Quasar Outflows at z>6 in Cosmological Hydrodynamical Simulations

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Introduction

❖ AGN Feedback:
- ➢ Energy output from central SMBHs affect host galaxies
- ➢ *Negative* - Quench star-formation, Reduce the number of high-M_{star} galaxies
- ➢ *Positive* - SF induced by compression of cold clouds with AGN jets

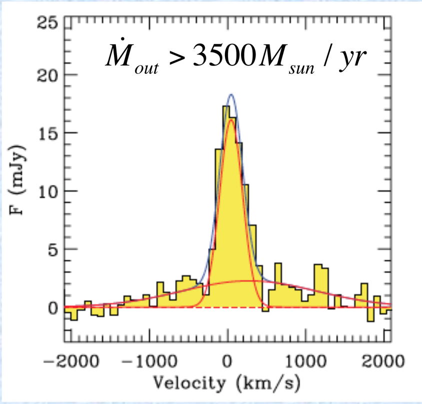
❖ AGN Outflows observed in different forms:
- Jets & cocoons: radio (Nesvadba+08)
- Blue-shifted broad absorption lines: UV & optical (Rupke&Veilleux11)
- Warm absorbers (Krongold+07) & ultra-fast outflows: X-rays (Tombesi+13)
- Molecular gas: far-IR (Feruglio+10)

❖ Our work
✓ Simulate massive, powerful gas outflows in quasars at cosmic epochs > 12.5 Gyr ago

❖ Observation of SDSS J1148+5251 at z = 6.4

- ○ (Maiolino+12, Cicone+15)
  - [CII] emission line at 158 μm
  - Broad wings tracing outflow
- ○ (Willott+03)

$M_{BH} = 3\times10^9 M_{sun}$

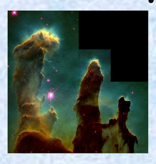


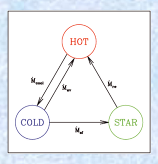
Numerical Methodology

- GADGET-3 code: Tree-PM (gravity) + SPH (Springel 2005)

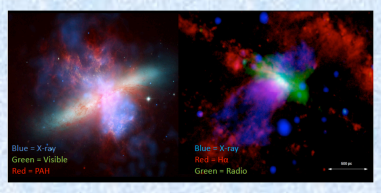
Baryonic Sub-Resolution Physics:

- Metal-line cooling, radiative heating (Wiersma et al. 2009)
  - ➢ UV photoionizing background (Haardt & Madau 2001)
- Star formation - Effective model of multiphase ISM (Springel & Hernquist 2003)

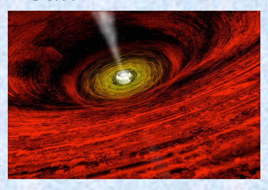




- Stellar evolution & chemical enrichment, metals: C, Ca, O, N, Ne, Mg, S, Si, Fe (Tornatore et al. 2007)
- SN feedback (Tescari et al. 2009, Barai et al. 2013)



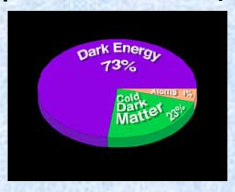
- AGN accretion + feedback (Barai et al. 2016)
  - ➢ BH (10^5 M_{sun}) seeded at galaxy (M_h > 10^9 M_{sun}) center
  - ➢ BH growth
    - ✧ Accretion of gas $\dot{M}_{BH} = \min(\dot{M}_{Bondi}, \dot{M}_{Edd})$
    - ✧ Merger with other BHs
  - ➢ BH feedback - Transfer of energy (kinetic) from BH to surrounding gas $\frac{1}{2}\dot{M}_w v_w^2 = \dot{E}_{feed} = \epsilon_f \epsilon_r \dot{M}_{BH} c^2$,

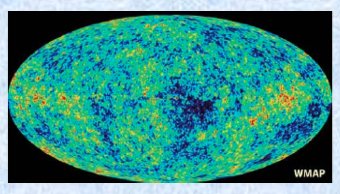


Prescriptions

Zoom-In Cosmological Hydrodynamical Simulation

- Initial condition - MUSIC code (Hahn & Abel 2011)
- Cosmological volume evolved using [DM + gas] particles
  - ✧ Start with gaussian Δρ at CMB epoch
  - ✧ ΛCDM parameters





