Exercises 12

The impact of AGN feedback on stellar properties of massive galaxies at z=0

1. Calculate the stellar baryon conversion efficiencies for the runs with and without AGN fb, plot them versus halo mass, and compare with predictions from semi-empirical models (e.g., *Moster+13*)
2. Plot the 3D distribution (or 3 diff. projected 2D distributions) of star particles ($<1/10R_{vir}$) for both runs, color-coded by stellar age, how do the stellar ages and morphologies change with AGN fb?
3. Where are the galaxies located in the stellar age-stellar mass plane compared to the observed mass-age relation? (table 2 in Gallazzi+05)?
4. Derive the star formation histories from the stellar ages (binning star particles in time, and dividing the stellar mass formed by the time bin), plot them as a function of lookback time.
5. Plot the projected half-mass radii of galaxies against galaxy stellar mass, and compare to the observed mass-size relation of ETGs (*Nipoti+09*).

Explain the differences between both runs, and interpret your results!

Helpful instructions:

- Stellar baryon conversion efficiency: $M_{stellar}/(f_{bar}*M_{halo})$,
  - stellar mass are star particles within 1/10 R_{vir} (as before)
- You will get two ascii-files, containing info for star particles, for runs of the same halo with and without AGN feedback
- These ascii files have the following format (code units as before):

  particle mass, x_position, y_position, z_position, a_birth

- The positions are centered on the main galaxy (center of mass: x=0.0, y=0.0, z=0.0)
- Note that the code outputs "the scale factor at the time of birth" of each star particle, meaning you have to convert that into birth time of a star particle, and by subtracting it from the Hubble time, you get the stellar age.
- Projected half-mass radius along z-axis: Radius, at which half of the total galaxy stellar mass ($<1/10R_{vir}$) is contained; for simplicity, one projection is enough.

