AGN Feedback-driven
Star Formation in Galaxies

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Introduction: AGN Feedback

- Galaxies harbour super-massive ($\sim 10^6 - 10^9 M_\odot$) black holes at their centres.

- Active Galactic Nucleus (AGN) Feedback: radiative and kinetic modes.

**accretion energy:**

$$E_{BH} \sim \eta_{acc} M_{BH} c^2$$

**binding energy:**

$$E_{galaxy} \sim M_{bulge} \sigma^2$$

$$\frac{E_{BH}}{E_{galaxy}} \gg 1$$

AGN feedback plays an important role in the formation and evolution of galaxies.
Black hole-galaxy relations

Observational correlations between central black hole (BH) and host galaxy:

- BH mass vs. bulge stellar velocity dispersion \((M_{BH} \sim \sigma^4)\)
- BH mass vs. bulge stellar mass \((M_{BH} \sim 10^{-3} M_*)\)

Several different AGN feedback models in the literature:

\((Silk \ & \ Rees \ 1998, \ Fabian \ 1999, \ Fabian \ et \ al. \ 2002, \ King \ 2003, \ 2005, \ Murray \ et \ al. \ 2005, \ Silk \ & \ Nusser \ 2010, \ ... \ Fabian \ 2012 \ for \ a \ review)\)

\[
M_{BH} = \frac{f_g \sigma^4}{\pi G^2 m_p} \sigma^4 \quad (= M_\sigma)
\]

- AGN feedback invoked to suppress star formation in the host galaxy (negative feedback)
The size evolution of massive galaxies

- “discovery” of the significant evolution of massive galaxies since $z \sim 2$

$z \sim 2$: $M_\star \sim 10^{11} M_\odot$, $R_e \sim 1$ kpc

Szomoru et al. (2012)
The role of AGN feedback

AGN feedback triggering star formation in the host galaxy?

(Ishibashi & Fabian 2012)

Consider the direct effects of radiation pressure on dusty gas (cf Fabian 1999)

General form of the equation of motion:

\[
\frac{d}{dt} [M_g(r) \dot{r}] = \frac{L}{c} - \frac{GM_g(r)M_{DM}(r)}{r^2}
\]

- L: central luminosity
- \(M_g(r)\): enclosed gas mass
- \(M_{DM}(r)\): dark matter mass

→ follow temporal evolution of the shell in the galactic halo

→ determine the shell's escape and/or trapping conditions
Isothermal potential

Isothermal sphere:

\[ \rho(r) = \frac{\sigma^2}{2\pi Gr^2} \]

\[ r(t) = \sqrt{r_0^2 + 2r_0v_0t + \left( \frac{GL}{2fgc\sigma^2} - 2\sigma^2 \right) t^2} \]

- \( r_0 \): initial position
- \( v_0 \): initial velocity

- critical luminosity (for shell expansion):

\[ L_c = \frac{4fgc\sigma^4}{G} \]
radial velocity:
\[
v(r) = \sqrt{\frac{r_0^2 v_0^2}{r^2}} + \left( \frac{G L}{2 f_g c \sigma^2} - 2\sigma^2 \right) \left( 1 - \frac{r_0^2}{r^2} \right)
\]

asymptotic velocity:
\[
v_\infty = \sqrt{\left( \frac{G L}{2 f_g c \sigma^2} - 2\sigma^2 \right)}
\]

escape condition:
\[
v_\infty \geq v_{esc} \implies \sqrt{\left( \frac{G L}{2 f_g c \sigma^2} - 2\sigma^2 \right)} \geq 2\sigma
\]

- critical luminosity (for shell escape):
\[
L \geq L'_c = \frac{12 f_g c \sigma^4}{G} = 3L_c
\]
Implications for the $M$-$σ$ relation

Eddington luminosity:

$$L_E = \frac{4\pi G c m_p}{\sigma_T} M_{BH} = \frac{4\pi G c}{\kappa} M_{BH}$$

Escape condition in the isothermal potential:

$$M_{BH} \geq 3 \frac{f g \kappa}{\pi G^2 \sigma^4} = 3 M_σ$$

(Ishibashi & Fabian 2012)

- $M_{BH} = M_σ$ is not sufficient to clear gas out of the galaxy
- $M_{BH} > 3M_σ$ is required for matter to escape the galaxy

Black holes lying on the observed $M$-$σ$ relation cannot expel material from the galactic halo by radiation pressure alone (Silk & Nusser 2010)
Triggering of star formation

Squeezing of the cold ISM during the ejection process may trigger star formation.

