Radio-loud AGN feedback: how and when does it work?

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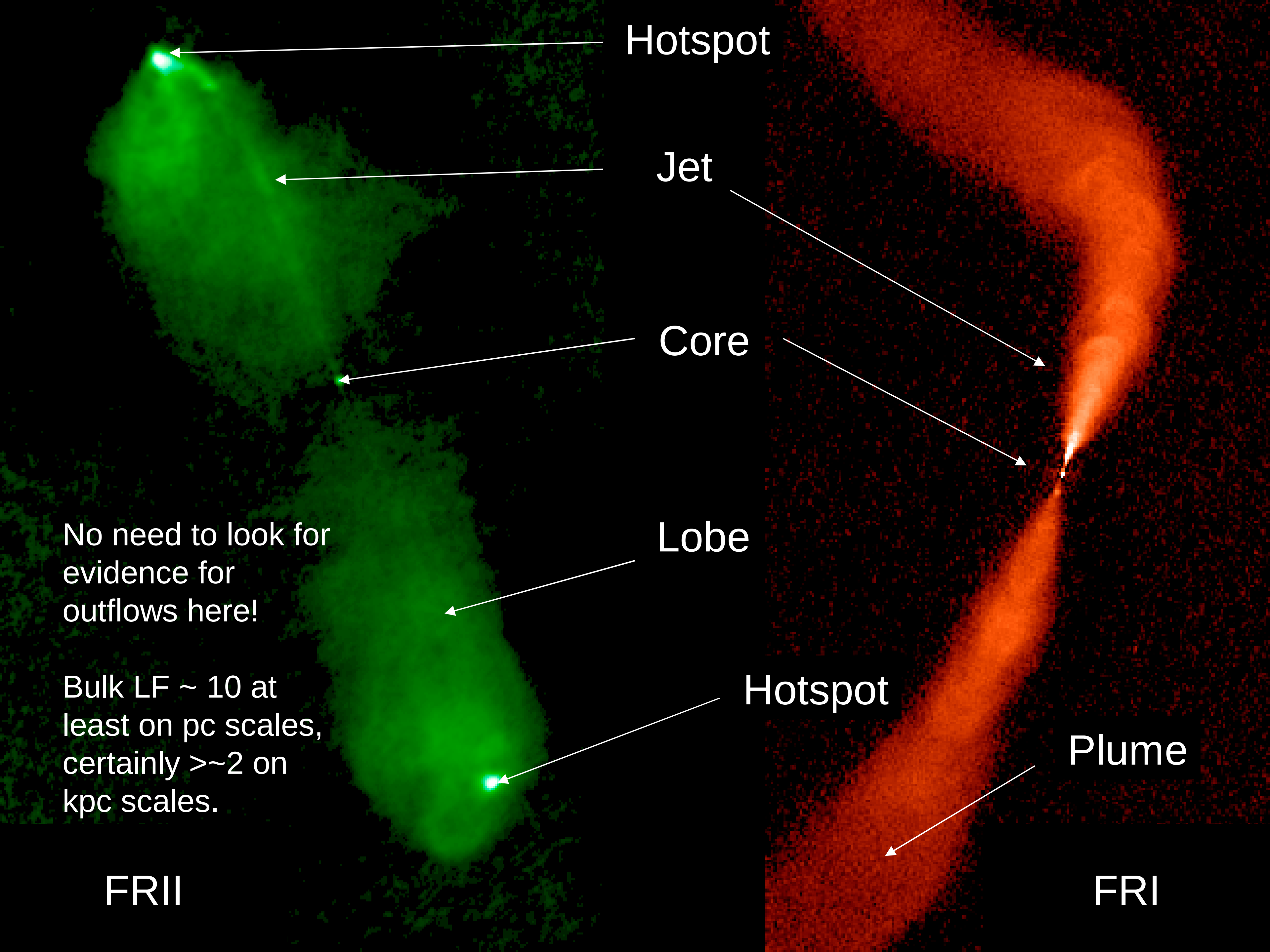
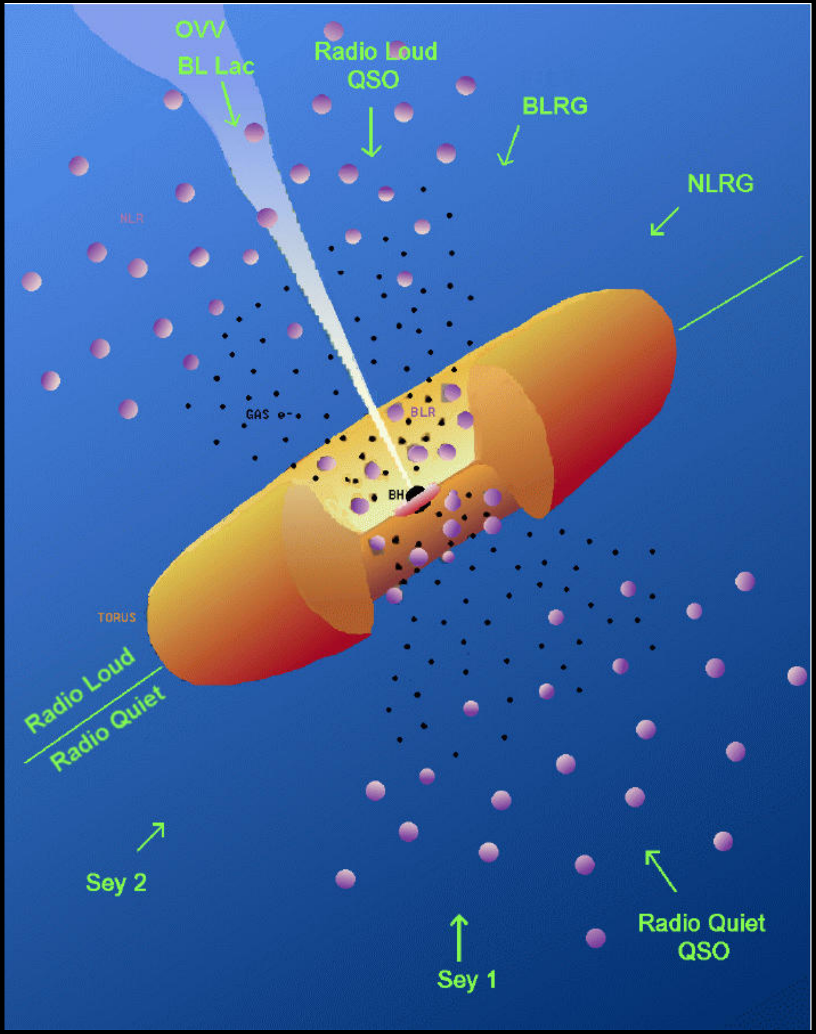
Outline

- Introducing radio-loud AGN
  - radio structures
  - active nuclei
- How do lobes and jets interact with their environments?
  - or, what physics do you need to put into your models?
- Problems and puzzles of 'feedback'

