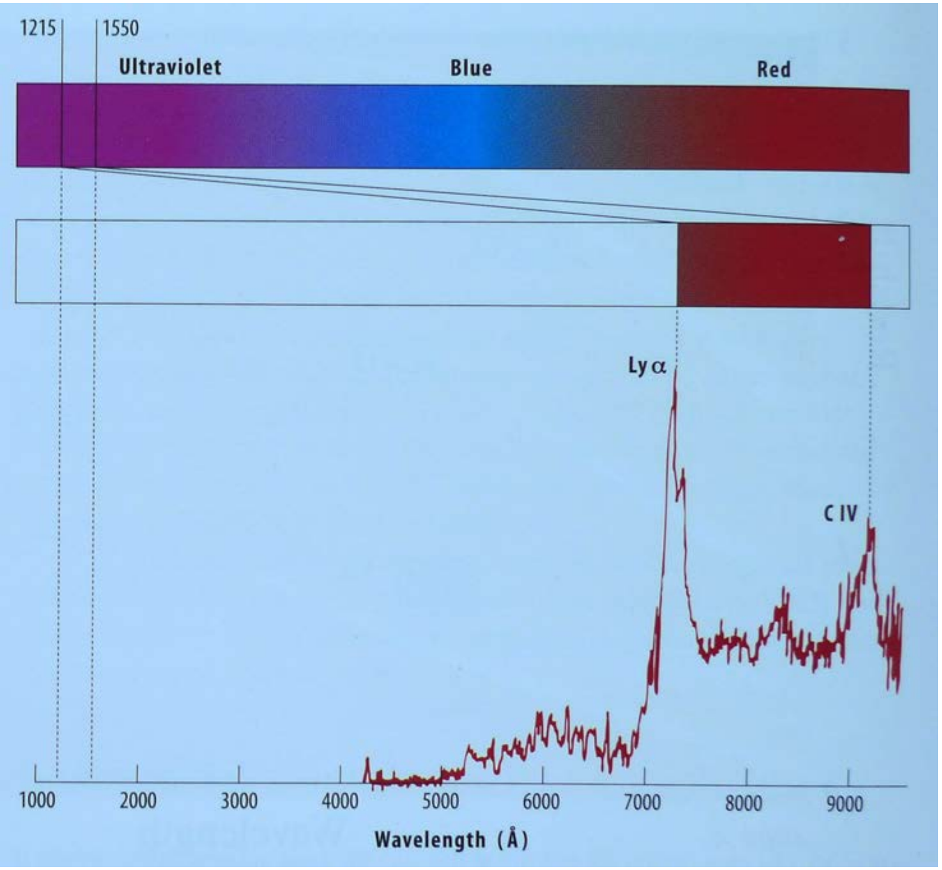
Cosmic Feedback

Evolution of Quasar Population

Notice that the Lyman α (λ_{rest}=1215 Å) and C IV (λ_{rest}=1550 Å) lines are redshifted into the red part of the spectrum.

Question: Estimate the redshist of PC 1247+3406 from the figure.

$$z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}}$$



Spectrum of PC 1247+3406

Evolution of Quasar Population

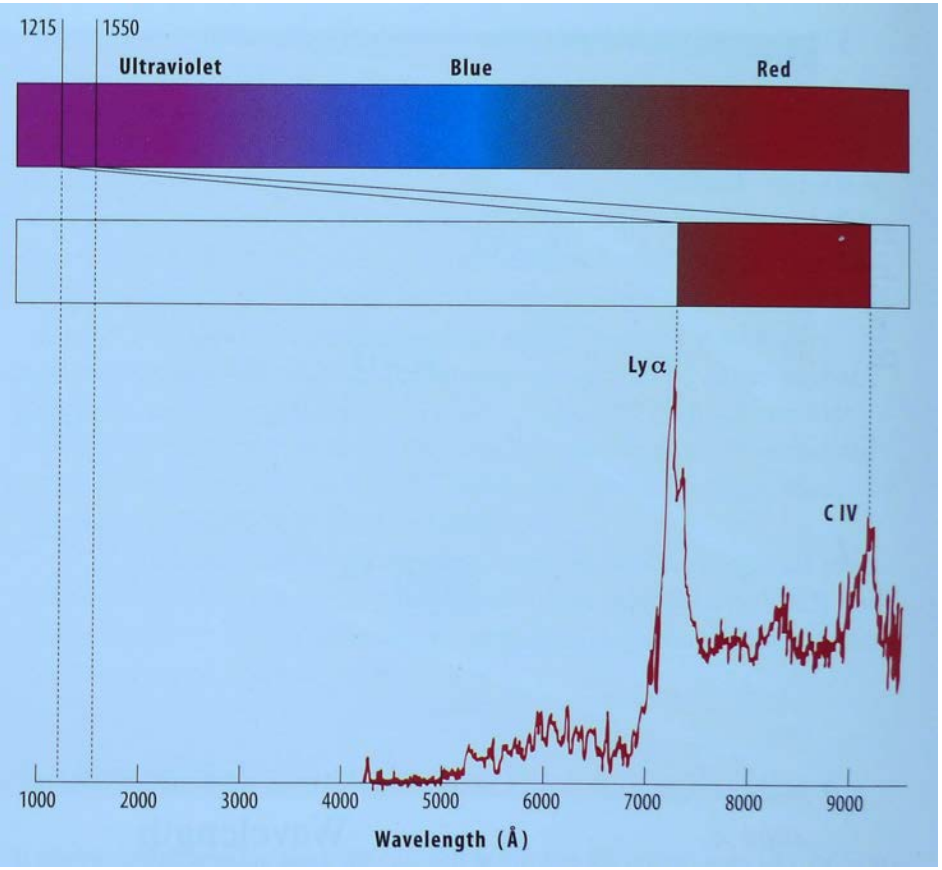
The quasar PC 1247+3406 has a high redshift of $z = 4.897$.

$$z = \frac{\lambda_{observed} - \lambda_{rest}}{\lambda_{rest}} = \frac{\lambda_{observed}}{\lambda_{rest}} - 1 \rightarrow$$

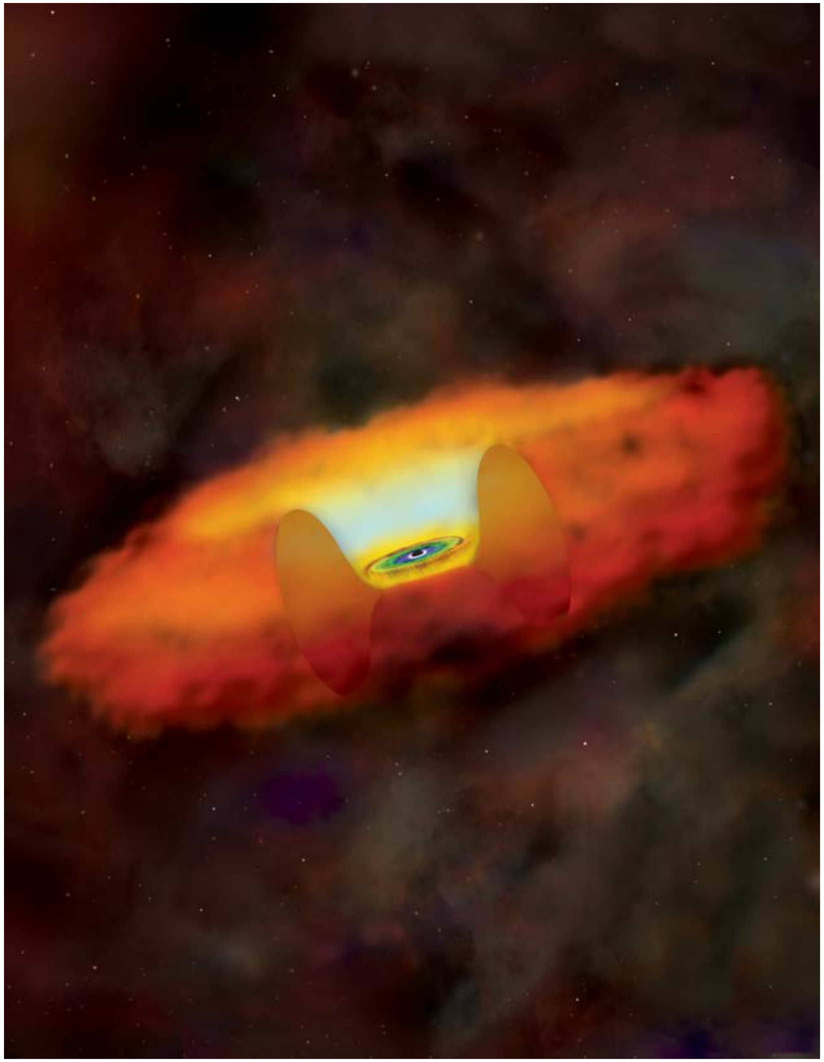
$$\frac{\lambda_{observed}}{\lambda_{rest}} = 1 + z$$

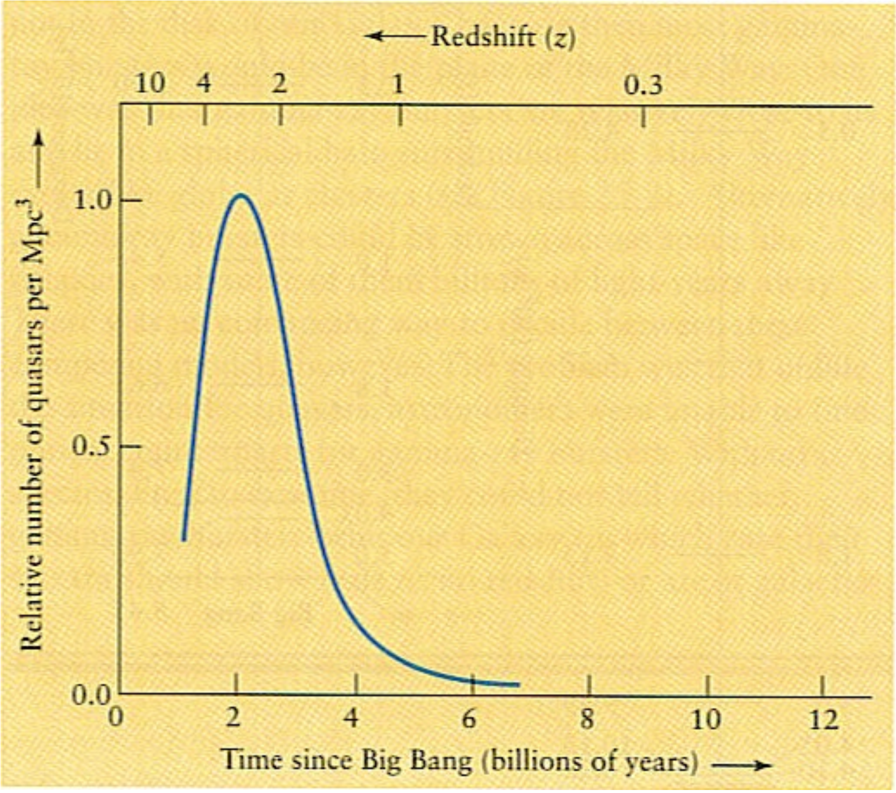
$\frac{\lambda_{observed}}{\lambda_{rest}}$ is equal to the factor by which the universe has expanded since the photon left the quasar.

