Dependence of galactic clumpiness on ISM models for high-density gas in cosmological simulations

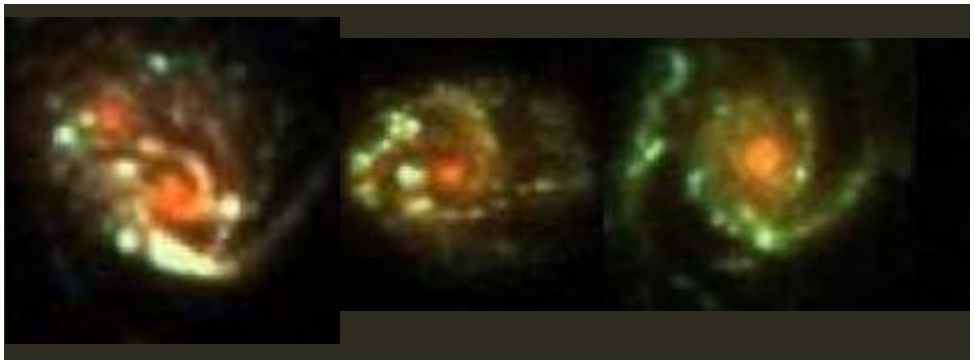
MNRAS submitted

Shigeki Inoue (Tsukuba / NAOJ)

Naoki Yoshida (Tokyo)

Clumpy galaxies

- Disc galaxies in their formative stages
  - Typically at z~1-3

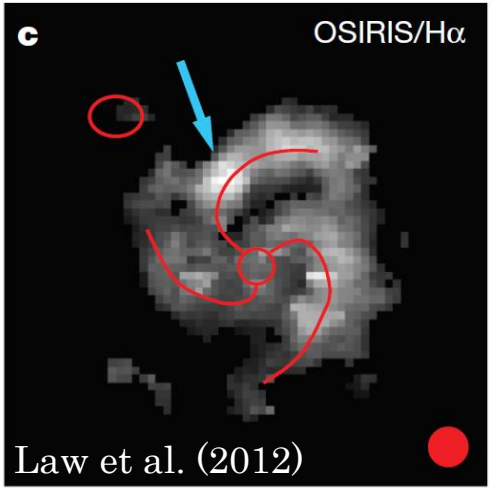


Guo et al. (2014)

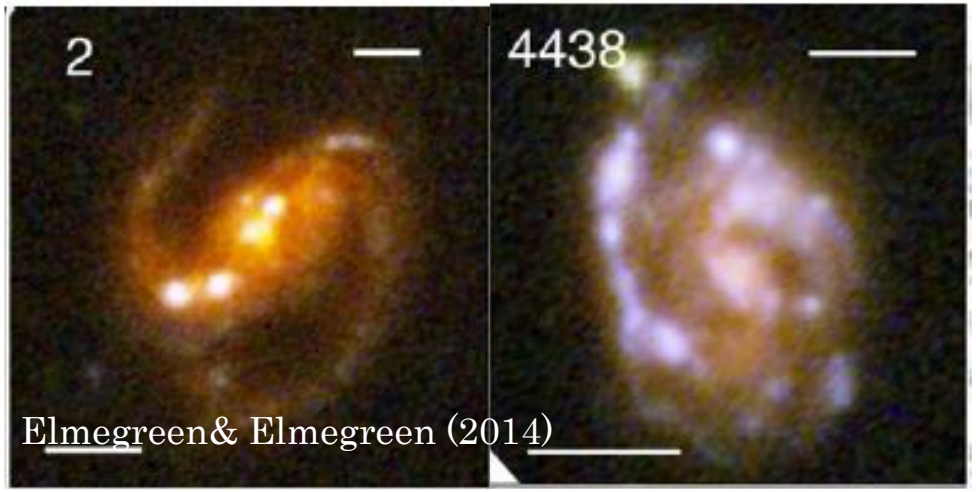
Clumpy galaxies

- **Giant clumps**
- Gas-rich (f_{gas}>30%)

- Toomre instability?
- Spiral-arm instability?
- Mergers?



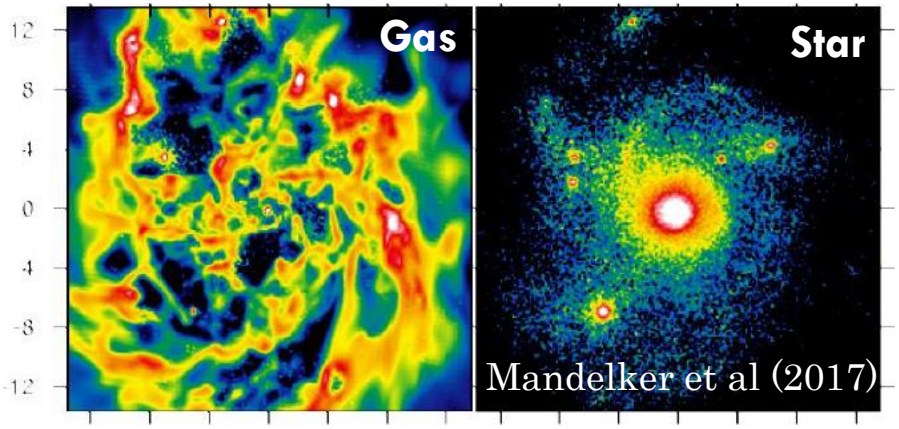
Law et al. (2012)



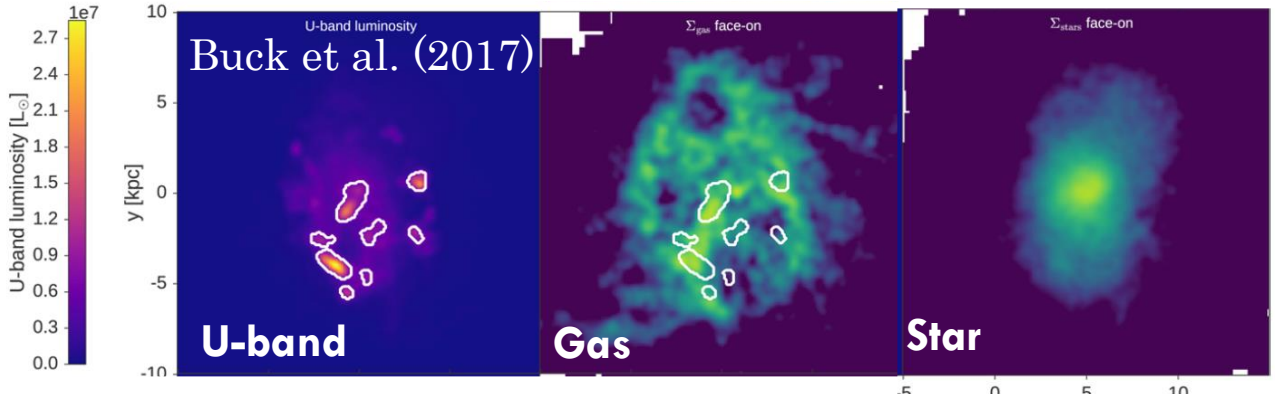
Elmegreen& Elmegreen (2014)

