Galaxy Formation and Evolution

Lecture 15: AGN feedback and outflows

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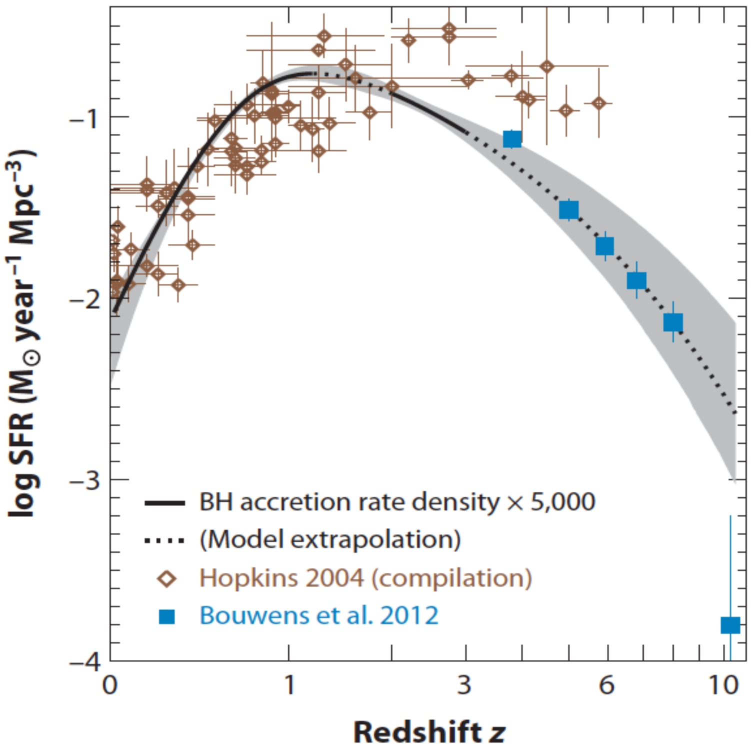
Indirect evidence for AGN and galaxy co-evolution

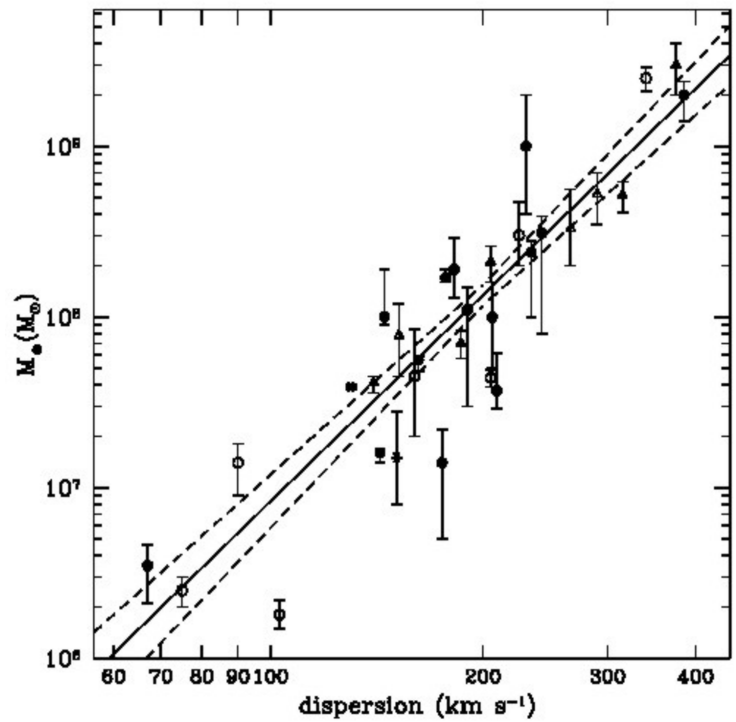
Evolution of activity and star formation



Kormendy & Ho (2013)

Triggering?

Black hole vs. galaxy bulge properties

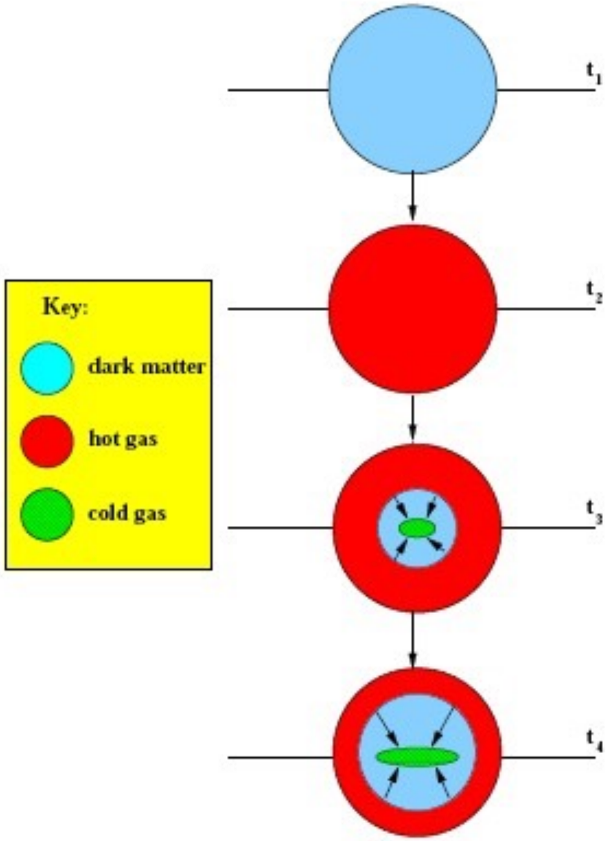


Tremaine et al. (2002)

Feedback?

