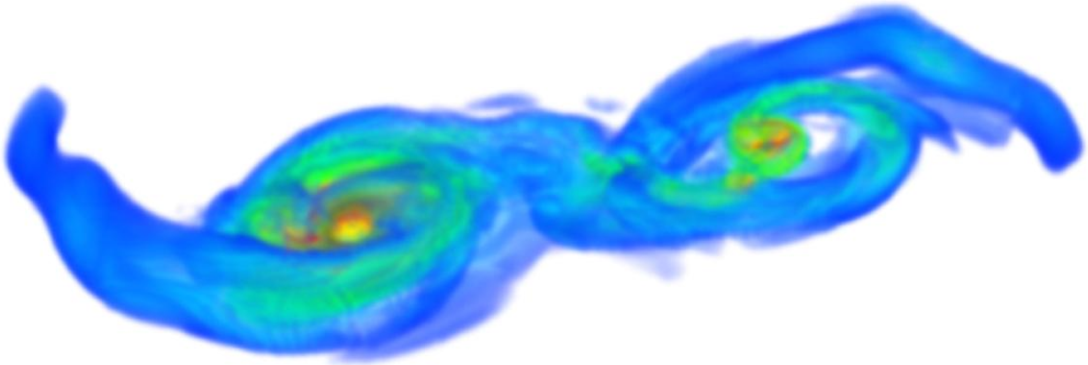
YKIS2019@YITP
Oct 10

binary star formation at low metallicities



Kazuyuki Omukai
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+ a lot of collaborators

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Tohoku University
古換再新青葉山

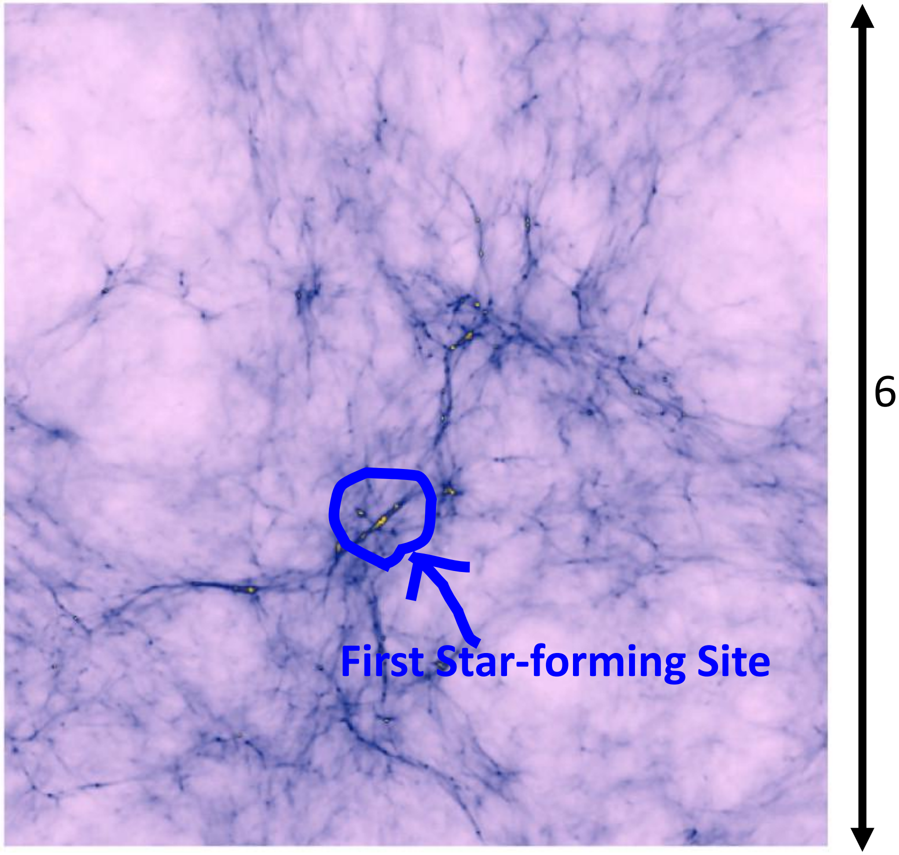
Contents

- First Star Formation
- First Binary Formation
- Metallicity Effect
- Toward MHD simulation:
  correct treatment of ionization degree

First Star Formation

First Star Forming Sites

ΛCDM cosmology
Simulate starting from the density fluctuations
up to the formation of first object



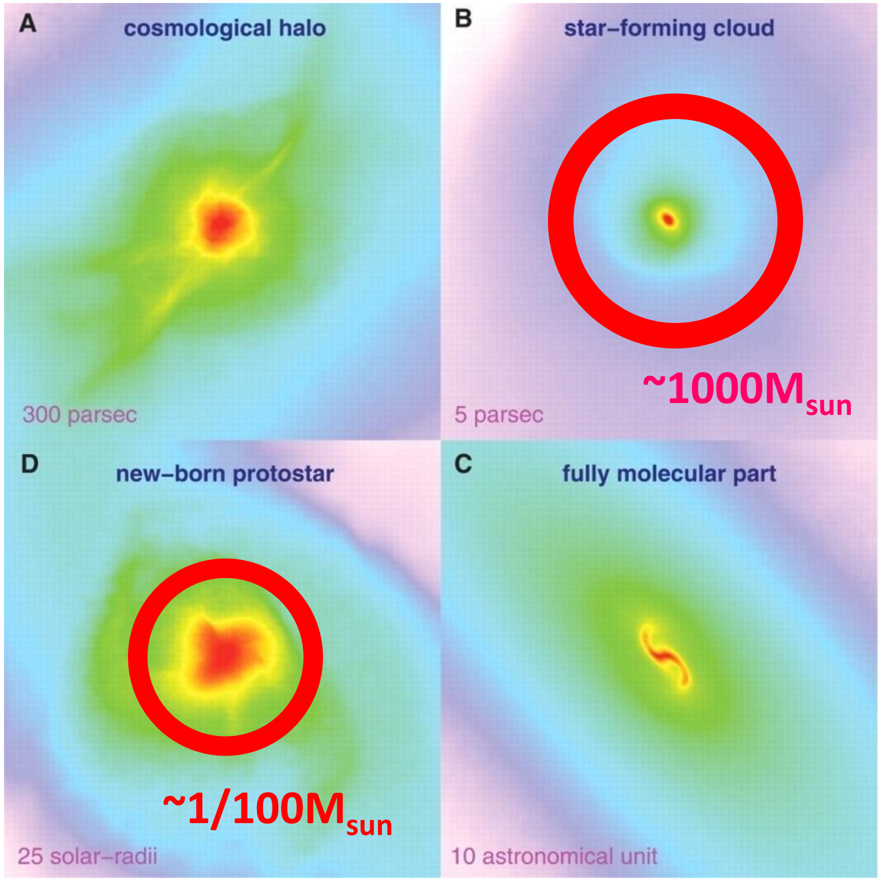
First Objects to form stars:
small halos with
virial temperature T_{vir} > 1000K
（minihalos ~$10^6 M_{sun}$, z~20-30）

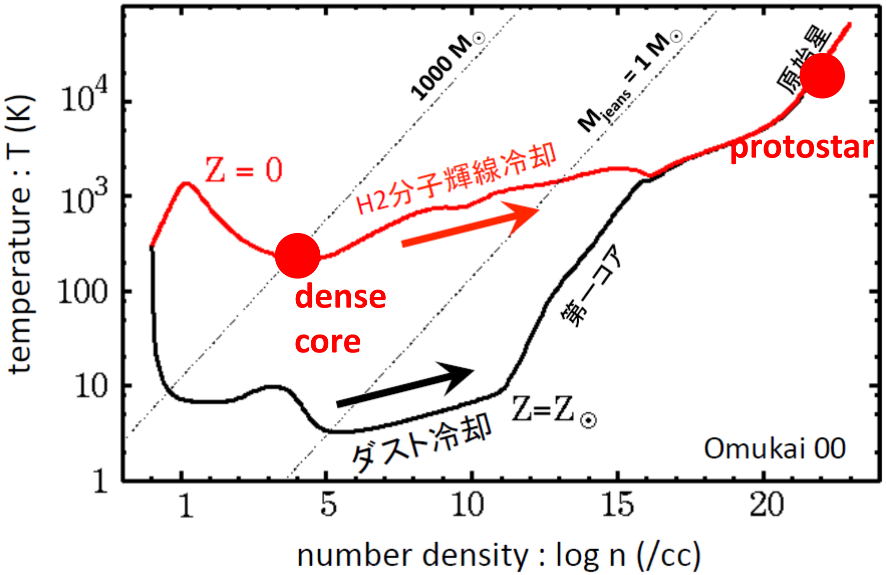
the gas in which cools by
H_2 line emission and
become denser

➔Star formation

Yoshida, Abel, Hernquist & Sugiyama (2003)

