Implementation of Kinetic AGN Feedback in GADGET-3

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Simulations Workshop,

Sesto,

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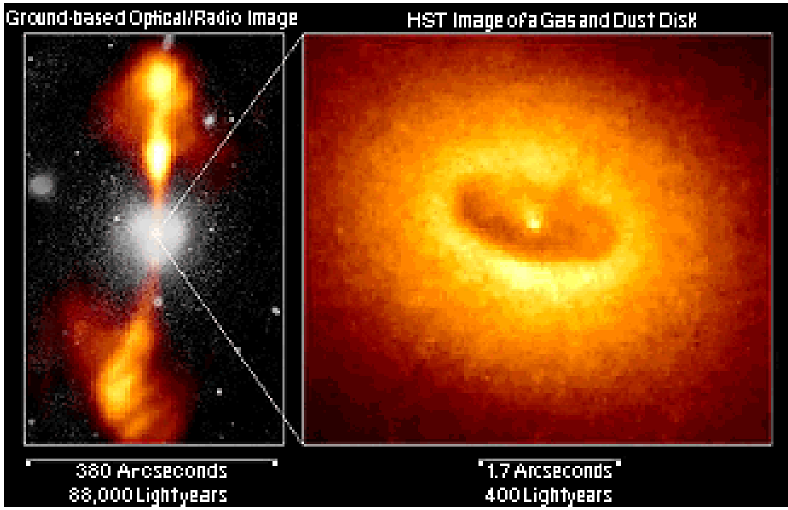
Coupling of Feedback Energy

- Fraction of radiated energy from SMBH is recoupled

- Thermal feedback (Springel, Di Matteo et al. 2005, 2008)
  - Energy is coupled thermally to heat up the surrounding gas
  - Excess thermal energy decays to attain effective EOS energy (multiphase SF model of Springel & Hernquist 2003) on a relaxation timescale

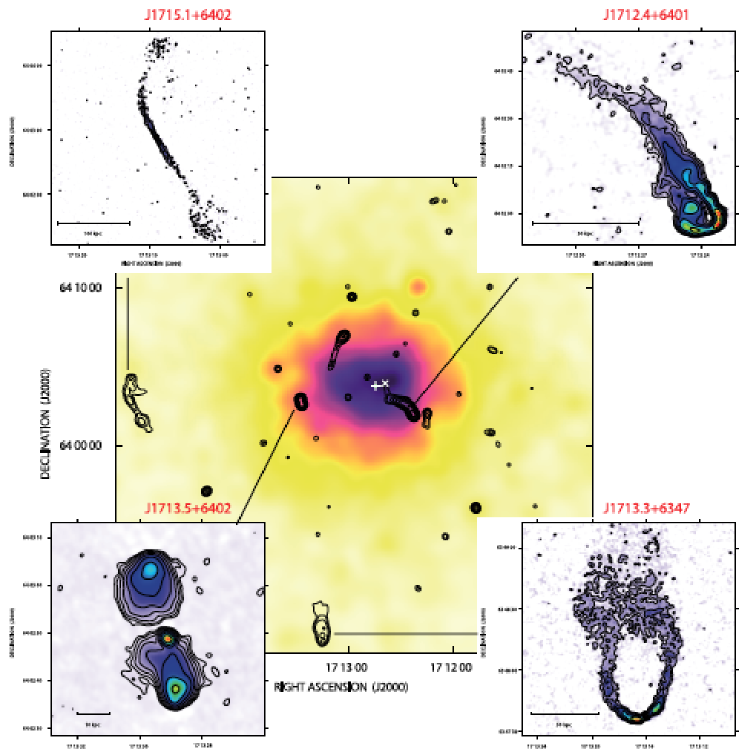
$$\tau_h = \frac{t_* \rho_h}{\beta(A+1)\rho_c}$$



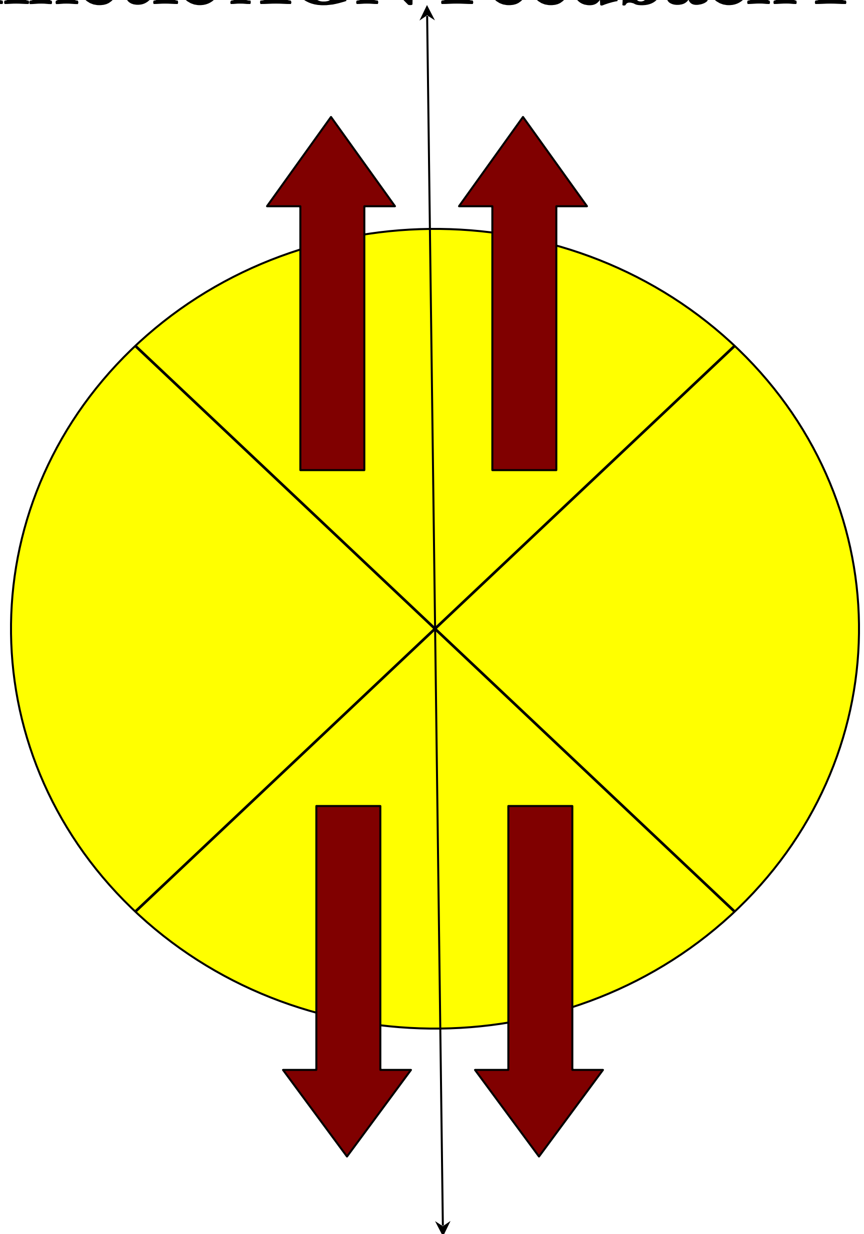
- Kinetic Feedback
  - Impart K.E. (Velocity kick) to gas
  - Recently implemented in Gadget-3 code
    - (Barai et al. 2014, MNRAS, 437, 1456)

Idealized Tests:
AGN Feedback at Center of Isolated Cluster

- Spherical gas distribution in hydrostatic equilibrium
- DM as background potential (NFW profile)
- Initial Condition:
  - Allow gas to cool for 2 Gyr and form a cold, dense core
  - Two tests with a hot core
- SMBH at center
  - No accretion
  - Only fixed energy output
  - Fixed duty-cycle



Kinetic AGN Feedback Physics & Implementation



- Create a BH particle at rest at center [0,0,0]
- Kick particles inside a bi-conical volume around BH
- Kick along fixed direction

$$\dot{E}_{out} = 10^{45} \, \mathrm{erg}/s$$

$$v_w = 5000, \; 10000 \; \mathrm{km/s}$$

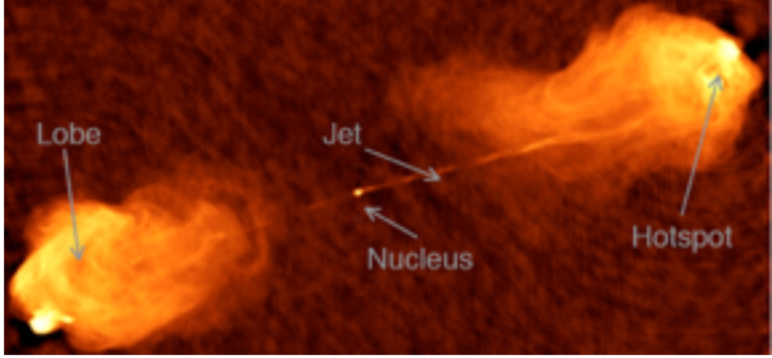
$$\frac{1}{2} \dot{M}_w v_w^{\,2} = \dot{E}_{out}$$

$$T_{on} = 50 \; \mathrm{Myr}$$

$$T_{off} = 100 \; \mathrm{Myr}$$

$$\text{Cone half angle} \; = \; 30^\circ$$

Physics & Implementation



- Energy-driven wind : $$\frac{1}{2}\dot{M}_w v_w^2 = \dot{E}_{out}$$

Free Parameters :

$\dot{E}_{out}$ = Output Power (to be related to BH accretion rate)

v_w = Wind Velocity

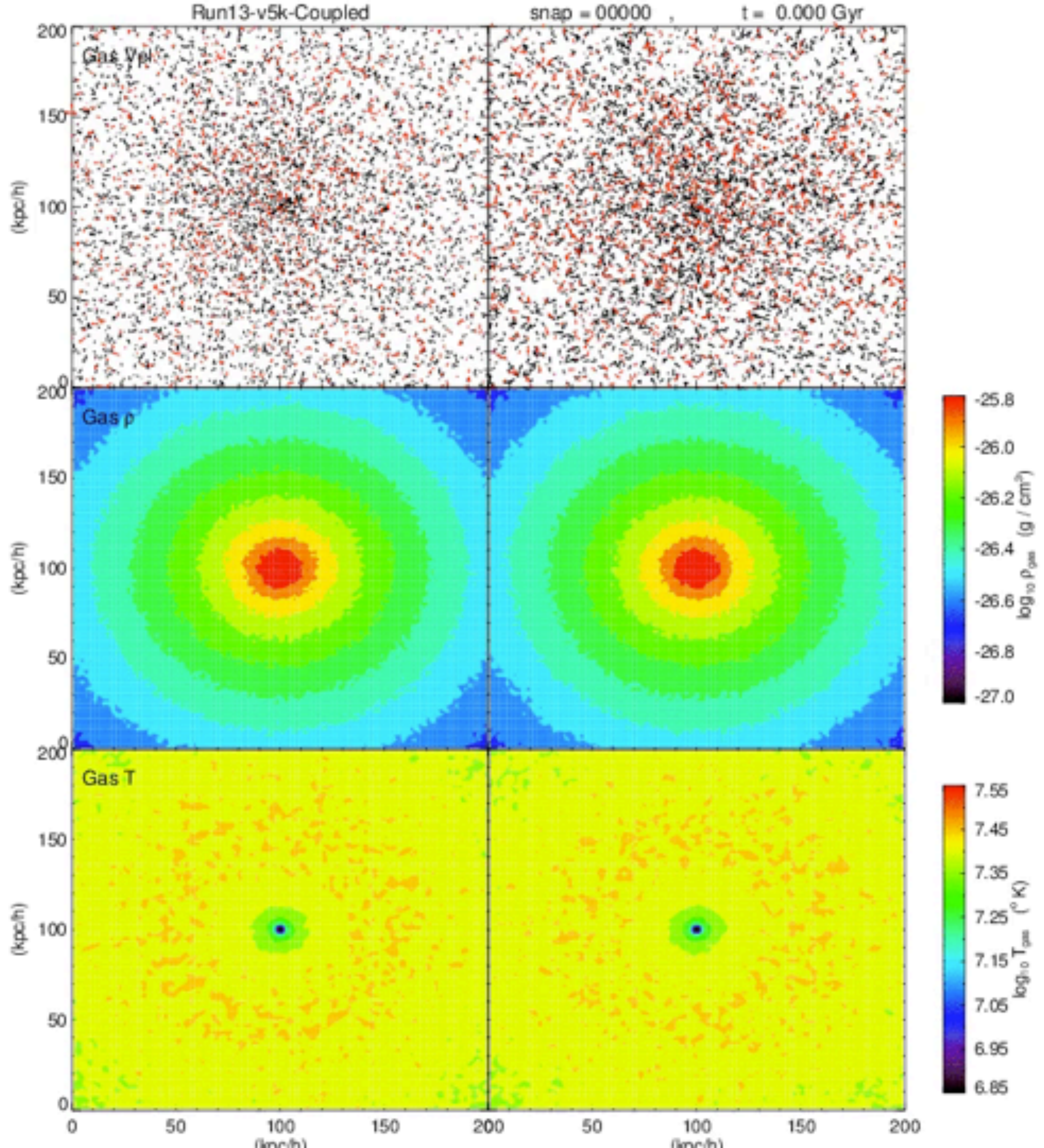
- Probabilistic method for kicking gas particles around BH