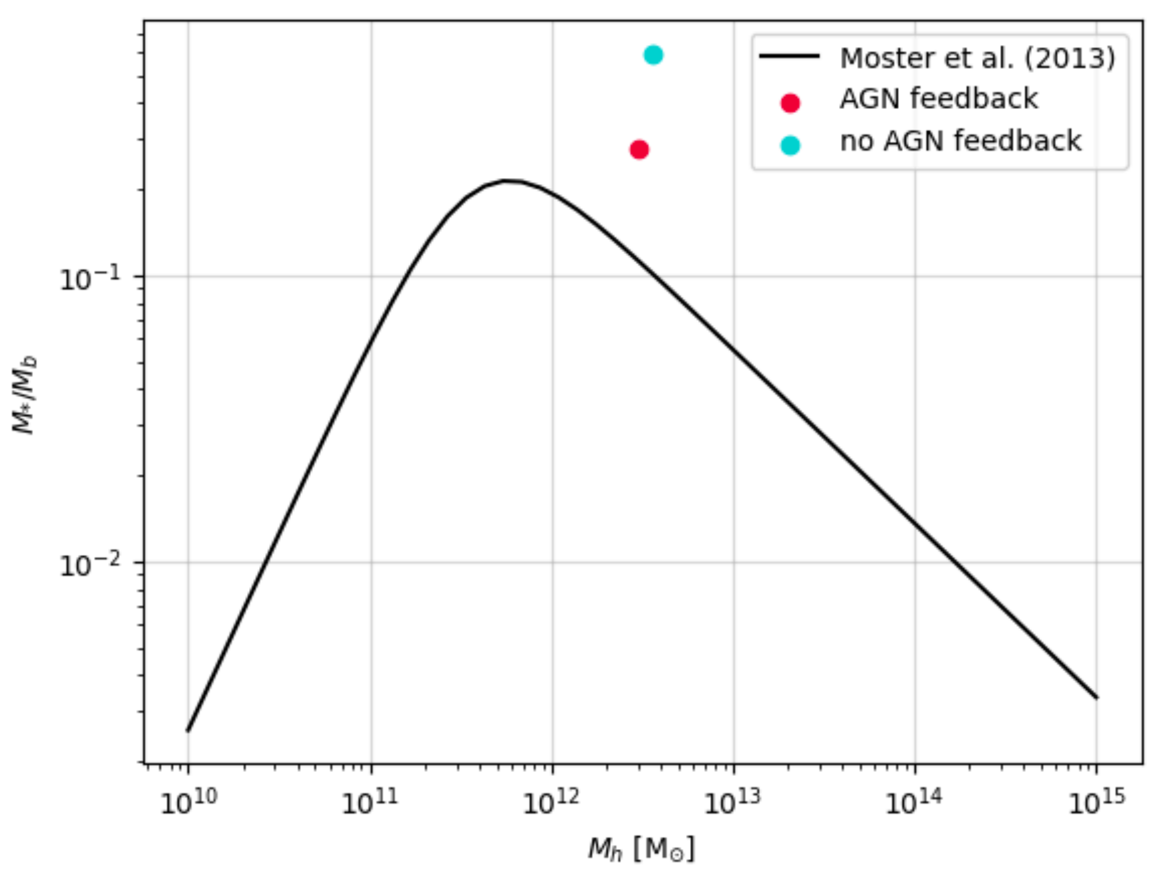
Exercises 12

Further information: 2 cosmological hydrodynamic zoom-in simulation of a massive halo at z=0 with and without AGN feedback

- WMAP3 cosmology, IC details described in *Oser+10, Hirschmann+12* (Halo 204)
- Run with a modified version of Gadget-3, for code details see *Choi+17/Hirschmann+17*
- Grav softening DM: 800pc; grav softening gas/stars: 400pc; Number of neighbours: 100
- *First simulation run without AGN fb* (*termed as "noAGN" in the ascii file name*), M_{halo}= 5.2e12 $M_{\odot}$/h, R_{vir}= 281 kpc/h
- *Second simulation run with* AGN fb (*termed as "AGN" in the ascii file name*), M_{halo}= 4.3e12 $M_{\odot}$/h, R_{vir}= 265 kpc/h
- Both runs are taken from *Hirschmann+17 (similar to Choi+17)*

Solutions - Exercise 12

1. Calculate the stellar baryon conversion efficiencies for the runs with and without AGN fb, plot them versus halo mass, and compare with predictions from semi-empirical models (e.g., *Moster+13*)



We find lower stellar baryon conversion efficiencies for the galaxy with AGN feedback than for the galaxy without this processes, differing by a factor of over 2. The run including AGN feedback, plotted in red, aligns more closely with the abundance matching predictions, than the no AGN feedback run, shown in light blue.

The kinetic AGN feedback model adopted in these simulations injects energy and momentum into the surrounding gas, both heating it, dispelling it from the centre as galactic outflows and reducing gas inflow rates. As stars are formed from cold gas collapsing under gravity, star formation is significantly reduced/supressed in the presence of AGN feedback, explaining the decreased baryon conversion efficiency in the no AGN feedback run.

However, to make more meaningful statements about the impact of AGN feedback, we would need to analyse a larger sample of galaxies of each type, which would allow us to estimate errors on our values.