Birth of the first protostar



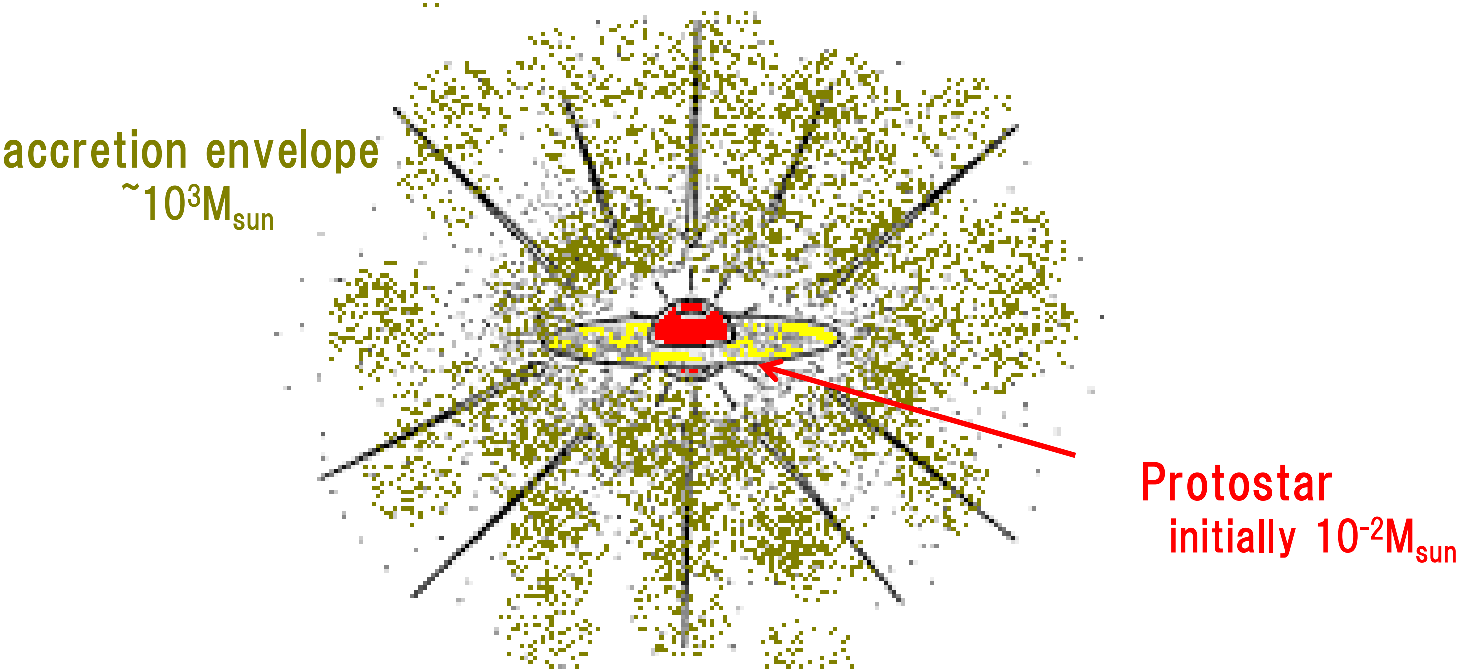


- **Dense core** (~1000M_{sun}) forms at ~10^4cm^{-3}

- **Hydrostatic protostar** (initial mass ~$10^{-2}M_{sun}$) forms at ~10^{21}cm^{-3}

Yoshida, KO,
Hernquist 2008

Protostellar mass accretion rate



$$\dot{M} \cong M_J / t_{ff} \cong (c_s t_{ff})^3 \rho / t_{ff}$$

$$\cong c_s^3 / G \propto \mathrm{T}^{3/2}$$

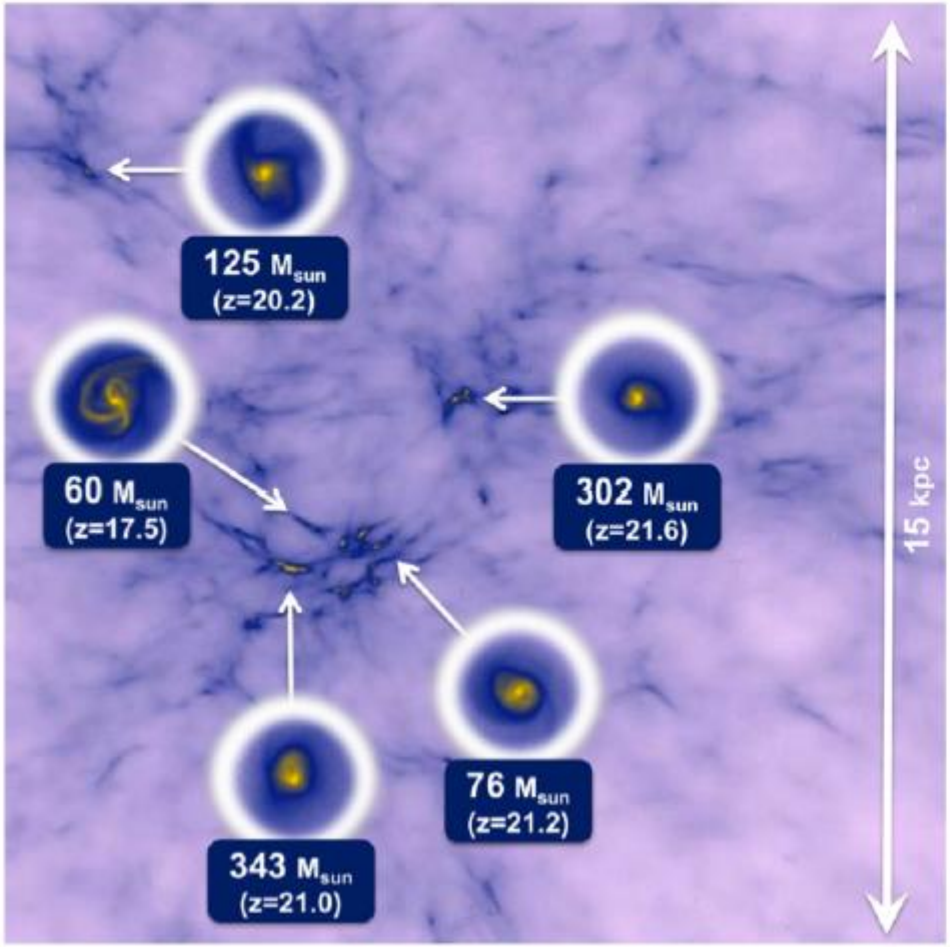
Pop I (10K) ~$10^{-6} M_{sun}$/yr,
Pop III (1000K) ~$10^{-3} M_{sun}$/yr

Much higher accretion rate in Pop III star formation

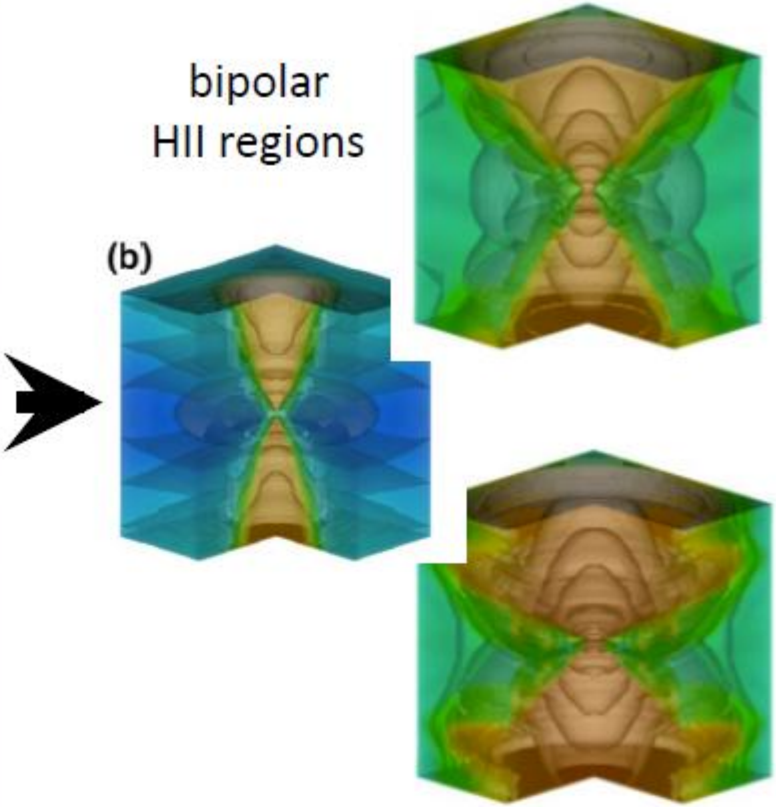
UV feedback sets the final stellar mass

3D cosmological simulation
+2D radiation hydro simulation
for star formation

Hirano et al. (+KO)
2014, 2015 studied
hundreds of halos.