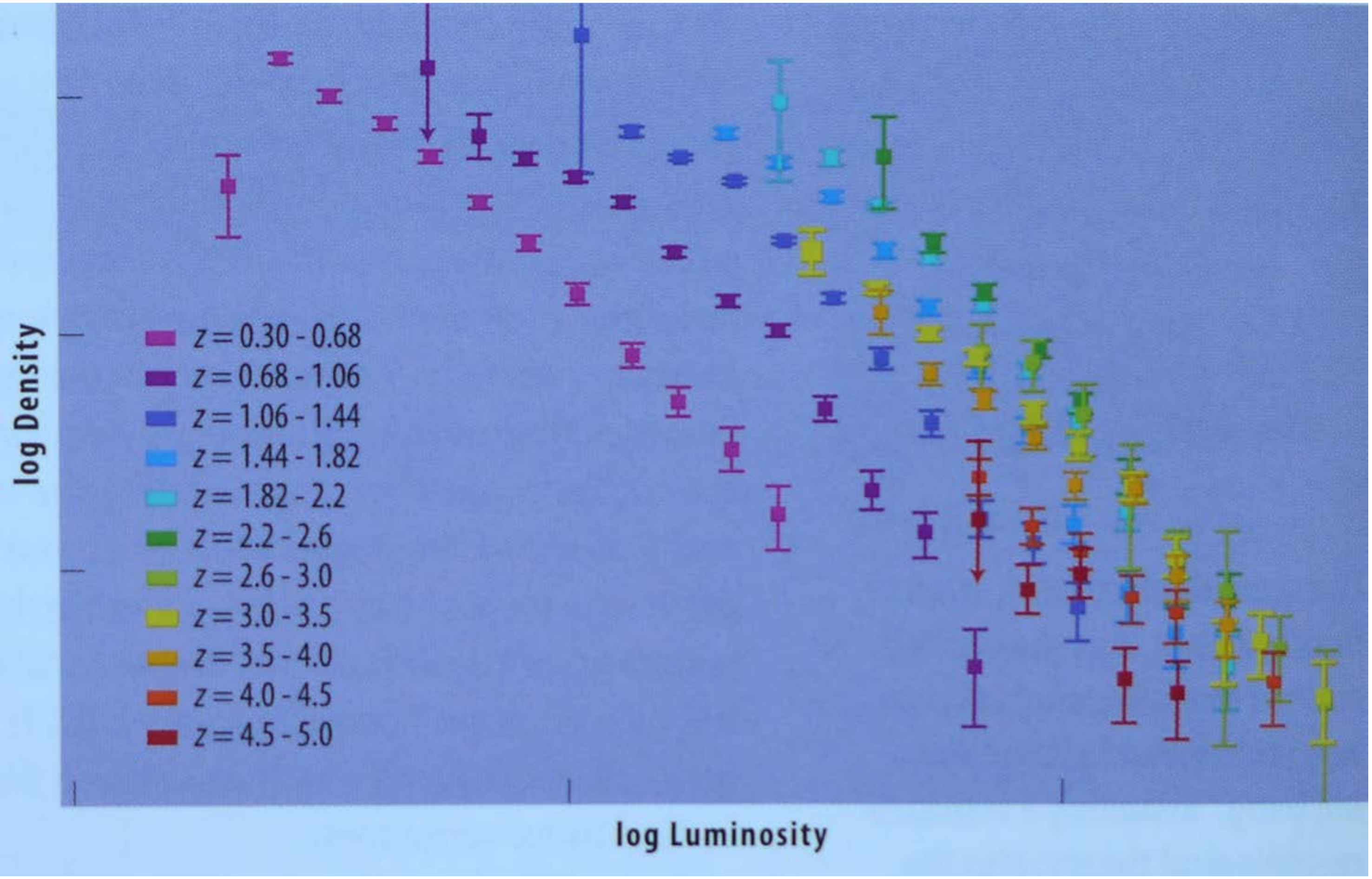
The Universe has expanded by a factor of (1+z)~5.9 since the light was emitted from this quasar.



Evolution of Quasar Population

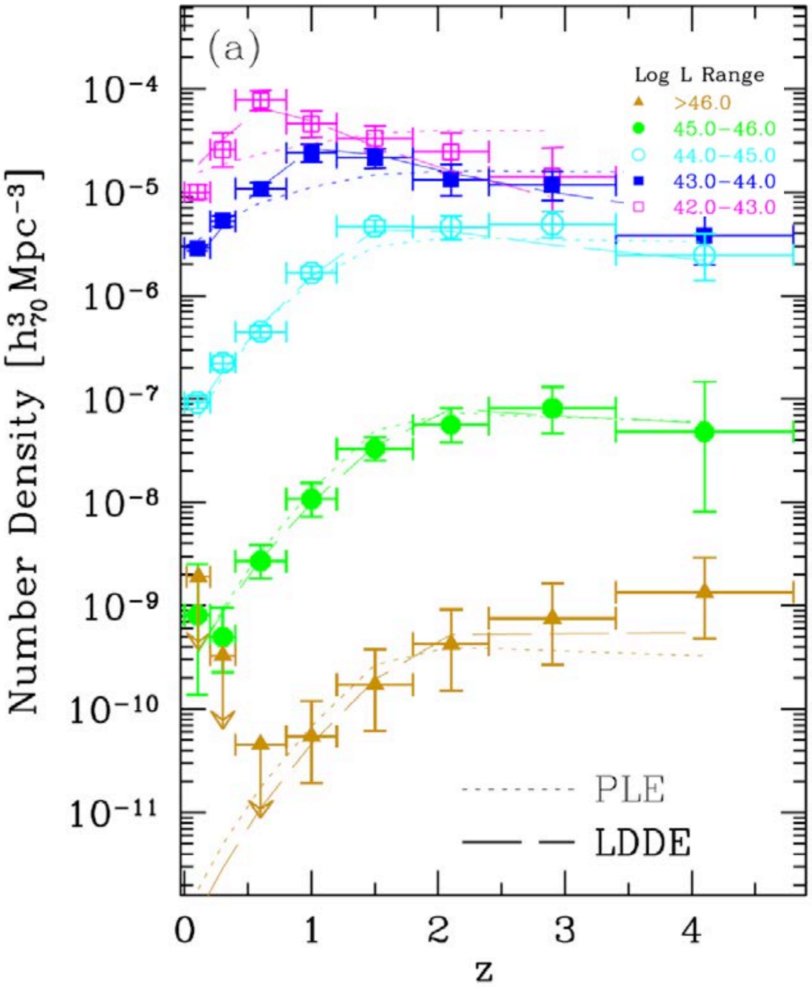






Each data point represents the density of quasars at a certain redshift range within a certain range of luminosities. The luminosity function of quasars changes with redshift. Each tick mark corresponds to a factor of 10 in either density or luminosity.

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.

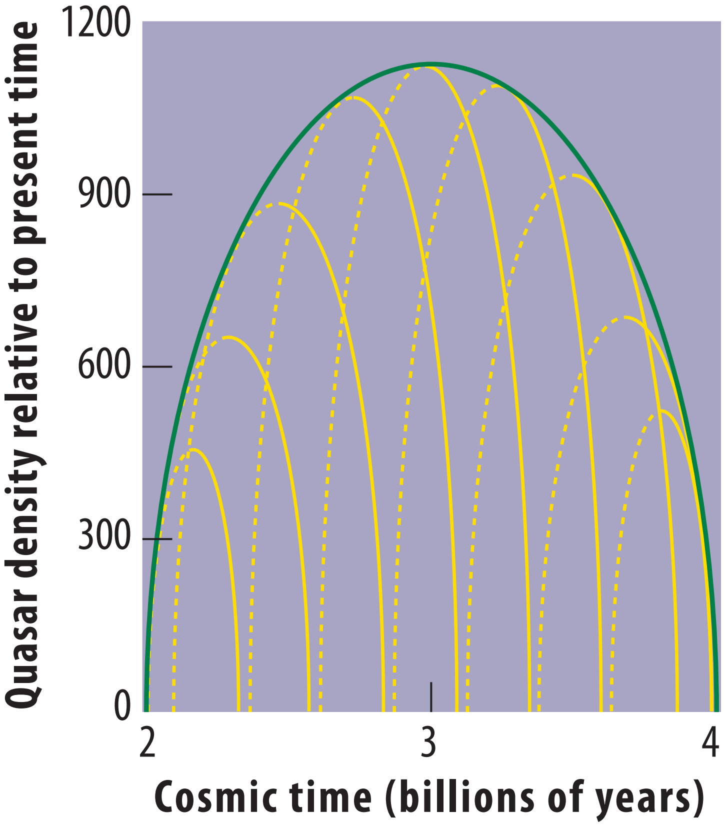
The redshift at which the space density peaks changes with luminosity from

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

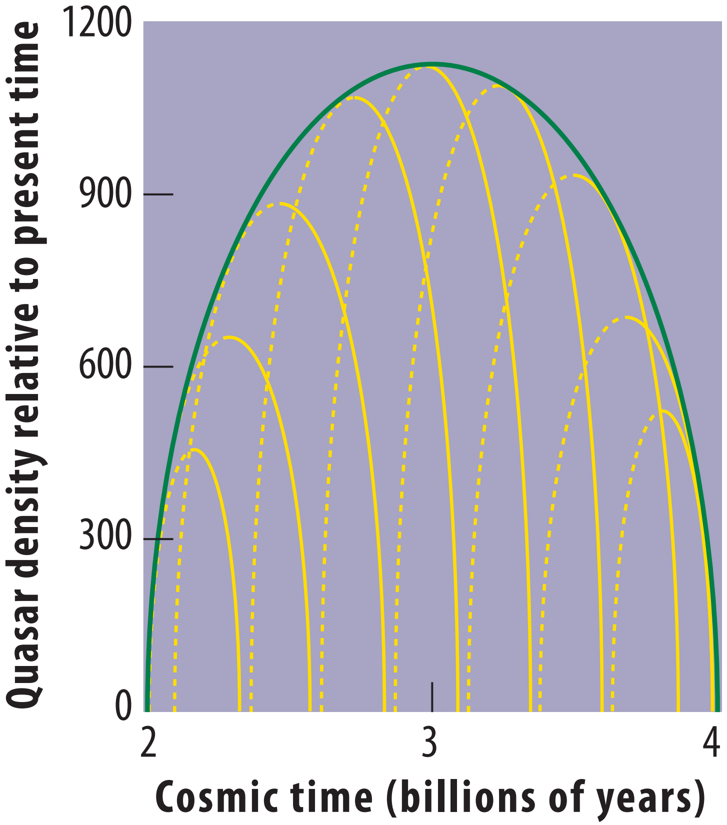
Relics of SMBHs in the Current Universe

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 ~ 10 $M_\odot$ /year

We can estimate M_{BH} from reverberation mapping.