Clumpy galaxies in simulations

- Gravitationally bound structures
  - **If feedback is weak**



- Unbound structures and/or disrupted soon
  - **If feedback is strong**

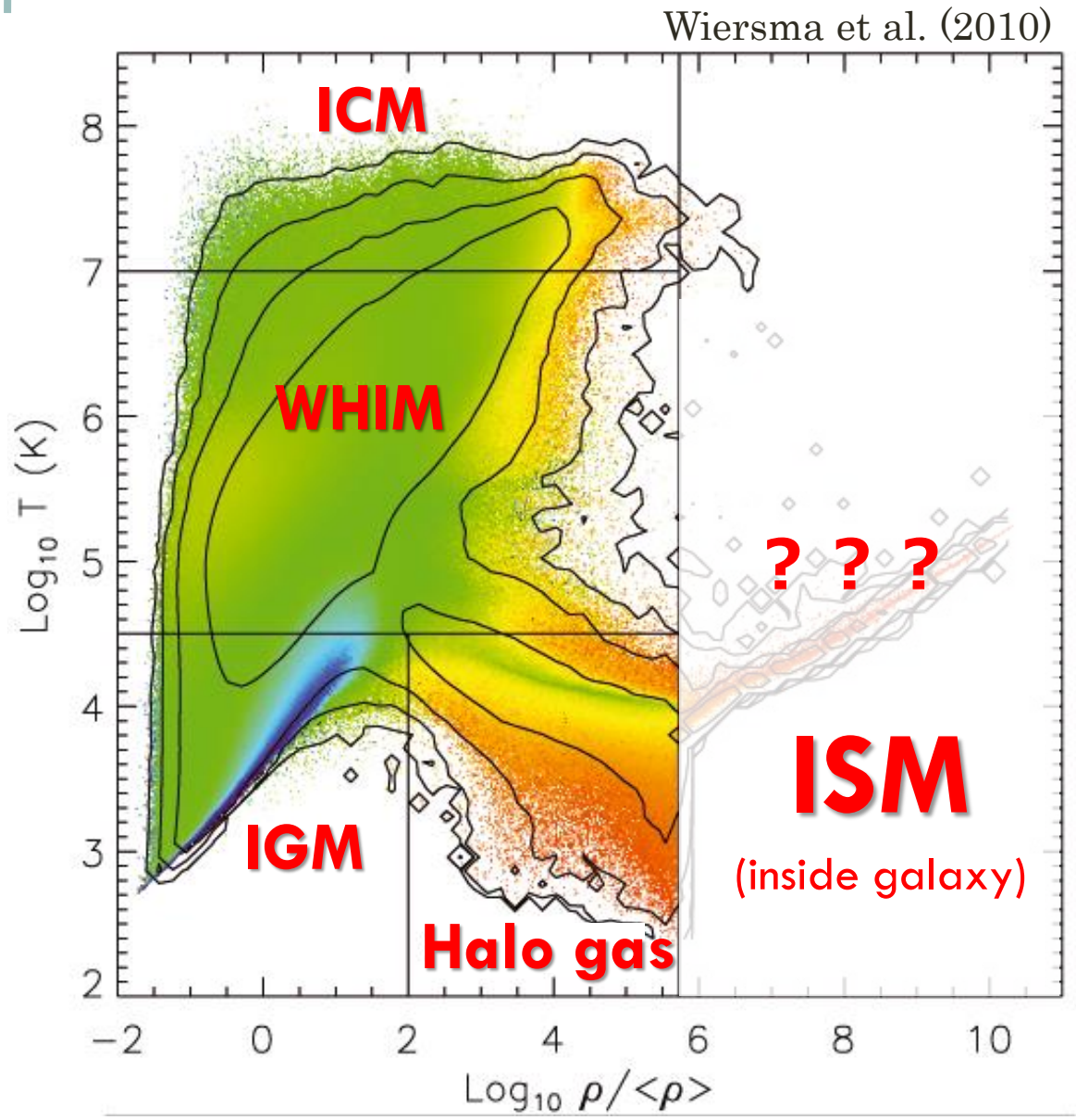


Clumpy galaxies in simulations

Is feedback the only key factor?
➡ ISM model can also affect clump formation

- Purpose:
  - We show how ISM model affects cosmological simulations,
    - Examine three ISM models that are widely used.
      - “Two-phase model” (Illustris-TNG)
      - “Polytrope model” (EAGLE)
      - “Single-phase model” (FIRE)

What is ISM model?

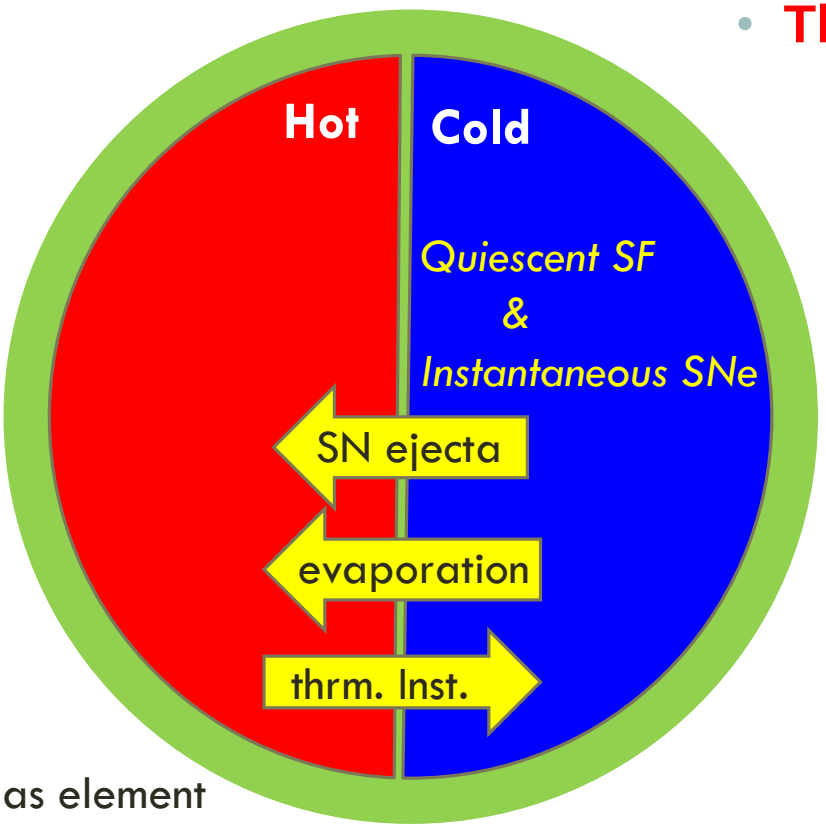


- ISM is gas inside a galaxy
  - i.e. star-forming
- **ISM properties are uncertain**
  - Various physics involves:
    star formation, supernovae, radiation, rapid cooling, turbulence etc…
- Simulations often assume ISM properties.
  - EOS by modelling ISM

Two-phase ISM model

For dense gas that can form stars ($\rho_{gas} > \rho_{SF}$)

- Yepes et al. (1997), Springel & Hernquist (2003)
  - **Illustris / Illustris-TNG simulations**
  - **Auriga simulations**



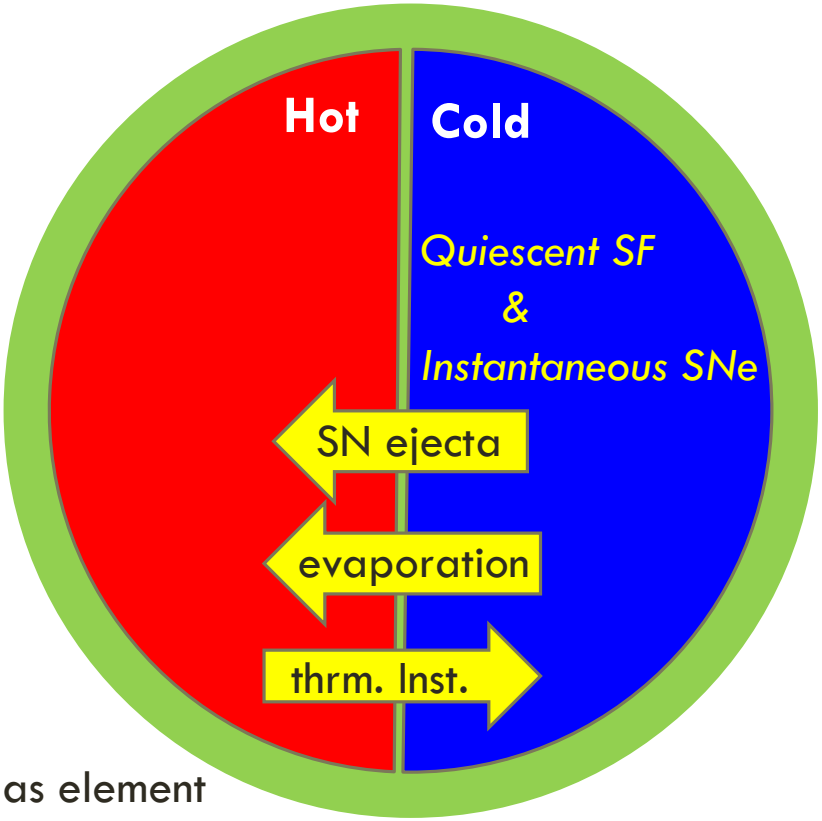
A gas element

- **This model gives a barotropic EOS.**
  - Considering pressure equilibrium,
    - with only a few parameters,
      - a cooling function given

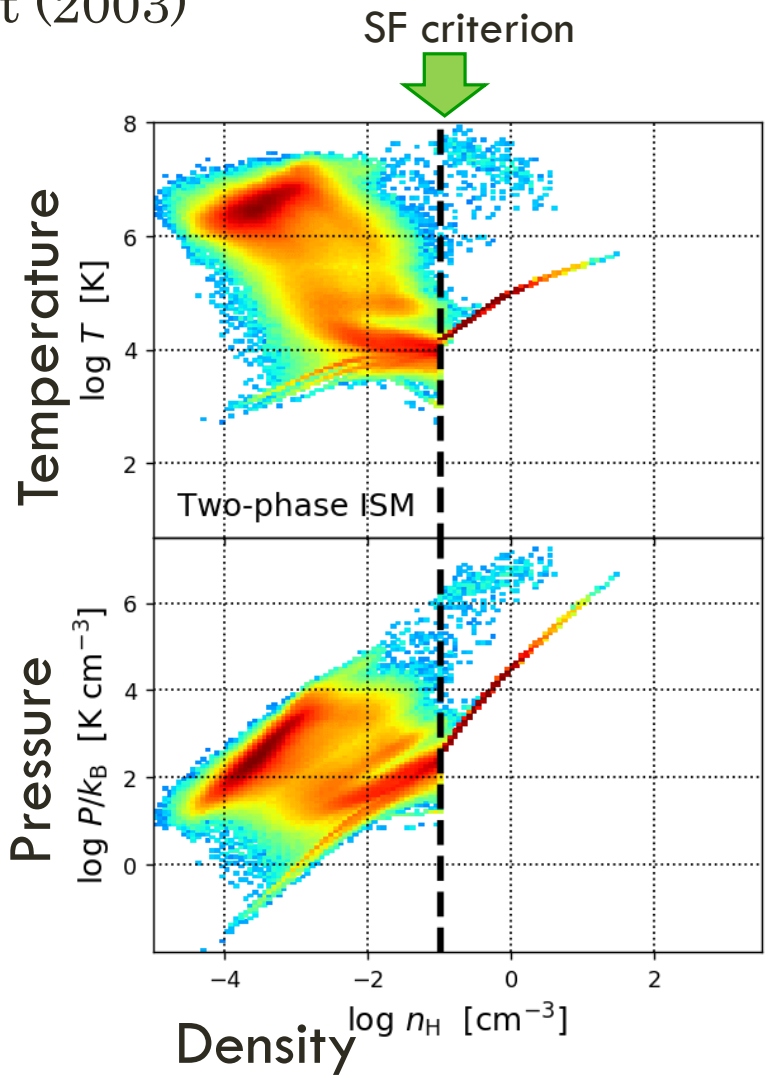
Two-phase ISM model

For dense gas that can form stars ($\rho_{gas} > \rho_{SF}$)

