The role of black holes in galaxy formation and evolution

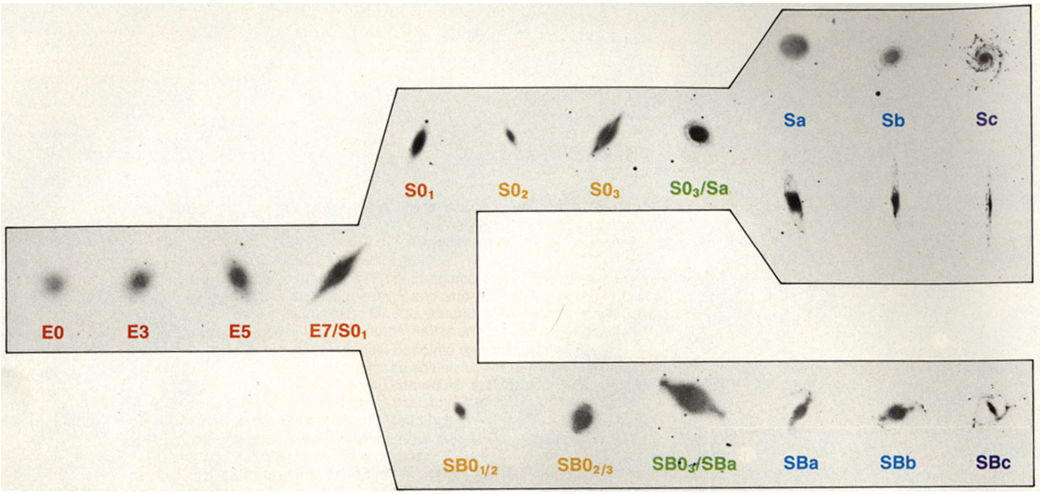
Andrea Cattaneo

Astrophysikalisches Institut Potsdam

Extragalactic nebulae

The Hubble Sequence

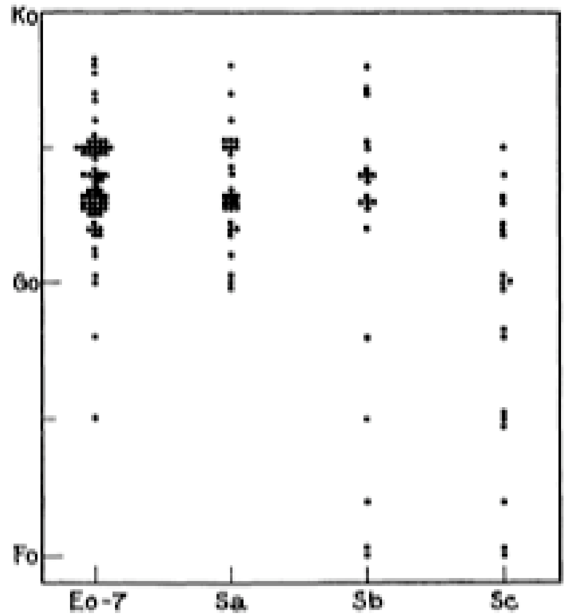
Hubble 26



The colour/morphology relation

Humason 36

Spectral type



Morphological type

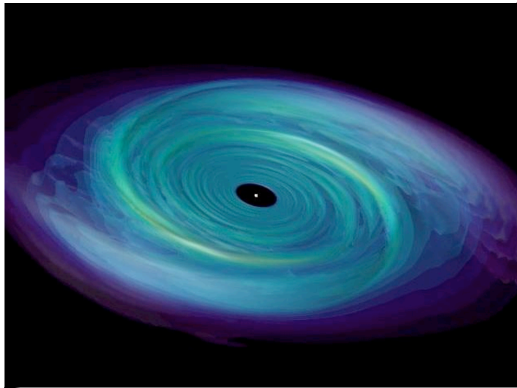
Galactic Nuclei as Collapsed Old Quasars

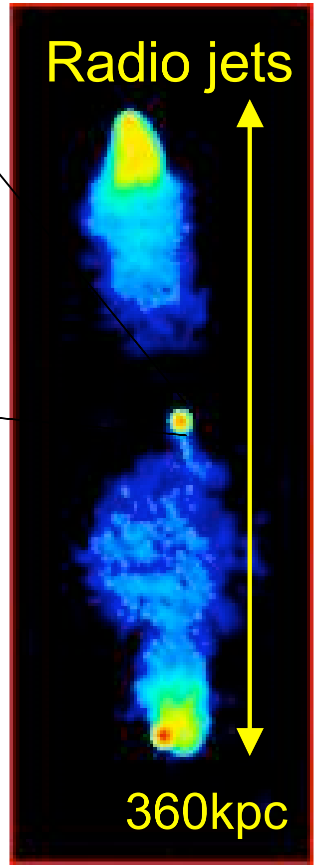
Lynden-Bell 69

$$E/m = 1/2v^2 - GM_\bullet/r = -1/2GM_\bullet/r = -\varepsilon c^2$$

$$\varepsilon \approx 0.06\text{-}0.4$$

Bardeen 70





No larger than the Solar System, the BH accretion disc can outshine the host galaxy

Most of the energy is dissipated by viscous torques in the accretion disc and radiated

Shakura & Sunyaev 76

AGN Feedback

Galactic Winds

Mathews & Baker 71

Why do most ellipticals show no evidence for interstellar mass in view of the many different kinds of stars?

Elliptical Galaxy Cooling Flows Without Mass Drop-Out

Tabor & Binney 93

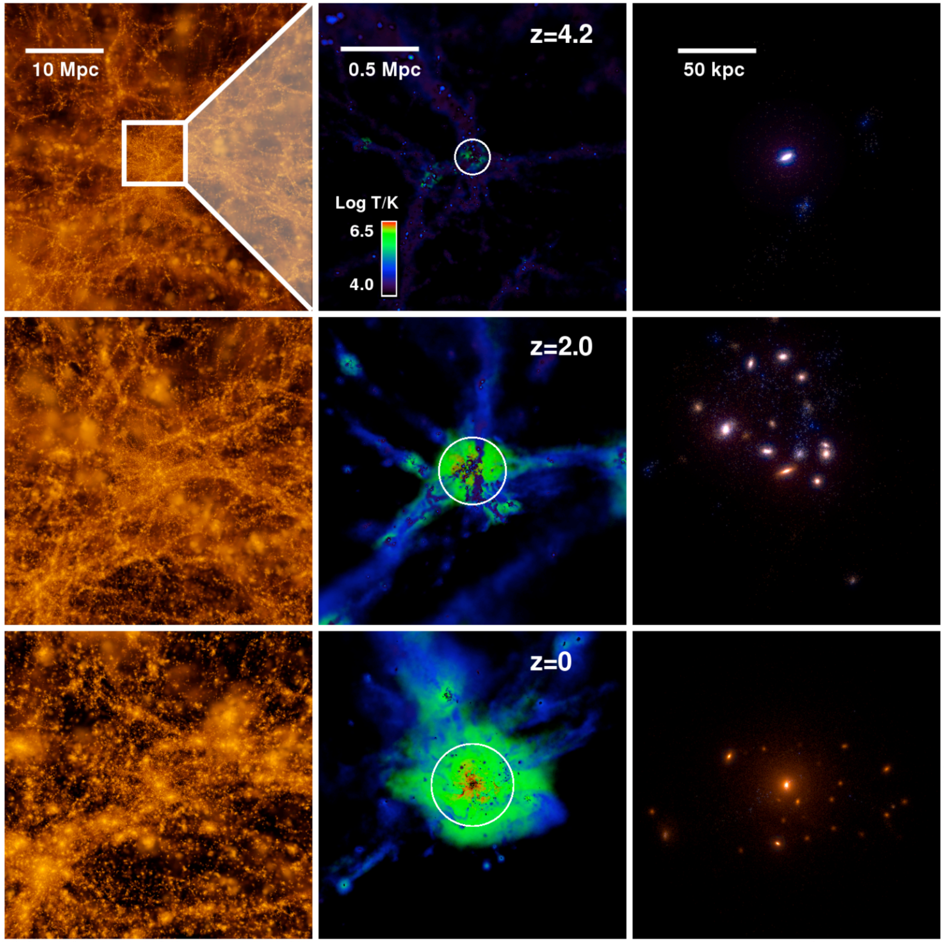
Why is the hot X-ray gas in giant elliptcals and galaxy clusters not cooling?

