Advancements in AGN, Galaxy, Cluster, and IGM Research

SIMULATING SUPER EARLY GALAXIES

Ranit Behera

Supervisor
Prof. Raghunathan Srianand

CUHP, Dharamsala
2024

29th March, 2024

BLUE MONSTER

Ziparo et al. (2023)

Blue Monsters refer to a population of galaxies discovered by the JWST:

- **Super-Early & Abundant**
  They exist at extremely high redshifts, with $z > 10$.
- **Relatively Massive**
  Their stellar mass ranges from $M_* \sim 10^{8-9} M_\odot$.
- **Evolved**
  Their metallicity is approximately $Z \sim 0.1 Z_\odot$.
- **Blue Spectra**
  Despite their early formation, they display blue spectra $\beta \geq -2.6$.
- **Minimal Dust Attenuation**
  Dust attenuation is remarkably low, with $A_V \leq 0.02$.

These observations are not compatible.

PROPOSALS:

Inayoshi et al. (2022)

Chemerynska et al. (2023)

- Enhanced SFE ($\epsilon_* \simeq 0.1 - 0.3$)
- Modification to Mass-to-Light ratio
- Top Heavy IMF at early epoch
- Super-Eddington accreting SMBH
- Galactic Outflow & Feedbacks

AIM:

Simulations to address these non-linear physics, primarily the effect of SFH & feedback on high redshift luminosity functions and spectral signatures.

MP-GADGET

Cosmological simulation.

- CLASS — Generate initial conditions from evolution of linear perturbations.
- TreePM — Efficient computation of gravitationally force.
- Physics — Gas pressure, cooling, sub-grid star formation, stellar winds, SMBH accretion and feedback.
- FoF — Includes Friends-of-friends halo finder algorithm.

ROCKSTAR (Galaxies)

Improved halo finder algorithm based on adaptive hierarchical refinement of friends-of-friends groups in six phase-space dimensions and one time dimension.

Behroozi et al. (2012)

Consistent-Trees

Halo merger algorithm.

Behroozi et al. (2012)

BAGPIPES

Spectral synthesis code.

Carnall et al. (2018)

INITIAL CONDITIONS

Initial conditions are generated from evolution of linear perturbations at z=99.

COSMOLOGY					
h	Ω_m	Ω_Λ	Ω_b	σ_8	n_s
0.697	0.2814	0.7186	0.0464	0.81	0.971

RESOLUTION				
BoxSize (cMpc/h)	Particle Count	Particle Mass ($M_\odot/h$)		
		DM	Gas	Star/BH
50	640^3	3.11×10^7	6.14×10^6	1.53×10^6
50	1008^3	7.96×10^6	1.57×10^6	3.93×10^5
140	700^3	5.22×10^8	1.03×10^8	2.57×10^7
140	896^3	2.49×10^8	4.91×10^7	1.22×10^7
140	1008^3	1.75×10^8	3.45×10^7	8.62×10^6

$$\rho_c = 27.754 \times 10^{10} h^2 M_\odot \mathrm{Mpc}^{-3}$$

Unresolved Gas Cloud → Stellar Population

N-BODY CODES

1) Force Calculation

Newtonian limits as scales are much smaller than Hubble radius $d_H = cH_0^{-1}(\approx 4200\text{Mpc})$.

PP	PM	P³M	Tree	TreePM
• Visit every particle • Apply force from every other particle. • Accurate but costly $\mathcal{O}(N^2)$	• Interpolate particles to grid for density • Solve Poisson equation in Fourier space • Interpolate force from grid to particle	• PP for short range • PM for long range • Costly if particles are too much clustered	• Generate Tree data structure • Open a node if cell opening criterion is met • Else apply force from center of mass of cell	• Tree for short range • PM for long range • $\mathcal{O}(N \log N)$

Bagla & Padmanabhan. (1997)

Bagla (2002)

2) Particle Movement

For velocity independent force : Leap-Frog method.

$$x_i(t+\epsilon) = x_i(t) + \epsilon v_i(t) + \frac{1}{2}\epsilon^2 a_i(t) + \mathcal{O}(\epsilon^3)$$
$$v_i(t+\epsilon) = v_i(t) + \frac{\epsilon}{2}\big(a_i(t) + a_i(t+\epsilon)\big) + \mathcal{O}(\epsilon^3)$$

STAR FORMATION MODEL

Springel & Hernquist (2003)

1

Star formation converts cold clouds into stars on a characteristic timescale $t_\star$.

2

A mass fraction of these stars are short-lived and instantly die as supernovae.

3

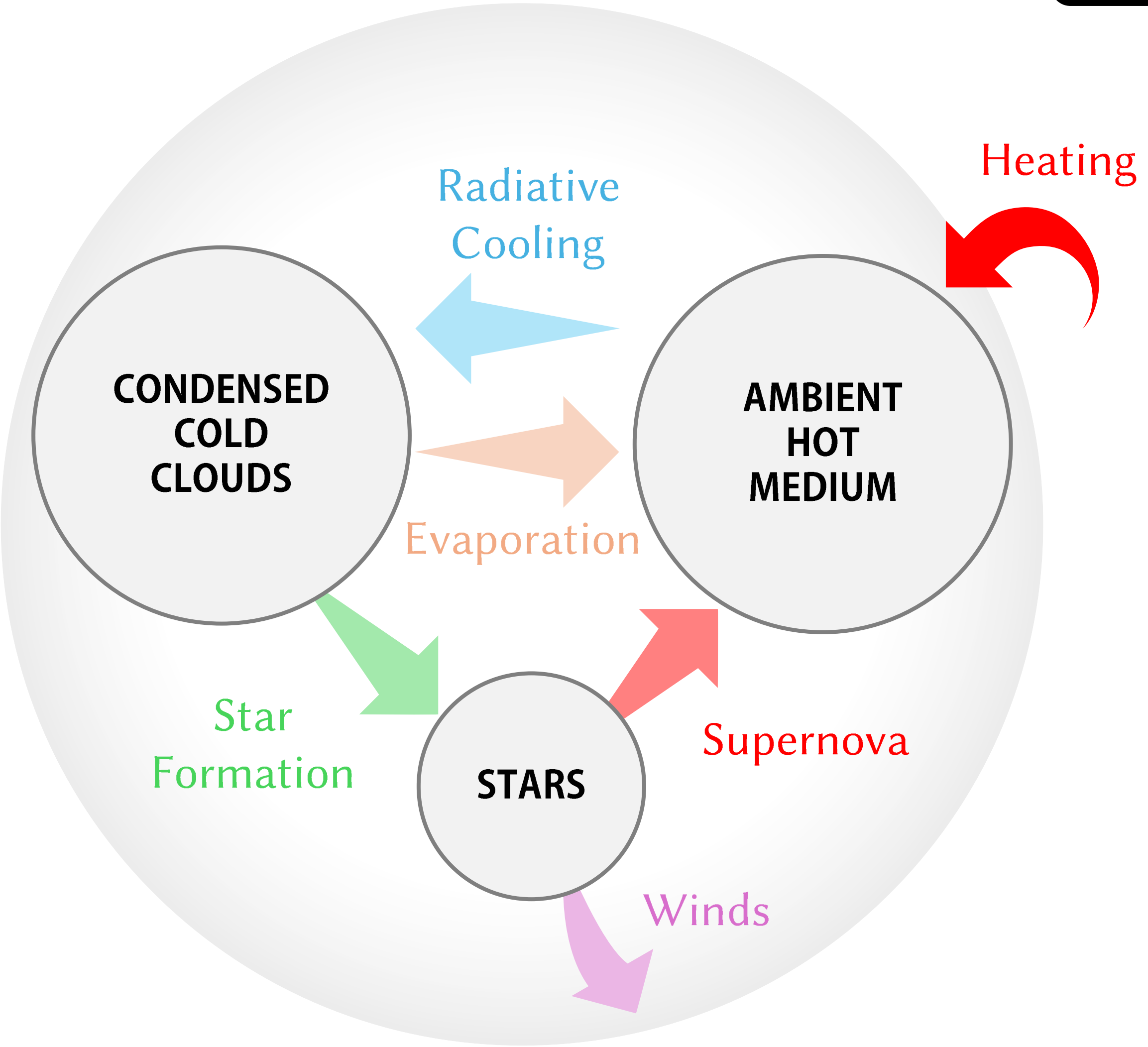
Cold clouds are evaporated inside the hot bubbles of exploding supernovae.

4

Radiative cooling by the hot gas leads to corresponding growth of the cold clouds.

5

Disk mass-loss rate that goes into a wind is proportional to the star formation rate itself.



