

Cosmic Feedback

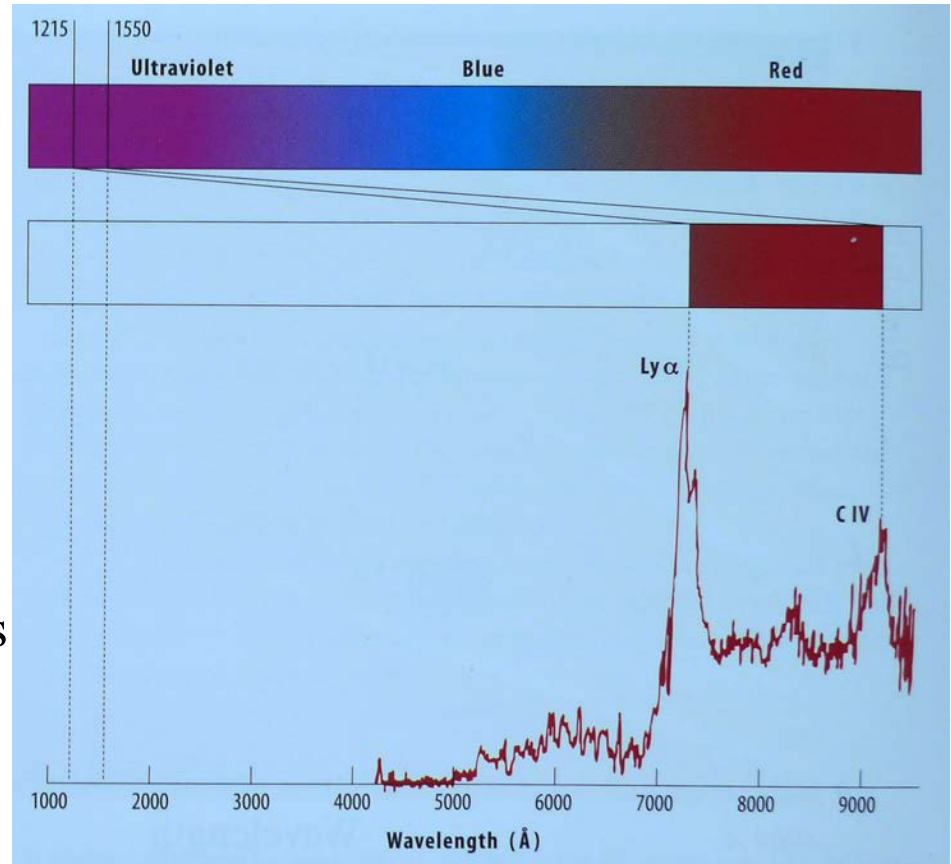


Evolution of Quasar Population

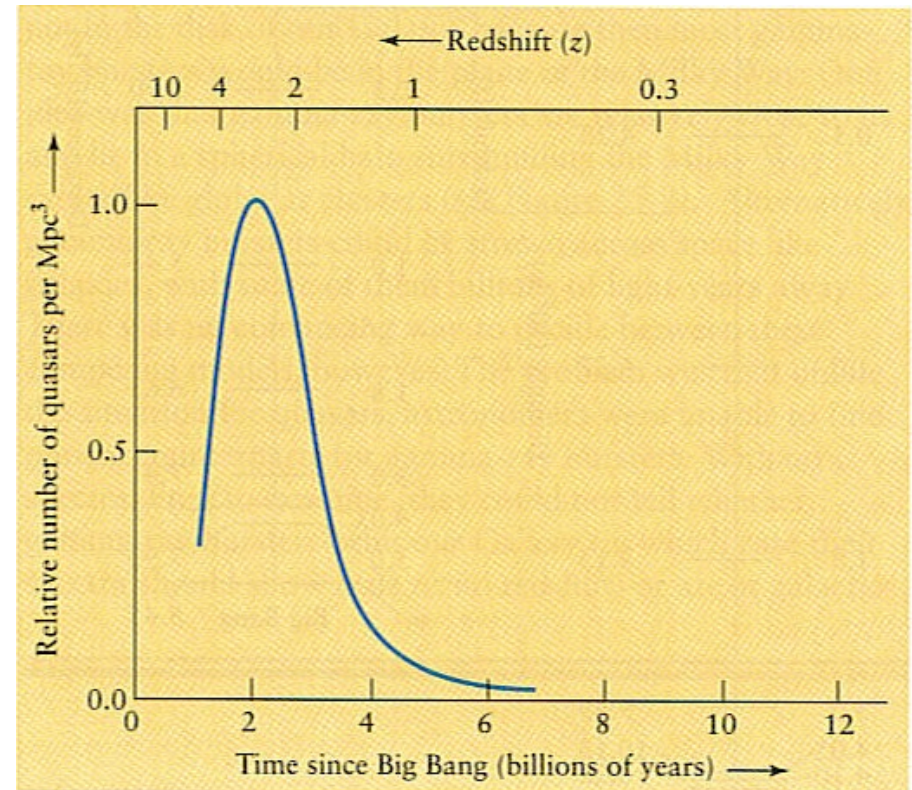
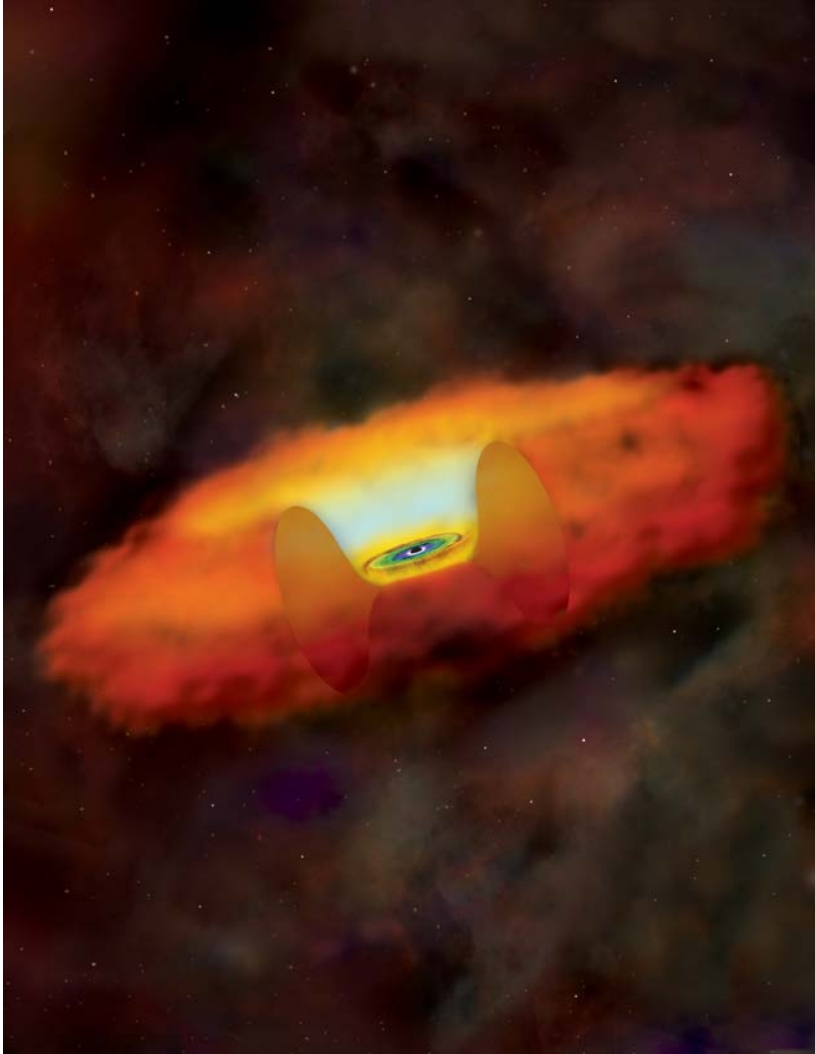
The quasar PC 1247+3406 has a high redshift of $z = 4.897$.

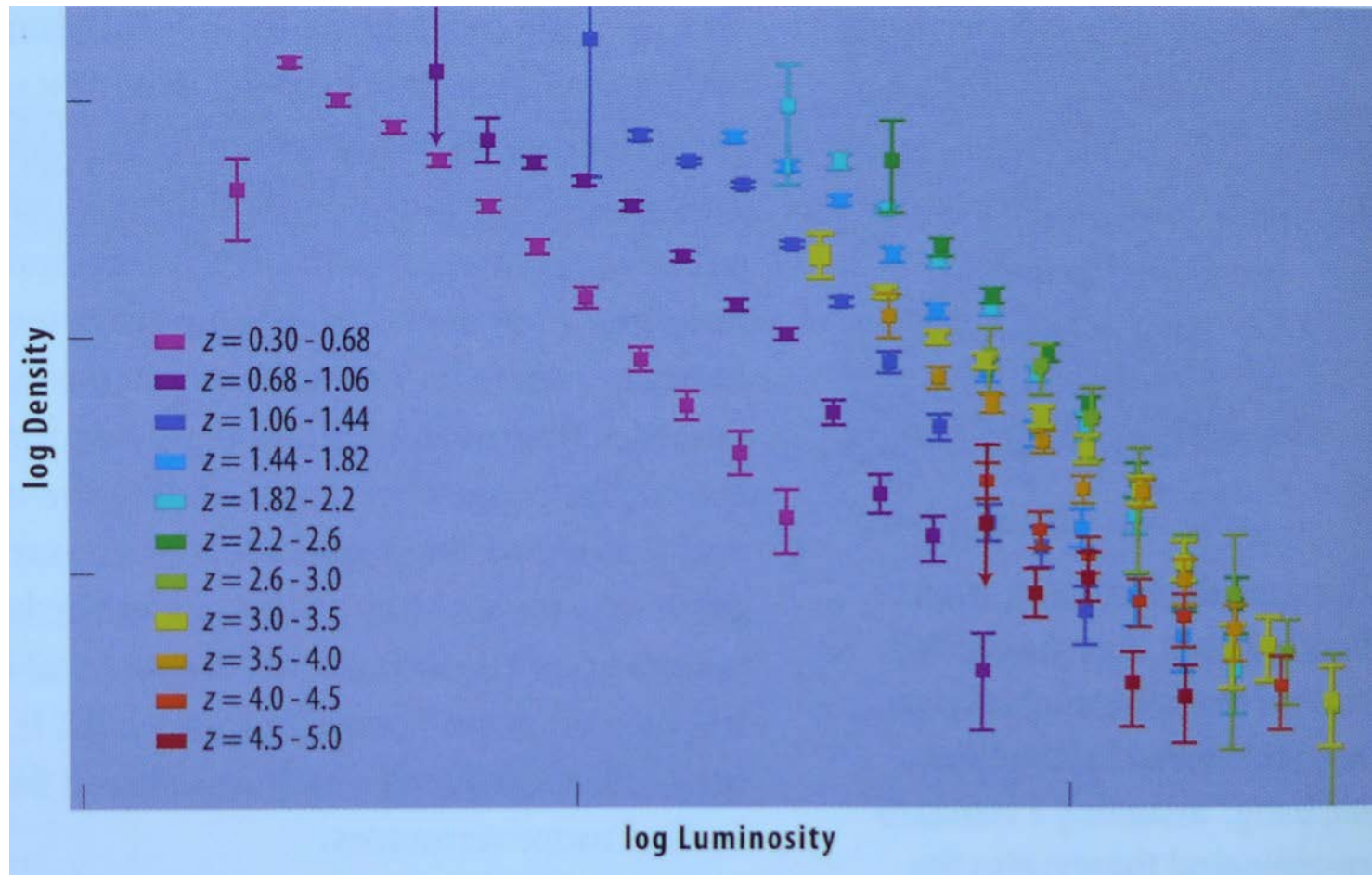
Notice that the Lyman α ($\lambda=1215 \text{ \AA}$) and C IV ($\lambda=1550 \text{ \AA}$) lines are redshifted into the red part of the spectrum.

