AGN and their host galaxies

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Abstract

Large scale cosmological hydrodynamic simulations are an important tool to study the co-evolution between black holes (BHs) and their host galaxies. However, in order to model the accretion onto BHs and AGN feedback we need sub-grid models which contain several free parameters. The choice of these parameters has a significant impact on the properties of the BHs and their host galaxies. Therefore, we improve the accretion model and the AGN feedback model based on both theory and observations to eliminate most free parameters. In that way, the slope of the observed relation between BH mass and stellar mass is reproduced self-consistently. We performed a few extremely large simulation runs as part of the Magneticum Pathfinder simulation set, combining a high resolution with very large cosmological volumes, enabling us to study for example dual AGN, the role of galaxy mergers and AGN clustering properties.

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BH model

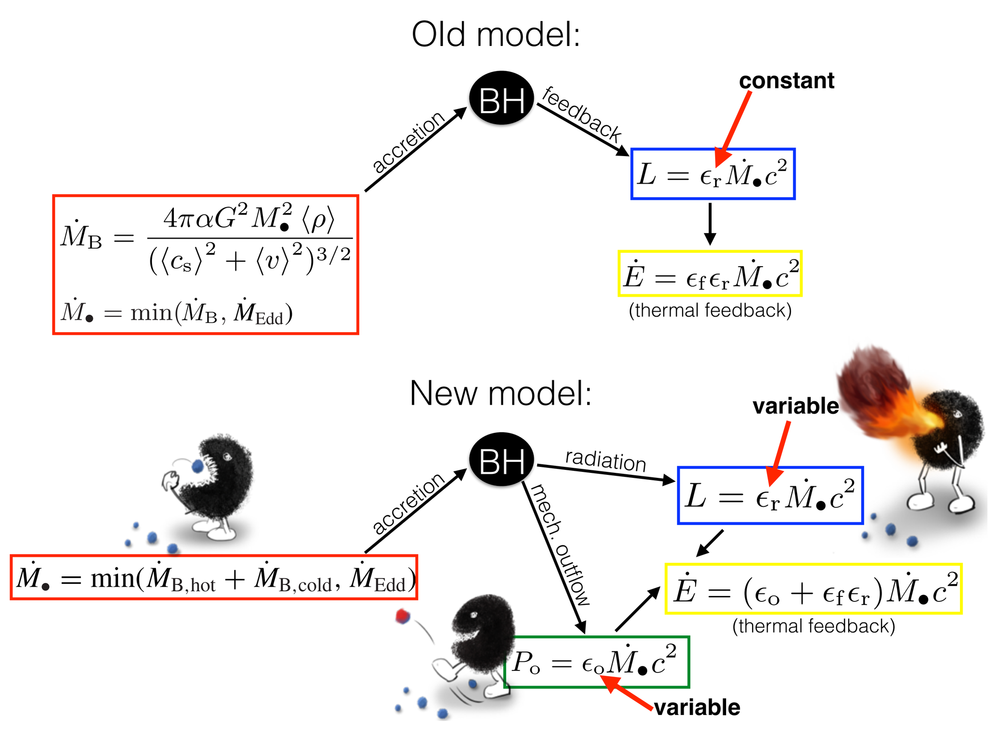
The model for BHs and their associated AGN feedback is based on Springel et al. (2005). In order to model BHs in a cosmological simulation we need three ingredients:

- **Seeding:** In galaxies which do not yet contain a BH and which exceed a stellar mass threshold depending on the resolution, we replace the star particle with the highest binding energy by a BH sink particle.
- **BH growth:** BHs grow by merging with each other and by accreting the surrounding gas, following the Bondi-Hoyle formalism.
- **AGN feedback:** A fraction of the accreted gas is ejected as radiative or mechanical energy, both heating up the surrounding gas.

