Modeling Supernovae based on high resolution simulations

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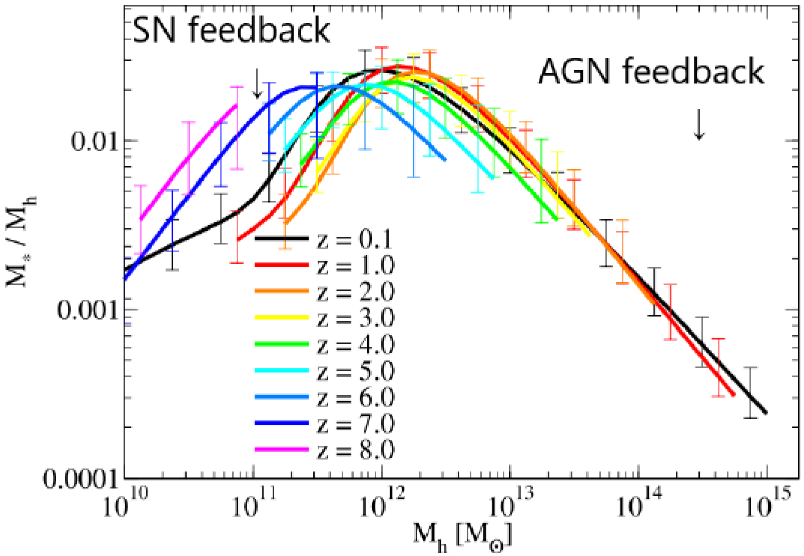
Stellar Feedback

(See also Nagamine-san's talk)

- Massive stars release energy into circumstellar region. (Stellar wind, Supernova)
- Such events suppress star formation (stellar feedback).
- Feedback from supernovae is thought to be a dominant process to surpress star formation.
- Supernova feedback is also important for
  - morphology of galaxy
  - galactic outflow
  - metal enrichment of IGM, CGM
  - turbulence in interstellar medium.



(Behroozi+ 2013)

Feedback Models

(See also Nagamine-san's talk)

- Many types of supernovae feedback models are constructed to overcome overcooling problem.

- Feedback models have evolved from phenomenological models based on galactic properties to direct models based on local properties .

  - Mechanical feedback model (Kimm & Cen 14, Hopkins 18): inject momentum calculated from local properties (ρ, Z)
    - We need functional form of momentum $\mathbf{p}(\rho, \mathbf{Z})$
      - Environment dependence ?

In this work we

1. investigate momentum of supernova remnant (SNR) using high-reso sim.
2. introduce new feedback model
3. apply the result of (1) to galaxy simulation.

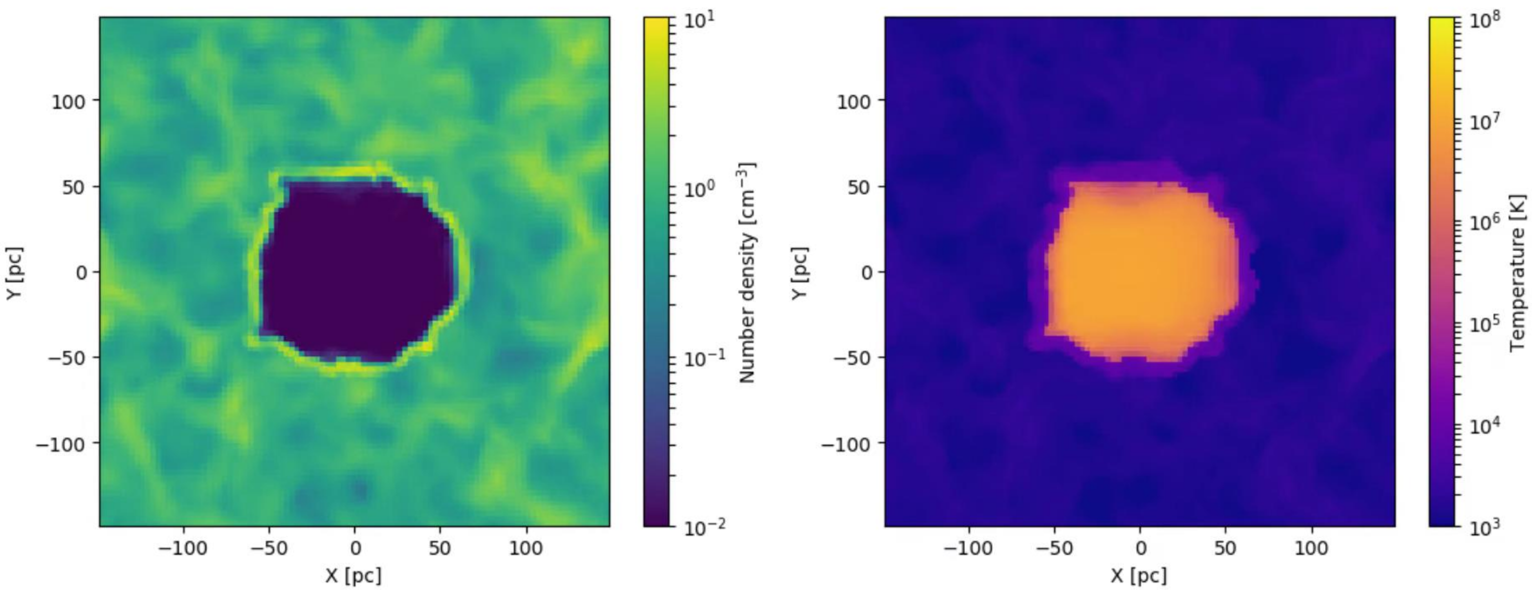
High-reso Simulation: Setup

- We run 3D hydrodynamical simulation using Athena++ code (Stone+ 20).