The Universe has expanded by a factor of $(1+z) \sim 5.9$ since the light was emitted from this quasar.



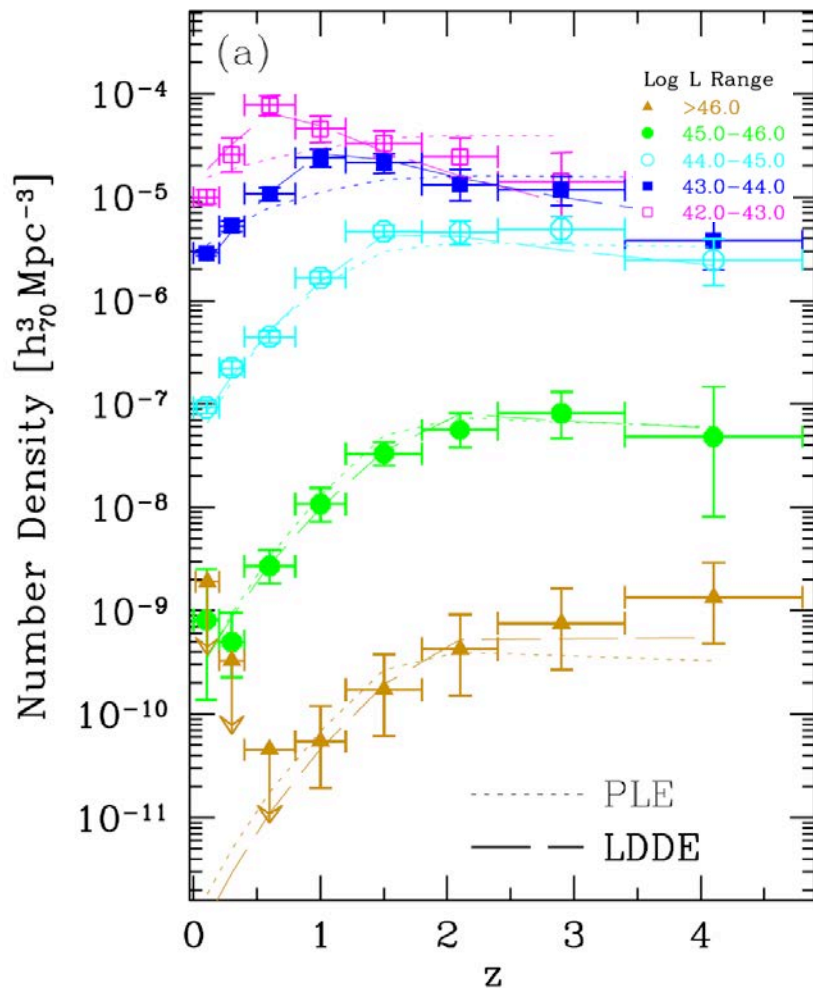
Evolution of Quasar Population





Each data point represents the density of quasars at a certain redshift range within a certain range of luminosities. The luminosity function of quasars changes with redshift. Each tick mark corresponds to a factor of 10 in either density or luminosity.

Evolution of Space Density of type-I AGN



Hasinger et al (2005)

The space density of type-I AGN changes significantly with redshift and luminosity.

The redshift at which the space density peaks changes with luminosity from

$z \sim 0.5-0.7$ for $\log L_x = 42-43 \text{ ergs s}^{-1}$
to
 $z \sim 2$ for $\log L_x = 45-46 \text{ ergs s}^{-1}$.

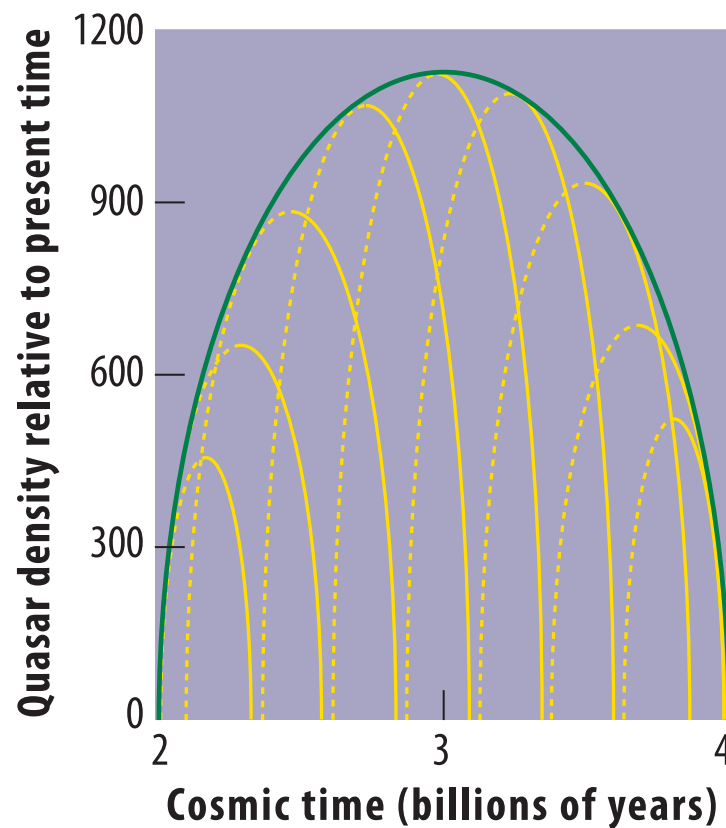
The space density of low luminosity AGN is found to decline at high redshift.

Relics of SMBHs in the Current Universe

The age of the average quasar need not be the time between the rise and fall of the quasar population that lasted for about 2 billion years.

Did only one generation of quasars appear appear on the scene for ~ 2 billion years or did many generations flare up and fade away during the quasar era?

We need to figure out the average age of a quasar.



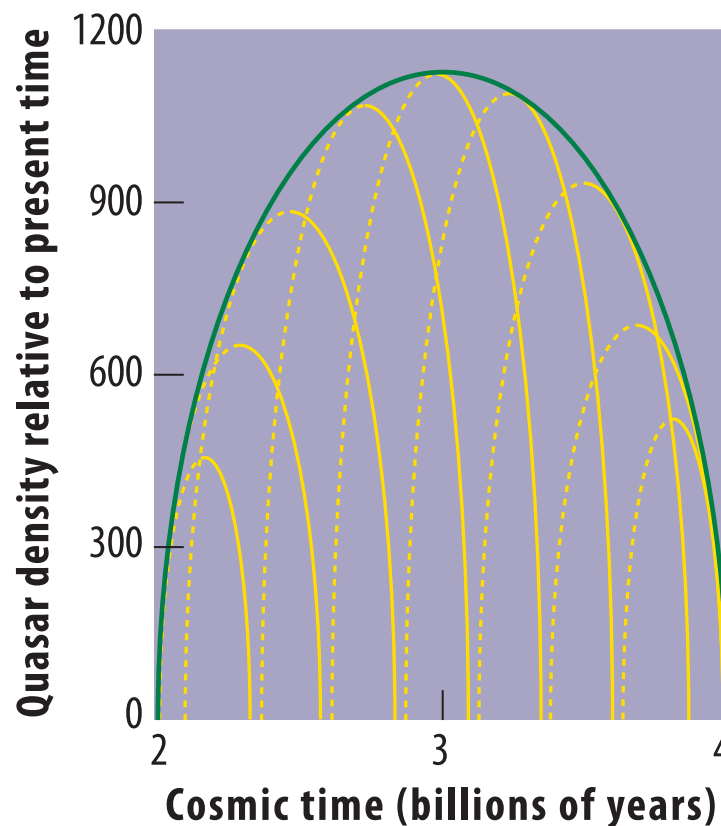
Relics of SMBHs in the Current Universe

To figure out the average age of a quasar we need to figure out the range of quasar masses and the typical accretion rates.

$$M_{BH} \approx \left(\frac{dM}{dt} \right) \times t_{quasar} \rightarrow t_{quasar} \approx \frac{M_{BH}}{dM/dt}$$

$$dM/dt \sim 10 M_{\odot} / \text{year}$$

We can estimate M_{BH} from reverberation mapping.