Steinborn et al. (2015)

In contrast to the original model we use several refinements (see Hirschmann et al. 2014, Steinborn et al. 2015, and Steinborn et al. 2016 for more details):

- **No pinning:** We do not pin BHs to the potential minimum. In that way, our simulations are able to better capture the dynamics of the BHs, such that almost all substructures above our chosen mass threshold contain a BH. Furthermore, one galaxy can contain more than one BH with distances down to about 2kpc.
  → **dual/offset AGN**
  → **AGN clustering**
- **Hot vs. cold gas accretion:** We compute the accretion rate separately for hot ($\alpha = 10$) and cold ($\alpha = 100$) gas.
- **AGN feedback model:** We consider both radiation and mechanical outflows with variable efficiencies ϵ_r and ϵ_0, depending on the BH mass and accretion rate.



Dual and offset AGN at $z = 2$

Recently, it became possible to observationally resolve galaxies with two distinct nuclei in their centre (e.g. Comerford et al. 2015 and references therein). Such objects are of particular interest, since they are tracers of galaxy mergers. If both nuclei are active, they are called dual AGN, if only one of them is active, it is called offset AGN. Since these events are very rare, it is still unclear which physical mechanisms drive dual AGN activity. To produce a reasonably large sample of dual and offset AGN self-consistently in a cosmological simulation, not only a high resolution, but also a large volume is required. In one of our most recent simulations, which ran down to a redshift of $z = 2$, this is finally possible. The resolution ($M_{dm} = 3.7 \cdot 10^7 M_\odot/h$ and $M_{gas} = 7.3 \cdot 10^6 M_\odot/h$) allows us to resolve BH pairs down to separations of roughly 2kpc in a volume of $(128\mathrm{Mpc}/h)^3$. Out of 14903 BHs, among them 1864 AGN with $L_{bol} > 10^{43}$erg/s, the simulation contains 9 dual AGN, 6 offset AGN, 8 unresolved offset AGN (here the inactive BH is not resolved in mass), and 11 BH pairs without AGN.

Steinborn et al. (2016)

