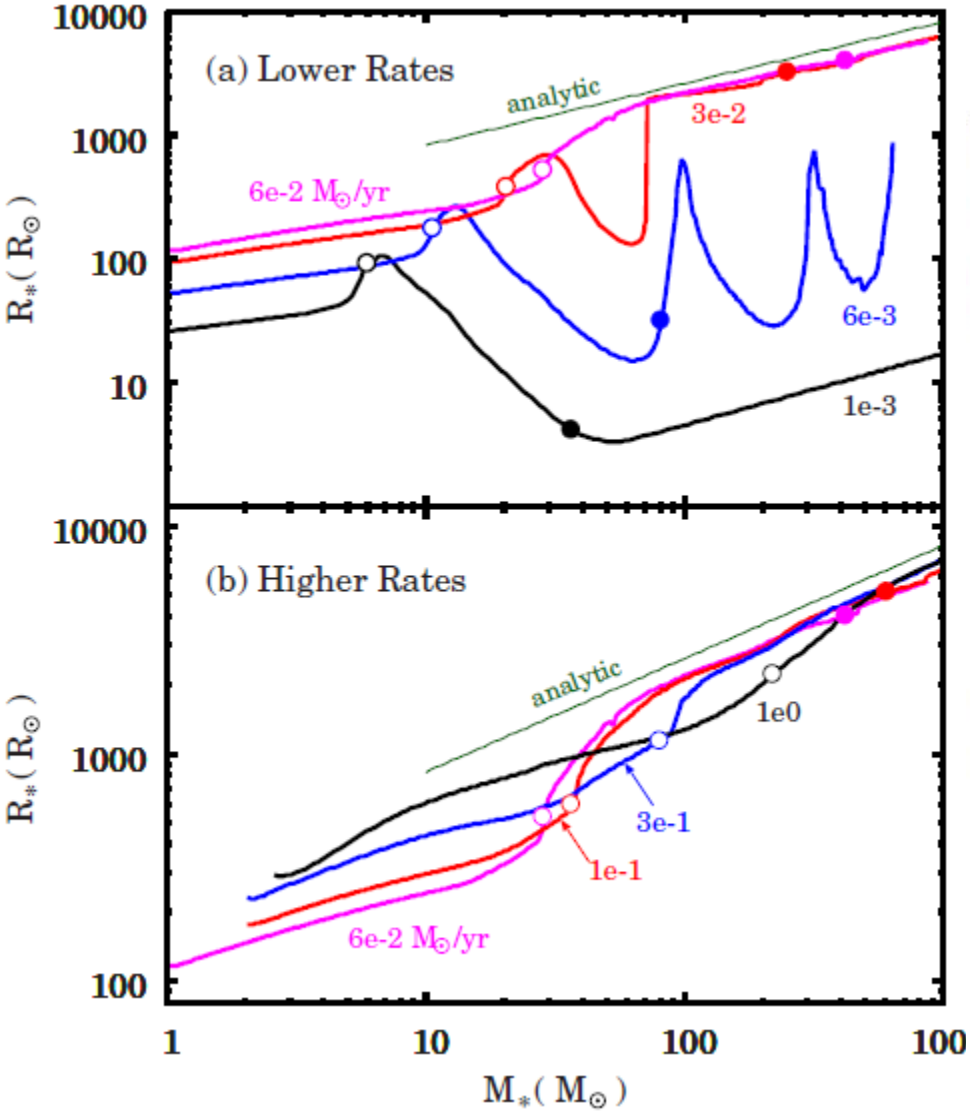


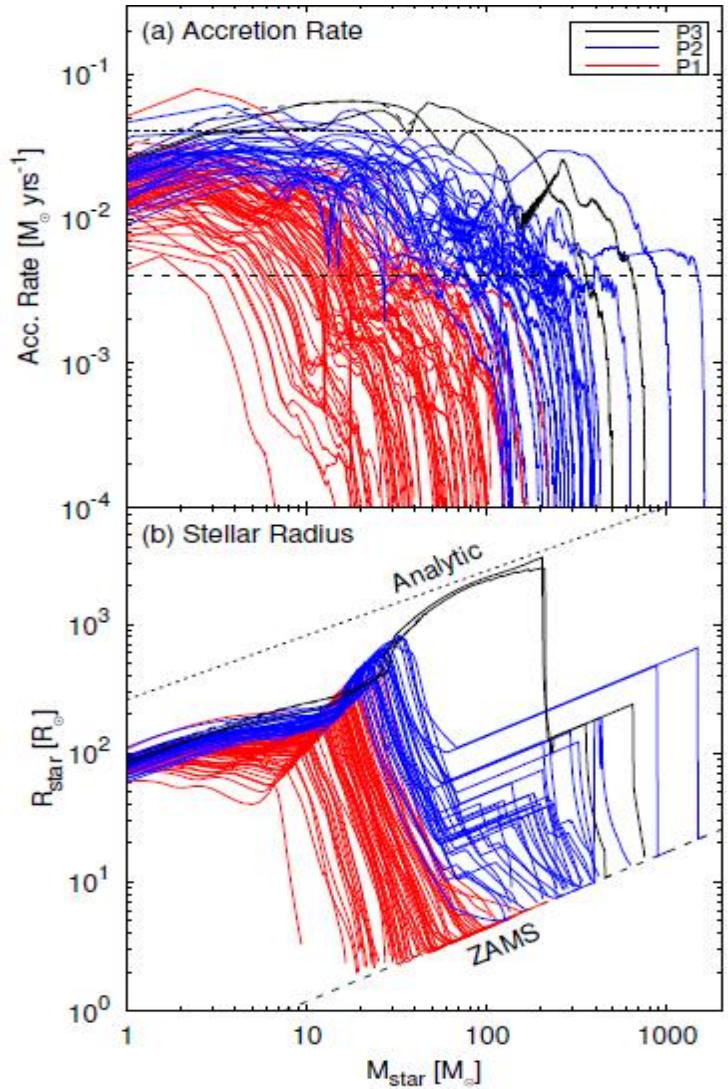
edback on protostellar accretion.
wth with no radiative feedback,
e 'with-feedback' case. The blue
it to the sink growth rate for the
otted line is a double powerlaw fit
shed line shows the growth of the
e 'with-feedback' case. Radiative
ion-induced starvation leads to a
ories in less than 1000 yr, and in
in sink does not grow beyond ~
ation.

Figure 7. Projected ionization structure of gas at 1500, 2000, and 3000 yr after initial sink formation. White lines depict the density contours of the disk at densities of $10^{7.5}$, 10^8, $10^{8.5}$, and 10^9 cm^{-3}. Box length is 40,000 AU. Note the pronounced hour-glass morphology of the developing ultra-compact H II region, roughly perpendicular to the disk. This structure gradually expands and dissipates the disk gas from above and below, reducing the scale height of the disk.

Very high mass accretion case

Hosokawa+2012,2013, Hirano+2014

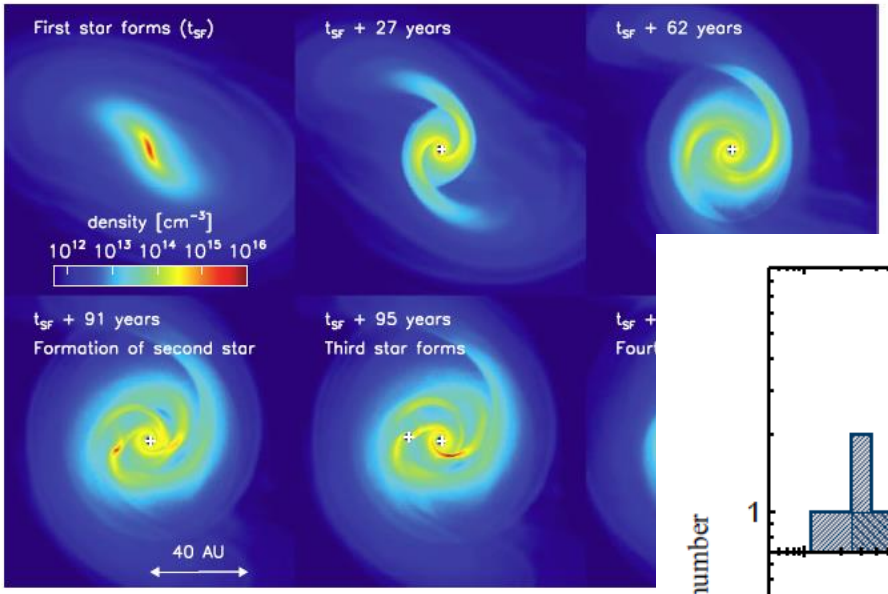




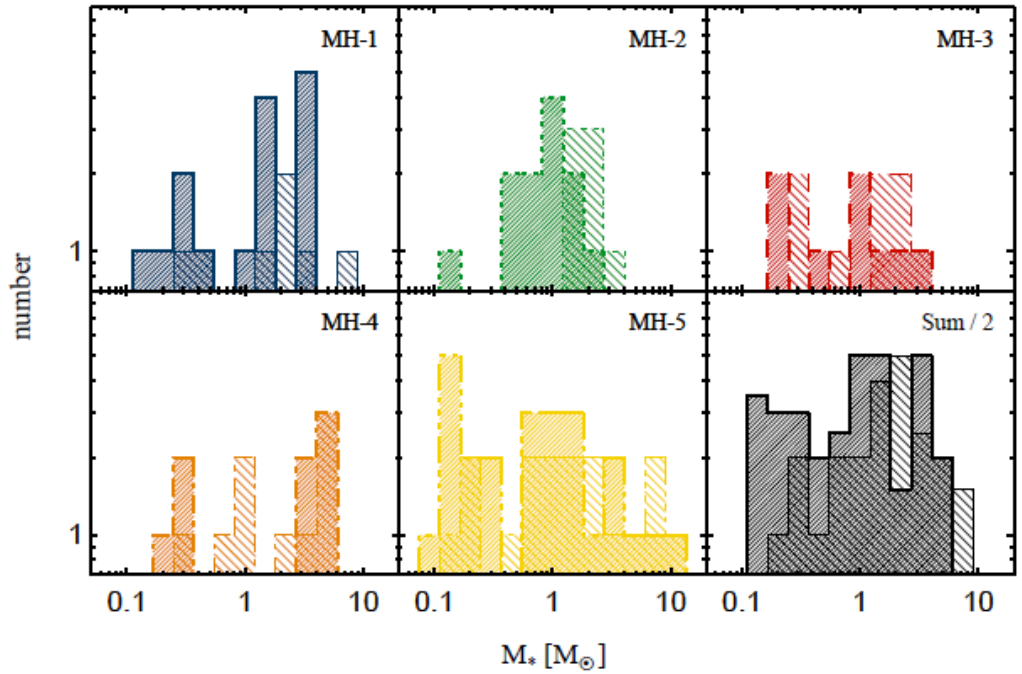
For dM/dt >∼ 1e-2, KH contraction phase disappears. → No UV feedback

Fragmentation @ r < 50AU

Fig. 1. Density evolution in a 120-AU region around the first protostar, showing the buildup of the protostellar disk and its eventual fragmentation. We also see "wakes" in the low-density regions, produced by the previous passage of the spiral arms.



