Equal- and unequal-mass mergers of disk and elliptical galaxies with black holes

Peter Johansson
University Observatory Munich

Physics of Galactic Nuclei workshop June 15th-19th 2009
Ringberg, June 18th, 2009

Johansson, Naab, Burkert, 2009, ApJ, 690, 802

The role of AGN feedback

- 1) Observed relic supermassive black holes - quasars.
- 2) Observed ULIRGs, merging galaxies with intense starburst and/or AGN activity.
- 3) The observed M_{BH}-σ & M_{BH}-M_{BULGE} relations. The coeval growth of black holes and galaxy bulges.
- Simplified feedback energetics: SN/AGN- energy coupling/ location:
- Supernova II feedback

$$\mathrm{Salpeter\ IMF} \Rightarrow 1\mathrm{SN}/125\mathrm{M}_\odot \text{ of } 10^{51}\mathrm{ergs} \rightarrow \mathrm{E}_{\mathrm{SNII}} \sim 5 \cdot 10^{48}\mathrm{erg}/\mathrm{M}_\odot$$

$$\Rightarrow (\Delta E)_{\mathrm{FB,SNII}} \sim 2.8 \cdot 10^{-6} m_\star c^2$$

- AGN feedback

$$m_{BH}/m_\star = 10^{-3}, \quad \Delta E_{\mathrm{rad}}/m_{BH}c^2 = 10^{-1}, \quad \Delta E_{\mathrm{BH}}/\Delta E_{\mathrm{rad}} = 5 \cdot 10^{-2}$$

$$\Rightarrow (\Delta E)_{\mathrm{FB,AGN}} \sim 5 \cdot 10^{-6} m_\star c^2$$

LMU USM

BH feedback model: Accretion

- The Schwarzschild radius of a SMBH with M~10^7 M_{sun} is R_S~10^{-6} pc. Numerical Galaxy simulations at best resolve details down ~10 pc -> effective subresolution model.
- Use the Tree-SPH GADGET-2 code (Springel et al. 2005) with cooling +SF+SN feedback+BH feedback based on a Bondi-Hoyle accretion model (Bondi 1952):

$$r_B = \frac{GM_{\rm BH}}{c_\infty^2} = 50{\rm pc}\left(\frac{\rm M_{BH}}{10^7 {\rm M}_\odot}\right)\left(\frac{\rm c_\infty}{\rm 30km/s}\right)^{-2}$$

$$\dot{M}_B = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \qquad \alpha\sim 100$$

$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_r \sigma_T c}$$

$$\dot{M}_{\rm BH} = \min(\dot{\rm M}_{\rm Edd}, \dot{\rm M}_{\rm B})$$

BH feedback model: Energetics

- The radiative efficiency ε_r~0.1 (Sunyaev&Shakura 1973) and the thermal coupling ε_f~0.05 resulting in a total BH feedback energy efficiency of = 0.5%.

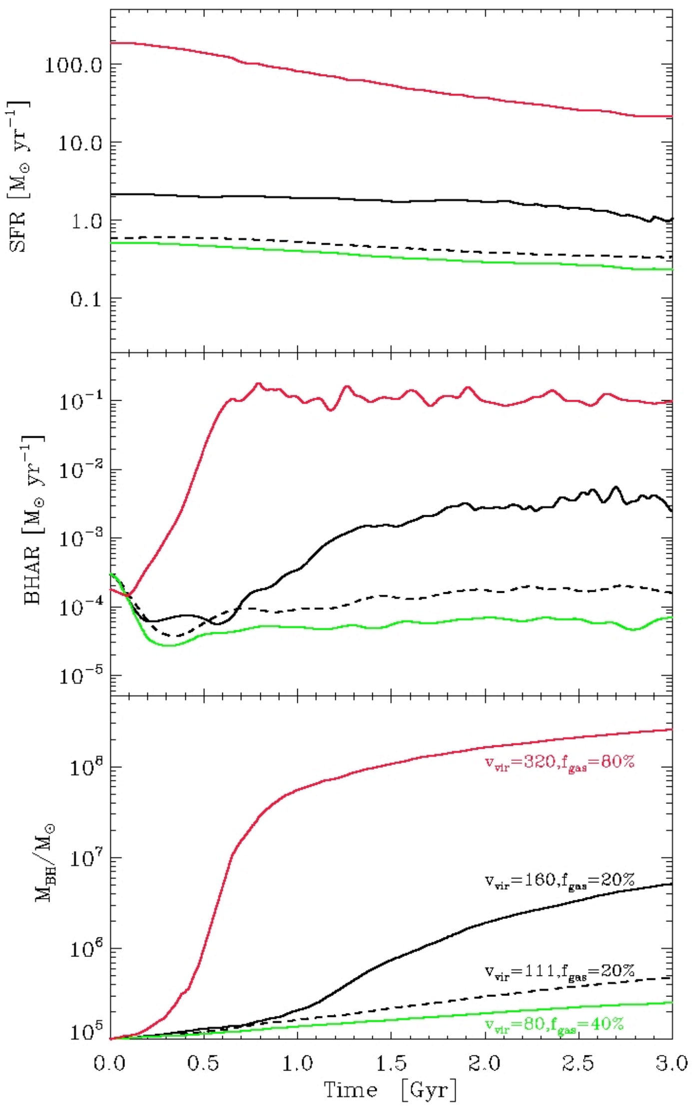
$$\epsilon_r = \frac{L_r}{\dot{M}_{\rm BH} c^2} = 0.1 \quad \dot{E}_{\rm feed} = \epsilon_f L_r = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2, \epsilon_f \sim 0.05$$

- The SPH kernel is used to calculate the average gas density, temperature as well as the gas bulk velocity relative to the BH.
- The BH mass grows stochastically by absorption of gas particles, include also smooth internal black hole mass, which is used to determine the accretion rate.
- BHs will merge instantly if they come within a smoothing length and if their relative velocity is smaller than the local soundspeed.
- Thermal FB energy distributed weighted within the SPH kernel.

Model setup and BHs in isolated galaxies

- Using the Springel (2000) method based on Hernquist (1993) we setup disk galaxies with Hernquist DM profiles+bulges& exponential discs with f_{gas}=20%, 40%, 80%.
- The BH is initially at rest in the centre of each model galaxy with a seed mass of 10^5 M_{sun}.
- We simulate a sample of isolated galaxies, 1:1 and 3:1 mergers, dry E-E and mixed E-Sp mergers.