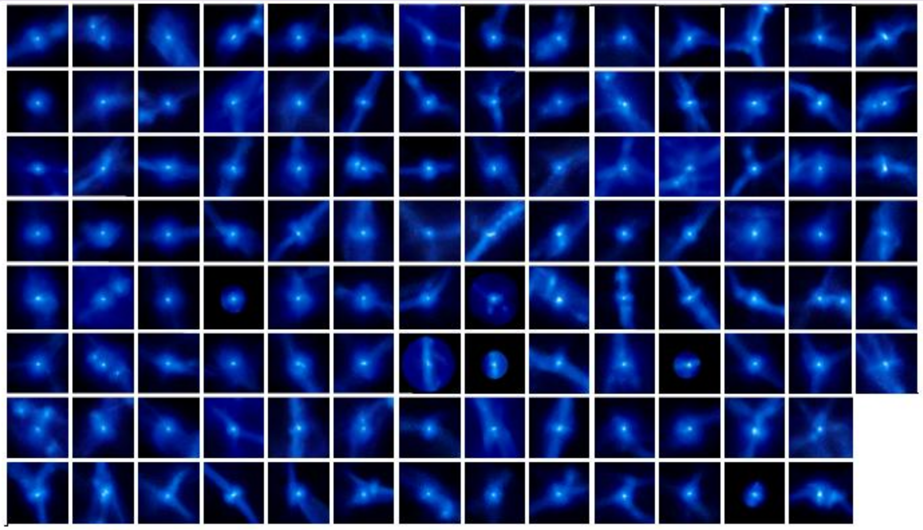
bipolar
HII regions

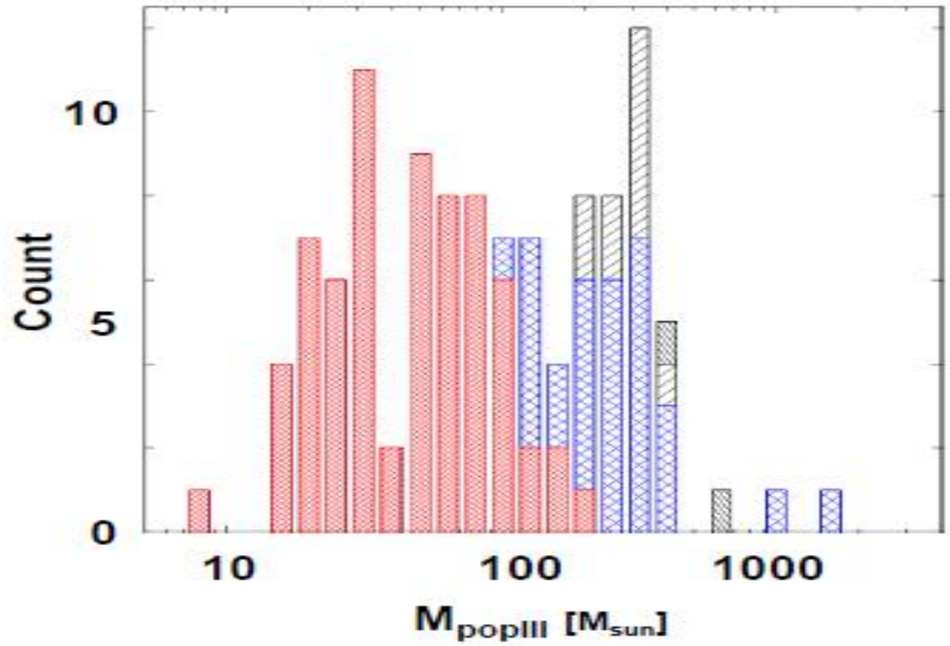


The UV feedback finally shuts off the mass accretion in all the cases

Pop III IMF

Hirano et al. (+KO) 2014, 2015





✓with wide mass range: a few 10s- 100s M_{sun}

✓Even 1000M_{sun} first stars can be formed

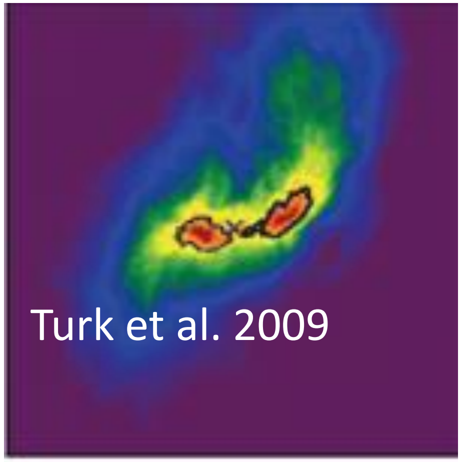
But, 2D simulation:
→ no binary
by construction

First Binary Formation

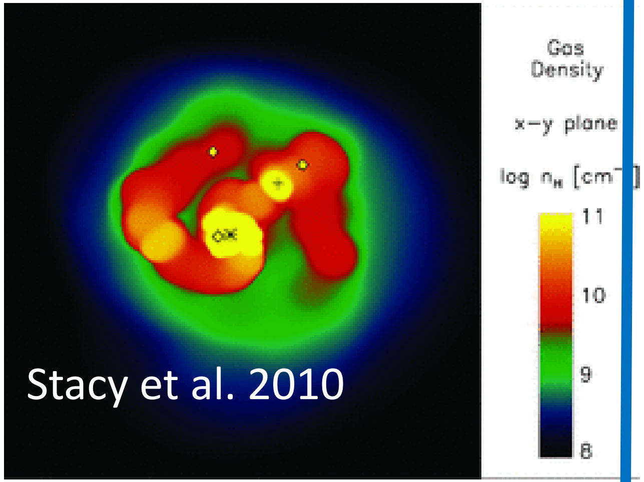
Some first stars were also binaries

fragmentation during the collapse

("turbulent fragmentation")

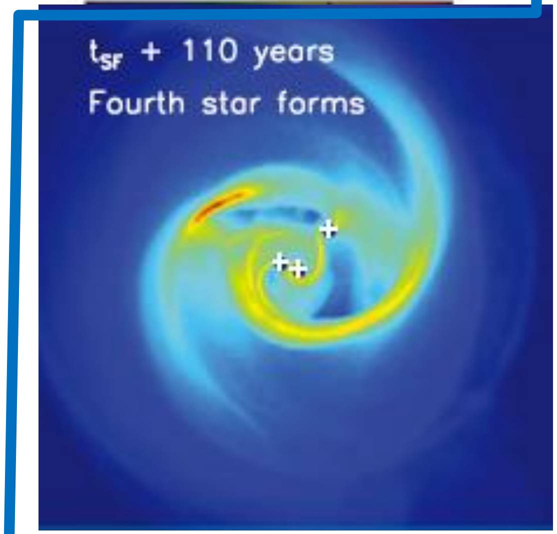


Turk et al. 2009

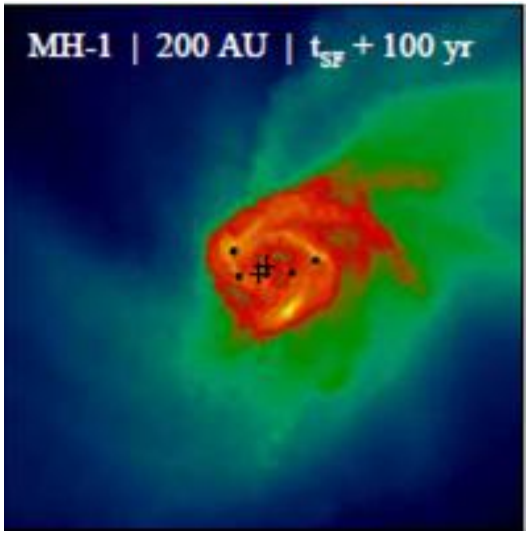


Stacy et al. 2010

From 2009 onward, it becomes known that binaries/multiples are formed in the first star formation.



Clark et al. 2011



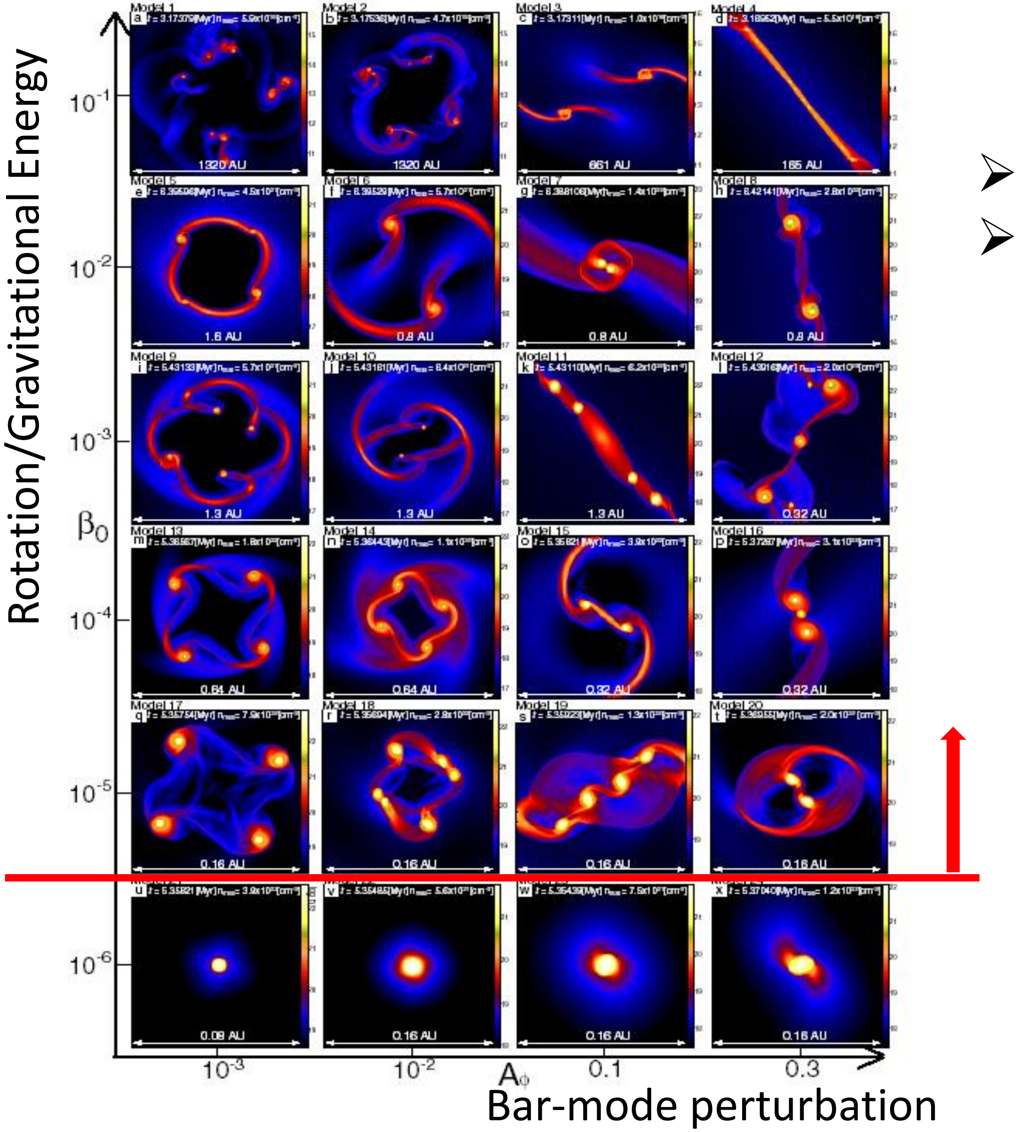
Greif et al. 2011

fragmentation of circumstellar disk after protostar formation

("disk fragmentation")

Earlier work on first binary formation

Machida, KO+ 2008



- ➢barotropic EOS from one−zone model
- ➢idealistic initial condition:
  - ➢BE sphere ($10^3 cm^{-3}$)
  density x 1.01 (α_0=0.83)
  - ➢Rotation β_0
  - ➢Perturbation (bar A_φ + m=3)

All the cores with some rotation (β_0> 10^{-6} - 10^{-5} fragment.

