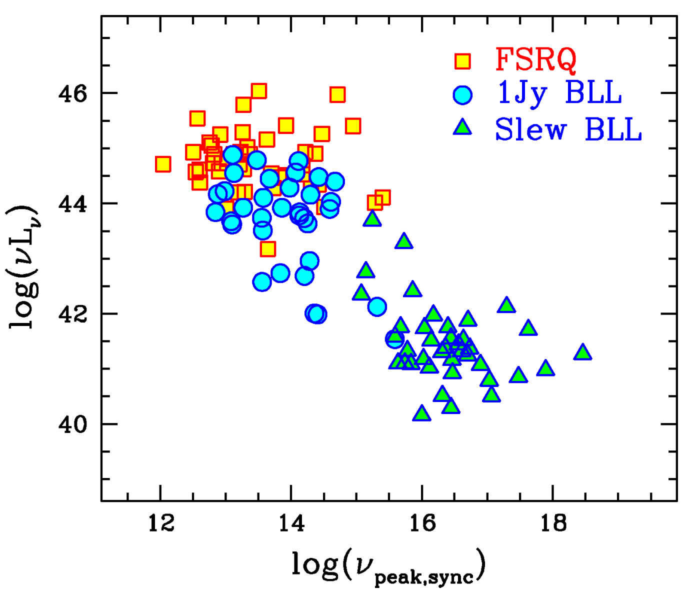
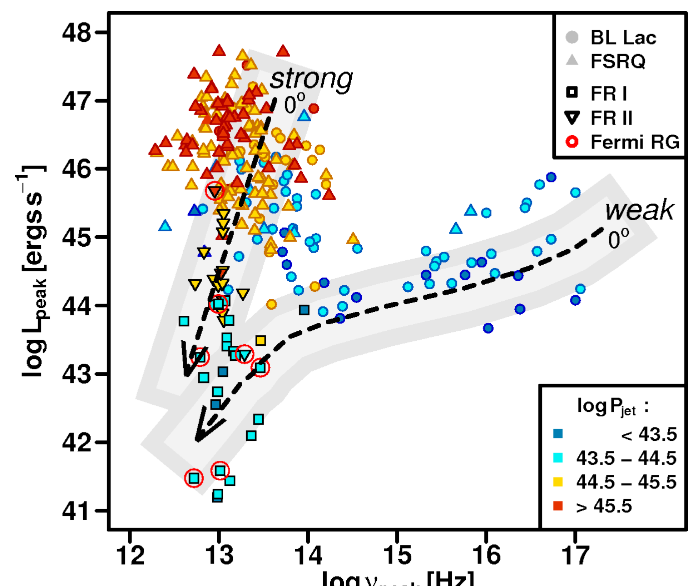
the broken sequence and the torn blazar envelope

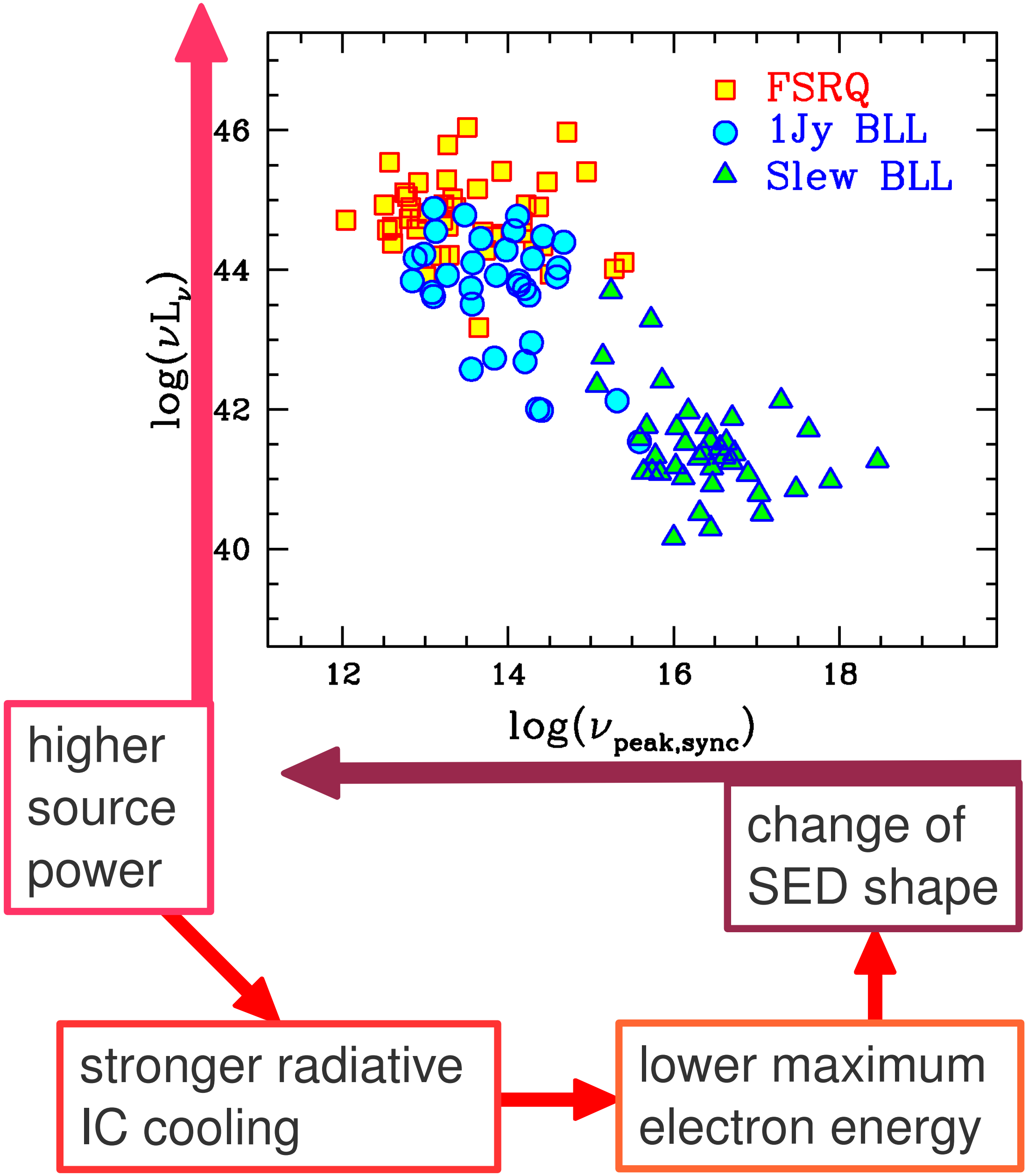
Eileen Meyer (STScI)
Giovanni Fossati (Rice)
Markos Georganopoulos (UMBC)
Matthew Lister (Purdue)

Meyer et al. 2011, ApJ, 740, 98
Meyer et al. 2012, ApJ, 752, L4





the good old blazar sequence

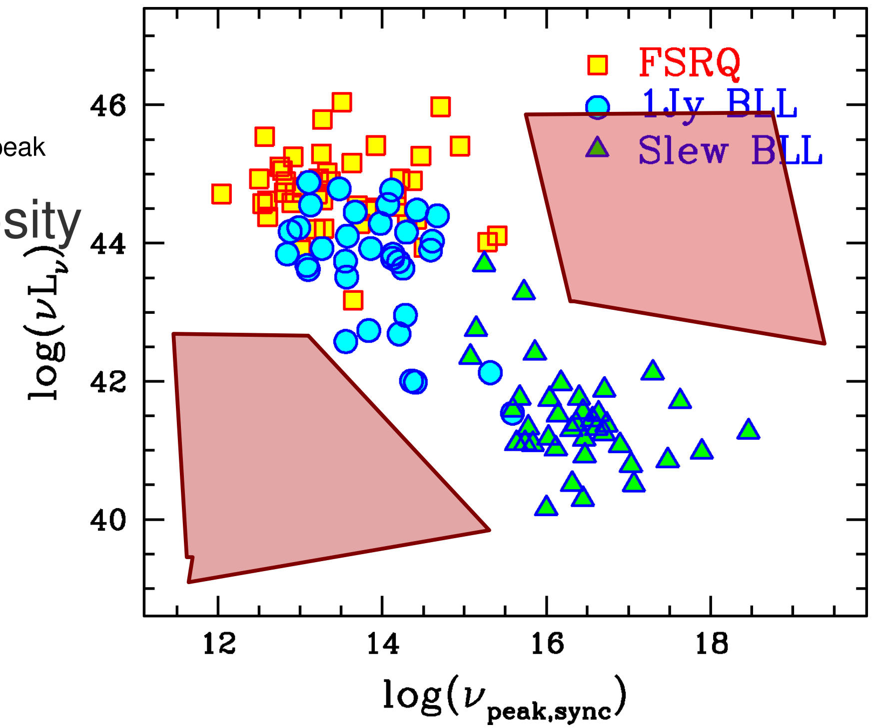


The sequence paradigm. The source power is the unique fundamental parameter, and it regulates the intensity of the diffuse radiation surrounding the jet.

The characteristic energy of the radiating particles in the jet is determined by the extent to which they cool on these ambient photons, and it hence determines the SED shape, and in turn the classification into a blazar “flavor”.

challenges to an aging *paradigm*

- The old scheme has been slowly taking on water (Padovani+ 2003, Nieppola+ 2006, Anton&Browne 2005, Caccianiga&Marcha 2004, Landt+ 2008).
  - Finding of low ν_{peak}, low L_{peak} sources
  - BL Lacs are found over a wide range of ν_{peak}
  - For BL Lacs, ν_{peak} uncorrelated with luminosity
  - High-power (FSRQ-like) BL Lacs
  - Low-power FSRQ

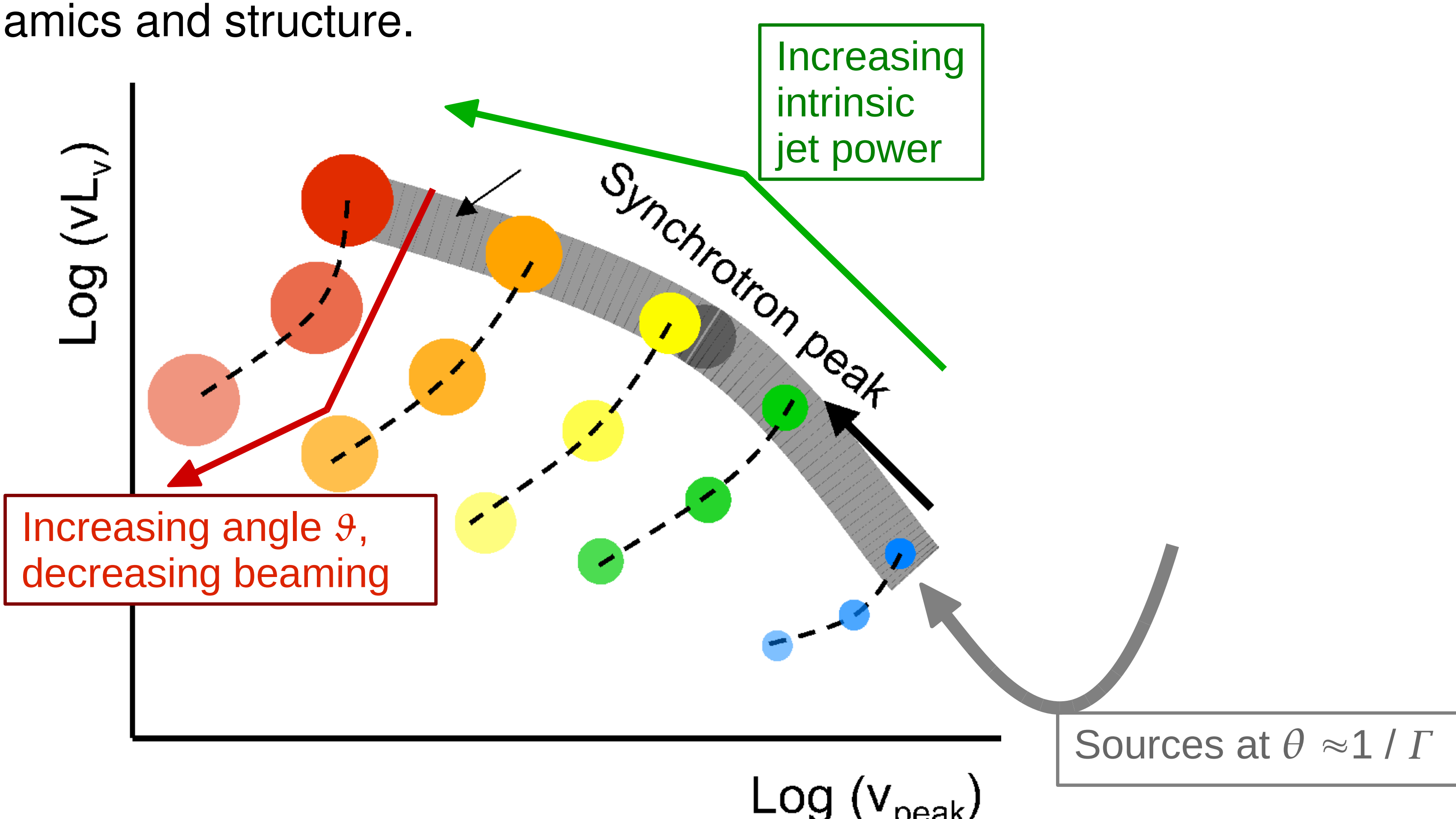


- **Is there a** (mono-parametric) **sequence?**
  Do we need anything more?

