1 Scope

"Uniform Volumes with Baryonic Physics"
e.g., ILLUSTRIS, EAGLE, MAGNETICUM, + MUFASA, + HORIZON AGN, + MASSIVE BLACK. From Fabian (2012)::

$$\begin{aligned} E_{\rm gal} &\approx M_{\rm gal}\sigma^2 && (1)\\ M_{\rm BH} &\approx 1.4\times10^{-3}M_{\rm gal} && (2)\\ & && (3)\end{aligned}$$

(From Somerville & Davé, 2015) A simple calculation indicates that the amount of energy that must have been released in growing these BHs must exceed the binding energy of the host galaxy, suggesting that it could have a very significant effect on galaxy formation Silk & Rees (1998);

$$\begin{aligned} E_{\rm BH} &\approx 0.1M_{\rm BH}c^2 && (4)\\ &\approx 0.1\times10^8M_\odot c^2 && (5)\\ &\approx 0.1\times10^8\cdot2\times10^{30}c^2 && (6)\\ &\approx 10^7\cdot2\times10^{30}\cdot9\times10^{16} && (7)\\ &\approx 1.8\times10^{54}\text{Joules} && (8)\\ &\approx 1.8\times10^{61}\text{erg} && (9)\\ & && (10)\end{aligned}$$

(Joules in $\mathrm{kg}\cdot\mathrm{m}^2\cdot\mathrm{s}^{-2}$;-)

$$\begin{aligned} E_{\rm BE} &= \frac{3GM^2}{5R} && (11)\\ &= \frac{(3\cdot6.674\times10^{-11}\cdot(10^{11}\cdot2\times10^{30})^2)}{5\cdot3.086\times10^{19}}\text{ Joules} && (12)\\ &\approx 5.19\times10^{52}\text{ Joules} && (13)\\ &\approx 5\times10^{59}\text{ ergs} && (14)\\ & && (15)\end{aligned}$$

for a $M_{\rm Sph}=10^{11}M_\odot$ and 1 kpc bulge. Half this for a 2 kpc bulge etc.
$\Rightarrow$
$E_{\rm BH}\approx35E_{\rm BE}$ for a $M_{\rm BH}=10^8M_\odot$ in a $10^{11}M_\odot$ host galaxy with a 1 kpc bulge.

However, it is still uncertain how efficiently this energy can couple to the gas in and around galaxies. Observational signatures of feedback associated with active galactic nuclei (AGNs) include high-velocity winds, which may be ejecting the cold ISM from galaxies, and hot bubbles apparently generated by giant radio jets, which may be heating the hot halo gas (for recent reviews see Fabian, 2012; Heckman & Best, 2014). AGN feedback is treated using subgrid recipes in current cosmological simulations.

In cosmological simulations, the usual approach is to place seed BHs by hand in halos above a critical mass ($M_{\rm halo} \gtrsim 10^{10} - 10^{11} M_{\odot}$). In some cases, seeds of a fixed mass are used; in others, the seed mass is chosen in order to place the BH on the local $M_{\rm BH}\sigma$ relation. The results that we discuss here are generally insensitive to the details of the seeding procedure. One must then calculate how rapidly these seed BHs accrete gas and grow in mass. The currently predominant model relies on the idea that BH growth is limited by Bondi accretion of mass within the sphere of influence (Bondi 1952), given by

$$M_{\rm Bondi} = \alpha_{\rm boost} \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \tag{16}$$

where $M_{\rm BH}$ is the mass of the BH, c_s is the sound speed of the gas, v is the bulk velocity of the BH relative to the gas, ρ is the density of the gas, and $\alpha_{\rm boost}$ is a boost parameter included because models typically lack the spatial resolution to resolve the Bondi radius (Booth & Schaye, 2009; **?**).

Early models took $\alpha_{\rm boost}$ to be constant (typically $\sim$100), but some simulators make $\alpha_{\rm boost}$ a function of density (e.g., Booth & Schaye, 2009) and some recent simulations resolve the Bondi radius and therefore adopt $\alpha_{\rm boost} = 1$. Typically, the accretion rate is capped at the Eddington rate. As galaxies merge, their BHs are assumed to merge when they come within some distance of each other, typically a softening length (thereby ignoring GR timescales for BH inspiral).