More prone to fragmentation than present-day

Radiative feedback in 3D

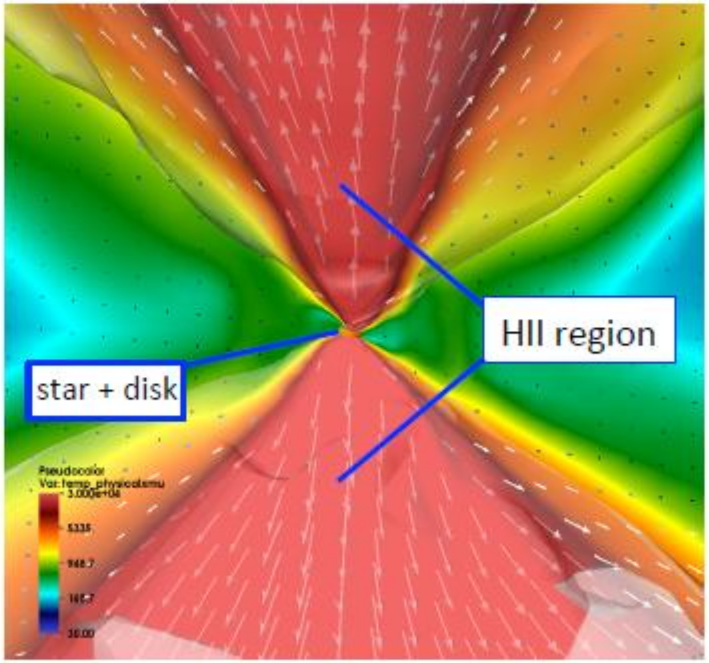
Hosokawa + (KO) 2016

Public multi-D MHD code: PLUTO (e.g., Mignone et al. 07)

A modified version developed for studying present-day high-mass star formation (R.Kuiper+10 etc.)
+ self-gravity + FLD solvers

+

- UV radiation transfer + chemistry
- Stellar evolution (Yorke & Bodenheimer 08)
- Cosmological initial condition (Hirano+14)



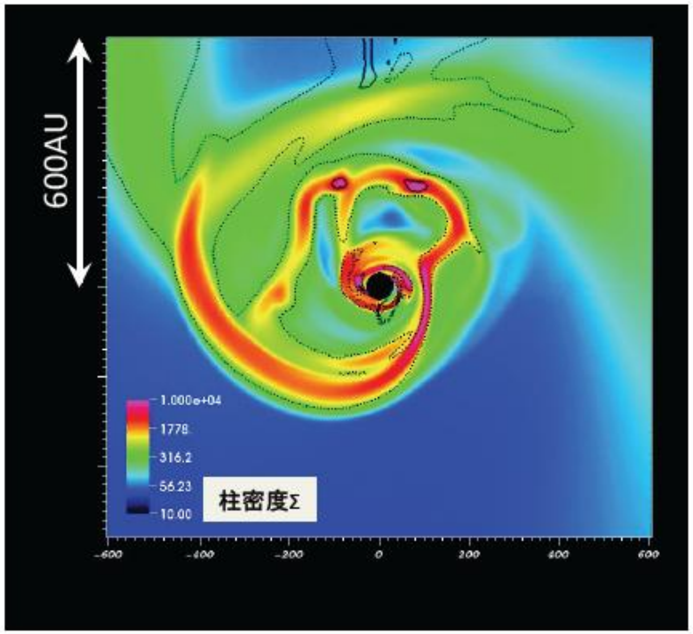
polar coordinate + central sink (radius of 30AU and spatially fixed)

Follow the long-term (～10^5 yrs) evolution
with ionizing (EUV) and dissociating (FUV) feedback in 3D

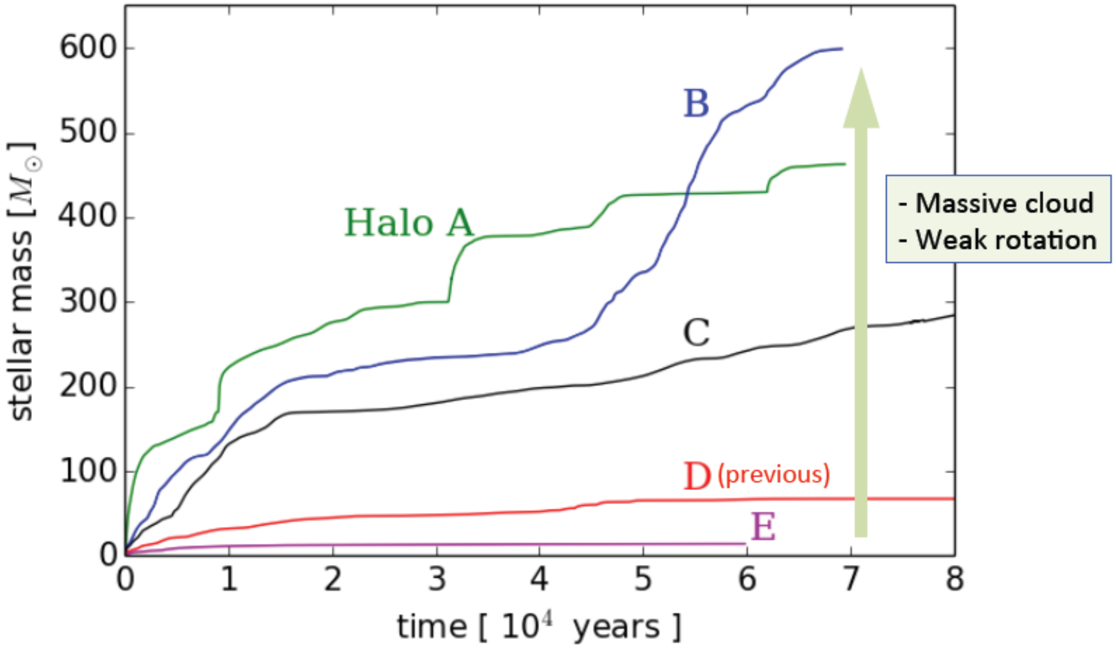
fragmentation and migration…

Hosokawa + (KO) 2016

Evolution over ～100 yrs



Contour: Toomre Q parameter
solid: Q=0.1, dotted: Q=1.0

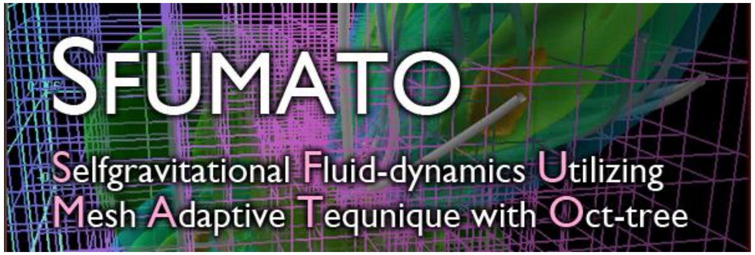


The central star grows very massive
before the UV feedback shut off the accretion.

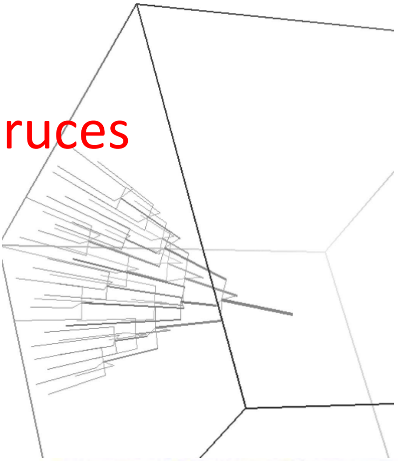
But, radiation comes only from the central source.
→ massive binary formation remains unexplored.

Multi-source simulation in AMR

Sugimura +(KO). in prep.



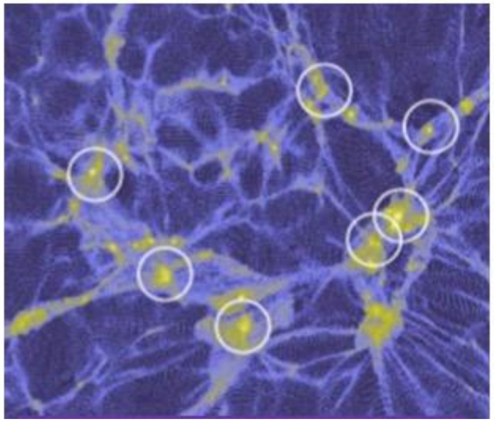
AMR + (M)HD + self-gravity
+ sink particle method
(Matsumoto 07 etc.)



+ adaptive ray-tracing (ART) method for multiple soruces
(e.g., Abel & Wandelt 02; Rosen et al. 2017)
of EUV (H ionizing) & FUV (H2 dissociating) rad.

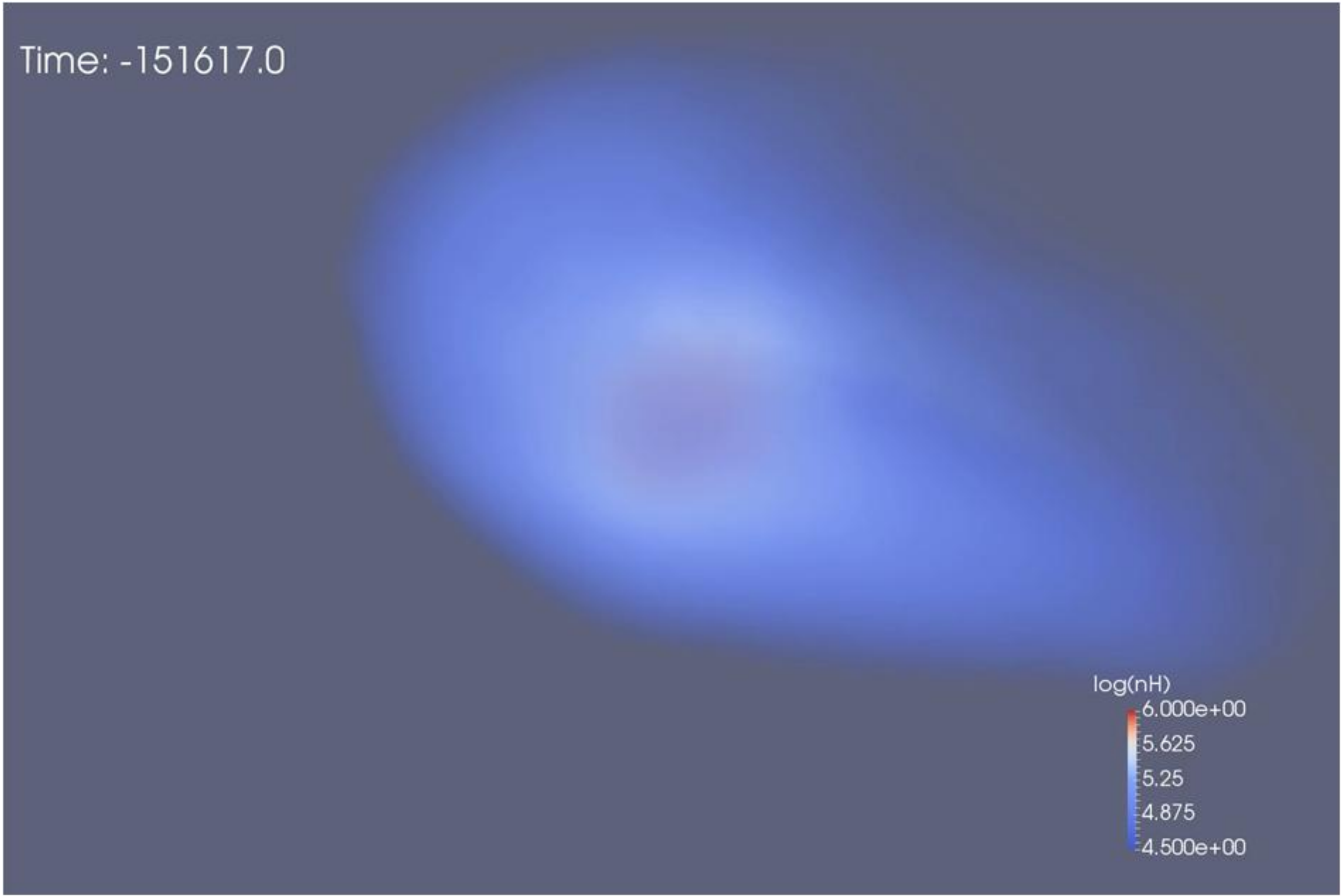
+ chemistry network & cooling/heating processes
w/ the primordial composition (zero metallicity)

