From Sequence to Envelope

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RICE

Outline

- Active Galactic Nuclei (AGN)
- Relativistic jets in AGNs.
- Blazars (and radio-galaxies.)

- Blazars population unification
  - Blazar sequence
  - Blazar envelope

- Multiwavelength variability of bright objects
  - Time-dependent 2D modeling

"Black Hole Models for AGNs" (Rees, 1984)

Martin J. Rees, Baron Rees of Ludlow

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  - The Queen's Piper
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Astronomer Royal

The title Astronomer Royal is an honour awarded to a renowned scientist working in the field of astronomy.

There are two officers, the senior being the title Astronomer Royal, which dates from 22 June 1675, and the second the post of Astronomer Royal for Scotland, which dates from 1834.

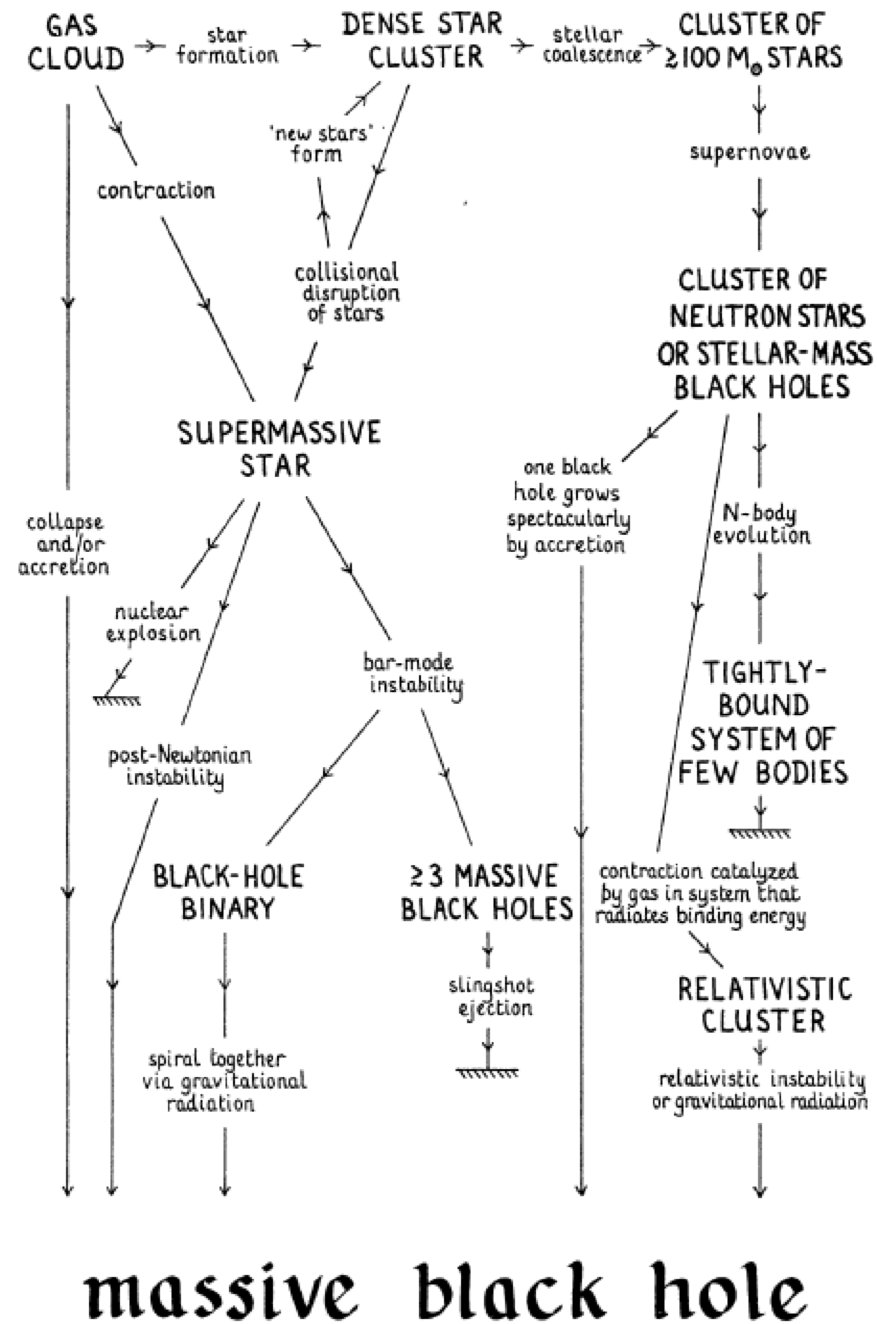
The position of Astronomer Royal is nowadays largely honorary, though he remains available to advise the Sovereign on astronomical and related scientific matters.

The appointment is made by the Sovereign upon the advice of the Prime Minister.

The Astronomer Royal receives a stipend of £100 a year and is a member of the Royal Household.

"Black Hole Models for AGNs" (Rees, 1984)

- *"It is now 20 years since AGNs became widely acknowledged as an important astrophysical phenomenon. Over the entire subsequent period, one of the few statements to command general agreement has been that the power supply is primarily gravitational."*
- *"Such arguments suggest that massive black holes should exist in the nuclei of all galaxies that have experienced a violently active phase."*
- *"Furthermore physical processes involving black holes offer a more efficient power supply than any of the 'precursor' objects. So, massive black holes may not merely be the defunct remnants of violent activity; they may also participate in its most spectacular manifestations."*



[Rees 1984]

"Black Hole Models for AGNs" (Rees, 1984)

- *"Two obvious features of Active Galactic nuclei are*
  (a) the production of continuum emission, which in some cases at least must be non-thermal,
  (b) the expulsion of energy in two oppositely directed beams."
- *"Although this* [the region surrounding the BH] *is where the power output is concentrated, many conspicuous manifestations of AGNs –the emission line, the radio components, etc.– involve some reprocessing of this energy on larger scales."*
- *"The synchrotron and inverse Compton lifetimes of relativistic electrons is* $\ll r_g/c$ *[…] so in any model involving such mechanisms, the radiating particles must be injected or repeatedly accelerated at many sites [...]".*
- *"The direct evidence for jets pertains exclusively to scales much larger than the primary power source. […] The only evidence for smaller-scale beaming comes from indirect arguments about the physics of 'blazars'. There are theoretical reasons for postulating that the relativistic outflow is initiated on scales of order* r_g*".*
- *"The only direct clue for physical conditions in the central region (i.e. within a radius of, say, 100* r_g*) is the rather featureless continuum luminosity."*

Broad goals of (multiwavelength) studies of extragalactic relativistic jets

- HOW DO RELATIVISTIC FLOWS BEHAVE?
- HOW DO MASSIVE BHs FORM AND GROW?
- HOW DO AGN OUTFLOWS AFFECT FORMATION & EVOLUTION OF COSMIC STRUCTURE (GALAXIES, CLUSTERS…)?

More directly specific to jet properties:

- Study of the matter, energy content, structure of jets.
- Insight on particle acceleration.
- Connection between accreting supermassive BH and jet formation and properties.

Roger Blandford's 10 challenges

1. Locate the sites of radio, optical, X-ray, γ emission
2. *Map jet velocity fields*
3. Identify the emission mechanism
4. Understand the changing composition
5. Measure external pressure
6. Deduce jet confinement mechanism
7. Infer jet powers, thrusts
8. Test and apply *central hypothesis*
9. BH GRMHD capability
10. Quantify role in clusters

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Us

The broad goal of my research is the identification and validation of the fundamental principles regulating blazar phenomenology.

- Our investigation encompasses a broad range of aspects of **observations** and data analysis, for various wavebands, and **modeling.**
- It is articulated in two broad areas:
  - **bright archetypical individual objects -** detailed studies of selected “laboratory” objects to understand the properties of relativistic flows and shocks in jets, through the characteristics of multiwavelength variability.
  - **large survey samples -** statistical study of the properties of samples of objects to reveal and understand the phenomenology of the radio-loud AGNs, the relationship between accretion and relativistic outflows.
- The observational aspects encompass data mining and multiwavelength observational campaigns.
- The modeling currently involves time-dependent 2D radiative transfer simulations, and population synthesis.

The AGN unification paradigm

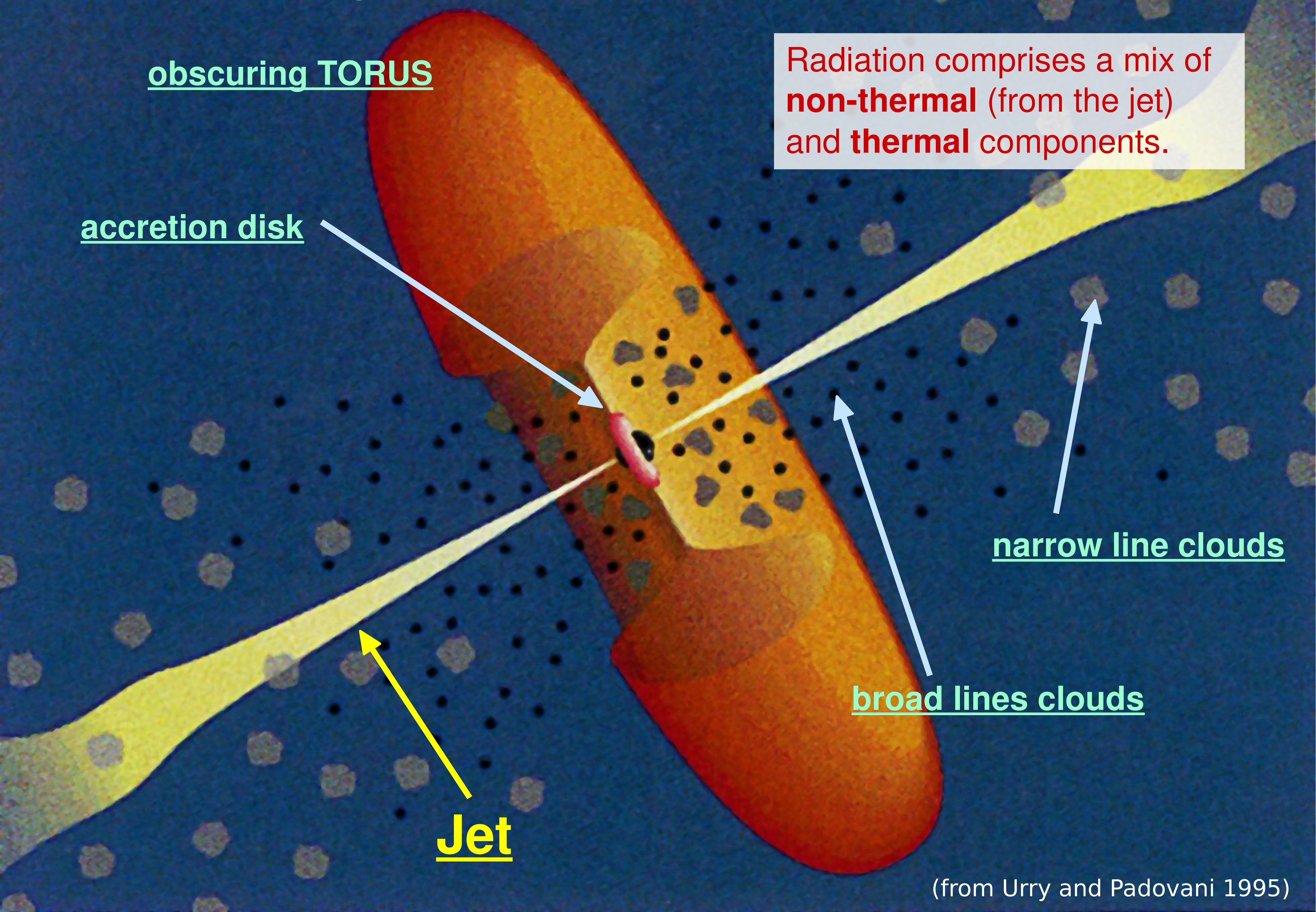
The magic word in AGN research is **UNIFICATION**.
The zero-th order idea is that the wild variety of (observed) AGN types is merely due to the combination of an **anisotropic emission**/geometrical structure of the source with our **viewing angle**.

The whole AGN phenomenology may be interpreted on the basis of three main ingredients:

- A jet
- An accretion disk
- A "*torus*"*, e.g. additional matter in a configuration such that it can **hide** the very central regions from our view.

*Theoretical Object Required by Unification Schemes

The central regions of a (radio-loud) AGN

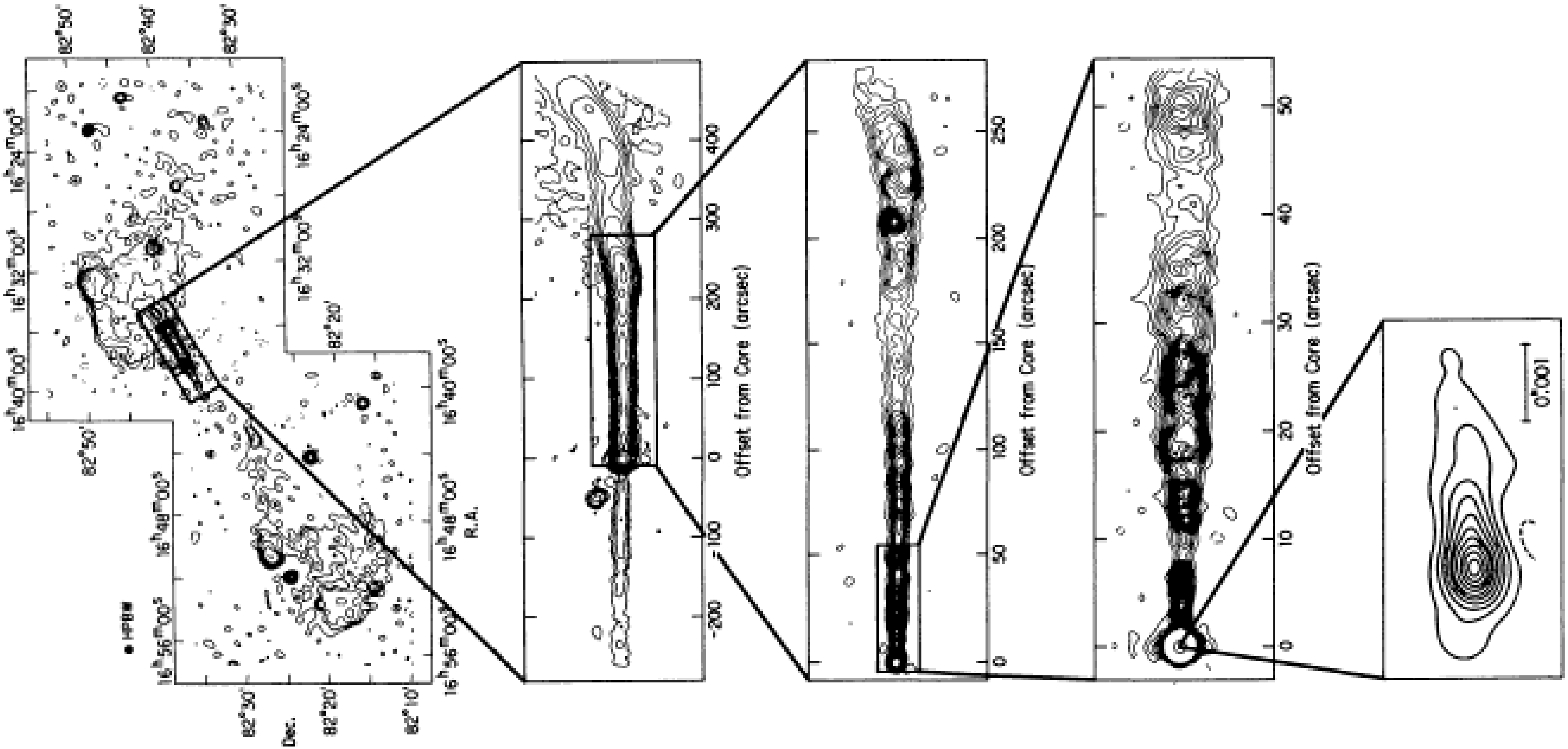


(from Urry and Padovani 1995)

