Numerical simulation of galaxy formation

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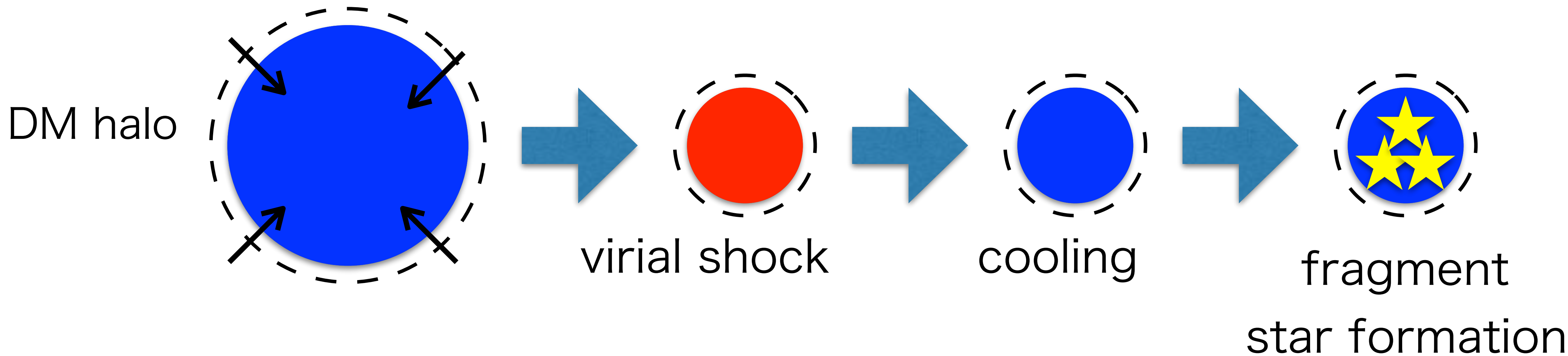
IGM-galaxy workshop@CCS   2018/8/9

Theory of galaxy formation

- A standard scenario

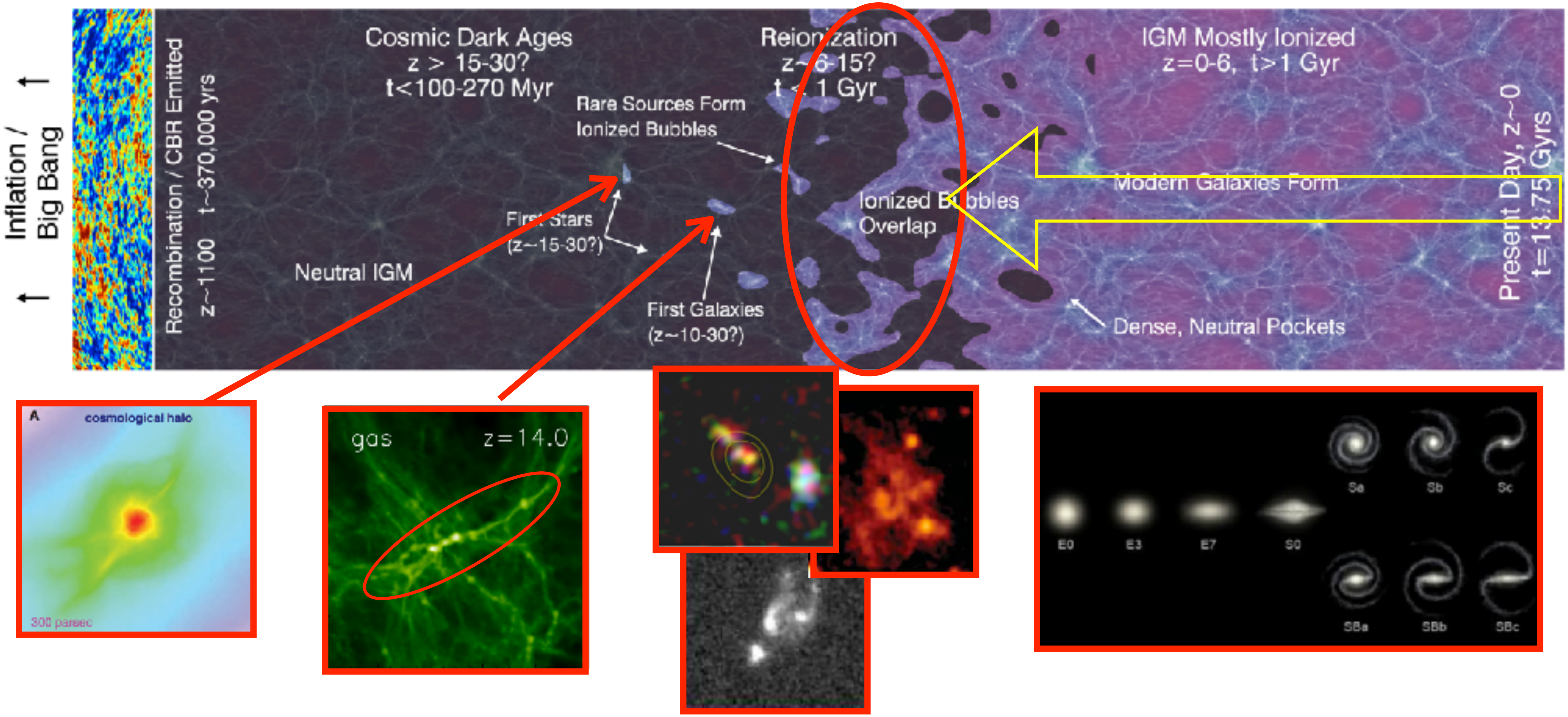


  - if $t_{cool} < t_{grav}$
    - cooling, stars are beging to form in DM halo (galaxy formation)
  - if $t_{cool} < t_H$
    - stars never form (within Hubble time)

(e.g., Rees & Ostriker '77)

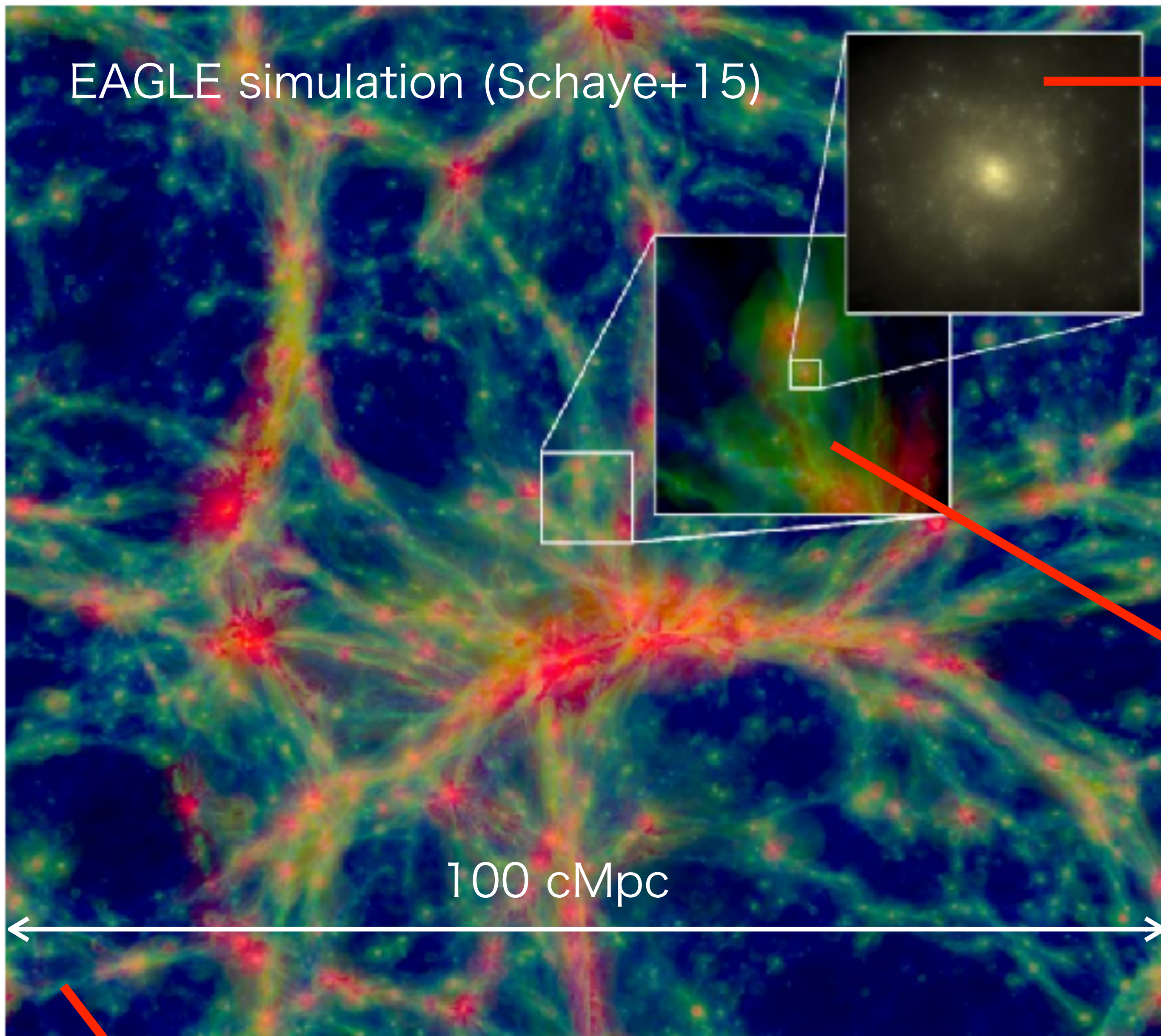
Purpose of the numerical simulation

Robertson+10



- How the galaxies evolve? What is the origin of the diversity?
    - simulate the complex physical processes, reproduce the observation and reveal the origin
- give a theoretical model/suggestion to the observation

Processes of galaxy formation/evolution



- star formation
- **feedback** (SN, stellar, BH)
  - metal enrichment
  - ionization
  - gas recycling
- BH formation/evolution
- merging

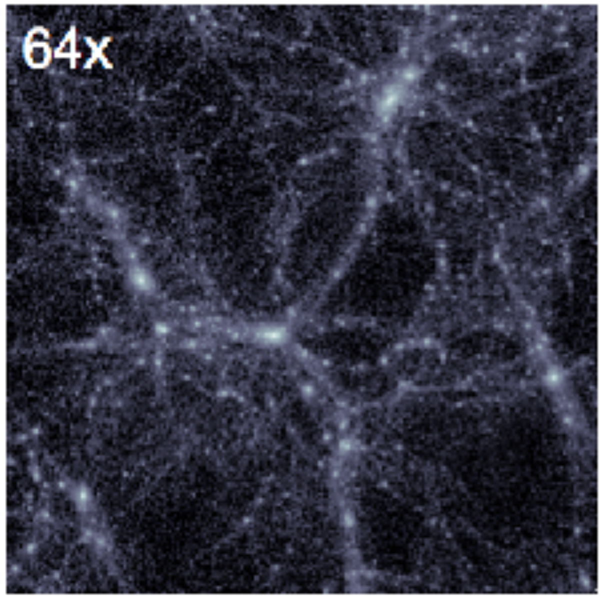
荒田氏・一色氏・宮川氏

- galaxy-IGM
  - outflow (metal enrich)
  - inflow (Lya?)
  - ionization (HII bubble?)

渡邉氏・加藤氏・五十嵐氏・永野氏

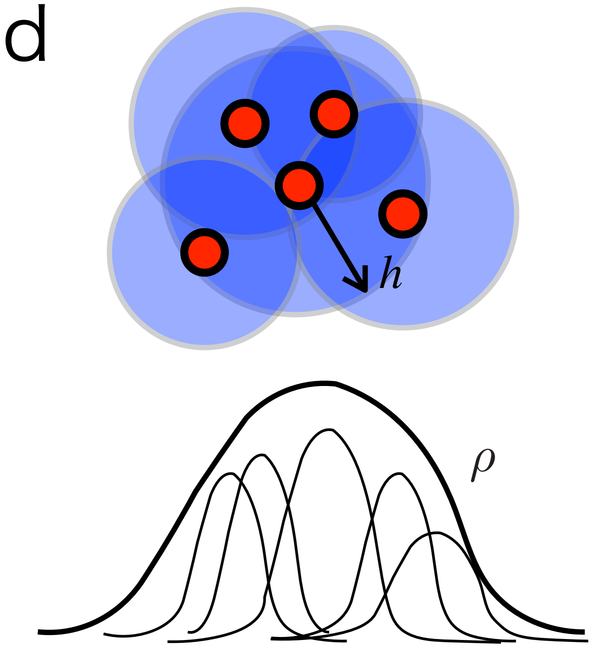
- statistic feature
  - Luminosity function, etc

Simulating the galaxy formation



(MUSIC use's guide, Hahn & Abel 11)

- Initial condition : ΛCDM
- physical processes
  - self-gravity (gas + DM + star)
  - gas dynamics (baryon physics)
    - solver : wide dynamic range should be treated
    - cooling/heating processed
      - chemical reaction, SN feedback, radiative feedback (stellar, BH)
    - Star formation



some modeling is required (due to the limitation of the resolution)

⇒ subgrid physics

Subgrid model in star formation

- Treatment of “stellar component” in the simulation
  - Star cluster particles, formed in low-temp., high-density region
    - cannot resolve the single star formation

$$n > n_{\rm th} \qquad T < T_{\rm th} \qquad (\ \nabla \cdot \vec{v} < 0 \quad y_{\rm H_2} > y_{\rm H_2,th}\ )$$

  - simple (single) stellar population (SSP)
    - stellar particle, having its own IMF and metallicity

✓ Schmidt law (density base)

$$\frac{d\rho_*}{dt} = c_* \frac{\rho_{\rm gas}}{t_{\rm dyn}}$$

c_* : parameter of SFE ~ 10^{-2}

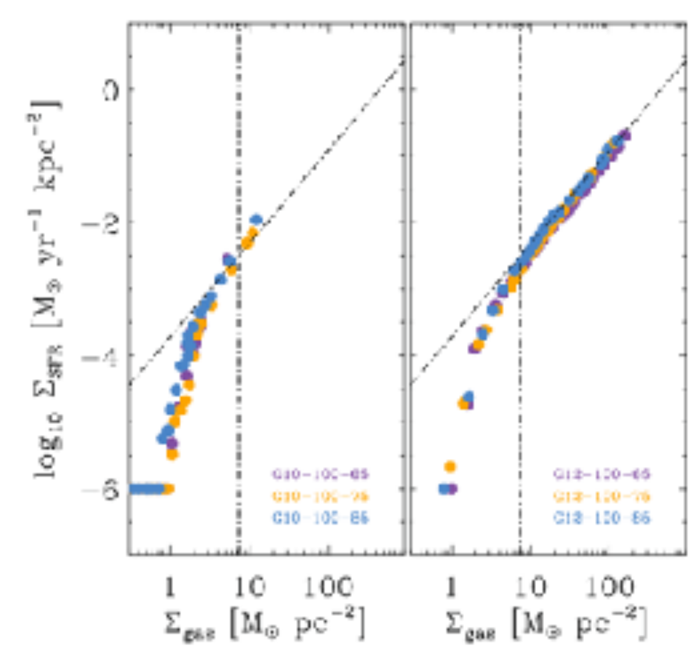
✓ Kennicutt-Schmidt law (pressure base)

$$\dot{m}_* = m_{\rm gas} A (1\ M_\odot\ {\rm pc}^{-2})^{-n} \left(\frac{\gamma}{G} f_{\rm g} P\right)^{(n-1)/2}$$

$$A \sim 10^{-4}\ M_\odot\ {\rm kpc}^{-2}\ {\rm yr}^{-1}$$

$$n = 1.4$$

(Schaye & Dalla Vecchia 08)

