Black Hole Feedback

What is it?
What does it do?

GALFORM: RGB + Benson, Lagos, Fanidakis, Frenk, Lacey, Baugh & Cole +++

EAGLE: Booth, Dalla Vecchia, Crain, Furlong, Rosas-Guevara, Schaye, RGB, Theuns, McCarthy, Springel, Frenk, White+++
“Micro-physics” vs “Macro-physics”

• Hydrodynamic simulation
  – You know the equations, so solve them
    • SPH
    • AMR
  – Add cooling (OK), star formation (?), supernovae (?), black holes (?)

• “Semi-analytic” model
  – Follow the spirit of the original papers…
  – Reduce the problem to a coupled set of non-linear differential equations

\[
\rho_i = \sum m_j W(r_{ij}, h) \\
P_i = K_i \rho_i^\gamma \\
\frac{dv_i}{dt}_{\text{hydro}} = -\sum m_j \left[ \frac{\rho_i}{\rho_j} \nabla W_{ij}(h_i) + \frac{\rho_j}{\rho_i} \nabla W_{ij}(h_j) \right] \\
\frac{dv_i}{dt}_{\text{visc}} = -\sum m_j \Pi_{ij} v_{ij} \quad \text{where } \Pi_{ij} \text{ is a viscosity} \\
\frac{dK_i}{dt} = \frac{1}{2} \rho_i^{\gamma-1} \sum m_j \Pi_{ij} (v_{ij} \cdot \nabla W_{ij})
\]

A little history

- The puzzle is to reshape the halo mass function to obtain the galaxy mass function.
- It needs a lot of tweaking!
- “the physics of galaxy formation” = understanding the relationship between these two mass functions.
- “Phenomenological” (“semi-analytic”) models have been very successful once BH feedback is included.

Black Holes may be important!

- Thermal energy of a \(10^{13} \, \text{M}_\odot\) halo: \(10^{61}\) erg
- Accretion energy of a \(10^9 \, \text{M}_\odot\) black hole: \(2 \times 10^{62}\) erg

Data from Bell et al; Li & White

Example from Bower et al 2006/2012
A little history

BH scaling relations

Galaxy Star Formation Rates

Evolution of stellar mass function

QSO luminosity evolution (Fanidakis et al 2012)

Bower et al. (2006; 2008; 2012) (see also Croton et al. 2006; De Lucia & Blaizot 2007; Somerville et al. 09)
Three Reasons to Believe

• The black-hole - galaxy bulge correlation
• The break in the stellar mass function
• The X-ray scaling relations of galaxy groups
The black-hole - galaxy bulge correlation

• Does black hole formation truncate the formation of the bulge?

• Does bulge formation strangle fuelling of the black hole?

• Is it simply the central limit theorem? (Janhke et al 2011)
The black-hole - galaxy bulge correlation

• Does black hole formation truncate the formation of the bulge?

• Does bulge formation strangle fuelling of the black hole?

• Is it simply the central limit theorem?

What observations can distinguish these?
The black-hole - galaxy bulge correlation

• What triggers the growth of the black hole?
  – Mergers?
  – Disk instabilities?
  – “cold flows”

But mergers are rather rare!
Fits in with increase in the gas abundance of galaxies

Eh?

Springel, Di Matteo et al; RGB 06; White & Frenk 91; Keres 2003
The black-hole - galaxy bulge correlation

- What triggers the growth of the black hole?
  - Mergers?
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But mergers are rather rare!

Fits in with increase in the gas abundance of galaxies Eh?
• What triggers the growth of the black hole?
  – Mergers?
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  – “Cold flows” (White & Frenk 91; Keres et al. 03)

But mergers are rather rare!

Fits in with increase in the gas abundance of galaxies

Eh?

Simulation from the EAGLE project: illustrates gas content of the universe
Three Reasons to Believe

- The black-hole - galaxy bulge correlation
- The break in the stellar mass function
- The X-ray scaling relations of galaxy groups
The break in the stellar mass function

- What sets the cut-off scale?
  - Rapid cooling or hydrostatic halo cooling?
  - The mode of black hole fuelling: accretion disk or Bondi?

- SS vs ADAF disk accretion?

Nothing to do with black holes!

...or...
The break in the stellar mass function

- What sets the cut-off scale?
  - Rapid cooling or hydrostatic halo cooling?
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...or...

SS vs ADAF disk accretion?

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The break in the stellar mass function

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…or…

Nothing to do with black holes!

SS vs ADAF disk accretion?
The break in the stellar mass function

- How does the black hole feedback create the break?
  - Expelling the ISM from the galaxy?
  - Heating the surrounding gas?
  - Expelling the surrounding IGrM from the halo?

What stops gas falling back?
Why does black hole affect the whole galaxy?

Feedback energy heats the gas halo, cancelling radiative cooling
Feedback energy overheats the gas halo, ejecting it
Feedback expels the ISM of the galaxy.
Perhaps there’s a connection to…
Three Reasons to Believe

- The black-hole - galaxy bulge correlation
- The break in the stellar mass function
- The X-ray scaling relations of galaxy groups

AGN redistributes halo gas

Width set by formation history

RGB et al 2008
The X-ray scaling relations of galaxy groups

- What causes the low $L_x$ of galaxy groups?
  - Gas converted to stars
  - Gas expelled at early times
  - Gas heated as the halo grows

By radio galaxies?
By Quasars?

