Intermediate-Mass Black Holes in Dwarf Galaxies

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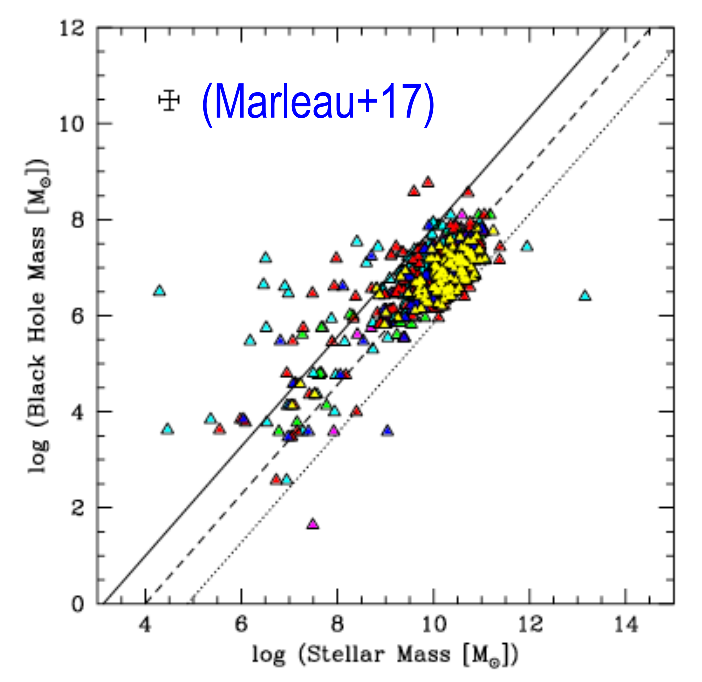
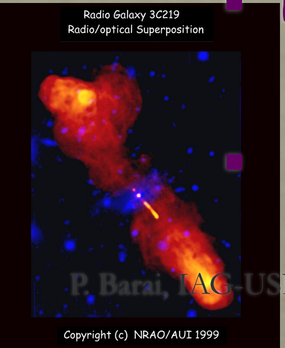
- **SNe-driven galactic outflows**
  - **Barai et al. (2013, 2015)**
- **AGN feedback ([M_{BH} - σ_*] relation, cool-core galaxy cluster)**
  - **Barai et al. (2014, 2016)**
- **Quasar outflows at high-z**
  - **Barai et al. (2017, submitted)**

Black Holes and Feedback

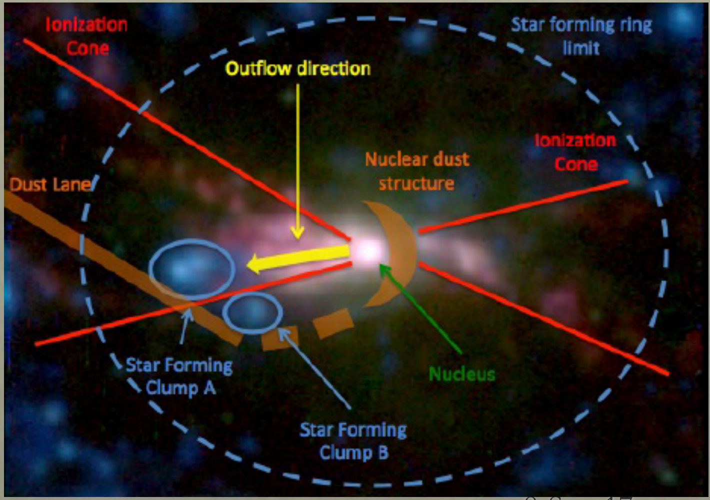
- Black holes are mostly observed to be
  - Stellar-mass (< 100 $M_\odot$), or
  - Supermassive (> 10^6 $M_\odot$)
- Naturally, there should be a population of Intermediate-Mass Black Holes (IMBHs: 100 - 10^6 $M_\odot$)
  - Started to be observed recently



- AGN Feedback
  - Energy from central BHs affect host galaxies
    - Negative feedback: Quench star-formation
    - Positive feedback: SF induced



AGN Outflows



(Cresci+15)

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(Silk 2017)

CrossMark

Feedback by Massive Black Holes in Gas-rich Dwarf Galaxies

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Abstract

Could there be intermediate-mass black holes in essentially all old dwarf galaxies? I argue that current observations of active galactic nuclei in dwarfs allow such a radical hypothesis that provides early feedback during the epoch of galaxy formation and potentially provides a unifying explanation for many, if not all, of the dwarf galaxy anomalies, such as the abundance, core-cusp, "too-big-to-fail," ultra-faint, and baryon-fraction issues. I describe the supporting arguments, which are largely circumstantial, and discuss a number of tests. There is no strong motivation for modifying the nature of cold dark matter in order to explain any of the dwarf galaxy "problems."

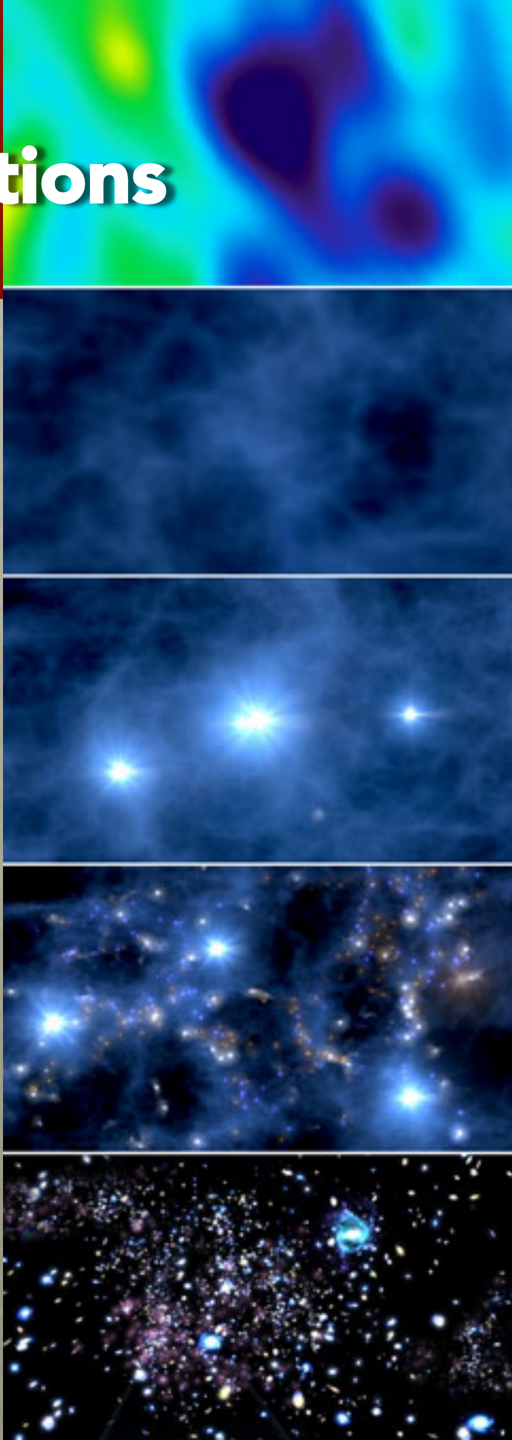
Key words: galaxies: active – galaxies: dwarf – galaxies: formation

