Low-Frequency Observations as a Proxy for Jet Power in RL AGN and the Connection of Jet Power and Jet Speed

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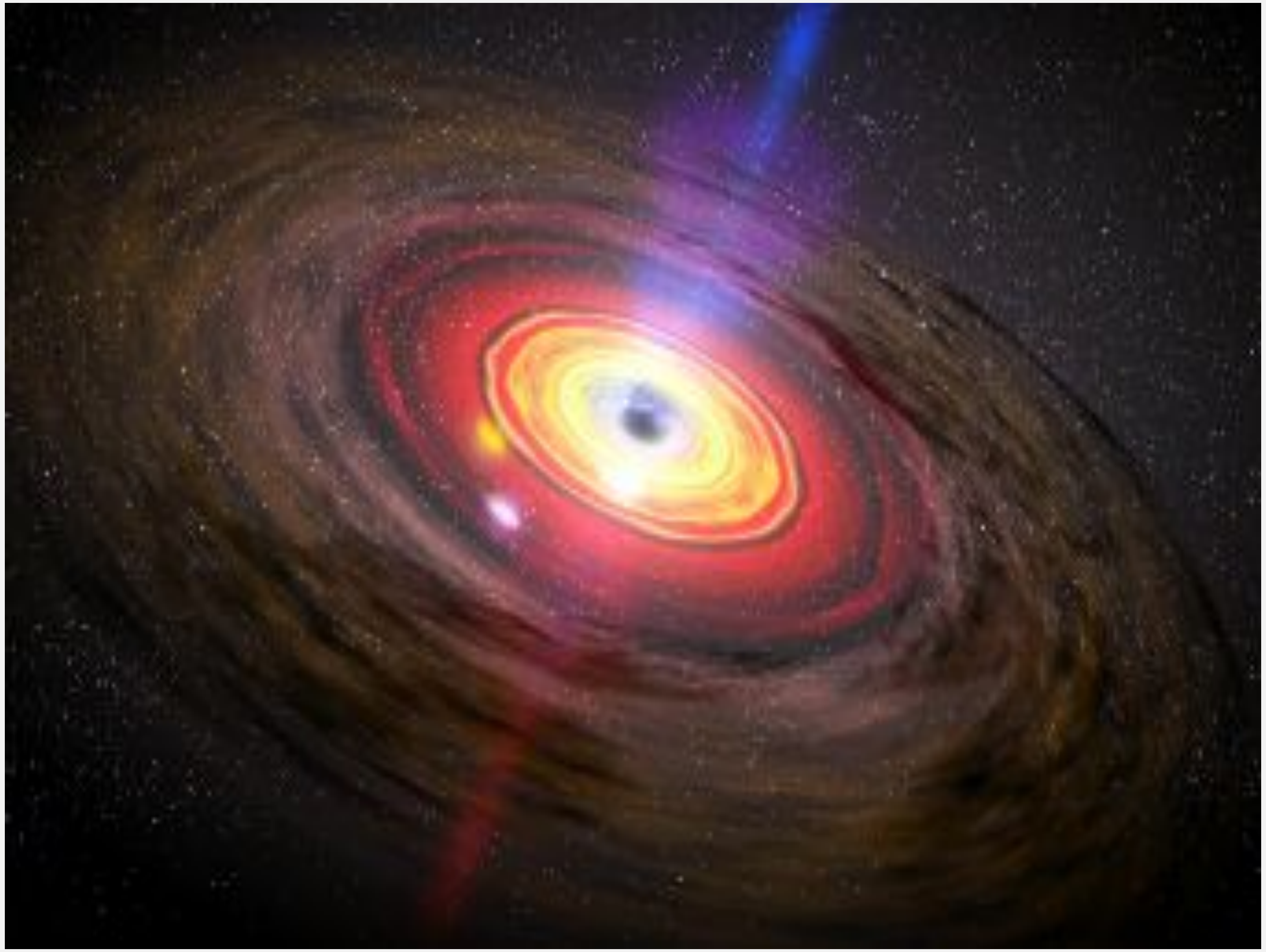
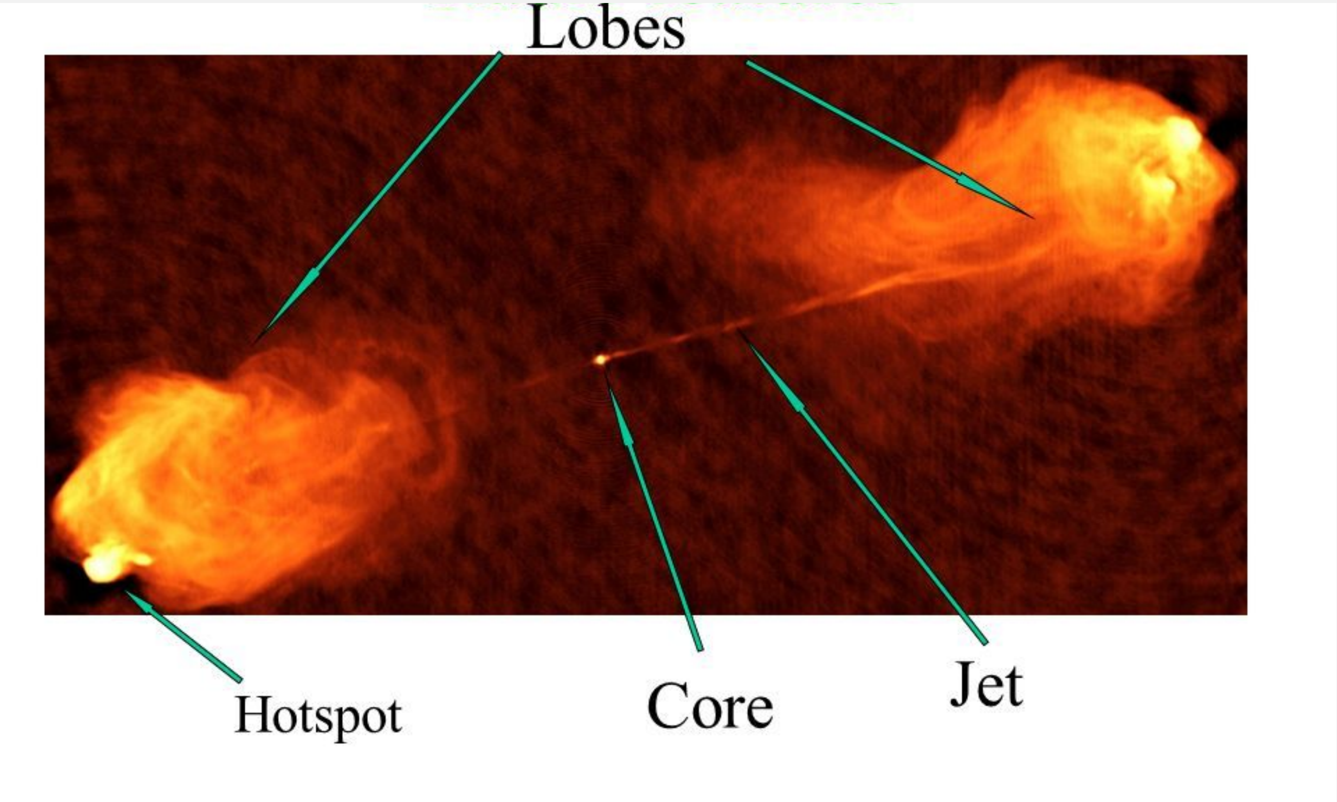
ACTIVE GALACTIC NUCLEI (AGN)

- Active Galactic Nuclei (AGN) are powered by the accretion of matter onto a supermassive black hole in the center of a galaxy.
  - Very luminous
  - Broadband spectrum: emit from radio all the way to gamma rays.



