BH Astrophys Ch1~2.2

http://www.astro.princeton.edu/~burrows/classes/250/distant_galaxies.html

http://abyss.uoregon.edu/~js/ast123/lectures/lec12.html

Outline

Ch1.

1. Why do we think they are Black Holes?(1.1-1.2)
2. How heavy are they?(1.3)

Ch2.

1. Overview of the unification
2. Early understanding of seyferts (2.1)
3. Radio Galaxies, Quasars and their unification(2.2-2.2.3.2)
   * Basics of synchrotron emission and spectra
   * Beaming and superluminal motion
4. Blazars(2.2.3.4-2.2.3.5)
5. Cosmic Evolution of RGs and QSRs (2.2.4)

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The incredible energy output

First quasars discovered had luminosity $\sim 10^{46}$ erg/s

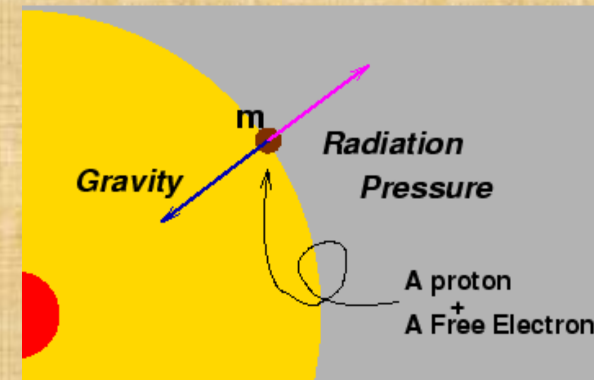
(for comparison, $L_{\odot} \sim 4\times 10^{33}$ erg/s)

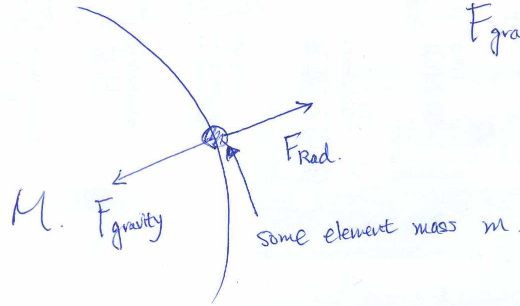
In order not to be “blown-off” the surface, one requires sufficient gravity.

The simplest estimate is using the Eddington limit.

$$L_{\rm Edd} \equiv \frac{4\pi GMc}{\kappa_{\rm es}} = 1.25\times 10^{38}\,{\rm erg\,s^{-1}}\;m$$

Eddington luminosity





$$F_{gravity} = \frac{GMm}{R^2}.$$

$$F_{radiation} = \frac{dP}{dt} = \frac{1}{c}\frac{dE}{dt} \text{ for photons.}$$

$\frac{dE}{dt}$ is "power" recieved by the mass element.

Recieved power is related to energy flux by

energy flux × cross section = recieved power

$\left(\frac{dE}{dA\,dt}\right)$ → $\frac{L}{4\pi R^2}$; σ (units of A) → For simple case, just use σ_T as first estimate ; $\frac{dE}{dt}$

$$\Rightarrow \frac{L}{4\pi R^2}\cdot\sigma_T\cdot\frac{1}{c} \sim \frac{GMm}{R^2} \Rightarrow L = \frac{4\pi GMc}{\sigma_T/m} = \frac{4\pi GMc}{\kappa_{es}}.$$

$$L_{\rm Edd} \equiv \frac{4\pi GMc}{\kappa_{\rm es}} = 1.25 \times 10^{38}\,{\rm erg\,s^{-1}}\; m$$

Thus, 10^{46} erg/s would require at least $10^8 M_\odot$!

How small are they?

1. Light crossing time estimate

An object's size can be estimated if its luminosity happens to vary. Nothing can travel faster than the speed of light. Therefore, if the brightness of an object varies by, say, 10%, in a time Δt, then the region from which that 10% of the light comes can be no larger than

$$r_{max} = c\,\Delta t \tag{1.3}$$

For example, if $\Delta t \approx 1$ month, then $r_{max} \approx 1$ light-month (or 10^{17} cm), so at least 10% of the actual object is probably considerably smaller than a light-month in size.

2. Assuming a black body

$$L = 4\pi R^2\,\sigma T_e^4$$

$$r_{bb} = \left(\frac{L}{4\pi\sigma\,T_e^4}\right)^{1/2}$$

For L~10^{45} erg/s, T~10^{7} K, we get r ~10^{10} *cm*
If we try to pack 10^{12} Suns into such volume, the distance between them would be ~10^{6} *cm*… that's 10km! Way smaller than the Sun!

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How heavy are they?

1. Weighing stuff in binaries

$$\frac{GMm}{R^2} = \frac{m v_{orb}^2}{R} \rightarrow M = \frac{R v_{orb}^2}{G} = \frac{P_{orb} v_{orb}^3}{2\pi G} \rightarrow v_{mes} < v_{orb} \rightarrow M_{infer} < M$$

*we can only measure the projected orbital velocity.

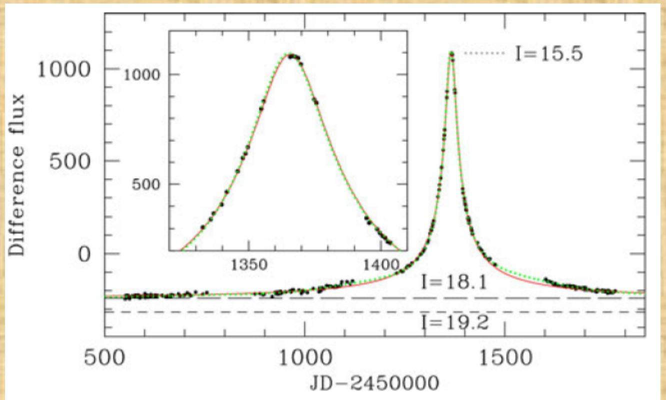
Our milky way center $\sim 4 \times 10^6 M_\odot$

2. Monsters lurking in galactic centers

SMBHs measured in other galaxies have masses ranging from $\sim 10^5 M_\odot - 10^{10} M_\odot$

3. Isolated Black Holes

micro-lensing of background stars



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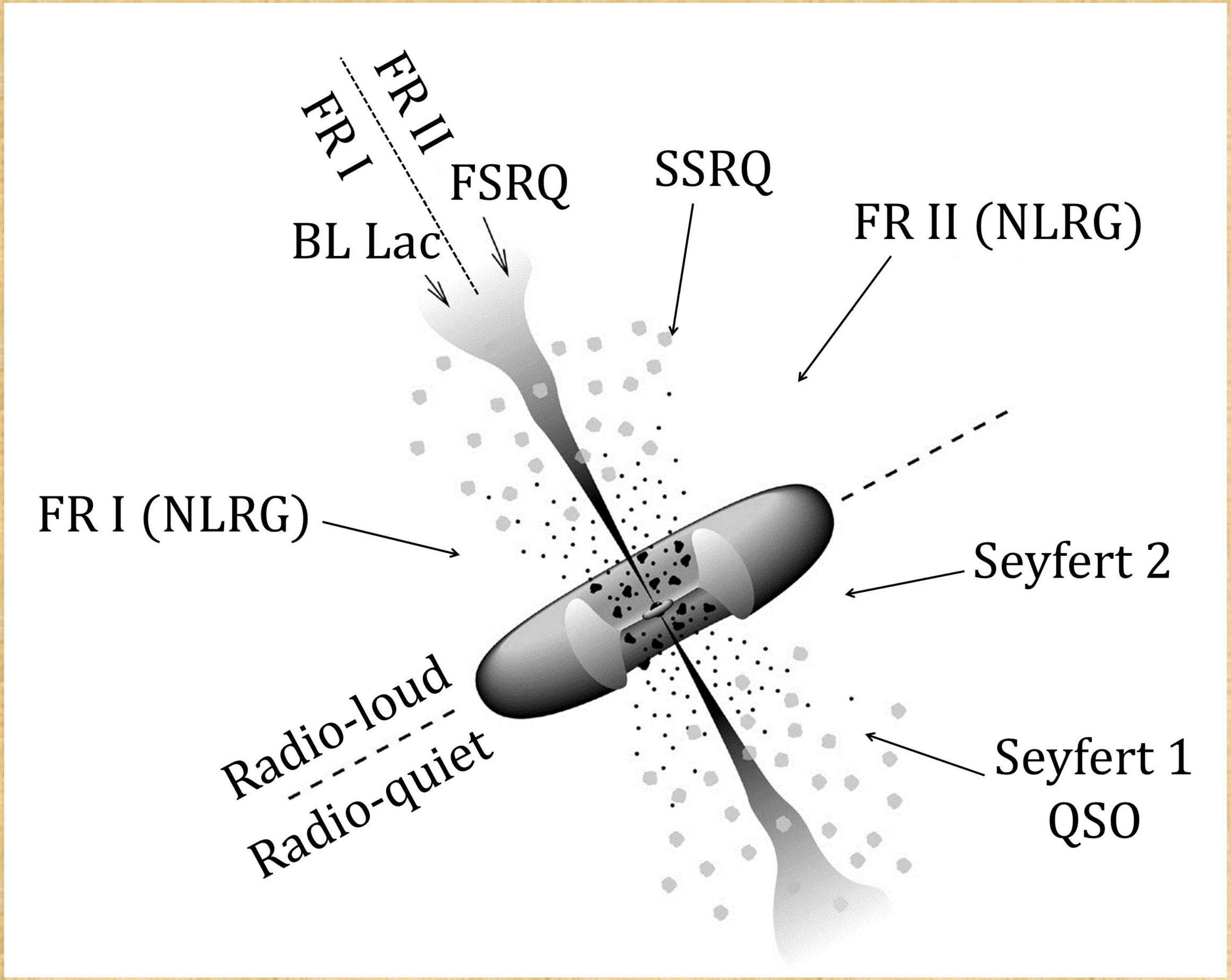
Overview of the unification