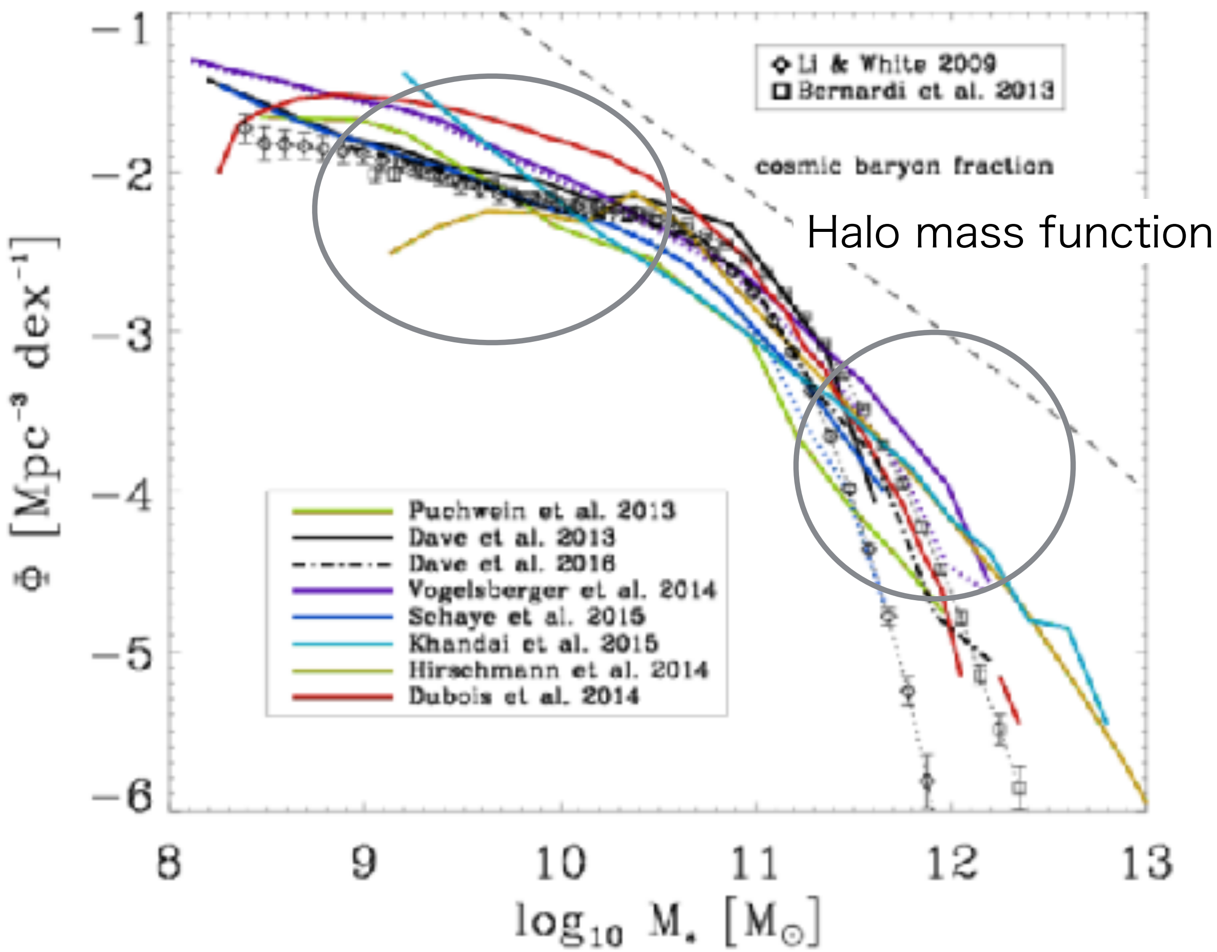


➡ stochastically form the stellar particle

$$p_* = \frac{\dot{m}_* \Delta t}{M_*}$$

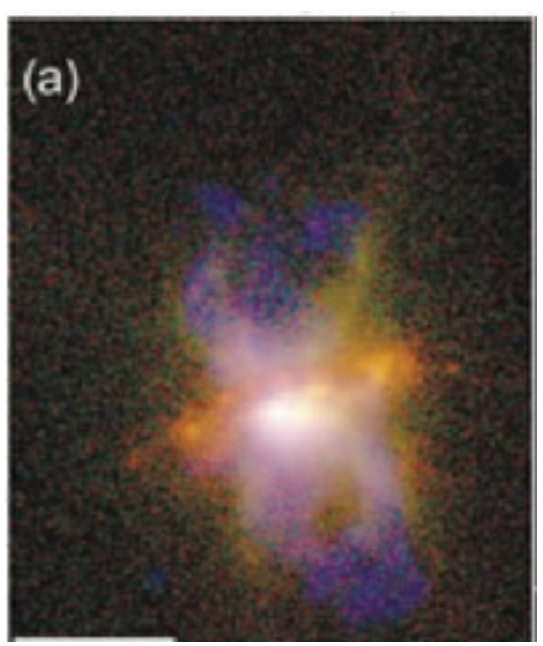
SN feedback

Naab & Ostriker (2017)



- Stellar mass function and DM halo mass function
  - suppression of the star formation by baryonic process

➡ SN feedback (massive galaxy → AGN?)



Veilleux+05

- energetic source of galactic wind
  - galaxy-IGM evolution
  - IGM metal enrichment

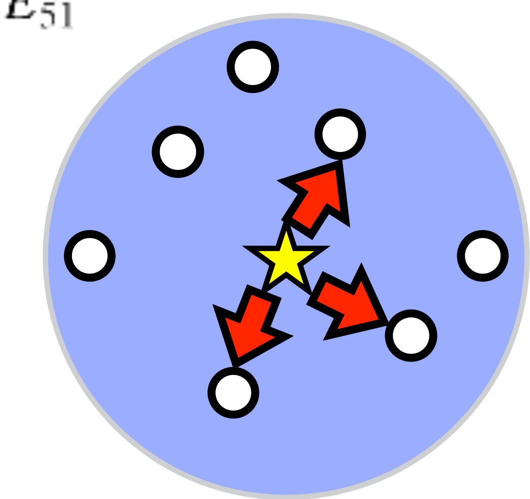
渡邉氏、五十嵐氏、永野氏talk

Modeling of SN feedback

- IMF and its mass range → SN energy from the stellar particle

$$n_{\mathrm{SN\,II}} = \int_{M_0}^{M_1} \Phi(M)\,\mathrm{d}M \qquad \epsilon_{\mathrm{SN\,II}} = 8.73 \times 10^{15}\,\mathrm{erg\,g^{-1}} \left(\frac{n_{\mathrm{SN\,II}}}{1.736 \times 10^{-2}\,\mathrm{M_\odot^{-1}}} \right) E_{51}$$

    - spread the energy and yield



- input the energy in thermal form
    - feedback is inefficient in the high-density region (cooling time is too short)

    ➡ switch off the cooling (e.g., Thacker+01)

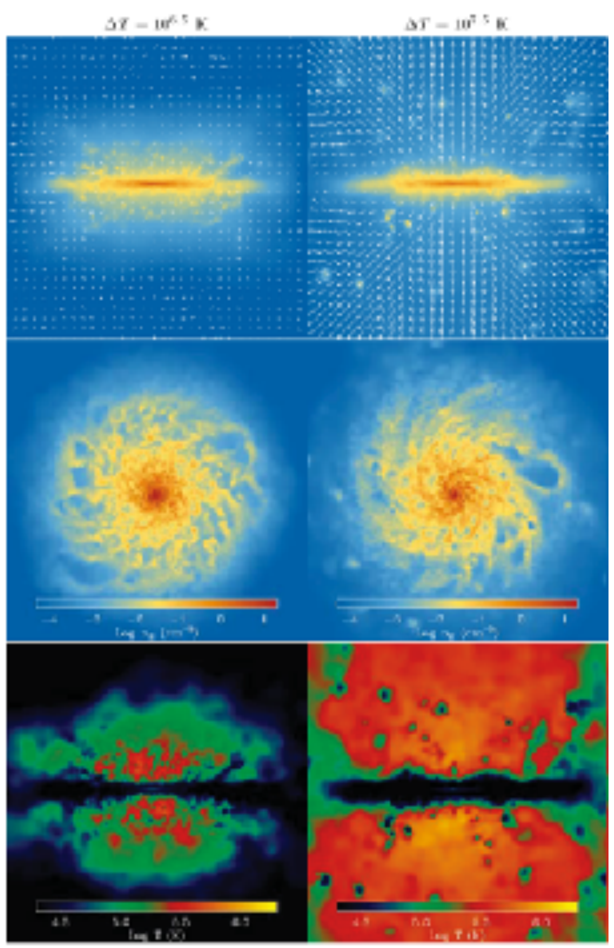
- input the energy in kinetic form
    - gas element cannot
        - switch off the hydro-term (Springel & Hernquist 03)

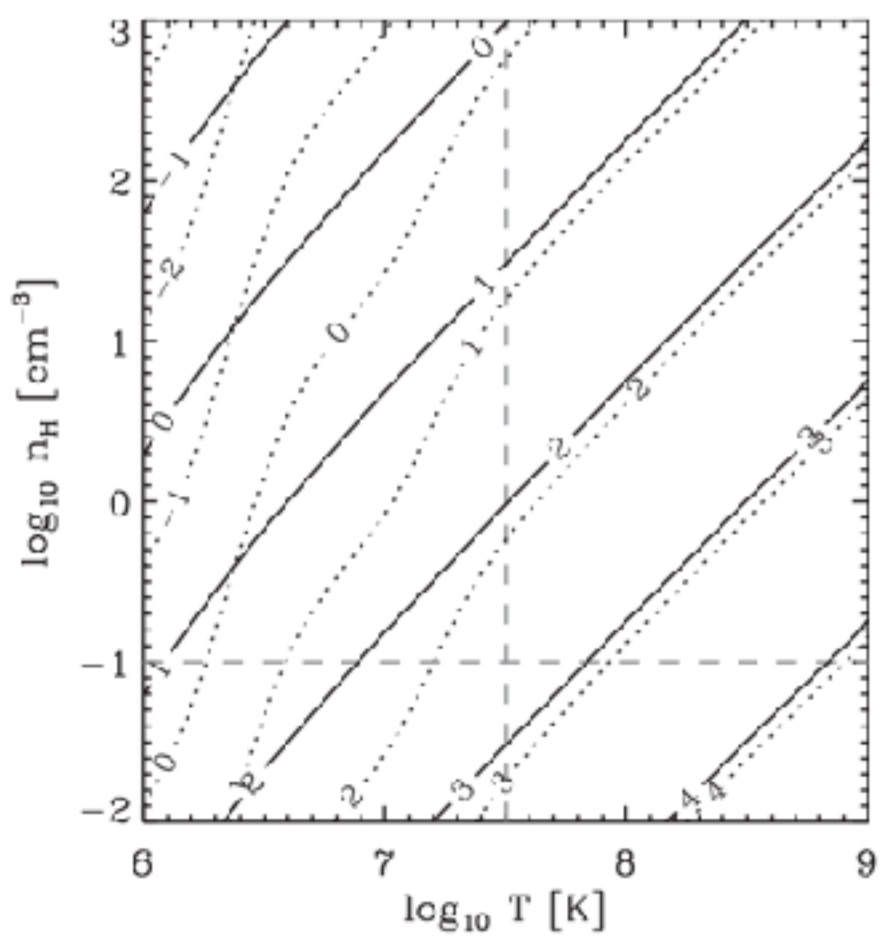
Stochastic thermal feedback

- developed by Dalla Vecchia & Schaye (2012)
    - inefficiency of feedback → mass resolution is insufficient

$$\Delta T = 4.23\times 10^{7}\ \mathrm{K}\left(\frac{n_{\mathrm{SNII}}}{1.74\times 10^{-2} M_{\odot}^{-1}}\right) E_{51}\boxed{\frac{m_*}{m_{\mathrm{g,heat}}}}$$

- partially stochastically input the energy to the (single) particle rather than all neighbors



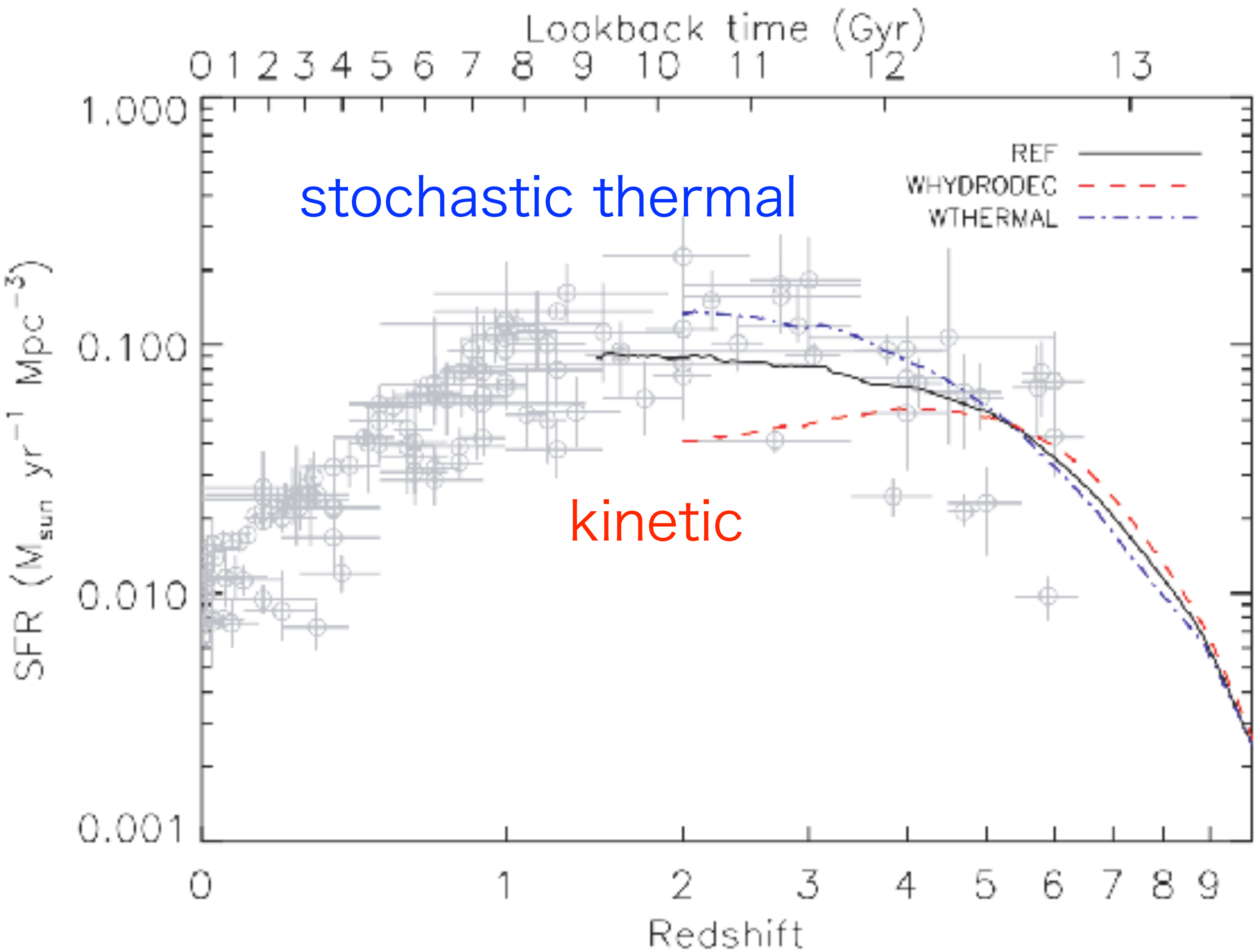


contour: $t_{\mathrm{cool}}/t_{\mathrm{sound}}$

condition for efficient thermal-kinetic conversion :

$$n_{\mathrm{H}} \sim 100\ \mathrm{cm}^{-3}\left(\frac{T}{10^{7.5}\ \mathrm{K}}\right)\left(\frac{m_{\mathrm{g}}}{10^{4}\ M_{\odot}}\right)^{-1/2}$$