- IMBHs present in essentially all old Dwarf Galaxies (DGs)
- Early feedback by IMBHs can output energy, and affect the host gas-rich dwarf galaxies at $z = 5 - 8$
  - ✓ Quench star-formation
  - ✓ Reduce the number of DGs
  - ✓ Can potentially solve multiple dwarf galaxy problems (e.g. core-cusp, number) within the ΛCDM cosmology

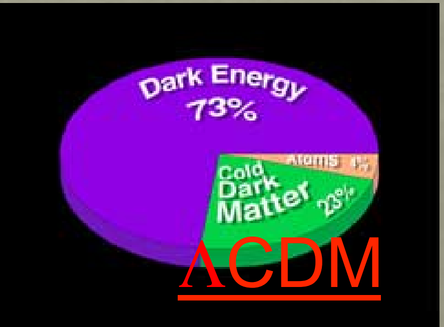
Our Study

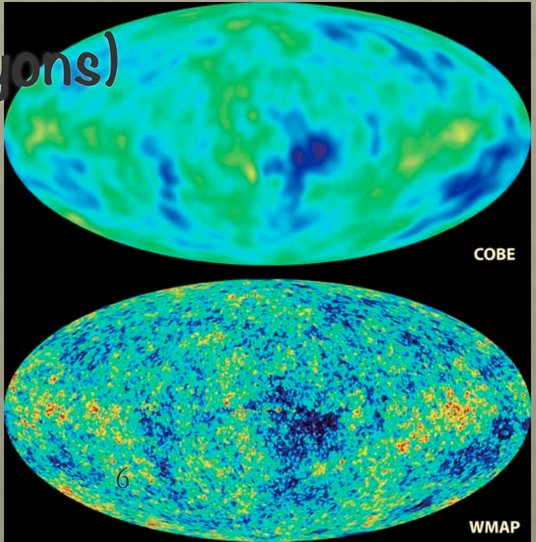
- ✓ Perform Cosmological Hydrodynamical Simulations by including IMBHs at the centers of Dwarf Galaxies
  - ✓ Test if IMBHs would grow at DG centers
  - ✓ Quantify the impact of IMBHs on DGs; esp. the effects on star formation at cosmic epochs $z=4-2$

The Universe in a Box: Cosmological Hydrodynamical Simulations



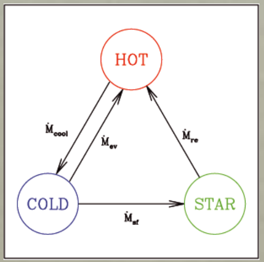
- Computational box ⇔ representative volume of Universe
- Resolution elements (e.g. particles) in box ⇔ matter
- Initial condition
  - CMBR: 3×10^5 yrs after Big Bang
  - Primordial density fluctuations – Gaussian
- Follow the non-linear evolution of matter
  - Gravity (dark matter + Baryons)
  - Hydrodynamics (Baryons)





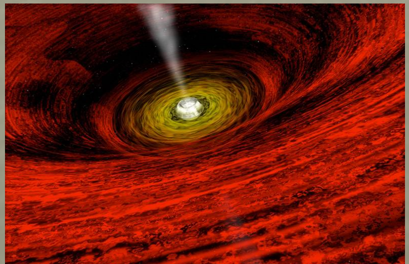
Modified-GADGET3 code: Sub-Resolution Physics

- 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)



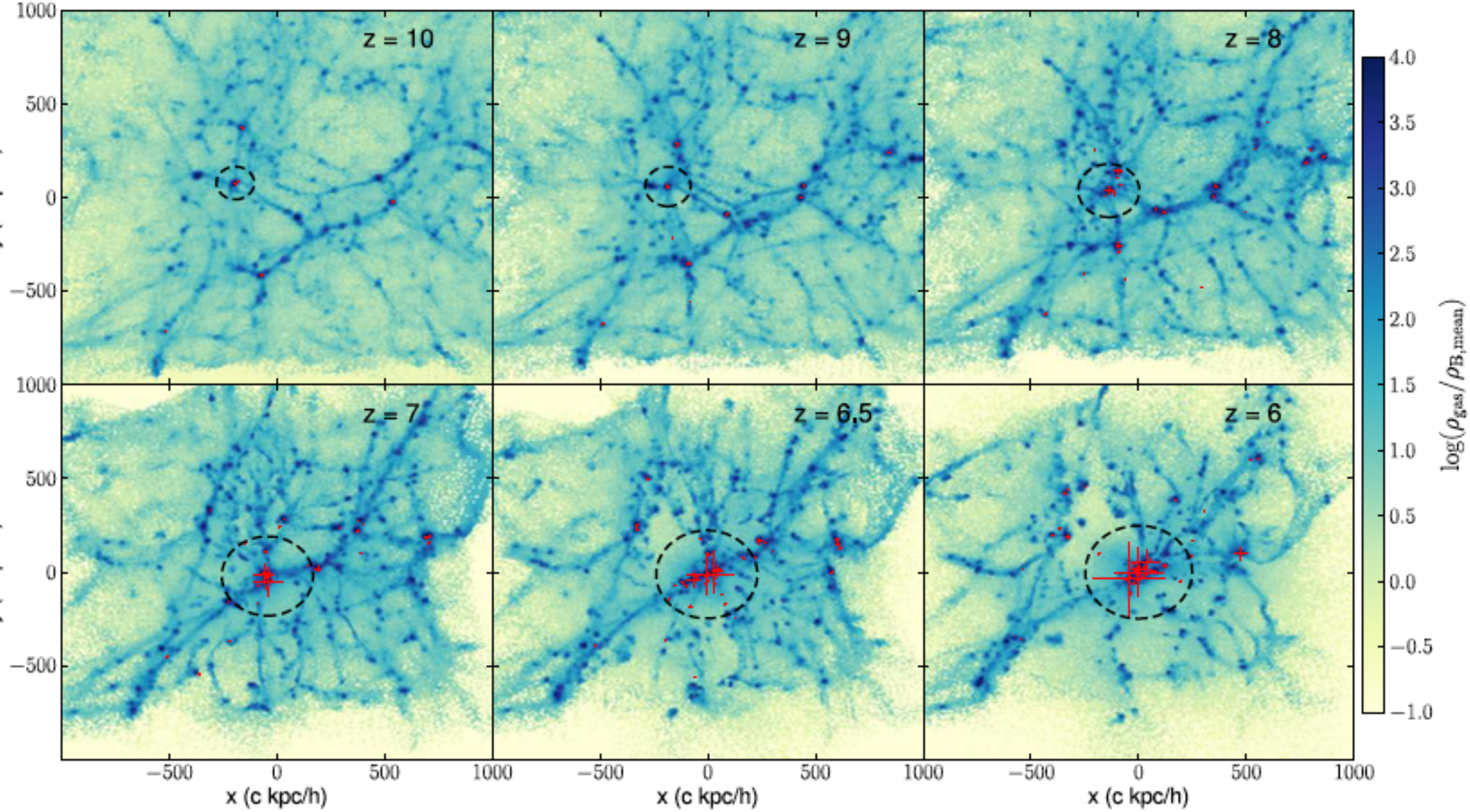
- Stellar & Chemical Evolution (Tornatore+07)
  - Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) from SN type-II, type-Ia, & AGB stars
- SN Feedback (Tornatore+07, Tescari+09, Barai+13)
  - Kinetic feedback (↑ v)