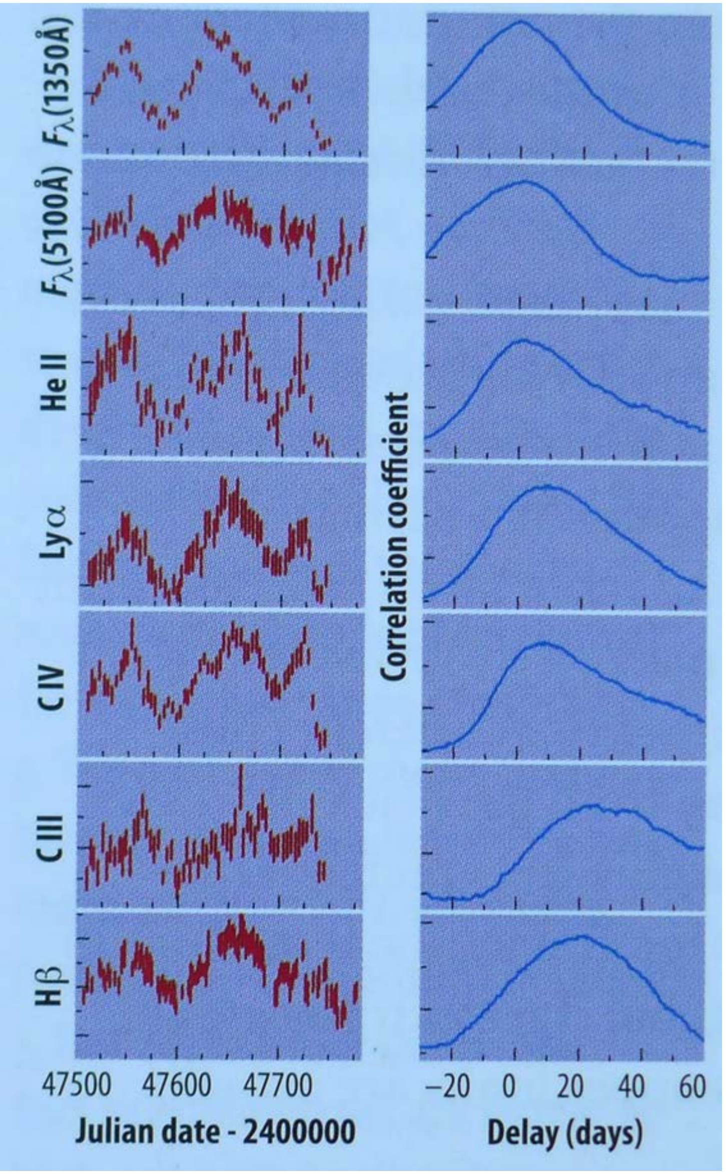
Reverberation Mapping

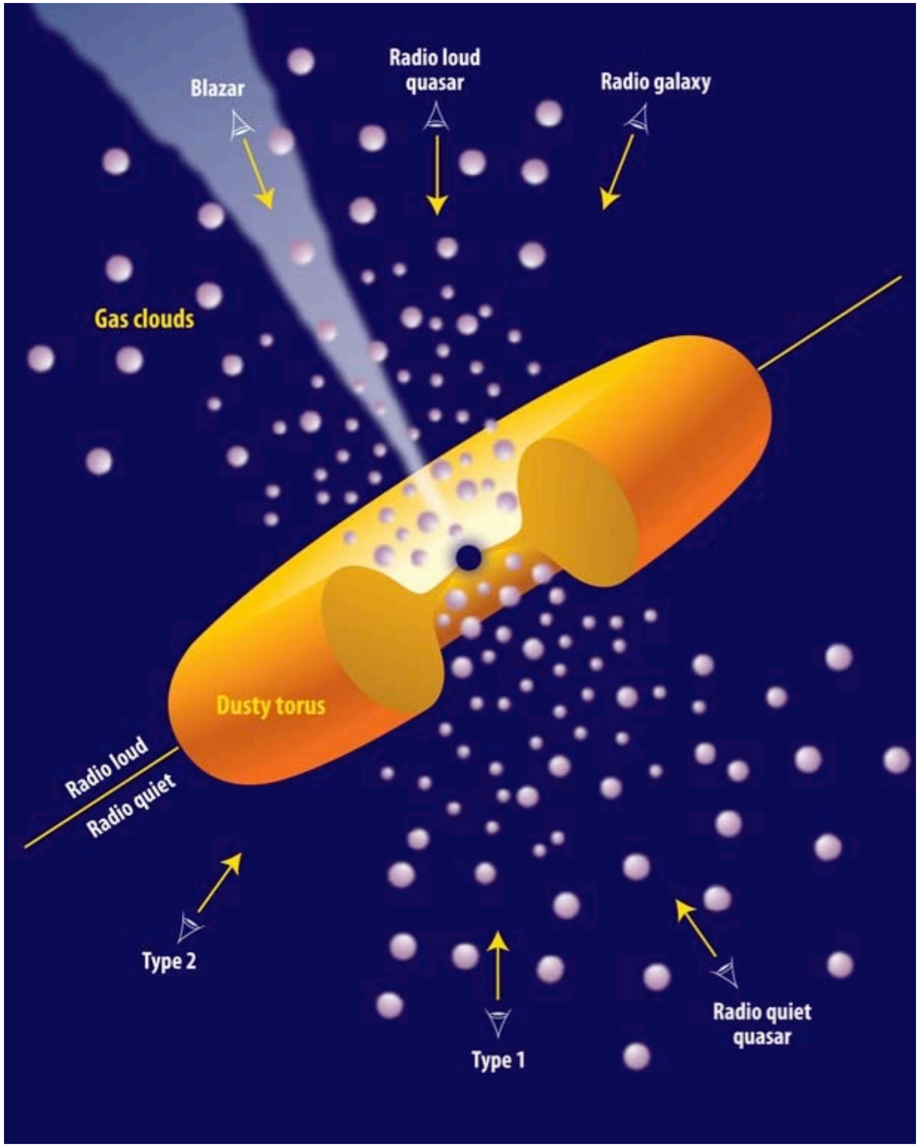
The strength of the BLR emission lines rise and fall in response to changes in the ultraviolet radiation from the accretion disk with a time delay. The time delay depends on the distance between the UV source and the BLR cloud. If one also measures the velocity width Δv of the line they can infer the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

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

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

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

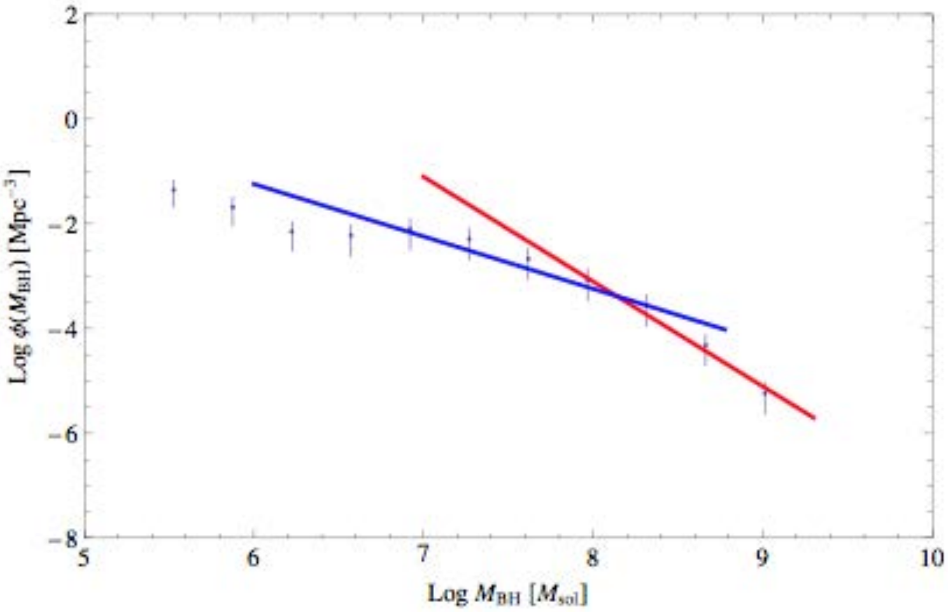



Radio loud quasar
Blazar
Radio galaxy
Gas clouds
Dusty torus
Radio loud
Radio quiet
Type 2
Type 1
Radio quiet quasar

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

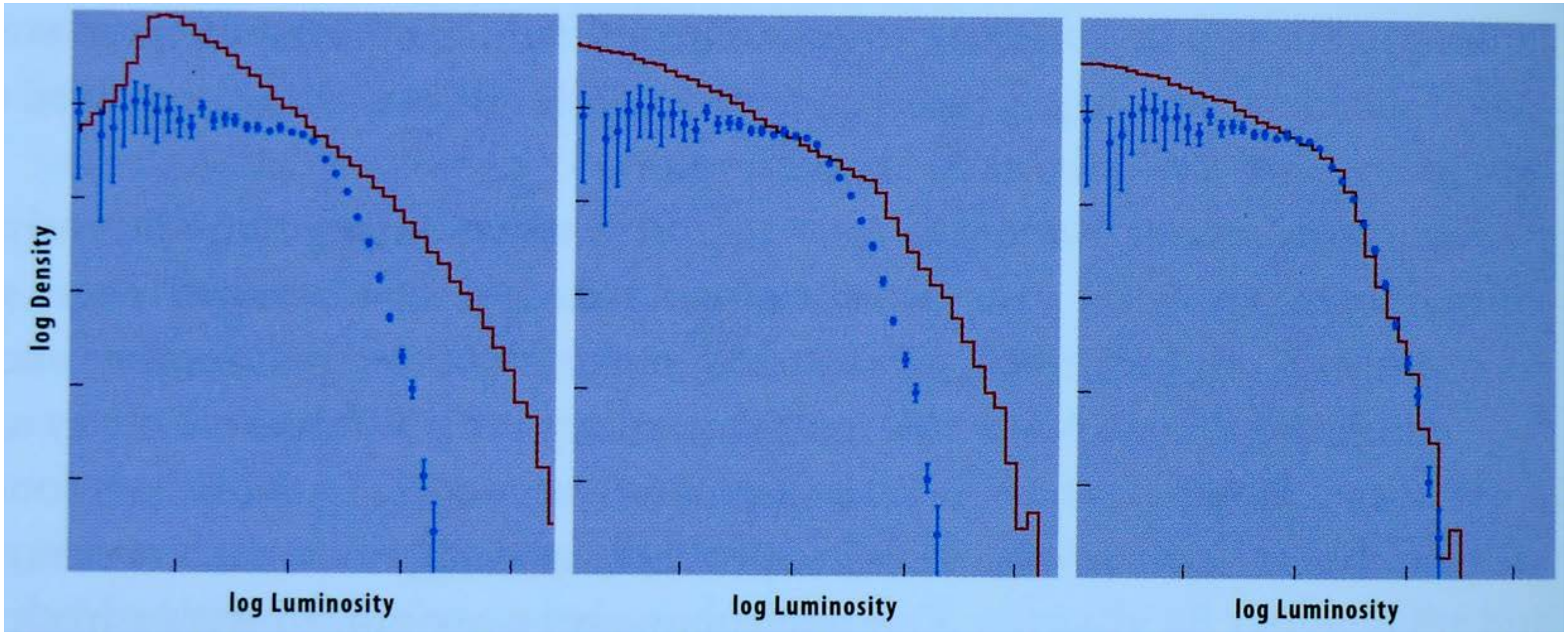
Soltan's argument: Compare the total mass of all SMBHs in quasars over cosmic history (z = 0.5-6) with the total mass of all SMBHs in normal galaxies of the nearby Universe.