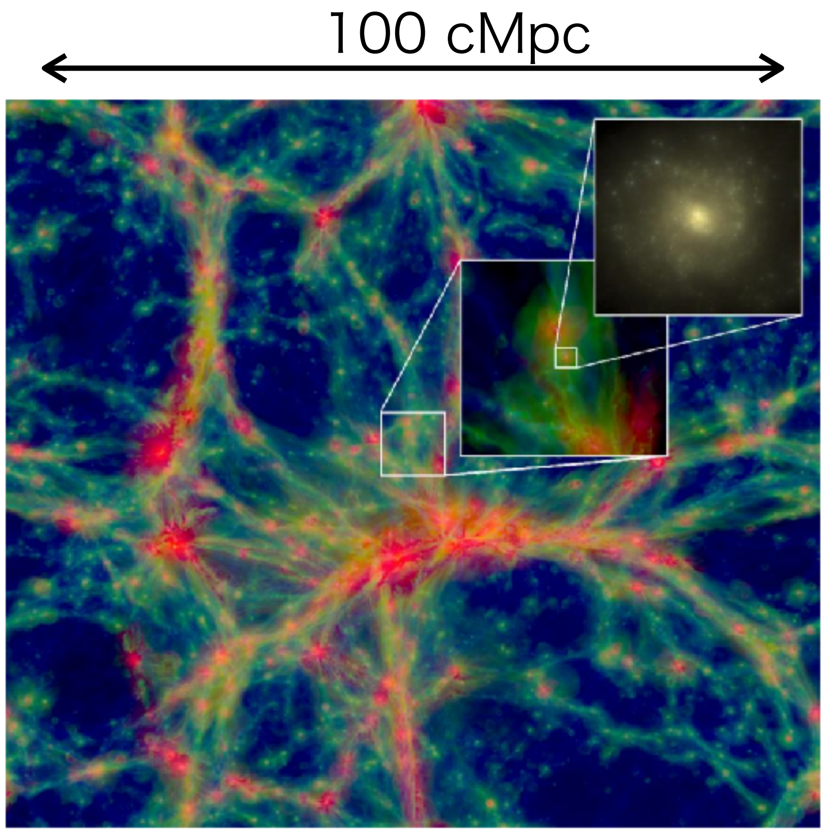
Thermal vs. Kinetic



SFRD (Schaye+10)

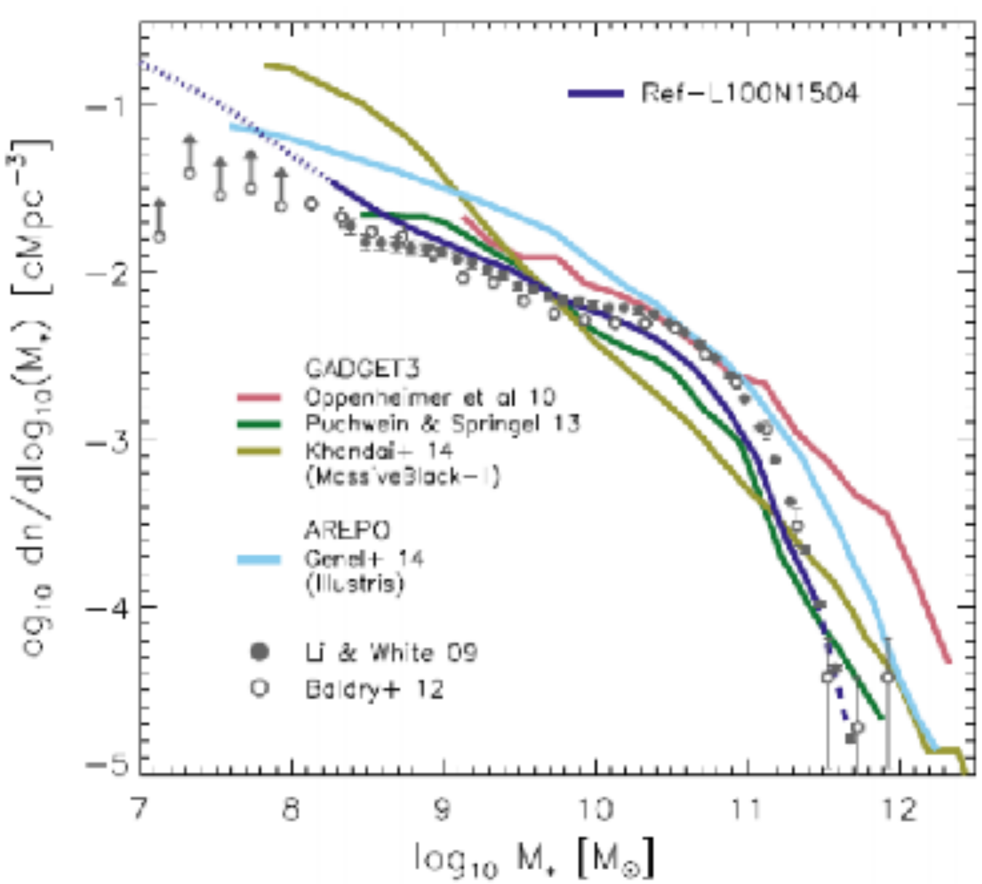
- kinetic form overestimate the feedback in low-z
  - no gas drag in kinetic form, number of wind particle increase with increasing SF
- stochastic thermal form seems to be in good agreement with observation

Thermal SN feedback in cosmological simulation



- EAGLE simulation

Name	L (cMpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ_{com} (comoving kpc)	ϵ_{prop} (pkpc)
L025N0376	25	376^3	1.81×10^6	9.70×10^6	2.66	0.70
L025N0752	25	752^3	2.26×10^5	1.21×10^6	1.33	0.35
L050N0752	50	752^3	1.81×10^6	9.70×10^6	2.66	0.70
L100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70



- luminosity function at z = 0
    - seems to be in good agreement with the observation

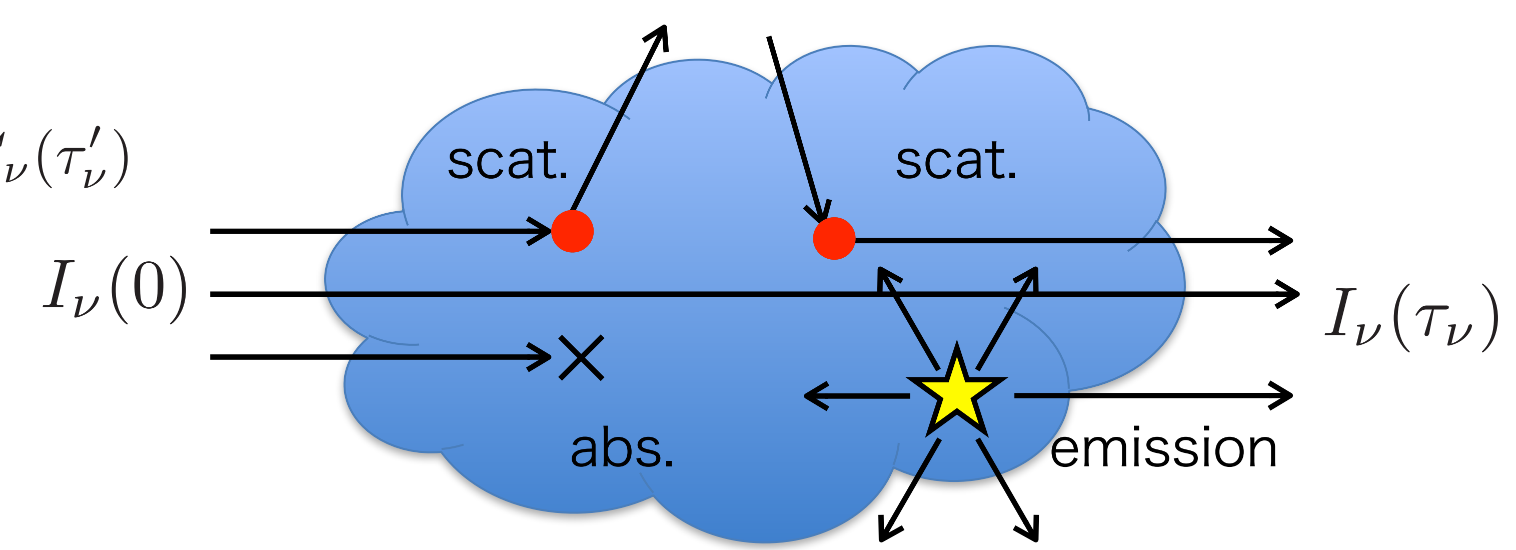
Radiative transfer and galaxy formation

- importance of the radiative transfer (RT) calculation
  - observation
    - optical properties (LAE, LBG, SMG..)
    - post-process
  - physical state of the gas
    - radiation from stars/BH (internal), UV (external)
    - photo-ionization、dissociation (heating, destruction of coolant)
    - radiation pressure (ionizing photon、Lya、IR)

      → radiation hydrodynamics (fully coupled with hydro)

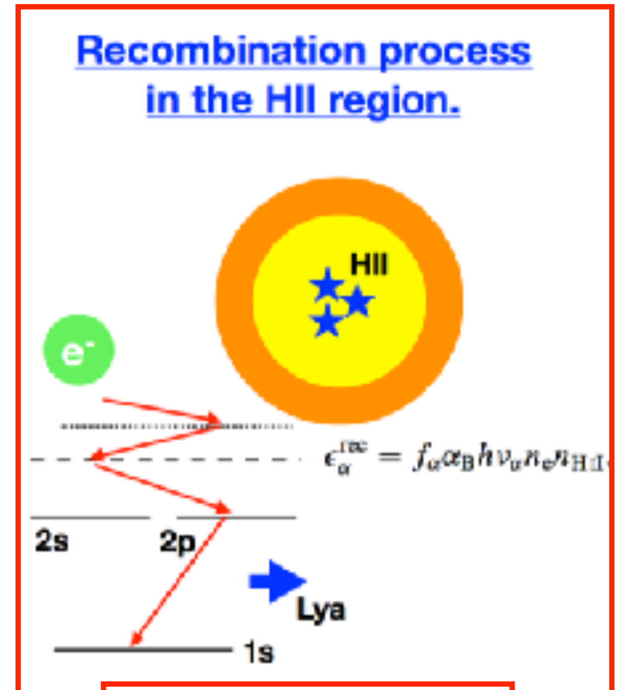
荒田氏・一色氏

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu} + \int_0^{\tau_\nu} d\tau'_\nu (1 - e^{-\tau'_\nu}) S_\nu(\tau'_\nu)$$

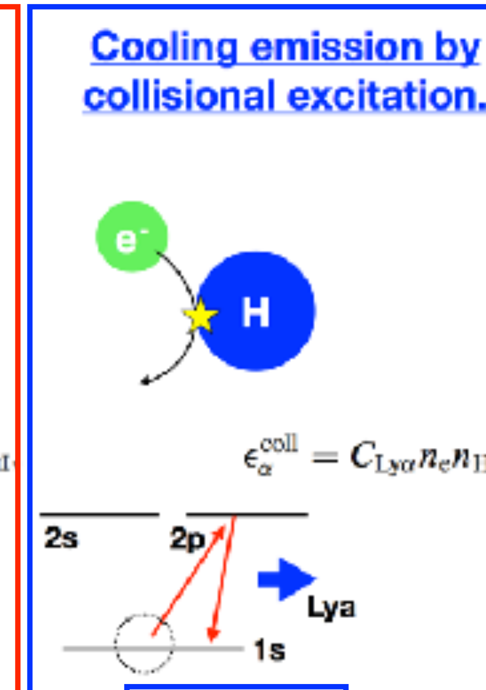


High-z LAEs

- strong Lya line
  - origin of Lya emission ?
  - intrinsic properties
    - spectrum, luminosity, SB profile