Cooling of gas within DM haloes

The formation of galaxies in semi-analytic models



← Dark matter halo following most recent merger

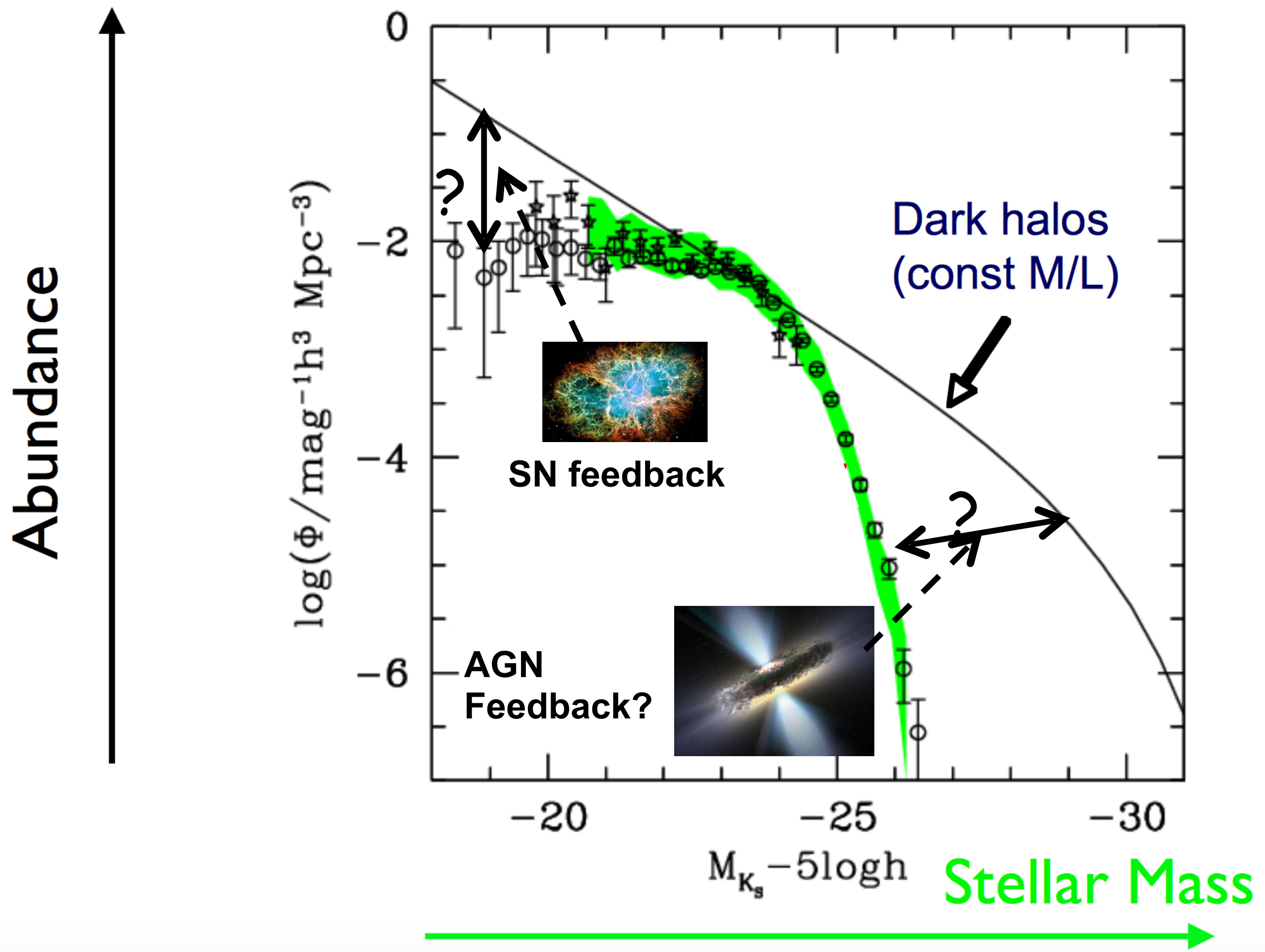
← Gas falling into DM halo is shocked and heated up to virial temperature

$$T_{vir} = \frac{1}{2}\frac{\mu m_H}{k}\frac{GM_{tot}}{r_{vir}}$$

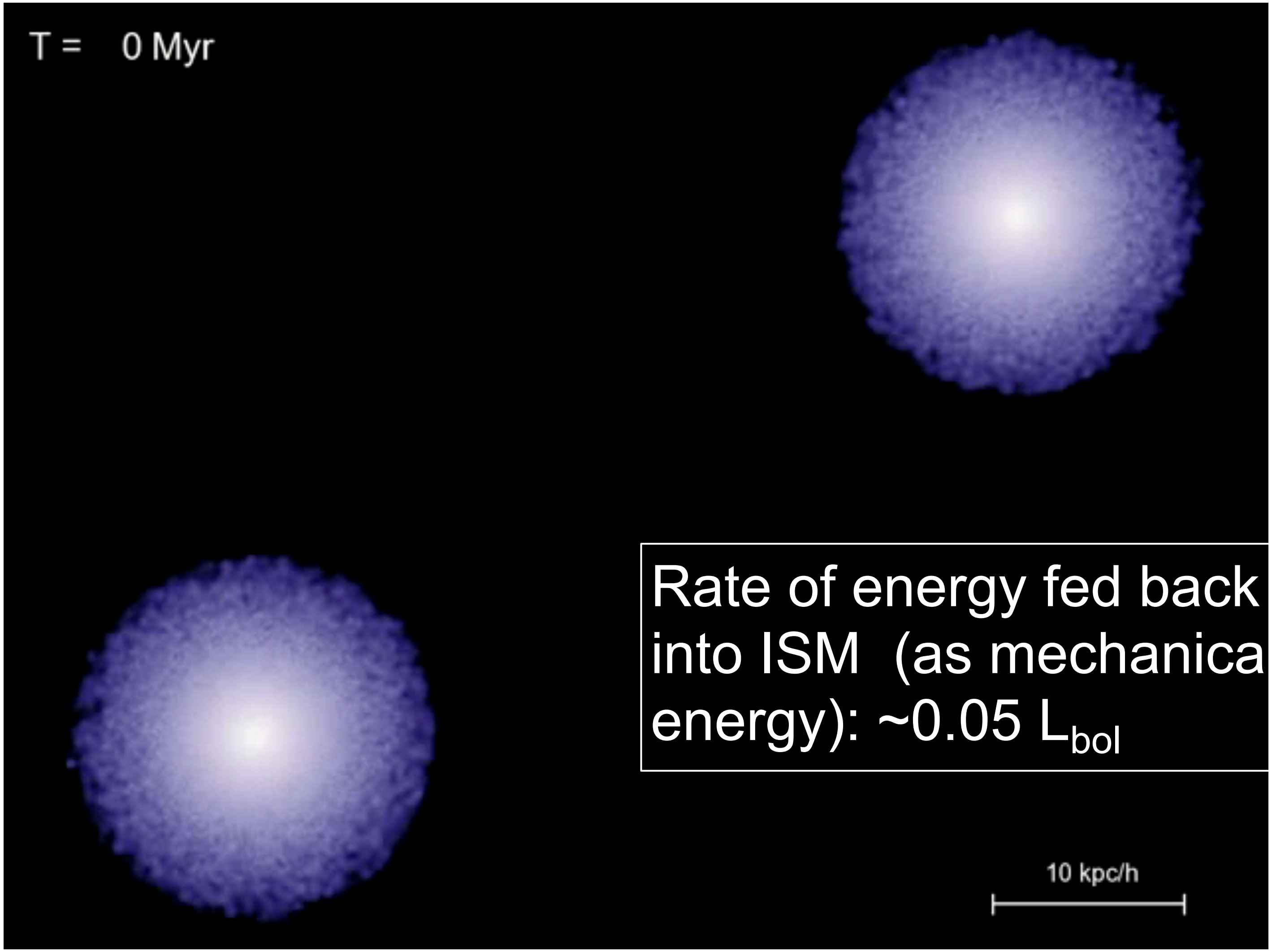
← Hot gas cools starting from the centre outwards