The unresolved multiphase structure of gas cloud

STAR FORMATION MODEL

Springel & Hernquist (2003)

Star Formation | Supernova | Evaporation | Cooling/Heating | Winds

	Mass Exchange	Energy Exchange
COLD	$\frac{d\rho_c}{dt} = -\frac{\rho_c}{t_\star} - A\beta\frac{\rho_c}{t_\star} + \frac{1-f}{u_h - u_c}\Lambda_{\mathrm{net}}(\rho_h, u_h)$	$\frac{d}{dt}(\rho_c u_c) = -\frac{\rho_c}{t_\star}u_c - A\beta\frac{\rho_c}{t_\star}u_c + \frac{(1-f)u_c}{u_h - u_c}\Lambda_{\mathrm{net}}(\rho_h, u_h)$
HOT	$\frac{d\rho_h}{dt} = \beta\frac{\rho_c}{t_\star} + A\beta\frac{\rho_c}{t_\star} - \frac{1-f}{u_h - u_c}\Lambda_{\mathrm{net}}(\rho_h, u_h)$	$\frac{d}{dt}(\rho_h u_h) = \beta\frac{\rho_c}{t_\star}(u_c + u_{\mathrm{SN}}) + A\beta\frac{\rho_c}{t_\star}u_c - \frac{u_h - f u_c}{u_h - u_c}\Lambda_{\mathrm{net}}(\rho_h, u_h)$

$t_\star$	:	Time scale of star formation	ϵ	:	Average thermal energy per unit volume $(\rho_h u_h + \rho_c u_c)$
ρ_c	:	Density of cold clouds	ϵ_{SN}	:	Average SN energy returned per $M_\odot$ of star formed
ρ_h	:	Density of hot ambient medium	β	:	Mass fraction of Massive stars ($> 8M_\odot$) via IMF
$\rho_\star$	:	Density of stars	u_{SN}	:	$(1-\beta)\beta^{-1}\epsilon_{\mathrm{SN}}$
ρ	:	Total gas density $(\rho_h + \rho_c)$	A	:	The efficiency A of the evaporation process
u_h	:	Energy per unit mass of hot medium	f	:	If thermally instable $f = 0$ ($\rho > \rho_{\mathrm{th}}$), else $f = 1$
u_c	:	Energy per unit mass of cold cloud	Λ_{net}	:	Cooling function

STAR FORMATION MODEL

Springel & Hernquist (2003)

Summery:

- **Self-regulated**:
  In equilibrium of quiescent mode of star formation, the growth of clouds is balanced by their evaporation.
- **Temperature :**
  Cold clouds are assumed to be at fixed temperature around 10^3K. The temperature of the hot medium evolve towards $u_h = u_c + [u_{\mathrm{SN}}/(A+1)]$. For sufficiently rapid star formation, the temperature of the hot phase is maintained typically at 10^6K.
- **Cold Gas Fraction** :
  The cold gas fraction $x_c = \rho_c/\rho$ is given by $x_c = 1 + \frac{1}{2y} - \sqrt{\frac{1}{y} + \frac{1}{4y^2}}$; $y = \frac{t_\star \Lambda_{\mathrm{net}}(\rho, u_h)}{\rho(\beta u_{\mathrm{SN}} - (1-\beta) u_c)}$
- **Effective Pressure** :
  It is given by $P_{\mathrm{eff}} = (\gamma - 1)[\rho_h u_h + \rho_c u_c] = (\gamma - 1)\rho[(1 - x_c)u_h + x_c u_c] = (\gamma - 1)\rho u_{\mathrm{eff}}$.
- **Star Formation Rate** :
  It is given by $\dot{\rho_\star} = (1-\beta)\,\rho_c/t_\star = (1-\beta)\,\rho x_c/t_\star$. In discrete particles approximation using SPH :

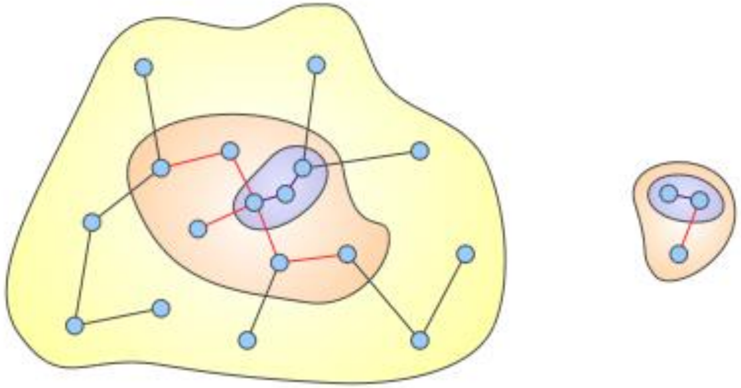
$$\dot{M}_\star = (1-\beta) M x_c / t_\star$$

- **Winds** :
  Rate at which gas is fed to wind is proportional to SFR as $\dot{M}_w = \eta \dot{M}_\star$ carrying a fixed fraction χ of the supernova energy as $^1/_2\ \dot{M}_w v_w^2 = \chi \epsilon_{\mathrm{SN}} \dot{M}_\star$.

Behroozi et al. (2012)

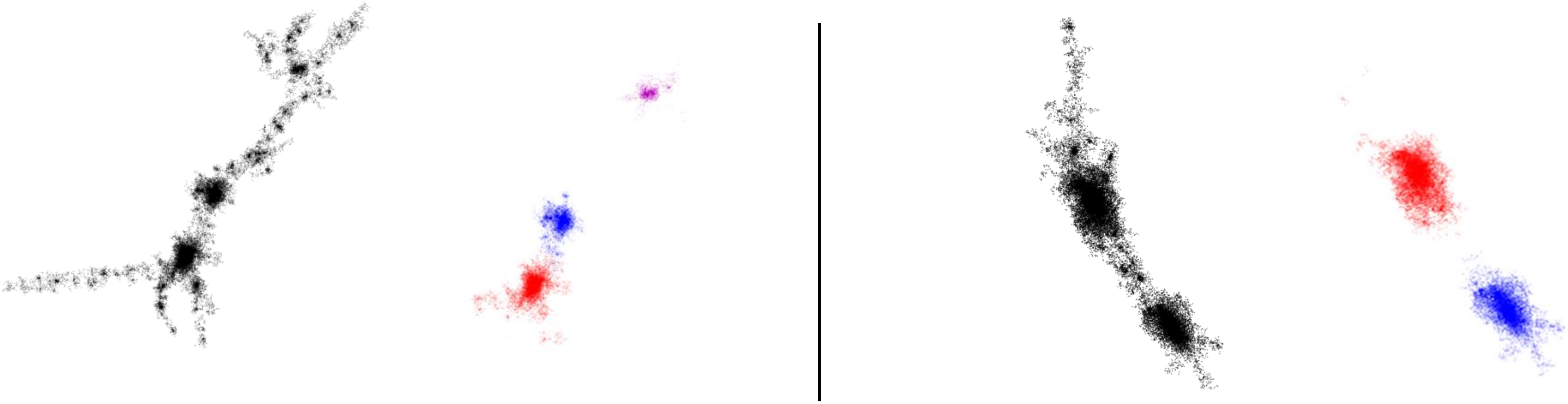
FOF

- Particles are "linked" together if their distance lies below the "linking length".
- Limitations : Sub-halos, Halo Bridging, Filaments



ROCKSTAR

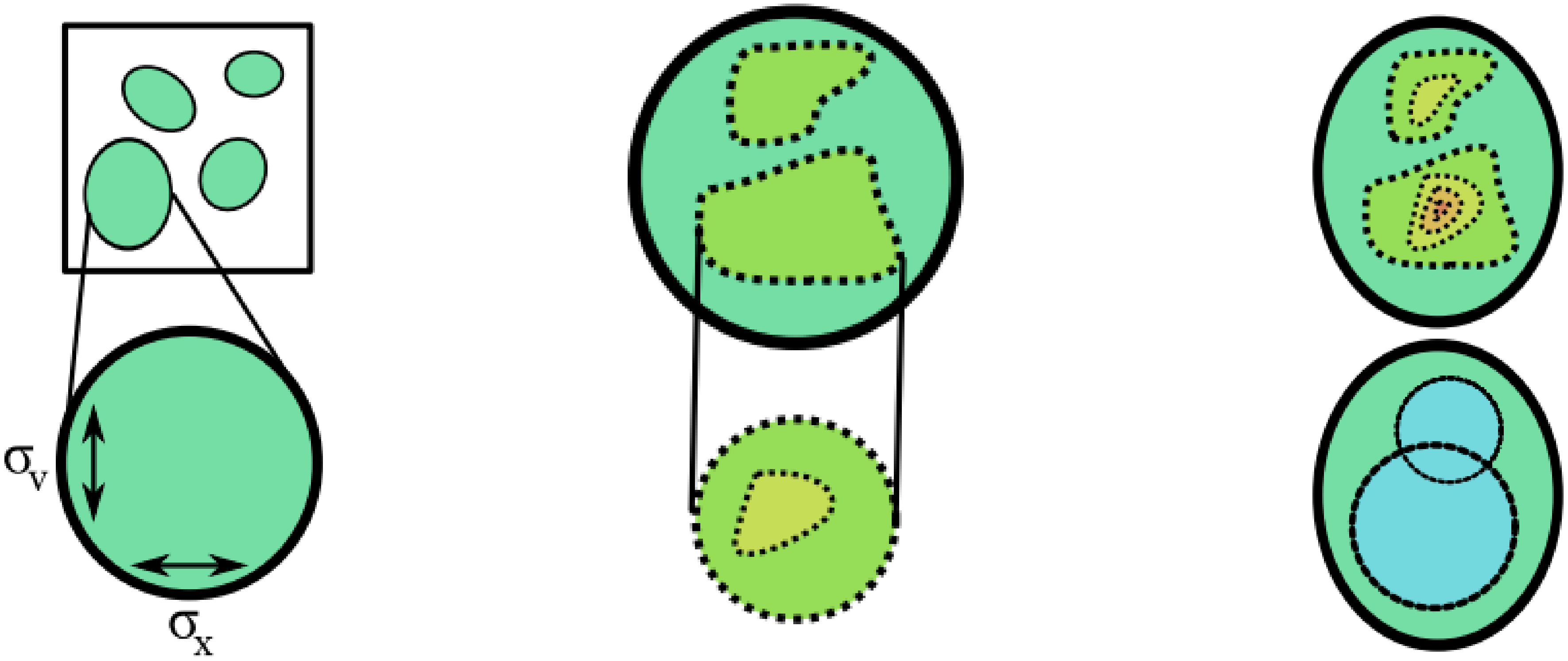
- FoF but in 6D phase space with adaptive linking length.



