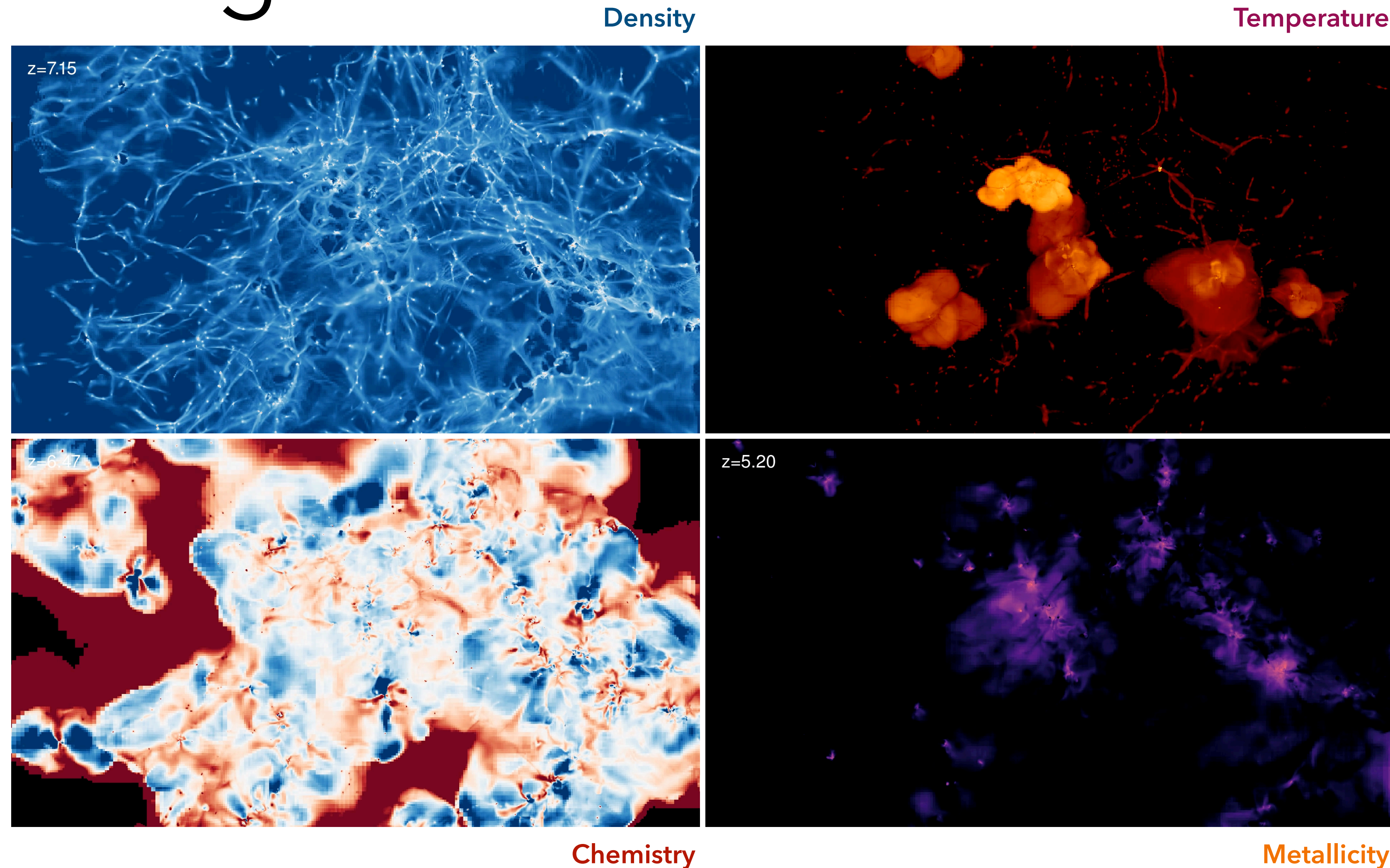


Modes of star formation in zoom-in cosmological simulations of MW-like galaxies

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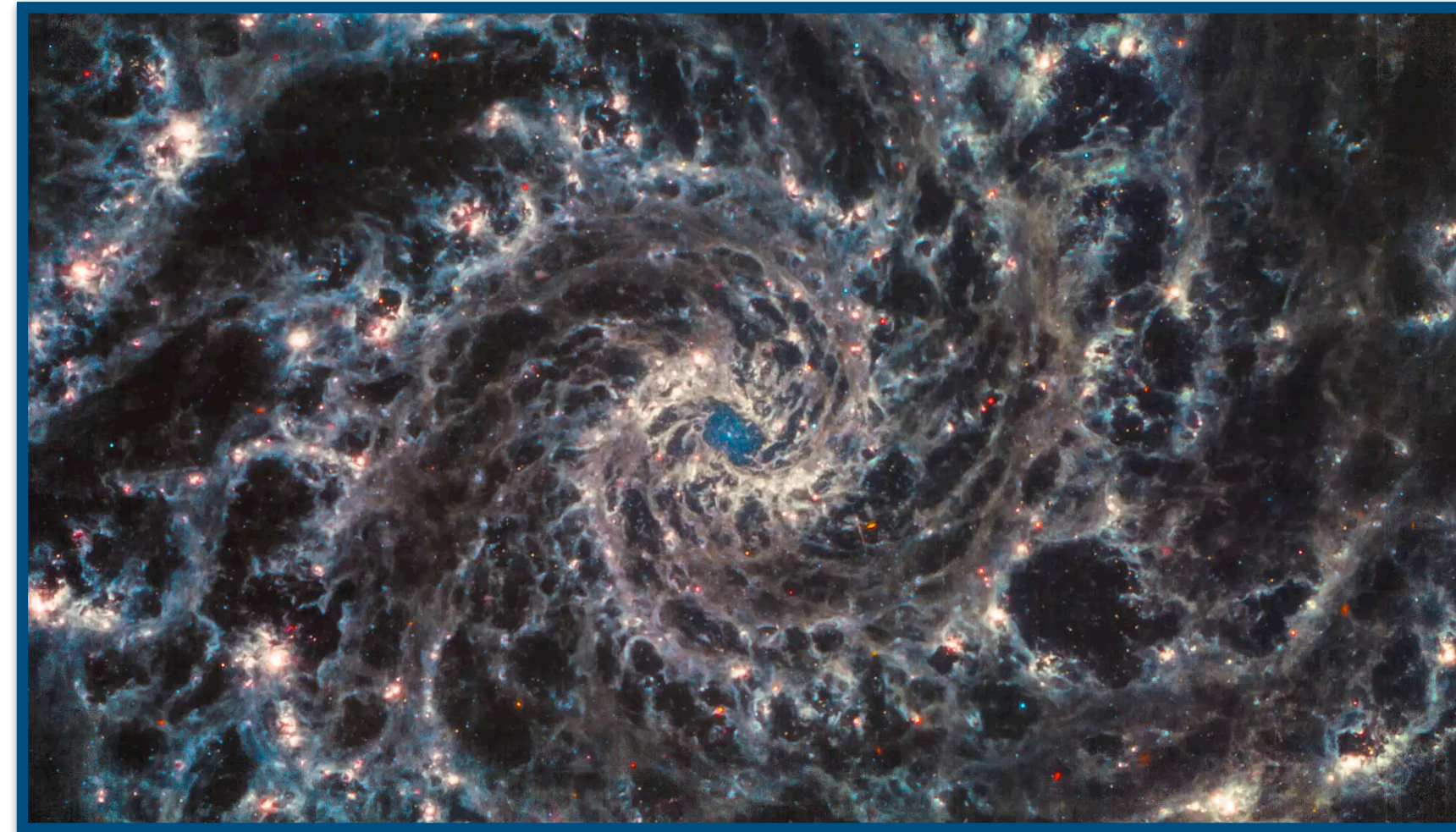
Cooling, turbulence
in clouds

Small scale



Star forming regions

Star formation history



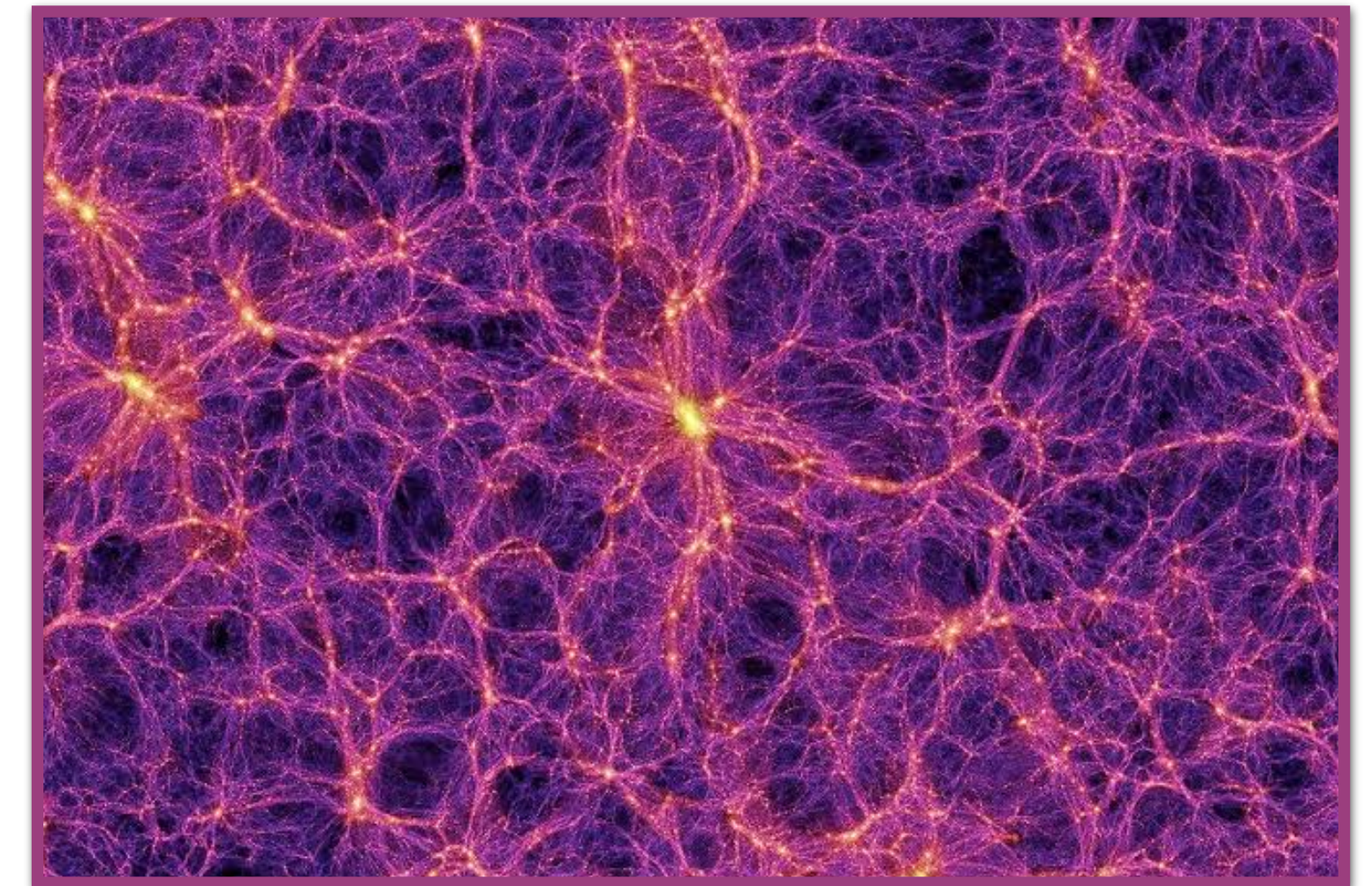
DM halo: $\sim 10^{12} M_{\odot}$
Stellar mass: $\leq 10^{11} M_{\odot}$
Gas fraction: $\leq 20\%$
Radius: ~ 15 kpc
Shape: disk