  - Multiplicity: 10 times SNe
  - Metallicity dependence
  - Thermal conduction
  - Turbulent ISM
  - Time interval

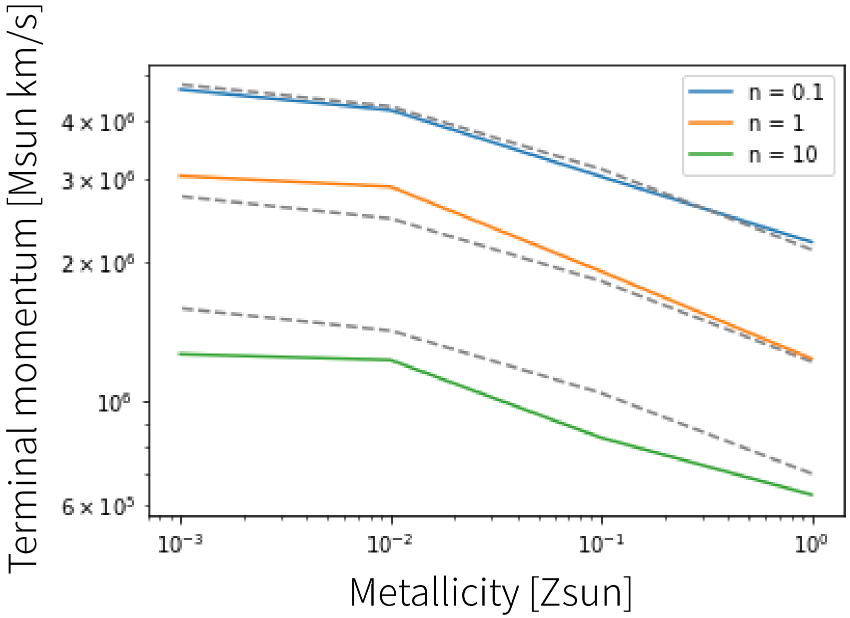
Initial conditions
($3 \times 4 \times 3 = 36$ pattern)

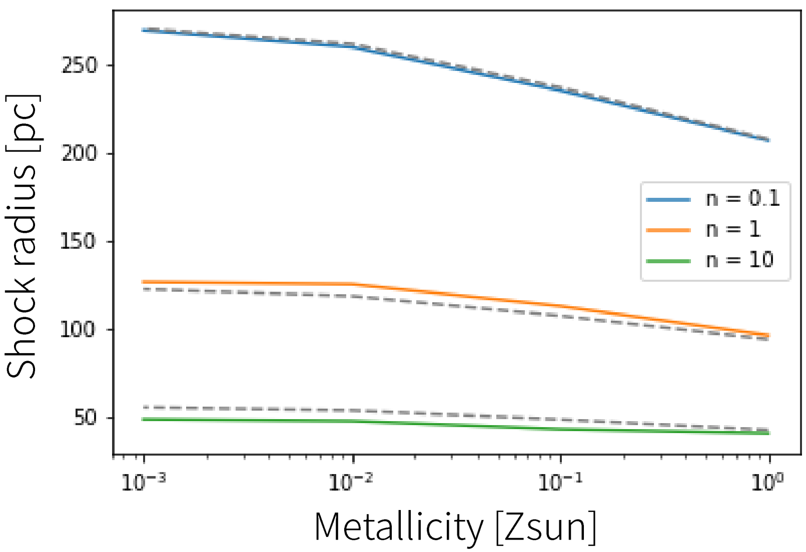
$n_{\rm H}$ [cm^{-3}]	0.1, 1, 10
$\log Z$ [$Z_\odot$]	-3, -2, -1, 0
$t_{\rm interval}$ [Myr]	0.01, 0.1, 1



High-reso Simulation: Results

Terminal momentum & shock radius averaged over $t_{interval}$.





- Terminal momentum increase by factor 2 in low metallicity ISM.
- Fitting functions
  - Terminal momentum:

$$p_{term}(n,E,Z) = 1.22\times10^5 \left(\frac{n}{1cm^{-3}}\right)^{-0.24} \left(\frac{Z}{Z_\odot}+9.59\times10^{-3}\right)^{-0.179} \left(\frac{E}{10^{51}erg}\right) M_\odot \text{ km/s}$$

  - Shock radius:

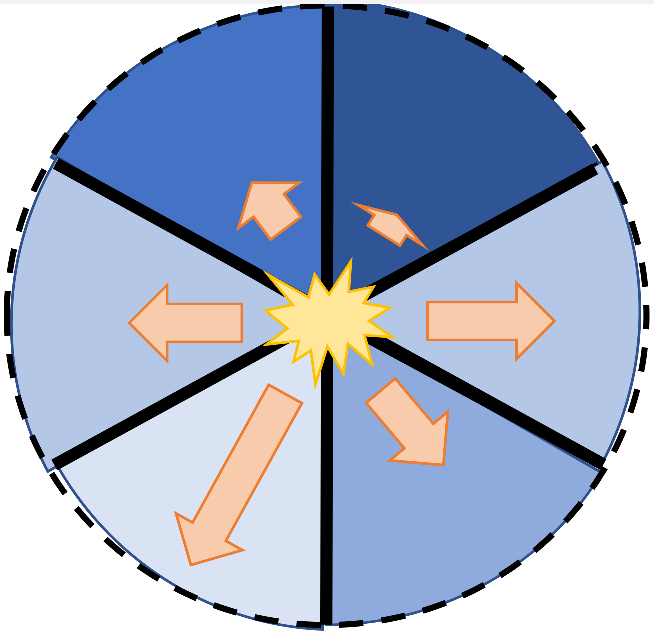
$$R_{shock}(n,E,Z) = 43.8 \left(\frac{n}{1cm^{-3}}\right)^{-0.343} \left(\frac{Z}{Z_\odot}+1.15\times10^{-2}\right)^{-0.06} \left(\frac{E}{10^{51}erg}\right)^{1/3} \text{pc}$$

Modeling Supernovae

Previous feedback models

- search neighbor particles inside smoothing length h_{sml}
  → Over estimation of feedback effect
- inject momentum calculated from local density.
  → Violation of momentum conservation

A turbulent ISM is divided into some cones. Injected momentum is calculated for each cone separately.



New model (centroid feedback model)

- search neighbor particles inside shock radius R_{shock}
- inject momentum calculated from local density and particle distribution so that momentum is conserved.

Modeling Supernovae

Overview of centroid feedback model

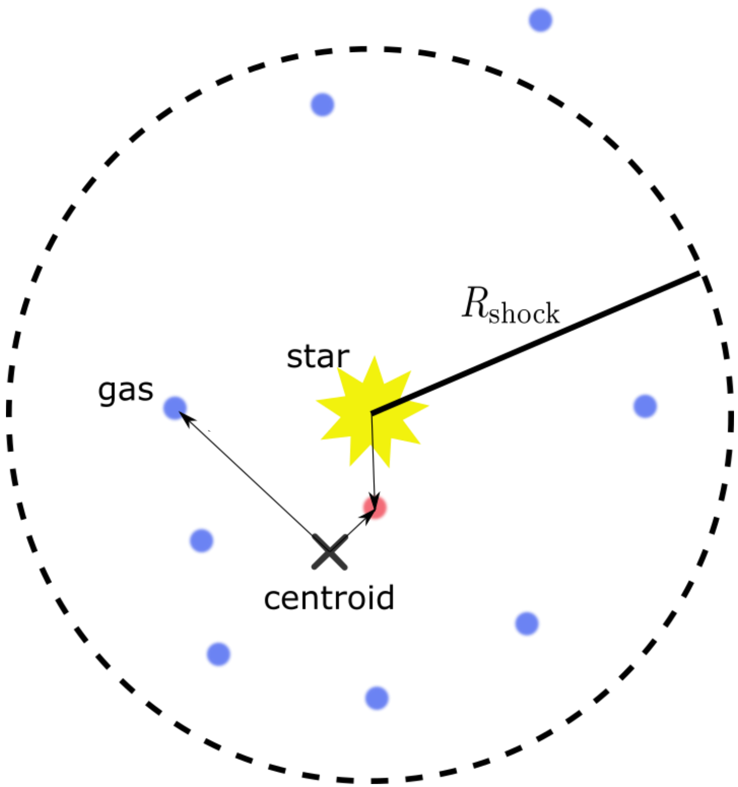
1. Search gas particles inside R_{shock}.
2. Calculate density-weighted centroid point

$$\vec{r_c} = \frac{1}{N_{ngb}} \sum_i m_i \, \rho_i^{\alpha} \, \vec{r_i}$$

3. Add momentum $\vec{p}_i$ to gas particles

$$\vec{p}_i = C \, (m_i \, \rho_i^{\alpha} \, \vec{r}_i - \vec{r}_c)$$

$$p_{term} = \sum_i |\vec{p}_i|$$



- Total momentum is conserved

$$\sum_i \vec{p}_i = C \left(\sum_i m_i \, \rho_i^{\alpha} \, \vec{r}_i - \sum_i \vec{r}_c \right) = C\left(N_{ngb} \, \vec{r}_c - N_{ngb} \, \vec{r}_c\right) = 0$$

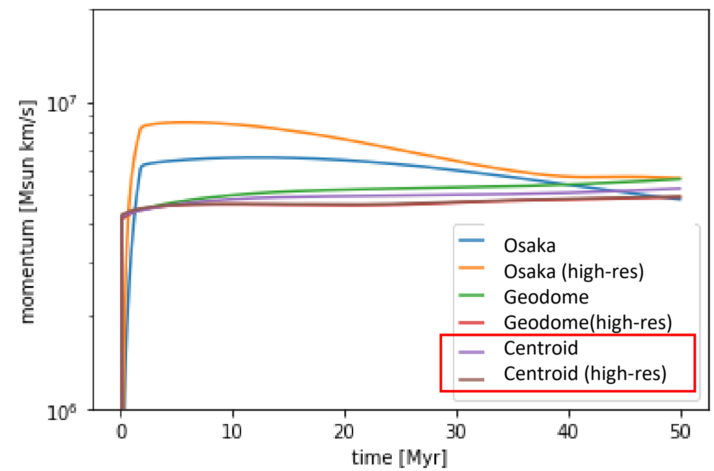
- negative α $\rightarrow$ more momentum to lower-density particles.