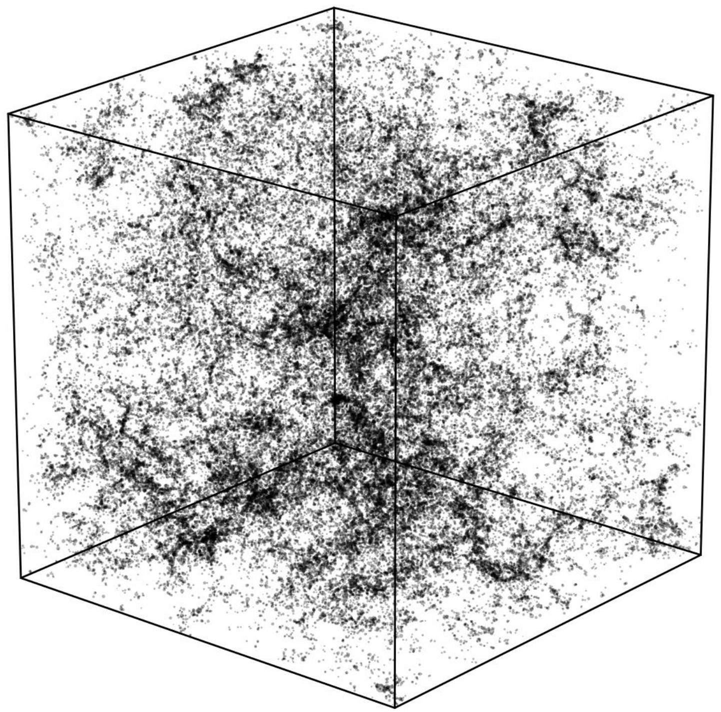
FoF in black-and-white vs ROCKSTAR (Galaxies) in coloured.

HALO IDENTIFICATION

Behroozi et al. (2012)

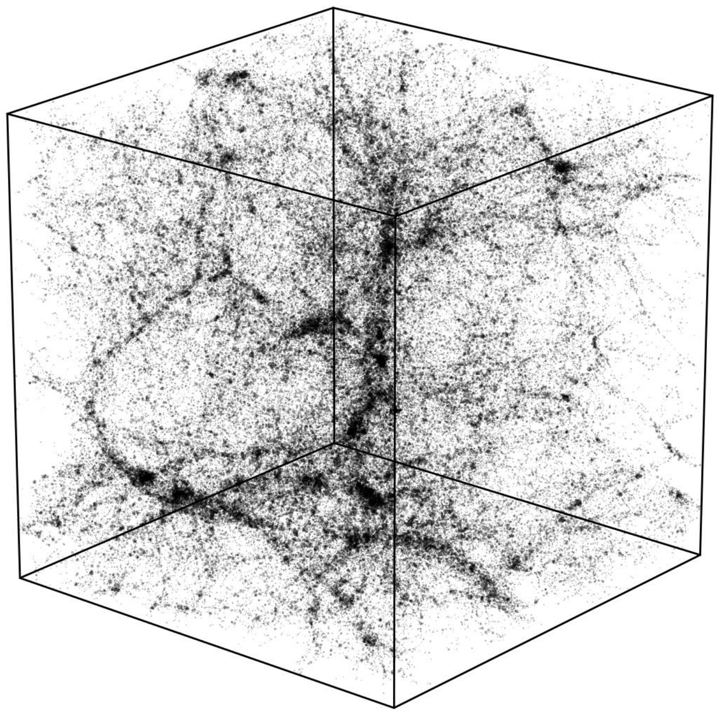


L50N640
z=8.0
N_{halo} = 99625



Halo Definition = 32

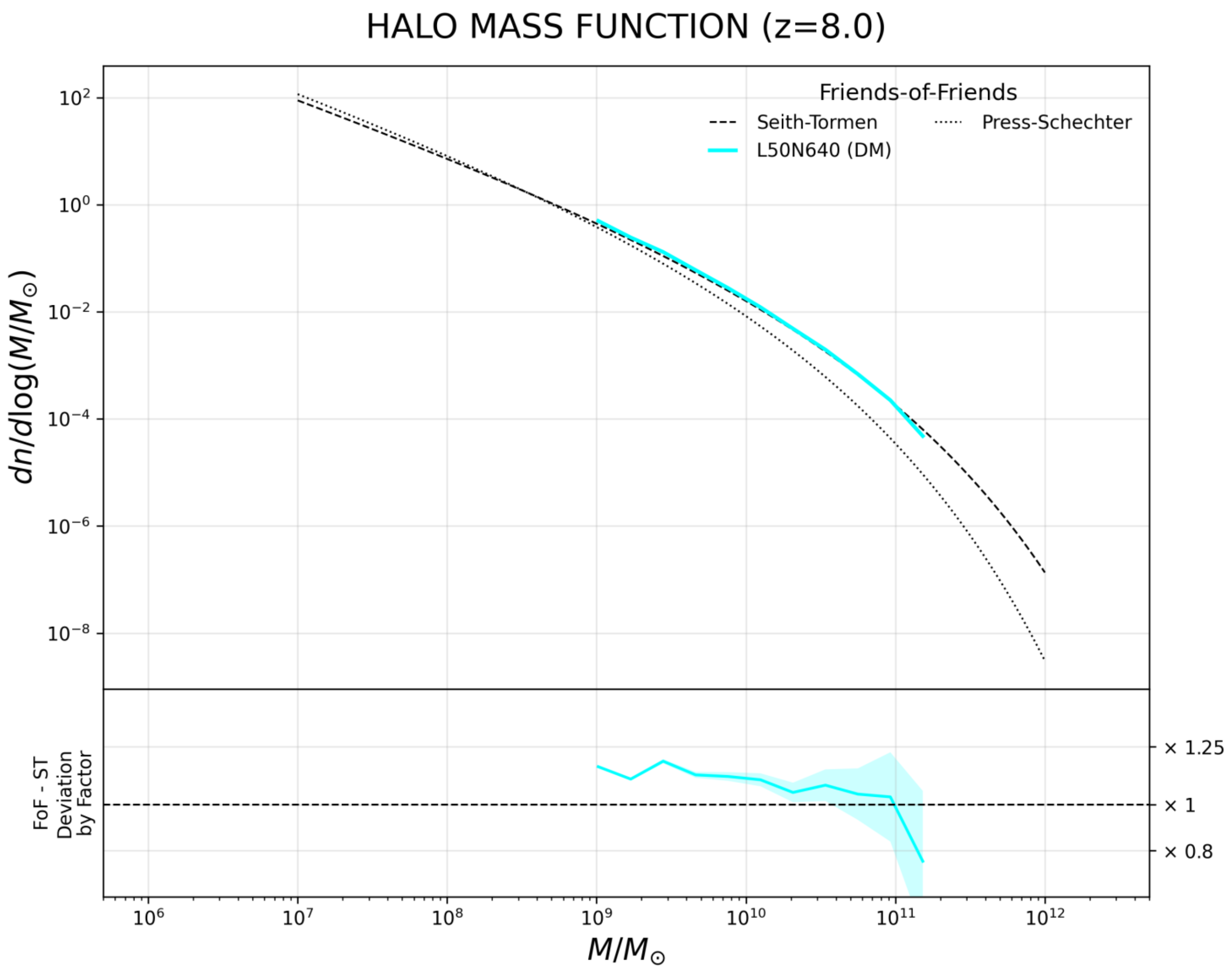
L50N640
z=0.0
N_{halo} = 198757



Each point represents a halo/sub-halo found by **ROCKSTAR (Galaxies)**.