Maintenance problem already in observations

Galaxy formation

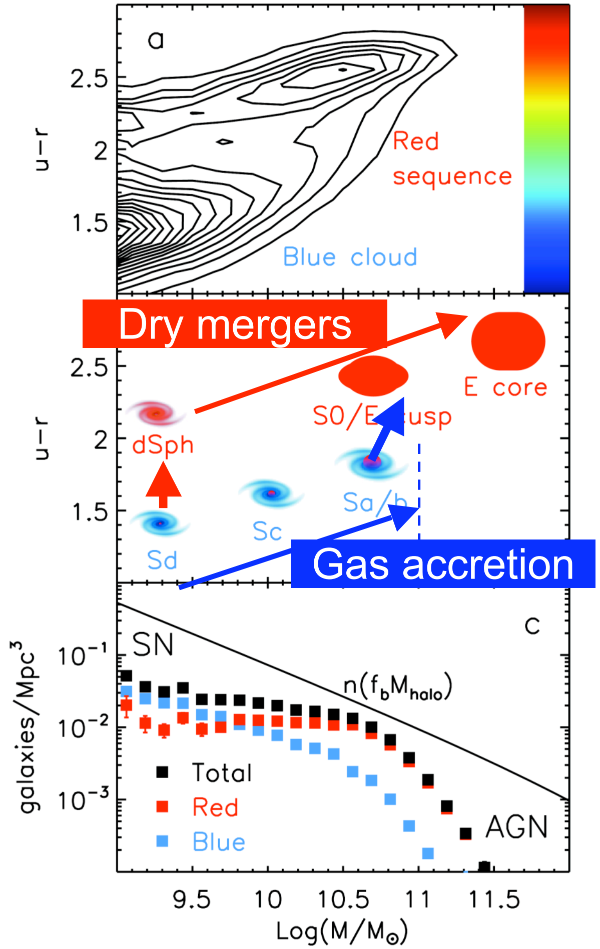
Blumenthal et al 84
White & Frenk 91

- **CDM model** Structures from gravitational instability of primordial density fluctuations
- **Galaxies** form by dissipational infall of baryons inside DM haloes
- Competition between gravitational heating and radiative cooling determines the **galaxy mass**
- Gas accretion only forms **discs**
- **Spheroids** are the product of galaxy mergers



The galaxy bimodality

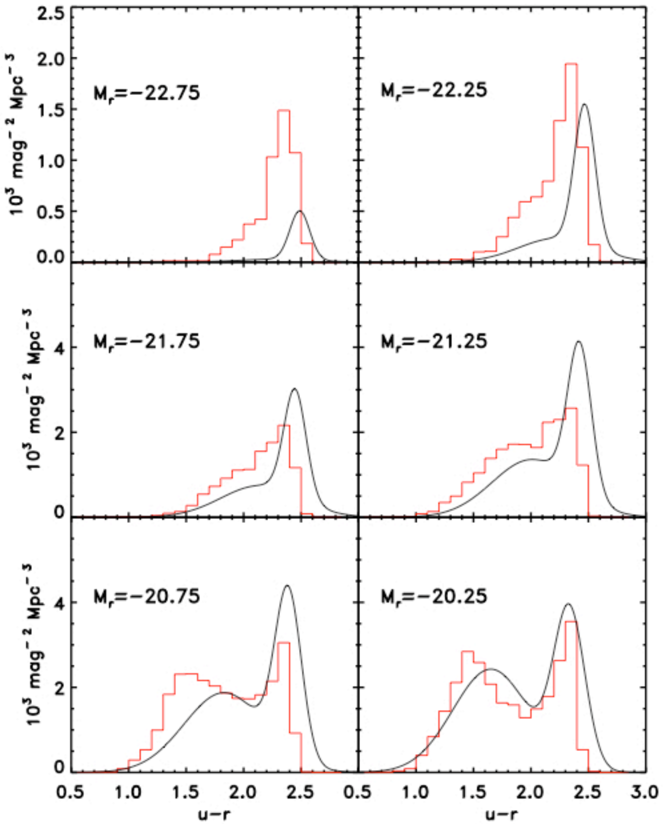
- Red and blue galaxies are different populations
  SDSS Baldry et al 04
- Red sequence from quenching of blue galaxies
  Bell et al 04, Faber et al 07
- Halo-mass quenching explains galaxy bimodality and elliptical dychotomy if hot gas never cools
  Dekel & Birnboim 06, Cattaneo et al 06, 08



