Quasar Outflows at z>=6 in Zoomed Cosmological Hydrodynamical Simulations

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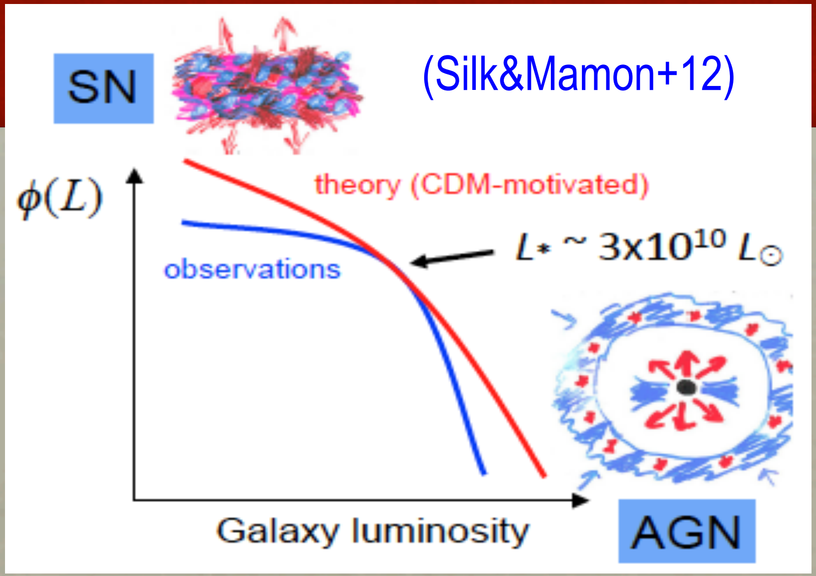
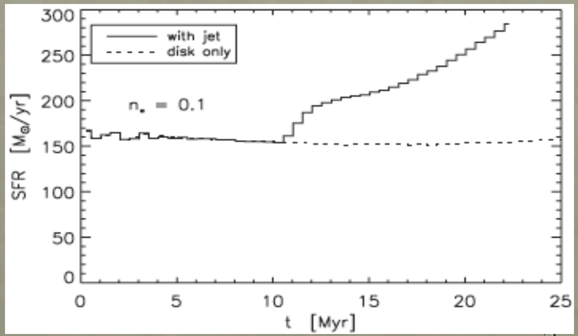
AGN Feedback

- Energy output from central SMBHs affecting host galaxies

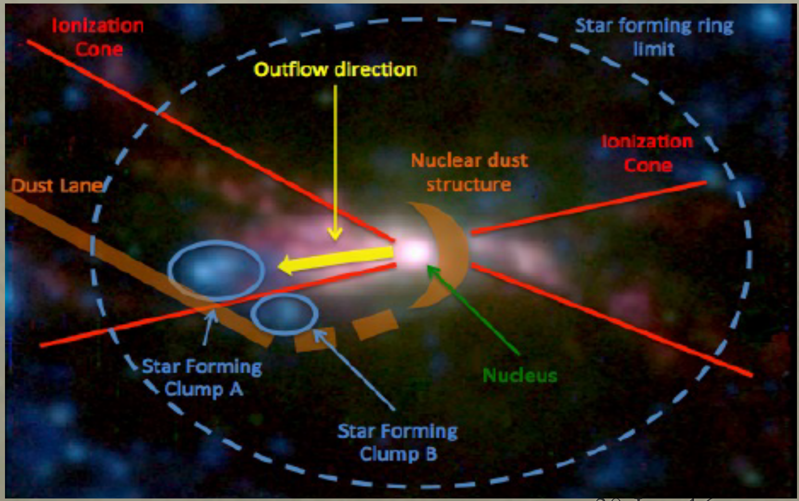
- Negative feedback
  - Quench star-formation
  - Reduce the number of galaxies at high-mass end of stellar-mass-function



- Positive feedback
  - SF induced by compression of cold clouds in multi-phase ISM with AGN-driven jets



(Gaibler+12)



(Cresci+15)