Supernovae,
stellar winds

Outflows,
fountains

Mergers,
filamentary accretion,
voids, clusters

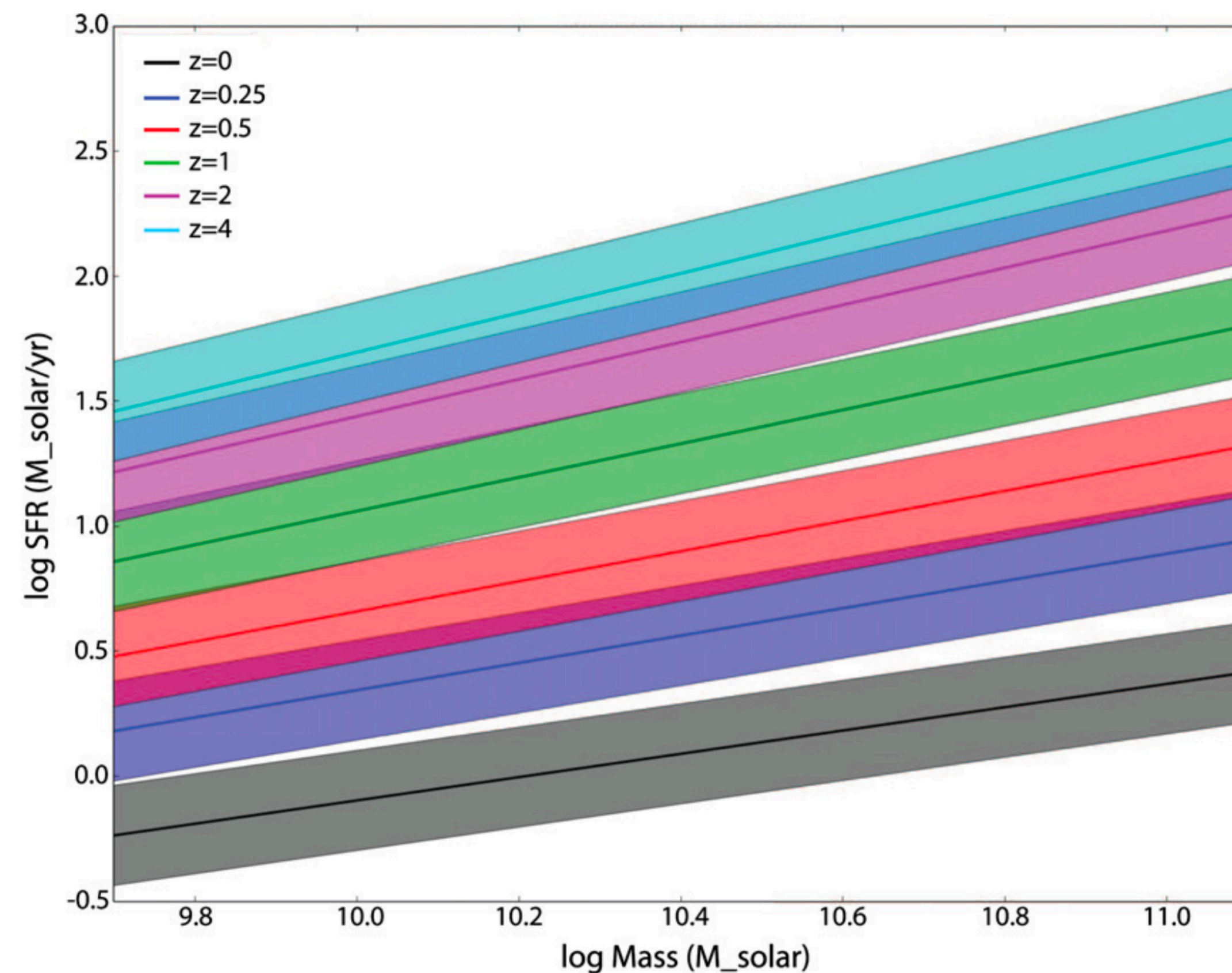
Large scale



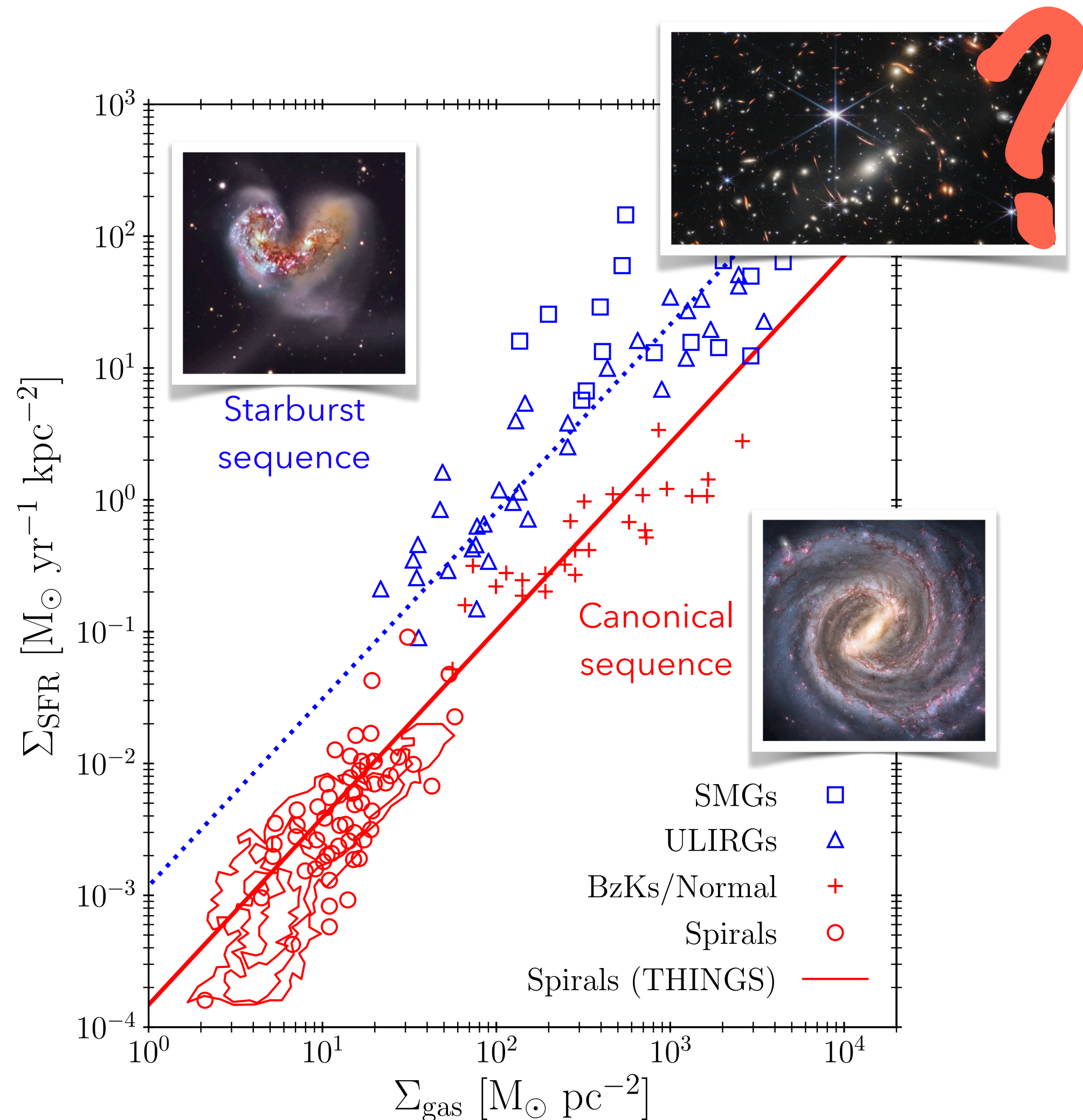
Cosmological environment

Star formation on the Main Sequence (MS)

- ◆ About 90% of star formation up to $z \gtrsim 2$ proceeds in the main sequence. Starbursts and quiescent galaxies as outliers. [Noeske+07](#), [Elbaz+07;+11](#), [Tacconi+013](#)
- ◆ The normalisation and slope of the main sequence change with time. [Speagle+14](#), [Whitaker+14](#), [Genzel+15](#), [Saintonge+17](#)
- ◆ The main sequence can be misleading when identifying phases of star formation. [Puglisi+21](#), [Gómez-Guijarro+22](#), [Dimauro+22](#), [Daddi+22](#), [Popesso+22](#), [Renaud+22](#), [Ciesla+23](#)



Star formation in Kennicutt-Schmidt (KS) space



- SFR correlates with cold, dense, molecular gas.
Kennicutt+98, Bouché+07, Bigiel+08, Bothwell+09, Daddi+10a, Tacconi+10.

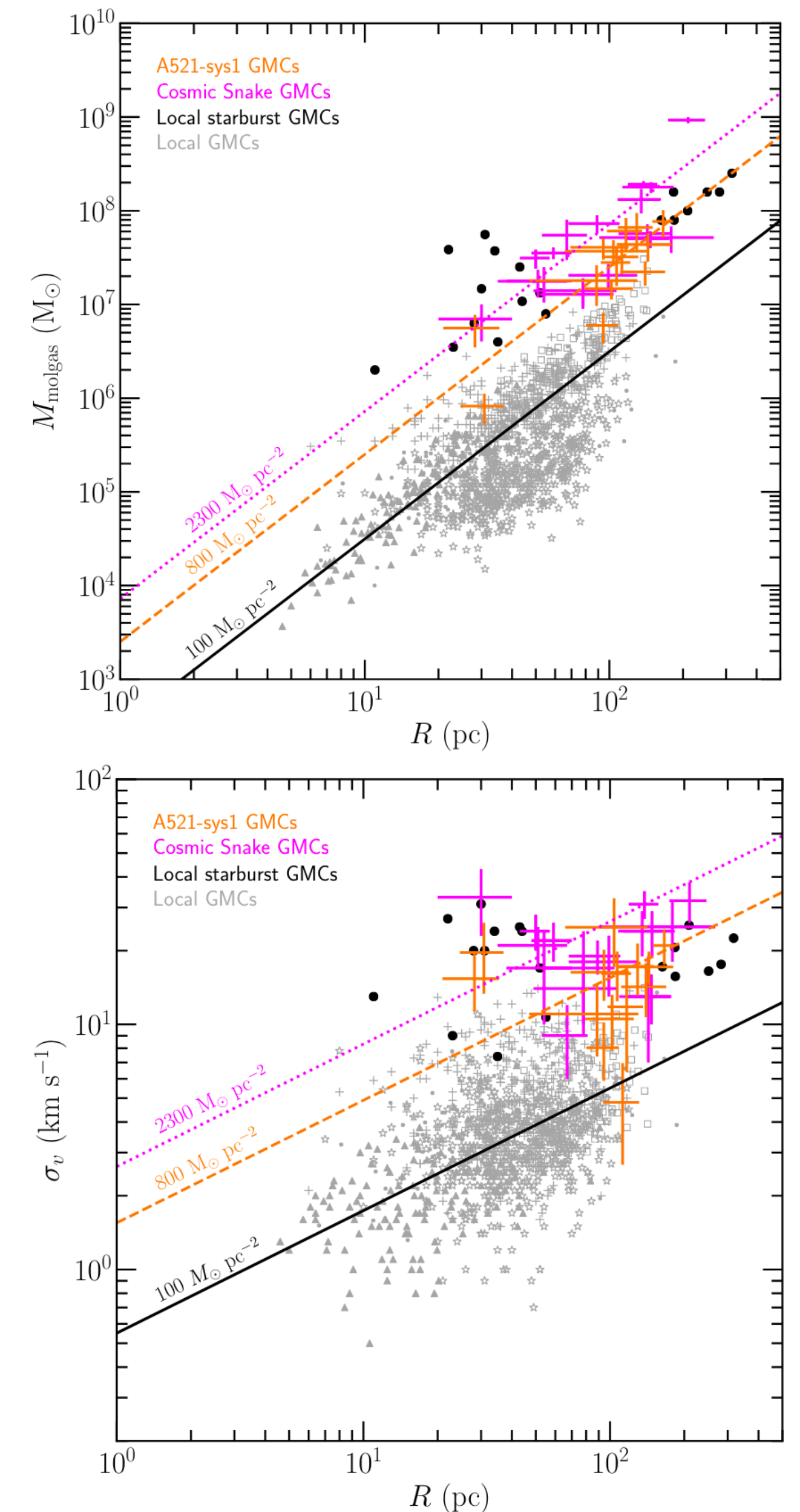
- Starbursts associated with mergers at low z , showing a drop in the gas depletion time.
Keel+85, Daddi+10b, Rodighiero+11, Kim+21