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First half of 20th century

1917
NGC 1068
line spectra hinted gas motion up to 3600km/s

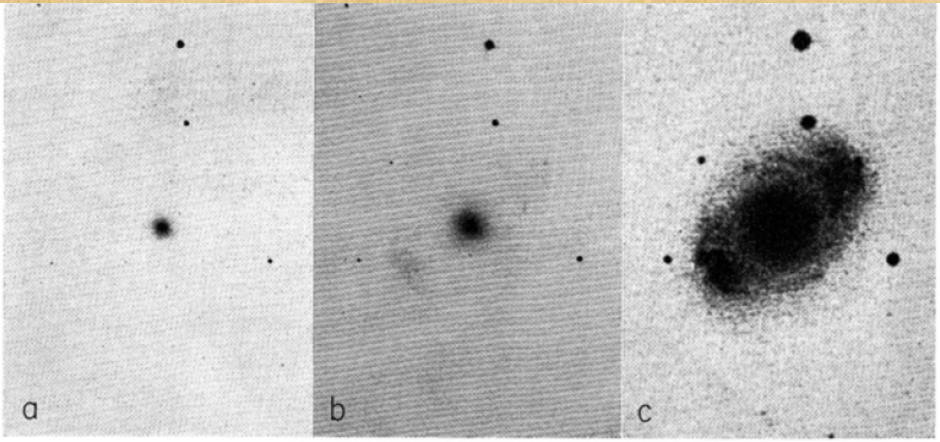
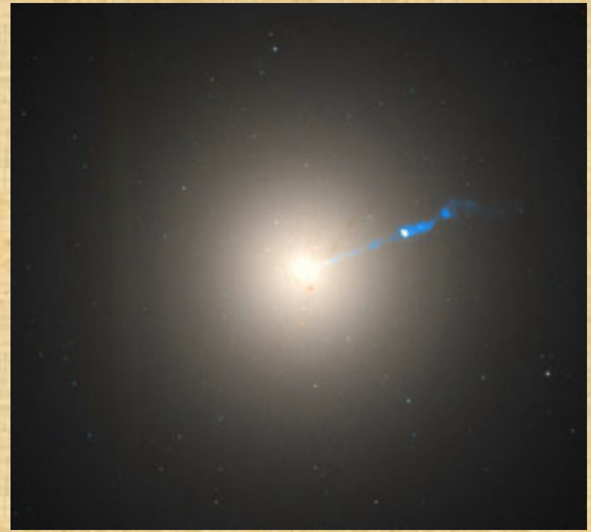


Fig. 2.1: Series of exposures of Seyfert 1 galaxy NGC 4151. Short exposure (left) shows the central unresolved Seyfert nucleus; intermediate exposure shows the ionized material surrounding the nucleus; deep exposure (right) shows the host galaxy [18]. Reproduced by permission of the AAS.

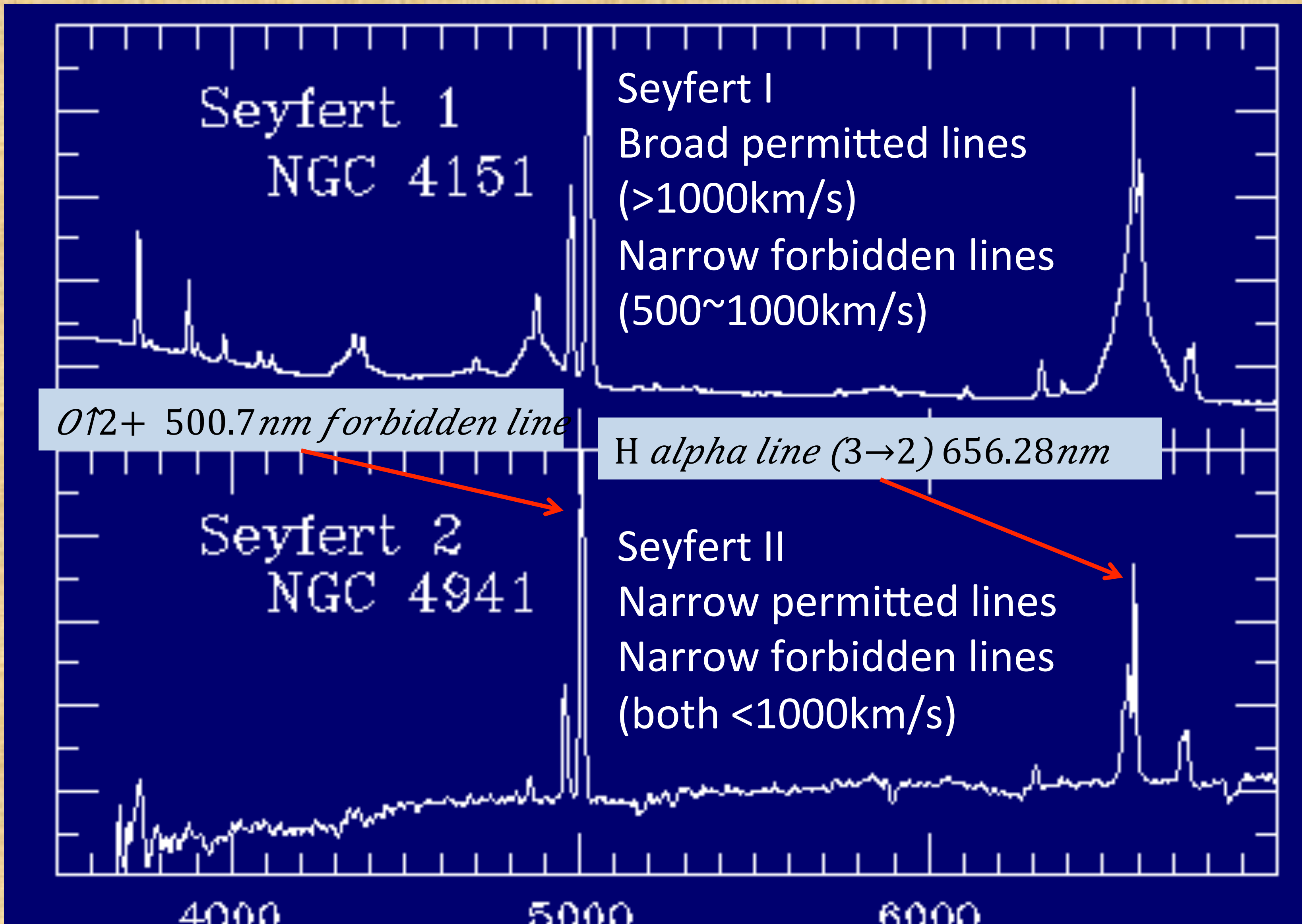
1918
NGC 4151
hinted gas motion of up to 7500 km/s! (0.025c)