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 luminosities (~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

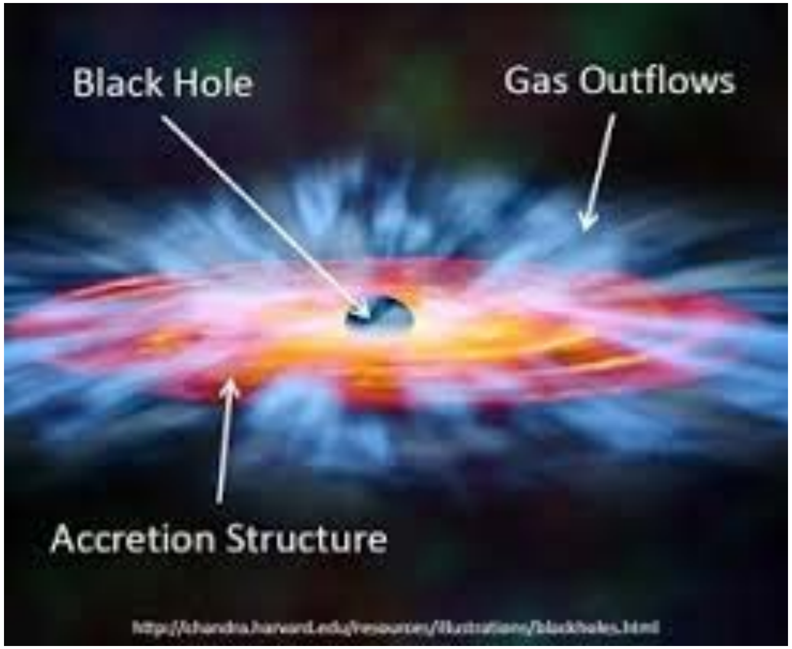
Many scientists now think that the SMBH is the destructive agent that inhibits the growth of its host galaxy.

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

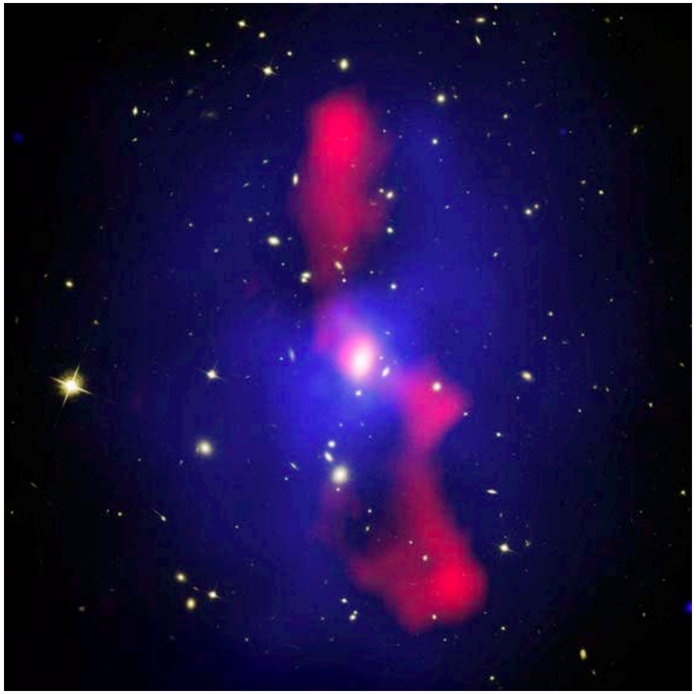
The problem is how does the energy released by a SMBH spread over large distances and how does it interact with the gas in the galaxy.

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

Modes of interaction of AGN with their environments



http://chandra.harvard.edu/resources/illustrations/blackholes.html

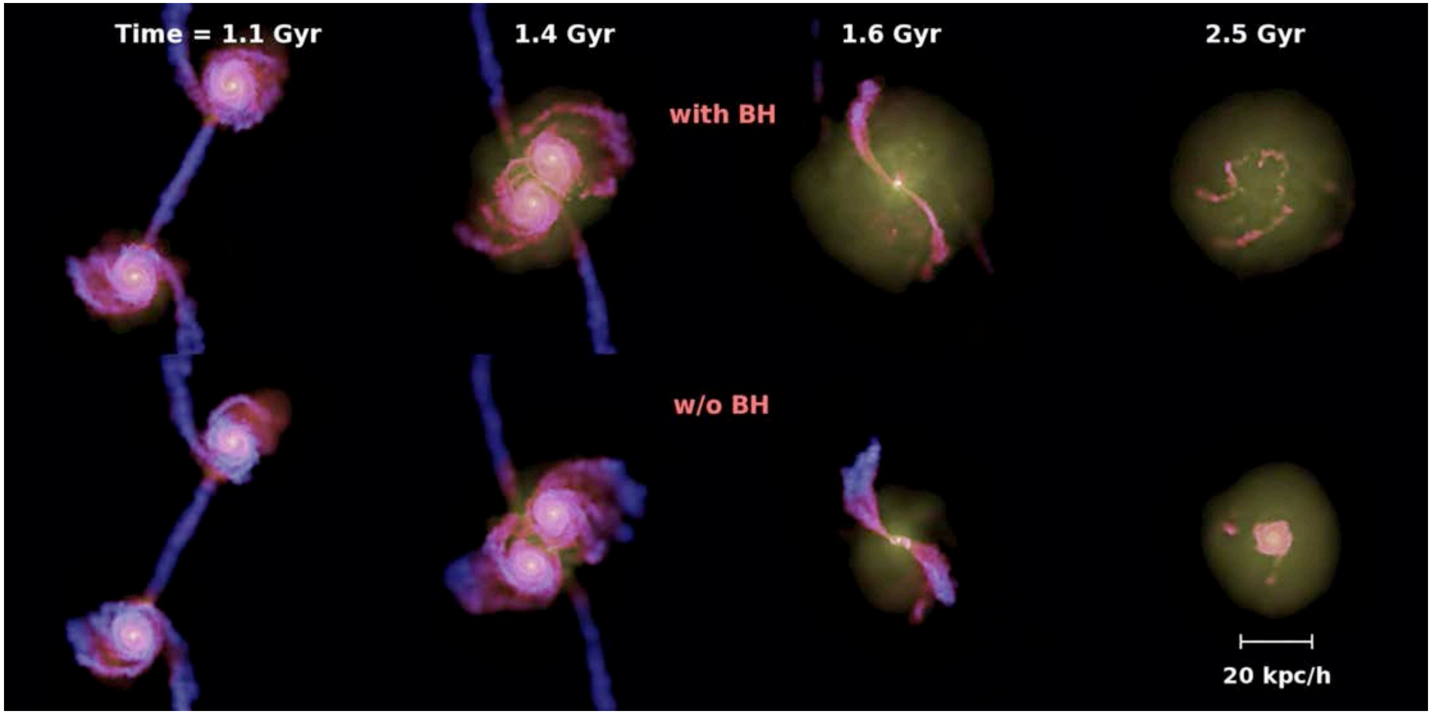


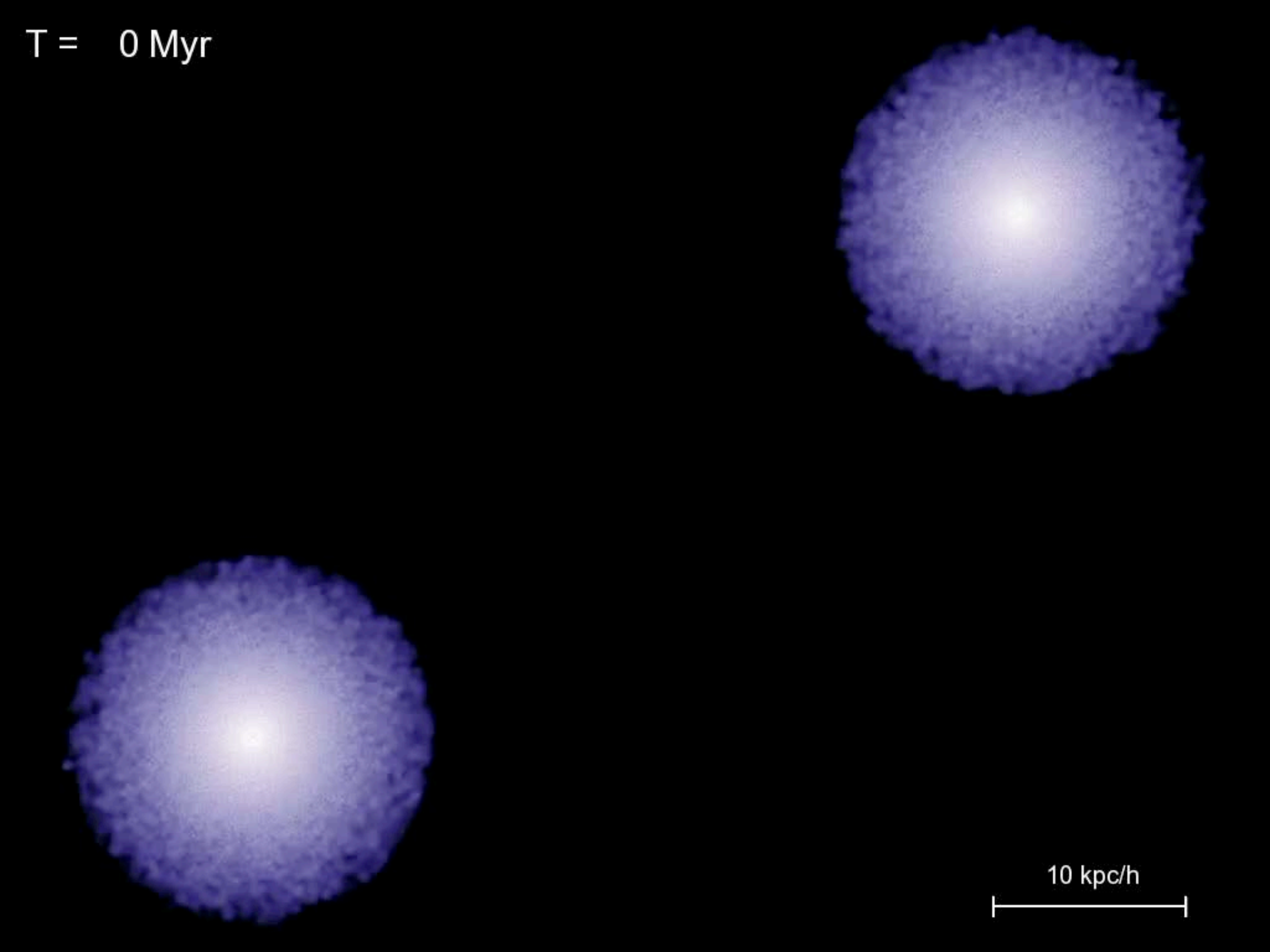
MS0735.6+7421 (McNamara & Nulsen 2007)