- Yepes et al. (1997), Springel & Hernquist (2003)
  - **Illustris / Illustris-TNG simulations**
  - **Auriga simulations**



A gas element



Polytrope ISM model

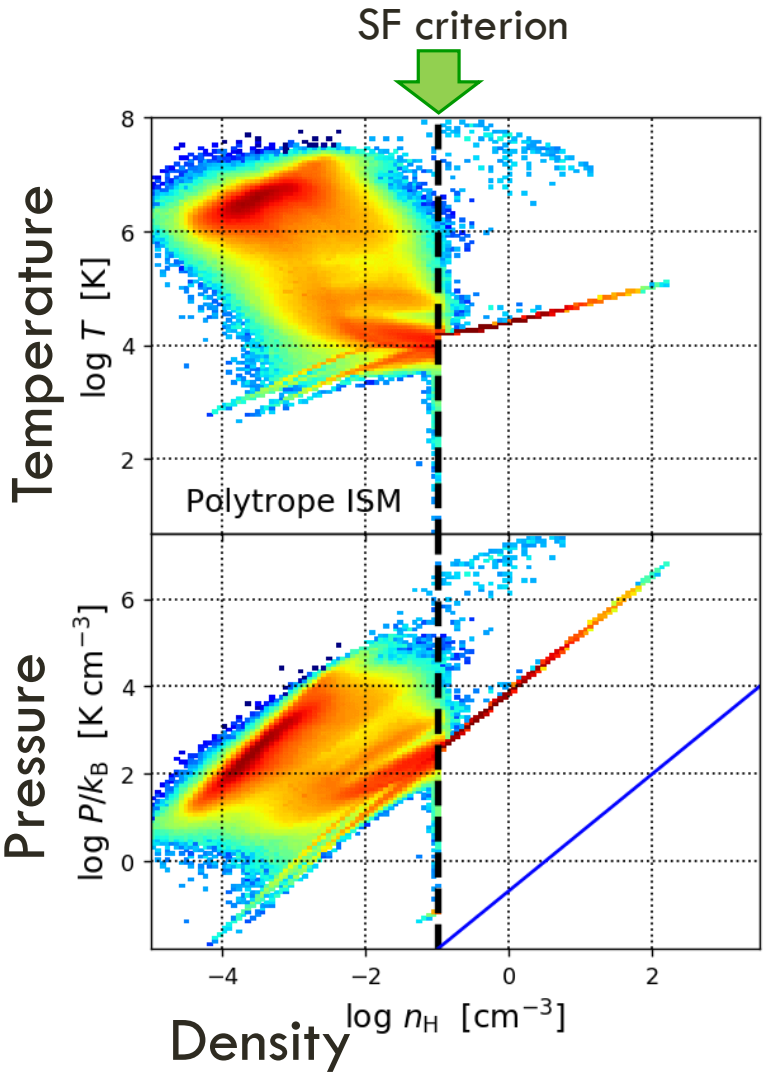
For dense gas that can form stars ($\rho_{gas} > \rho_{SF}$)

- Schaye & Dalla Vecchia (2008)
  - **OWLS / EAGLE simulations**
  - **APOSTLE simulations**
  - **Horizon-AGN simulations**

- In order to suppress fragmentation within a Jeans unstable cloud

$$P_{\rm floor} \propto \rho_{\rm g}^{4/3}$$

$$T_{\rm floor} \propto \rho_{\rm g}^{1/3}$$



Single-phase ISM model

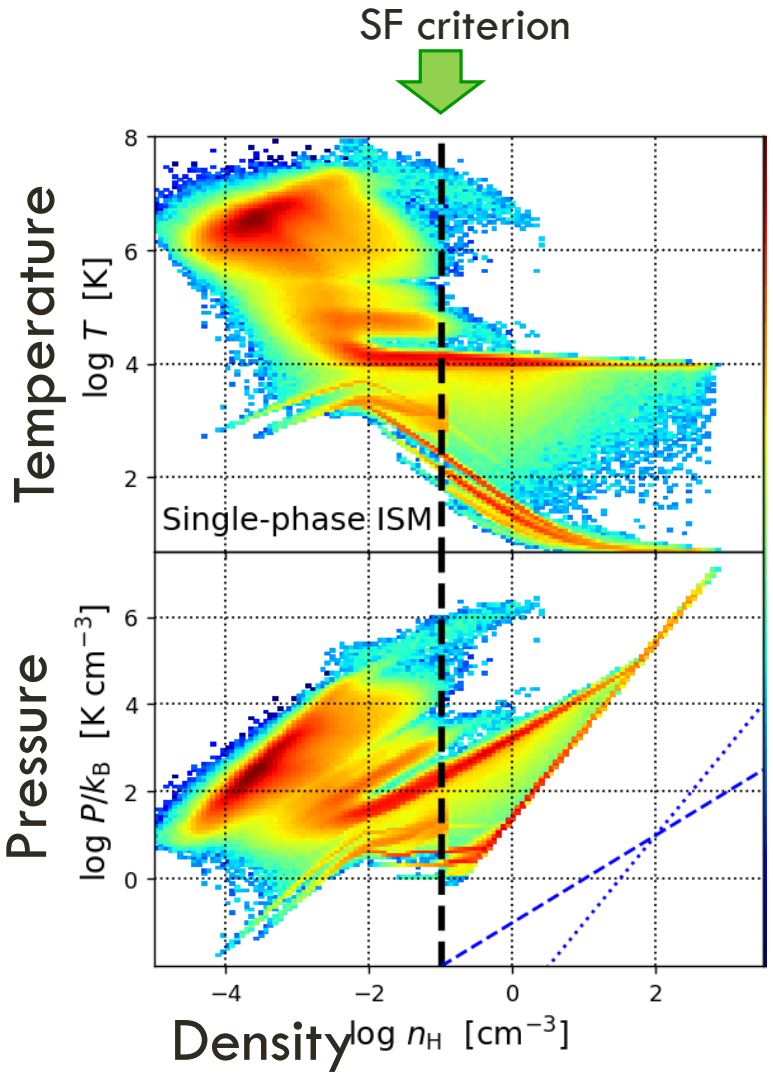
This model does not enforce EOS on gas

- The most standard and common method
  - **FIRE simulations**
  - **NIHAO simulations**
  - **VELA simulations**
  - **Etc…**

