AGN Feedback: Where, When & How?

rachel somerville
Max Planck Institute for Astronomy, Heidelberg
with thanks to T. Kimm, C. Maulbetsch, F. Fontanot, B. Moster (MPIA)
P. Hopkins, L. Hernquist, T.J. Cox, B. Robertson (CfA)
the GEMS team
the GOODS team
K. Noeske & the AEGIS team
If we accept the basic paradigm of $\Lambda$CDM:

- cosmological parameters well constrained
- structure formation in dominant dark matter component accurately quantified
- formation history of dark matter halos represented by ‘merger trees’

Springel et al. 2006

Wechsler et al. 2002
mapping dark matter to baryons

- in order to reconcile CDM (sub)halo mass function with galaxy LF or stellar MF, cooling/star formation must be inefficient overall

- baryon/DM ratio must be a strongly non-linear (and non-monotonic) function of halo mass

Somerville & Primack 1999; Benson et al. 2003
empirical mapping between halo mass & stellar mass

‘special’ scale for star formation
\( M_h \sim 10^{12} M_{\text{sun}} \)

(we also match observed galaxy clustering as a function of stellar mass)

in the spirit of Kravtsov et al. 2004, Tatsitsiomi et al. 2004, Conroy et al. 2006

\[ M_{\text{bar}} / M_{\text{halo}} f_b \]

Milky Way (Klypin, Zhao & rss 2003)

stellar masses of BCG’s (Lin & Mohr 2004)

Moster, rss et al. in prep
galaxy formation in a CDM Universe

- gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and expel?) cold gas
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids

White & Frenk 1991; Kauffmann et al. 1993; Cole et al. 1994; Somerville & Primack 1999
the galaxy overcooling problem

Somerville & Primack 1999; Cole et al. 2001; Kauffmann et al. 1999; Benson et al. 2003; Croton et al. 2006; *n.b. also seen in hydro sims*

baryons expelled by SN-driven winds

stellar mass function

---

**Diagram Notes:**

- The left graph shows the baryonic fraction $M_{\text{bar}}/M_{\text{halo}}/f_b$ as a function of $\log \left( M_{\text{(sub)halo}}/M_{\text{sun}} \right)$, with data points and model curves illustrating the trend.
- The right graph depicts the stellar mass function with $\log dN/(d\log M_*) [\text{Mpc}^{-3} \text{dex}^{-1}]$ plotted against $\log M_* [M_{\text{sun}}]$, highlighting the distribution of stellar masses across different mass ranges.

---

**Legend:**

- ssh et al. 2007

---

**Additional Text:**

- The overcooling problem is a significant issue in galaxy formation theory, where galaxies are expected to be more massive than observed due to insufficient star formation.
- Models such as those by Somerville & Primack (1999) and Cole et al. (2001) have highlighted the importance of baryons expelled by supernova (SN) driven winds.
- Benson et al. (2003), Kauffmann et al. (1999), and Croton et al. (2006) have also contributed to understanding these dynamics through hydrodynamic simulations.
Cooling Flow Problem

- X-ray data allow us to determine density and temperature of ICM
- Cooling times in central regions short -- would expect significant cooling
- yet correspondingly large amounts of stars or cold gas not observed

Peterson & Fabian (2006)
local universe: galaxies are bimodal in color, morphology, & structure

old stars

young stars

strong correlation between stellar mass & type

Baldry et al. 2003

SDSS
red sequence, color bimodality, and the strong correlation with morphology persists to at least $z \sim 1-1.5$

see also Faber et al. 2004
Pre-AGN FB models could not produce enough massive red (dead) galaxies
why are massive galaxies red/dead? quenching and the critical mass

- most low-mass galaxies lie on a star forming ‘main sequence’
- appearance of ‘quenched’ galaxies above $m_* \sim m_{\text{crit}} \sim 3 \times 10^{10} \, M_\odot$
- $m_{\text{crit}}$ also corresponds to the transition between disk- and spheroid-dominated galaxies (Kauffmann et al. 2003)
- seen to $z \sim 1.5-2$ (Noeske et al. 2007; Bundy et al. 2006; Papovich et al. 2006; van Dokkum et al. 2006)

Brinchmann et al. 2003
massive galaxies in CDM simulations continue to accrete cold gas and form stars-->too many massive blue disk galaxies not enough massive red spheroid dominated galaxies at all redshifts $z<\sim 2$ (e.g. rss 2004)
color/bimodality problem: SPH simulations

- semi-analytic models & SPH simulations produced an inverted CM relation
- generically did not produce color bimodality

Dave et al., see also Nagamine et al.
enter ‘AGN feedback’...