AGN Winds and Radiation

Radio Jets

The Importance of Quasar Winds in Driving Quasar Evolution




T = 0 Myr
10 kpc/h

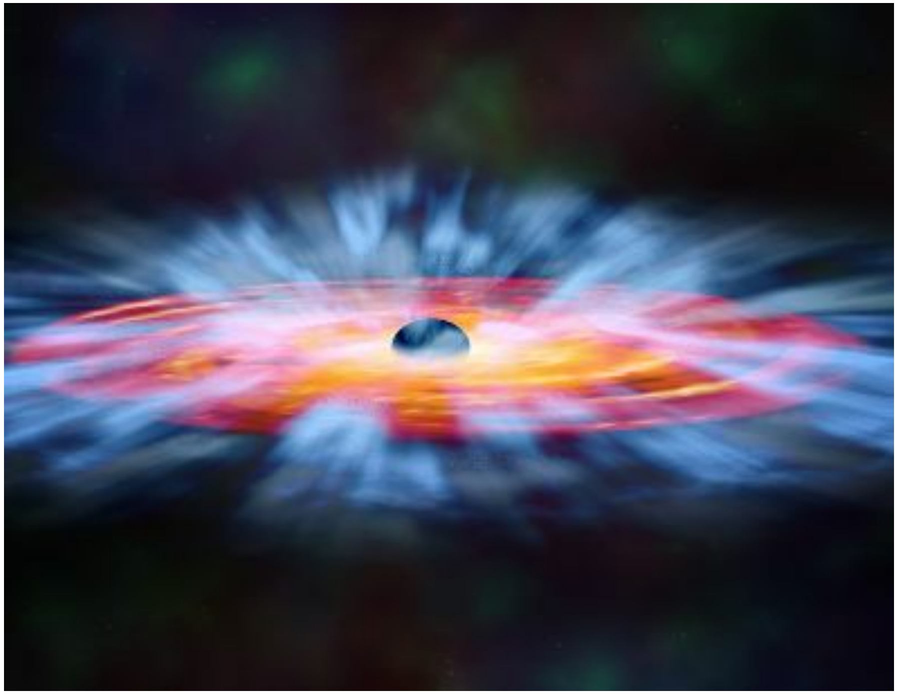
Quasar Winds

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

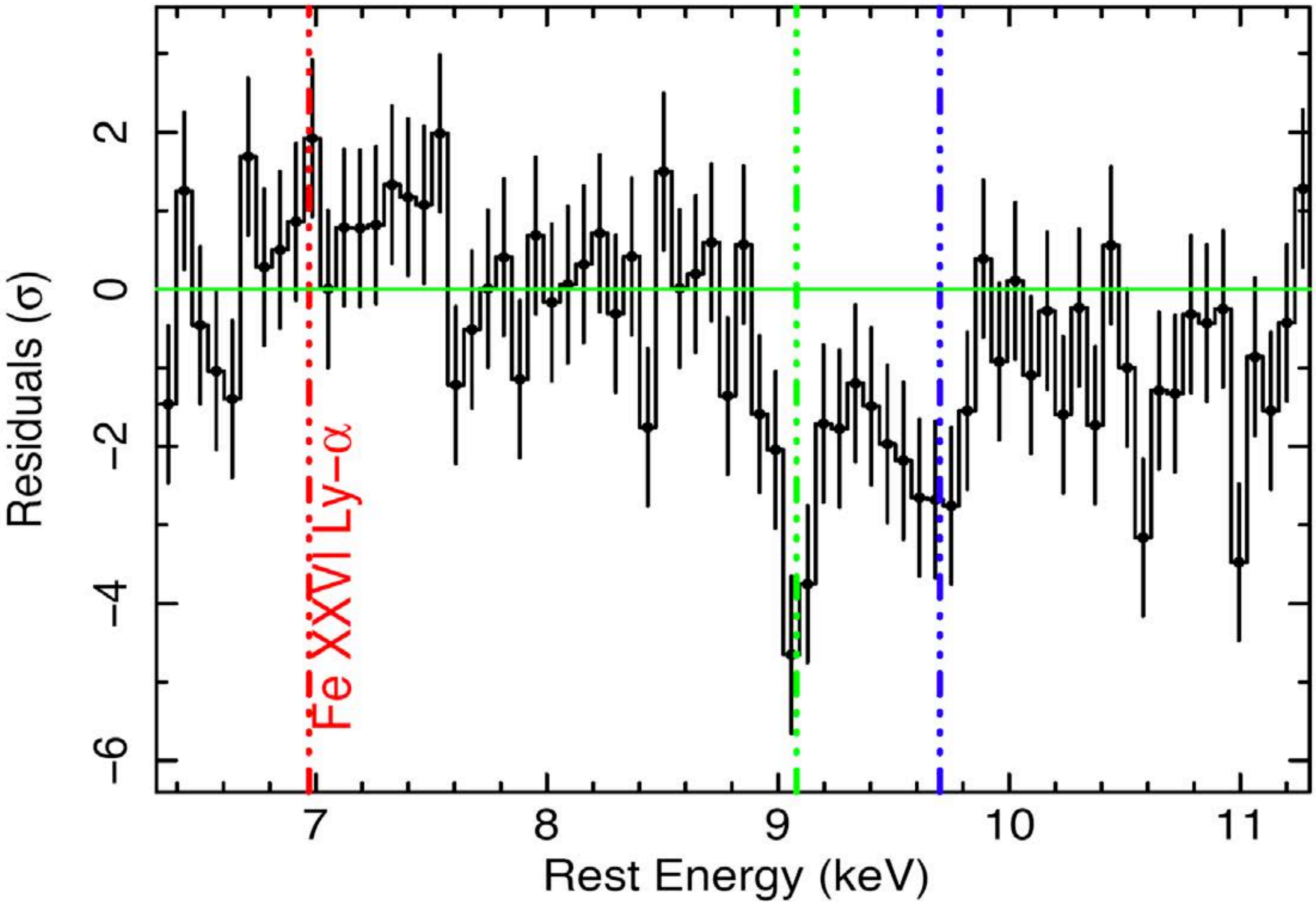
Quasar Winds

Proposed mechanisms for quasar wind acceleration include:

- radiative driving
- magnetic driving
- thermal driving

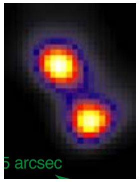


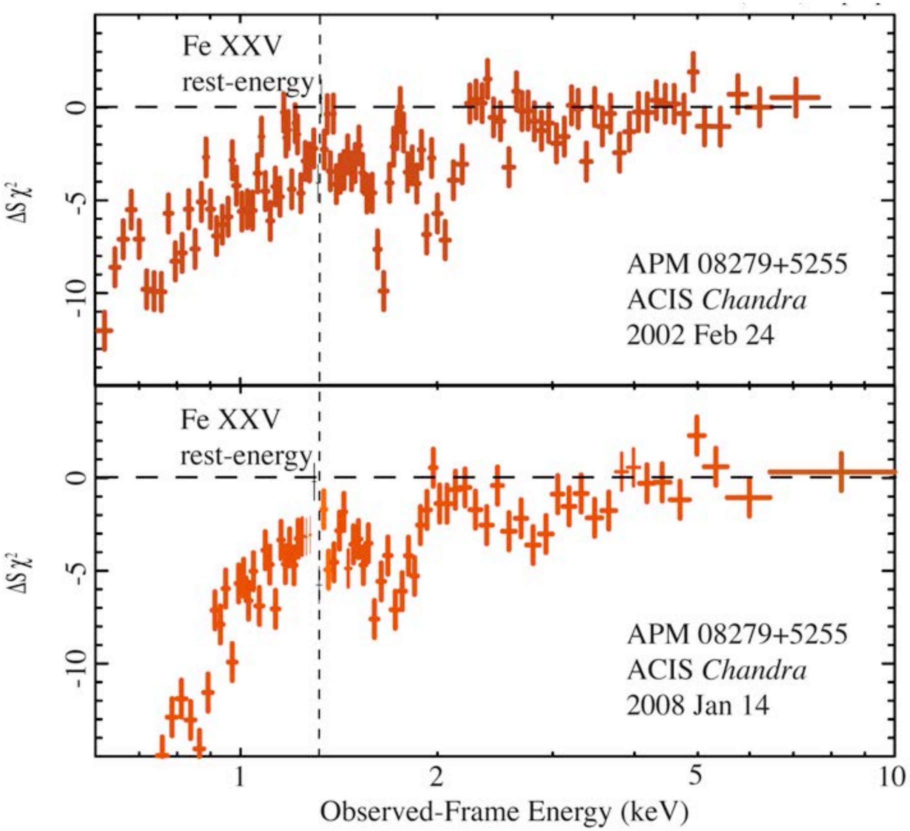
X-ray Observations of AGN Winds

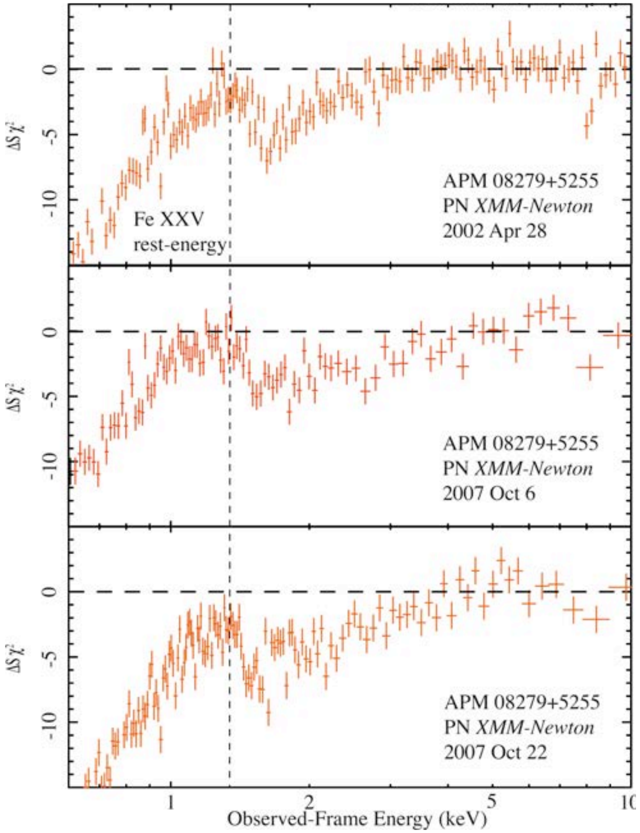


X-ray (Suzaku XIS) data from the observation of quasar PDS 456 compared with a simple power-law fit. Inferred outflow velocity of v = 0.25 - 0.3c (Reeves et al. 2008).

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:

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

Understanding the Influence of SMBH

Three Important Equations

1. $M_{SMBH} \sim 10^{-3} \times M_{Bulge}$

2. $M_{SMBH} \approx 3 \times 10^{8} M_{\odot}\, \sigma_{200}^{a}$

3. $R_{influence} \approx 8\ M_8/\sigma_{200}^{2}$ pc

where, $\sigma_{200} = \sigma/200$km/s

Significance

1.The mass of the SMBH is almost always a constant fraction of the mass of the bulge

2.The mass of the SMBH is tightly correlated to the velocity dispersion in the bulge

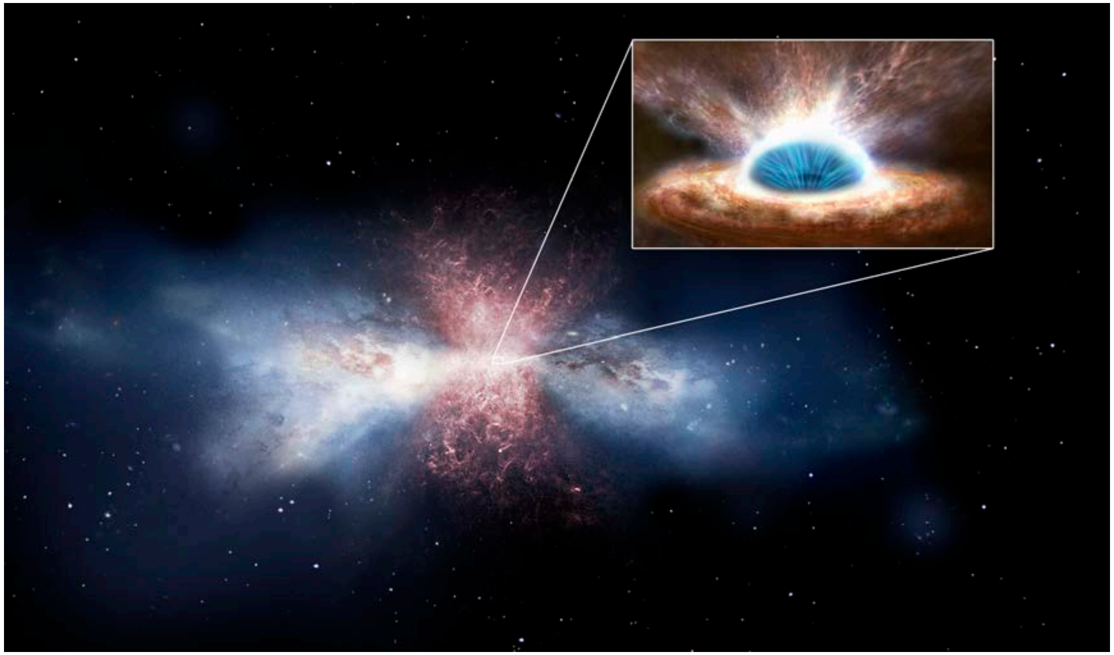
3. Most of the galaxy is gravitationally unaware of the SMBH