$$\tau_{\text{dep}} = \frac{M_{\text{gas}}}{\text{SFR}}$$

- How do we connect to high- z galaxies?
Fakhouri+10, Sargent+12, Perret+14, Schreiber+15, Fensch+17, Fensch+21, Dekel+22, Ceverino+22

Small scale physics

- Star formation in molecular clouds results from an interplay among gravity, turbulence, and magnetic fields. [Krumholz & McKee+05](#), [Padoan & Nordlund+11](#), [Hennebelle & Chabrier+11](#), [Federrath & Klessen+12](#), [Bruckhart & Mocz+19](#)
- Different molecular cloud (and ISM) properties at high redshift. [Wisnioski+15](#), [Übler+19](#), [Dessauges-Zavadsky+19](#), [He+23](#)
- How does this affect star formation theory in gas clumps? [Krumholz+12](#), [Padoan & Nordlund+12](#), [Semenov+16](#), [Miville-Deschênes+17](#), [Grisdale+19](#), [Dessauges-Zavadsky+23](#)



Modelling star formation

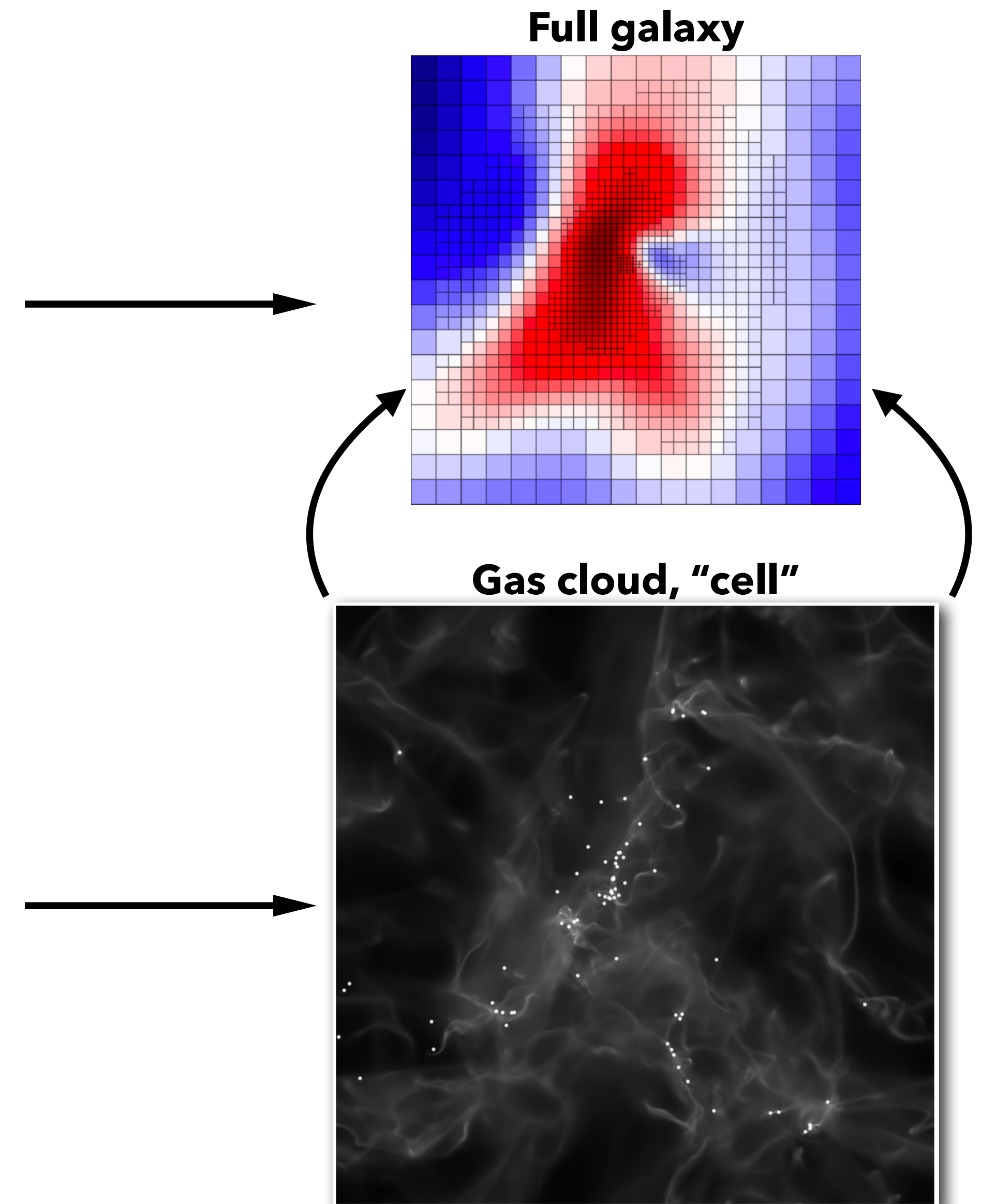
- Star formation in a cell ([Schmidt+59, Can & Ostriker+92](#)):

$$\rho_{\star} = \epsilon_{\text{ff}} \frac{\rho_{\text{g}}}{t_{\text{ff}}} \quad \text{for} \quad \rho_{\text{g}} > 100 \text{ cm}^{-3} \quad \& \quad T_{\text{g}} < 100 \text{ K}$$

- Free-fall time: $t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\rho_{\text{gas}}}}$

- Star formation efficiency per free fall time ([Padoan & Nordlund+12](#)):

$$\epsilon_{\text{ff}} = 0.5 \exp\left(-1.6 \frac{t_{\text{ff}}}{t_{\text{dyn}}}\right) \quad \text{with} \quad t_{\text{dyn}} = \frac{L}{2\sigma_{\text{gas}}}$$





THE VINTERGATAN SIMULATION

- Cheat Sheet

Agertz+21, Renaud+21a;+21b

Subgrid physics

- Star formation:

$$\rho_{\star} = \epsilon_{\text{ff}} \frac{\rho_{\text{g}}}{t_{\text{ff}}} \quad \text{for} \quad \rho_{\text{g}} > 100 \text{ cm}^{-3} \text{ \& } T_{\text{g}} < 100 \text{ K}$$

- Star formation efficiency per free fall time (Padoan+12):

$$\epsilon_{\text{ff}} = 0.5 \exp(-1.6 t_{\text{ff}}/t_{\text{dyn}})$$

- Feedback (Agertz+13, Agertz & Kravtsov 15; 16):

core-collapse and type Ia SNe, winds, radiation pressure

- IMF (Chabrier 03)

- Chemistry (Woosley & Heger 07):

iron and oxygen yields

- Cooling (Sutherland & Dopita 93, Rosen & Bregman 95):

metallicity dependent

- Heating (Haart & Madau 96):

epoch of reionization at $z = 8.5$

Set-up

N-body+hydrodynamic code RAMSES (Teyssier 02)

Λ CDM cosmology

AGORA *m12i* initial conditions (Hopkins+14)

Run for $100 < z < 0.17$ (~ 2 Gyr)

Metallicity floor: $10^{-3} Z_{\odot}$ (Wise+12)

Dark matter halo:

$$R_{200,m} = 334 \text{ pc} \text{ \& } M_{200,m} = 1.3 \times 10^{12} M_{\odot}$$