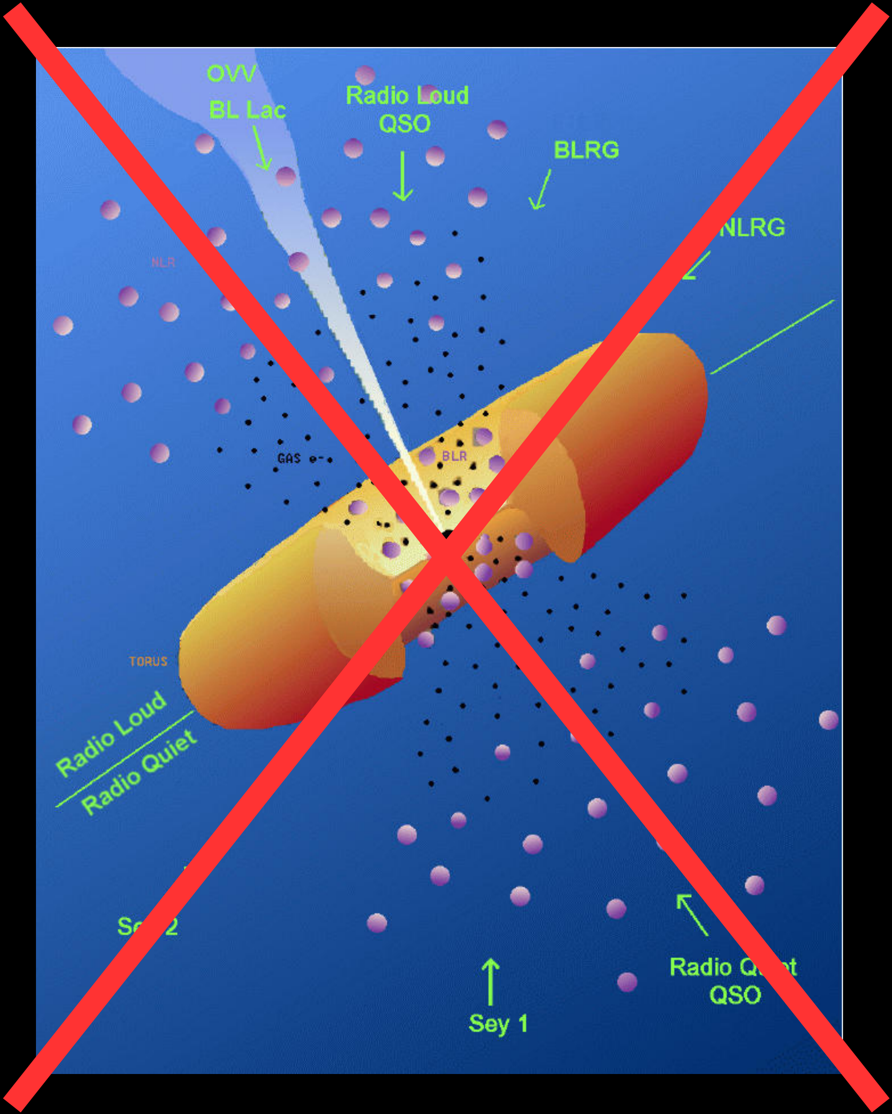

Hotspot
Jet
Core
Lobe
Hotspot
Plume
No need to look for evidence for outflows here!
Bulk LF ~ 10 at least on pc scales, certainly >~2 on kpc scales.
FRII
FRI

AGN properties



Straw man model #1: radio-loud AGN are exactly the same as RQ AGN but with the addition of a jet.

AGN properties



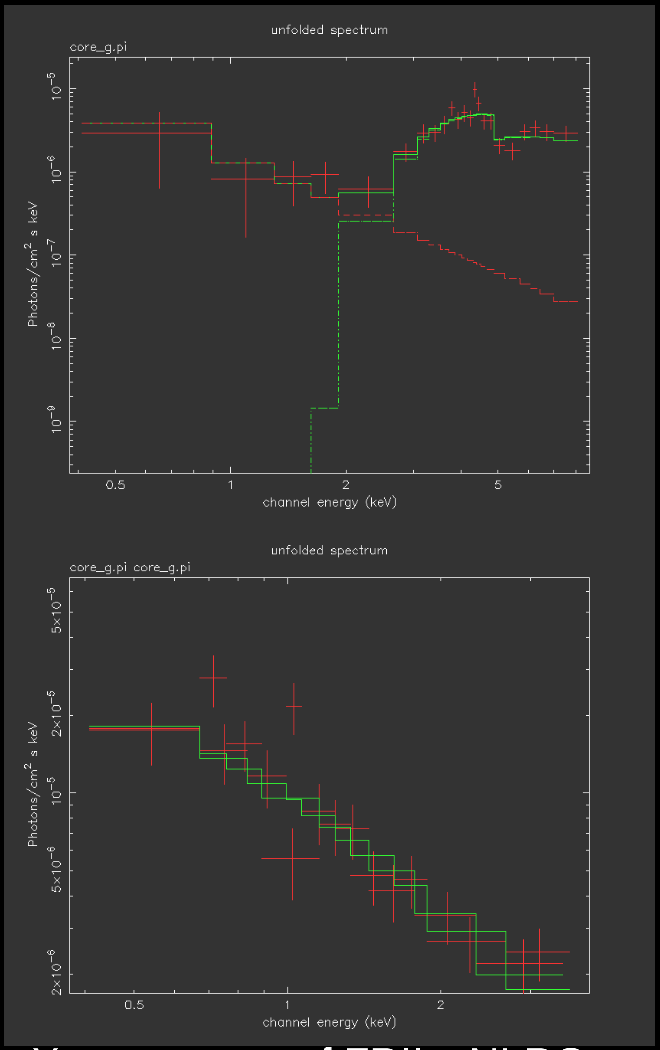
Straw man model #1: radio-loud AGN are exactly the same as RQ AGN but with the addition of a jet.

Straw man model is wrong!

There are RGs with powerful (Q ~ 10^{44} erg/s or more) jets that have no optical continuum above what is jet-related, no X-ray emission above what is jet-related (Varano+04), and no heavily obscured X-ray (MJH+06), and no mid-IR emission from a torus (Ogle+06, MJH+09).

Low and even comparatively high-power jet activity may come with none of the conventional trappings of an AGN.

AGN properties



X-ray spectra of FRIIs: NLRG (top) and LERG (bottom).

Straw man model #2: **all** radio-loud AGN are operating in this radiatively inefficient way.

This model is **also** wrong. There are radio-loud AGN that do have NLR, BLR, optical-UV continuum, a torus, and coronal X-rays. These are the radio-loud quasars and BLRG/NLRG (Evans+06, MJH+06, 09).

Why the 'radio mode' terminology is bad; also a problem for the XRB/AGN analogy.

AGN properties

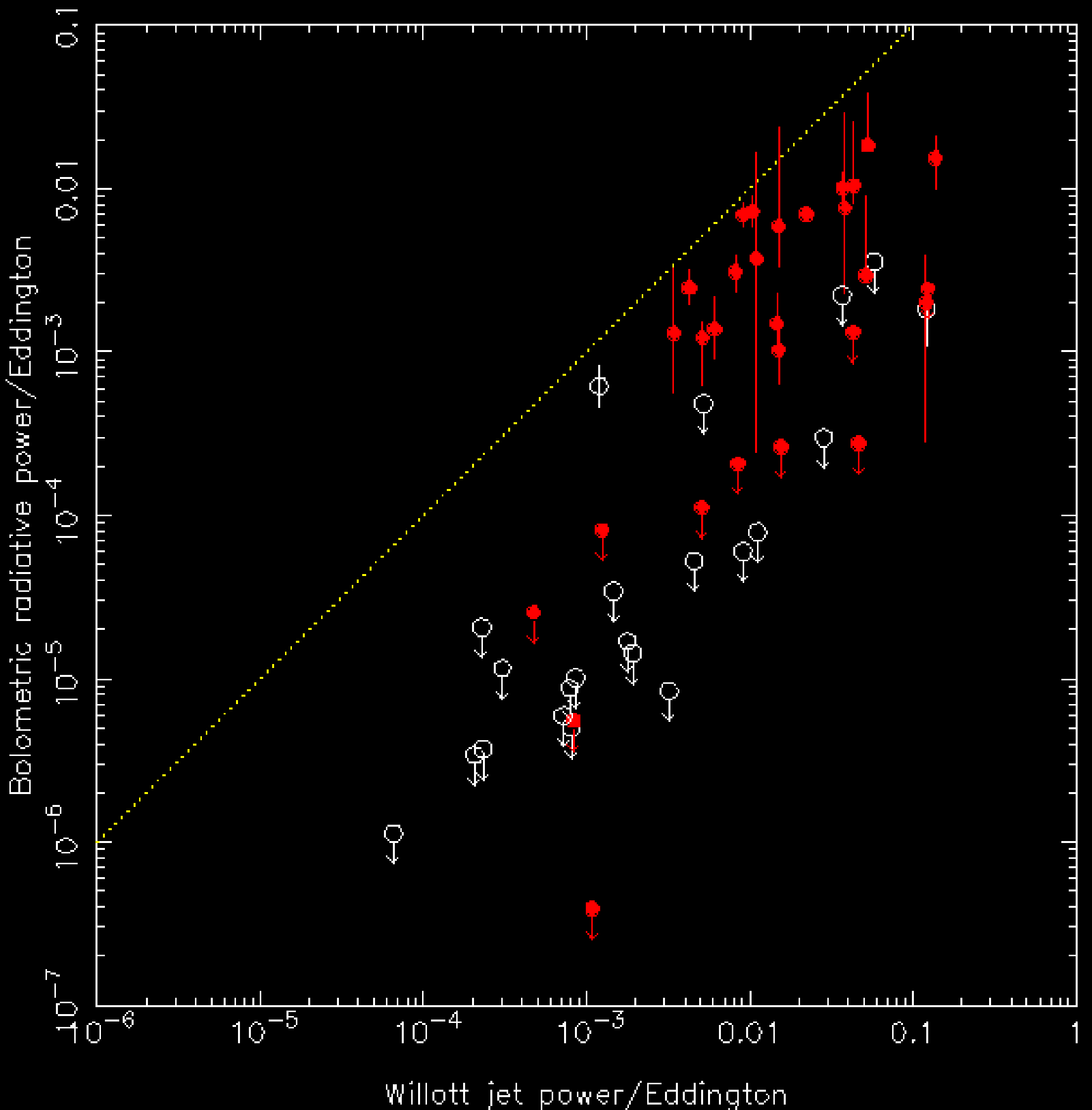
- XRB analogy does not seem to work:
  - No obvious analogue of the jetted, disky HERGs
  - No obvious 'switch' as a function of accretion rate...