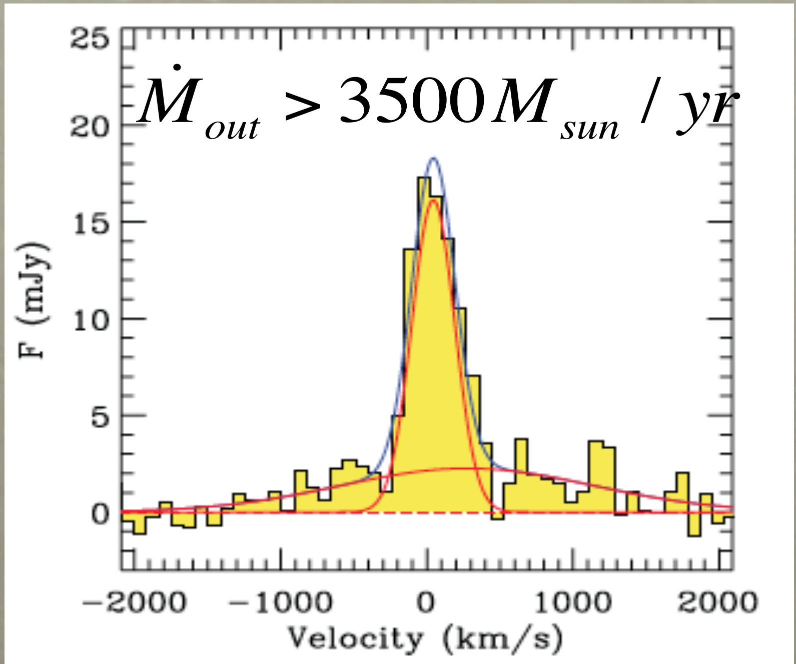
AGN Outflows

- Observed in different forms
  - Jets & cocoons: radio (Nesvadba+08)
  - Blue-shifted broad absorption lines: UV & optical (Rupke&Veilleux11)
  - Warm absorbers (Krongold+07) & ultra-fast outflows: X-rays (Tombesi+13)
  - Molecular gas: far-IR (Feruglio+10)

- This work

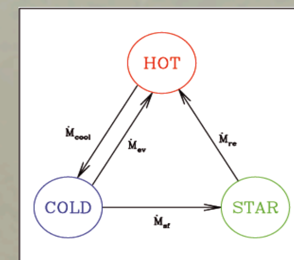
  ➔ Simulate massive, powerful gas outflows in quasars > 12.5 Gyr ago

- Observation SDSS J1148+5251, $z = 6.4$
  - (Maiolino+12, Cicone+15)
    - [CII] emission line at 158 μm
    - Detected broad wings tracing outflow
  - (Willott+03) $M_{BH} = 3 \times 10^9 M_{sun}$



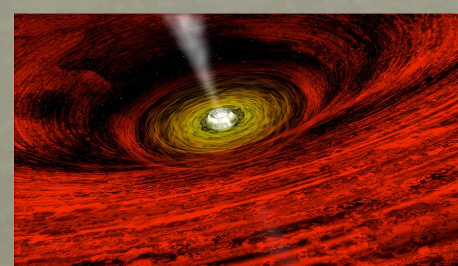
Modified-GADGET3 code: Sub-Resolution Physics

- GADGET3 : TreePM gravity + SPH hydro (Springel05)
- Metal-line cooling & radiative heating (Wiersma+09)
  - UV photoionizing background (Haardt&Madau01)



- Star-Formation
  - Effective model of multiphase ISM (Springel&Hernquist03)
- Stellar & Chemical Evolution (Tornatore+07)
  - Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) from SN type-II, type-Ia, & AGB stars; stellar age, mass & yield; different IMF; mass & metal loss from starburst
- SN Feedback (Tornatore+07, Tescari+09)
  - Kinetic feedback (↑ v)

- AGN accretion + feedback
  - (Rasia+16, Barai+14)



Zoom-In Cosmological Hydro Simulation

IC with MUSIC (Hahn&Abel+11)

1) Perform dark-matter only run of a periodic cosmological volume, starting from z=100

(previous similar work: Costa+14)

2) Select massive DM halo at z=6

3) Track-back $r<2R_{200}$ DM particles to z=100, & identify Lagrangian region

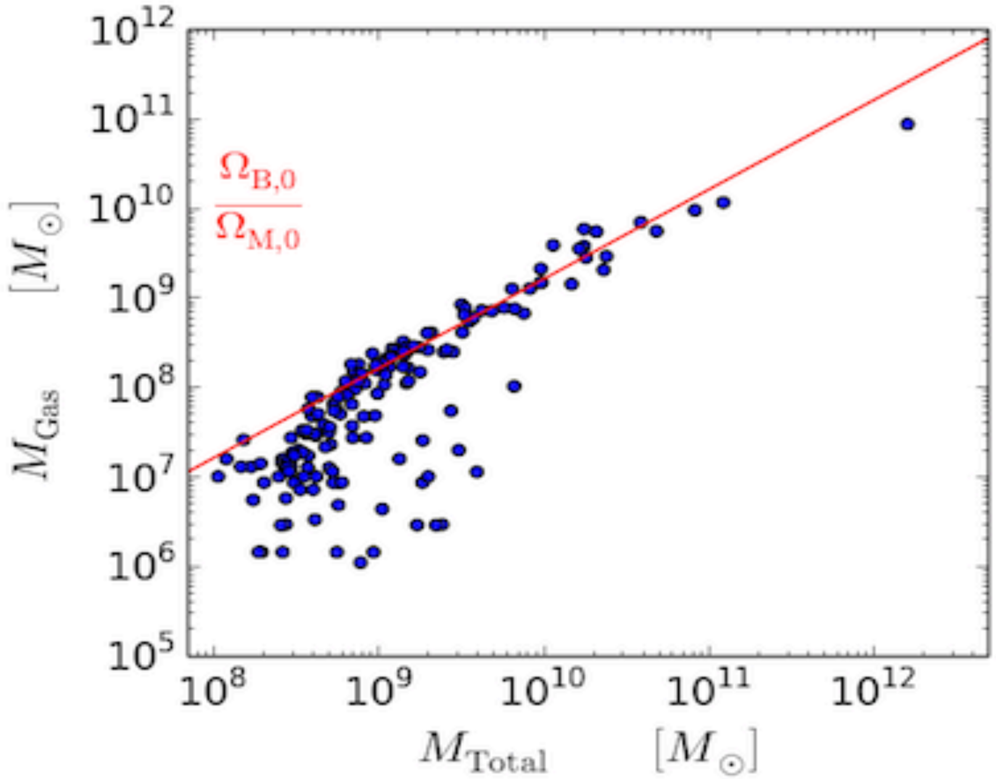
4) Generate Zoom-In IC, including baryons