- Need a fresh and broader look, starting by including *more directly* some of the *fundamental* properties:
  - **(intrinsic) jet power**
  - accretion power
  - viewing angle
  - jet Lorentz factor
  - *thermal* emission power
  - black hole masses
  - **radio-galaxies**

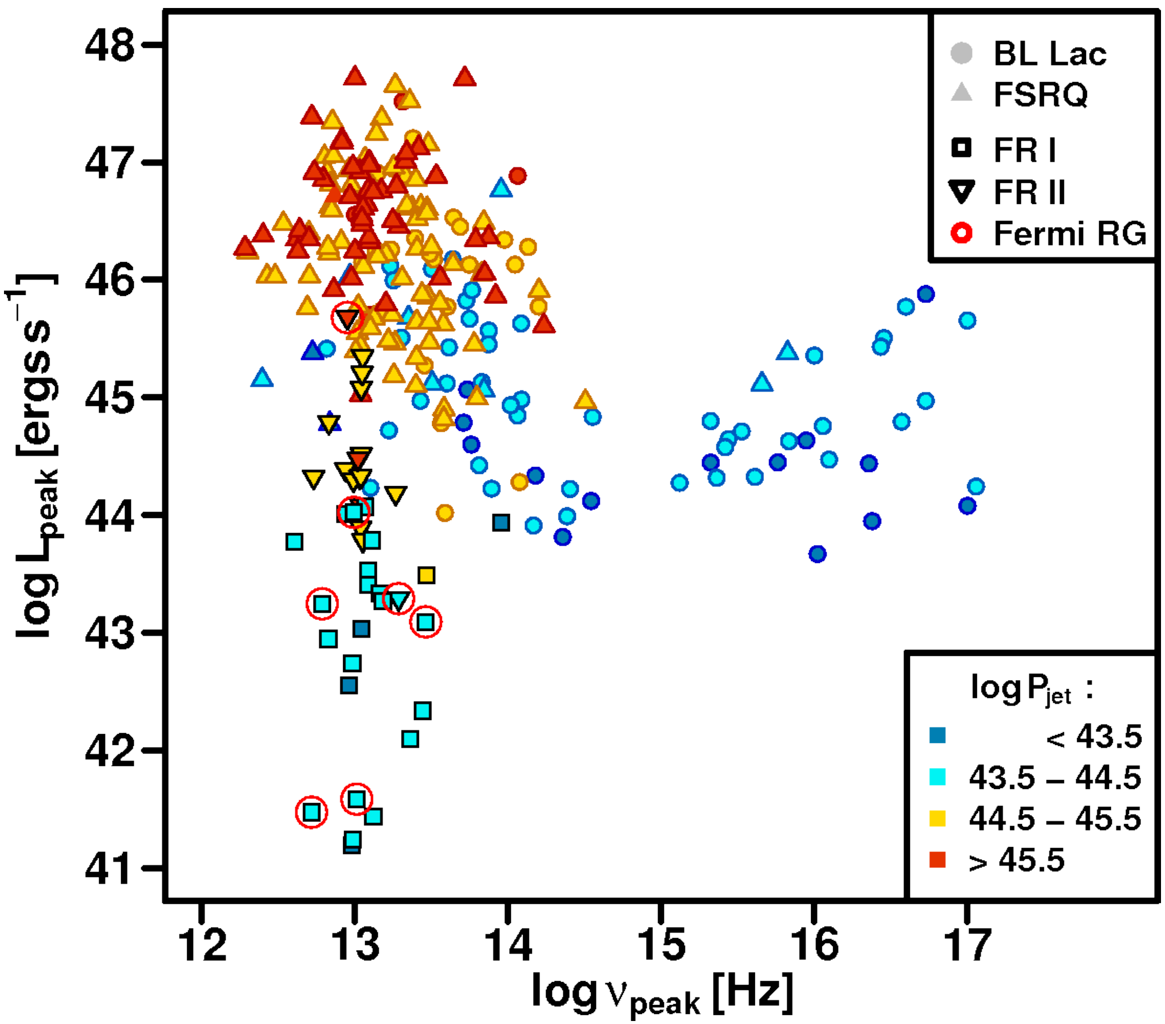
the minimally-extended observational hypothesis

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.



the *blazar envelope* space

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



- **No indication of *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}.
- Scarcity of objects with intermediate SED properties.

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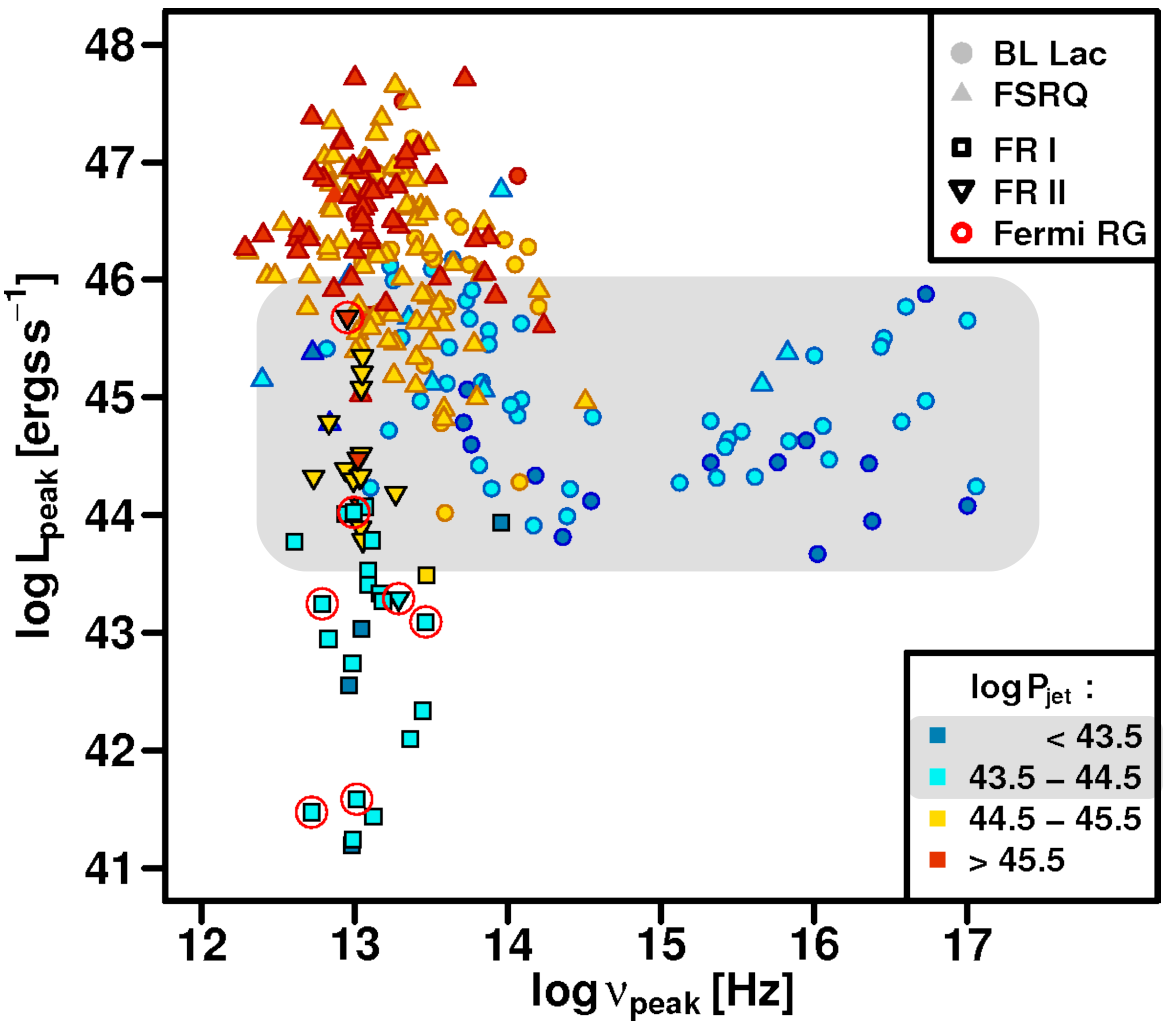

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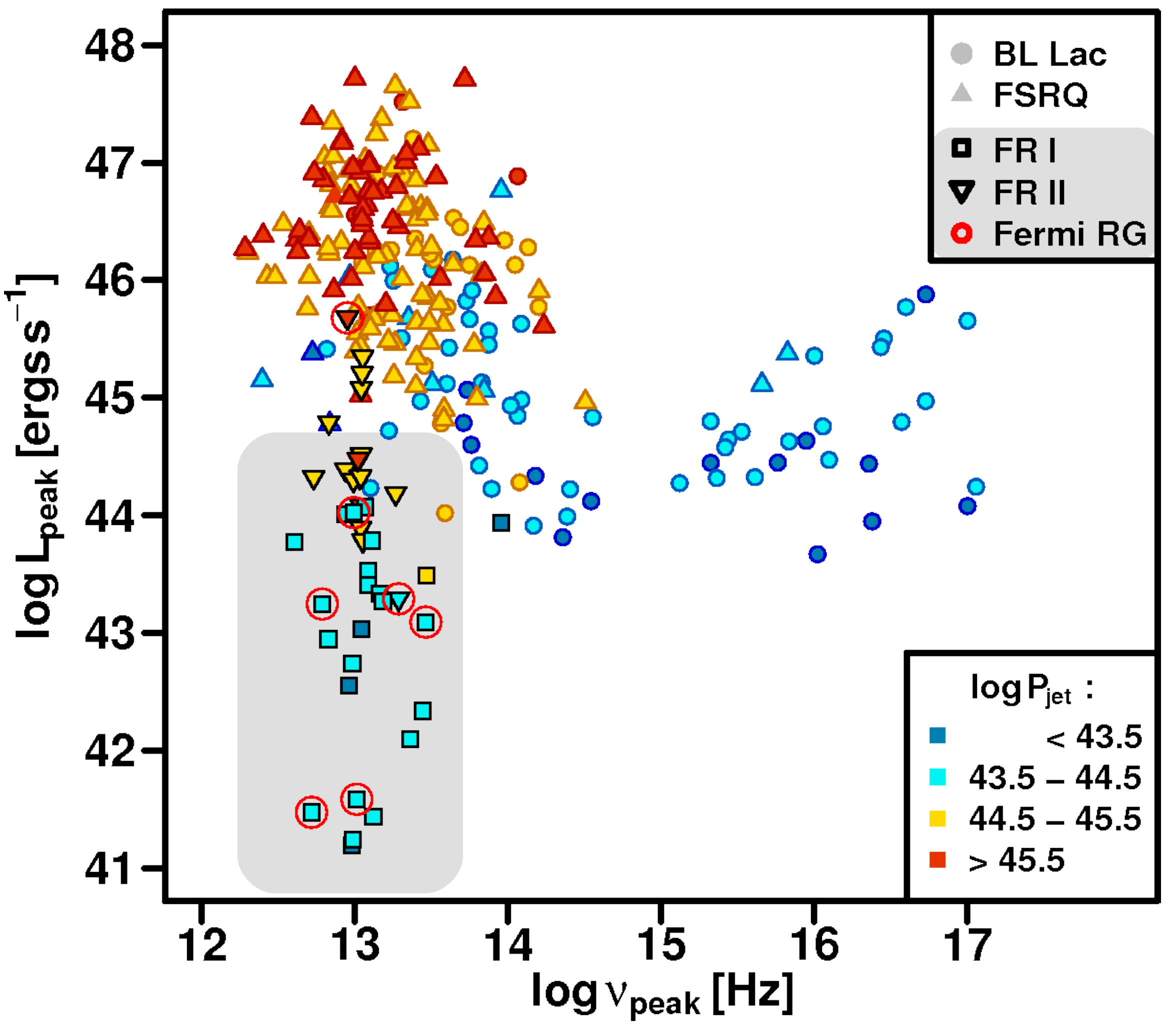

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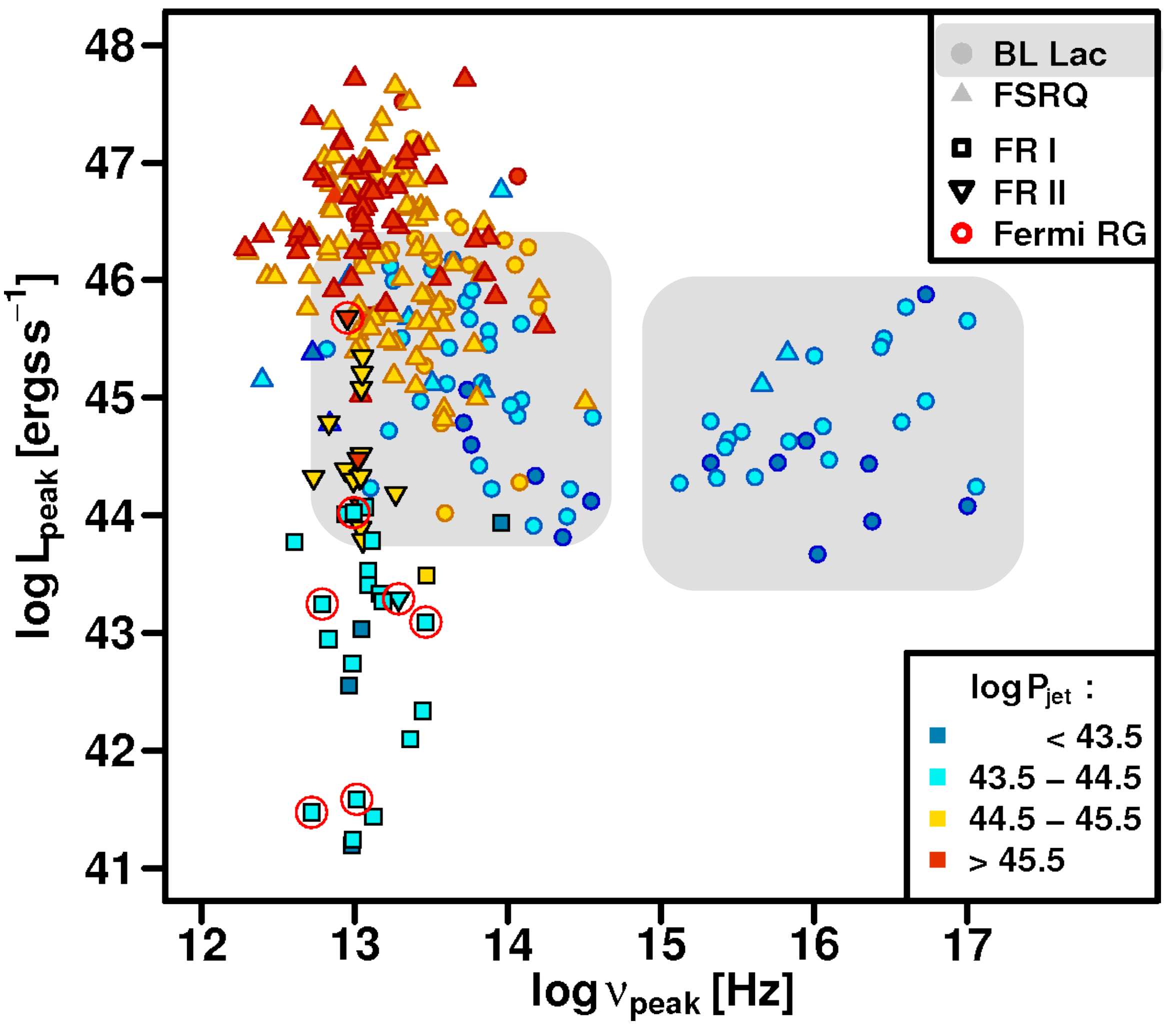