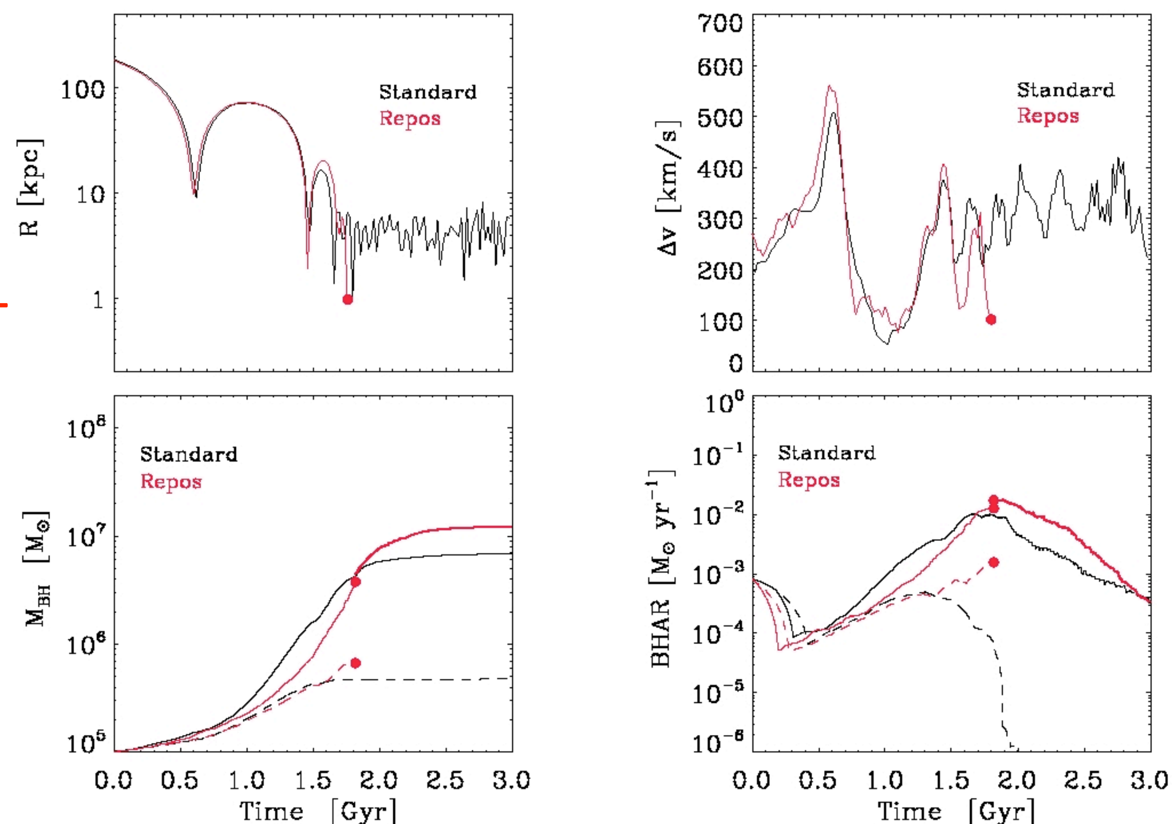
Isolated galaxies



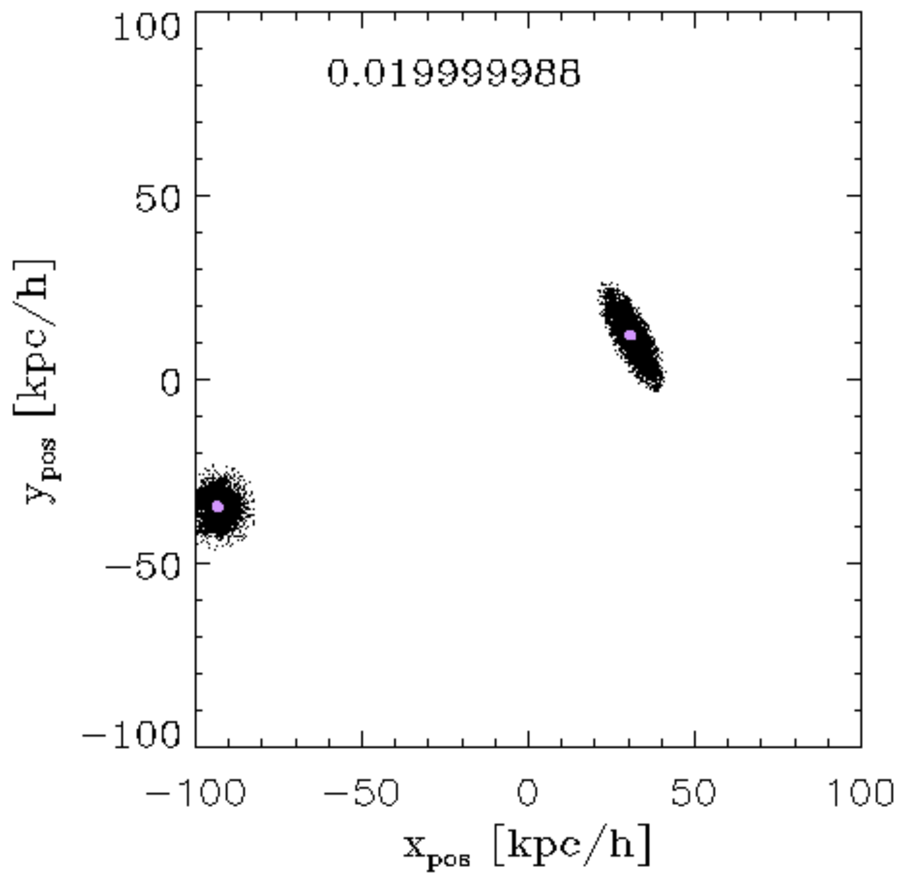
Numerical techniques ensuring BH merging

- The momentum is conserved in BH mergers.
- For unequal-mass mergers 'repositio-ning' of the BHs at the position of the minimum of the potential.
- The standard pre-scription is adequate for equal-mass mergers.