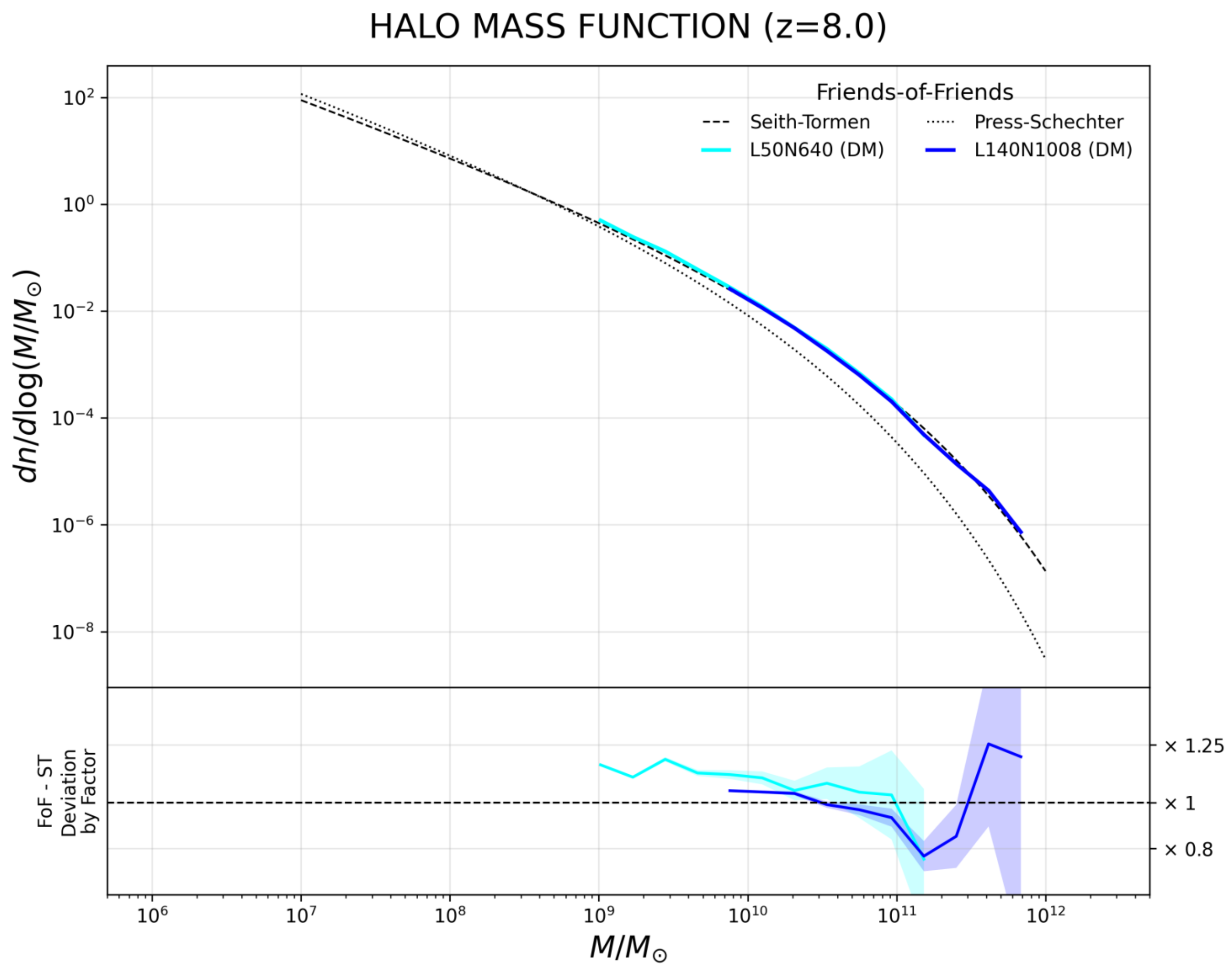
MASS CUT-OFF

- Lower : Resolution
- Higher : Cosmic Variance



MASS CUT-OFF

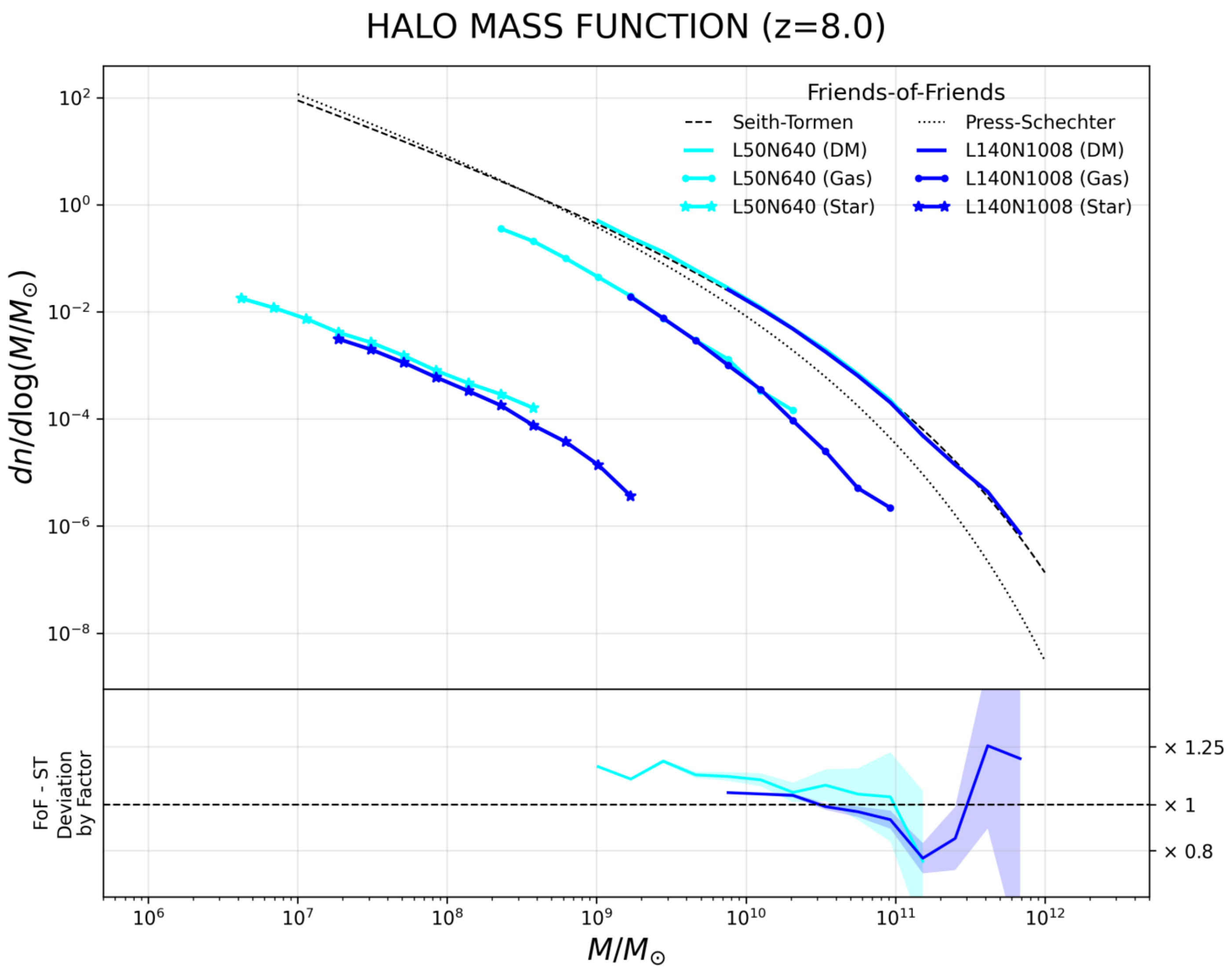
- Lower : Resolution
- Higher : Cosmic Variance



HALO MASS FUNCTION

MASS CUT-OFF

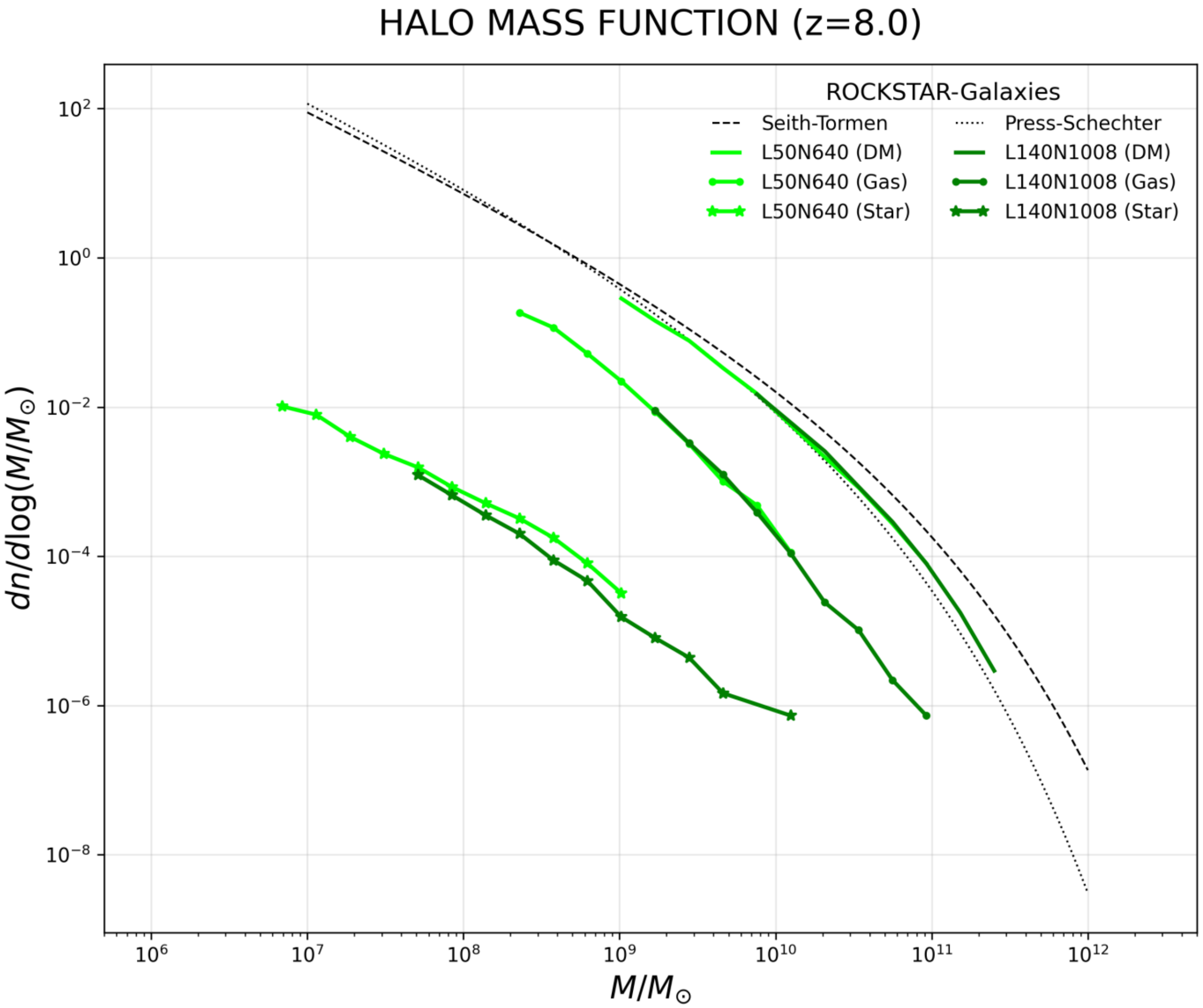
- Lower : Resolution
- Higher : Cosmic Variance