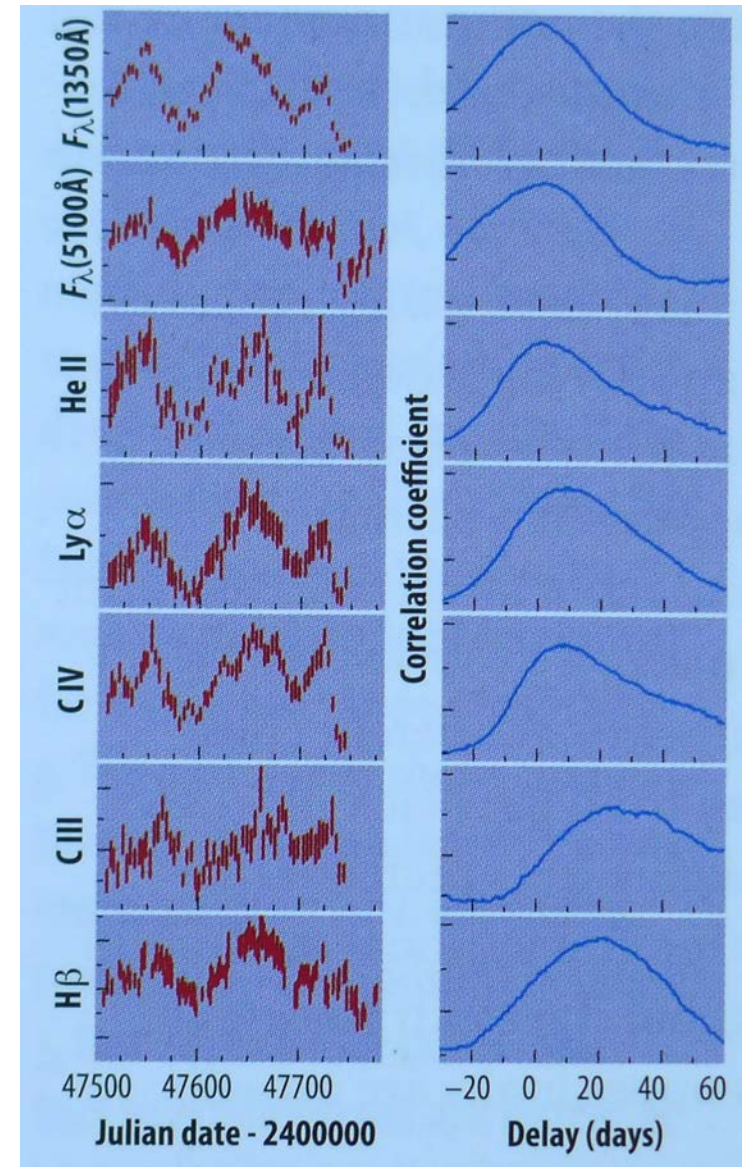
Reverberation Mapping

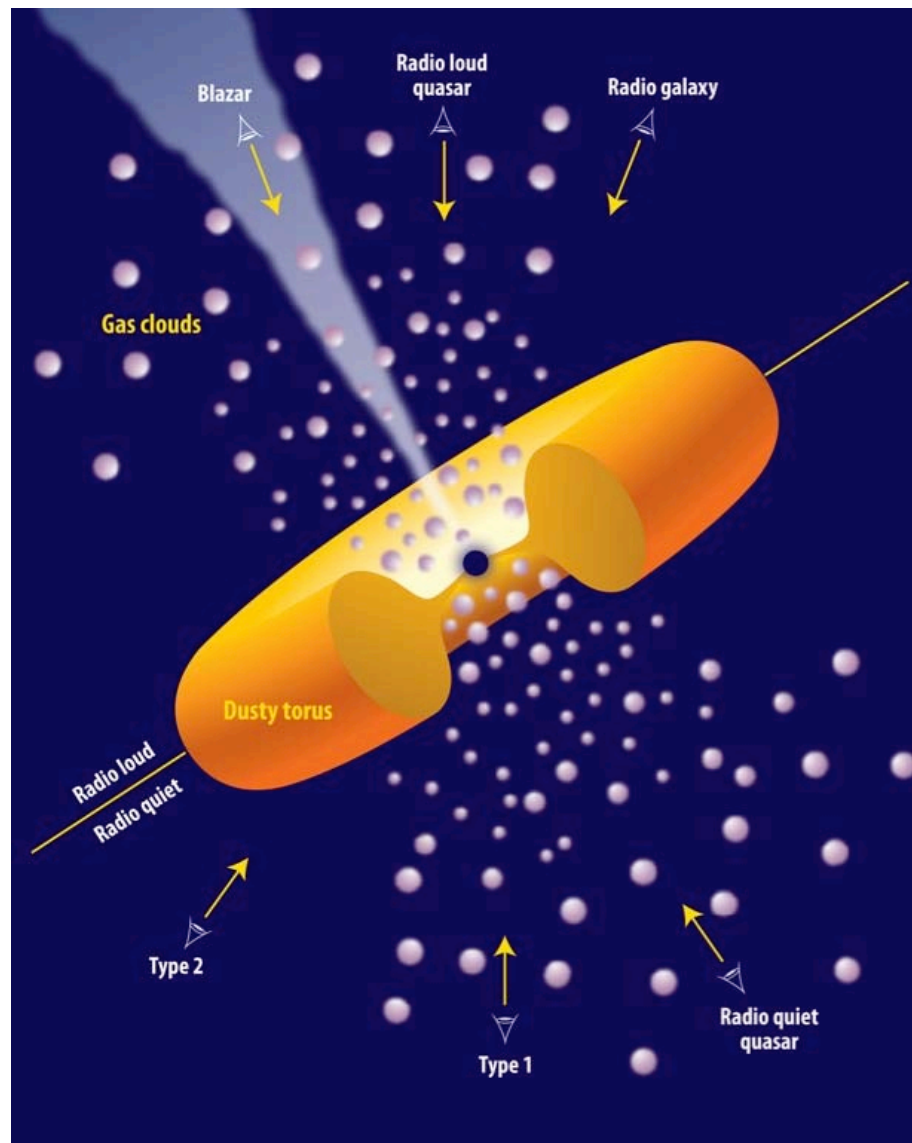
The strength of the BLR emission lines rise and fall in response to changes in the ultraviolet radiation from the accretion disk with a time delay. The time delay depends on the distance between the UV source and the BLR cloud. If one also measures the velocity width Δv of the line they can infer the mass of the black hole.

$$M_{BH} = \frac{f R \Delta v^2}{G}$$

Quasar masses are found to be $M_{BH} \sim 10^8 M_{\odot}$ to $10^9 M_{\odot}$. Quasar lifetimes are:

$$t_{quasar} \approx \frac{M_{BH}}{dM/dt} \approx \frac{10^{8-9} M_{solar}}{10 M_{solar} / year} = 10^7 - 10^8 \text{ years}$$



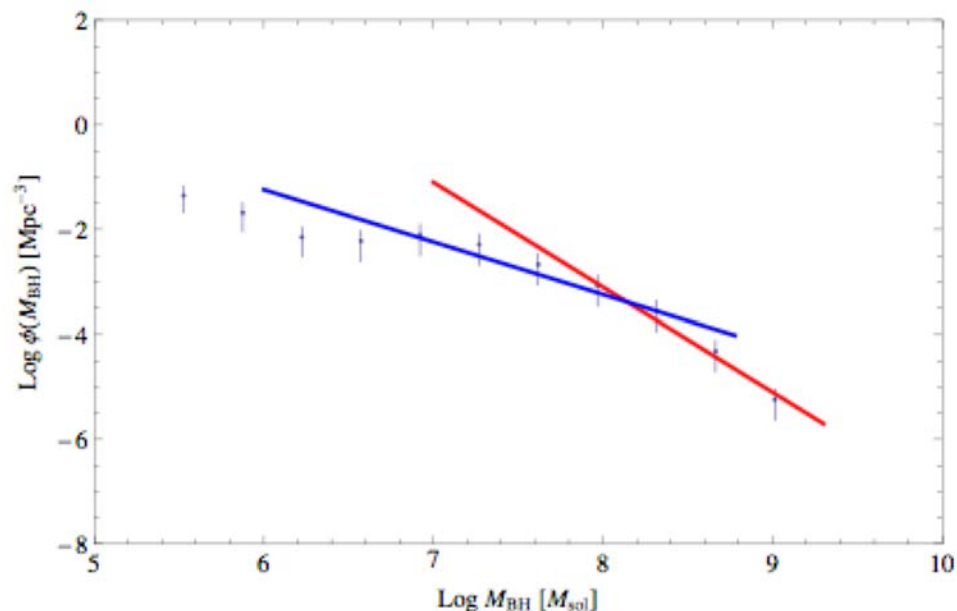


Relics of SMBHs in the Current Universe

If a large fraction of galaxies once went through the quasar phase we would expect a large fraction of “present day” non-active galaxies to contain the remnant SMBHs.

The mass of the SMBH of a normal galaxy can be estimated from the M_{BH} -sigma relation.

Right: mass function of the black holes of a sample of ~ 3000 nearby galaxies.