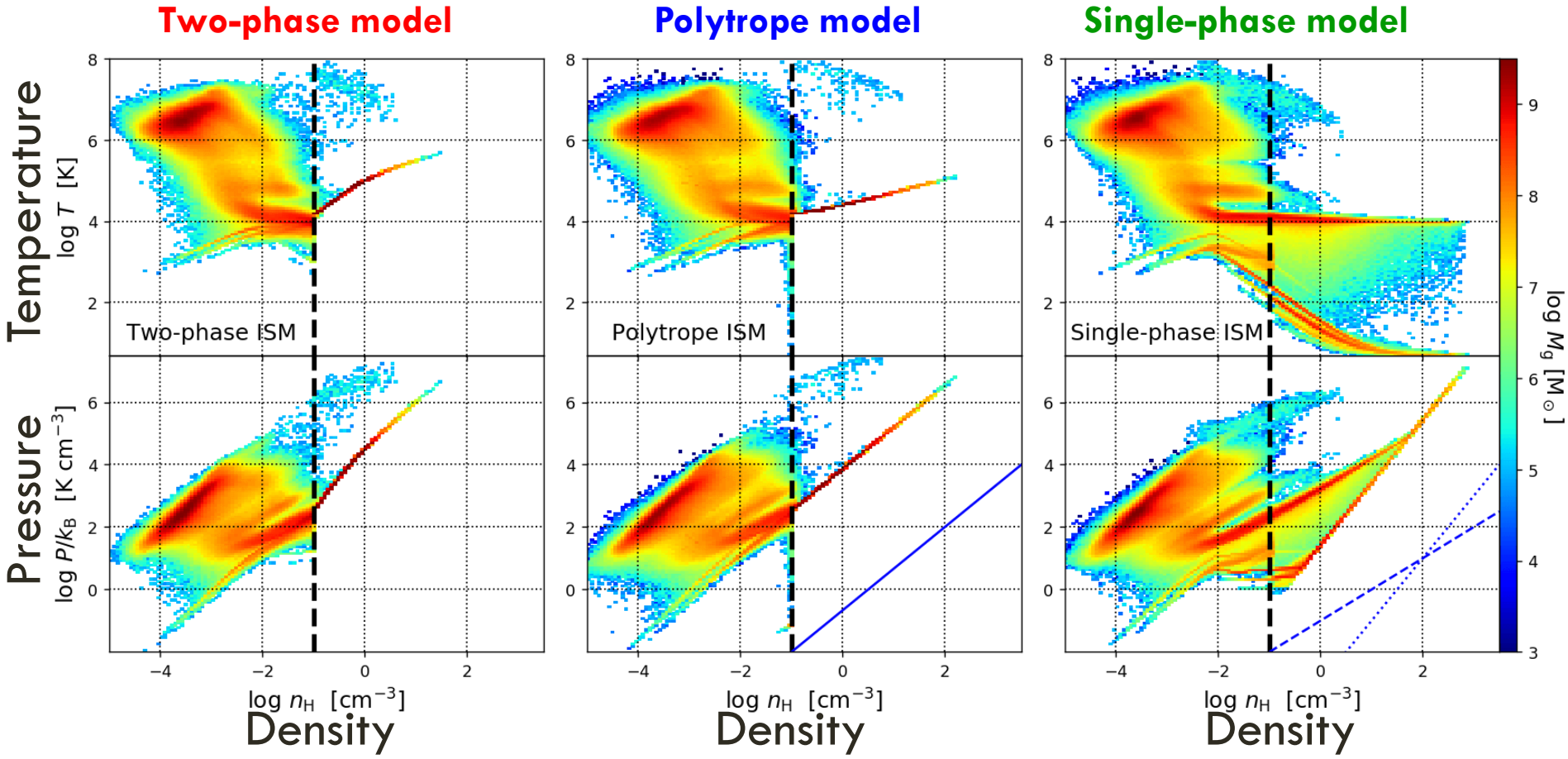
- Gas can cool according to cooling function
- But, a pressure floor is applied to prevent artificial fragmentation.
- Truelove-Ceverino condition (Ceverino et al. 2010)

$$P_{\rm floor} = \frac{G\rho^2 N_{\rm c}^2 \Delta^2}{\pi\gamma}$$

- $N_c = 7$
- Δ : spatial resolution
- $\gamma = \frac{5}{3}$



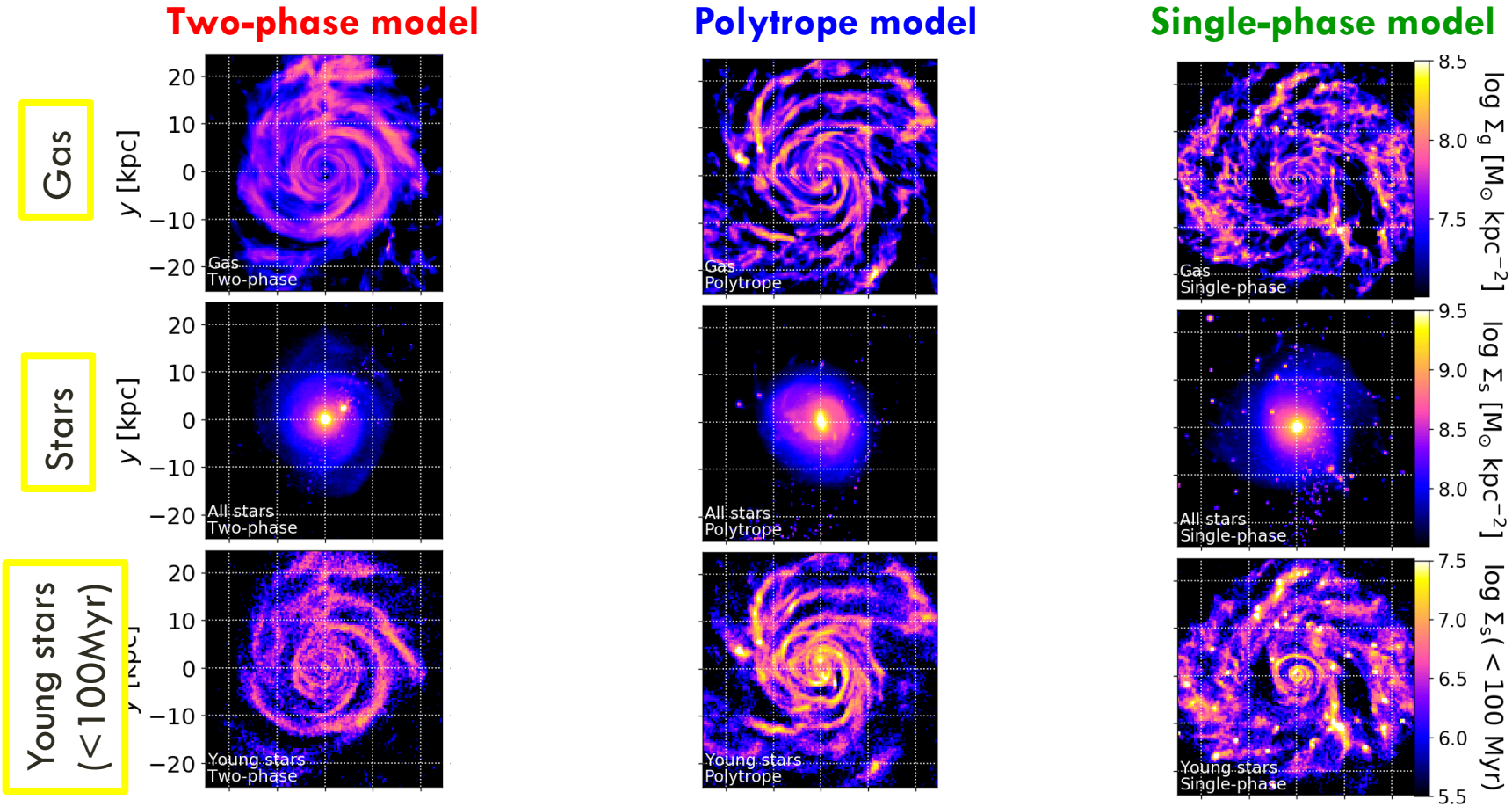
ISM models



Cosmological zoom-in simulations

- Arepo (moving-mesh code, Springel 2010)
- Resolution: $\sim 10^5$ $M_\odot$ for baryon
- Target: $\log(M_{star}/M_\odot) = 10.5 - 11.5$ at z=1