+ Cosmological initial cond. (Hirano et al. 15)
Halos C & D of Hosokawa+ (2016)



3D movie

halo C, r_{sink}=64au



sink particle evolution minihalo C, r_{sink}=64au

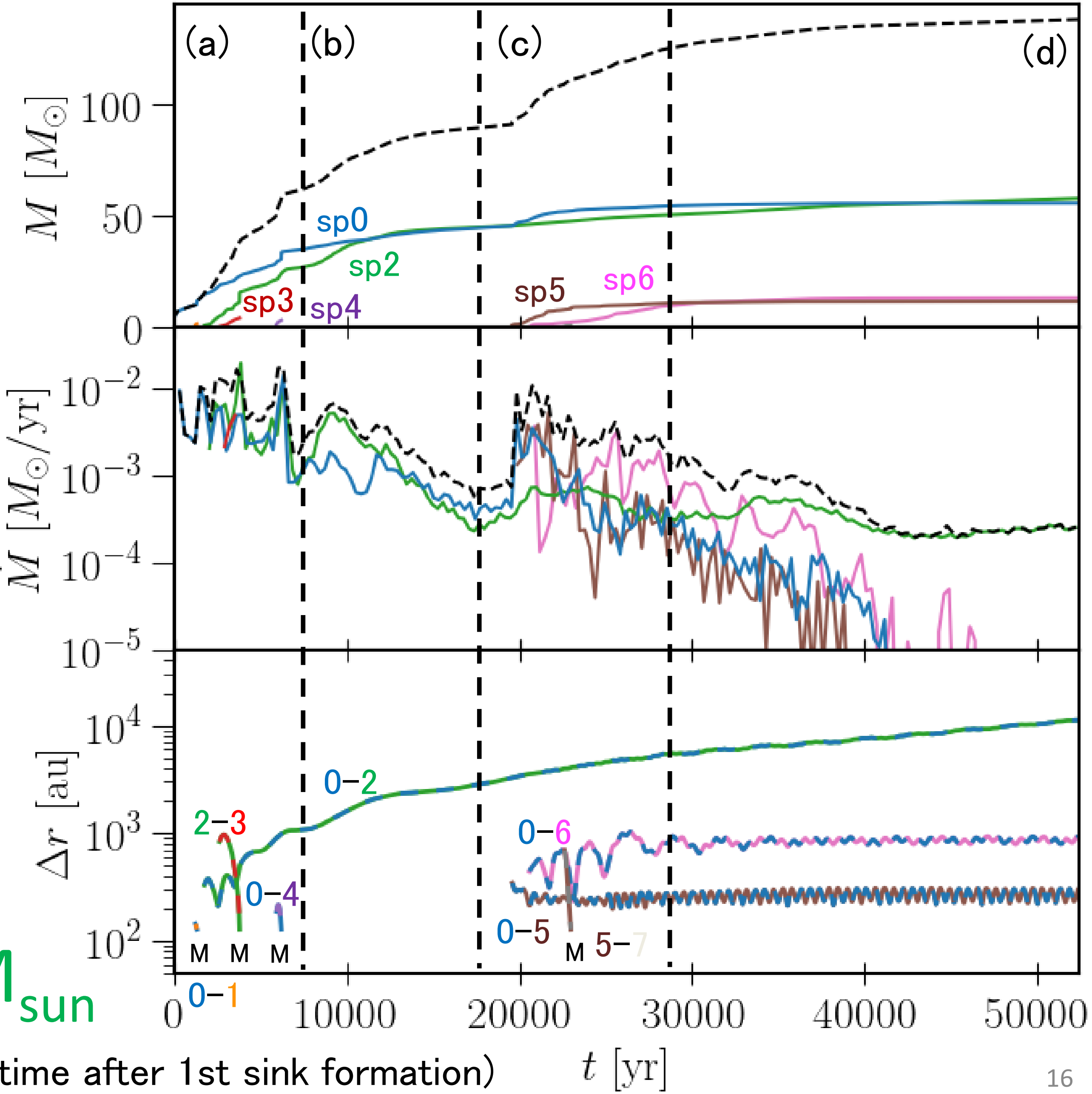
Evolutionary phases

(a) initial frag.

(b) acc. binary

(c) late−time frag.

(d) photo−evap. of mini−multiple system



$50M_{sun} + 50M_{sun}$

(t: time after 1st sink formation)

sink particle evolution

halo D, r_{sink}=64au

Evolutionary phases

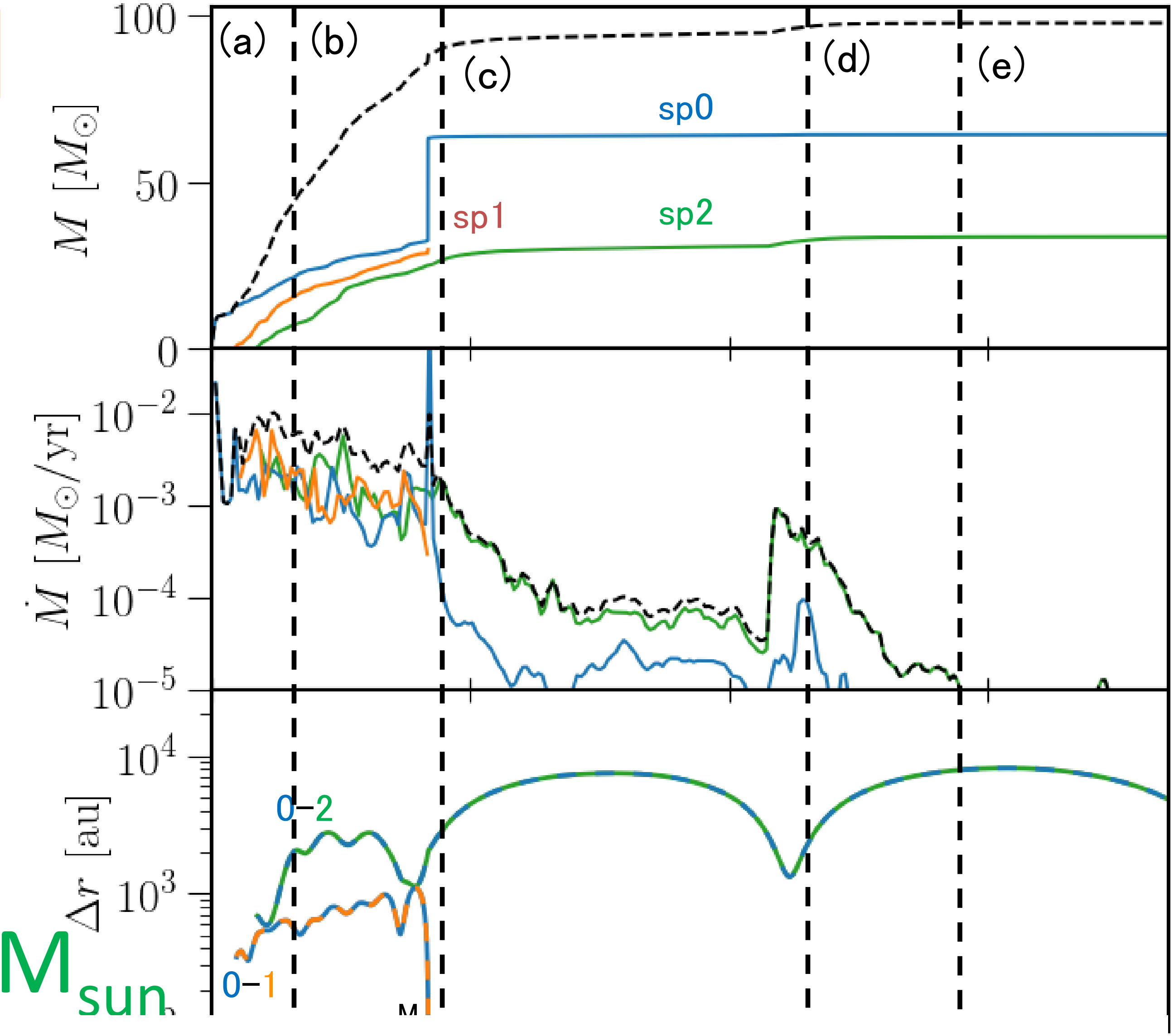
(a) initial frag.