← A disk will be formed at the centre of halo if angular momentum conserved during collapse

Indirect evidence for AGN and galaxy co-evolution



Galaxy Mergers



Rate of energy fed back into ISM (as mechanica energy): ~0.05 L_{bol}

di Matteo et al. (2005)

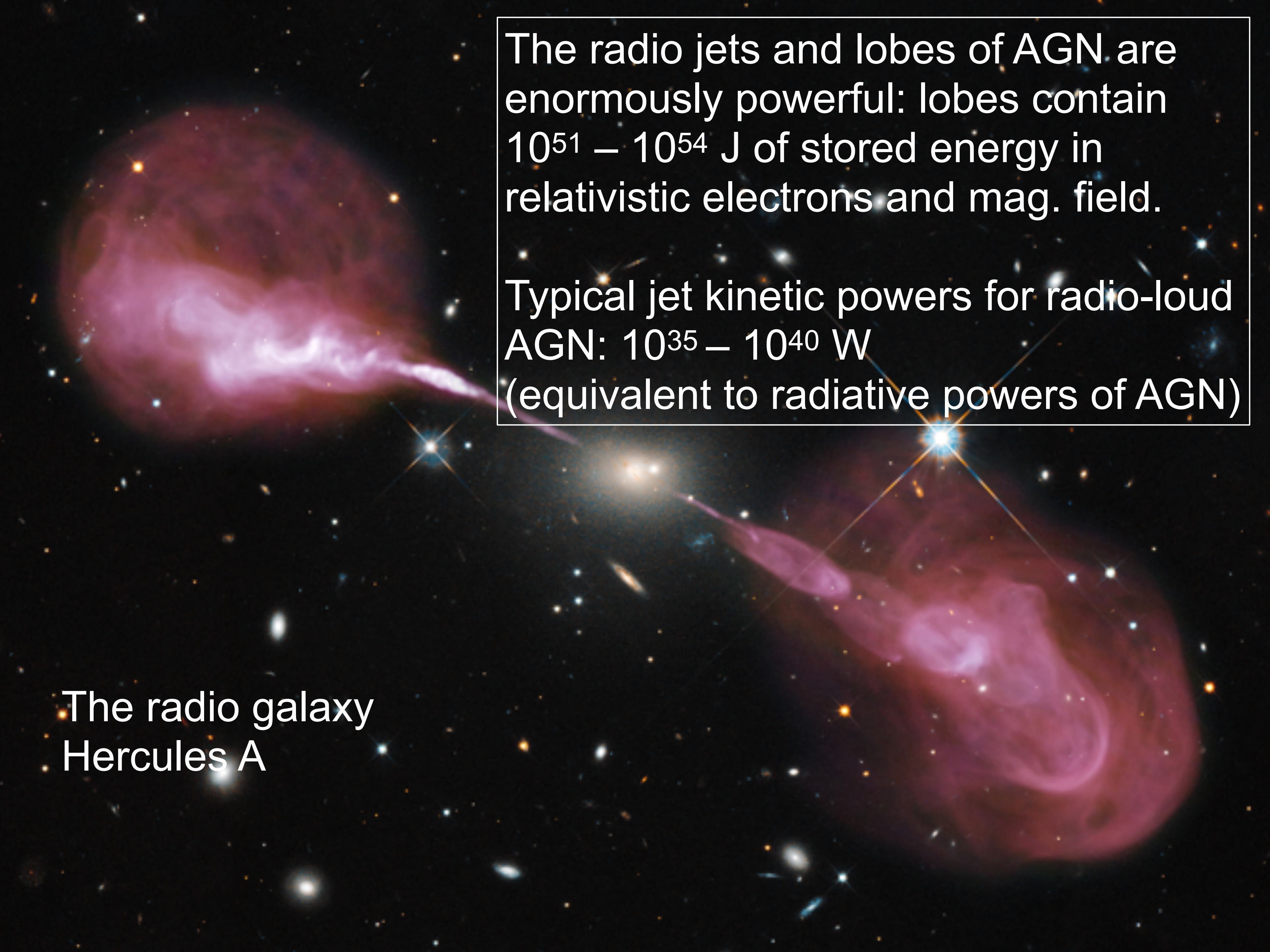
How AGN may affect galaxy evolution

1. Heating the hot gas in dark matter haloes and preventing it from cooling to form stars

2. Accelerating and heating existing cool gas in the host galaxies, ejecting it from the central regions and thereby directly affecting the galaxy star formation histories

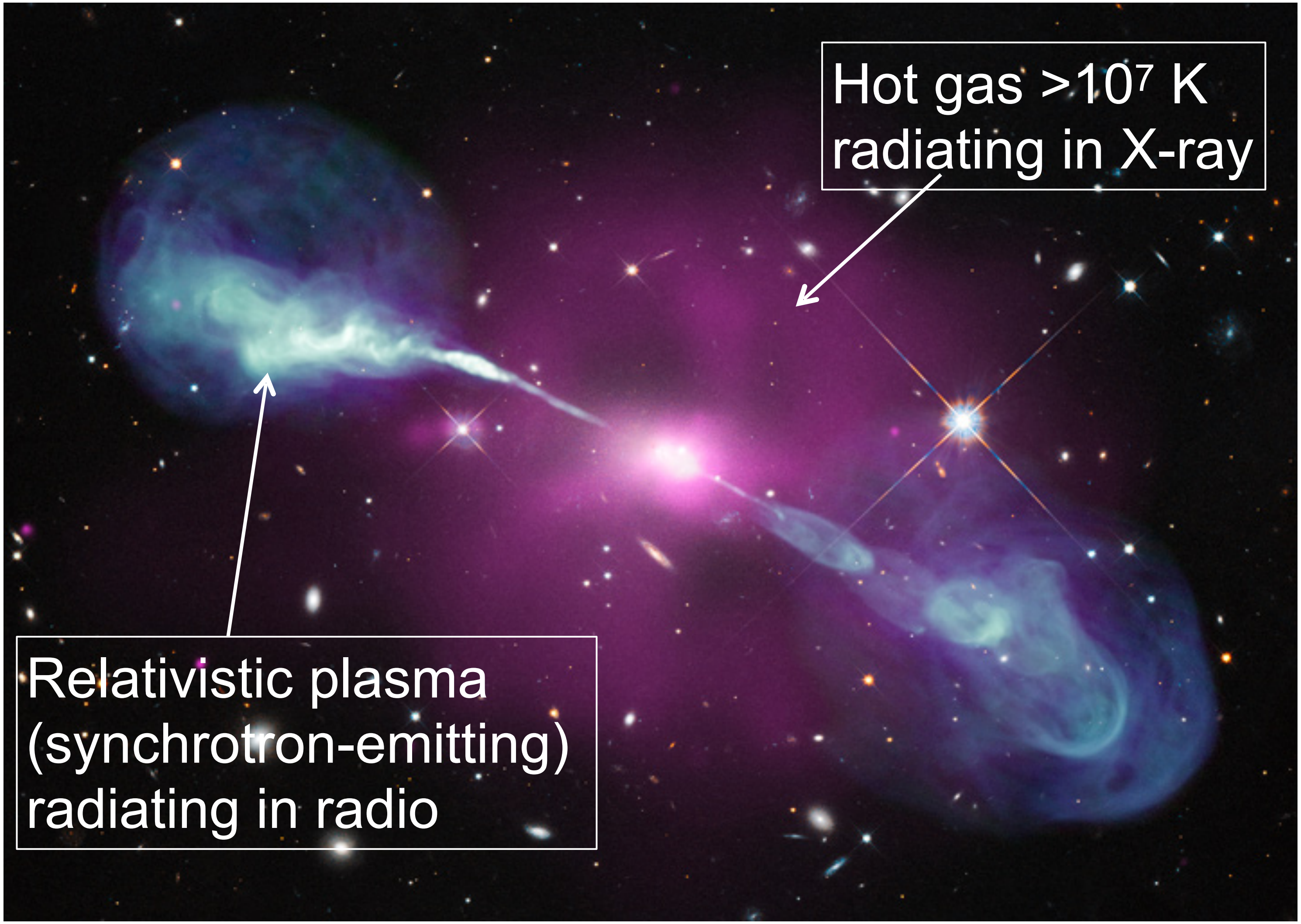
The radio jets and lobes of AGN are enormously powerful: lobes contain $10^{51} – 10^{54}$ J of stored energy in relativistic electrons and mag. field.