M87 optical jet



1943
Seyfert's found that these galaxies with broad emission lines are a distinct class of objects.

1971 The two Seyfert classes



As of late 1970s

*Small central source < 10^{15} cm

*Emitting 10^{43} ~ 10^{45} erg/s → ionizes gas → emission line

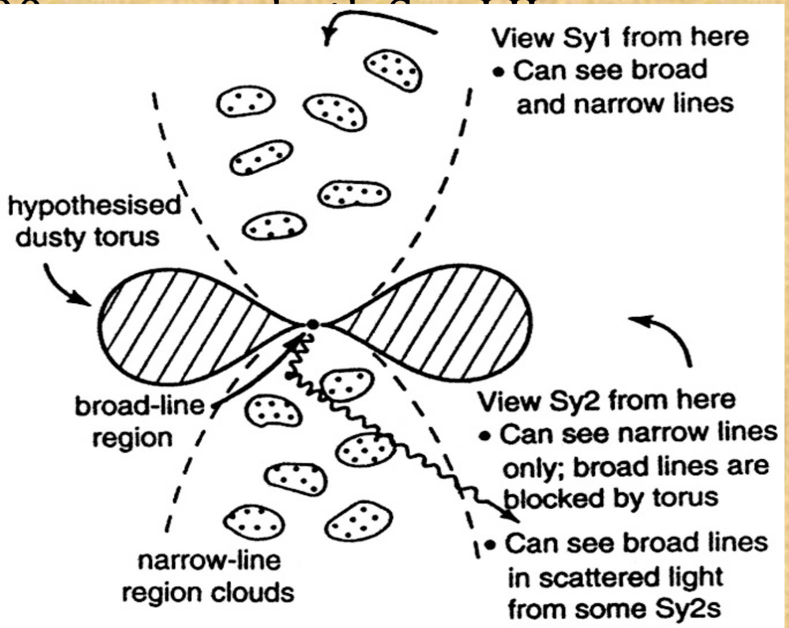
*Gas must be moving rapidly

*Around the central source

- Broad Line region (BLR) < 0.01pc in Sey I
- Narrow Line region (NLR) ~100-100

*Intermediates : less prominent or missing BLRs

SyII → SyI obscured BLR? Increasing presence of BLR?



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Radio galaxies

1950s

Started observation of radio sources, some initially thought to be mergers (Cyg A)

1960s

3CR catalog : 328 sources (>9Jansky) @ 178MHz

mid 1970s

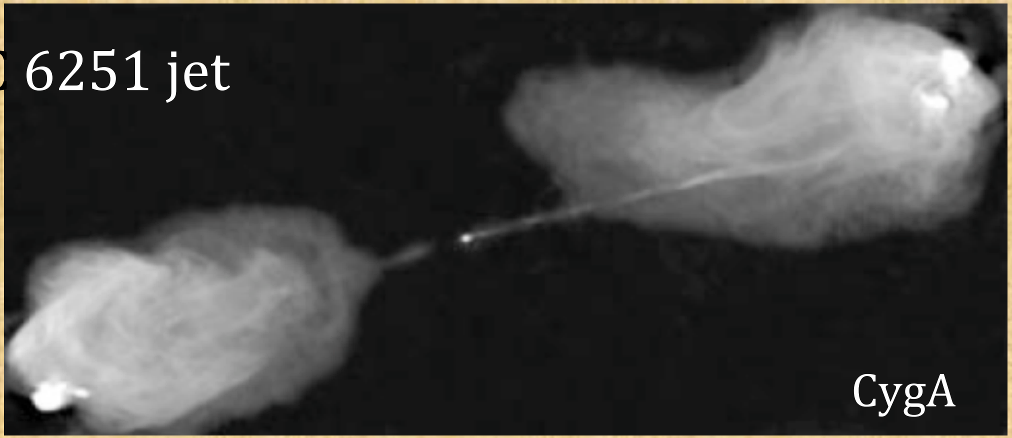
Double lobes had a galaxy halfway in between can't confirm jets must be from galaxy

1978

VLBI trace different scales of NGC 6251 jet

1980s

VLA produces the CygA image



Idea of VLBI

Larger area, better resolution.

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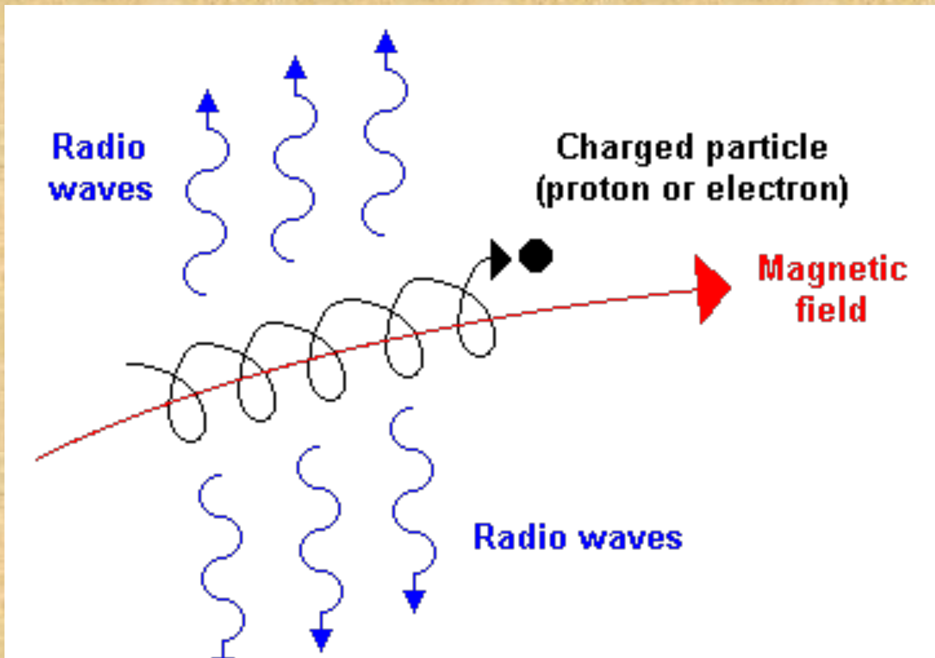
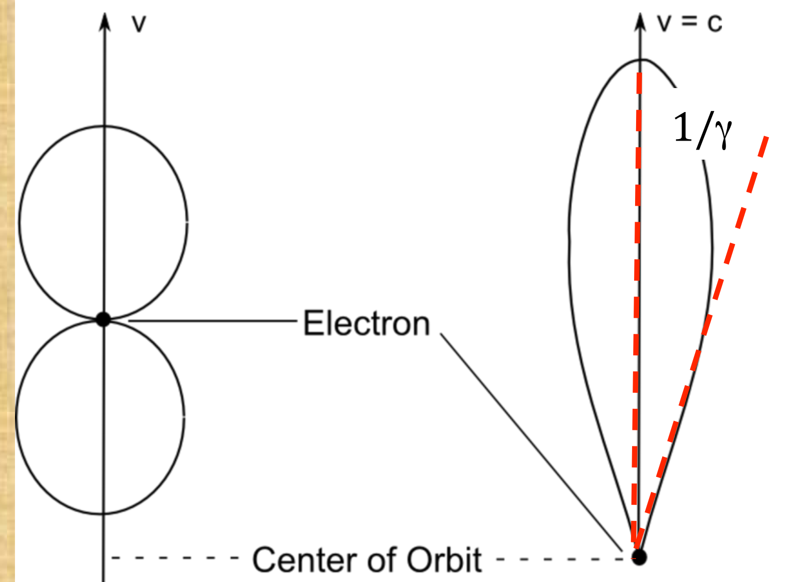
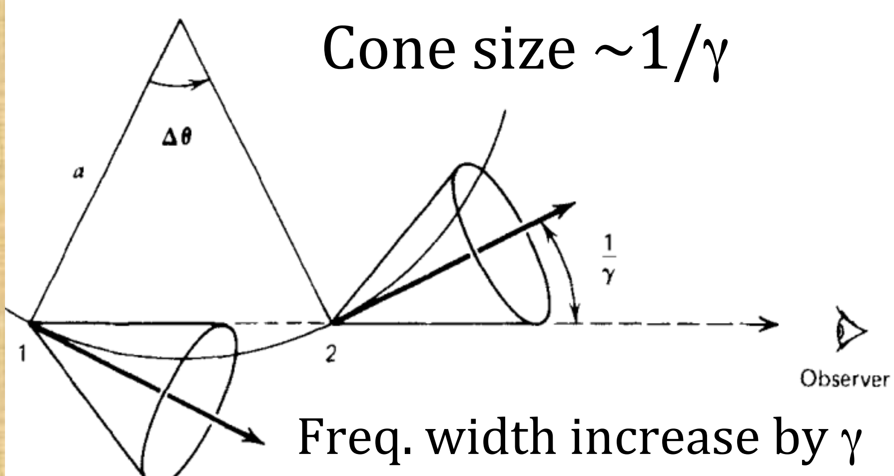
Basics of synchrotron emission