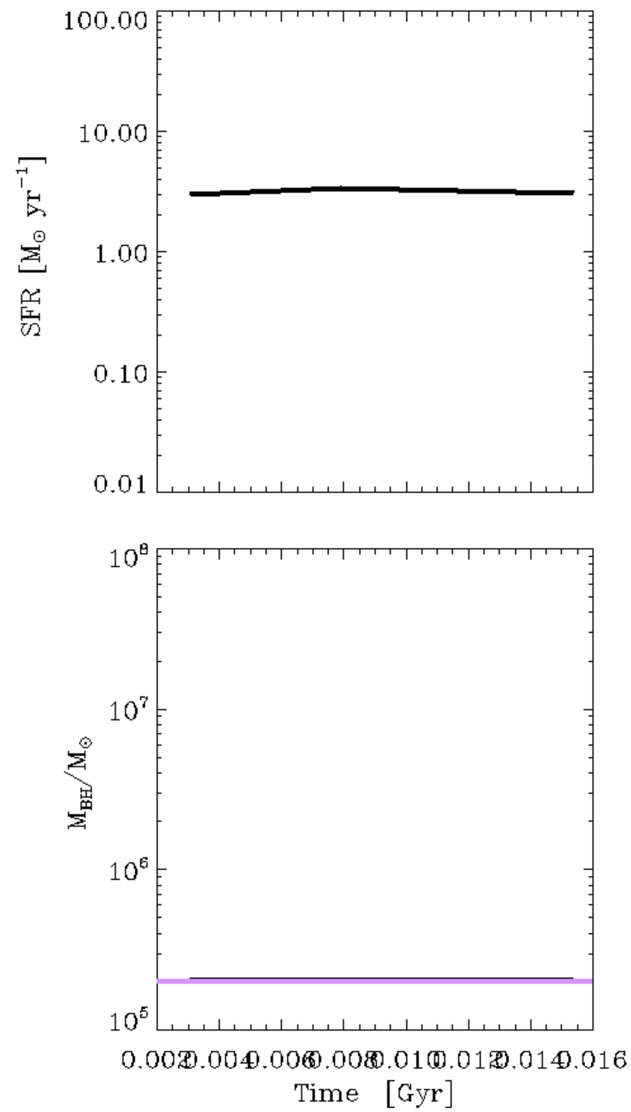
3:1 merger. Tests of BH merging prescription