Clumpiness of galaxies



# of clumps ($>10^8\ M_\odot$)

$N_{clump} = 0$

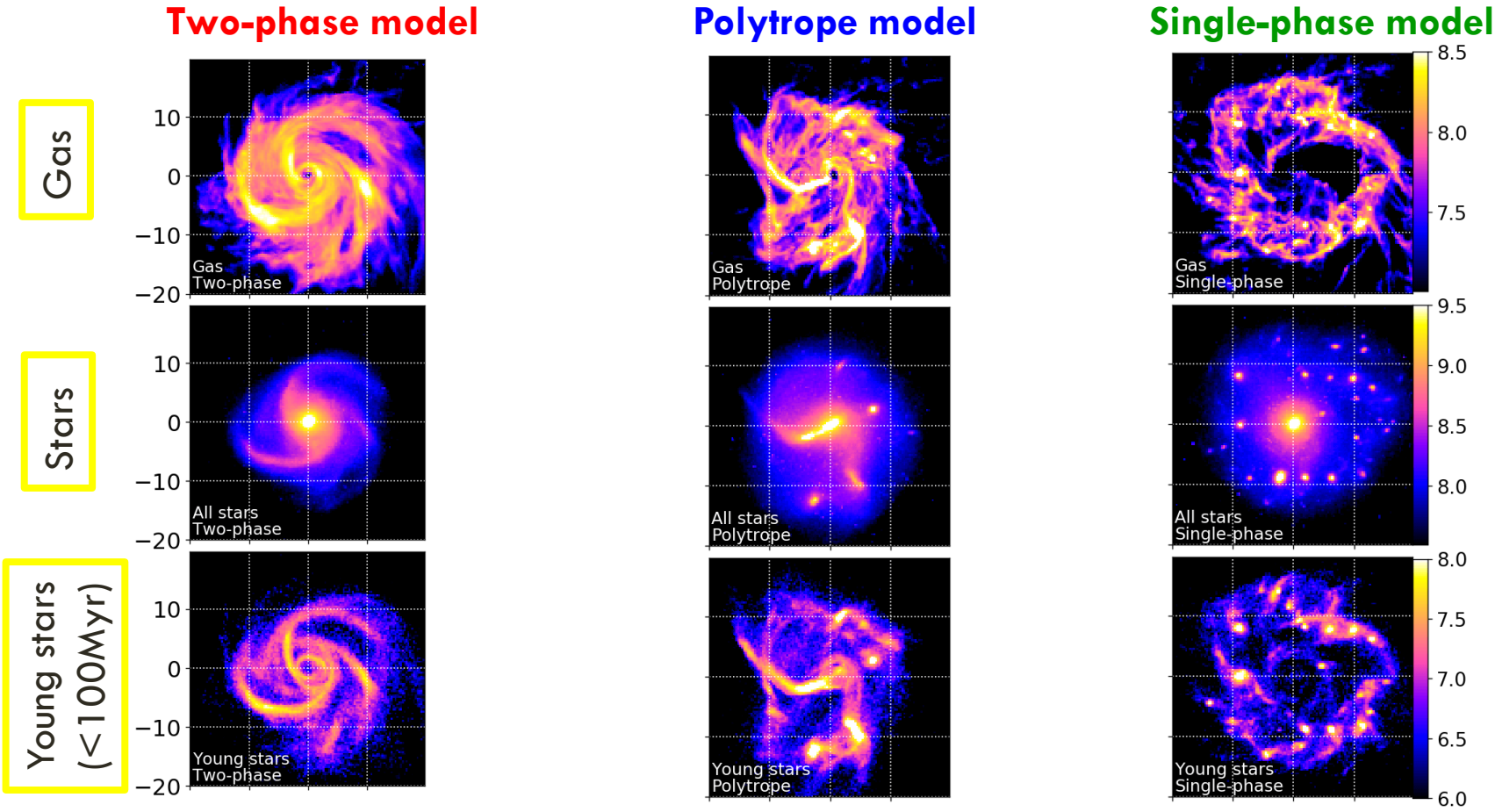
$N_{clump} = 8$

$N_{clump} = 49$

z=1.51

$\log(M_{star}/M_\odot) \cong 11.3$

Clumpiness of galaxies



# of clumps ($>10^8\ M_\odot$)

$N_{clump} = 0$

$N_{clump} = 6$

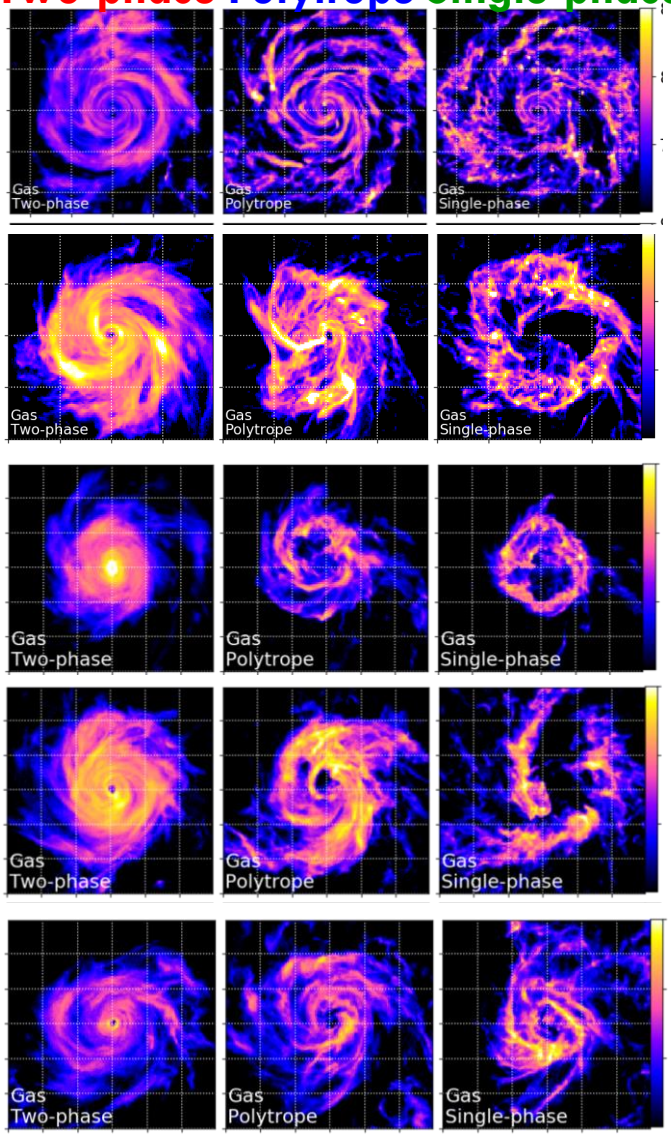
$N_{clump} = 35$

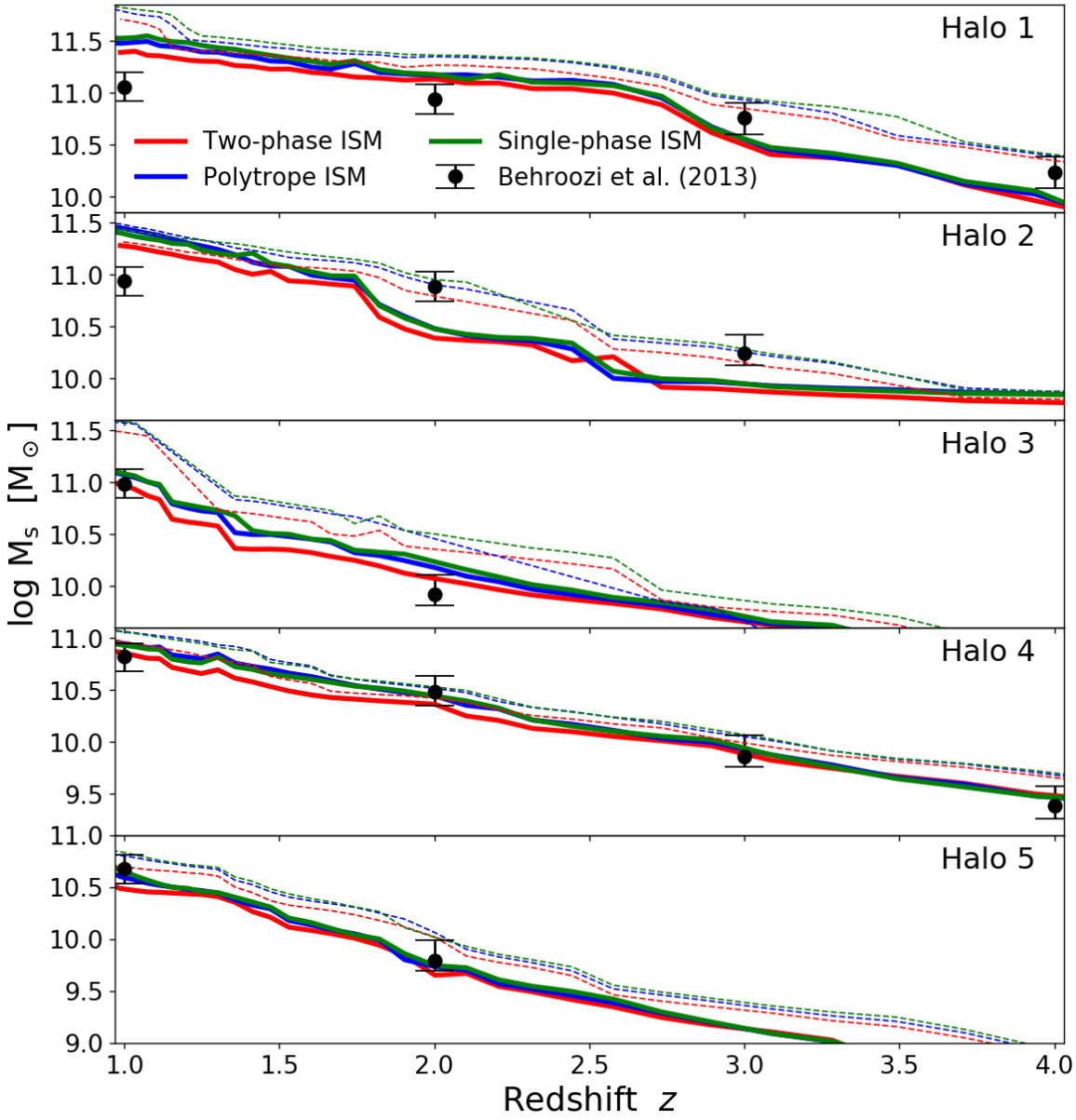
z=1.04

$\log(M_{star}/M_\odot) \cong 11.5$

Global properties (stellar mass)