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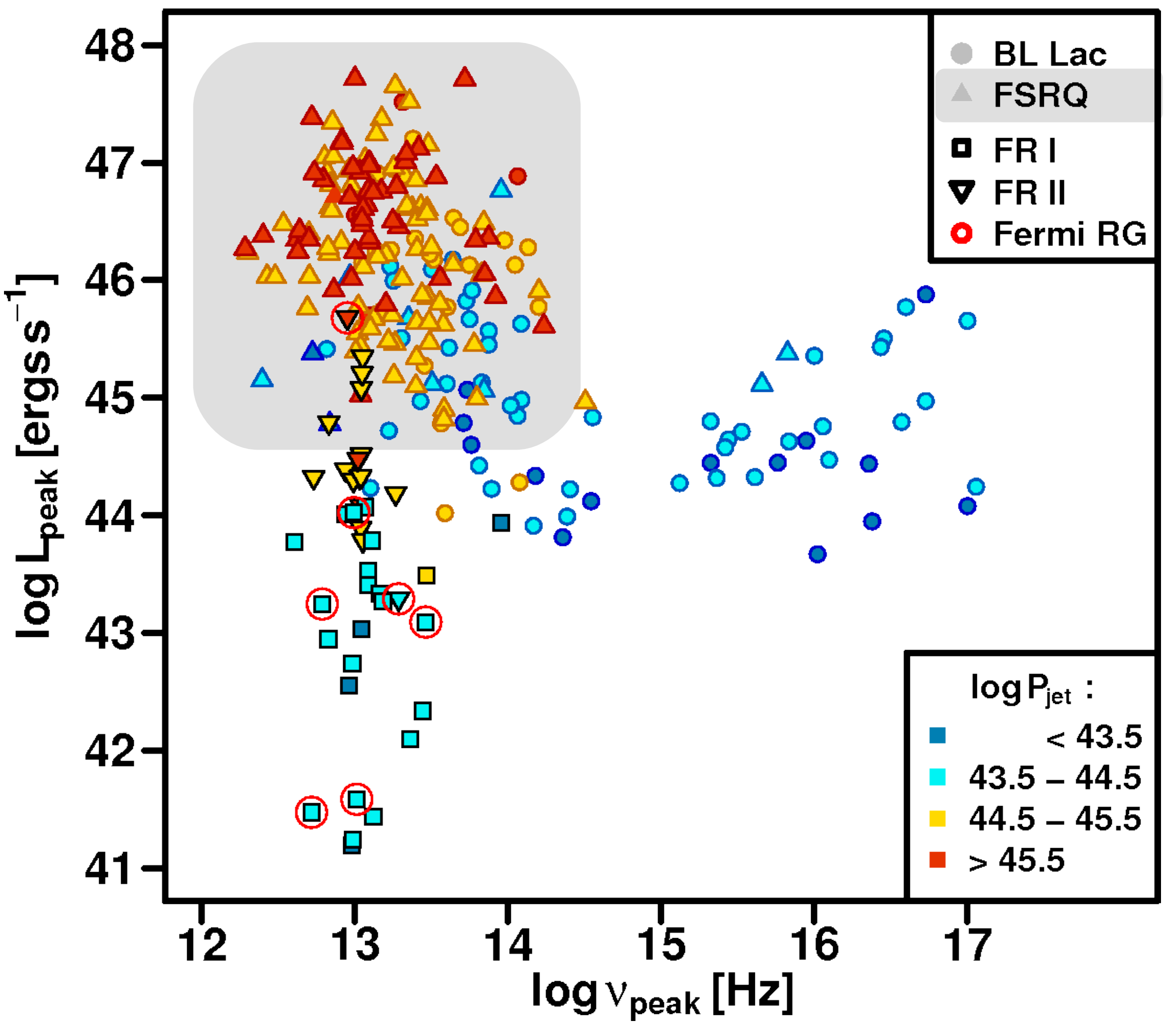

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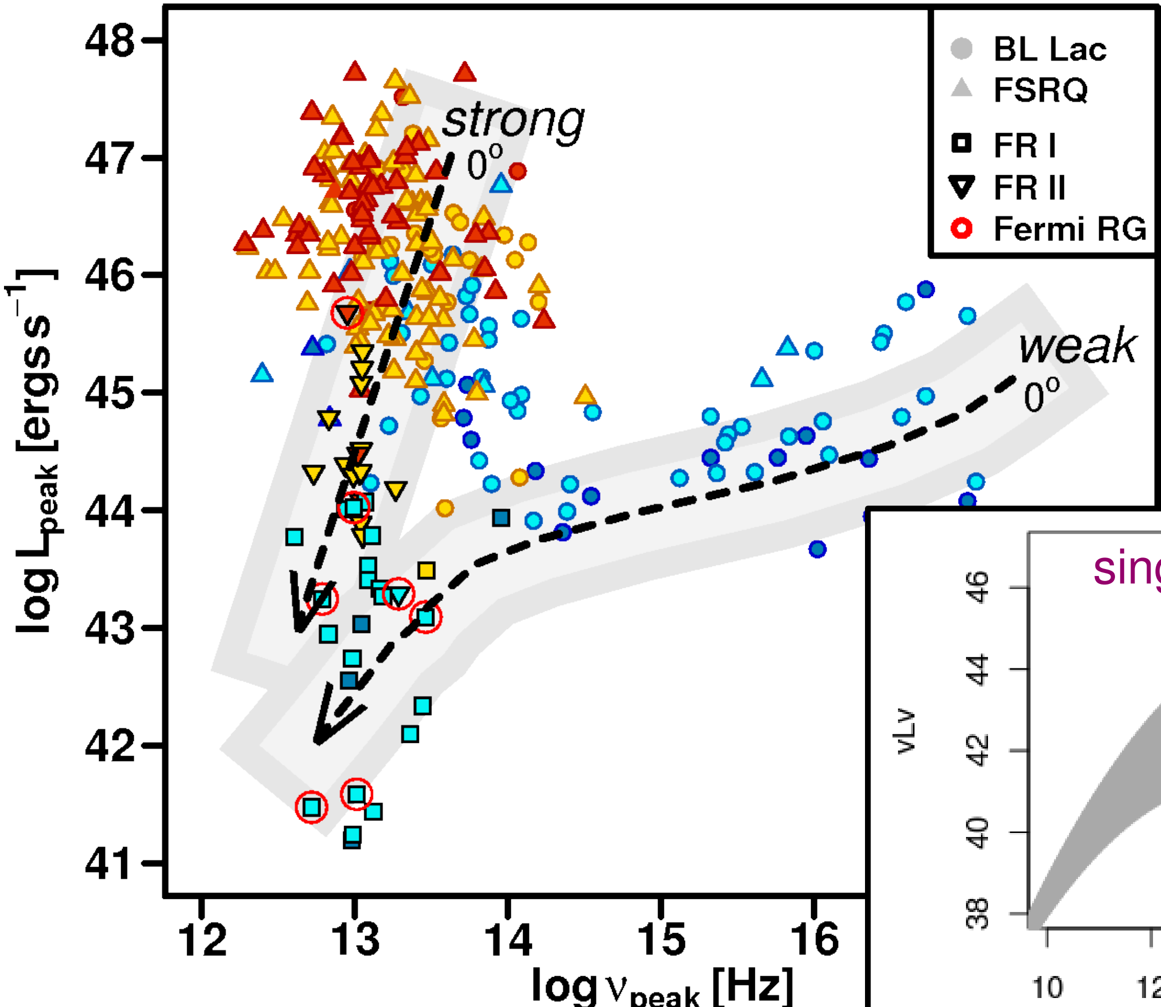
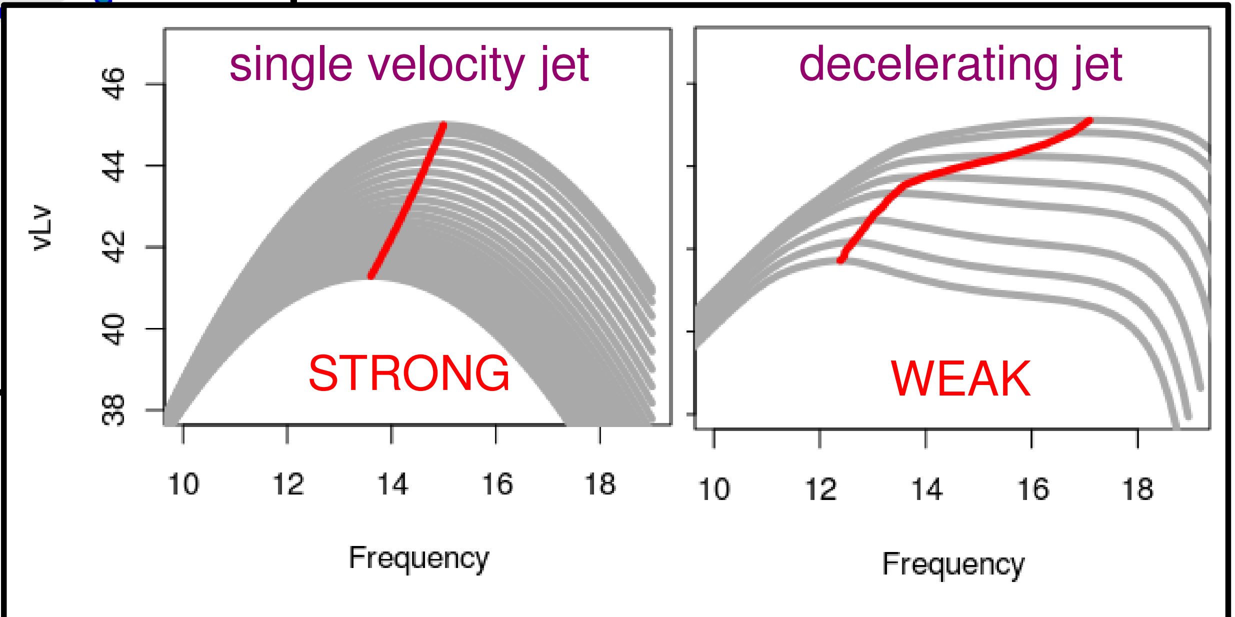
jet structure dichotomy?

- The source distribution and absence of the expected "patterns" suggest a dichotomy perhaps related to intrinsic jet power.



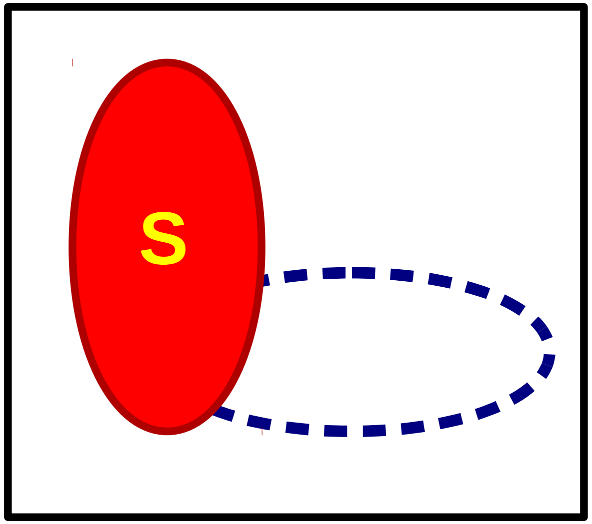
- Tracks correspond to the predictions of the *mis-alignment paths* for:
  - (*strong*) a single speed jet.
  - (*weak*) a decelerating jet.



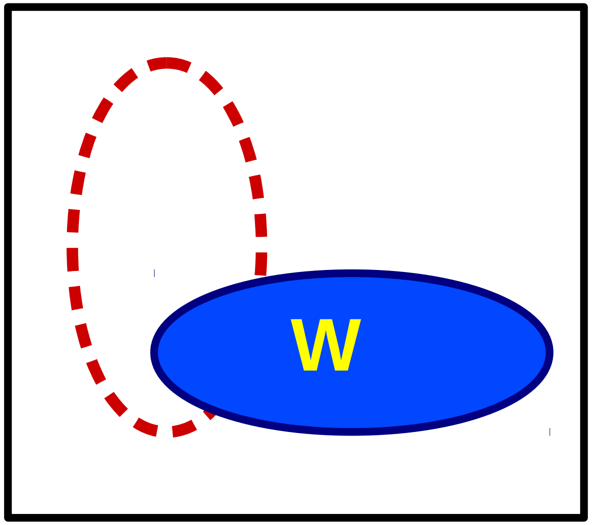
the *strong* and *weak* jets conjecture

- Radio-loud AGNs come in two different flavors, *strong* or *weak* jets, and within each group there might exist a spectral sequence.

- **Strong Jets:**
  - all with high L_{kin} (> $10^{44.5}$ erg s^{-1}), *some lower* L_{kin}
  - (nearly) all FSRQ, but many *BL Lacs*
  - low ν_{peak} (< 10^{15} Hz), reach highest L_{peak}
  - associated with FR IIs (based on L_{kin})

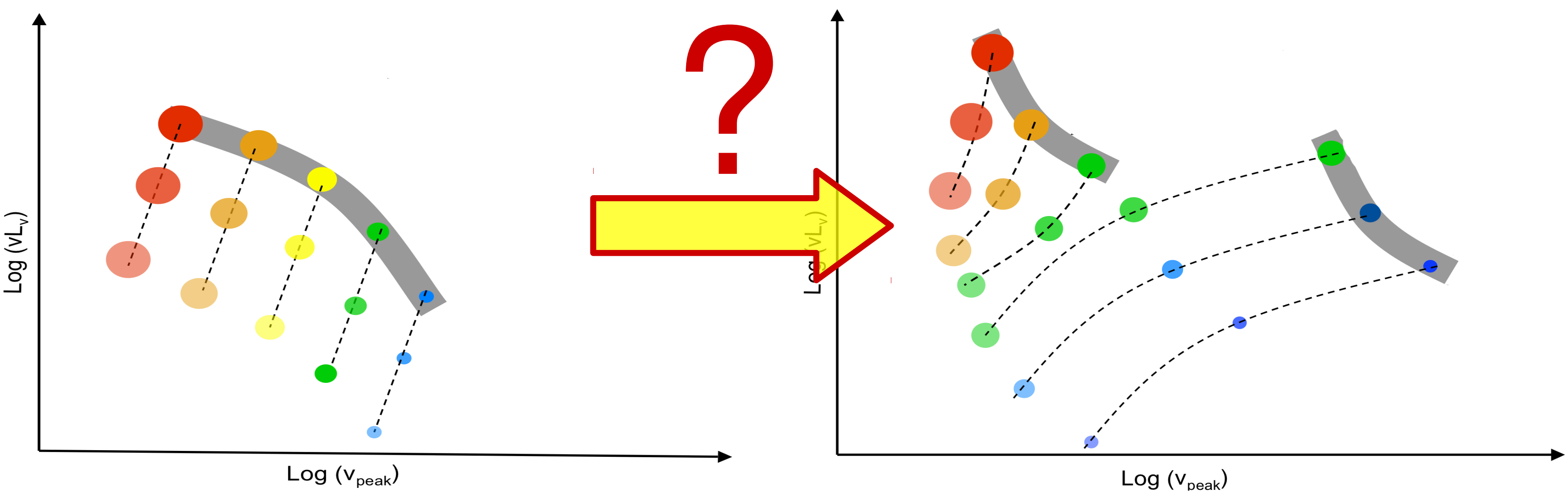


- **Weak Jets:**
  - only at low L_{kin} (< $10^{44.5}$ erg s^{-1})
  - (nearly) all BL Lacs
  - all high ν_{peak} (> 10^{15} Hz), some low ν_{peak} (?)
  - associated with FR Is (based on L_{kin})