3:1 merger movie



X-Y projection: Gas + BHs



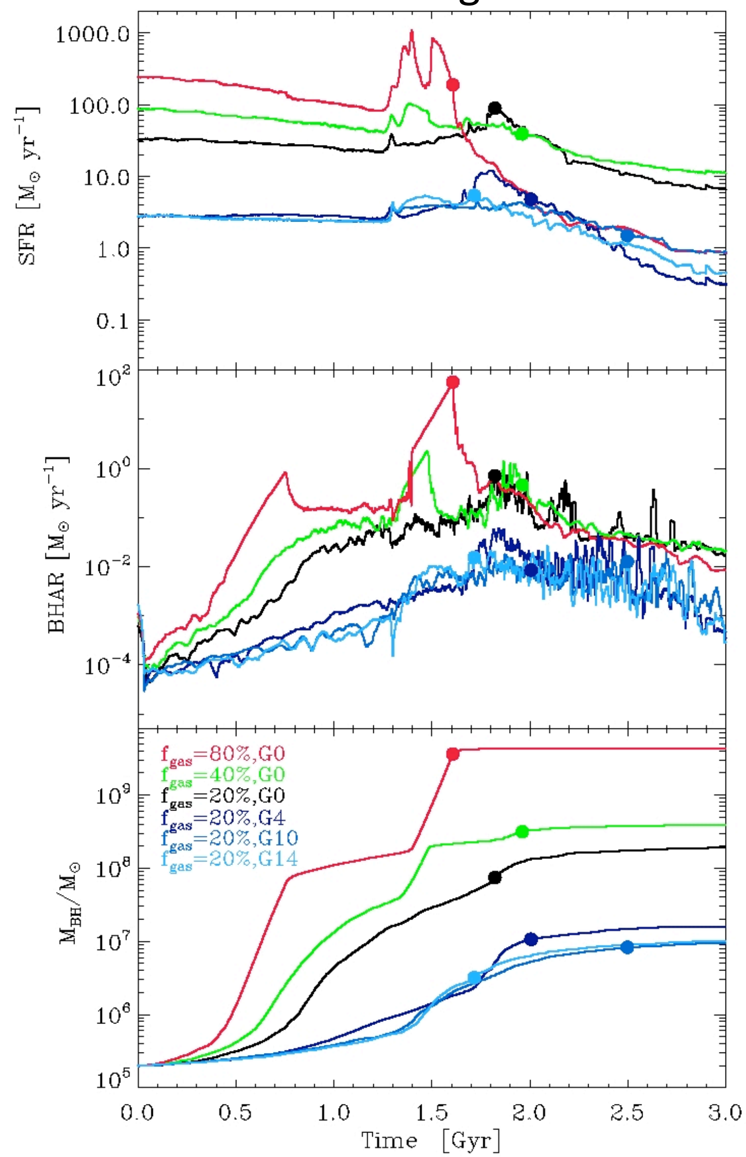
Total SFR

Total M_{BH}

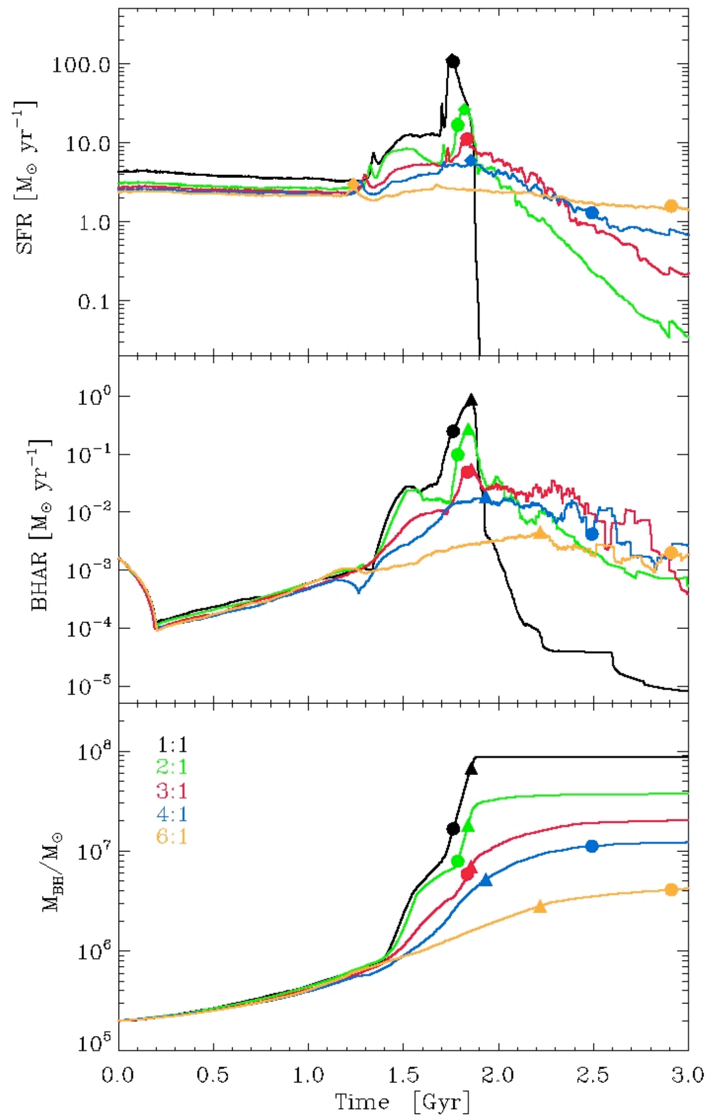
Varying the initial gas fraction and orbit

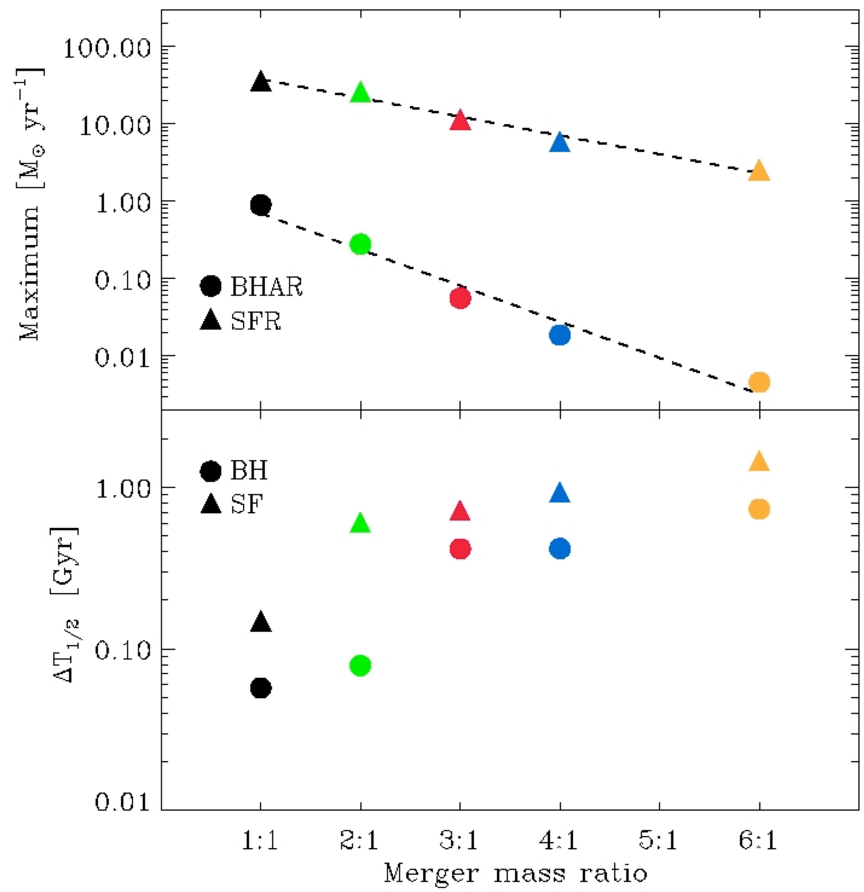
- Variations in the initial gas mass fraction produce large differences in the final BH mass, 20%, 40%, 80%.
- Variations in orbital geometry for a fixed initial gas mass fraction produce small differences in the final BH mass, shades of blue.

3:1 mergers



BH accretion as a function of merger mass ratio





- Systematic variations as a function of merger mass ratio.