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



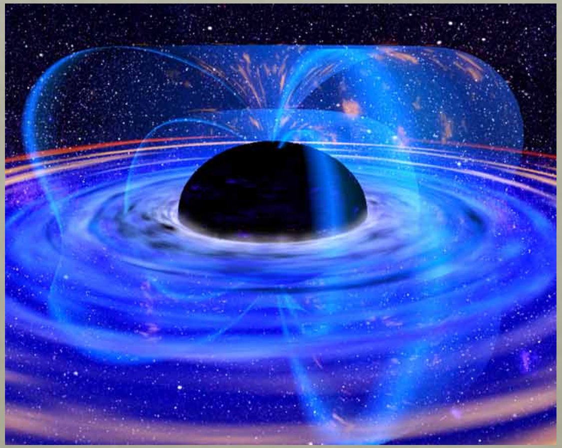
Formation of Structures between z=10 and z=6. Gas Overdensity in (2 Mpc)^3 Region

(Barai et al. 2017, submitted)



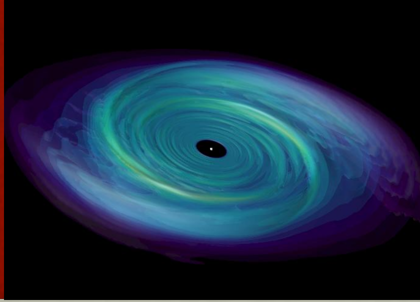
Modeling AGN Feedback in Galaxy Formation Simulations: the sub-resolution physics

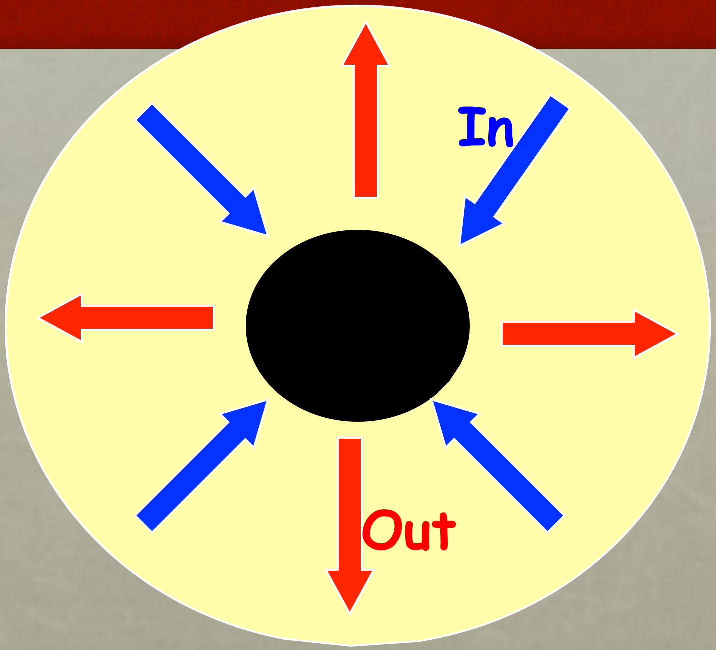
- Generation of seed BH ($10^2 - 10^3\ M_\odot$) at:
  - Center of galaxy ($M_{halo} > 10^6 - 10^7\ M_\odot$)
  - Minimum gravitational potential



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

Accretion & Energy Feedback





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

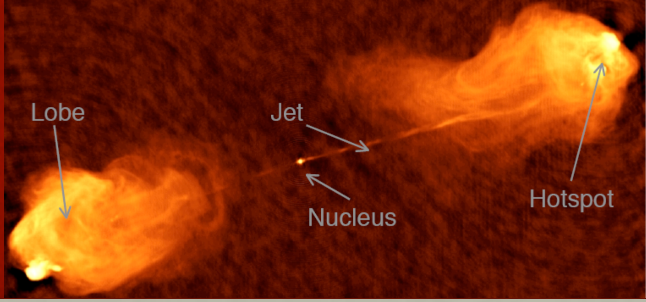
$$\dot{M}_{\rm BH} = \min\left(\dot{M}_{\rm Bondi}, \dot{M}_{\rm Edd}\right).$$

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

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

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

Kinetic Feedback from AGN
(Barai+16)



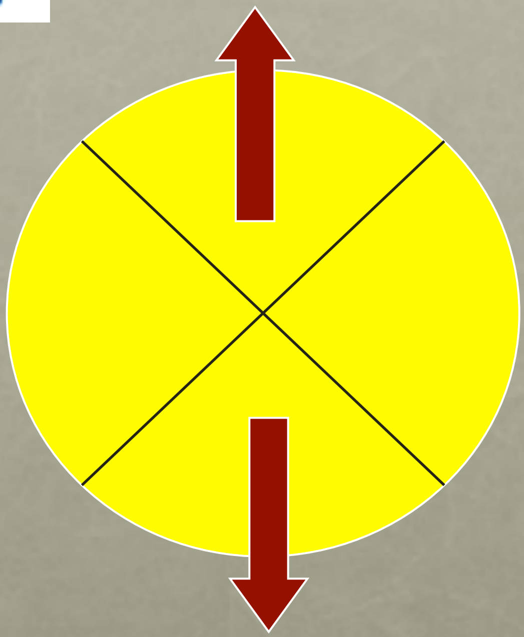
- Energy-driven wind $\frac{1}{2}\dot{M}_w v_w^2 = \dot{E}_{\rm feed}$