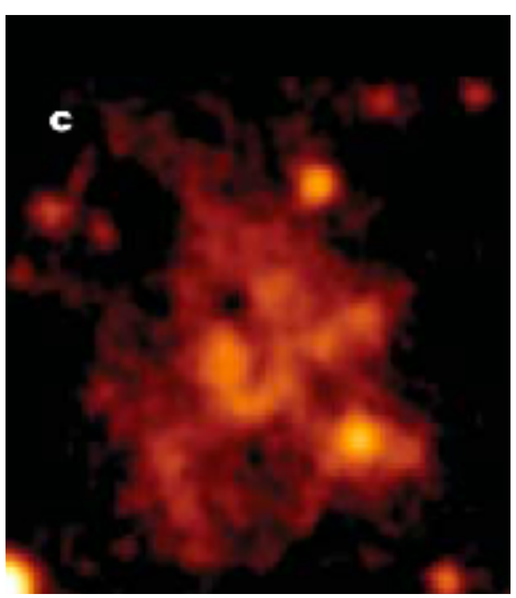


star formation

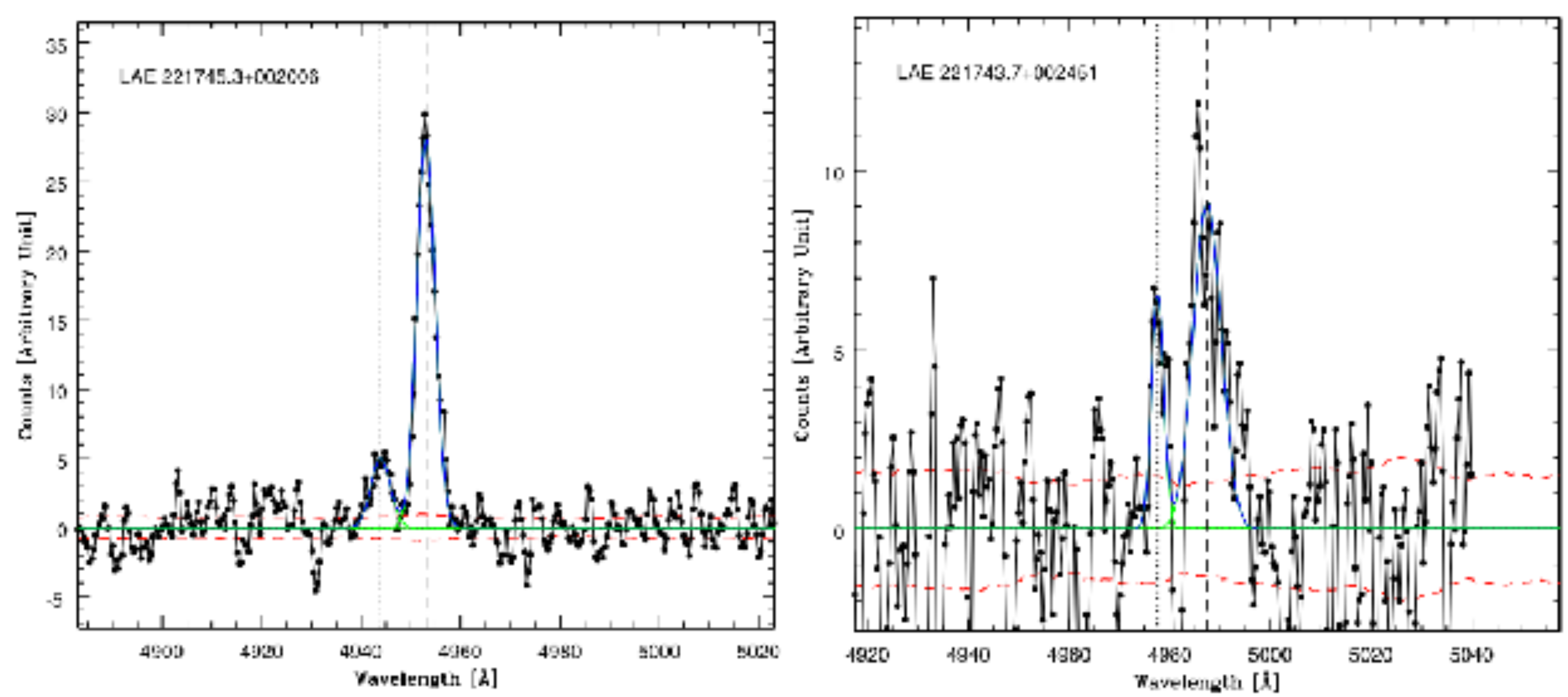


cooling

➡ solve the Lya RT (resonant scattering) in the galaxy



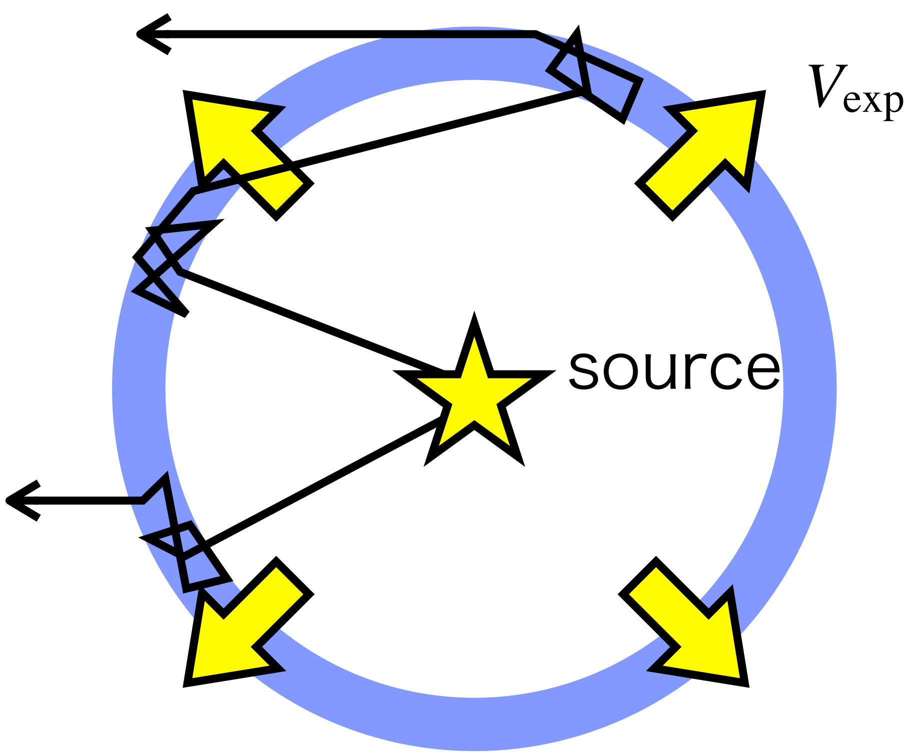
(Matsuda+)



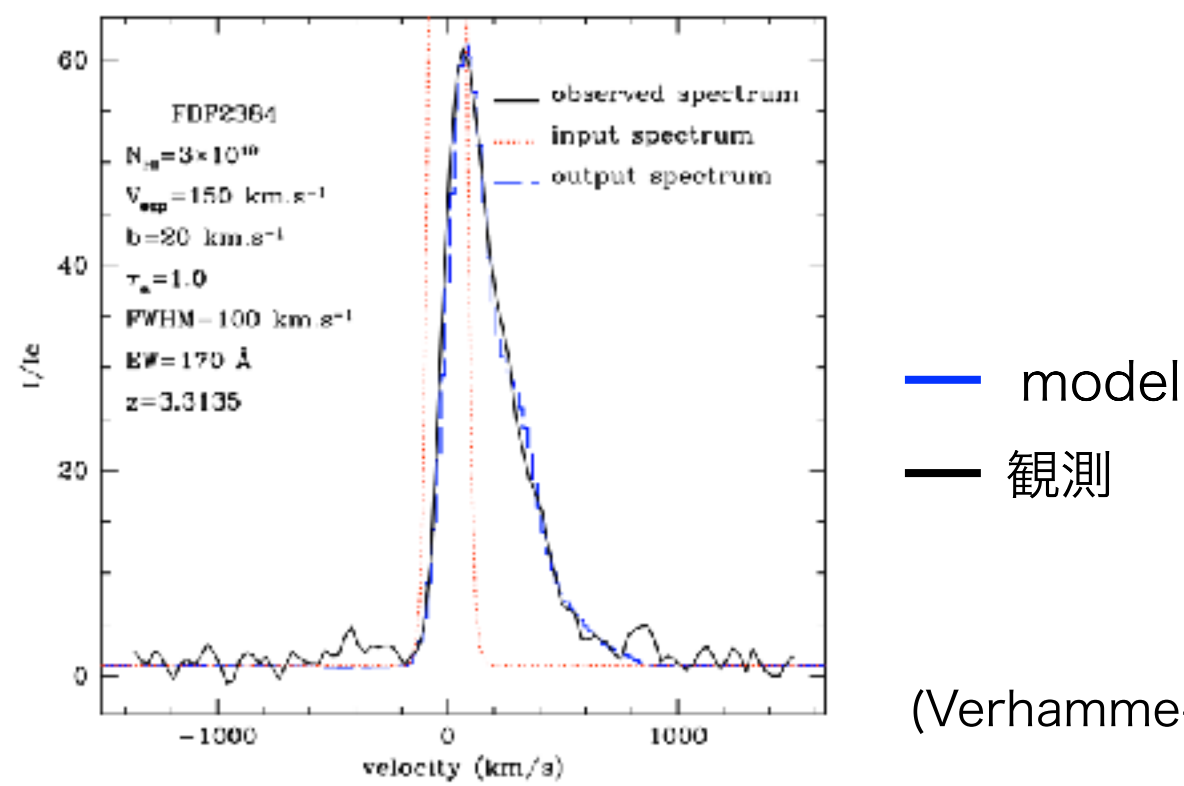
Lya emergent spectra (Yamada+12)

Simple model

- Expanding shell model (Verhamme+06)
  - successfully reproduce the redward emergent spectrum of LAE (e.g., Yamada+12)



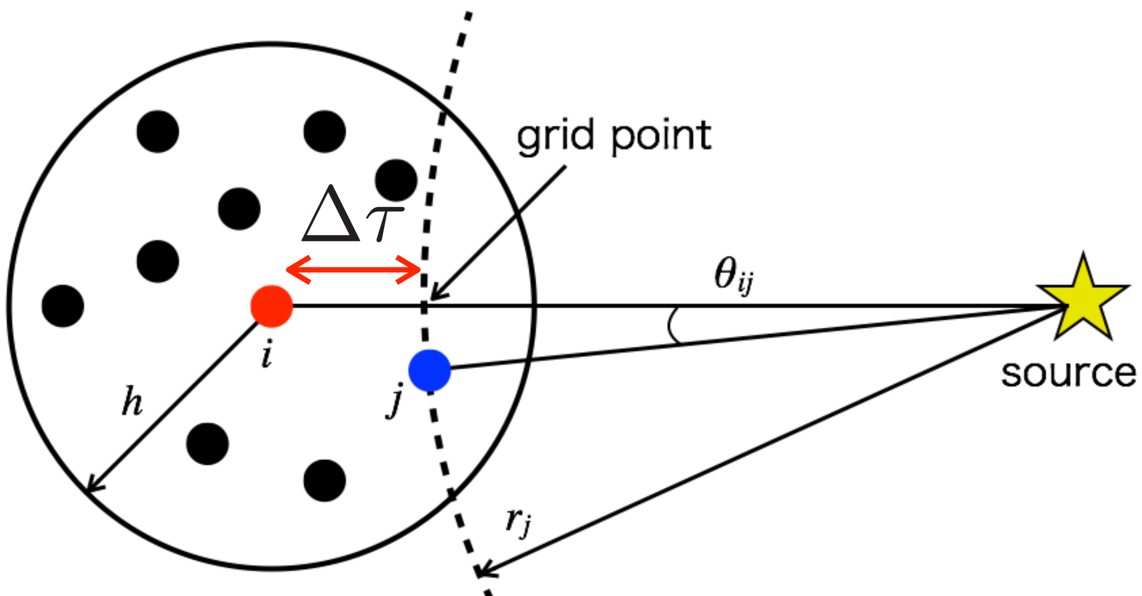
expanding HI shell



(Verhamme+08)

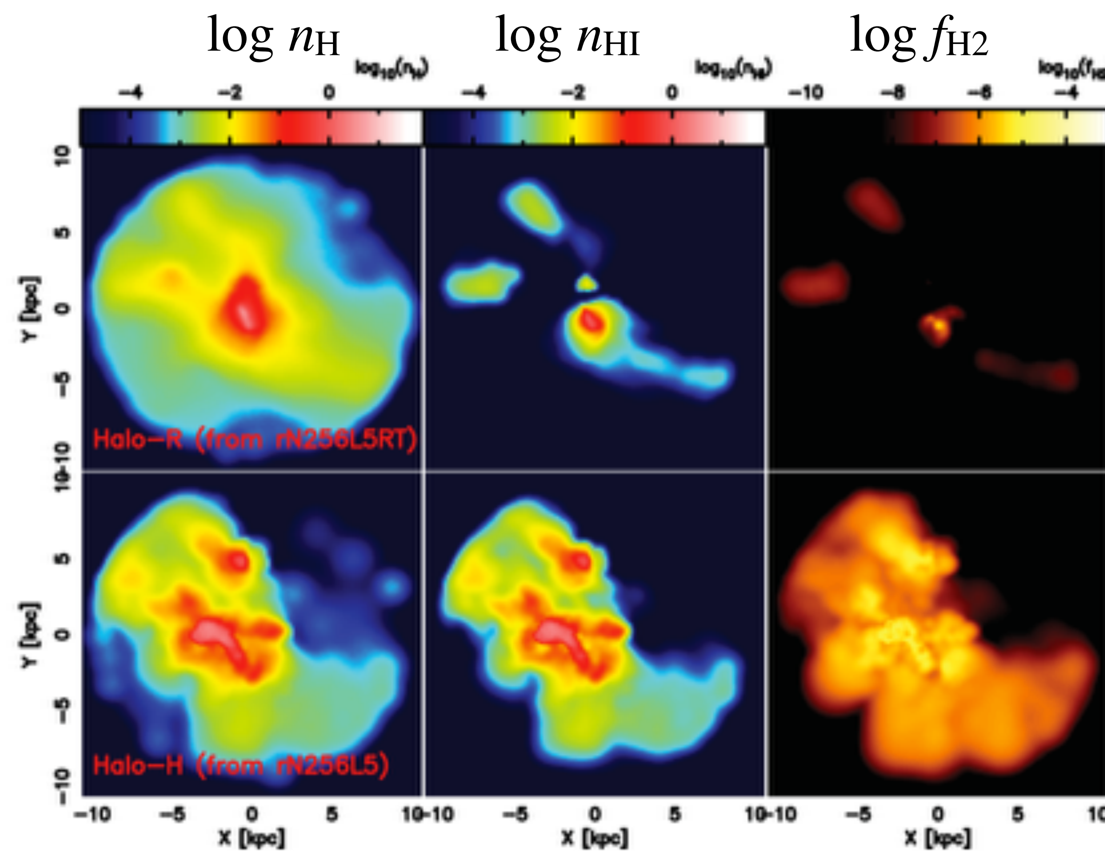
Galaxy model by UV RHD

- cosmological SPH+UV RT simulation
  - Hydro+non-equilibrium chem.+RT is consistently solved



ray-tracing in SPH (RSPH, Susa 06)

$$k = \int_{\nu_L}^{\infty} d\nu \int d\Omega \frac{\sigma_\nu I_\nu}{h\nu} \quad , \; \Gamma = \int_{\nu_L}^{\infty} d\nu \int d\Omega \frac{(h\nu - h\nu_L)\sigma_\nu I_\nu}{h\nu}$$



cosmological RHD simulation (Hasegawa&Semelin 13')
w/ (upper) and w/o (lower) stellar UV feedback

✓ density ✓ temperature ✓ ionization deg.

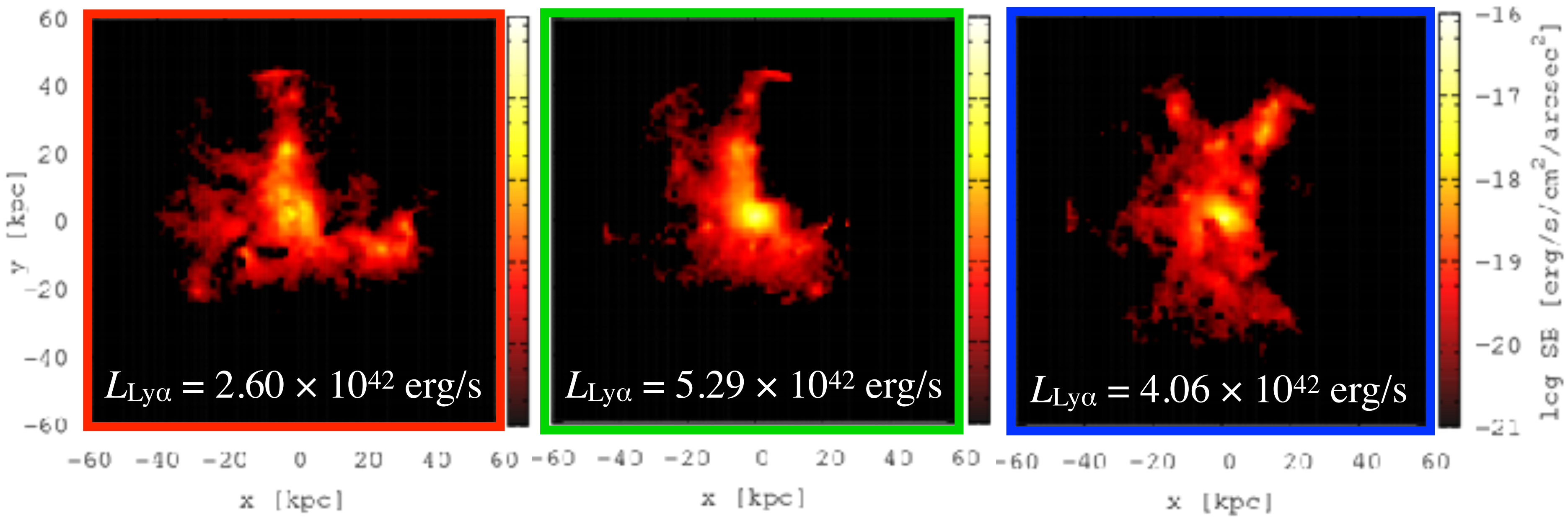
recombination $\epsilon_\alpha^{\rm rec} = f_\alpha \alpha_B h\nu_\alpha n_{\rm e} n_{\rm H_{II}}$

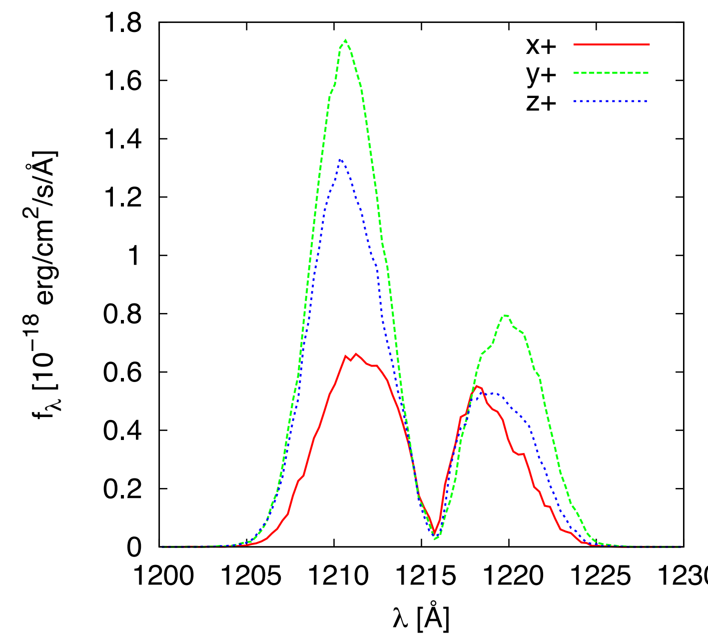
collisional $\epsilon_\alpha^{\rm coll} = C_{\rm Ly\alpha} n_{\rm e} n_{\rm H_I}$