Clark+ 2011

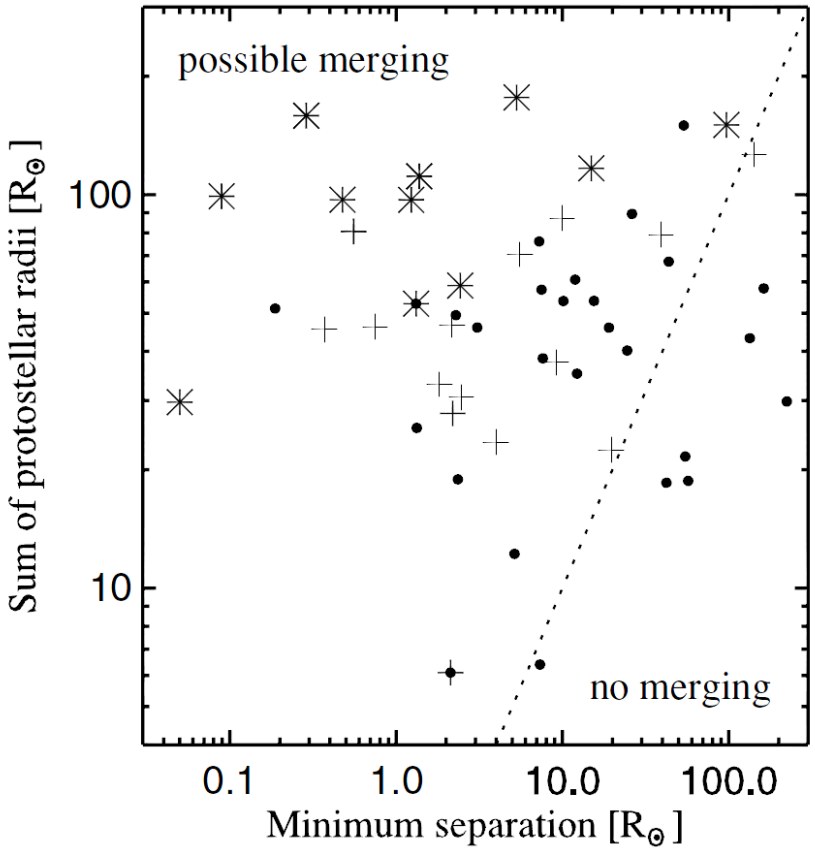


Greif+ 2011

- ～10 protostars
- But integrated time is too short to predict the final mass

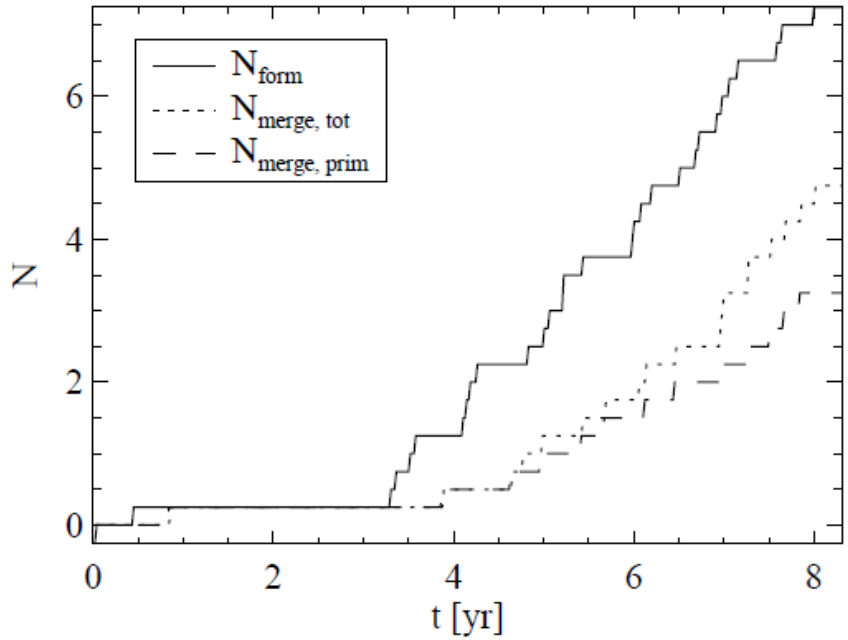
小さいスケールを分解するとそこでも同様に分裂する。

Merger of protostars



Greif+ 2011

星半径と最も近づいた時の関係
＊:　　M>3Msun
＋: 1Msun<M<3Msun
・:　　M<1Msun



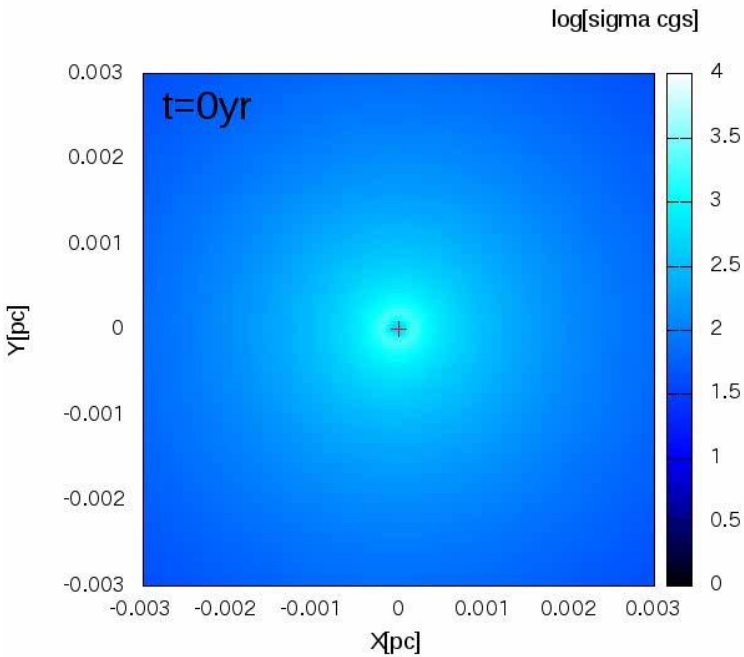
Greif+ 2012

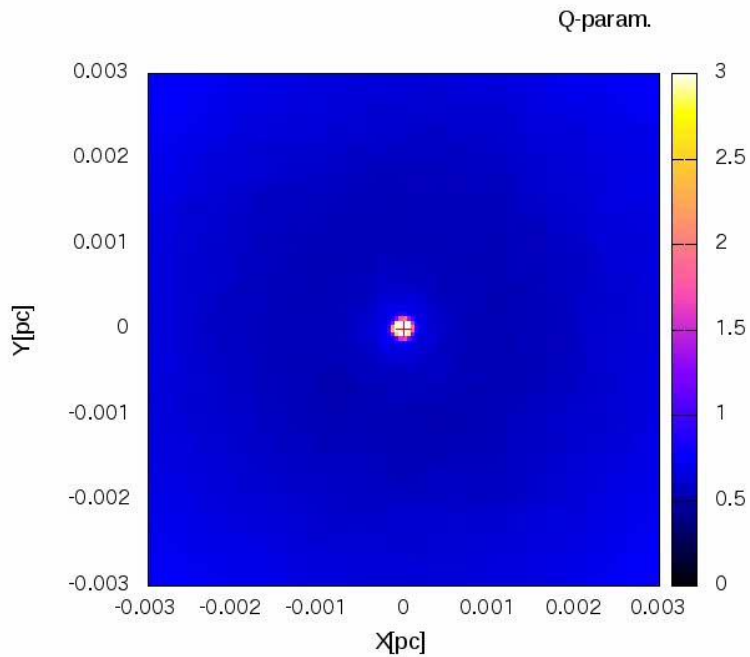
Sinkでない計算で、分裂片が合体した割合
合体しないのはおよそ1/3。
ただこの後分裂は続く。

3D(fragmentation)
RHD
Long term
High resolution

are needed

Fragmentaion of the disk (t <2000yr)