Resolution

Dark matter: $3.5 \times 10^4 M_{\odot}$

Star particles: $10^4 M_{\odot}$

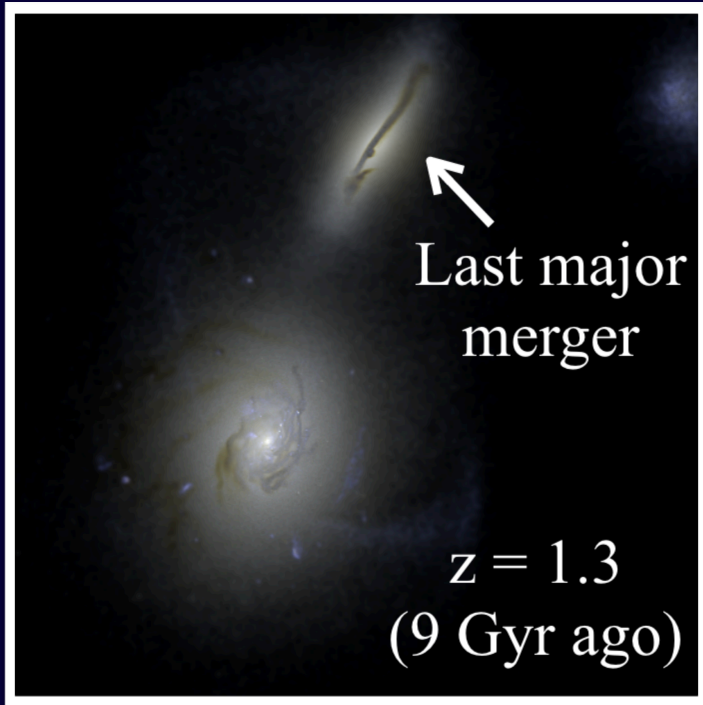
Gas mass: $7070 M_{\odot}$

Spatial: ~ 20 pc

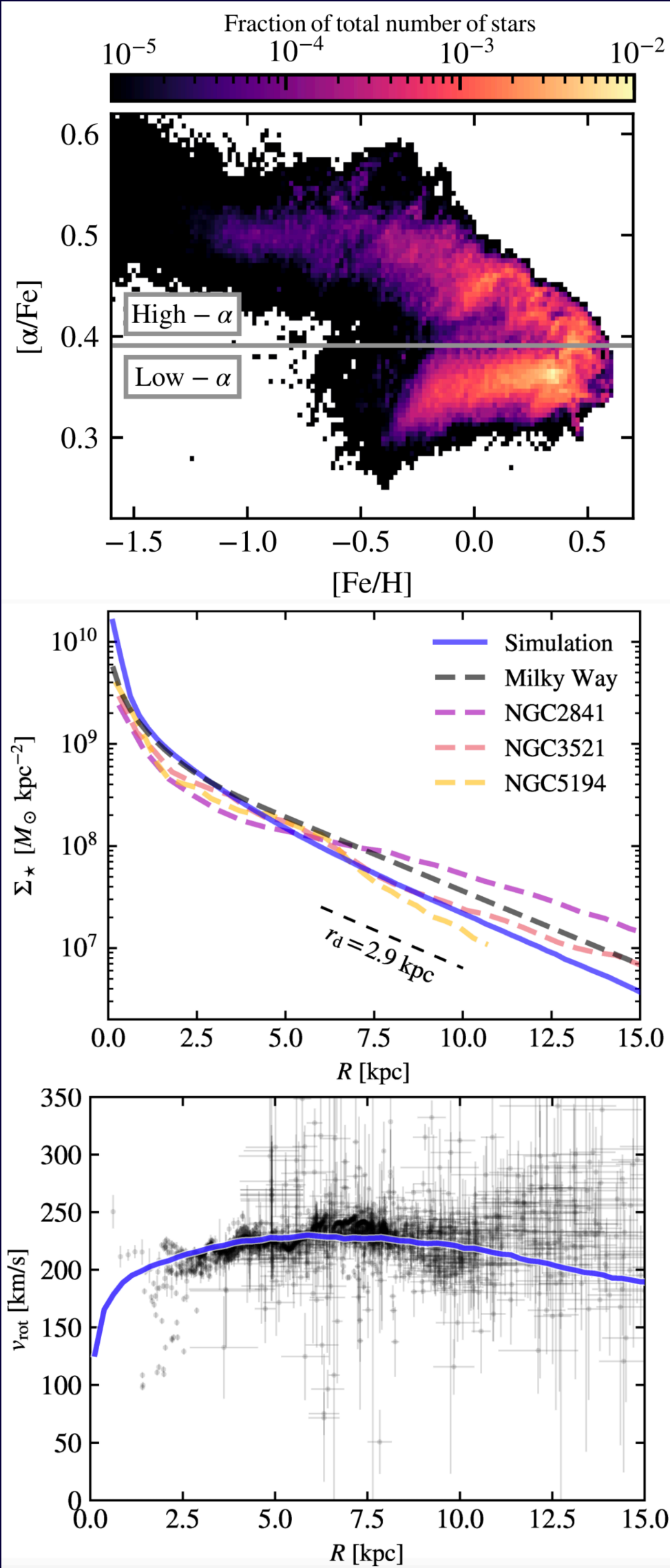
Density, $z=1.3$

 THE VINTERGATAN
SIMULATION

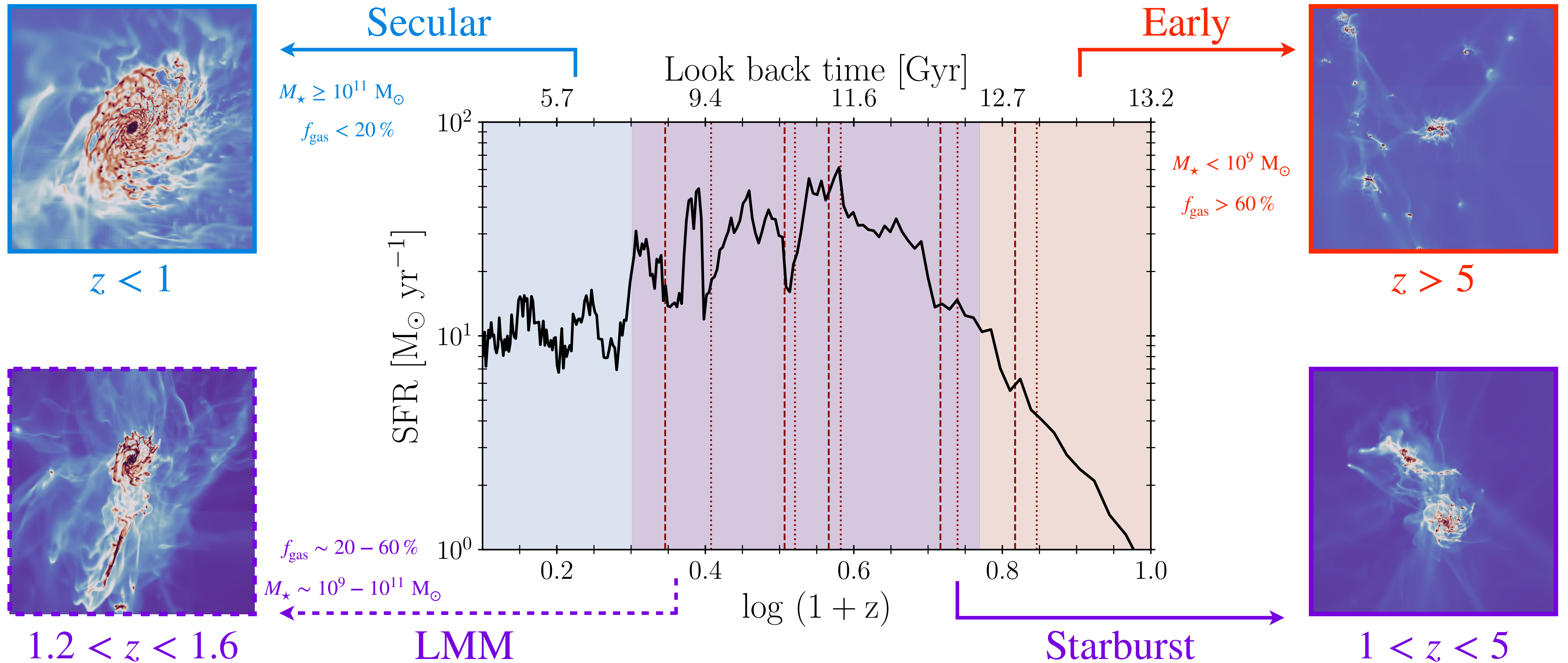
Agertz+21, Renaud+21a;+21b



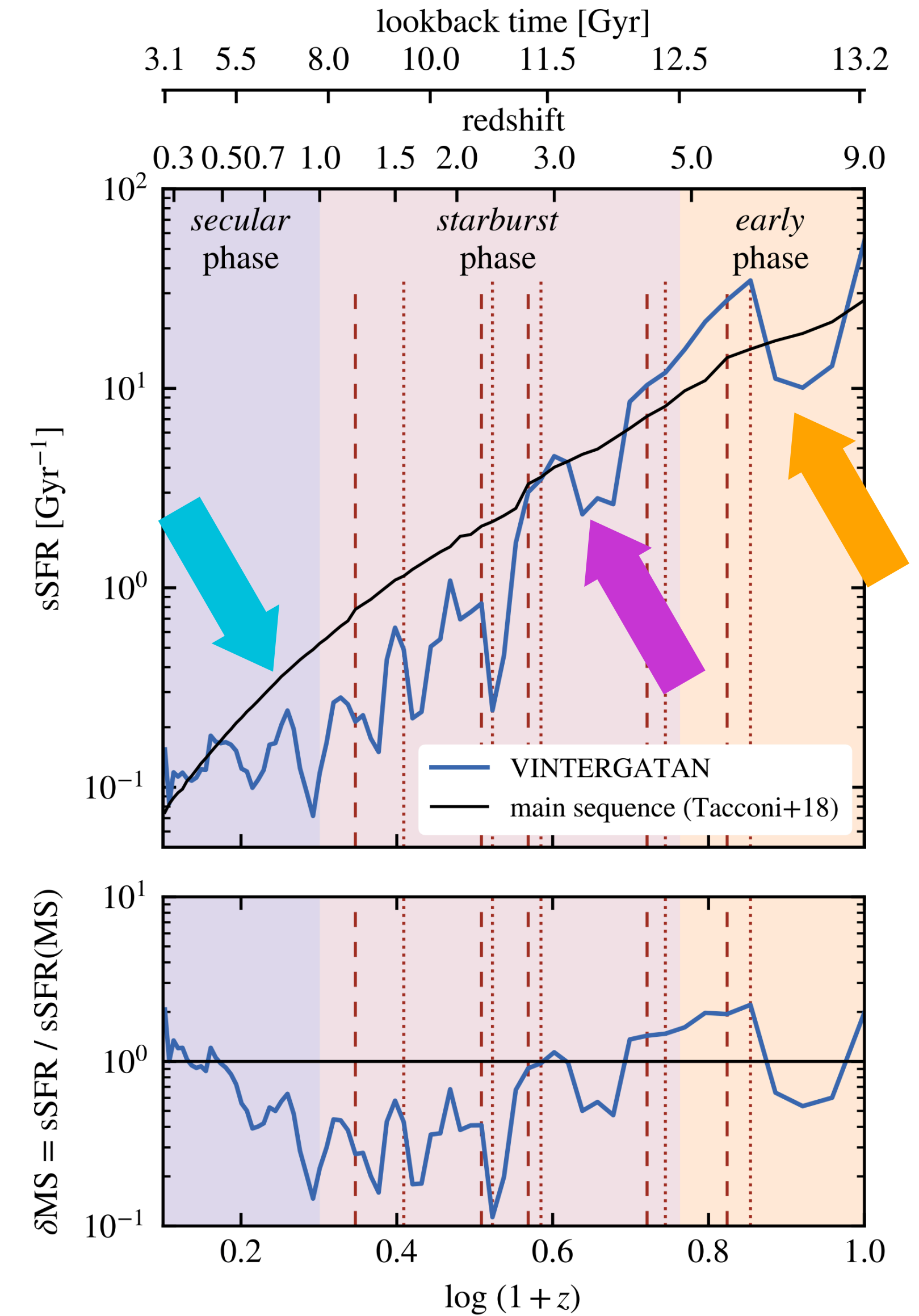
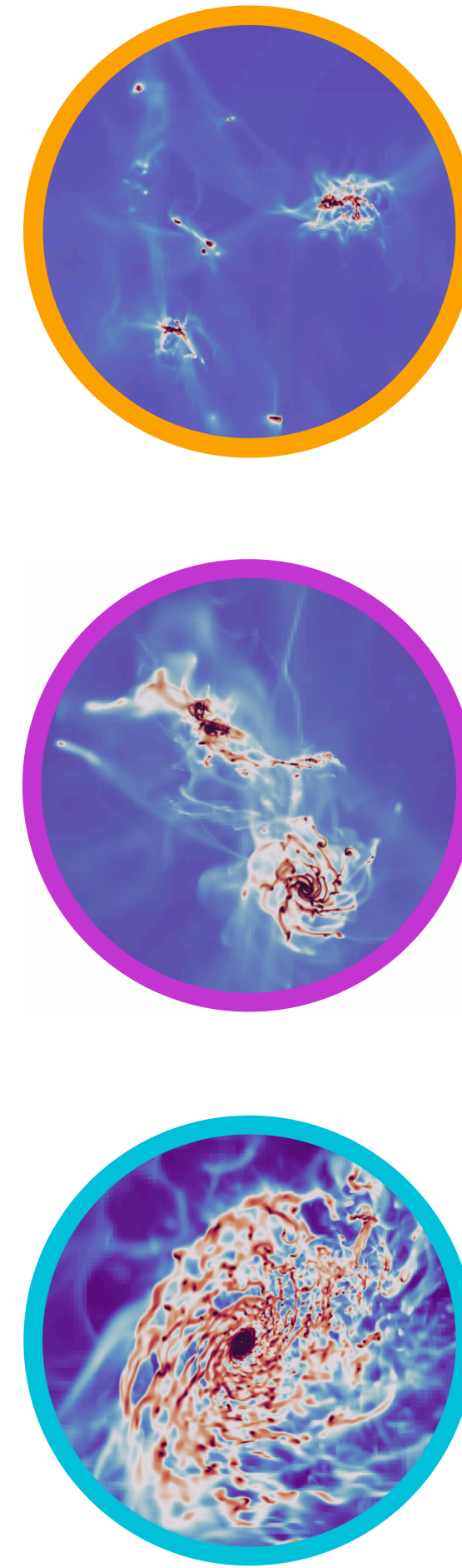
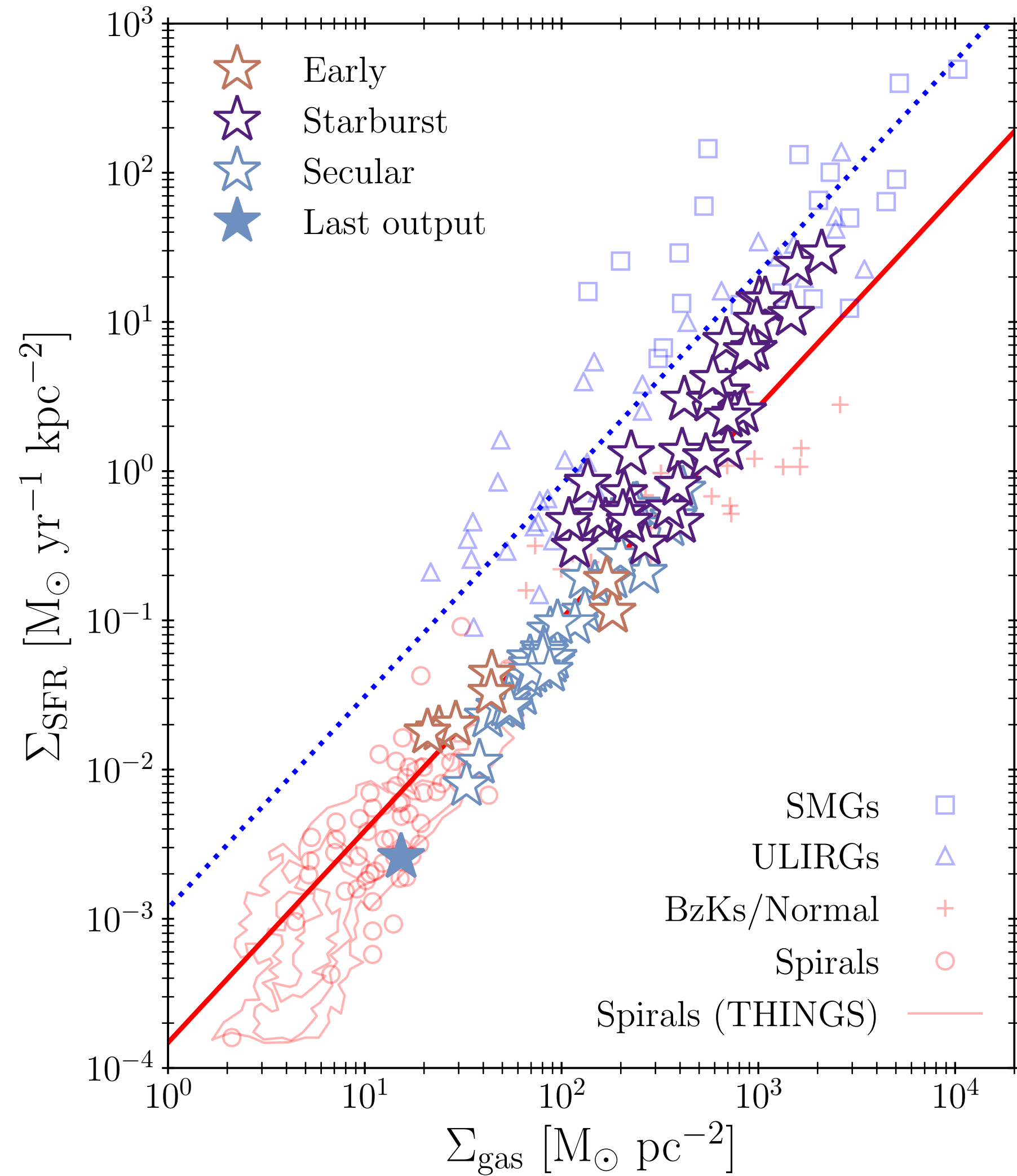
One galaxy in detail instead of galaxy population studies.
High resolution cosmological zoom-in simulation.
Observed features of Milky Way-like galaxies.