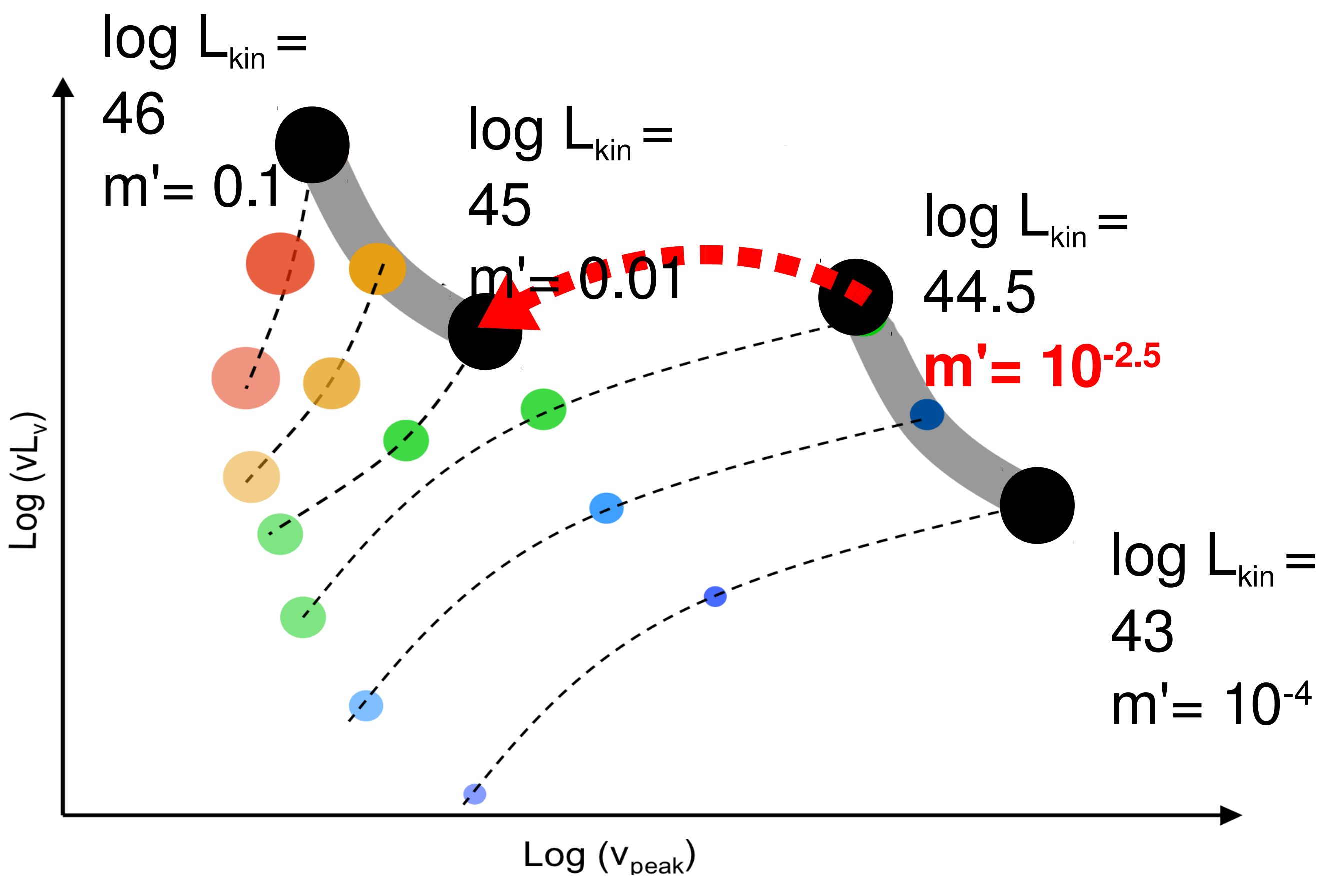
some new questions opened

- Is this divide real?
- Link to accretion (mode)?
  Optical spectral types mixed?
- Jet power? Not a clean divide.
- Is there a broken sequence?



broken sequence, BH mass and critical power

- Let's assume that there is a transition at a critical value of jet (accretion?) power (scaled to BH mass), say ~0.01.
- Let's *follow* the jet of a 10^9 solar masses BH (L_{Edd}~ 10^{47}) seen “aligned”.



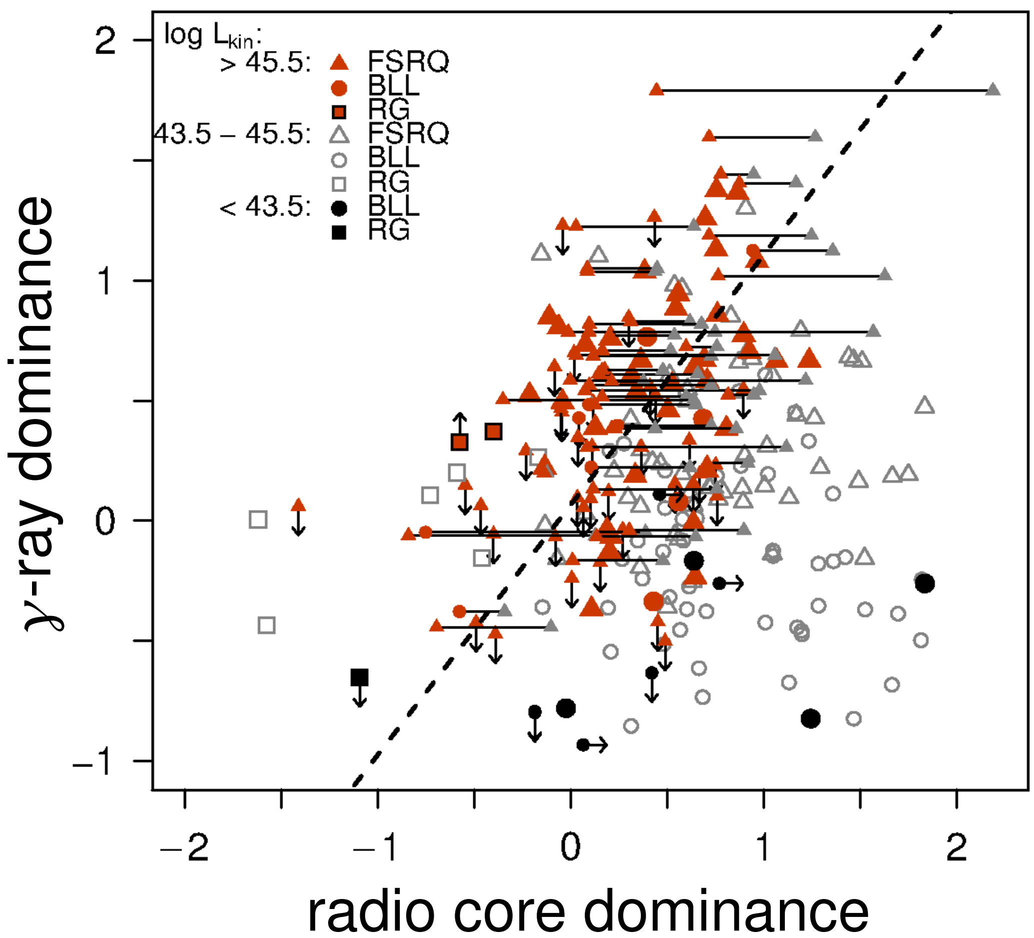
- Systems with less massive BHs would exhibit the same *behavior* but with transitions at lower jet power points.

γ-ray and radio core dominances

- We can define two quantities that are sensitive to beaming:
  - γ-ray dominance – the ratio between peak luminosities of :
    - the γ-ray component
    - the synchrotron component
  - radio core dominance – the ratio between:
    - beamed radio power (flat radio part)
    - unbeamed radio power (e.g. extended emission)
- 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 between γ-ray and radio core dominances:
  - **flat for SSC**: synchrotron and IC are subject to the same beaming
  - **steep for EC**: emission by EC is more strongly beamed than synchrotron's (Dermer 1995).

EC in very high power jets! …and the others?

- A trend of increasing gamma-ray dominance with jet alignment only emerges for the sources with the highest jet kinetic power.



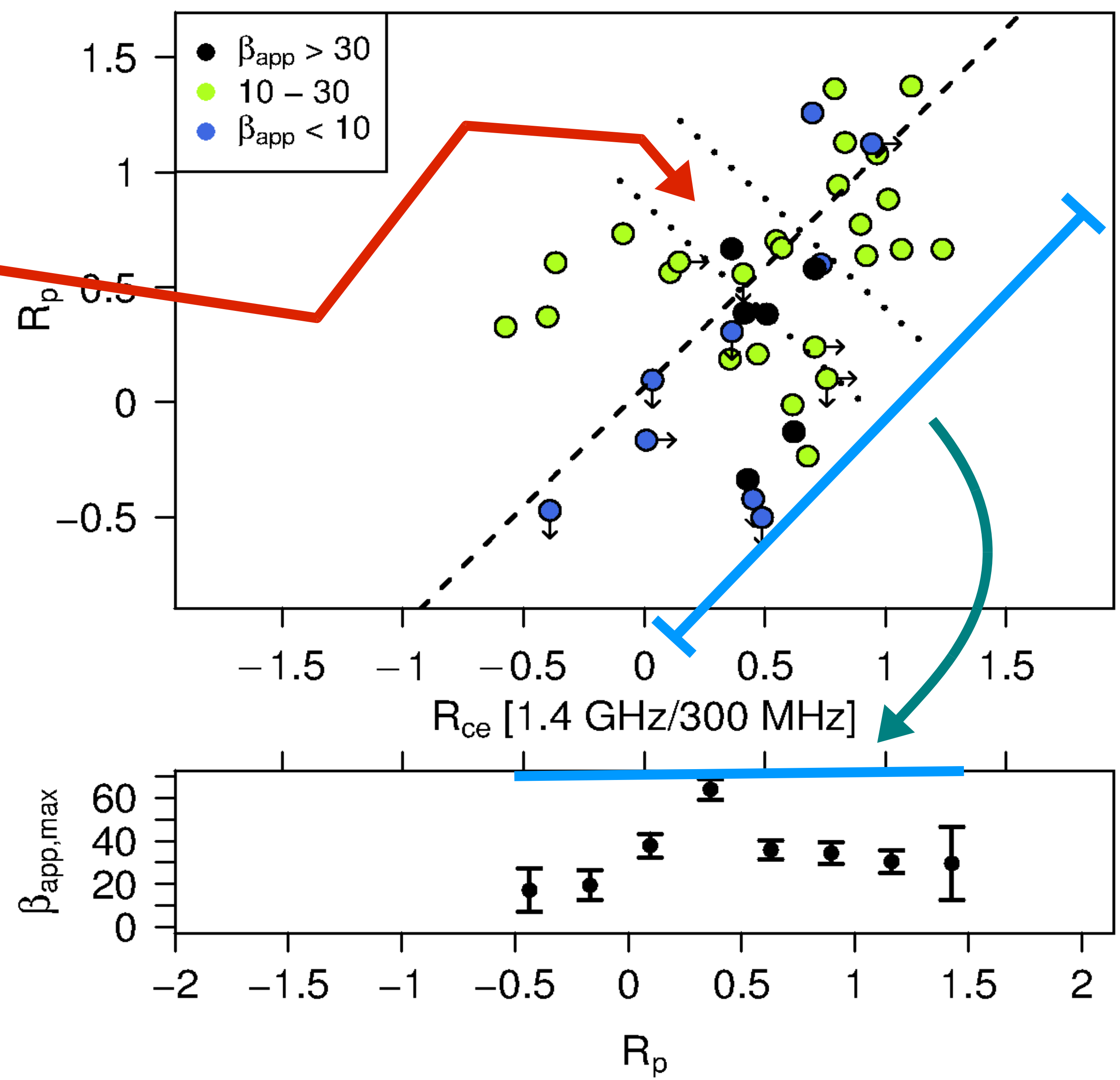
- The rest of the large population of FSRQ, still at high jet power, is consistent with no-trend, e.g. SSC origin for their γ-ray emission.
- The requirement of SSC dominating over EC (on BLR or torus emission) can be cast as a constraint on the Lorentz factor, $\Gamma \leqslant 8$ for BLR, $\Gamma \leqslant 16$ for torus.
- At VLBI scale powerful FSRQ seems to show Lorentz factors larger than those, possibly implying that their jets become dissipative at larger distance from the BH.

is that trend consistent with increasing beaming?

YES

(in zero-th approximation)

The measured apparent speed is maximum in the middle of the correlation, *as expected.*



summary

- Suggestion of two populations, weak and strong jets, associated with jet (velocity) structure.

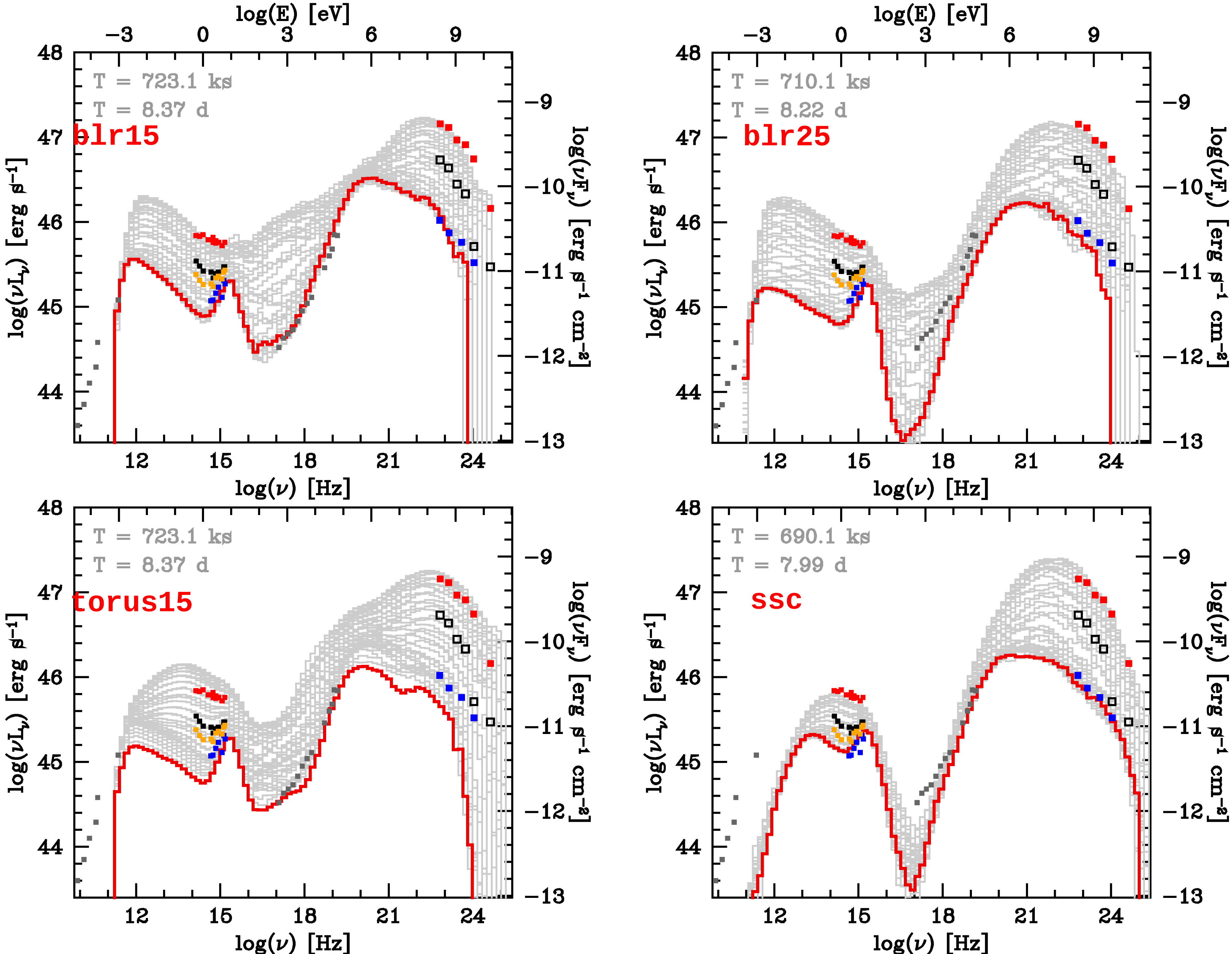
- Jet power may not be the sole fundamental parameter: accretion mode differences, BH mass play an important role.

- Observations consistent with a *change in accretion mode* at some critical scaled value of around 10^{-2}, ***linked*** *to a transition in jet SED properties.*

- *Spectral sequence(s)* may exist in a "broken" form.

- The highest power strong jets emit by EC, i.e. they become dissipative within the first parsec. Lower power jets, though still very powerful, don't exhibit a clear signature and may be consistent with SSC origin of their gamma-ray emission, and larger dissipation distances.