www.skyandtelescope.com

RADIO LOUD AGN

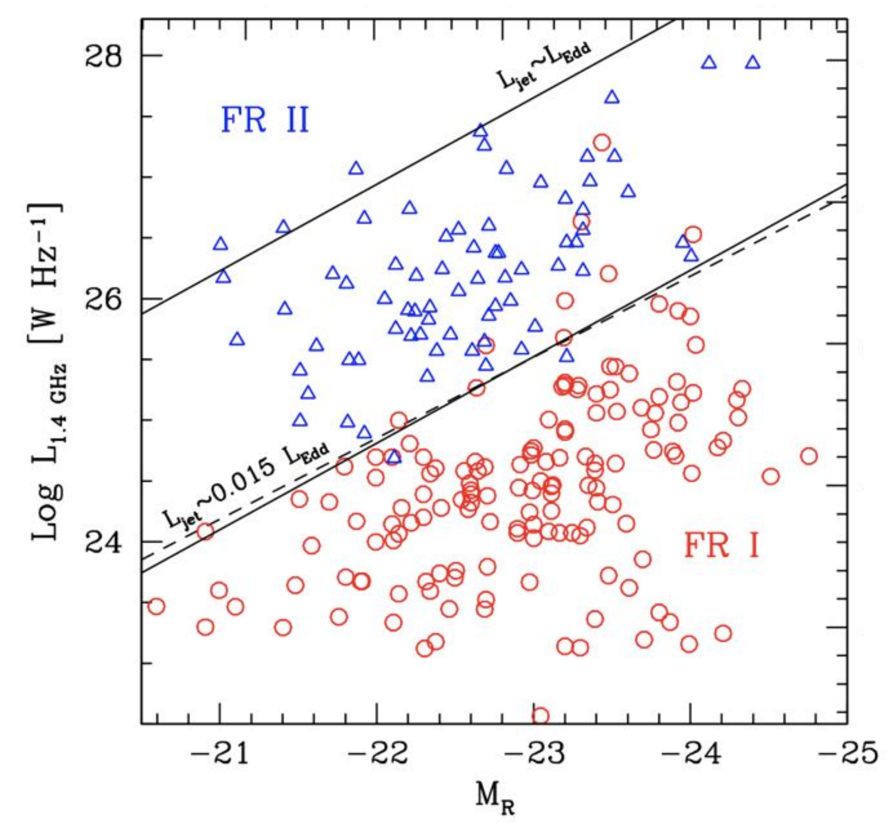


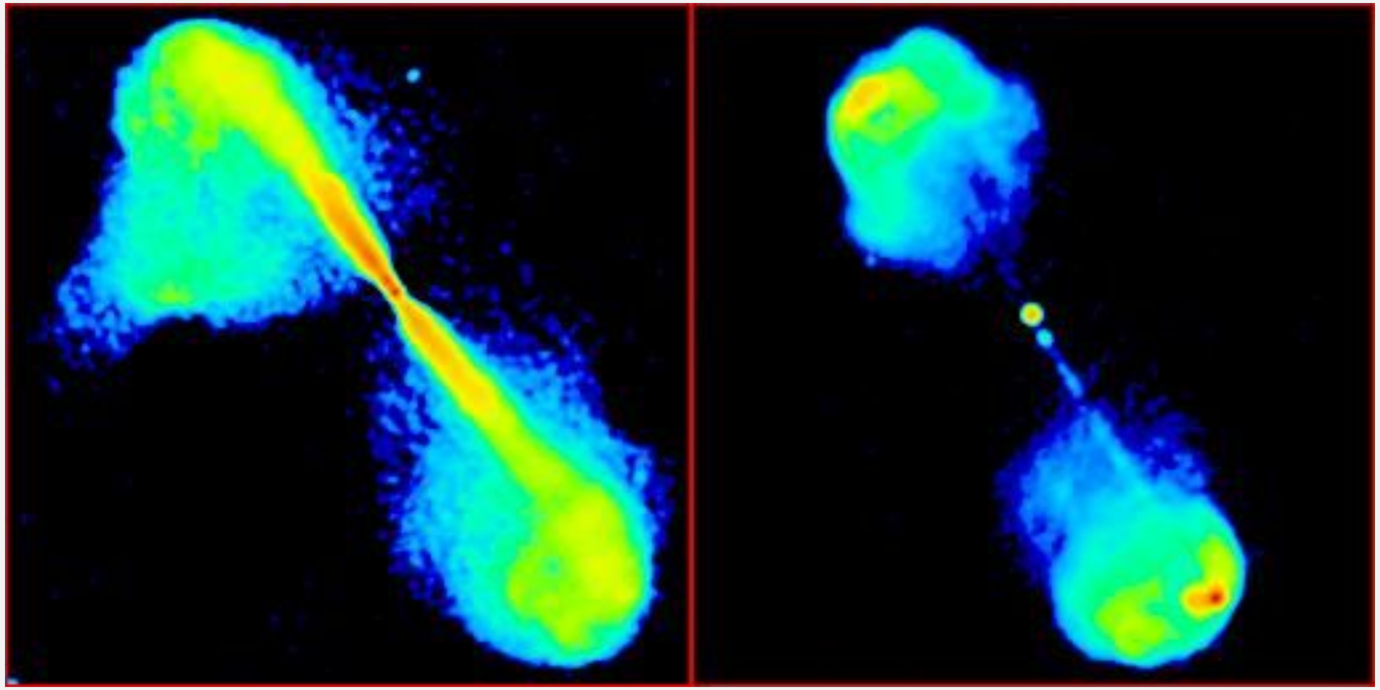
Radio image of Cygnus A

About 10% of AGN have relativistic jets

- Fully Ionized, relativistic plasma with bulk velocities close to c (Lorentz factors ~ 2-50)
- Extend from the core, can terminate in hotspots
- Slowed plasma accumulates into the lobe

RADIO GALAXIES





FR I (3C296)

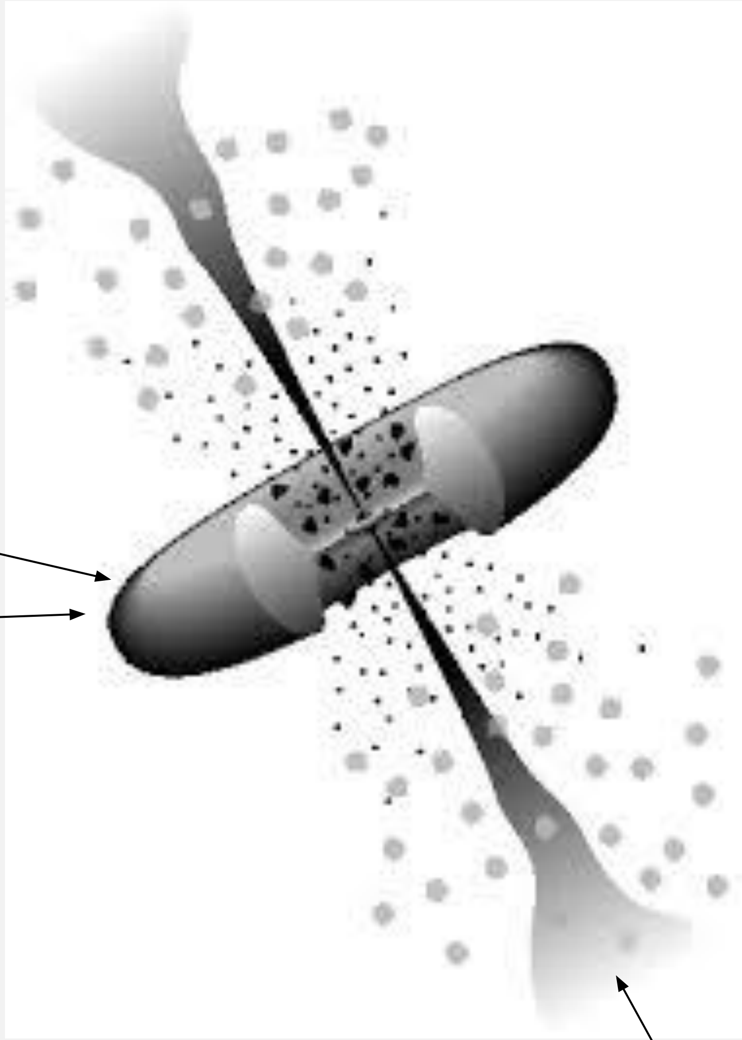
FR II (3C47)

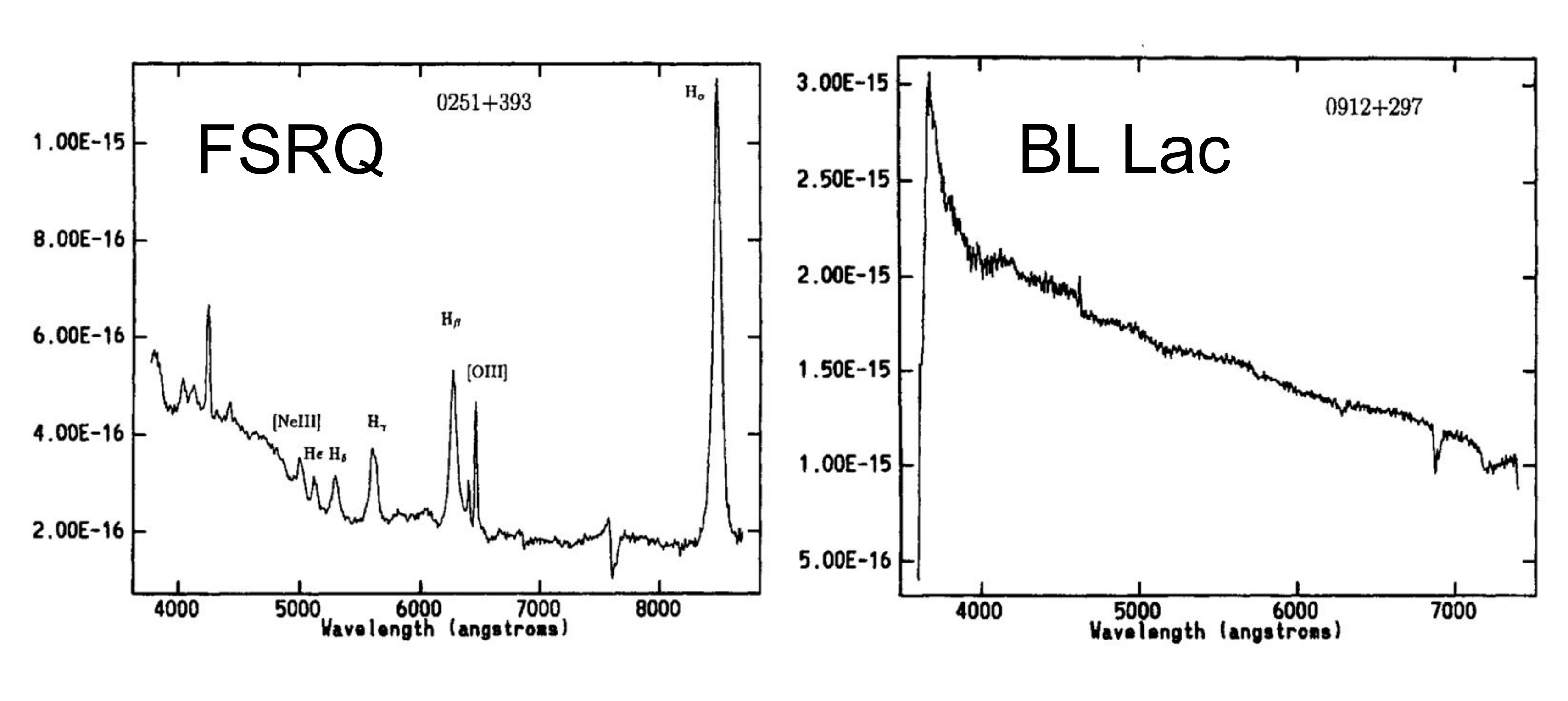
- In 1974, Fanaroff & Riley noticed difference in morphology, which resulted a distinction between FR I and FR II radio galaxies

- Ghisellini and Celloti (2001) found that this corresponded to a difference in the radio-optical plane