Epochs of star formation in VINTERGATAN

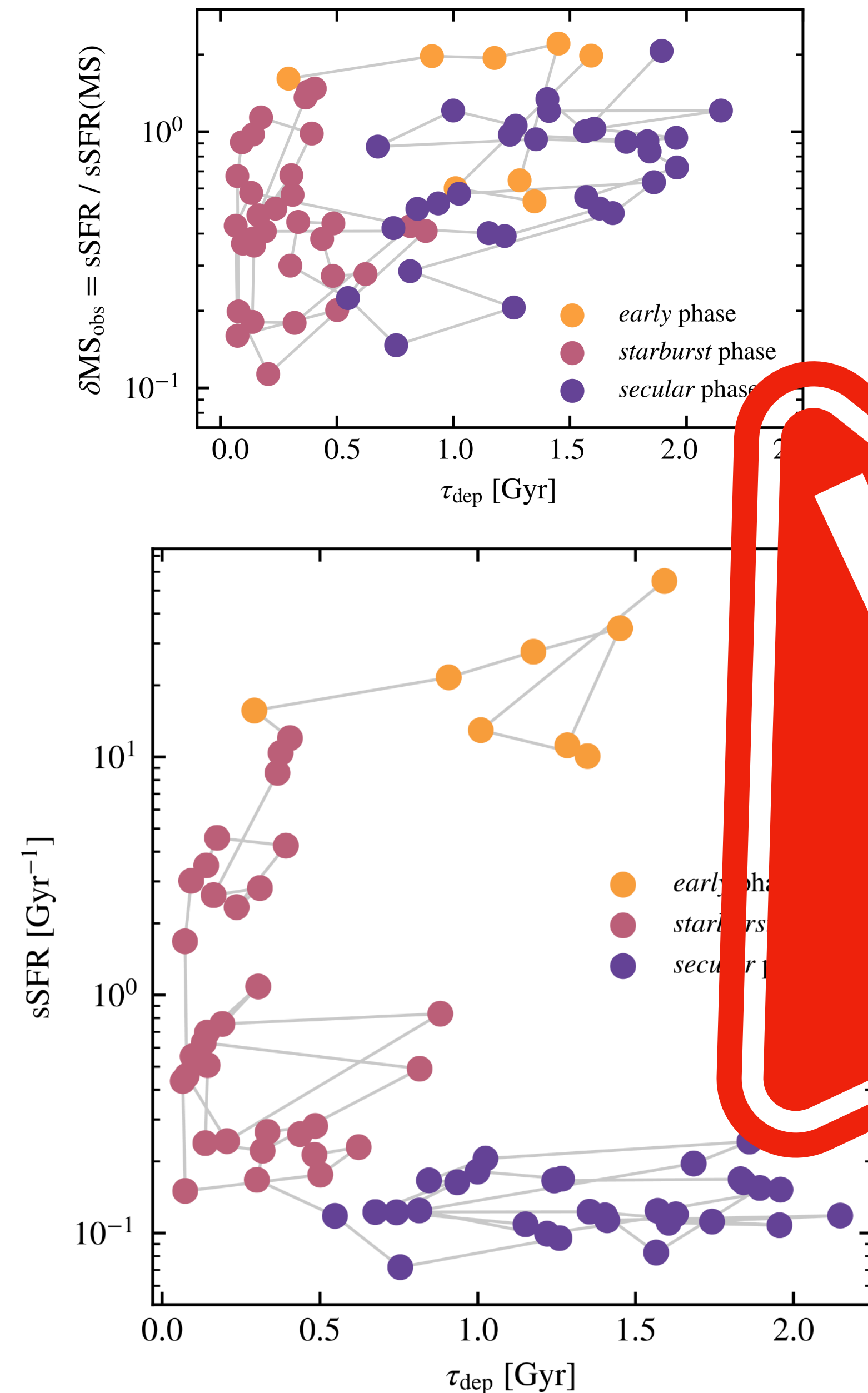


MS versus KS



Caution with the MS

- ◆ Two definitions of starburst: above the main sequence VS short τ_{dep}
- ◆ MS framework: *history* of stellar mass assembly
 τ_{dep} framework: *instantaneous* indicator
- ◆ Starbursts cannot be identified with by their sSFR. [Renaud, Segovia Otero & Agertz \(2022\)](#)

