Feedback from Supermassive and Intermediate-mass Black Holes at Galaxy Centers using Cosmological Hydrodynamical Simulations

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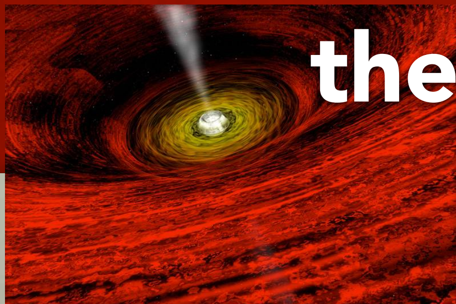
Sociedade Astronômica Brasileira (SAB) XLIII meeting

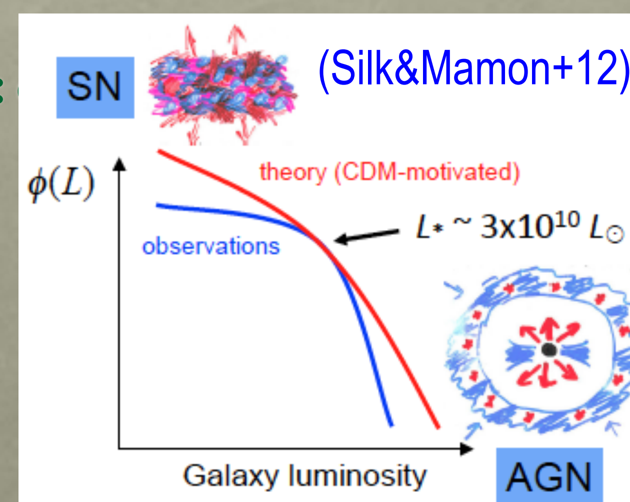
12 Sept. 2019

SMBHs affect their host galaxies & the large-scale environment



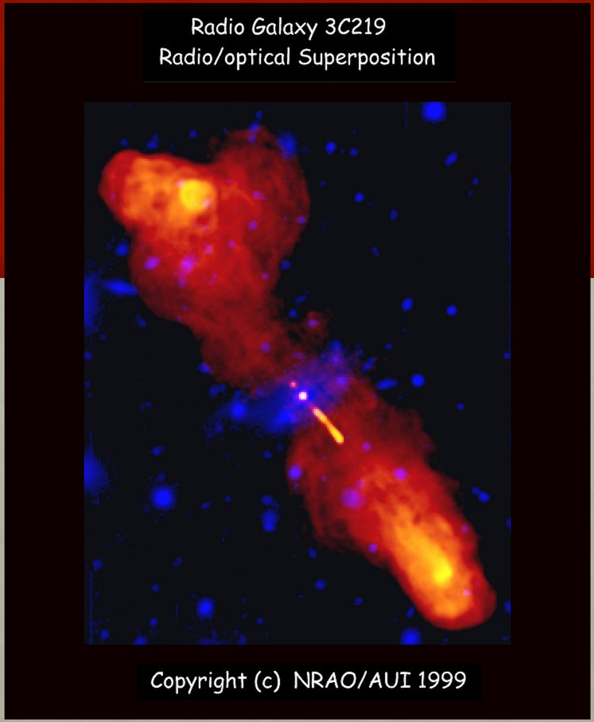
AGN FEEDBACK *: Energy output from central SMBHs (fraction of gas accretion energy) is fed back & coupled to the surroundings*

- Central BH - host galaxy correlations
  - $M_{BH} - \sigma$, $M_{BH} - M_{bulge}$
- Impact SF in galaxies
  - Quench SF by heating up or expelling gas
  - Trigger SF by compressing cold clouds in multiphase ISM
- Sharp cutoff at the bright end of galaxy luminosity function
- Galaxy - BH coevolution (self-regulated BH growth) :
  density both peaks at similar epoch (z ~ 2 - 3)
- Galaxy cluster
  - Heat up the cooling-flow
  - Pre-heating (entropy floor in cool-core clusters)



AGN Outflows

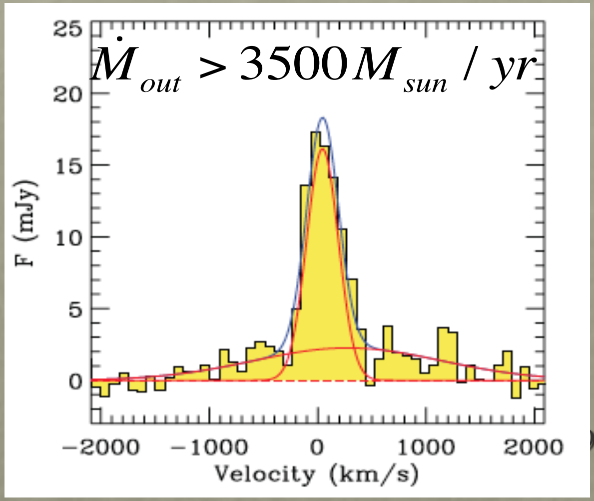
- Observed in many forms:
  - radio jets & lobes, uv BAL, X-ray warm absorbers & UFOs, far-IR molecular gas



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

(Barai et al. 2018, MNRAS)

- Observation SDSS J1148+5251, z = 6.4
  - (Maiolino+12, Cicone+15)
    - [CII] emission line at 158 μm
    - Detected broad wings tracing outflow



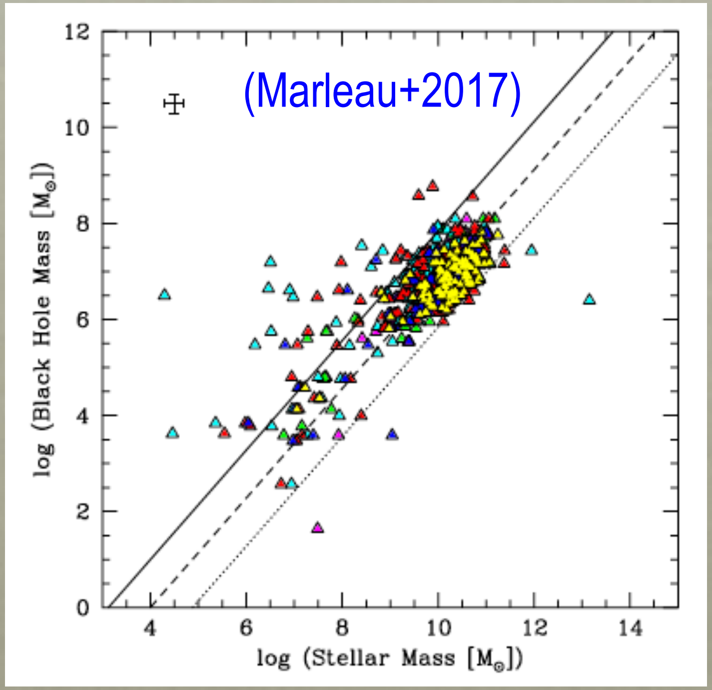
- (Willott+03)

$$M_{BH} = 3 \times 10^9 M_{sun}$$

Intermediate-Mass Black Holes

- **Black holes are mostly observed to be**
  - Stellar-mass (< 100 $M_\odot$), or
  - Supermassive (> 10^6 $M_\odot$)

- **What about the population of Intermediate-Mass Black Holes (IMBHs: 100 - 10^6 $M_\odot$) ?**
  - Started to be observed recently
  - These IMBHs should also have feedback



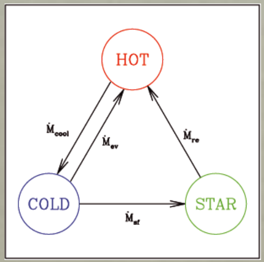
Our Study - IMBH

- ✓ Perform Cosmological Hydrodynamical Simulations by including IMBHs at the centers of Dwarf Galaxies
  - ✓ Test if IMBHs would grow at DG centers
  - ✓ Quantify the impact of IMBHs on DGs; esp. the effects on star formation at cosmic epochs z=6-4