H2

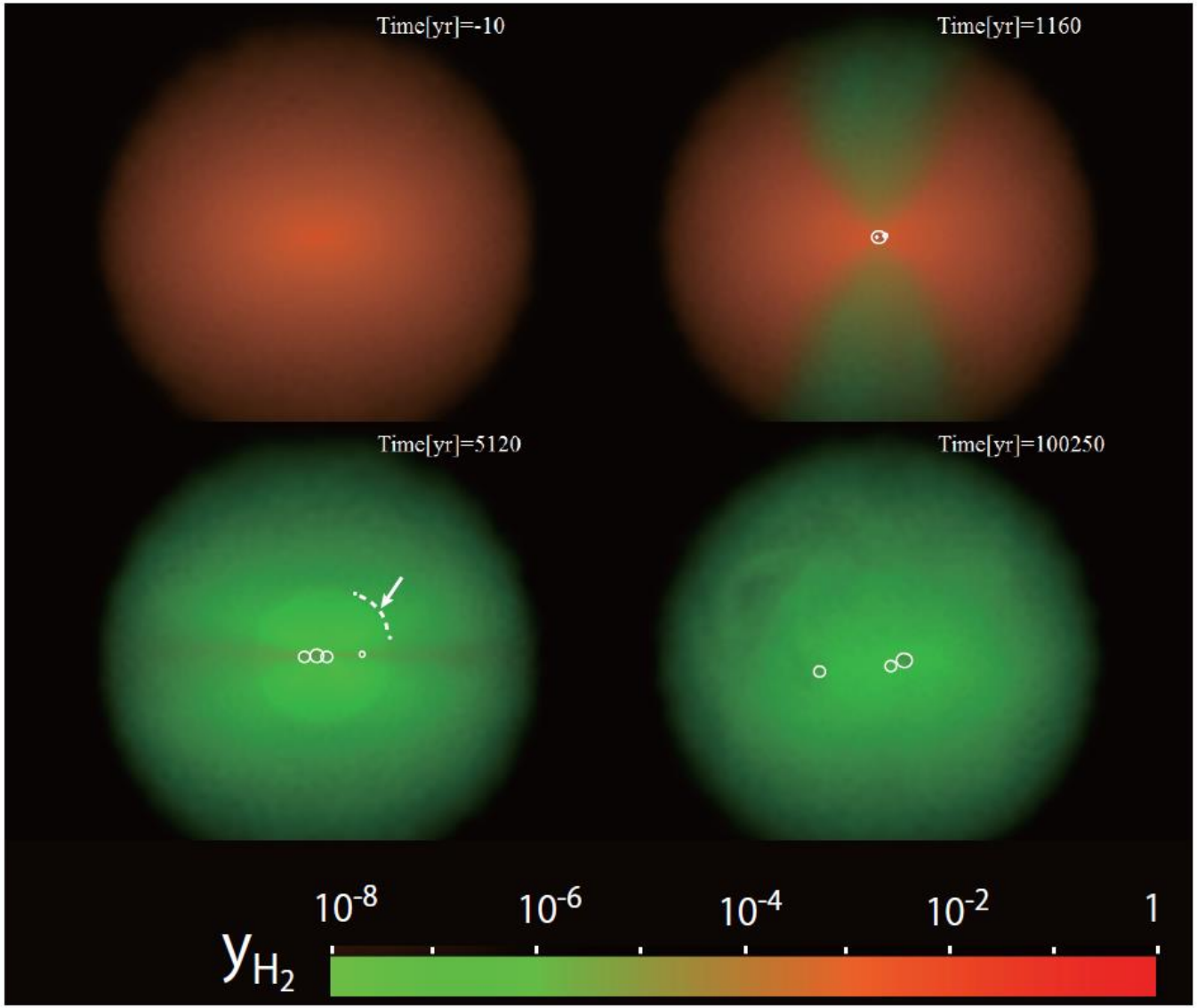
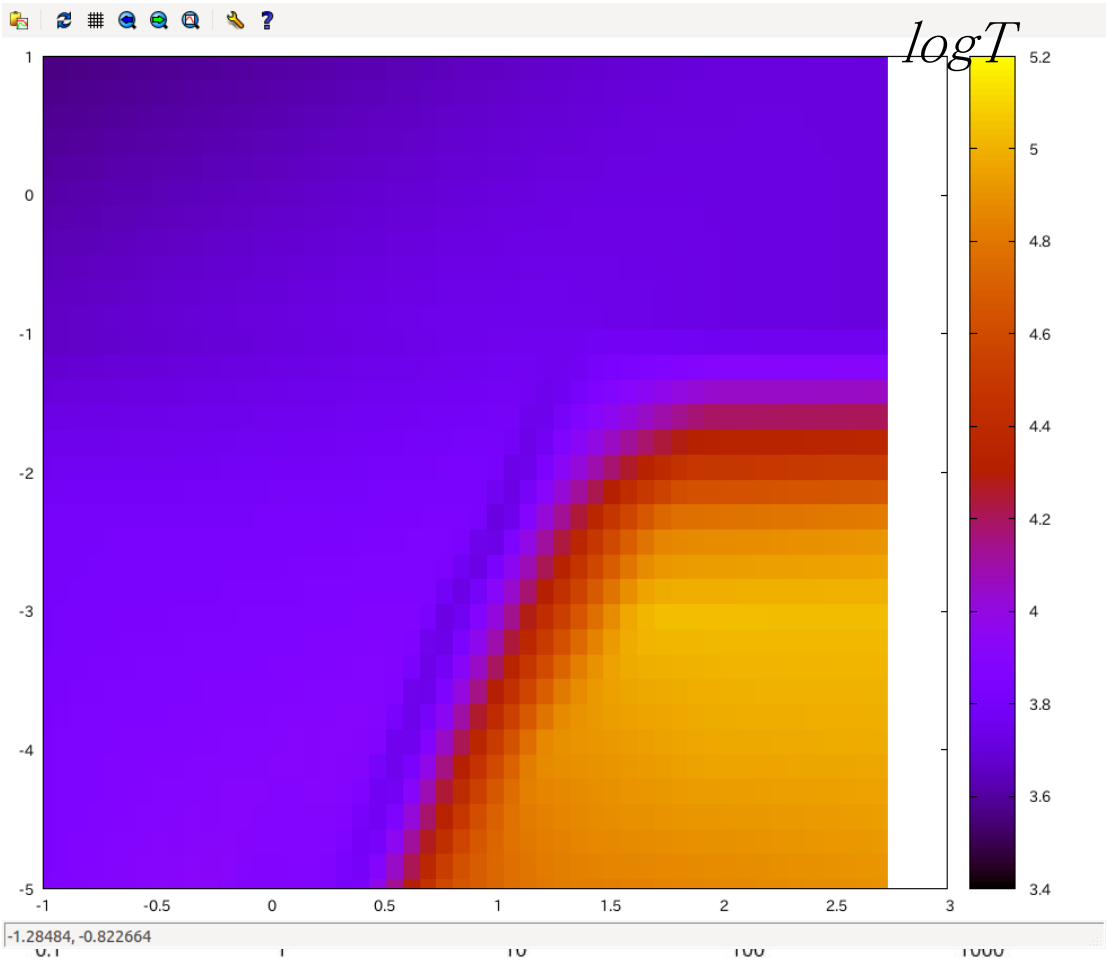


FIG. 2.— Edge-on views of gas distribution inside $r < 10^4$AU (0.05pc) at four snapshots. **Top row: from left to right, t =-10yr,1160yr. Bottom row:t = 5120yr, 100250yr. t represents the time after the first sink formation. Color shows the H_2 fraction, and the small spheres with white rim** represent the positions of sink particles. White arrow and dashed curve in the bottom left panel denotes the position of the shock front.

Protostellar evolution model

$\log(\dot{M})$



$\log(M / M_{sun})$

- Hosokawa numerical models dM/dt = 1e-5,1e-4,1e-3
- Hosokawa numerical model dM/dt = 4e-3 for M < 60Msun
- Analytic formula from Hosokawa & Omukai 2012 dM/dt > 1e-1

→ Interpolate

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) → $3H$ or $(2H+H_2)$: Cooling

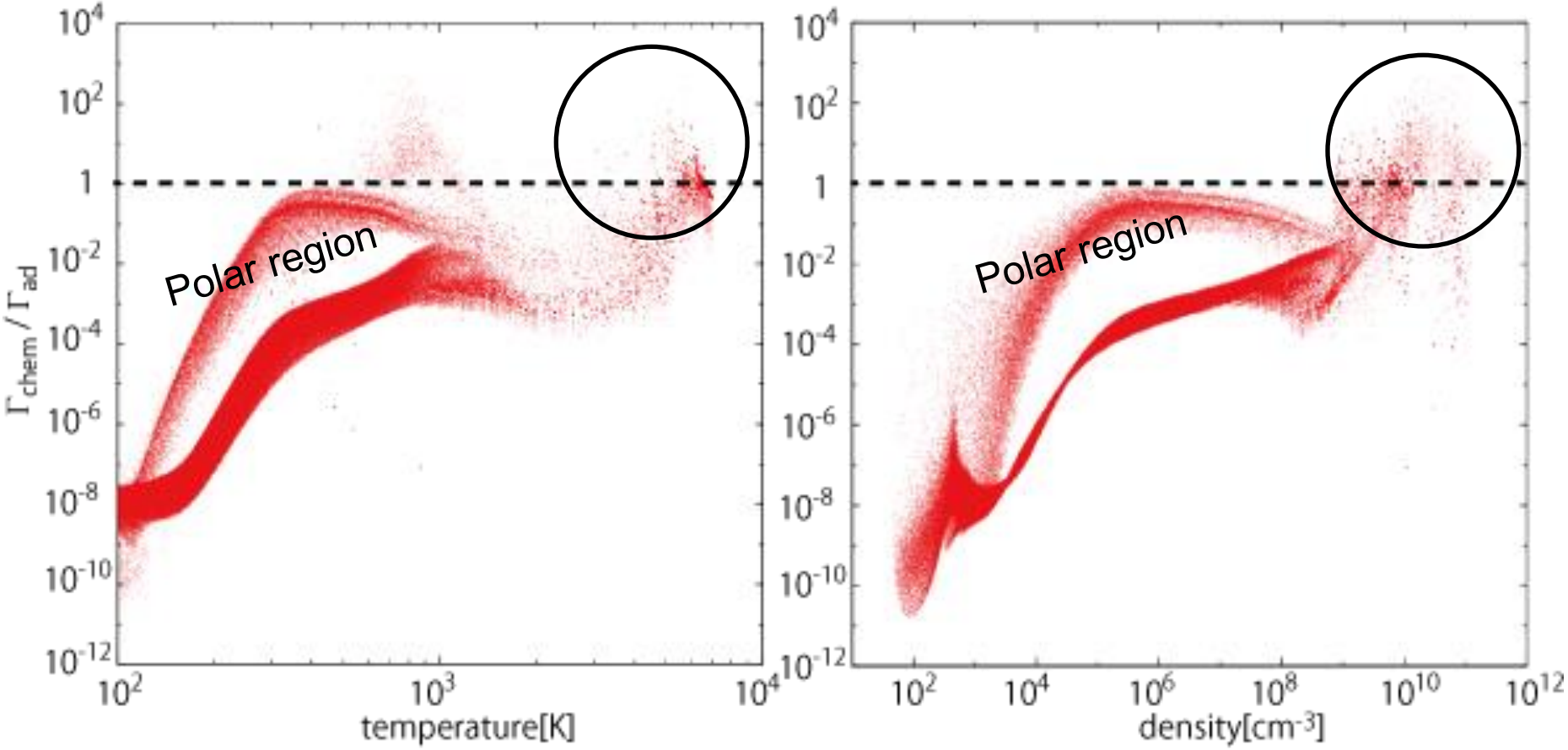
$3H \rightarrow H_2 + H$, $H+H^- \rightarrow H_2+e^-$: Heating

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

2step heating

Chemical Heating Rate

t=2030 yr



Photodissociation process is an important source of gas heating.

Evolution of sink mass

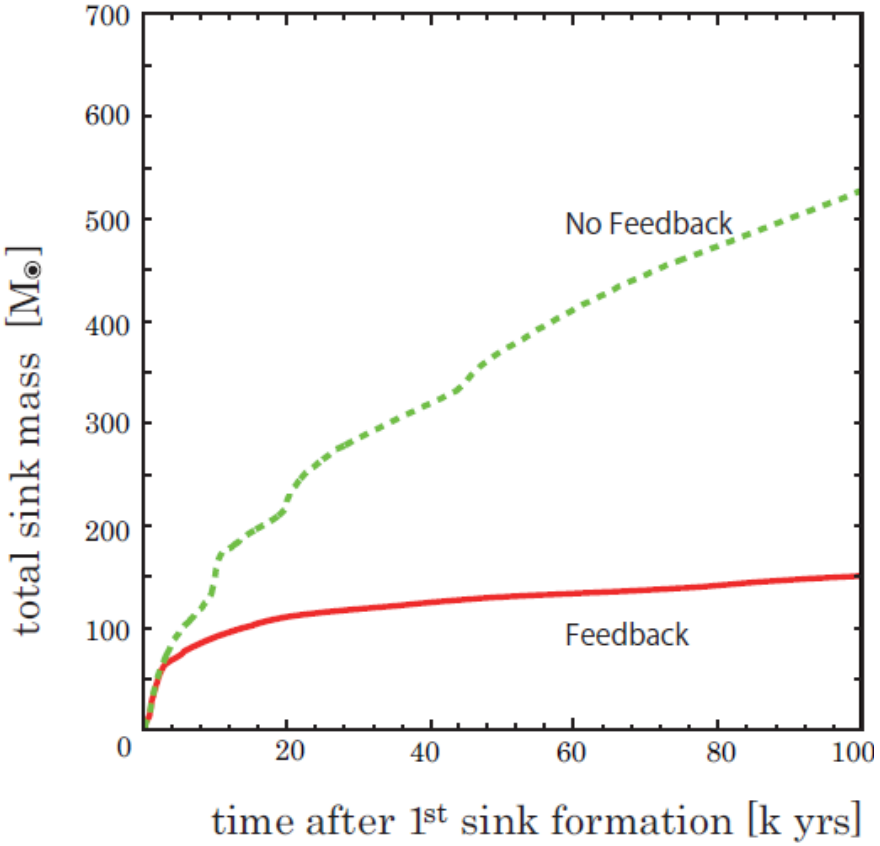


FIG. 4.— Evolution of the total mass incorporated in sink particles. The solid line corresponds to the case with feedback, while the dashed line represents the case without feedback.