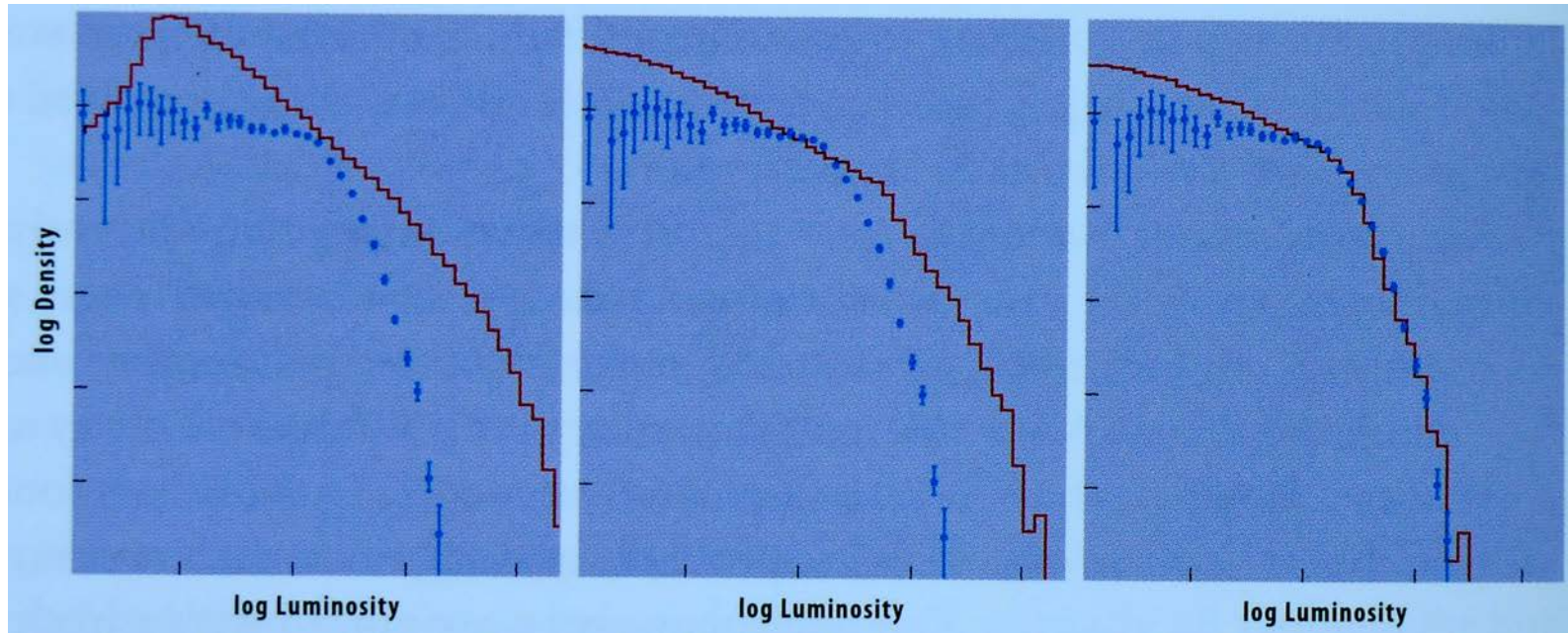
Relics of SMBHs in the Current Universe

Soltan's argument: Compare the total mass of all SMBHs in quasars over cosmic history ($z = 0.5-6$) with the total mass of all SMBHs in normal galaxies of the nearby Universe.

We can estimate the total mass of all SMBHs in distant quasars by converting their luminosities into mass.

$$L_{qso} = \eta \frac{dM}{dt} c^2 \rightarrow M_{qso} \approx \frac{L_{qso}}{\eta c^2} t_{life}$$
$$M_{Total} \approx \sum_i \frac{L_i}{\eta c^2} t_i, \text{ sum over all quasars}$$

It turns out that M_{Total} inferred from the luminosities of quasars is very close to the total mass in all the nearby SMBHs of normal galaxies. This indicates that the relic SMBHs are accounted for and that most of the mass of a SMBH can be accounted for by accretion.



The effects of feedback on the predicted distribution of galaxy masses compared to the observed distribution (blue).

(left) Without feedback galaxy formation theory predicts too many large galaxies and small galaxies.

(middle) Including feedback from supernovae the theory suppresses the formation of small galaxies but has little effect at large masses.

(right) Including feedback from the SMBH one can fit the observed numbers of massive galaxies as well.

Feedback

Another problem with hierarchical theory of galaxy formation is that **galaxies should have many small satellites** but this does not seem to be the case. For example our own galaxy has very few small satellites.

The observations are therefore telling us that there appears to be some missing **destructive agent** from the theory of galaxy formation.

A process (often referred to as **feedback**) is thought to release energy into the intergalactic medium and somehow inhibit the collection of too much gas in the halo.



According to Cold Dark Matter theory each galaxy-sized dark matter halo should contain large numbers of subhalos (dwarf-galaxies). However, observations do not find any subhalos that might be associated with luminous structures. A possible solution is that these dwarf galaxies may have very few stars.

Feedback

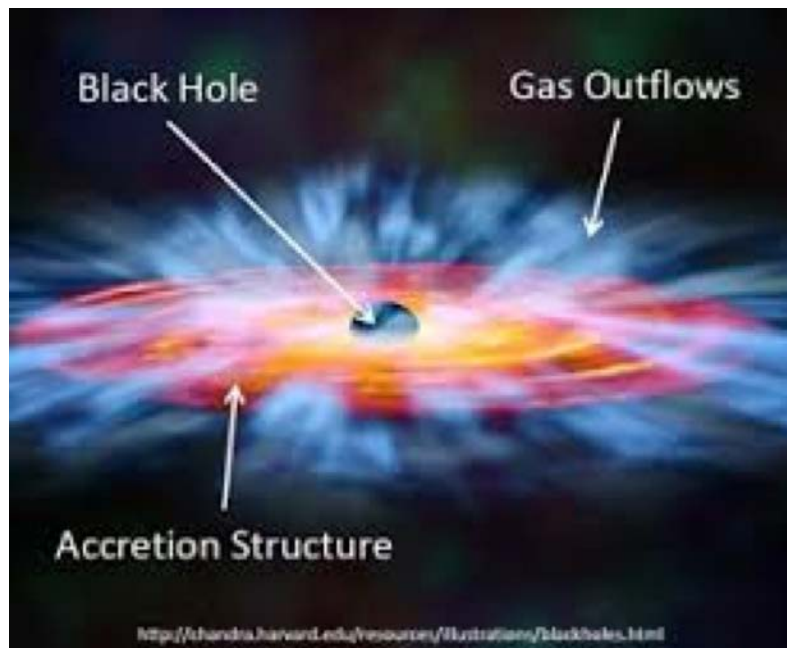
Many scientists now think that the SMBH is the destructive agent that inhibits the growth of its host galaxy.

In many cases the energy released by SMBHs seems to be adequate. For example $0.1 M_{\text{BH}} c^2$ would be more than enough energy to eject all the gas from the galaxy.

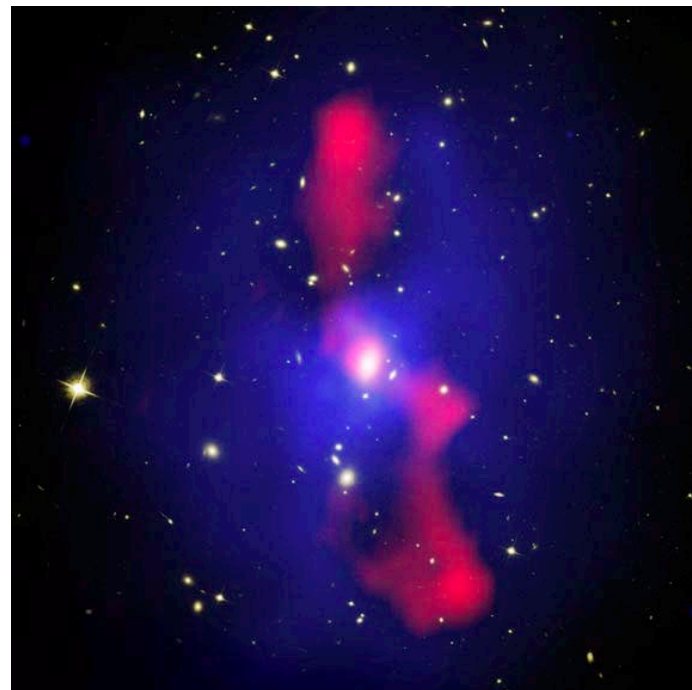
The problem is how does the energy released by a SMBH spread over large distances and how does it interact with the gas in the galaxy.

AGN put out energy in the forms of radiation, jets and winds.