Relativistic Particle Emission

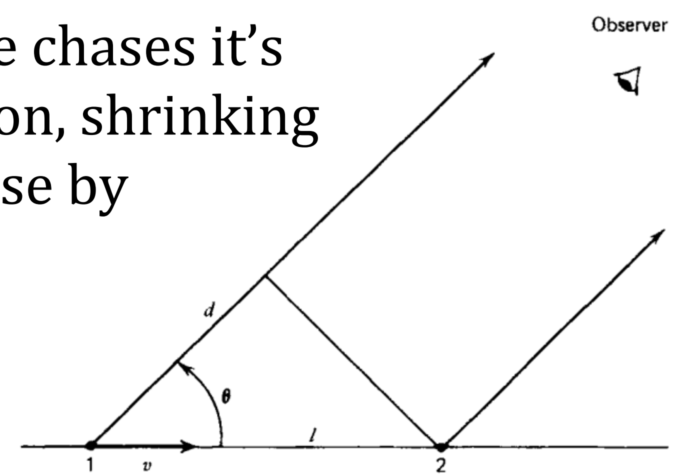


Cone size ~1/γ



Freq. width increase by γ

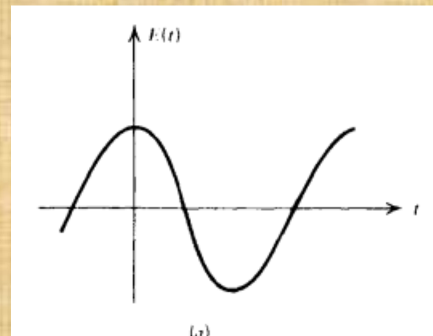
Particle chases it's Emission, shrinking the pulse by $1/\gamma^2$