An Eddington switch?

M_{BH} from K-M relationship; K-z relation for radio galaxies means this is similar for all our objects.

Willott jet power (i.e. scaling of radio luminosity) normalized to known jet powers.

Bolometric correction from 2-10 keV assumed to be 10.

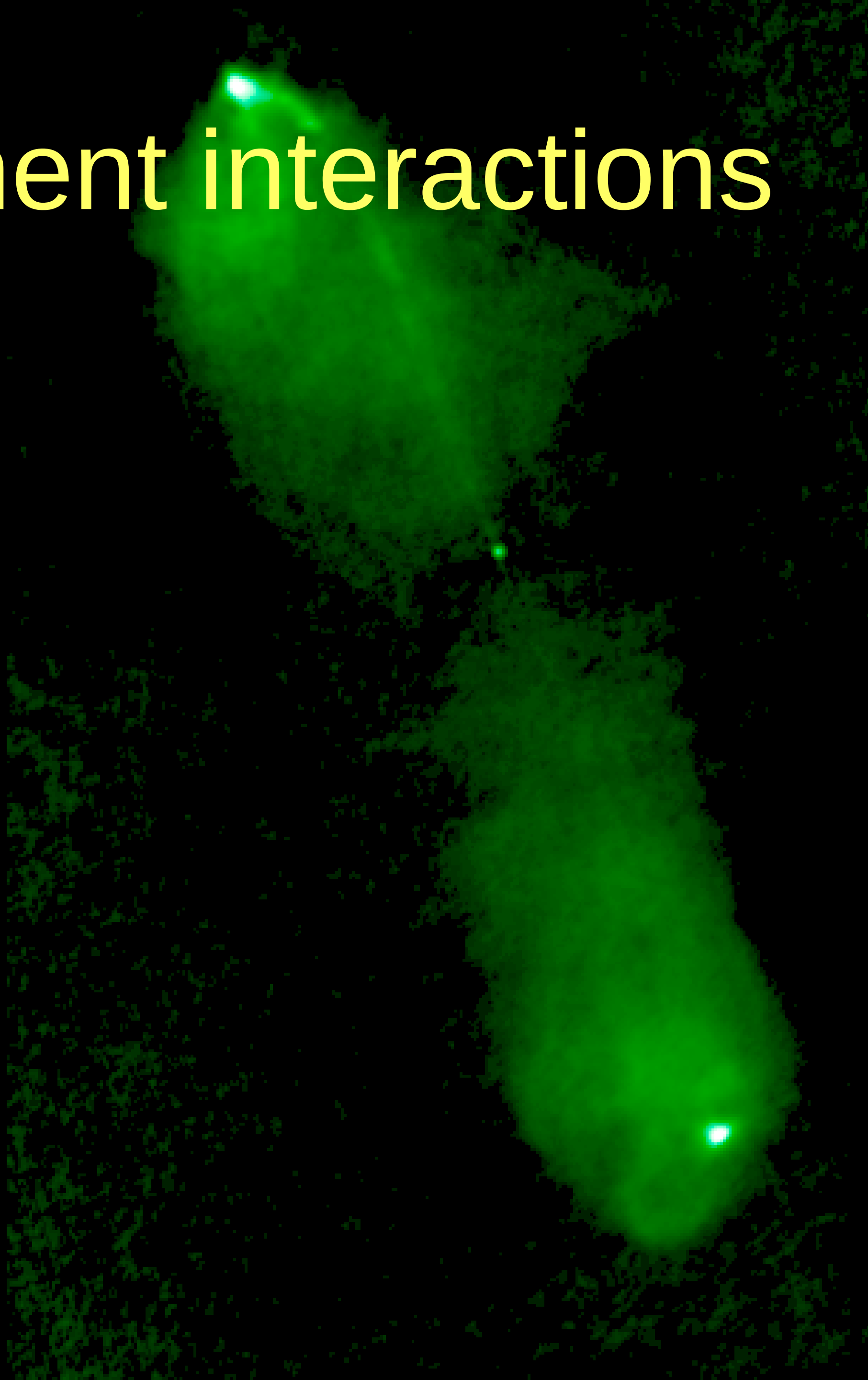


AGN properties

- We proposed that the radiatively efficient/inefficient RL AGN activity may be related to **source** of accreting material (MJH+07, 09). This is the 'hot mode' – 'cold mode' picture.
- Testable predictions – environments, population evolution (see Philip's talk).
- Does XRB analogy disfavour this? – not clear to me
- Not necessary to buy into this to realise that some RL AGN can be **radiatively** coupled to their environment while others may not.
- Hence in the second part of the talk we will neglect AGN radiation and discuss how kinetic power of RLAGN is coupled to their environments.

RLAGN-environment interactions

- Every time you see a bright radio structure you are seeing **direct** evidence for interaction with environment.



How can RLAGN affect environment?

- Jet plasma is low density but high pressure => interactions with **gas**, not stars
- Most jets will form lobes anyway (see later)
- Lobe boundaries appear to be impermeable (why?)
- => RG-env interactions are mostly interactions between hot, low-density bubbles and cooler, denser external medium.
- Highest-pressure phase of external medium is X-ray-emitting, so start there.