Assuming Bondi accretion requires the accompaniment of strong feedback to obtain BHs that follow the MBH relation, as this simple argument demonstrates (Anglés-Alcázar et al., 2013). Consider two BHs of mass $M_{\rm a}$ and $M_{\rm b}$. If they grow according to the general prescription $\dot{M}_{\rm BH} = D(t)\, M_{\rm BH}^p$ then

$$\frac{d}{dt}\left(\frac{M_a}{M_b}\right) = D(t)\frac{M_a^p}{M_b^p}\left[1 - \left(\frac{M_a}{M_b}\right)^{1-p}\right]. \tag{17}$$

It is "easy to show" that the two masses will diverge if $p > 1$, and they will converge if $p < 1$. For Bondi accretion, $p = 2$; hence for BHs to converge onto an $M_{\rm BH}\sigma$ relation, some strongly self-regulating feedback process must counteract Bondi accretion and make p effectively less than unity. We discuss possible feedback processes in Section 3.3.3, but in general such tuned self-regulation is not so straightforward to arrange, for the usual reason that outward energetic processes tend to escape through paths of least resistance, whereas inflows typically arrive through the dense, harder-to-disrupt gas.

It is worth emphasizing that the widely used Bondi model implicitly assumes that the accreting gas has negligible angular momentum, which

"Transition"	"Maintenance"
Radiative mode	Jet mode
Wind mode	Kinetic mode
Quasar mode, high $\dot{m}$	Radio mode, low $\dot{m}$
Moves mass from Blue to Red	Keeps things Red
Rapid, ($\sim 10^7$ years)	Long-lived (∼Hubble time)
BH accreting efficiently	accretion rate low cf. Eddington rate
hot, nuclear wind feedback	energy injected by relativistic jets
pushes cold gas about	jets in hot halo
Small(er) scales (∼pc-kpc)	Large (halo) scales
Gas-rich/Dissipational Mergers	Hot Haloes & Dry Mergers
Regulates BLACK HOLE mass	Regulates GALAXY mass

Table 1: Modified from Hopkins talk: www.astro.caltech.edu/q50/Program.html

is unlikely to be a good assumption in general. Recently, the problem of dissipating angular momentum to enable BH accretion has received more attention in the cosmological milieu. Hopkins & Quataert (2010, 2011) studied angular momentum transport in disks with nonaxisymmetric perturbations both analytically and in sim- ulations, showing that such secular processes can significantly fuel BH growth, as also suggested by **?** and **?**. Implementing this analytic work into zooms and cosmological simulations, Anglés-Alcázar et al. (2013, 2014) showed that this torque- limited accretion behaves qualitatively differently than Bondi accretion, because in the Hopkins & Quataert (2011) model, the exponent of BH growth is $p = 1/6$. Although this model also must incorporate feedback, such feedback does not have to strongly couple to the inflow to achieve self-regulation.

1.1 The Radiative (or Wind, or Quasar) Mode

(from Fabian, 2012);

$$M_{BH} \sim \frac{f\sigma^5\sigma_T}{4\pi G^2 m_p c} \tag{18}$$

where σ_{T} is the Thomson cross section for electron scattering and f is the fraction of the galaxy massingas.The galaxy is assumed to be isothermal with radius r, so that its mass is $Mgal = 2\sigma^2 r/G$. The maximum collapse rate, $\sim 2fsigma3/G$, is equivalent to the gas content, $fMgal$, collapsing on a free-fall time, $r/sigma$, requiring a power of $\sim f\sigma 5/G$ to balance it, which is limited by the Eddington luminosity, $LEdd = 4\pi GM_{BH}m_p c/\sigma_{\mathrm{T}}$. The argument is based on energy that is necessary but may not be sufficient for ejecting matter (the rocket equation, for example, is based on momentum).