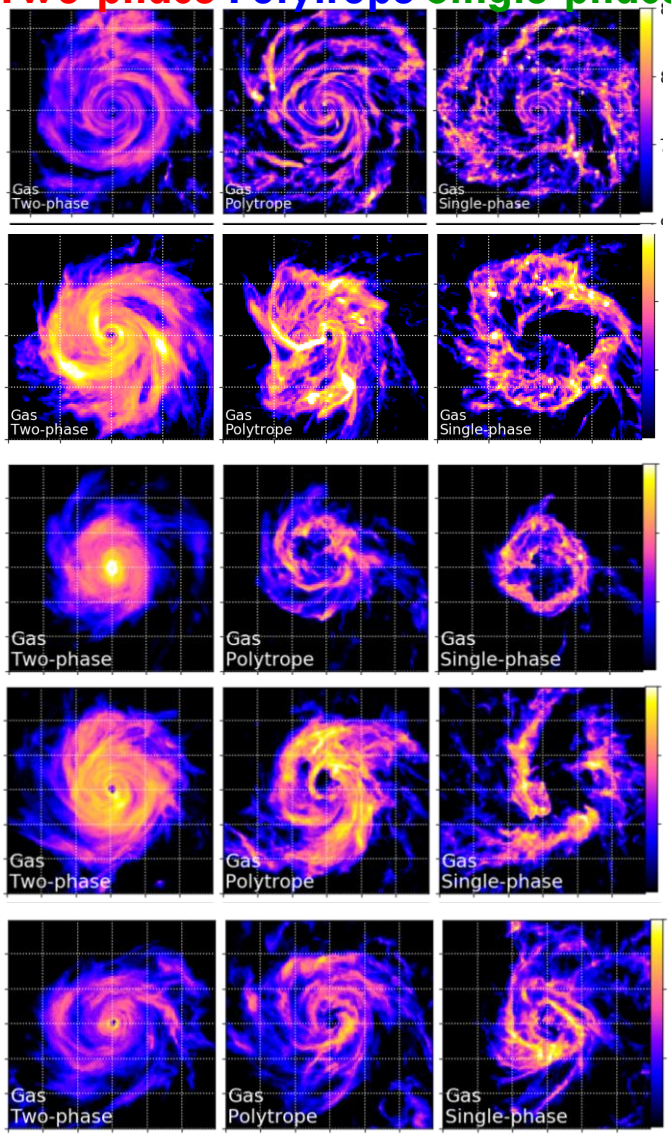
Two-phase **Polytrope** **Single-phase**

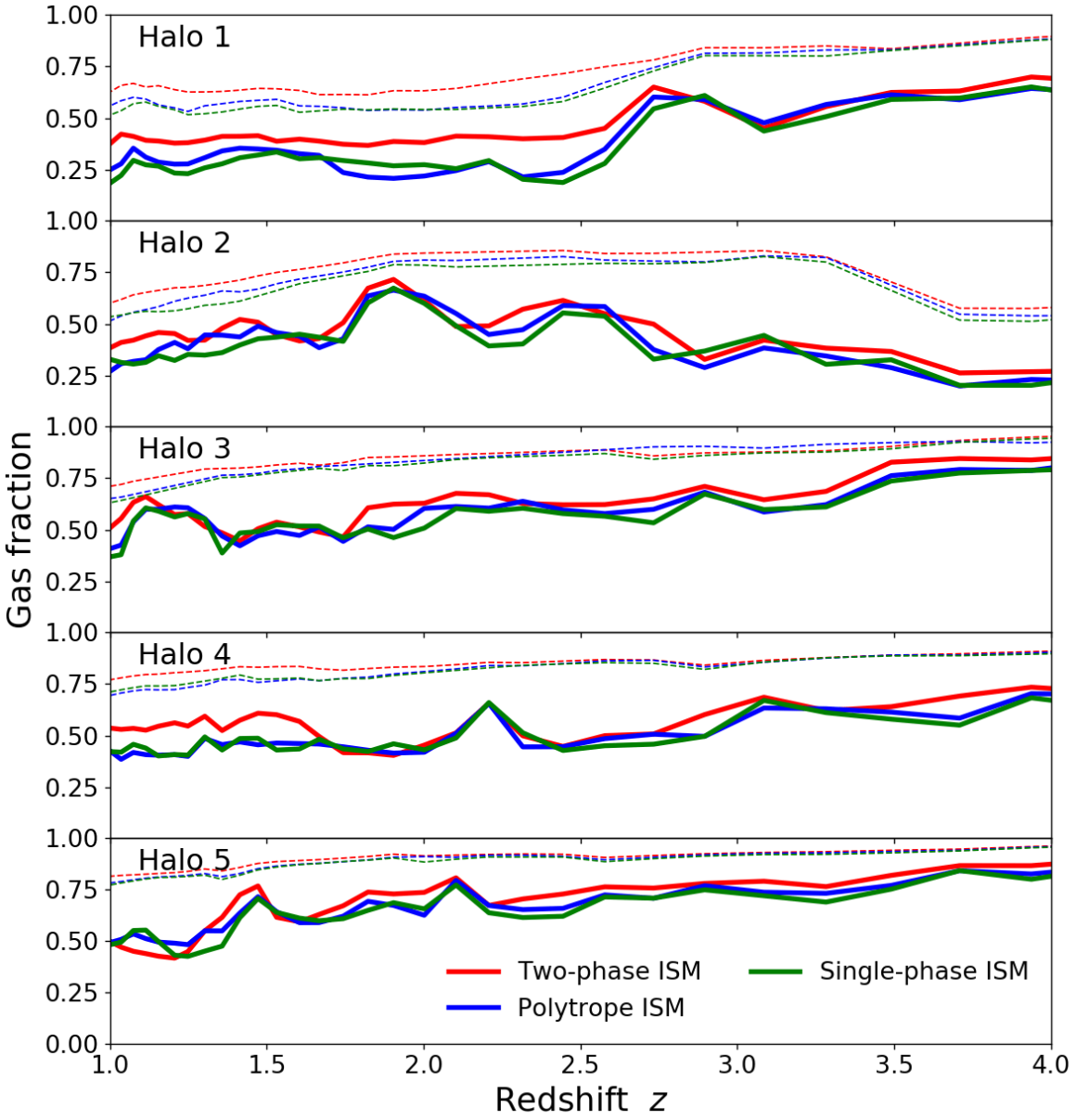




Global properties (gas fraction)

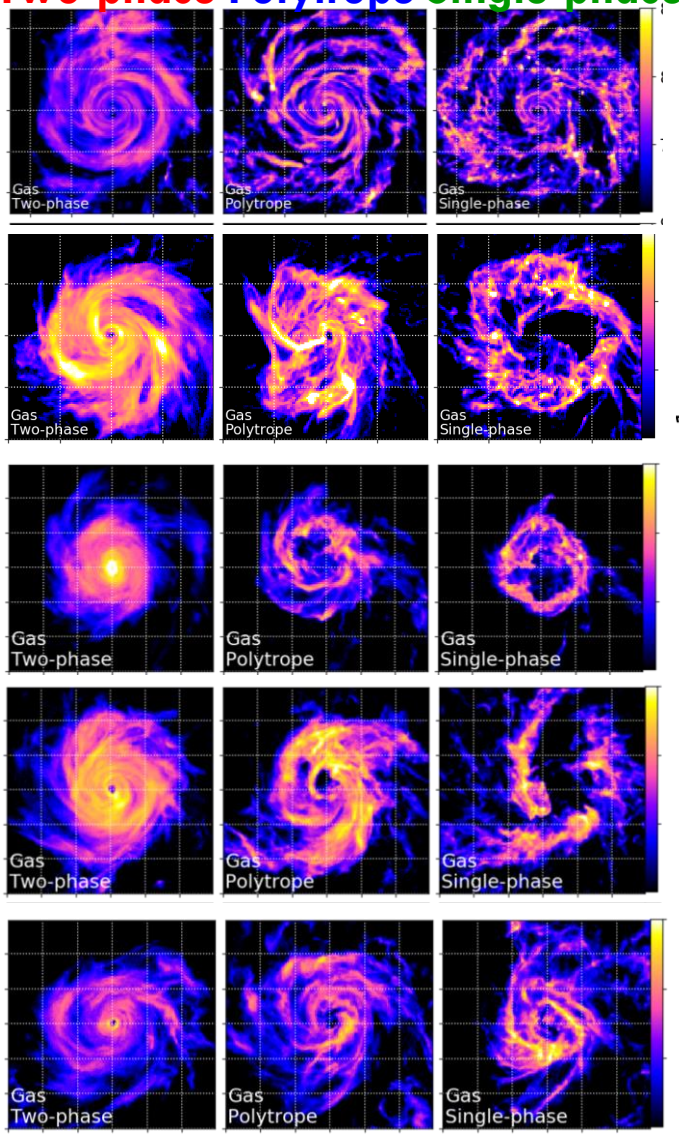
Two-phase **Polytrope** **Single-phase**