Perseus A radio+optical+X-ray

Lobe dynamics + interactions

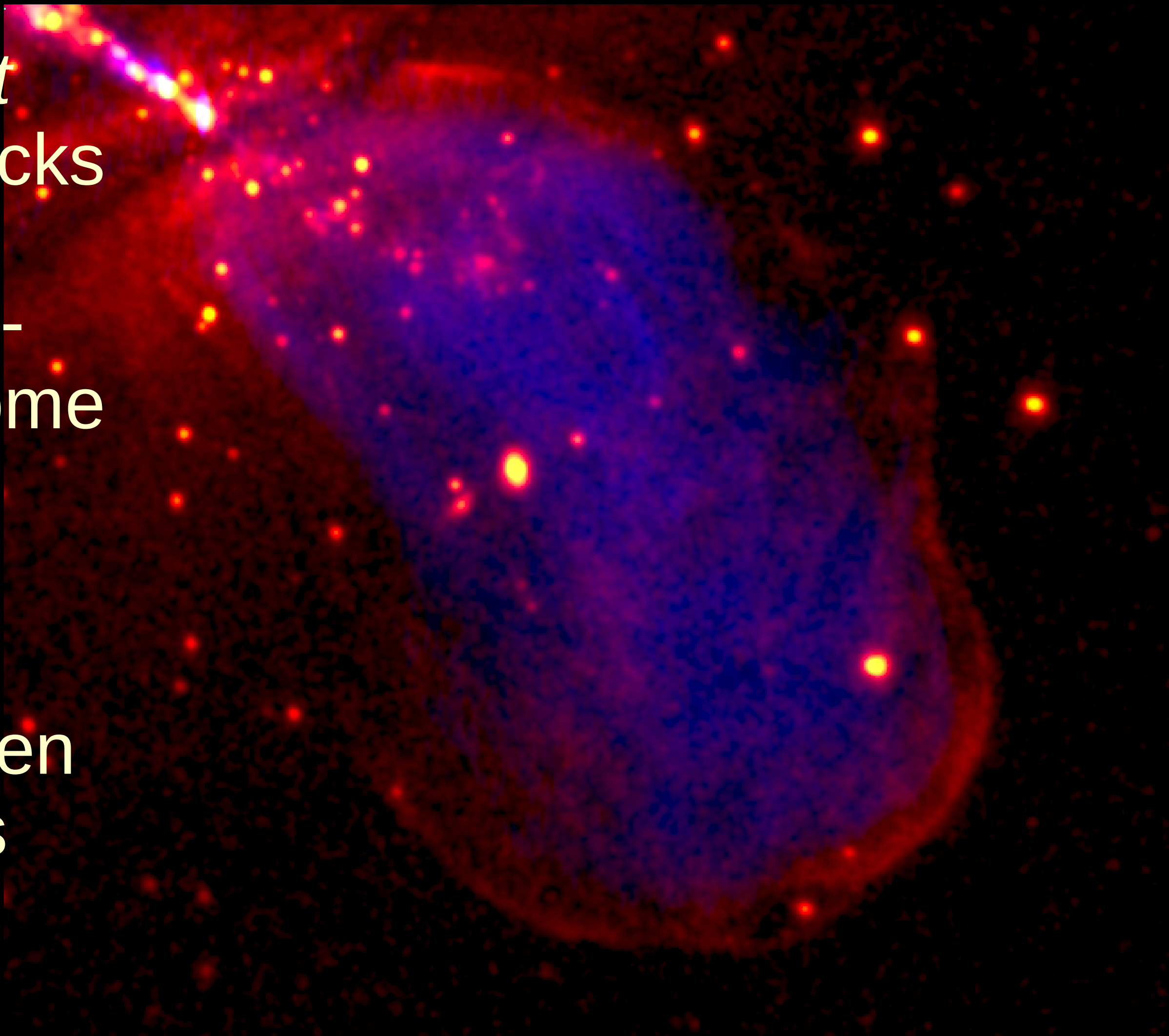
- Basic picture from Scheuer (1974) still valid.
- Newly formed lobes will expand supersonically, driving shocks
- Internal lobe pressure drops as lobe expands and (observationally) lobes can come into rough pressure balance.
- Once jet activity terminates, lobe continues to expand and move out buoyantly (relic)
- Finally, lobes must dissipate (mixing)
- Each phase will deposit energy in the hot gas, but not all will change the entropy.

Supersonic expansion – where are the shocks?

- Strongly overpressured sources will drive shocks throughout their lifetime (Scheuer 74).
- Used to be an article of faith in the FRII modelling community (e.g. Begelman & Cioffi 89, Kaiser & Alexander 97, and many more).
- Numerical models of FRII environment impact may make this assumption (e.g. Basson & Alexander 03) although more recently some have allowed it to vary (Vernaleo & Reynolds 07).

Where are the shocks?

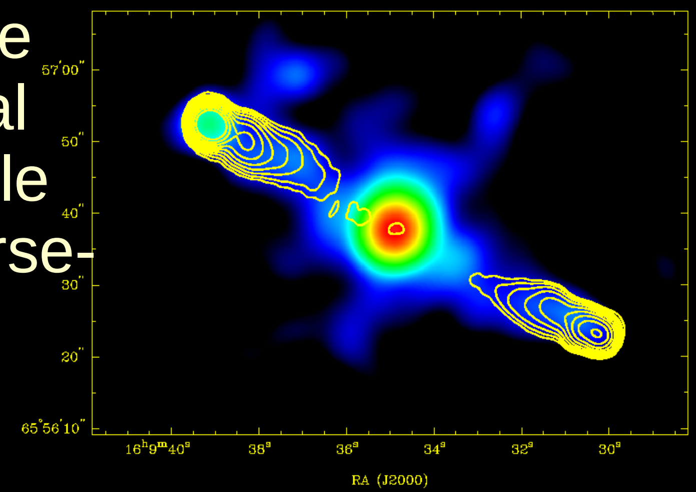
- So far best *direct* evidence for shocks in hot phase is around the small-scale lobes of some nearby FRIs
- Evidence for shocks around FRIIs is weak even in the best cases (e.g. Cyg A)

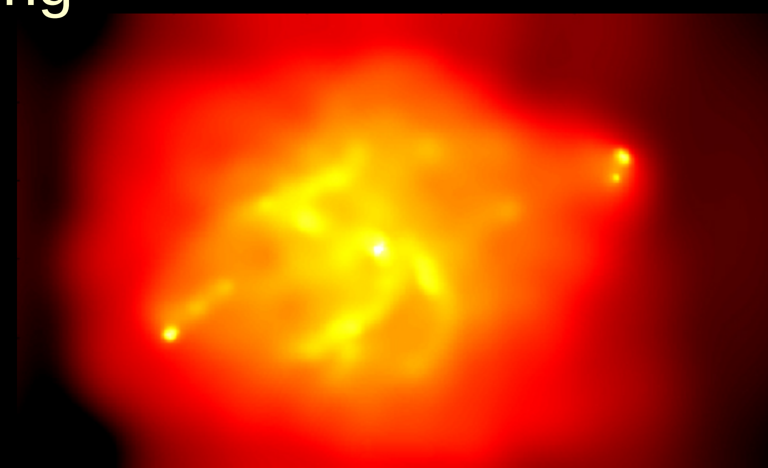


Cen A lobe shock, Croston+ 09

Where are the shocks?

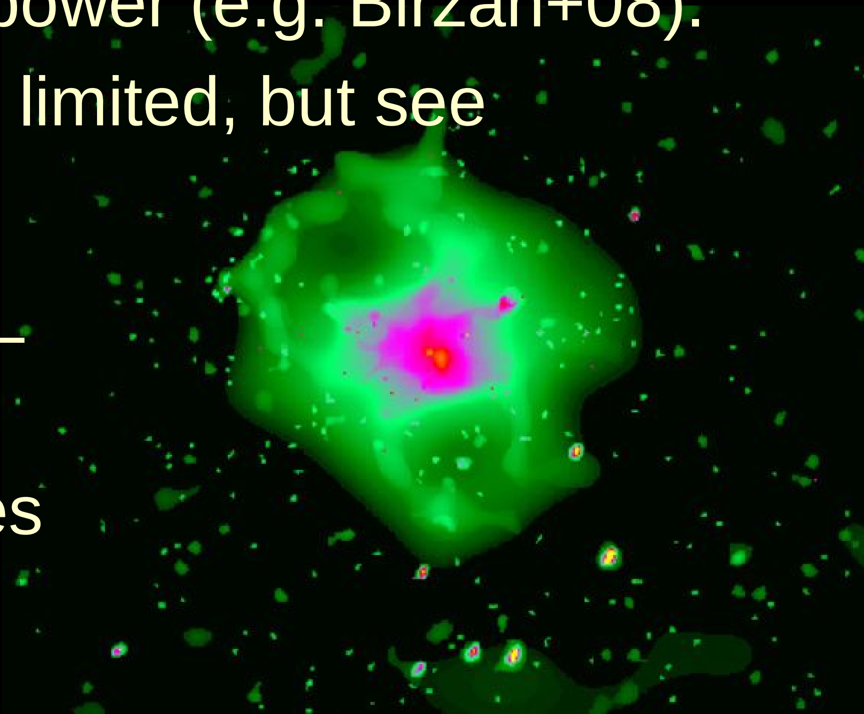
- At the same time, growing evidence that the internal pressures of typical 100-kpc-scale FRIIs are comparable to the internal pressures from inverse-Compton (e.g. MJH+02).
- => lobe dynamics more complex (MJH+Worrall 00)
- => most FRIIs are not driving strong elliptical shocks (may still be supersonic at far end)
- => effect of shocks is limited for these sources.
- NB 'relic' shocks may still be detectable in X-ray observations