$$p_i = \frac{w_i \dot{M}_w \Delta t}{\rho}$$

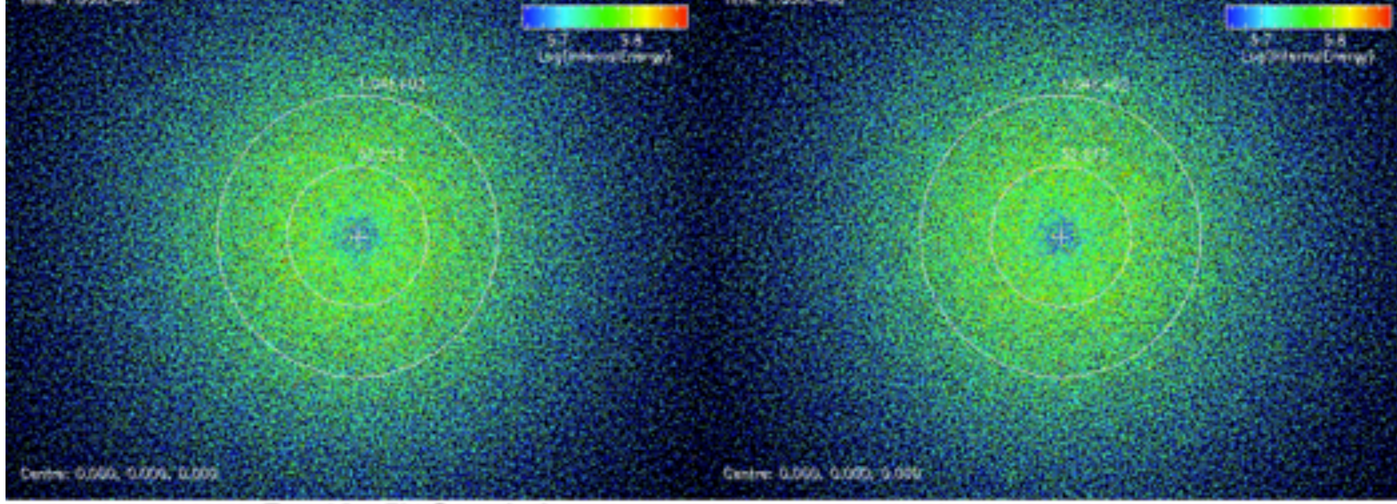
- New particle velocity $$v_{new} = v_{old} + v_w \hat{n}$$ $$\hat{n} \rightarrow \vec{v} \times \vec{\nabla}\phi$$

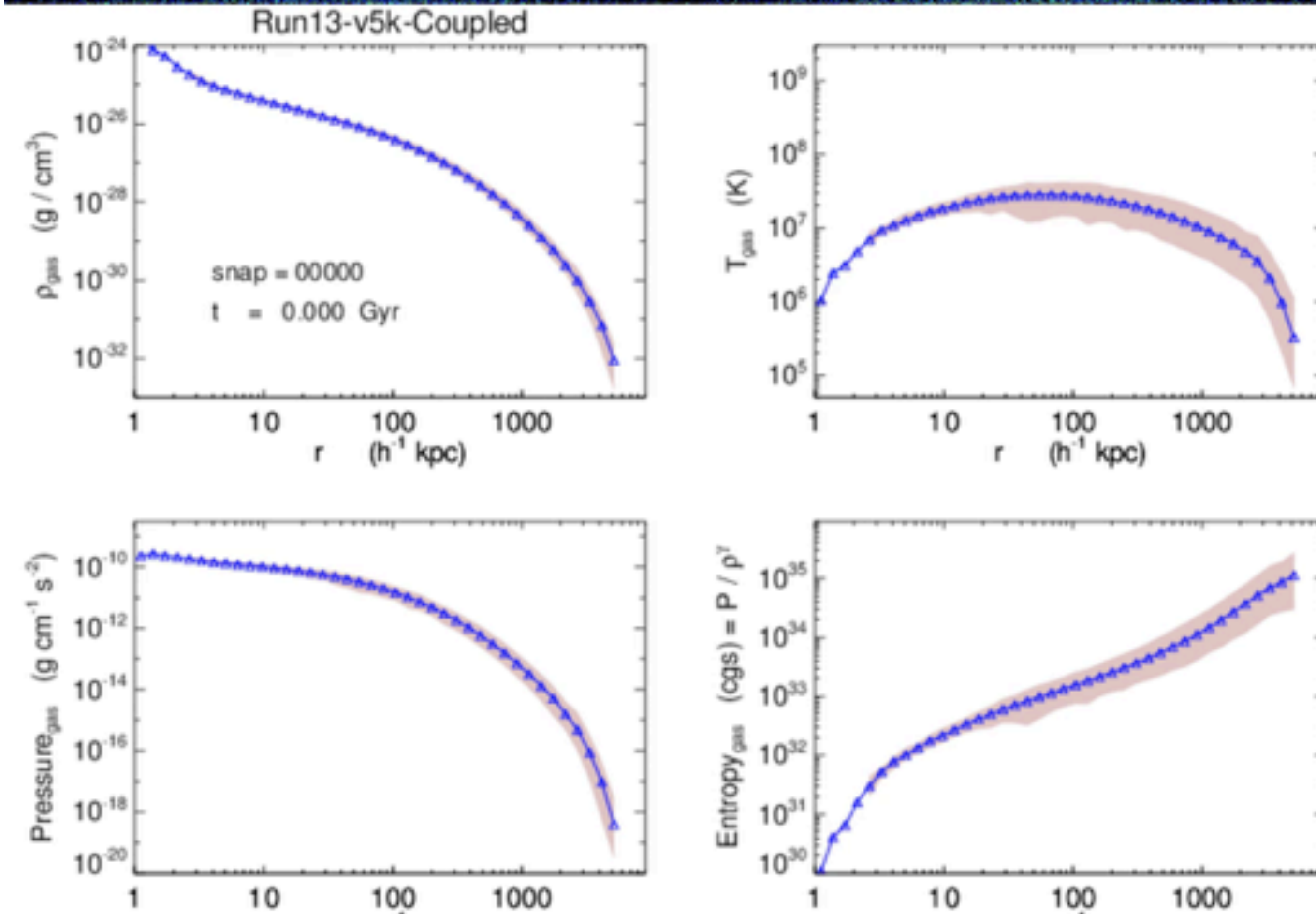
- Consider coupling and decoupling of kicked wind particles from hydrodynamic interactions of remaining gas