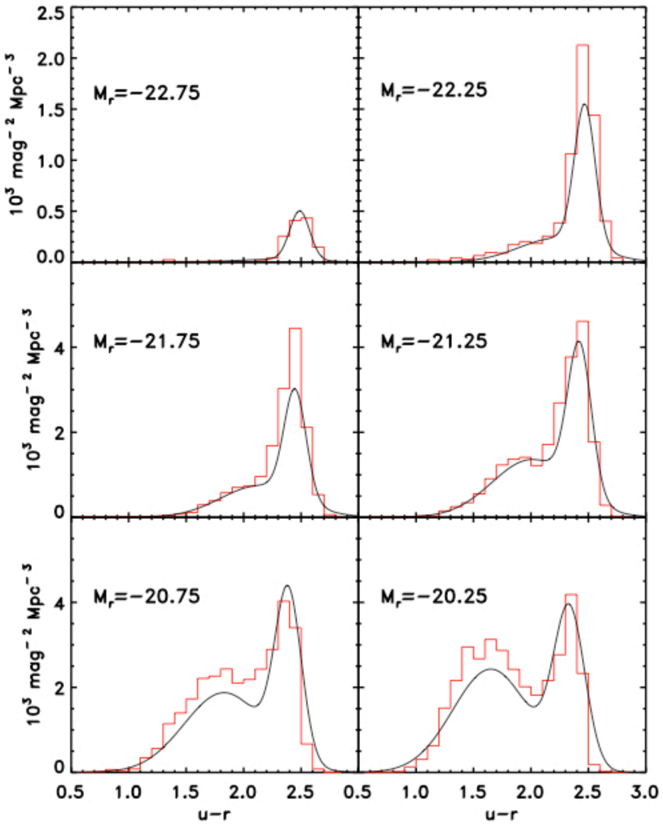
Bimodality from shutdown

Cattaneo et al 06, 08

Cooling in massive haloes allowed

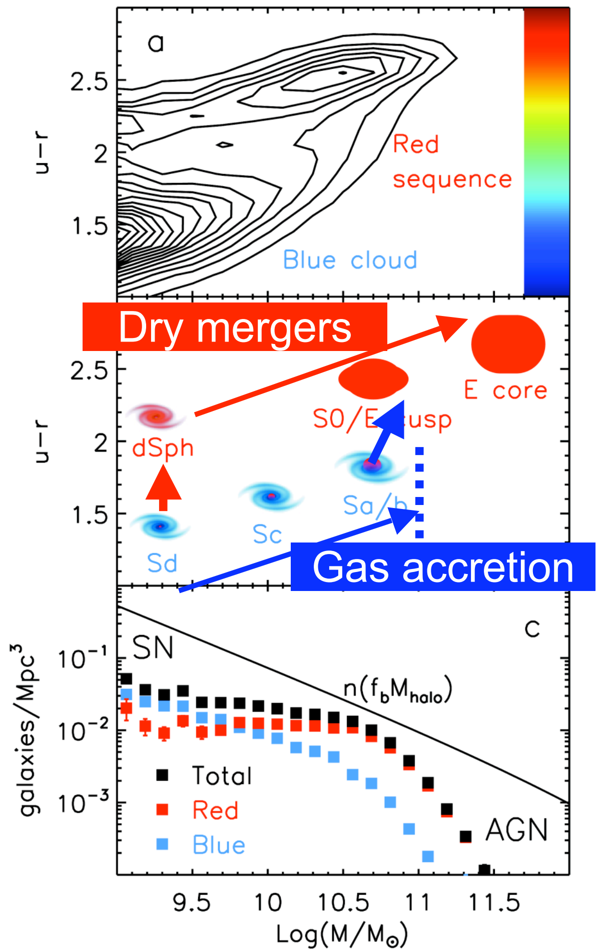


Cooling in massive haloes inhibited



The galaxy bimodality

- Red and blue galaxies are different populations
  SDSS Baldry et al 04
- Red sequence from quenching of blue galaxies
  Bell et al 04, Faber et al 07
- Halo-mass quenching explains galaxy bimodality and elliptical dychotomy if hot gas never cools
  Dekel & Birnboim 06, Cattaneo et al 06, 08



QUENCHING PROBLEM
How did red cuspy ellipticals form?

MAINTENANCE PROBLEM
How do ellipticals remain red?

The quenching problem

How could mergers of spirals form red cuspy ellipticals?

Mergers trigger starbursts e.g. ULIRGS
but in hydro simulations residual star formation persists for several Gyr
Cattaneo et al 05, Springel et al 05, Cox et al 06

THE QUASAR FEEDBACK SCENARIO

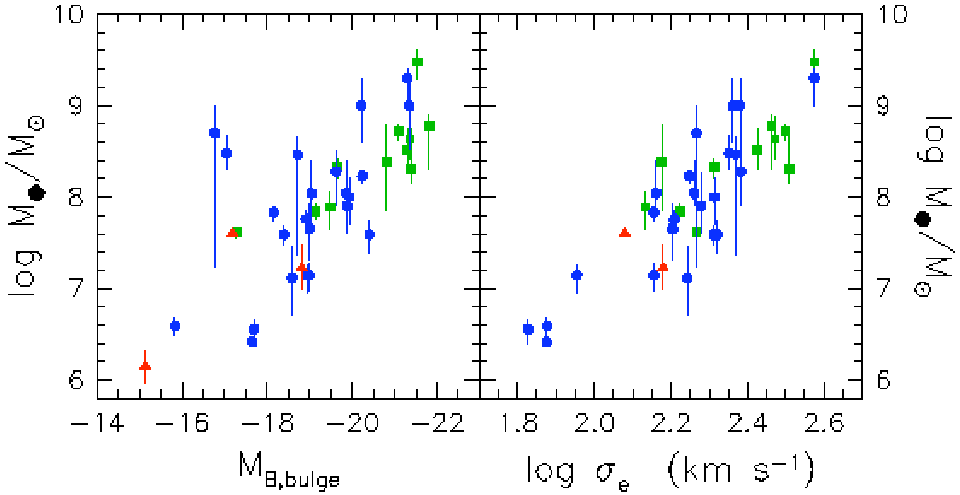
Merger ⇨ ULIRG ⇨ QSO ⇨ Red elliptical

Sanders et al 88

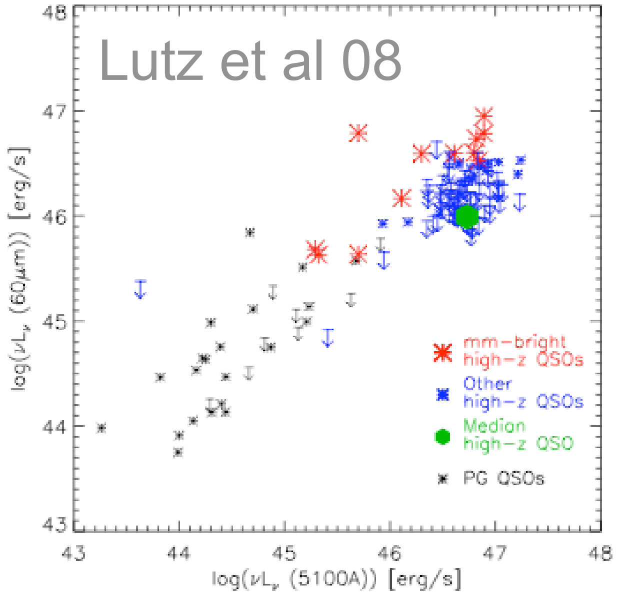
Jet-induced starbursts Silk 05

The black hole - bulge mass relation

$M_\bullet \approx 10^{-2.7\pm0.3} M_b$ Magorrian et al 98, Marconi & Hunt 03, Häring & Rix 04



BHs and SF fuelled by same processes Cattaneo et al 99



$M_\bullet \propto \sigma_b^4$ Tremaine et al 02

$M_\bullet \propto \sigma_b^5$ Ferrarese & Merritt 00

The BH grows until it can blow the gas out Silk & Rees 98, Fabian 99

Energy and momentum feedback

THERMAL WINDS

Silk & Rees 98

$0.1M_\bullet c^2 \approx 10^2 M_b \sigma_b^2$

$0.1M_\odot c^2 \approx 200 E_{SN}$

$$L > M_{gas}\sigma_b^2/\min(t_{dyn},t_{cool}) \approx M_{gas}\sigma_b^3/r \cdot \max(1, t_{dyn}/t_{cool}) \approx f_{gas}\sigma_b^5/G \cdot \max(1, t_{dyn}/t_{cool})$$

MOMENTUM (e.g. RADIATION PRESSURE) DRIVEN WINDS

Fabian 99, Fabian et al 06

Energy and momentum feedback

THERMAL WINDS

Silk & Rees 98 | $0.1M_\bullet c^2 \approx 10^2 M_b \sigma_b^2$

$0.1M_\odot c^2 \approx 200E_{SN}$

$$L > M_{gas}\sigma_b^2/\min(t_{dyn},t_{cool}) \approx M_{gas}\sigma_b^3/r \cdot \max(1,t_{dyn}/t_{cool}) \approx f_{gas}\sigma_b^5/G \cdot \max(1,t_{dyn}/t_{cool})$$

MOMENTUM (e.g. RADIATION PRESSURE) DRIVEN WINDS

Fabian 99, Fabian et al 06 | $0.1M_\bullet c \approx 0.1M_b\sigma_b$

$$L/(4\pi r^2 c)\sigma/\max(1,\tau) > GMm/r^2$$

$$L > Gc/\kappa\, M \max(1,\tau)$$

$$L_{Edd} = Gc/\kappa_{es} M_\bullet$$

$$L > Gc/\kappa\, M f_{gas} M/(4\pi r^2) \approx Gc/(4\pi\kappa)\, f_{gas}\sigma_b^4$$

Quasar Feedback in Merger Simulations

Springel et al 05

- Bondi 52 model for black hole accretion rate

$$\dot{M}_\bullet = 4\pi r_B^2 \rho_B c_s = 4\pi \rho_B c_s^{-3} (G M_\bullet)^2$$

- 5% of the accretion power thermalised in the black hole immediate environment

Quasar Feedback in Merger Simulations

- These simulations are important because they show what can happen
- But they do not model the physics of the AGN/gas interaction