⇨ Lya RT (post-process)

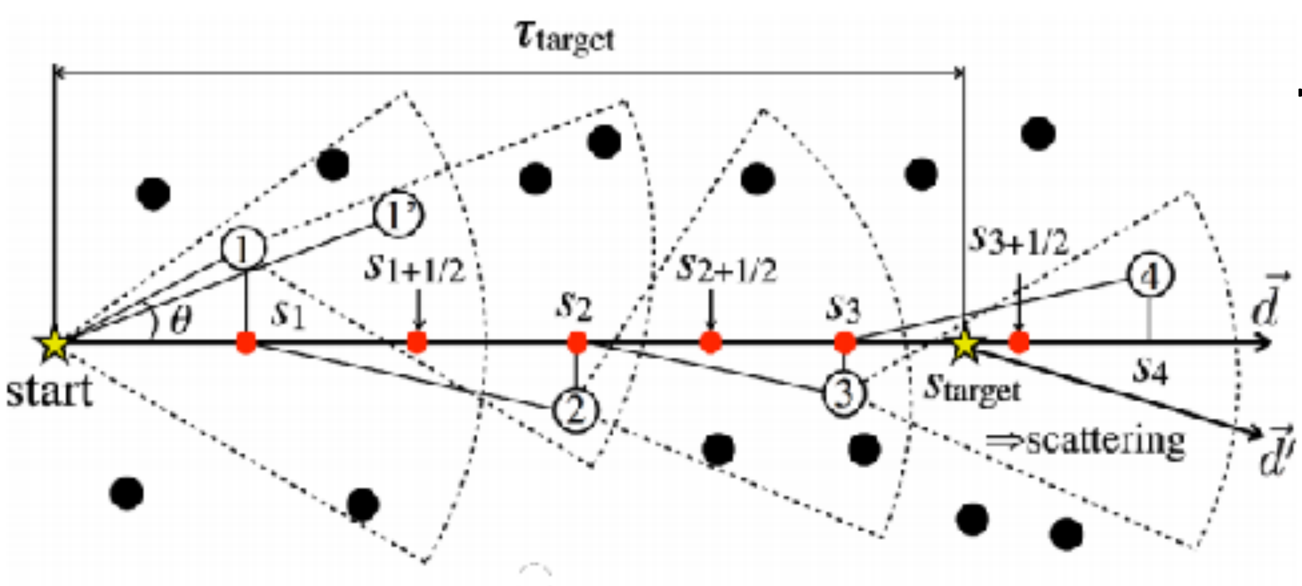
Surface brightness, emerging spectrum

model : $M = 5\times10^{10}\,M_{\odot}$, $z \sim 6$





Lya RT: calculated by SEURAT (MA+18)

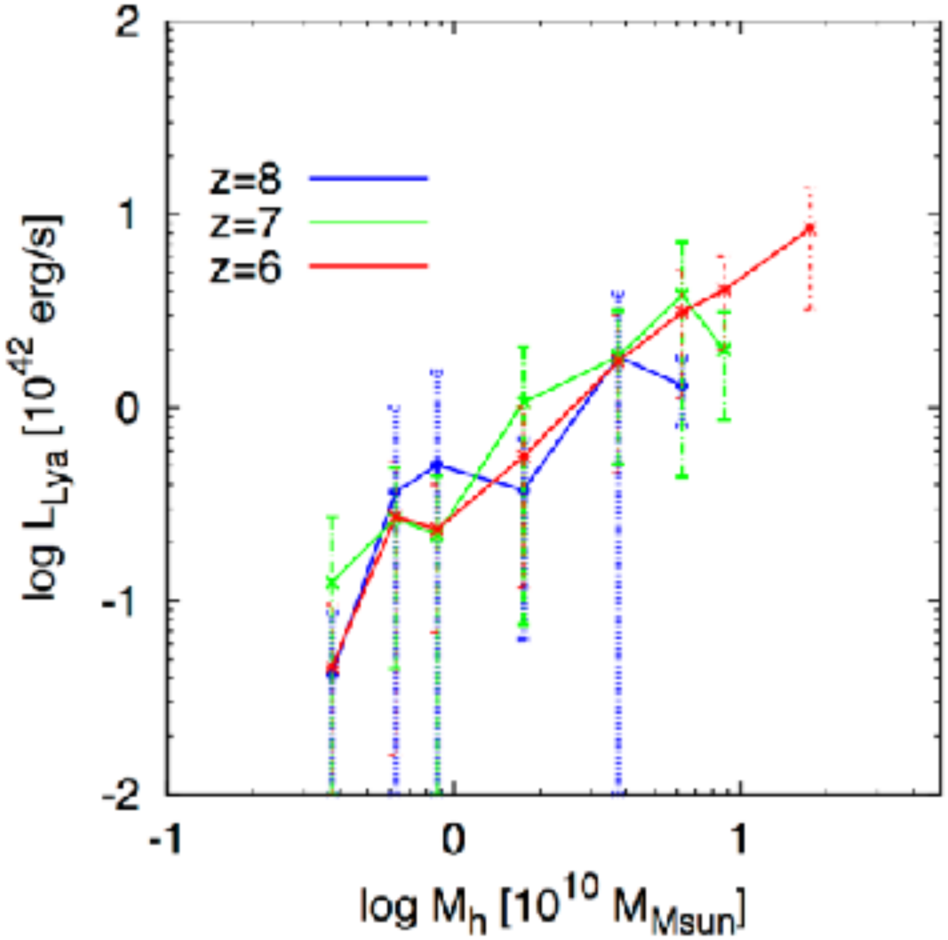


particle-based Lya RT (Monte Carlo)

- Lya properties depend on the viewing direction
  - three-dimensional RHD simulation may be required to model the LAE

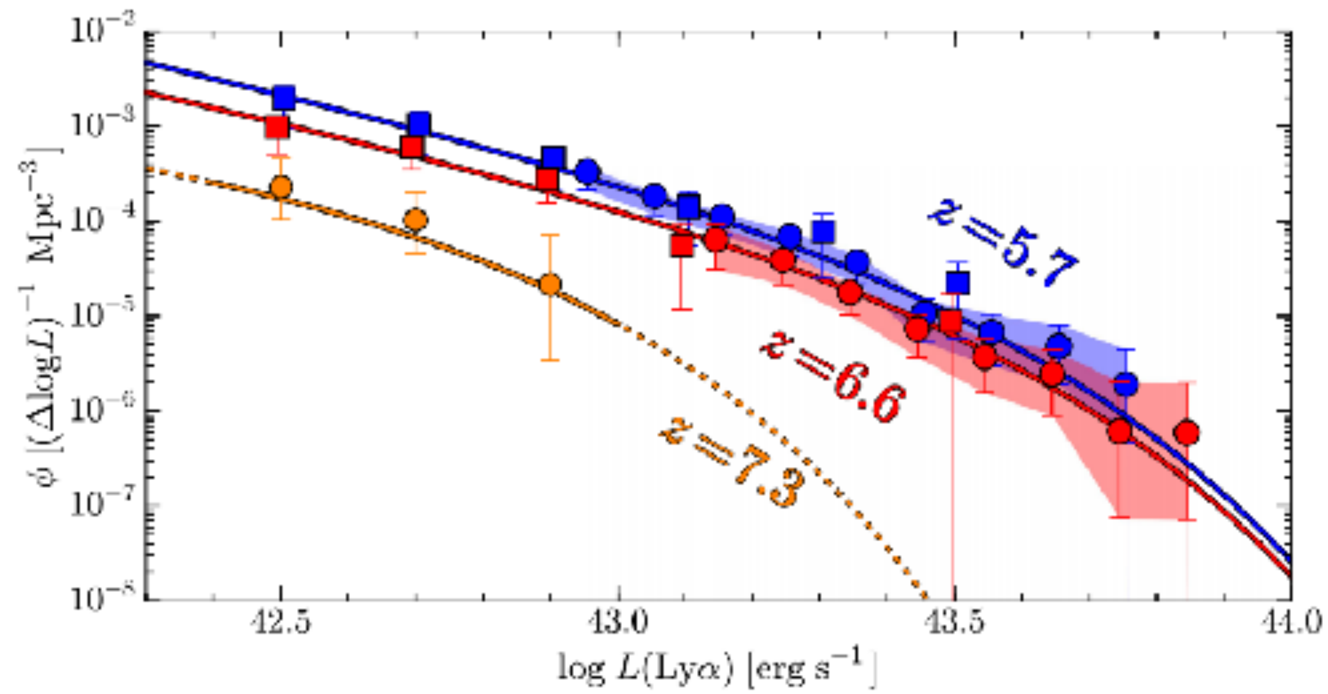
intrinsic LAE luminosity function

theoretical model



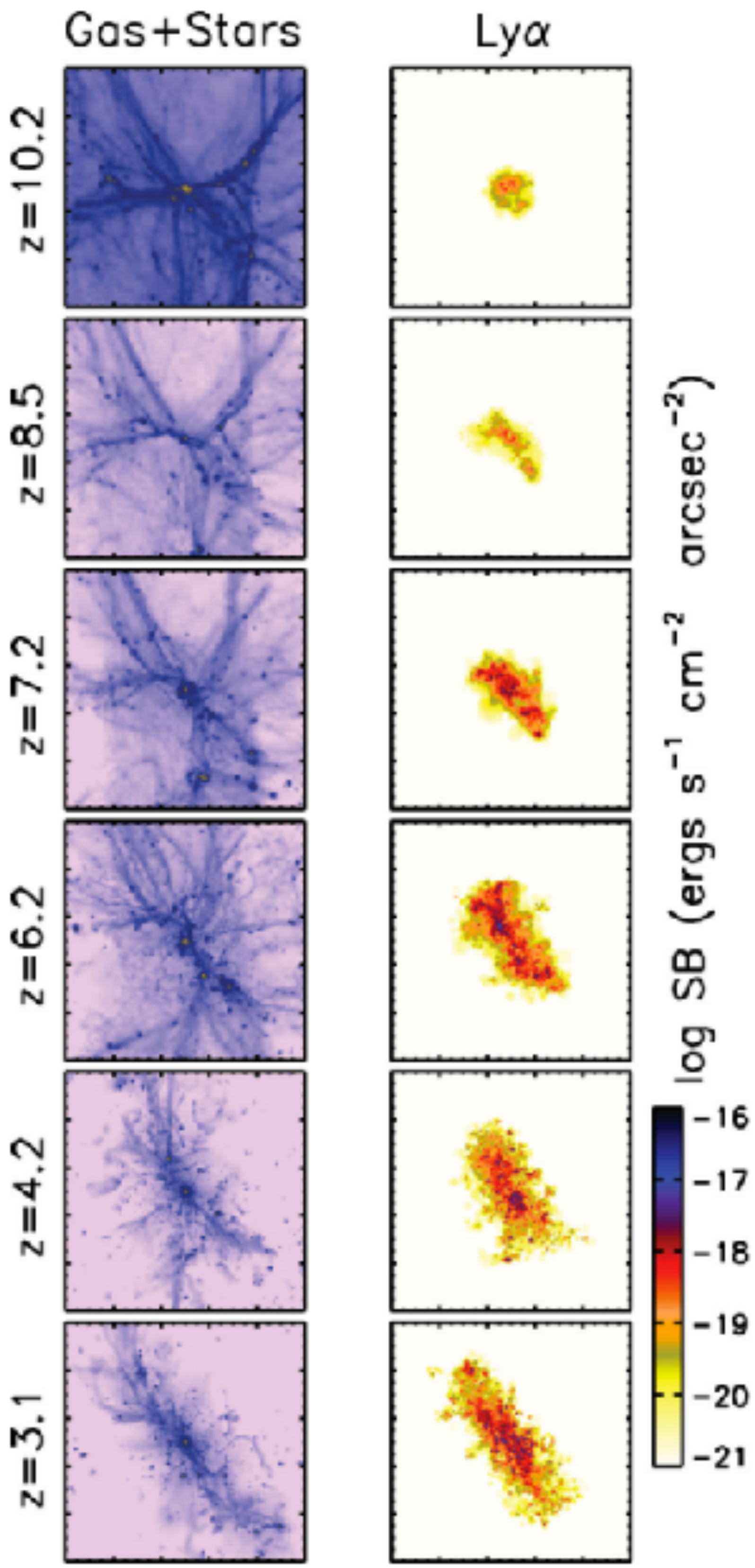
no evolution?

Konno+18

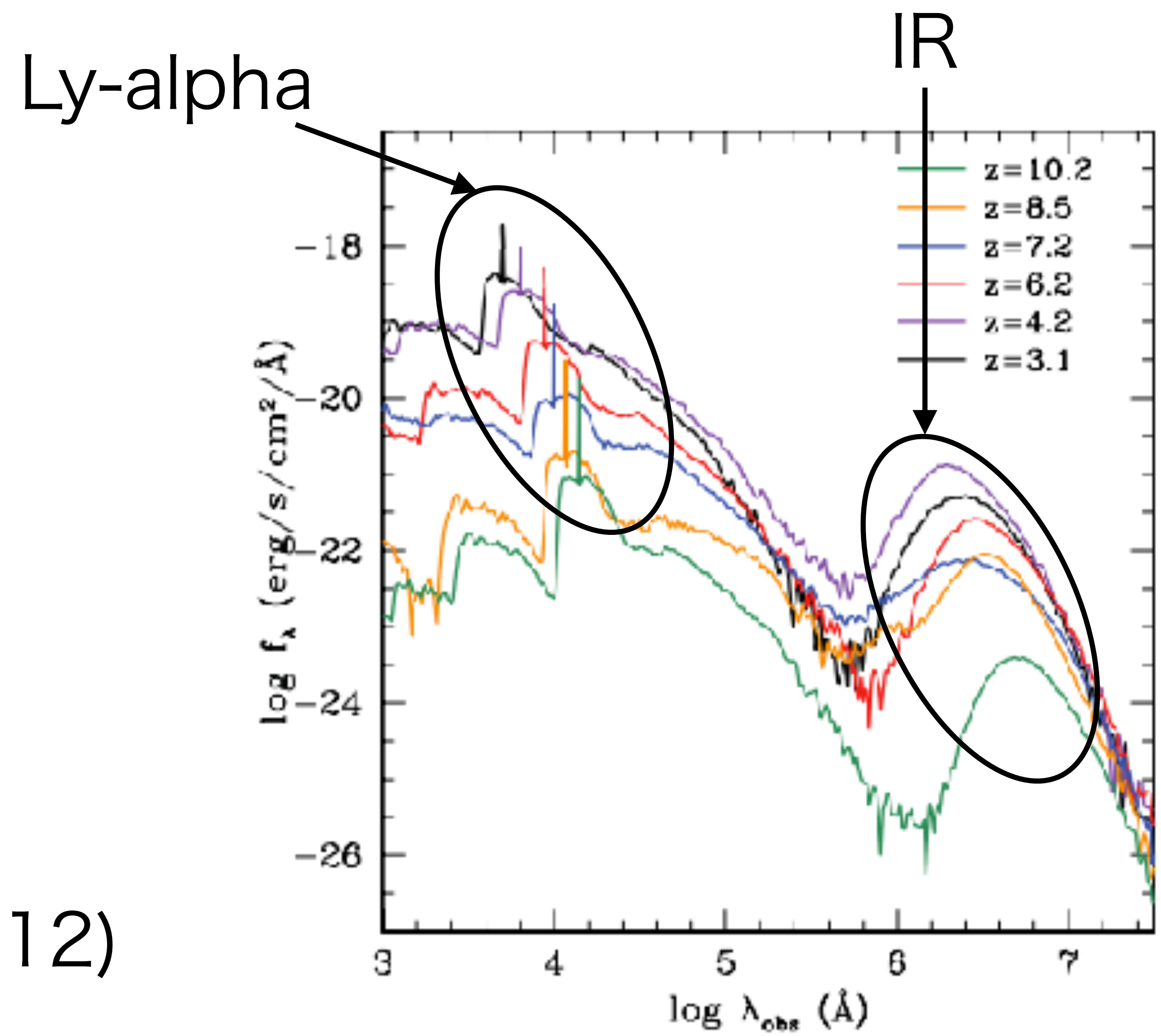


evolution of LF

Radiative transfer with multi-wavelength



- optical properties (SED) of high-z galaxy may reflect the state of ISM
- modeling of diversity of high-z galaxies
  - cosmological simulation + multi-wavelength RT (post-process)