Typical jet kinetic powers for radio-loud AGN: $10^{35} – 10^{40}$ W
(equivalent to radiative powers of AGN)



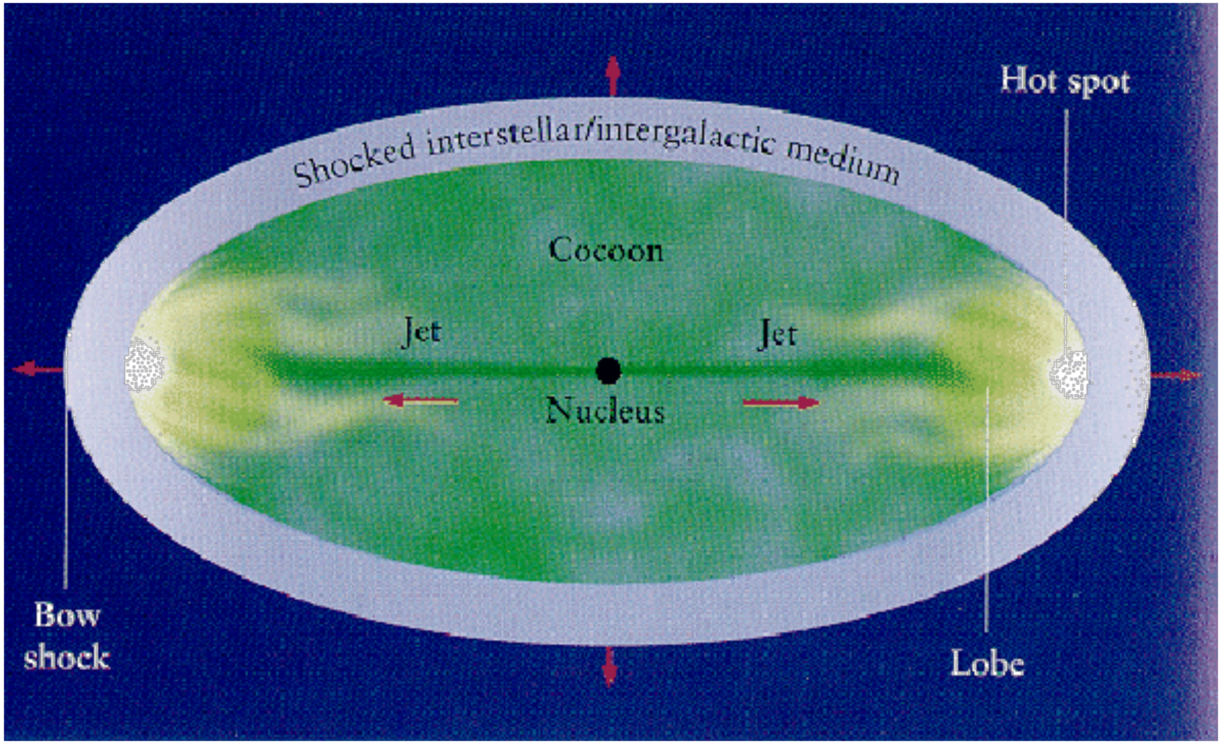
The radio galaxy
Hercules A

Hercules A: hot X-ray halo



Impact of the radio sources

Impact on hot gaseous haloes of host galaxies/clusters



The jet and lobes of the expanding radio sources expel and form cavities in the hot gas. The expanding radio source cocoons also drive shocks into the hot ISM, heating and compressing it. Radio jets can project the power of the AGN on 100 kpc – 1 Mpc scales.