Centaurus A: the closest (radio-loud) AGN

Radio (VLA) and optical (HST) images composite

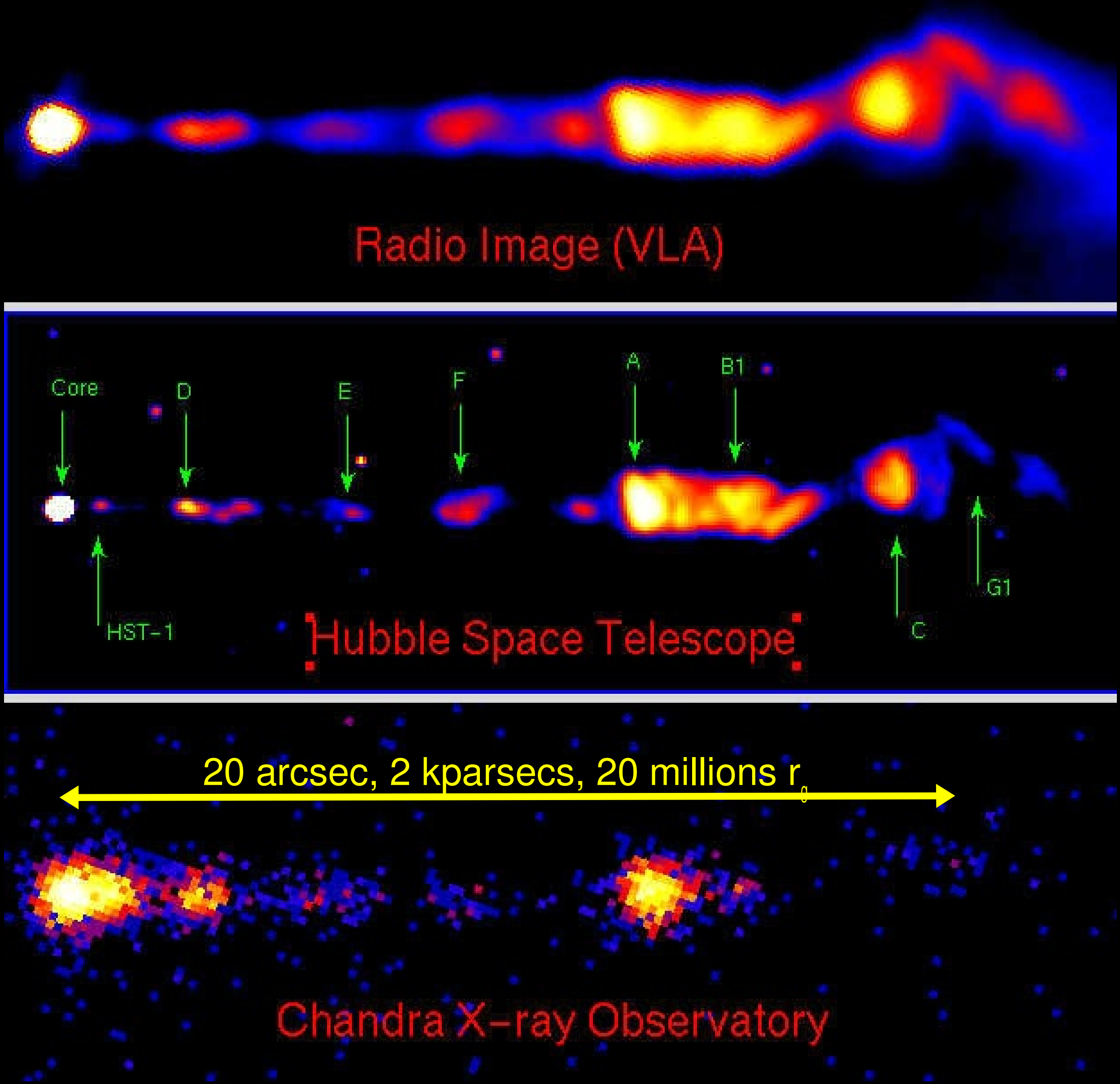
The jet of the radio-galaxy NGC 6251



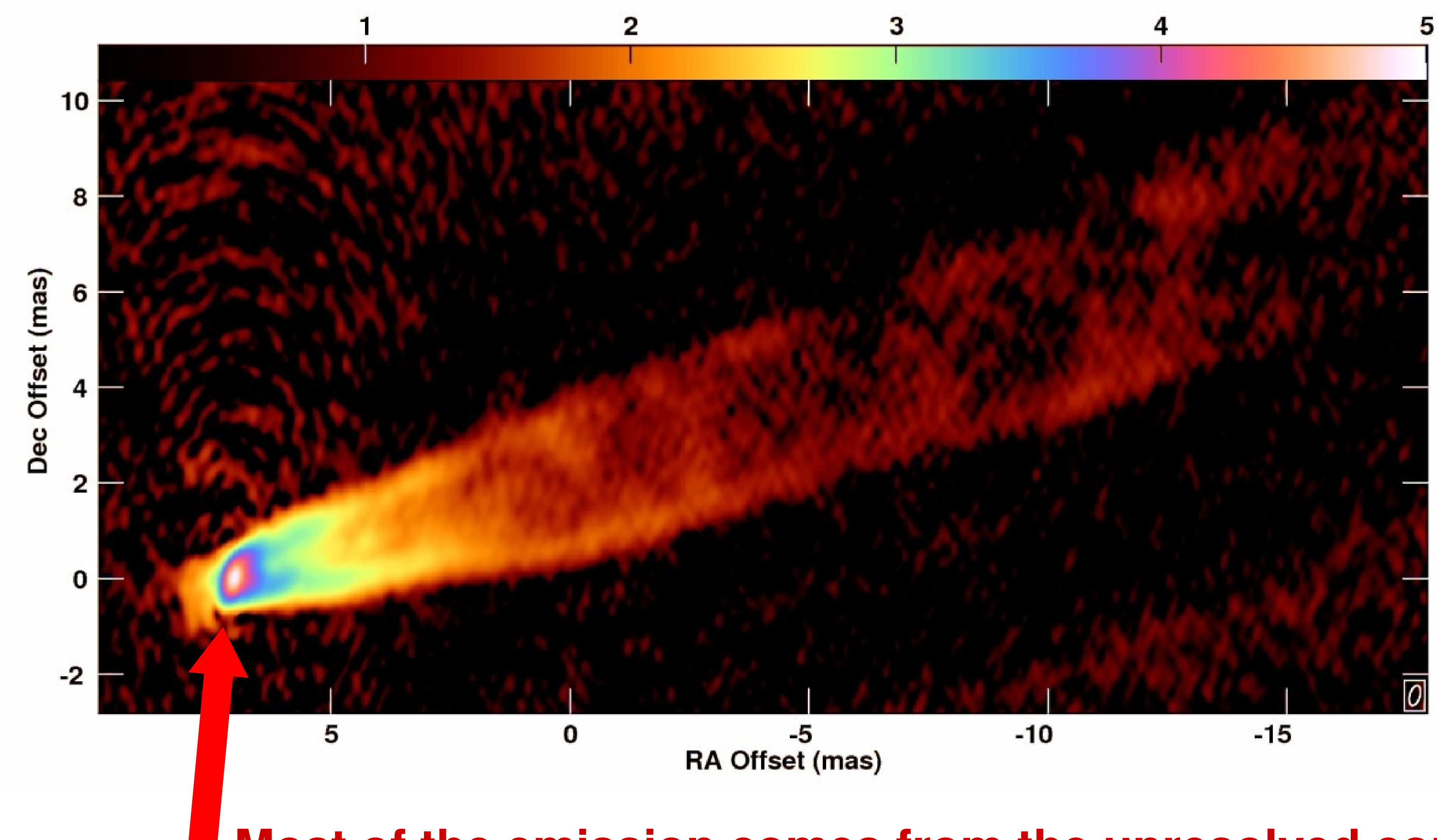
- At a redshift z=0.024, about 100 Mpc from us, an angular size of 1 milliarcsec corresponds to about 0.5 pc, 1.5 x 10^{18} cm, 50,000 gravitational radii for its estimated BH mass.
- At the highest achievable imaging resolution we are not getting very close to the central engine.

M87: multiwavelength images of its large-scale jet

- At a redshift z=0.0043, about 20 Mpc from us,
  - an angular size of 1 milliarcsec corresponds to
  - about 0.09 pc,
  - 3 x 10^{17} cm,
  - 500 gravitational radii (for the inferred mass of M87 BH, a few billion solar masses).

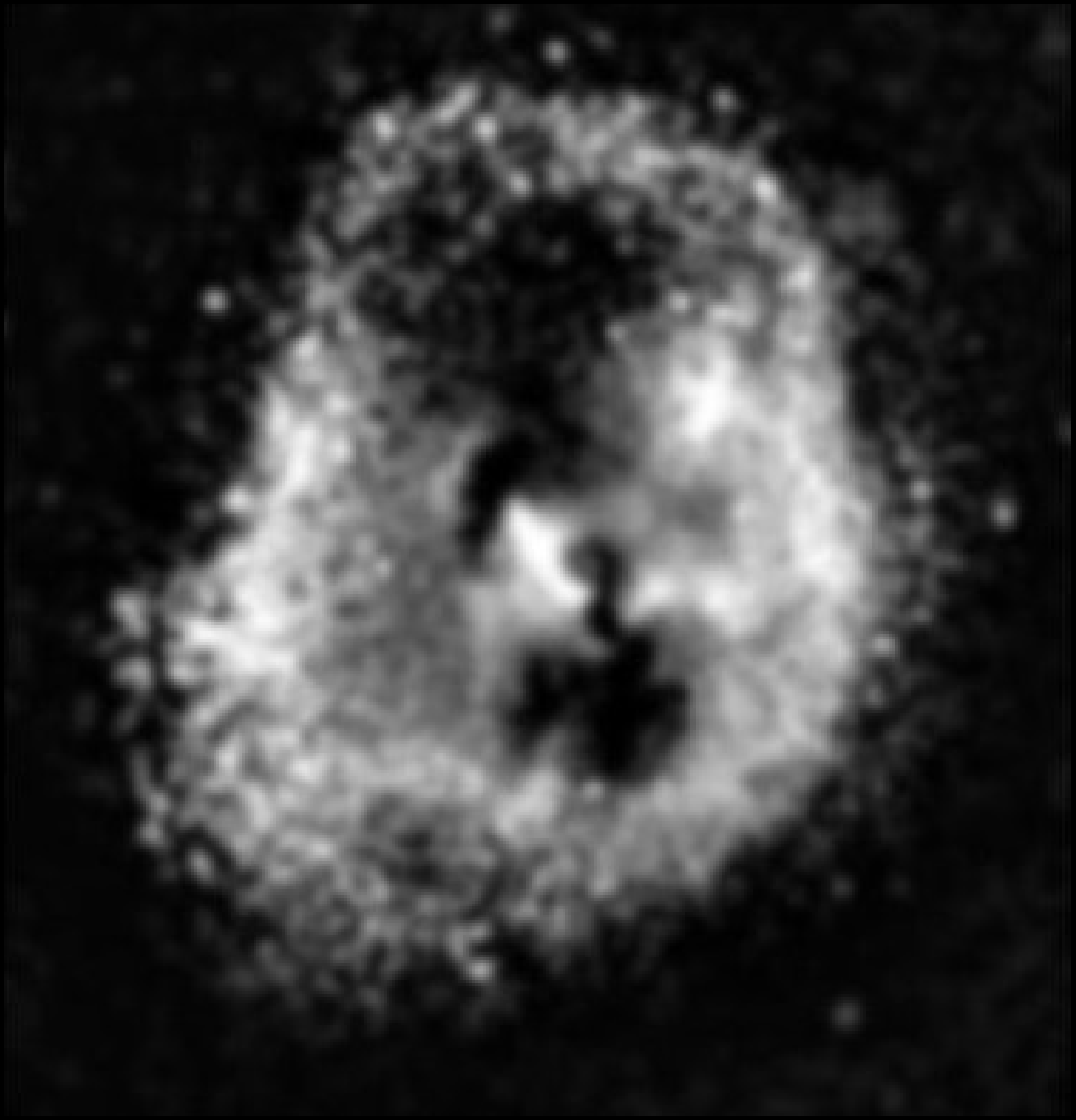


M87: the “base” of the jet (radio image)



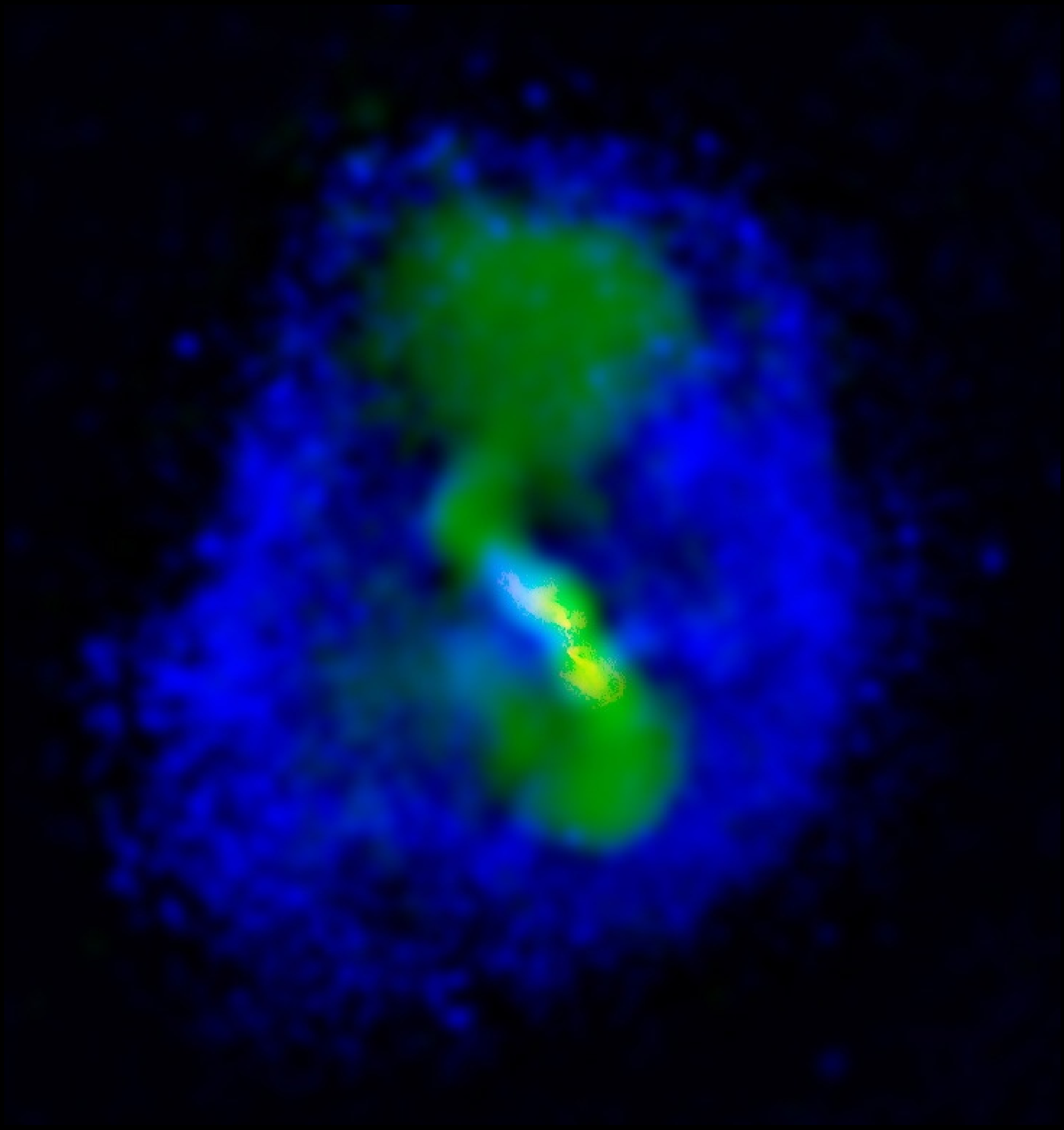
Most of the emission comes from the unresolved core!
Likely another factor of 10+ beyond our resolution, and M87 is among the closest objects.

Hydra A: a jetted AGN in a cluster of galaxies



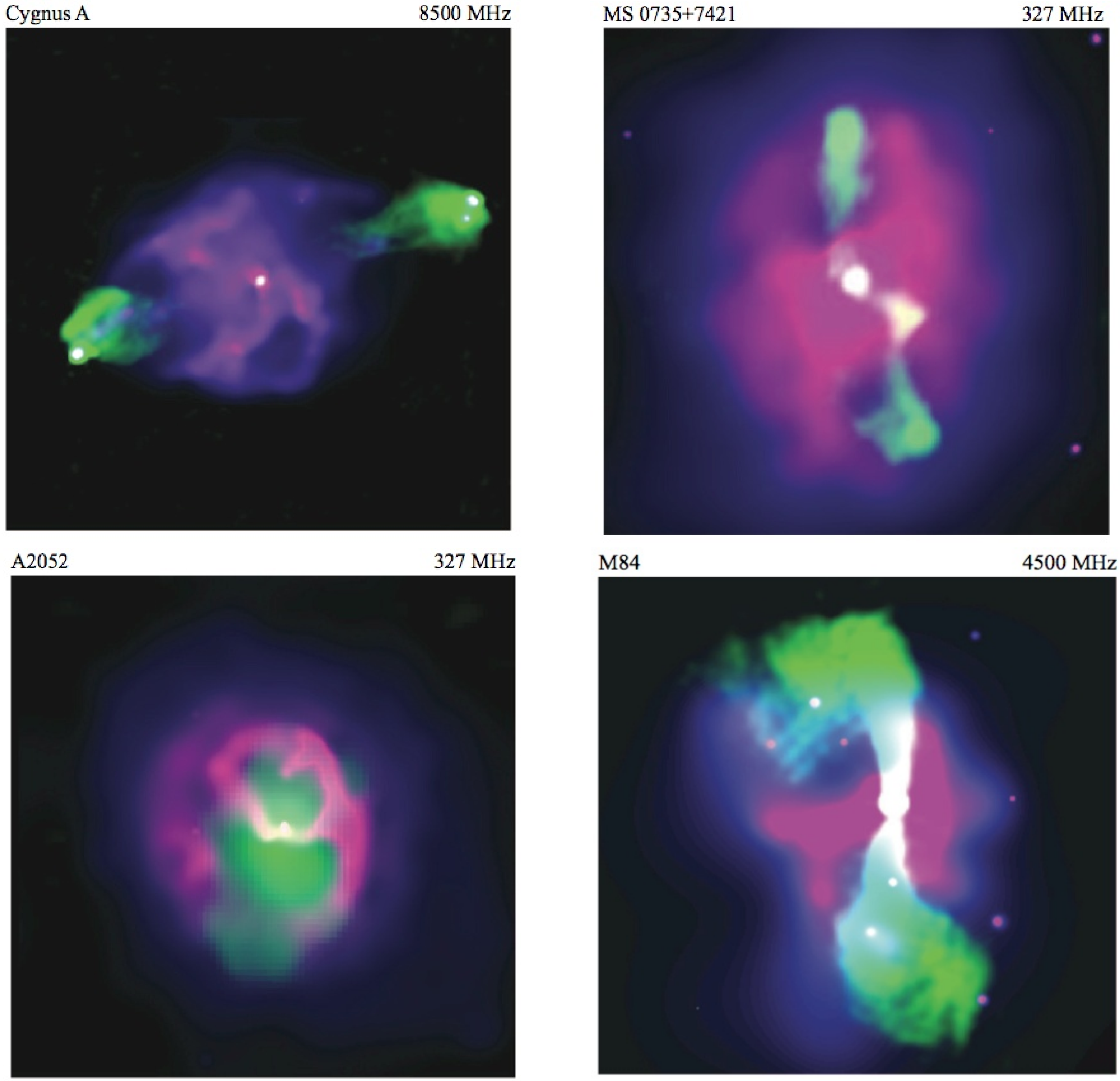
- X-ray image of the galaxy cluster Hydra A, hosting a powerful AGN.
- The X-ray emission comes from hot (millions of degrees) intracluster gas.
- The gas temperature is very inhomogeneous, showing cavities and hotspots.