HALO MASS FUNCTION

MASS CUT-OFF

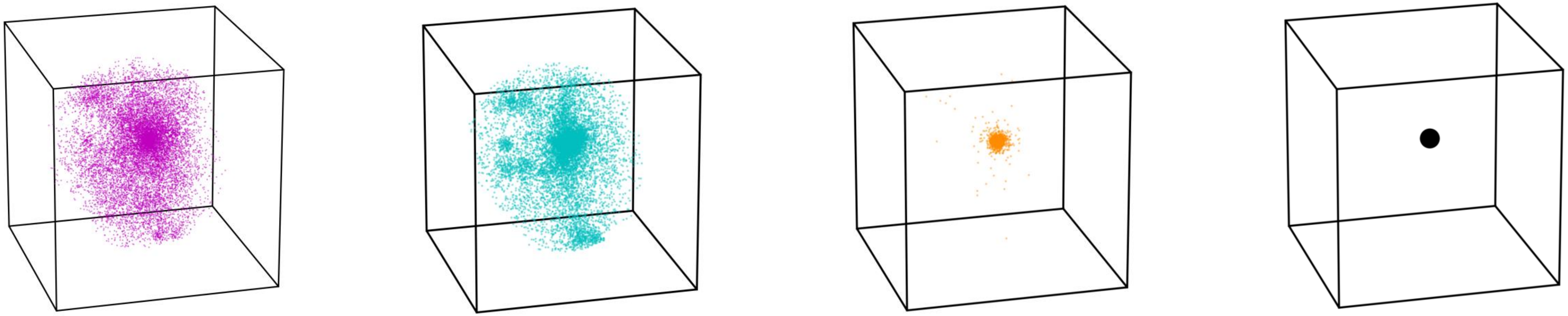
- Lower : Resolution
- Higher : Cosmic Variance



PARTICLE DISTRIBUTION

SFH is needed for stellar population synthesis.

Dark Matter | Gas Cloud | Star Cluster | Blackhole



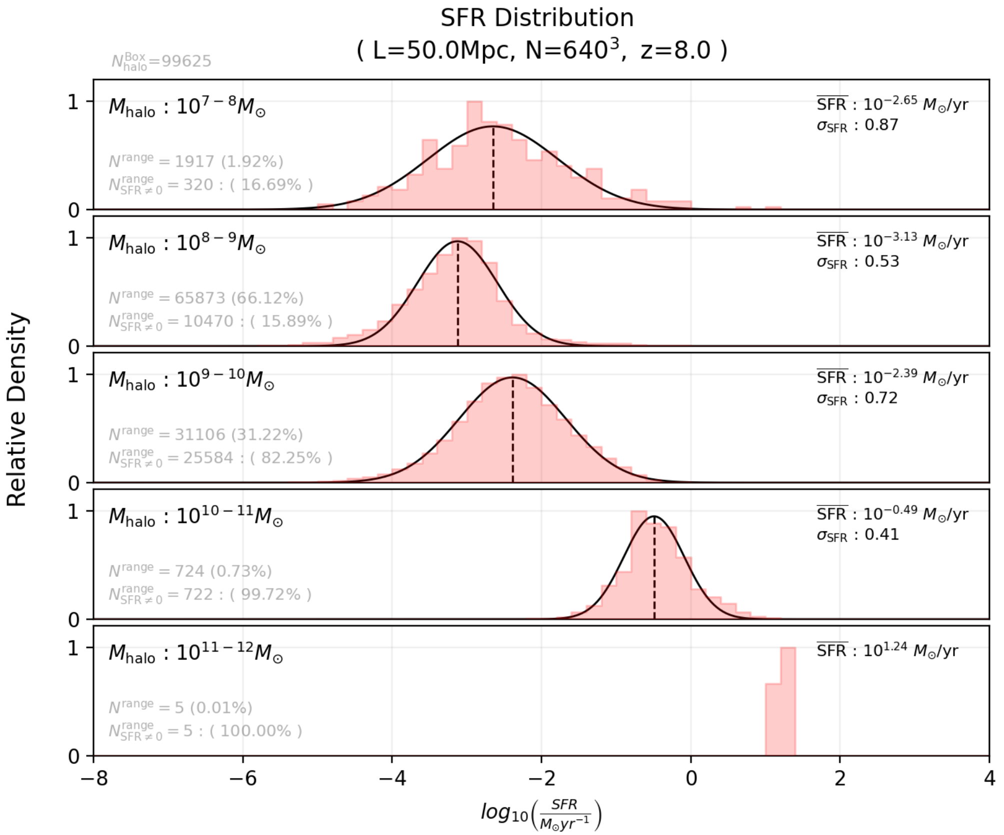
SFH by adding SFR of backtracked gas particles.

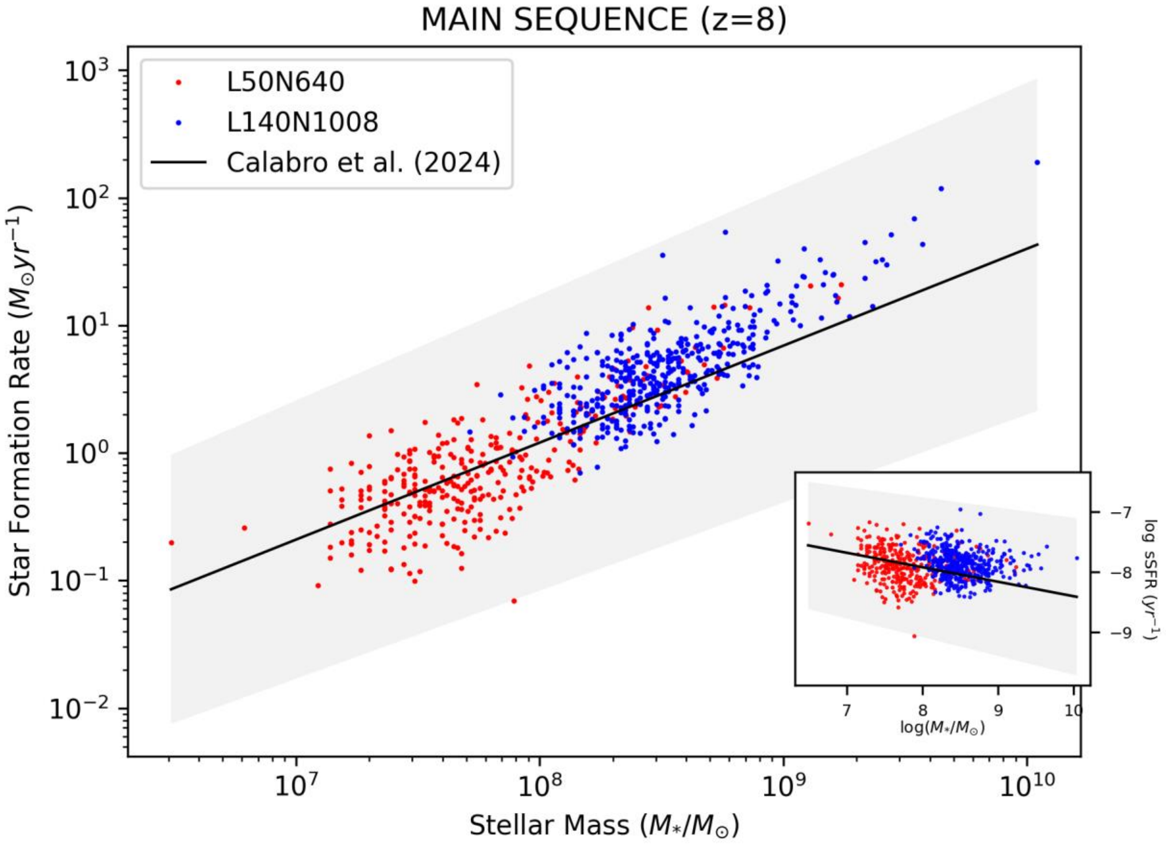
Contribution from central SMBH accretion (QSO).