Single Supernova Test

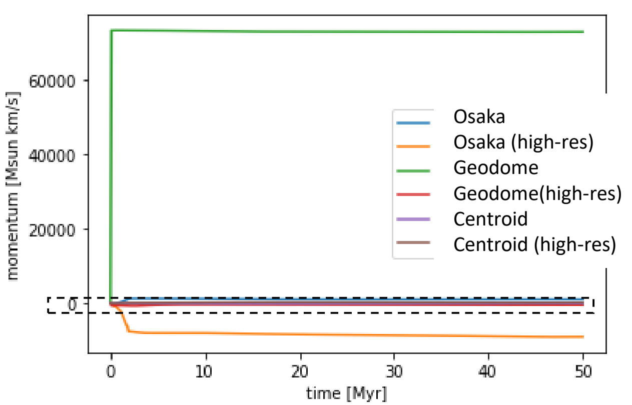
We implement centroid model to GADGET3-Osaka code (Aoyama+17, Shimizu+ 19).
We test our feedback model in homogenious ISM.

- Total radial momentum converge with resolution.
- Total momentum is conserved.

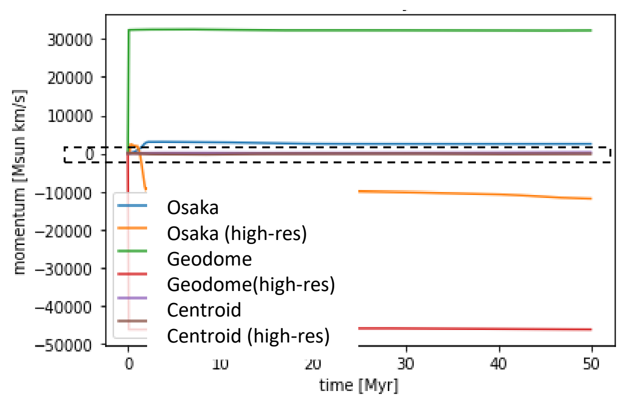
Radial momentum



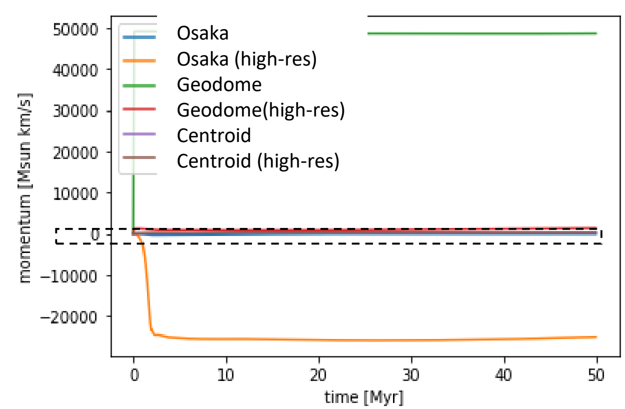
Total momentum in X direction



Total momentum in Y direction



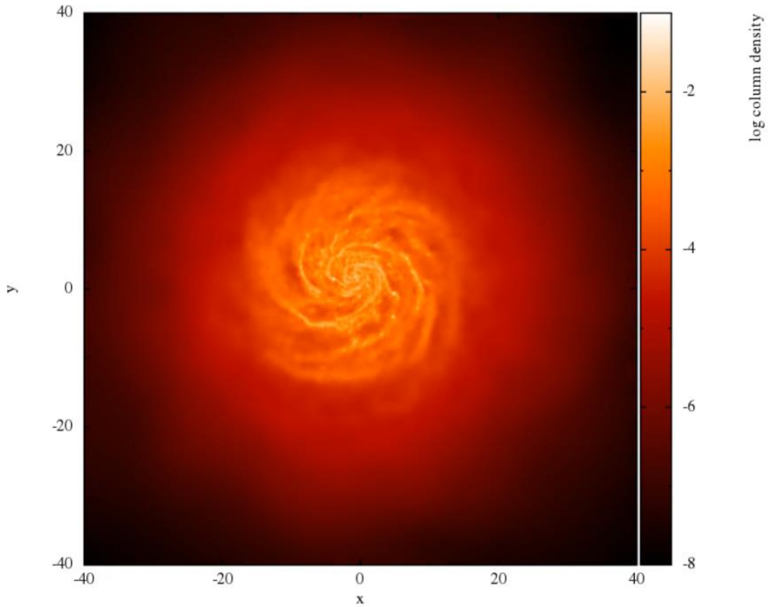
Total momentum in Z direction

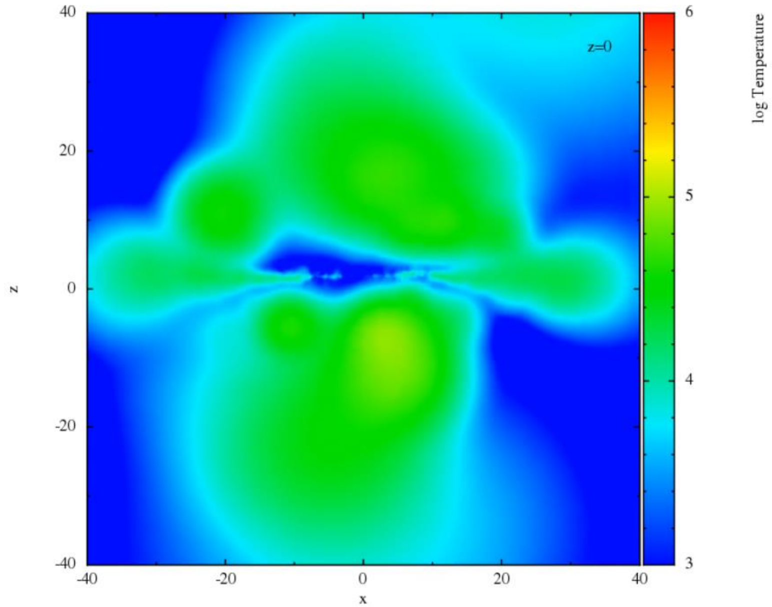


Isolated Galaxy Simulation

We run simulations of isolated galaxy with properties characteristic of Milky Way-mass galaxies at $z \sim 1$ (Kim+ 16).