Methods of Communication

Mechanical Feedback: gas is driven through the galaxy by radiation and magnetic pressure and interacts with the interstellar medium

Jets vs. Winds

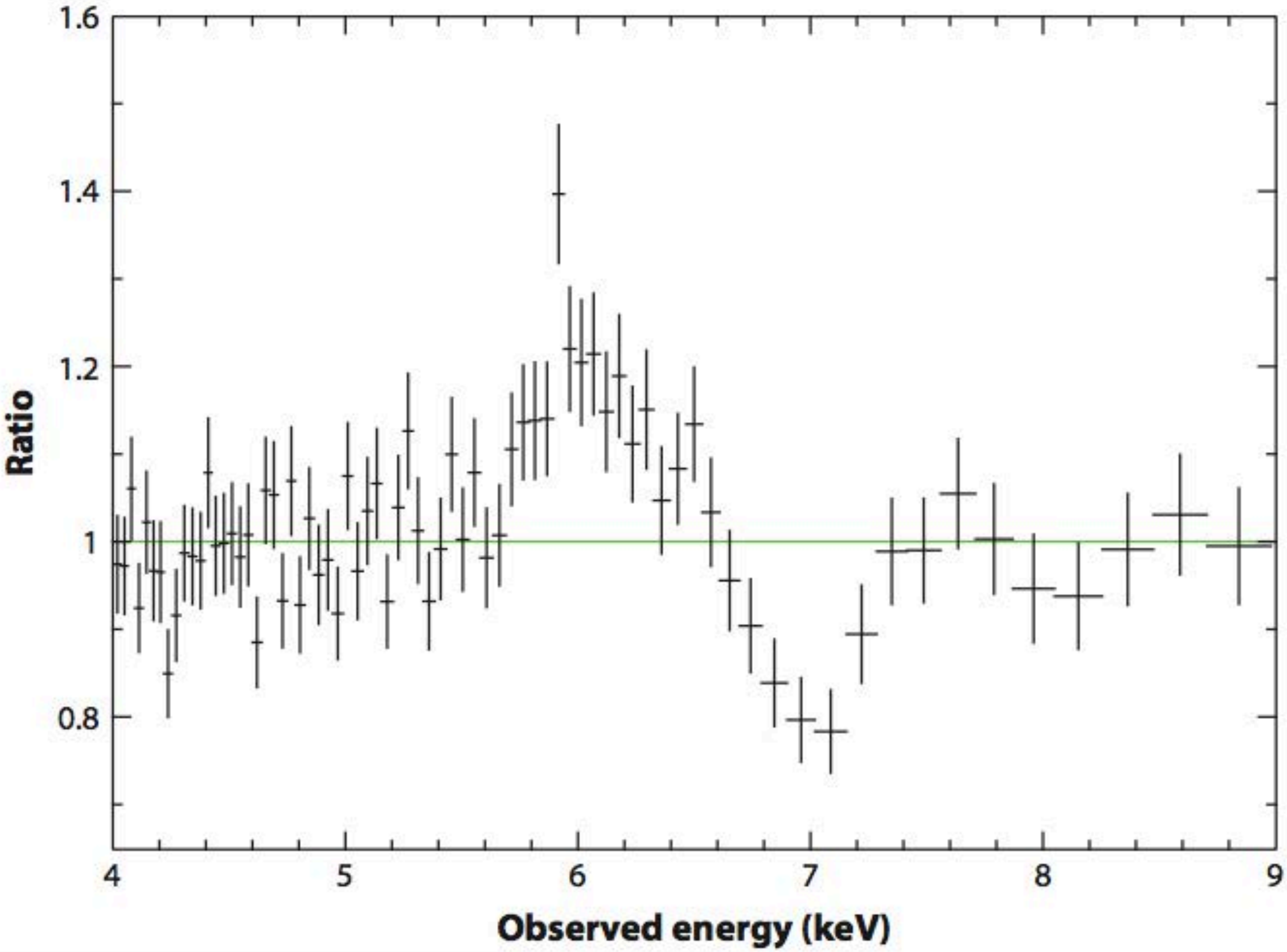
Jets: highly collimated flows driven from very near the SMBH, somewhat rare



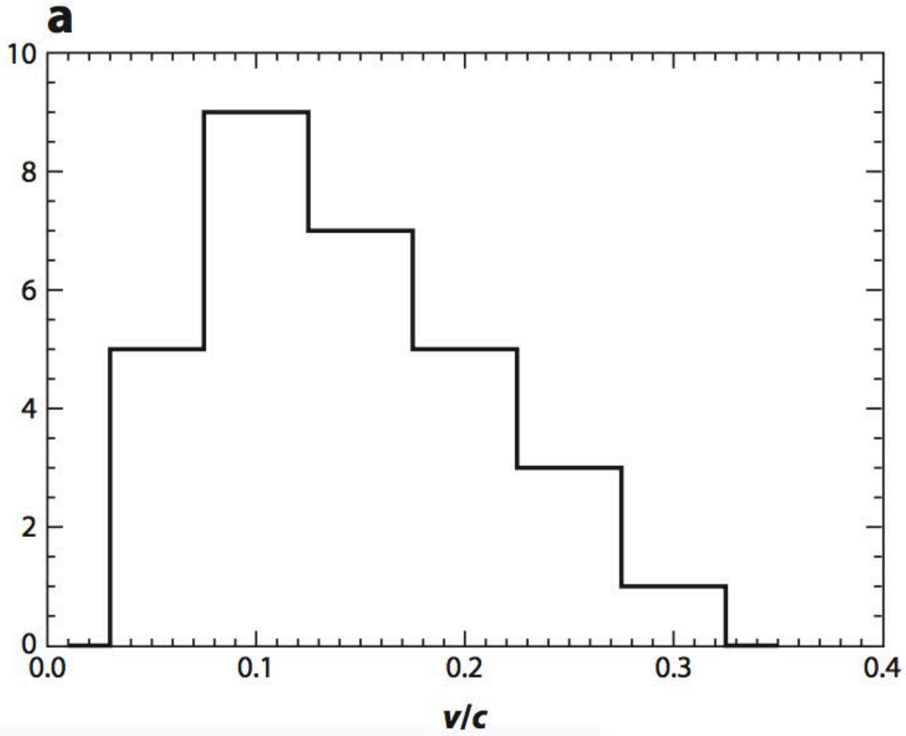
Winds: nearly isotropic outflows, common to many AGN

IRAS F11119+3257 artist depiction

Detecting Winds: Spectrum of PG1211+143



Observational Evidence of UFOs (Ultra-Fast Outflows)



Cappi 2006 found 7 AGN with
v ~ 0.1c

Tombesi et al. 2010 found outflows in 15/42 radio-quiet objects,
v ~[0.1c – 0.3c]

Gofford et al. 2013 found similar outflows in 20/51 AGN, also with
v ~ [0.1c – 0.3c]

→ UFO’s Rather common

Energy Output and Binding Energies

$$E_{\mathrm{BH}} \simeq \eta M c^2 \sim 2 \times 10^{61} M_8 \text{ erg}$$

$$E_{\mathrm{bulge}} \sim M_{\mathrm{b}} \sigma^2 \sim 8 \times 10^{58} M_8 \sigma_{200}^2 \text{ erg}$$

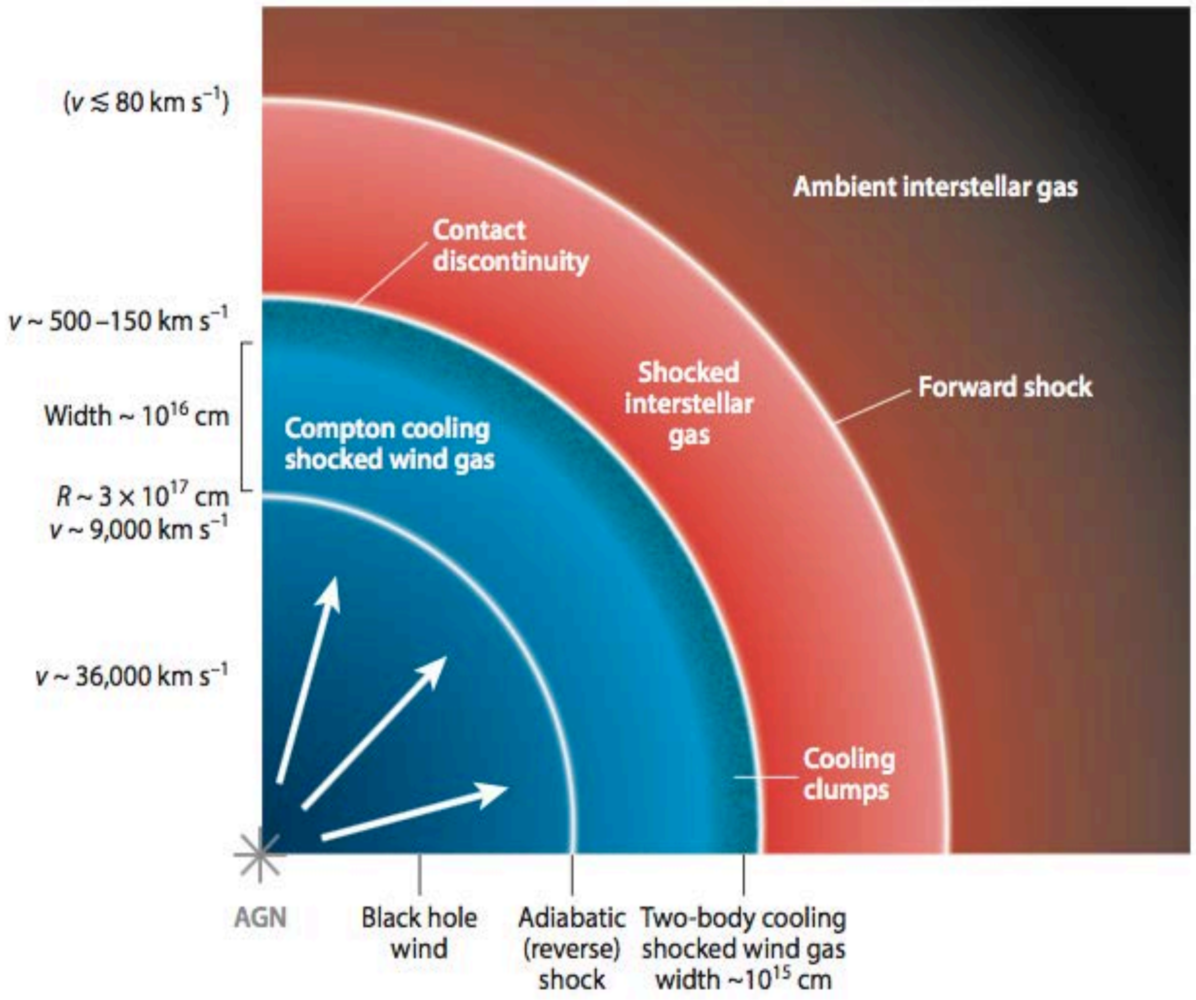
Black hole mass should be related to galaxy properties that depend on galactic gas, since it is through accretion of this galactic gas that it grows

$$E_{\mathrm{gas}} = f_{\mathrm{g}} E_{\mathrm{bulge}}, \quad E_{\mathrm{BH}} \sim 2 \times 10^3 E_{\mathrm{gas}}$$

The important comparison is between E_{BH} and E_{gas}

The black hole energy is more than enough to disrupt all of the gas in the bulge of the galaxy, so it must not be communicated efficiently → slowed outflows

Shocked Outflows



1. Black hole drives a fast wind

2. Wind collides with gas in the galaxy and is slowed in a shock.

3. Quasar's radiation cools the shocked gas, removing its thermal energy and strongly compressing and slowing it over a narrow radial extent.