The Physics of Quasar Feedback

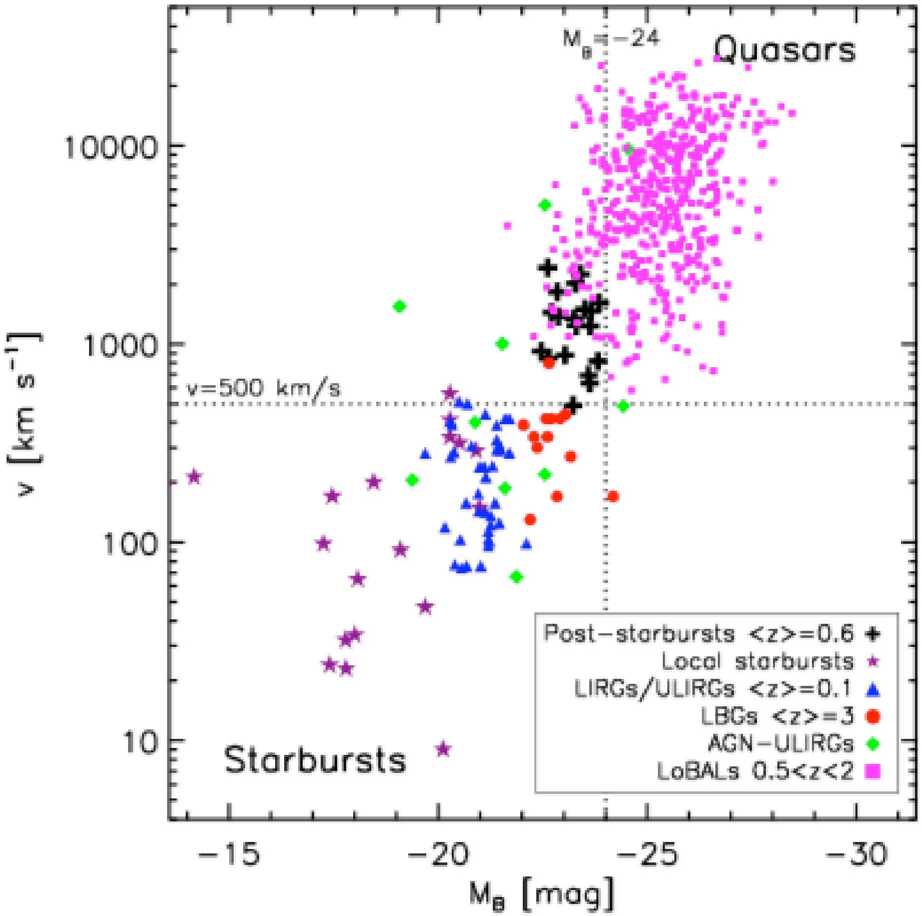
		Energy	Momentum
Radiation	Electron scattering	$\Delta\nu/\nu = h\nu/m_e c^2$	$L > L_{edd} M/M_\bullet$
	Photoionization	Metals (Fe)	
	Line scattering		BAL QSOs?
	Dust absorption		$\times\min(\tau_{dust}, 1)/\tau_T$
Jets		Shocks	Entrainment

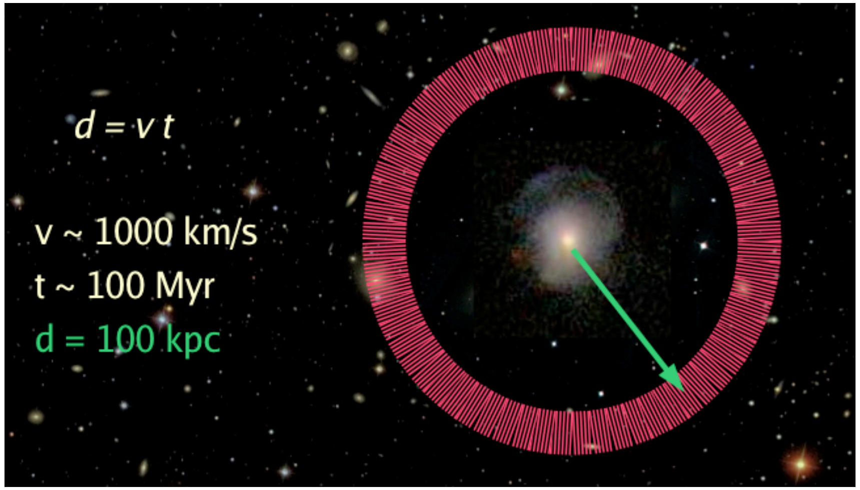
Quasar feedback and observations

- Is there any evidence for quasar winds?
- Is there any evidence that quenching is due to quasar winds?
  - AGN winds in post-starburst galaxies?
  - A link between transition galaxies and AGN?

Winds in quasars and poststarburst galaxies

Tremonti et al 07





Migration to the red sequence - A link to activity?