- Mass
  - $M_{halo} = 1.3 \times 10^{12}\ M_\odot$
  - $M_{star} = 3.8 \times 10^{10}\ M_\odot$
  - $M_{gas} = 8.6 \times 10^{9}\ M_\odot$
- Mass resolution
  - $m_{DM} = 1.3 \times 10^{7}\ M_\odot$
  - $m_{gas} = 8.6 \times 10^{4}\ M_\odot$
- Gravity softening length $\epsilon_{grav} = 80$ pc

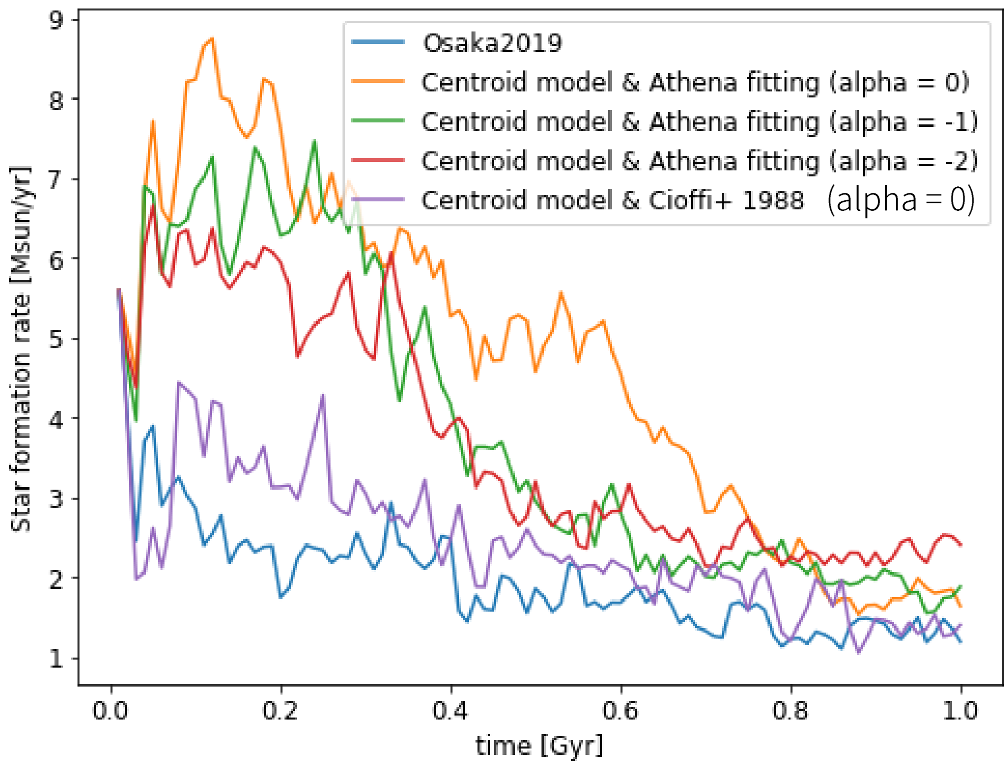




Results: Star Formation Rate

- Osaka2019: 70% thermal + 30% kinetic, shutoff cooling for t_{hot} (Shimizu+ 19)
- Centroid : 70% thermal + terminal momentum
  - Athena fitting: $p_{term} = 1.2 \times 10^5\ M_{sun}$ km/s
  - Cioffi+ 1988 : $p_{term} = 4.8 \times 10^5\ M_{sun}$ km/s