(Barai & de Gouveia dal Pino 2019, MNRAS)

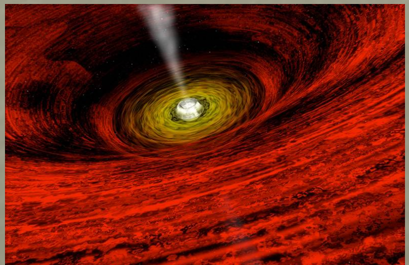
Modified-GADGET3 code: Sub-Resolution Physics

- **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)



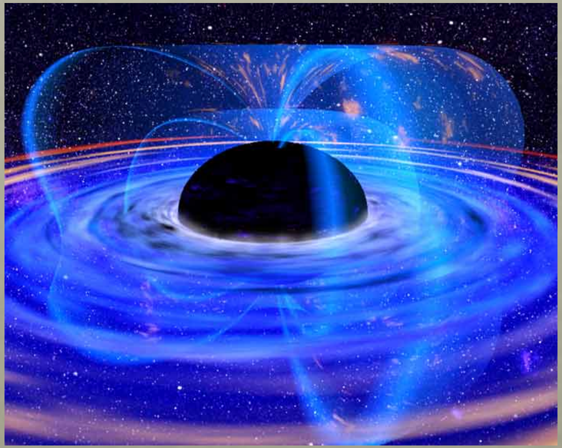
- **Stellar & Chemical Evolution** (Tornatore+07)
  - Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) from SN type-II, type-Ia, & AGB stars
- **SN Feedback** (Tornatore+07, Tescari+09, Barai+13)
  - Kinetic feedback (↑ v)

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



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

- Generation of seed BH (10^2–10^3 $M_\odot$, 10^5 M_{sun}) at:
  - Center of galaxy (M_{halo} > 10^6–10^7 $M_\odot$, 10^9 M_{sun})
  - Minimum gravitational potential



- BH growth
  - Accretion of gas
  - Merger with other BHs
- Feedback
  - Transfer of energy from BH to surrounding gas

SMBH: Zoom-In Cosmological Hydro Simulation

IC with MUSIC (Hahn&Abel+11)

1) Perform dark-matter only run of a periodic **(500 Mpc)^3** cosmological volume, starting from z=100

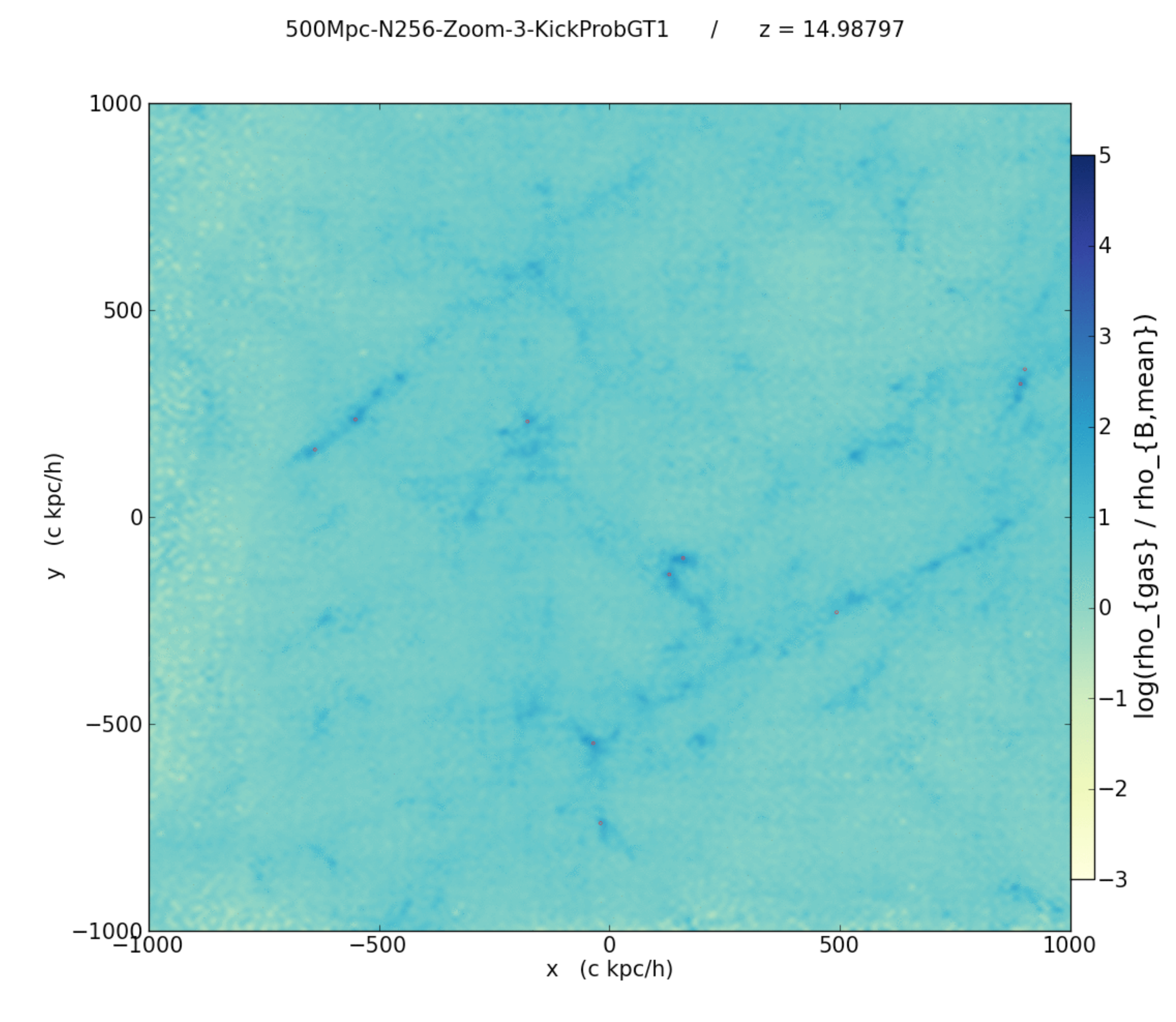
(previous similar work: Costa+14)

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

(Barai et al. 2018, MNRAS)