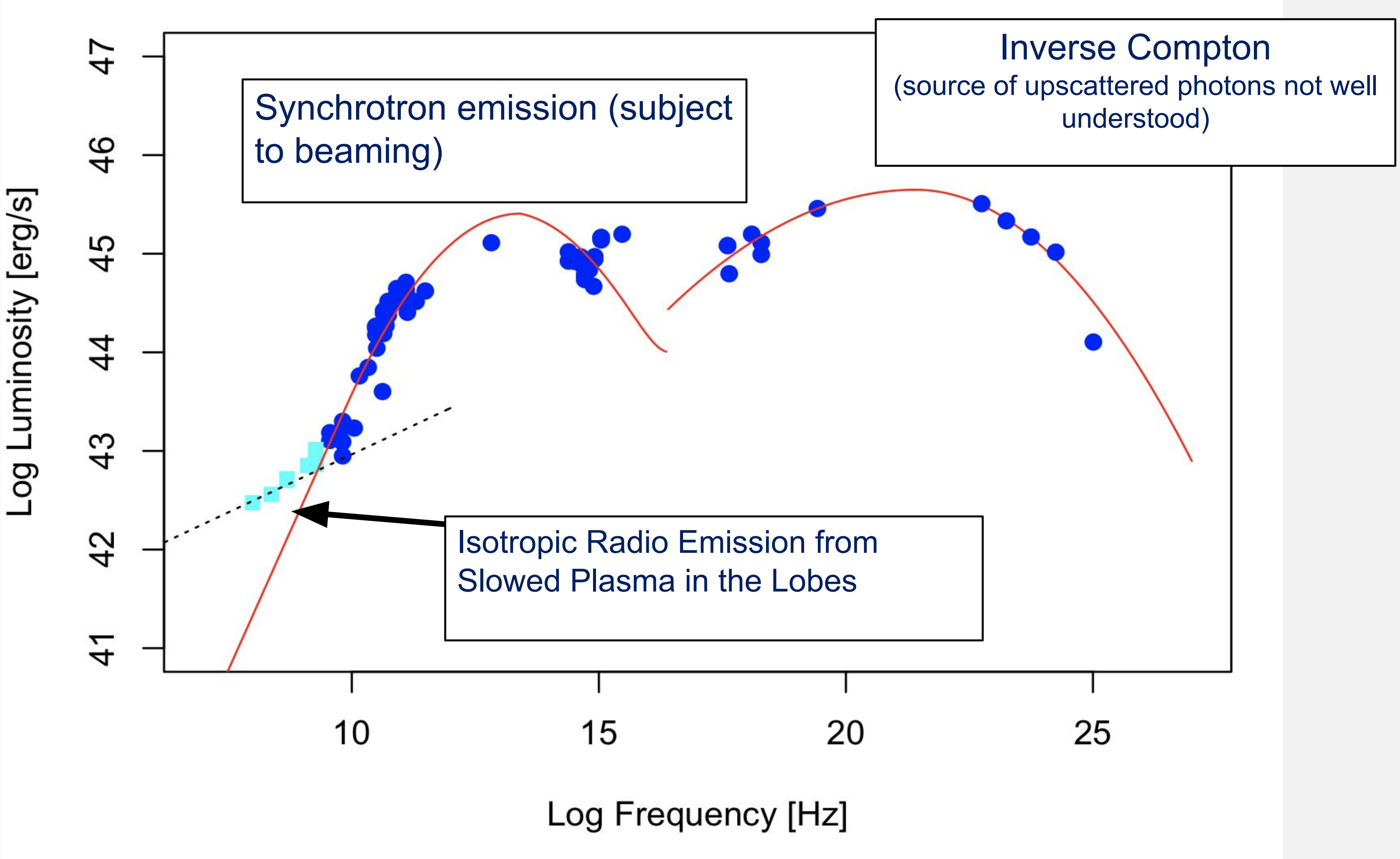
BLAZARS

- Blazars are radio galaxies with the jet oriented along the line of sight
- Two Types:
  - BL Lacertae Objects (BL Lacs)
  - Flat Spectrum Radio Quasars (FSRQ)



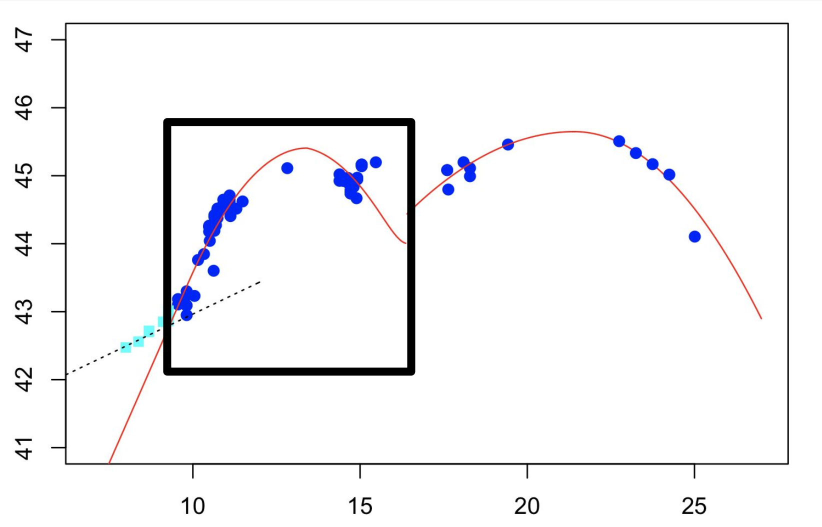


SPECTRAL ENERGY DISTRIBUTION (SED)



SYNCHROTRON PEAK

- Highly Doppler boosted emission from the core



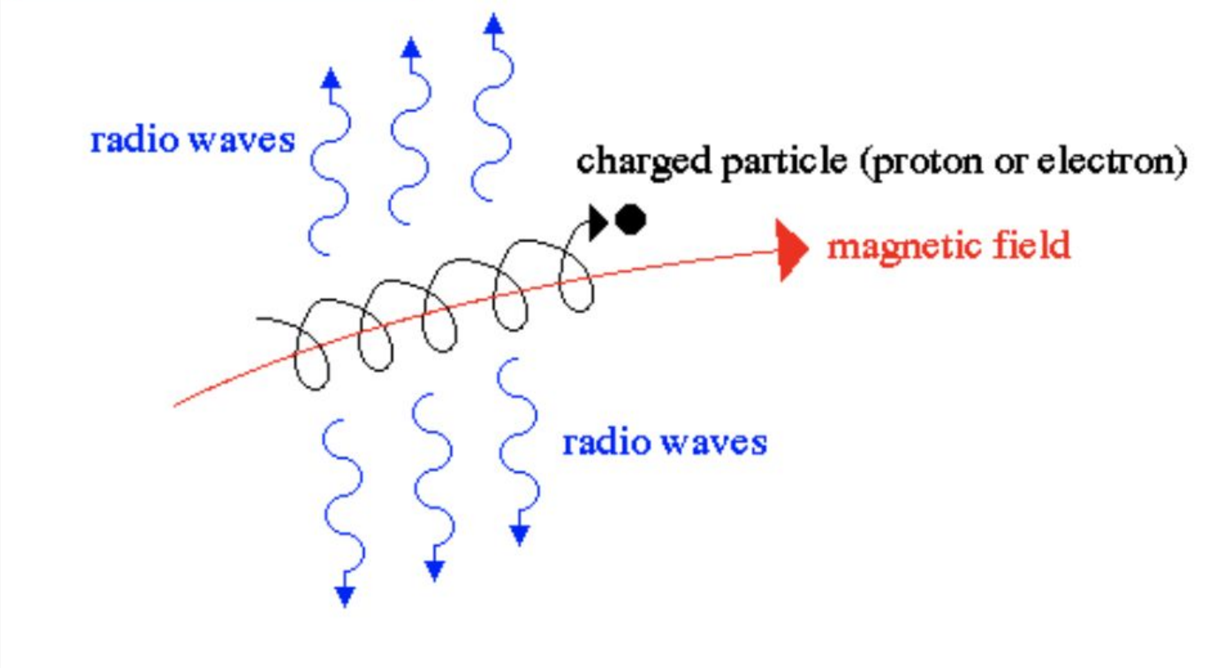
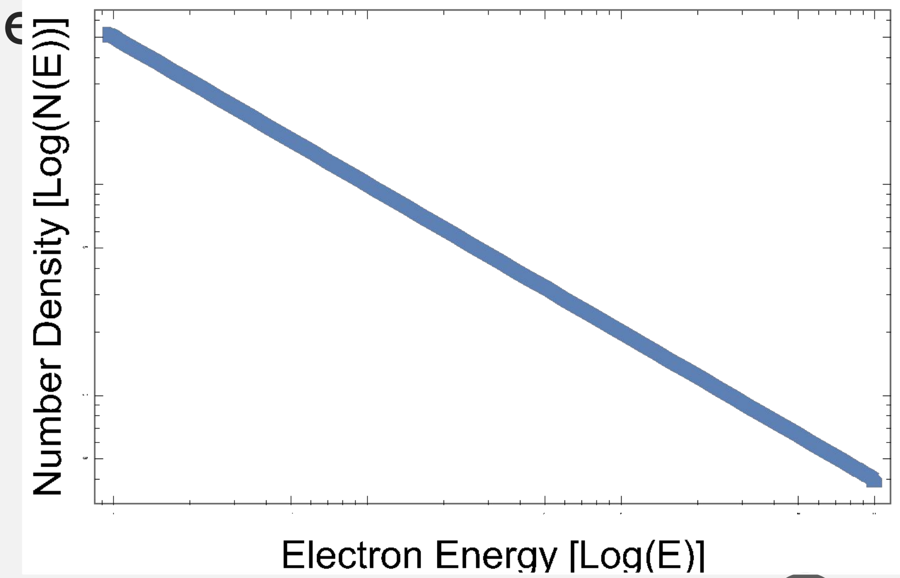