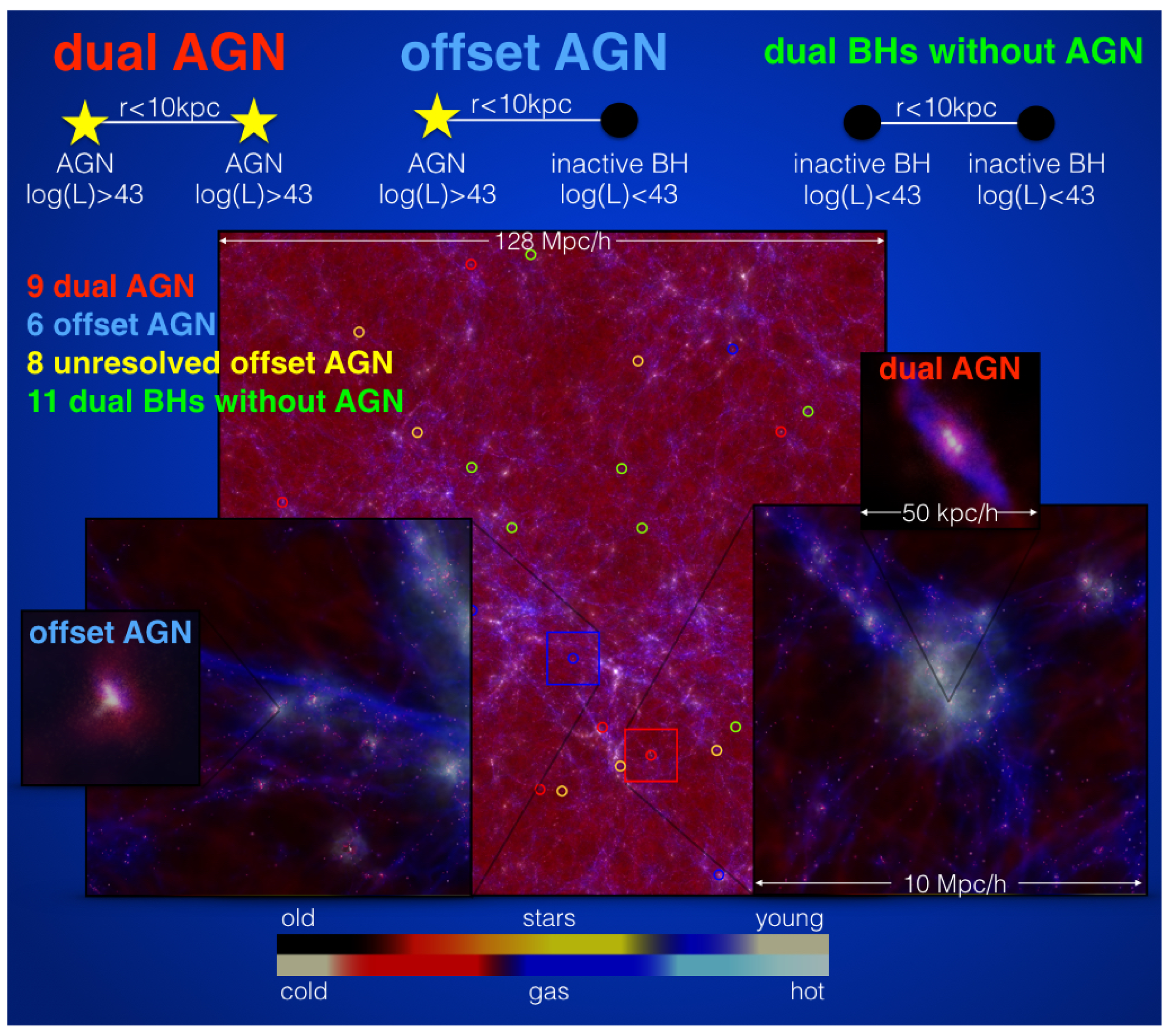


Fig. 1: Visualizations of the total box and zoom-ins into two galaxies, one of them containing a dual AGN and, the other containing an offset AGN. The figures show baryons, i.e. gas and stars, colour-coded by the gas temperature and the age, respectively. The coloured circles mark the positions of the BH pairs.

In Steinborn et al. (2016) we used this sample of BH pairs to study the different origins and properties of dual AGN, offset AGN and dual BHs without AGN. We find some very interesting facts:

- *Dual AGN activity increases down to smaller spatial separations.*
- *The merger mass ratio, the gas mass and the gas accretion history are important factors in triggering dual AGN activity.*
- *Dual AGN have similar BH masses.*
- *During the merger, the activity of both AGN increases in dual AGN, while offset AGN suppress the activity of their inactive counterpart.*
- *In dual AGN, the BH with the higher Eddington ratio $M/\dot M_{Edd}$ always comes from the less massive progenitor galaxy.*
- *Dual AGN accrete more gas from filaments than offset AGN and inactive BH pairs.*