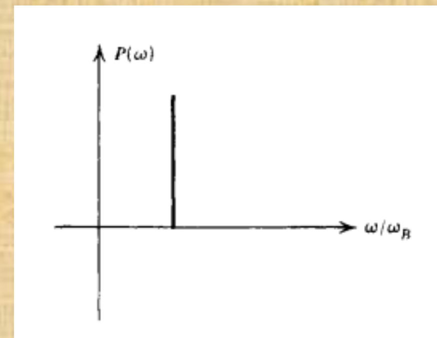


Freq. width increase by γ^2

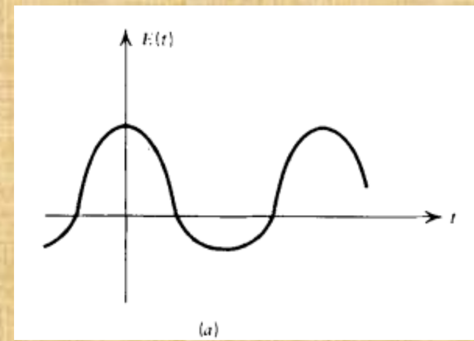
Synchrotron spectra

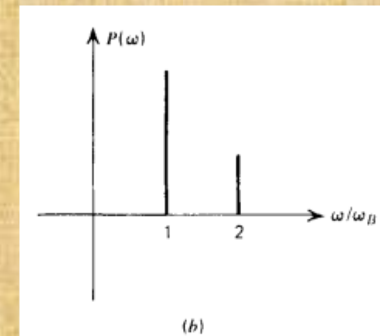
Single frequency wave



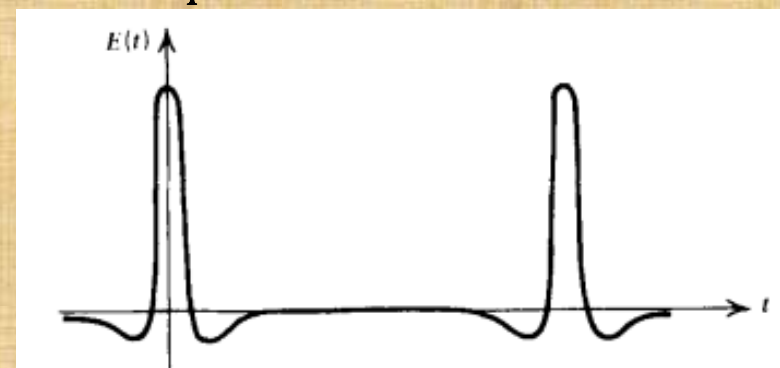


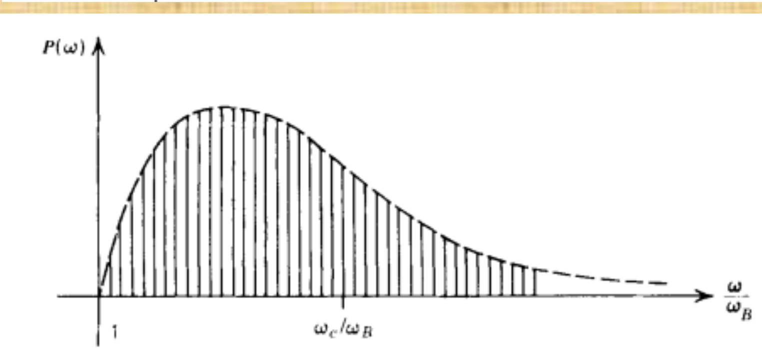
Slightly squashed periodic wave





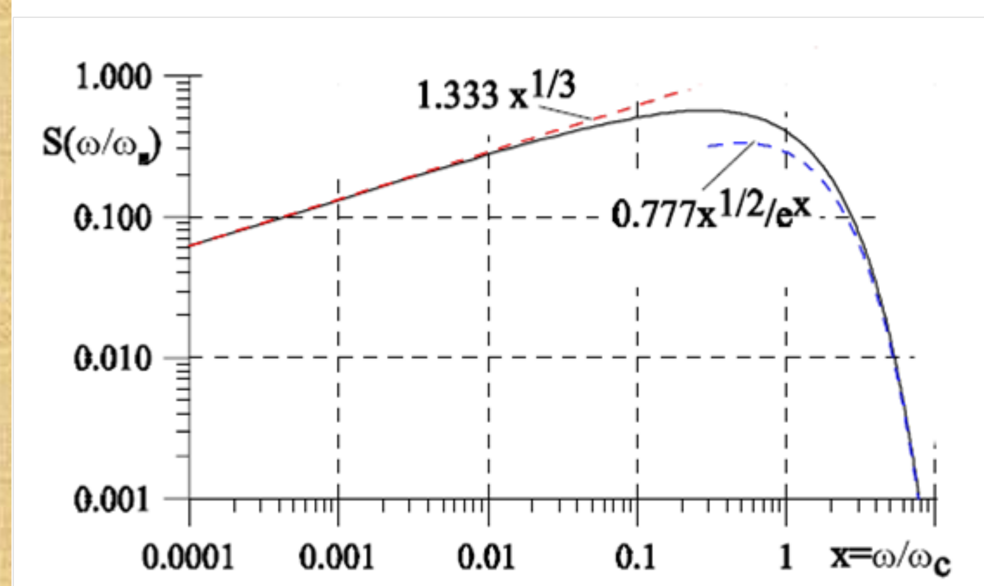
Squash it even further





Full spectra for single particle

$\omega_c = \gamma^3 \omega_B$; $\omega_B = qB/\gamma mc$



Synchrotron spectra for PL electrons

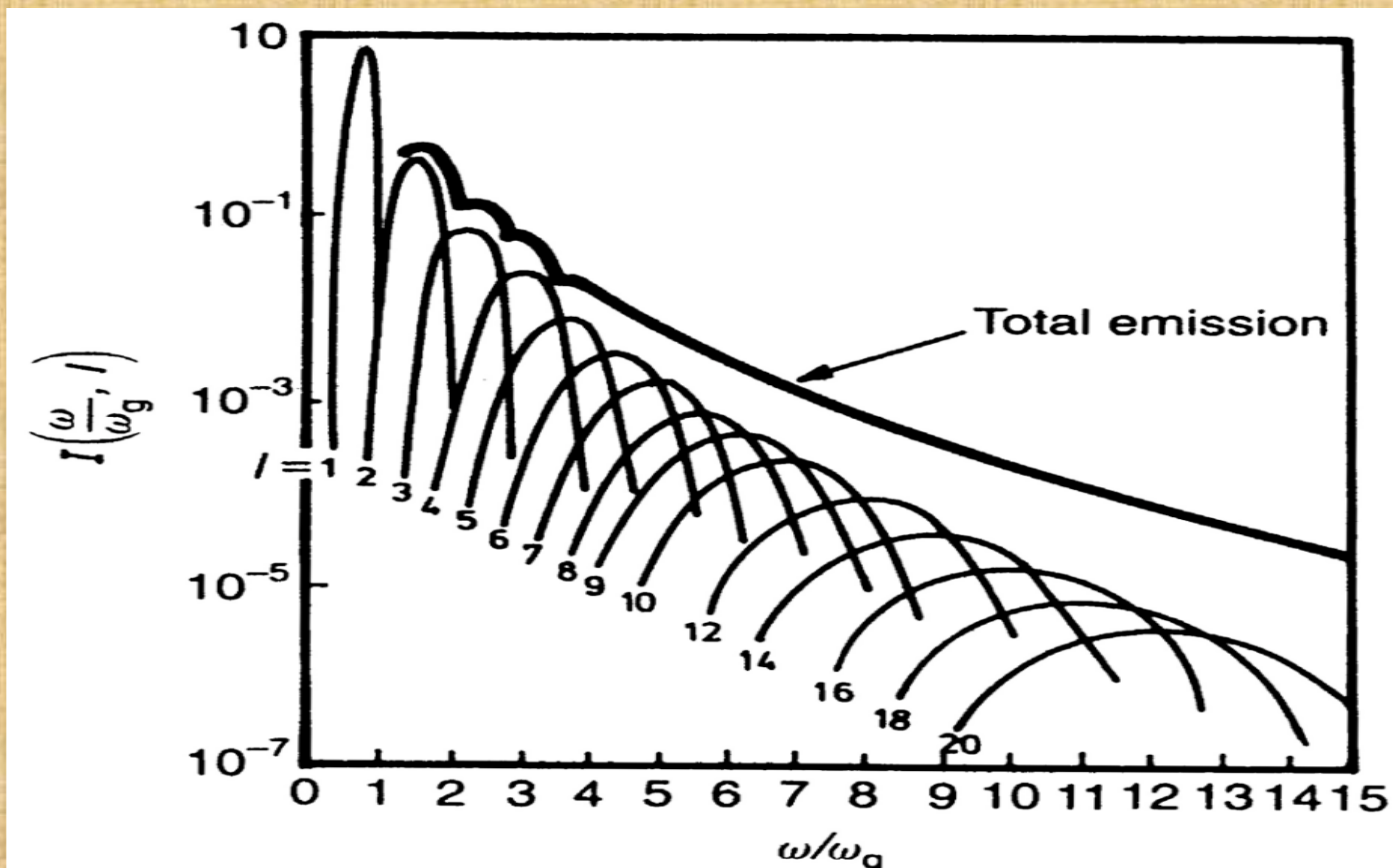
Particle energy distribution

$N(E)\mathrm{d}E = KE^{-\delta}\,\mathrm{d}E$

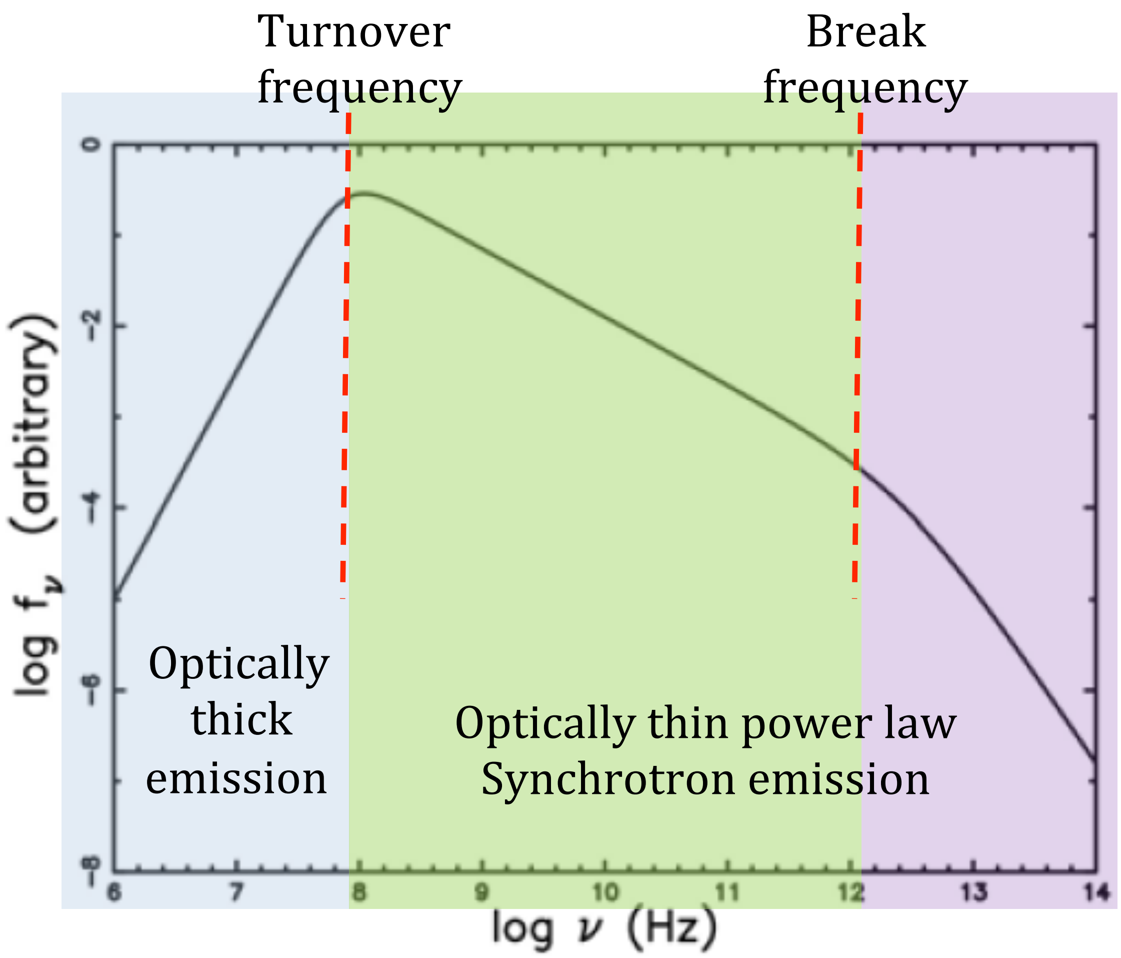
→

Synchrotron radiation spectra

$P(\omega)\mathrm{d}\omega = K'\omega^{-(\delta-1)/2}\,\mathrm{d}\omega$



Putting the spectra together

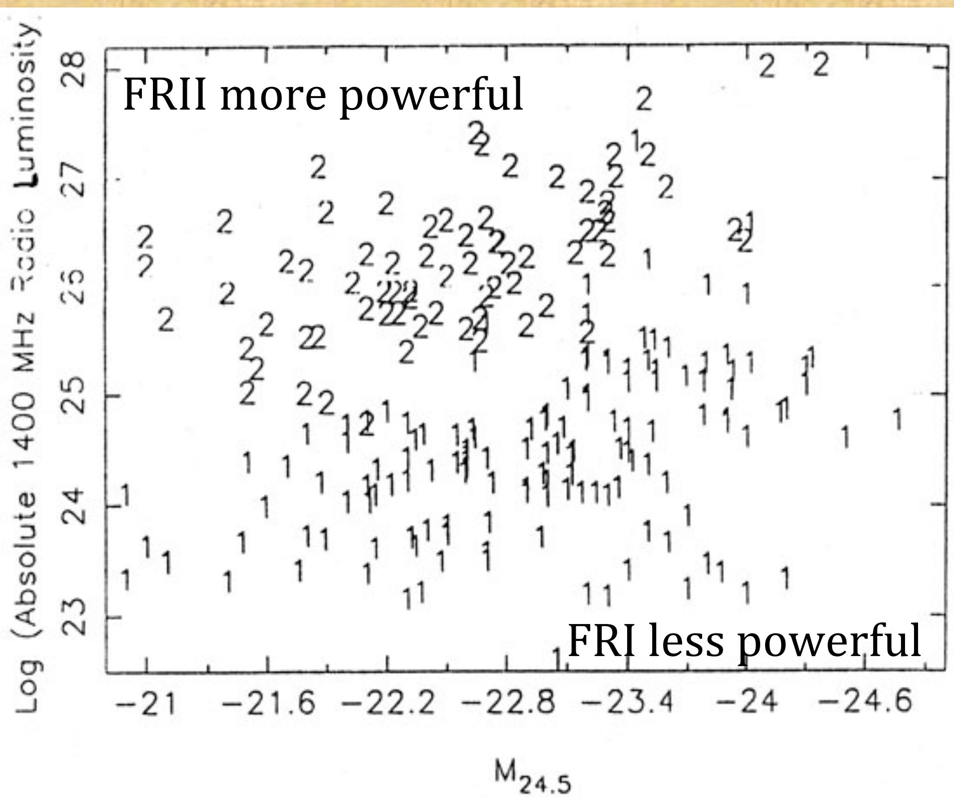


Typical B field strength in Jets = ?