pdV work

- Typical radio-selected AGN where jets are embedded in lobes will spend most of their lives doing *pdV* work
- We know that lobes expand without much mixing from observations of cavities, so $p = p_{ext}$ and $V = V_{lobe}$. Can use this to calculate jet power (e.g. Birzan+08).
- *Direct* evidence for *pdV* work limited, but see Croston+ 05. Recently we have been trying to use RG host groups as calorimeters – watch this space.
- This type of energy input does not solve entropy problems.



Buoyancy

- Disconnected lobes will continue to rise and expand – this can drag out cold material and continues to do *pdV* work, tapping the internal energy of the lobe.

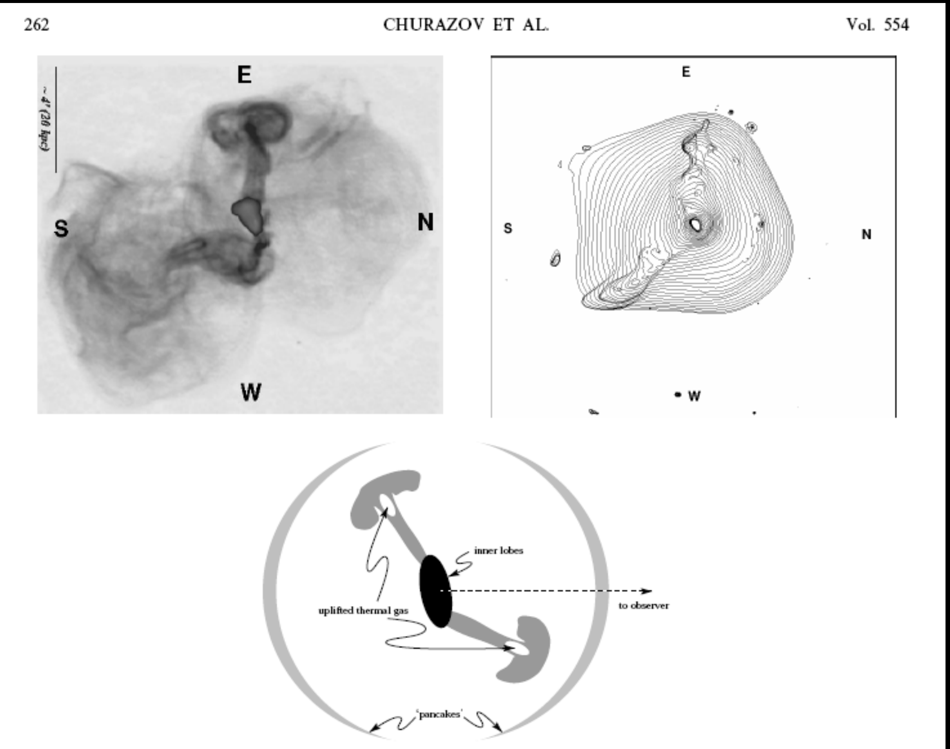
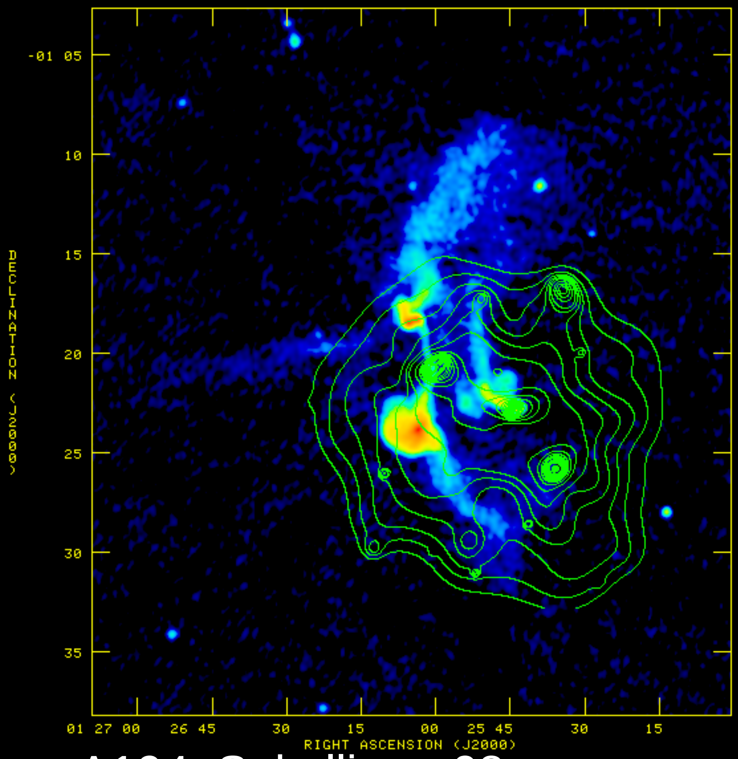


FIG. 1.—*Upper left*: 14.'6 × 16.'0 map of the radio halo of M87 at 327 MHz rotated 90° clockwise (north is to the right, and east is up). The map was kindly provided by F. Owen (see Owen et al. 2000 for original data). *Upper right*: Adaptively smoothed *ROSAT* HRI X-ray image. The size and orientation of the image are the same as for the radio image. *Bottom*: Possible geometry of the source inspired by analogy with mushroom clouds produced by powerful atmospheric explosions. The black region in the center denotes the inner radio lobes, gray mushrooms correspond to the buoyant bubbles already transformed into tori, and the gray lens-shaped structures are the pancakes formed by the older bubbles. To explain the observed morphology, the source must be oriented close to the line of sight (*dashed line*). The pancakes are shown edge-on as shaded regions.

Mixing

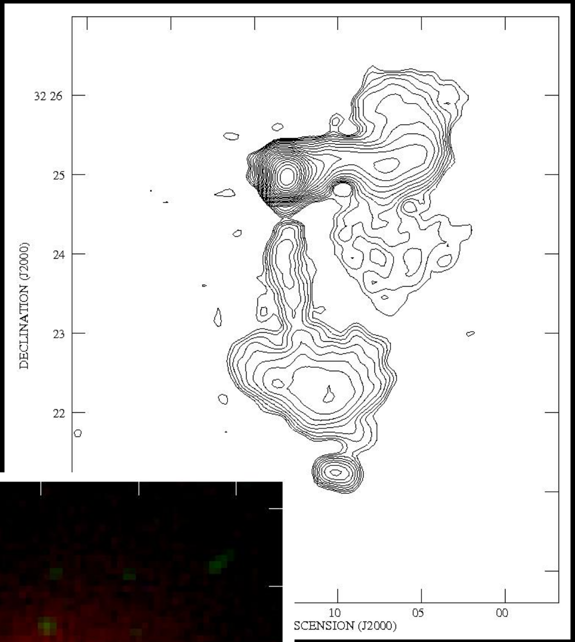
- The elephant in the room – very large amount of energy in internal energy of lobes, which will be released at some point (changes entropy too).
- When does lobe material start to mix?
- Some evidence for diffuse synchrotron emission in groups with RGs, plus radio haloes/relics in clusters.
- Timescale for thermalization of particle population very long (Coulomb losses). Hard to observe these processes!