Schawinski et al 08

Visually selected SDSS ellipticals

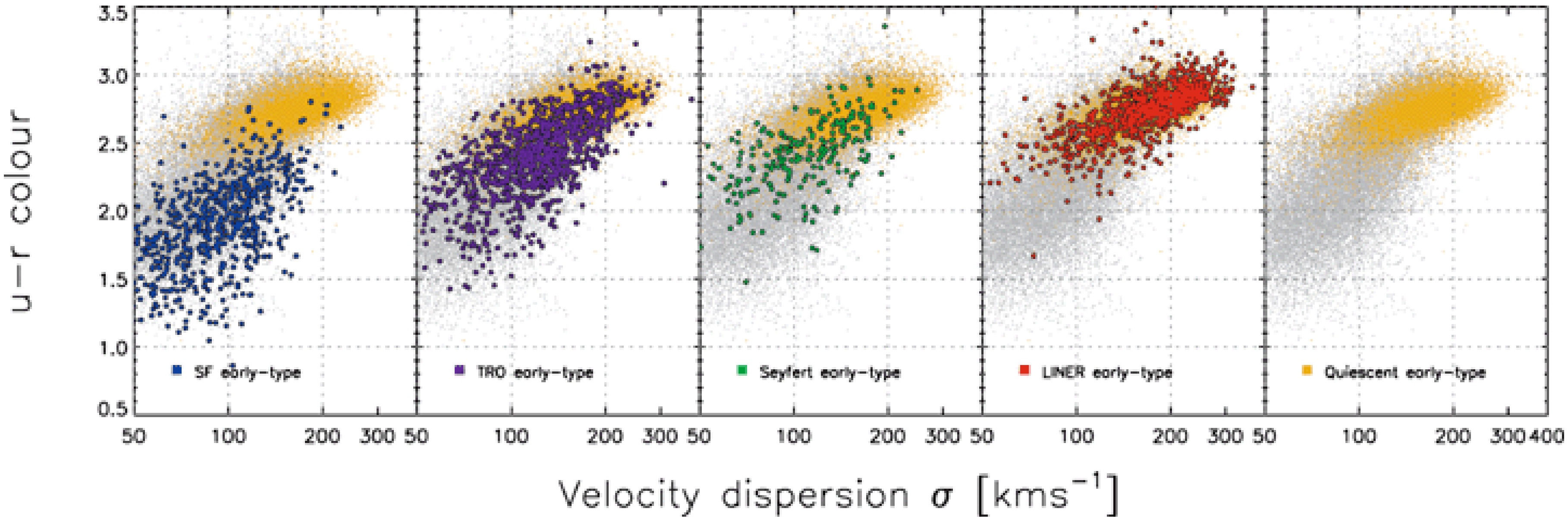
STAR FORMING

STAR FORMING PLUS AGN

SEYFERT GALAXIES

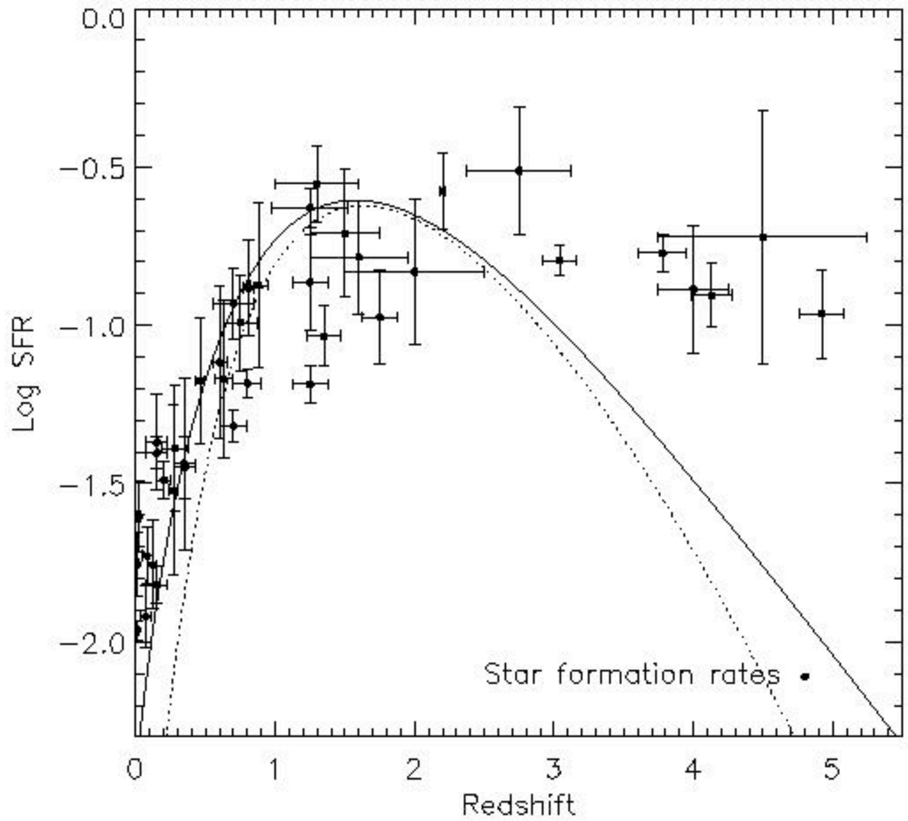
LINERS

PASSIVE



Black hole/galaxy coevolution

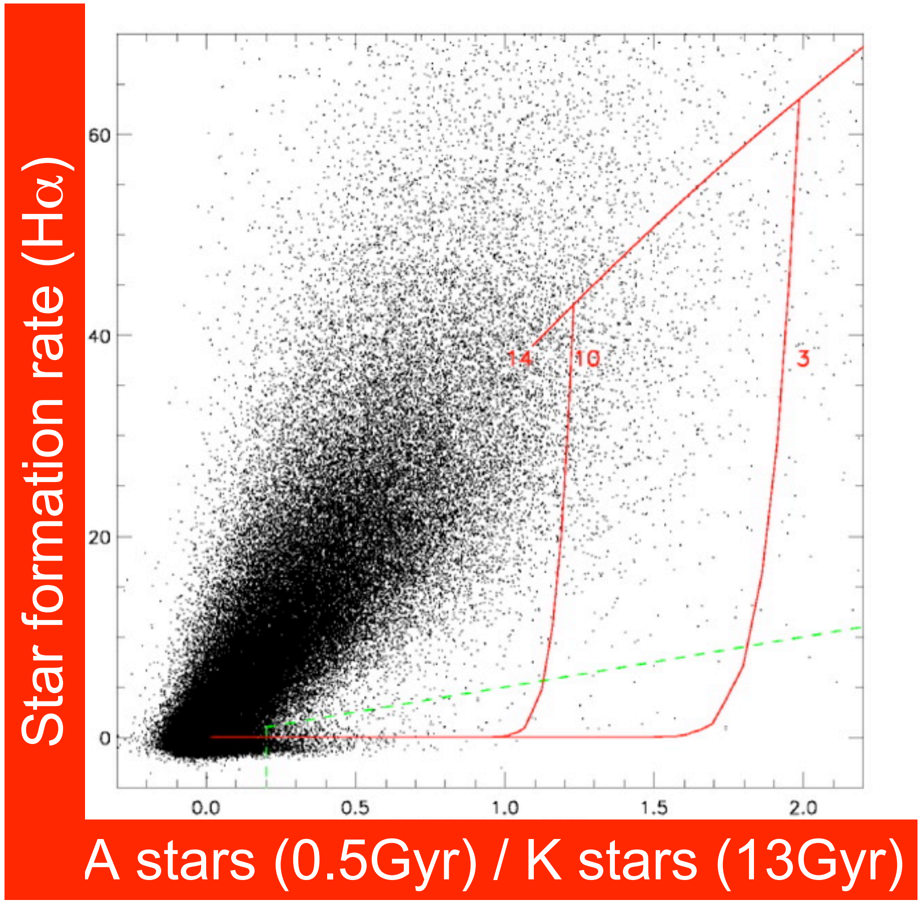
Cattaneo & Bernardi 03, Silverman et al 08



How abrupt is the quenching of red galaxies?

Quintero et al 04

Most galaxies that are moving to the red sequence are doing it slowly



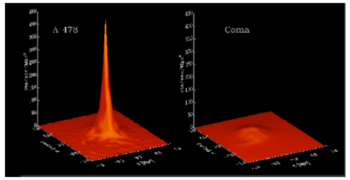
A few final words on quasar feedback

- Several processes can couple quasar energy and momentum to the ambient gas but all contain inefficiencies, large for radiative heating
- Quasar winds could plausibly blow away a gas mass equal to 10% of the stellar mass but this value is highly uncertain
- There is observational evidence for quasar winds but their masses are equally uncertain
- If quasar feedback determines the black hole - bulge relationship, it does it by limiting the black hole mass, not the galaxy mass
- Evidence linking green ellipticals to AGN seems to conflict with evidence that most galaxies are quenching slowly
- Simulations supporting the need for AGN feedback contain large uncertainties too

Circumstancial evidence for quasar quenching

The maintenance/cooling flow problem

Reviews: Peterson & Fabian 06, McNamara & Nulsen 07



- 90% X-ray selected groups and clusters have cuspy atmospheres (50% at $M_{\rm vir}>10^{14}M_{\odot}$ Chen et al 07)
- Cooling time <1Gyr throughout much of the cluster core
- The temperature drops toward the centre (cool core clusters) only by a factor of 3
- The gas that cools below this temperature is 10 times less than expected (the soft X-ray lines Fe XVII and Fe XXIV are absent or weak)

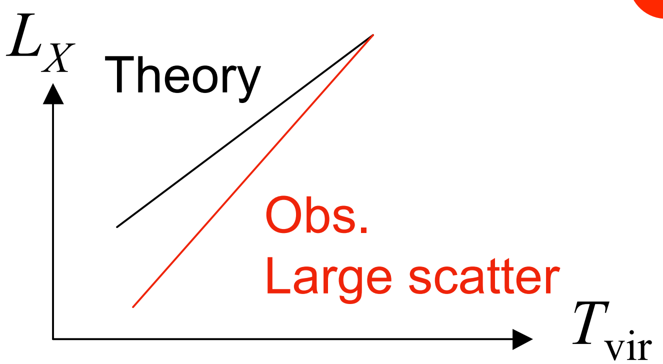
In galaxies, at 3×10^5K and below, most of the cooling is in the extreme and far UV

The entropy problem

Theory $L_X \propto n^2 T_{vir}^{1/2} r_{vir}^3 \propto n^{1/2} T_{vir}^2$

Obs. $L_X \propto T_{vir}^3$

The observed L_X - T_{vir} relation is steeper because the gas in low-mass clusters is underdense



Therefore it is on a higher **ADIABAT**

$kT = Kn^{\gamma-1}$

Heating: when and by what?