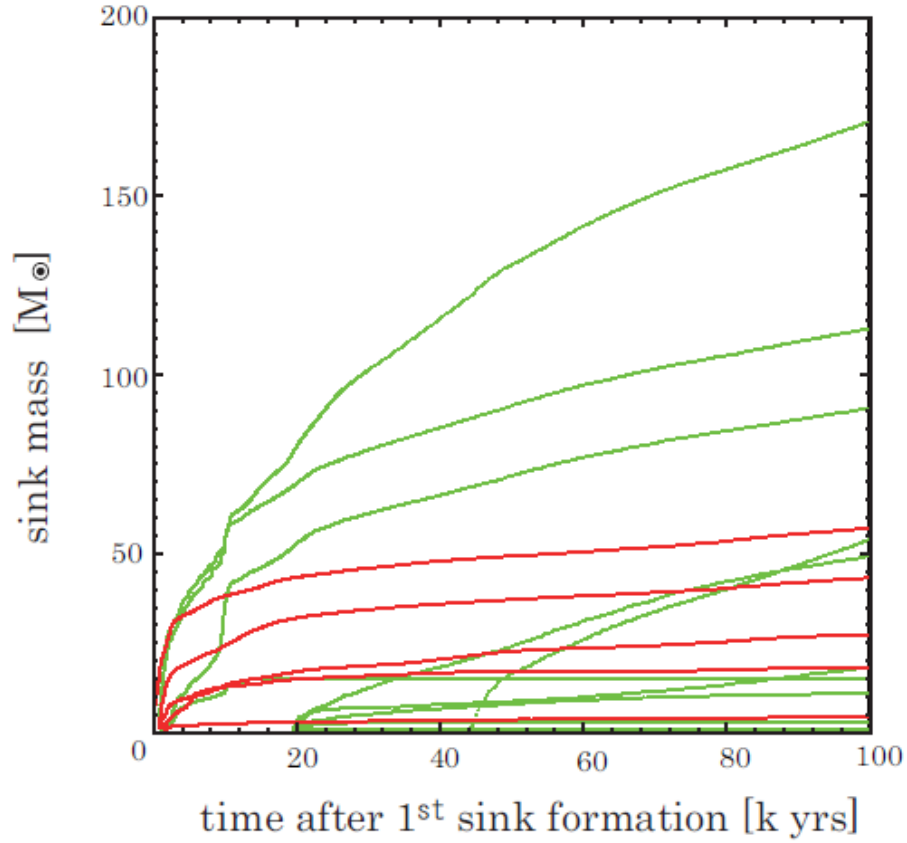


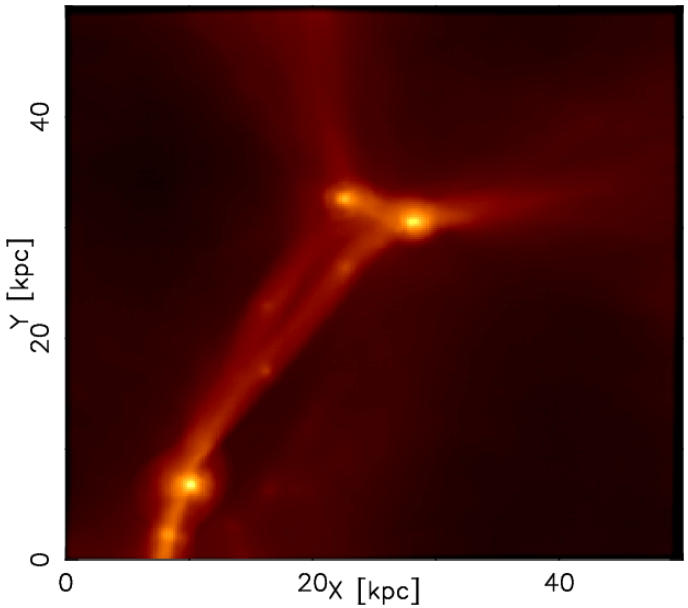
FIG. 5.— The mass of individual sink particles are plotted as functions of time after the first sink formation. Red curves for the runs with feedback, while the green curves for the case without feedback.

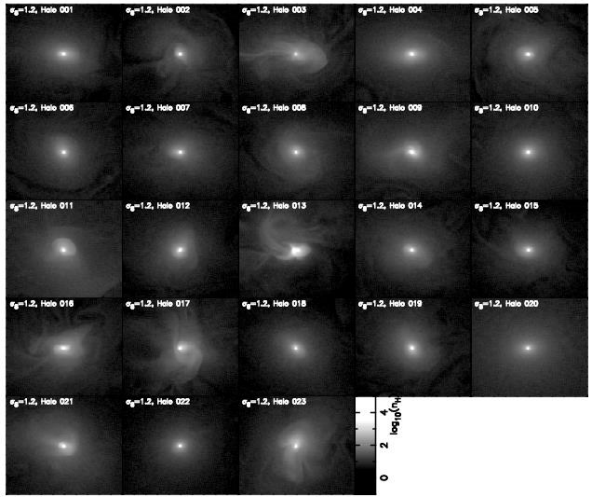
But this is the result of a realization of simplified initial condition,
we need more statistical argument by the cosmological simulations

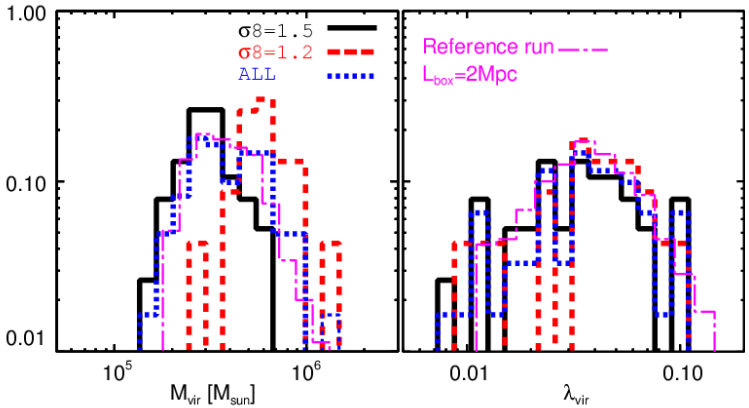
Cosmological Simulations

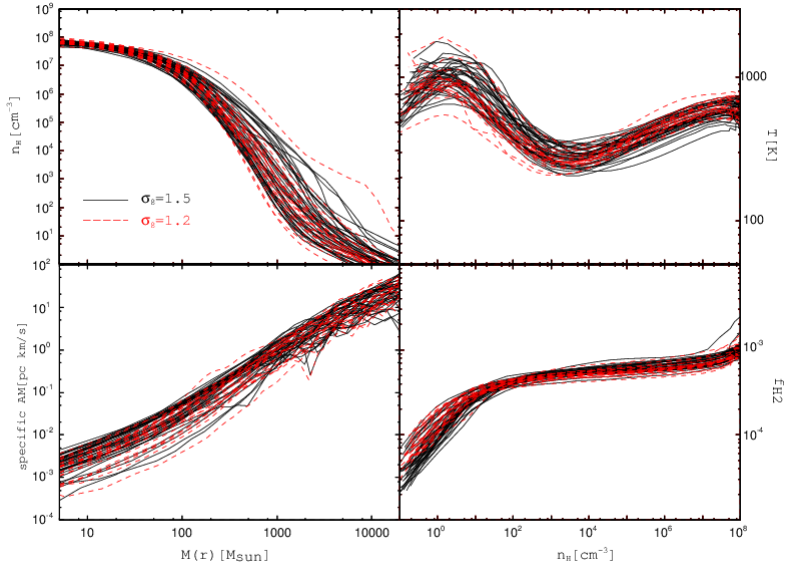
- Cosmological Run by Kenji Hasegawa on K.
- 100kpc box ～48 runs
- Sigma boosted (19runs:σ=1.2, 29runs:σ=1.5).
- 60 halos
- Trace up to n=1e8 cm-3
- Switch to local RHD simulation
- Particle splitting at the beginning of local simulation (1→10).
-