Solutions - Exercise 12

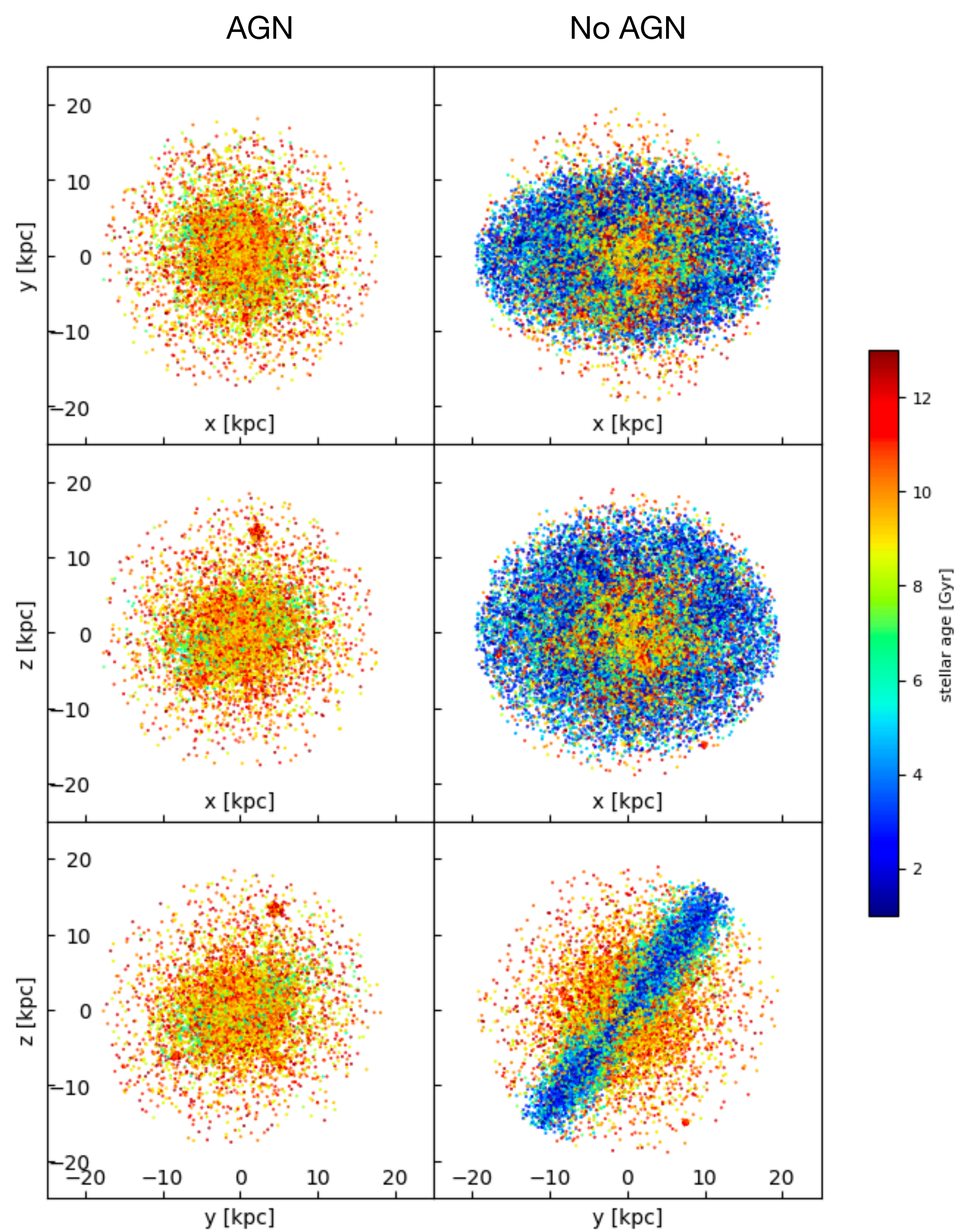
2. Plot the 3D distribution (or 3 diff. projected 2D distributions) of star particles ($<1/10R_{vir}$) for both runs, color-coded by stellar age, how do the stellar ages and morphologies change with AGN fb?

The AGN feedback run shows barely any stars younger than around 6 Gyrs and is dominated by older stars. Stellar concentration increases towards the centre, with a few regions of higher star concentration, mostly comprised of old stars around 10-12 Gyrs, color coded in orange and red. The shape is roughly spheroid with no discernible disk.

Instead, the no AGN feedback run shows a much larger stellar population in general and contains many young stars of 3 Gyrs or younger. The core still looks to be dominated by older stars but still contains a sizable fraction of young stars. The last panel on the right, showing the y-z plane also exhibits a striking disk feature, in which the young stars are organised.

These morphologies match our current understanding of galaxy formation. Disks form due to smooth accretion of gas conserving angular momentum, where the newly formed stars trace the shape of the accretion disk. This is seen in the no AGN feedback run.