$$\frac{4\pi GM_{\mathrm{BH}}m_p}{\sigma_{\mathrm{T}}} = \frac{L_{\mathrm{Edd}}}{c} = \frac{GM_{\mathrm{gal}}M_{\mathrm{gas}}}{r^2} = \frac{fGM_{\mathrm{gal}}^2}{r^2} = \frac{fG}{r}\left(\frac{2\sigma^2 r}{G}\right)^2 \tag{19}$$

i.e.

$$\frac{4\pi GM_{\mathrm{BH}}m_p}{\sigma_{\mathrm{T}}} = \frac{f4\sigma^4}{G} \tag{20}$$

Cosmological (M)HD Simulations
e.g. AREPO (Springel 2010): moving-mesh code
Illustris
IllustrisTNG
Auriga
FIRE-2
MUFASA

or SPH/Particle Codes
(e.g. GADGET-n, GASOLINE, P-SPH)
for EAGLE
Massive-Black
Magneticum
ERIS
NIHAO
FIRE

or
GRID/AMR Codes
(e.g. RAMSES,
for the HORIZON-AGN)

	ILLUSTRIS	TNG	EAGLE	FIRE	MUFASA
Codes	AREPO	AREPO	GADGET-3 (“ANARCHY”)	?	AREPO
$(\Omega_\mathrm{m}, \Omega_\lambda, \Omega_\mathrm{b}, h, \sigma_8)$			(0.307, 0.693, 0.04825, 0.6777, 0.8288)		
comoving box size			100		
N DM particles			1504^3		
initial baryonic particle mass			1.81×10^6		
DM particle mass			9.70×10^6		
ϵ_com			2.66		
ϵ_prop			0.70		

Table 2: `Ref-L100N1504` model from EAGLE. BH Feedback: BH seeding and accretion. BHs are usually placed by hand as“sink particles”: they can grow in mass by ‘accreting’ material from the surroundings (Pillepich Edinburgh talk, 20171011). Comoving, Plummer-equivalent gravitational softening length (ϵ_com) and maximum proper softening length (ϵ_prop.

2 TNG

Key references:: Weinberger et al. (2017a,b); Pillepich et al. (2017, 2018)

$$\dot{M}_{\rm BH} = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \tag{21}$$

$$\dot{M}_{\rm Edd} = \frac{4\pi\alpha\, G\, M_{\rm BH}\, m_p}{\epsilon_{\rm r}\sigma_{\rm T} c} \tag{22}$$

3 EAGLE

Key references::Schaye et al. (2015); Crain et al. (2015)

3.1 From Schaye et al. (2015)

We choose to implement only a single mode of AGN feedback with a fixed efficiency. *The energy is injected thermally at the location of the BH at a rate that is proportional to the gas accretion rate.*

$$E_{\mathrm{inj,thermal}} \propto \dot{m}_{\mathrm{gas}} \tag{23}$$

This implementation may therefore be closest to the process referred to as quasar-mode feedback.

EAGLE implementation consists of two parts: *(i)* prescriptions for seeding low-mass galaxies with central BHs and for their growth via gas accretion and merging (we neglect any growth by accretion of stars and dark matter) and *(ii)* a prescription for the injection of feedback energy. Our method for the growth of BHs is based on the one introduced by Springel et al. (2005) and modified by Booth & Schaye (2009) and Rosas-Guevara et al. (2015), while our method for AGN feedback is close to the one described in Booth & Schaye (2009).

3.2 From Bower et al. (2017)

3.2 Black holes and galaxies in the EAGLE simulations
In the EAGLE simulations, the accretion on to a black hole is detrmined by a subgrid model which accounts for the mean density, effective sound speed and relative motion and angular momentum of the surrounding gas as detailed in Rosas-Guevara et al. (2015, , with the exception that, in the EAGLE simulations, we do not in- crease the accretion rate to account for an unresolved clumping factor). The model assumes that once gas reaches high densities on sub-kpc scales around the black hole, it will be accreted on to the black hole at the Bondi rate unless its angular momentum is sufficiently high to prevent this. Our simulations allow us to understand how the density on sub-kpc scales around the black hole is determined by the interaction of star formation, feedback and gas accretion (on scales of 1 kpc and greater) without making the simplifications adopted in the analytic model. Importantly, the simulation does not impose a galaxy transition mass scale by varying the black hole feedback efficiency as a function of halo mass or accretion rate. We always assume that the energy generated by feedback is 1.5 per cent of the rest mass energy of the accreted material.