Pick up minihalos

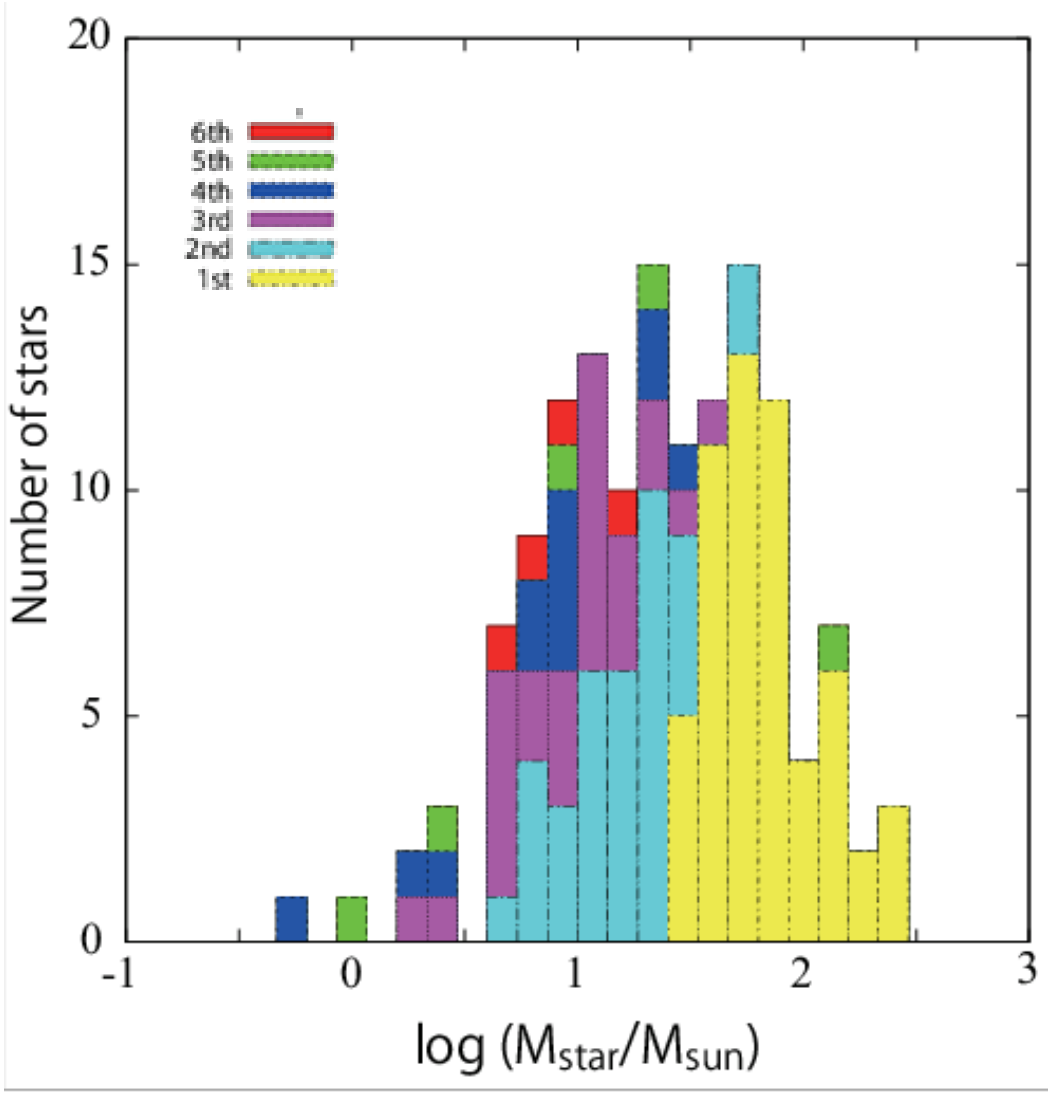


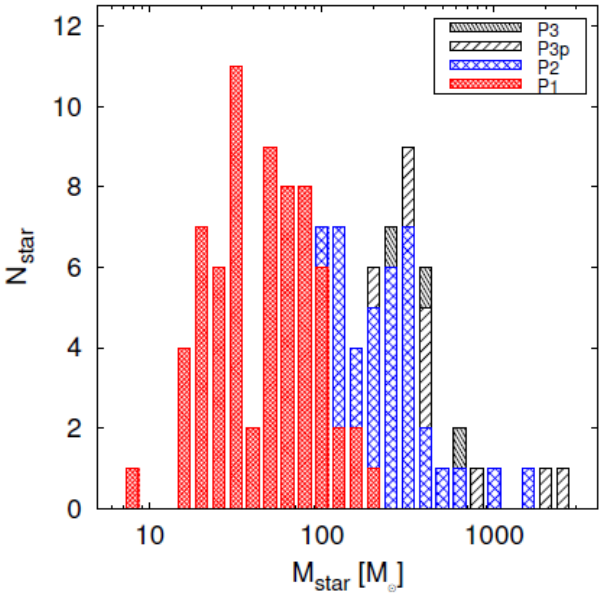






Sink Mass distribution

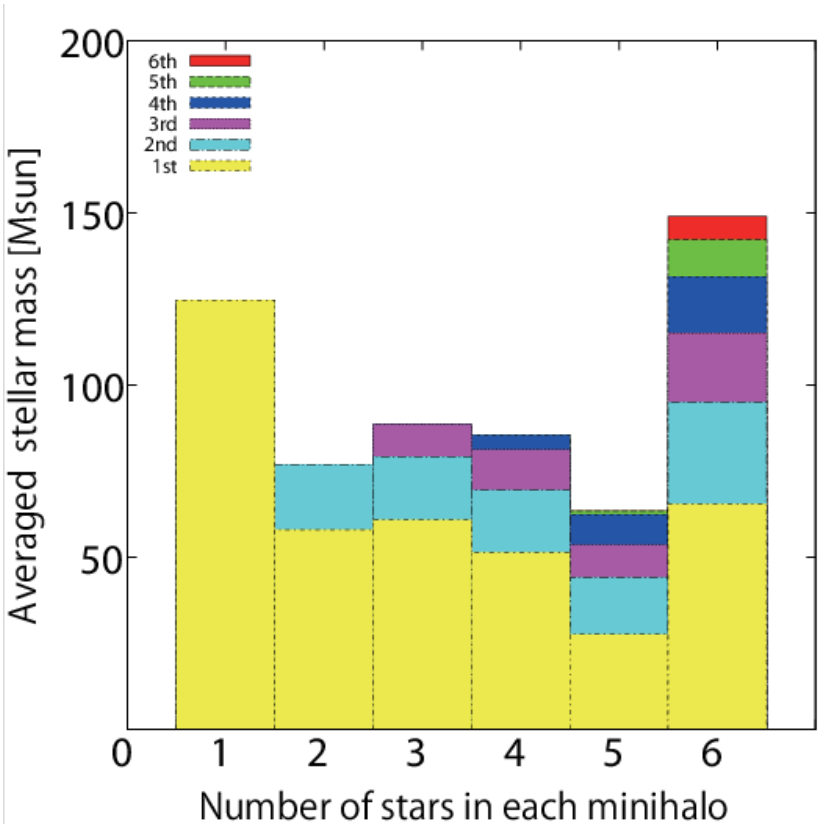




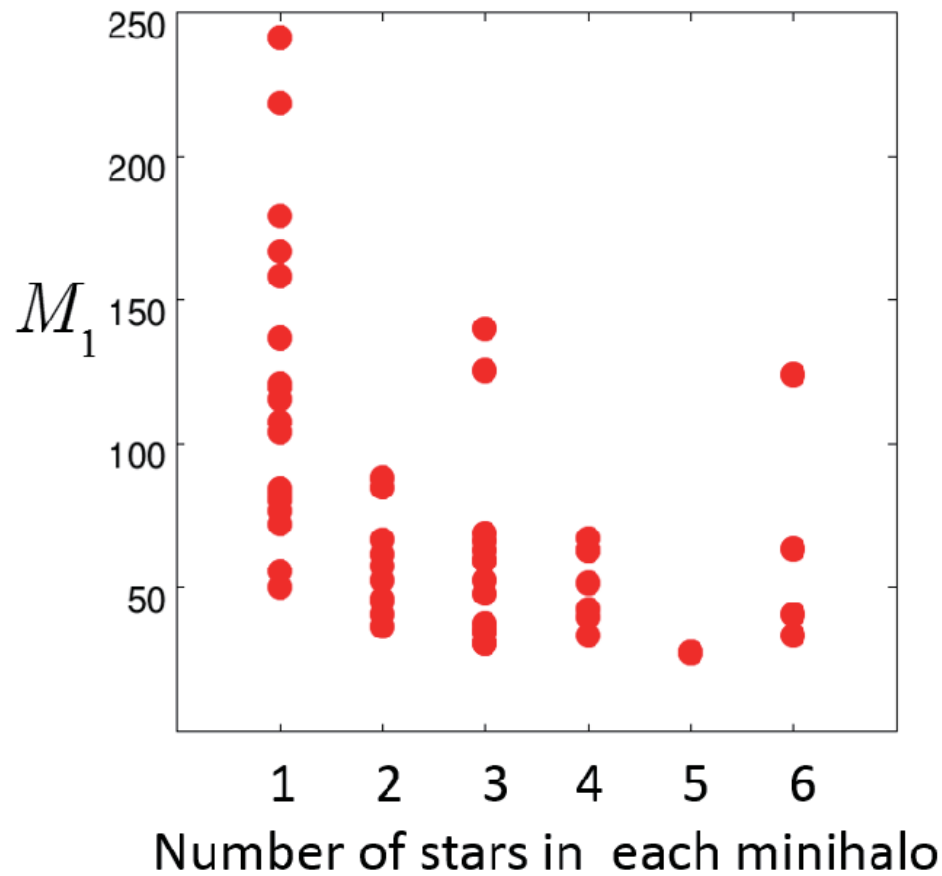
C.f. Hirano+2014

平野さん講演

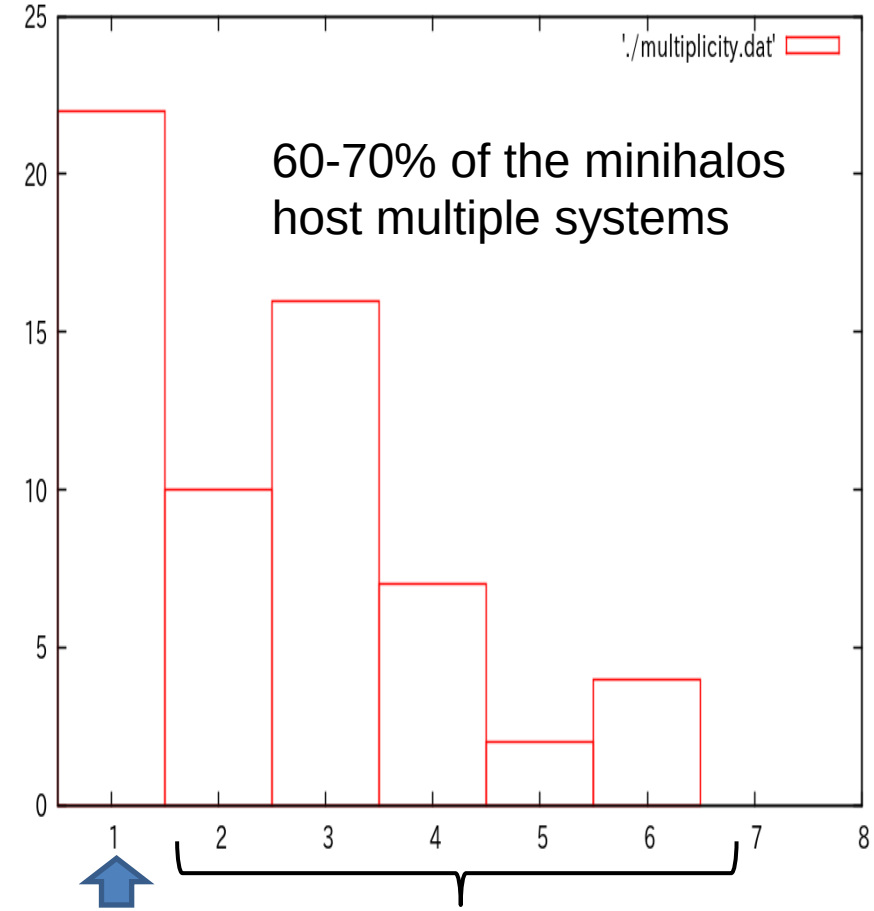
Mass budget in minihalos



Mass of the primary stars in minihalos