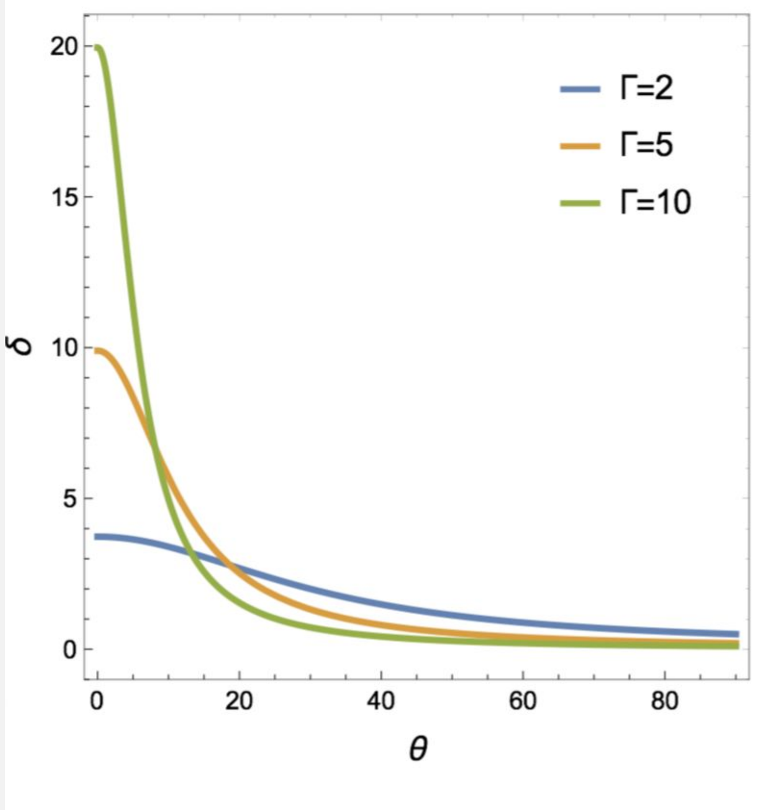
Image Credit: uoregon.edu

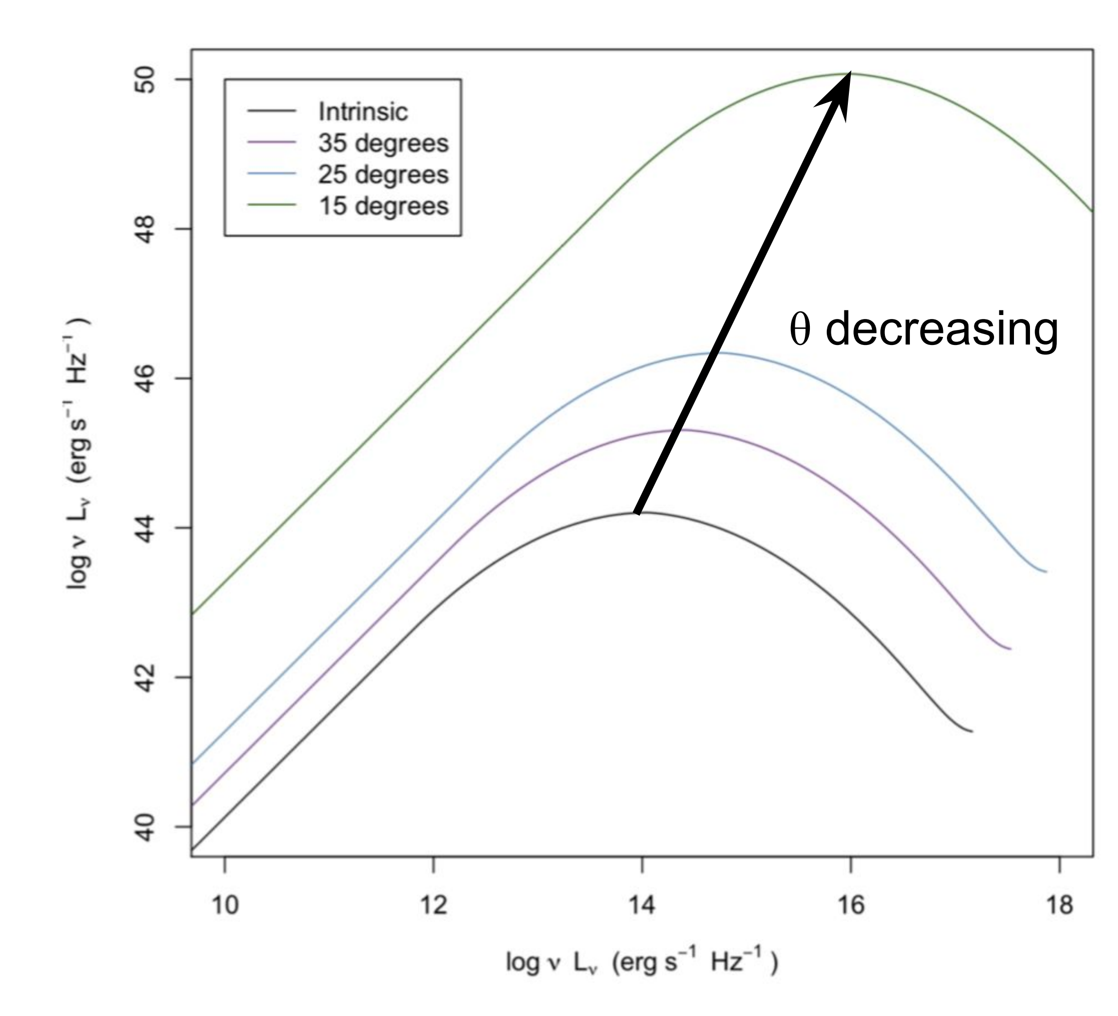
- Very broad spectrum, reflects a power-law energy distribution of e



DOPPLER BOOSTING

When the plasma is relativistic, the Apparent Luminosity/Frequency is dependent on θ, Γ





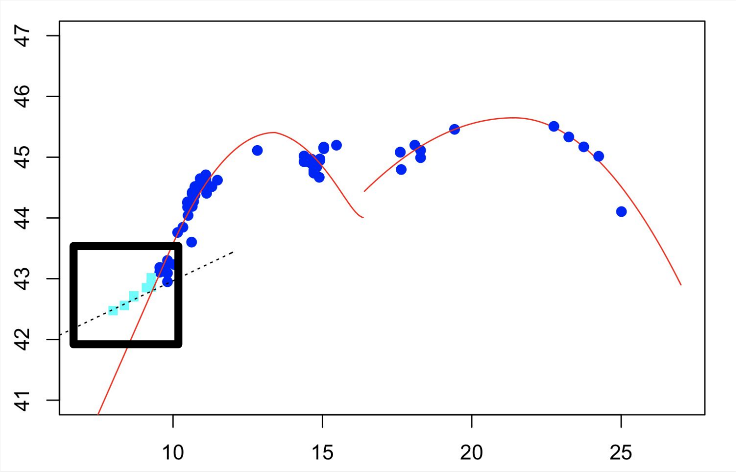
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

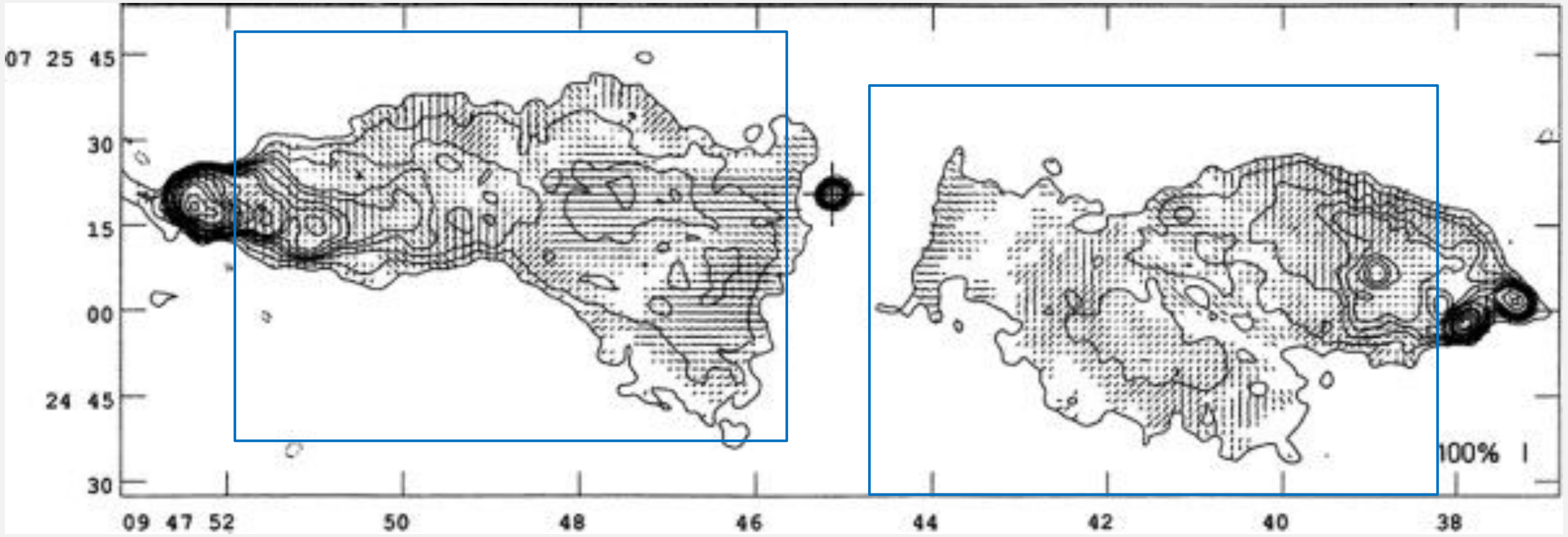
$$L_{intrinsic} = L_{observed}\,\delta^{n}$$

Can be enhanced by orders of magnitude! (in both Luminosity and Frequency)