Spheroid galaxies are, instead, thought to form via galactic merging, which removes angular momentum and destroys the star forming disk, producing a rounder galaxy. However, hydrodynamical simulations have shown that after a stellar disk has been destroyed via a merger, it can even re-form, if there is continued accretion high-angular momentum gas at late cosmic times. Thus, to form a spheroid, we need significantly reduced gas inflow rates, as produced by AGN feedback.



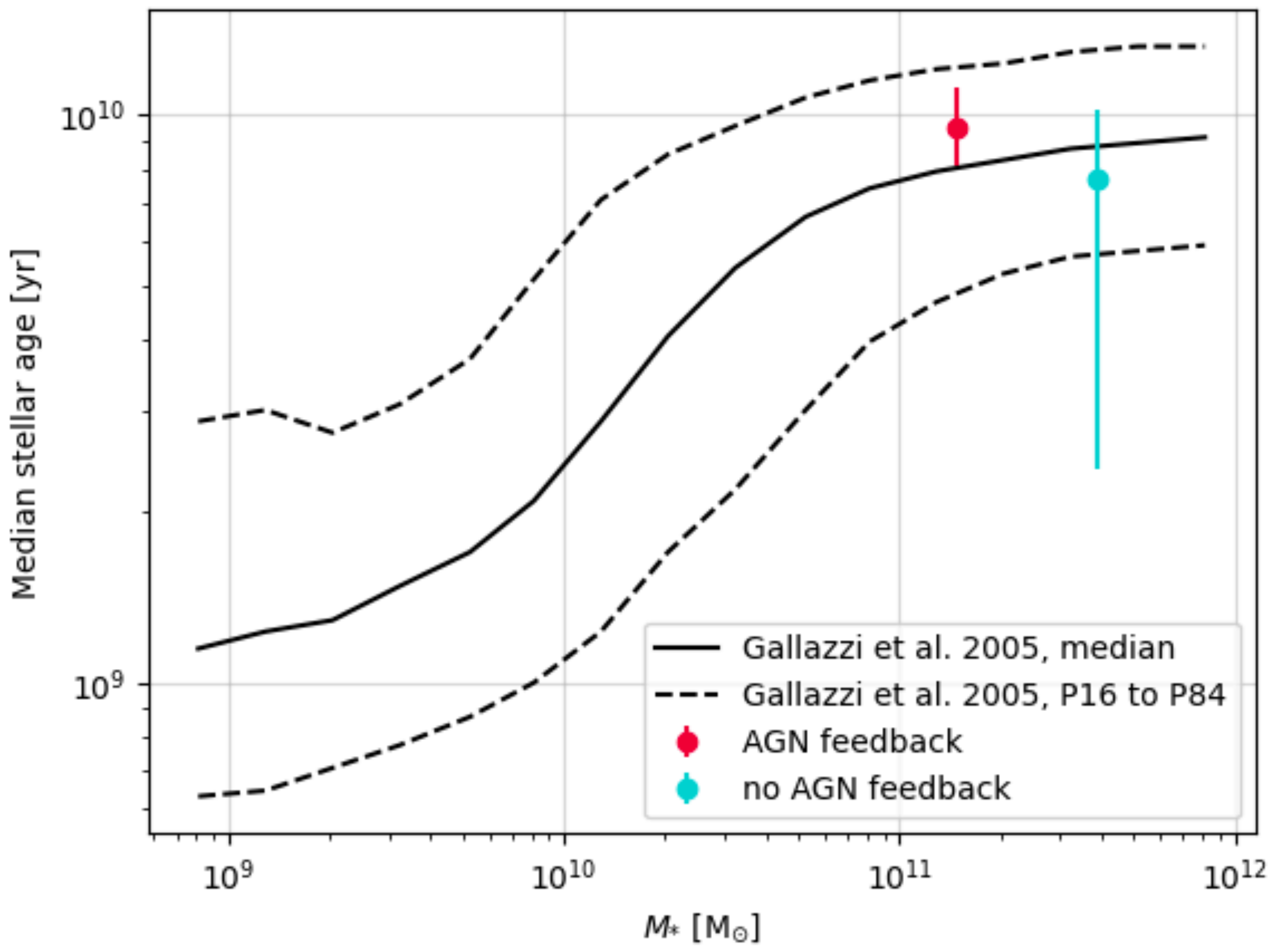
Solutions - Exercise 12

Where are the galaxies located in the stellar age-stellar mass plane compared to the observed mass-age relation (table 2 in Gallazzi+05)?