3.3 From McAlpine et al. (2017)

BH seeding follows the prescription first introduced by Springel et al. (2005), whereby BHs are introduced as collisionless sink particles placed in the centres of dark matter haloes more massive than 1.475×10^{10} $M_\odot$, which do not already contain one. BHs enter the simulation with a seed mass $m_{seed} = 1.475 \times 10^5$ $M_\odot$ and subsequently grow via accretion of surrounding gas or mergers with other BHs.

BHs grow via accretion of nearby material at a rate estimated from the modified BondiHoyle formalism introduced in Rosas-Guevara et al. (2015). In short, the model is an extension of the spherically symmetric case of Bondi & Hoyle (1944) accounting now for the circularization velocity of the surrounding gas, capped at the Eddington limit. Contrary to Rosas-Guevara et al. (2015), we do not use an additional boost factor (α).

AGN feedback is implemented as a single mode, where it is injected thermally and stochastically into the surrounding inter- stellar medium (ISM) as per Booth & Schaye (2009). Feedback is performed assuming a single efficiency, independent of halo mass and accretion rate.

McAlpine et al. (2017) report that throughout their investigation, they have consistently found no evi- dence supporting a simple underlying relationship between the rate of a galaxys star formation and the accretion rate of its central BH.

4 FIRE-2

5 MUFASA

6 Illustris

Key references:: Sijacki et al. (2015)
"We find that black holes and galaxies co-evolve at the massive end, but for low mass, blue and star-forming galaxies there is no tight relation with either their central black hole masses or the nuclear AGN activity." (Sijacki et al., 2015).
From (Sijacki et al., 2015)::
2.4.1 Black hole accretion
In the Illustris simulations collisionless black hole particles with a seed mass of 1.42×10^5 $M_\odot$ ($10^5 h^{-1}$ M_{odot}) are placed with the aid of the on-the-fly friends-of-friends (FOF) algorithm in all haloes more massive than 7.1×10^{10} $M_\odot$ that do not contain a black hole particle already. Thereafter, the black hole seeds can grow in mass either through gas accretion, which we parametrize in terms of Ed- dington limited BondiHoyleLyttleton-like accretion (for further details see Di Matteo et al., 2005; Springel et al., 2005),

or via mergers with other black holes. At $z = 4$ our high-resolution Illustris simulation already tracks 9414 black holes, at $z = 2$ this number more than doubles leading to 24 878 black holes in total, while at $z = 0$ there are 32 542 black holes in total with 3965 black holes more massive than 10^7 $M_\odot$ black hole accretion.

	ILLUSTRIS	TNG
BH Seed Mass	$1 \times 10^5 h^{-1}$ $M_\odot$	$8 \times 10^5 h^{-1}$ $M_\odot$
FoF Halo Mass for BH seeding	$5 \times 10^{10} h^{-1}$ $M_\odot$	$5 \times 10^{10} h^{-1}$ $M_\odot$
BH accretion	$\alpha = 100$ Boosted Bondi-Holye	Unboosted Bondi-Hoyle (w/v_A)
BH accretion	parent gas cell, Eddington limited	nearby cells, Eddington limited
BH positioning	fixed to halo potential minimum	fixed to halo potential minimum

Table 3: What are the similiarties and differences between Proto-stellar and AGN accretion disks?

7 Conroy & White

8 Some general and left-field thoughts

How *exactly* does the energy output from the central engine shutdown the SF??
(Do we observe?) Ripples/concentric rings of shut-down star-formation??

9 Glossary

AREPO:: – moving-mesh code (Springel, 2010).
GADGET:: – SPH/Particle code
GASOLINE:: –SPH/Particle code
P-SPH:: –SPH/Particle code

9.1 Radiative Feedback

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10 Resources

Evidence For Feedback: A highly biased review

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