References

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AGN and galaxy mergers

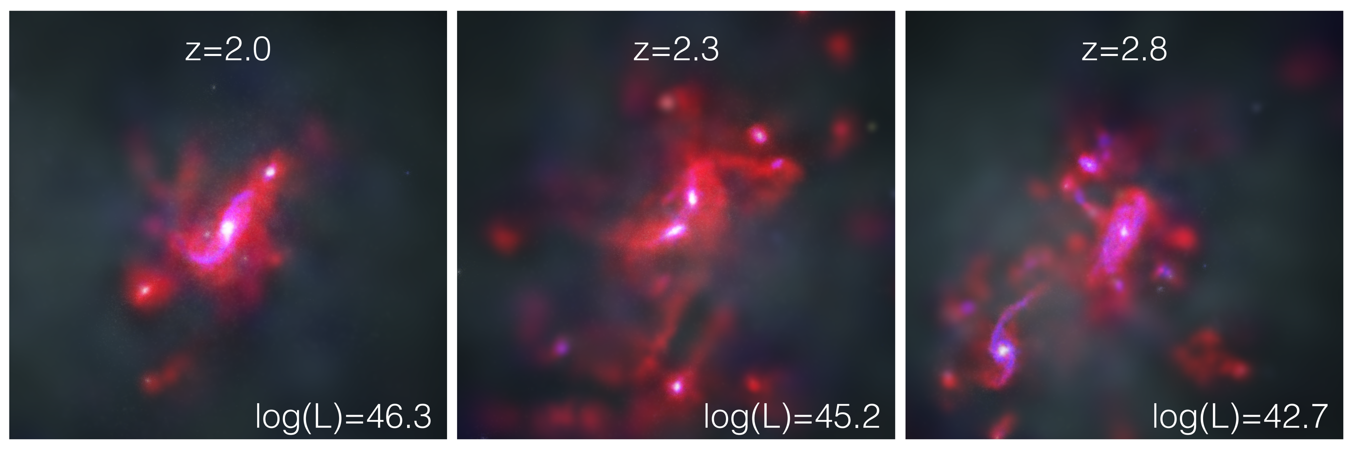

Fig. 2: Visualization of a 2:5 merger in the 68Mpc/uhr simulation, which significantly increases the AGN luminosity. The colour-coding is the same as in Fig. 1.

As demonstrated in Fig. 2, galaxy mergers can trigger AGN activity. However, from observations it is not yet fully understood how relevant mergers are in contrast to other AGN trigger mechanisms. One problem can be that the merger is not necessarily visible anymore, while the AGN is still active. Fig. 3 shows that galaxy mergers (yellow and magenta symbols representing major and minor merger) typically lie below the $M_\bullet$-M_* relation, i.e. *the stellar mass grows earlier than the BH mass.*

In our simulations, we use merger trees to identify mergers independent of their visibility. Fig. 4 shows the fraction of AGN hosted by galaxies which merged during the last Gyr, depending on the AGN luminosity. Red and blue curves show the result for the 500Mpc/hr simulation and the 68Mpc/uhr simulation. In both simulations, we see a clear increase of the merger fraction with luminosity. Thus, *mergers are important for triggering the most luminous AGN.* For less luminous AGN they are less relevant, although the merger fraction is still enhanced in contrast to inactive galaxies (arrows on the left), in particular for minor mergers. Exemplarily, we show the result only for $z = 2.0$ where the simulation contains most AGN. However, the same trend can also be seen at lower redshifts.

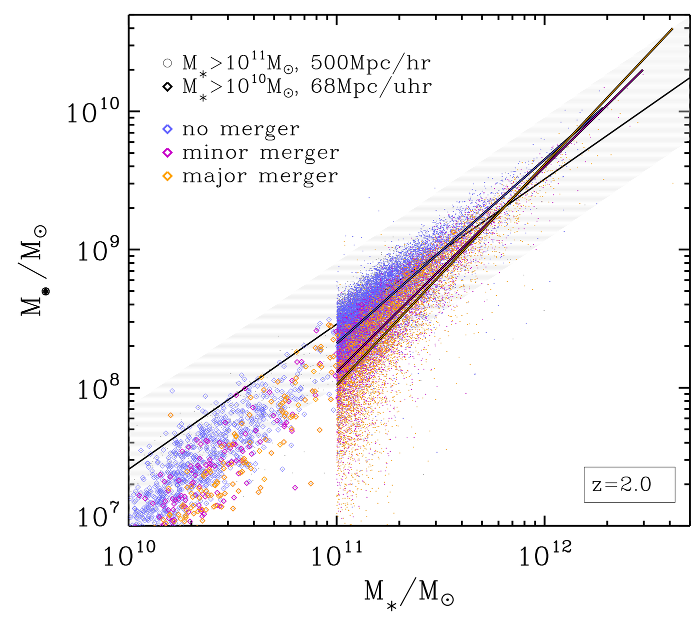

Fig. 3: $M_\bullet$ versus M_* for two different simulations, i.e. 500Mpc/hr and 68Mpc/uhr, at $z = 2.0$. We show only galaxies above our chosen resolution threshold, i.e. $M_* > 10^{11} M_\odot$ for the 500Mpc/hr simulation and $M_* > 10^{10} M_\odot$ for the 68Mpc/uhr simulation. The grey dots represent all BHs and their host galaxies, while the coloured symbols represent only AGN with a luminosity $L > 10^{43}$erg/s. Blue corresponds to AGN, which are not triggered by a merger. Magenta and yellow symbols represent minor and major mergers, respectively. The coloured lines show the corresponding fits for the 500Mpc/hr simulation. For orientation we show the observed $M_\bullet$-M_* relation from McConnell & Ma and the corresponding scatter as black line and light grey shaded area.