(missing poster 1.5)



Thank you

(and to US taxpayers)

EC vs. SSC

Very High Power jets → EC
Moderately High Power jets –> ? … SSC?

Only *Very High Power FSRQ* show this collective behavior: a possible clue to the gamma-ray emission site?

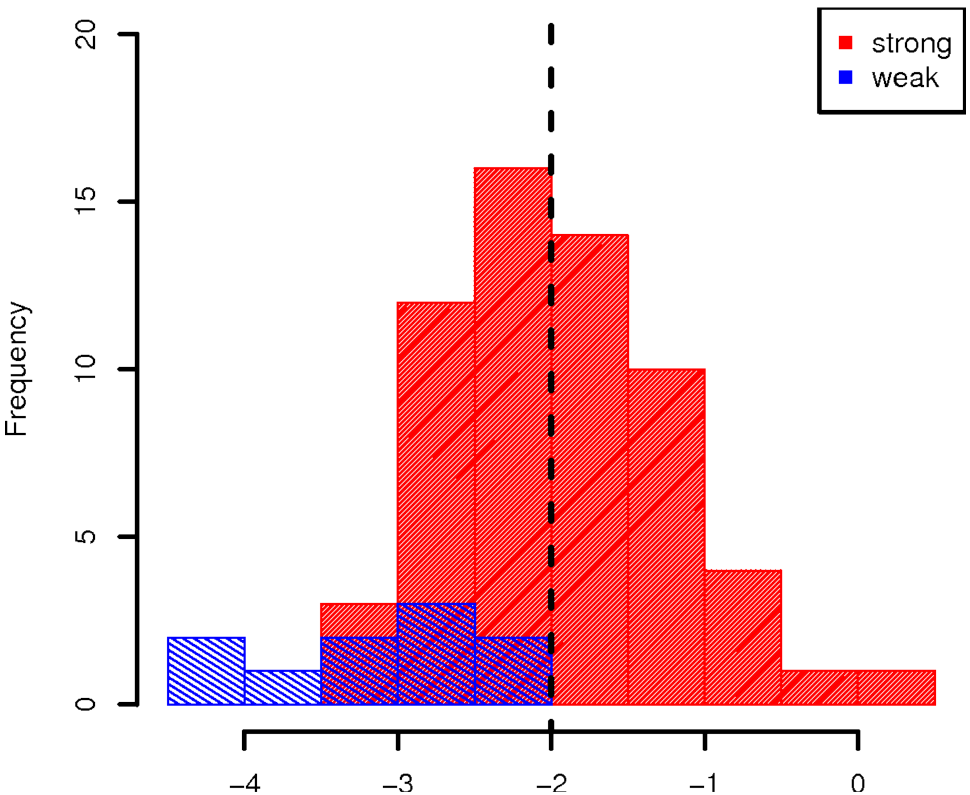
<u>BLR</u> versus <u>Molecular Torus</u>: IF SSC dominates in moderate FSRQ, synchrotron energy density must be greater than external photon energy density - while the reverse holds in powerful FSRQ.
This can be cast as a critical value of Lorentz Factor :

$$\Gamma_{cr} < \left(\frac{3L_s}{16\pi c^3 t_{var}^2 U_0} \right)^{\frac{1}{8}} = 16.2 \left(\frac{L_{s,47}}{t_{var,6h} U_{0,-4}} \right)^{\frac{1}{8}}$$

MT: critical value ~ 16
BLR: critical value ~ 8

jet-disk connection: *jet type* and L_{kin}/L_{Edd} ($\dot{m}_{jet}$)

- The rough correspondence between jet *strength* and optical spectral classification (FSRQ vs. BL Lacs) may suggest that the jet type depends on the accretion properties, e.g. Eddington-scaled mass accretion rate, $\dot{m}_{disk}$.
- **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 has been conjectured to be a 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).

SSC vs. EC beaming

- SSC – upscatters synchrotron photons.
  - IC peak is a "copy" of the synchrotron peak.
  - Beaming pattern is the same:
    - $\mathbf{L \sim \delta^{3+\alpha}}$
  - Therefore the IC/synchrotron ratio does NOT depending on viewing angle, it's constant.
- EC – upscatters photons from outside the jet (BLR, molecular torus, disk origin)
  - Beaming pattern of EC is different from that of synchrotron emission:
    - synchrotron : $\mathbf{L \sim \delta^{3+\alpha}}$
    - IC peak : $\mathbf{L \sim \delta^{4+2\alpha}}$
  - As viewing angle changes, EC beaming changes more than synchrotron's, yielding a correlation between an angle "indicator" and the ratio between EC and synchrotron intensity.

the *blazar envelope* space

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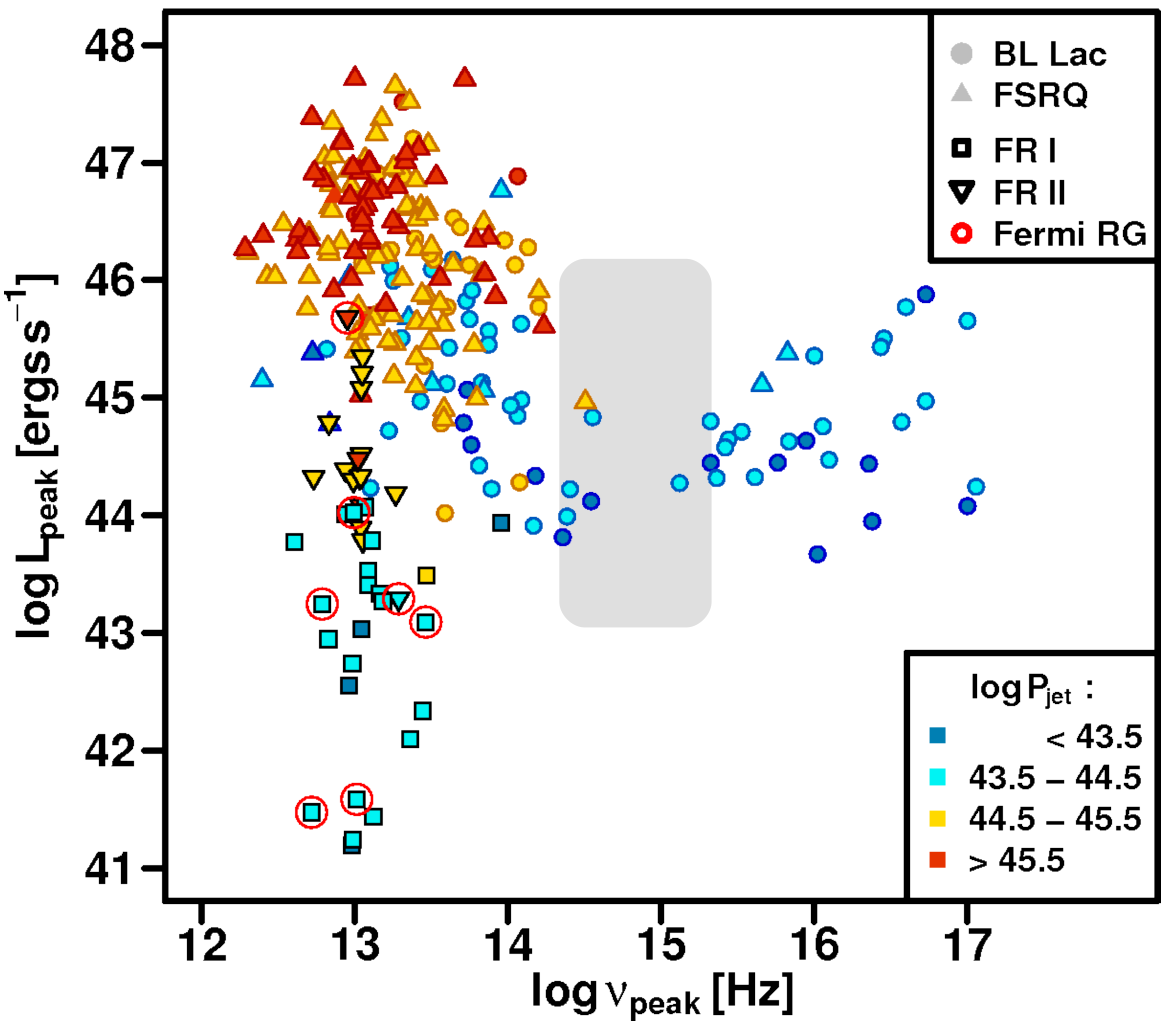
- Color coding on intrinsic jet power (3rd dimension).



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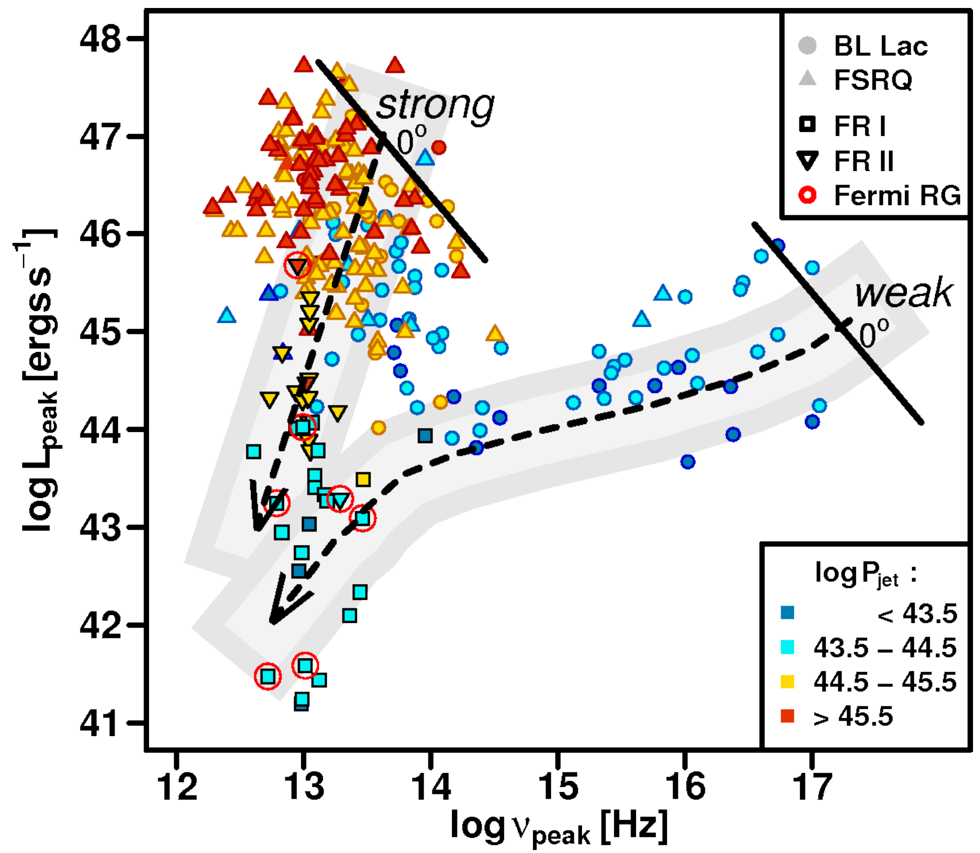
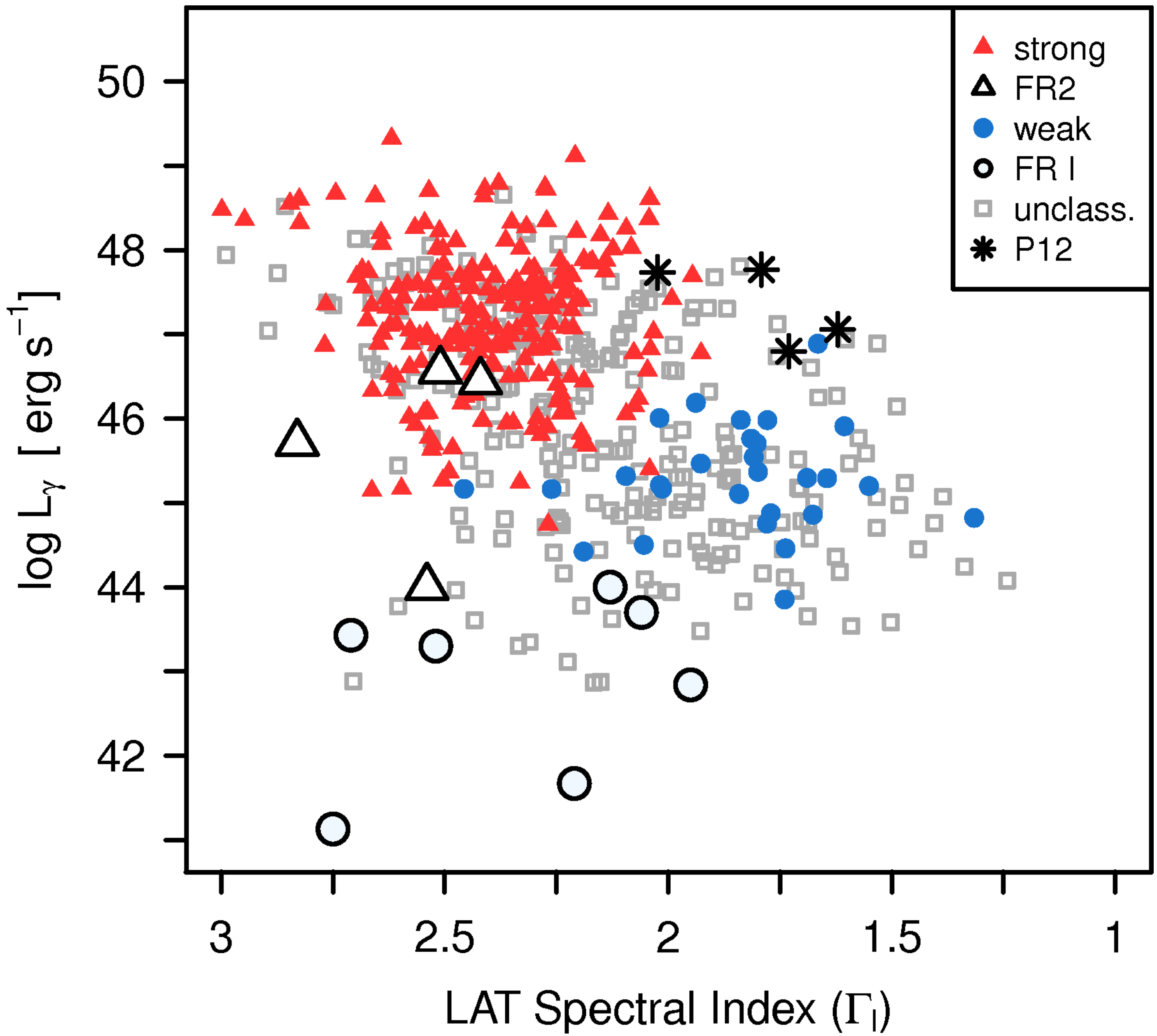
some questions answered