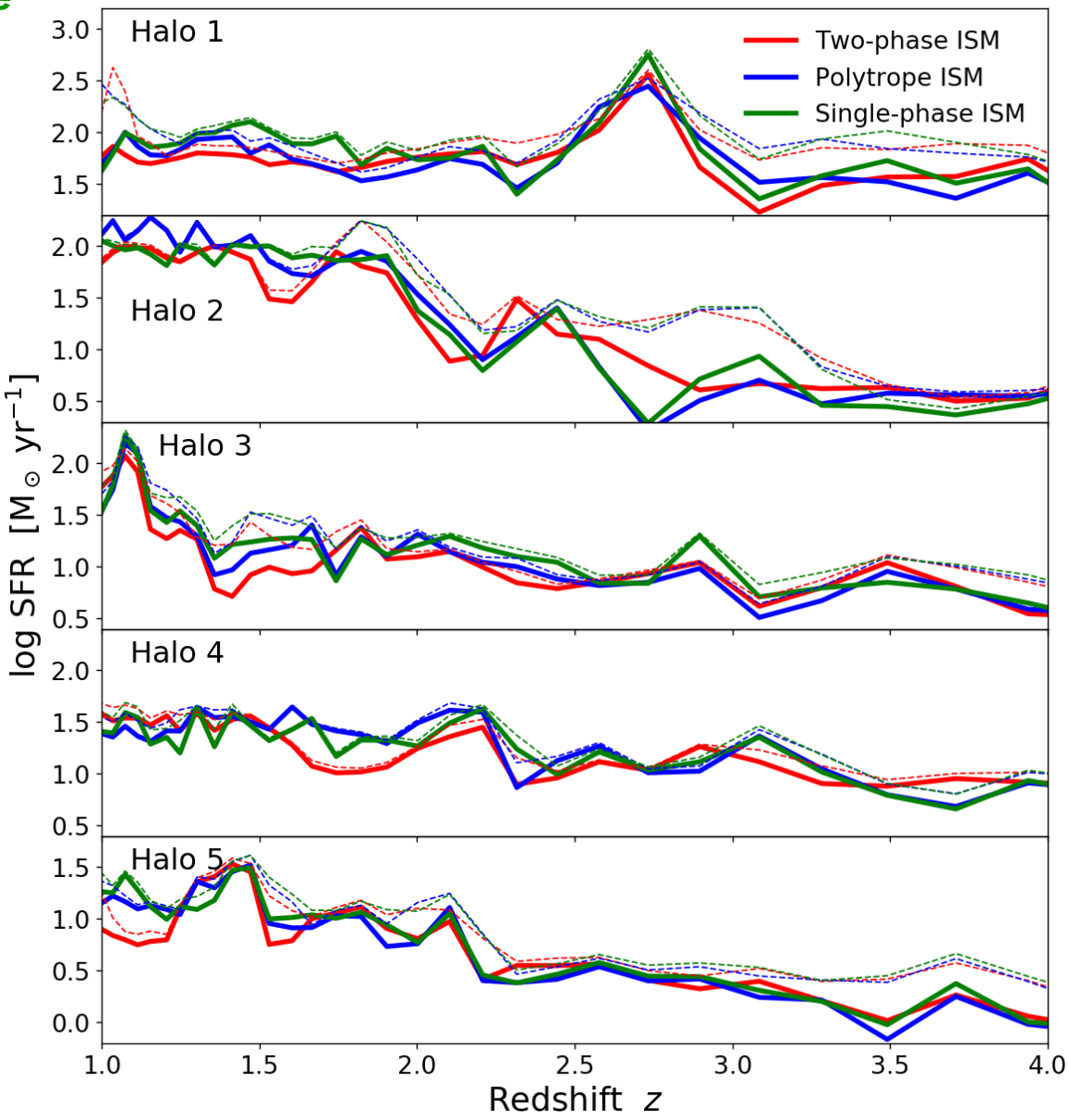




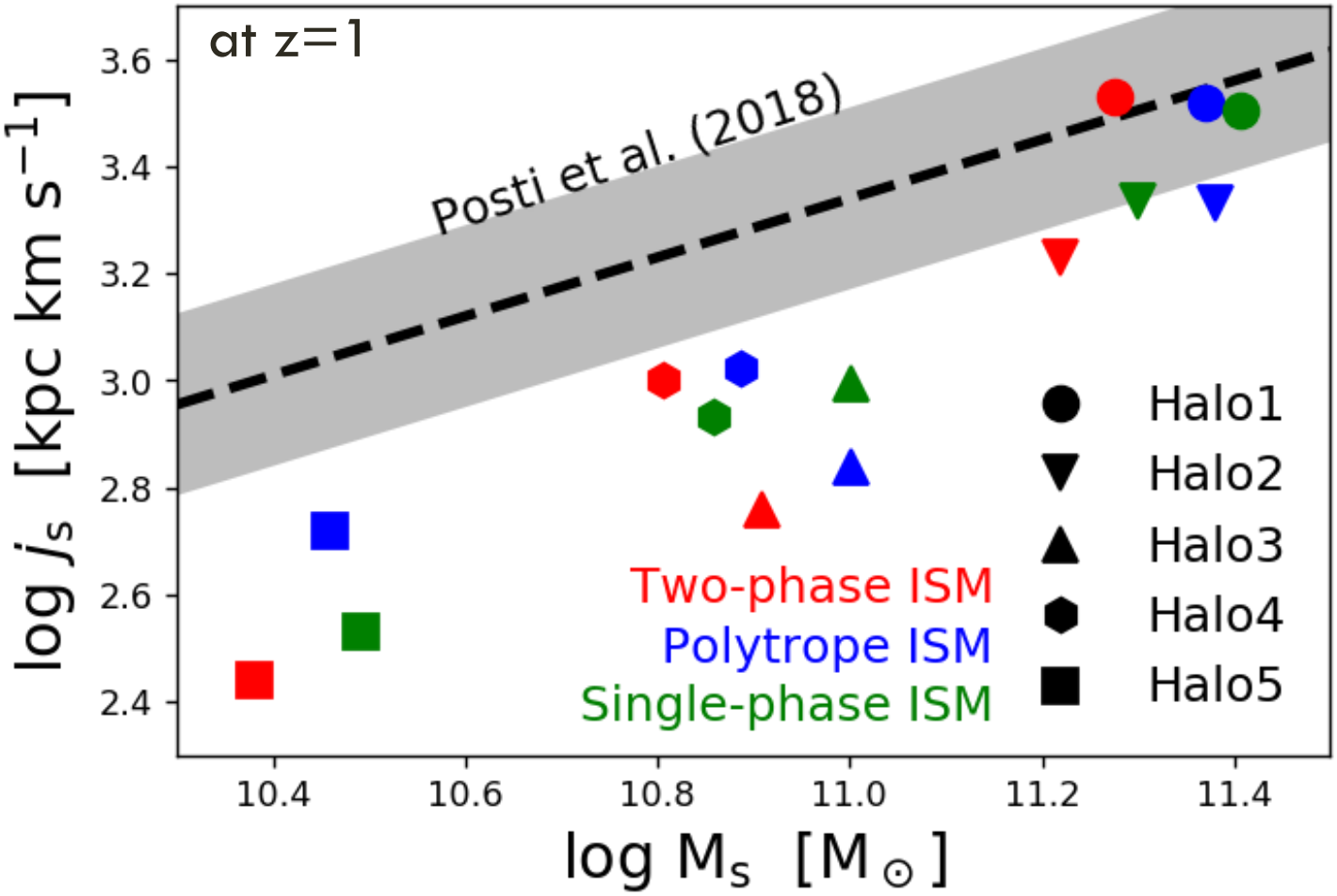
Global properties (SFR)