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

- 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

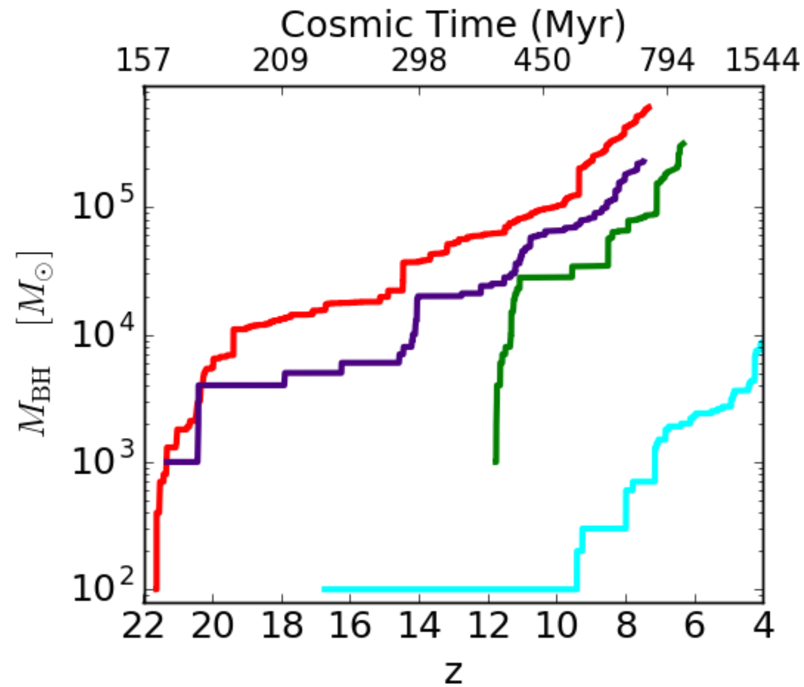
$$\vec{v}_{\rm new} = \vec{v}_{\rm old} + v_w \hat{n}$$

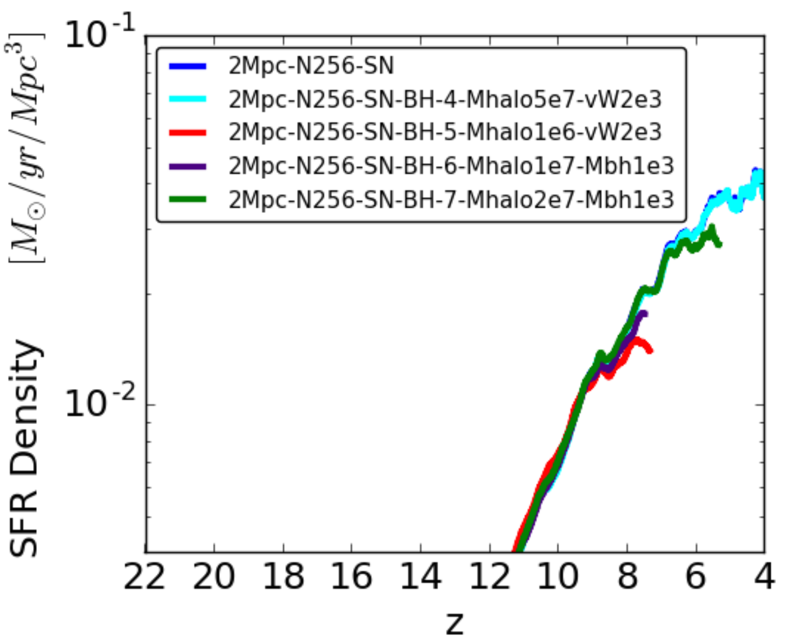
Cosmological Hydrodynamical Simulation

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

Run name	BH present	Min. Halo Mass for BH Seeding $[M_\odot]$	Seed BH Mass $[M_\odot]$	BH kinetic feedback kick velocity v_w (km/s)
noBH	No	–	–	–
BH4	Yes	$5h^{-1} \times 10^7$	10^2	2000
BH5	Yes	$h^{-1} \times 10^6$	10^2	2000
BH6	Yes	1×10^7	10^3	2000
BH7	Yes	2×10^7	10^3	2000
BH8	Yes	3×10^7	10^3	2000