With AGN feedback the average age of the stellar content of the simulated galaxy is around 10 Gyrs, while without AGN feedback the average age is around 7 Gyrs. This is because AGN feedback significantly reduces the formation of new stars at late cosmic epochs so that overall the stellar populations are older compared to the run without AGN. [Note that instead of median stellar age, you could also compute and plot the median or mean for the logarithm of the stellar age.]

Compared to the observed mass-age relation of Gallazzi+05, both median stellar ages lie within the 16th to 84th percentile of the stellar age-stellar mass plane, with the no AGN run even lying closer to the median and including it in its 16th to 84th percentile range. However the lower error bar shows that there is a bias toward much lower stellar ages. The 16th percentile lies far outside the observed plane, indicating that the stellar ages in the no AGN feedback run might not align with the observed plane as well as the pure median value suggests. The AGN feedback run shows a very small variation across the 16th to 84th percentiles and is entirely within the range of the observed distribution.

Thus, we can conclude that the locations of the two galaxies on the observed stellar age-stellar mass plane both represent reasonable values and one galaxy alone is not enough to assess the need of AGN feedback to create realistic galaxies —> larger statistics would be needed!



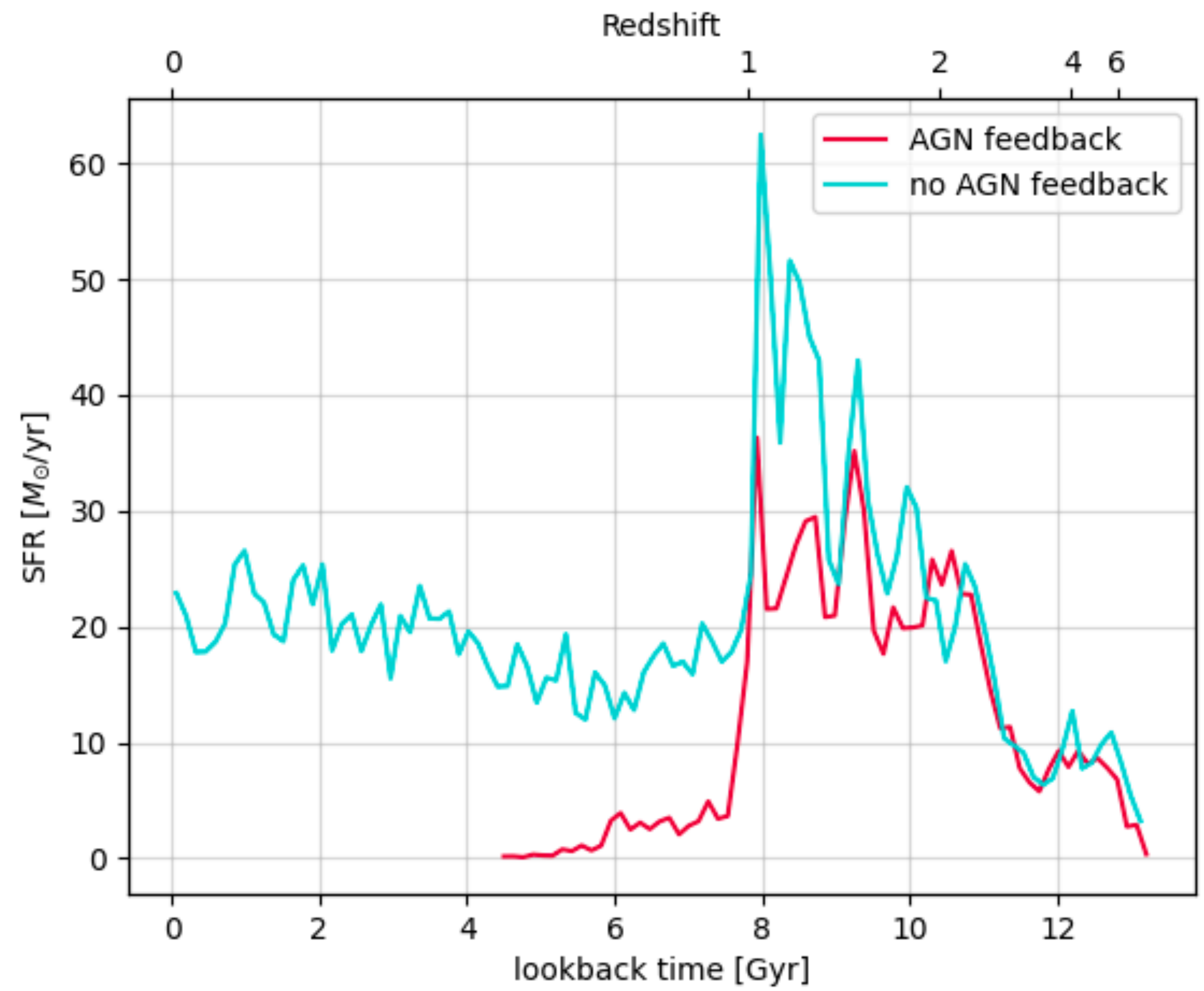
Solutions - Exercise 12

Derive the star formation histories from the stellar ages (binning star particles in time, and dividing the stellar mass formed by the time bin), plot them as a function of lookback time.

The star formation rate evolves concurrently in both runs until z ~ 2, i.e.10 Gyrs ago. Then, in the no AGN run many more new stars re formed with respect to the AGN feedback run. Just before redshift 1, i.e. 8-9 Gyrs ago, we see a SFR nearly twice as high as with AGN fb.