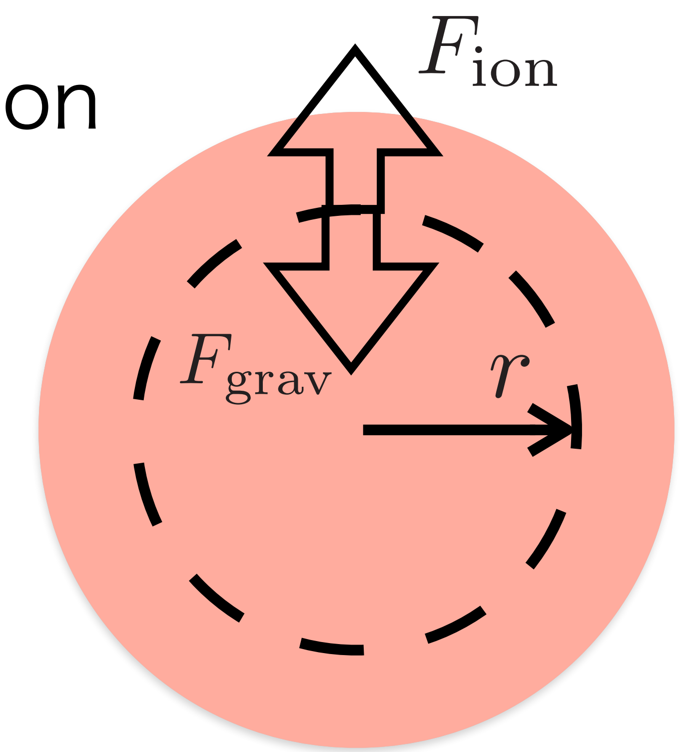
(Yajima+12)

Momentum transfer

Momentum transfer from ionizing radiation

$$F_{\rm ion} = \frac{\chi^2 \alpha_{\rm B} h\nu_{\rm ion} n_{\rm H}}{c}$$

$$F_{\rm grav} = \frac{GM(r)m_{\rm p}}{r^3} = \frac{4\pi G m_{\rm p}^2 n_{\rm H} r}{3}$$



spherical homogeneous cloud

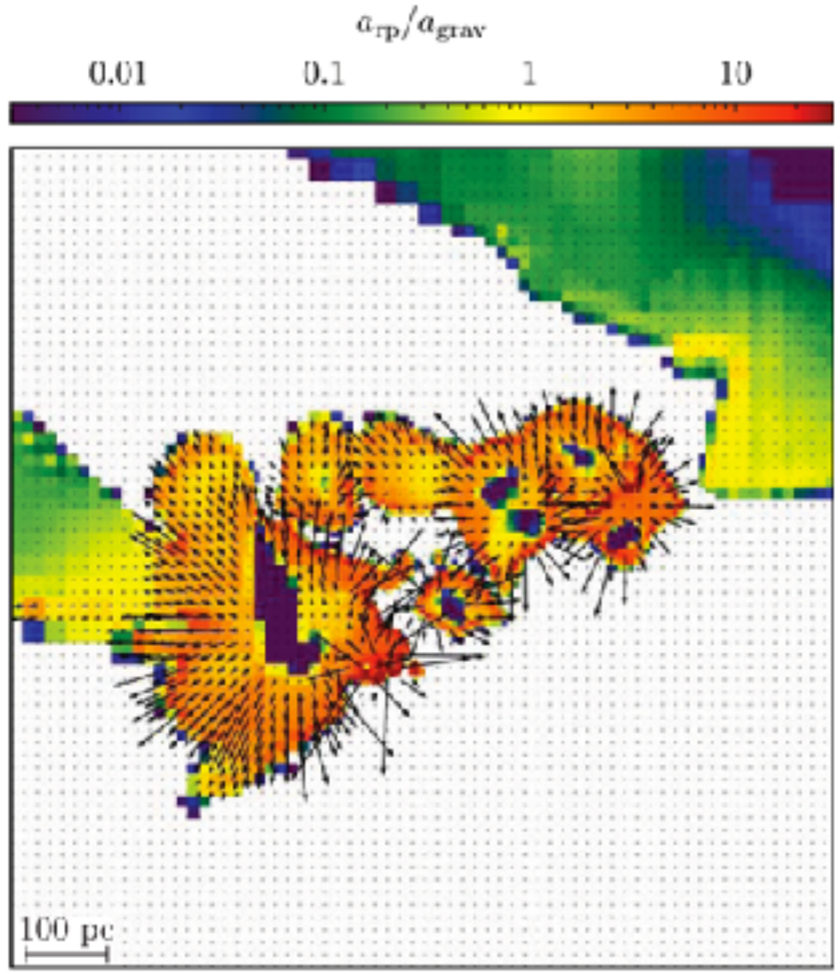
radiation pressure exceed the gravity :

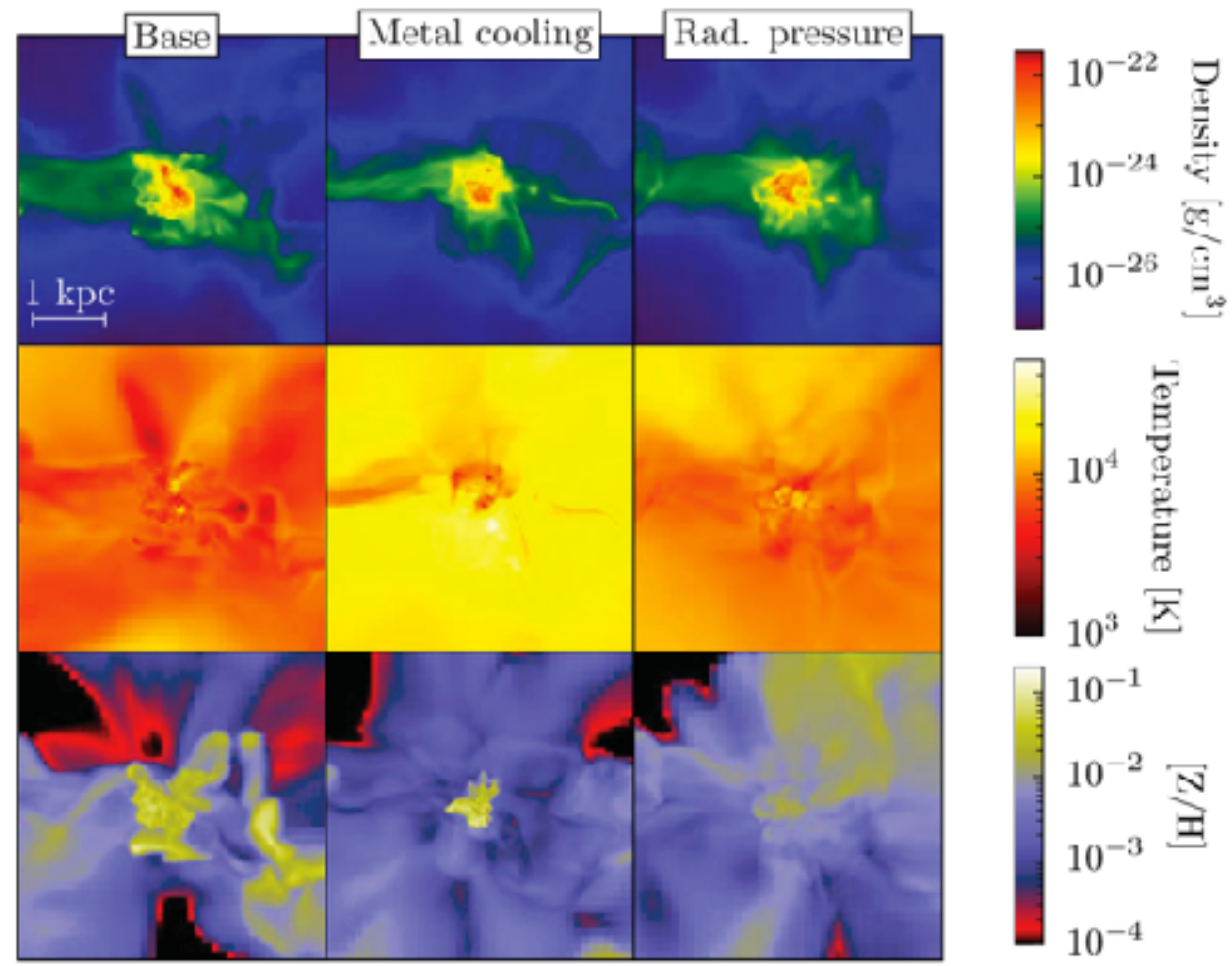
$$r_{\rm rp} = \frac{3\alpha_{\rm B} h\nu_{\rm ion}}{4\pi c G m_{\rm p}^2} \sim 100 \ {\rm pc}$$ (Haehnelt 95)

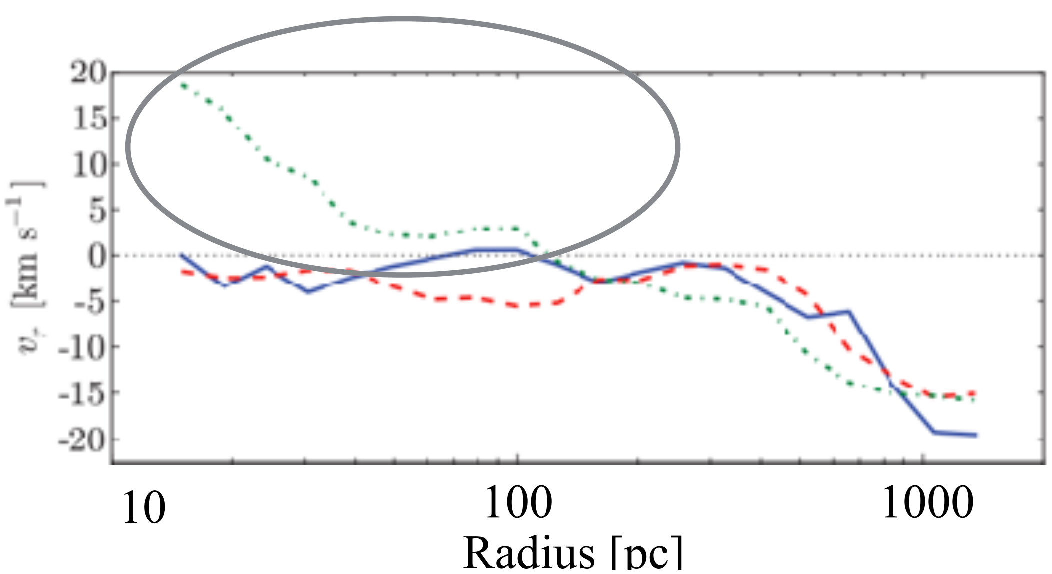
affect the star formation in the galaxies？

Radiative momentum transfer

- momentum transfer of ionizing radiationin dwarf galaxy (Wise+12)

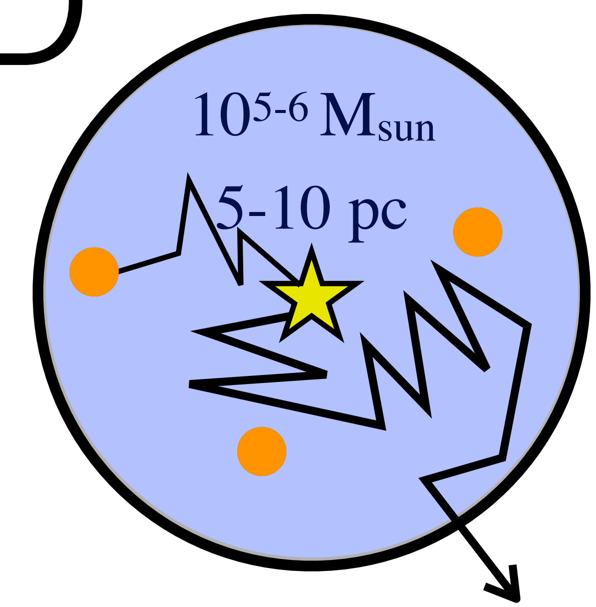






- w/o radiation pressure → overcool
  - metal cooling is too effective, compact star-forming region at the centre of the galaxy

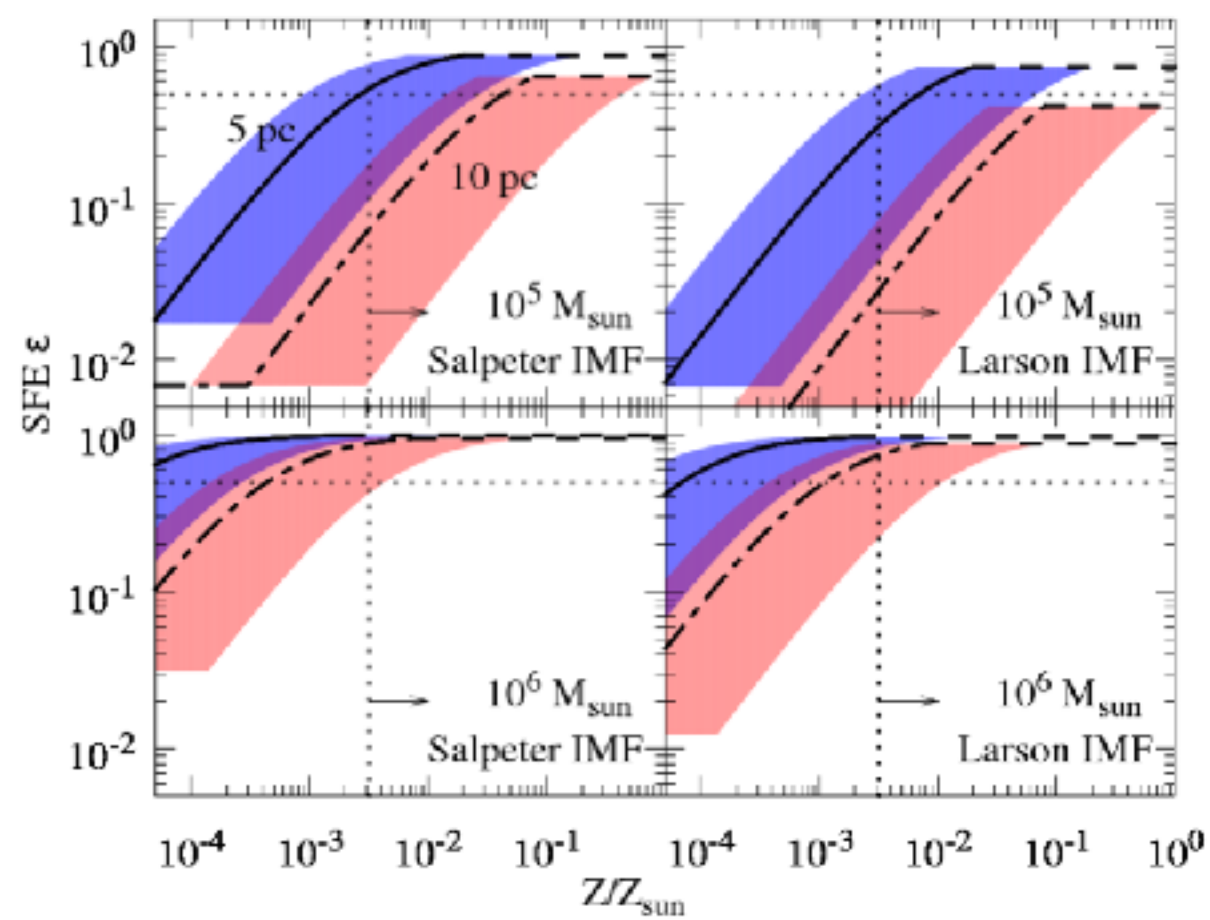
Recent topic: Lya RHD



- Lya radiation force
  - ✓ trapping the Lya photons in the cloud, increase the photon density

$$F_{\rm rad}^{\rm Ly\alpha} \sim \frac{t_{\rm trap}}{t_{\rm cross}} \frac{L_{\rm Ly\alpha}}{c} \equiv f_{\rm boost} \frac{L_{\rm Ly\alpha}}{c},$$