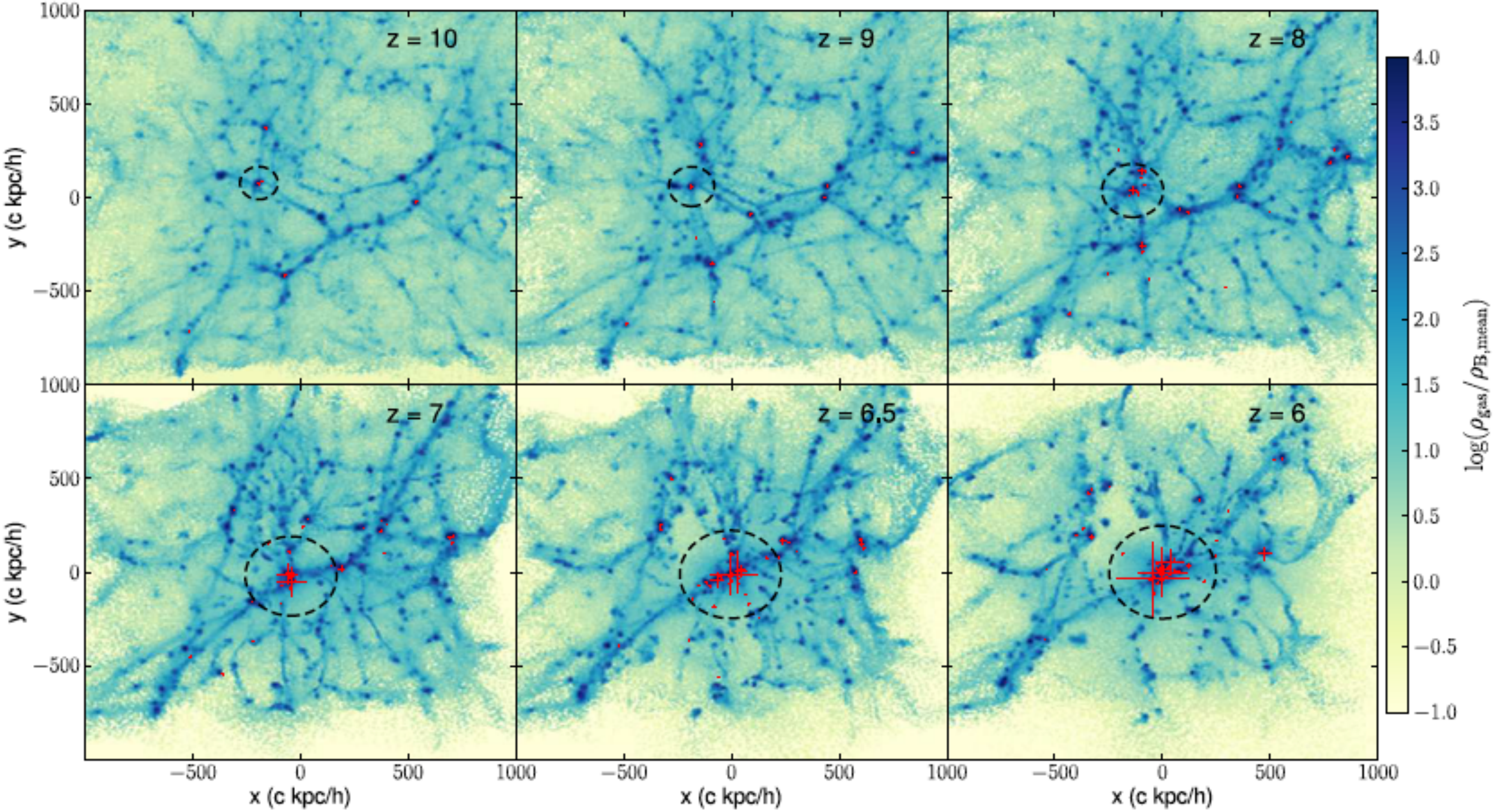
Run name	AGN feedback algorithm	Reposition of BH to potential-minimum	Geometry of region where feedback energy is distributed	Half opening angle of effective cone
SF	No BH			
AGNoffset	Kinetic	No	Bi-Cone	45°
AGNcone	Kinetic	Yes	Bi-Cone	45°
AGNsphere	Kinetic	Yes	Sphere	90°

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



Formation of Structures between z=10 and z=6.
Gas Overdensity in Zoomed Cosmological Simulation.

(Barai et al. 2018, MNRAS)



IMBH: Cosmological Hydrodynamical Simulation

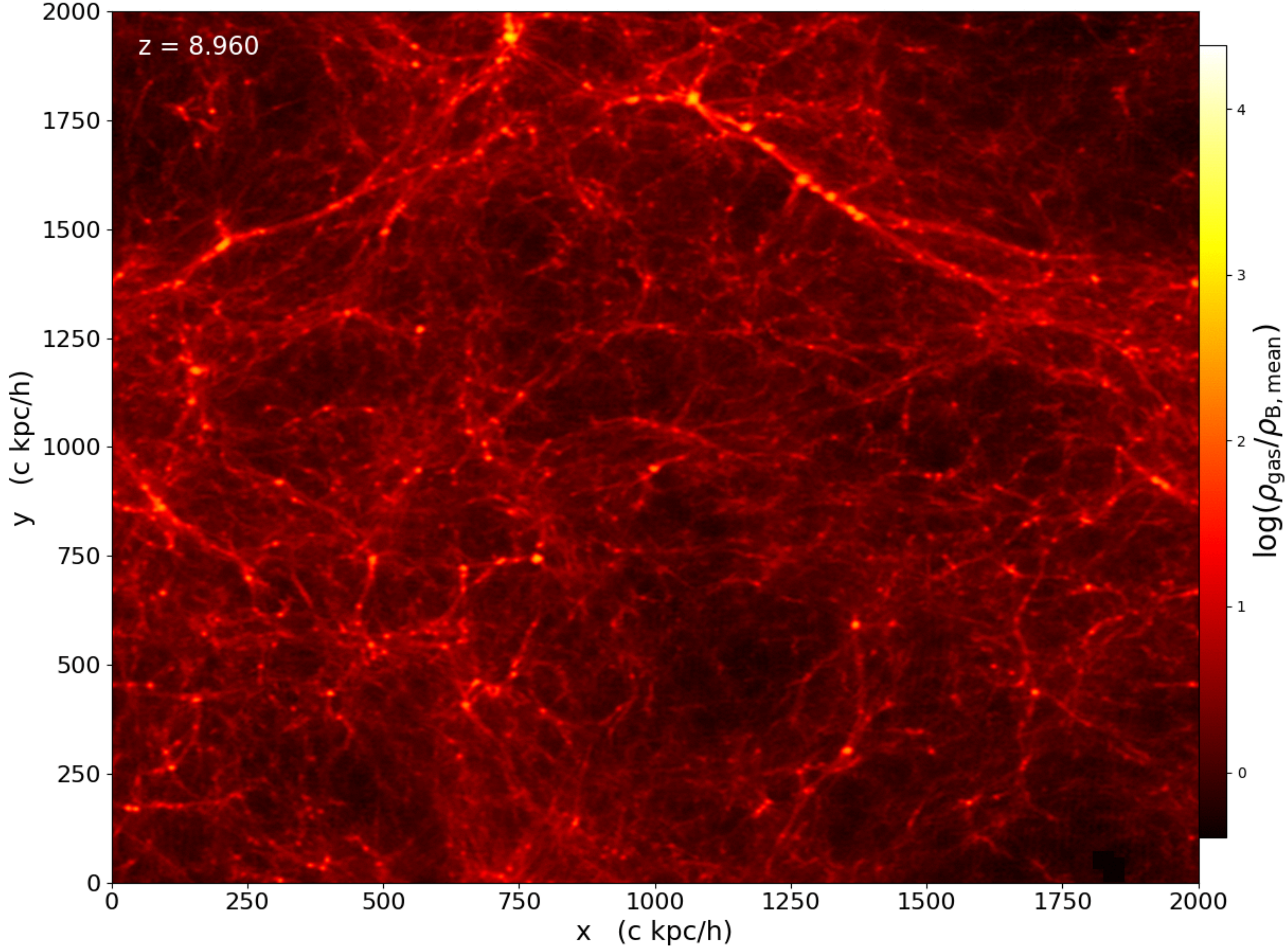
IC with MUSIC (Hahn&Abel+11)

- Run small (2 Mpc)^3 boxes with periodic boundary conditions
  - Starting from z=100
  - Up to z=4–2

(Barai & de Gouveia dal Pino 2019, MNRAS)