ISOTROPIC LOBE EMISSION

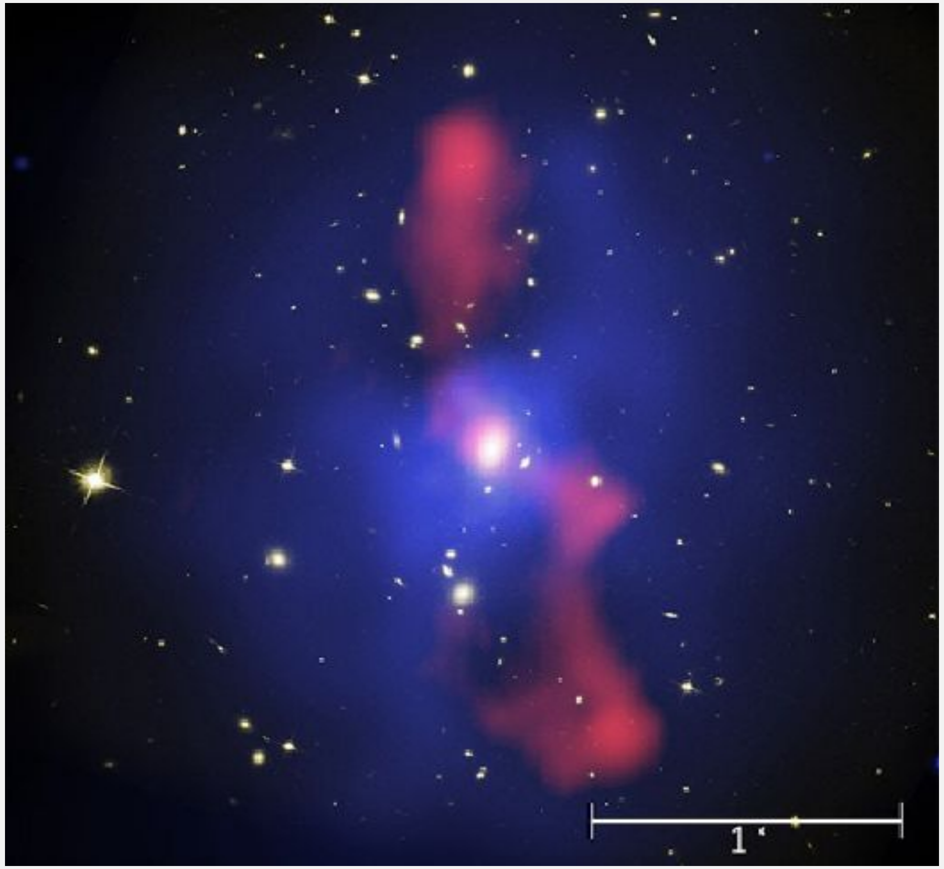
- Also synchrotron emission
- Emitted by the slowed plasma in the lobes
- Not subject to Doppler boosting
- Built up over the lifetime of the source



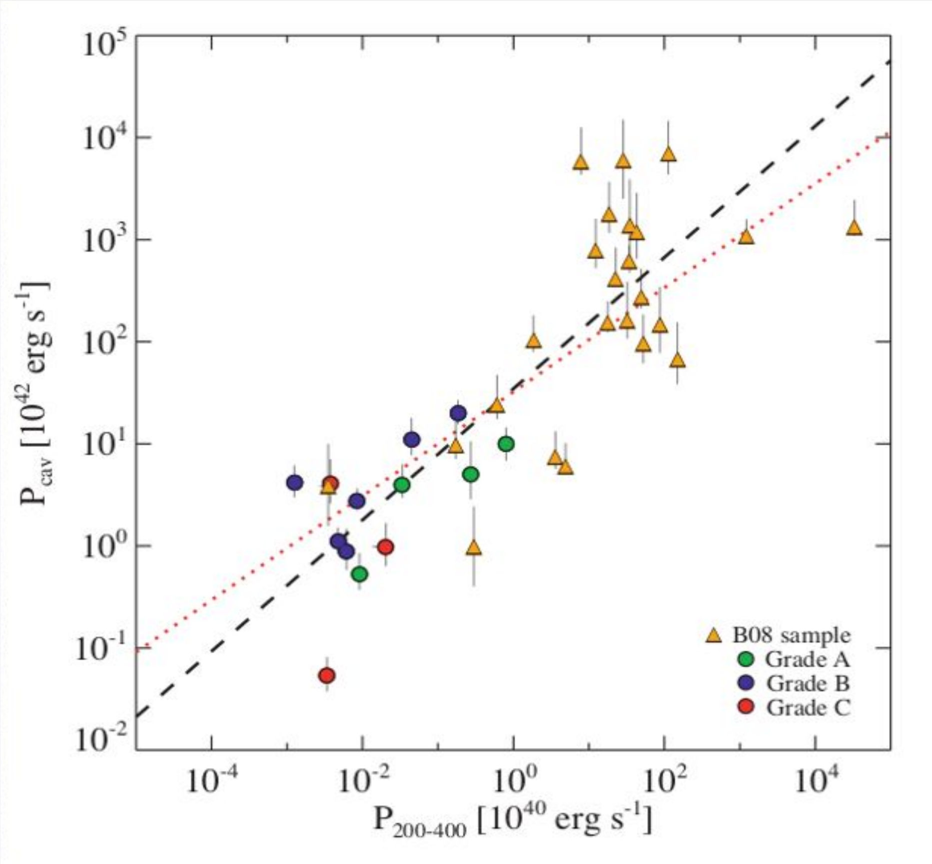


Radio Image of 3C 227

LOW-FREQUENCY OBSERVATIONS AS A PROXY FOR JET POWER

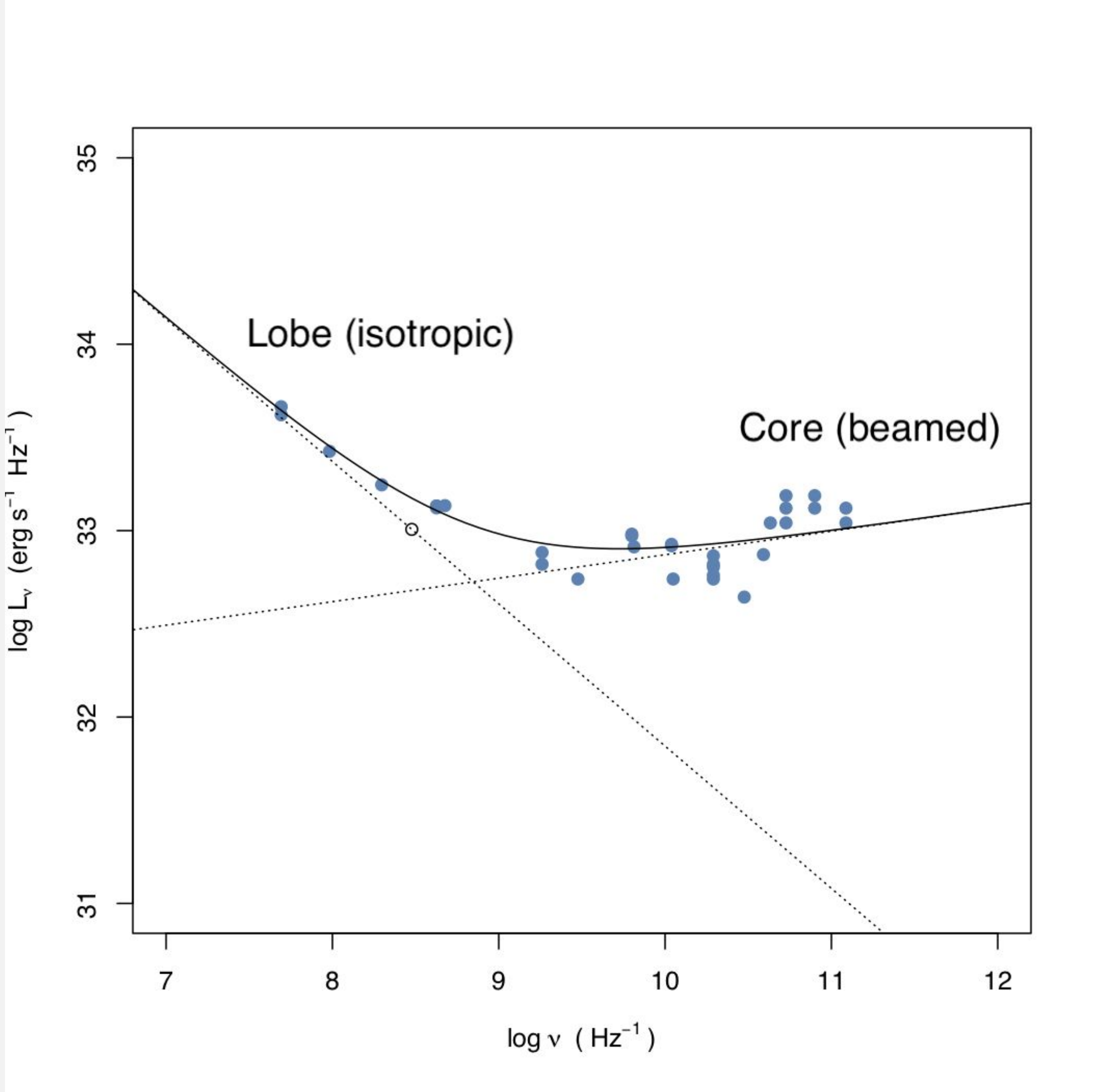


MS0735.6 (McNamara et al. 2009) shows the x-ray emission in blue and radio emission in red. Jets inflate cavities in hot X-ray emitting gas.



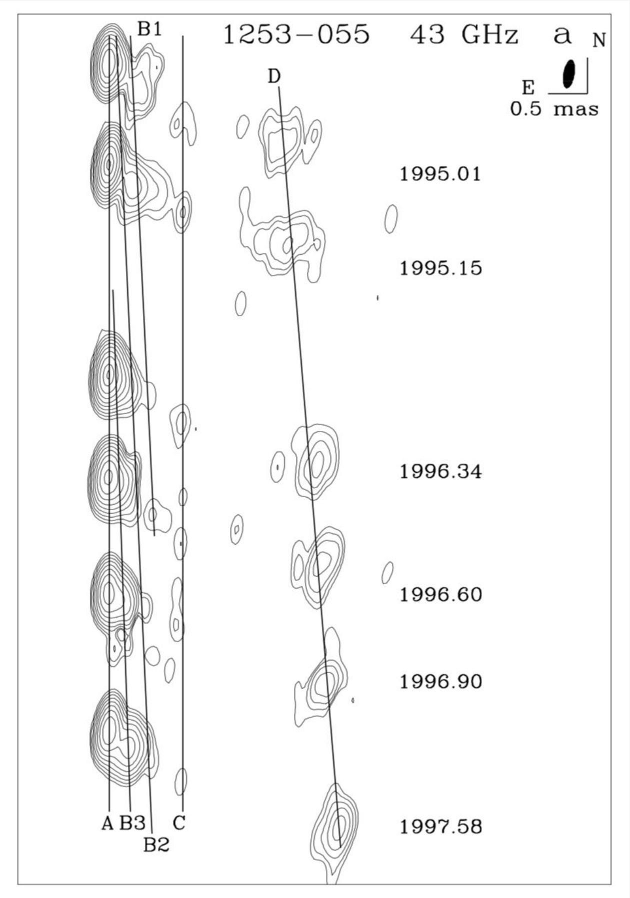
Cavagnolo, et al., 2010 estimated the work required to inflate the cavities of FR Is, and found that it is correlated with the low frequency emission.