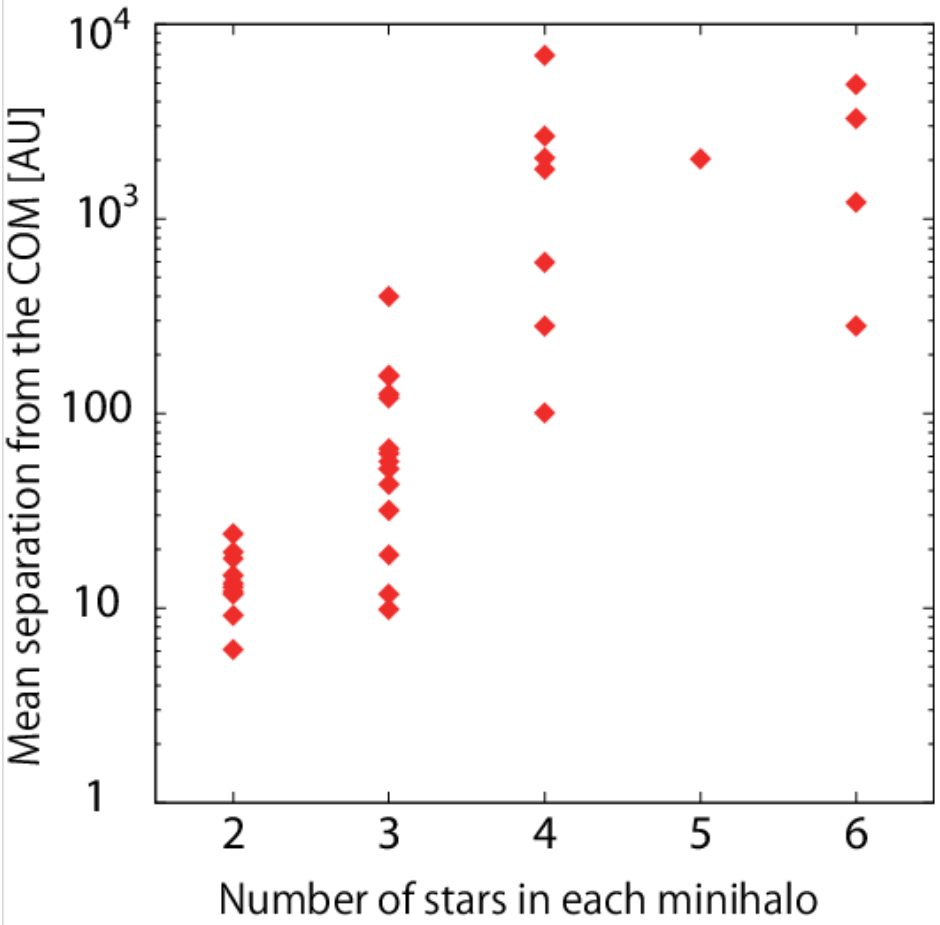


Frequency distribution of number of sinks in minihalos

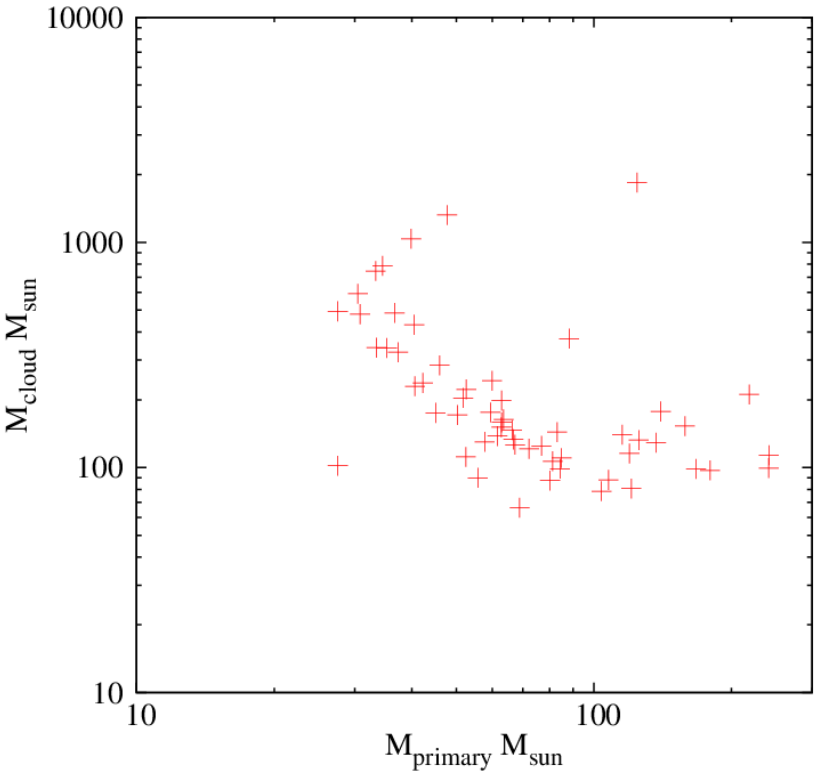


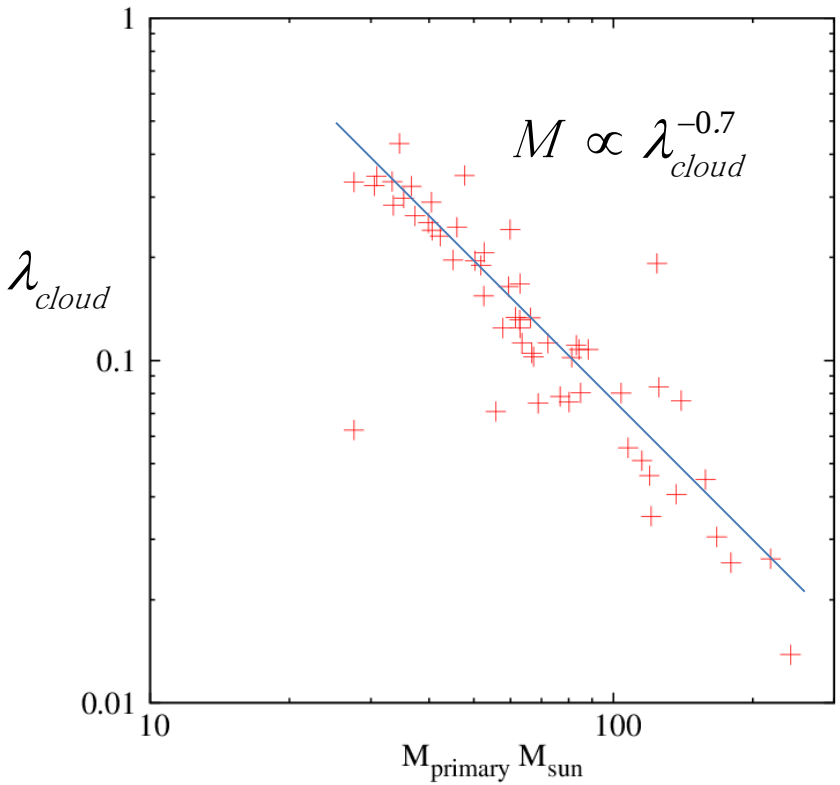
Single star Multiple system

Mean Separation from COM

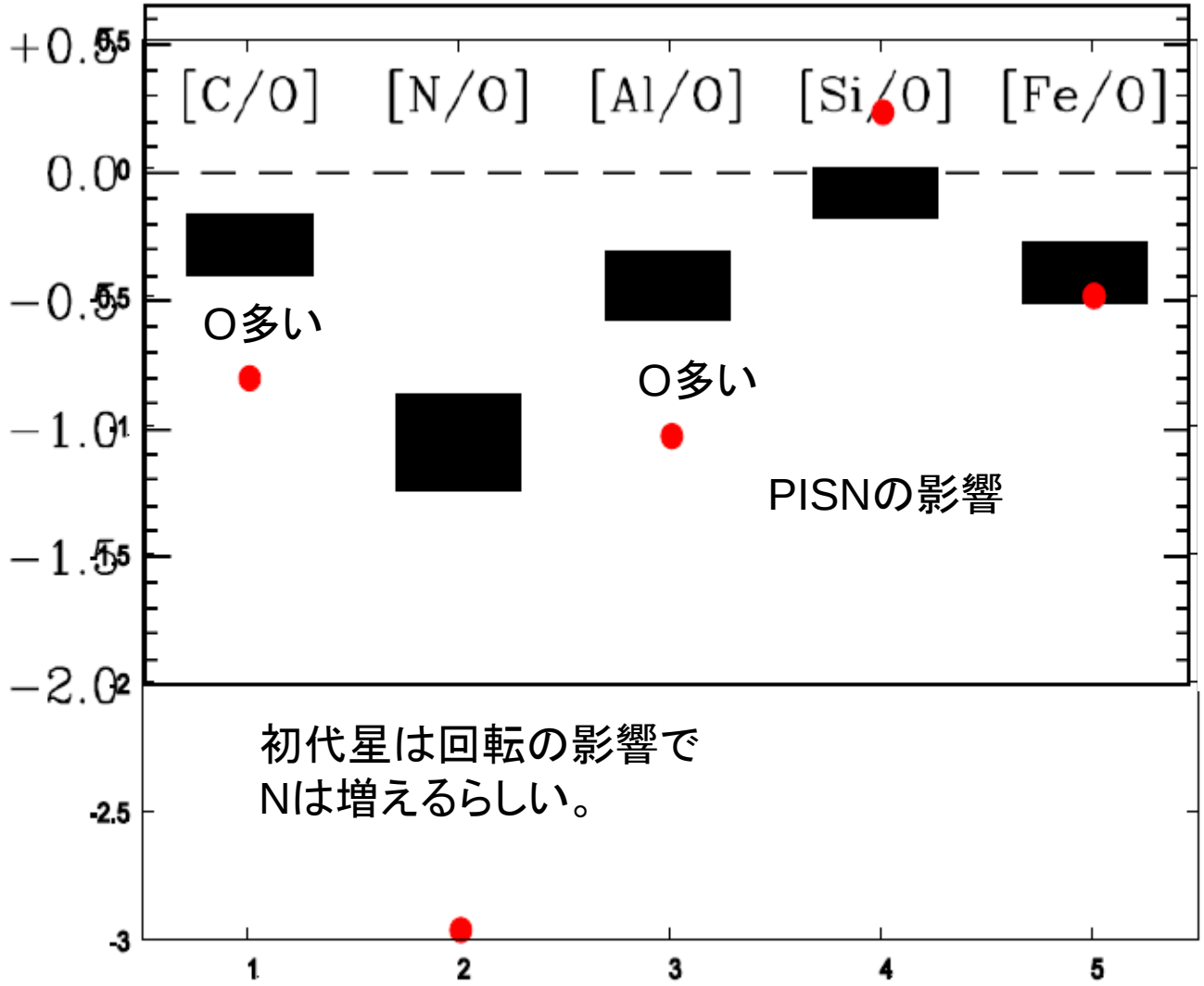


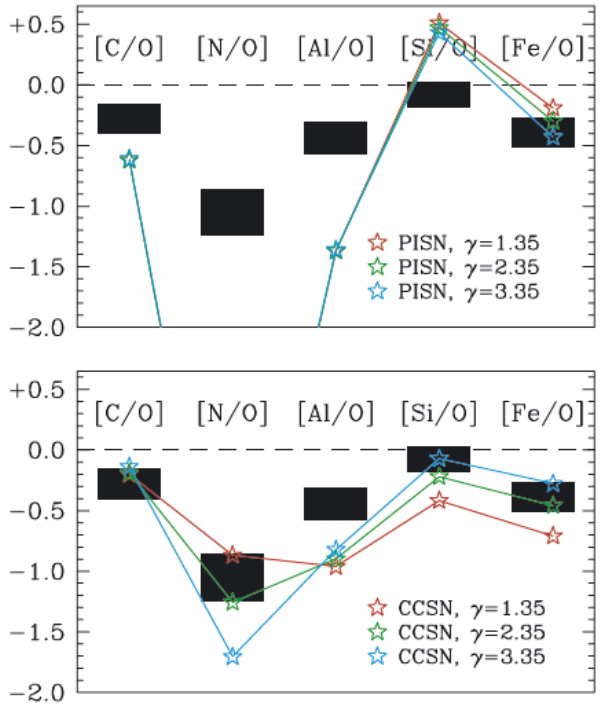
Mass of Primary Star v.s. cloud props.