LMU USM

M_{BH}-σ & M_{BH}-M_* relations for 3:1 and 1:1 mergers

M_{BH}-σ

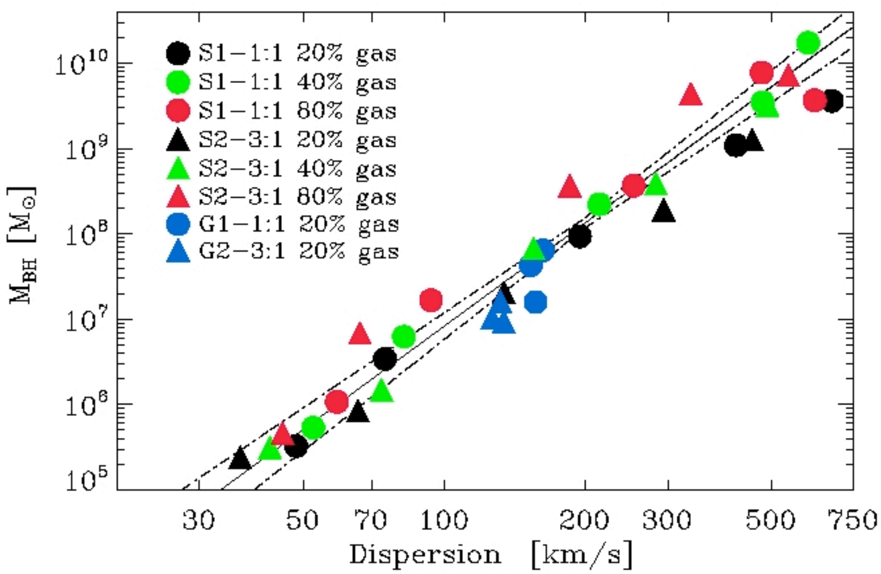


Table 4: Best fit $M_{BH} - \sigma$ relation for 3:1 and 1:1 mergers

Sample	N	a	b	$\Delta_{\log M_{BH}}$
Tot sample	36	8.07 ± 0.06	3.82 ± 0.15	0.29
3:1 sample	18	8.06 ± 0.08	3.78 ± 0.18	0.33
1:1 sample	18	8.05 ± 0.07	3.77 ± 0.18	0.26
S1-S2 20% gas sample	10	7.85 ± 0.04	3.47 ± 0.12	0.13
S1-S2 40% gas sample	10	8.13 ± 0.05	3.96 ± 0.13	0.14
S1-S2 80% gas sample	10	8.35 ± 0.10	3.77 ± 0.28	0.29
Observed sample[18]	31	8.13 ± 0.06	4.02 ± 0.32	0.25-0.3

M_{BH}-M_*

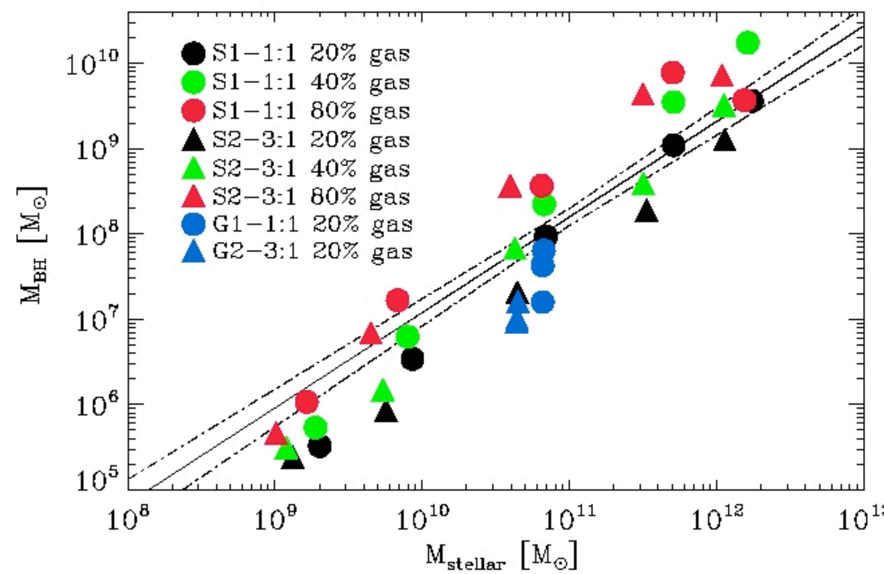


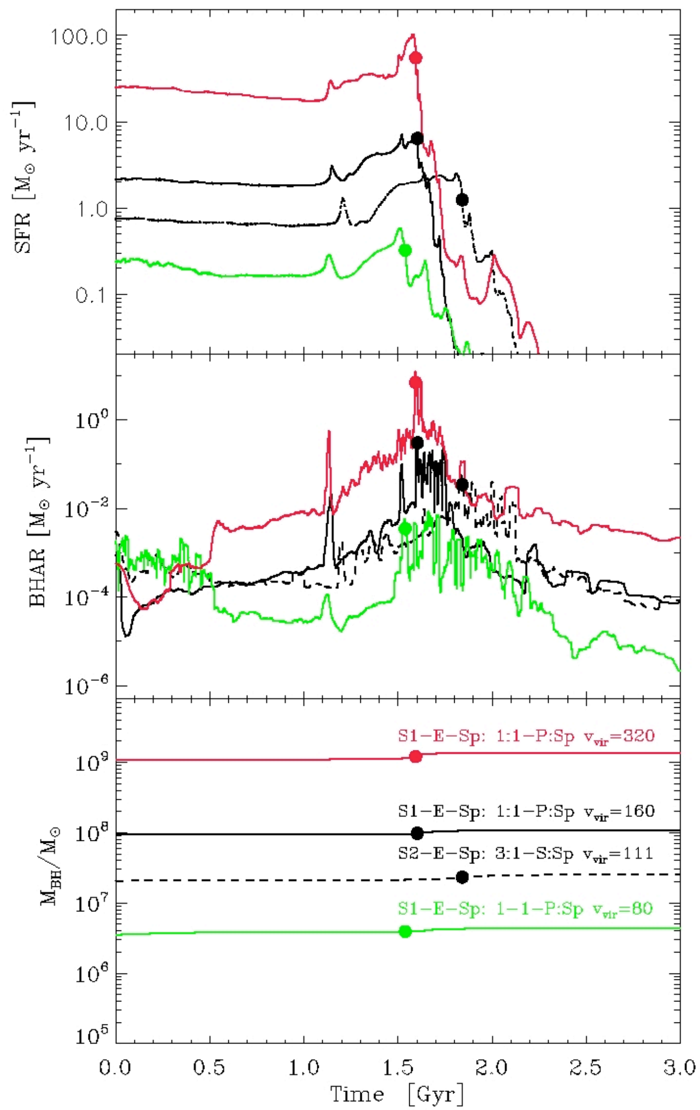
Table 5: Best fit $M_{BH} - M_*$ relation for 3:1 and 1:1 mergers

Sample	N	c	d	$\Delta_{\log M_{BH}}$
Tot sample	36	8.17 ± 0.10	1.40 ± 0.07	0.44
3:1 sample	18	8.04 ± 0.11	1.34 ± 0.08	0.47
1:1 sample	18	8.24 ± 0.10	1.41 ± 0.10	0.38
S1-S2 20% gas sample	10	7.86 ± 0.07	1.34 ± 0.05	0.17
S1-S2 40% gas sample	10	8.28 ± 0.08	1.45 ± 0.06	0.22
S1-S2 80% gas sample	10	8.68 ± 0.13	1.36 ± 0.12	0.29
Observed sample[19]	30	8.20 ± 0.10	1.12 ± 0.06	0.30