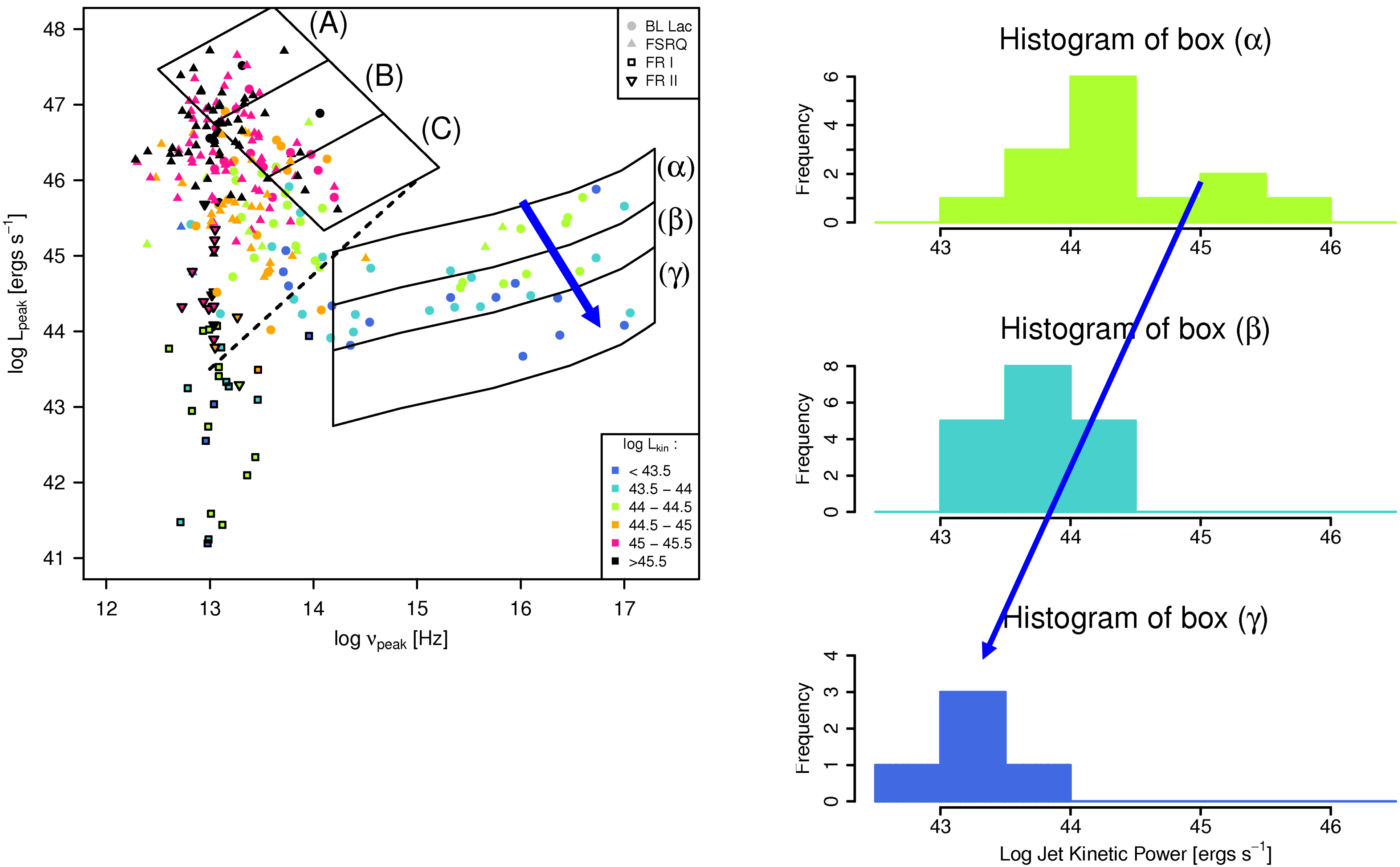
- **low ν_{peak} , low L_{peak} sources?**
  - These appear to be misaligned.
- **ν_{peak} does not vary with L_{kin} for BL Lacs?**
  - velocity gradients introduce a dominant horizontal shift.
- **Sources at low ν_{peak} have a range of L_{kin}?**
  - All *misalignment paths* meet at low ν_{peak}



the *gamma-ray envelope* space



the broken power sequence



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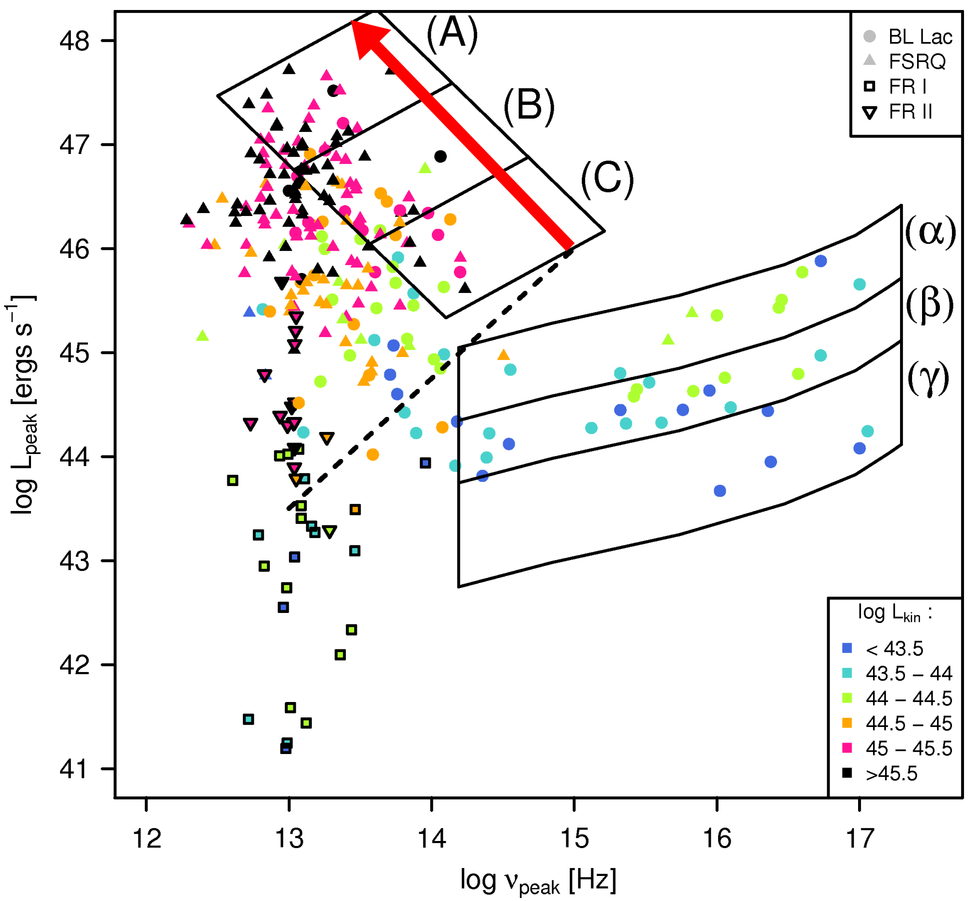
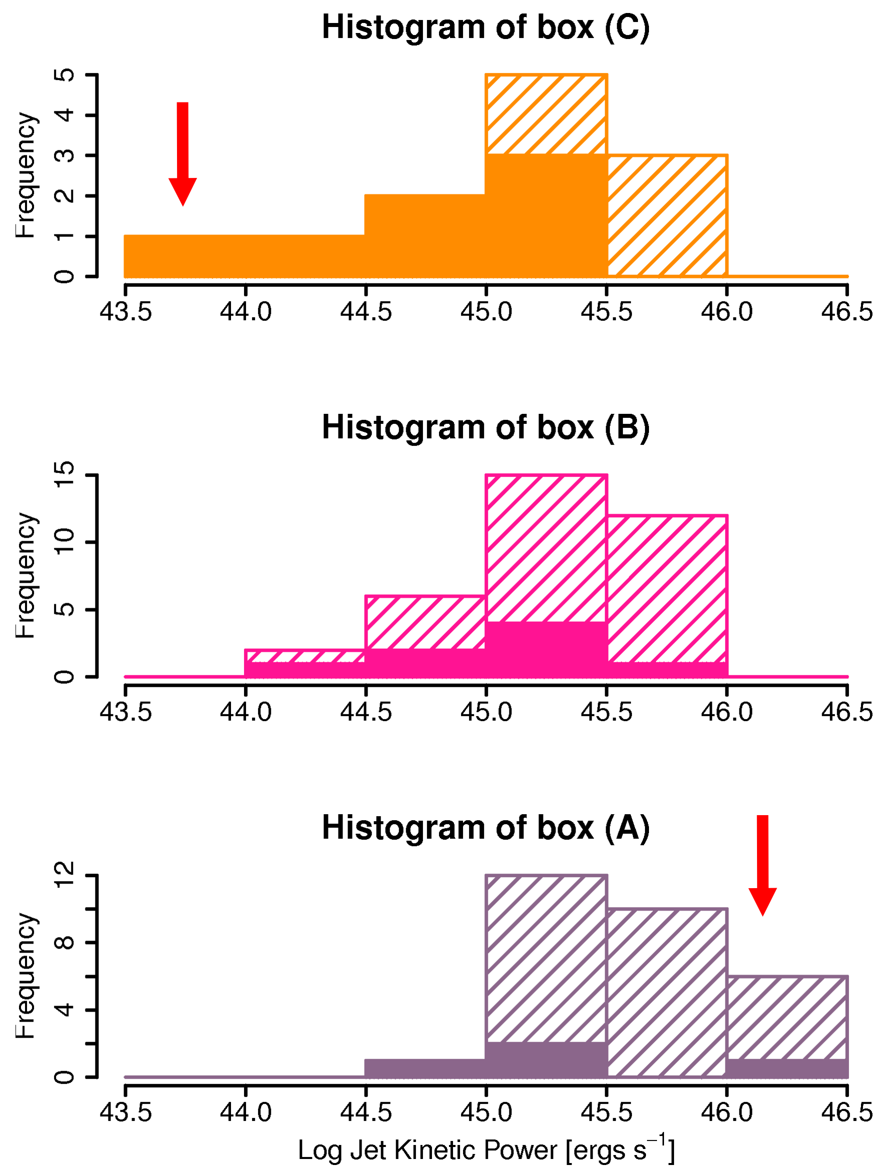
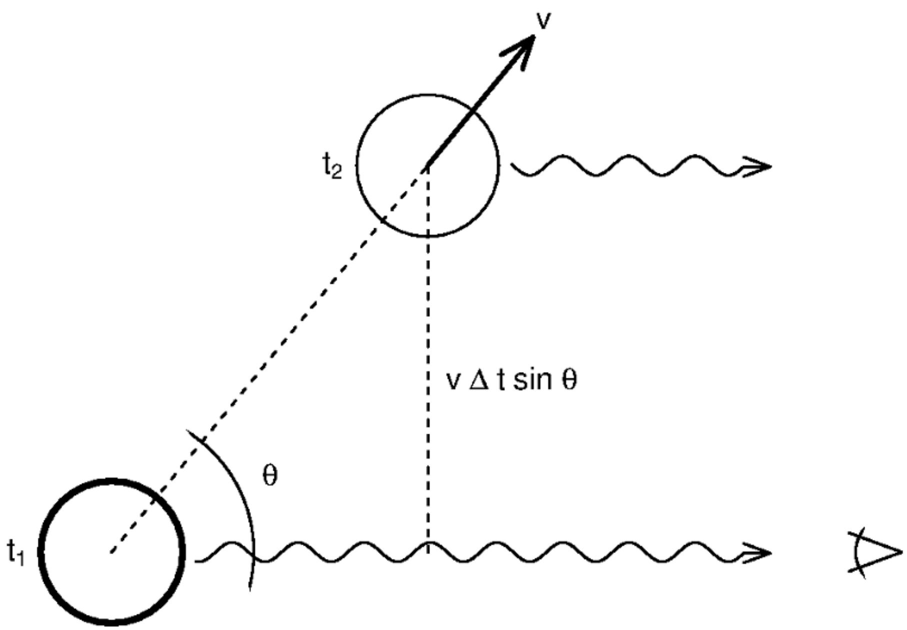
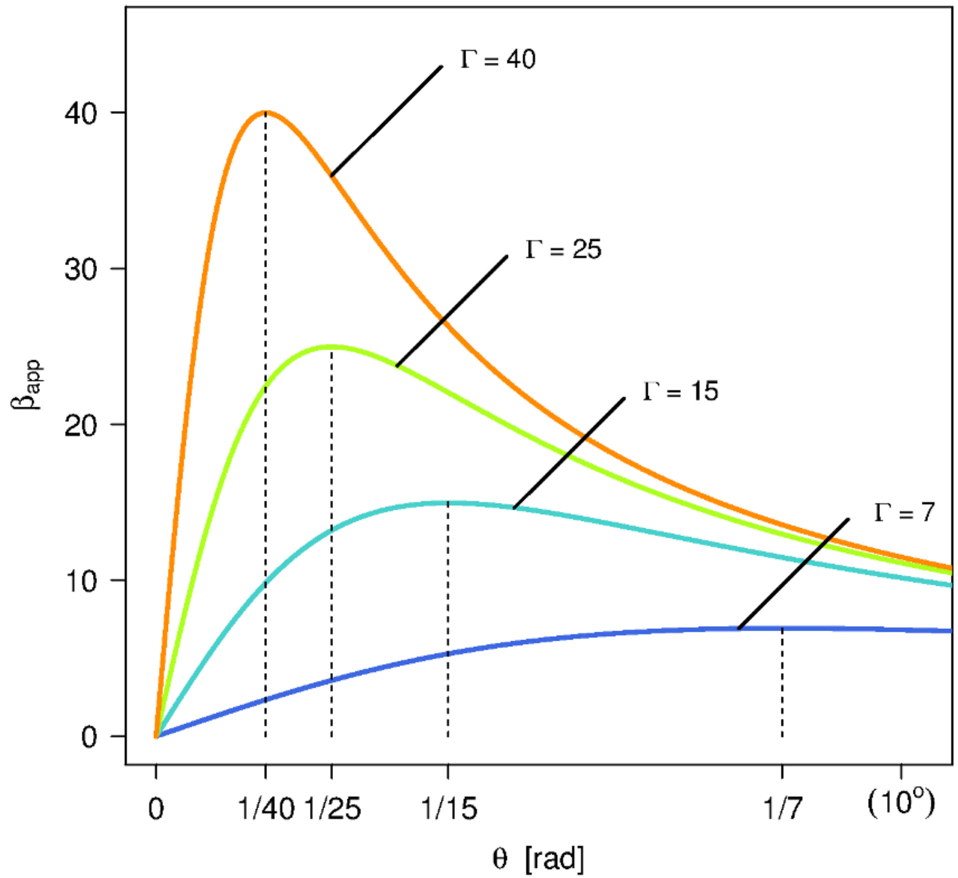