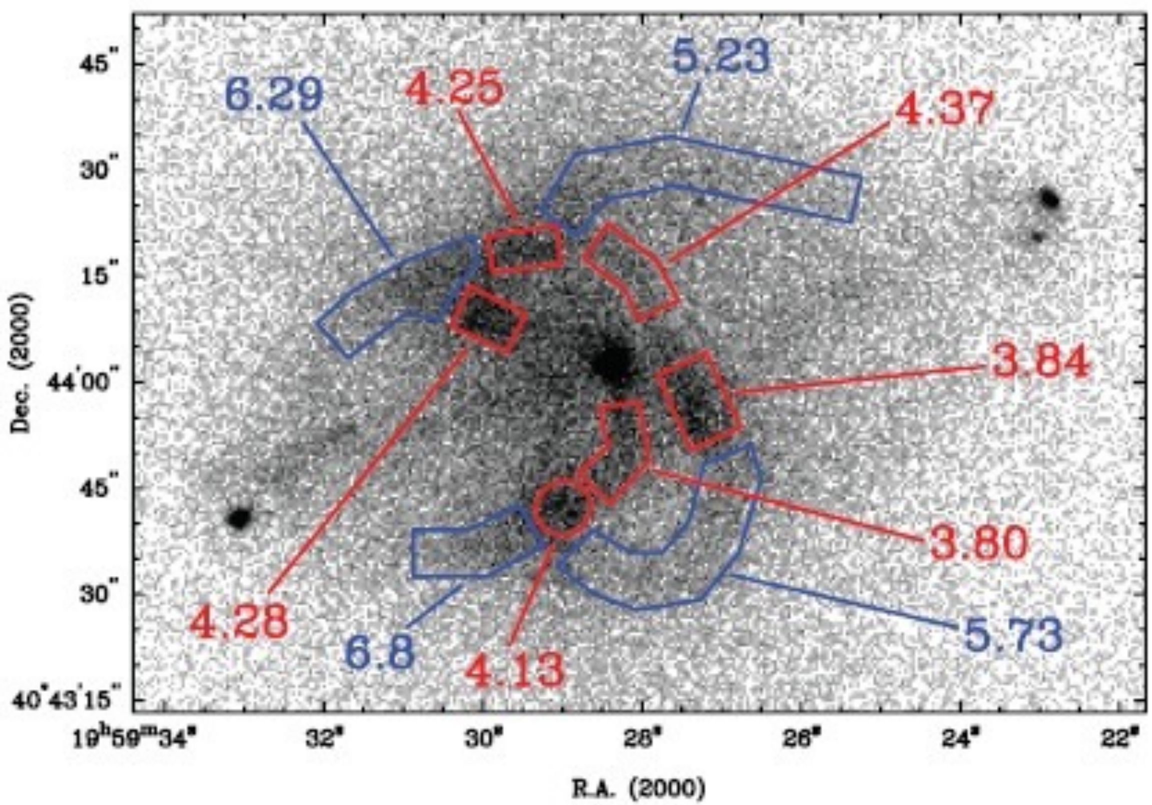
Astrophysical shocks I.

- Astrophysical shocks are discontinuities in gas pressure and density that move through the ISM at speeds greater than the local speed of sound
- Gas heated, compressed and accelerated as it enters the shock front
- Shocks are driven by a "piston", for example a supernova, jet, or expanding bubble of hot gas

Jet mode I.

X-ray observations of Cygnus A

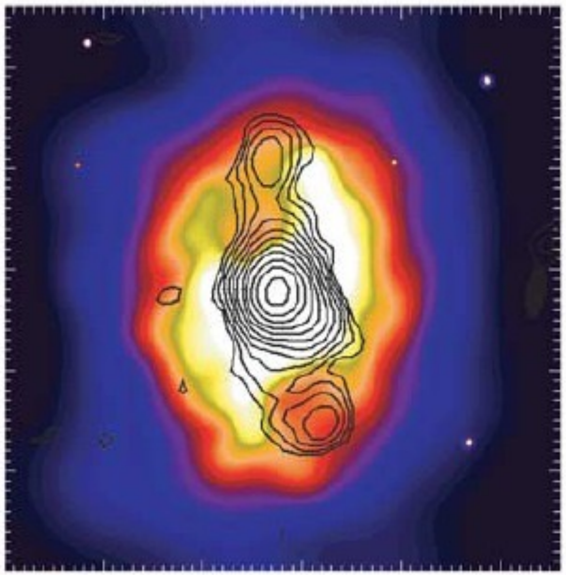
Chandra X-ray image (Wilson et al. 2006)



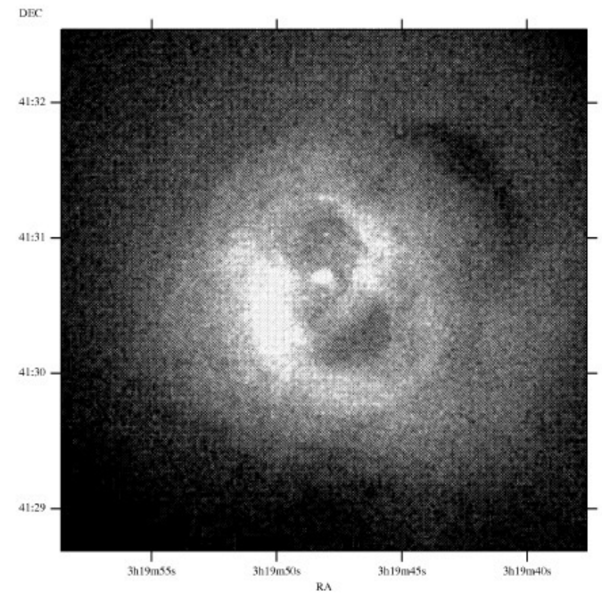
Deep X-ray observations of Cygnus A provide evidence for a cavity in the hot X-ray gas hollowed out by the radio jets as well as shocked regions around the radio lobes.

Jet mode II. Radio-excavated cavities

Cavities in the X-ray haloes of radio sources



MS0735.6+7421
McNamara et al. (2005)