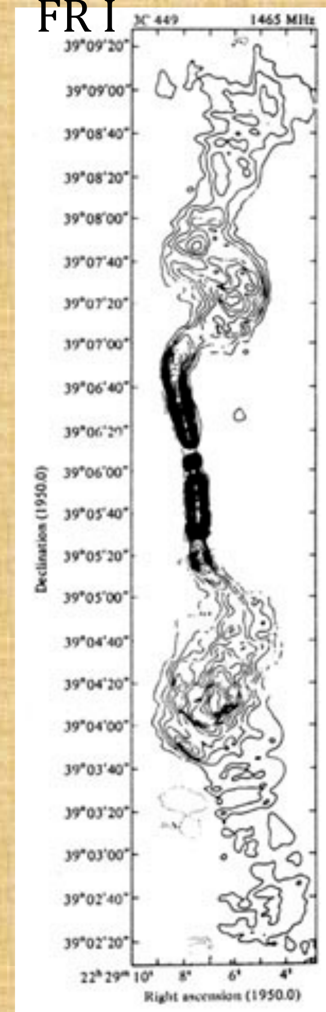
Fig. 2.6: Typical radio synchrotron spectrum, with $\nu_{\max} \approx 10^8$ Hz and $\nu_b \approx 10^{12}$ Hz.

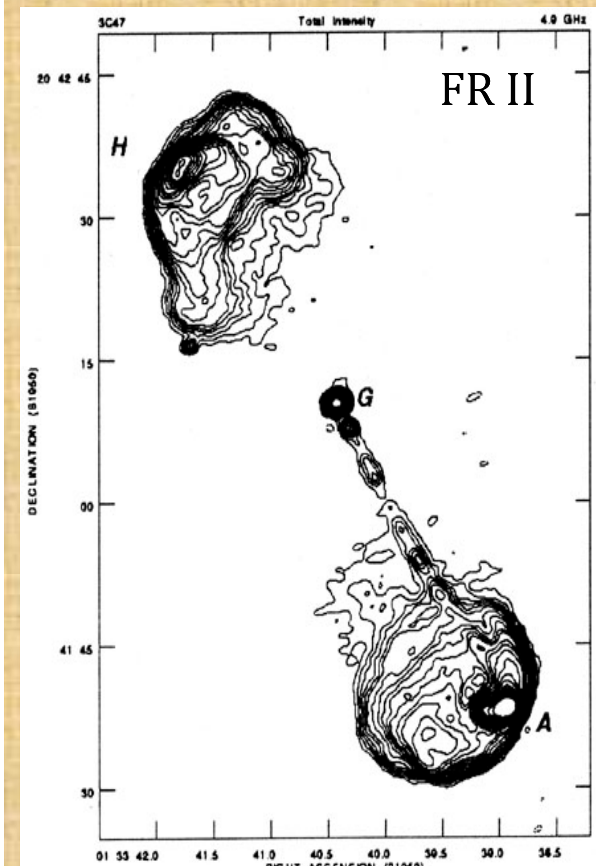
1974 The FRI/FRII classes

Using 3CR sources *with known distance & luminosity*, two classes are found: Fanaroff-Riley Class I, Class II



FR I



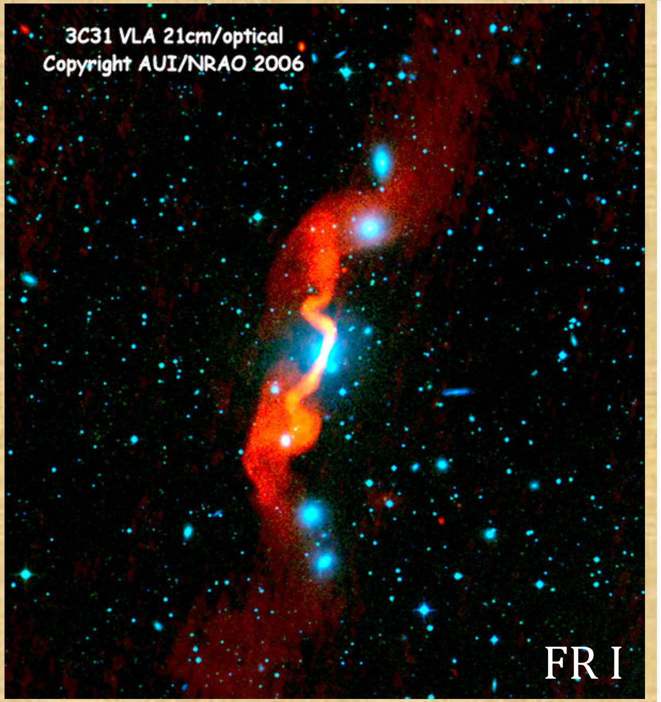


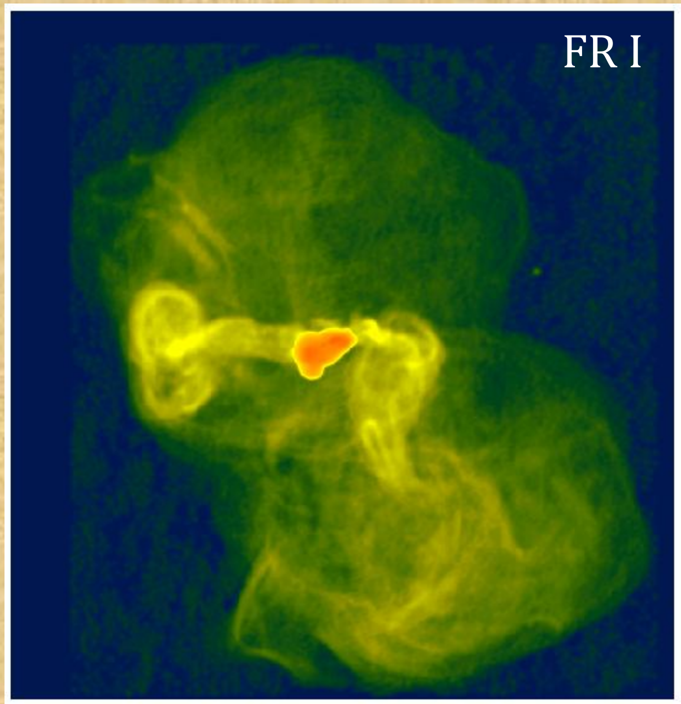
Boundary is 10↑41 erg/s (radio power)

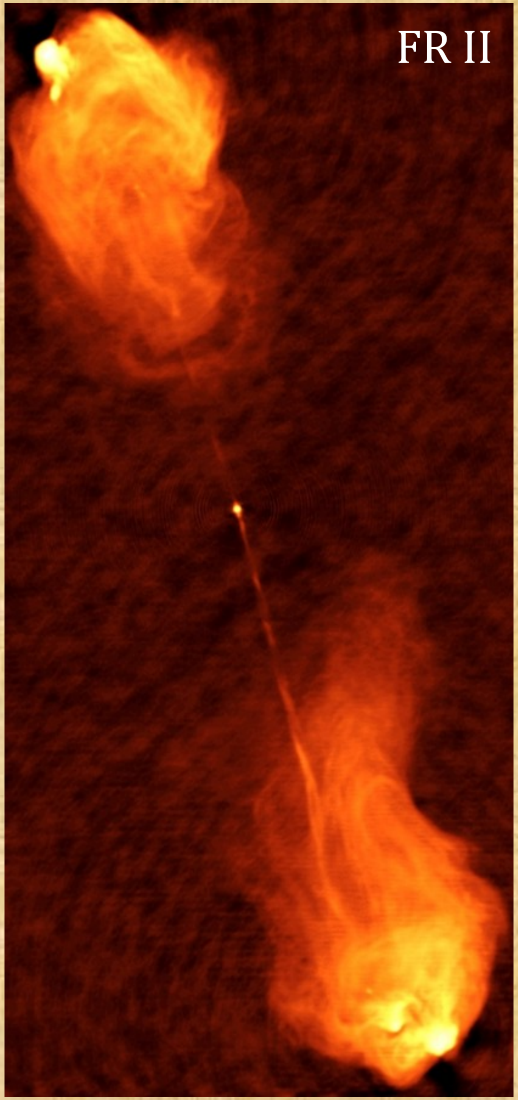
http://ned.ipac.caltech.edu/level5/Glossary/Essay_fanaroff.html