- ➢ Perform dark-matter only run of a periodic (500 Mpc)^3 box, starting from z=100, up to z=6
- ➢ Select massive DM halo at z=6
- ➢ Track-back r<2R_{200} DM particles to z=100, & identify Lagrangian region
- ➢ Generate zoom-in IC, including baryons
- ➢ 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	

Results

Quasar-Central Supermassive Black Hole Growth

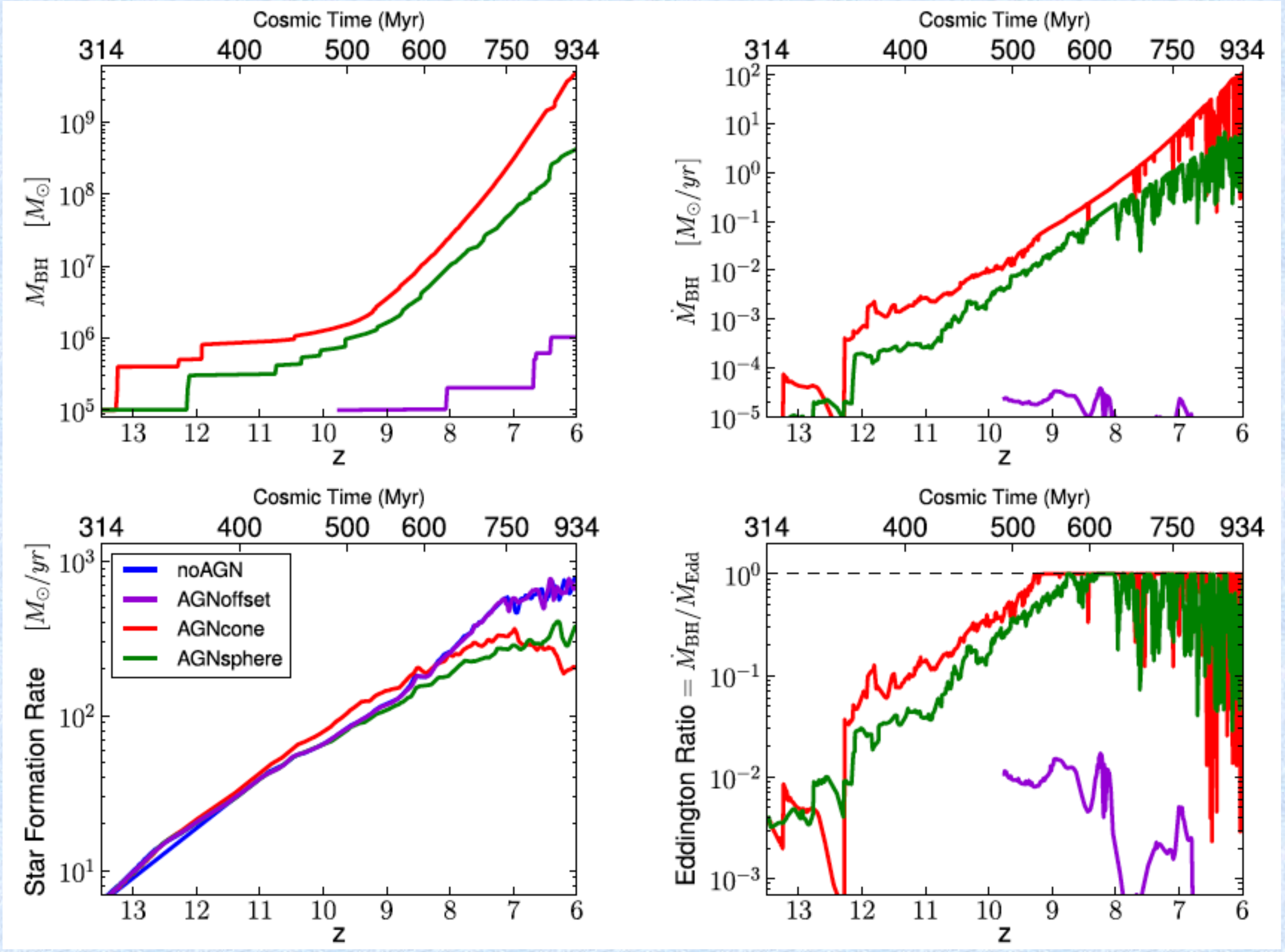
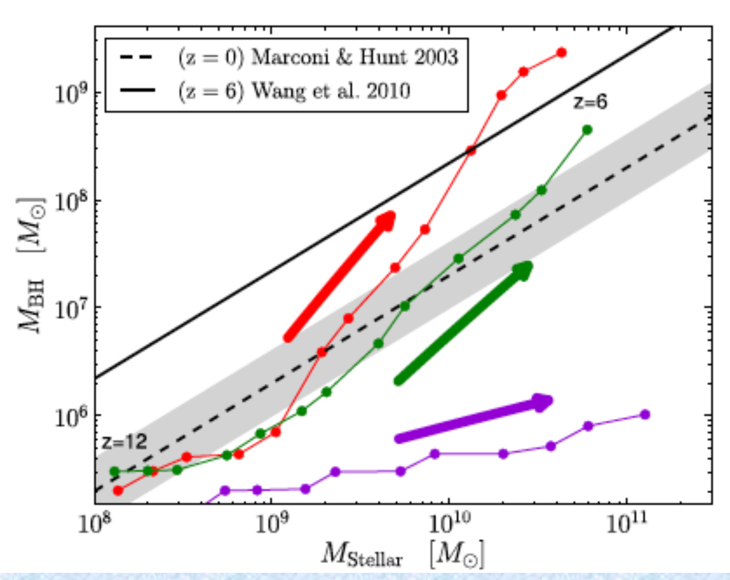