Hydra A: a jetted AGN in a cluster of galaxies

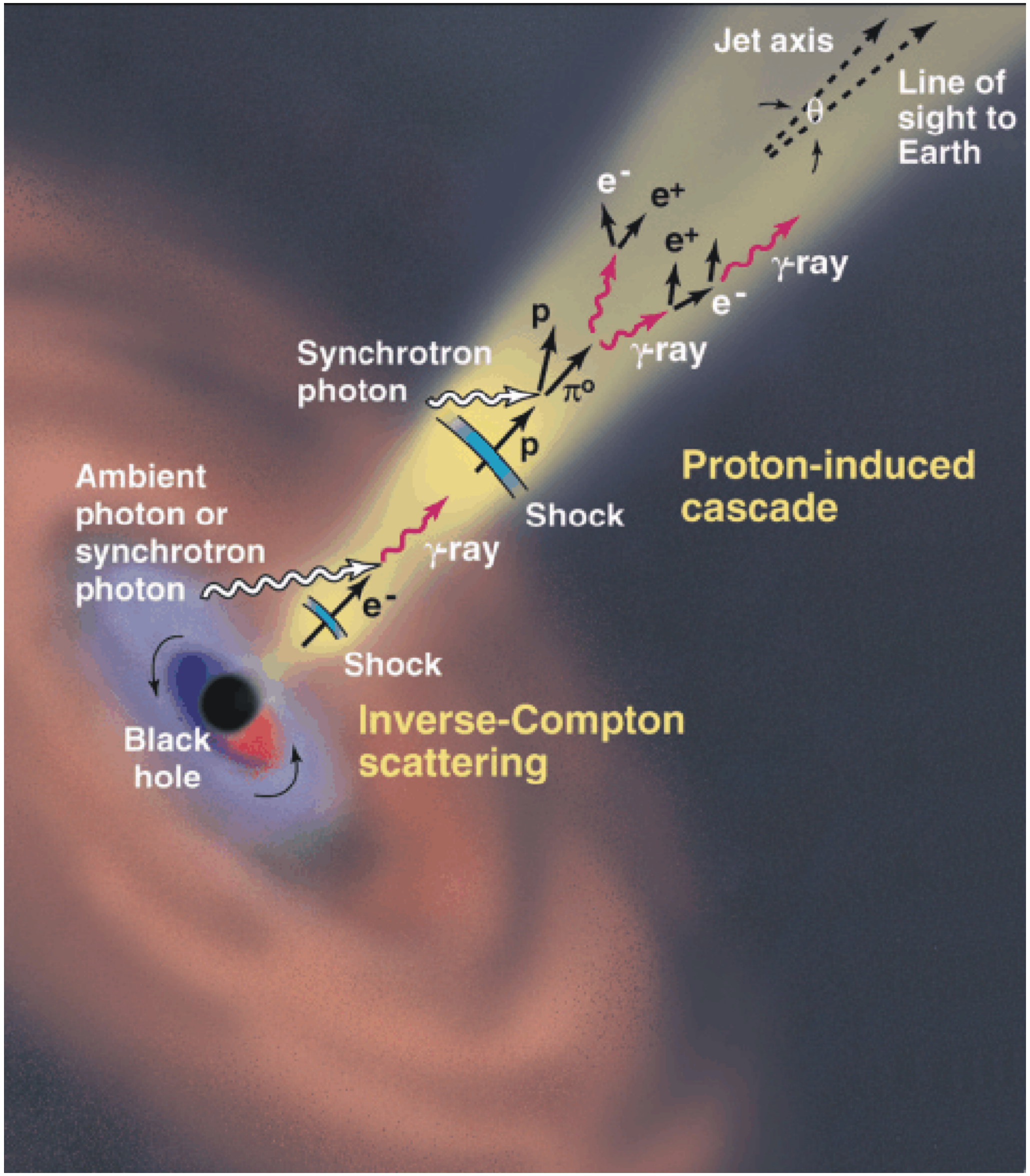


- The X-ray image is blue is now combined with a radio image in green.
- The radio emission maps non-thermal radiation from particles in the jet of the Hydra A AGN.
- It is apparent that the relativistic jets of the AGN have created and support the cavities (*radio bubbles*).
- This suggest that the presence of the AGN and its jet can have a profound influence on the evolution of the cluster, and its galaxies.

Intracluster gas and AGN jets

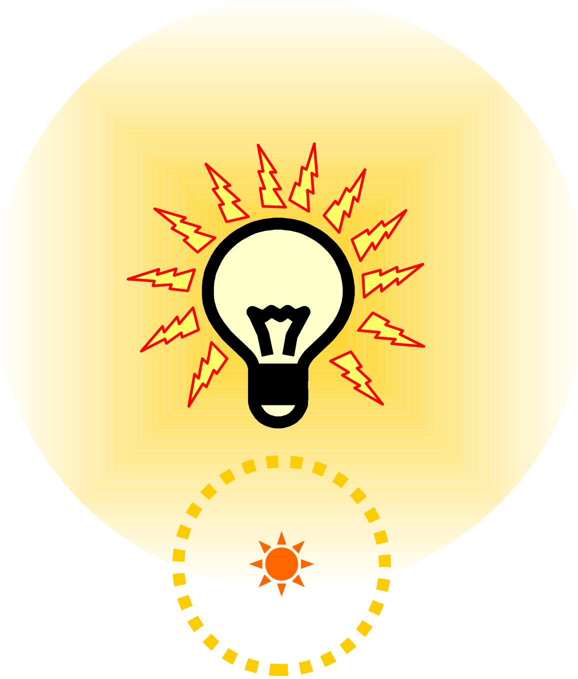


Jet, shocks, radiative processes

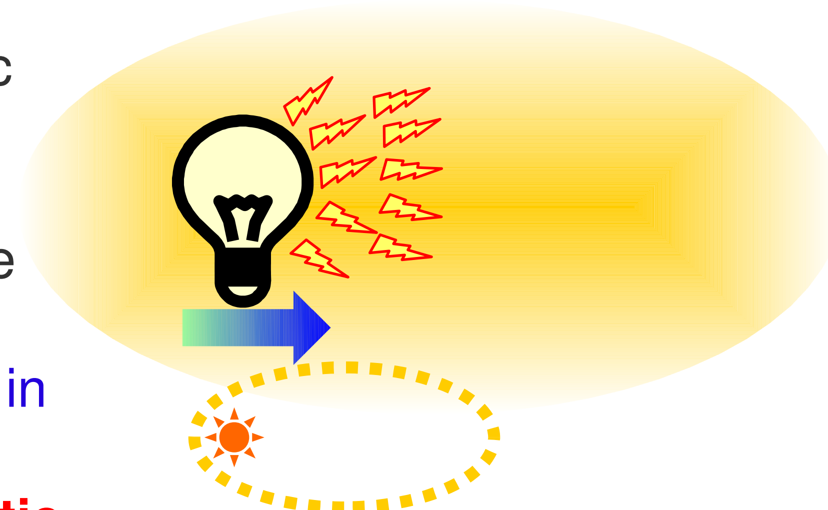


- **Internal shock model.**
  - Emission from the jet is interpreted as being due to high energy particles accelerated *in situ* in relativistic shocks caused by collisions between “shells” of gas ejected from the central regions with different speeds.
  - The dominant radiative processes are synchrotron and inverse Compton scattering. This latter could be on the synchrotron photons themselves (synchro-self-Compton, SSC), or on photons emitted elsewhere, including from the surroundings of the jet (external Compton, EC).

Relativistic beaming



The radiation emitted by a "blob" moving at relativistic speed is affected by *"relativistic beaming".*
In the observer's reference frame...
radiation is **concentrated** in a very small solid angle,
photons are **more energetic**,
timescales are contracted.



$$L_{obs} \sim \delta^{p} L', \quad p = 2 + \alpha$$

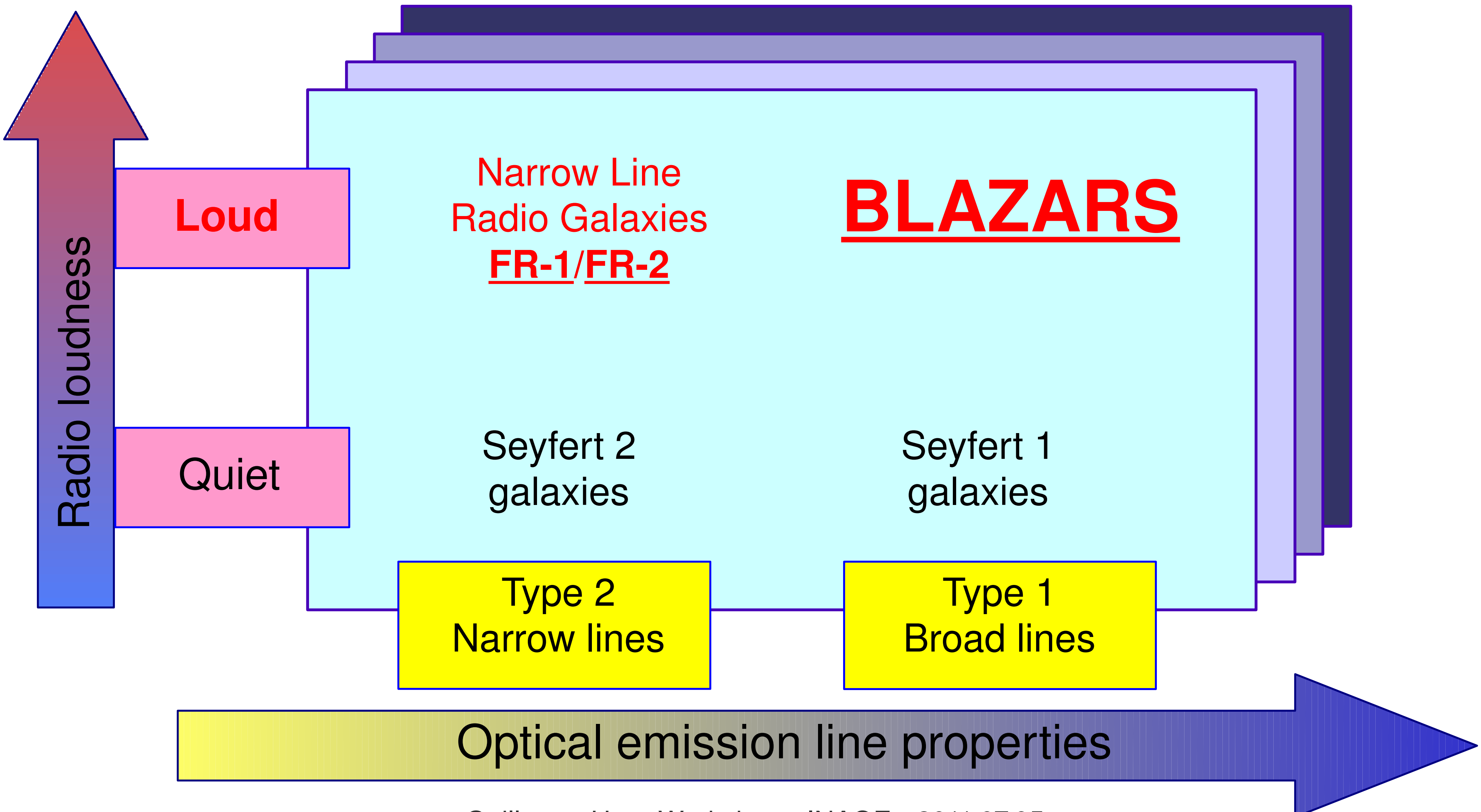
$$\nu_{obs} \sim \delta \, \nu'$$

$$\Delta t_{obs} \sim \delta^{-1} \Delta t'$$

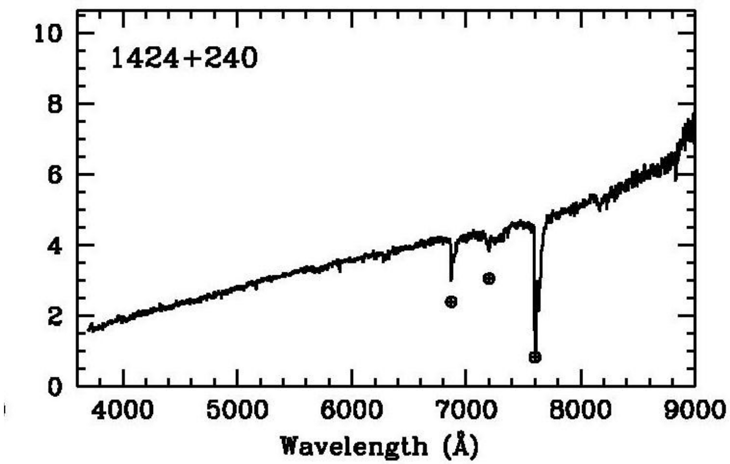
$$\delta = \frac{1}{\Gamma(1 - \beta \cos\theta)}$$

Very basic AGNs' taxonomy

AGNs population comprises a real ZOO of different names, detection criteria, and spectral and variability characteristics.
As in biology, the first approach is TAXONOMY.



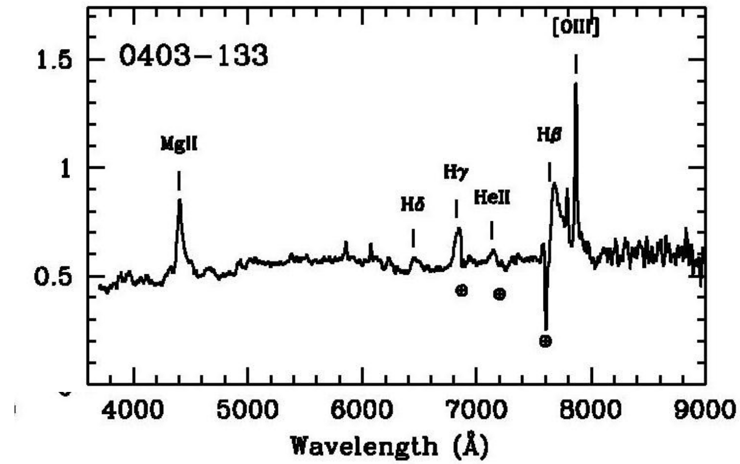
Blazars classes: optical spectra (thermal properties)



featureless optical spectrum

↓

BL Lac objects



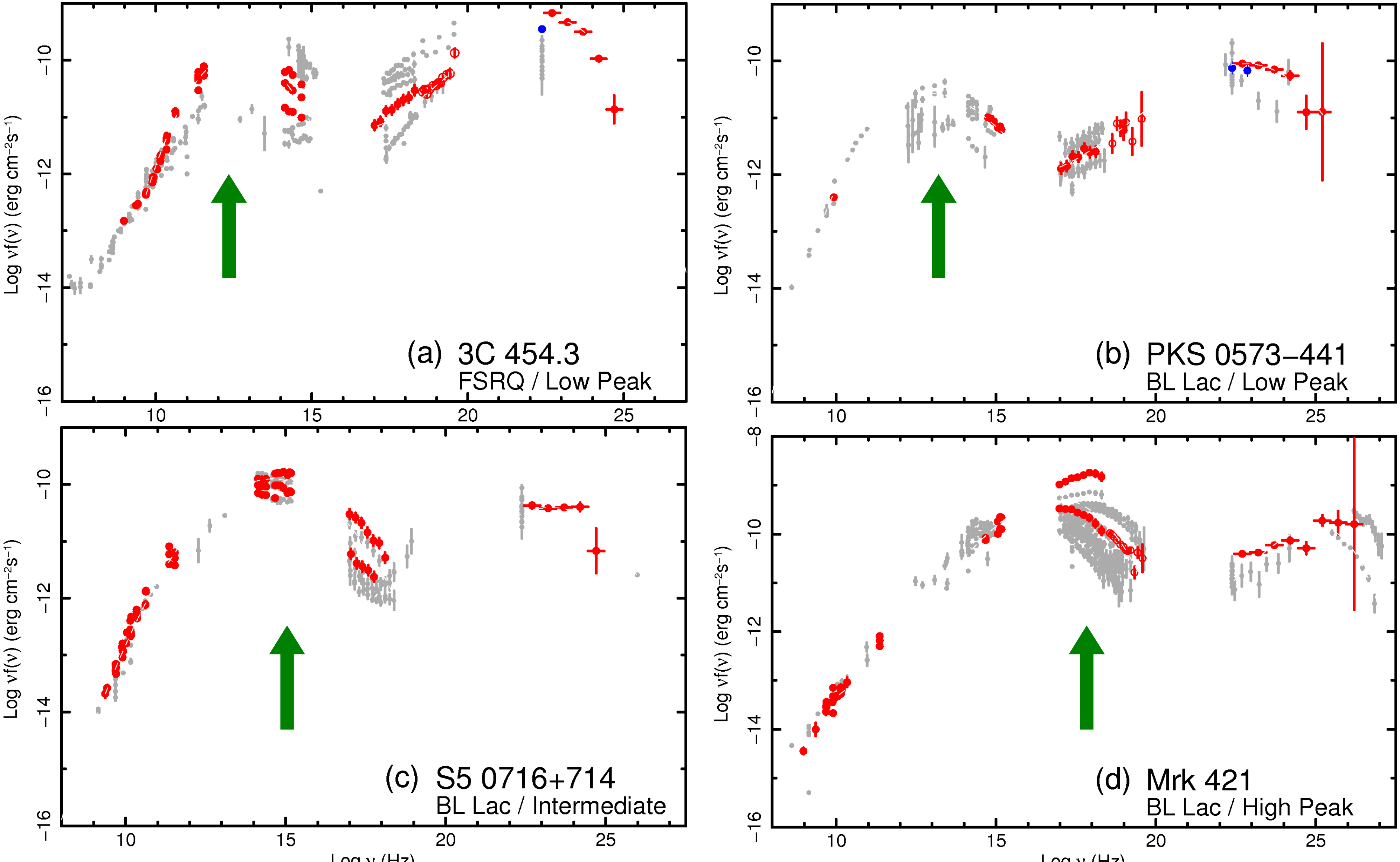
quasar-like emission line spectrum

↓

Flat Spectrum Radio Quasars (FSRQ)