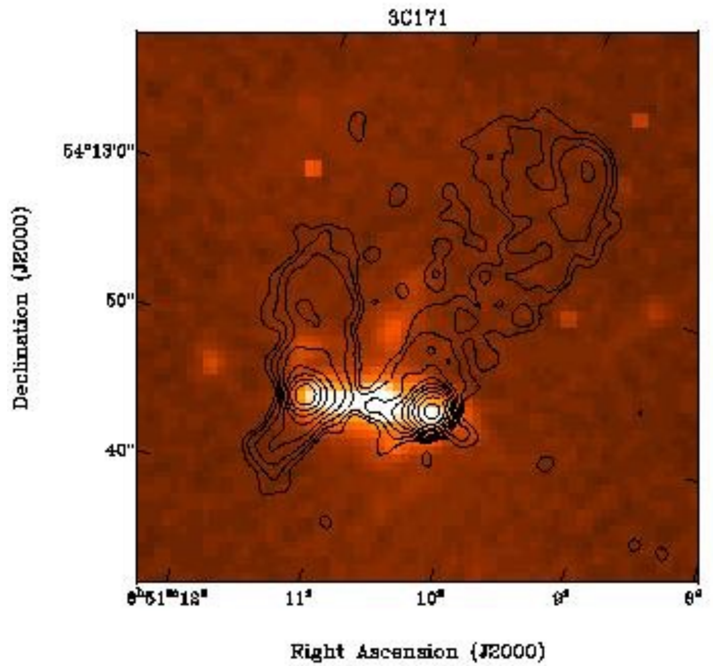


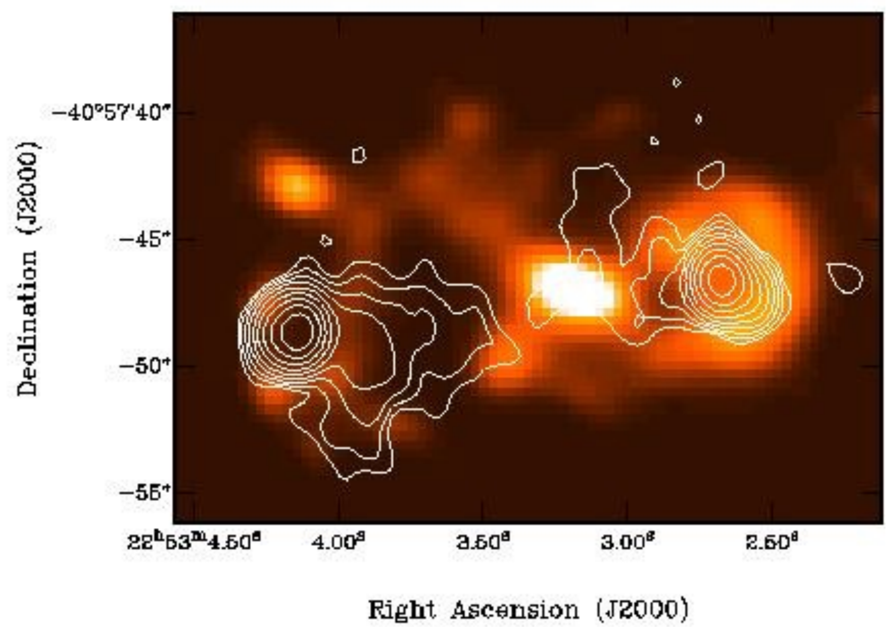
Perseus A
Fabian et al. (2003)

The energy associated with the expanding radio jet cavities ($4PV \sim 10^{51} - 10^{55}$ J) is sufficient to stop the hot gas from cooling, and the central galaxies from growing by accreting the cooling gas.

Jet mode III. The impact of jets on warm ISM

Radio–Optical Morphological Associations



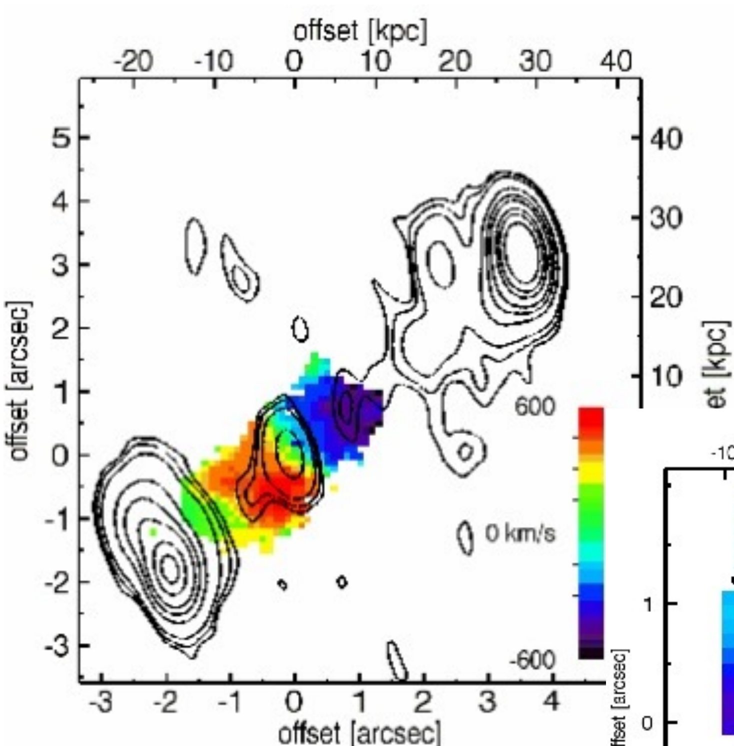


3C171 (z=0.238)
Halpha/6cm

PKS2250–41(z=0.310)
[OIII]/6cm

Radio jets are sufficiently energetic to disrupt (ionize, heat, eject) the entire interstellar medium in a typical galaxy.

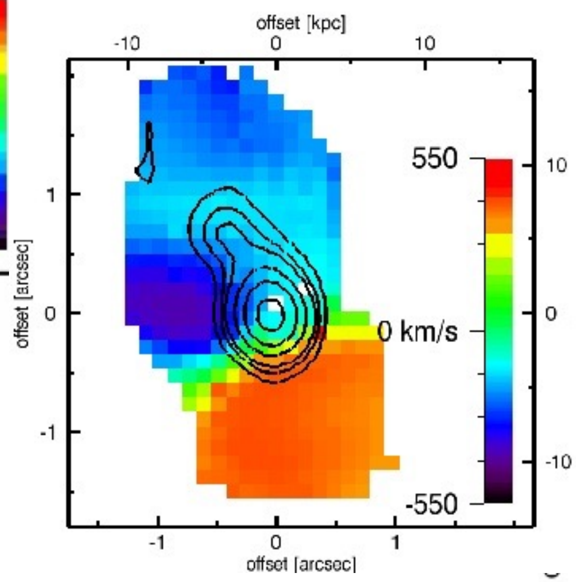
Jet mode IV. Outflows in radio galaxies (z~2)