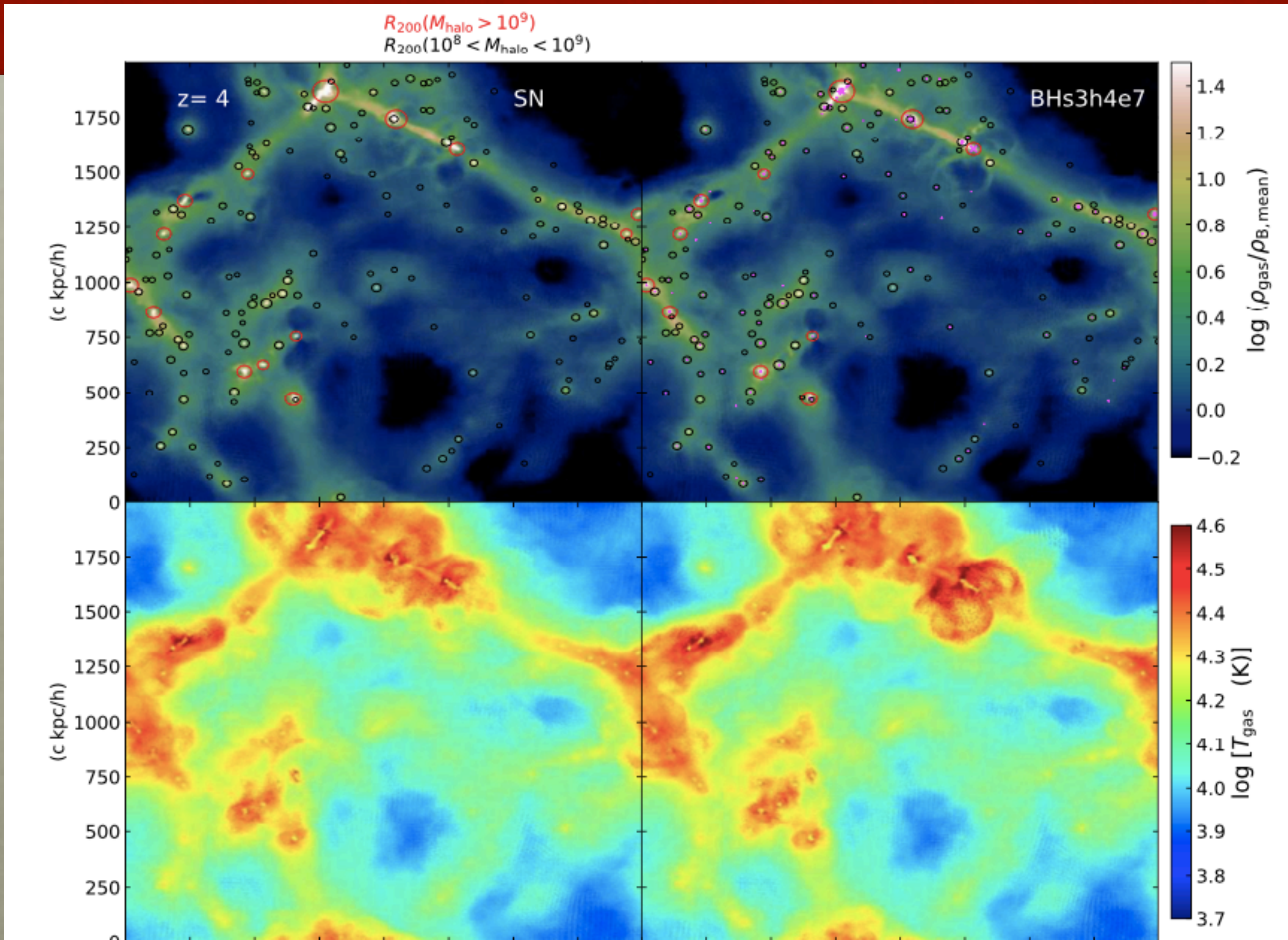
Run name	BH present	Min. Halo Mass for BH Seeding, $M_{\rm HaloMin} [M_{\odot}]$	Seed BH Mass, $M_{\rm BHseed} [M_{\odot}]$	BH kinetic feedback kick velocity v_w (km/s)
SN	No	–	–	–
BHs2h1e6	Yes	1×10^6	10^2	2000
BHs2h7e7	Yes	5×10^7	10^2	2000
BHs3h1e7	Yes	1×10^7	10^3	2000
BHs3h2e7	Yes	2×10^7	10^3	2000
BHs3h3e7	Yes	3×10^7	10^3	2000
BHs3h4e7	Yes	4×10^7	10^3	2000
BHs3h4e7v5	Yes	4×10^7	10^3	5000
BHs3h5e7	Yes	5×10^7	10^3	2000
BHs4h4e7	Yes	4×10^7	10^4	2000