RADIO SPECTRAL DECOMPOSITION



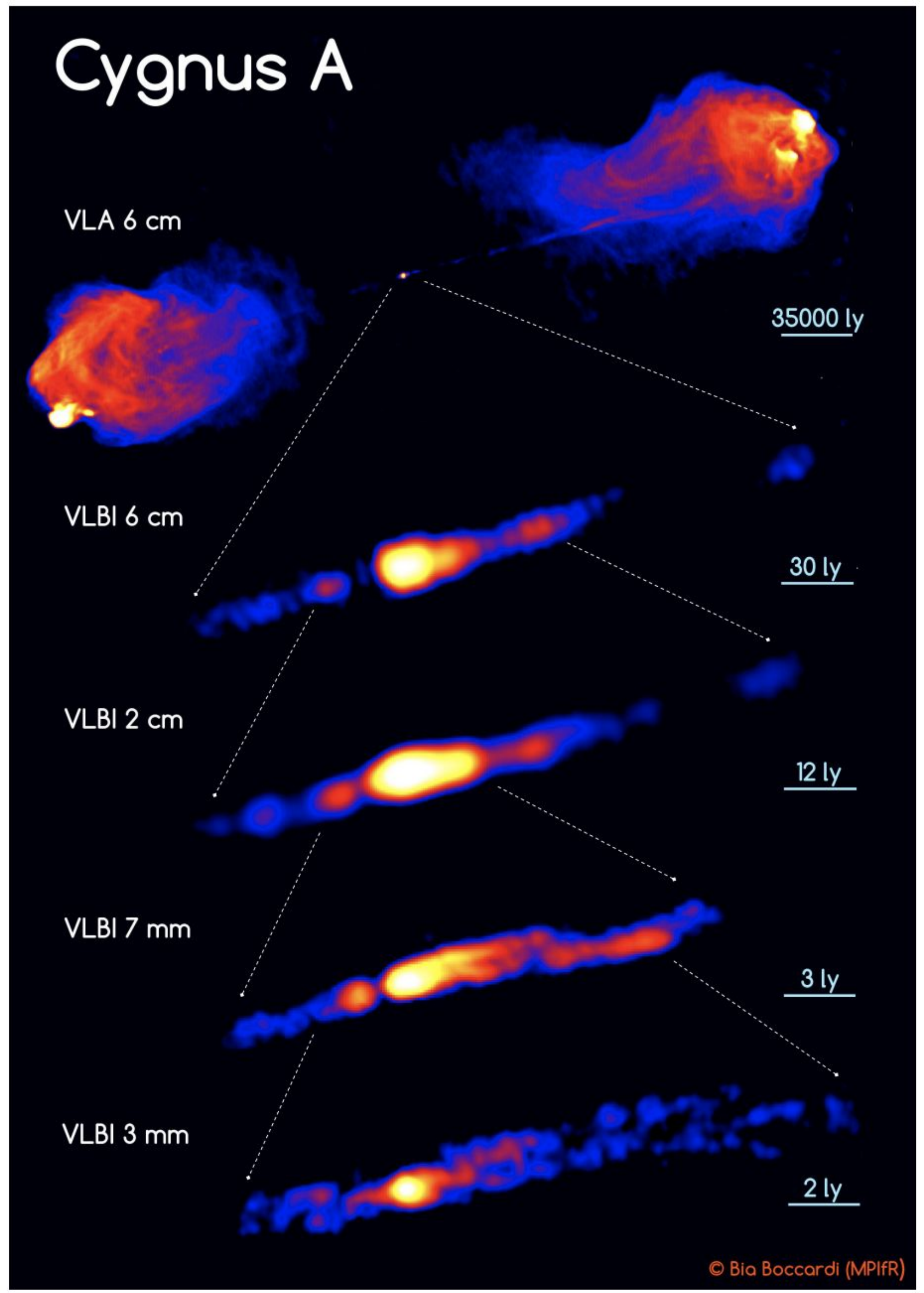
- The spectra can be decomposed by looking for a spectral break in ν vs L_ν
  - Lobe emission is falling
  - Core emission is flat
- Model components with individual power law fits
- Fits can then be extrapolated to

VLBI PROPER MOTIONS

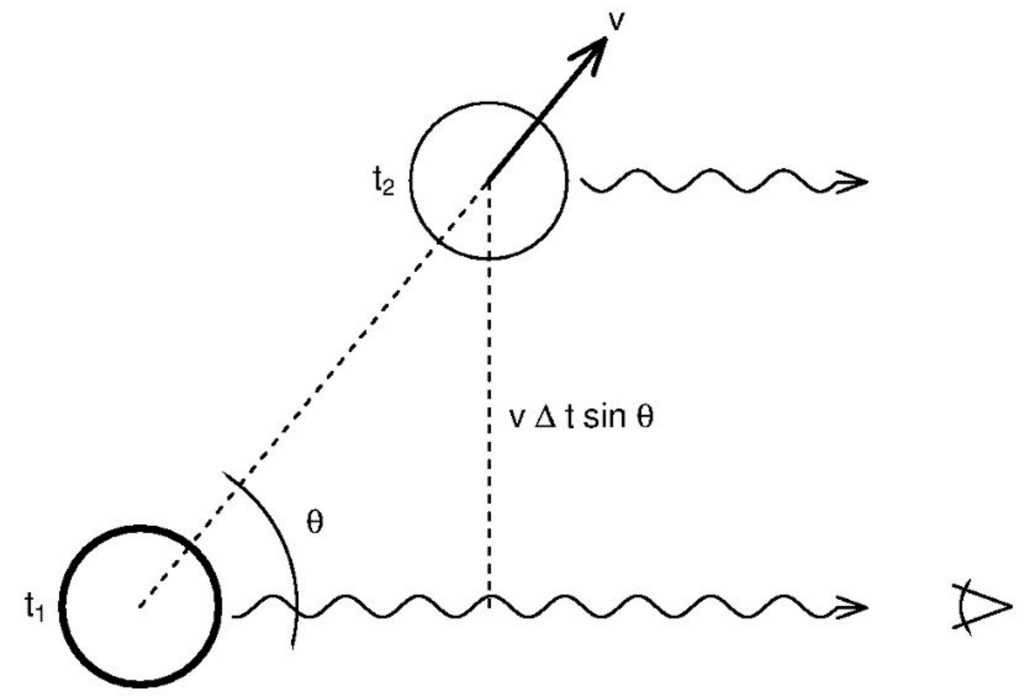


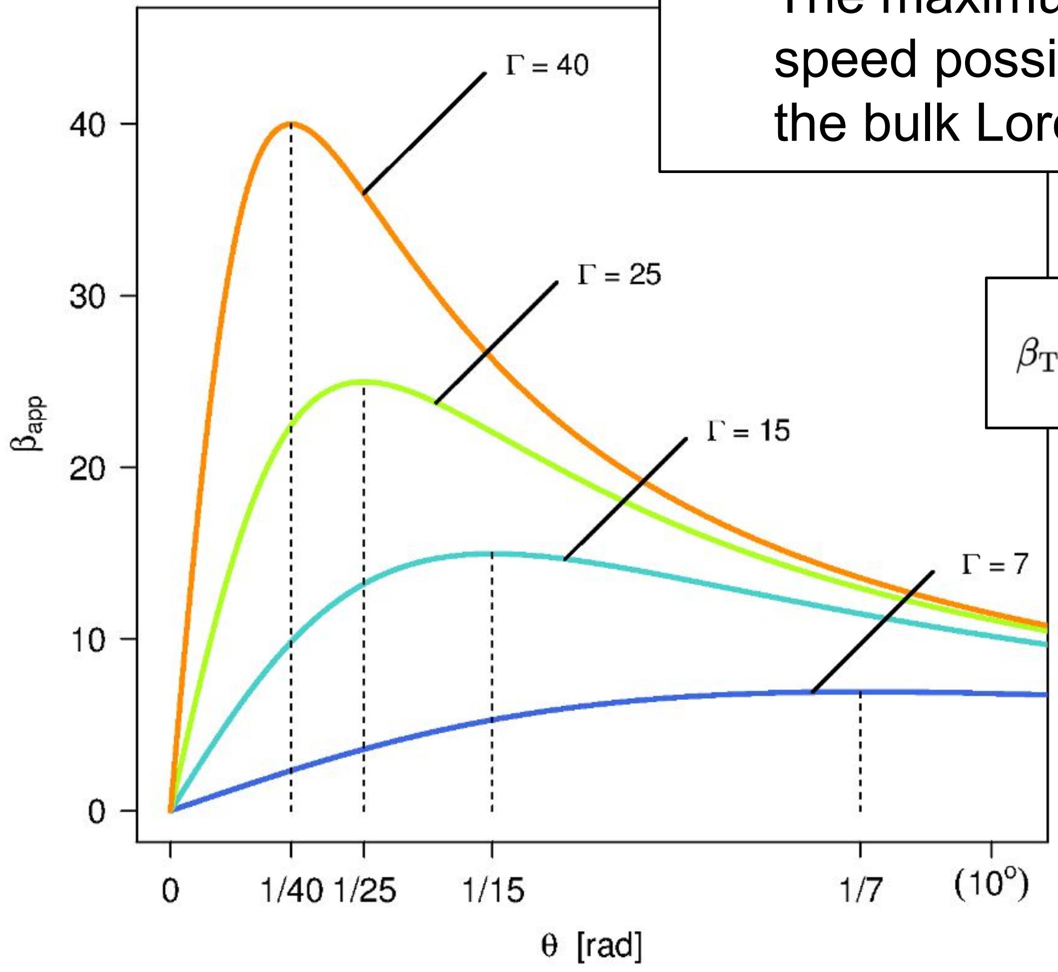
Jorstad+ 2001

- VLBI Images have a high enough resolution to resolve knots on the parsec scale.
- Proper Motions are the apparent angular motion of features within the jet