PREHEATING

Valageas & Silk 99
Oh & Benson 03

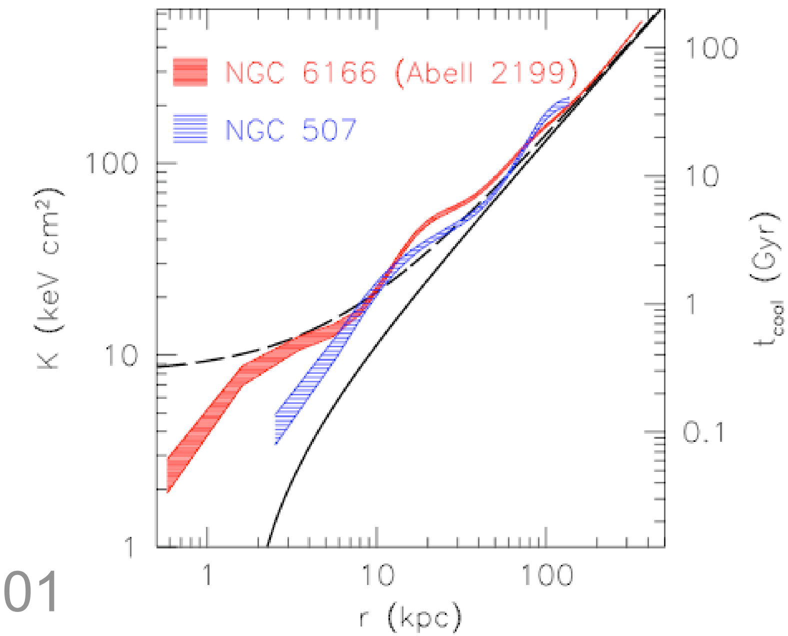
The ICM is heated by quasars in z~2-3 groups

High-entropy gas has a long cooling time
Preheating may solve the entropy problem

EPISODIC HEATING

Binney & Tabor 95

The ICM cooling time is short



AGN heating must continue at low z

In the local Universe there is only one quasar every 10^4 galaxies Wisotzki et al 01

The radio galaxies/ICM interaction

70% of CCC cD galaxies are radio galaxies — Burns 90, Best et al 07

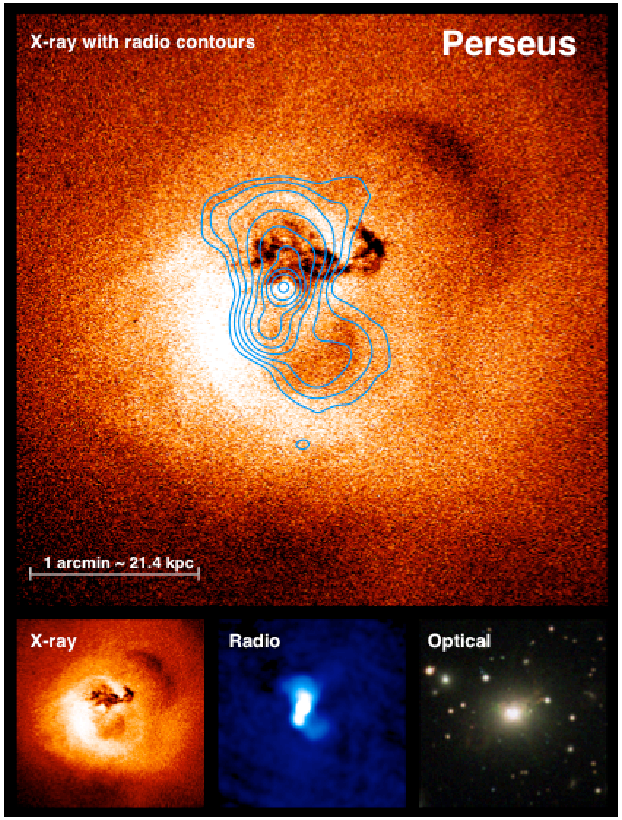
70% of CCCs contain X-ray cavities — Dunn & Fabian 06

Perseus is one of the clearest and best studied examples Fabian et al 03, 06

The jet synchrotron emitting relativistic plasma displaces the X-ray emitting thermal plasma

$$P_{cav} \sim [1/(\gamma-1) p_{cav} V_{cav} + p_{gas} V_{cav}]/t_{cav} \geq$$
$$\geq \gamma/(\gamma-1) p_{gas} V_{cav}/(r_{cav}/c_s)$$

Perseus's cD is the blue Seyfert NGC 1275



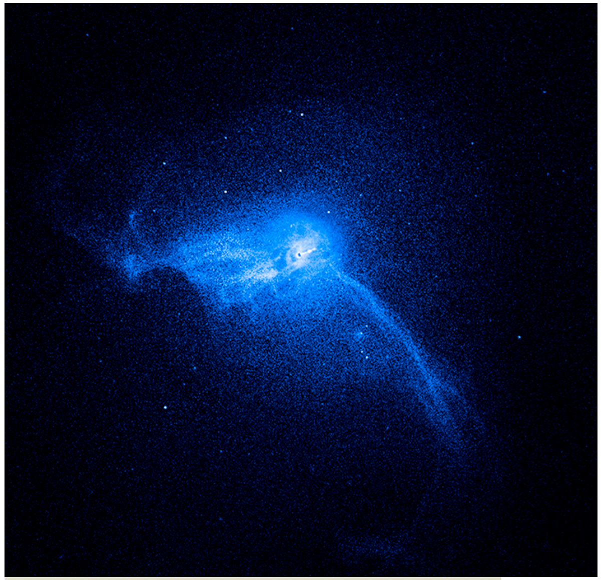
Radiatively inefficient radio sources

M87 is a weaker radio source than NGC 1275

Effervescence of small bubbles

$P_{\mathrm{cav}} \sim 0.1 \dot{M}_{\mathrm{Bondi}} c^2 >> P_{\mathrm{rad}}$ Di Matteo et al 03

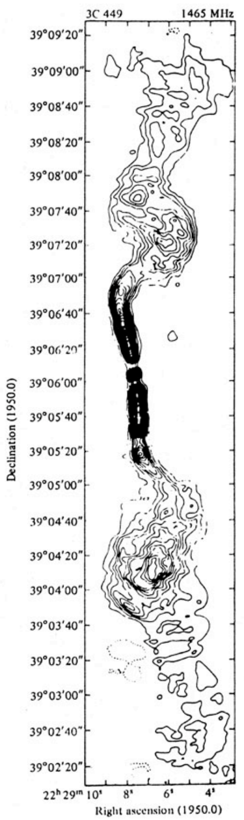
At $\dot{M}_{\bullet} < 10^{-2} \dot{M}_{\mathrm{Edd}}$, the accretion disc plasma may not be dense enough to radiate efficiently
⇨most of the power may be channelled into jets
ADIOS Blandford & Begelman 99