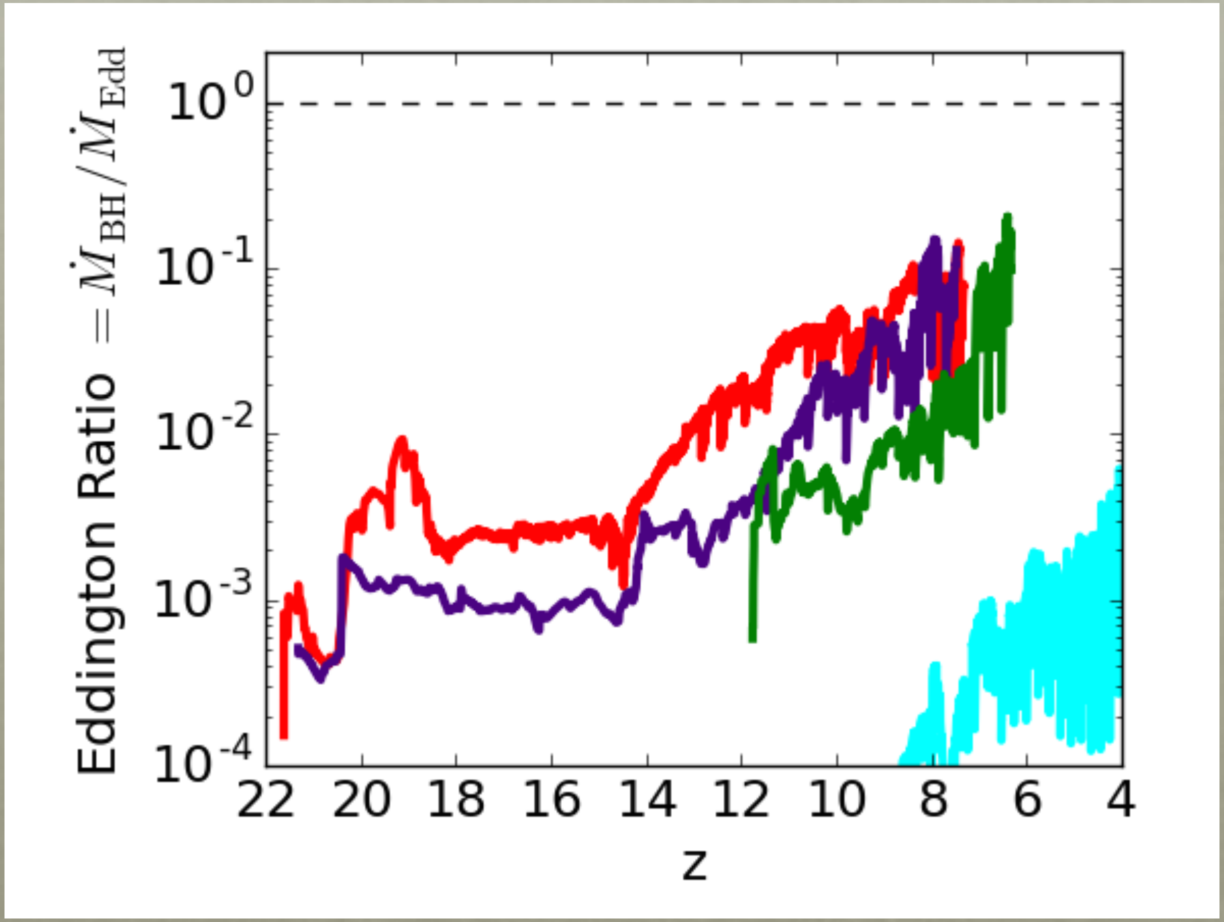


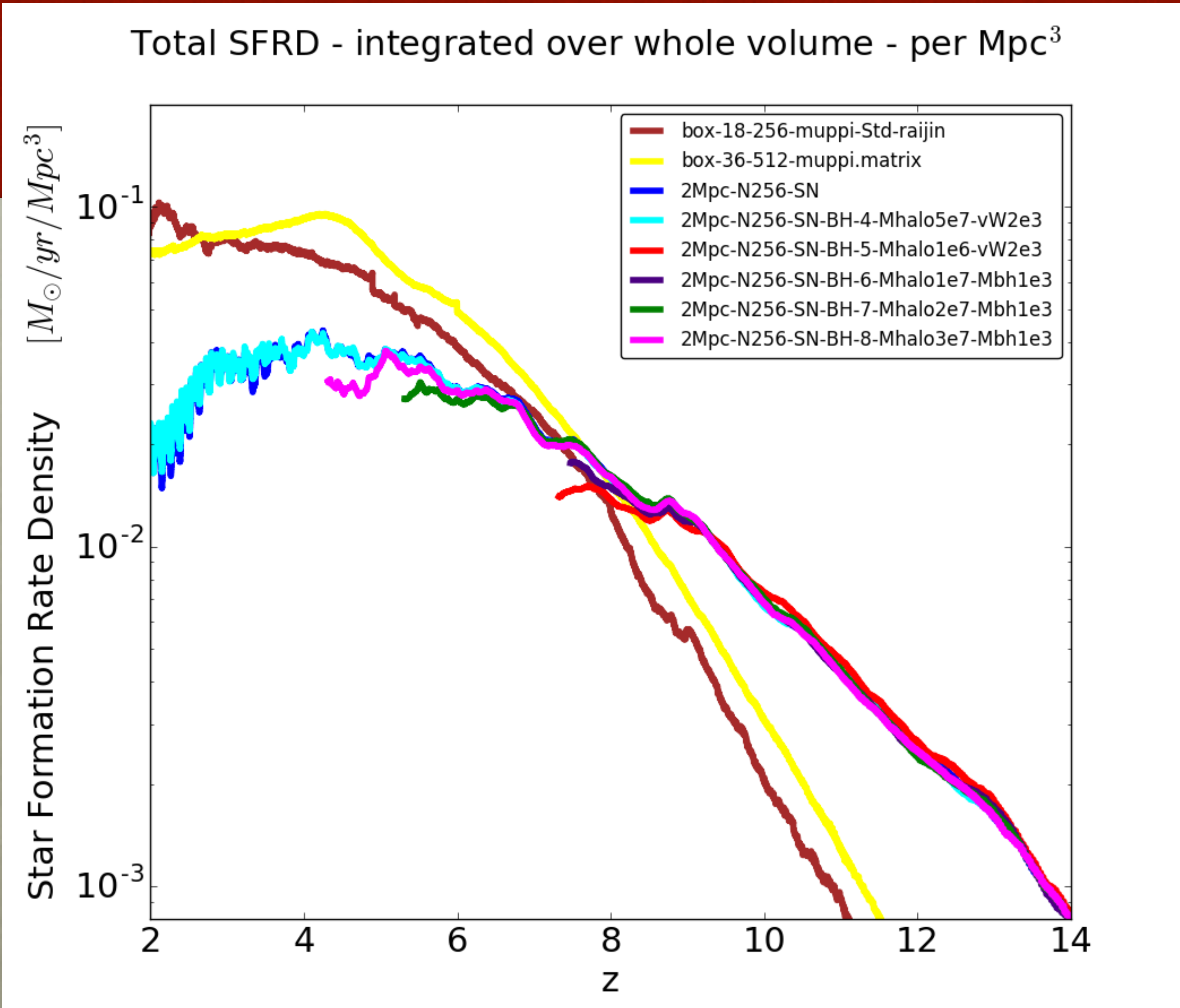


Intermediate-Mass Black Hole Growth at DG center

Impact on Star-Formation-Rate

BH Accretion Eddington Ratio

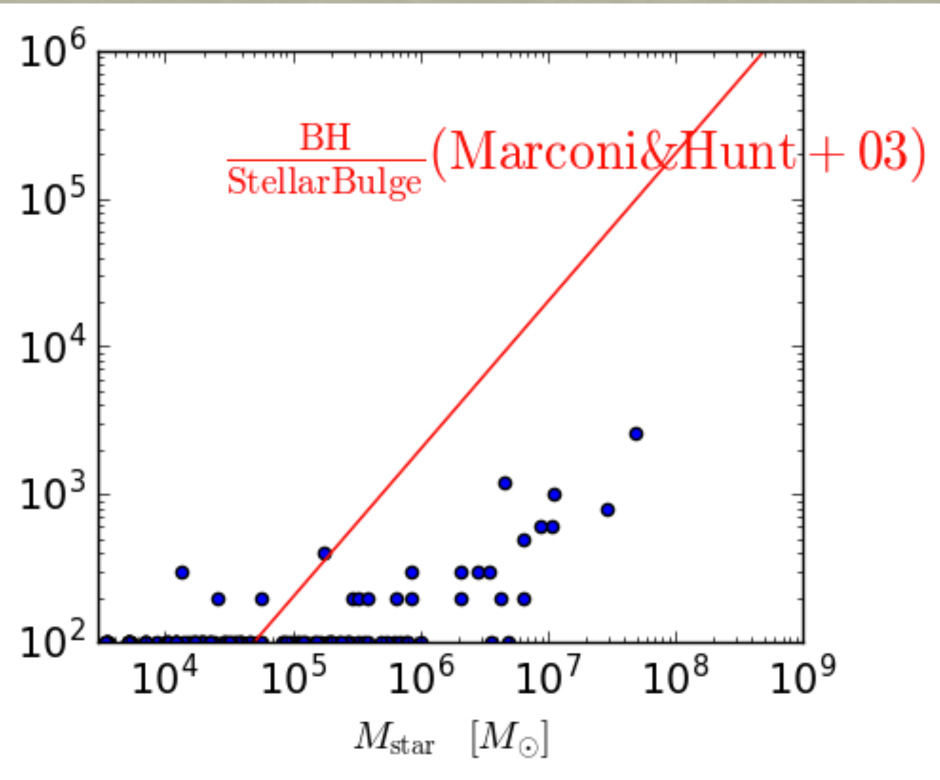


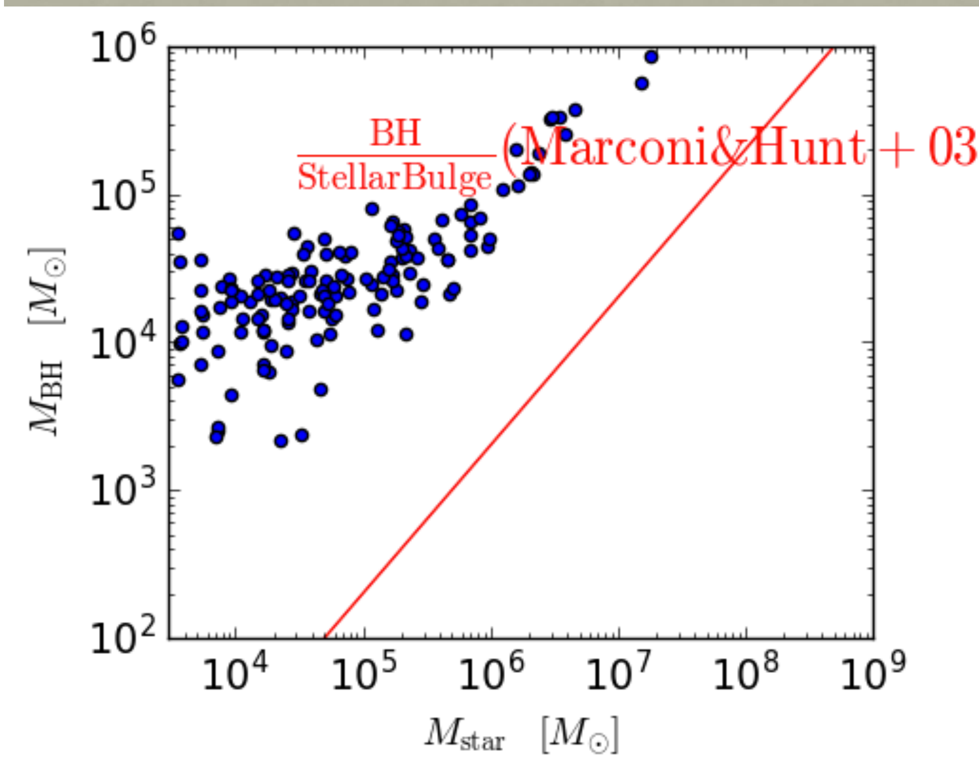


Star Formation Rate Density Evolution

(BH – Galaxy Stellar) Mass Correlation

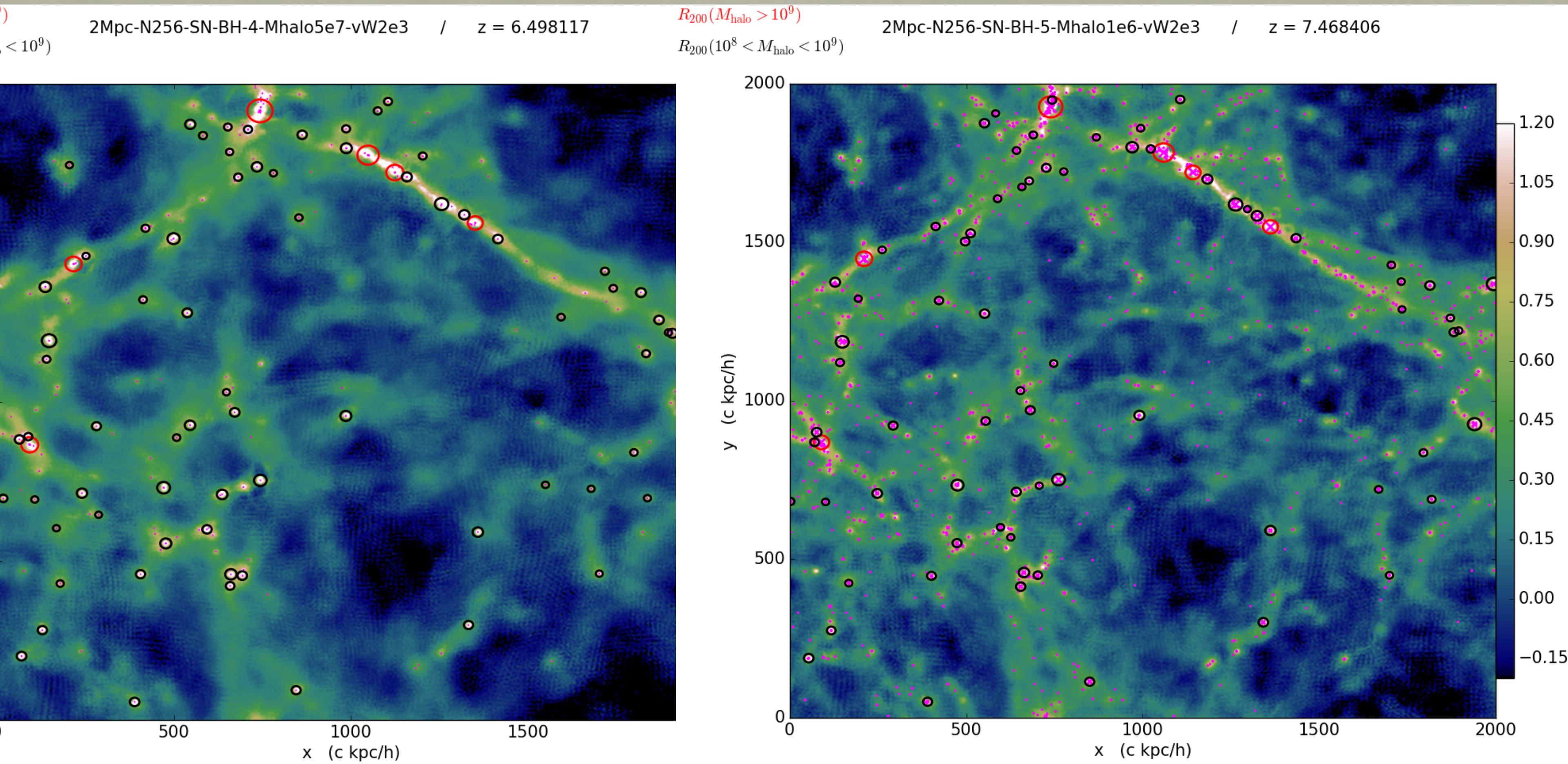
Central BH mass versus stellar mass of all galaxies in two simulation volumes at high-*z*. Red line shows the observed correlation of local galaxies (*z=0*).





Gas Density

Projected gas density in 2 runs at high-*z*. Red and black circles denote the virial radius R_{200} of galaxy halos. Magenta symbols indicate BHs, symbol size proportional to BH mass.