Two-phase Polytrope Single-phase





Stellar angular momentum



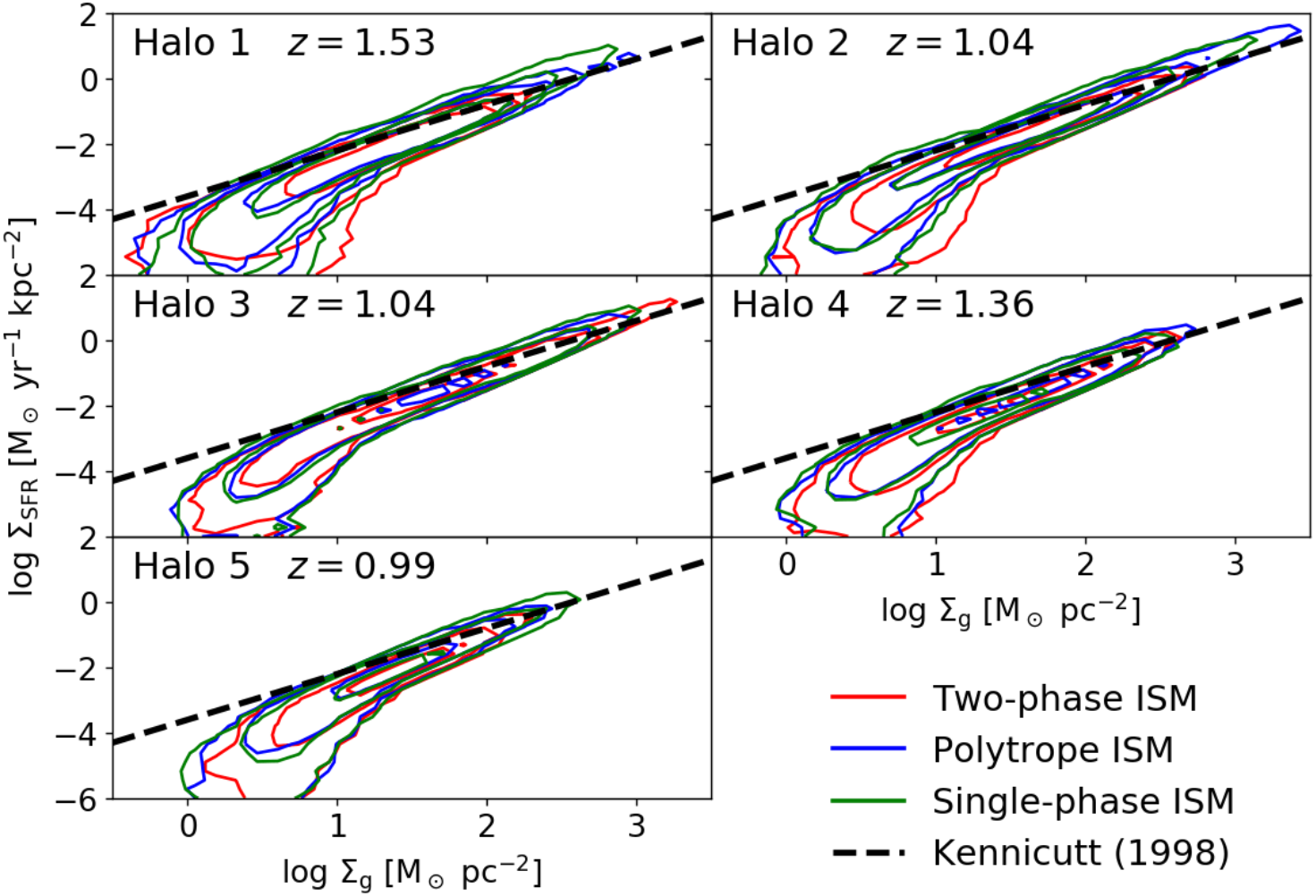
the Kennicutt-Schmidt law

In simulations

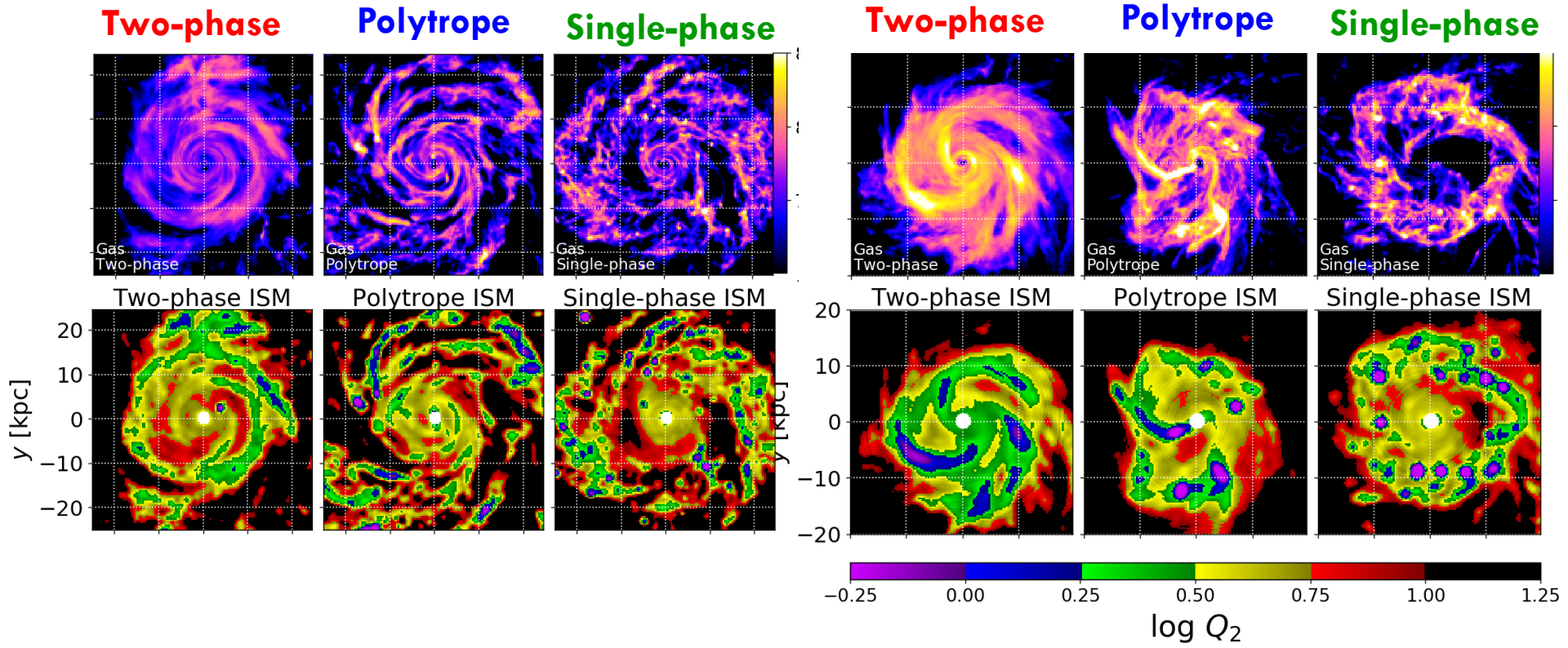
$$\rho_{\rm SFR} \propto \rho_{\rm gas}^{1.5}$$

EOS

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4} \ ?$$

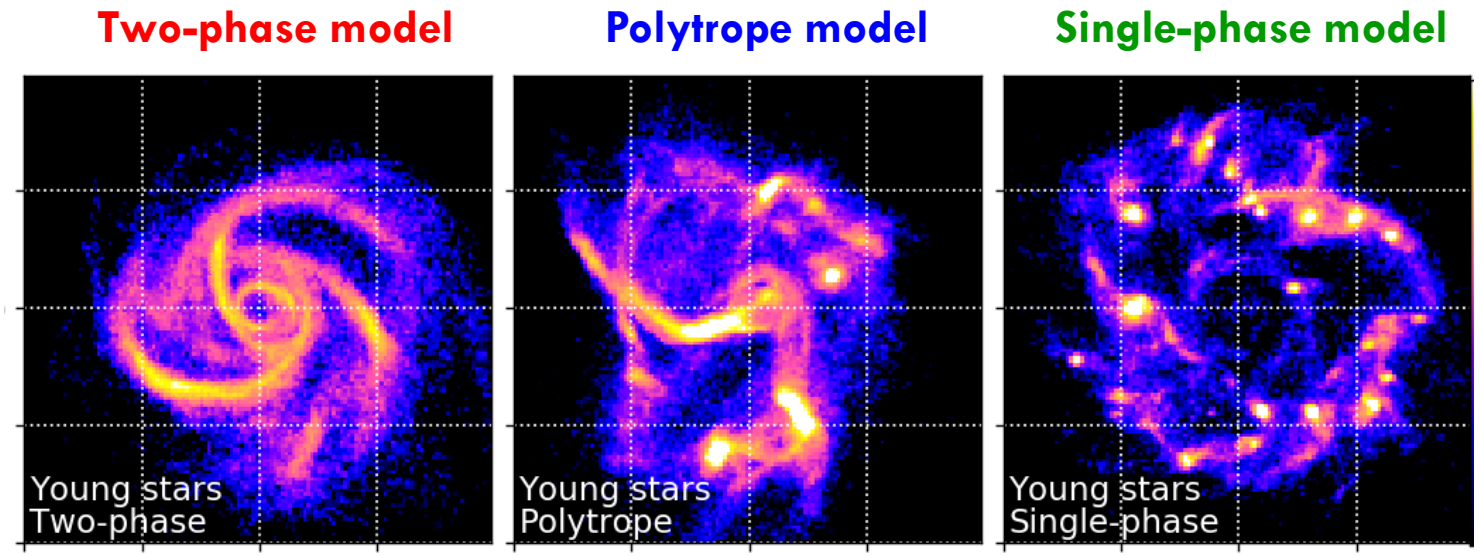


Toomre Q


Two-phase
Polytrope
Single-phase
Two-phase
Polytrope
Single-phase
Gas
Two-phase
Gas
Polytrope
Gas
Single-phase
Gas
Two-phase
Gas
Polytrope
Gas
Single-phase
Two-phase ISM
Polytrope ISM
Single-phase ISM
Two-phase ISM
Polytrope ISM
Single-phase ISM
y [kpc]
20
10
0
−10
−20
y [kpc]
20
10
0
−10
−20
−0.25
0.00
0.25
0.50
0.75
1.00
1.25
log Q_2

Conclusions ①

- **ISM models can dramatically change "clumpiness" of galaxies.**
  - All of the models are currently used in recent cosmological simulations.
    - Two-phase ISM model, e.g. Illustris-TNG simulations
    - Polytrope ISM model, e.g. EAGLE simulations
    - Single-phase ISM model, e.g. FIRE simulations
  - **Not only feedback but ISM model is also important!**



Conclusions ①

- **ISM models can dramatically change "clumpiness" of galaxies.**
  - All of the models are currently used in recent cosmological simulations.
    - Two-phase ISM model, e.g. Illustris-TNG simulations
    - Polytrope ISM model, e.g. EAGLE simulations
    - Single-phase ISM model, e.g. FIRE simulations
  - **Not only feedback but ISM model is also important!**

- **However, the ISM models hardly change global properties.**
  - E.g. Stellar mass, gas fraction, SFR, angular momentum, K-S law
  - **Simulations are usually calibrated to match these properties with observations.**
  - **Problem: Which ISM model should we accept / reject?**

- **ISM model (EOS of ISM) should be calibrated with observations.**

Conclusions ②

- **An ideal test to investigate influence of clump formation.**
  - **Changing ISM models can control clump formation**
    - **With the same initial conditions and feedback**

- **Clump formation little affects galaxies.**

  - **e.g. SFRs are enhanced only by a factor ~2-3.**
    - **High cosmic SFR density at z~2 is NOT due to clump formation**

- **Clump formation would not cause starburst or quenching.**