Forman et al 05

Feedback does not require a luminous AGN

The Fanaroff-Riley classification



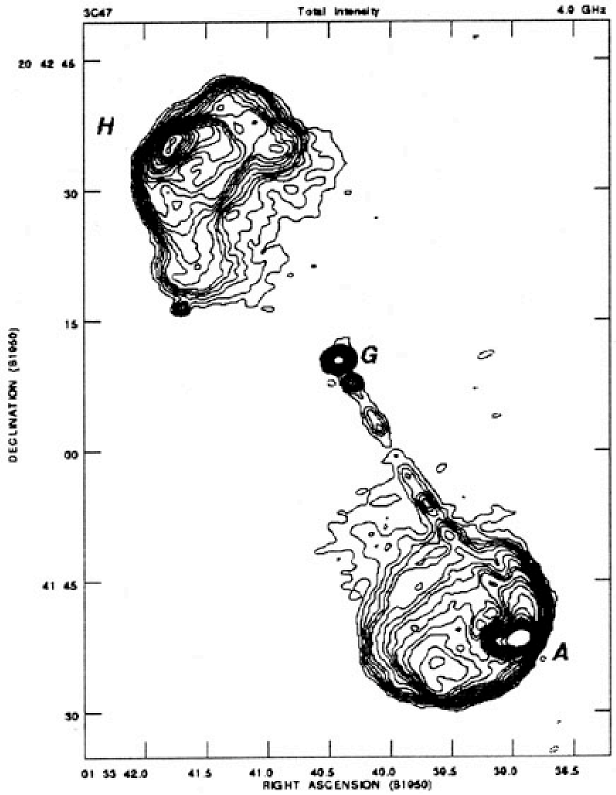
FR I

Core-dominated

Subsonic

Less powerful

cD galaxies



FR II

Lobe-dominated

Supersonic/ relativistic

More powerful

Loose groups/cluster outskirts

FR I/II ≠ radiatively inefficient/efficient

Blundell & Rawlings 01, Hardcastle et al 07

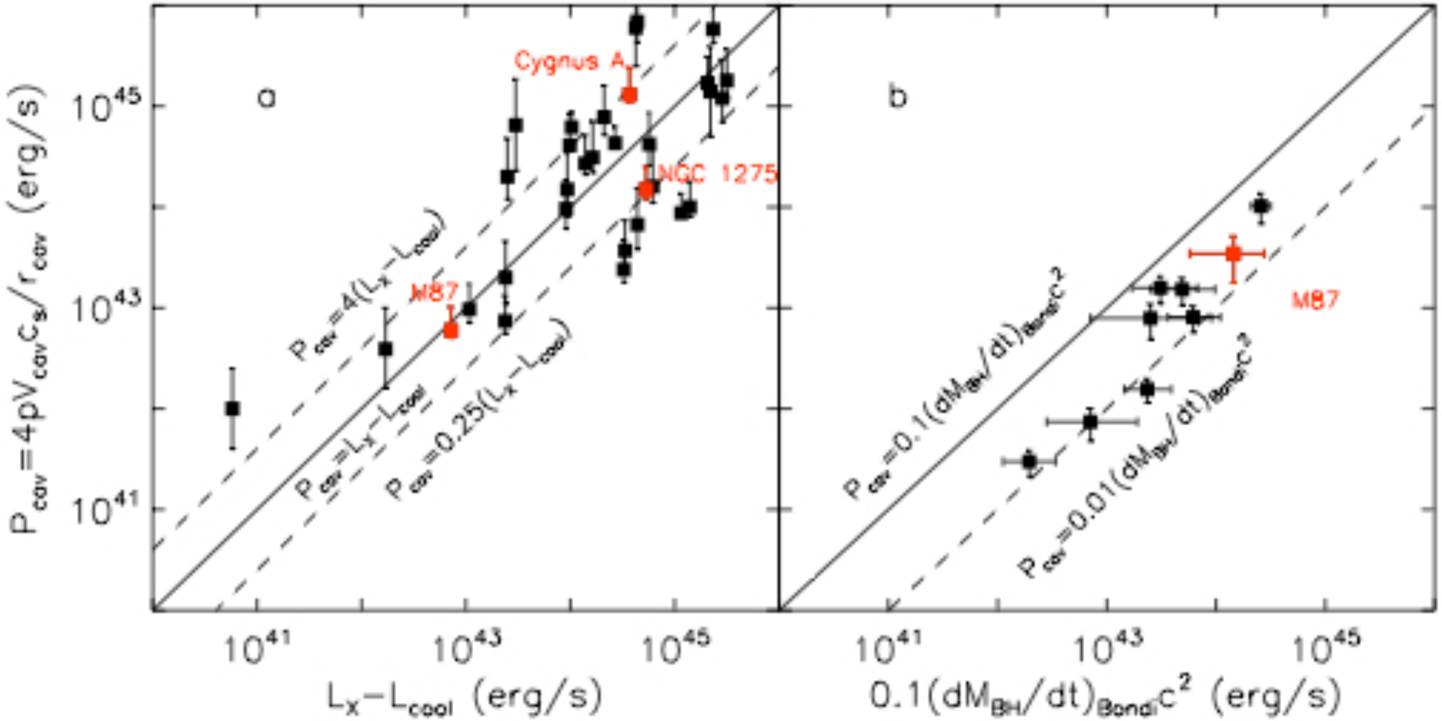
The heating/cooling balance

Heating rate ≈ cooling rate

Rafferty et al 06

Lower entropy, higher accretion rate

Allen et al 06

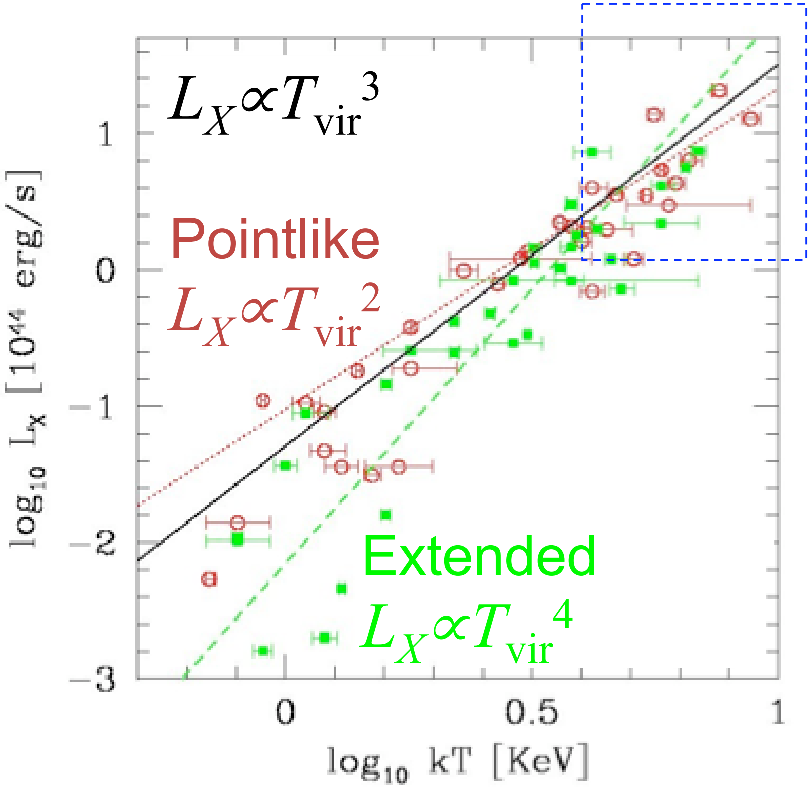


BH/ICM self-regulation

Anaytical Churazov et al 01 Hydro Cattaneo & Teyssier 07

Further evidence for jet heating

Magliocchetti & Brüggen 07



Pointlike sources are either weak or have not had time to expand

In systems with point like sources feedback has not occurred yet

The gas is denser and has lower entropy

Low-entropy clusters have blue cDs

Bildfell et al 08

How do jets heat the ICM?