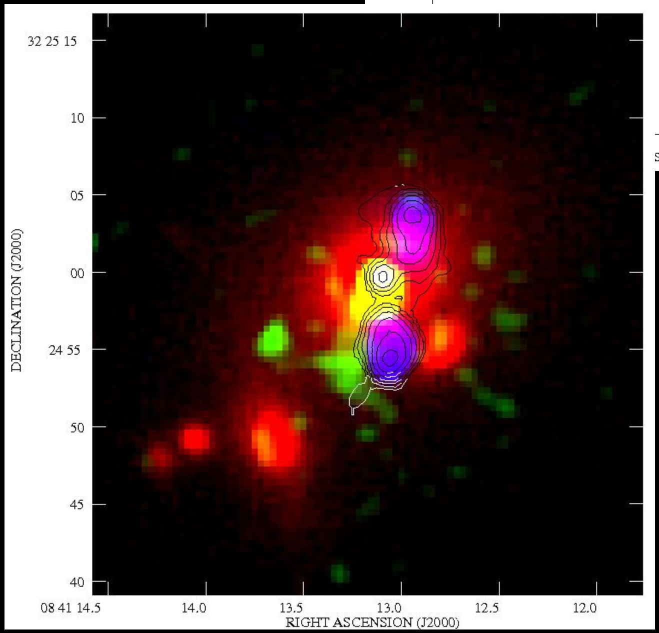


A194, Sakelliou+ 08

Intermittency

- Many sources, and perhaps even most low-power radio galaxies, show evidence for recurrent activity.
- => Many (all) of these processes may be going on simultaneously!
- Both duty cycle and timescales will depend on jet power and environment (e.g. Perseus)

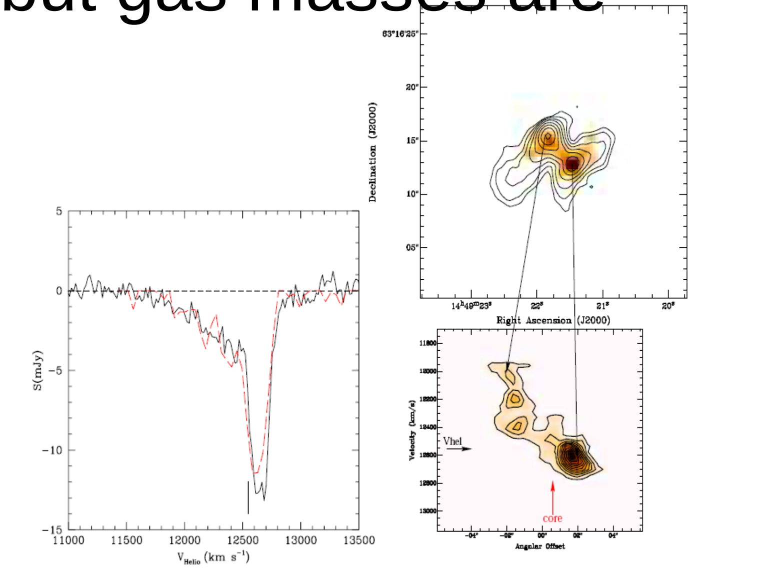




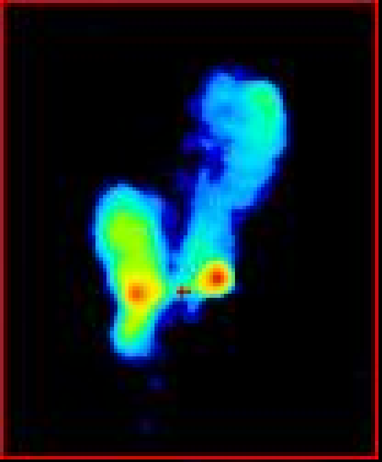
Jetha+ 08; shocks and rising, buoyant relic lobes in a low-power radio galaxy.

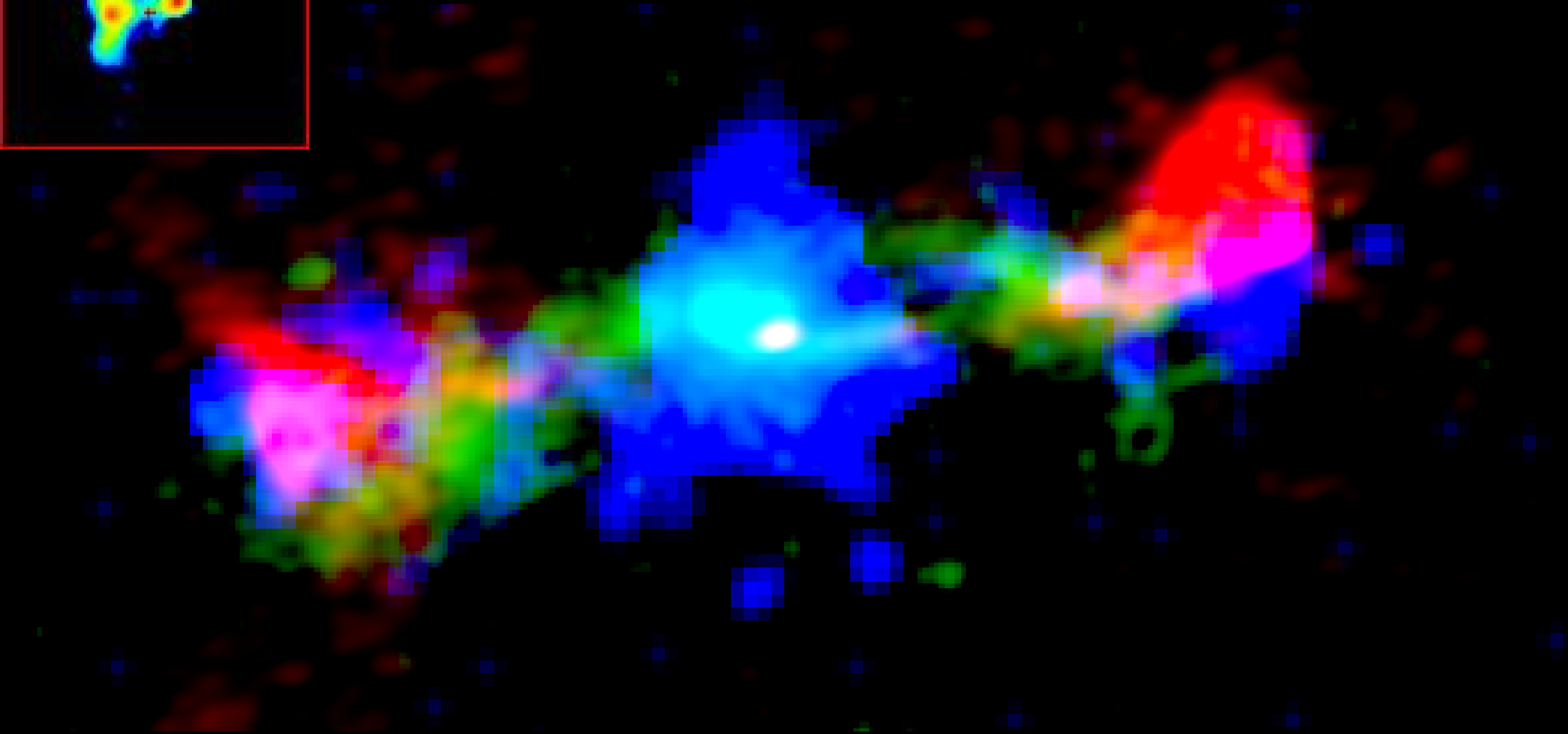
Interactions with cold gas

- Extended (10-100 kpc scale) emission-line regions seen in high-z objects imply some means of ionizing cool (10^4 K) gas.
- Shock ionization implies direct(ish) interaction between jets and cold gas (e.g. Nesvadba+ 08).
- Kinematics often imply outflow, but gas masses are not significant at low z. But...
- ... outflows of *neutral* hydrogen – necessarily at low z – imply higher mass outflow rates. Necessarily kinetically coupled (Morganti+05,10)