(b) merger induced by a–few–body effect

(c) accreting binary

(d) internal photo–evaporation

(e) external photo–evaporation



$60M_{sun} + 30M_{sun}$

Massive binaries are common among first stars

Metallicity Effects

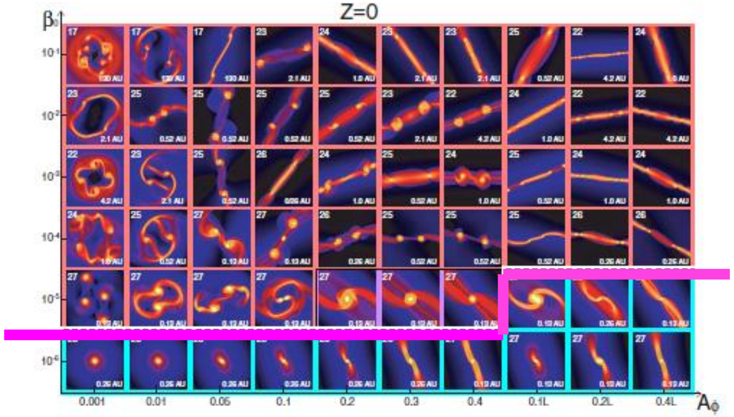
Metallicity effects on fragmentation during the collapse

Machida, KO et al. 2009

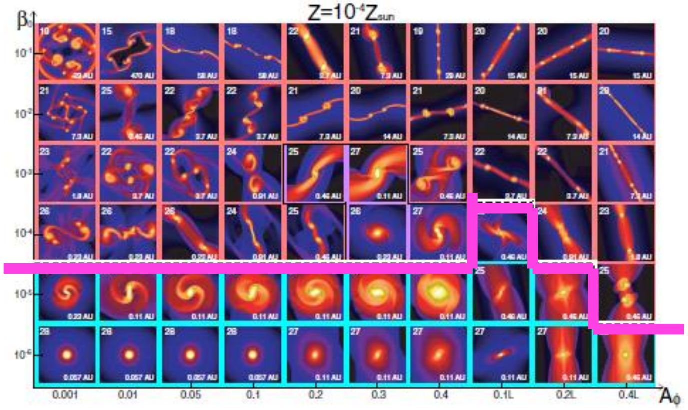
barotropic EOS from one-zone model

rotation

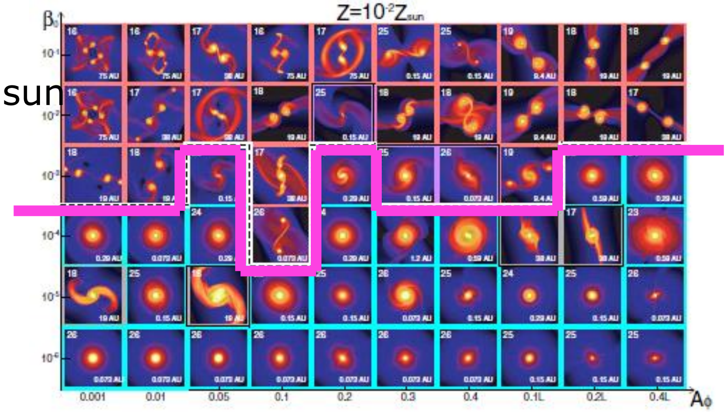
Z=0



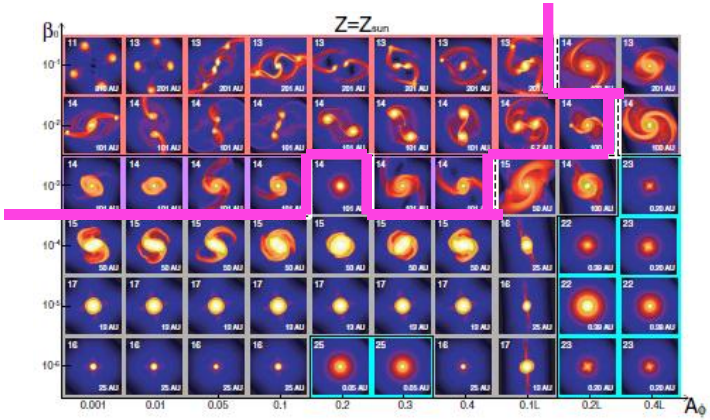
$10^{-4}Z_{sun}$



$10^{-2}Z_{sun}$



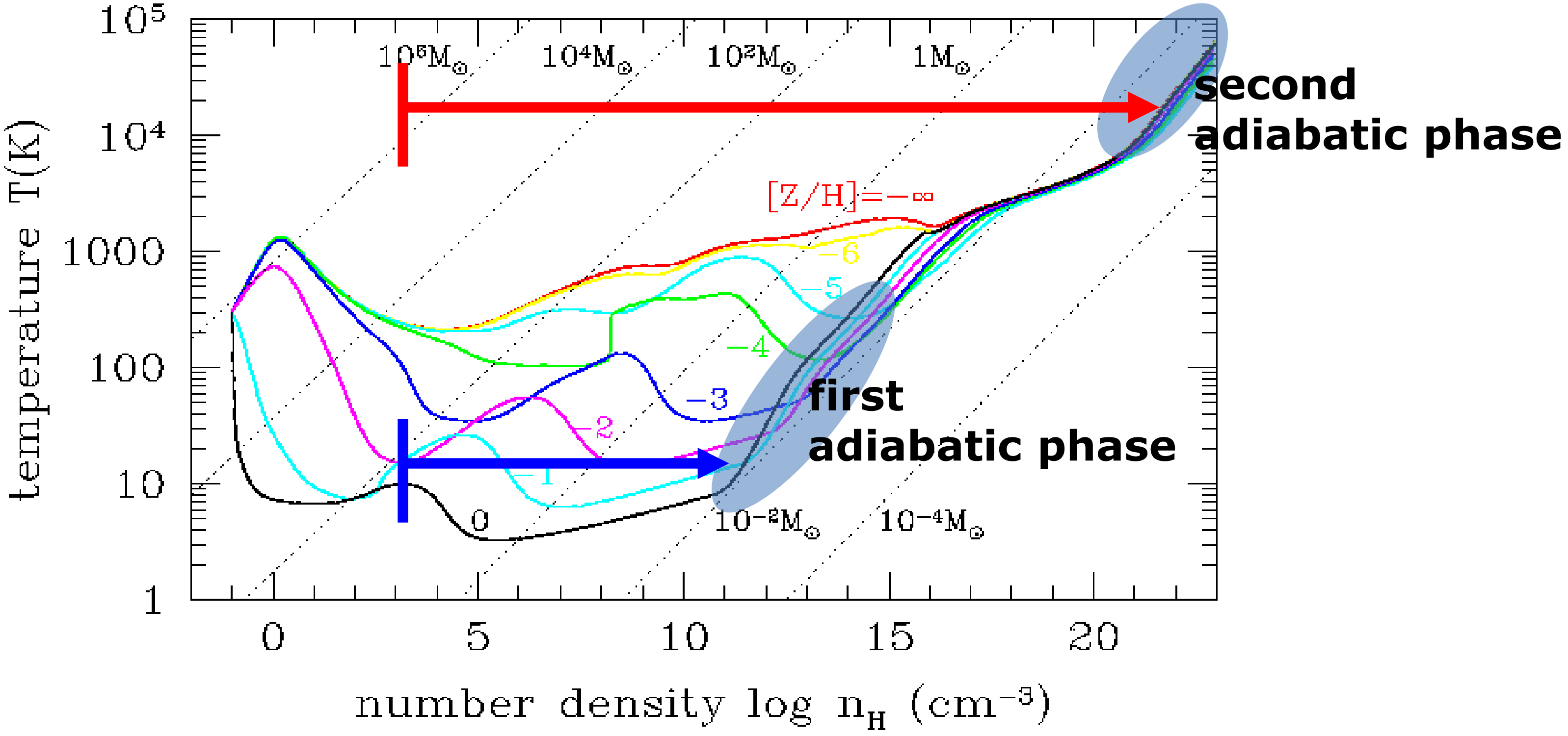
Z_{sun}



bar mode

lower-Z core fragments to binary even with slower rotation rate

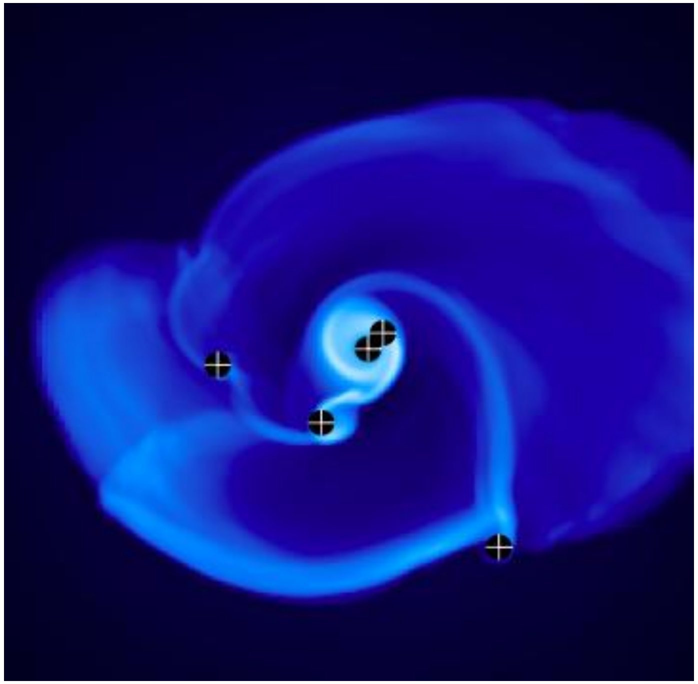
Why more fragmentation at low-Z?



✓ Lower Z cores have longer density interval to spin-up.
→ slowly rotating cores can fragment

✓ Fragmentation tends to occur at higher density.
→ tend to form closer binaries ?