Run13-v5k-Coupled



Run13-v5k-Coupled





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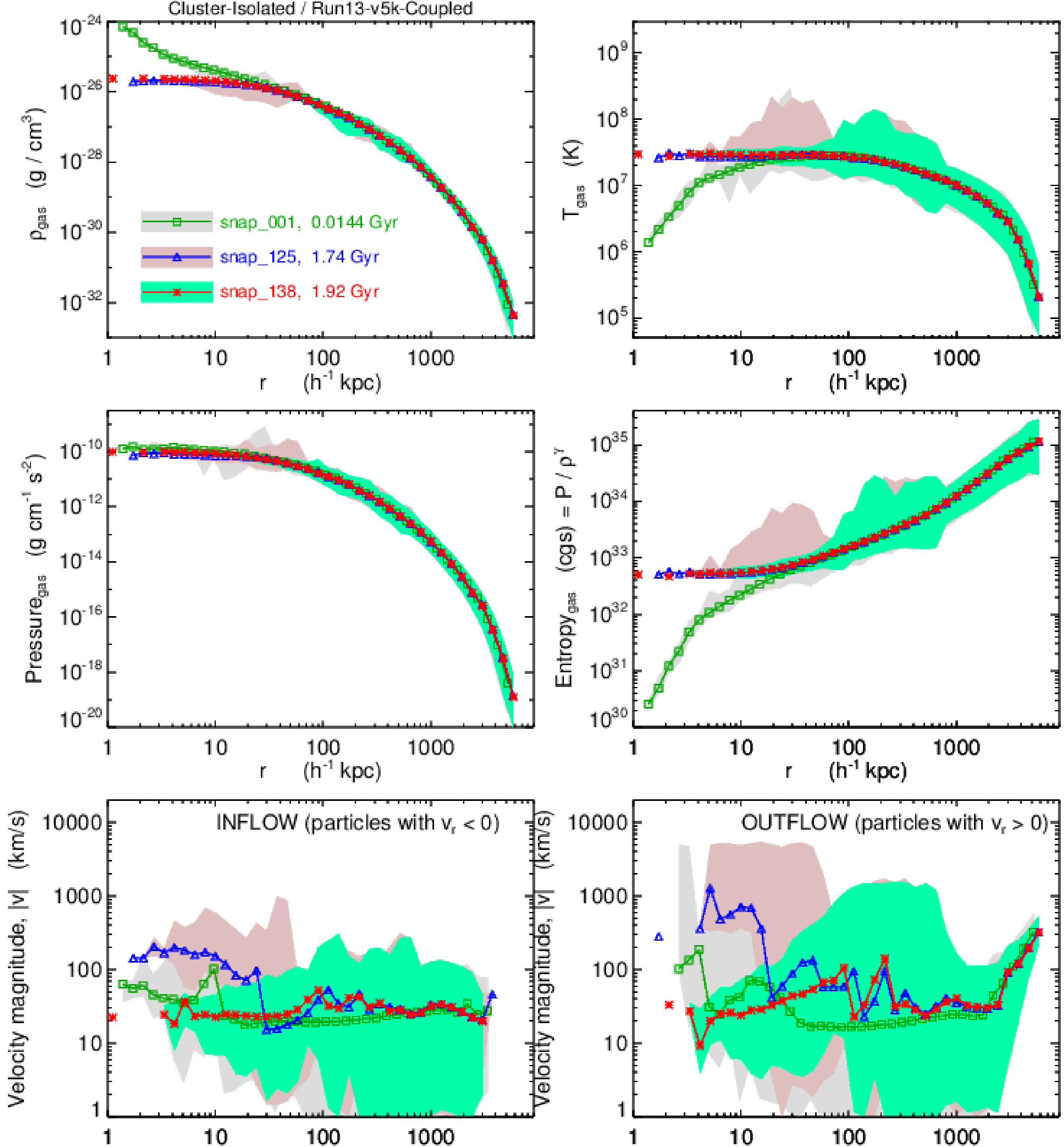
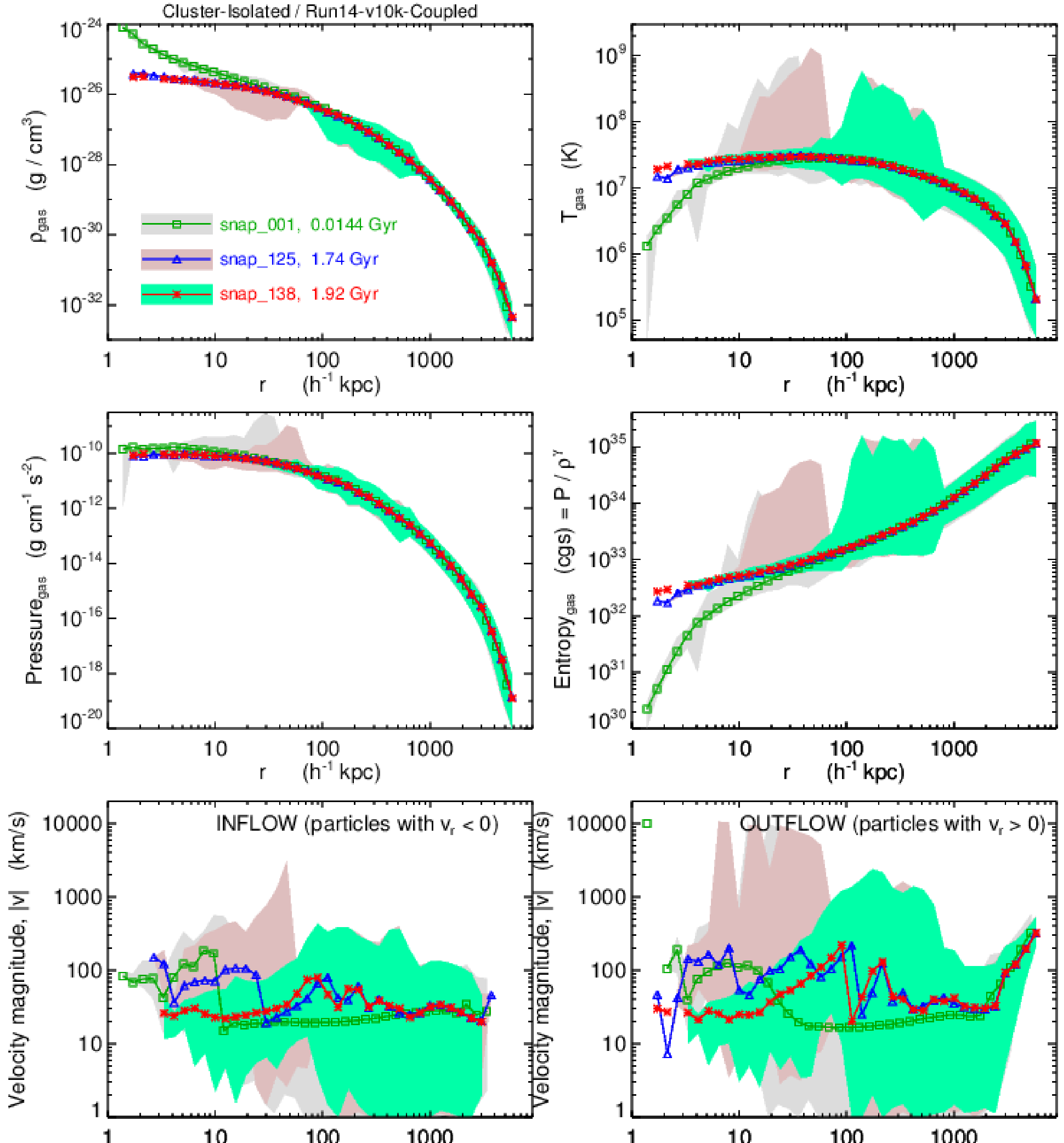
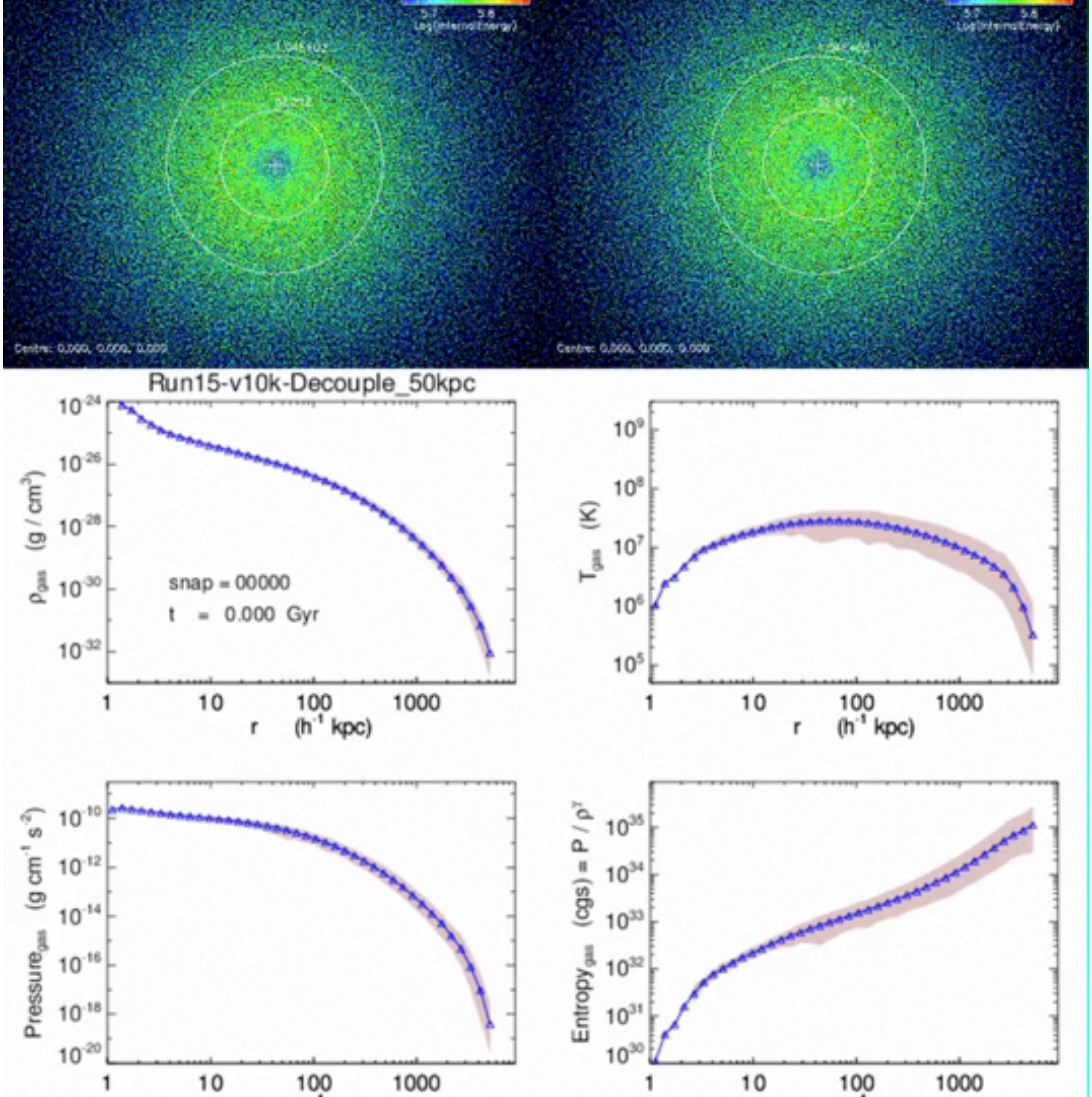
Run13-v5k-Coupled