$(n = 1\ cm^{-3}, \mathrm{Z} = \mathrm{Z}_{\odot})$



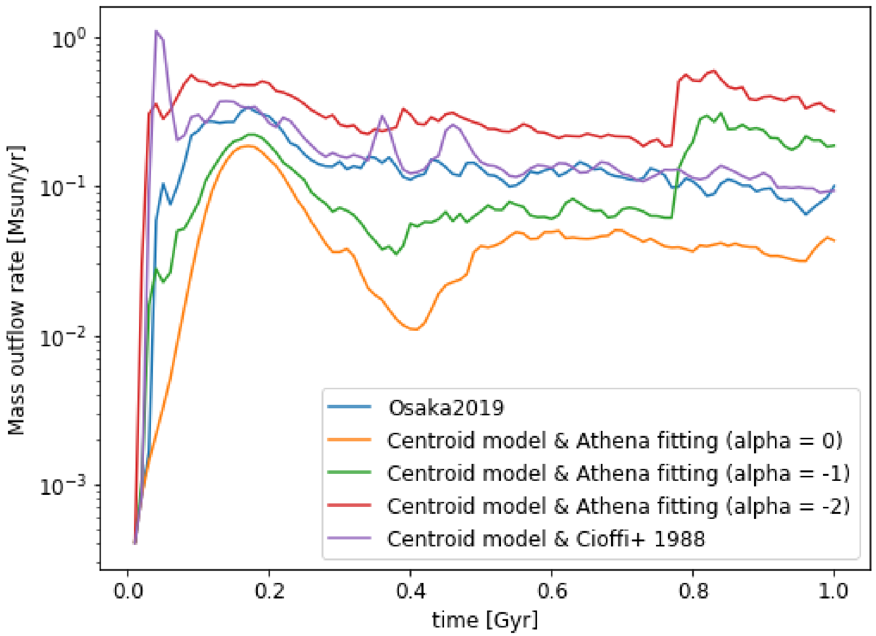
- In Athena fitting cases, a feedback effect is weak.
- In our previous studies, Osaka model produces stars too much compared to observations.

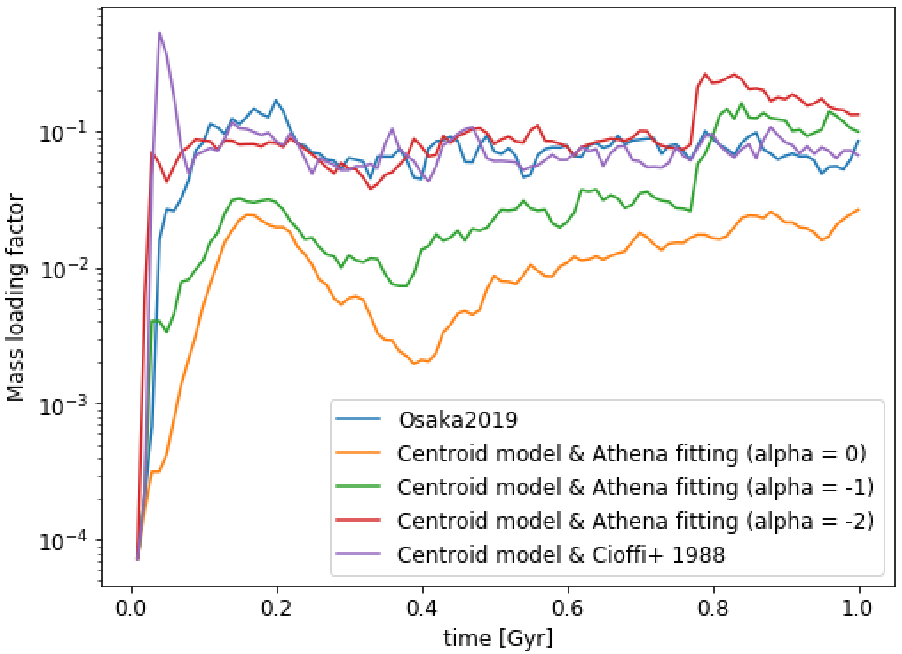
Results: Mass Outflow

Outflow at H = 4 kpc from galactic disk.

- Mass outflow rate $\dot{M}$
  - α decrease → $\dot{M}$ increase
  - In α = -2 case, $\dot{M}$ is larger than Osaka model