Fig 1: Growth of most-massive BH in our simulations. The different panels show redshift evolution of BH mass (top-left), BH accretion rate (top-right), Eddington ratio (bottom-right), and star formation rate (bottom-left).

Fig 2: Redshift track of central BH mass versus host galaxy stellar mass. Black lines indicate the observed BH versus stellar bulge mass correlation of local galaxies (dashed line), and z=6 quasars (solid line).



Outflow Properties

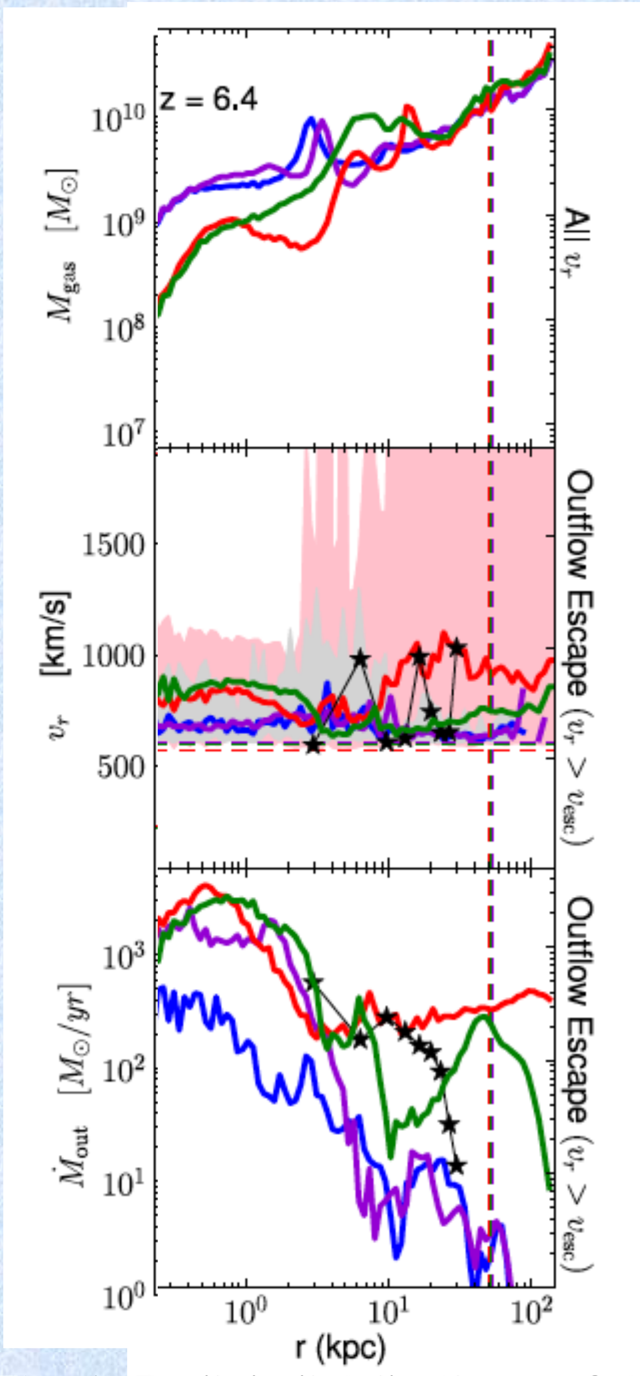


Fig 4: Radial distributions of total gas mass (top panel), median-v_r & its radial scatter (middle), mass outflow rate (bottom), of 4 runs at z=6.4. Black star symbols denote observational data from Cicone+15.