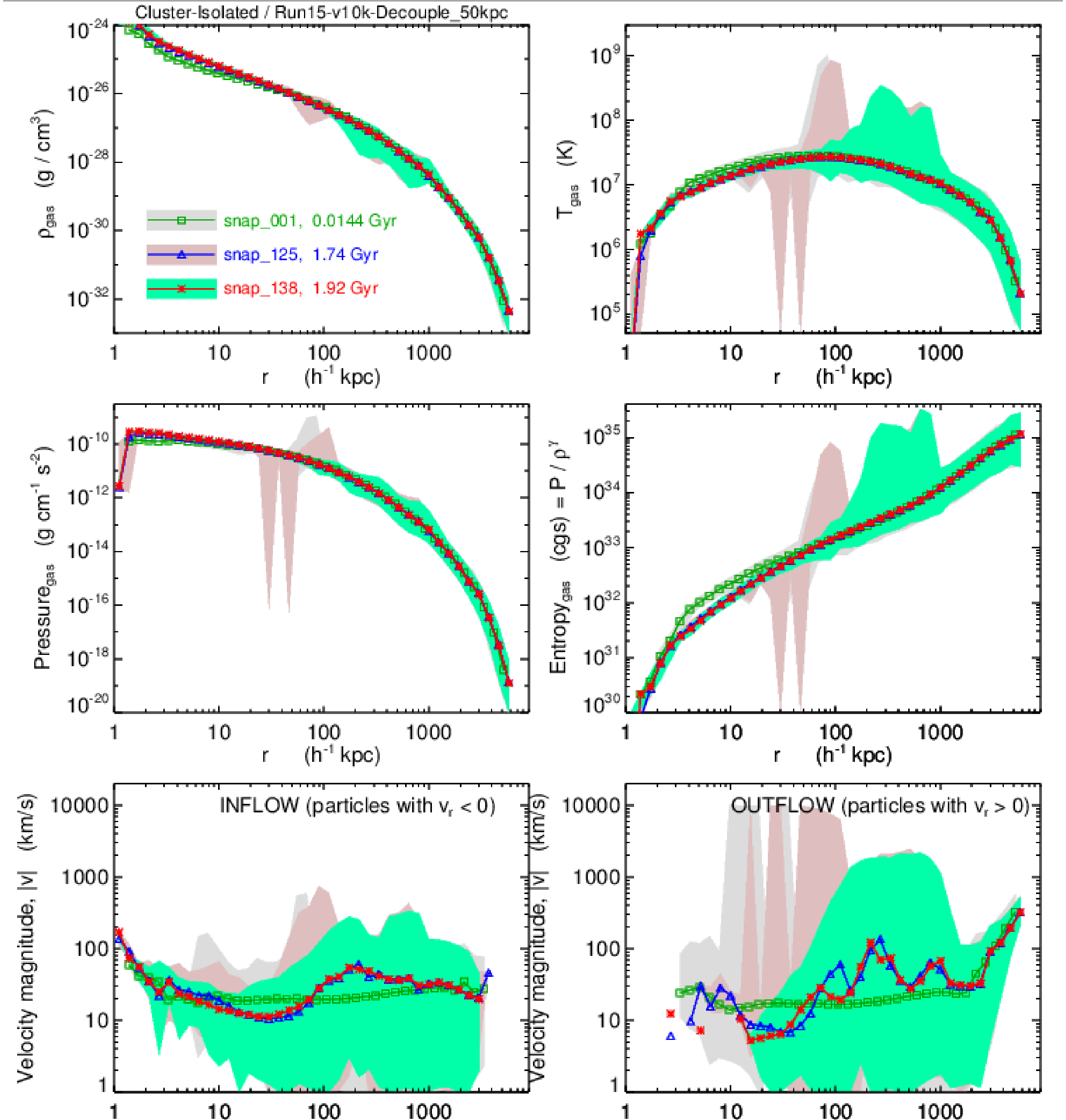
Run14-v10k-Coupled



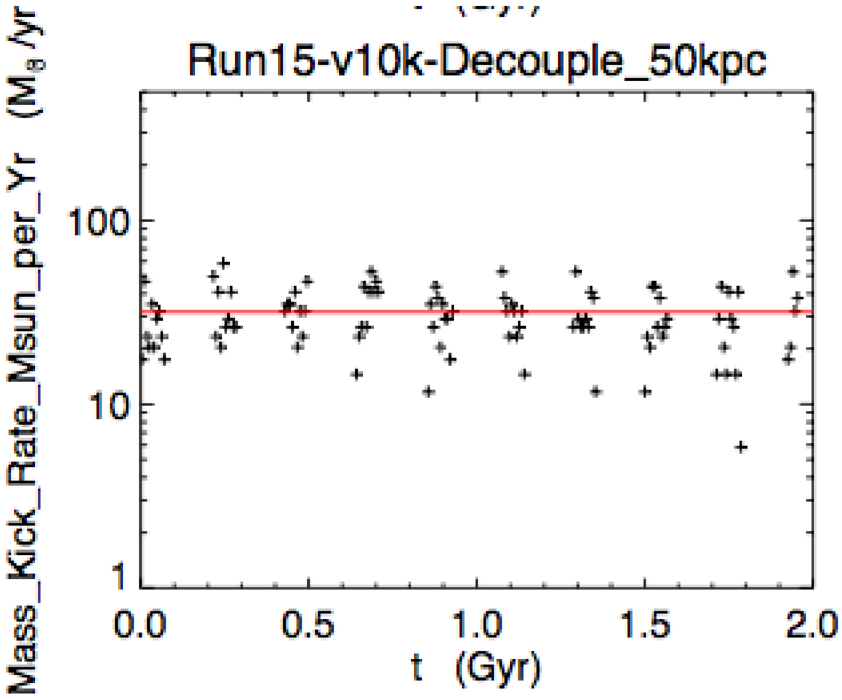
Run15-v10k-Decouple_50kpc

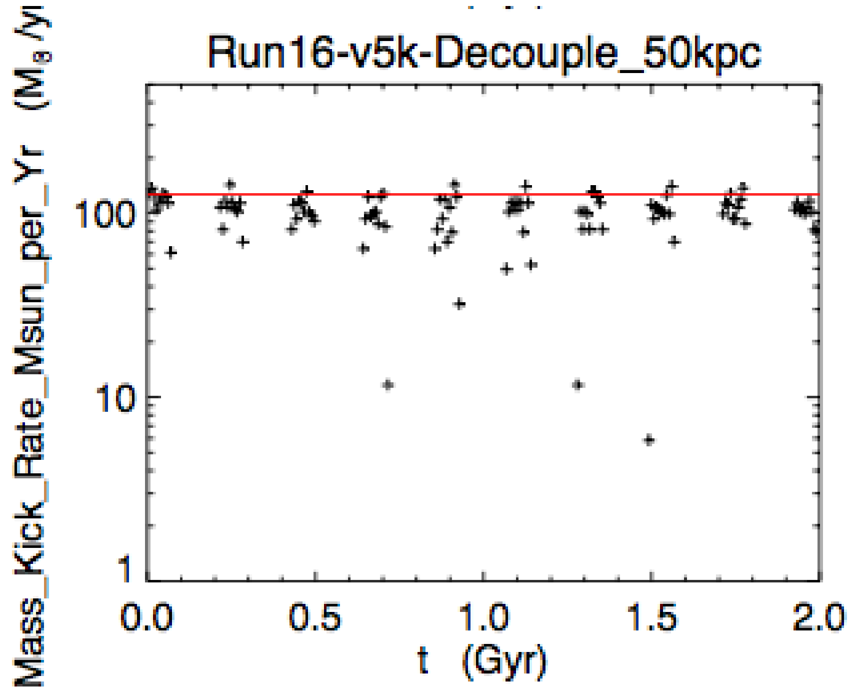


Run15-v10k-Decouple_50kpc

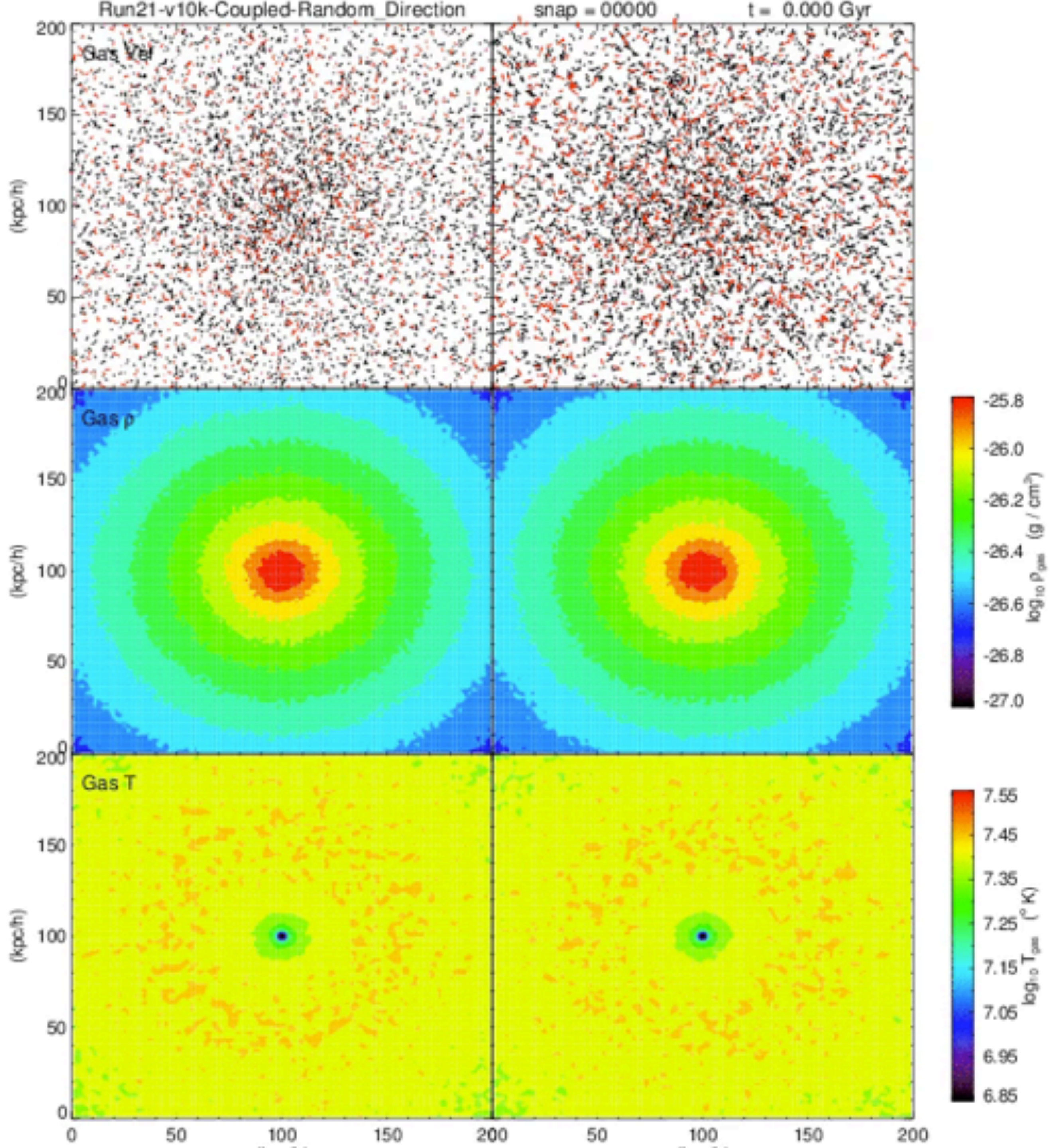


Analytical vs. Numerical Mass Kick Rate

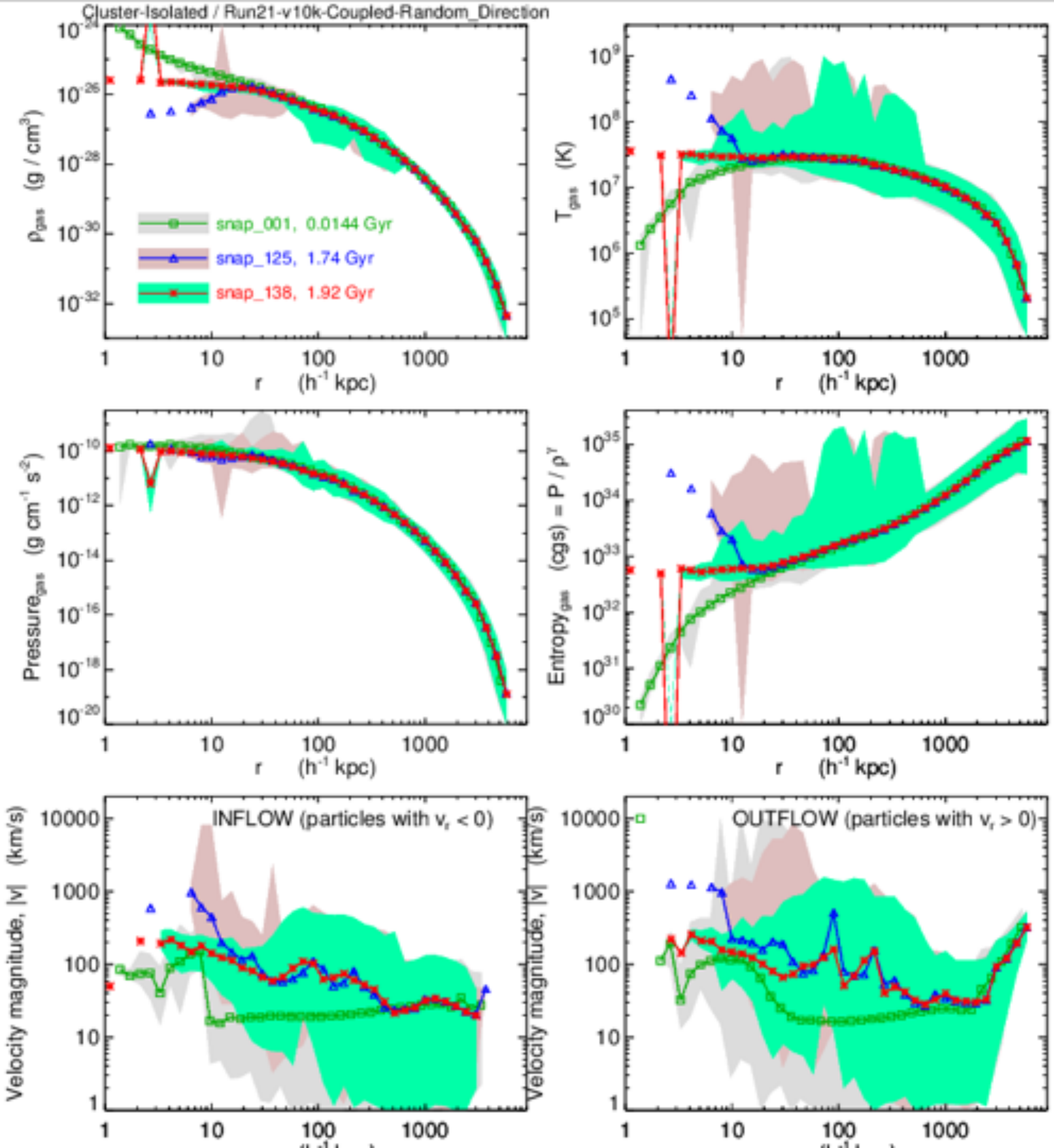




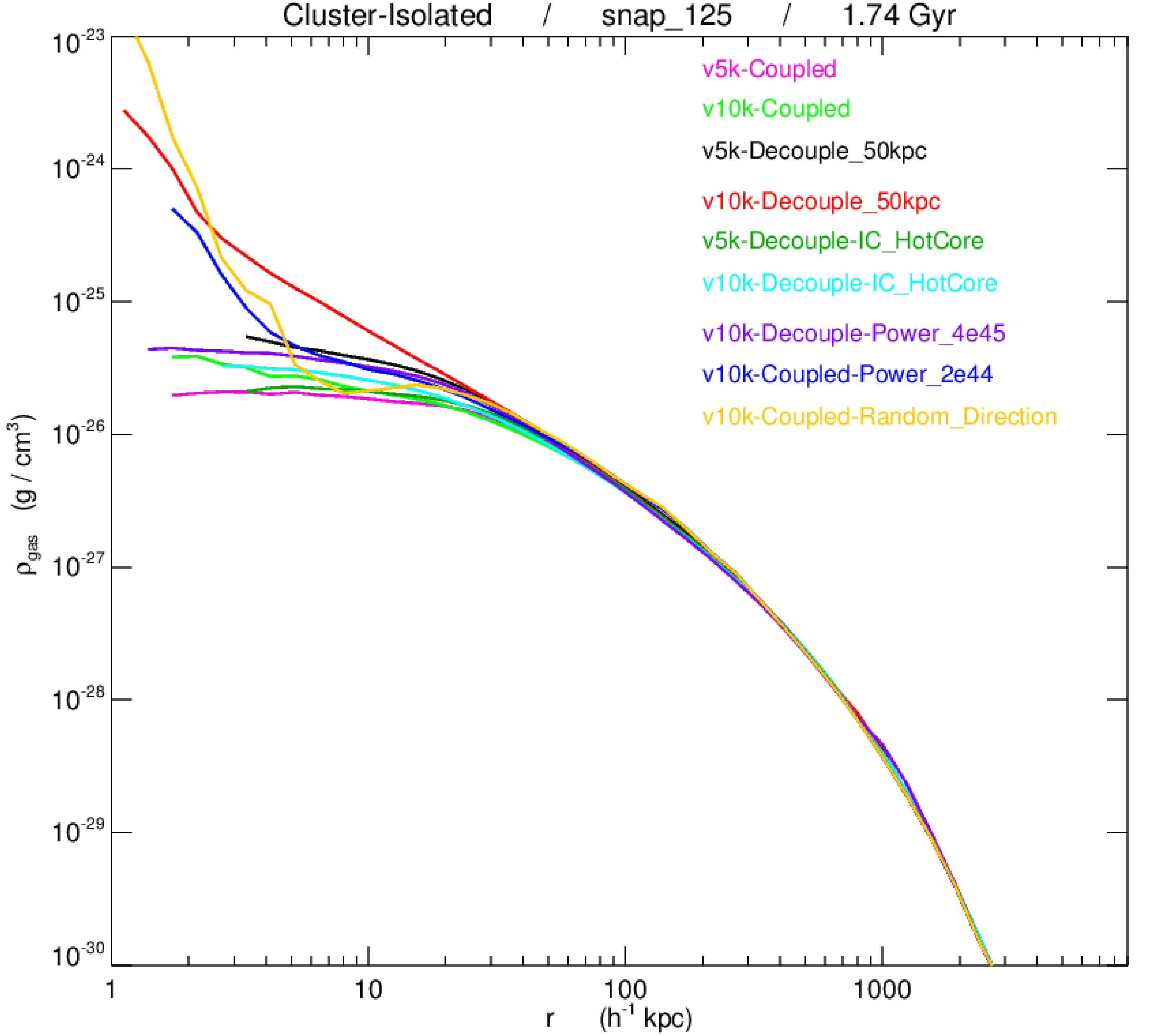
Run21-v10k-Coupled-Random_Direction (between duty cycles)



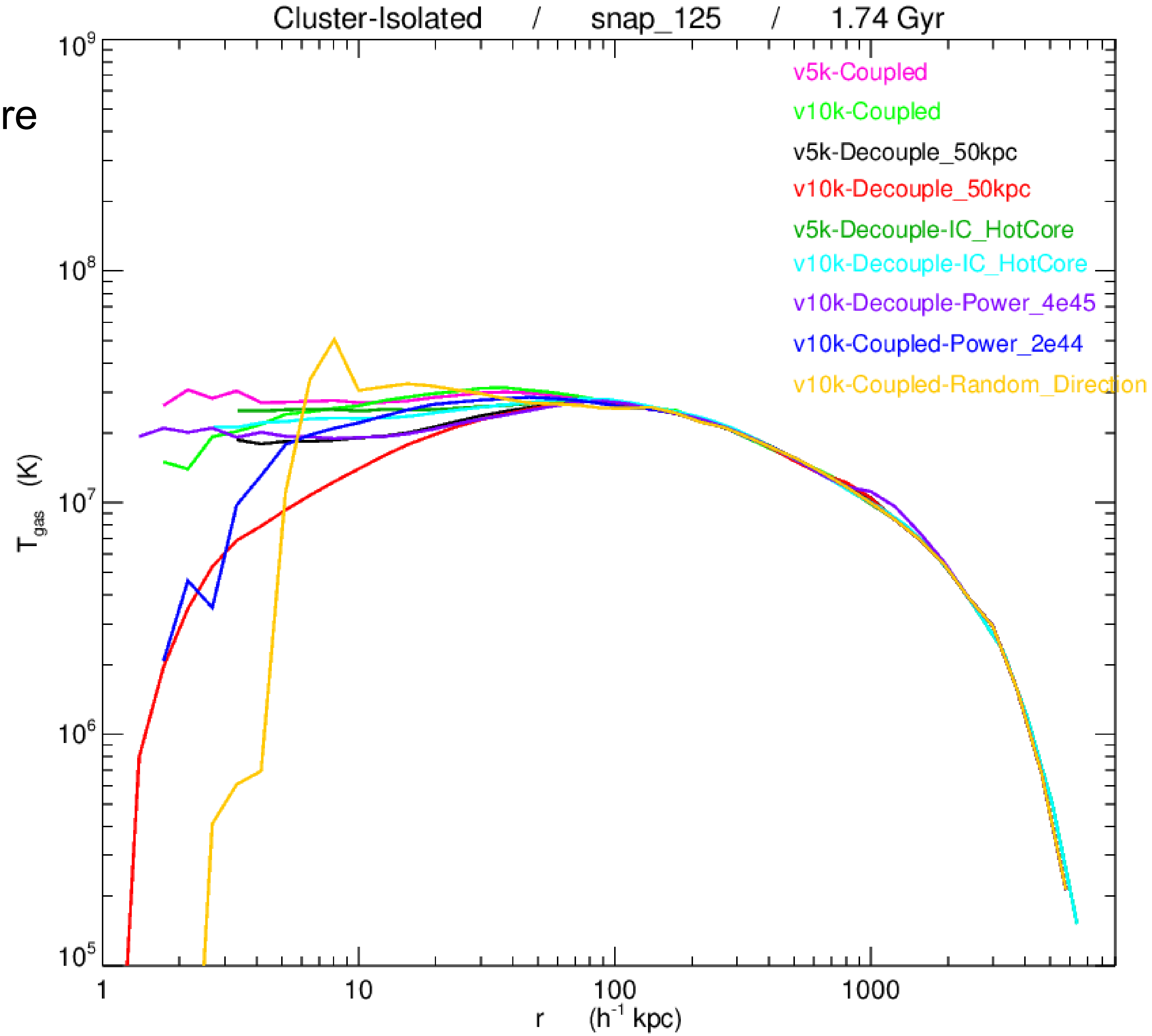