SFR DISTRIBUTION

- All massive halos are star forming with high SFR.
- Star formation is less in low mass halos as gas can escape from shallow gravitational potential via winds.

Calabro et al. (2024)





STAR FORMATION HISTORY

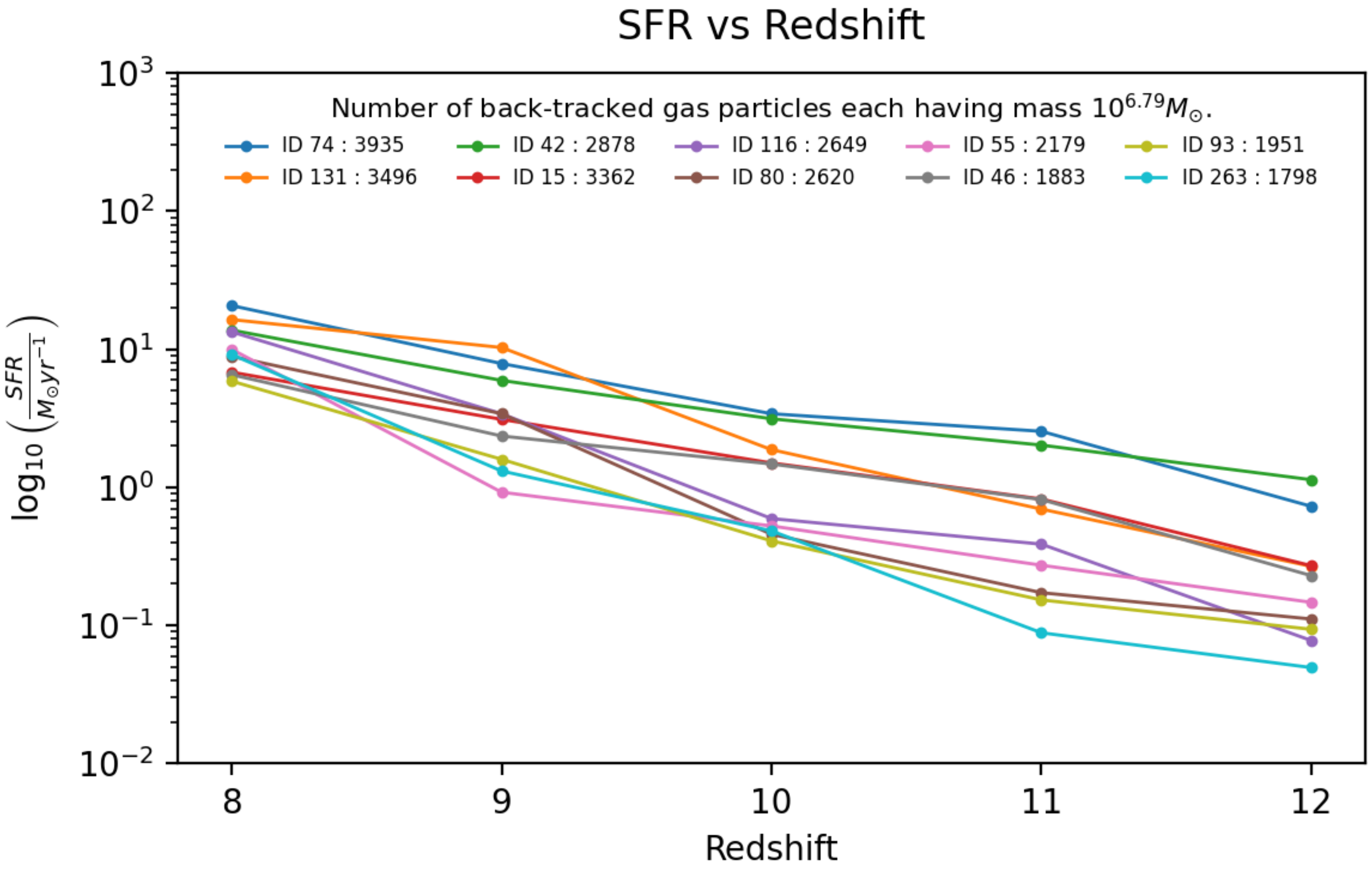
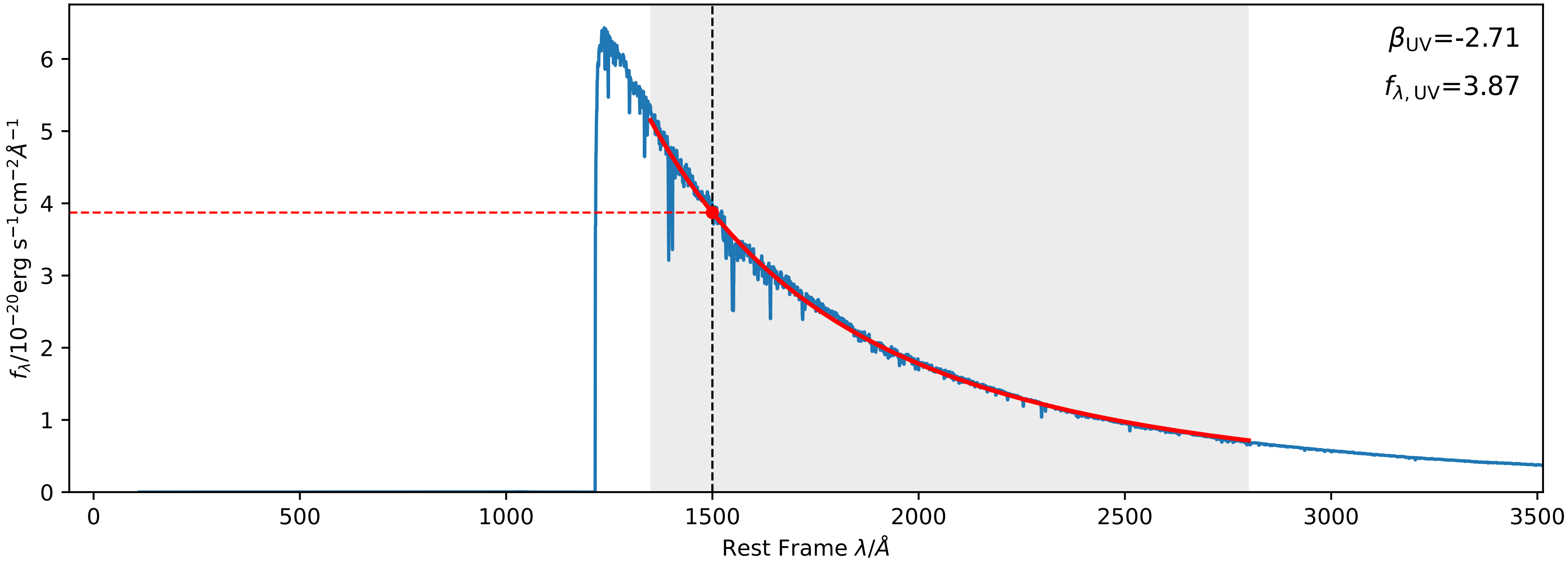


Figure : The SFR vs redshift plots for top ten massive halos by virial mass at redshift z=8 are shown. The SFR for these halos at higher redshifts are obtained by adding SFRs of back-tracked gas particles found within the halo at lower redshift z=8. The IDs (external) of selected halos at redshift z=8 are shown in legend with corresponding number of gas particles back-tracked.