Gas Density Evolution Movie

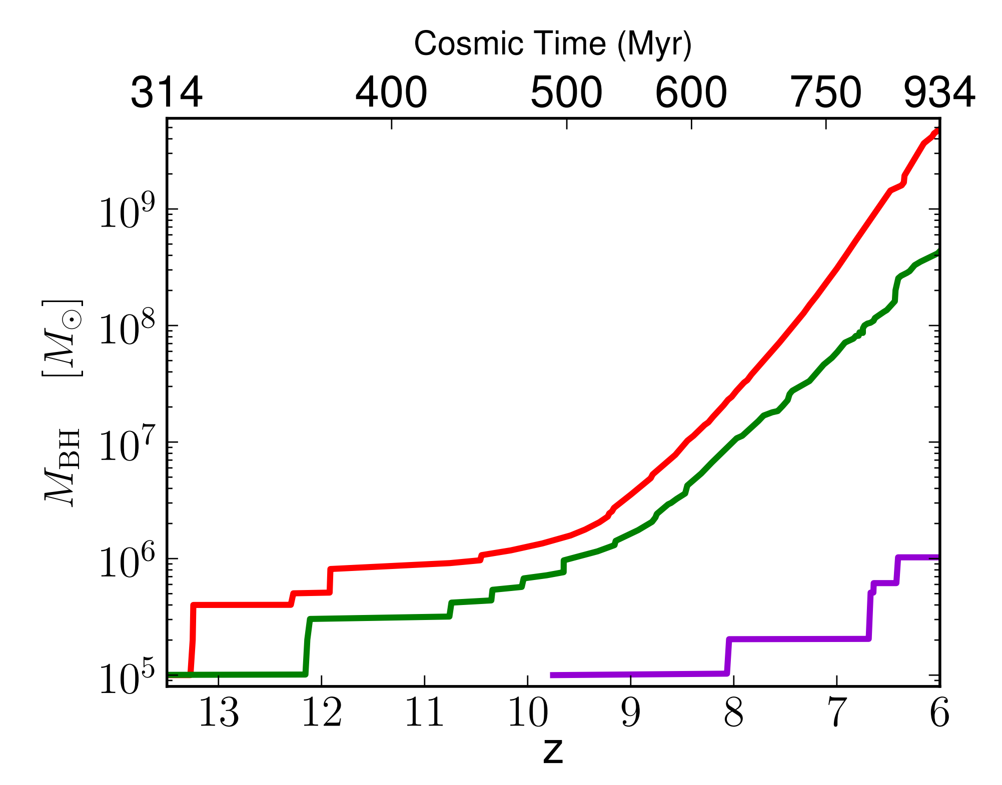


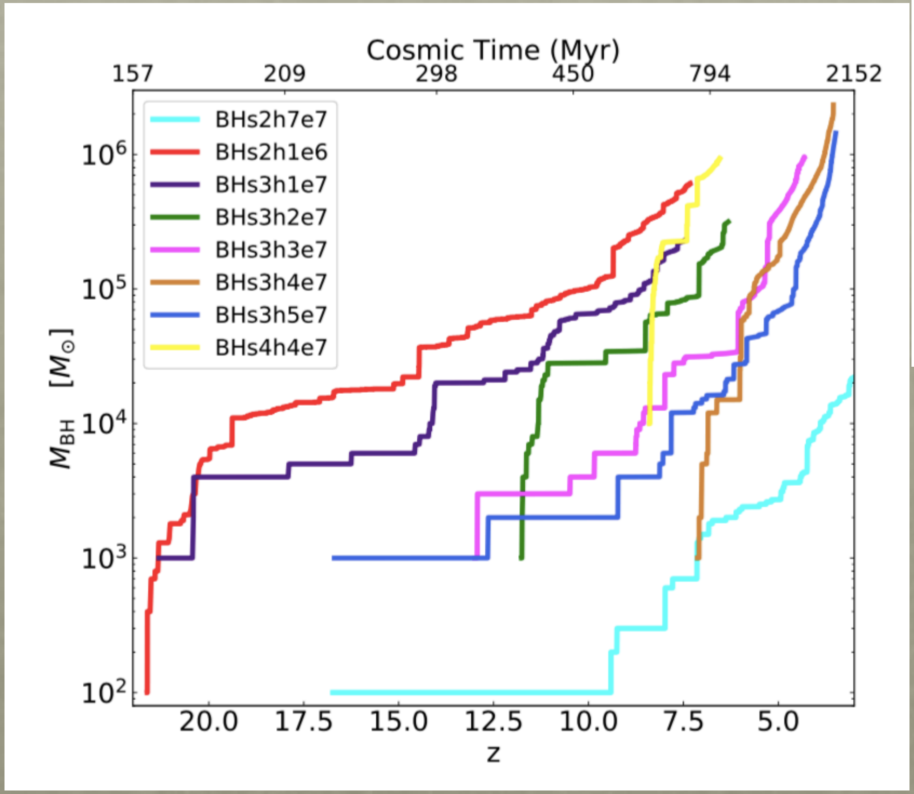
Gas Density & Temperature in 2 runs at z=4. *(Red and black circles denote the virial radius R_{200} of galaxy halos. Magenta symbols indicate BHs, symbol size proportional to BH mass.)*

IMBH feedback in DGs create only weak outflow signatures

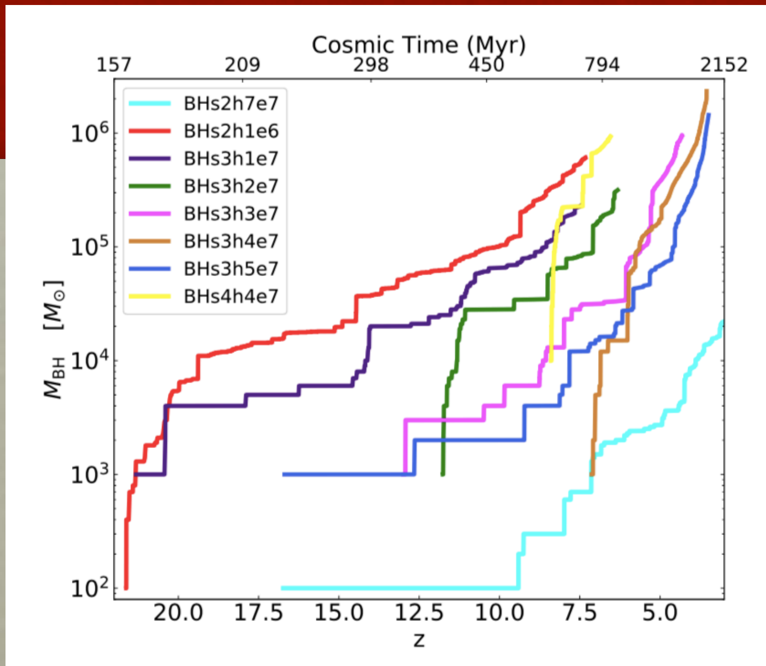


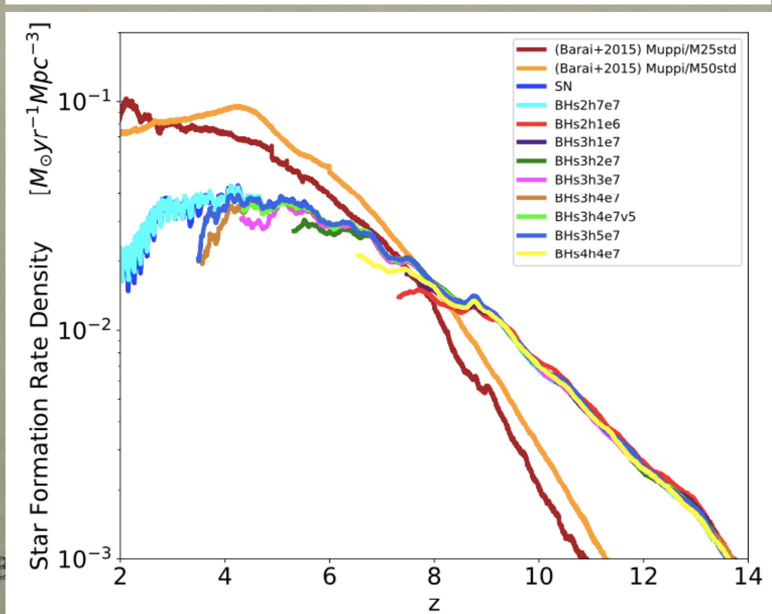
Growth of IMBHs & SMBHs at Galaxy Centers