disk fragmentation ?
after protostar formation

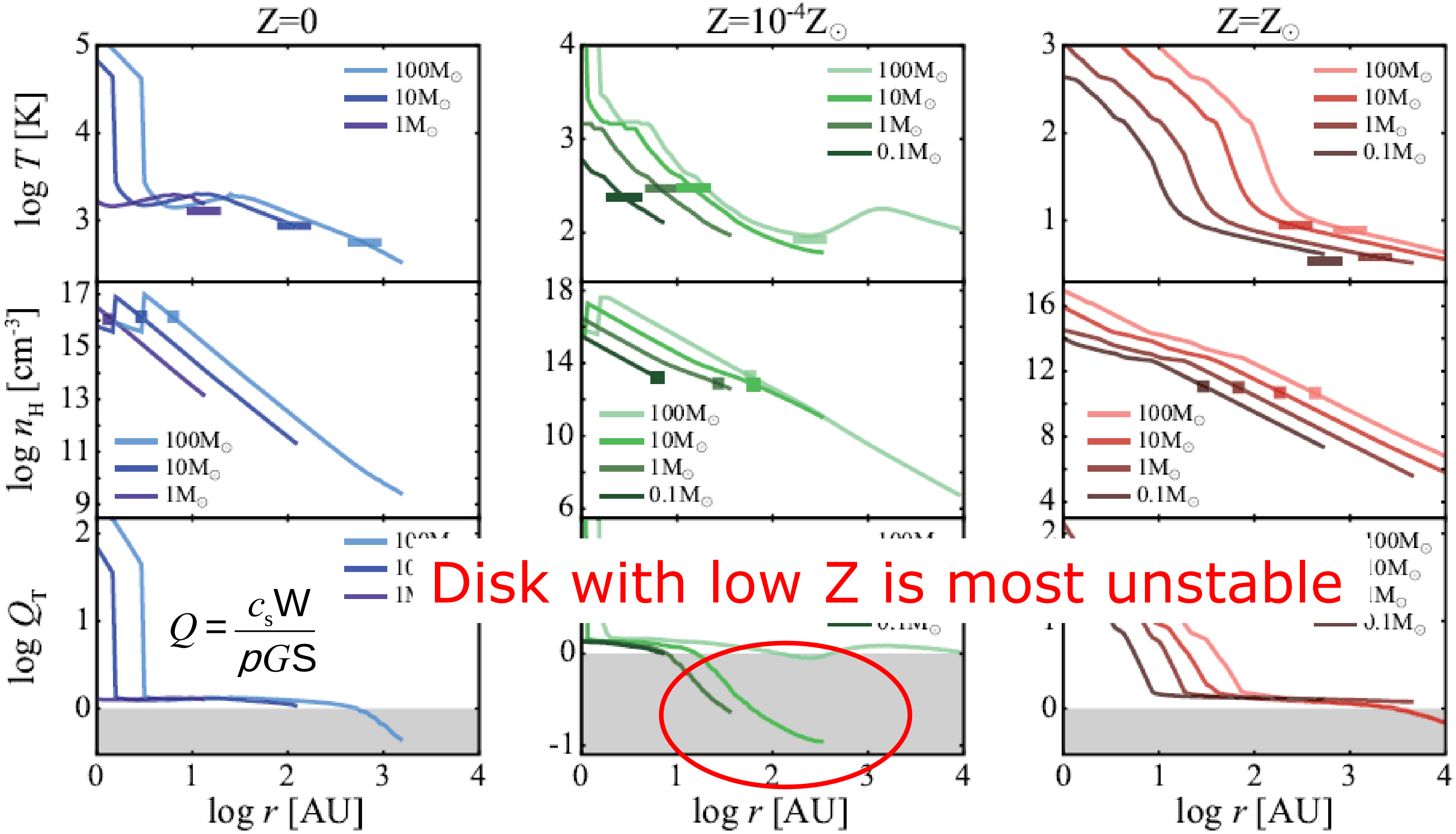


Kratter+10

Steady state disk structure and stability

K. Tanaka & KO (2014)

$f_{Kep}=\Omega/\Omega_{Kep}=0.5$

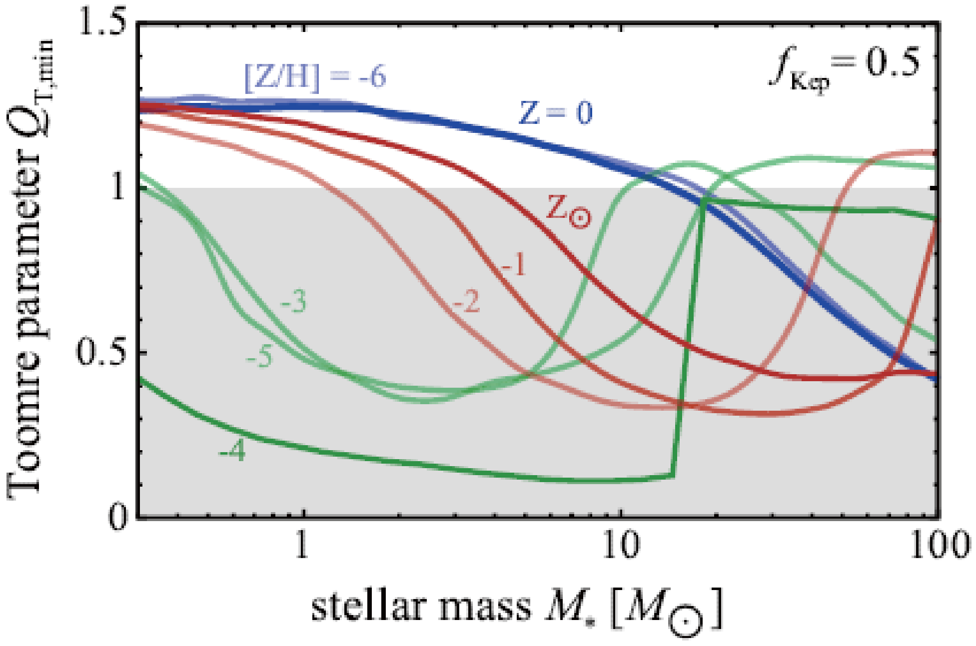


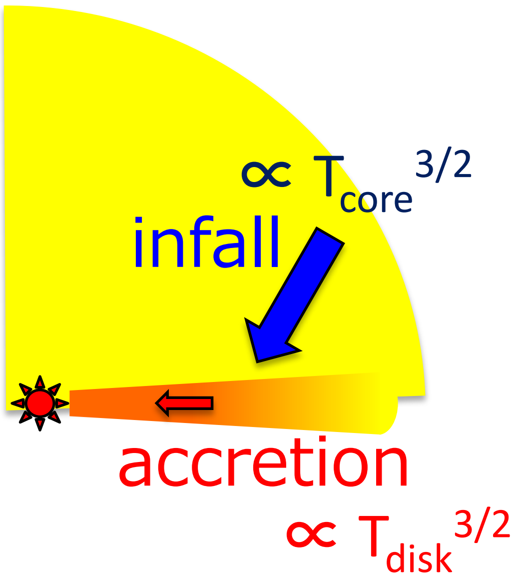
$$Q = \frac{c_s W}{pGS}$$

Disk with low Z is most unstable

- Pop II Protostellar disk is most unstable and would fragment → binary formation preferred ?

Why are extreme Pop II disks unstable?





$\propto T_{\rm core}^{3/2}$

infall

accretion

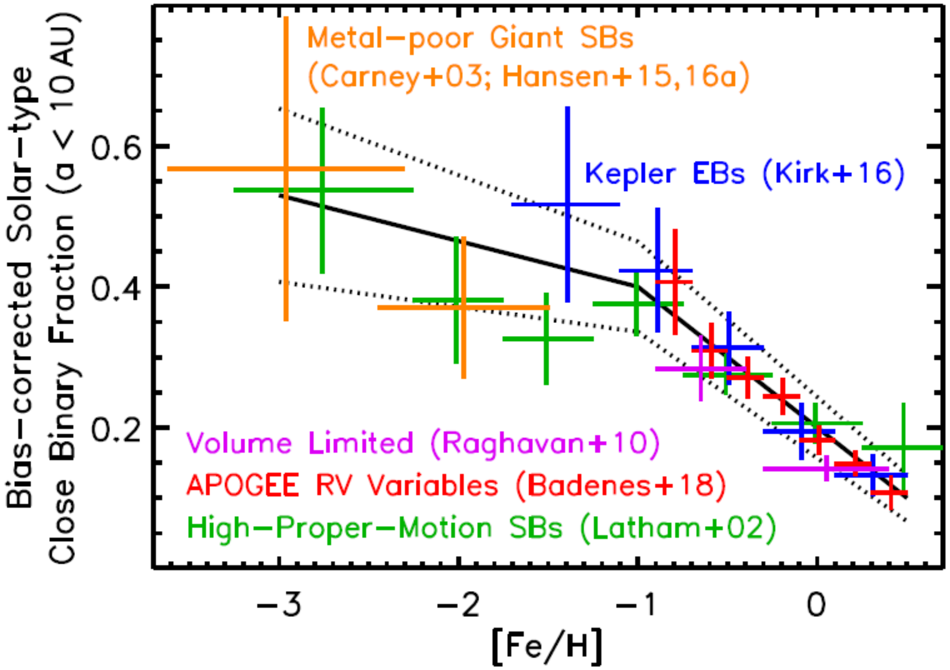
$\propto T_{\rm disk}^{3/2}$

$$Q \sim \frac{c_{\rm s,disk}^3 / G}{c_{\rm s,core}^3 / G} \sim \left(\frac{T_{\rm disk}}{T_{\rm core}} \right)^{3/2}$$

✓disk is unstable if $T_{\rm disk} < T_{\rm core}$

✓Due to dust cooling operating at high density, disk can be colder than envelope at low Z.

Recent observation of low-Z binaries



- close binary fraction of low-mass stars increases toward lower-metallicity at -3<[Fe/H]<0.5. (Moe + 2019)

- Also, an UMP close binary (([Fe/H]=-4.07, a=0.2au, 0.76+0.14M_{sun} stars) is found (Schlaufman + 2018)

These findings may support our claim of high binary fraction for Pop II stars.

Toward MHD calculation:

accurate ionization degree modelling needed

Magnetic fields will change the picture ?