4. Two body cooling becomes important in the most compressed gas and the flow cools and slows over a narrow region labeled "cooling clumps"

5. The cooled gas exerts the ram pressure on the galaxy's gas and sweeps it up into a dense shell (snowplow).

6. The shell's motion then drives an outward shock into the ISM.

7. The shock stalls unless the SMBH reaches the value M_σ that satisfies the $M - \sigma$ relation.

What happens at M_σ and Beyond

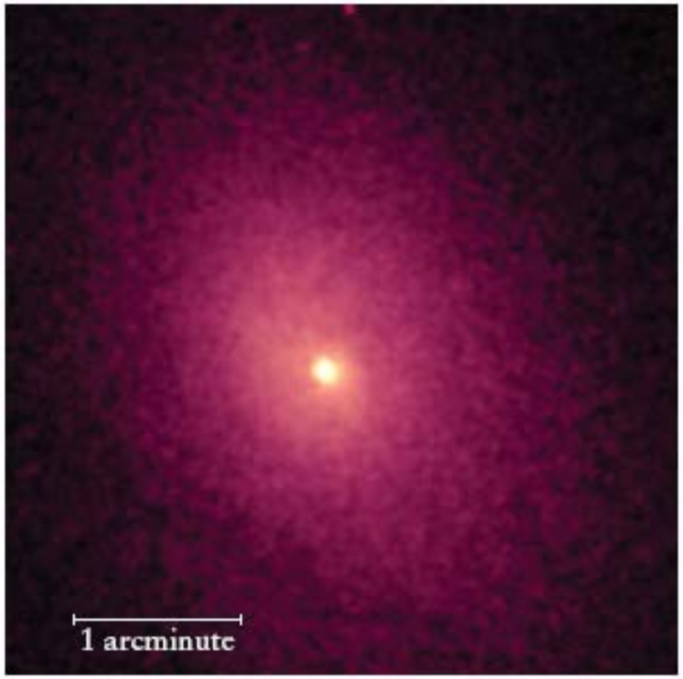
Something must happen to halt black hole growth when $M>>M_\sigma$ → The black hole must expel all the gas

For $M>>M_\sigma$, the shock wave becomes energy driven, and can extend for kpc scales → Quasar Winds can clear out gas from galaxy when $M>>M_\sigma$

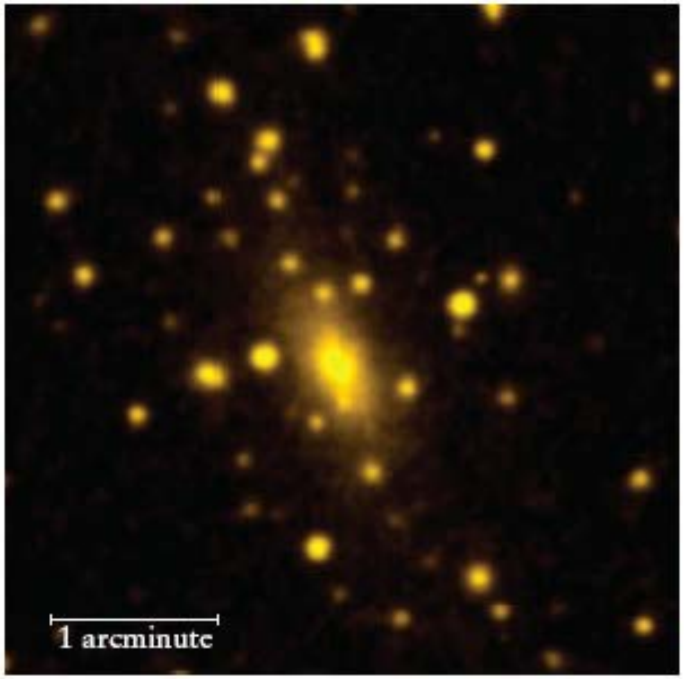
Feedback in Clusters of Galaxies

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.



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

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

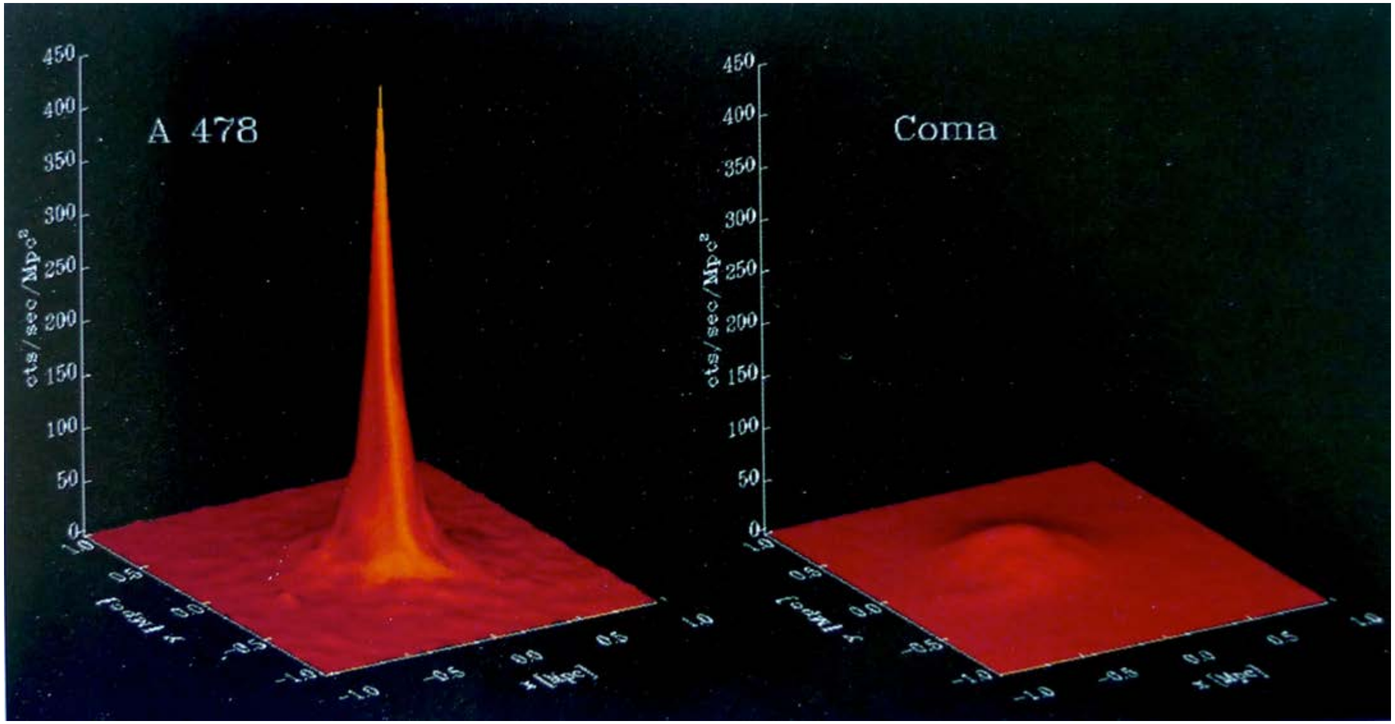
Small clusters and groups of galaxies show evidence of **excess heating**. This excess heating is thought to “puff up” the gas, reduce the density of the gas and thereby reduce the luminosity.

It is thought that SMBHs at the centers of clusters are the sources of extra heating of the intrucluster 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



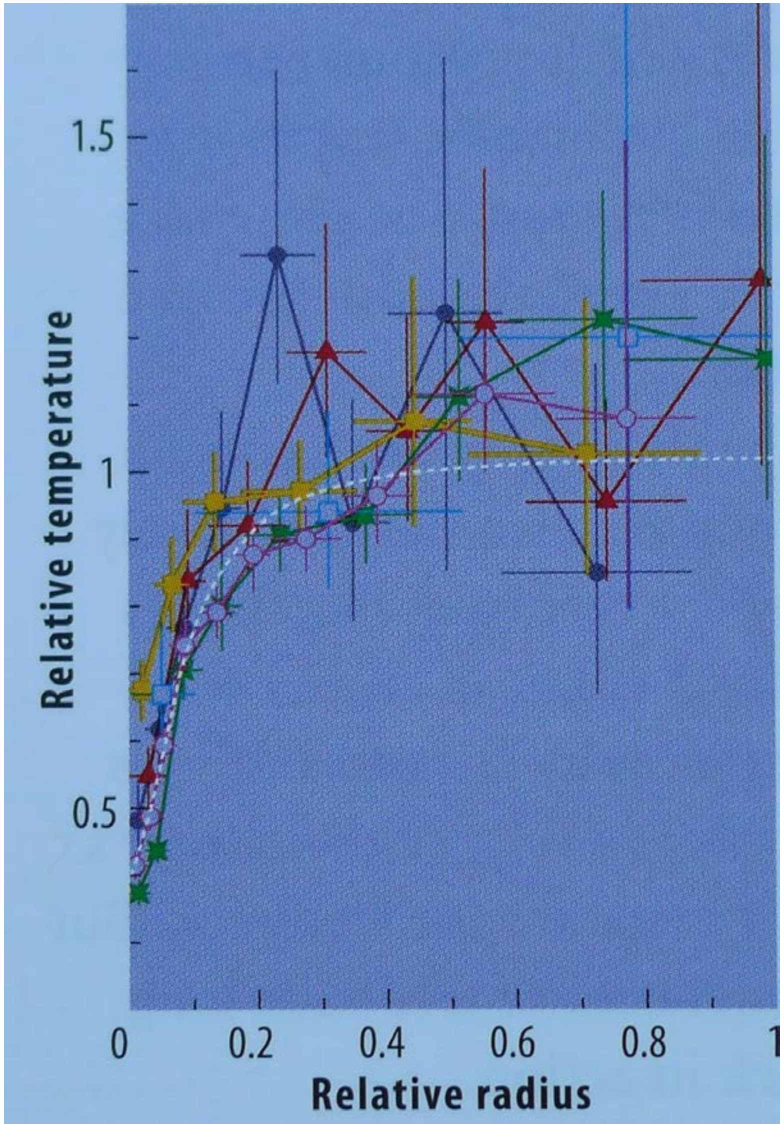
X-ray brightness versus position on the sky for a **cool core** cluster (Abell 178: left) compared to a cluster without a cool core (Coma Cluster: right). The spike in the X-ray brightness shows that gas in the inner part of the galaxy is radiating away its thermal energy at a rapid rate.

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.