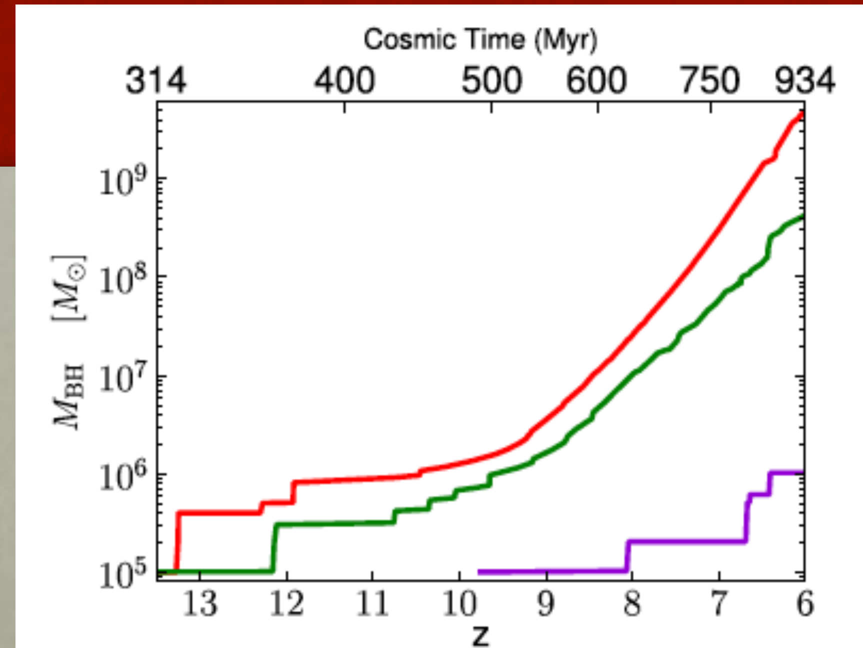


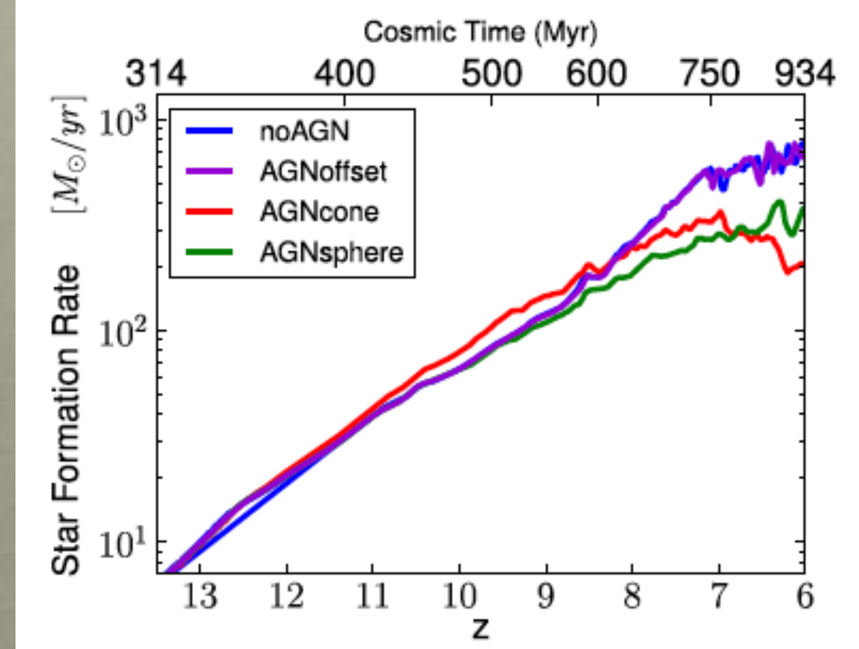


BH Growth Quenching Star Formation

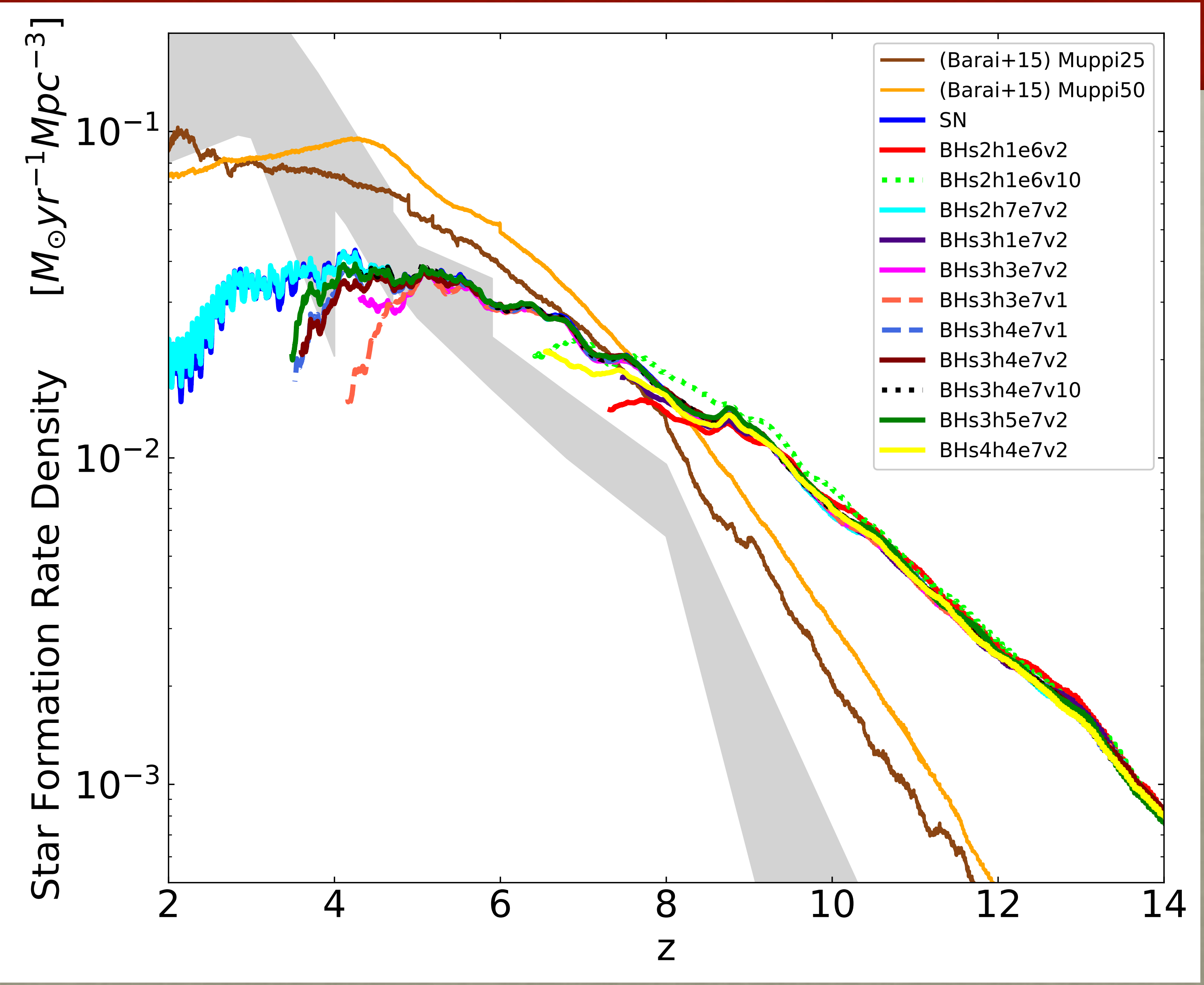








Star Formation Rate Density Evolution (IMBH sims)



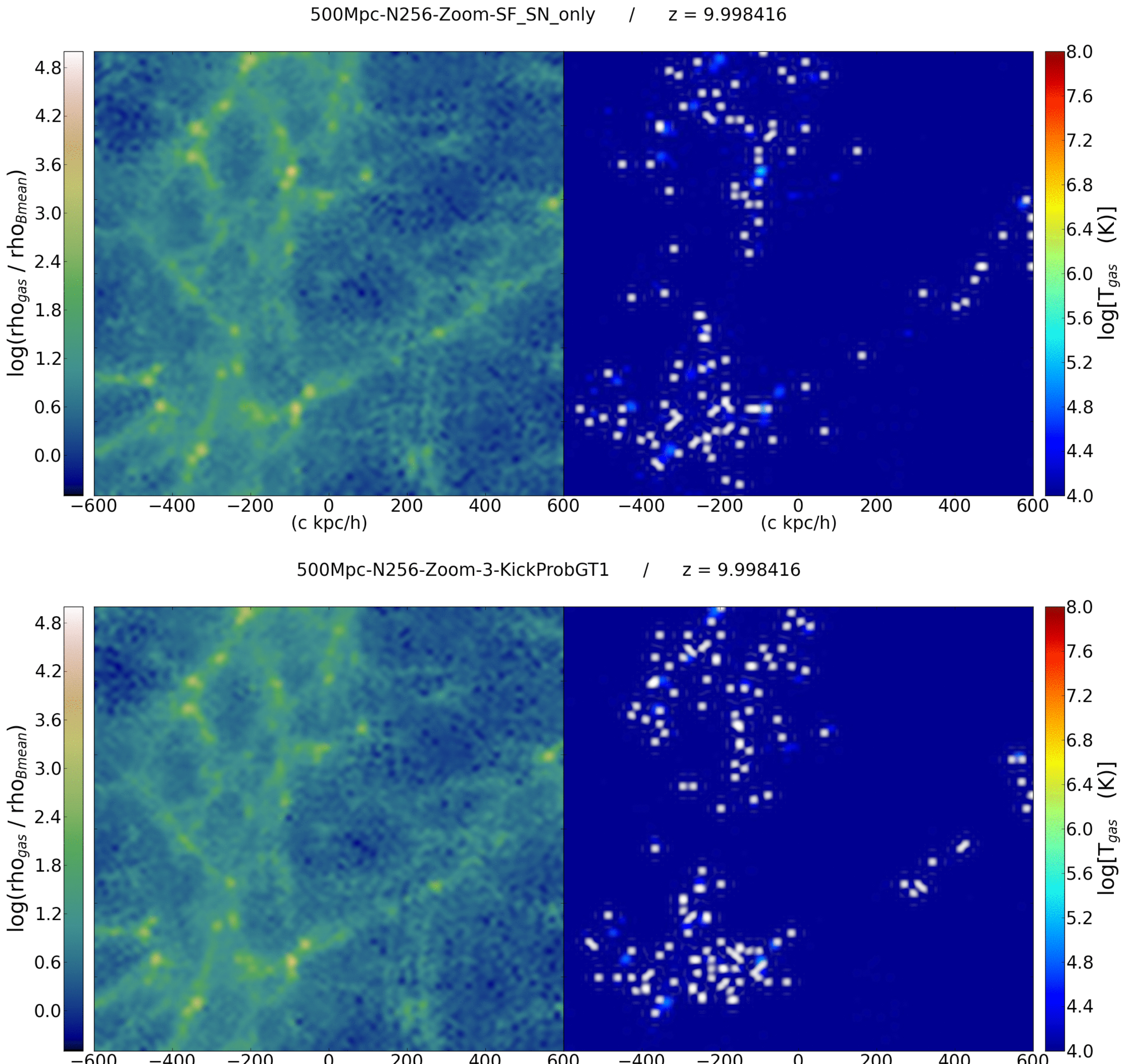
Impact on SFR

2D maps of Gas Density & Temperature

SF & SN-feedback only run

vs.