Modes of interaction of AGN with their environments



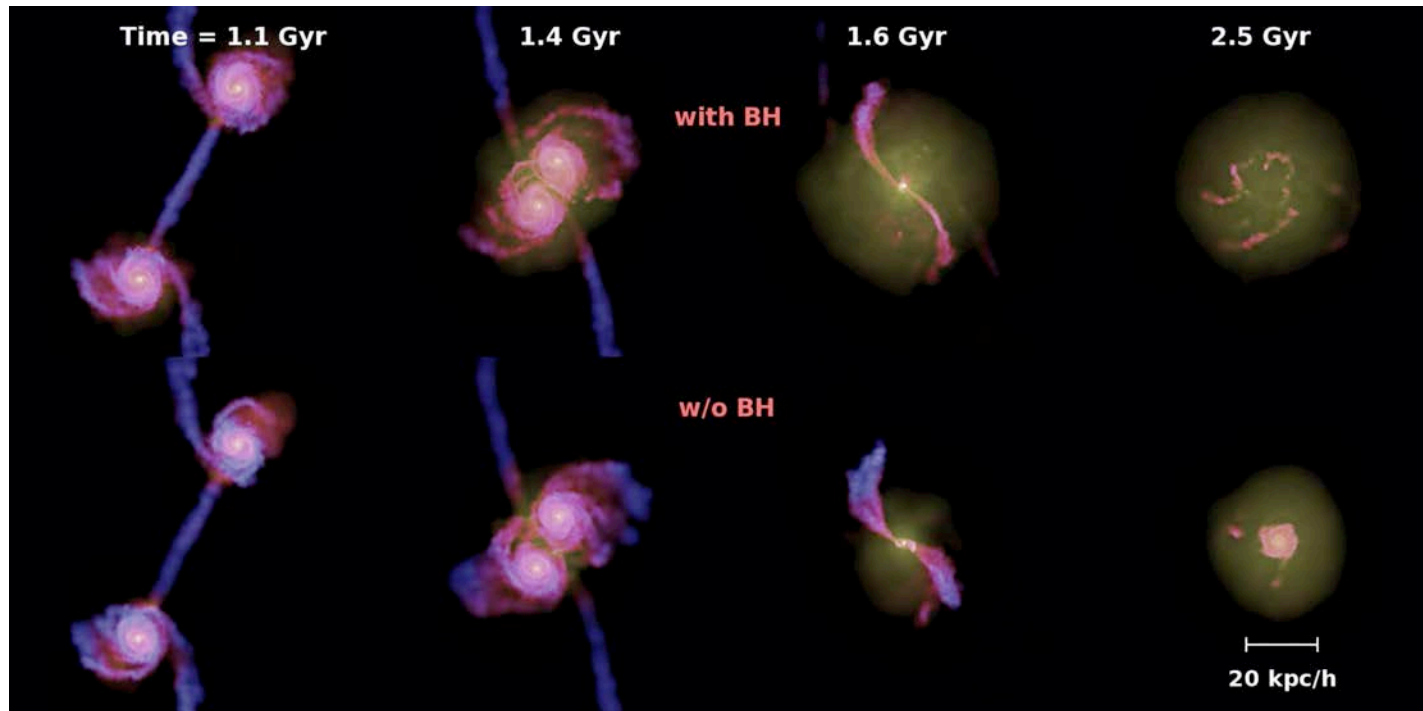
AGN Winds and Radiation



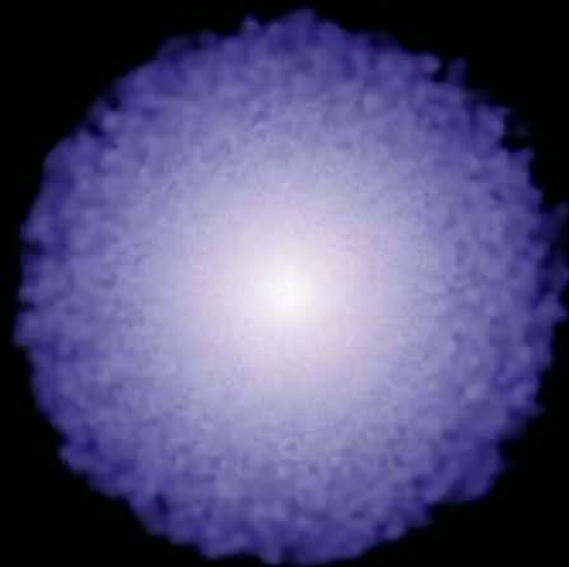
MS0735.6+7421 (McNamara & Nulsen 2007)

Radio Jets

The Importance of Quasar Winds in Driving Quasar Evolution



$T = 0$ Myr



10 kpc/h



Quasar Winds

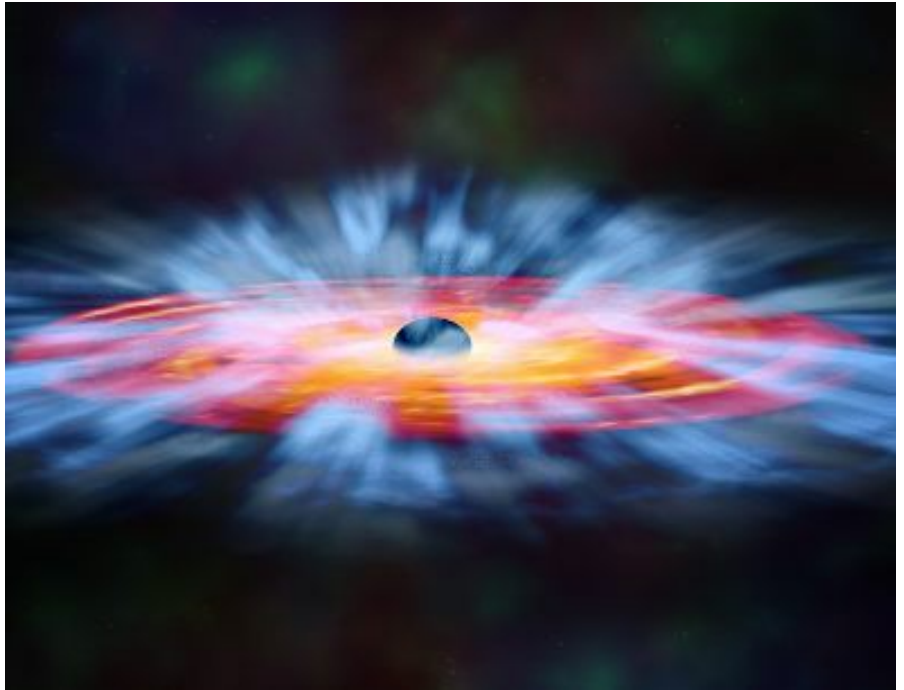


Density evolution of a disk wind driven by radiation pressure on spectral lines. Proga Stone & Kallman (2000)

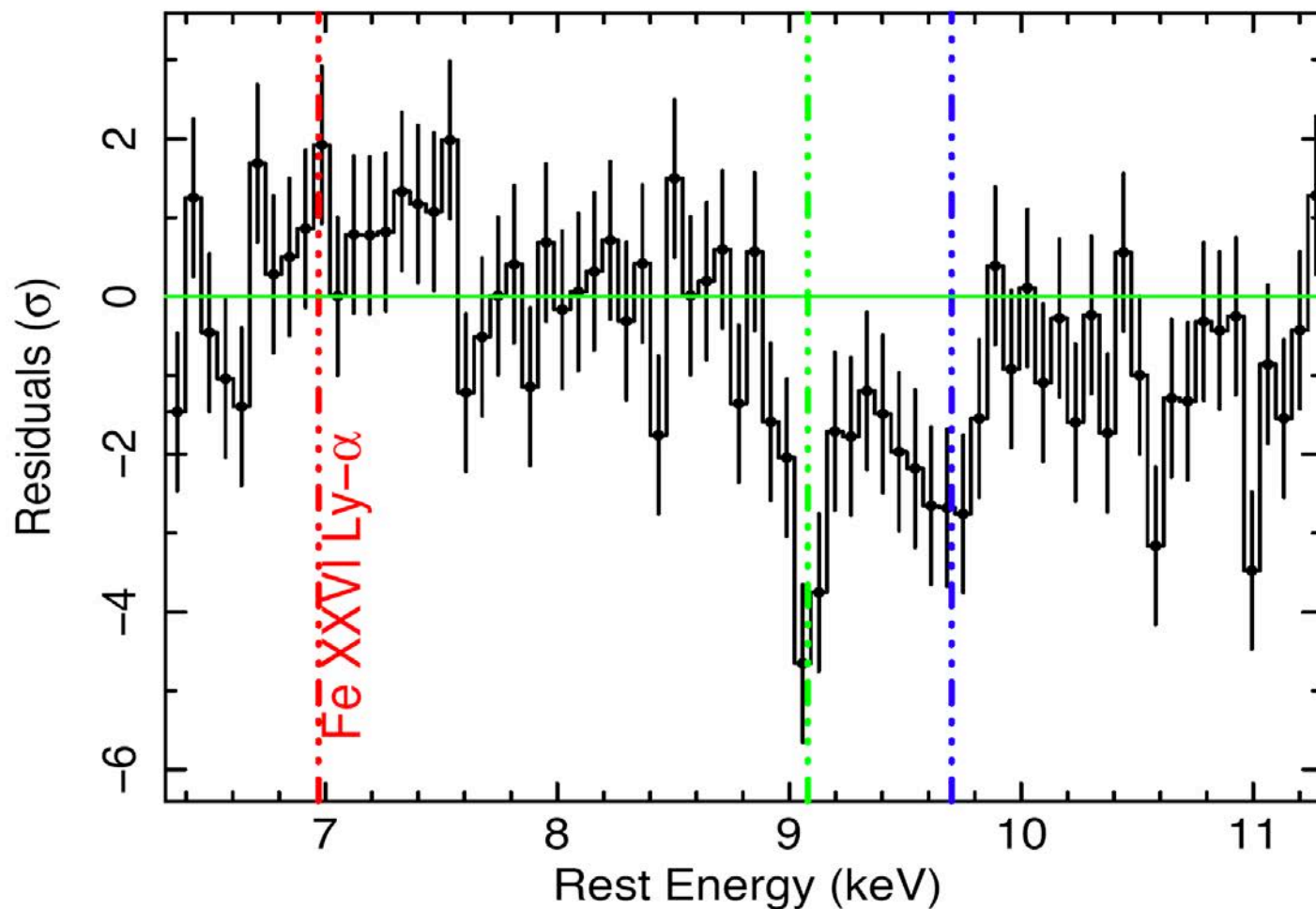
Quasar Winds

Proposed mechanisms for quasar wind acceleration include:

- radiative driving
- magnetic driving
- thermal driving

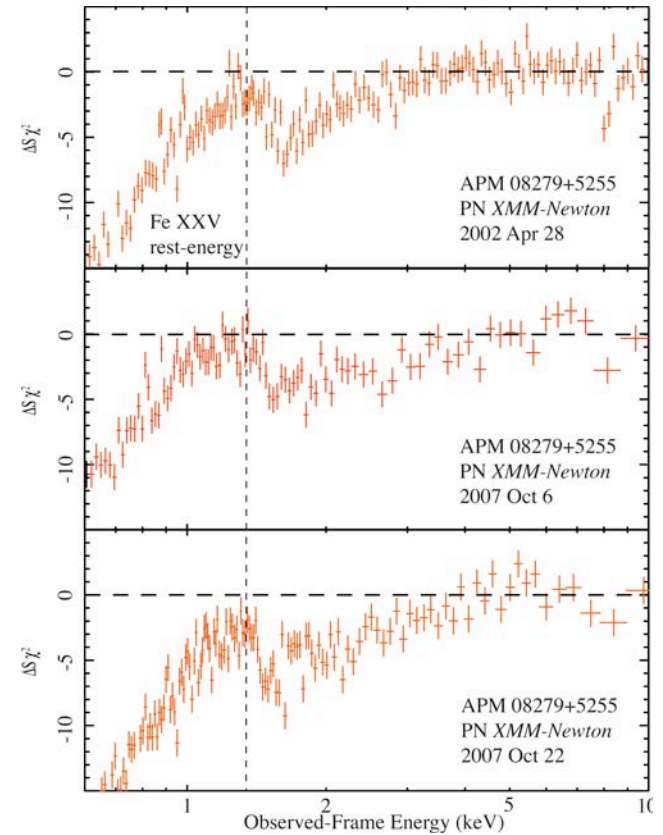
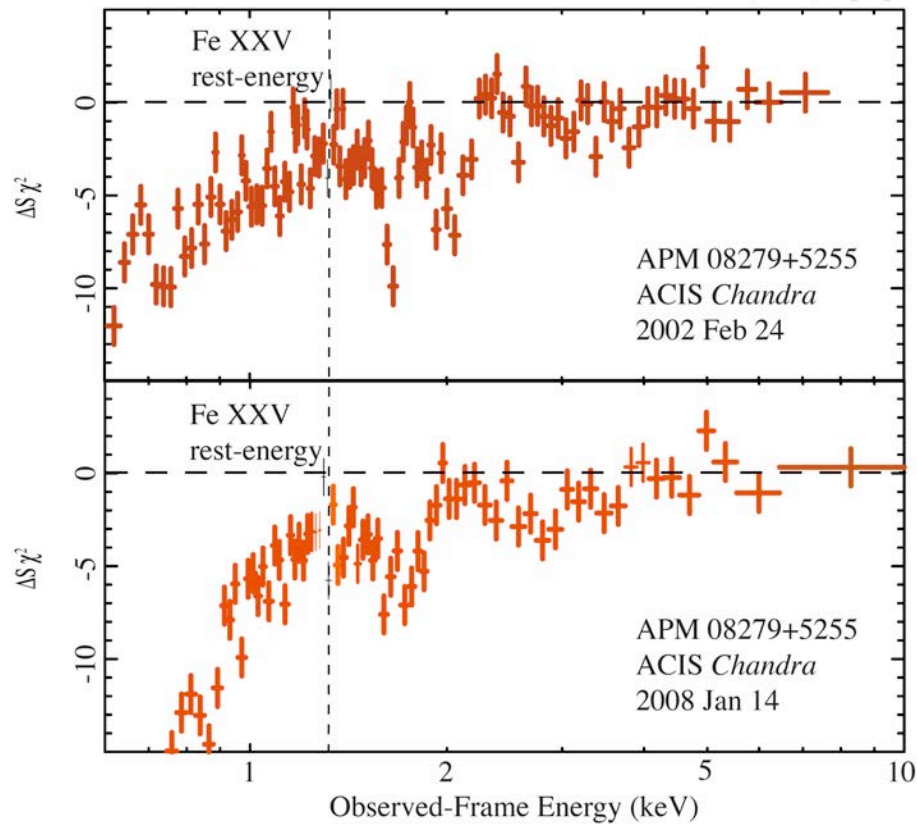


X-ray Observations of AGN Winds



X-ray (Suzaku XIS) data from the observation of quasar PDS 456 compared with a simple power-law fit. Inferred outflow velocity of $v = 0.25 - 0.3c$ (Reeves et al. 2008).

X-ray Observations of AGN Winds



Interpreting X-ray Observations of AGN Winds

The mass outflow rate is:

$$\dot{M} = 4\pi r \left(\frac{r}{dr} \right) N_H m_p v_{wind} f_c$$

The outflow efficiency is:

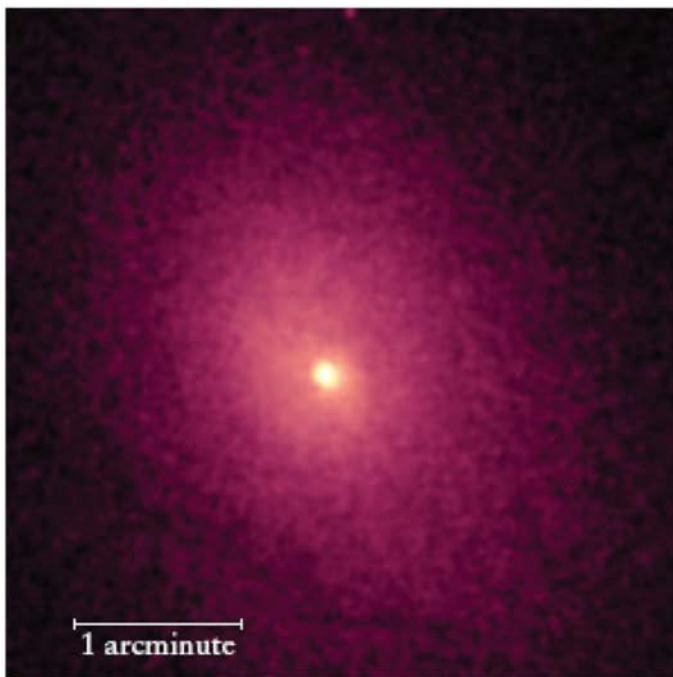
$$\varepsilon_{k,i} = \frac{1}{2} \frac{\dot{M}_i v_{wind,i}^2}{L_{Bol}} = 2\pi f_{c,i} R_i (R_i / \Delta R_i) N_{H,i} m_p \frac{v_{wind,i}^3}{L_{Bol}}$$

Feedback in Clusters of Galaxies



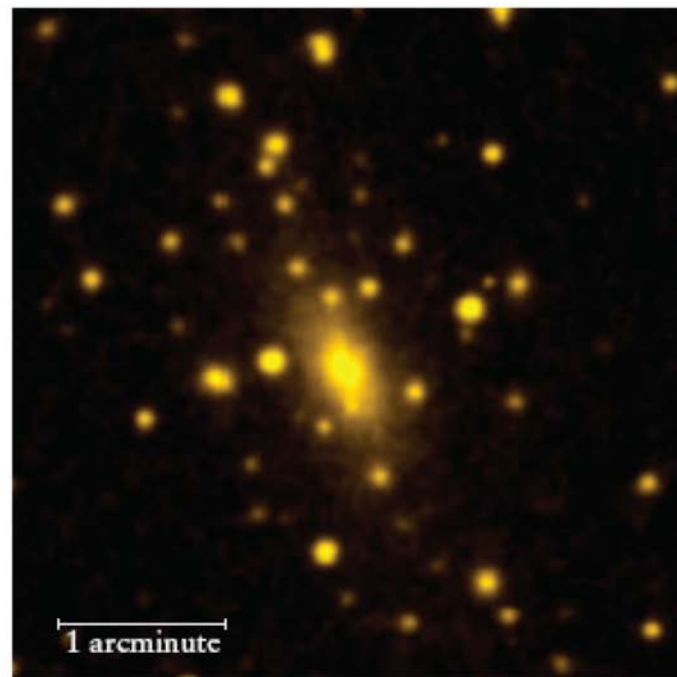
Clusters of galaxies are the largest gravitationally bound objects in the Universe. Based on simulations the smallest structures collapsed first and eventually build the largest structures, such as clusters of galaxies. Shown above is the Hercules Cluster of galaxies (rich in Spiral galaxies) just 650 million ly away.

Heating of the Intracluster Medium



(a) An X-ray image of Abell 2029 shows emission from hot gas.

R I V U X G



(b) A visible-light image of Abell 2029 shows the cluster's galaxies.

R I V U X G

The **Intracluster Medium** is heated to high temperatures primarily by the gravitational energy released during the formation of the cluster from smaller structures. Additional heating is provided by (a) winds from supernovae in the galaxies interacting with the ICM (b) by heating provided by the active galactic nucleus at the center of the cluster (c) collisions between galaxies and the ICM.

Excess Heating of Intracluster Medium

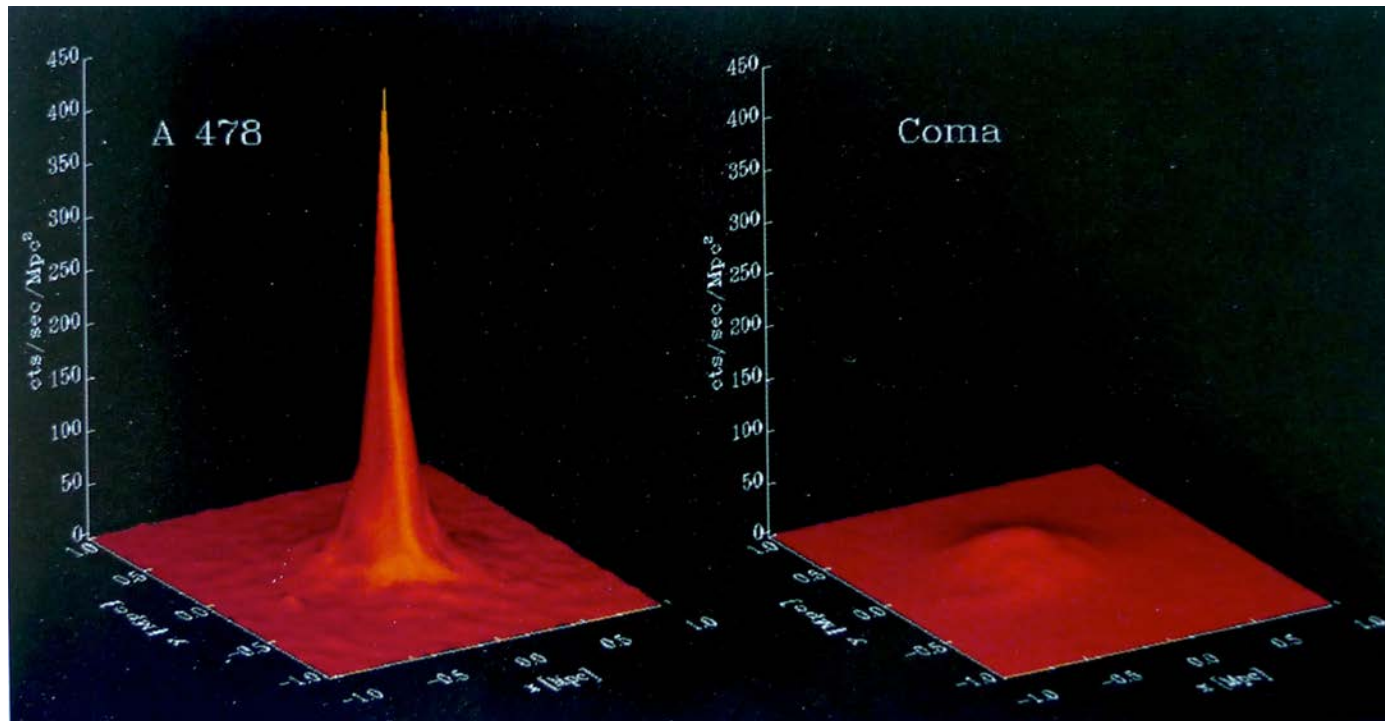
Small clusters and groups of galaxies show evidence of **excess heating**. This excess heating is thought to “puff up” the gas, reduce the density of the gas and thereby reduce the luminosity.