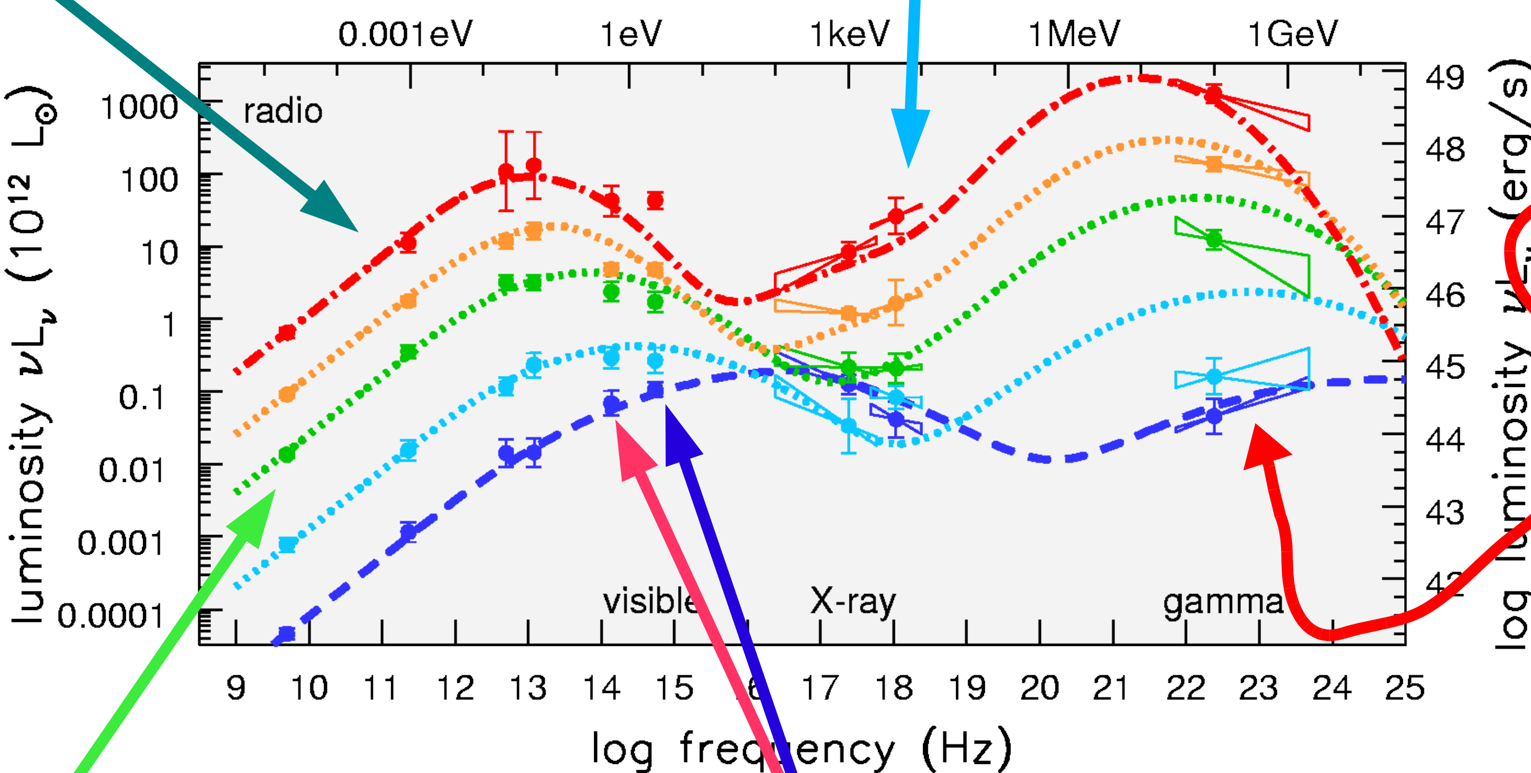
Spectral Energy Distributions (SED)

Phenomenologically blazars are coarsely classified on the basis of their **synchrotron peak position**, into low-peaked and high-peaked objects.



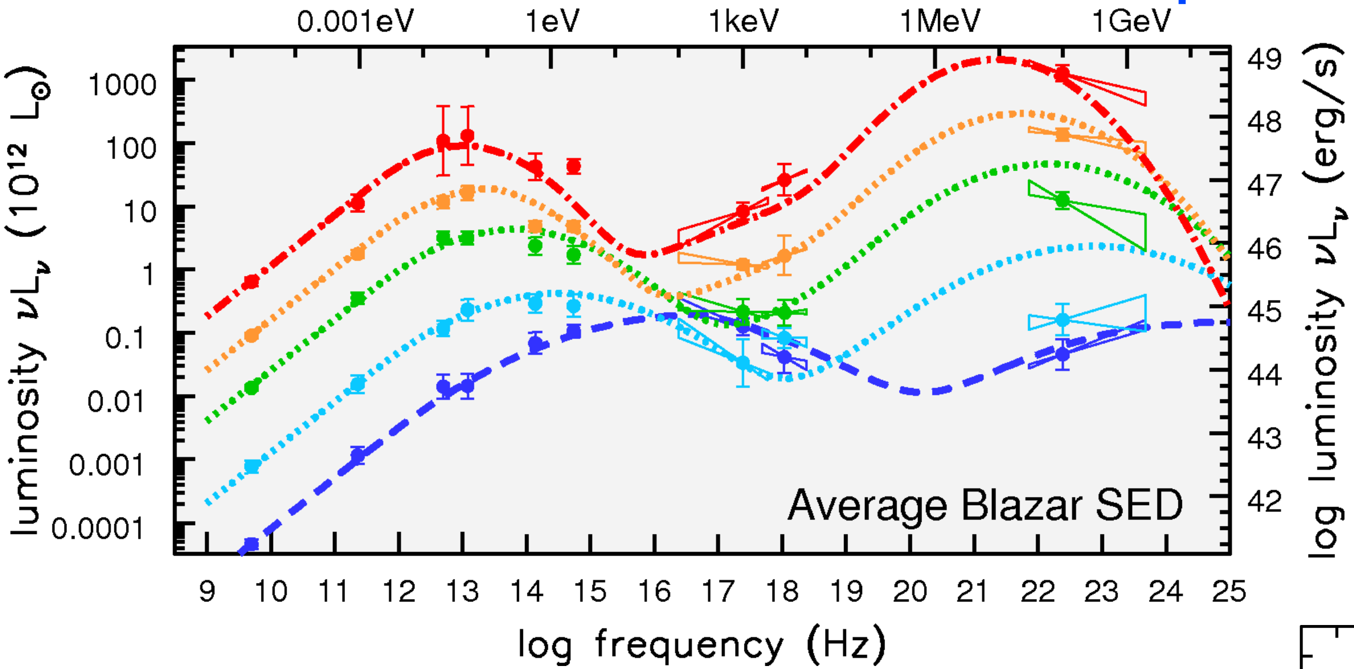
Observations

- **Millimeter**: LMT/GMT, Planck, ALMA
- **X-ray/soft-γ-ray:** Swift , Chandra, Suzaku, XMM
- **Fermi/LAT**

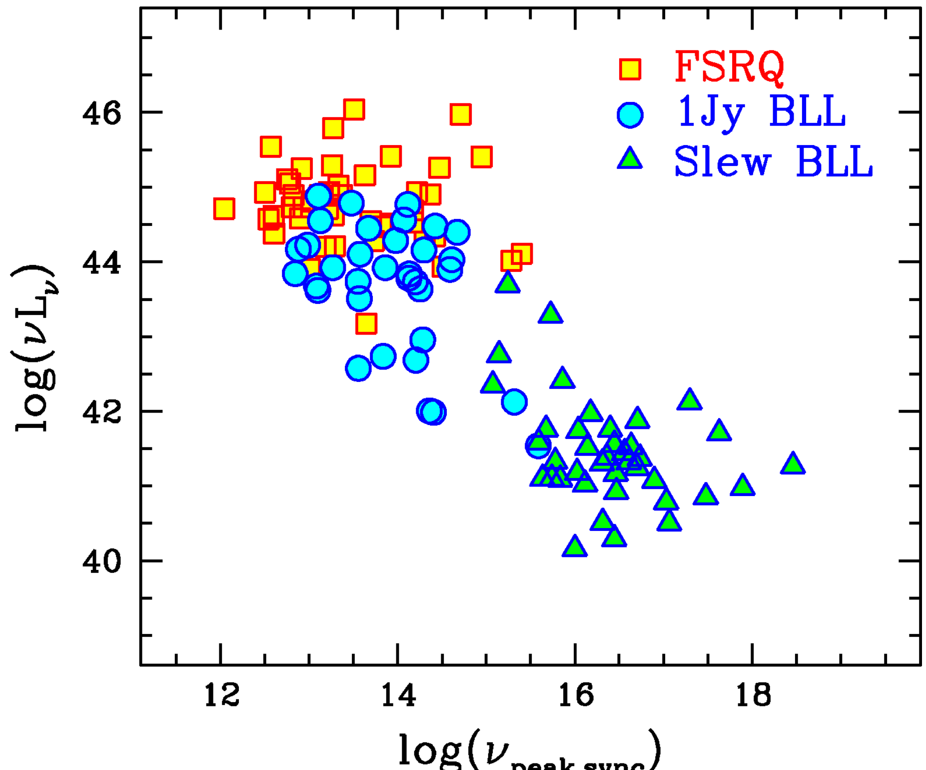


- **RADIO**: FIRST, NVSS, EVLA, +
- **OPTICAL/IR**: spectroscopy. Spitzer. WISE AKARI, ground-based

The blazar sequence



Blazar SEDs averaged in bins of source power (Fossati et al. 1998).



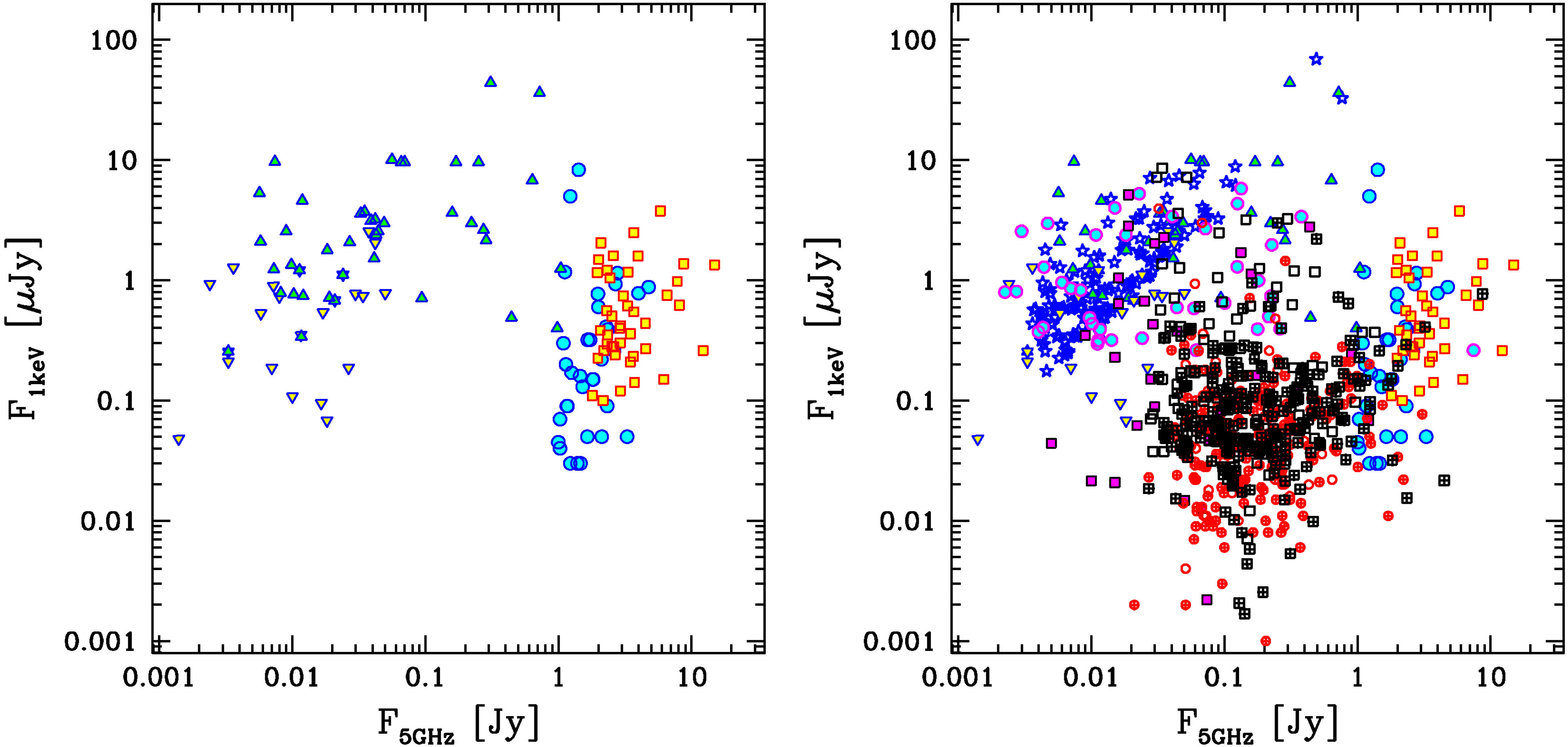
Observational evidence that source power and SED spectral properties are linked forming a sequence of blazar types.

The “thermal” properties also seem to dovetail with this correlation, in particular with the presence of a luminous emission lines and accretion disk limited to the most luminous types.

Blazar “sequences”

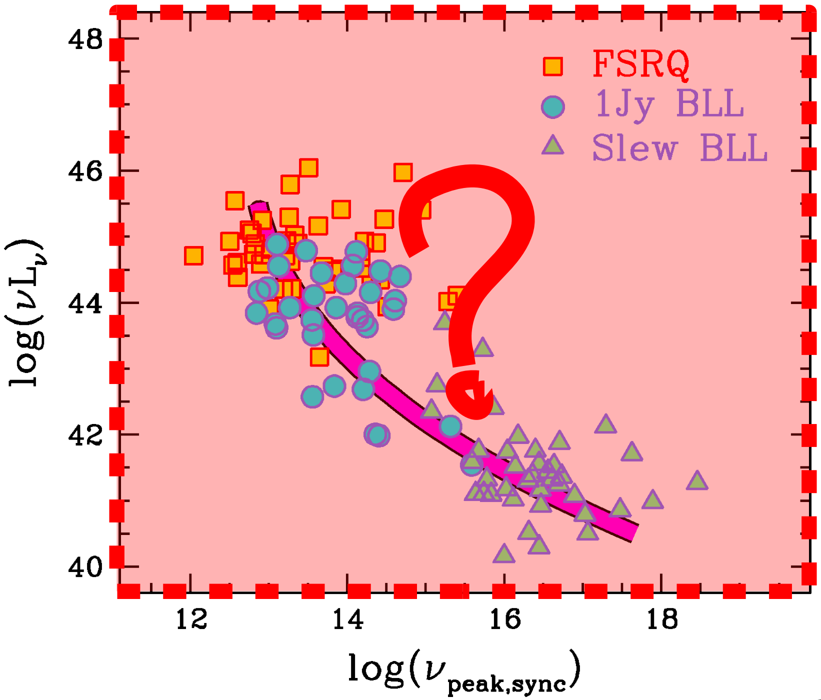
- There are several observational properties which seem to be all tightly connected to each other, possibly through a common correlation with the jet power:
  - Non-thermal jet emission.
  - Optical emission line properties
    (i.e. thermal component associated with accretion).
  - Cosmological evolution.
- Blazar phenomenology *as we see it* seems to be governed by a high degree of internal order.
- There is a strong suggestion that the true dimensionality of the blazars parameter space is reduced to a few (2?) key physical properties.
- The hypothesis of “**blazar sequence**” was introduced.

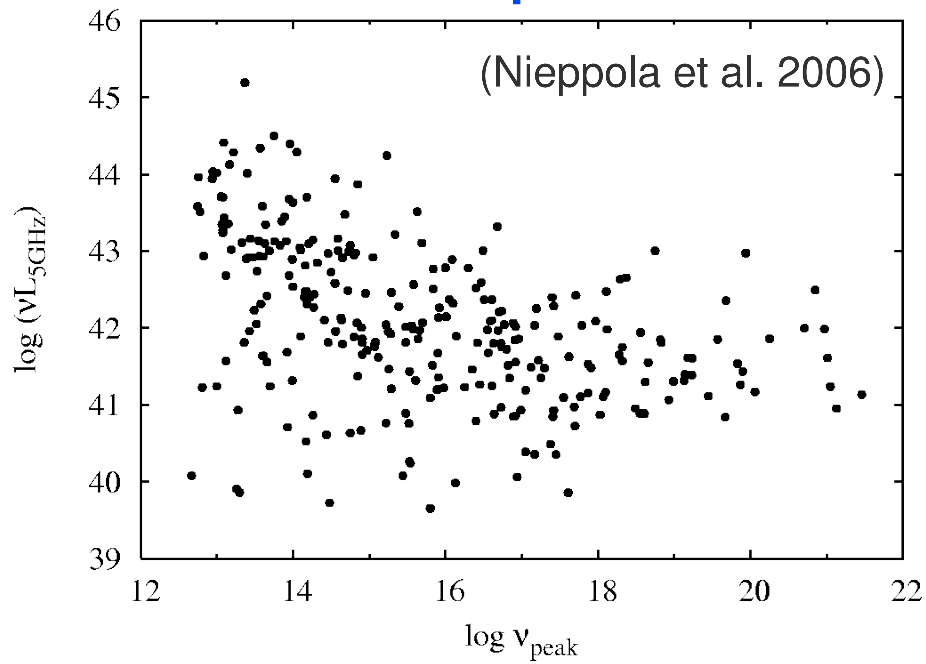
The growth of blazar demographics

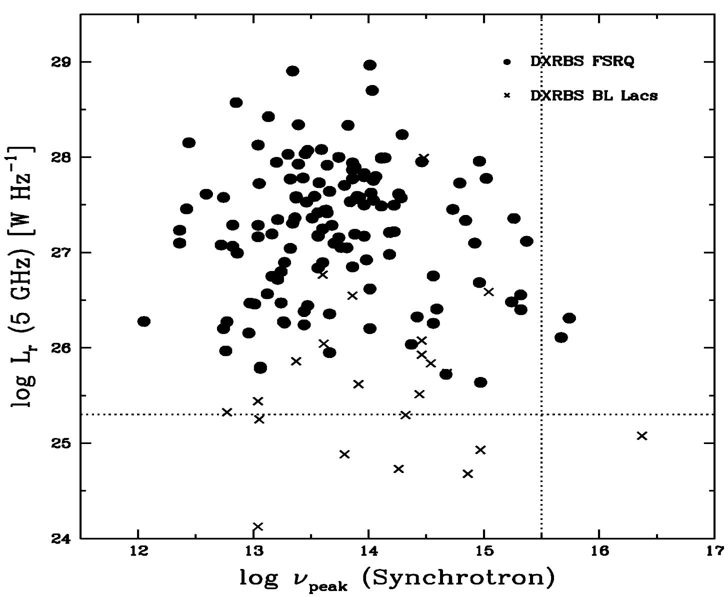


- There are now thousands of blazars and candidates, for hundreds of which the multiwavelength data coverage is sufficient to determine unambiguously their radio to X-ray SEDs.