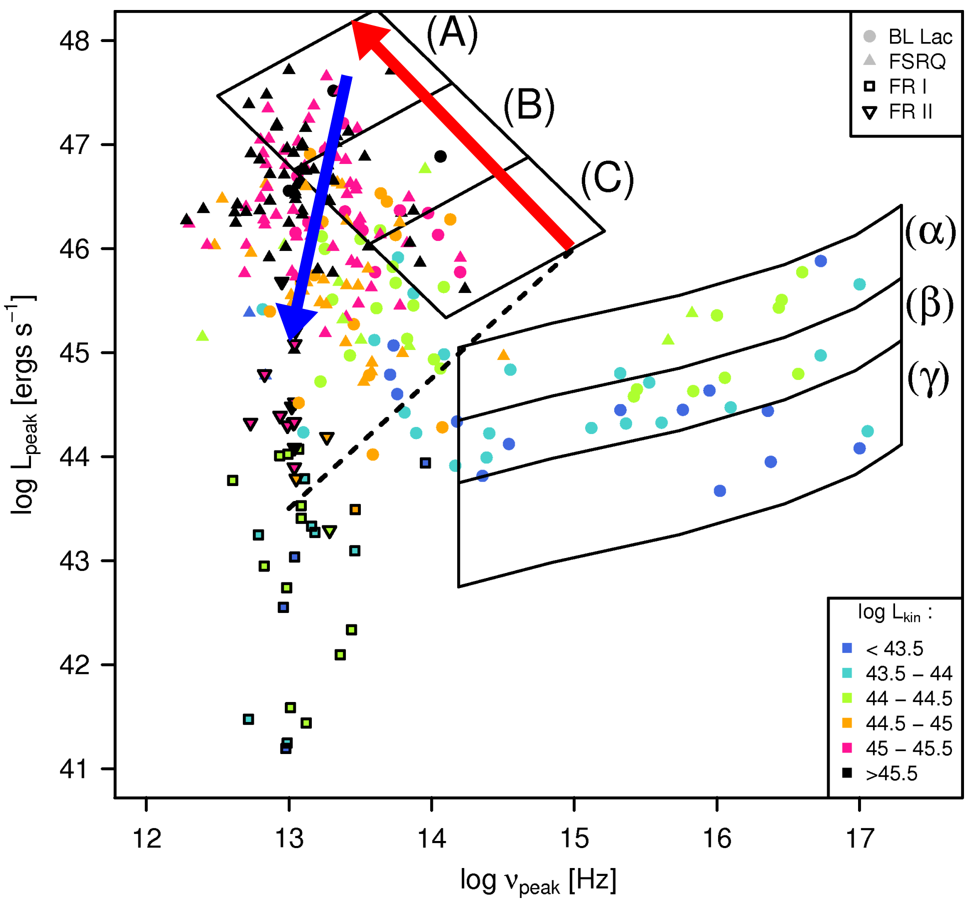


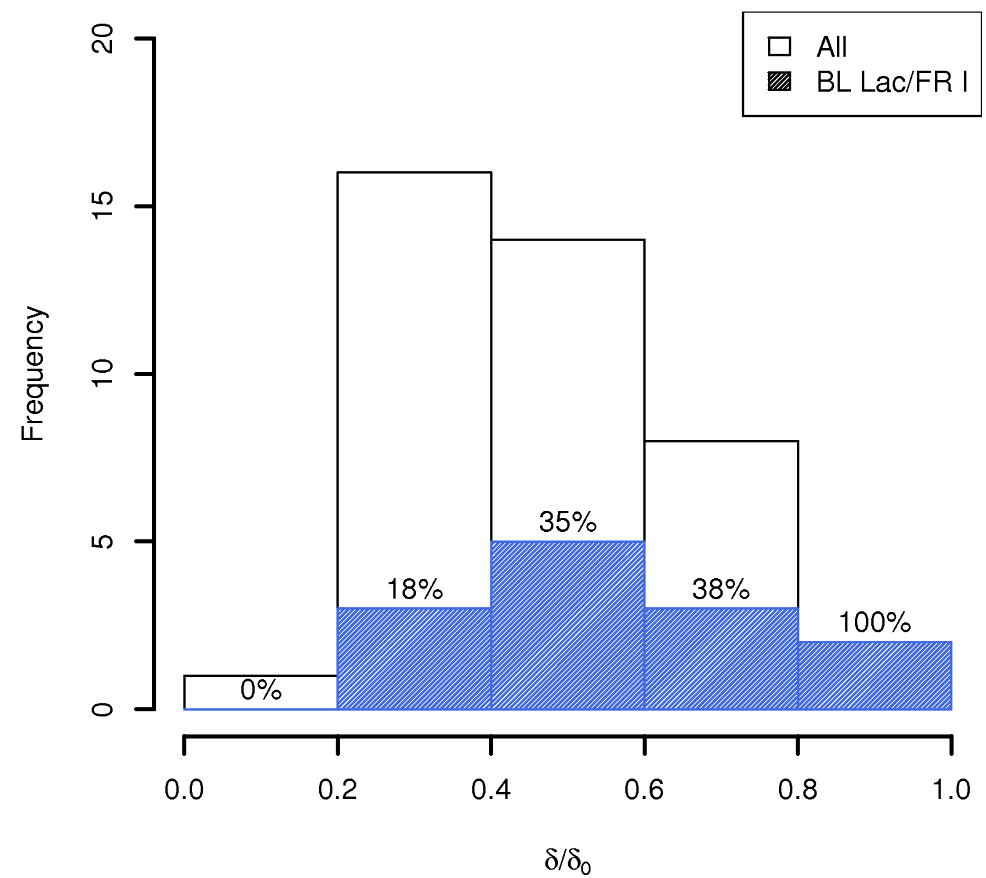
Apparent jet speed





BL Lacs on the strong branch?

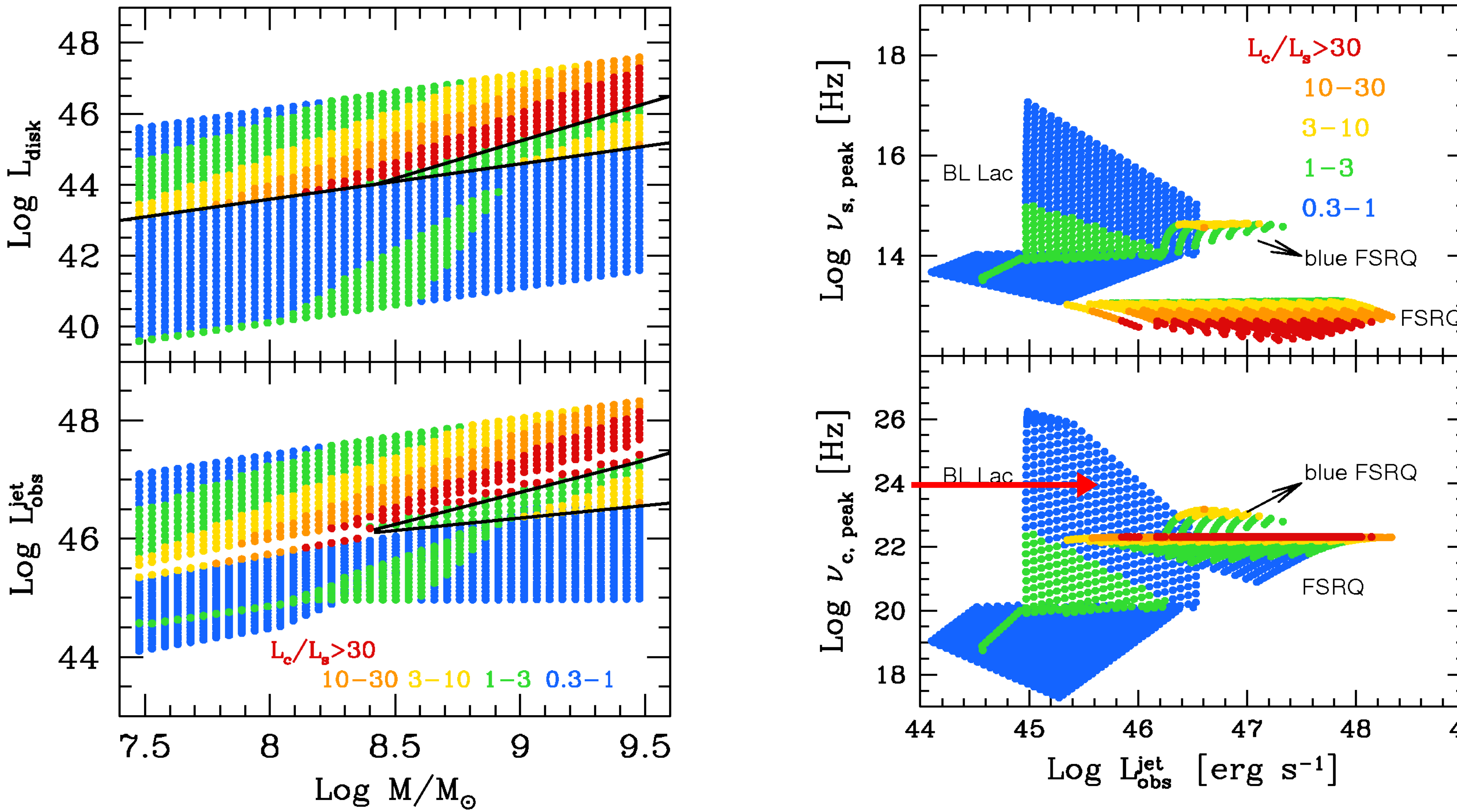




1:4 Δfrequency:ΔLuminosity

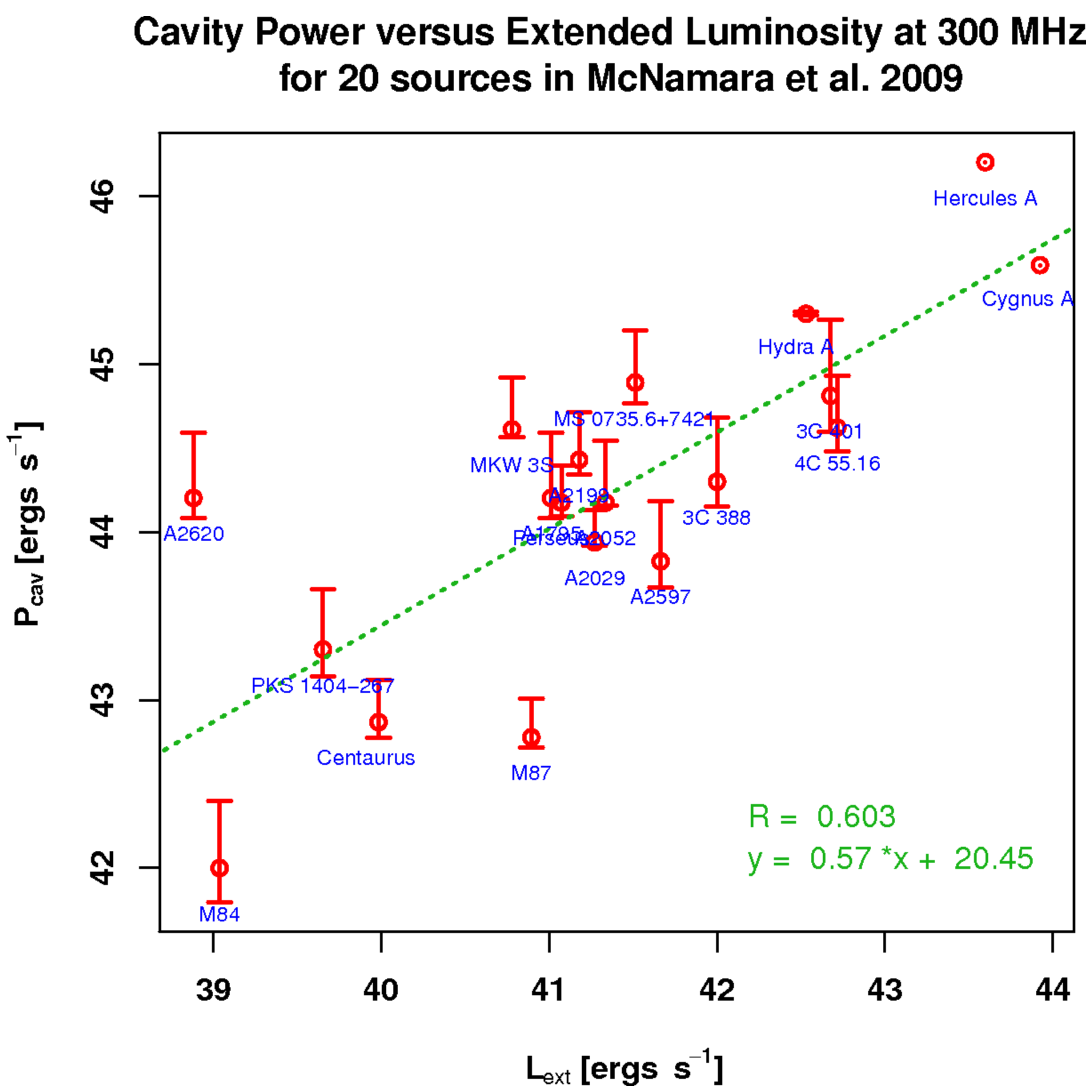
$\delta/\delta_0 = \nu_{peak}/\nu_0$

New perspective

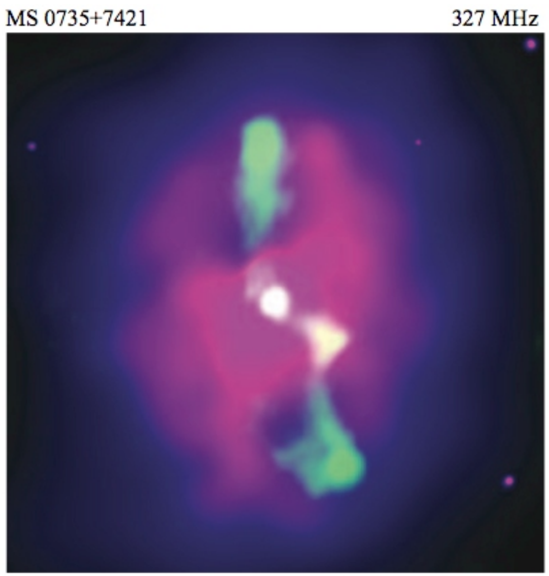


A study of the SED properties starting from a set of relationships among physical parameters (Ghisellini & Tavecchio '08, color coding on *gamma-dominance.)*
The "sequence" parameter space seems to open up.
These plots do not however "know" about "*density*" of sources in these spaces.