Run21-v10k-Coupled-Random_Direction



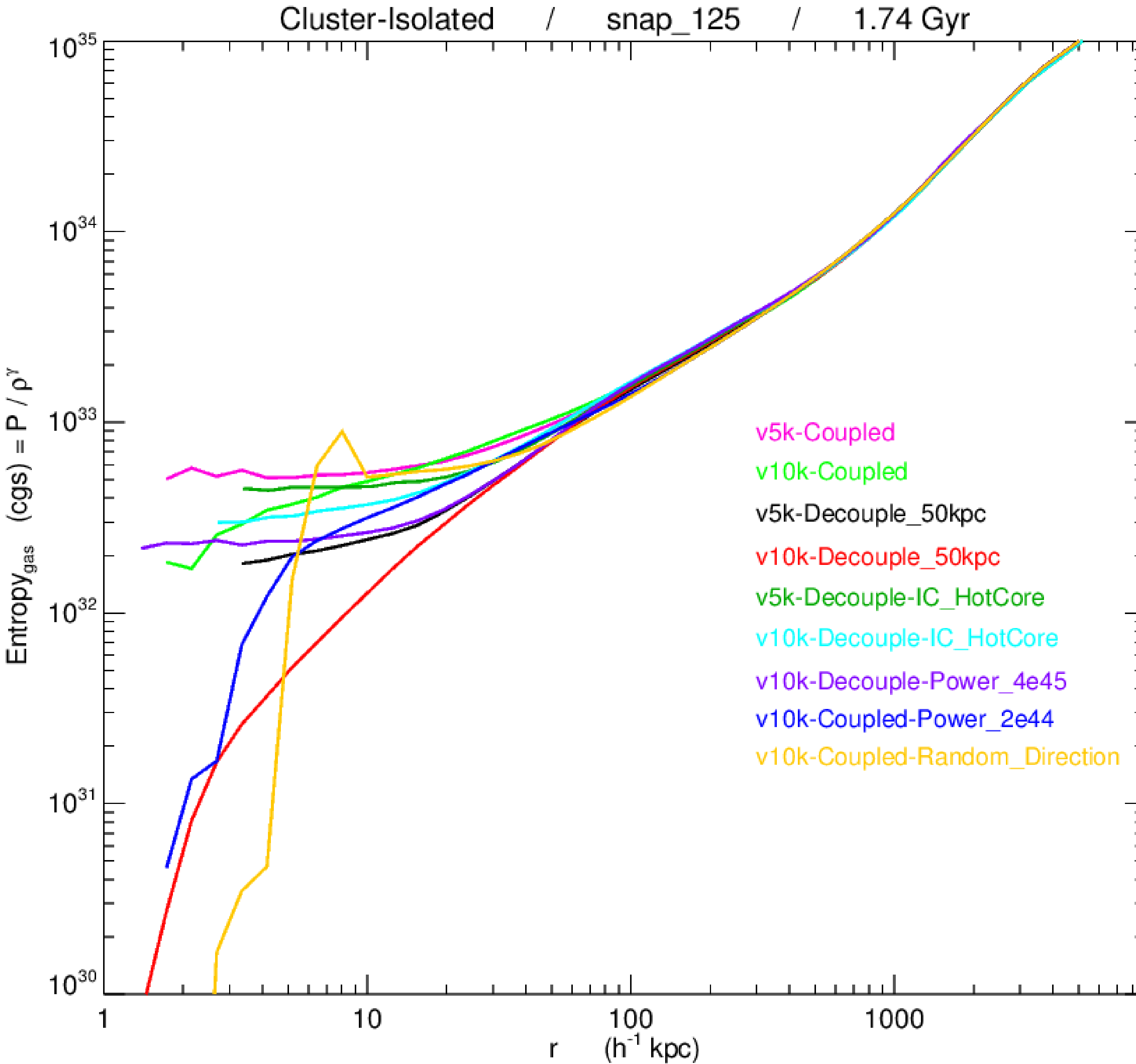
Density Profile



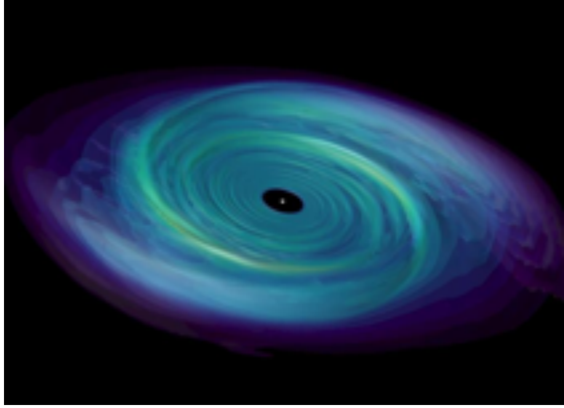
Temperature Profile



Entropy
Profile

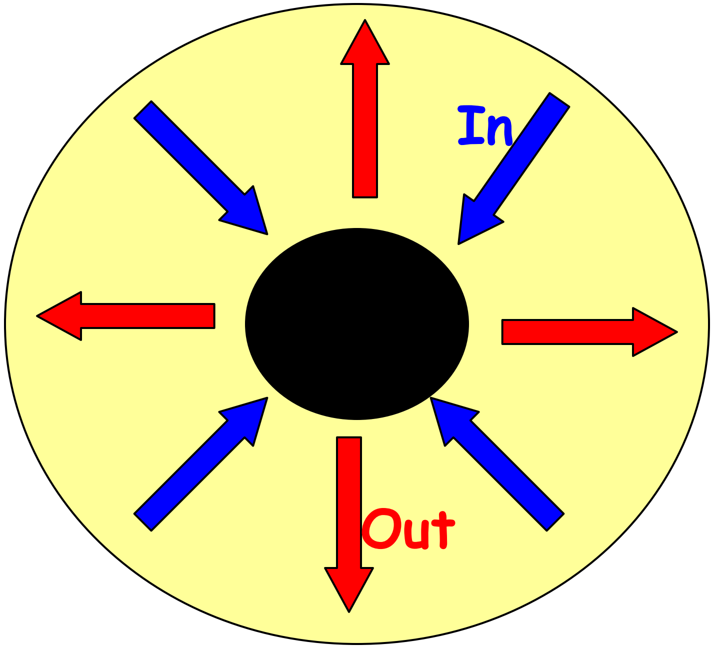


Accretion & Energy Feedback



$$\dot{M}_{Bondi} = \alpha \left(4\pi G^2\right) \frac{M_{BH}^{\ 2} \rho_\infty}{\left(c_{s,\infty}^2 + v^2\right)^{3/2}}$$

$$\alpha = 100$$



$$L_{Edd} = \frac{4\pi G M_{BH} m_p c}{\sigma_T} = \varepsilon_r \dot{M}_{Edd} c^2$$