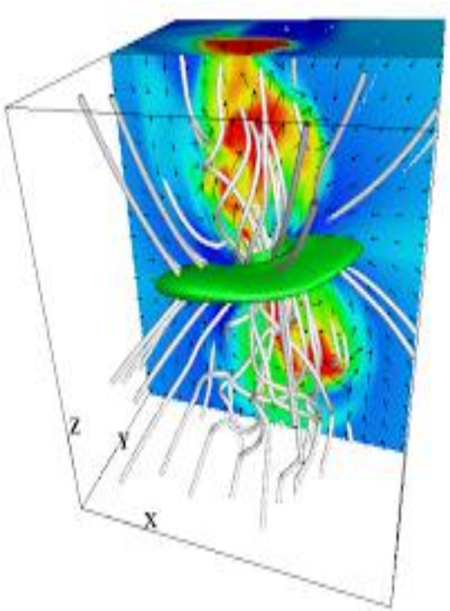
In Galactic ISM, B-fileds are almost in energy equi-partition:

$E_B \sim E_{kin} \sim E_{grav}$

Roles:

- Support against the collapse
- Jet/Outflow launching
- Angular momentum transport
  by magnetic braking, magneto-rotational instability
- Suppressing fragmentation of disk

→determines frequency of binary formation



(e.g., Machida & Doi '13)

Even in low-metallicity ISM, significant B-fields may be present
seed field ($\sim 10^{-19}$G) amplified by e.g., small-scale dynamo

Magnetic field dissipation

Ionization degree in star forming clouds is low → magnetic dissipation can occur

e.g., Wardle 2007

balance of Lorentz and drag forces for charged particles j

$$Z_j e \boldsymbol{E}' + Z_j e \frac{\boldsymbol{v}_j}{c} \times \boldsymbol{B} - m_j \gamma_j \rho \boldsymbol{v}_j = 0$$

$$\longrightarrow \quad \boldsymbol{J} = \textstyle\sum_j n_j e Z_j \boldsymbol{v}_j = \sigma_O \boldsymbol{E}'_\parallel + \sigma_H \hat{\boldsymbol{B}} \times \boldsymbol{E}'_\perp + \sigma_P \boldsymbol{E}'_\perp$$

Hall parameter

$$\beta_j = \frac{|Z_j| e B}{m_j c} \frac{1}{\gamma_j \rho}$$

with Ohmic, Hall, and Pedersen conductivities

$$\sigma_O = \frac{ec}{B} \sum_j n_j |Z_j| \beta_j \quad \sigma_H = \frac{ec}{B} \sum_j \frac{n_j Z_j}{1+\beta_j^2} \quad \sigma_P = \frac{ec}{B} \sum_j \frac{n_j |Z_j| \beta_j}{1+\beta_j^2}$$

$$\boxed{\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) - \nabla \times [\eta_{\mathrm{O}} \nabla \times \boldsymbol{B} + \eta_{\mathrm{H}} (\nabla \times \boldsymbol{B}) \times \hat{\boldsymbol{B}} + \eta_{\mathrm{A}} (\nabla \times \boldsymbol{B})_\perp]}$$

Ohmic, Hall and ambipolar diffusivities

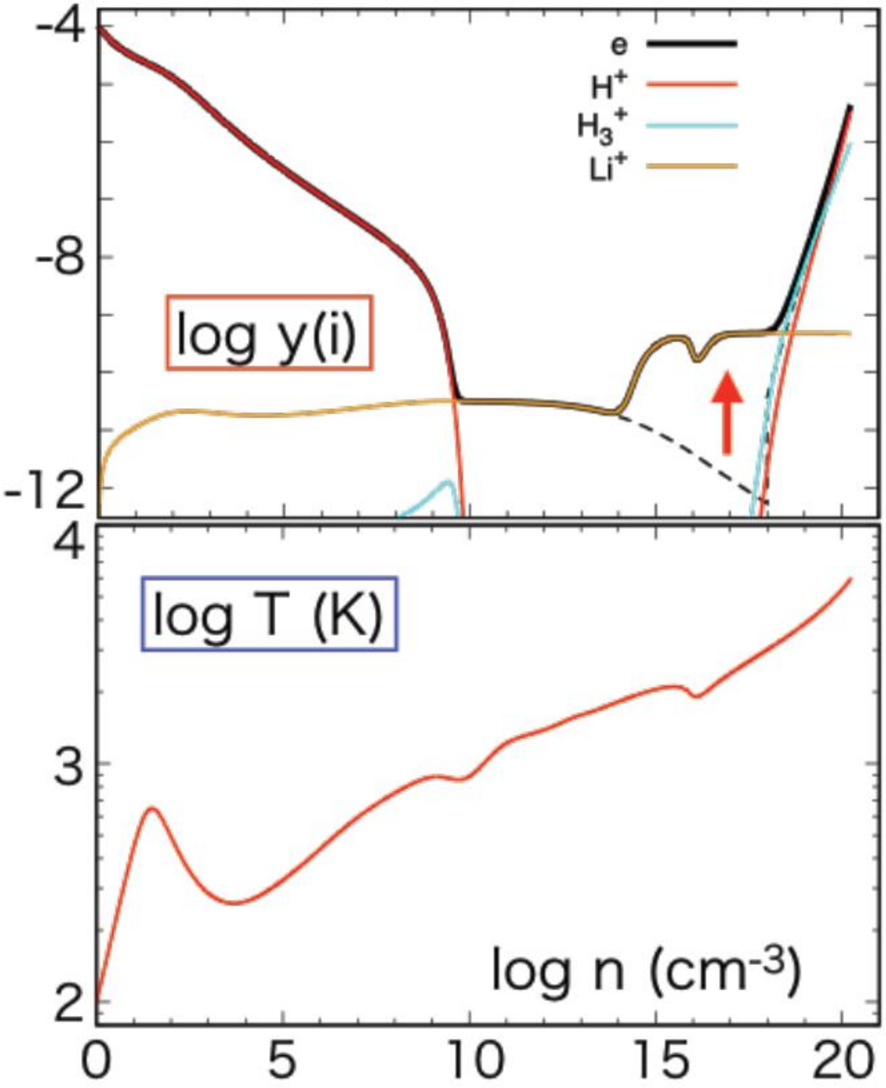
$$\eta_O = \frac{c^2}{4\pi \sigma_O} \qquad \eta_H = \frac{c^2}{4\pi \sigma_\perp} \frac{\sigma_H}{\sigma_\perp} \qquad \eta_A = \frac{c^2}{4\pi \sigma_\perp} \frac{\sigma_P}{\sigma_\perp} - \eta_O$$

$$\sigma_\perp = \sqrt{\sigma_H^2 + \sigma_P^2}$$

Ionization degree controls magnetic dissipation

accurate treatment of ionization degree in primordial gas

Nakauchi, KO, Susa 2019



204 reactions (all reversed) among 23 species:

H, H_2, e^-, H^+, H_2^+, H_3^+, H^-, He, He^+, He^{2+}, HeH^+, D, HD, D^+, HD^+, D^-, Li, LiH, Li^+, Li^-, LiH^+, Li^{2+}, Li^{3+}.

major positive ions:

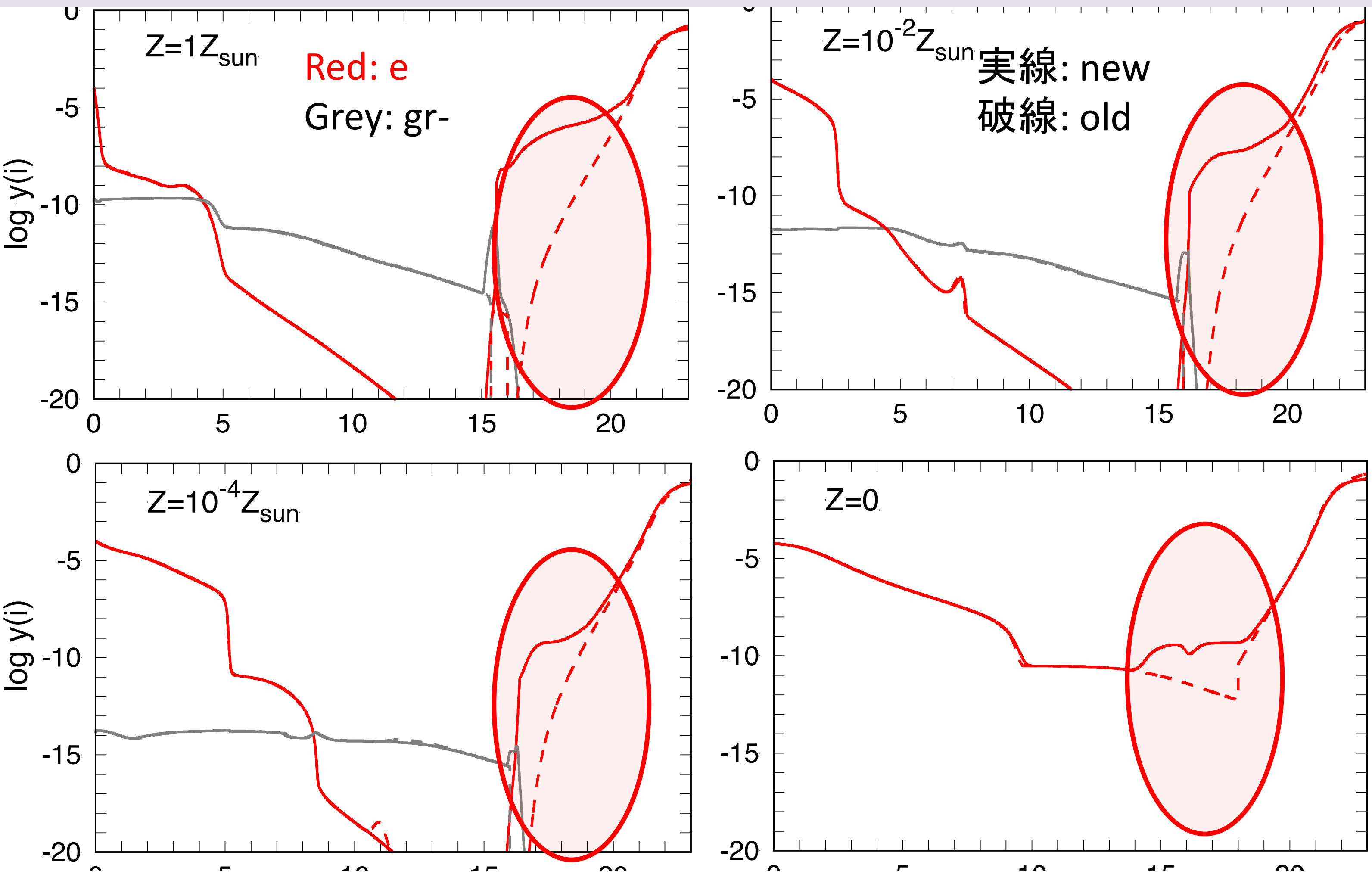
$H^+ \rightarrow Li^+ \rightarrow H_3^+ \rightarrow H^+$

Li ionization by thermal photons enhances ionization degree at >10^{14}cm^{-3}

$$\mathrm{Li}^+ + e \rightleftharpoons \mathrm{Li} + \gamma$$

cases with other metallicities

Nakauchi, KO + in prep.



higher ionization degree than in previous model due to ionization of alkali metals (Li, K, Na).

SUMMARY

- Massive binaries seem to have been common among first stars

- Binaries are more common among extreme Pop II (10^{-5}-$10^{-3}Z_{sun}$) stars

Caveat:

  - higher resolution, longer time evolution needed to be followed
  - How about close binaries?

Toward future MHD simulations:

- Chemical model for correct ionization degree constructed