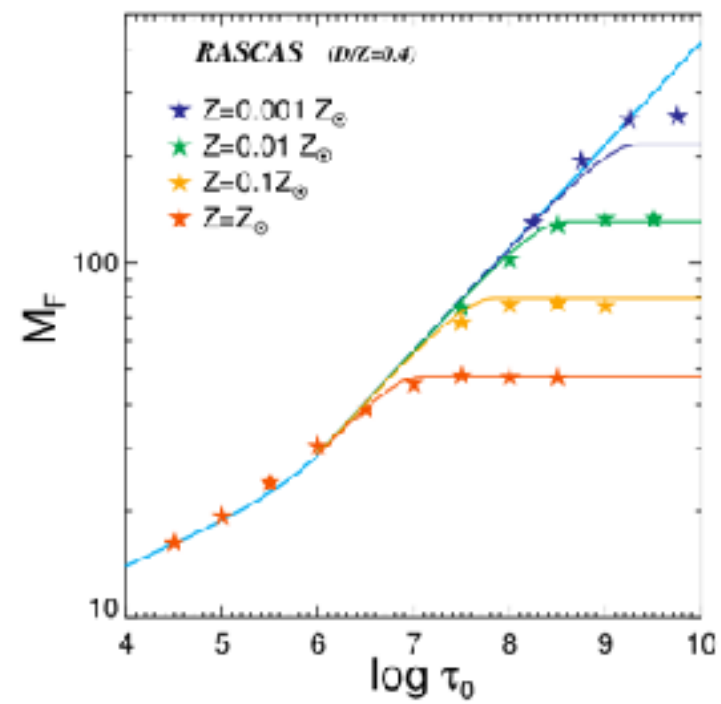
- ✓ boost factor decrease with increasing the metallicity (by dust abs.)
  - ➡ Lya feedback is effective in low-metal gas



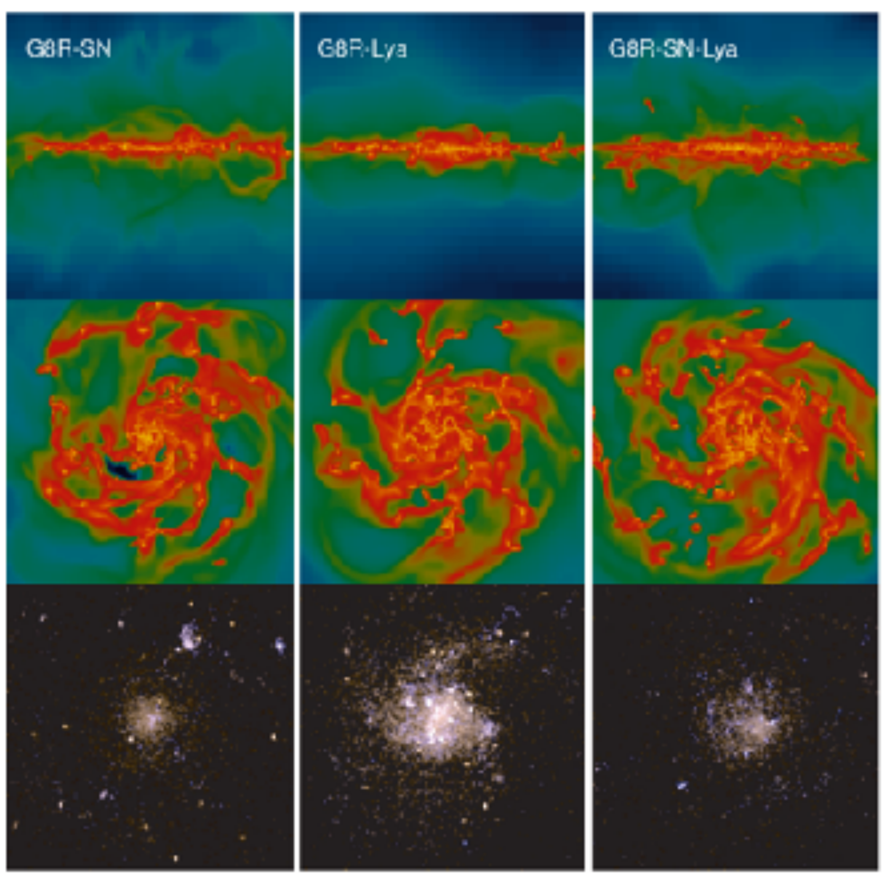
MA & Yajima (2018)

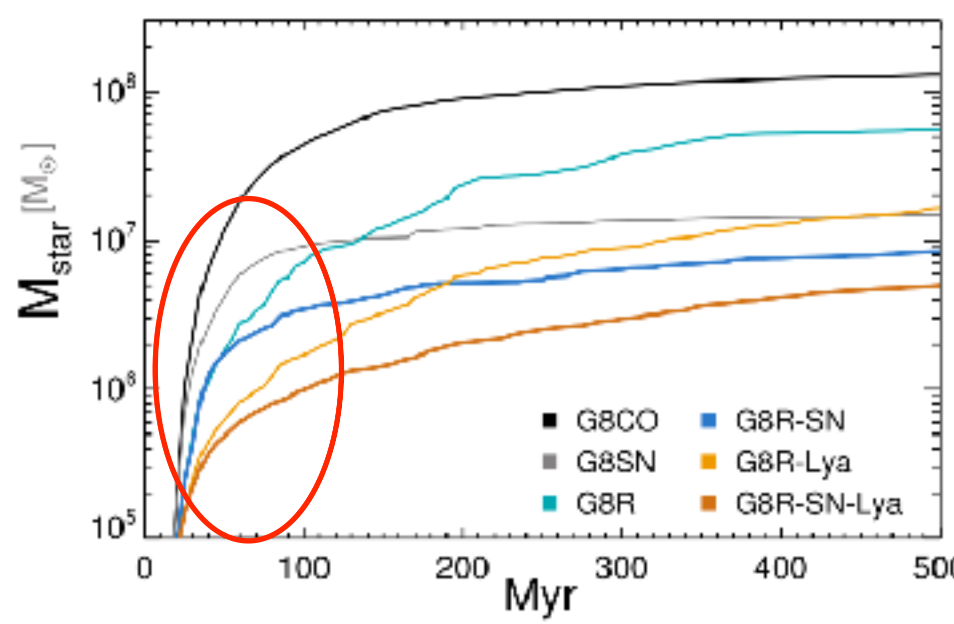
Lya feedback in the galaxy

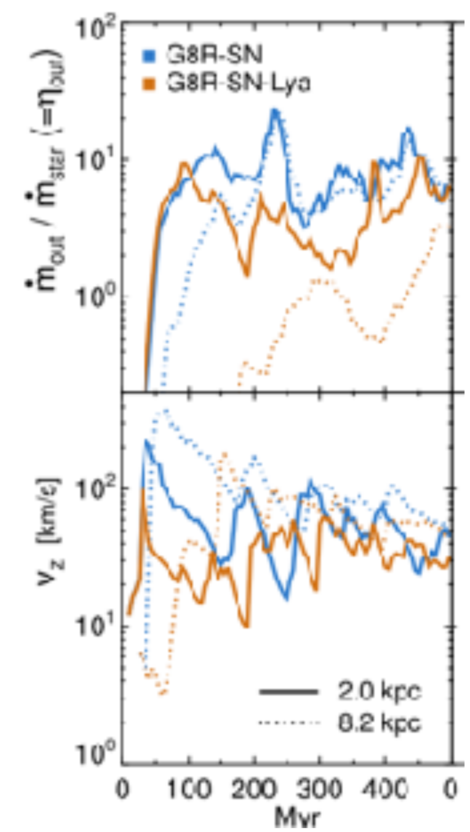
- subgrid modeling by Kimm+18
    - estimate the local boost factor (trapping time) from optical depth
      ＊neglect velocity structure



metal-poor dwarf galaxy



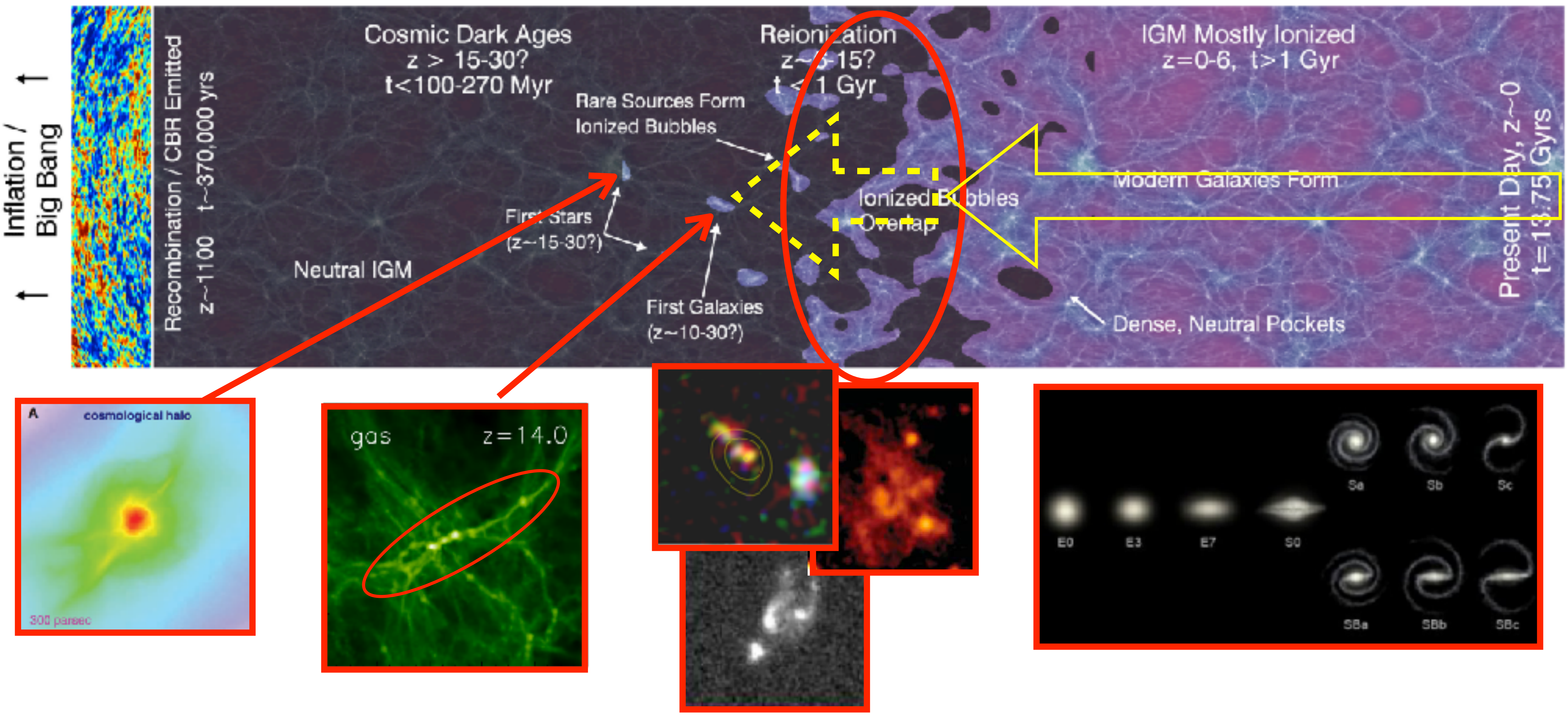




- Lya feedback is efficient at early phase
- SN suppress the subsequent SF

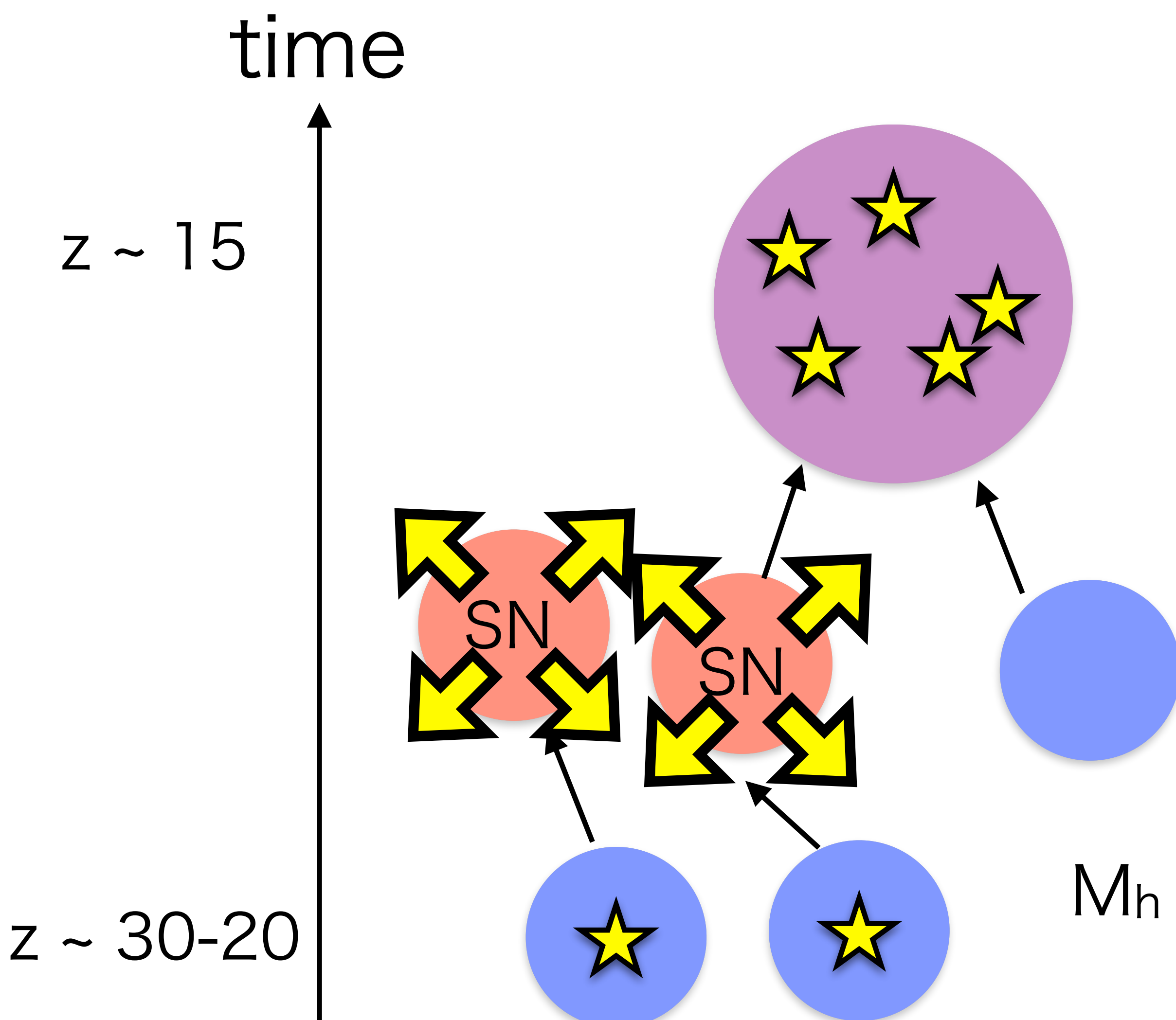
First galaxies

Robertson+10



First galaxies

- target in the JWST era?



first galaxy: $M_h > \sim 10^8\ M_\odot$

Pop II (+ Pop III ?)