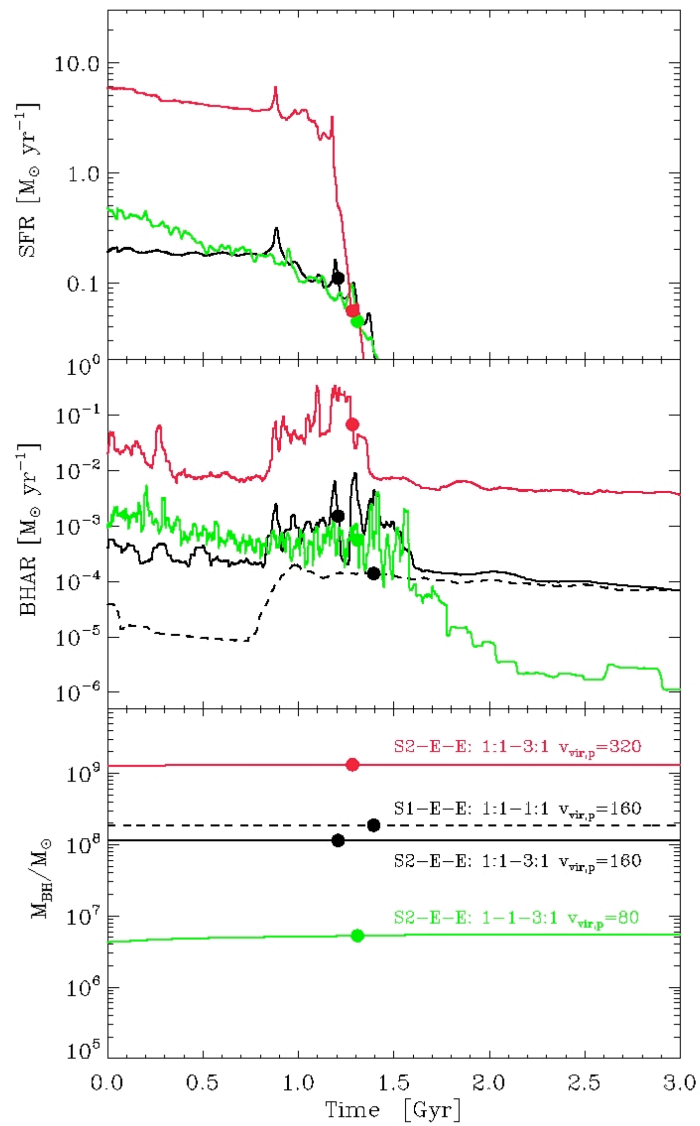
Lines: Observed relations - Tremaine et al. (2002) and Häring&Rix (2004).

SFR&BH accretion for mixed and dry mergers

Mixed mergers (E-Sp): $f_{BH,ins}$~20-30%



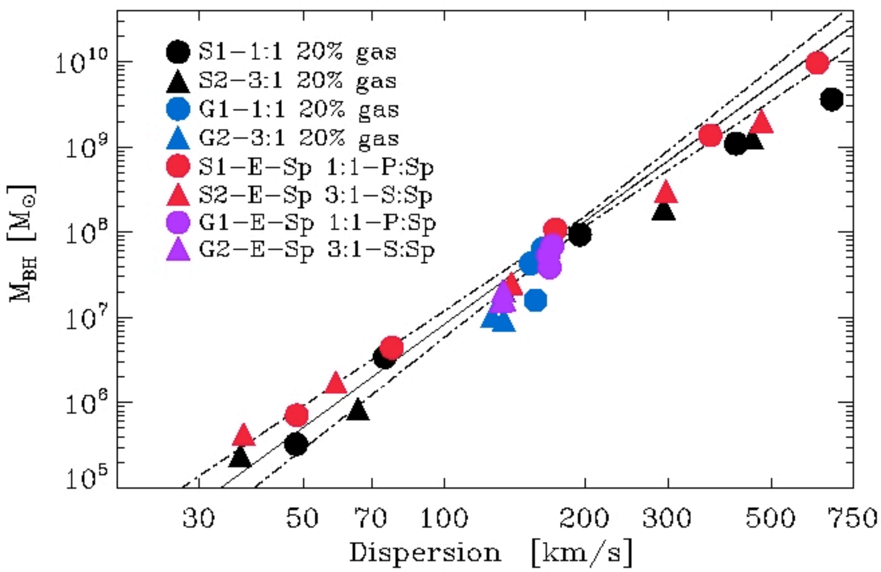
Dry mergers (E-E) : $f_{BH,ins}$~1-10%



LMU USM

M_{BH}-σ & M_{BH}-M_* relations for mixed mergers

M_{BH}-σ



M_{BH}-M_*

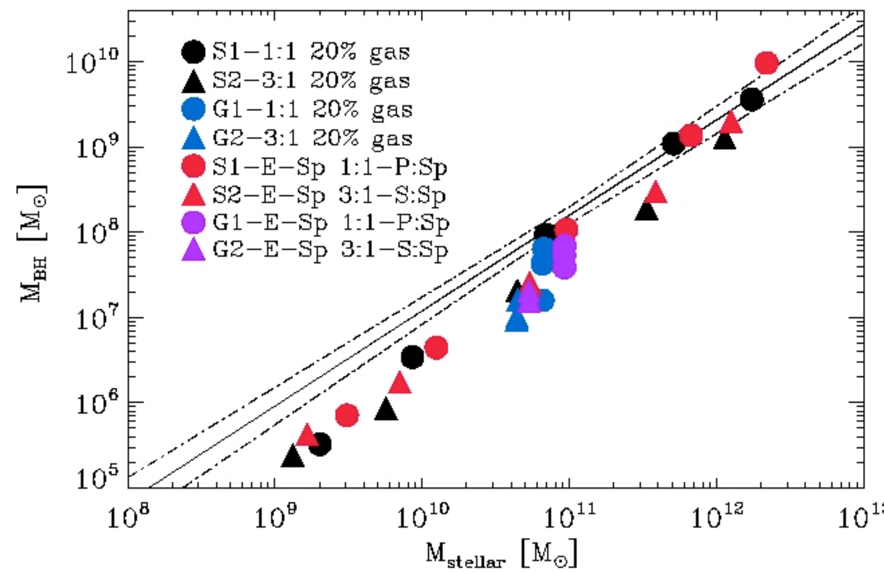
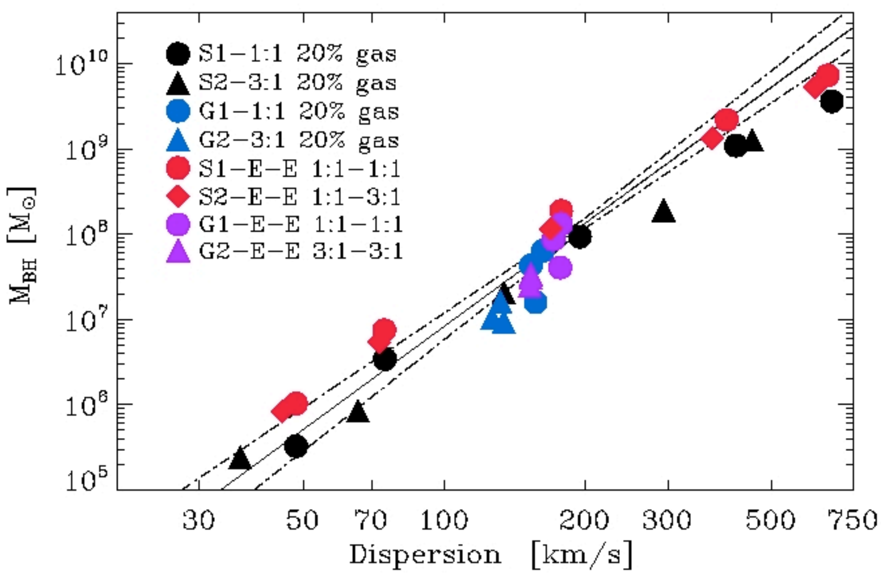