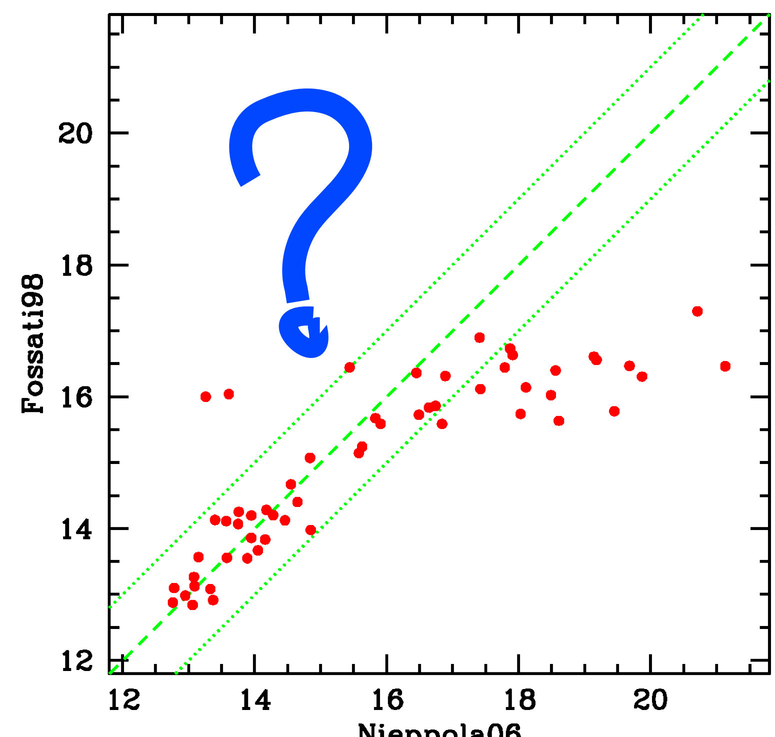
Blazar sequence follow-ups







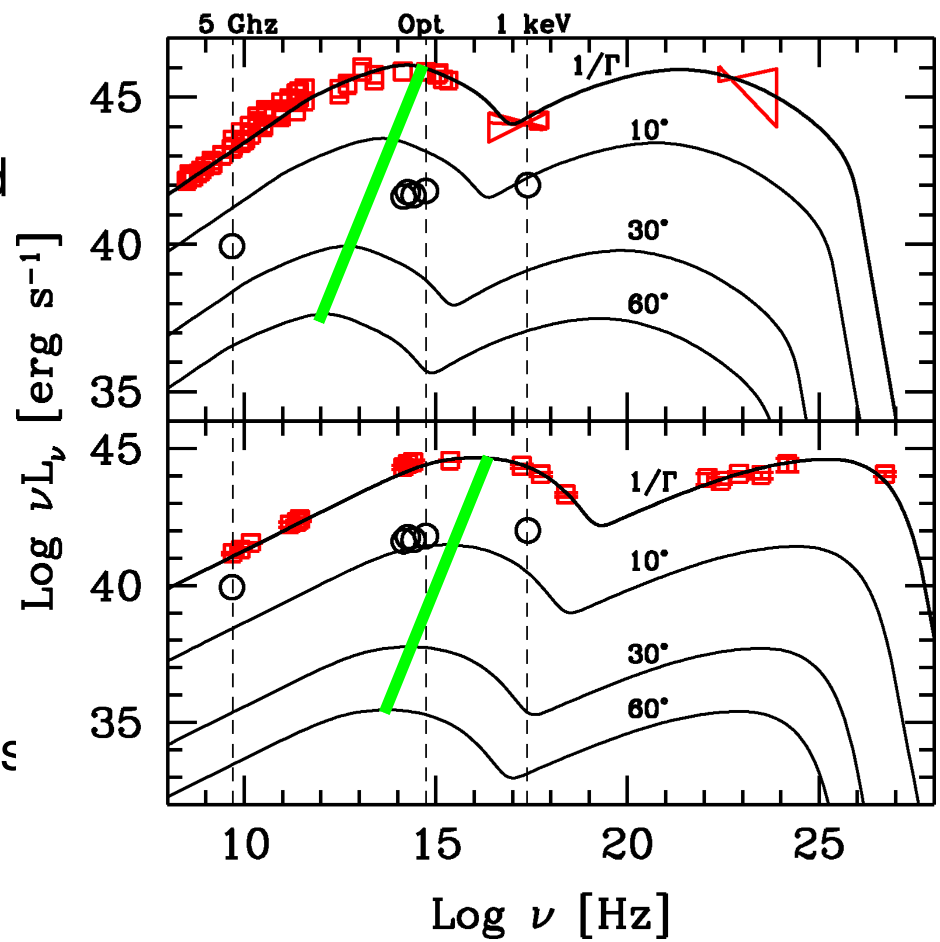
(Padovani et al. 2004)



From blazar sequence to envelope

Even in the simplest scenario of intrinsic jet properties being governed by just one fundamental parameter, e.g. jet power, and all jets had the same Lorentz factor, observationally at some point we should be seeing the spread produced by the varying beaming / viewing angle.

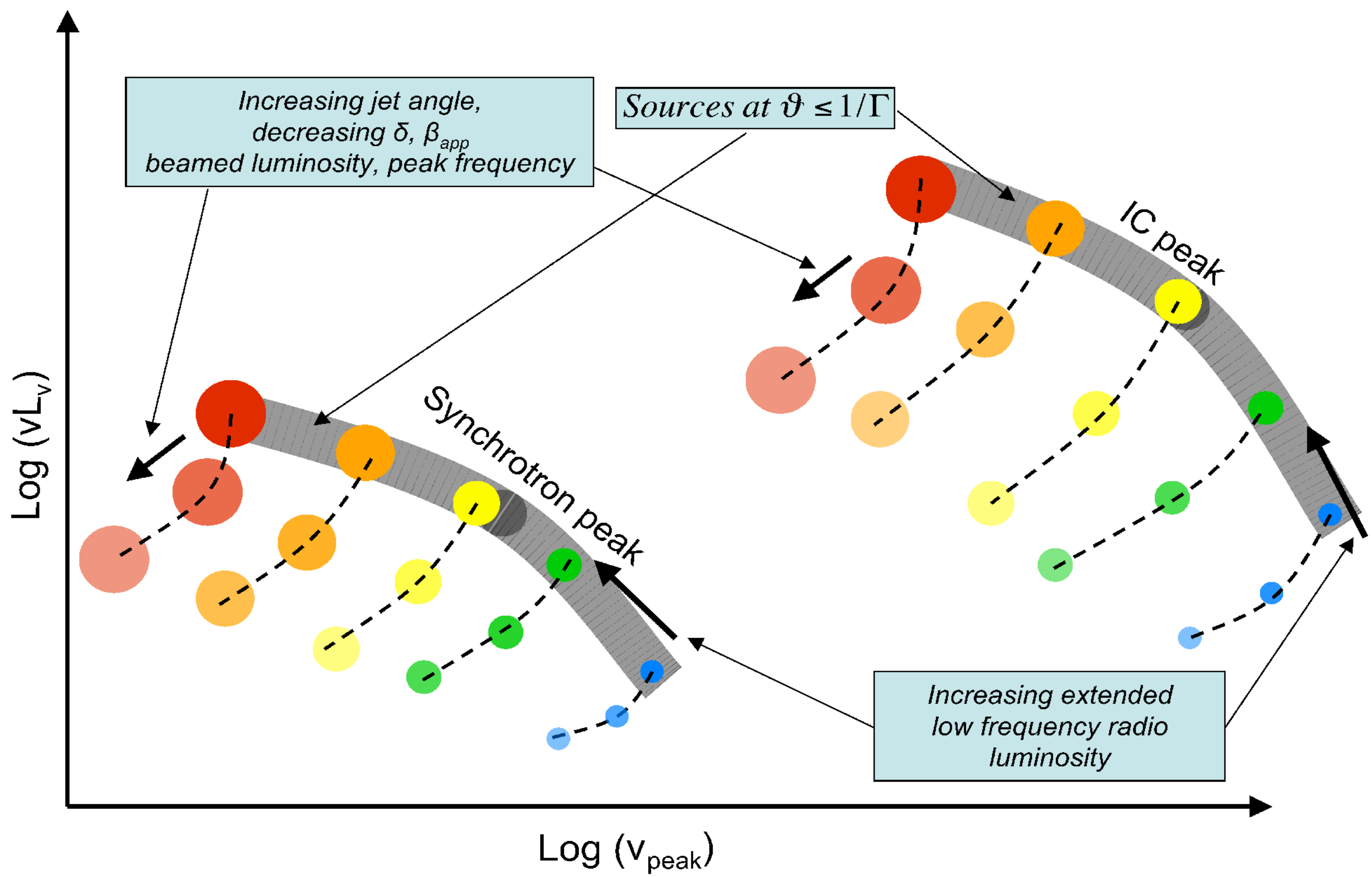
- If we could see a given source from a different direction, its luminosity would appear lower and the SED peaks would be shifted to lower frequencies.
- These would be found in the *sequence space* below the “starting point”.
- If what we had been seeing were the most highly beamed sources, preferentially selected because of limited sensitivity, more sensitive surveys should progressively detect less beamed objects.



[Chiaberge+ 2000]

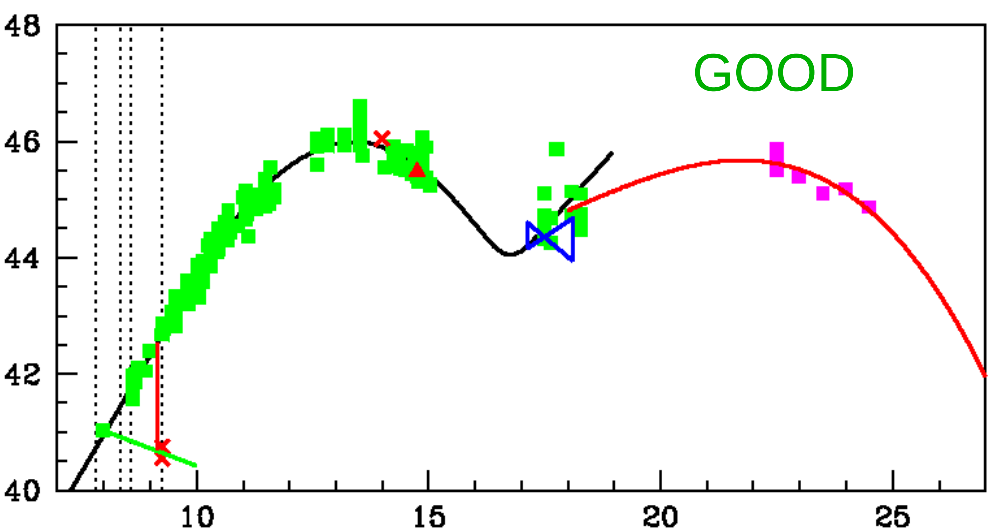
The extended observational hypothesis

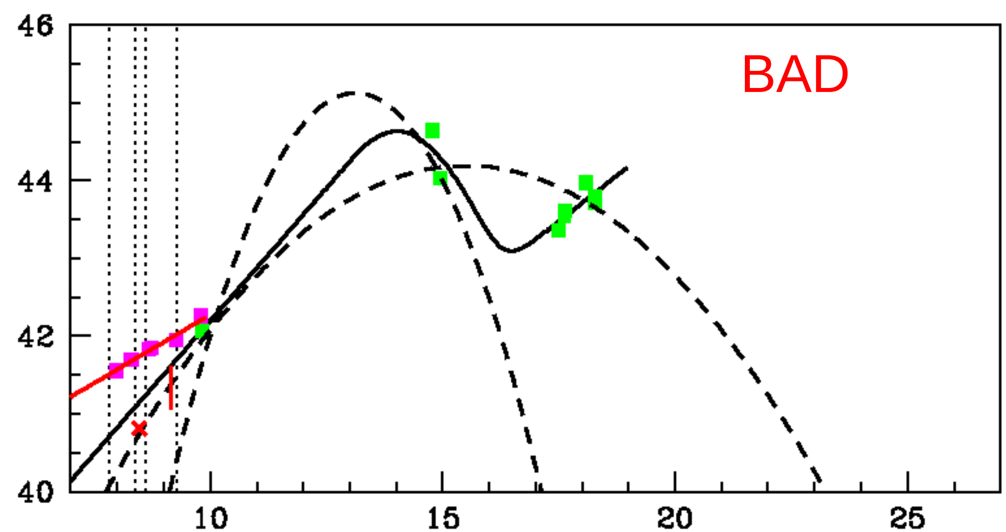
1. Intrinsic jet power determines the position of a “jet” along the *aligned blazar sequence,* i.e. its SED (radiative) luminosity and synchrotron peak position.
2. Misaligned blazars would fill the space below it, along tracks of changing viewing angle. Unfortunately we can not measure this latter directly.
3. The slope and possibly the shape of the tracks are sensitive to some aspects of jet dynamics and structure.



Unveiling the envelope: SED characterization

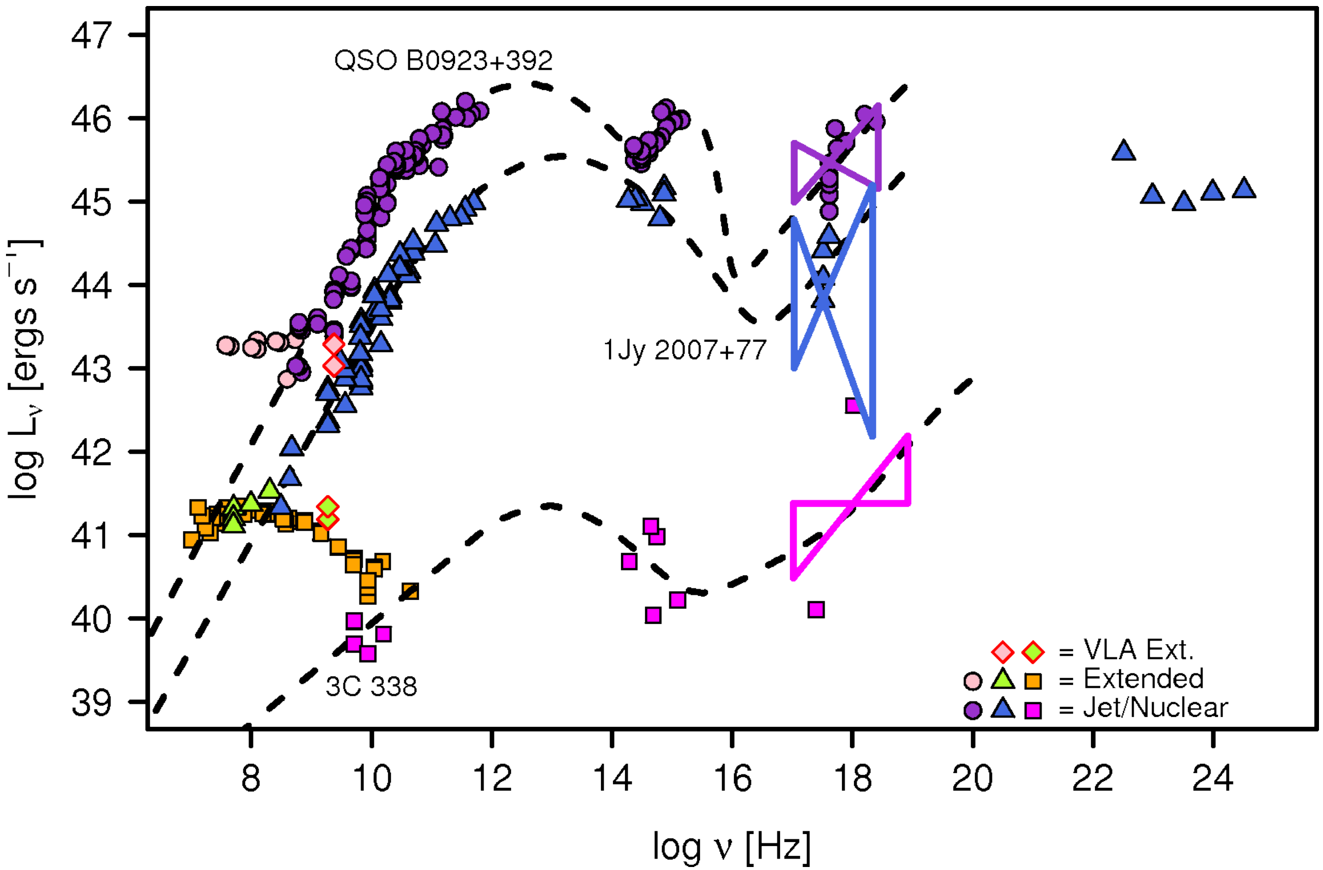
- We need to expand the sample and improve our ability to determine the basic SED parameters, peak frequency and luminosity of the two main non-thermal continuum emission components.
  - Unprecedented data mining effort to collected and organize the most comprehensive multiwavelength observations database.
  - Of about 3000+ *candidates* comprising all sources from every flux-limited sample of radio-loud AGN (blazars and radio-galaxies), 1700 with sufficient radio to X-ray data coverage.
  - Direct fitting of the synchrotron SED.
  - For about 700 of these we obtain a satisfactory SED fit, yielding reliable ν_{peak} and L_{peak}.