SPECTRAL SYNTHESIS

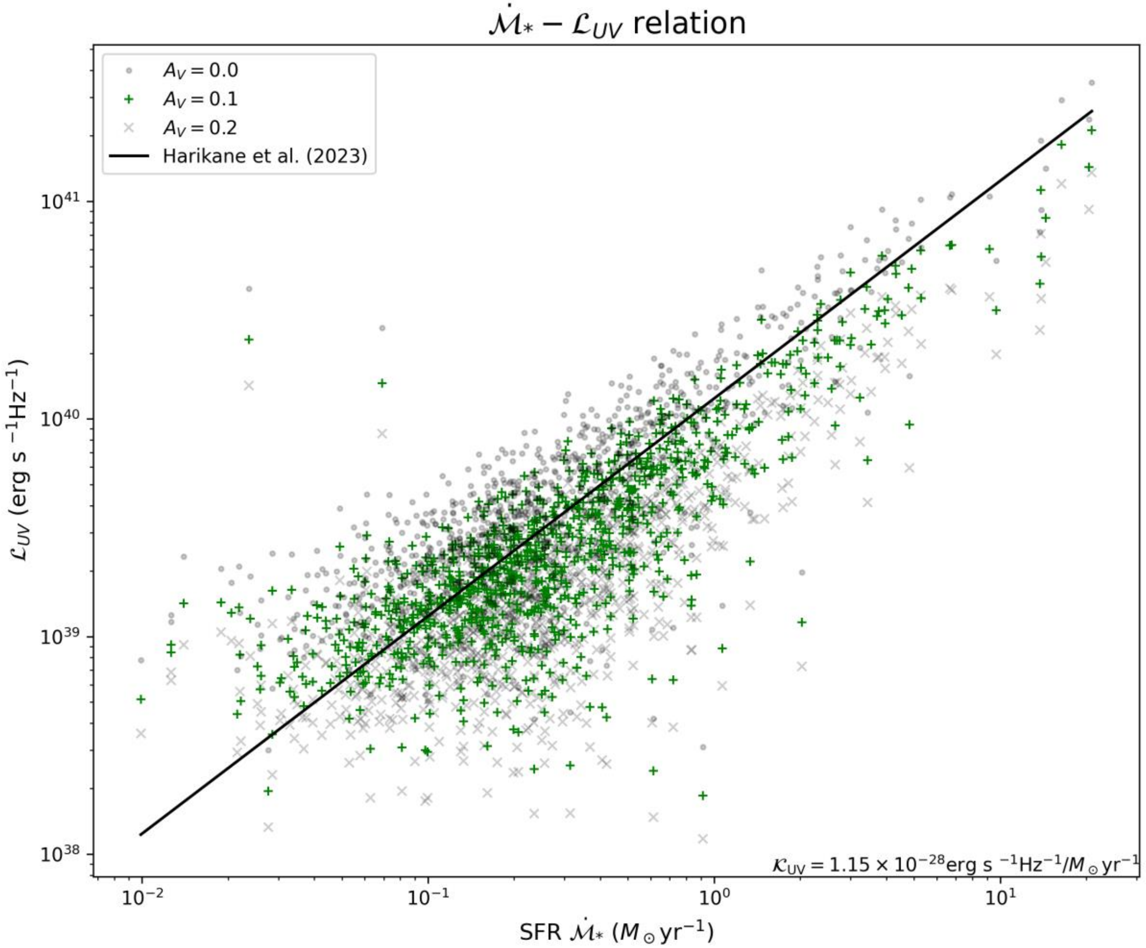
The SED at any given time can be obtained by summing the spectra of coeval populations with different ages once the SFH and the IMF are specified.

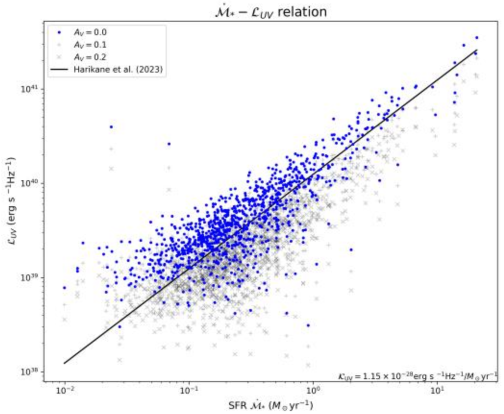
Normalised IMF	Coeval Population	Composite Population
$\int_{m_l}^{m_u} m\phi(m)dm = 1M_\odot$	$\mathcal{L}_\lambda^{(cp)}(\tau) = \int \mathcal{L}_\lambda^\star(m,\tau)\frac{\phi(m)}{M_\odot}\,dm$	$\mathcal{L}(t) = \int \mathcal{L}_\lambda^{(cp)}(t-t')\,\dot{M}_\star dt'$

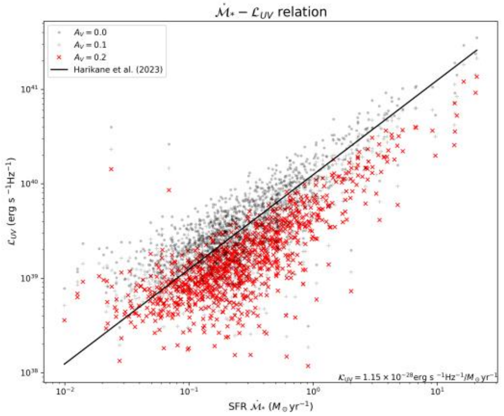


SCALING RELATION

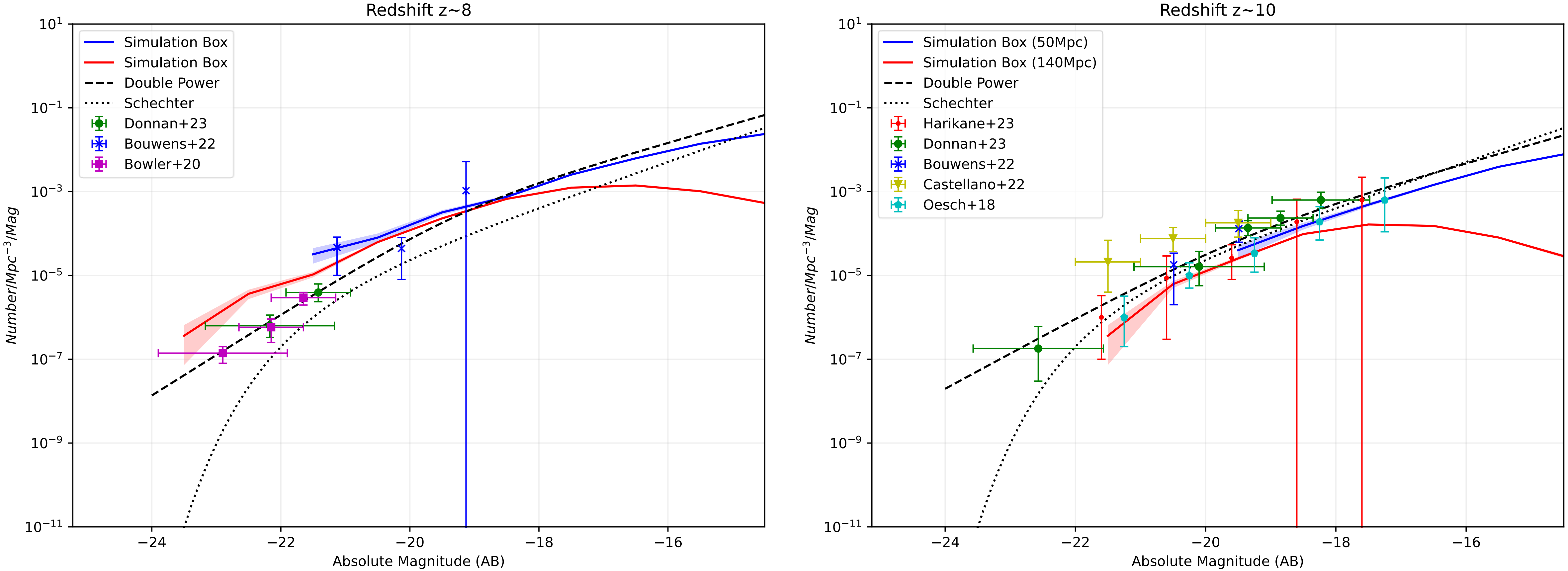
$$\mathcal{K}_{\rm UV} = \frac{\mathcal{L}_{\rm UV}}{\rm SFR} = 1.15 \times 10^{-28} {\rm erg\ s^{-1}\ Hz^{-1}}/M_{\odot}{\rm yr^{-1}}$$