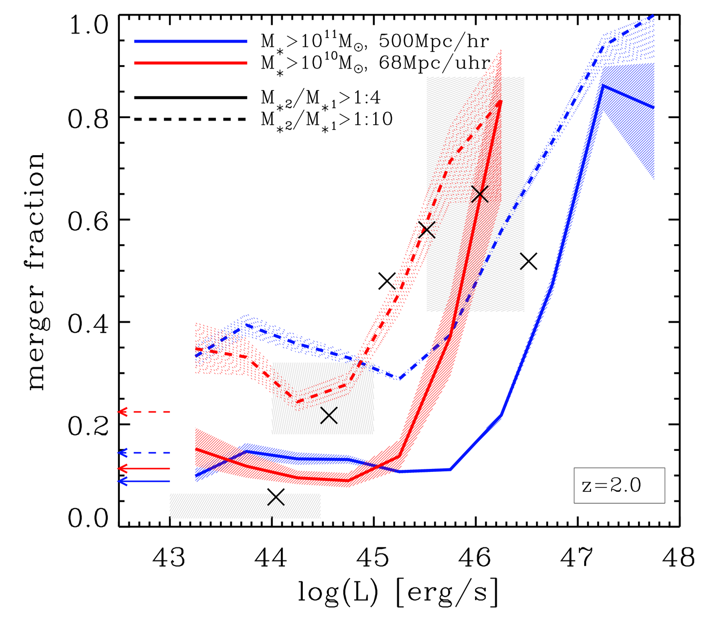

Fig. 4: This figure shows the fraction of AGN which are triggered by galaxy mergers, depending on the bolometric AGN luminosity. Blue and red lines represent the 500Mpc/hr and the 68Mpc/uhr simulation, respectively, while the shaded areas mark the corresponding binomial errors. Note that the resolution threshold depends on the resolution, i.e. $M_* > 10^{11} M_\odot$ for the 500Mpc/hr simulation and $M_* > 10^{10} M_\odot$ for the 68Mpc/uhr simulation. We distinguish between major and minor mergers (solid and dashed lines). The arrows on the left show the merger fraction for inactive galaxies, where $L < 10^{43}$erg/s. For comparison with observations we show the data summarized by Treister et al. (2012) as black crosses and shaded areas, demonstrating the observed luminosity ranges as well as the error on the y-axis.

How many AGN does a dark matter halo contain?

Finally, it is interesting to look at the large scale distribution of AGN. Particularly, we are interested in the mean number of AGN in a dark matter halo of mass M_{halo}. This is shown in the top panel of Fig. 5 for several redshifts. We define a simulated BH as an AGN if $L_{SXR} > 10^{42}$erg/s. In the middle and bottom panel, we consider only AGN which are associated to substructures and central AGN, respectively.