アバンダンスパターン





全体に低質量側
にIMFがシフトする
と合うセンス

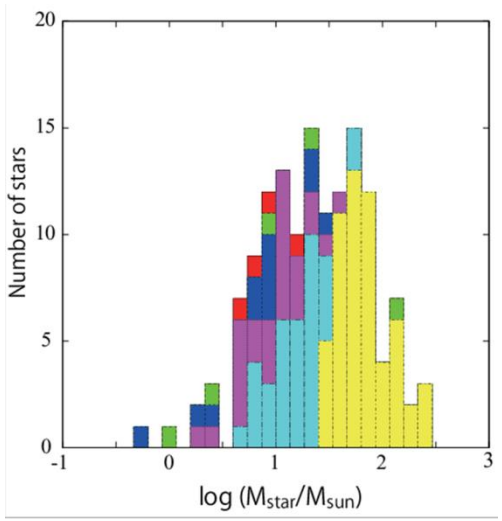
もっとも合うべきである
理由はない

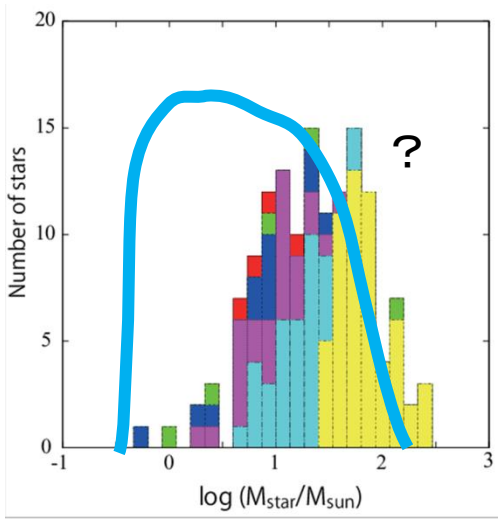
Cooke+11

7DLAs of Z <0.01Zsun

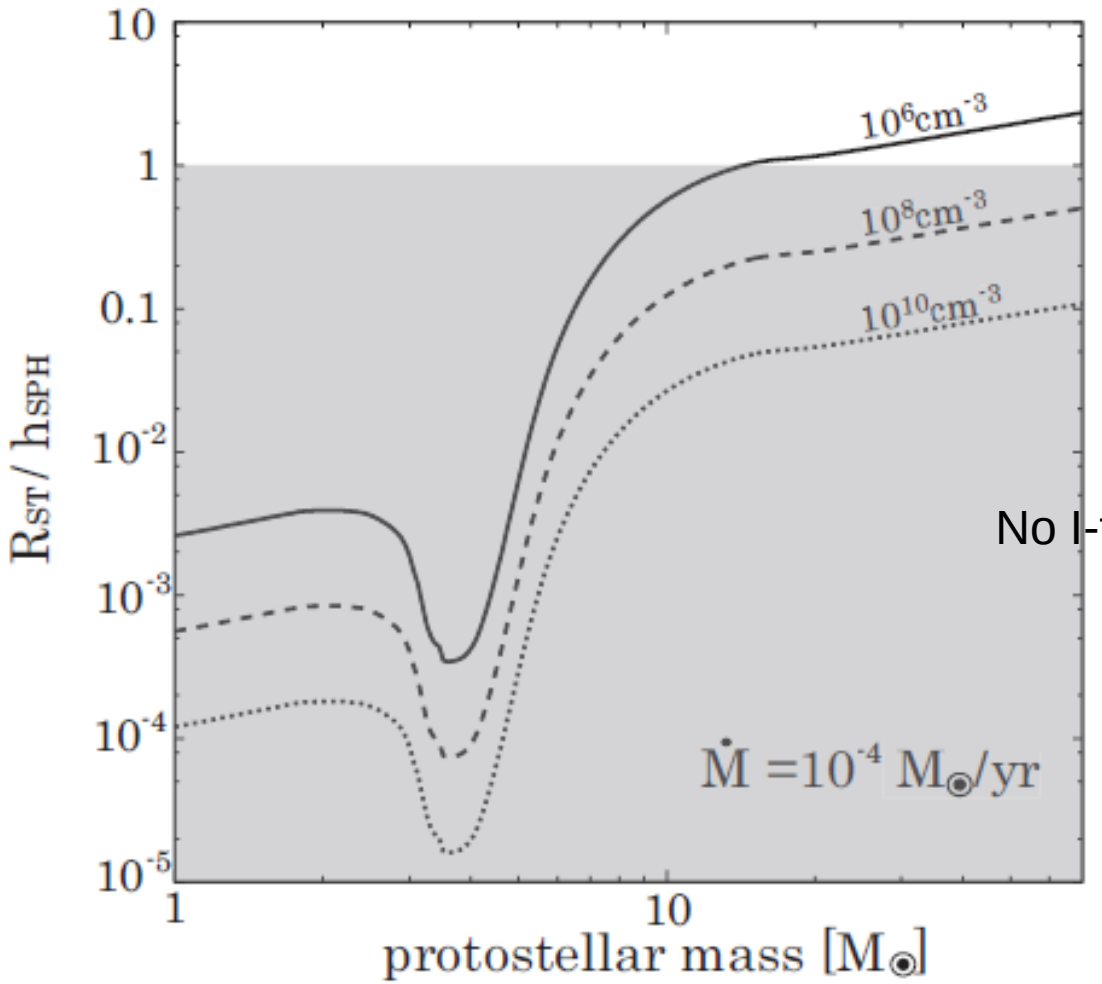
まとめ

- 1Msun<M < 300Msun.
- M～10-100Msun is the main part.
- Resolution issue
  - I-front breakout → Enhance the Feedback effect
  - Fragmentation at smaller scale (< 30AU) → Increase low mass stars?
  - Inner edge of the disk → Unknown
- Increase the number of low mass stars & reduce the upper bound ?





Stromgren Radius v.s. h_{SPH}



No I-front breakout

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

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. Thus, we underestimate the feedback effects in this simulation.

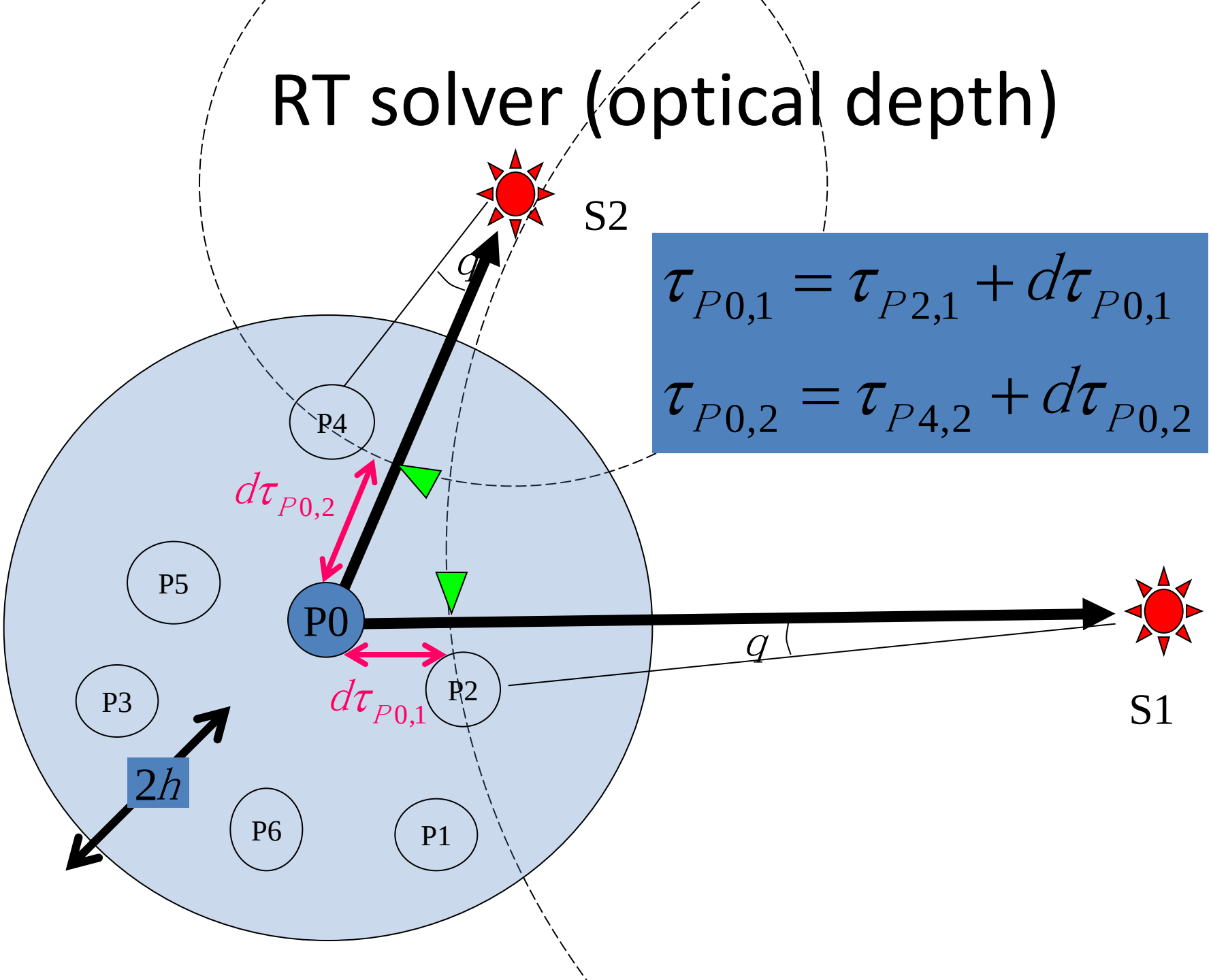
Both of two limitations enhance the mass of sink particles.
→ Obtained mass of sinks are regarded as an upper limit.