Unveiling the envelope: intrinsic jet power by proxy

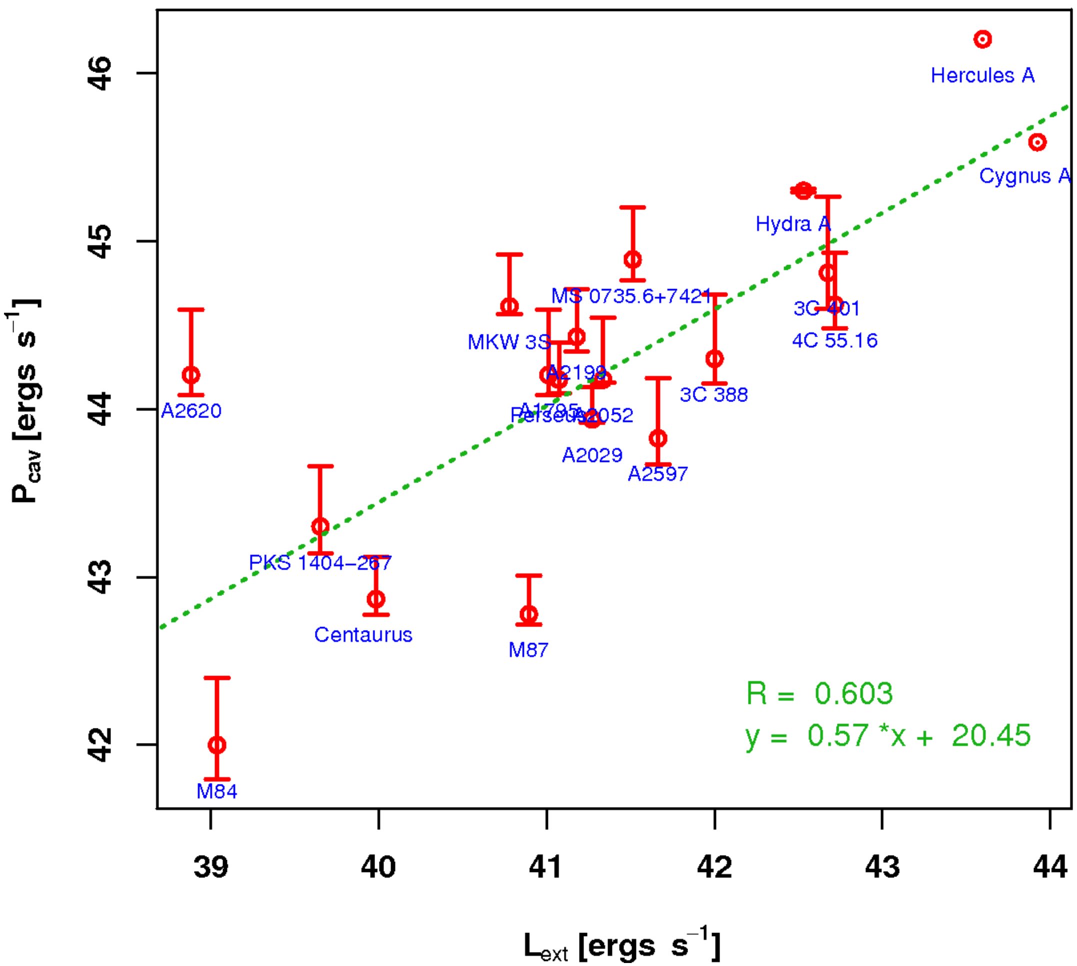
- We need a measure of the **intrinsic** jet power, non altered by the effects of relativistic beaming. The best consensus estimator is the luminosity of the extended radio emission:
  - It is assumed to be emitted isotropically.
  - It represents a long term average of the jet power.
  - It is not variable.



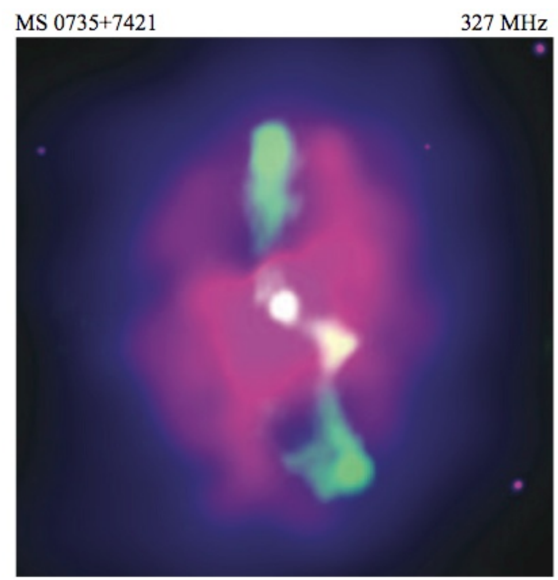
- It typically dominates the spectrum at low frequencies (below the GHz range) because of its different –steep- spectral shape.
  - We combined spectral decomposition to recognize the steep component and
  - imaging radio data allowing a direct estimate of the spatially extended flux.

Extended luminosity and intrinsic jet power

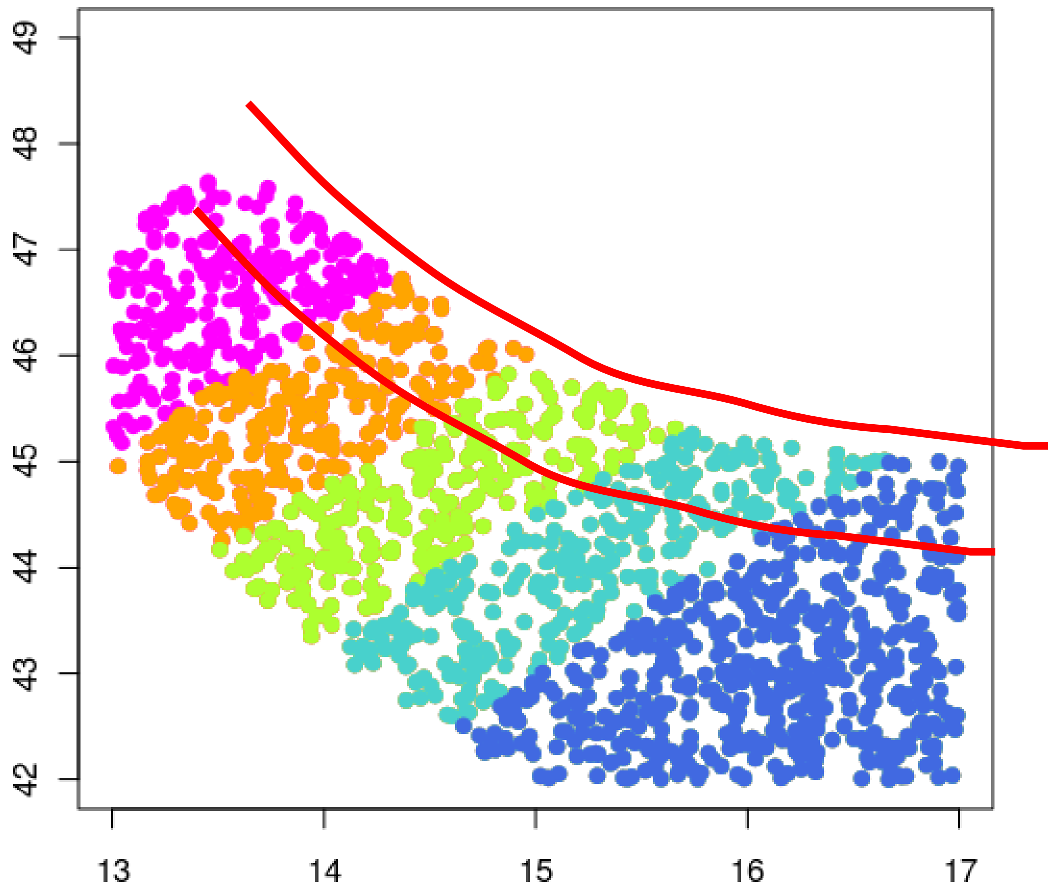
Cavity Power versus Extended Luminosity at 300 MHz for 20 sources in McNamara et al. 2009

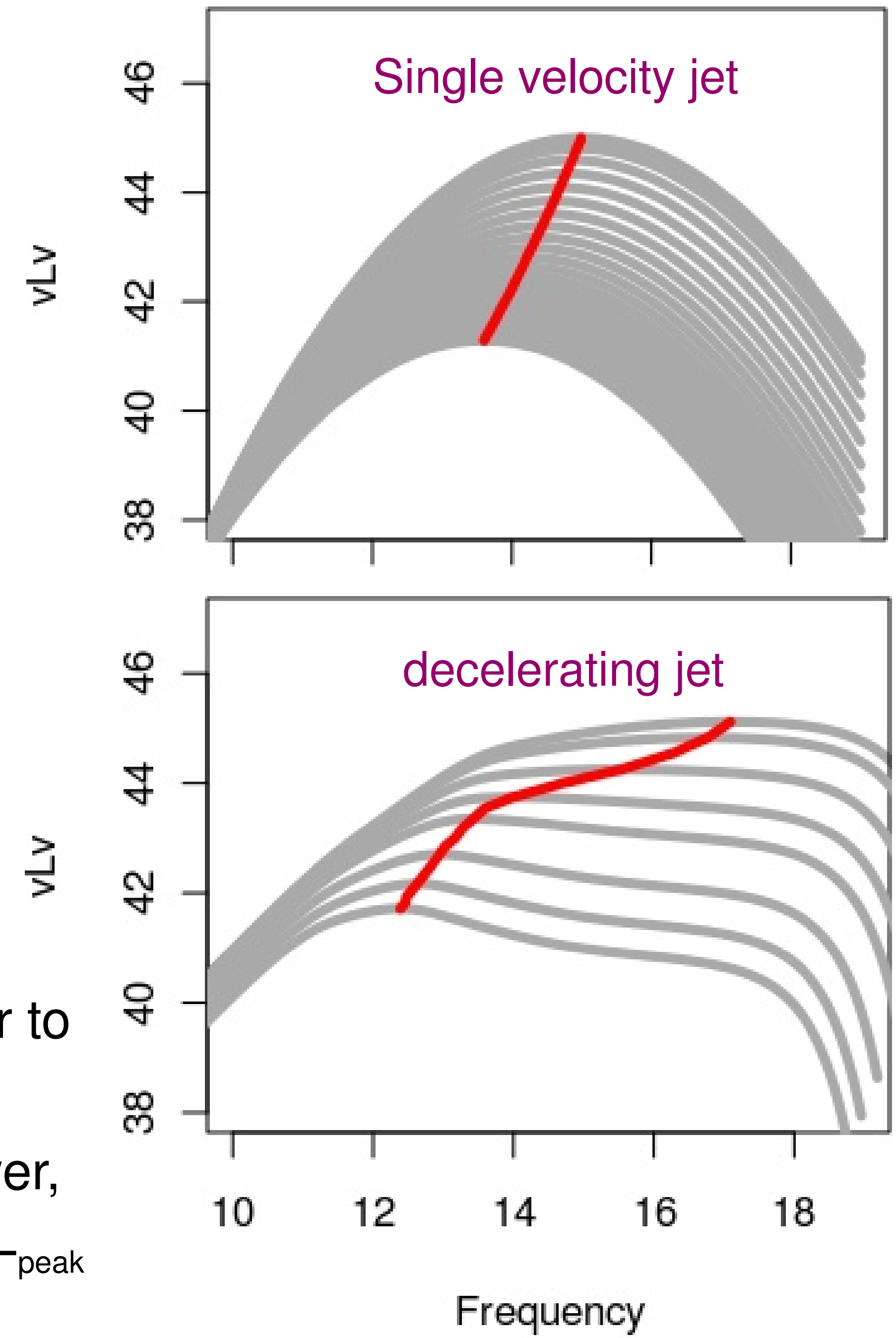


- For a sample of radio-galaxies found in clusters of galaxies the intrinsic jet power can be estimated by the study of the cavities that their jets inflated in the intracluster medium.
- This accurate and physically well defined measure of jet power correlates well with our best estimate of the extended radio luminosity.



The naïve expectation

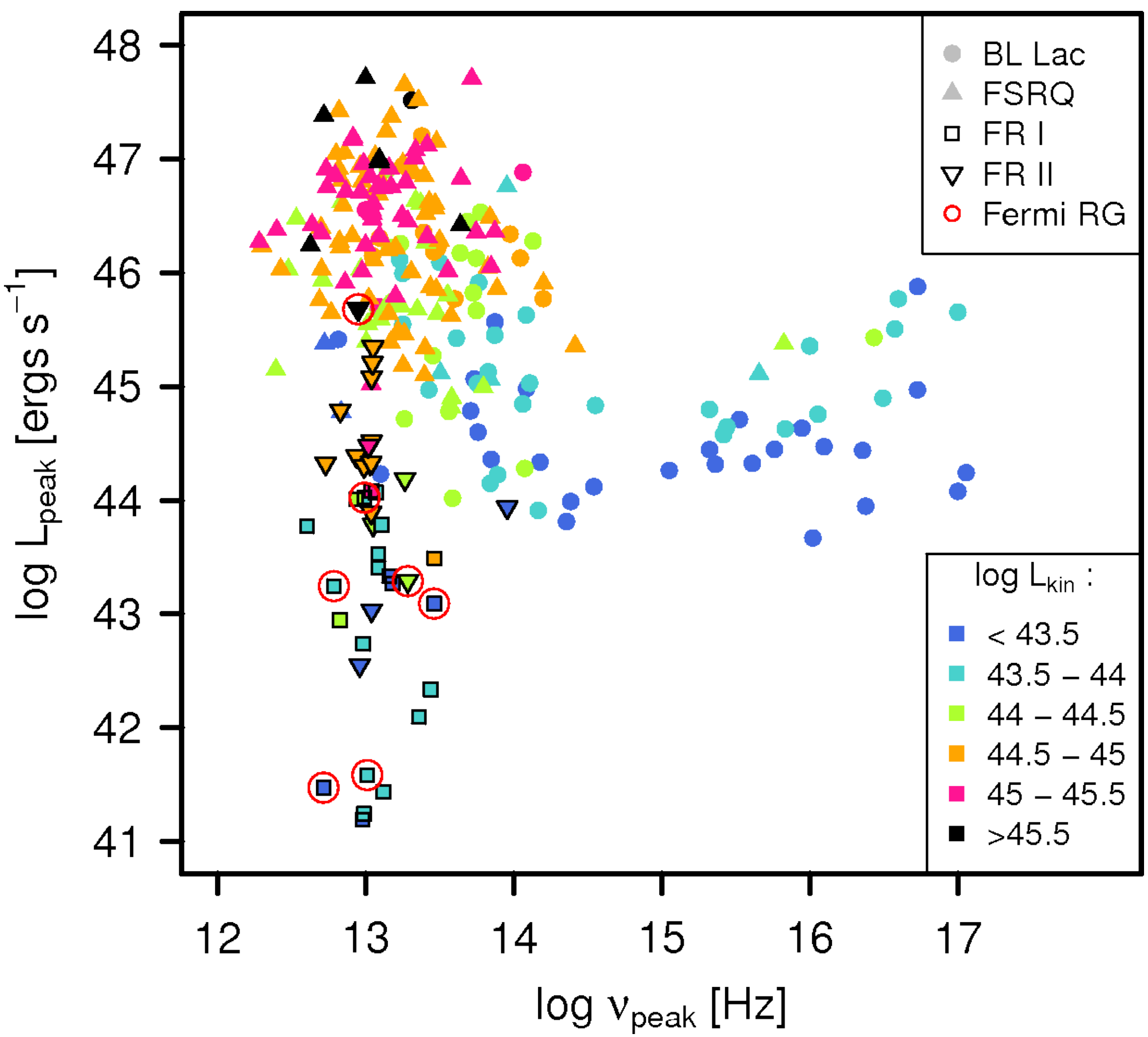




- Objects will fill the space below the “original equence” that was traced by the object easier to detect, i.e. most beamed ones.
- Swaths of source with similar intrinsic jet power, occupying different positions in the ν_{peak} and L_{peak} space depending on the viewing angle.

The *blazar envelope* space

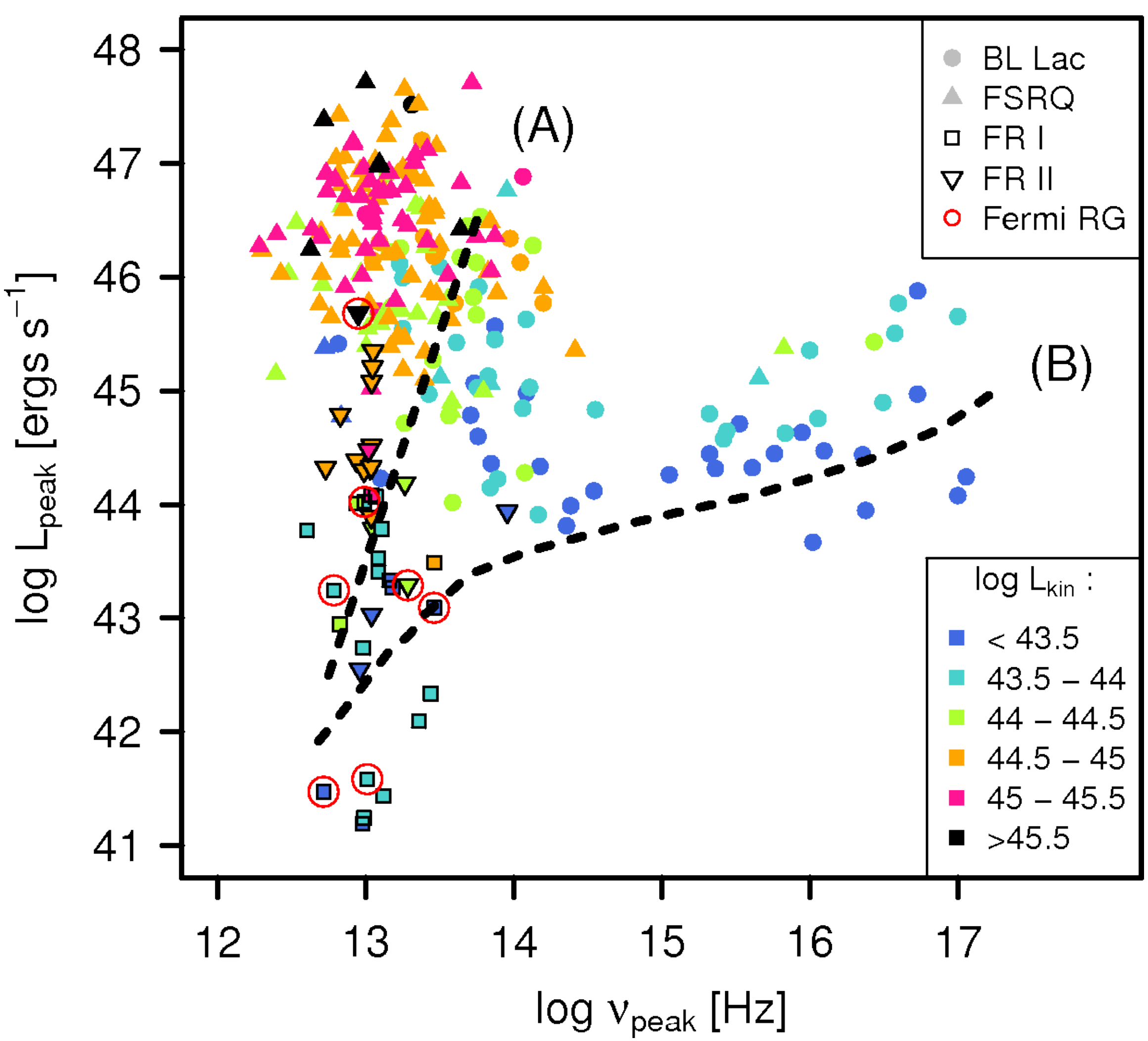
- Synchrotron SED peak frequency and power.
- Color coding on intrinsic jet power (3rd dimension).