1974 The FRI/FRII classes

Just some more examples:







Modern interpretation:

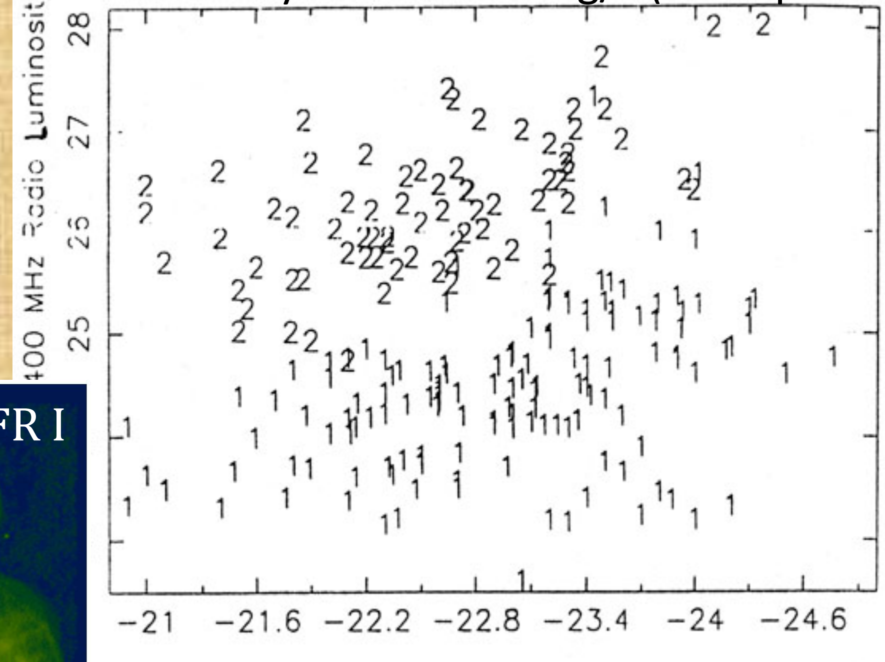
FRI sources are less powerful (and slower) thus fail to blast through their galaxies' ISM.

Is that correct?

http://ned.ipac.caltech.edu/level5/Glossary/Essay_fanaroff.html

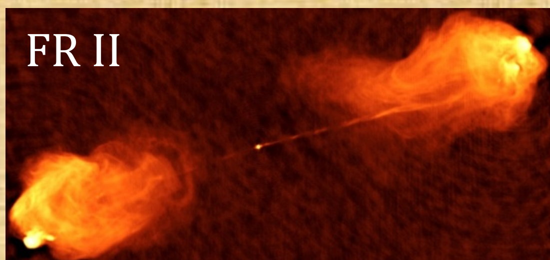
Hybrid jets

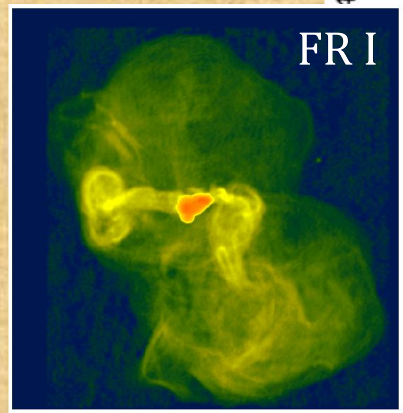
Boundary was 10↑41 erg/s (radio power)



*1990s

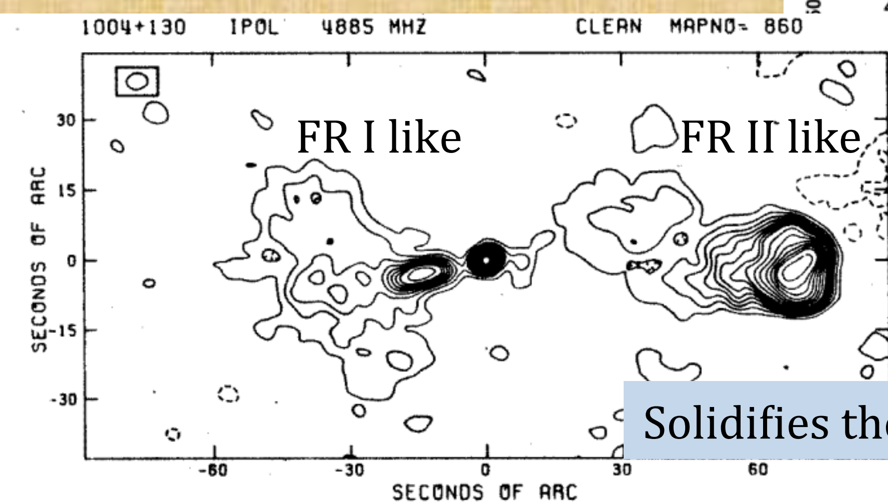
Found that FRI-FRII break depends on galaxy mass. (more gas is more difficult to breakthrough)

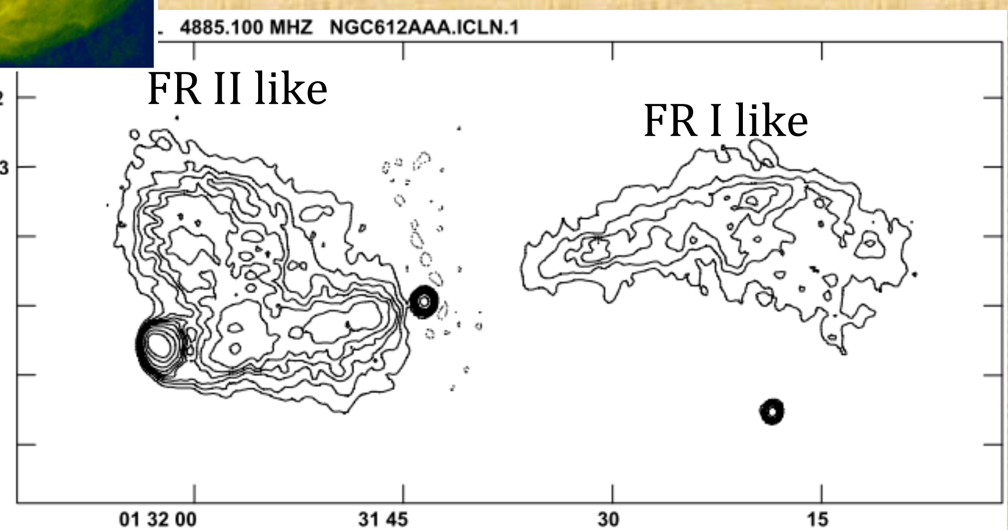




*A&A, 363, 507 (2000)

Hybrid objects found





Solidifies the view that environment effects class boundary.