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

RT solver (optical depth)



$$\tau_{P0,1} = \tau_{P2,1} + d\tau_{P0,1}$$

$$\tau_{P0,2} = \tau_{P4,2} + d\tau_{P0,2}$$

dM/dt >0.1Msun/yr

$$R_* \simeq 26\, R_\odot \left(\frac{M_*}{M_\odot}\right)^{0.27} \left(\frac{\dot{M}_*}{10^{-3}\, M_\odot\, \mathrm{yr}^{-1}}\right)^{0.41}, \qquad (6)$$

$$L = \frac{GM\dot{M}}{R_*}$$

Accretion lum. ($M < M_{*,teq}$)

$$M_{*,\mathrm{teq}} \simeq 14.9\, M_\odot \left(\frac{\dot{M}_*}{10^{-2}\, M_\odot\, \mathrm{yr}^{-1}}\right)^{0.26}. \qquad (A1)$$

$$R_* \simeq 2.6 \times 10^3\, R_\odot \left(\frac{M_*}{100\, M_\odot}\right)^{1/2}. \qquad (11)$$

$$L_{\mathrm{Edd}}(M_*) \simeq 3.8 \times 10^6\, L_\odot \left(\frac{M_*}{100\, M_\odot}\right). \qquad (5)$$

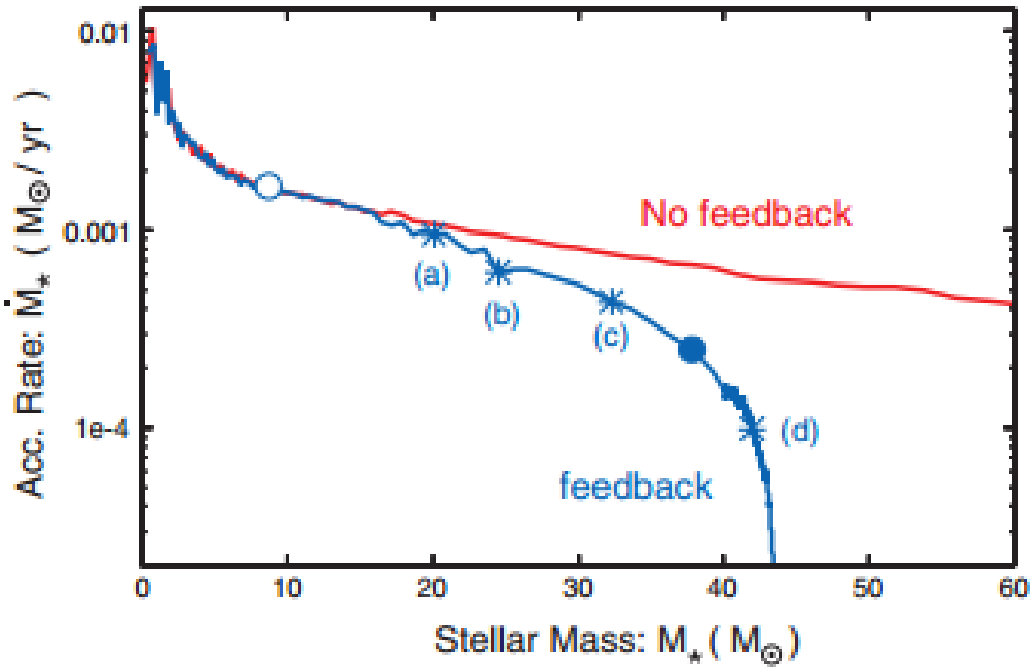
Eddington lum.($M > M_{*,teq}$)

質量降着期のシミュレーション

Feedback from protostar(s)

Hosokawa+2011

2D RHD



Stacy+2012

3D RHD

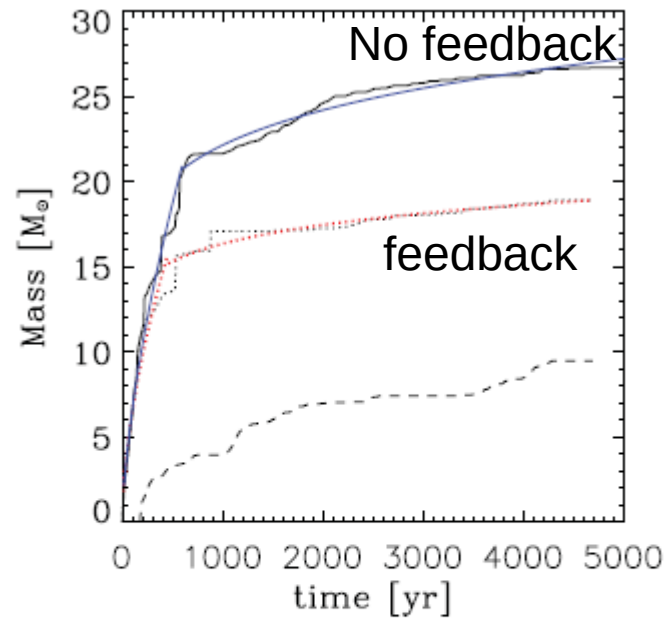


Figure 10. Effect of radiative feedback on protostellar accretion. Black solid line shows mass growth with no radiative feedback, while black dotted

~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.

UV Feedback by the protostars

Depth of gravitational potential around proto-stellar disk

$$\frac{GM}{r_{disk}} > f^{-2}\frac{GM_J}{r_J} = f^{-2}\frac{G\frac{4\pi}{3}r_J^3\rho}{r_J} = \frac{\pi^2\gamma f^{-2}}{3\mu_{env}m_p}kT_{env}$$

Corresponding temperature

$$kT > \frac{GMm_p}{r_{disk}} = \frac{\pi^2\gamma f^{-2}}{3\mu_{env}}kT_{env} = 9.2kT_{env} \Rightarrow 9200K\left(\frac{T_{env}}{10^3K}\right)$$

✓ If kT $\sim >$ 9200K, gas is photo evaporated

dM/dt >0.1Msun/yr

$$R_* \simeq 26\, R_\odot \left(\frac{M_*}{M_\odot}\right)^{0.27} \left(\frac{\dot{M}_*}{10^{-3}\, M_\odot\, \mathrm{yr}^{-1}}\right)^{0.41}, \qquad (6)$$

$$L = \frac{GM\dot{M}}{R_*}$$

Accretion lum. ($M < M_{*,teq}$)

$$M_{*,\mathrm{teq}} \simeq 14.9\, M_\odot \left(\frac{\dot{M}_*}{10^{-2}\, M_\odot\, \mathrm{yr}^{-1}}\right)^{0.26}. \qquad (A1)$$

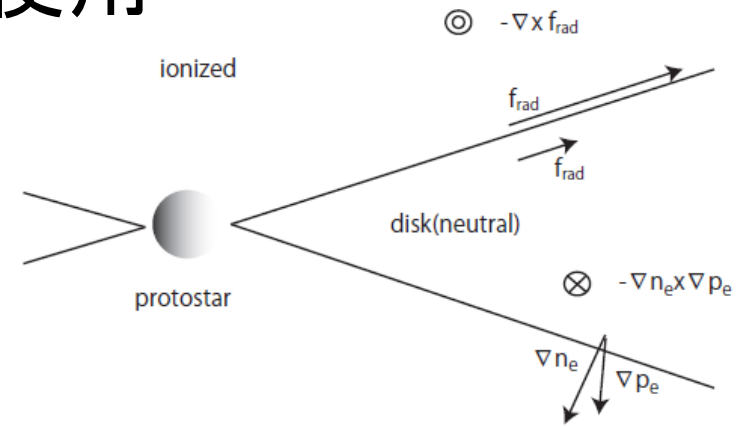
$$R_* \simeq 2.6 \times 10^3\, R_\odot \left(\frac{M_*}{100\, M_\odot}\right)^{1/2}. \qquad (11)$$

$$L_{\mathrm{Edd}}(M_*) \simeq 3.8 \times 10^6\, L_\odot \left(\frac{M_*}{100\, M_\odot}\right). \qquad (5)$$

Eddington lum.($M > M_{*,teq}$)

初代原始星周りの磁場生成

- 細川計算を背景として使用
- ポストプロセス

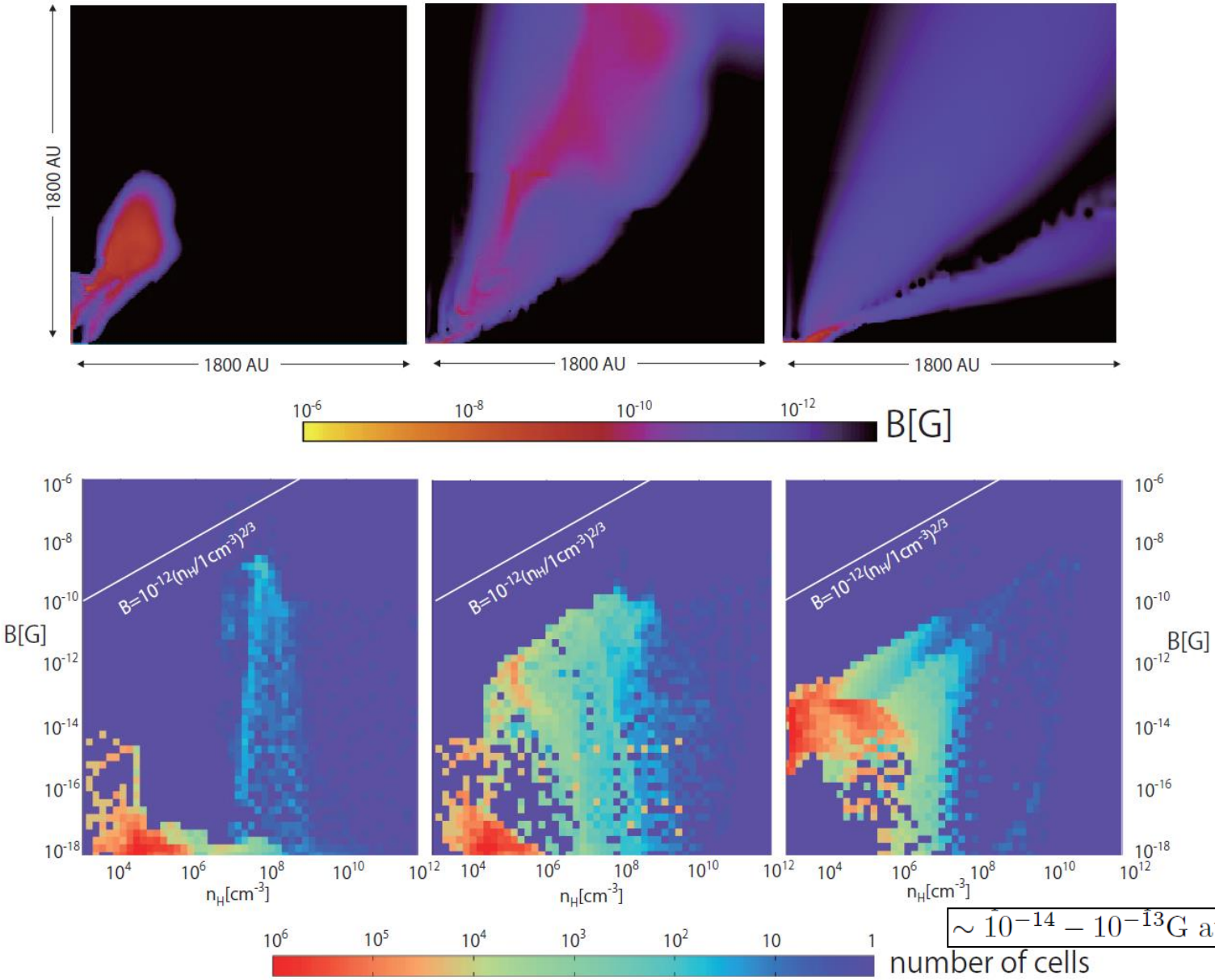


- 微弱磁場の生成を計算する

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B) - \frac{c}{e n_{\rm e}^2} \nabla n_{\rm e} \times \nabla p_{\rm e} - \frac{c}{e} \nabla \times f_{\rm rad}$$

Shiromoto, Susa, Hosokawa 2014

微弱磁場の発展



$\sim 10^{-14} - 10^{-13}\mathrm{G}$ at $n_\mathrm{H} = 10^3\mathrm{cm}^{-3}$