Blowing hot and cold

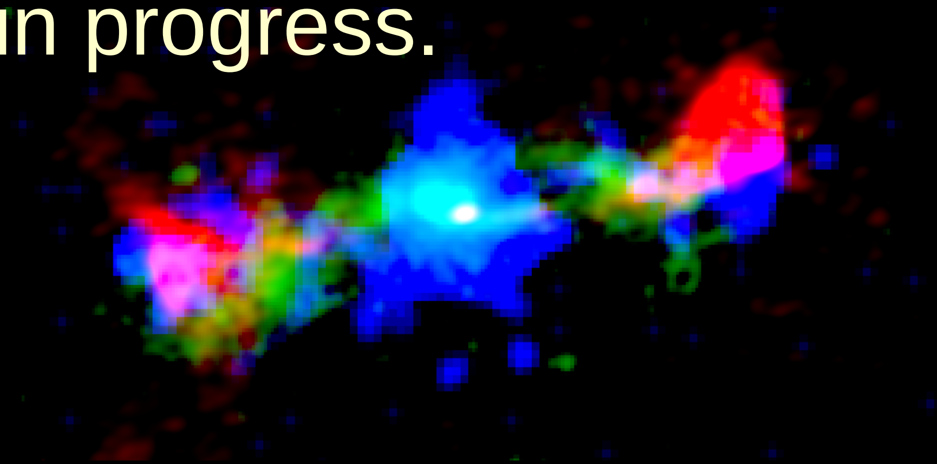




In 3C171 (MJH+10) we see radio (red), [OIII] (green) and X-ray (blue) are all aligned. [OIII] kinematics imply outflow: optical and X-ray properties imply shock ionization: taken together we have 3 x 10^9 solar masses moving out at ~1000 km/s.

Blowing hot and cold

- How do we get this jet-cold gas coupling?
- Not yet clear, but shock driven by jet through hot phase may be sweeping up and ionizing cold gas.
- Potentially important feedback mechanism, esp. at high z where more cold gas available; more work in progress.

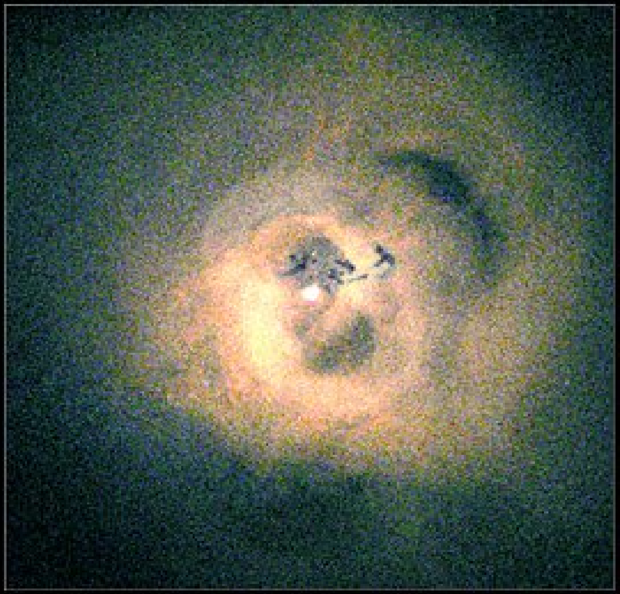


Problems and puzzles of 'feedback'

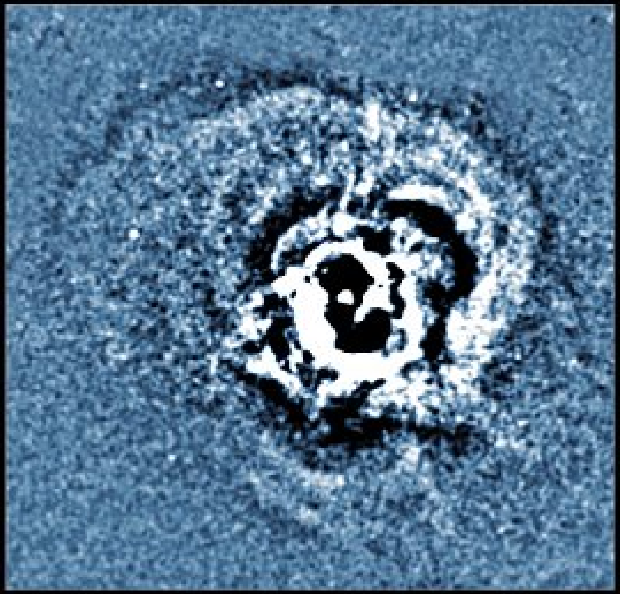
- Following are some examples of problems in radio-loud feedback models.
- Not intended to be exhaustive.
- Scare-quotes highlight difference between X-ray astronomers' and galaxy-evolution modellers' feedback...
- I am mostly talking about the former (i.e. how to prevent catastrophic cooling of hot gas while not getting rid of the hot phase altogether).

Central heating

- Cooling rates are highest at the centre, but AGN heating can often be poorly coupled to the central gas.
- Rapid bubbling with many shocks may work in cluster centres (Fabian+) but most RLAGN outside cluster centres are not like this.



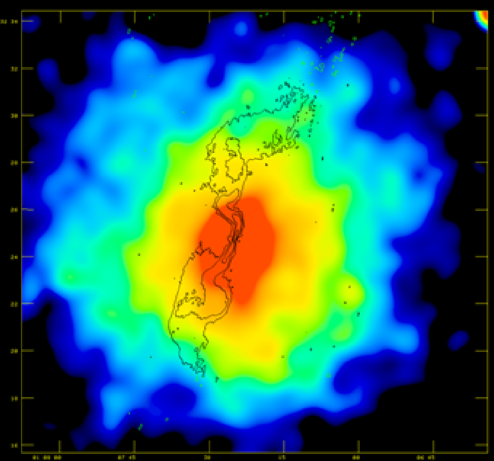
CHANDRA X-RAY [3-COLOR]