- No strong indication of tracks, nor *striping!*
- Wide range of SED peak position below some value of jet power!
- Radio-galaxies cluster at low ν_{peak}.
- BL Lac (circles) are the only type of source with high ν_{peak}, but they also exist at low ν_{peak}.
- All FSRQ (triangles) are in a narrow range at low ν_{peak}.
- Lack of objects with intermediate SED properties.

Jet structure dichotomy?

- The source distribution and absence of the expected "patterns" may hint at a dichotomy of jet properties, perhaps related to intrinsic jet power.

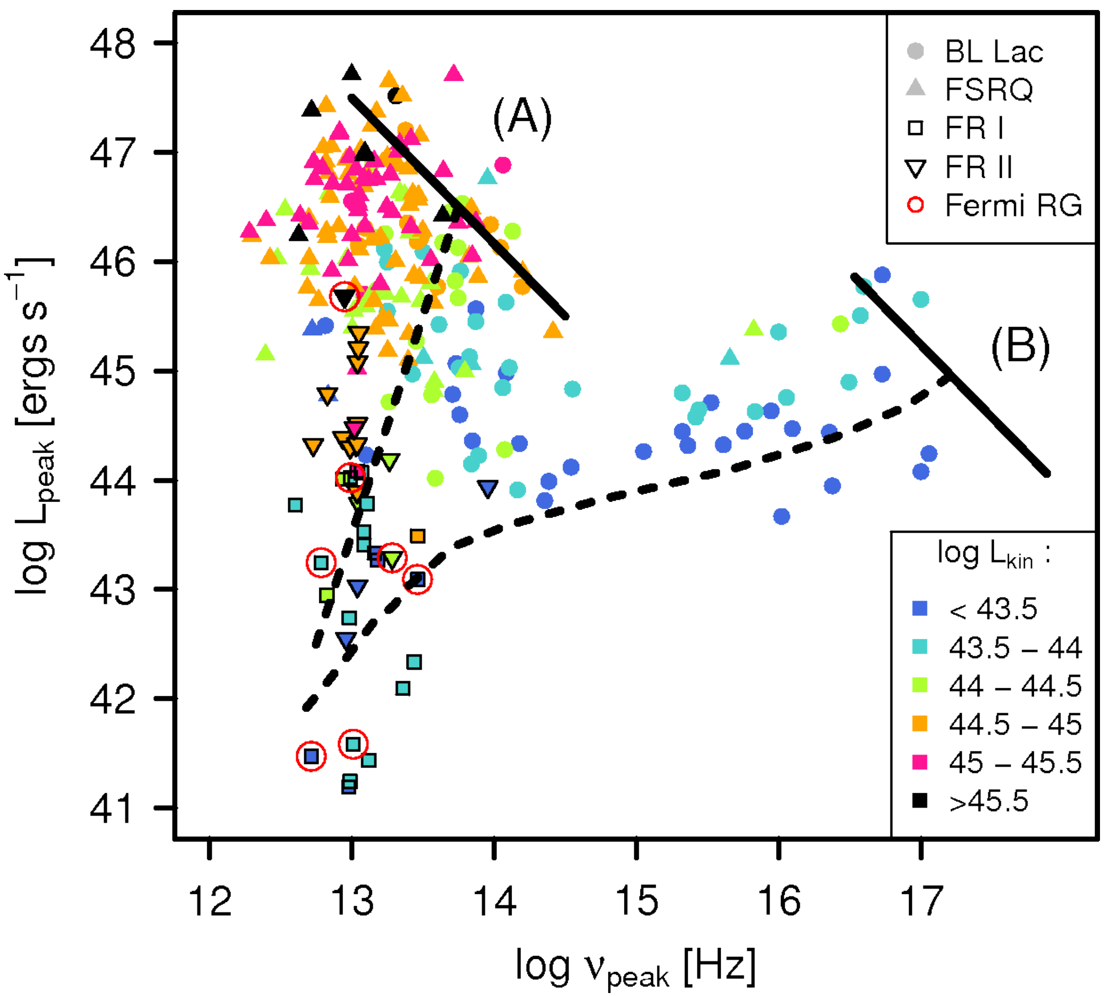


- Black tracks correspond to the predictions of the *mis-alignment tracks* for:
  - (A) a single speed jet.
  - (B) a decelerating jet.
- In a decelerating jet we observe emission from regions affected by different degrees of beaming.

  The drop due to (de)beaming is tempered by the fact that the emission from slower regions doesn't have a strong dependence on viewing angle.

Strong and *weak* jets conjecture.

- Radio-loud AGNs might come in two different flavors.
- The approximate correspondence between jet *strength* and optical spectral classification may suggest that the jet type depends on the accretion properties, commonly characterized in terms of Eddington-scaled mass accretion rate, $\dot{m}_{disk}$.

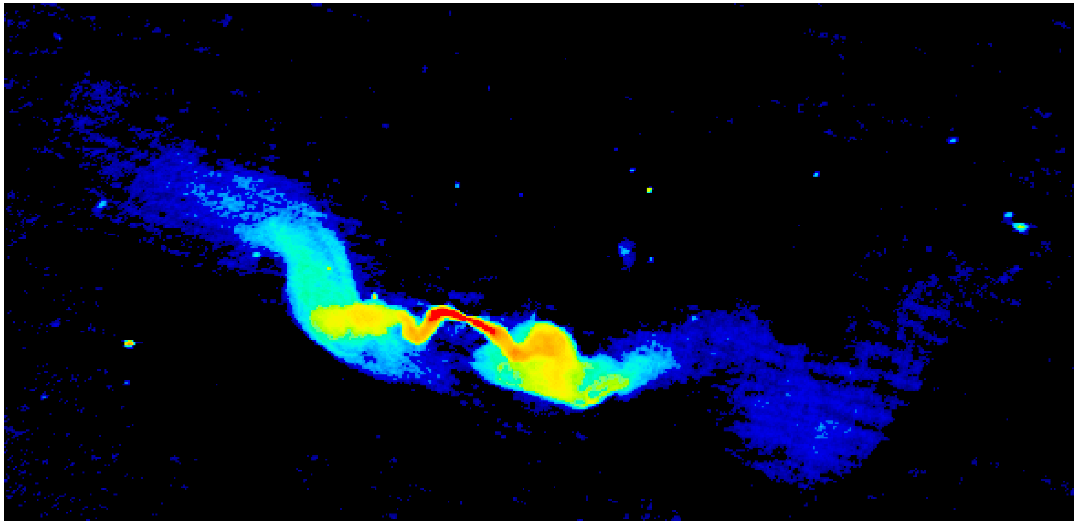


- Black tracks correspond to the predictions of the *mis-alignment tracks,* as shown previously, with the addition of the possibility that within each jet type there remains a sequence/correlation between SED luminosity and peak frequency.

Jets in radio galaxies – Fanaroff-Riley classes

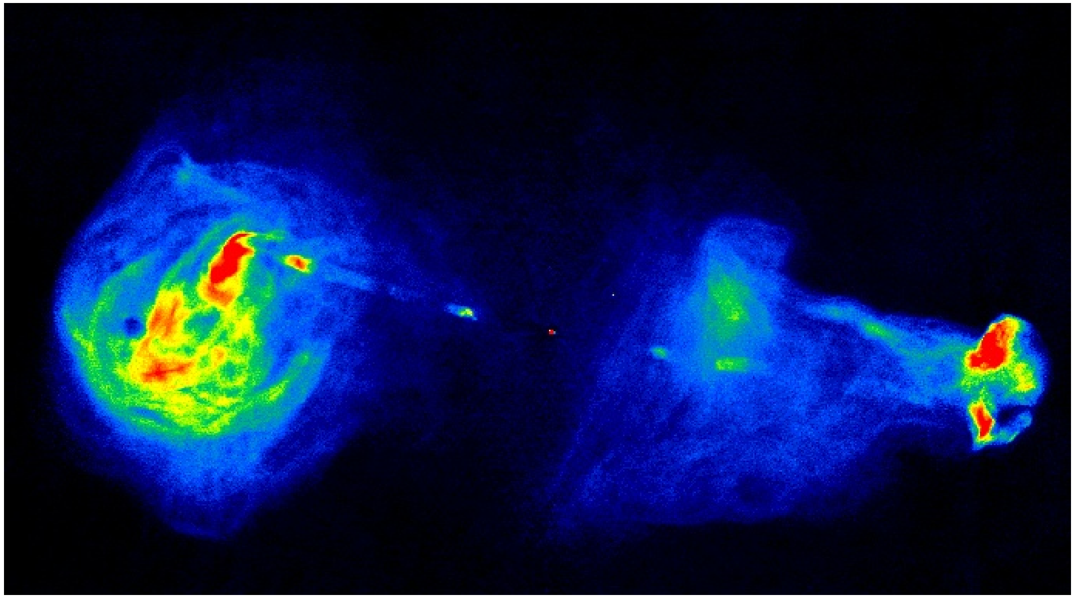
There is significant evidence supporting the idea that jet power correlates with several AGN properties, starting with morphology of the jets at large scales.

FR1 – low power

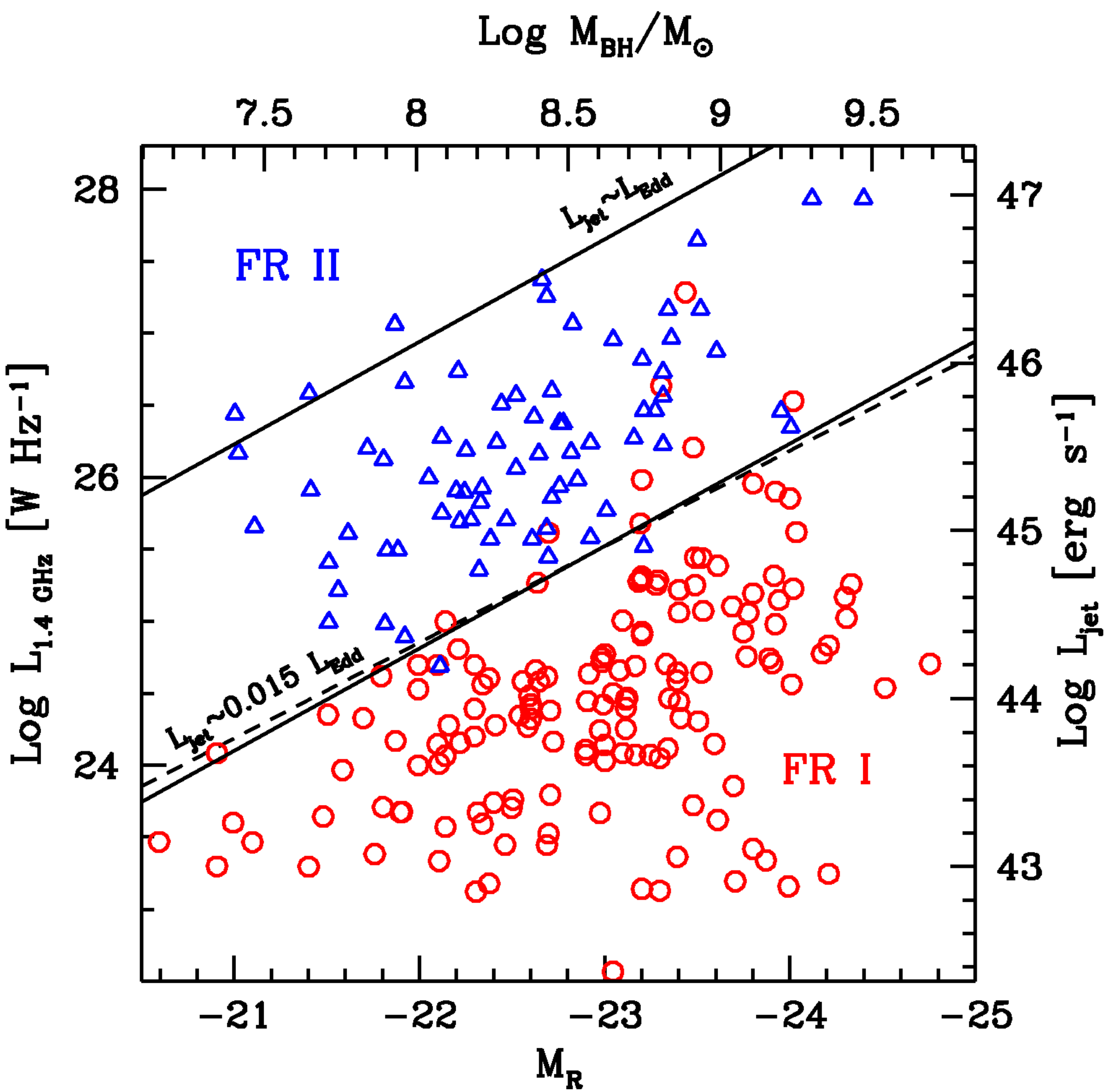


Morphological Classification, matching a division in radio power.

FR2 – high power



FR1/FR2 division

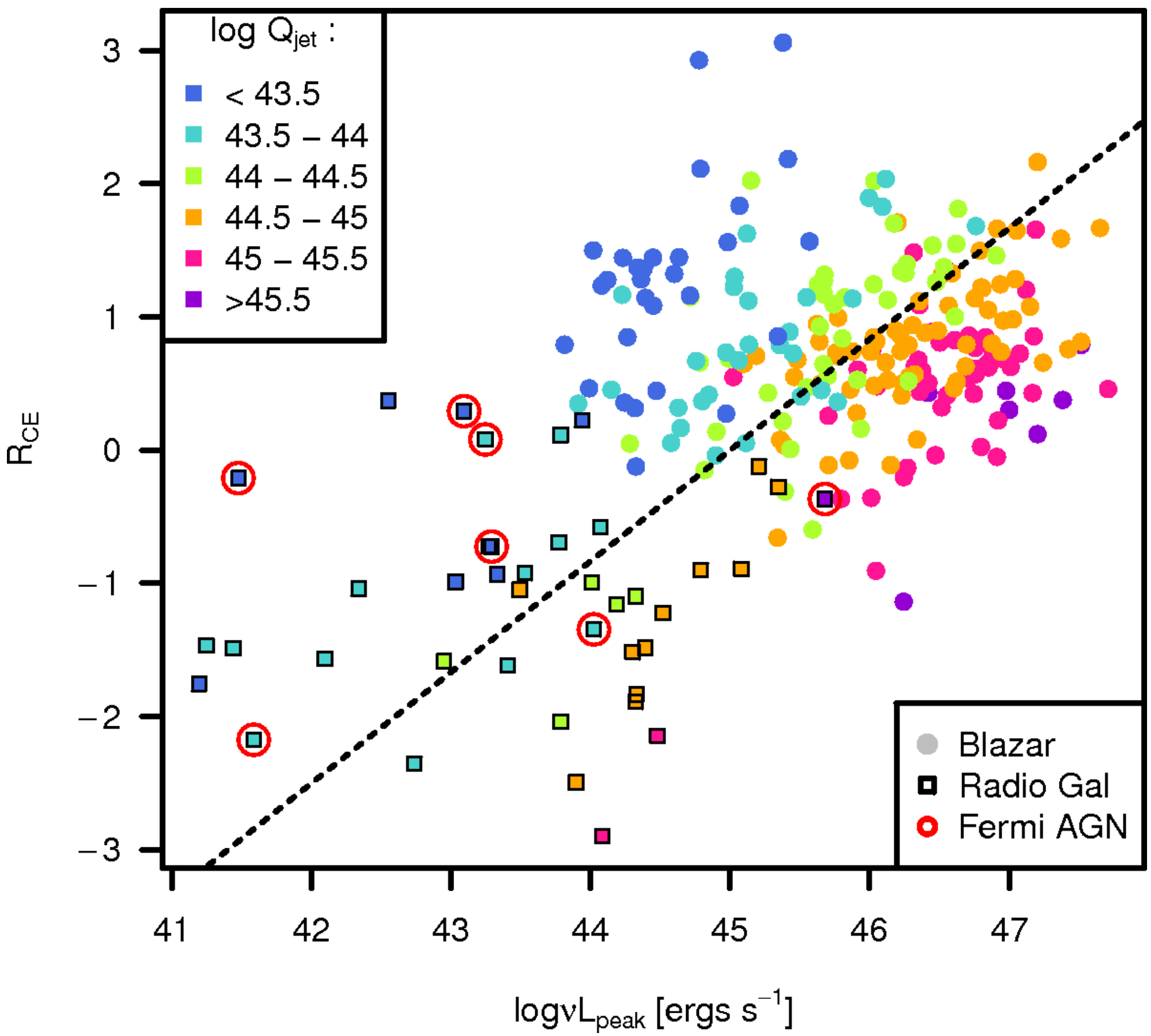


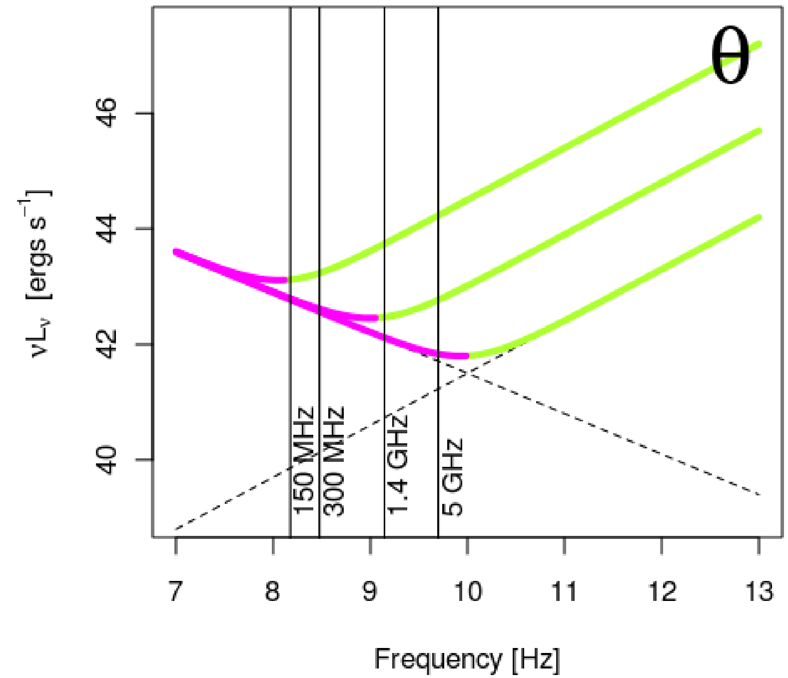
FR classes are clearly divided in the radio luminosity – stellar luminosity plane

[Ledlow & Owen 1996]
[Ghisellini & Celotti 2001]

Core Dominance

- Core Dominance, R, the ratio of the beamed (core) flux to the extended flux, is an estimator of the jet alignment, if jets have similar Lorentz factors.