Table 7: Best fit $M_{BH} - \sigma$ relation for E-E and E-Sp mergers

Sample	N	a	b	$\Delta_{\log M_{BH}}$
Progenitor sample	16	7.83 ± 0.04	3.53 ± 0.11	0.16
E-Sp Mixed sample	16	8.03 ± 0.04	3.55 ± 0.12	0.13
E-E Remerger sample	16	8.13 ± 0.05	3.41 ± 0.10	0.18

M_{BH}-σ & M_{BH}-M_* relations for dry mergers

M_{BH}-σ



M_{BH}-M_*

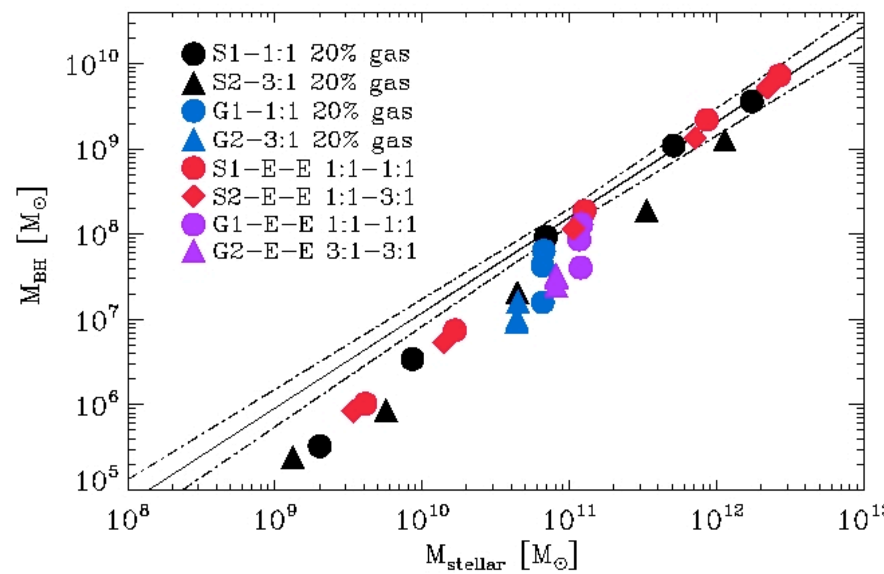
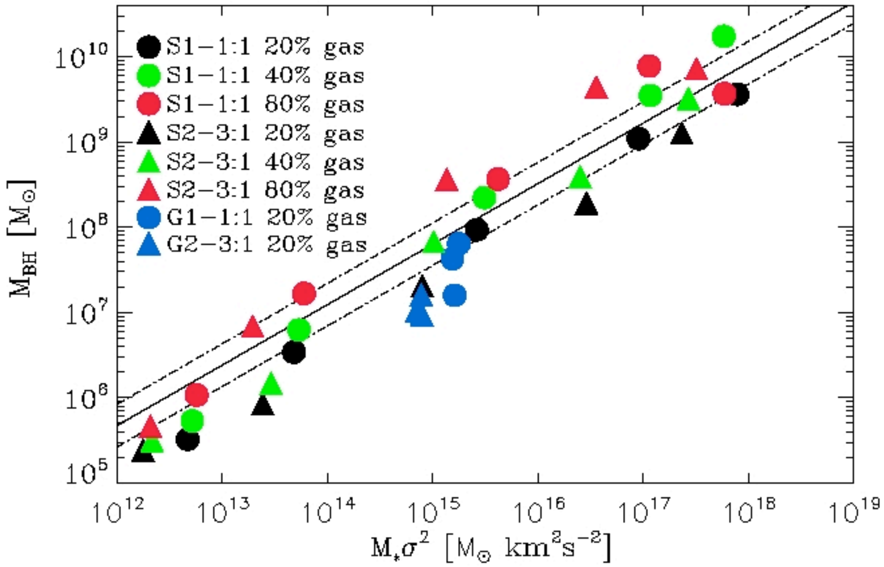