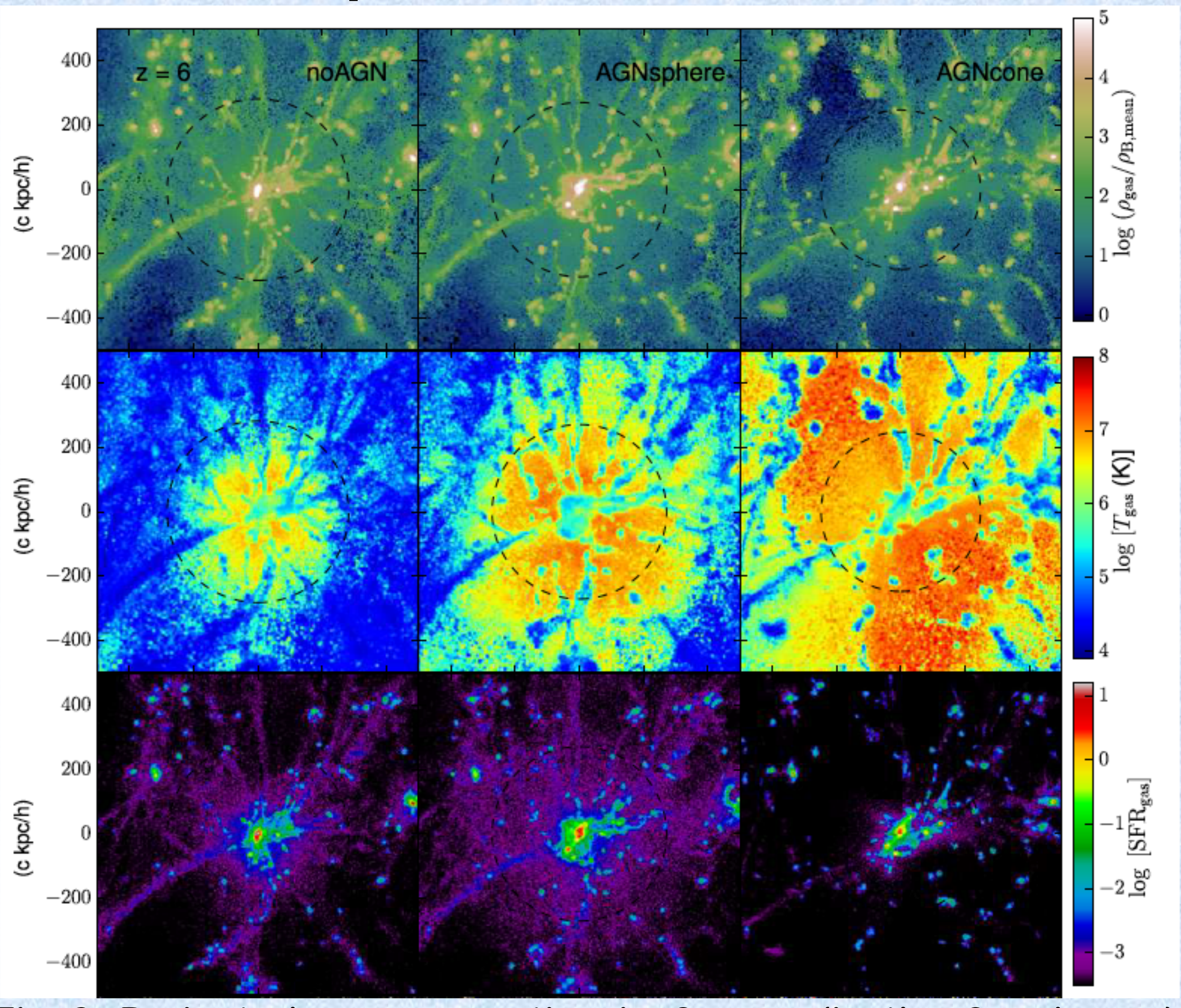


Fig 3: Projected gas properties in 3 runs (in the 3 columns) presenting outflow morphology at z=6. The rows show: density (top), temperature (middle), and SFR (bottom). Black dashed circle is galaxy R_{200}.

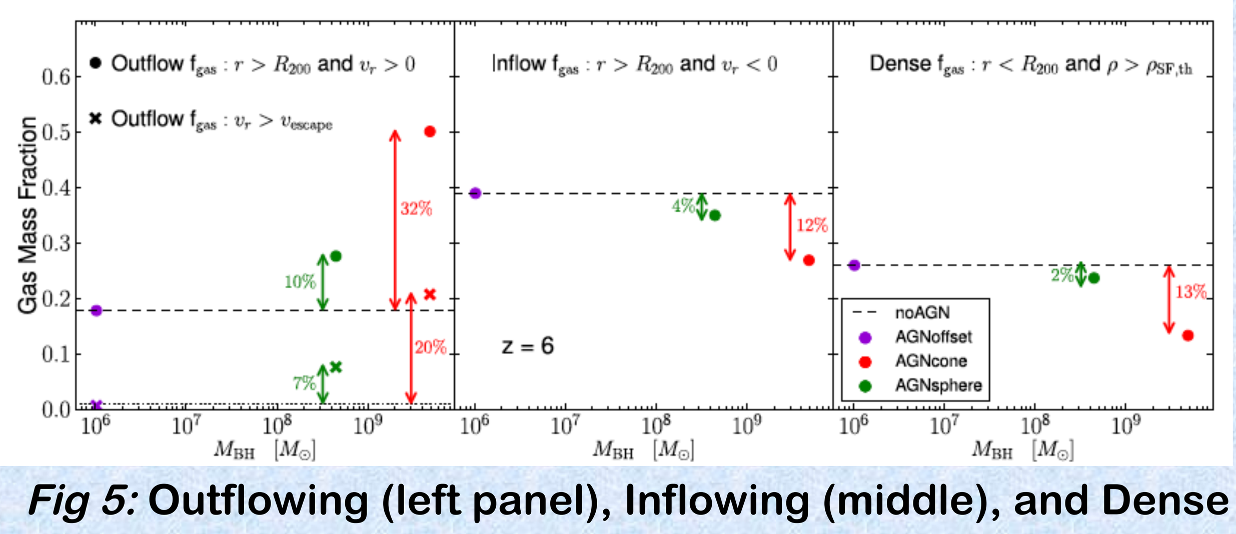


Fig 5: Outflowing (left panel), Inflowing (middle), and Dense (right) gas mass fraction.

Conclusions

- ➢ Starting 10^5 M_{sun}, a BH can grow to 10^9 M_{sun} by z=6 in a cosmological environ
  - ✓ Need growth at Eddington accretion rate over z=9-6 (for 100s Myr)
- ➢ Massive BHs generate powerful high-velocity outflows
  - ✓ Outflow mass is increased (& inflow is reduced) by 20%
  - ✓ Despite the feedback, 30-40% cosmic gas continues to inflow
  - ✓ SF is quenched dominantly by (i) fast outflowing gas ejected away, which affects 2 times the fraction of gas as compared to (ii) cosmic inflows halted, or, (iii) dense gas reduced

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