• need mechanism to:
  – reduce/stop cooling in massive halos
  – quench star formation in massive galaxies

• n.b. stellar/SN feedback does not work
  – not enough energy
  – little/no star formation in the systems where the energy input is needed

Ferrarese & Merritt 2000
Gebhardt et al. 2000
AGN feedback 1: bright mode

- optical/X-ray luminous AGN/QSO, produced during periods of efficient feeding (mergers?)
- high accretion rates ($0.1-1 \, L_{\text{Edd}}$), fueled by cold gas via thin accretion disk --> BH grows rapidly
- rare-->duty cycle short
- thermal coupling of AGN energy with ISM is probably fairly weak (<5%)

Di Matteo, Springel & Hernquist 2005
Hydrodynamic simulations of galaxy mergers including black hole growth and feedback

- self-regulated BH growth, reproducing $M_{BH}$-σ relation (di Matteo et al. 2004)
- AGN-driven wind removes residual cold gas at the end of the merger, leading to lower SFR and redder colors in the spheroidal remnant (Springel et al. 2004)
- characteristic AGN ‘lightcurve’
circumstantial evidence that AGN are associated with quenching of SF...

- weak AGN at z=0 live in massive, spheroids with young stellar pops; many are post-starburst (Kauffmann et al. 2003)
- strong correlation of $\sigma$ with color; almost all ‘green valley’ galaxies host weak AGN (Kaviraj et al. 2006; Kauffmann et al. 2006; Salim et al. 2007)
- similar results seen for AGN to z~1 (GEMS; Sanchez et al. 2004; AEGIS; Pierce et al. 2006)
AGN feedback 2: Radio Mode

- many massive galaxies are ‘radio loud’
- radio activity believed to be associated with BH’s in ‘low accretion state’ (low Eddington ratio, $<10^{-3}$) -- (spherical, Bondi accretion or ADAF?)
- jets often associated with cavities visible in X-ray images
- coupling of jet energy with hot gas very efficient
effervescent heating

- Intermittent jet with a duty cycle of $\sim 10^7$ yr leads to efficient heating of a large fraction of the cluster gas (Ruszkowski et al. 2004)
- Combination of sound waves, weak shocks and bubble-ICM interface
- Heating rate may be able to balance radiative cooling for reasonable input luminosities


Bruggen, Ruszkowski & Hallen 2005
• simulations produce cavities and ‘cold fronts’ that look similar to those seen in X-ray images of clusters

Bruggen, Ruszkowski & Hallen 2005

Chandra image of hot gas in real cluster

Fabian et al.
X-ray bubbles as ‘calorimeters’

jet power (measured via bubble energy) scales with BH mass (n.b. ‘PV’ argument may underestimate energy e.g. Binney et al. 2007)

Allen et al. 2006
Best et al. 2006
see also Birzan et al. 2004
The challenge of simulating BH growth and AGN FB in a cosmological context

- **Dynamic range:**
  - Gpc (luminous QSO)
  - few 100 Mpc (LSS)
  - 10’s of kpc (ICM, jets)
  - sub-kpc (star formation, stellar FB)
  - few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  - pc & sub-pc (accretion disk, BH mergers, etc)

- **Poorly understood physics** (B-fields, conduction, cosmic ray pressure, turbulence, feeding problem, ...)
NEW Self-consistent model for the co-evolution of galaxies, black holes, and AGN

- top-level halos start with a \( \sim 100 \, M_{\text{sun}} \) seed BH
- mergers trigger bursts of star formation and accretion onto BH; **efficiency** and **timescale** parameterized based on hydrodynamical merger simulations (\( \mu, B/T, V_{c}, f_{g}, z; \) Cox et al., Robertson et al.)
- BH accrete at Eddington until they reach ‘critical mass’, then enter ‘blowout’ (power-law decline) phase
  \[
  \frac{\text{d}m_{\text{acc}}}{\text{d}t} = \frac{m_{\text{Edd}}}{1 + (t/t_{Q})^{\beta}}
  \]
- energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

rss, Hopkins, Hernquist, Cox, Robertson et al. 2007
momentum-driven winds: critical mass

\[ L_{\text{crit}} = \frac{4 f_g c \sigma^4}{G} \]

Murray, Quataert & Thompson 2004

\[ L_* = \eta_{\text{Edd}} L_{\text{Edd}} \]
\[ M_{*,\text{crit}} / M_{\text{sun}} = 0.12 \eta_{\text{Edd}}^{-1} \left( \frac{f_g}{0.1} \right) \left( \frac{\sigma}{\text{km/s}} \right)^4 \]

rss et al. 2007

SDSS 'transition mass' ~3x10^{10} M_{\text{sun}}

critical mass (M_{\text{sun}})

critical bulge mass

velocity dispersion (km/s)

MBH-\sigma rln
momentum-driven winds: galactic outflows

\[
\frac{\varepsilon_{\text{wind}} E_{BH}}{c} = M_{out} v_{esc}
\]

\[
E_{BH} = \eta \frac{dm_{acc}}{dt} c^2
\]

\[
\frac{dM_{out}}{dt} = \varepsilon_{\text{wind}} \eta \frac{c}{v_{esc}} \frac{dm_{acc}}{dt}
\]

from hydrodynamic simulations of merging galaxies (Springel, di Matteo & Hernquist; Hopkins et al.)
“radio mode” heating