- Bondi-Hoyle-Lyttleton rate
- Limited to the Eddington rate

$$\dot{M}_{BH} = \min\left(\dot{M}_{Bondi}, \dot{M}_{Edd}\right)$$

- Fraction of the accreted mass energy is radiated away

$$L_r = \varepsilon_r \dot{M}_{BH} c^2$$

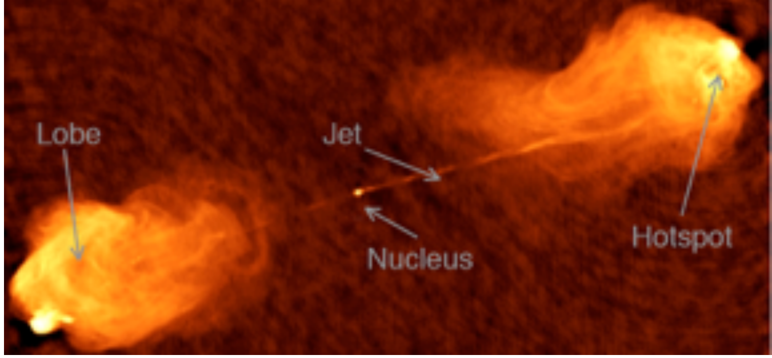
$$\varepsilon_r = 0.1$$

- Radiatively efficient accretion (Shakura & Sunyaev 1973)
- Some of the radiated energy is fed back & coupled to the surroundings

$$\dot{E}_{feed} = \varepsilon_f L_r$$

$$\varepsilon_f = \text{Feedback Efficiency}$$

Kinetic Feedback



- Energy-driven wind :

$$\frac{1}{2}\dot{M}_w v_w^2 = \dot{E}_{feed}$$

$$\dot{M}_w = 2\varepsilon_f \varepsilon_r \frac{c^2}{v_w^2} \dot{M}_{BH}$$

Free Parameters : ε_f

v_w = Wind Velocity = $(2.5,\ 5,\ 10) \times 10^3$ km/s

- Probabilistic method for kicking gas particles around BH

$$p_i = \frac{w_i \dot{M}_w \Delta t}{\rho}$$

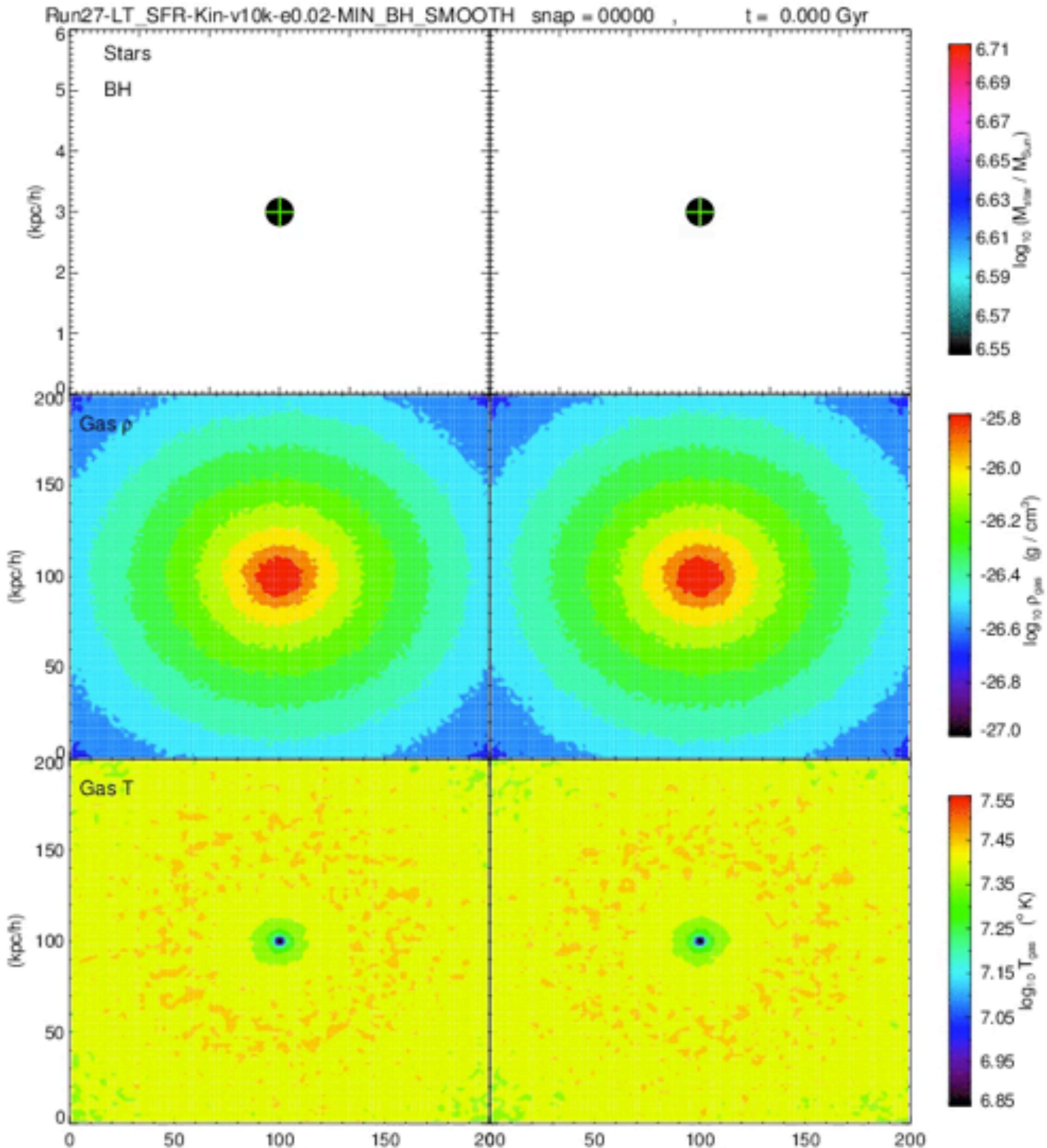
- New particle velocity

$$v_{new} = v_{old} + v_w \hat{n}$$

$$\vec{n} \rightarrow fixed$$

- Wind particles always coupled to hydrodynamic interactions

Run27-LT_SFR-Kin-v10k-e0.02



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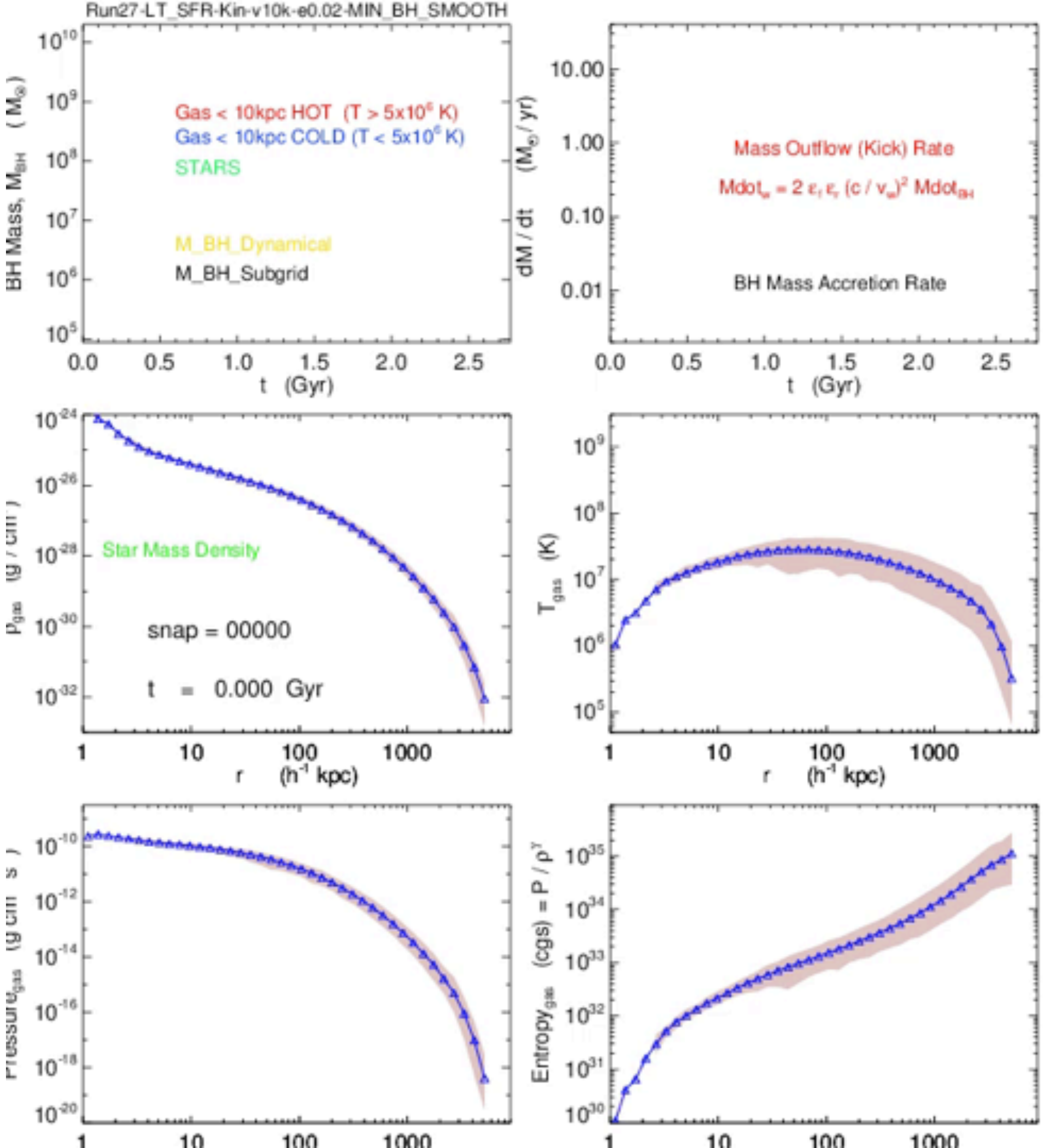
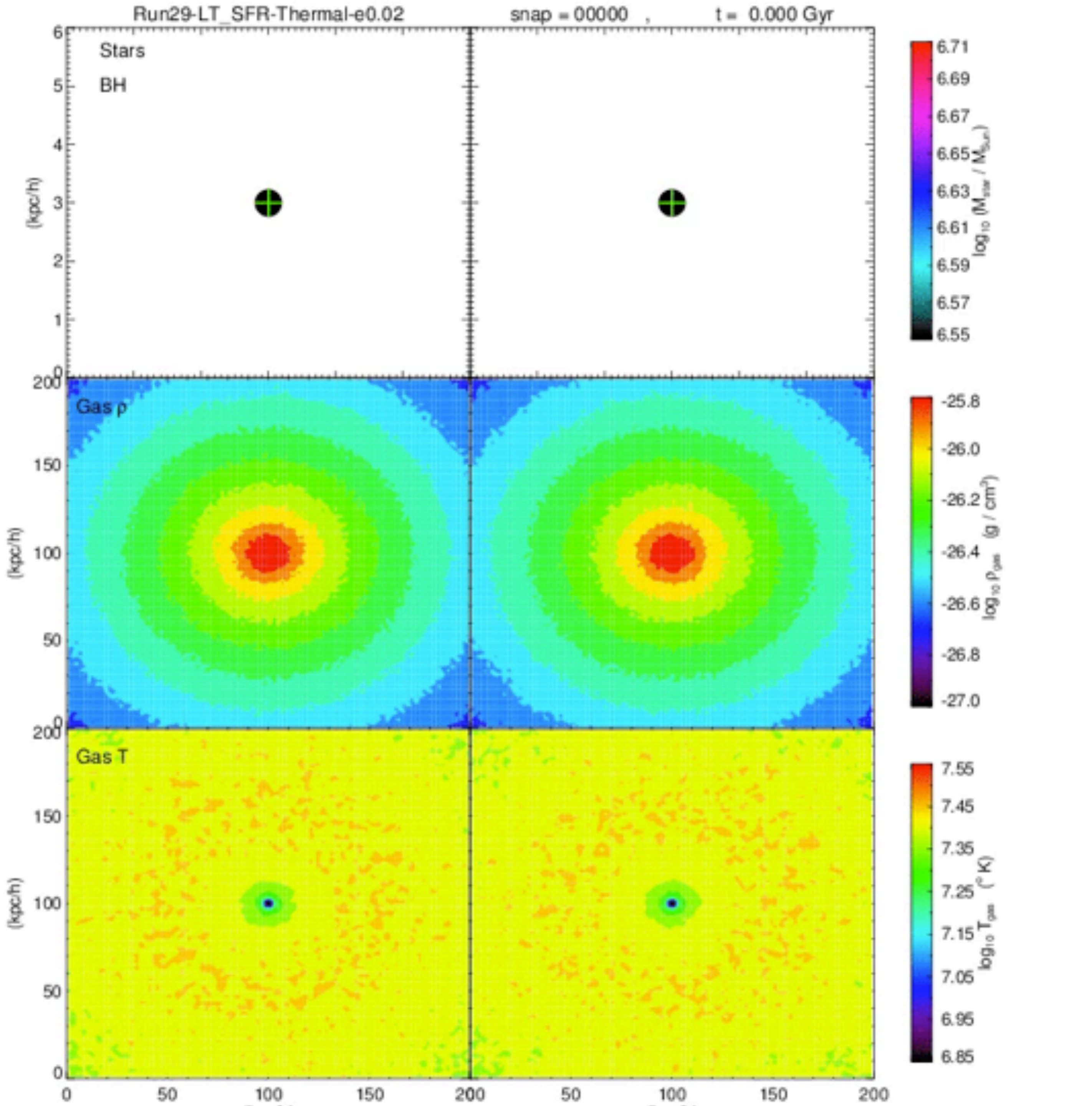
Run27-LT_SFR-Kin-v10k-e0.02