The X-ray scaling relations of galaxy groups

- What causes the low $L_x$ of galaxy groups?
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  - Gas heated as the halo grows

...or...

Feedback energy overheats the gas halo, ejecting it

By radio galaxies?

By Quasars?
A quick lesson on thermodynamics

“Entropy” \( (T/\rho^{2/3}) \) is a key variable

- Does not depend on dark matter halo
- Only changed by heating and cooling
- Fixed cooling time \( \sim \) fixed entropy
The X-ray scaling relations of galaxy groups

- What causes the low $L_x$ of galaxy groups?
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McCrath et al 2011; Gabor et al 2011; RGB et al 2012
The X-ray scaling relations of galaxy groups

- What causes the low $L_x$ of galaxy groups?
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By radio galaxies?  
By Quasars?

Feedback energy overheats the gas, ejecting it

$z=3$ ?

$z=0.5$ ?

Quasar heating drives galaxy mass function to a power-law

Halo heating targets most massive haloes

Heating by QSO
Heating by radio galaxies

EAGLE project: Rosas-Guevara 2012
The Eagle Project: testing these ideas in a simulated universe

Which is the universe with black holes?
The Eagle Project:

testing these ideas in a simulated universe

Which is the universe with black holes?

The EAGLE simulation is a Dirac/VIRGO consortium flagship project
Three Reasons to Believe: what’s the answer?

• The black-hole - galaxy bulge correlation
• The break in the stellar mass function
• The X-ray scaling relations of galaxy groups

My opinion! (as a theorist!)

The formation of the bulge limits fuelling of the black hole

The hydrostatic/rapid cooling regime sets the mass-scale for the break in the mass function

Expelling gas from the halo as it grows prevents further growth of the galaxy and creates the deficit of gas in galaxy groups

• but what do observations tell us about the real universe?
Three Reasons to Believe:
what’s the answer?

- The black-hole - galaxy bulge correlation
- The break in the stellar mass function
- The X-ray scaling relations of galaxy groups

The aim of this meeting:
- Can theorists agree on a picture?
- Can observers tell us the answers?

Some of the issues tackled in the next session:
- Origin of scaling relations: Bennet, Balantyne, Bongiorno, Civano, Goulding
- Effect of BH activity of galaxies: Rosario, Mullaney, Hickox, Kocevski, Disken, Aird, Glikman, Alexander

...but what do observations tell us about the real universe??

Three Reasons to Believe:
what’s the answer?
Summary: The task of this workshop!

• The black-hole - galaxy bulge correlation
  – Does black hole formation truncate the formation of the bulge?
  – Does bulge formation strangle fuelling of the black hole?
  – What triggers the growth of the black hole?

• The break in the stellar mass function
  – What sets the cut-off scale?
    • Hot vs Cold accretion or SS vs ADAF disk?
  – How does the black hole feedback create the break?
    • Expelling the ISM; or Heating/Expelling the IGrM

• The X-ray scaling relations of galaxy groups
  – What causes the low $L_x$ of galaxy groups?
    • Quasars or radio galaxies?
The Eagle Wedding Cake

Explore a wide range of physics

Simulate a large volume of the universe

Resolve the Jeans instability in galaxy disks!

100 Mpc

Match key observational data at z=0!
Some details of the Eagle calculations

- N-body + SPH simulation using Gadget3

- Particle mass
  - $10^6$ Msol gas particles
  - Maximum resolution of 500 pc
  - Sufficient to resolve onset of Jeans instability in disks

- Scaling up in box size
  - Smallest runs in 6 Mpc box
  - Large haloes calculated using zoom technique
  - Small boxes take days to complete
  - Used to explore effect of parameter choices

- Largest run:
  - $100\text{Mpc}^3$ box
  - $1500^3$ DM particles + $1500^3$ SPH particle
  - This run will take 6 months

See Poster by Michelle Furlong
Sub-grid physics in EAGLE

• 9 element chemical enrichment model (Wiersma et al. 2008)
  – Cooling including photoionisation
  – Updated yields and SNIa rates, including mass loss from AGB stars

• Star formation law from Dalla Vecchia & Schaye 2008
  – Implicitly uses Kennicut-Schmidt relation
  – Metallicity dependent star formation threshold

• AGN feedback from Booth & Schaye 2009
  – Important impact on brightest galaxies
  – Model results in correct scaling of X-ray properties of groups and clusters

• Thermal feedback in EAGLE
  – Stochastically heat particles to target temperature (Dalla Vecchia & Schaye 2012)
  – Heating to fixed T ensures particles are hot enough not to cool immediately
  – Probability of heating ensures that correct energy is input

• Learning from Semi-Analytics:
  • Heat to a fixed temperature or scale with halo mass?
  • Keep energy input per SN fixed, or scale it with halo mass?
  – Select the best physics by comparison to the data
  – Ultimately justify the approach by high resolution calculation
Eagle - the movie

Only gas is shown!

• Colour scale:
  • Blue: cold gas (ISM), $T < 10^{4.5}$
  • Green: warm gas, $10^{4.5} < T < 10^{5.5}$
  • Red: hot gas $T > 10^{5.5}$