APPARENT SUPERLUMINAL MOTION





The maximum apparent speed possible is equal to the bulk Lorentz factor **Γ**

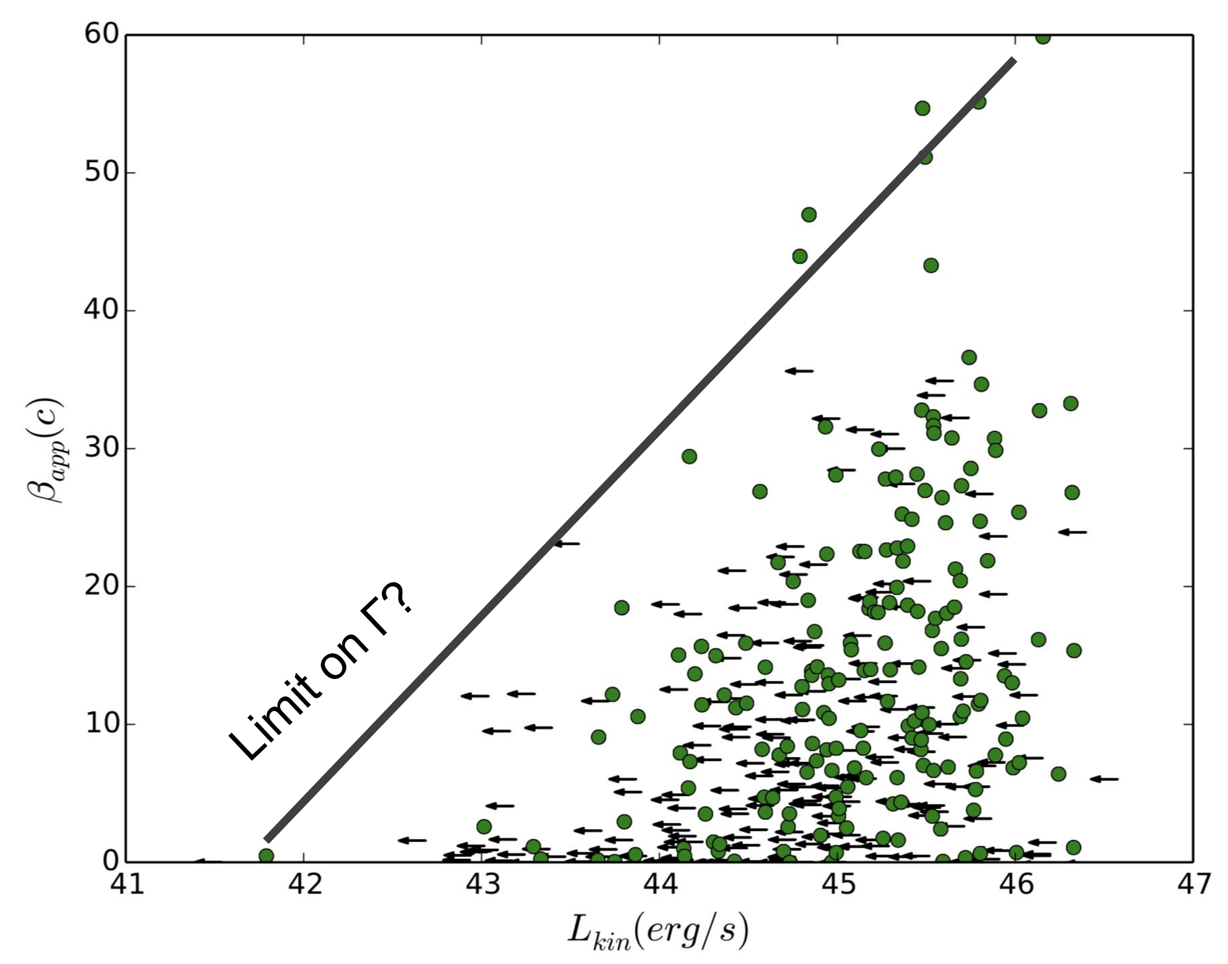
$$\beta_{\mathrm{T}} = \frac{v_{\mathrm{T}}}{c} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}$$

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

JET POWER – JET SPEED (PRELIMINARY) RESULTS

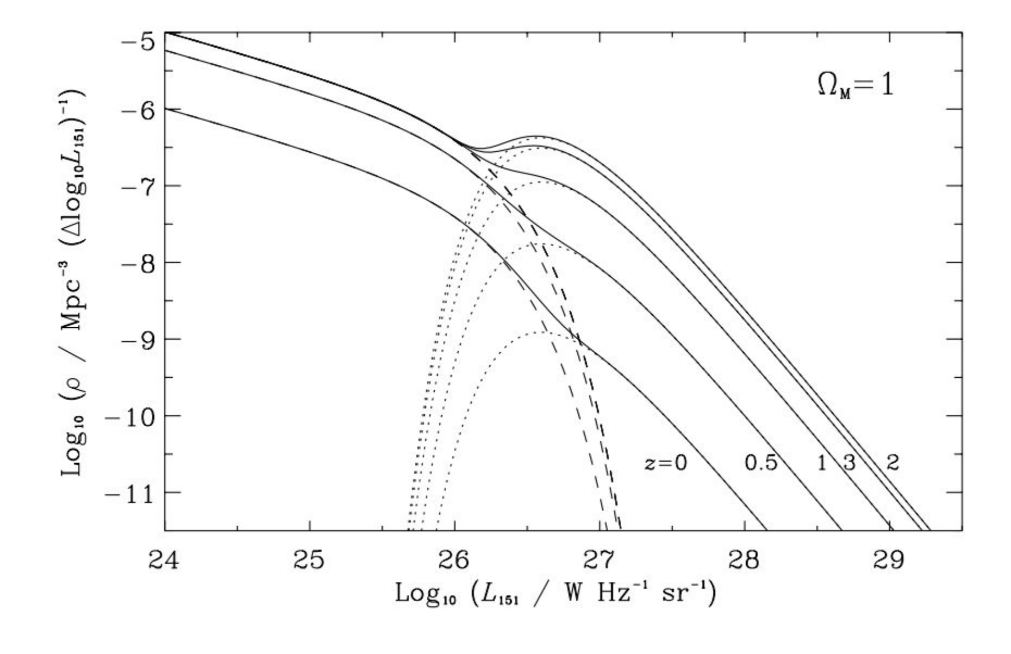
- Question: Can the data be explained by a one-to-one relation between **Γ** and L_{ext}? Or does L_{kin} set an upper limit on **Γ**?

- **Limit on Γ is due to the jet being oriented at the critical angle**



POPULATION MODELING

- Drew three parameters to classify each source:
  - Redshift: drawn from shell of constant co-moving volume
  - Extended Luminosity drawn from the model in Willott et al. 2001
  - Angle: selected randomly
- Need estimates for the Core Luminosity and the Lorentz factor



Willott Model

$$\rho(L, z) = \rho_{\mathrm{l}} + \rho_{\mathrm{h}}$$

where

$$\rho_{\mathrm{l}} = \rho_{\mathrm{l}\circ}\left(\frac{L}{L_{\mathrm{l}*}}\right)^{-\alpha_{\mathrm{l}}} \exp\left(\frac{-L}{L_{\mathrm{l}*}}\right)(1+z)^{k_{\mathrm{l}}} \qquad \text{for } z < z_{\mathrm{l}\circ},$$

$$\rho_{\mathrm{l}} = \rho_{\mathrm{l}\circ}\left(\frac{L}{L_{\mathrm{l}*}}\right)^{-\alpha_{\mathrm{l}}} \exp\left(\frac{-L}{L_{\mathrm{l}*}}\right)(1+z_{\mathrm{l}\circ})^{k_{\mathrm{l}}} \qquad \text{for } z \geqslant z_{\mathrm{l}\circ},$$

$$\rho_{\mathrm{h}} = \rho_{\mathrm{h}\circ}\left(\frac{L}{L_{\mathrm{h}*}}\right)^{-\alpha_{\mathrm{h}}} \exp\left(\frac{-L_{\mathrm{h}*}}{L}\right) f_{\mathrm{h}}(z).$$

$$f_{\mathrm{h}}(z) = \exp\left[-\frac{1}{2}\left(\frac{z - z_{\mathrm{h}\circ}}{z_{\mathrm{h}2}}\right)^2\right]$$