Run29-LT_SFR-Thermal-e0.02



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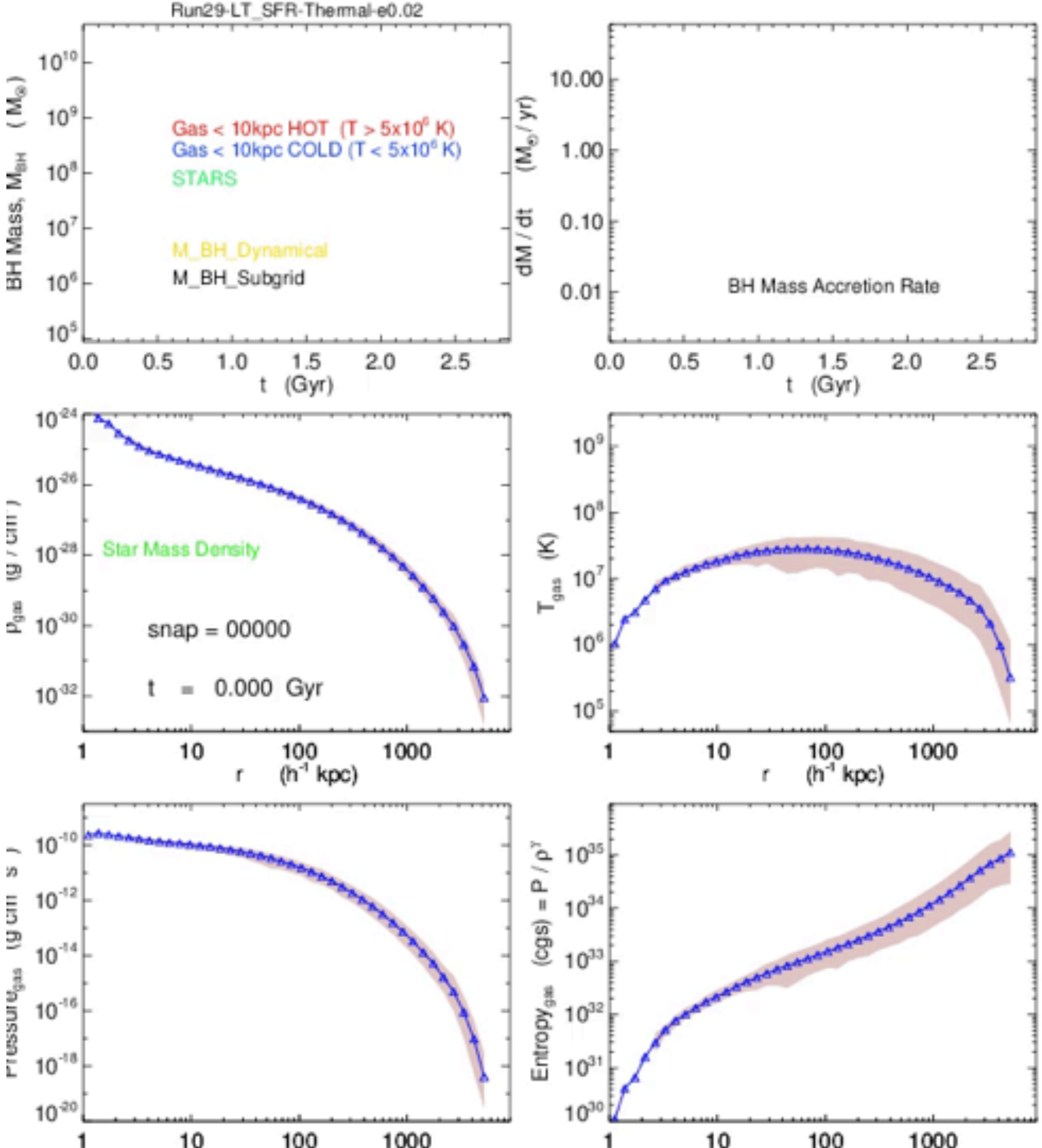
Run29-LT_SFR-Thermal-e0.02



Run30-LT_SFR-LB_Outflow_Kinetic

(Steinborn+ 2015 with outflow power as kinetic feedback)

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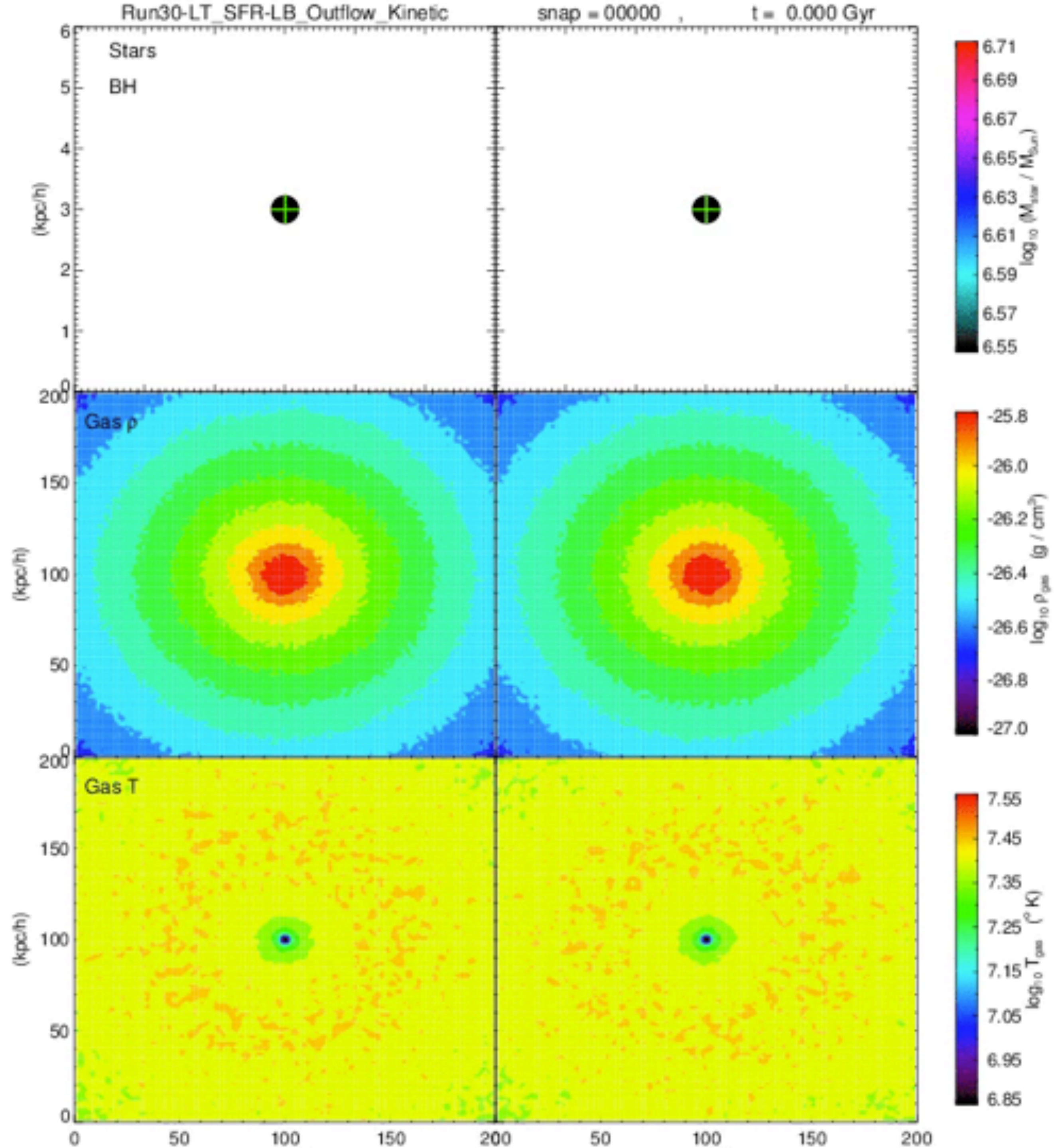
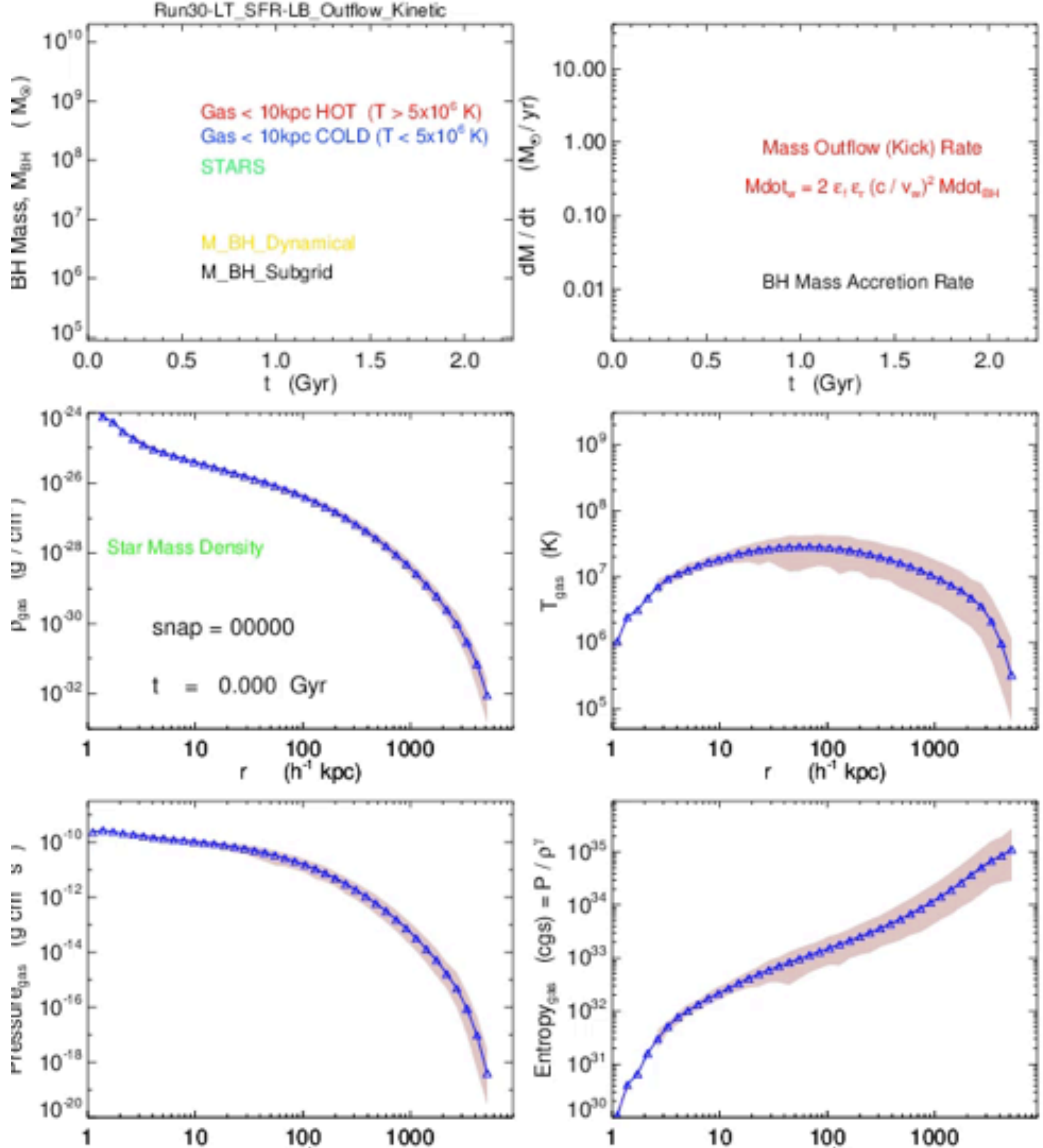