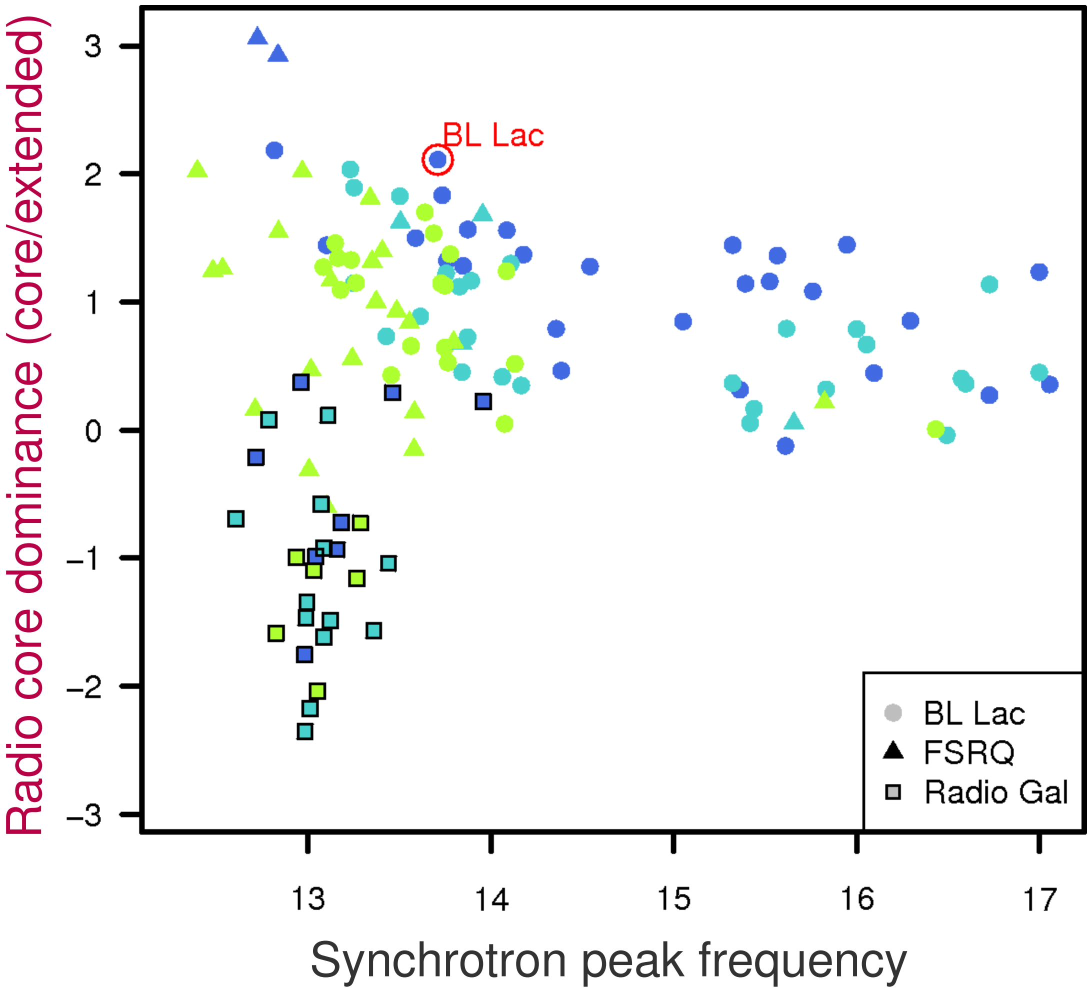




- Peak luminosity shows a dependence on R at all jet powers, suggesting that indeed within each group of jet power the peak radiative *observed* luminosity changes with viewing angle.
- The *envelope* is the result of beaming.

The puzzle of low jet-power sources

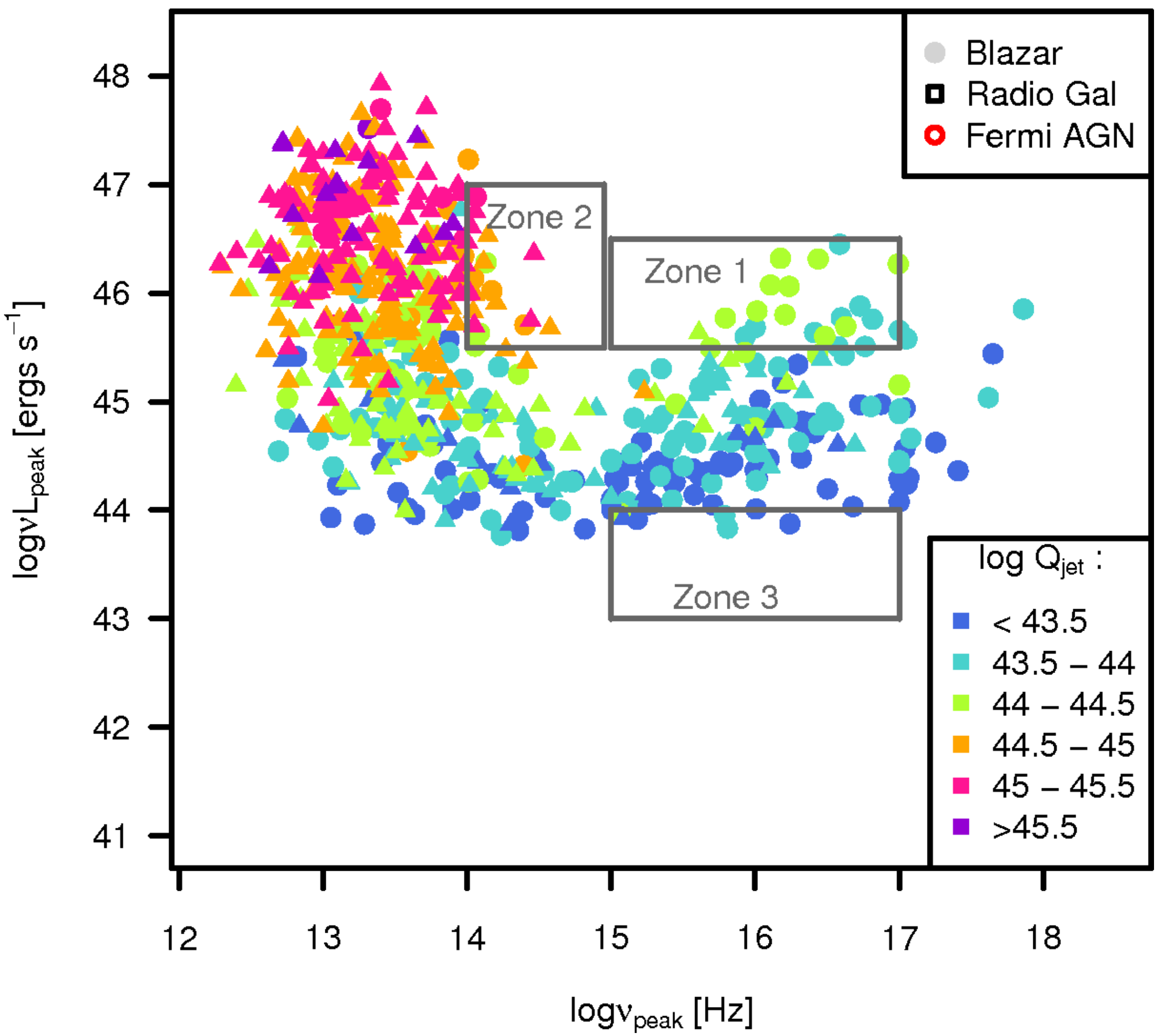
- For jet powers below 10^{44} erg/s the picture is mixed.
- What is the nature of the low power jets?



- We find objects with high core dominance both at high and low peak frequencies.
- This lends support to the possibility of a dichotomy in jet properties, BUT it does not play in favor of jet-power as the main parameter.
- The hypothesized low – intermediate – high peak frequency sequence as a function of intrinsic jet power may be broken, split.
- Are intermediate peak SED types rare because they can only exist as misaligned high-peak objects?

Blazar envelope with upper limits

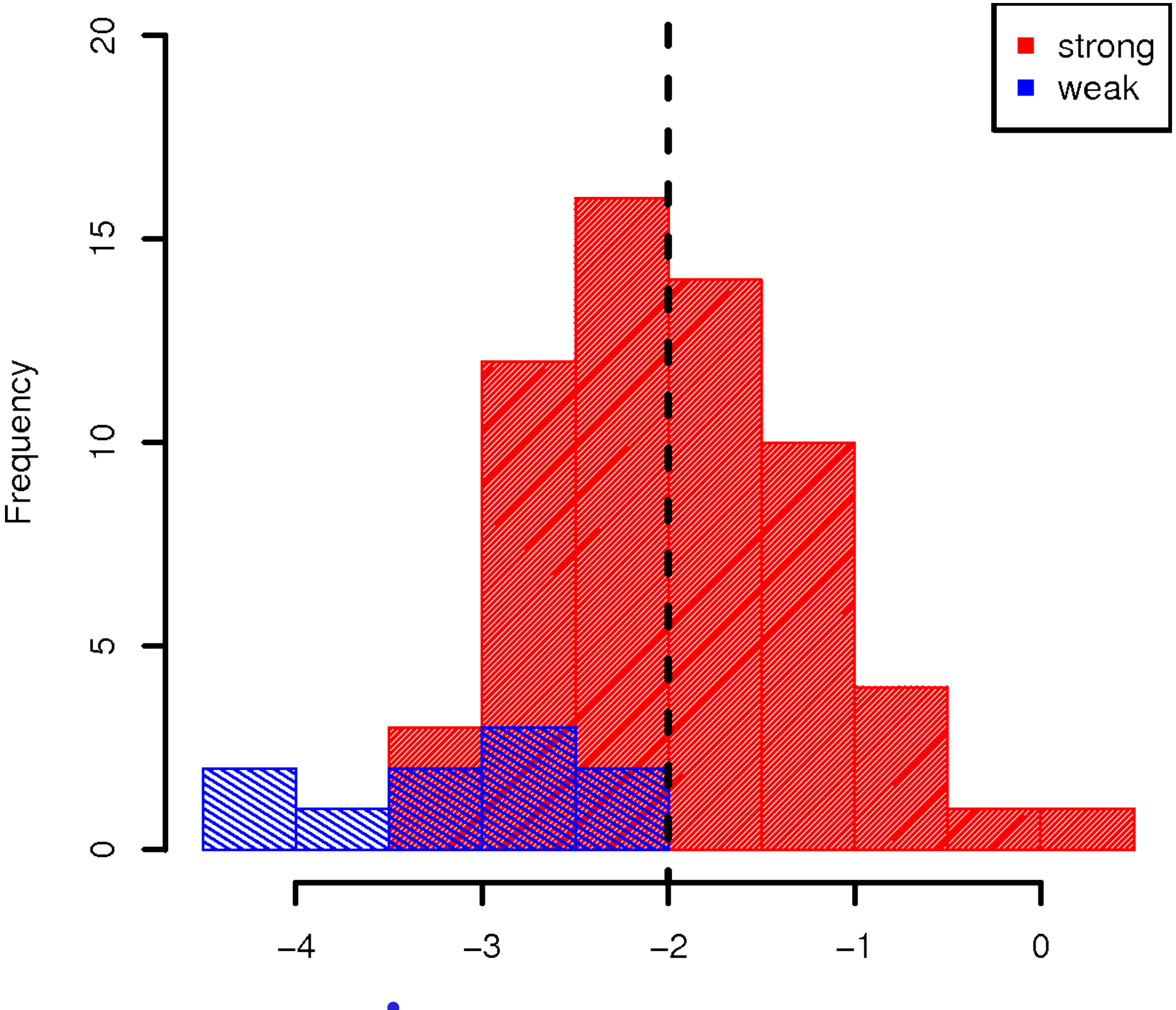
- There are several hundred more sources for which we still lack some data (spectral or imaging) to estimate their intrinsic jet power, but for which the synchrotron SED can be reliably characterized.



- There are no obvious "violations" of the previous findings.
  - Low jet power objects keep the exclusive of high frequency synchrotron peak.
  - The L-shape remains, as well as the hint that intermediate SED objects are not common.
  - We have tested the detectability of objects in the grey boxes: current observations are sensitive enough that the lack or scarcity of objects is significant.

Jet type and L_{kin}/L_{Edd} ($\dot{m}$)

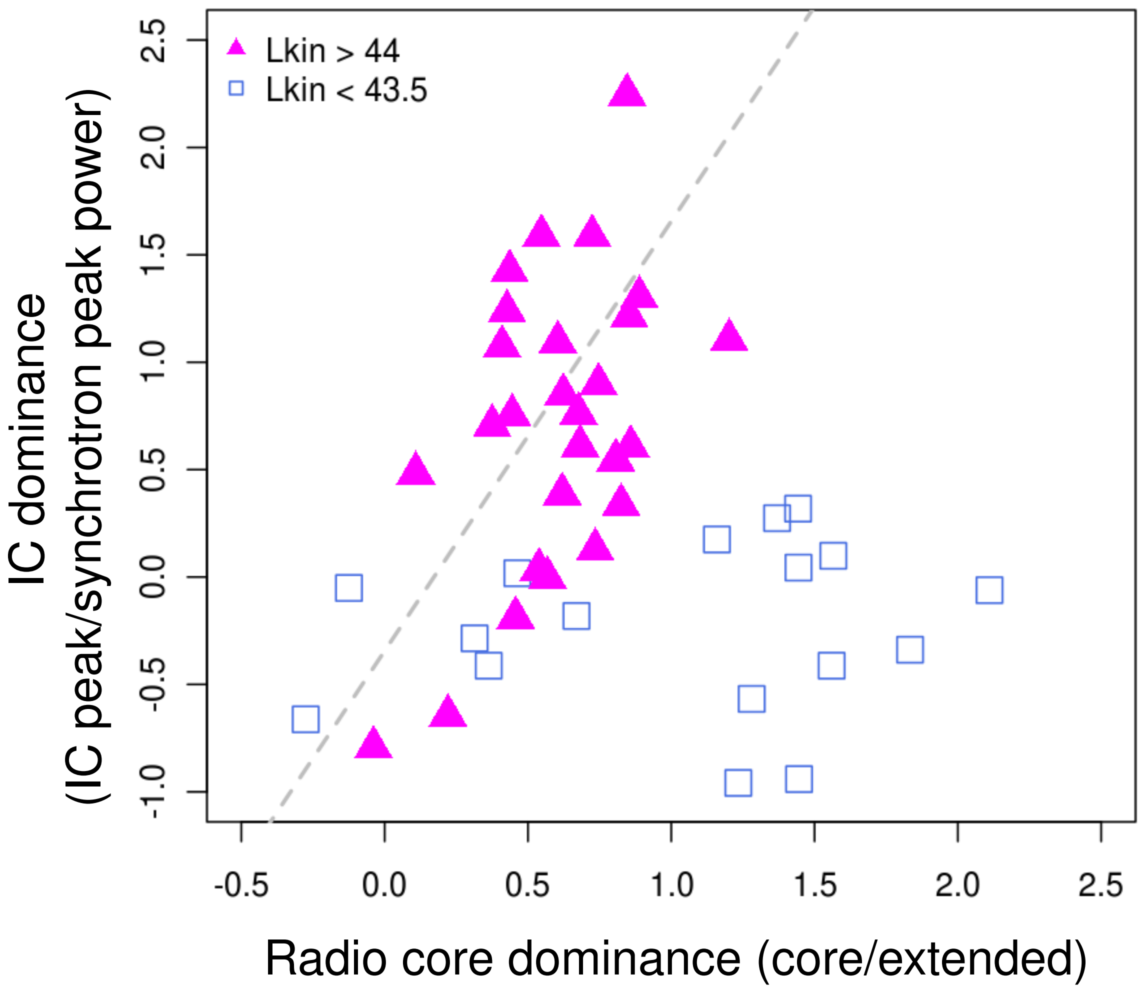
- In red: objects belonging to the strong jet branch, all FSRQs, i.e. sources where we expect high $\dot{m}_{disk}$, based on their *thermal* emission properties.
- In blue: objects from the weak jet branch, all BL Lacs, i.e. sources that we would associate with low $\dot{m}_{disk}$.



- Weak-jet objects seem to be limited to values of $\dot{m}_{jet}$, up to what it has been conjectured to be the critical value for $\dot{m}_{disk}$.
- Strong-jet objects, however don't seem to *obey* this threshold: they can have jets weaker than their accretion power $\dot{m}_{jet} < \dot{m}_{disk}$ (also Fernandes+ 2011).

γ-ray dominance

- The ratio between the peak luminosities of the γ-ray (IC) and synchrotron components behaves differently as a function of radio core dominance for high and low jet power sources.



- Radio core-dominance is sensitive to beaming.
- The trend between these two quantities is sensitive to differences in beaming (if any) between the IC and synchrotron components.
  - SSC and external Compton (EC) origins for the γ-ray emission would yield different trends.

Key points

- SED properties and thermal emission.
  - High-peak sources are almost exclusively BL Lacs (i.e. blazars not showing signs of emission from accretion disk or other non-jet thermal source.)
  - Low-peak sources encompass the full range of thermal emission properties.
- Intrinsic jet power:
  - It does not show the simple relationship with SED properties that would be expected if the traditional blazar sequence hypothesis was correct.
  - There seems to be a dichotomy in jet properties, possibly associated with simple vs. complex jet (velocity) structures.
  - However, this apparent dichotomy does not match well with jet power being the sole fundamental parameter.
    Black hole spin and accretion rate are obvious candidates.
- The accretion power may only set an upper limit on the jet power
- Intermediate-peak sources are not common and they may not exist intrinsically, but just results from debeaming.
  - They may be a key diagnostic population..

Thank you

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