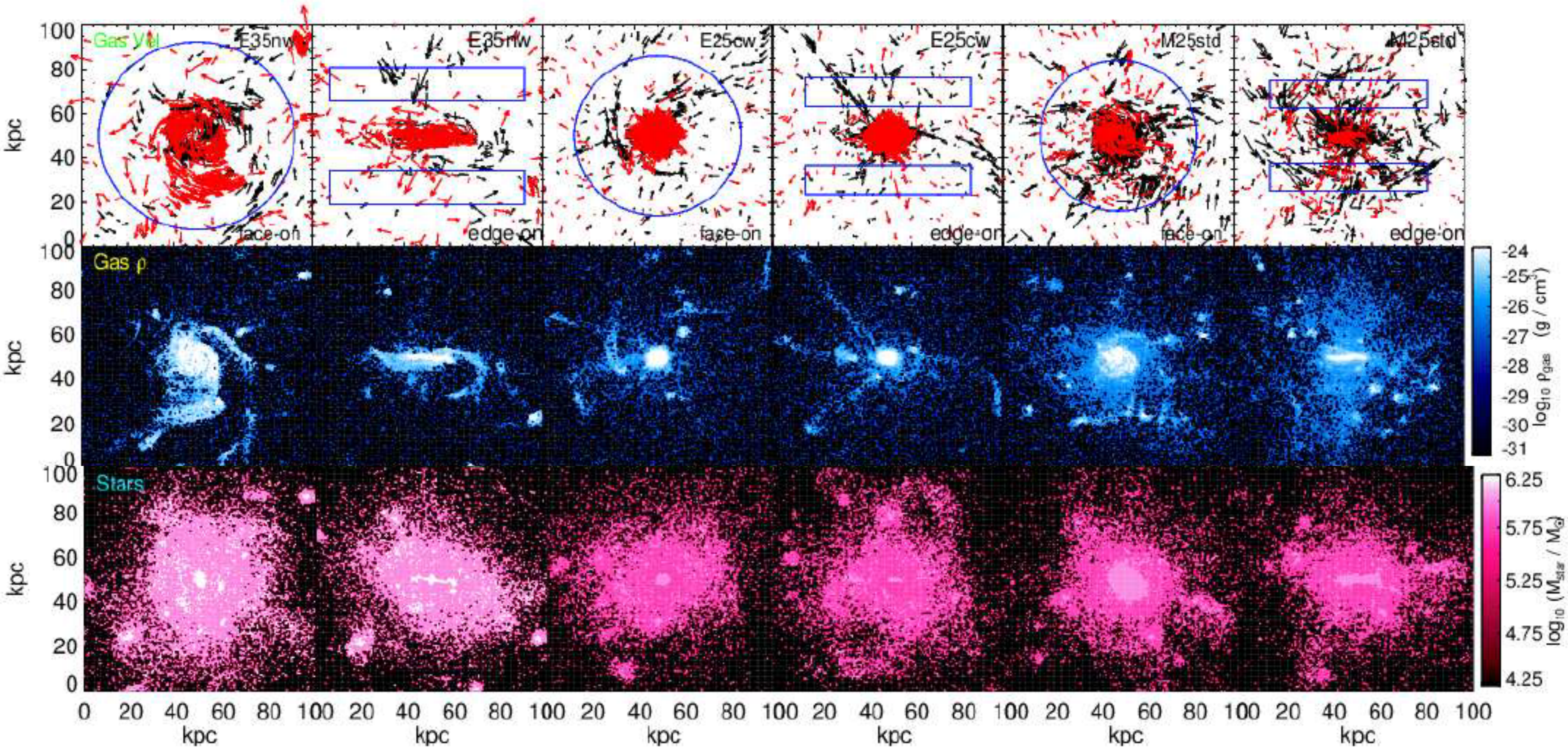
Conclusions

- Starting as $10^2 – 10^3$ $M_{\odot}$ seeds at the centers of Dwarf Galaxies, BHs can grow to 10^6 $M_{\odot}$ by z=6–4 in a cosmological environment
  - ✓ Maximum Eddington accretion ratio = 0.1
- Star formation is quenched, when BHs have grown to few x 10^4 $M_{\odot}$
- Future work: explore more parameter space, wind velocity, halo mass for BH seeding, seed BH mass