It is thought that SMBHs at the centers of clusters are the sources of extra heating of the intracluster gas.

One of the unresolved issues of the cluster feedback model is explaining **how the AGN energy is distributed evenly over distances of Mpc**.

The supporting evidence for ongoing AGN feedback in clusters are the detection of X-ray cavities and ripples, especially in **cool cluster cores**.

Feedback in Clusters of Galaxies



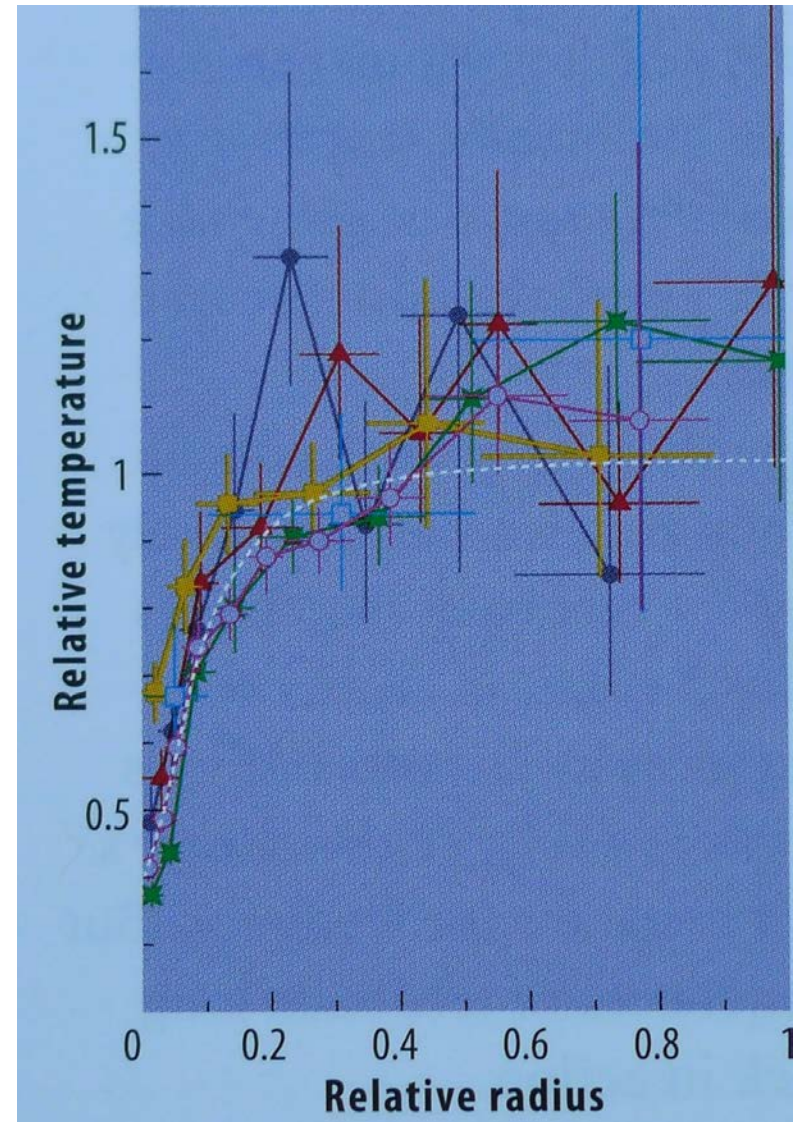
X-ray brightness versus position on the sky for a **cool core** cluster (Abell 178: left) compared to a cluster without a cool core (Coma Cluster: right). The spike in the X-ray brightness shows that gas in the inner part of the galaxy is radiating away its thermal energy at a rapid rate.

Cool-core clusters have relatively low temperatures and high densities in their centers leading to significant radiation in their core. It turns out however that **the temperature in the core is higher than what is expected** if there is no additional heating.

Plot of the **temperature of the hot gas** of a cool-core cluster as a function of distance from its center.

The temperature drops and then levels off due to feedback.

Without feedback it is predicted that the temperature would drop to lower levels near the cluster center.

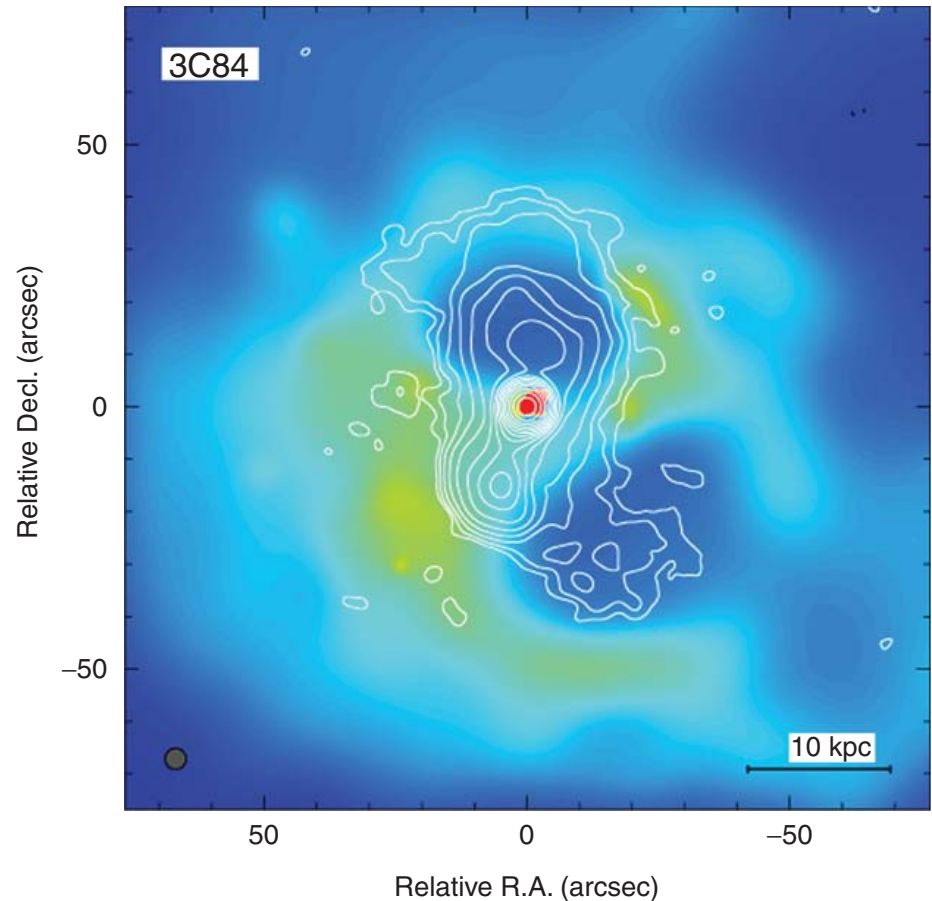


Radio Jet Mode

X-ray observations reveal **cavities** in the center of the Perseus cluster.

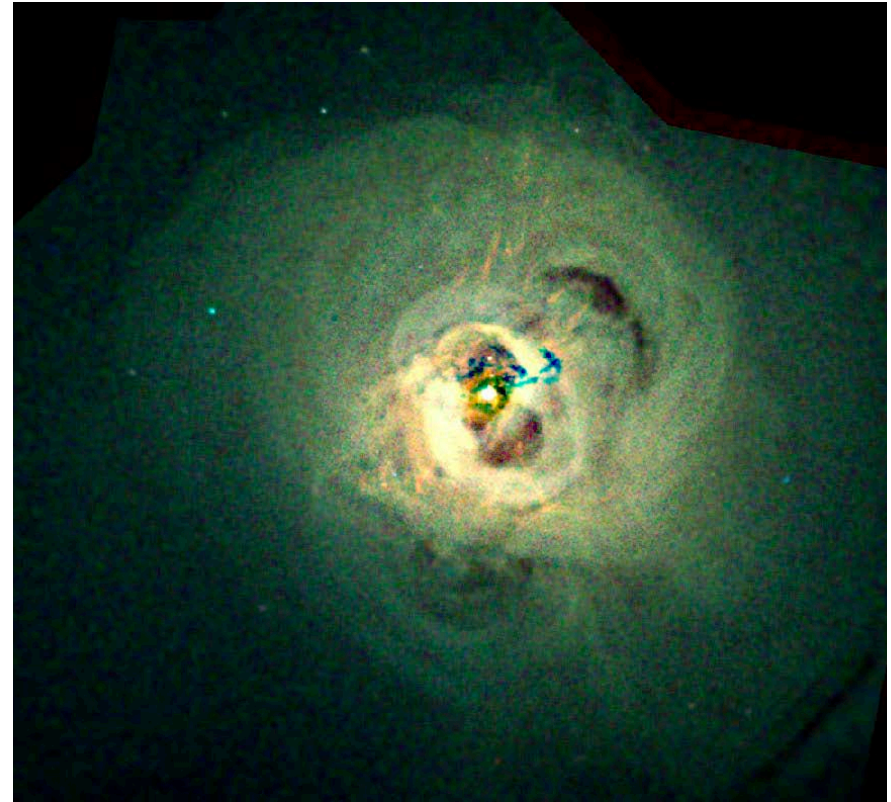
The overlaid contours represent radio emission from gas in the cavities. The contours shape imply that **the jets** from the central radio galaxy have **supplied the energy to displace the gas**.

The X-ray bright regions on the cavity boundaries are cooler suggesting that the **holes are gently inflated bubbles** rather than violent blasts.



Radio Jet Mode

- Radio jets can heat the Intracuster Medium and prevent **cooling flows**
- The radio jet mode is observed in Clusters and giant elliptical galaxies
- Work required to INFLATE cavities
 - $pV \sim 10^{55}$ erg in giant Ellipticals
 - $pV \sim 10^{61}$ erg in rich clusters



X-ray Cavities in the Perseus cluster. Notice bubbles further out. These may have formed earlier and floated away by buoyancy.