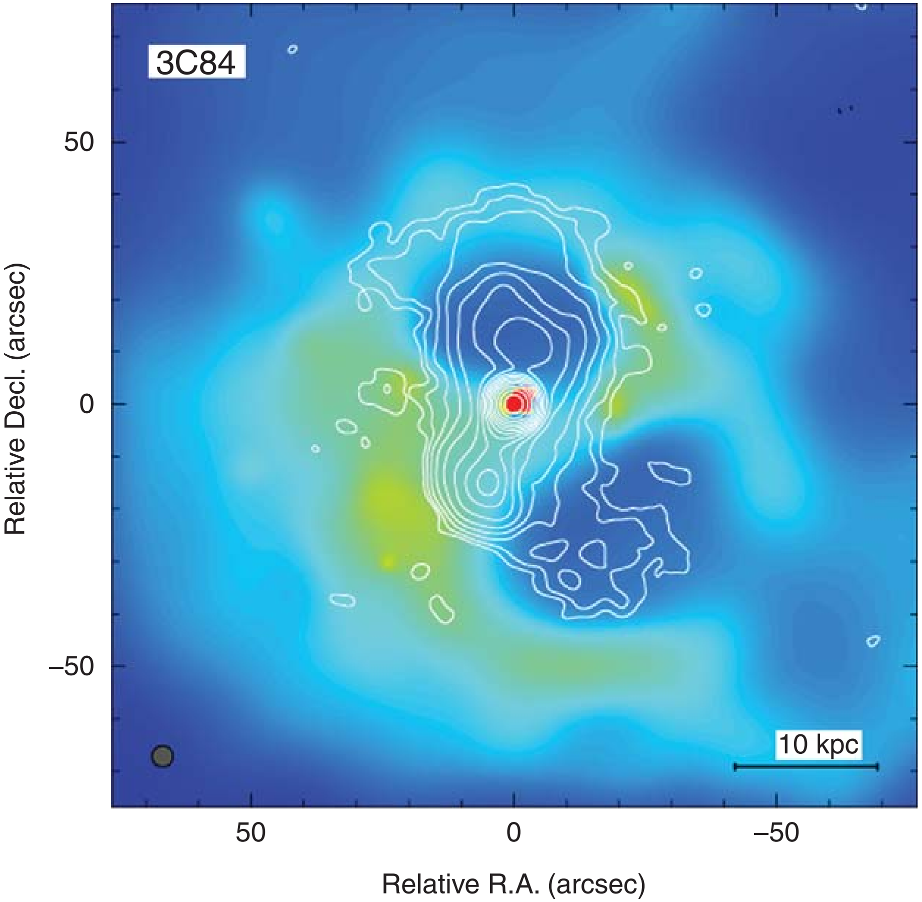


Radio Jet Mode

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.



The Effects of a “Clear out” Considering Galactic Morphology

Spiral Galaxies

Elliptical Galaxies

Eventually the outflow must encounter the galactic disk. The resistance causes the flow proceed above and below the disk.

→ Triggered star formation

In the absence of a disk, the energetic outflows proceed uninterrupted, leaving spherical galaxies “**red** and dead”

Different morphologies and locations in which galaxies are found will yield different interactions between galaxies and their environments.

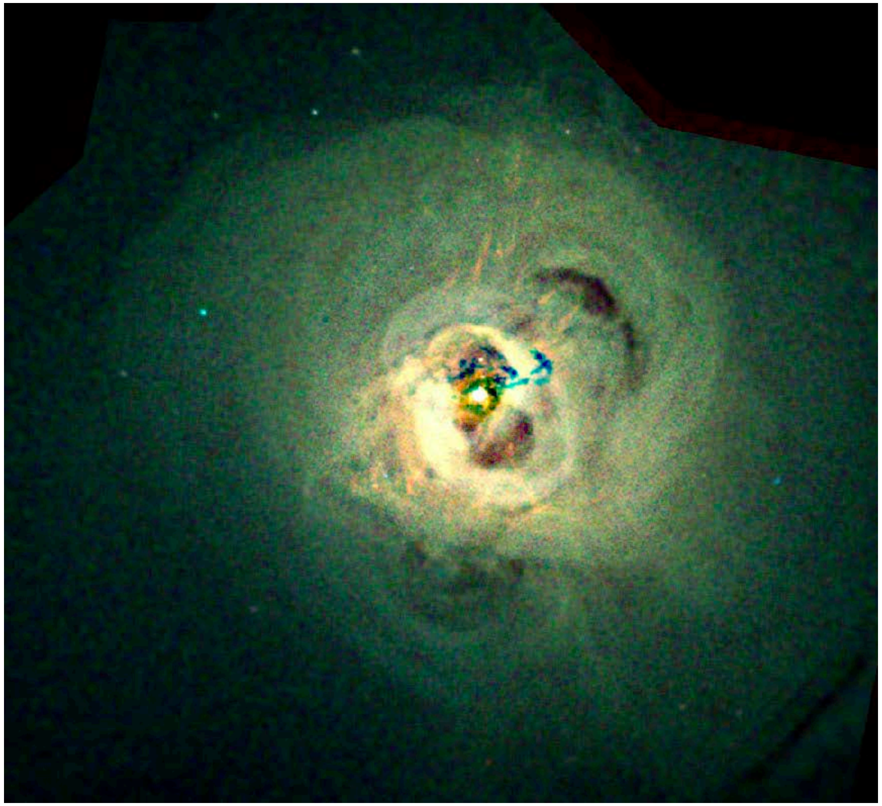
Radio Jet Mode

- Radio jets can heat the Intracluster Medium and prevent **cooling flows**

- The radio jet mode is observed in Clusters and giant elliptical galaxies

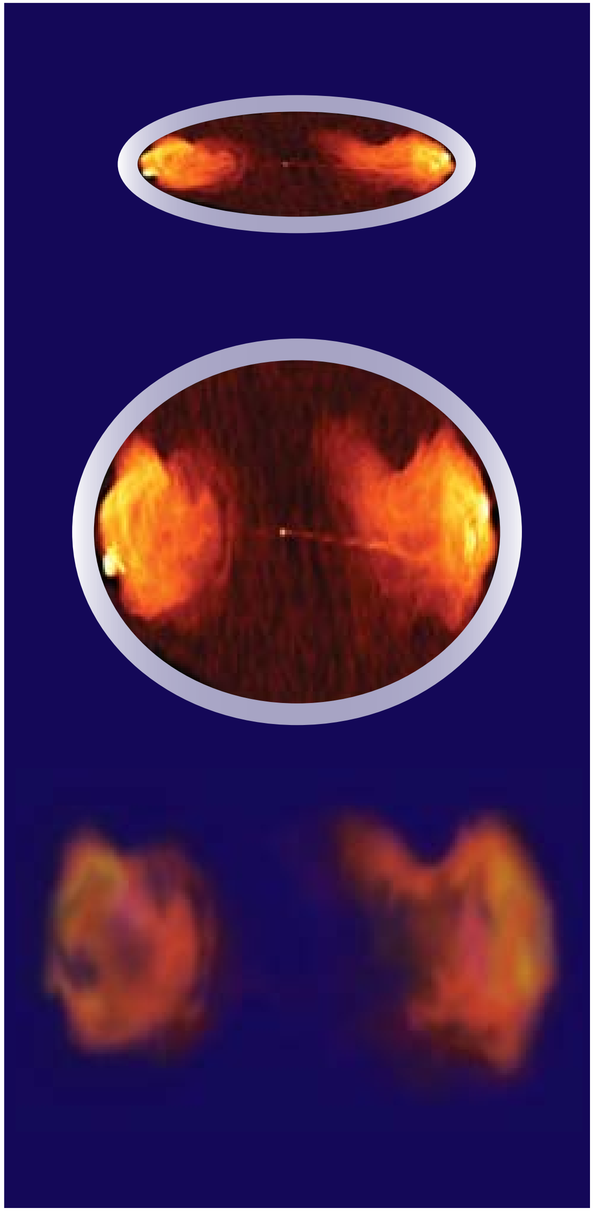
- Work required to INFLATE cavities

  pV ~ 10^{55} erg in giant Ellipticals
  pV ~ 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.

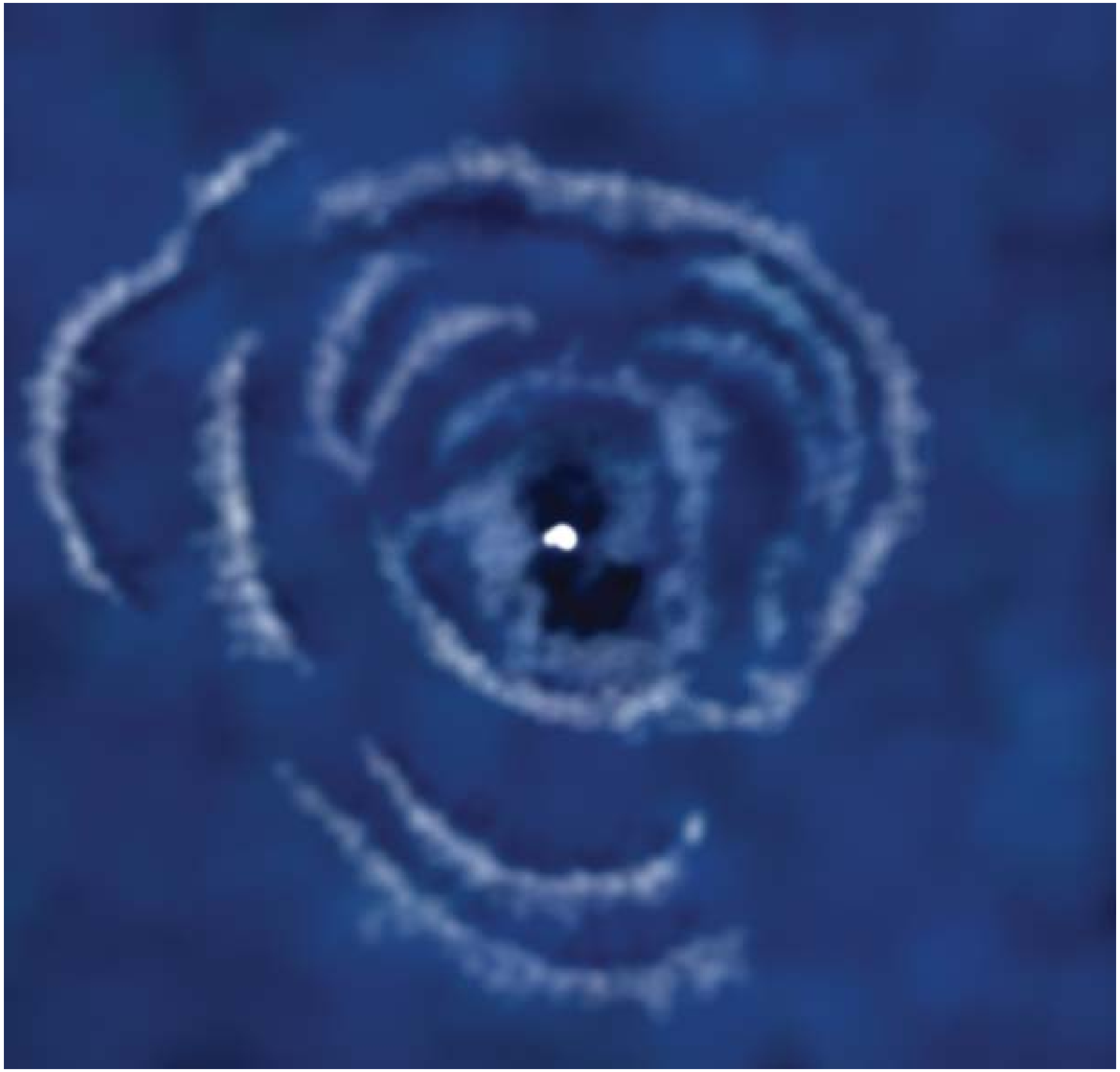
Energy Dominated Phase

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 (~1000km/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.