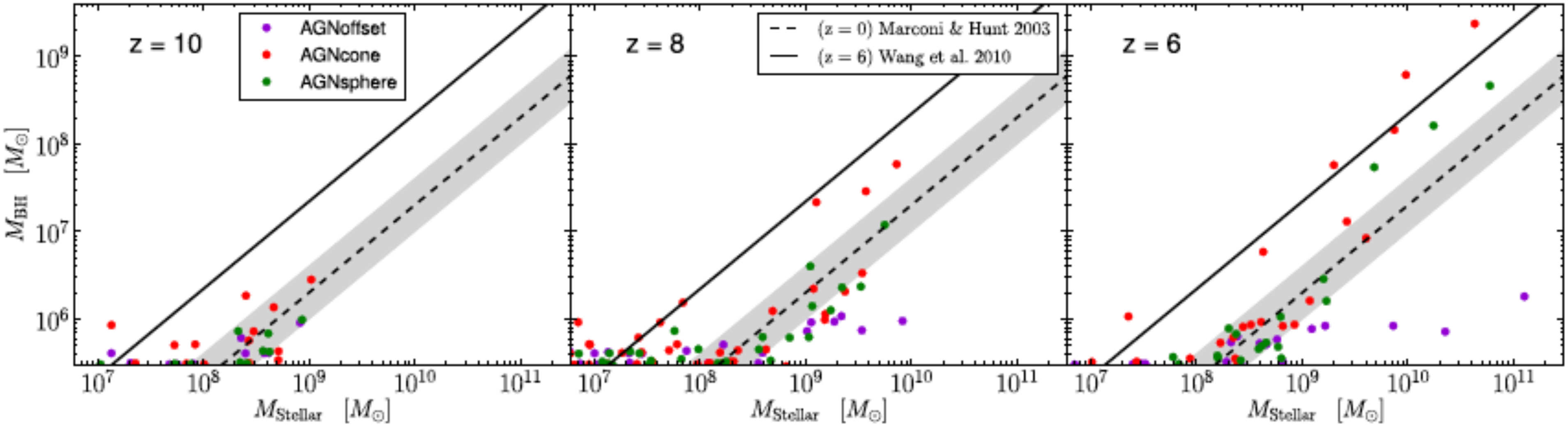
Extra Slides

Galaxies with Different Morphologies at z=2

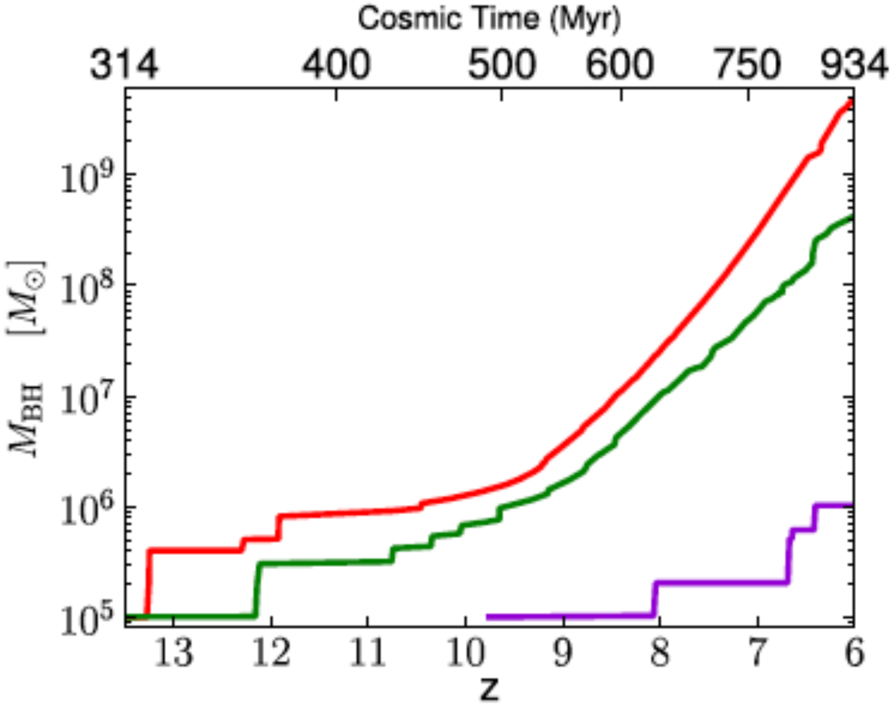
(Barai et al. 2015, MNRAS, 447, 266)

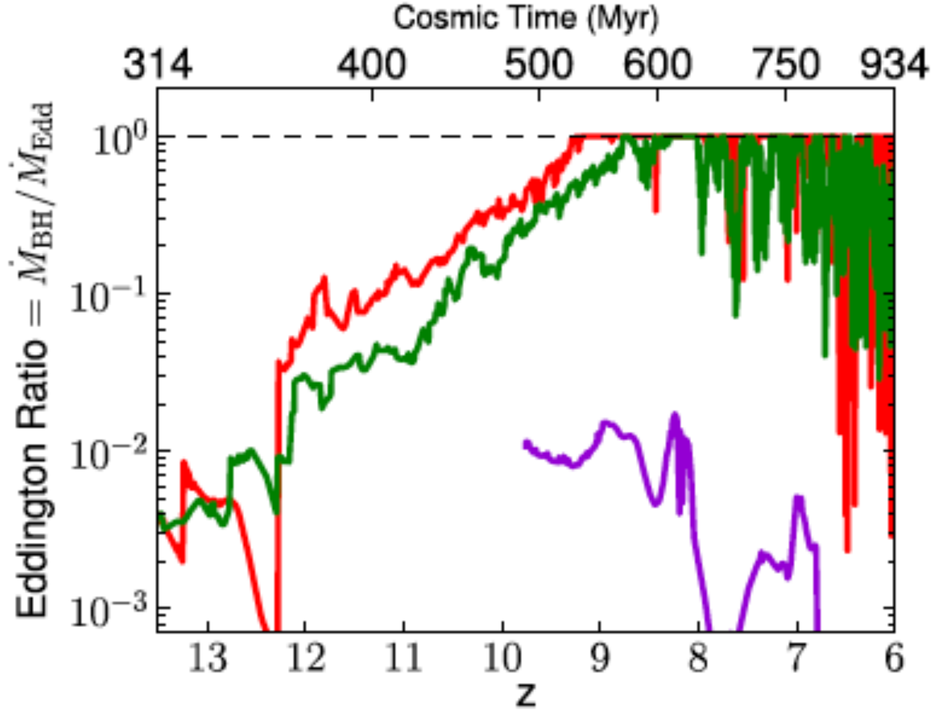


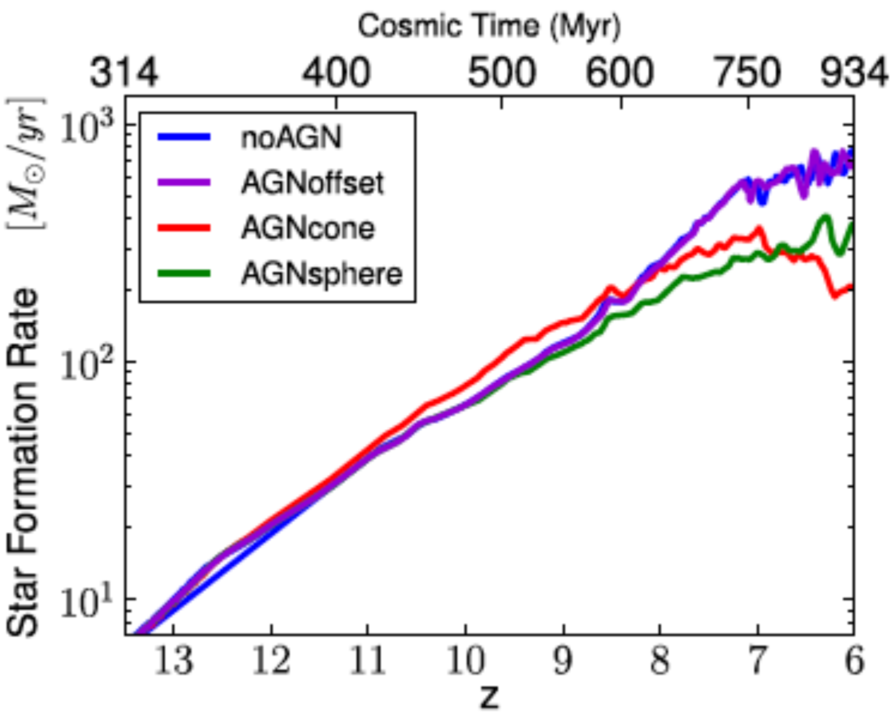
(BH – Galaxy Stellar) Mass correlation



- **Barai, P., Gallerani, S., Pallottini, A., Ferrara, A., Marconi, A., Cicone, C., Maiolino, R. & Carniani, S. 2017, submitted, arXiv:1707.03014**


Cosmic Time (Myr)
314
400
500
600
750
934
10^9
10^8
10^7
10^6
10^5
$M_{\rm BH}$ $[M_\odot]$
13
12
11
10
9
8
7
6
z


Cosmic Time (Myr)
314
400
500
600
750
934
10^0
10^{-1}
10^{-2}
10^{-3}
Eddington Ratio = $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$
13
12
11
10
9
8
7
6
z


Cosmic Time (Myr)
314
400
500
600
750
934
noAGN
AGNoffset
AGNcone
AGNsphere
10^3
10^2
10^1
Star Formation Rate $[M_\odot/yr]$
13
12
11
10
9
8
7
6
z