Fabian et al. 2008

Stages in the Evolution of a Radio Galaxy

Momentum Phase

In the early stages **radio jets** bore through the intergalactic gas and **inflate** a cigar shaped **cocoon**. Since the momentum is large during this phase the inflated cocoon is long and narrow reflecting the directionality of the jets.

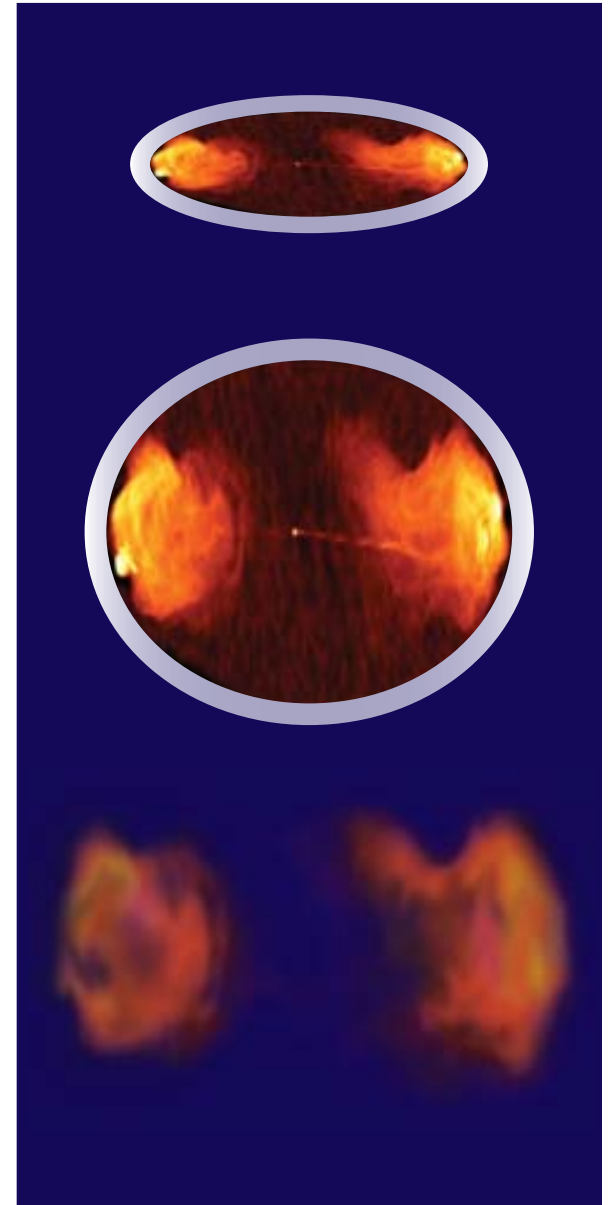
Energy Dominated Phase

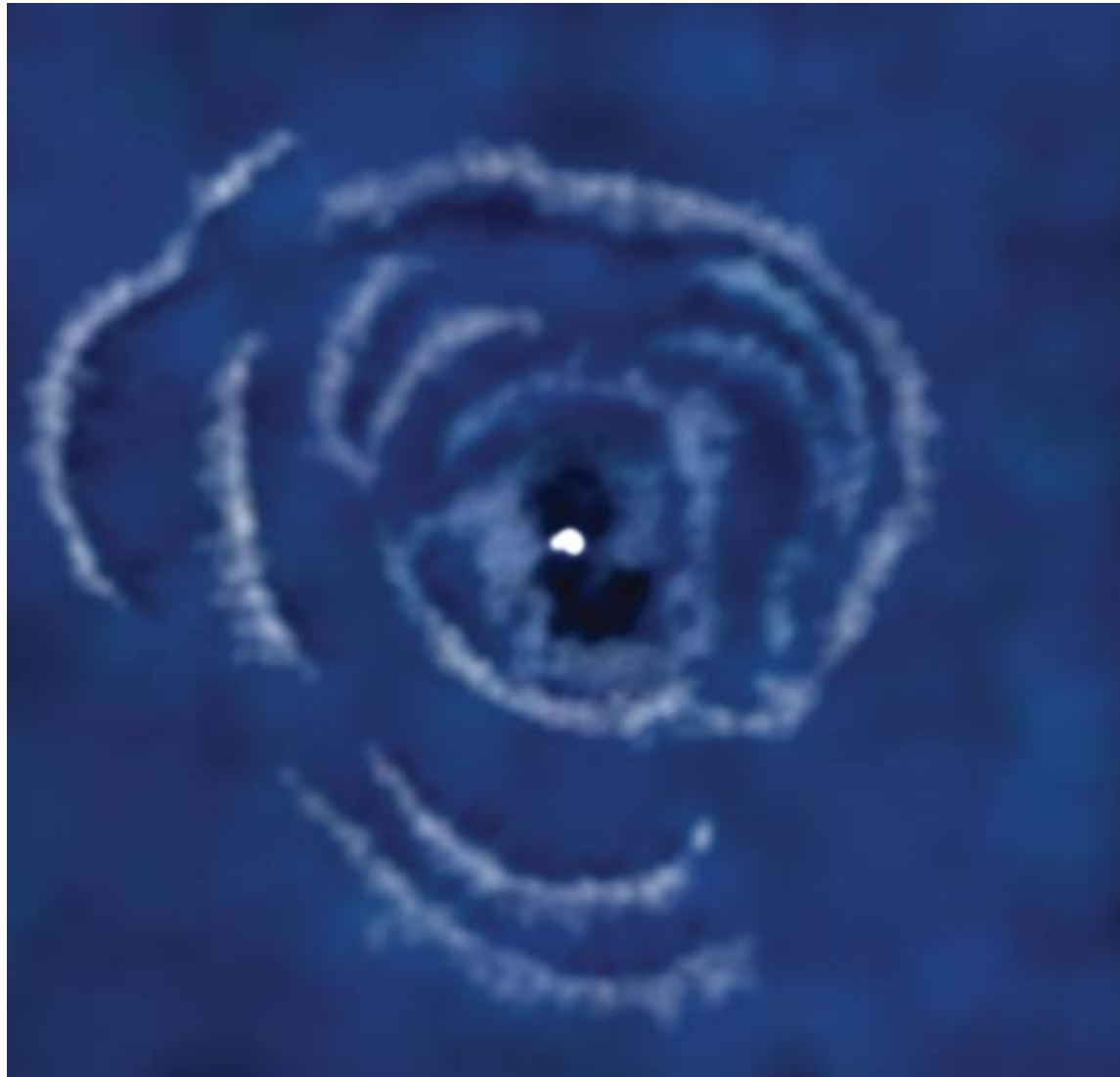
Initially the cocoon grows along the jet but as more energy gets injected it also begins to expand sideways and becomes spherical.

Bubble Phase

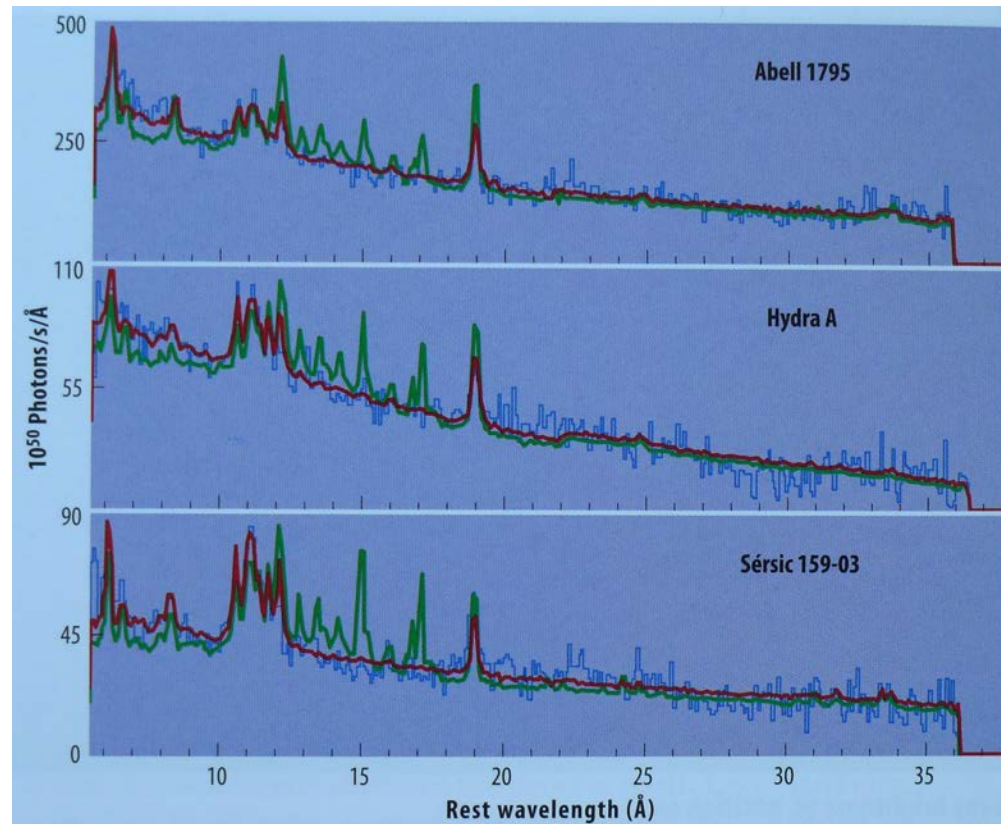
The expansion starts at about $0.1c$ and gradually slows down below the sound speed ($\sim 1000\text{km/s}$)

The energy released by the disrupted cocoon is carried away in low-density pockets of gas (bubbles).





Discovery of sound waves in the Virgo Cluster.



The **green colored** X-ray emission lines are **simulated** and show what lines were expected from the cluster gas near the core. The **red colored** X-ray emission lines are simulated at a higher temperature to match the blue spectrum that is actually **observed**. The observations imply a higher core temperature.

The central SMBH is possibly responsible for preventing the gas from cooling below some temperature.