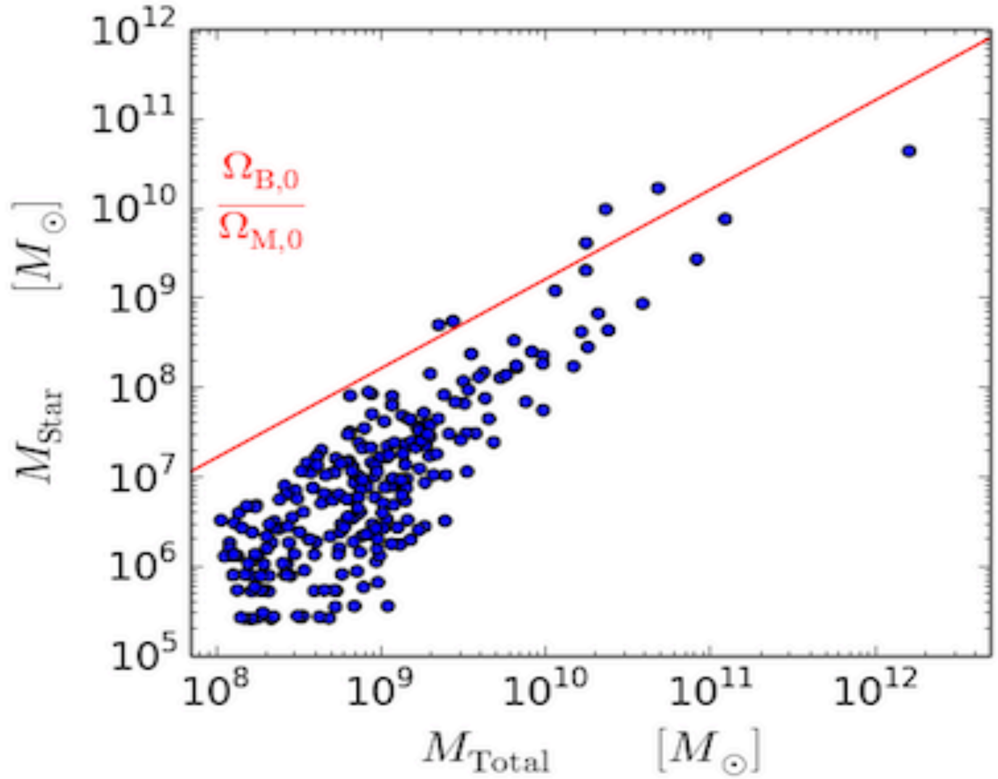
5) Perform Zoom-In sim from z=100

L_{box} [Mpc]	N_{DM}	N_{gas}	m_{DM} [$M_\odot$]	m_{gas} [$M_\odot$]	L_{soft} [$/h$ kpc]	Model	$M_{halo,max}$ [$M_\odot$]
500	17224370				33	Coarse	4.4×10^{12}
5.21	591408	591408	7.54×10^6	1.41×10^6	1	Hydro	

Galaxy Correlations

500Mpc-N256-Zoom / z = 5.998093 / SubFind-SubHalos

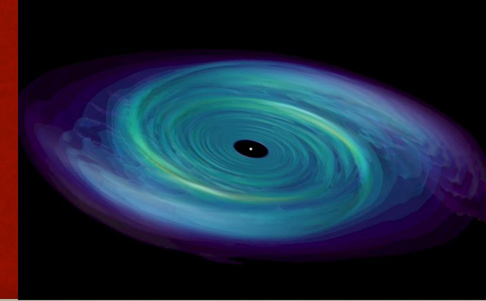


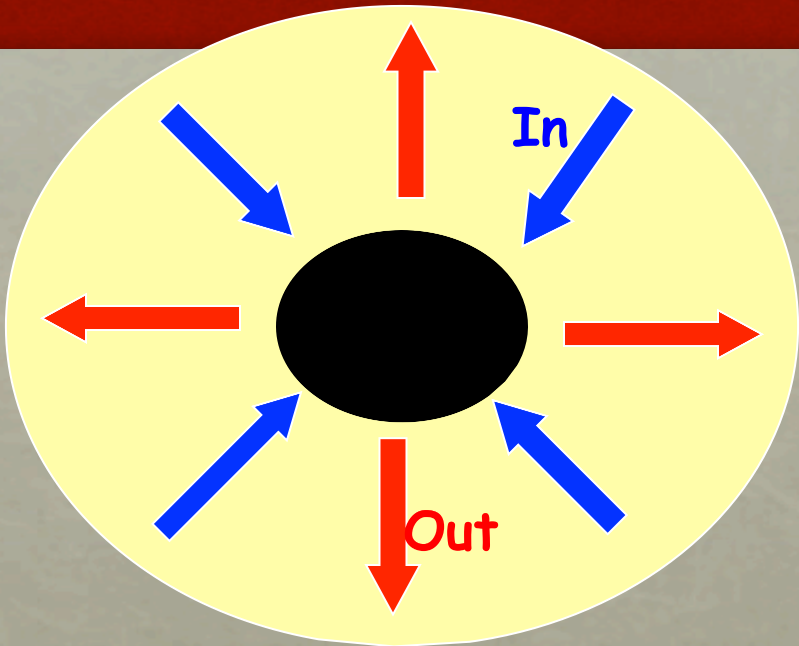


Modeling AGN Feedback in Galaxy Formation Simulations: the sub-resolution physics