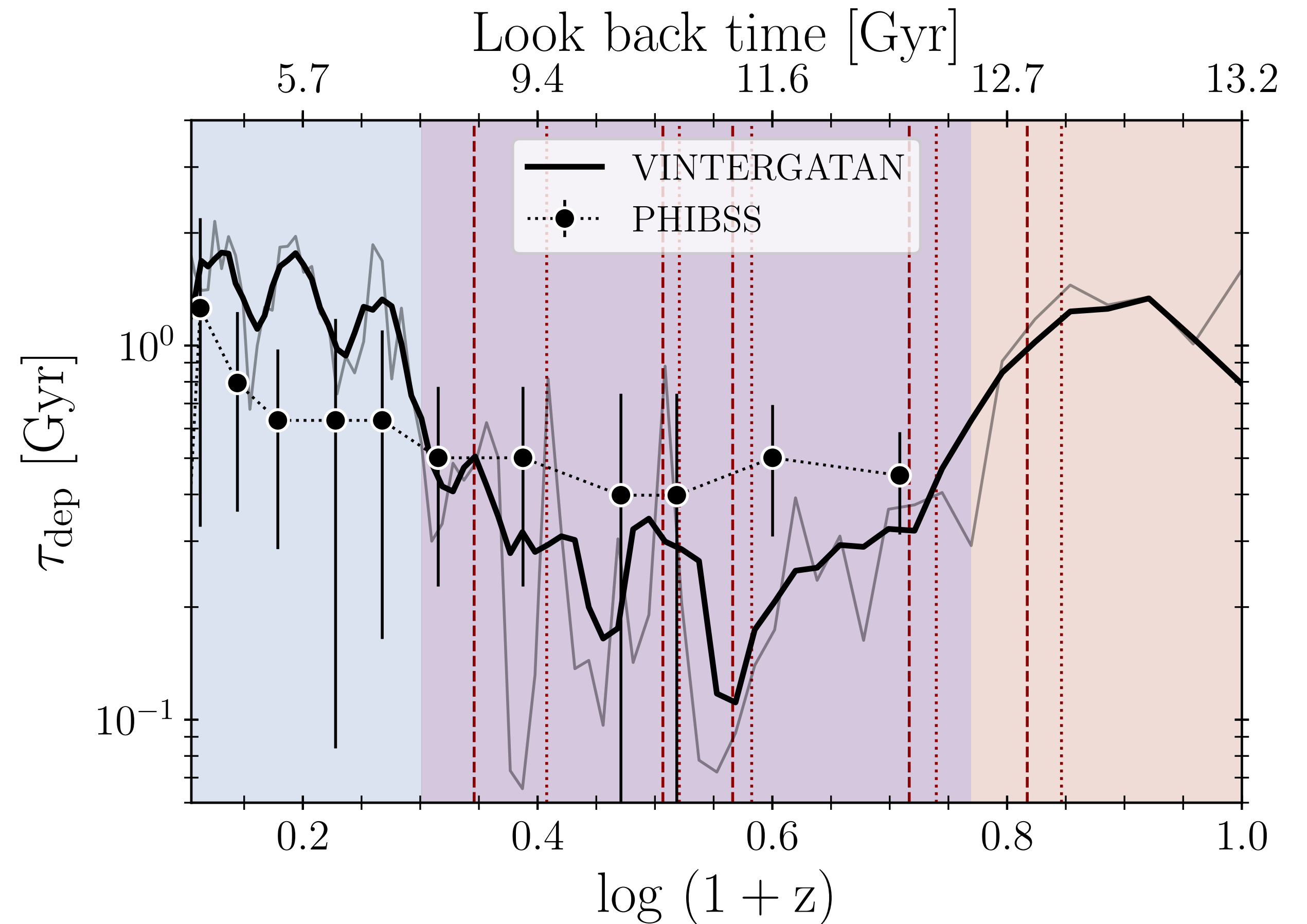


Depletion time to track starburstiness

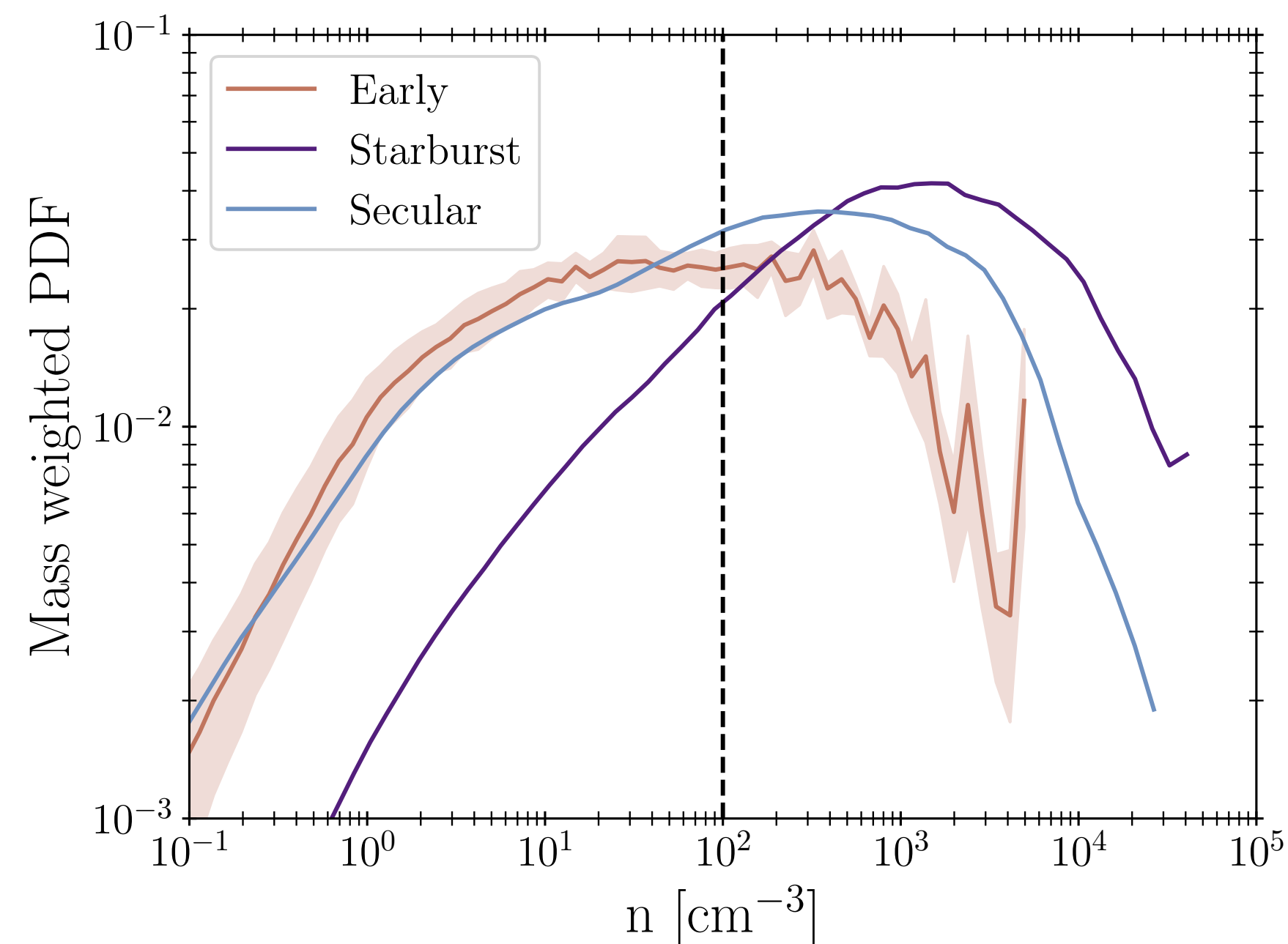
$$\tau_{\text{dep}} = \frac{M_{\text{gas}}}{\text{SFR}}$$

- ◆ Tenfold drop in τ_{dep} at $1 < z < 5$. Mergers are necessary but not sufficient!
- ◆ Non-monotonic trend with redshift
- ◆ Beware of the α_{CO} conversion factor!

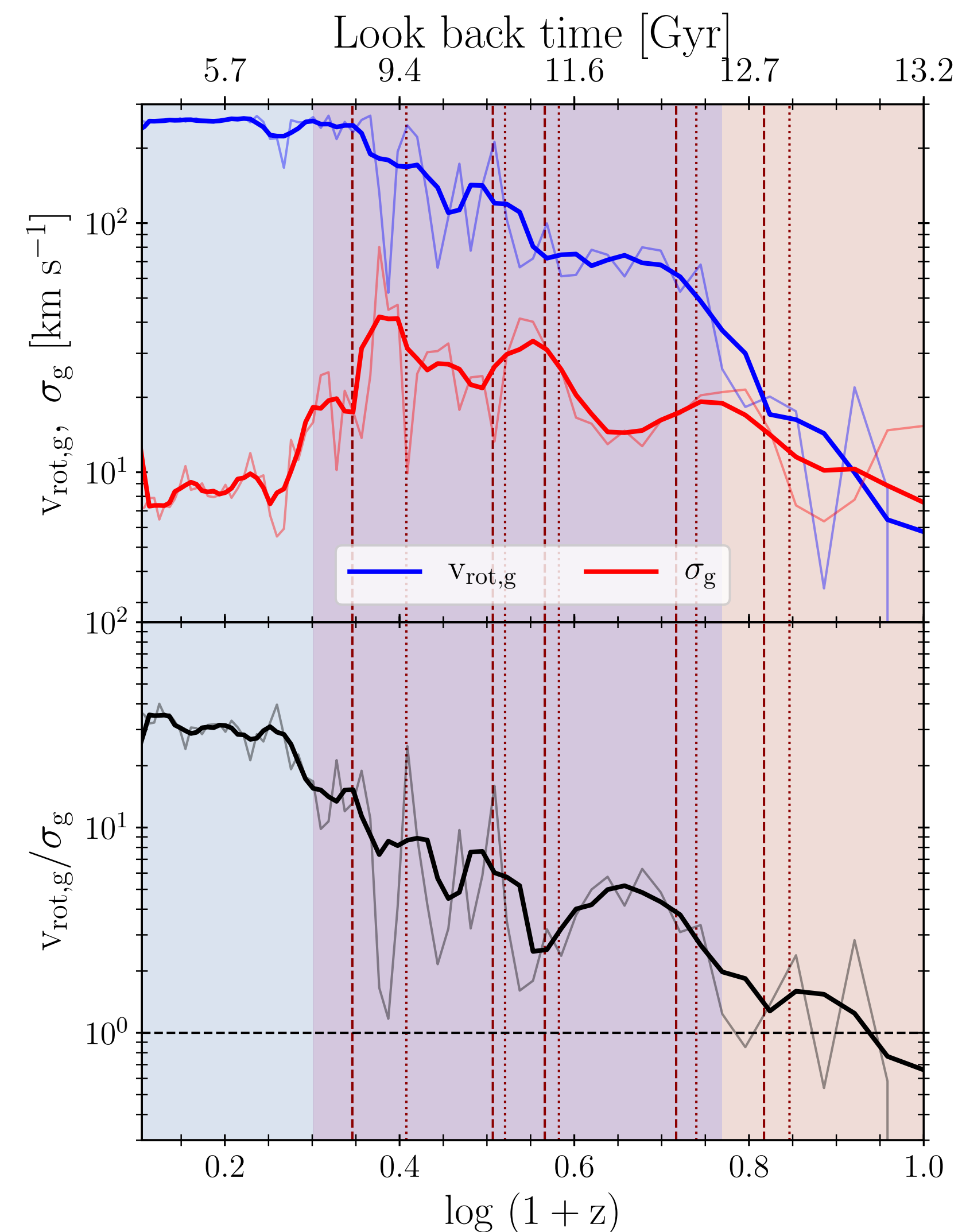
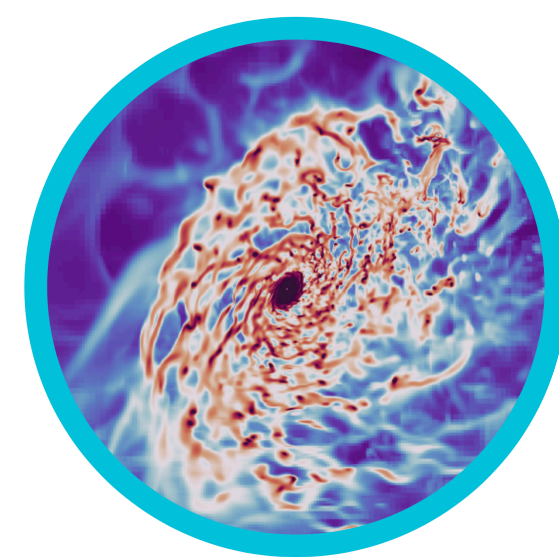
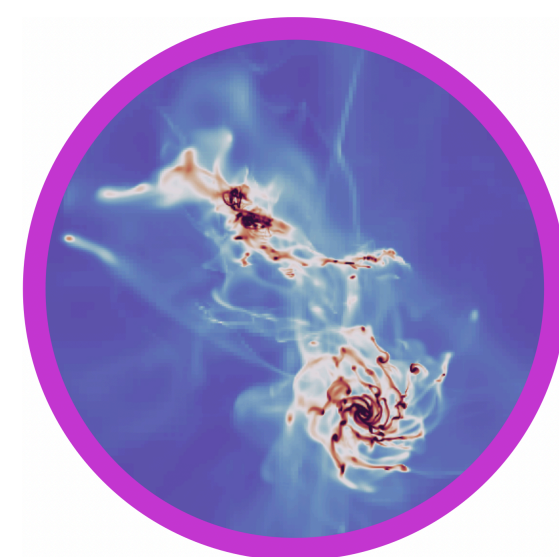
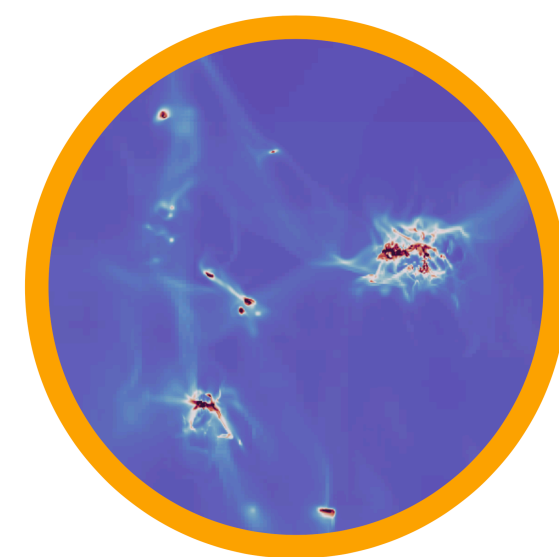
$$\alpha_{\text{CO}} = \frac{M_{\text{gas}}}{L_{\text{CO}}}$$