- assume continuous ‘Bondi-like’ accretion

\[ \dot{m}_{\text{acc},R} = f_{\text{Edd},R} L_{\text{Edd}} M_{\text{BH}}^{\alpha_R} \]

- fixed fraction \( \kappa \) of released energy in kinetic form (jet)

Allen et al. clusters; Best et al. study w/ factor 6 boost (Binney et al. 2007)
hot vs. cold flows

- when $r_{\text{cool}} < r_{\text{ff}}$, gas is shock heated to virial temperature then cools in a “cooling flow”
- when $r_{\text{cool}} > r_{\text{ff}}$, gas never shock heats, “falls in cold”
- halos with primarily cold vs. hot flows separated by a critical mass of few $10^{11}-10^{12} \, \text{M}_\odot$ (e.g. Birnboim & Dekel 2003; Keres et al. 2004)
- heating by radio jets may only be effective when a quasi-static hot gas halo is present (i.e. in large mass halos; Cattaneo et al. 2006)
radio mode heating

- predicted heating rate is subtracted from cooling rate at each timestep in which cooling is from a quasi-static hot halo
- ‘cold mode’ cooling is unaffected
radio mode heating

- energy is sufficient to offset cooling in massive halos
total mass

stellar/bulge mass

cold gas

black hole mass

SFR

BH accretion rate
predicted $M_{\text{BH}}$-$M_{\text{bulge}}$ relationship

in our model, arises from ‘bright mode’ feedback

matches slope & scatter of observed relation

large symbols:
Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex

cyan: predicted median, 10th, & 90th percentile
predicted scatter: ~0.15 dex

rss et al. 2007
implementing the heating term leads to a much-improved galaxy mass/luminosity function at z~0
stellar mass function by type

rss et al. 2007
baryonic mass function

cold gas (H_1 + H_2)  stars plus cold gas
luminosity functions
massive galaxies are quenched

SDSS data

simulation

specific star formation rate

log(SFR/\(M_\odot\))

log \(m_\ast\) [\(M_\odot\)]

‘active’

‘passive’
massive galaxies are quenched

- the transition from active to quenched galaxies occurs at the right stellar mass scale $\sim 3 \times 10^{10} M_{\text{sun}}$ (Kauffmann et al.)
- some indication of ‘over-quenching’
quenching caught in the act?

‘strong’ AGN occur in the most massive galaxies that still have star formation... in qualitative agreement with observations (e.g. Kauffmann et al. 2003, Salim et al. 2007)
history of star formation and black hole accretion

star formation history

QSO luminosity density

starbursts

AGN
“bright” vs. “radio” mode accretion

BH growth over most of cosmic history is dominated by bright mode, in agreement with Soltan arguments. Radio mode becomes more important at late times (z<1).
stellar mass function evolution

data from Borch et al. (COMBO-17);
Drory et al. (MUNICS, GOODS, FDF)  rss et al. in prep
quenching of massive galaxies

massive galaxies were more actively star forming in the past

Papovich et al. 2005
‘staged’ star formation

data from AEGIS
Noeske et al. (2007)
downsizing?

• more rapid decline in SSFR for massive galaxies (but only mildly; Zheng et al. 2007)

• overall decline due to gas consumption, plus quenching for massive objects

• SFR estimates at z~2 contaminated by AGN?
SF quenching as a function of galaxy mass and environment

- make use of SDSS DR5 group catalog (van den Bosch & collaborators)
  - galaxies assigned to groups using FOF
  - halo masses estimated
  - central and satellite galaxies identified
- also make use of SFR from GALEX-matched sample (Salim et al.)
log galaxy (stellar) mass

log halo mass

central

satellite

g-r color

by SSFR (NUV-r)

log halo mass
log galaxy (stellar) mass

log halo mass

central

satellite

observed (by color)

AGN wind + radio mode
observed
(by SSFR)

central

satellite

log galaxy (stellar) mass

log halo mass

AGN wind + radio mode

log galaxy (stellar) mass

log halo mass
central galaxies
satellite galaxies
where are the black holes?
where are the AGN?
fraction of quenched galaxies

halo mass
Summary

• ‘old’ CDM-based galaxy formation models suffered from a set of interlinked problems
  - overcooling/cooling flow problem & obese galaxies
  - color-magnitude/color bimodality problems at high and low redshift

• Two kinds of AGN feedback are important:
  - “bright mode” feedback may regulate BH formation & temporarily quench star formation, but is not a viable ‘maintenance’ mechanism
  - low-accretion rate ‘radio mode’ FB a promising mechanism for counteracting cooling flows over long time scales
  - combined effects of strangulation plus winds quenches star formation in massive galaxies

• downsizing and “staged” star formation: massive galaxies ok, low-mass galaxies a problem. ditto AGN.

• studying demographics and habitats of quenched galaxies, massive BH and AGN activity a very promising way to constrain models