- Generation of seed BH (10^5 M_{sun}) at:
  - Center of galaxy ($M_{halo} > 10^9$ M_{sun})
  - Minimum gravitational potential
- BH growth
  - Accretion of gas
  - Merger with other BHs
- Feedback
  - Transfer of energy (kinetic) from BH to surrounding gas
- BH advection
  - Reposition BH to center of halo

Accretion & Energy Feedback





$$\dot{M}_{\rm Bondi} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}.$$

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

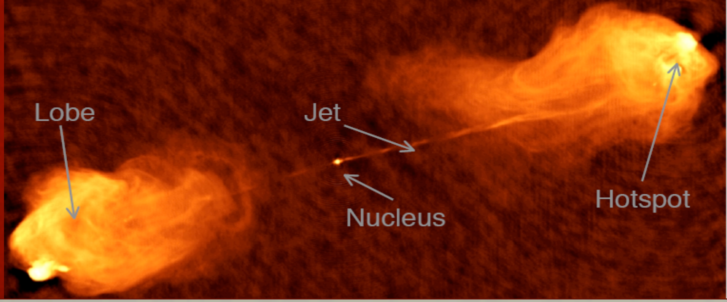
- Bondi-Hoyle-Lyttleton accretion rate (Bondi52)
  - Limited to the Eddington rate
- Fraction of the accreted mass energy is radiated away
- Radiatively efficient accretion (Shakura&Sunyaev73)
- Some of the radiated energy is fed back & coupled to the surroundings

$$L_r = \epsilon_r \dot{M}_{\rm BH} c^2,$$

$$\epsilon_r = 0.1$$

$$\dot{E}_{\rm feed} = \epsilon_f L_r = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2.$$

Kinetic Feedback from AGN
(Barai+16)



- Energy-driven wind

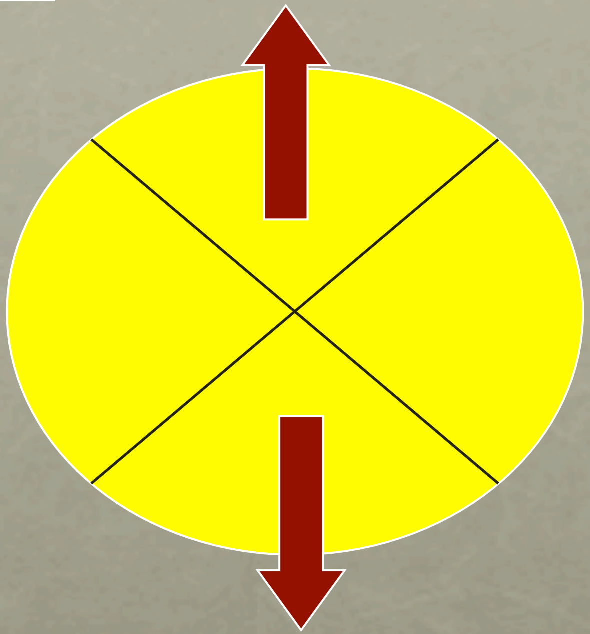
$$\frac{1}{2}\dot{M}_w v_w^2 = \dot{E}_{\rm feed}$$

$$\dot{M}_w = 2\epsilon_f \epsilon_r \dot{M}_{\rm BH} \frac{c^2}{v_w^2}.$$

- Free parameters:

$$\epsilon_f = 0.05,\ v_w = 10,000 \text{ km/s}$$

- Probabilistic method for kicking gas particles around BH



$$p_i = \frac{\dot{M}_w \Delta t}{M_{\rm gas}^{\rm cone}}.$$

- New particle velocity
  - Radially away from SMBH

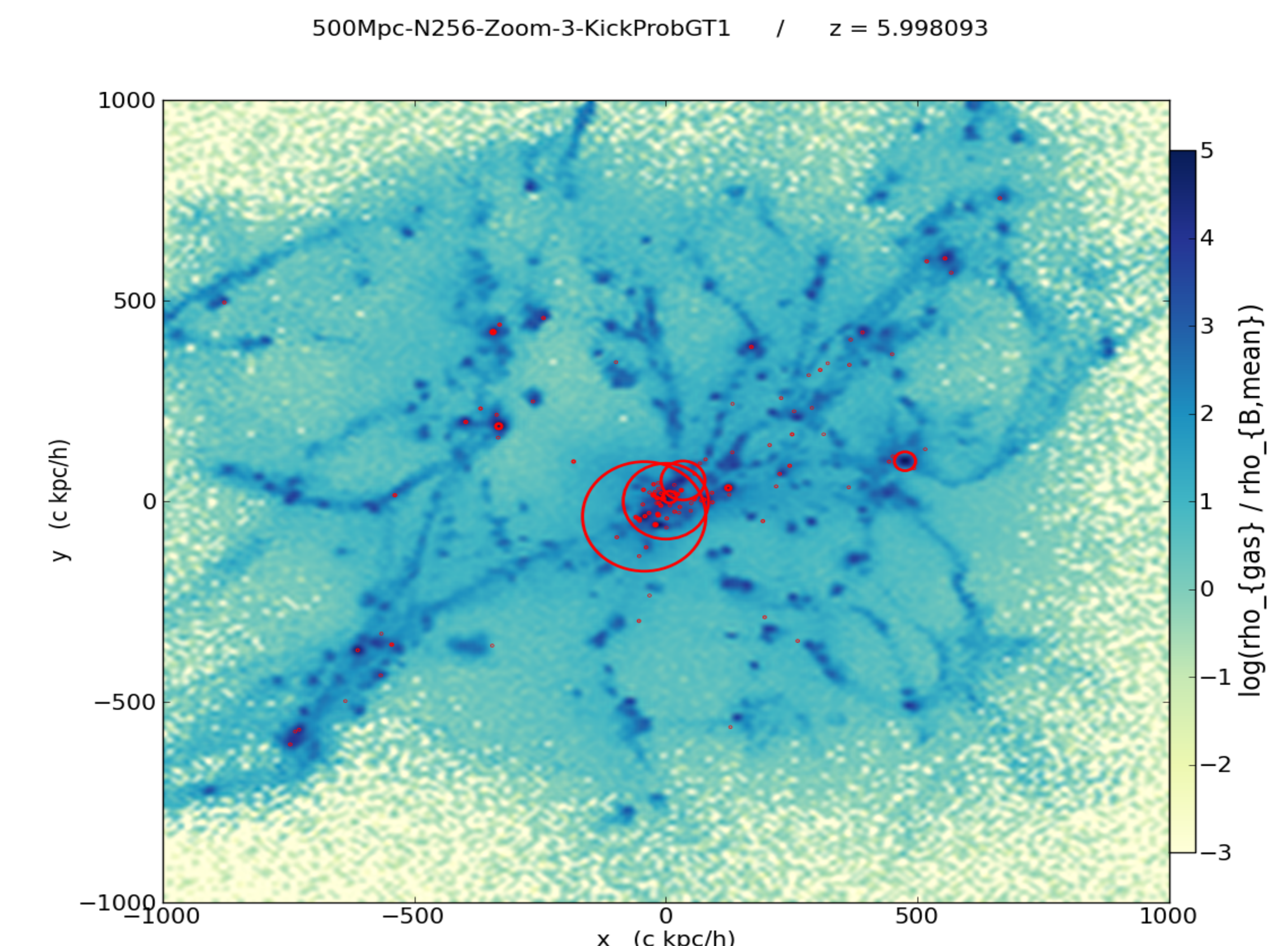
$$\vec{v}_{\rm new} = \vec{v}_{\rm old} + v_w \hat{n}$$

- Wind particles always coupled to hydrodynamical interactions

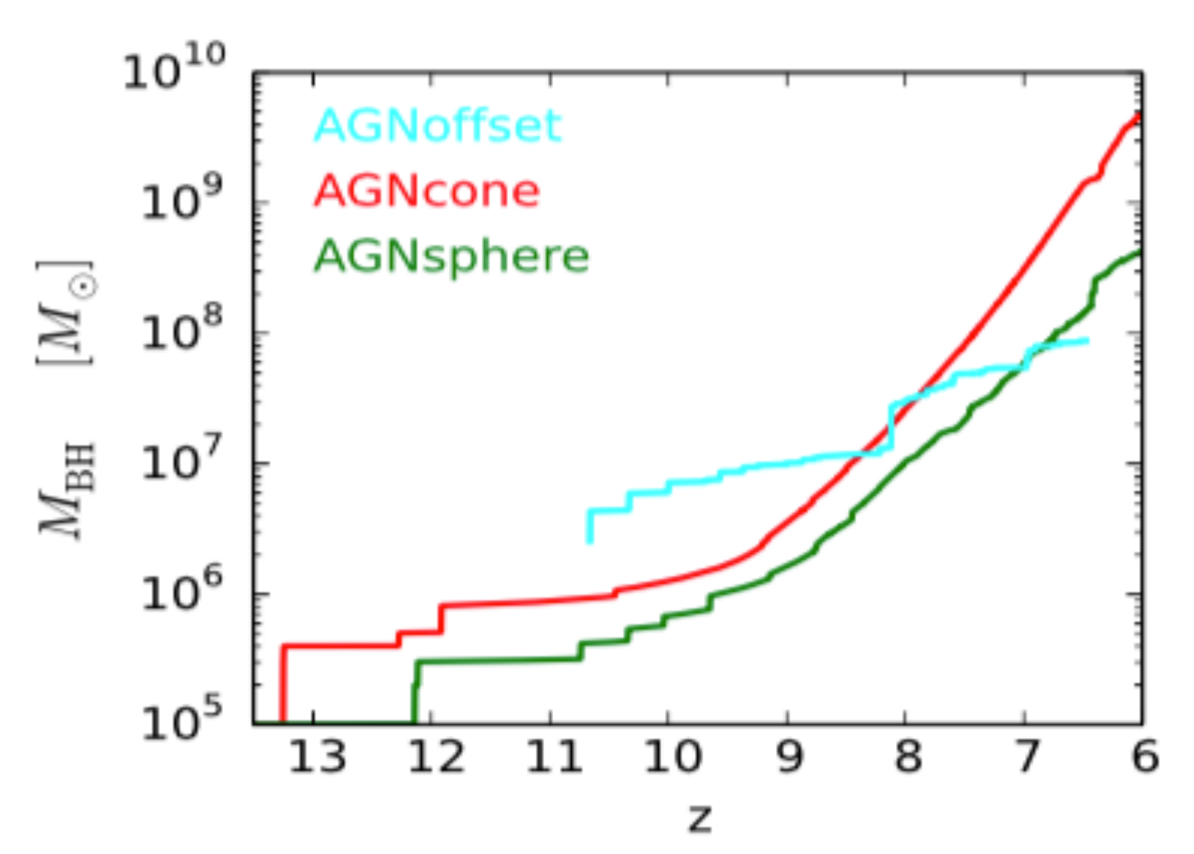
Simulation Parameters (Barai in prep.)