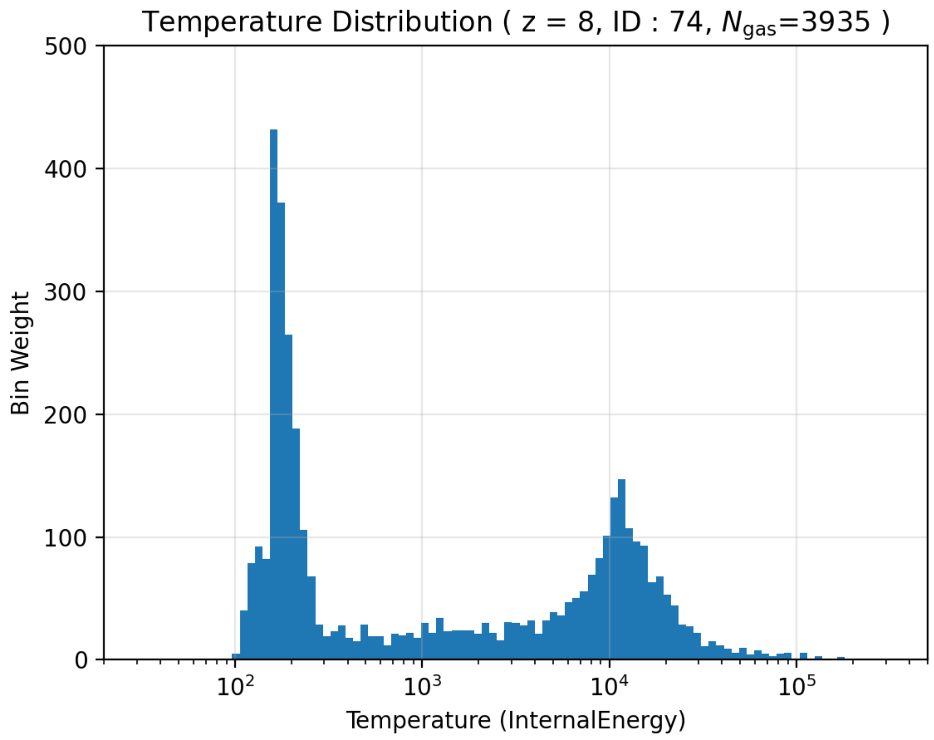


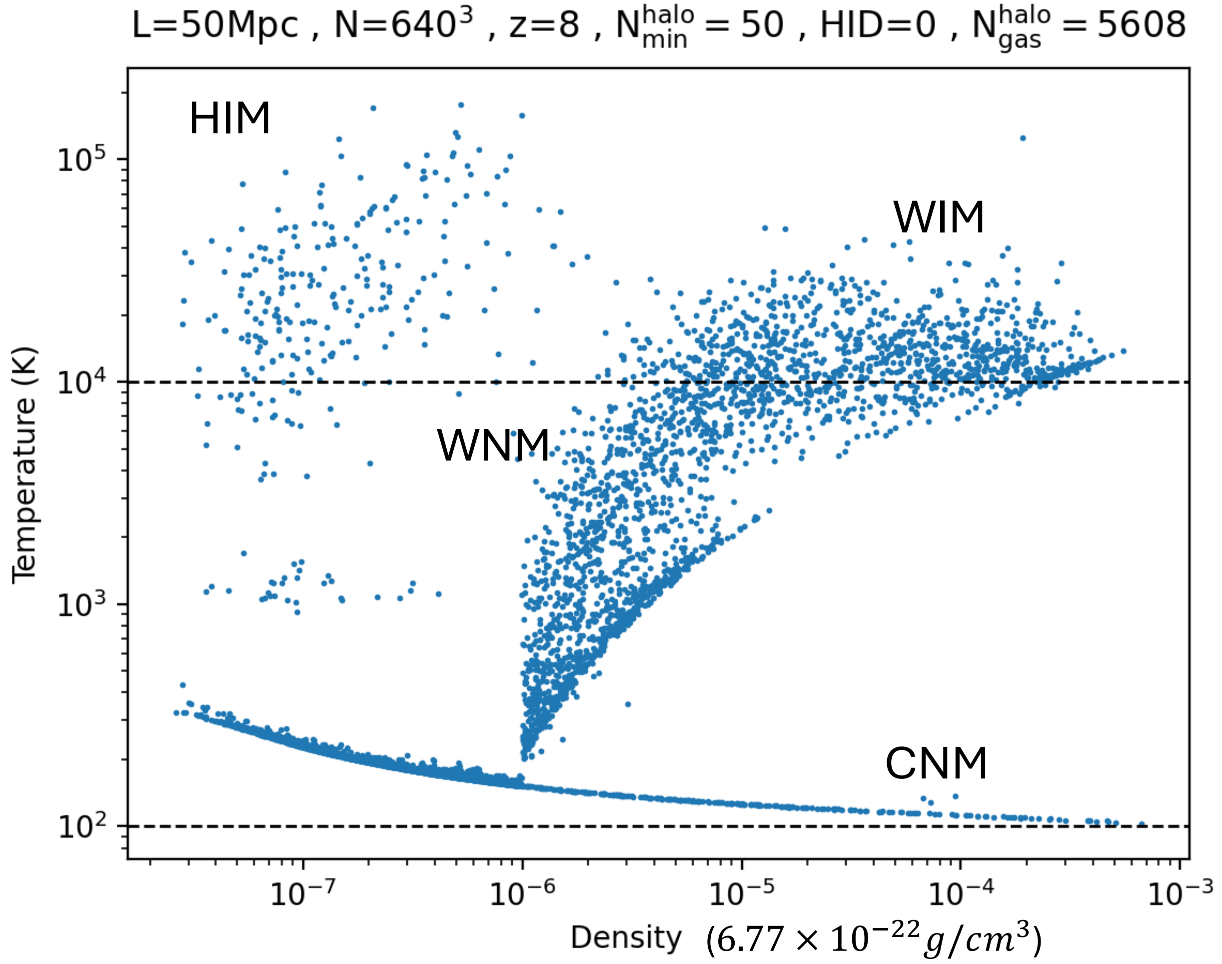


LUMINOSITY FUNCTION



GAS COMPONENTS



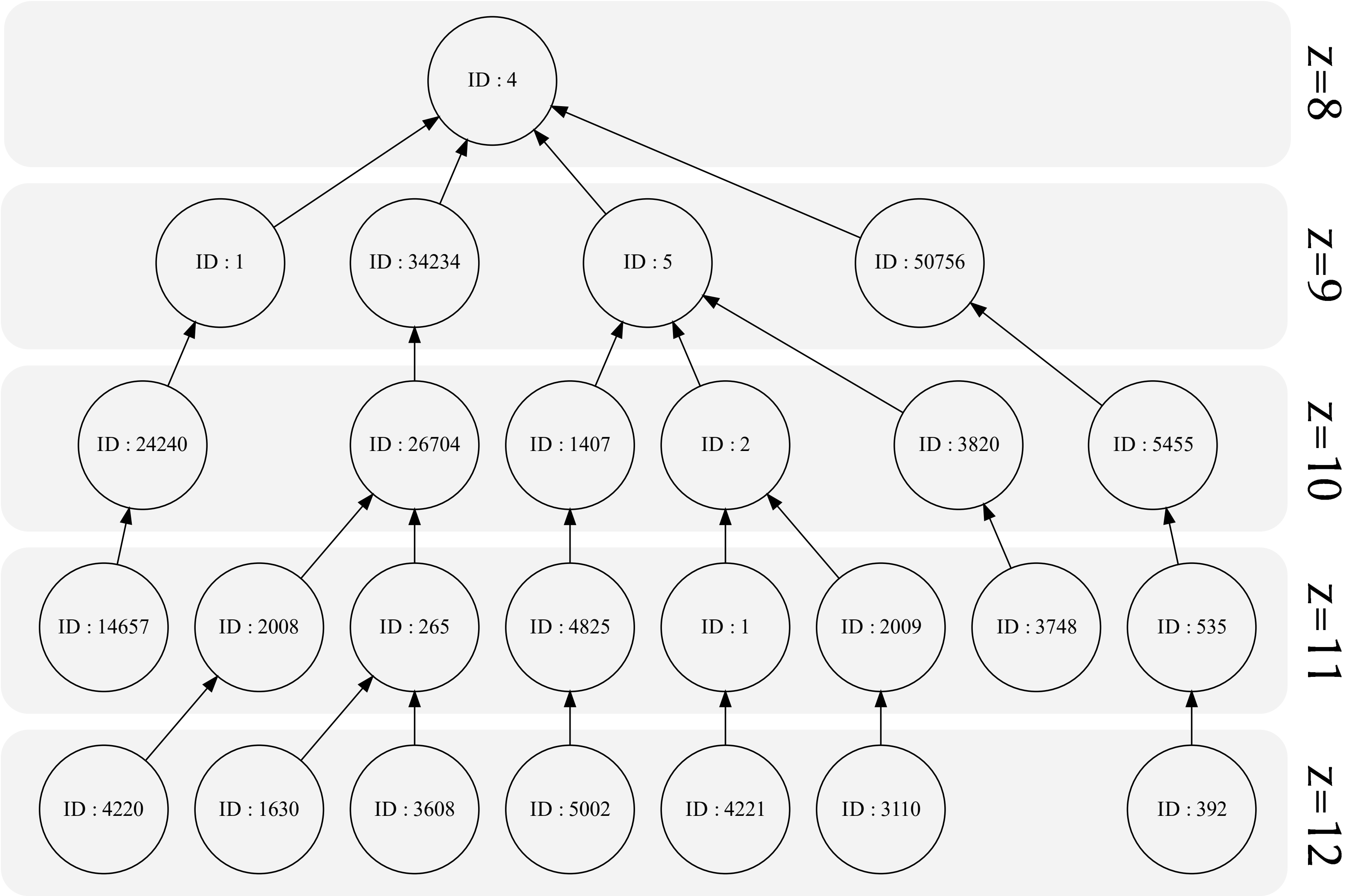


MERGERS

Galaxy mergers can:

- Chemically enrich ISM, enhance SFR.
- Trigger feedbacks.

Galaxy Spectra
↓
Radiative transfer through ISM and CGM
↓
IGM absorption
↓
Observed



FUTURE PLANS

- Nebular Emission Lines
- Contribution from central SMBH accretion (QSO).
- Radiative Transfer through ISM, CGM, IGM
- Alter various simulation and post-processing parameters for statistical analysis.

Cosmology | Gas Cooling | Star formation | Wind model | QSO model | Metal return model | IMF

FUTURE PLANS

- Nebular Emission Lines
- Contribution from central SMBH accretion (QSO).
- Radiative Transfer through ISM, CGM, IGM
- Alter various simulation and post-processing parameters for statistical analysis.

Cosmology | Gas Cooling | Star formation | Wind model | QSO model | Metal return model | IMF

Thank You