AGN run



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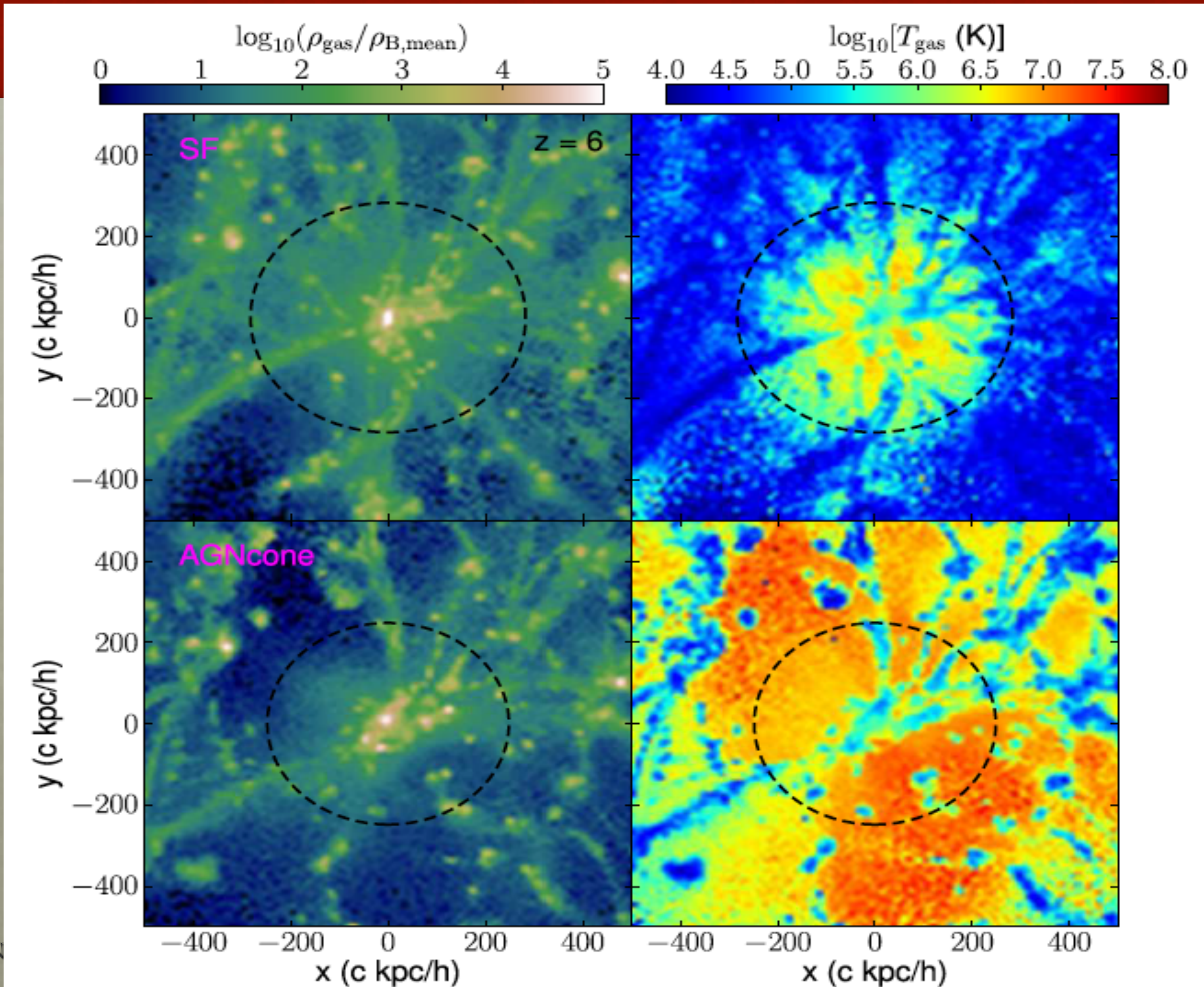
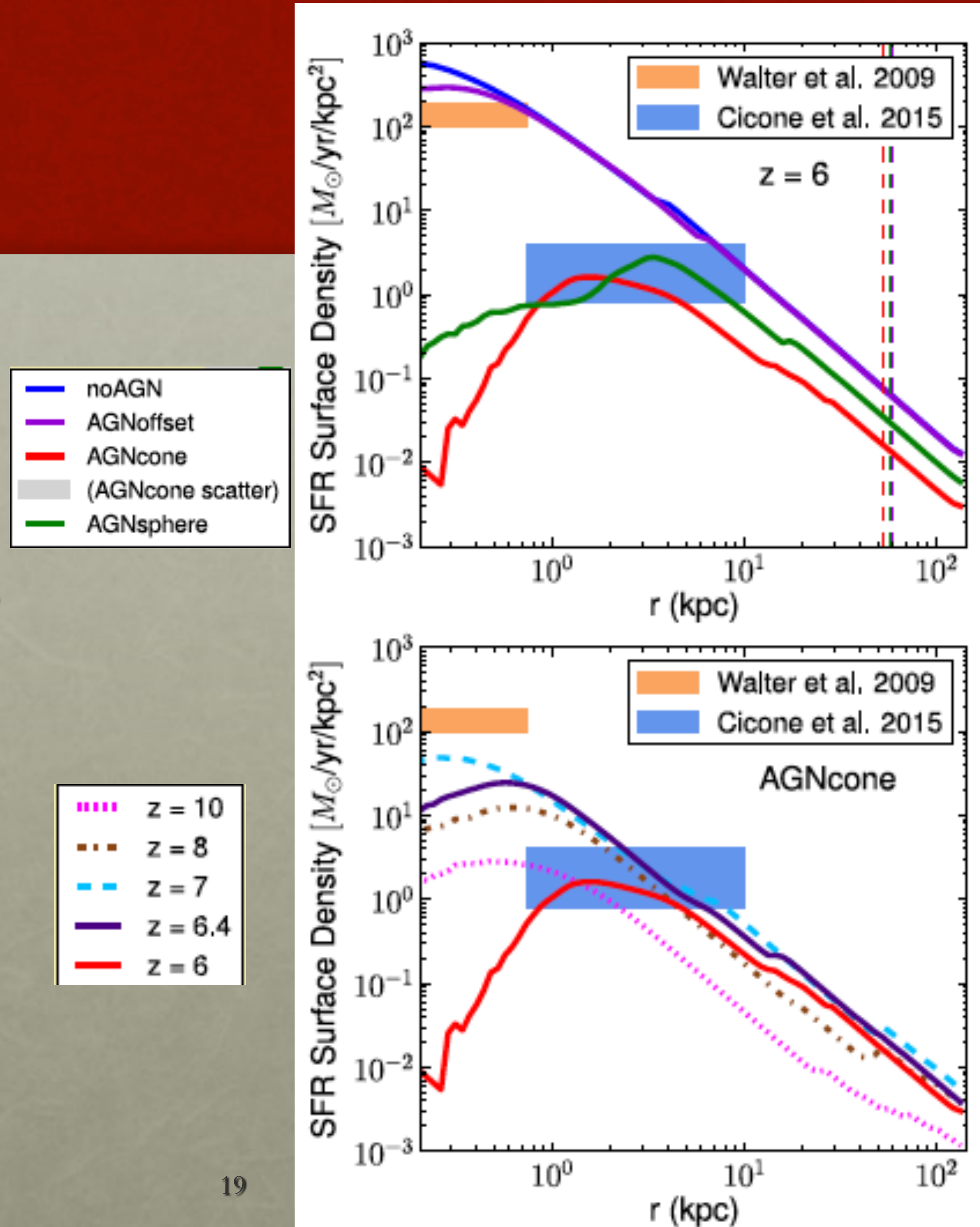
2D maps of gas density & temperature at z=6: SMBH feedback in Quasar creates strong outflow