Run30-LT_SFR-LB_Outflow_Kinetic



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BH Mass Growth

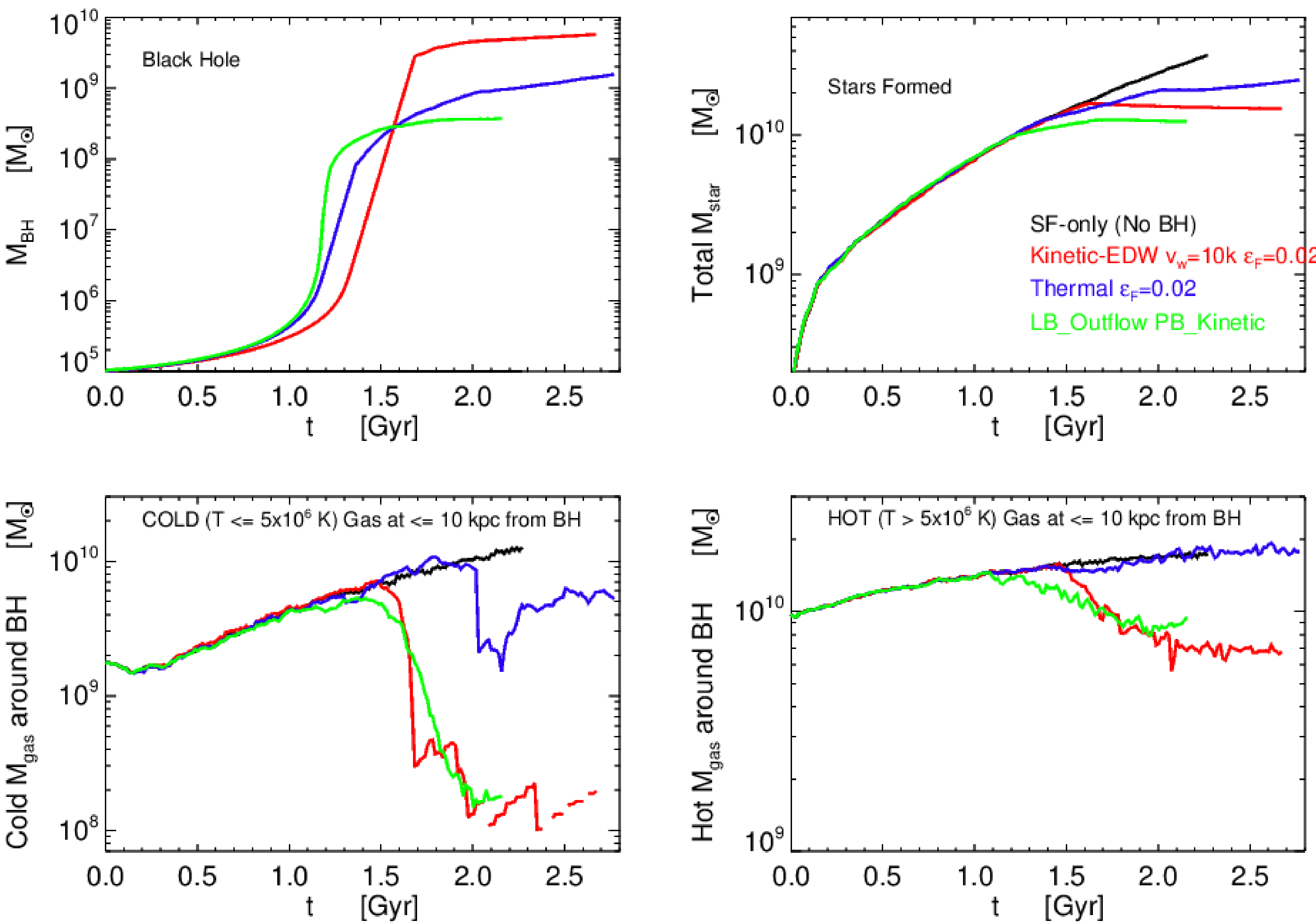
- BH grows at Eddington accretion rate, from a certain time
  - Exponential mass growth with time

$$L_{Edd} = \frac{4\pi G M_{BH} m_p c}{\sigma_T} = \varepsilon_r \dot{M}_{BH,Edd} c^2$$

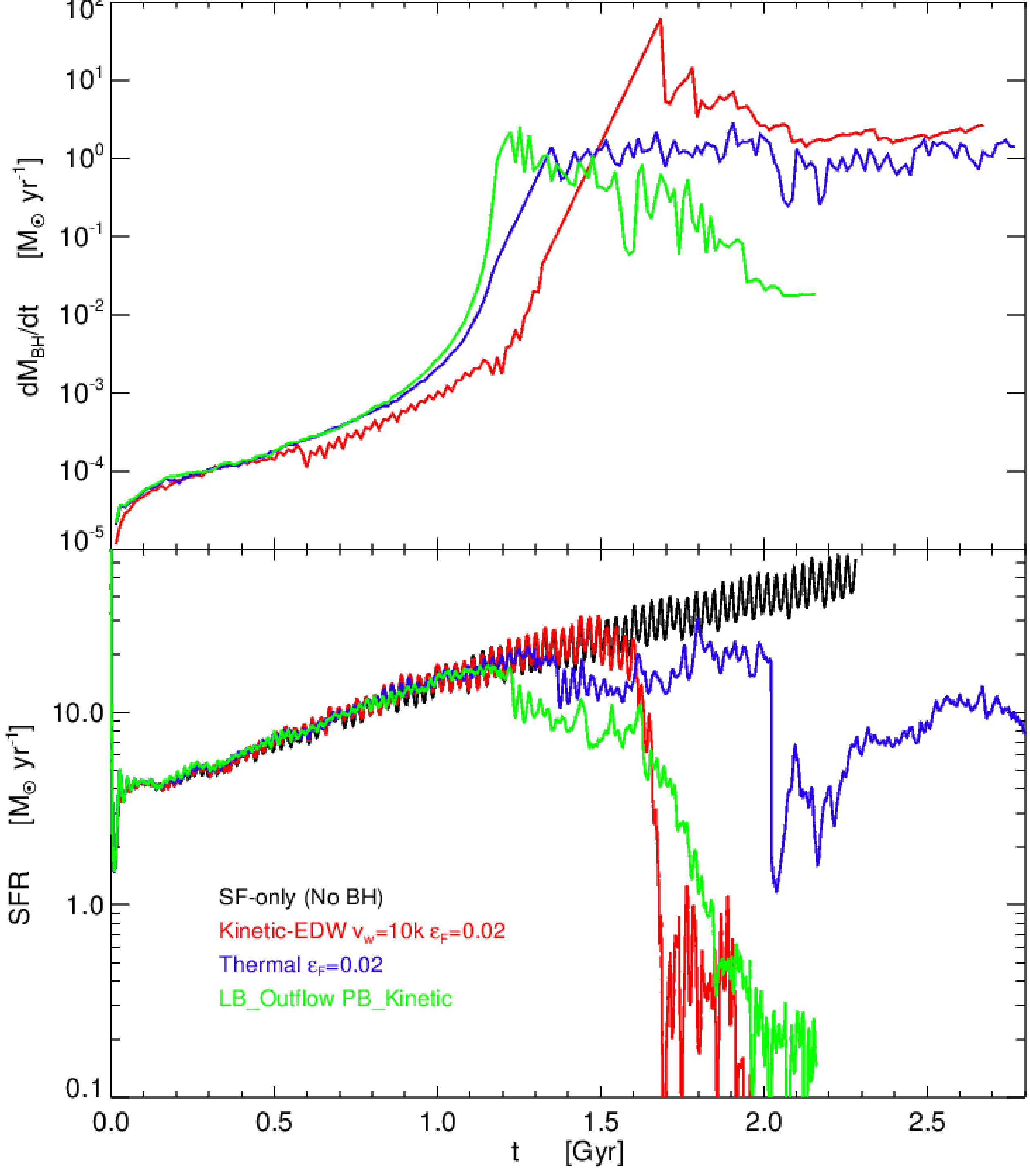
$$\Rightarrow \; M_{BH} \sim e^{factor * t}$$

- BH mass saturates, when the surrounding gas density has dropped

- Slow mass growth subsequently



Black Hole
M_{BH} [$M_\odot$]
t [Gyr]
Stars Formed
Total M_{star} [$M_\odot$]
SF-only (No BH)
Kinetic-EDW v_w=10k ϵ_F=0.02
Thermal ϵ_F=0.02
LB_Outflow PB_Kinetic
COLD (T <= 5x10^6 K) Gas at <= 10 kpc from BH
Cold M_{gas} around BH [$M_\odot$]
HOT (T > 5x10^6 K) Gas at <= 10 kpc from BH
Hot M_{gas} around BH [$M_\odot$]



dMBH/dt [M⊙ yr-1]
SFR [M⊙ yr-1]
t [Gyr]
SF-only (No BH)
Kinetic-EDW vw=10k εF=0.02
Thermal εF=0.02
LB_Outflow PB_Kinetic

Summary

- BH kinetic feedback in Gadget-3 cluster simulations
- Kick velocity predicts T, entropy deviation at shock
- Cool-core heated with 5000 km/s kick, coupled or decoupled
- 10000 km/s kick, decoupled wind
  - Cool-core remains cold
  - Hot-core remains hot

- BH growth and resulting feedback depends on way of coupling the energy to the surrounding gas
  - Same eps_f gives different results with various methods

➢ <u>Future</u>

- Cosmological simulations
  - Thermal feedback in Quasar-mode & Kinetic feedback in Radio-mode