Star formation rate:

\[ \dot{M}_* \sim \epsilon_\star \frac{M_g(r)}{t_{\text{flow}}(r)} \]

\[ \dot{M}_* \sim \epsilon_\star \frac{2f_g\sigma^2}{G} v(r) \]

\[ \dot{M}_{*,\infty} = \dot{M}_*(r \to \infty) \sim \epsilon_\star \frac{2f_g\sigma^2}{G} v_\infty \]

- star formation rate: \( \dot{M}_* \sim 100M_\odot \text{ yr}^{-1} \)
- additional stellar mass: \( M_* \sim 10^{10} M_\odot \)
Size and mass growth

Newly formed stars drop out from the outflowing shell → radial orbits

Initial conditions:
\[ r_*,0 = r_{\text{shell}} \quad v_*,0 = v_{\text{shell}}(r_*,0) \]

Mean radius:
\[ \bar{r} = \frac{\int r(t) dt}{\int dt} \]

Size increase:
\[ \sigma < v_\infty < 2\sigma \quad \Rightarrow \quad r_*,0 < \bar{r} < 2r_*,0 \]

New stars formed at increasingly larger radii in the galaxy → outer growth

Several AGN feedback-driven star formation episodes may contribute to galaxy growth
Some observational predictions

( Ishibashi et al. 2013 )

- Significant increase in galaxy size, but little increase in stellar mass
- Good correlation between star formation and outflow properties
- Compton heating may inhibit star formation in the central region
- Negative radial colour gradient
- Dust extinction and reddening → obscured star formation
- Cyclic scenario and recycling of material
  (cf Thom et al. 2012, Prochaska et al. 2013, ...)
- AGN feedback-triggered star formation at high redshift (z~2)
Observations: “inside-out” growth

- strong increase in size, but modest increase in stellar mass
- mass growth at large radii, ~no growth at small radii
- compact galaxies as central cores of present-day ellipticals?

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*Patel et al. (2012)*

![Graph showing $\log \Sigma (M_\odot \text{ kpc}^{-2})$ vs. $r (\text{kpc})$ with different redshift ranges: $0.25 < z < 0.50$, $0.50 < z < 1.0$, $1.0 < z < 1.5$, $1.5 < z < 2.0$, $2.0 < z < 2.5$, $2.5 < z < 3.0$.]

*Bezanson et al. (2009)*

![Graph showing Stellar Density [$M_\odot \text{ kpc}^{-3}$] vs. Radius [kpc] with different masses: $M \approx 1 \times 10^{11} M_\odot$, $3 \times 10^{11} M_\odot$, $5 \times 10^{11} M_\odot$.]
Two main physical models discussed in the literature: “puffing-up” and “mergers”

- **“Puffing-up”**: expansion at fixed stellar mass 
  *(Fan et al. 2008, 2010)* but: mild evolution in $\sigma$ since $z \sim 2$ 
  *(Cenarro & Trujillo 2009)*

- **“Major mergers”** (~1:1): linear increase in size and mass but: very massive ($\sim 10^{12} M_\odot$) galaxies
**Physical interpretations II**

- **“Minor mergers”** (~1:10):
  
  significant increase in size with relatively small increase in mass, accreted material in outer regions (e.g. Naab et al. 2009, Oser et al. 2012, ...)

but: CANDELS survey suggests minor mergers may only explain the galaxies size growth at $z < 1$ (Newman et al. 2012)

$\rightarrow$ additional physical mechanisms required at $z > 1$

\[\text{Newman et al. (2012)}\]
AGN feedback-triggered star formation?

Different physical interpretations: puffing-up, major mergers, minor mergers, ...

- New stars formed in the AGN feedback-driven outflow
- Observations: “inside-out” growth pattern
- Dust required to drive feedback → dust-obscured star formation
- Feedback-triggered star formation mode may be important at high z

Minor mergers may explain the observed size growth at low redshifts (0 < z < 1), while AGN feedback-driven star formation may provide the additional mechanism required to explain the rapid growth observed at higher redshifts (1 < z < 2)