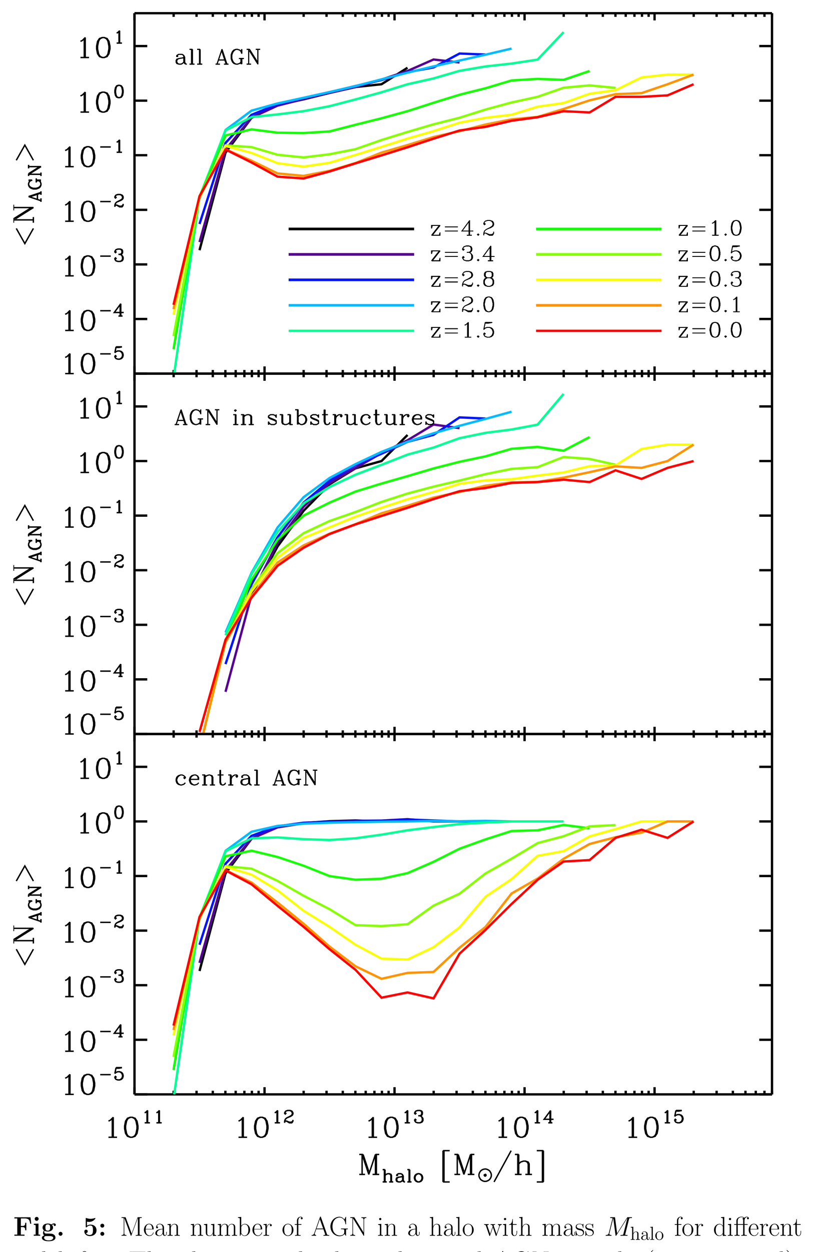

Fig. 5: Mean number of AGN in a halo with mass M_{halo} for different redshifts. The three panels show the total AGN sample (upper panel), only AGN in substructures (middle panel) and central AGN (bottom panel).

The HOD slope for all AGN:
At $z = 0.3$, for example, our simulation predicts a slope $\alpha = 0.57$ above a cut-off mass for all AGN. This slope is often called the HOD slope α. Interestingly, it is clearly smaller for AGN than for luminous red galaxies (LRGs), where $\alpha \approx 1$, indicating that *AGN are distributed differently than galaxies.* This means that AGN, in general, prefer a less dense environment.

Central AGN are special:
However, while the number of AGN in substructures increases continuously following the HOD slope, central AGN show a more complex behaviour: at low redshifts, there is a peak at roughly $M_{halo} \approx 5 \cdot 10^{11} M_\odot$. Then, due to AGN feedback, the mean number of central AGN decreases up to $M_{halo} \approx 10^{13} M_\odot$, i.e. the regime of galaxy groups. Above that mass, AGN activity increases again due to the increasing BH mass. We can thus roughly distinguish between three regimes:

- $M_{halo} < 5 \cdot 10^{11} M_\odot/h$: *accretion dominated,*
- $5 \cdot 10^{11} M_\odot/h < M_{halo} < 10^{13} M_\odot/h$: *AGN feedback dominated,*
- $M_{halo} > 10^{13} M_\odot/h$: *BH mass/gravity dominated.*

Furthermore, we find that *at high redshifts ($z \geq 2.0$) almost all dark matter haloes with $M_{halo} > 10^{12} M_\odot$ contain a central AGN.*

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