- Mass loading factor $\eta = \dot{M}/SFR$
  - α controls outflow efficiency

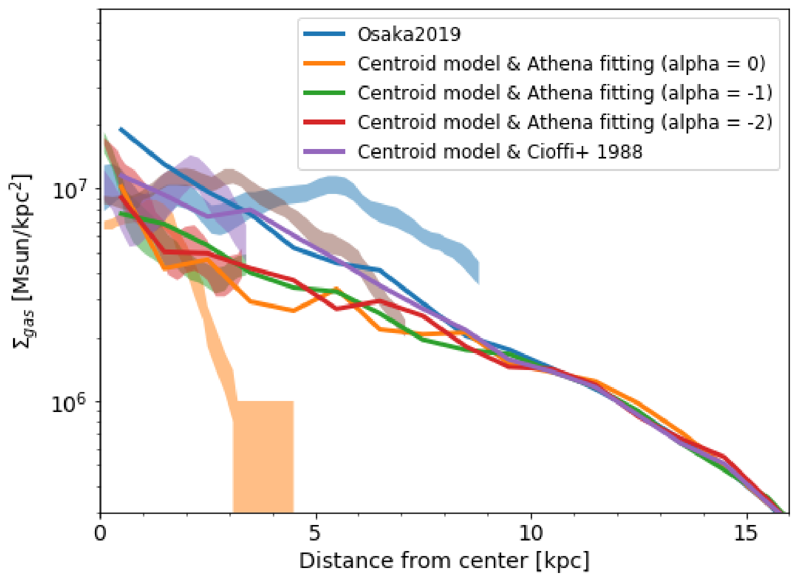




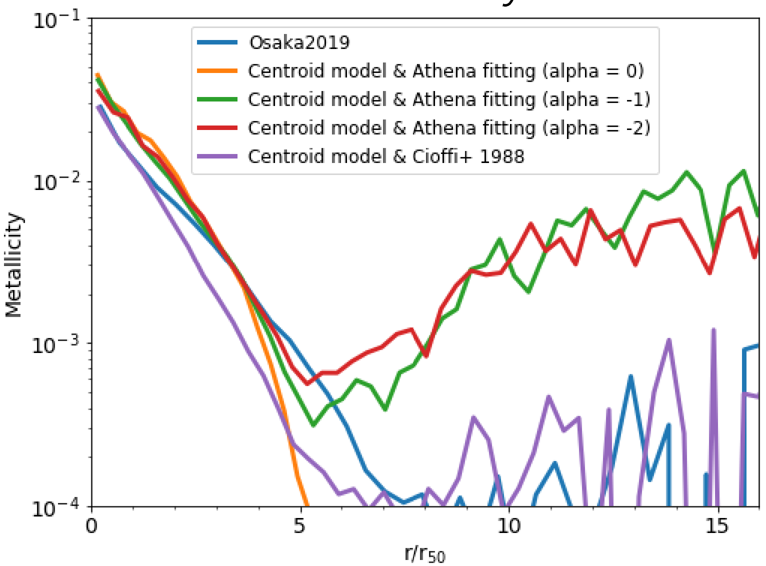
Results: Surface Density Profile

- Gas surface density profile differs at inner region.
- High SFR & High $\dot{M} \rightarrow$ More metal enrichment at outer region.

Gas surface density



Metallicity



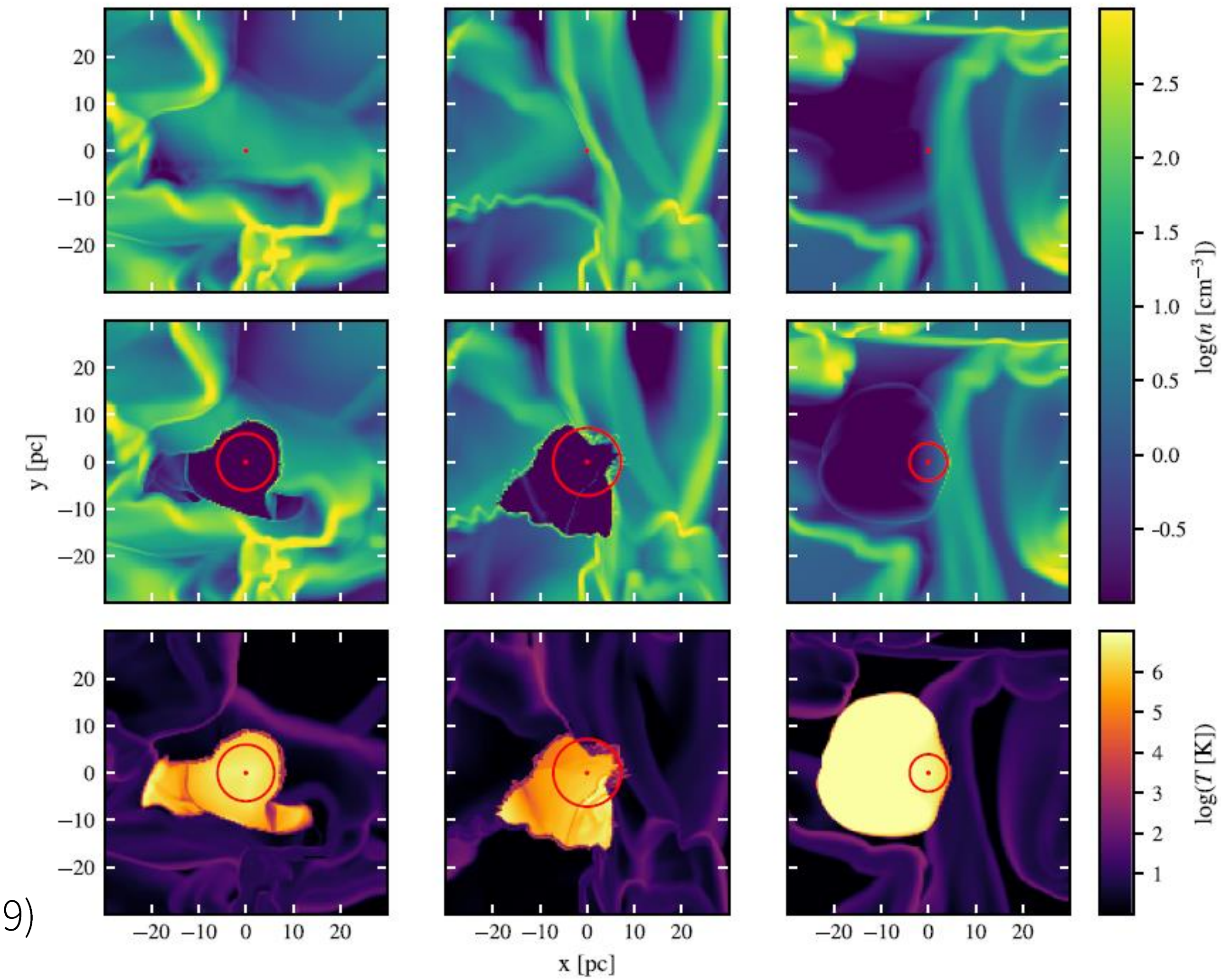
(Colored region is observational data of nearby galaxies (Leroy+ 08))