- PopIII ⇒ SN explosion (CCSN / PISN)
  - metal enrichment
  - gas ⇒ evacuated from mini-halo

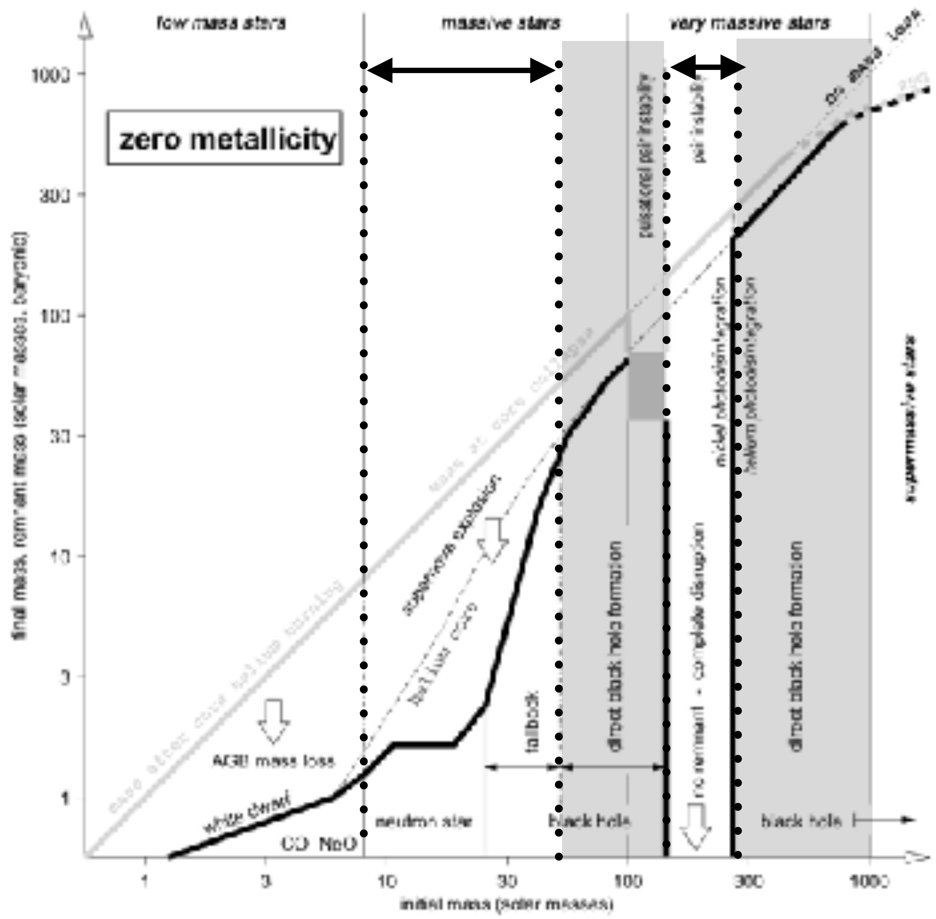
$M_h = 10^6\ M_\odot$

Pop III formation

- Properties of the first galaxy?
  - SFR, SFH (Pop III ⇒ Pop II transition), metallicity

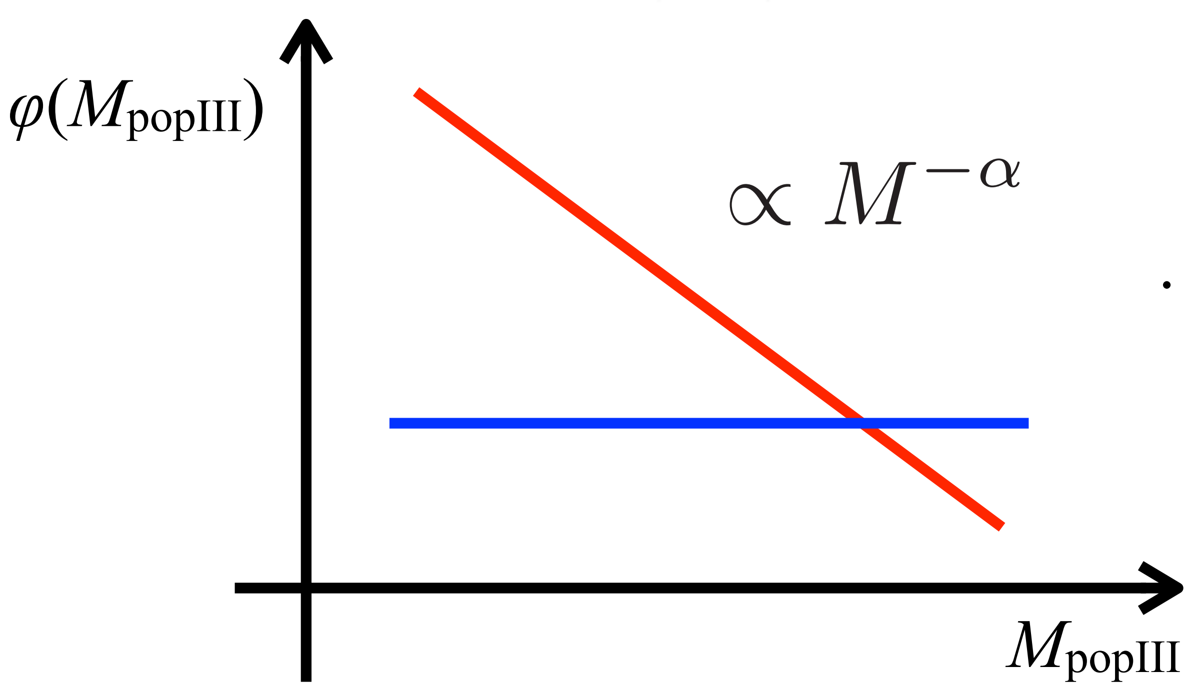
Pop III IMF information in first galaxy

- Shape of Pop III IMF: still controversial



- CCSN (8 - 40 M◉): ~10^{51} erg
- PISN (140 - 260 M◉) : ~ 10^{53} erg
- DC (shaded region)

(e.g., Heger & Woosley 01)



- Pop III IMF ⇔ first galaxy
  - signature of shape of IMF?
    - SFR, SFH, metallicity
- cosmological zoom-in simulation

$M_{\rm h} \sim 10^8 M_\odot$ (at z ~ 9) (from 4 cMpc box)

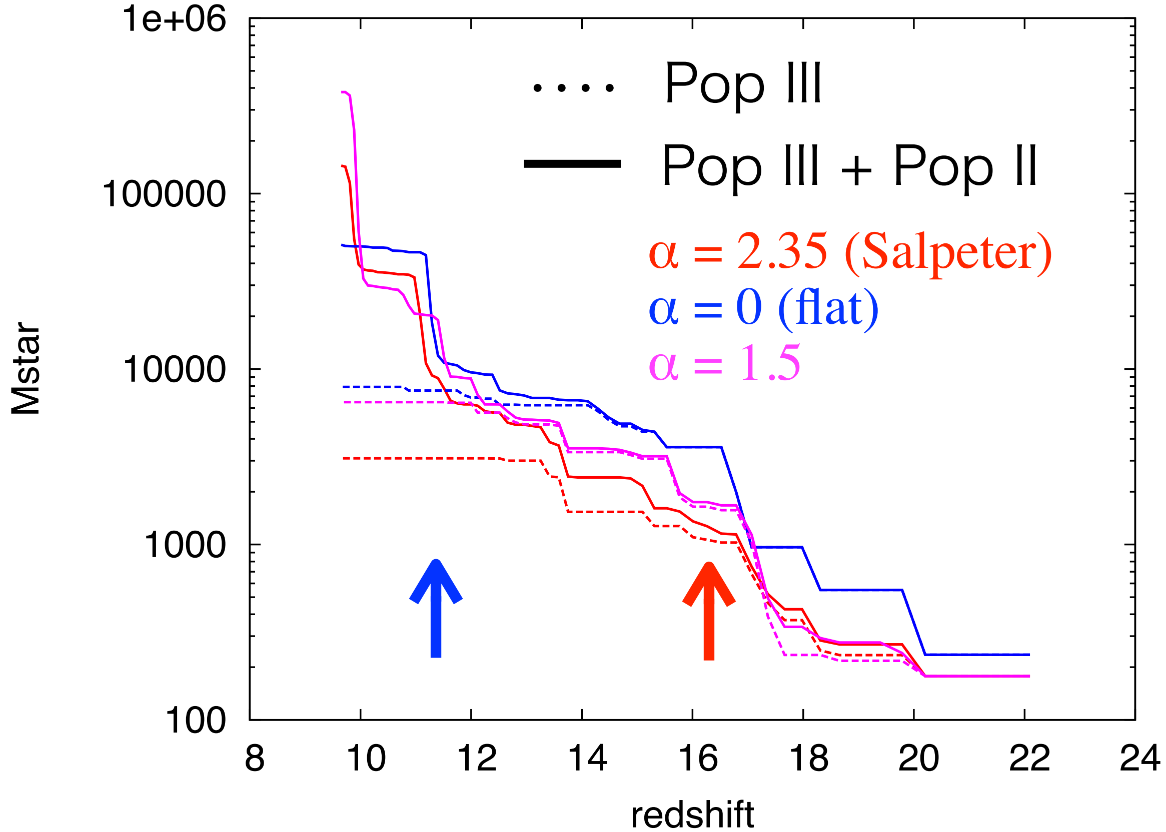
$m_{\rm SPH} \sim 10\ M_\odot$

code: FiBY-GADGET (Johnson+13)

Evolution of first galaxy

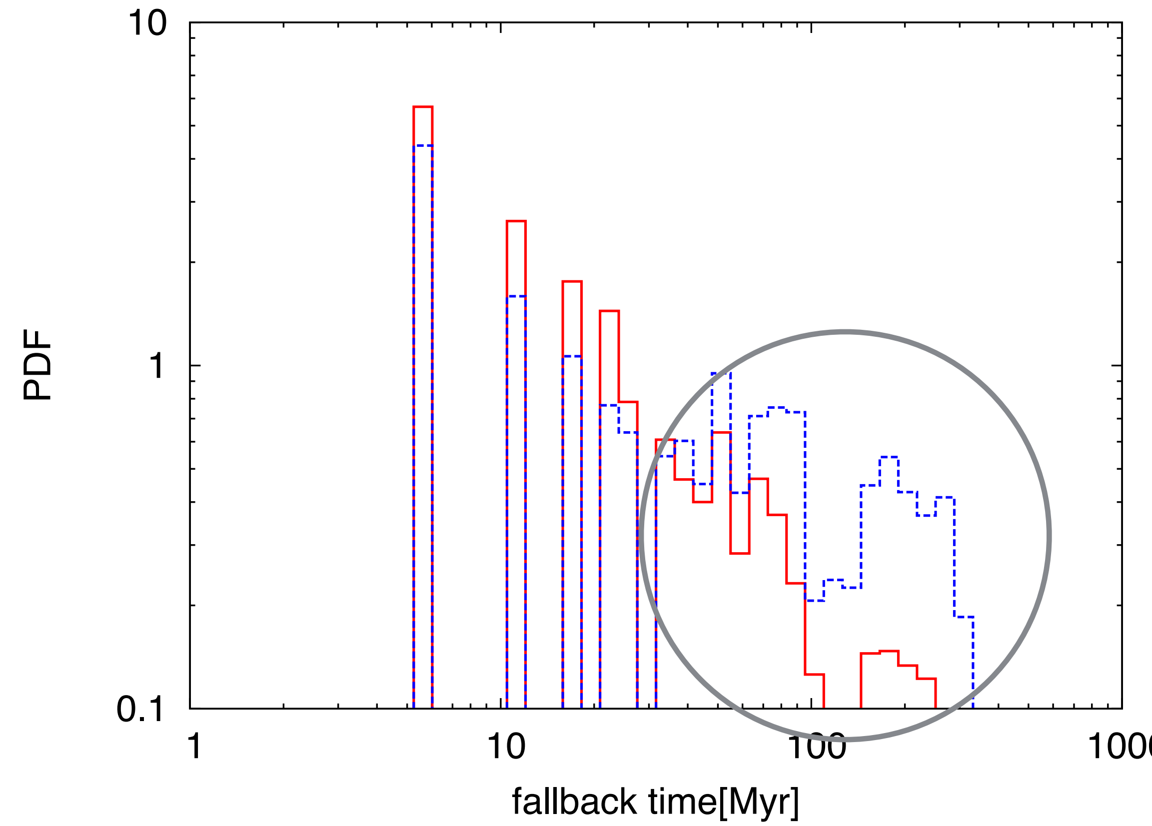
(MA & Yajima in prep.)

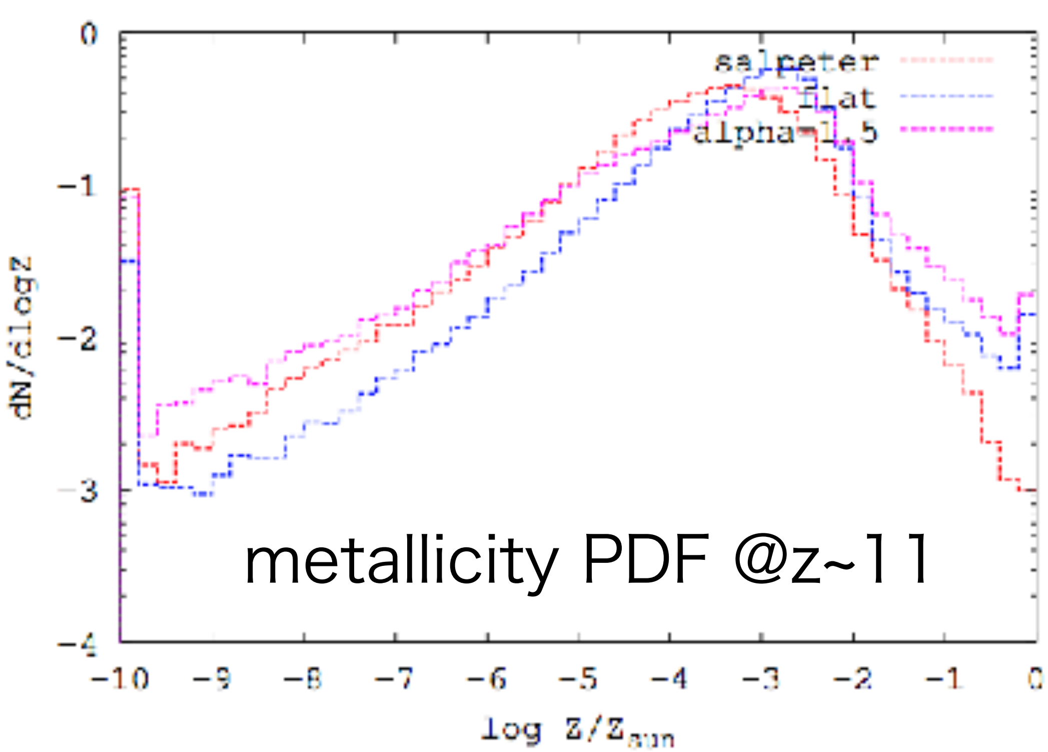
cumulative stellar mass



fallback time

(trajectory of mini-halo gas)





- take long recover time in flat IMF
  - ➡ delayed metal enrich and last the Pop III phase
- SFR ~ 0.01 $M_\odot$/yr
  - ➡ larger system should be investigated ?

Summary

- Numerical simulation is required to solve the baryonic physical processes during the galaxy formation and evolution
    - SN feedback would be one of the key processes to regulate the SF in the galaxy (stochastic thermal feedback seems to be reasonable)
    - radiation transfer is important regarding both observation and dynamics
- first galaxy simulation for next-generation observational instrument era like JWST