Gas density PDF and disk assembly

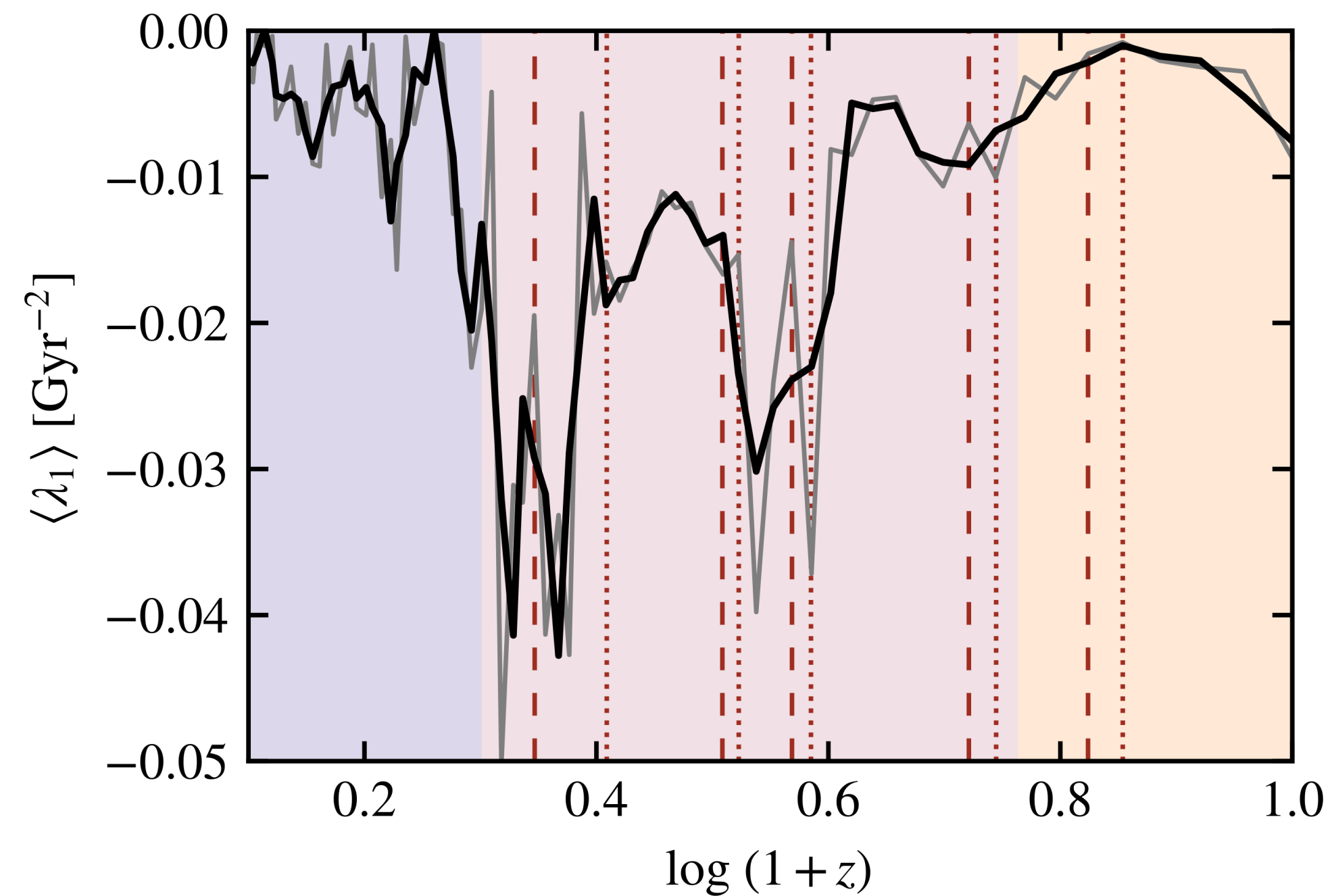


- Integrated gas above density threshold.
- v_{rot} : coherent motion of cold gas.
- σ_g : gas turbulence

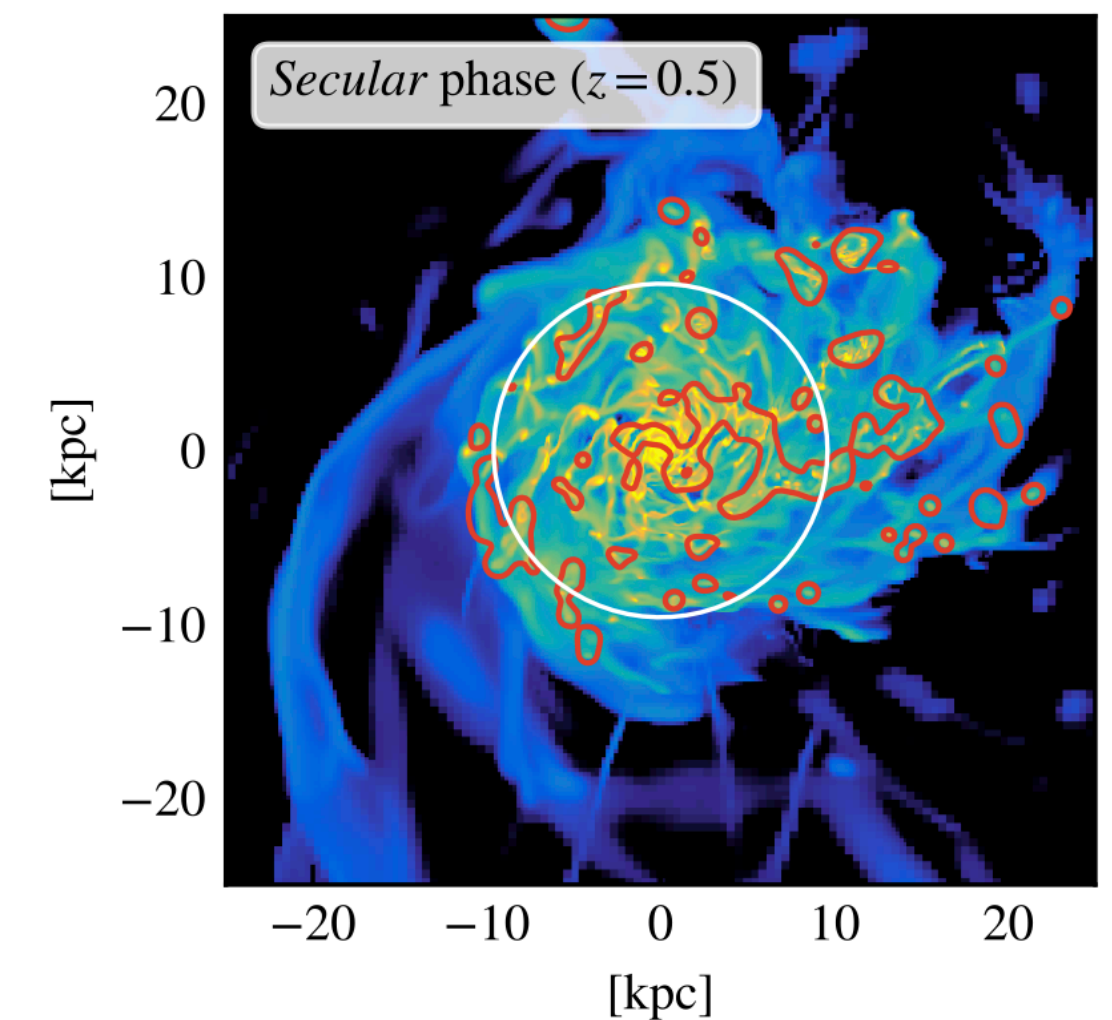
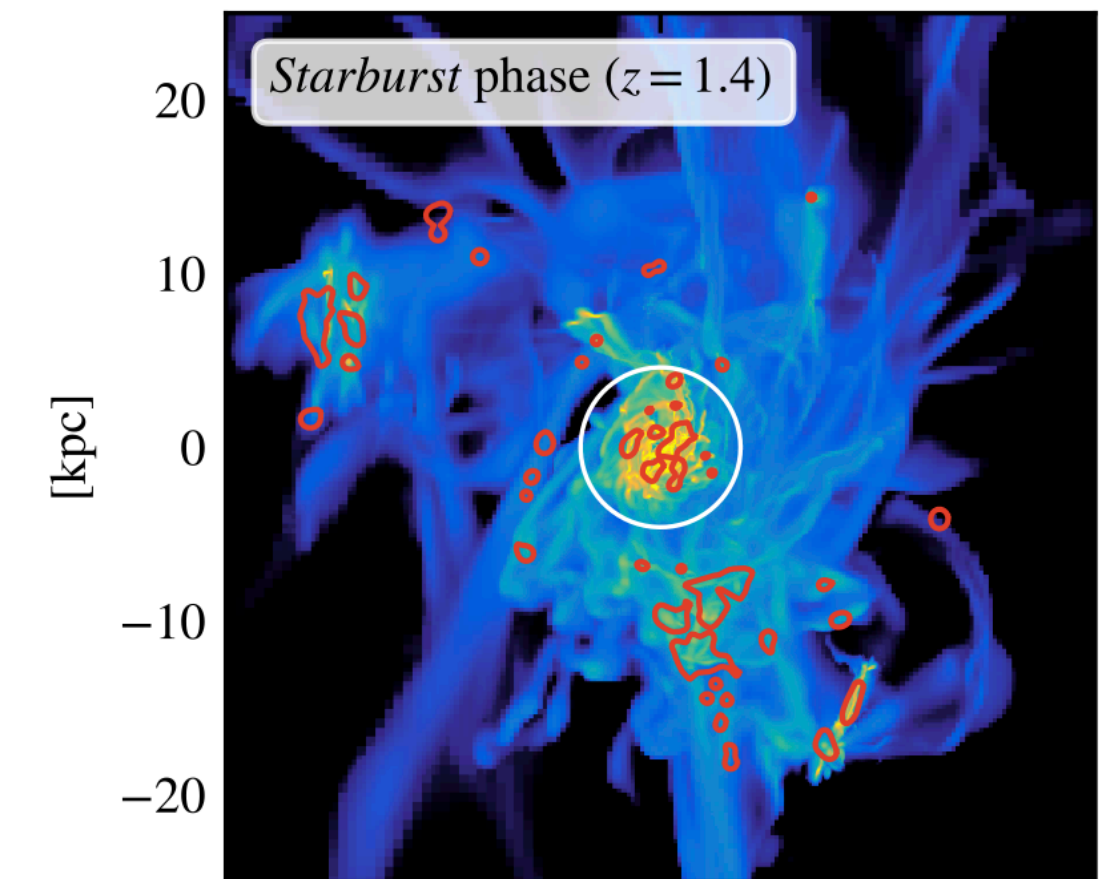
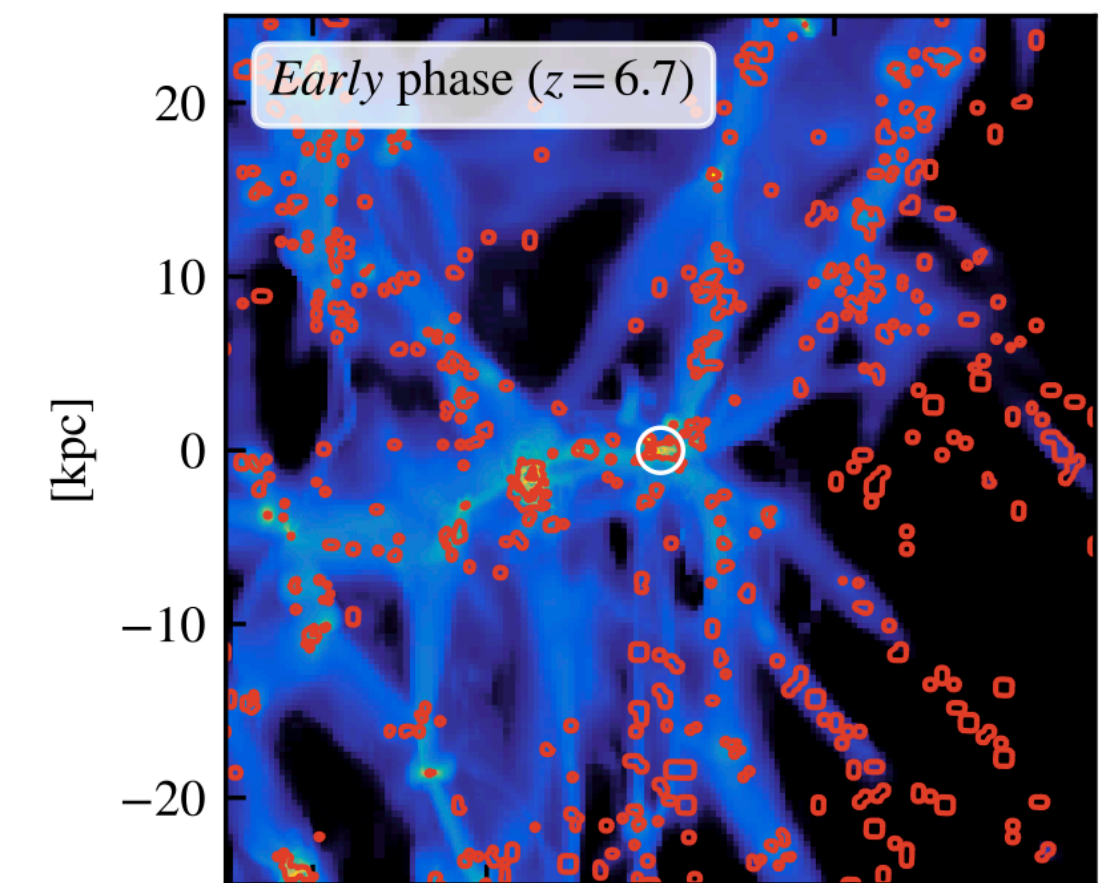