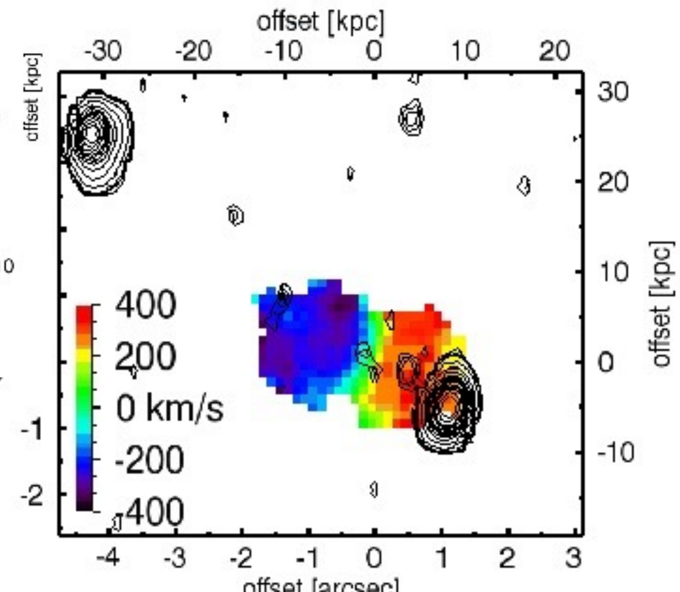


$$300 < \dot{M} < 1000\ M_{sun} yr^{-1}$$

$$10^{37} < \dot{E} < 10^{39}\ W$$

$$0.001 < \dot{E}/L_{edd} < 0.1$$



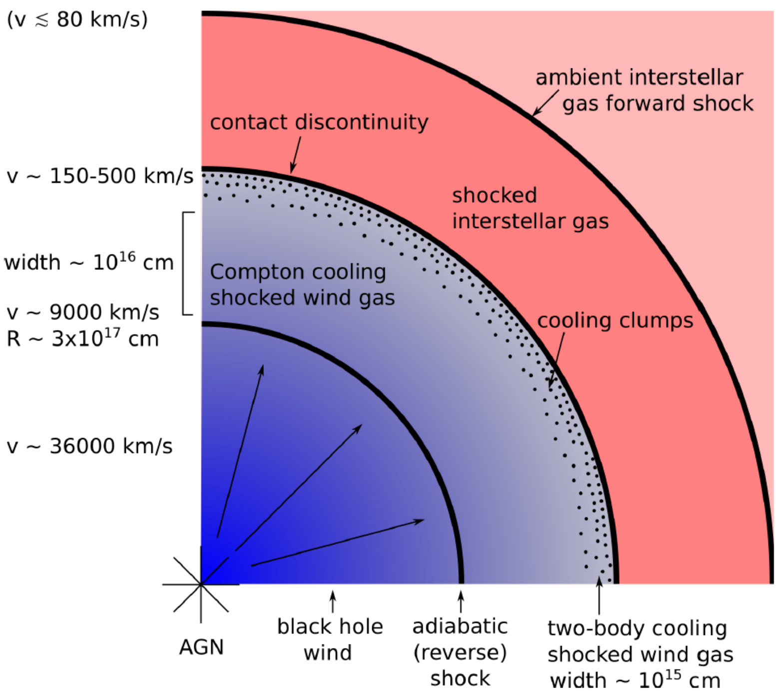


Nesvadba et al. (2006, 2008)

Jet mode feedback summary

- The X-ray cavities provide excellent evidence that the expanding radio jets and lobes have a major effect on the hot (> 10^7 K) X-ray haloes of host elliptical galaxies and clusters
- The heating due to the the expanding radio components can balance the cooling via X-ray radiation, thus preventing the gas from cooling and forming stars
- Helps to explain the dearth of high luminosity galaxies relative to predictions of models of cooling in dark matter haloes without feedback
- The expanding radio sources also have a major impact on the cooler phases of the ISM (< 2×10^4 K), driving shocks that heat and accelerate the gas, expelling it from the host galaxies
- Jets are good at projecting the powers of AGN (in mechanical form in the the haloes of the host galaxies and clusters of galaxies)
- But not all AGN are radio-loud…

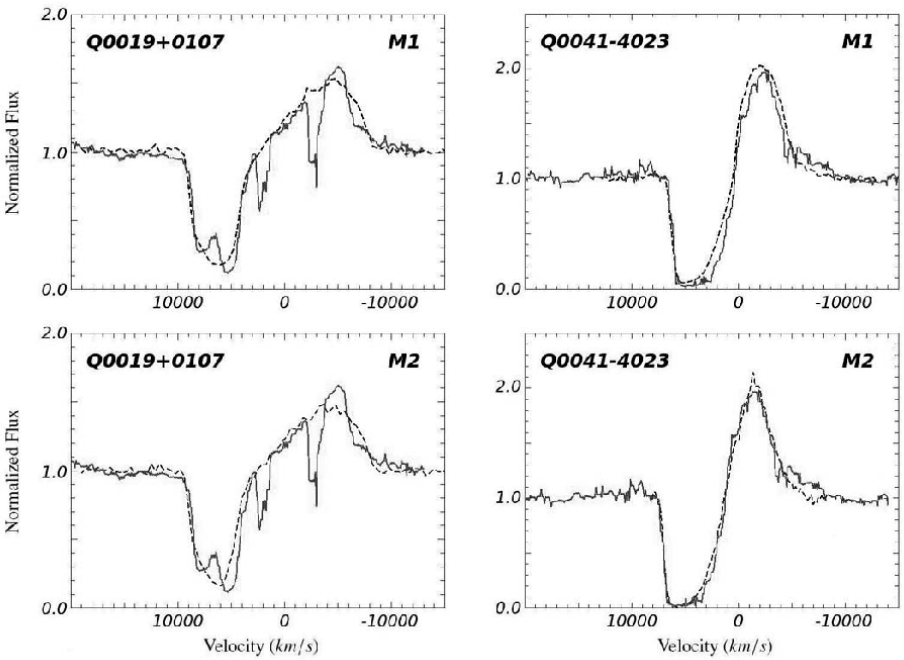
Quasar winds



King & Pounds (2015)

- AGN heat the gas close to the centre (r < 1 pc) and accelerate it via radiation pressure (~L_{bol}/c)
- The pressure of the expanding bubble of hot gas drives shocks into the cooler gas at larger radii, heating and accelerating it
- In this case the "piston" for the shocks is the expanding bubble of hot gas accelerated close to the AGN

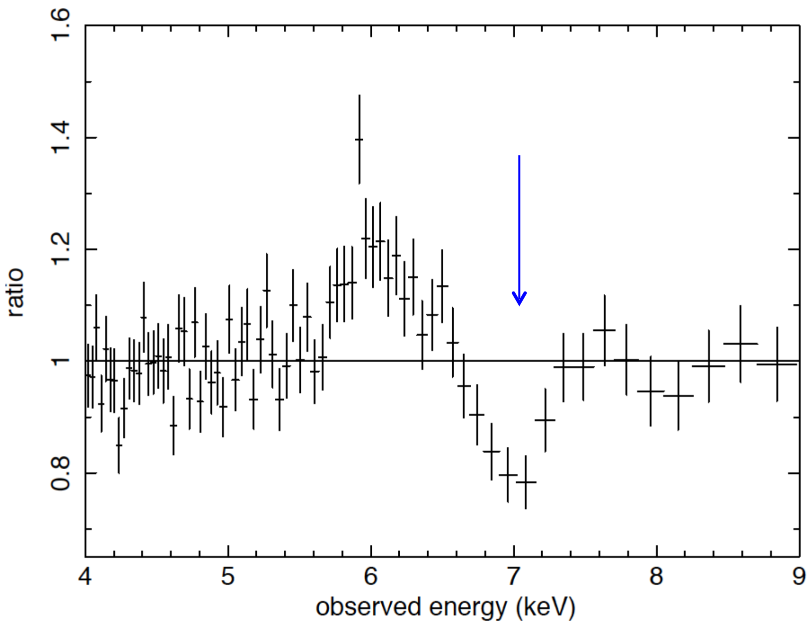
Broad absorption line (BAL) quasars



BALs defined to have:
FWHM > 3,000 km/s
Δv_{max} > 5,000 km/s

- A significant fraction of quasars (~10 – 20%) show broad, blueshifted absorption lines
- Broad absorption detected in UV resonance resonance lines(e.g. CIVλ1548, NVλ1240)
- Maximum velocities can be as high as 60,000 km/s, but more typically Δv ~ 5,000 – 10,000 km/s
- Outflows on scales < 10 pc
- Provides strong evidence for highly ionized, quasar-driven winds close to the AGN