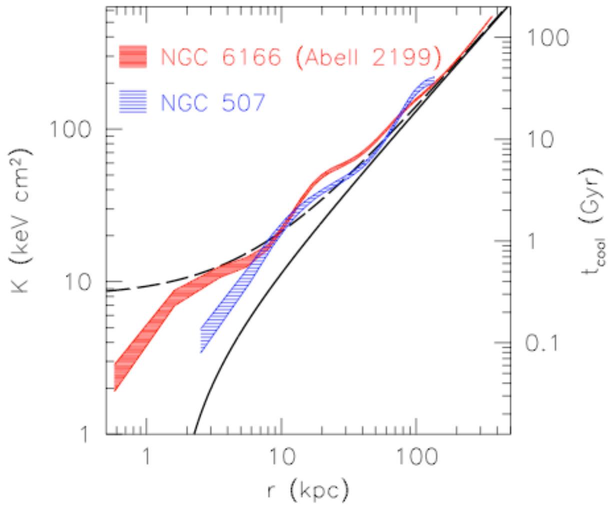
Shock heating $K \sim kT/n^{2/3} \sim \mu m_p v^2/n^{2/3}$

Jet phase
$v \sim (P_{jet}/\rho r^2)^{1/3}$

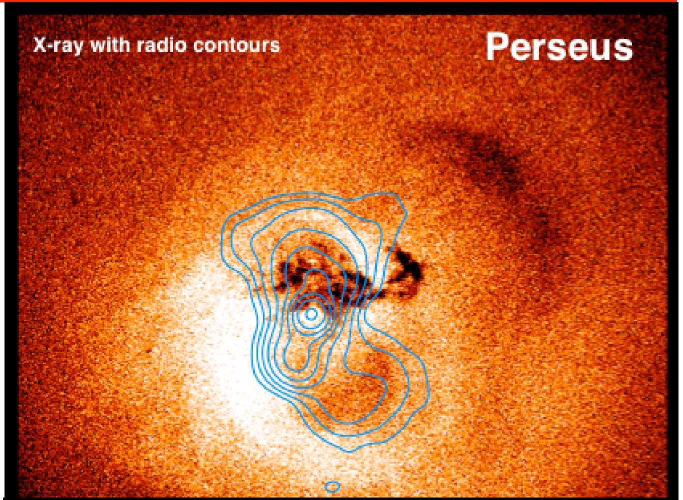
Energy-driven phase
$v \sim (P_{jet} t_{jet}/\rho r^3)^{1/3}$

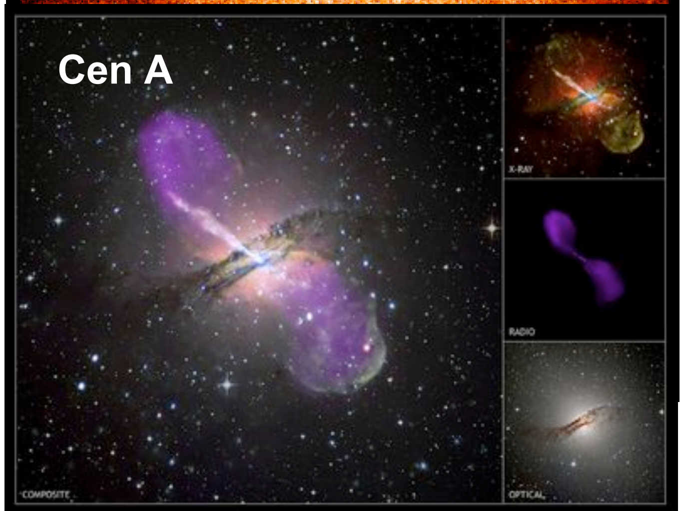
Buoyancy phase

Voit & Donahue 05



Cattaneo et al 09





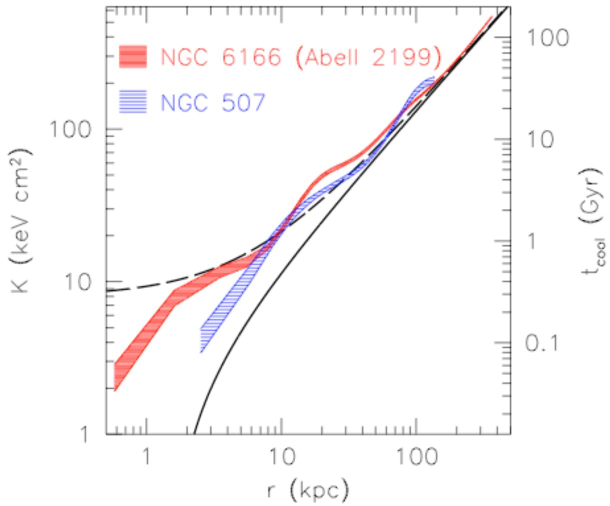
How do jets heat the ICM?

Shock heating $K \sim kT/n^{2/3} \sim \mu m_p v^2/3n^{2/3}$

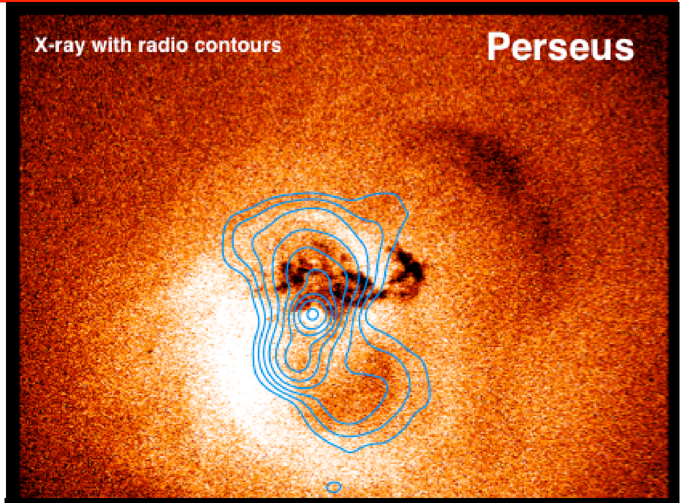
Jet phase
$v \sim (P_{jet}/\rho r^2)^{1/3}$

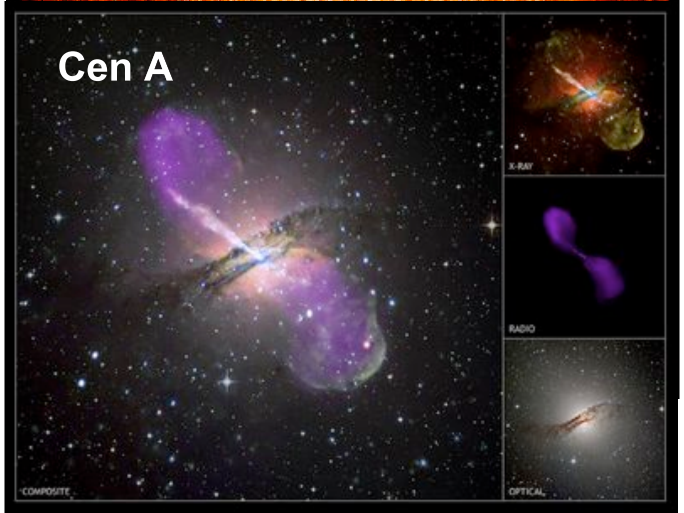
Energy-driven phase
$v \sim (P_{jet} t_{jet}/\rho r^3)^{1/3}$

Buoyancy phase



Distributed heat from turbulent Binney 05 or viscous Ruszkowski et al 04 Fabian et al 06 dumping





Maintenance of individual ellipticals

- Jets are usually collimated on kpc scales
- Subkpc knots: evidence for jet/ISM interaction?
- X-ray and radio power both scale as luminosity square
  O'Sullivan et al 01
- If jets cannot couple to ISM, cooling catastrophe and AGN activation

⇨ episodic quasar heating Ciotti & Ostriker 07

We still lack a systematic investigation of the predictions of this model

Conclusion

- Black hole growth/star formation cosmic coevolution
- Red galaxies from quenching of blue galaxies
- Observationally it is not obvious that mergers and/or quasars are a necessity for quenching - e.g. M31
- Evidence for quasar winds but masses are unclear
- Thus it is unclear if the black hole bulge relation is determined by AGN feedback or fuel availability
- What is clear is that the hot gas around massive ellipticals is not cooling and flowing onto them
- Evidence of this being due to jet heating is getting strong
- Alternative proposals exist but do not heat the gas at a rate proportional to the cooling rate - observations suggest self-regulation
- It is unclear if jets can thermalized within individual elliptical or episodic radiative heating is necessary, e.g. photoionization heating