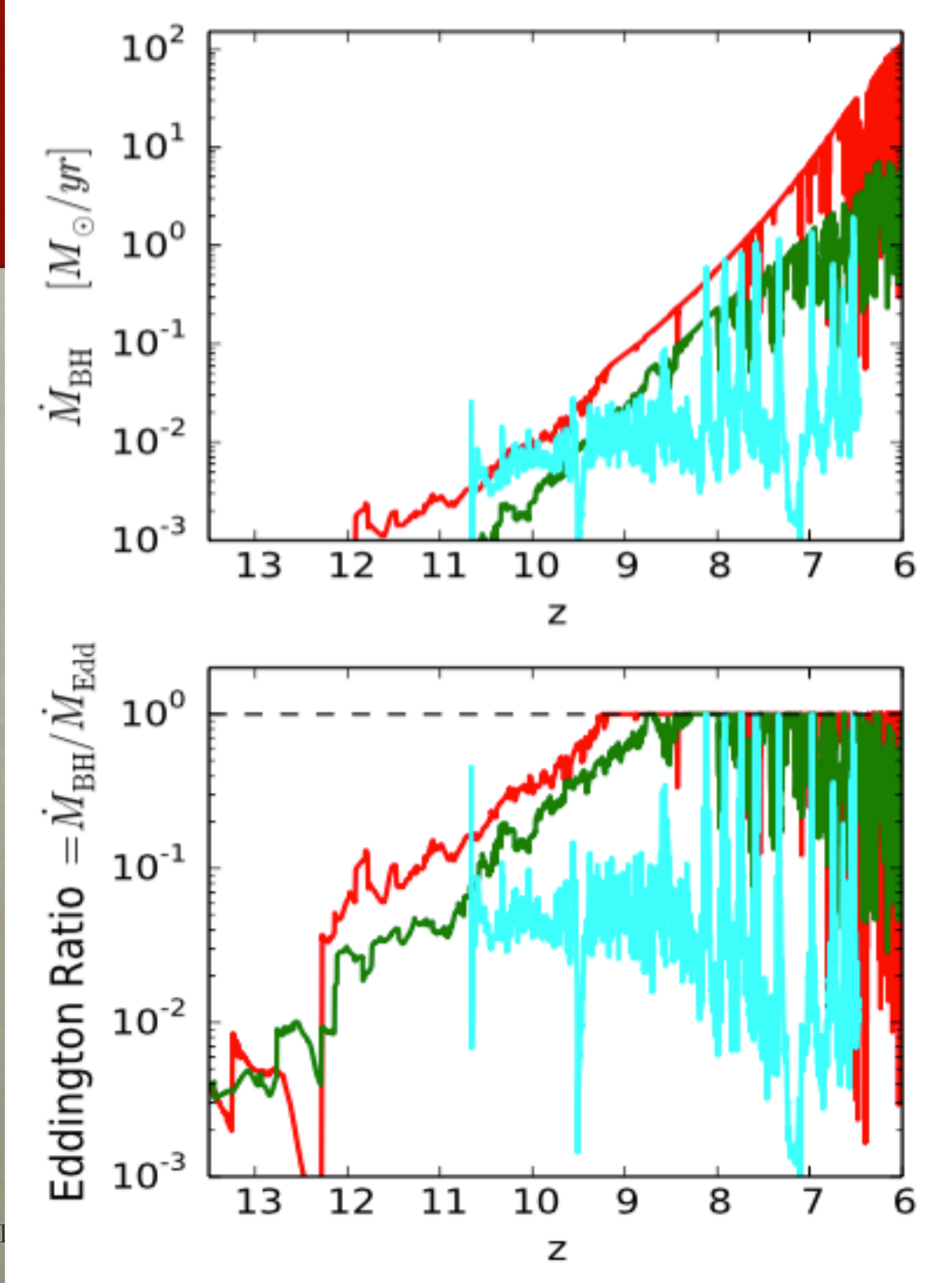
Run name	AGN feedback algorithm	Reposition of BH to potential-minimum	Geometry of region where feedback energy is distributed	Half opening angle of effective cone
SF	No BH			
AGNoffset	Kinetic	No	Bi-Cone	45°
AGNcone	Kinetic	Yes	Bi-Cone	45°
AGNsphere	Kinetic	Yes	Sphere	90°