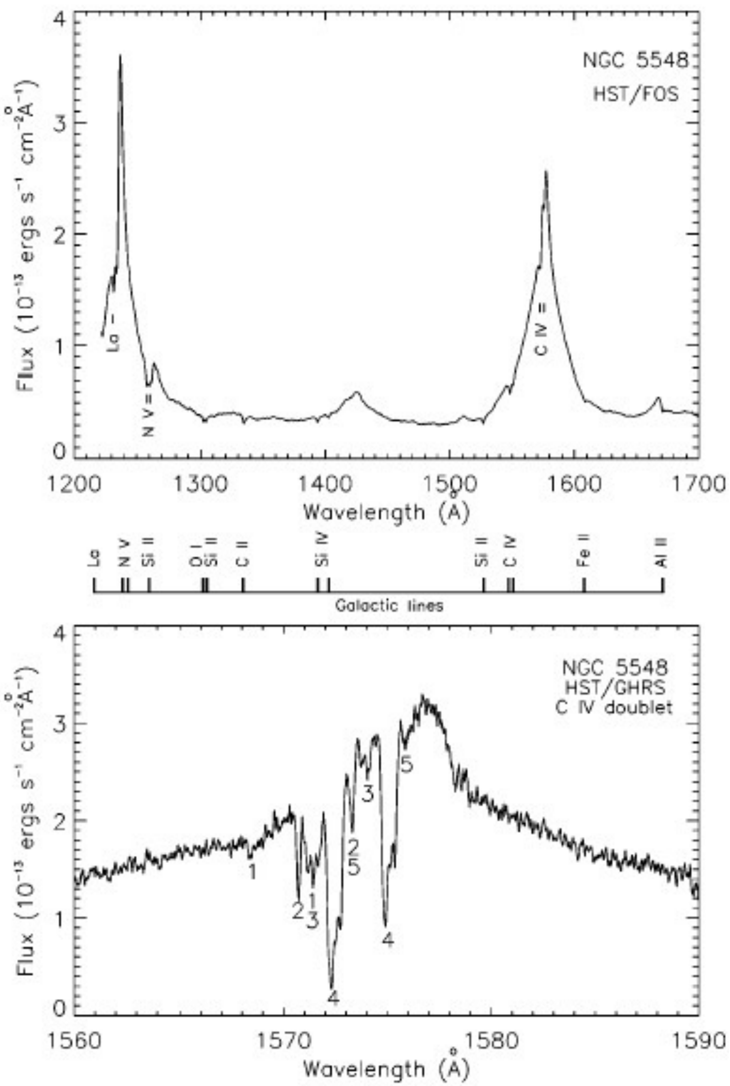
Ultra-fast outflows (UFOs)



(e.g. Pounds et al. 2003)

- Several nearby AGN show broad, blueshifted absorption features in deep X-ray spectra
- Features due to FeXXV or FeXXVI ions (transitions from the ground state)
- The outflow velocities extreme 15,000 < Δv < 90,000 km/s (0.05 – 0.3c)
- Outflows on scales <1pc.
- These UFOs are highly energetic, with kinetic powers a significant fraction of the Eddington luminosity (P_{out}~$0.1L_{bol}$)

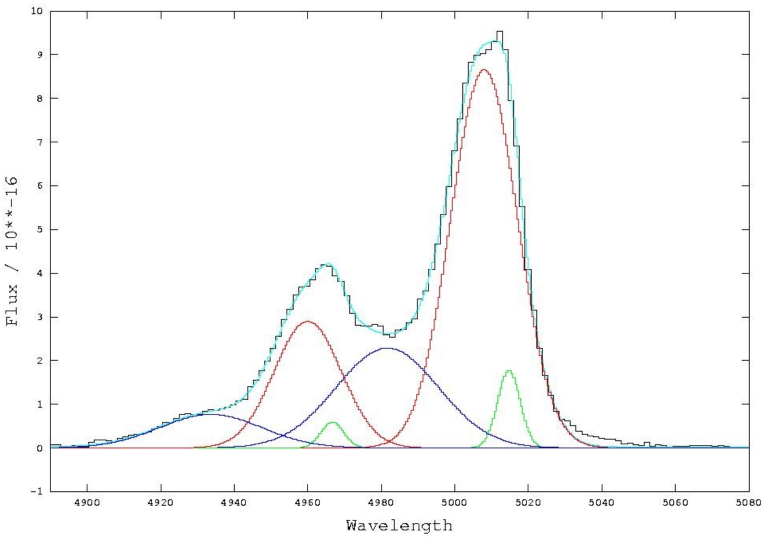
Narrow (<1,000 km/s) UV absorption lines



- Detected in UV/X-ray spectra of ~60% of nearby type 1 AGN
- Absorbing gas has a high ionization state
- Absorption features strongly blueshifted ($-2100 < \Delta V < 0$ km s^{-1}) ➔ high ionization *outflows* close to the central AGN
- Mass outflow rates and energies of the outflows are relatively modest -- much less than required by the galaxy evolution models (but large uncertainties in radii, geometries, physical conditions of absorption line systems).

- e.g. Crenshaw et al. (2003)

Emission line outflows in NLR



(e.g. Holt et al. 2003)

- A large fraction (> 60%) of nearby AGN, show broad, blueshifted (Δv > 500 km/s) wings to their [OIII] forbidden lines.
- Blue wings can extend to -2,000 km/s relative to line centres
- The broad, blueshifted emission lines provide strong evidence for AGN-driven outflows in the near-nuclear regions (< 1.0 kpc).
- However, the kinetic powers of these warm gas outflows are difficult to quantify, because of uncertainties about radii, densities and reddenings of outflowing gas.

Quasar mode feedback summary

- Blueshifted absorption and emission features now provide evidence for near-nuclear outflows in a large fraction of the nearby AGN population
- In some cases (e.g. UFOs) these outflows may be energetic enough to expel the gas from the bulges of the galaxies, preventing further star formation
- But the outflow energetics can be hard to quantify because of lack of information about the radial scales and physical conditions in the outflowing gas
- Also, we currently lack observational evidence that the quasar winds extend on galaxy-wide scales (many kpc), as required by the models
- And the AGN radiation doesn't couple well with the hot gas in the haloes of the host galaxies and galaxy clusters (because σ_T is small)

Lecture 15: learning outcomes

- Understand that the gravitational influence of the SMBH on the bulge is extremely small
- Knowledge of the ways in which AGN might affect the evolution of the host galaxies
- Understanding of the differences between jet mode and quasar mode feedback
- Knowledge of the direct observational evidence for radio and quasar mode feedback, and the impacts on the host galaxies and clusters