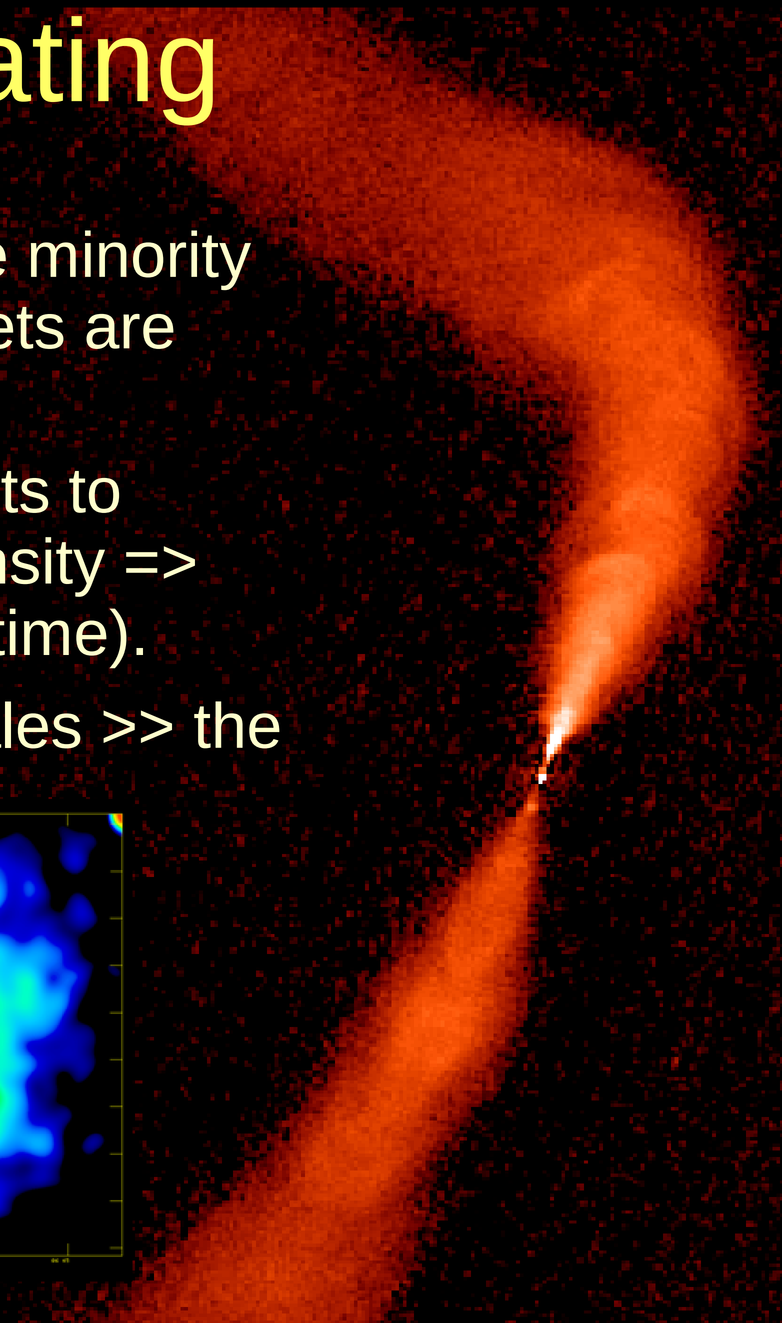


CHANDRA X-RAY [SOUND WAVES]

Central heating

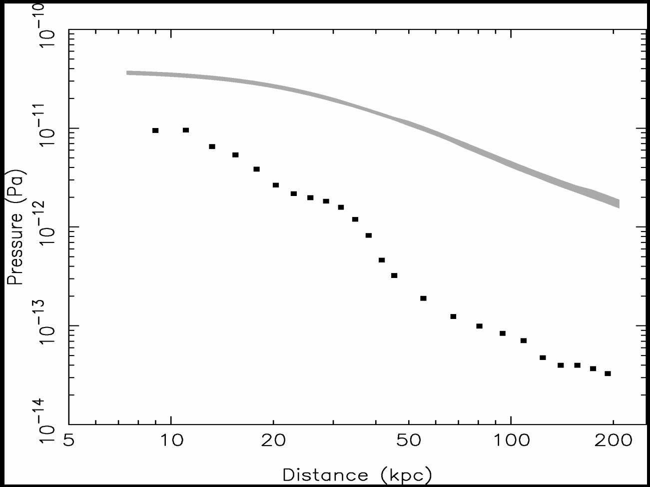
- Particularly acute problem with the minority of powerful FRIs where powerful jets are embedded in the hot medium.
- Jets require high pressure gradients to collimate them => high central density => short cooling times (<< source lifetime).
- But jet energy is dissipated on scales >> the central few kpc. How are the central pressure and density gradients maintained?

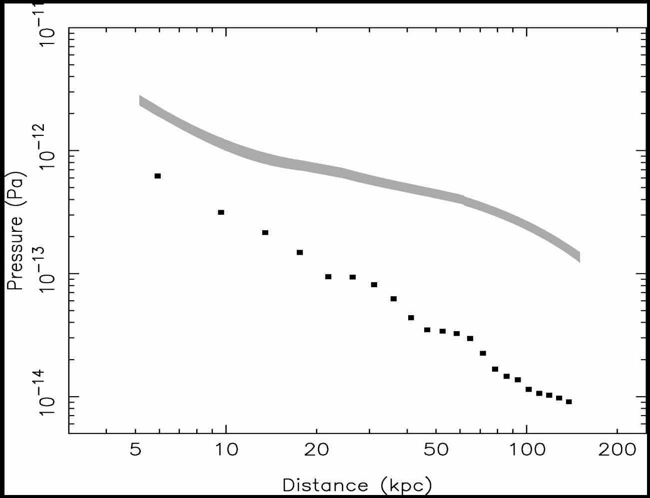




Particle (& field) content

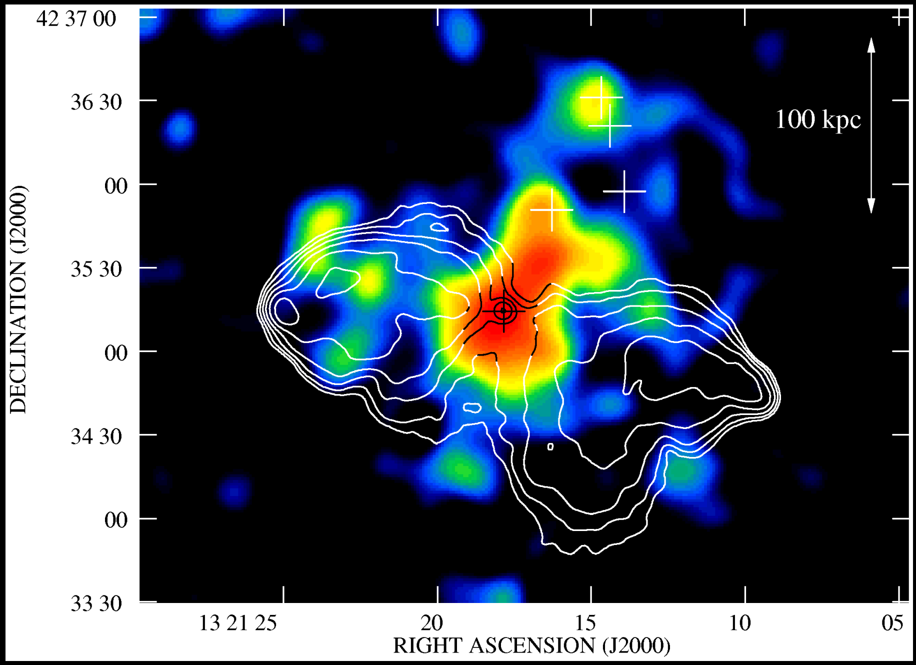
- What provides the lobe pressure?
- In FRIIs e+e- and fields close to equipartition can do it
- In FRIs, particularly jetted ones (Croston+09) large discrepancy between min and external pressure
- To understand these sources we need to know what particles provide the internal pressure. Entrainment may be implicated (Croston+10).





Over-reaction

- Often a good coupling between jet power and required heating, but some radio sources in group/cluster environments are way too powerful.
- We suggest that these are powered by accretion of **cold** material (these sources all have 'traditional' AGN) & so uncoupled from the hot phase.
- => **Unregulated** heating of the IGM is taking place.
- Bower's 'expulsive feedback'?



3C285, MJH+08

Closing the feedback loop

- For true (X-ray-astronomers') feedback we need the jet (AGN) output to be coupled to the properties of the hot phase, as well as the reverse.
- Direct accretion from the hot phase? Or intermediate cooling?
- What happens below the Bondi radius?
- Bondi rate is adequate for many RGs – if you can get high efficiency of jet formation – but some sources need more (see Brian's talk).
- Can we really infer accretion source from accretion mode?

Summary

- Interactions between radio-loud AGN and both hot & cold gas are present at all epochs, though best studied at low z.
- They are *not* associated with any particular accretion mode – but their effects may depend strongly on their fuel source.
- The 'microphysics' of energy transfer is extremely complex, poorly understood in places, and operates on a wide variety of timescales.
- Many remaining unresolved questions even for the 'solved' problem of radio-source suppression of cooling in clusters & groups.