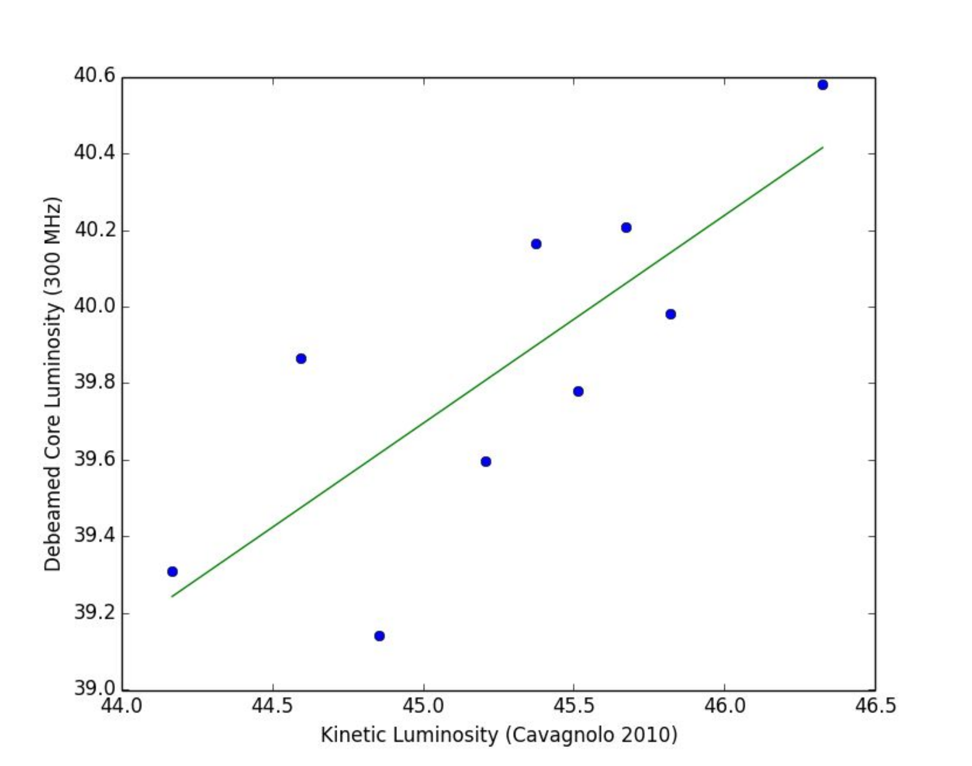
CORE LUMINOSITY ESTIMATION

- Assumed that the $L_{core,intrinsic}$ is linearly related to the $L_{kinetic}$
  - Binned the sample by $L_{kinetic}$
  - Took three sources from each bin, with the highest measurements of $\beta_{apparent}$ and took the corresponding $L_{core,observed}$.
  - Assumed $\theta = \theta_{critical}$ in order to "debeam" $L_{core,observed}$ for an estimate of $L_{core,intrinsic}$
  - Averaged $L_{core,intrinsic}$ for the relation

$$\log L_{core,intrinsic} = 0.542 \log L_{kinetic} + 15.276$$

$$L_{core,observed} = L_{core,intrinsic}\, \delta^n$$

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



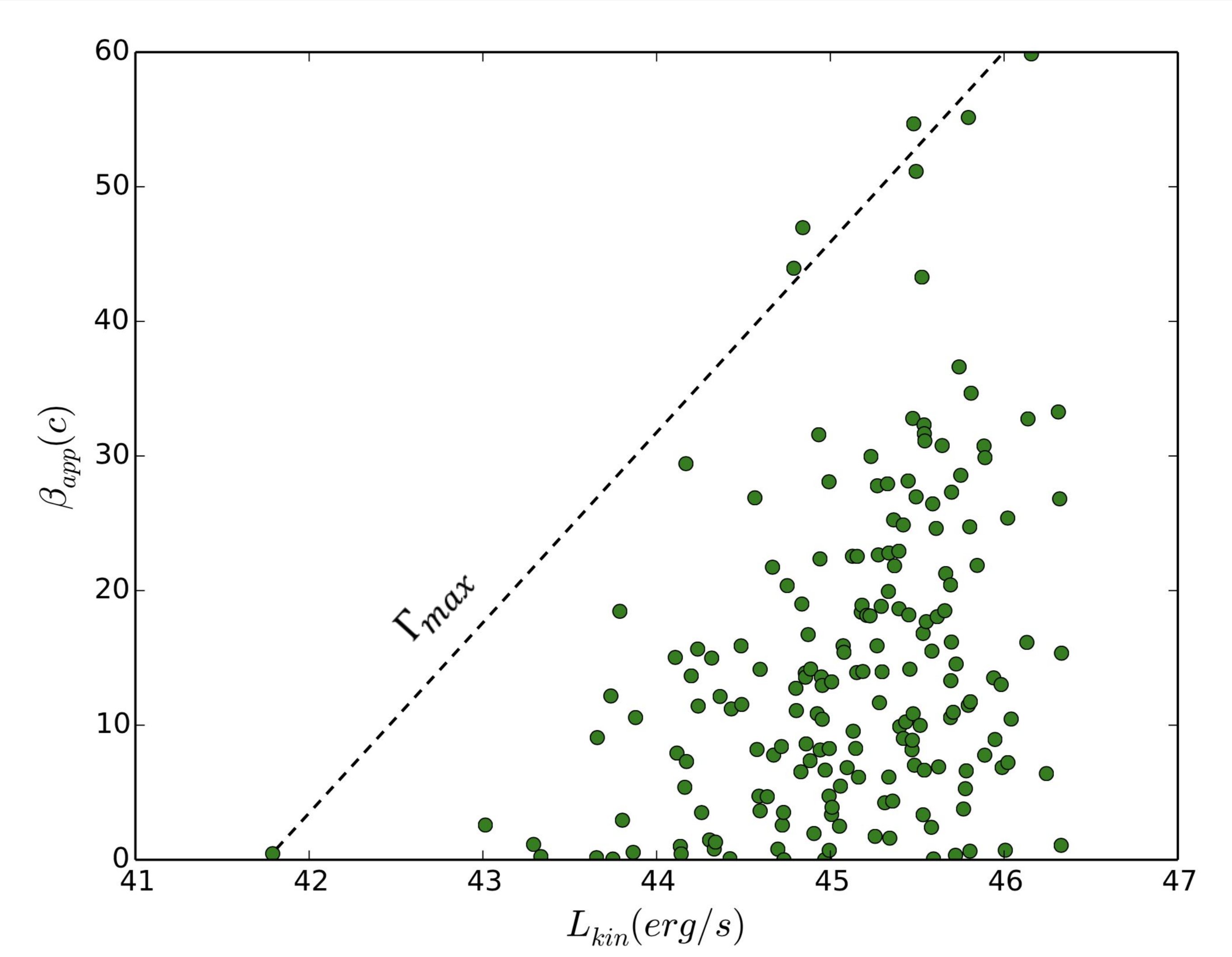
Note: Core Luminosities are taken at 300 MHz

LORENTZ FACTOR

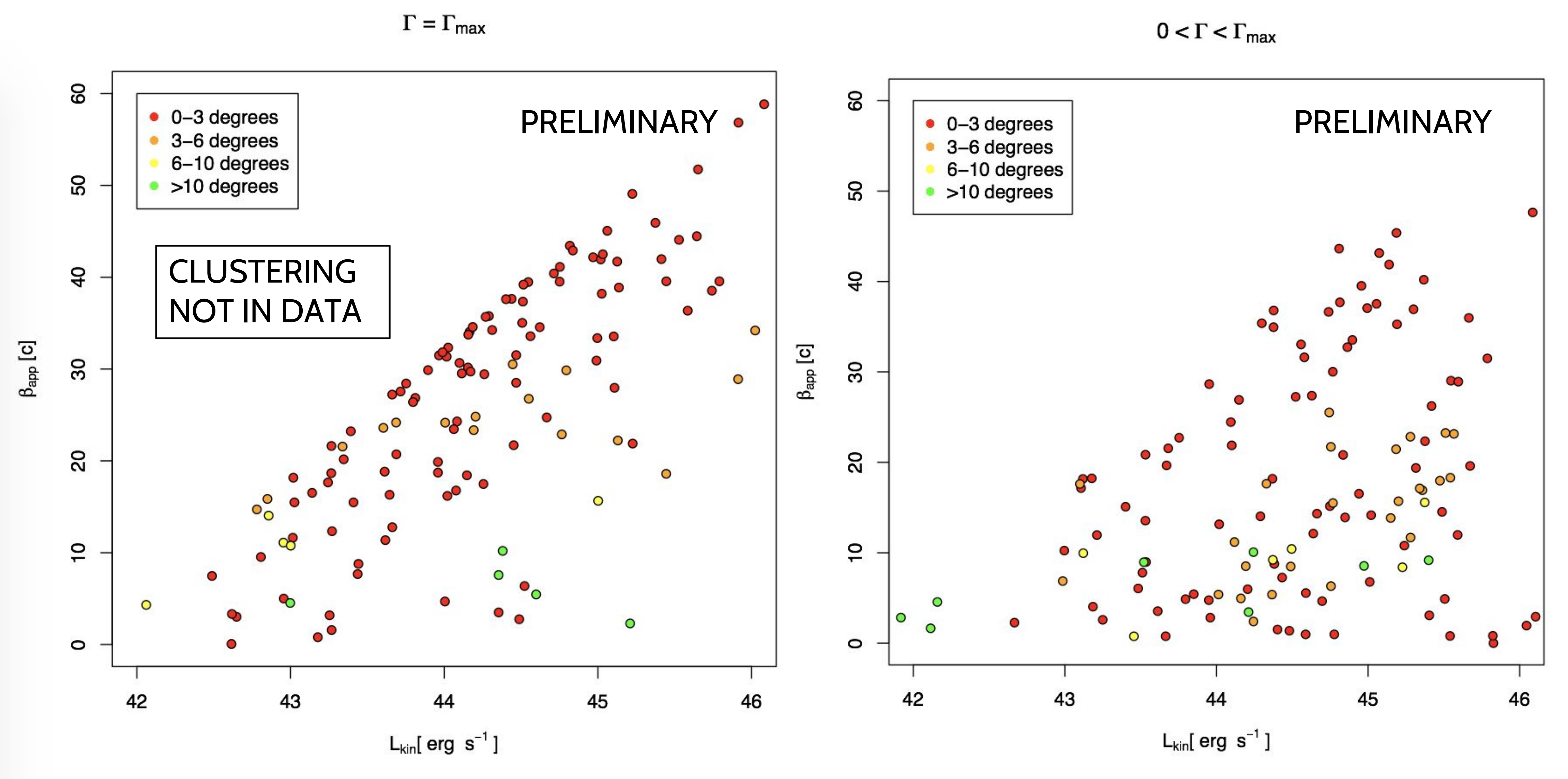
- For sources at the critical angle: $\Gamma \cong \beta_{apparent}$
- Assumed that the upper edge is at the critical angle and Γ is linearly related to $L_{kinetic}$

$$\Gamma_{max} = 14\, L_{kinetic} - 584$$

- Note: this relation was fit by eye
- Looking into two cases:
  - $\Gamma = \Gamma_{max}$
  - $0 < \Gamma < \Gamma_{max}$



RESULTS OF POPULATION MODEL



INCREASING THE SAMPLE

- Increasing the sample:
  - Spectral decompositions: ~400 sources total, 180 of them have good spectra (>200 are currently upper limits)
  - Analyzing radio/sub-mm archival data to fill in low frequency spectra