Summary

- We run 3D hydro simulation and derive fitting function of terminal momentum of SNR .
- We construct momentum-conserving supernova feedback model.
- Momentum feedback derived from our high-reso simulation (Athena fitting) may be too weak to suppress star formation compared to observations.
    - Other physics (cosmic ray, magnetic field) may need to be considered.
- When α is small, a strong outflow is launched.
- When α is small, outer region is enriched by more metals.

Free parameter α

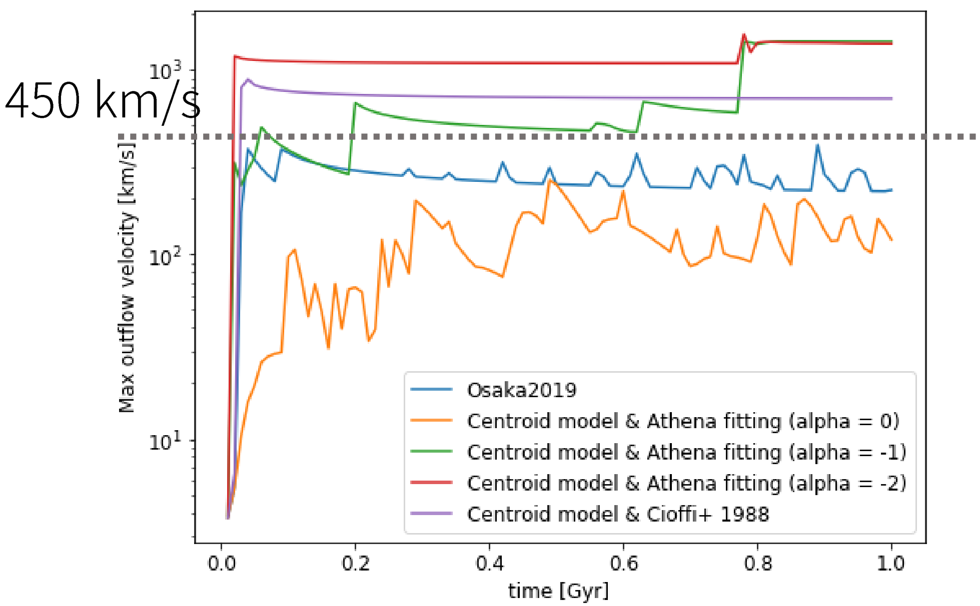
- SNR expands through low-density channel.
- α is a parameter of this effect.

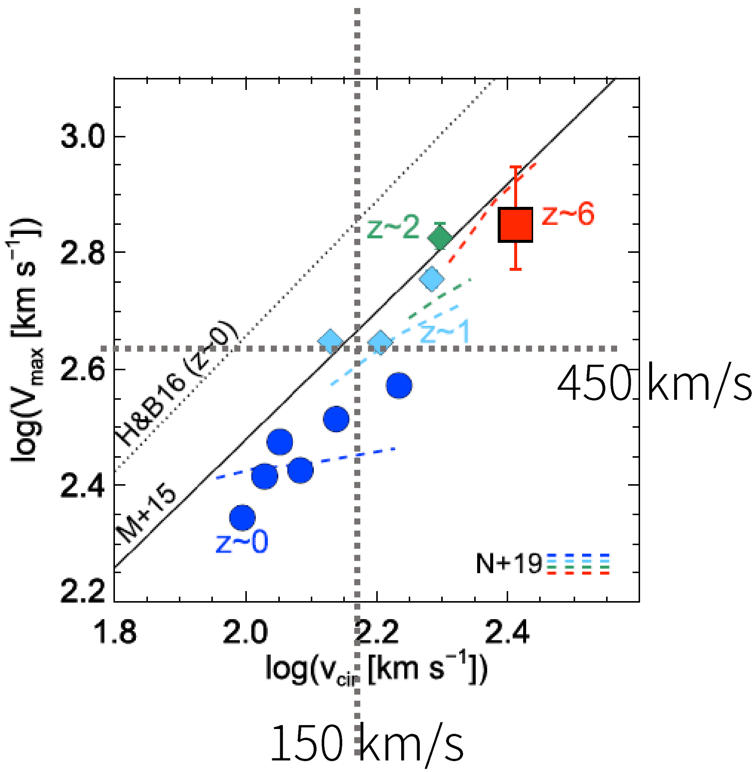


(Ohlin+ 19)

Outflow Velocity

- Max outflow velocity: velocity of the fastest gas particle (upper limit)





Kennicutt-Schmidt Relation

- Surface density is averaged over 750 pc x 750 pc patches
- Slope = 1.5 - 2 ?