BH locations & projected Gas Overdensity in 2-Mpc zoomed region



Growth of most-massive BH in each simulation

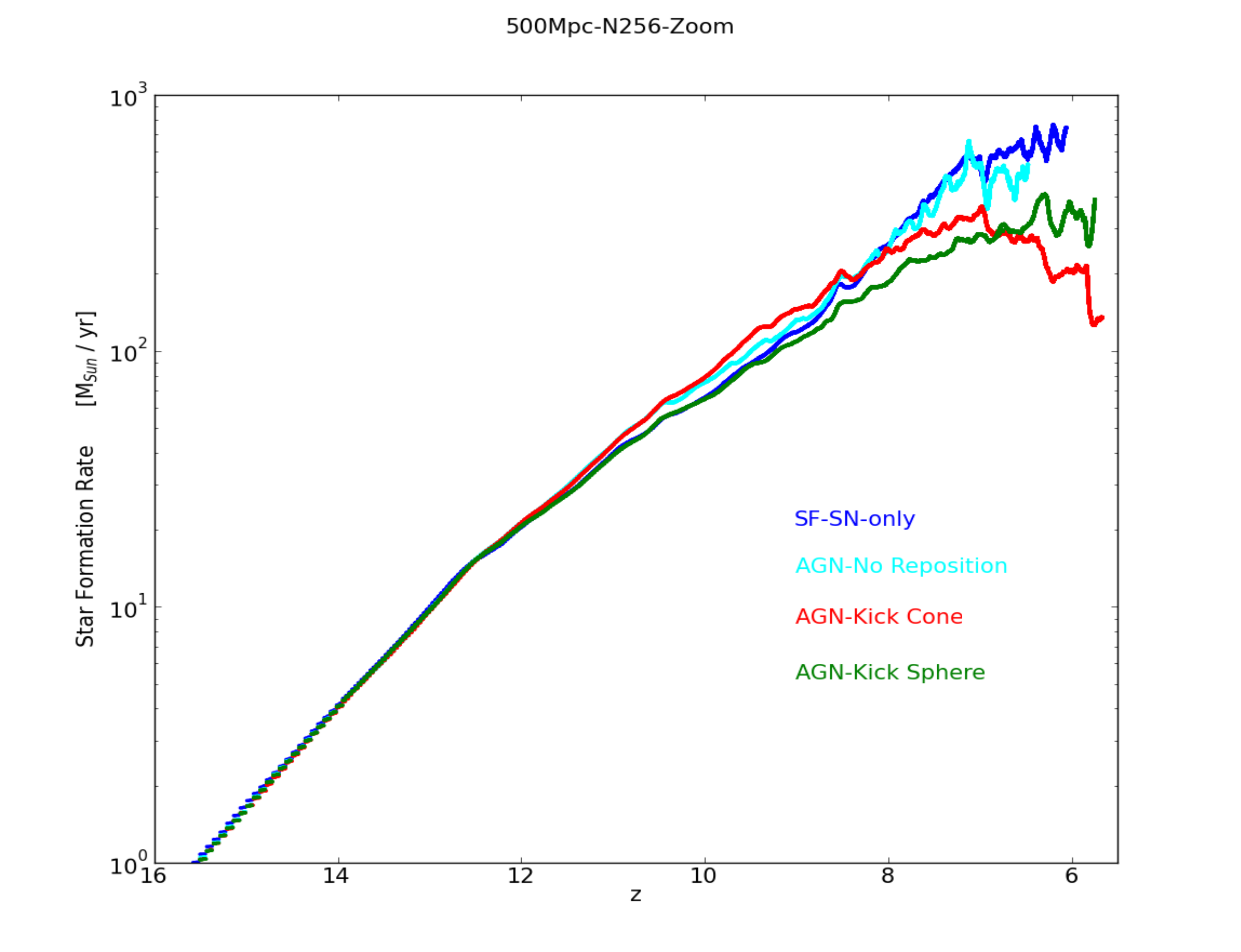




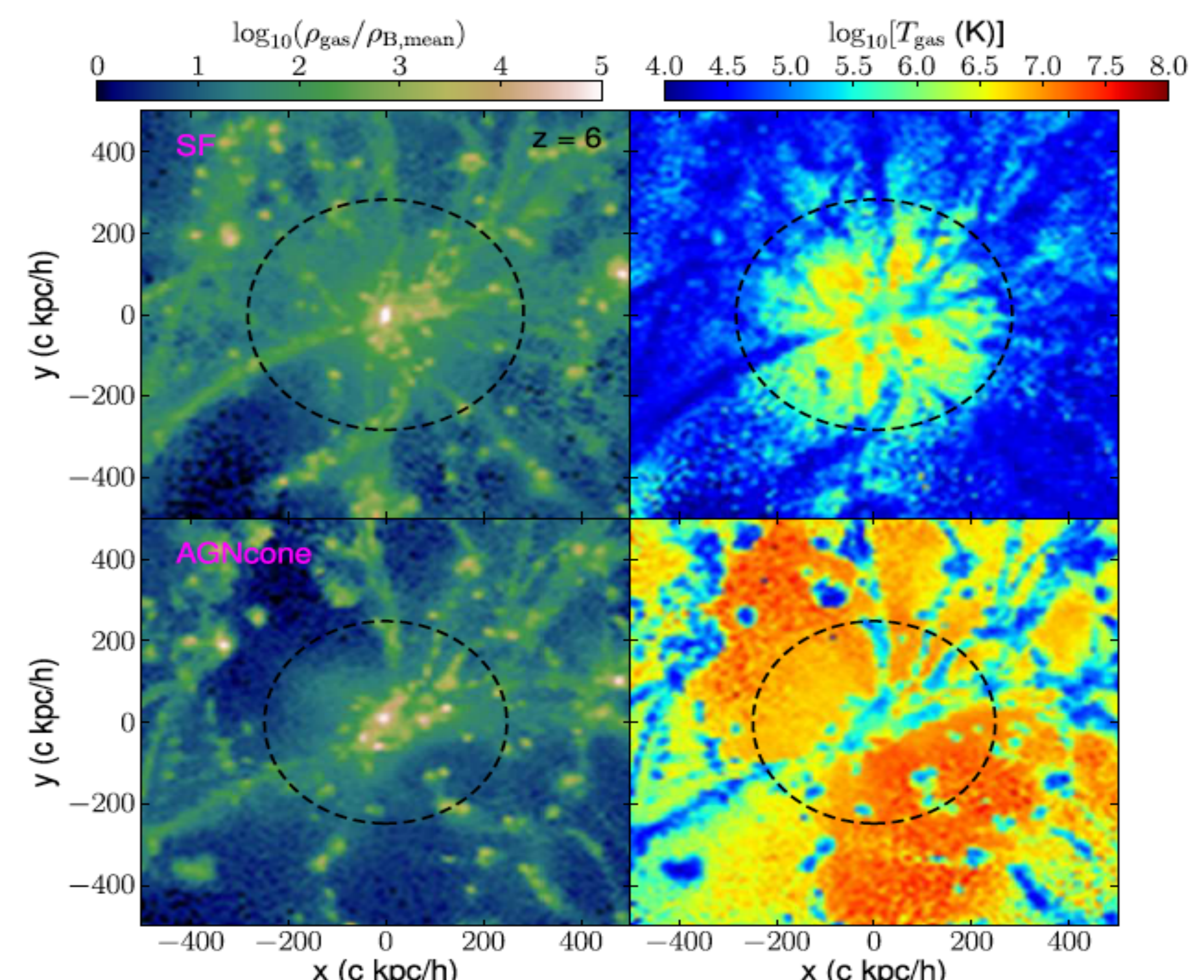
BH Accretion Rate

Eddington Ratio

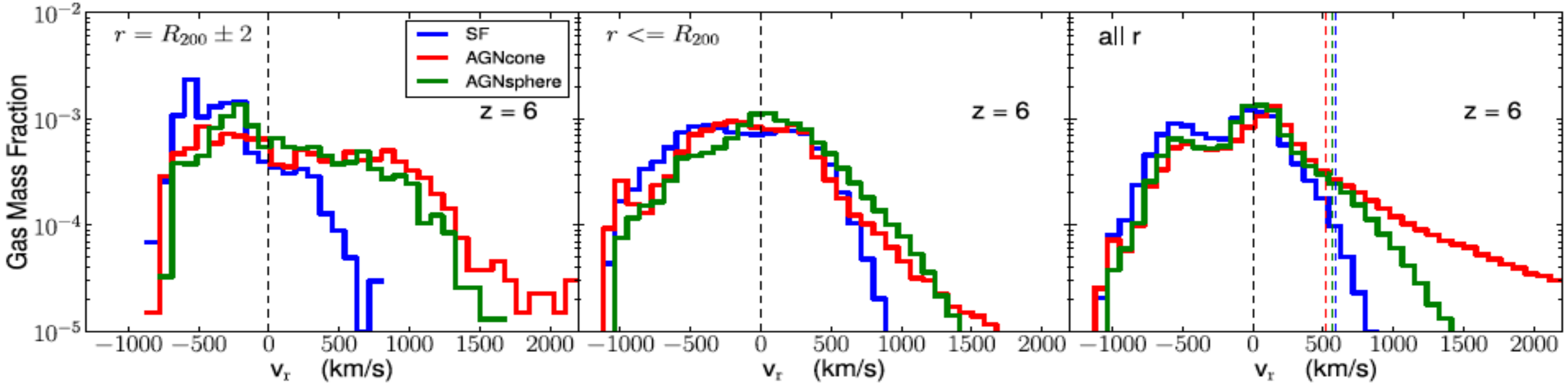
Star Formation Rate (total in zoomed volume)



2D maps of Gas Density & Temperature at z=6



Radial Velocity Histogram (around most-massive galaxy at z=6)



Conclusions

- Starting from 10^5 M_{sun} seeds, can grow BH to 10^9 M_{sun} in a cosmological environment
  - Need growth at Eddington accretion rate for 100s Myr
- Massive BHs generate powerful outflows
  - Outflow mass is increased (& inflow is reduced) by 20%

Future:

- Predict signatures of $z \geq 6$ AGN outflows that can be observed
- Post-processing analyses
  - Radiative transfer
  - Compute far-infrared emission, [CII] line spectra