While in the AGN feedback run, the SFR drops to almost 5 M⊙/yr and eventually 0 shortly after z ~ 1, in the no AGN feedback run star formation continues at a roughly constant rate between 15 and 25 M⊙/yr.

This fits into the previously discussed picture of AGN feedback quenching star formation via both gas heating and ejection and preventing (re-) accretion of gas. Judging by this plot, for this simulation of a DM halo with a mass of a few 1e12M⊙, this process becomes important around z ~ 2 and completely cuts off star formation after z ~ 1. This is linked to high gas accretions (related to the black hole mass in the Bondi scheme) needed to produce effective feedback. Regardless, the peak of star formation in both galaxies is placed between z ~ 1-2.



Solutions - Exercise 12

Plot the projected half-mass radii of galaxies against galaxy stellar mass, and compare to the observed mass-size relation of ETGs (*Nipoti+09*).

The effective radius of the galaxy with AGN feedback is slightly smaller than that without this process. This is primarily linked to the fact that without AGN feedback, the galaxy is also much more massive.

Compared to the observed mass-size relation for ellipticals, the AGN galaxy lies very close to the observed values, while the noAGN galaxies is too small at the given stellar mass, lying outside the 1-sigma scatter of the observed relation.

In fact, this is a general trend which can be seen when we consider the full sample of ~30 cosmological zoom simulation of massive galaxies (of Choi+17, Hirschmann+17), see bottom figure. This shows that at a given galaxy stellar mass AGN feedback can increase the effective radius of a massive galaxy due to adiabatic expansion and due to a larger fraction of low-mass satellites (since there is less SF happening inside the galaxy). In particular minor mergers with low-mass satellites, whose stars are primarily assembled at large radii of the massive galaxy can increase the radius (see e.g. Naab+09). This becomes more relevant for AGN galaxies as stellar mass growth via minor mergers is dominant if there is less star formation occurring in the main galaxy.