Table 8: Best fit $M_{BH} - M_*$ relation for E-Sp and E-E mergers

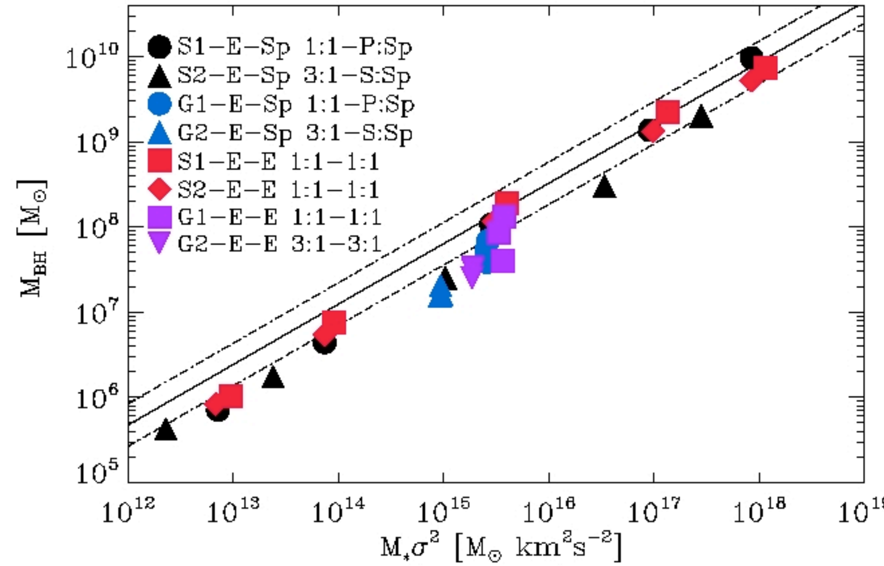
Sample	N	c	d	$\Delta_{\log M_{BH}}$
Progenitor sample	16	7.78 ± 0.07	1.35 ± 0.05	0.21
E-Sp Mixed sample	16	7.83 ± 0.05	1.39 ± 0.07	0.16
E-E Remerger sample	16	7.86 ± 0.05	1.38 ± 0.04	0.17

BHFP for disk and elliptical mergers

1:1 & 3:1 disk-disk mergers (Sp-Sp)



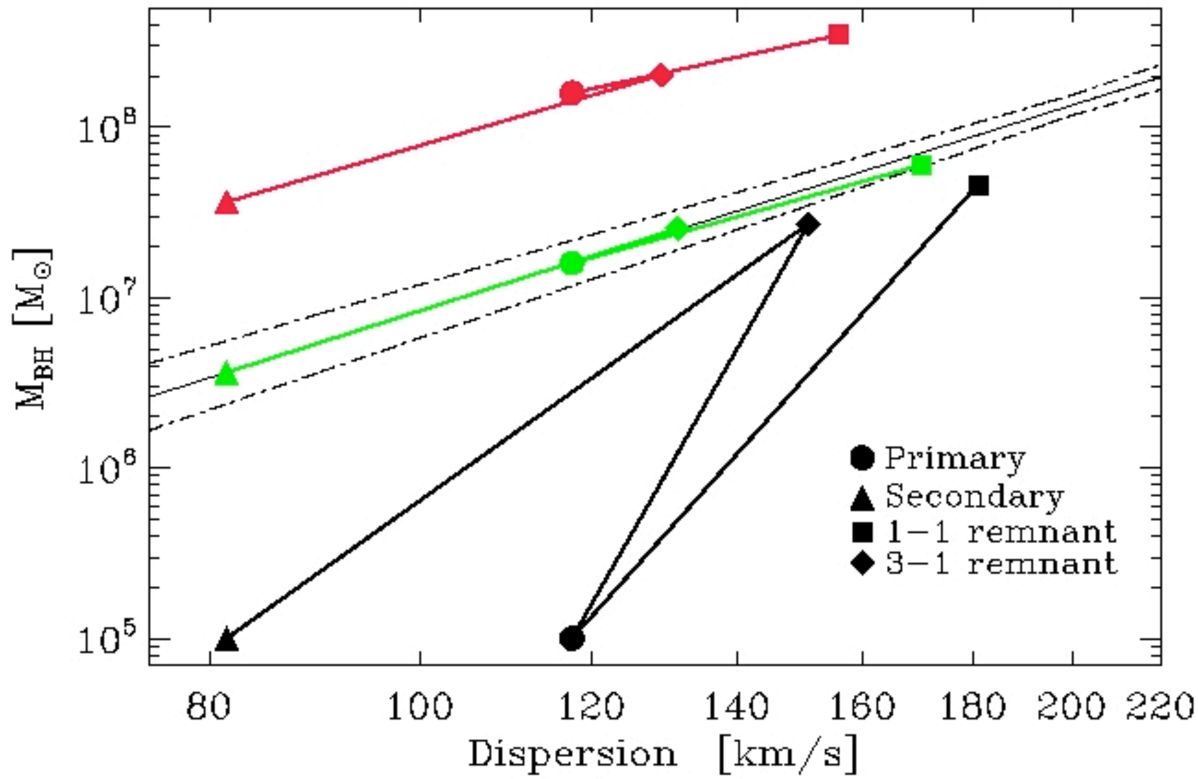
Mixed&dry mergers (E-Sp&E-E)



- Black hole fundamental plane (BHFP, Hopkins et al. 2007) $M_{BH} \sim \sigma^{3.0\pm0.3} R^{0.43\pm0.19}$ or $M_{BH} \sim M_*^{0.54\pm0.54} \sigma^{2.2\pm0.5}$.
- Statistically equivalent formulation M_{BH}-E_{bind}, $E_{bind} \sim M_* \sigma^2$.
- Lines: Observed relation from Hopkins et al. 2007:

  $\log(M_{BH}/M_{sun})=8.23\pm0.06+(0.71\pm0.06)\log(M_*\sigma^2/ M_0\sigma_0^2)$

Evolution of BH towards the M_{BH}-σ relation



- High-res simulations of 1:1 and 3:1 mergers starting below the relation, on the relation and above the relation with α=25.

Conclusions/Summary

- The simple BH accretion/feedback model works remarkably well in reproducing the observed M_{BH}-σ, M_{BH}-M_{BULGE} & M_{BH}-E_{bind} relation for equal, unequal, E-E dry and mixed mergers.
- The relation is the result of large-scale gas flows to the center of the galaxy and the self-regulation of M_{BH} due to feedback energy.
- Star formation is efficiently terminated in low merger ratio Sp-Sp mergers (≤3:1) and in mixed and dry mergers.
- The global properties of the galaxy are insensitive to the details of the BH feedback model, but what about the detailed properties? Surface density profiles, kinematics, orbits...
- Potential model improvements: Include spin of the BH, more physical accretion model, quasar mode vs. radio mode, jets....

LMU USM