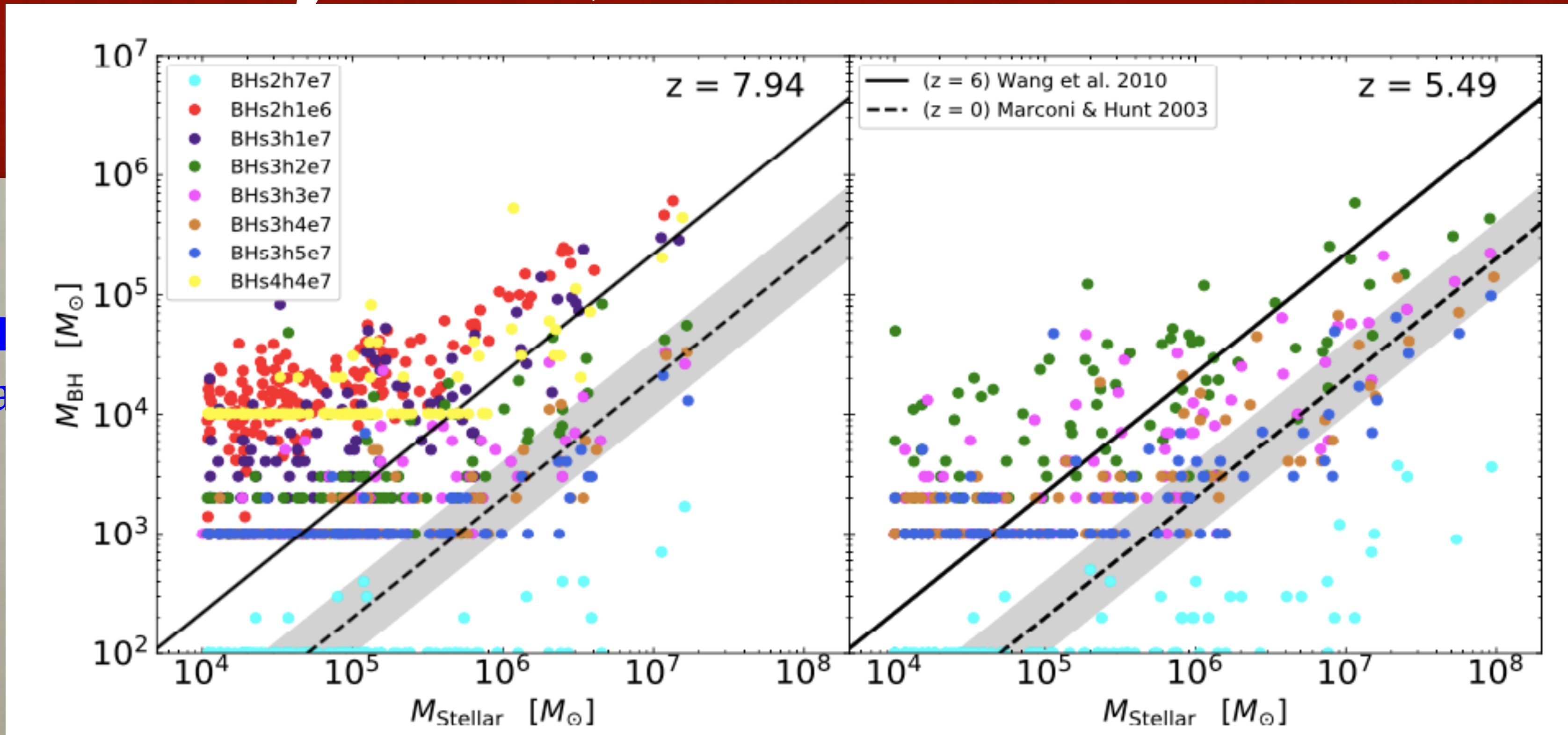
Radial Profiles of SFR Surface Density

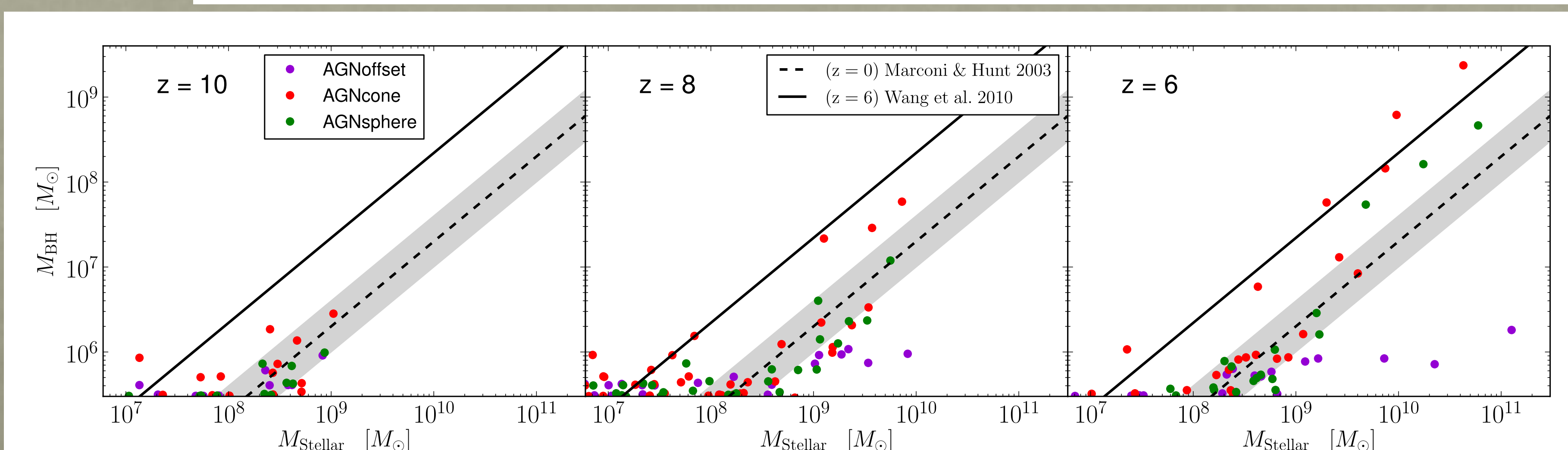


(BH – Galaxy Stellar) Mass Correlation

Central I

Solid a





Conclusions

(Barai et al. 2018, MNRAS)

- 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 over z=9-6 (for 100s Myr)
- Massive BHs generate powerful outflows
  - Outflow mass is increased (& inflow is reduced) by 20%

(Barai & de Gouveia dal Pino 2019, MNRAS)

❖ Starting as 10^3 $M_\odot$ seeds at the centers of Dwarf Galaxies, BHs can grow to 10^6 $M_\odot$ by z=6 in a cosmological environment

✓ Maximum Eddington accretion ratio = 0.9

❖ Star formation is quenched when central BHs have grown to few x 10^5 $M_\odot$

❖ ➔ IMBHs at the centers of DGs can be a strong source of feedback

❖ ➔ these DGs are turned passive already at high-z, with dormant BHs at their centers