Tidal compression $T^{ij} = -\frac{\partial^2 \Phi}{\partial x^i \partial x^j}$

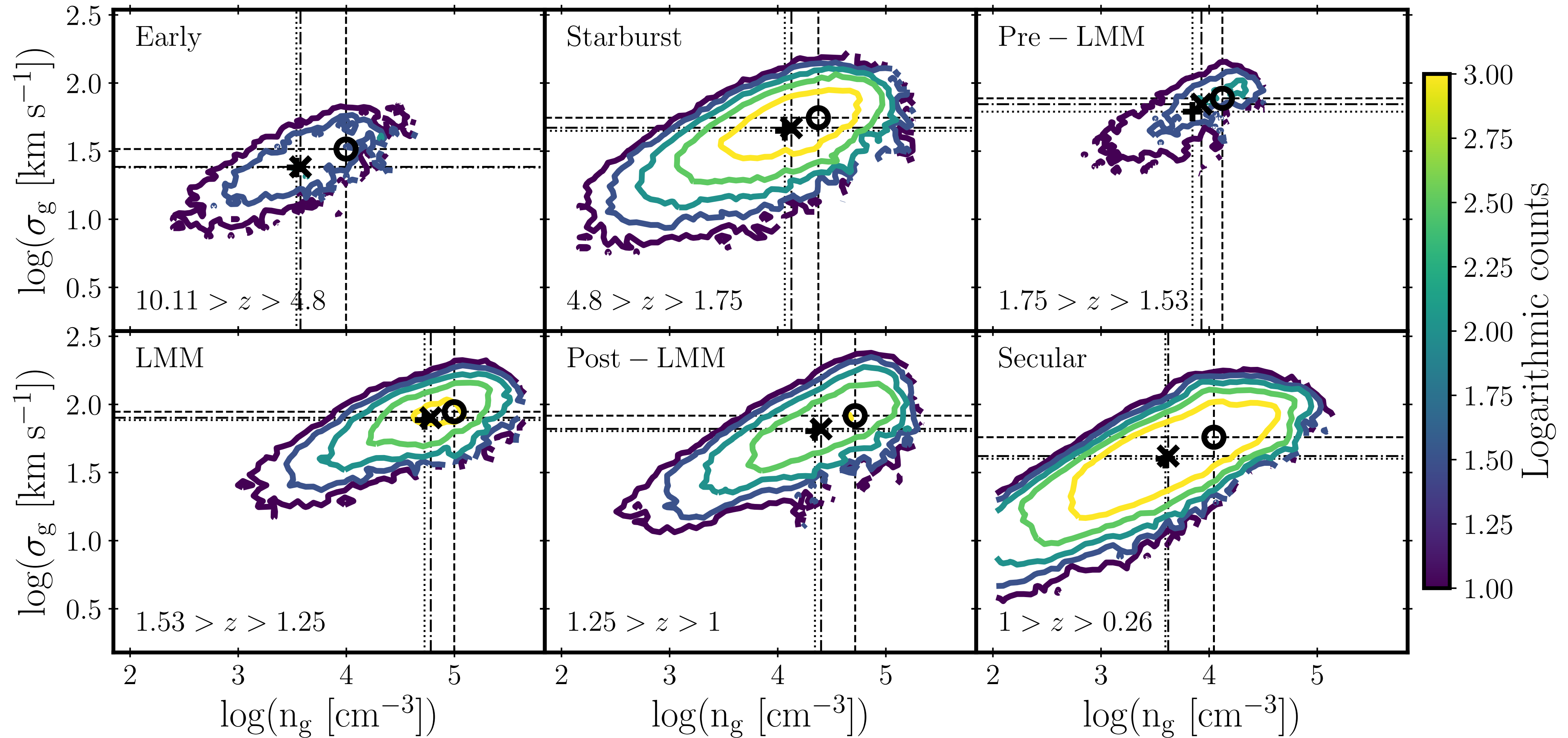
- ◆ Analyse the tidal field in our simulation



- ◆ Tidal compression cascades into compressive turbulence, which create an excess of dense gas.



On-the-fly data at 20 pc

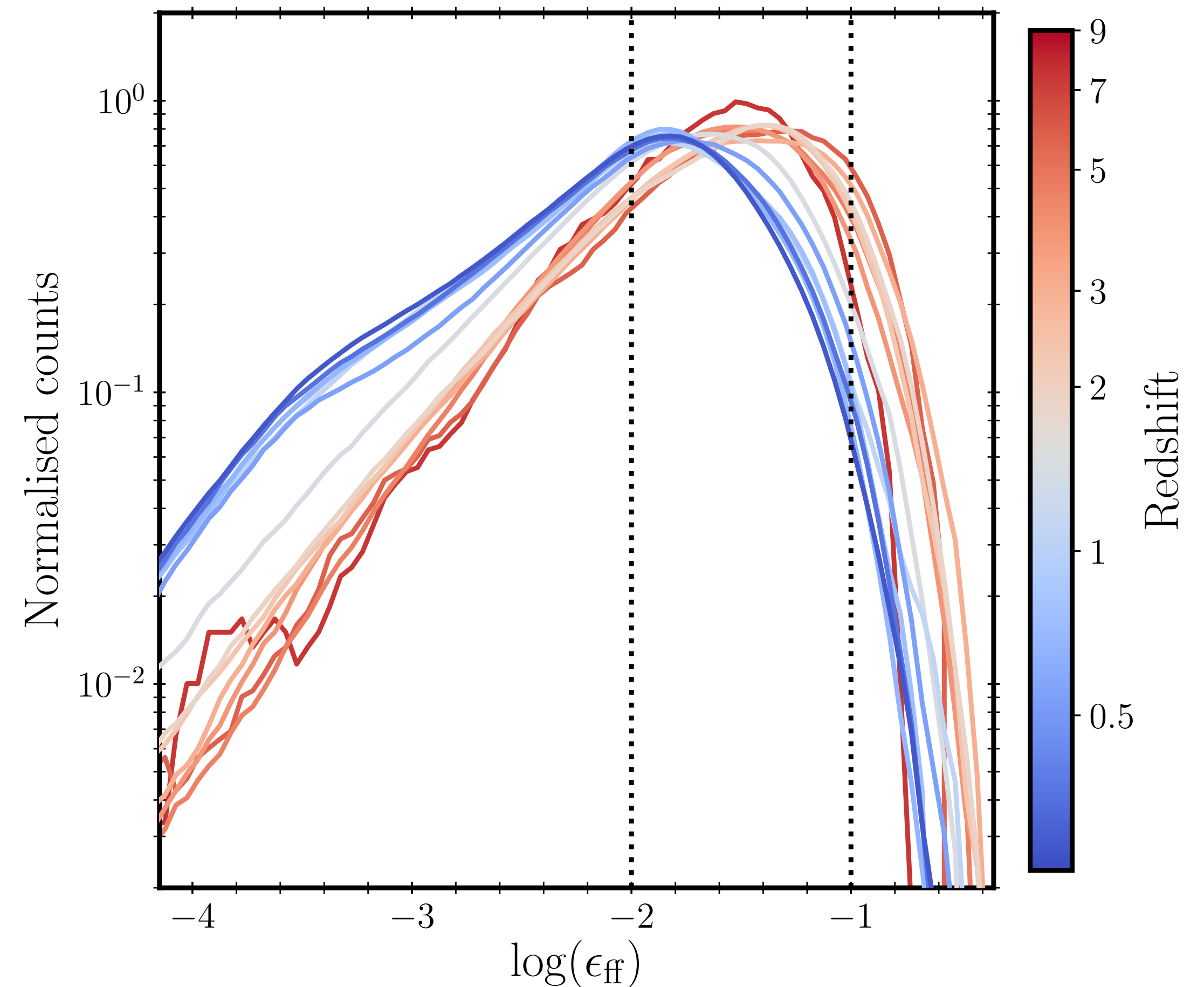


Constant star formation efficiency

$$\epsilon_{\text{ff}} \propto \exp(-C \sigma_g / \sqrt{n_g})$$

- ◆ Gas density and velocity dispersion distributions change as a function of cosmic time.
- ◆ They *conspire* to render a constant ϵ_{ff}
- ◆ Star formation is mainly driven by changes in the gas density distributions rather than the levels of turbulence.

$$\rho_{\star} = \epsilon_{\text{ff}} \frac{\rho_g}{t_{\text{ff}}} \longrightarrow \tau_{\text{dep}} = t_{\text{ff}} / \epsilon_{\text{ff}}$$



Conclusion

Segovia Otero+22
Renaud, Segovia Otero+22
Segovia Otero+ in prep.

- ◆ Different phases of star formation are observed in VINTERGATAN, applicable to disc galaxies in general.
- ◆ Starbursts are triggered when the ISM is tidally compressed towards high densities.
- ◆ This is observed as an order of magnitude decrease in the gas depletion time, enabled by the assembly of a disc at $z \approx 4.8$.
- ◆ ALMA and JWST will help us understand turbulence in gas clumps at high redshift.
- ◆ CAUTION with how you interpret the main sequence of star formation!