Extended luminosity and intrinsic jet power

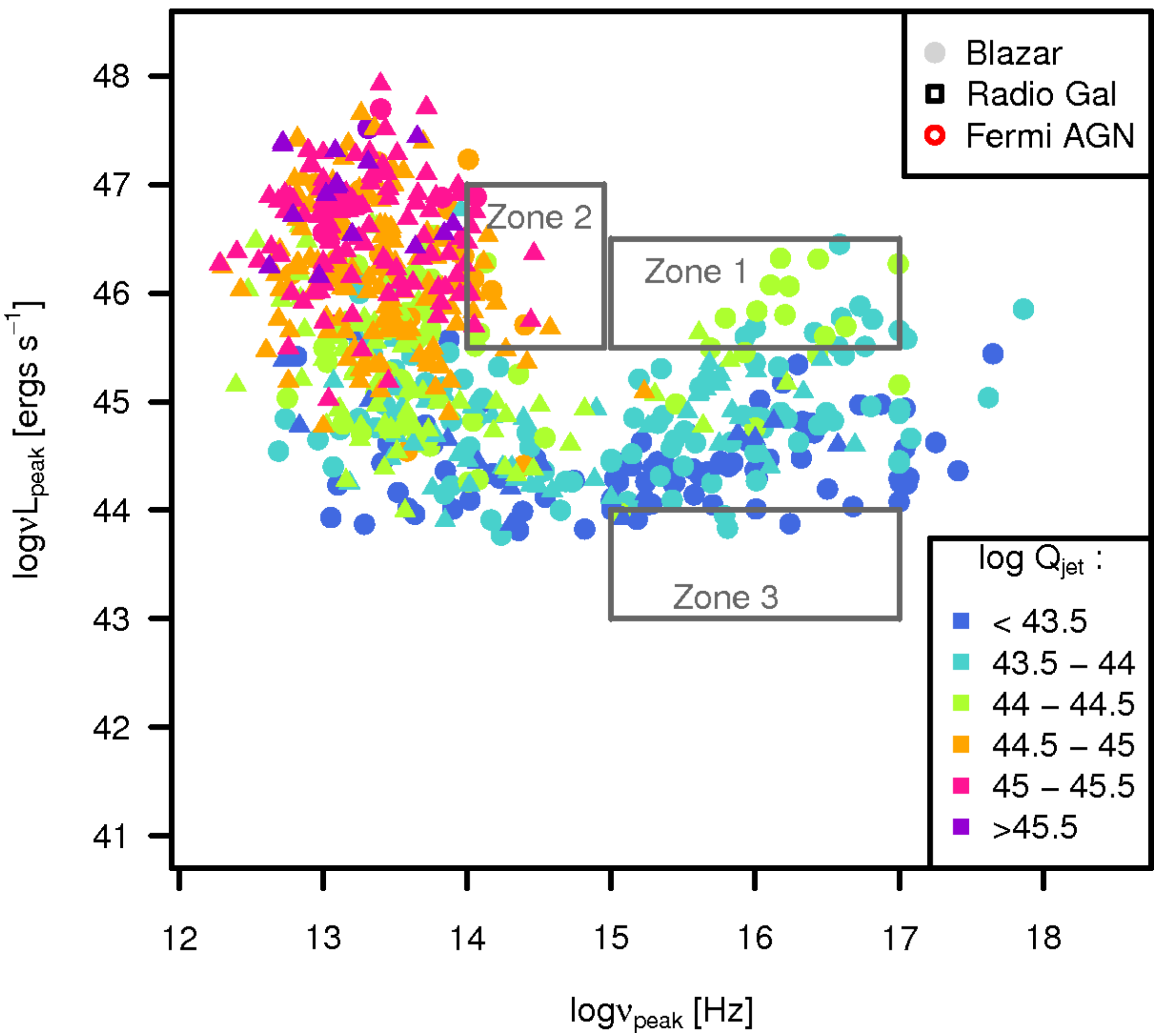


- For a sample of radio-galaxies found in clusters of galaxies the intrinsic jet power can be estimated by the study of the cavities that their jets inflated in the intracluster medium.
- This accurate and physically well defined measure of jet power correlates well with our best estimate of the extended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



Blazar envelope with upper limits

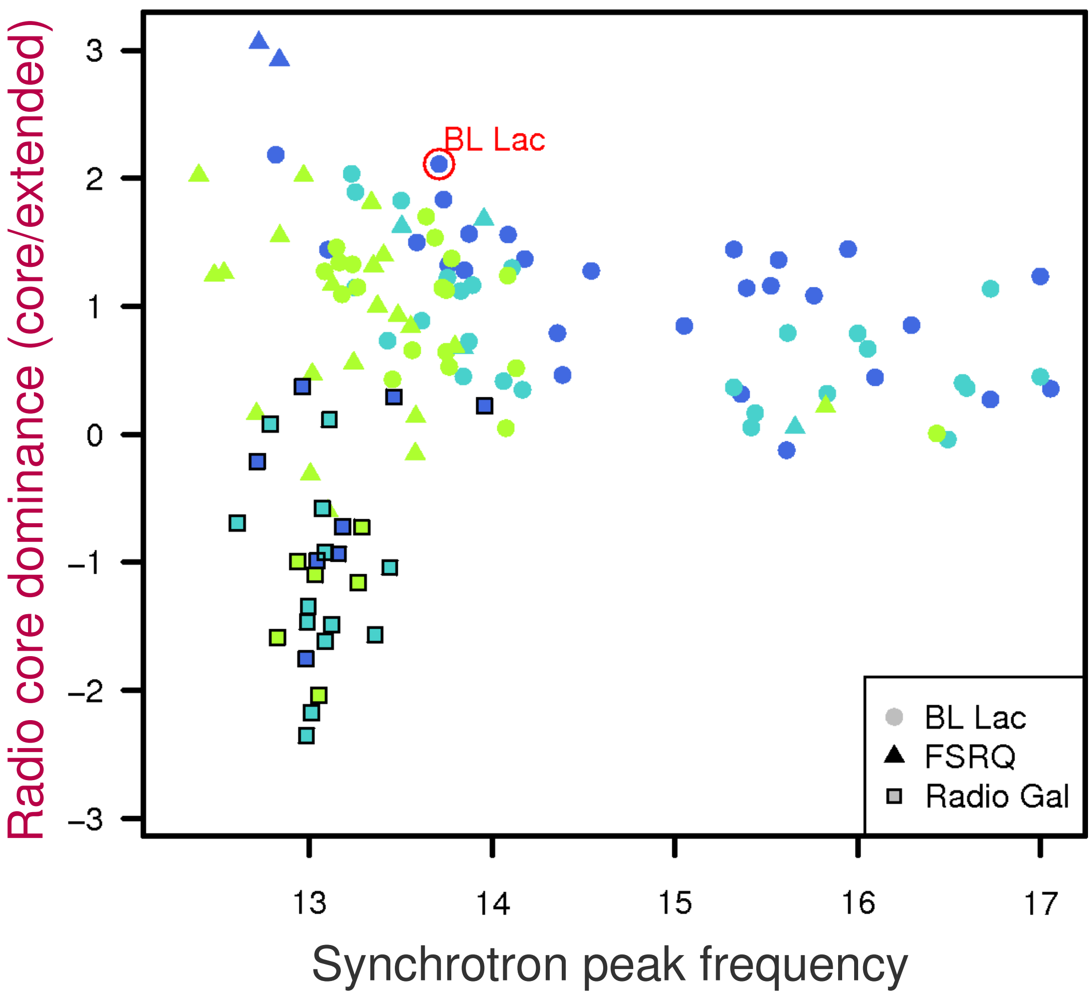
- There are several hundred more sources for which we still lack some data (spectral or imaging) to estimate their intrinsic jet power, but for which the synchrotron SED can be reliably characterized.



- 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.

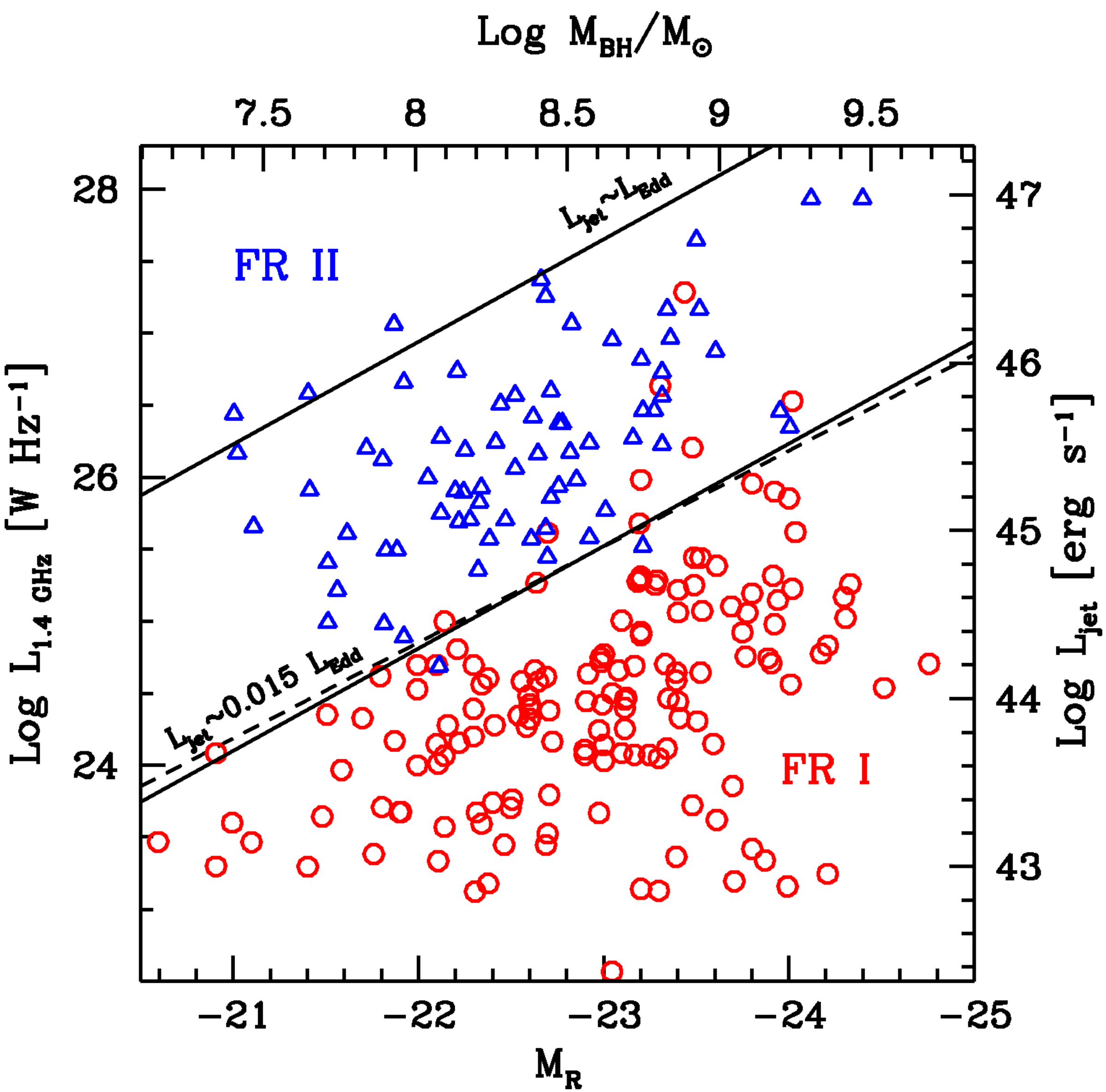
The puzzle of low jet-power sources

- 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?

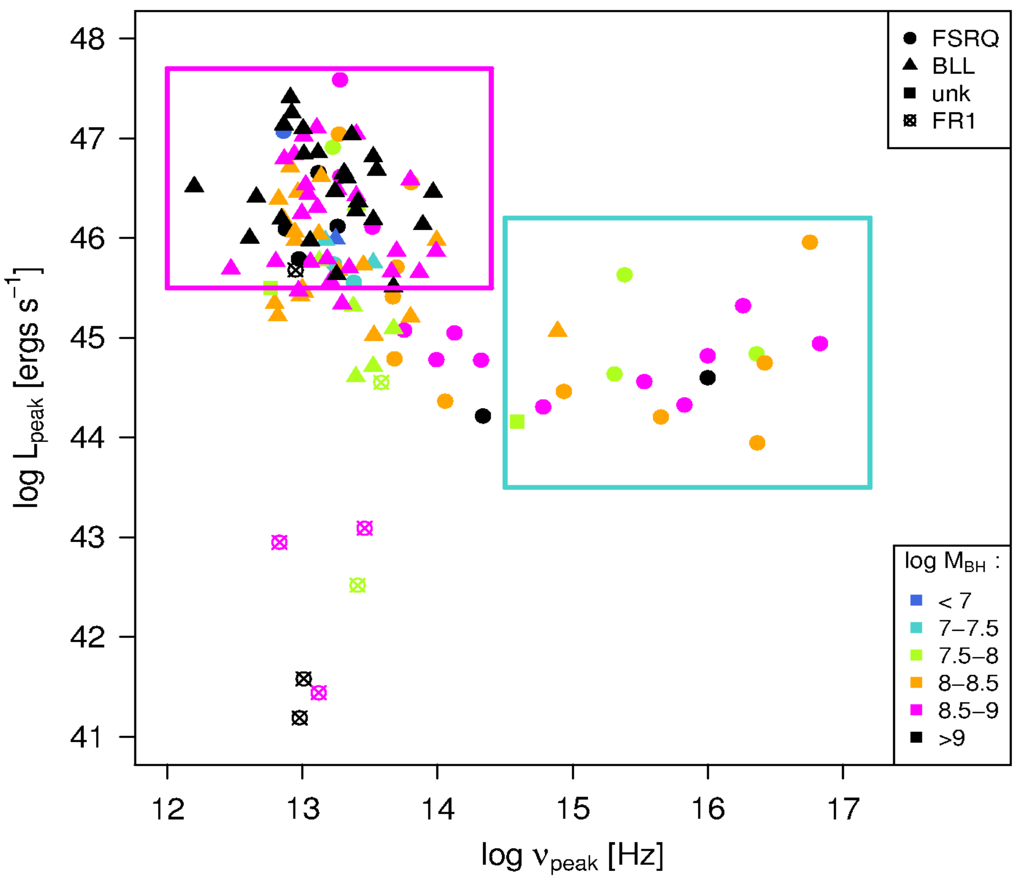
FR1/FR2 division

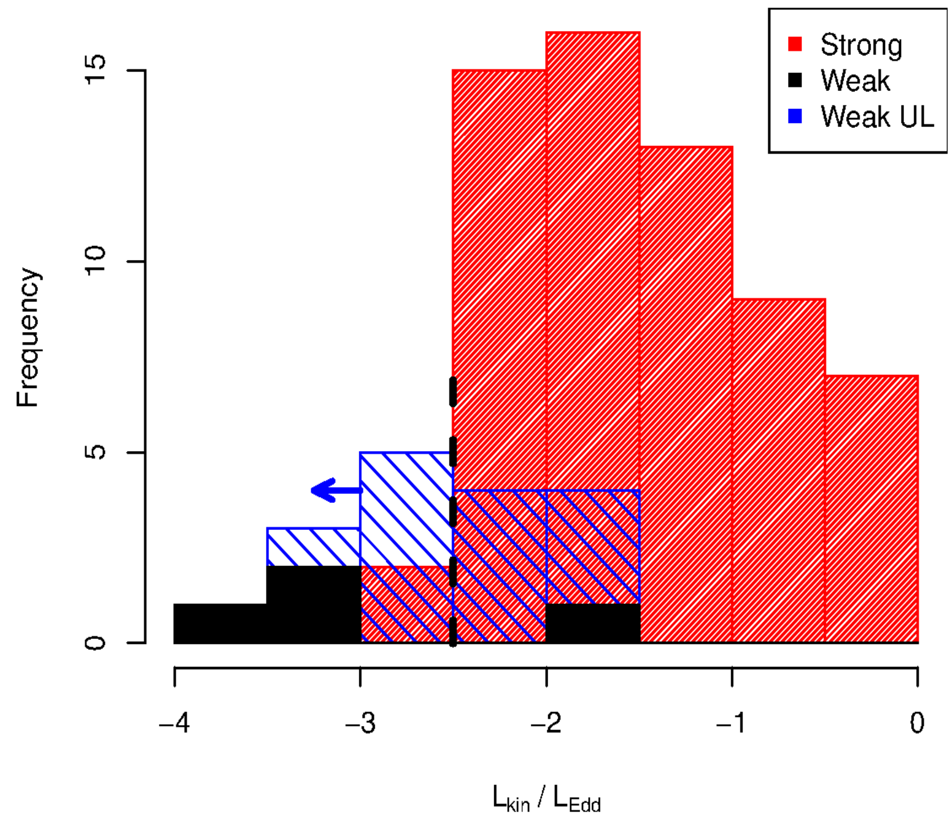


FR classes are clearly divided in the radio luminosity – stellar luminosity plane

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

L_{kin}, θ, … $\mathring{m}$?





(Mass estimates from reverberation mapping, velocity dispersions, mass-luminosity scalings)

Weak Jets = Inefficient

Strong Jets = Efficient

The Broken Power Sequence