RGs with bright optical nuclei

1960s

Some 3C radio galaxies have compact optical nuclei

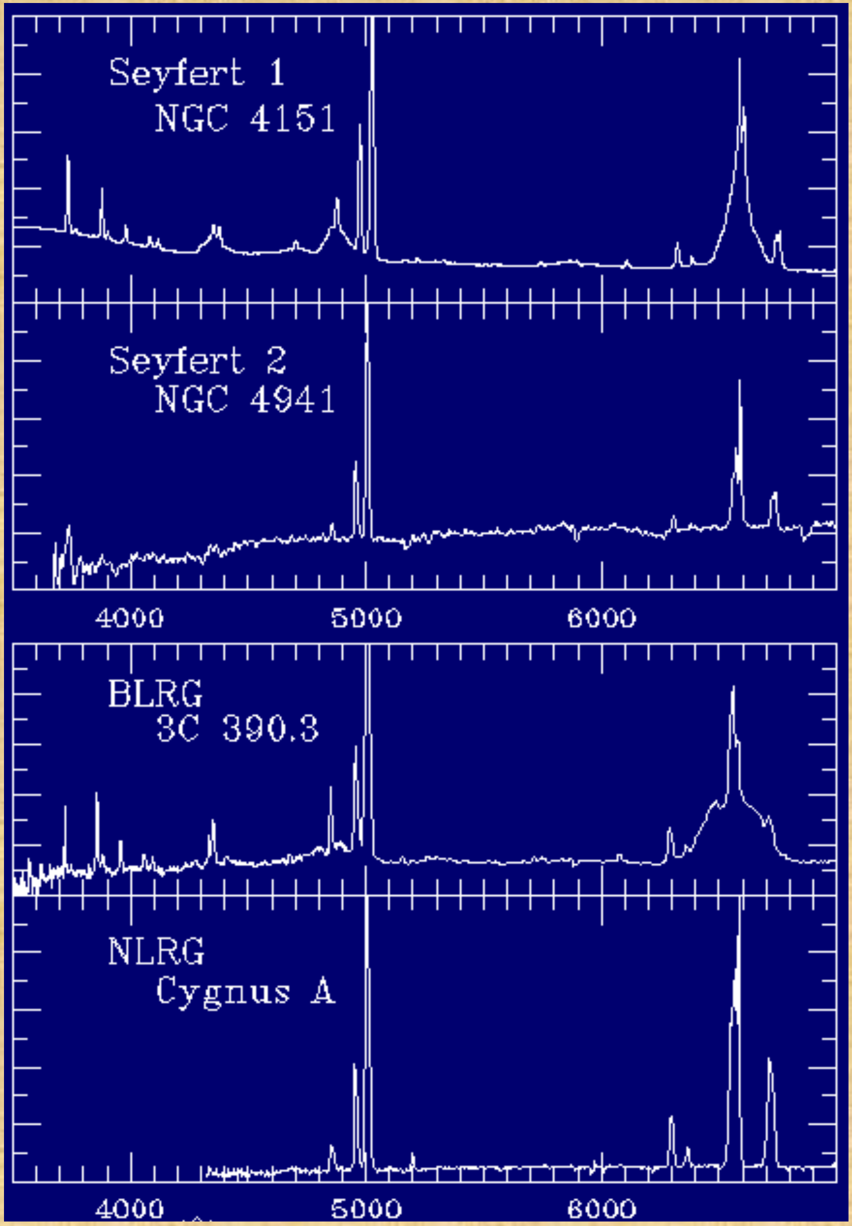
1970s

classification by line width

- BLRGs (broad permitted lines, narrow forbidden line)
- NLRGs (both permitted and forbidden lines narrow)

*All have FRII morphology and tend to occur in ellipticals only (much unlike seyferts)

*Seyferts rarely appear in radio surveys (and their hosts usually are spirals)



Discovery of the first quasars

1962

Radio sources with no optical galaxy in their vicinity, some look like point sources (stars) in optical, thus named quasars (quasi-stellar radio sources)

1963

Hydrogen lines were found to have redshifted by 0.16c (600Mpc)

*Most distant known galaxies at that time were ~600Mpc

Some other re-examined objects:

- 3C 48 z~0.367
- 3C 9 z~2.012

*Implied very high luminosities ~ 10^{44} ~10^{46} erg/s

*Variability implied size << 1light year

QSR radio and optical properties

Radio : extended or compact (like point sources)

- Extended source have steep spectrum (termed SSRQ)
- Compact sources have flat spectrum (termed FSRQ)

Optical

- Image : like point source
- spectra : like BLRGs

*Bright non-thermal continuum up to UV : should be the excitation source of the lines

What we have now

Optical line classification

-Seyfert I (broad permitted, narrow forbidden)

-Seyfert II (narrow permitted, narrow forbidden)

Radio Galaxies

-FRI (weak jet)

-FRII (strong jet)

- BLRGs (line spectra like Seyfert I)
- NLRGs (line spectra like Seyfert II)

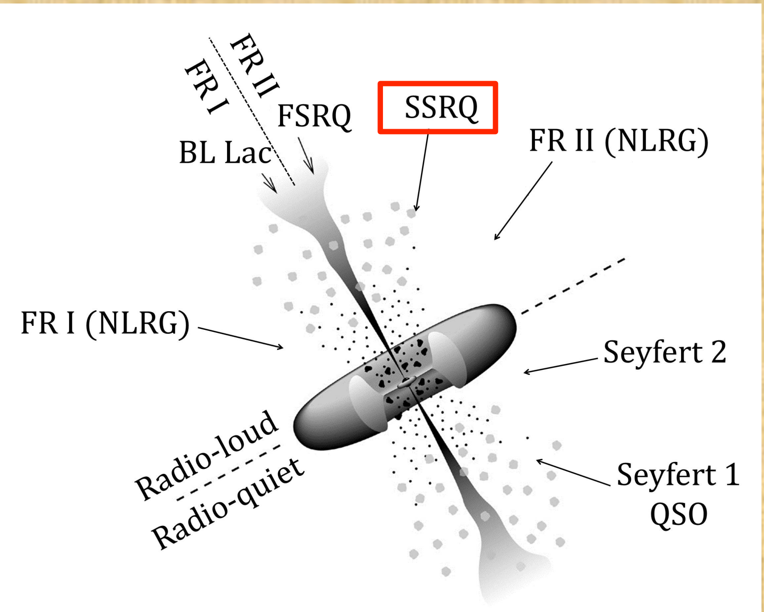
QSRs (high z, like points in optical, line spectra like BLRGs)

- Extended (steep spectrum)
- Compact (flat spectrum)

Unification of BLRGs and Extended QSRs

BLRGs
- FR II type radio lobes
- BLR observable

Extended QSRs
- FR II type radio lobes
- All QSRs have spectra similar to BLRGs



→Central engine too bright in QSRs such that galaxy is covered.

1970s-1980s

some low-z QSRs are found to have fuzzy galaxies around them

Unifying parameter – ratio of quasar to galaxy optical brightness

Unification of extended and compact QSRs by viewing angle

The flat spectrum hard to explain by single electron population WHY?

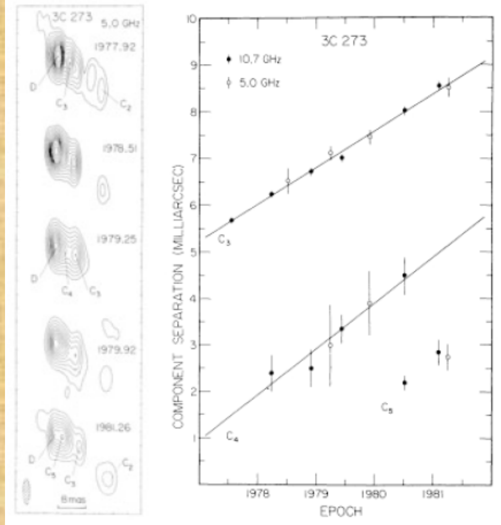
Spectra possibly from a stacking of multiple populations.

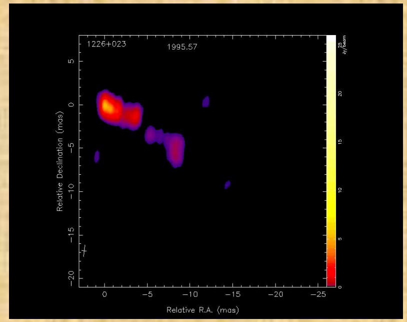
Using VLBI…we find

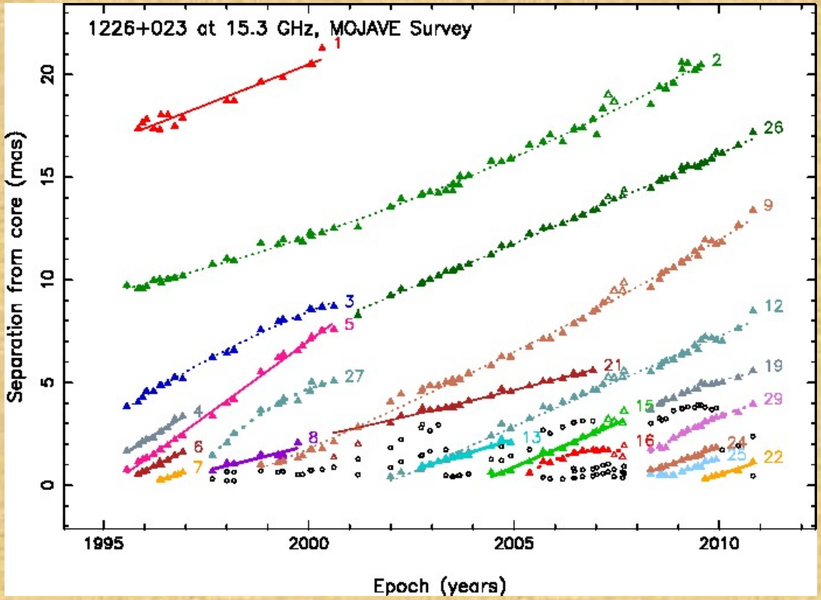
Compact sources contain :

- Core
- Single sided jet (sometimes resolved into components each having different synchrotron spectrum)

→ We are probably looking at small angles! What happens at such cases?







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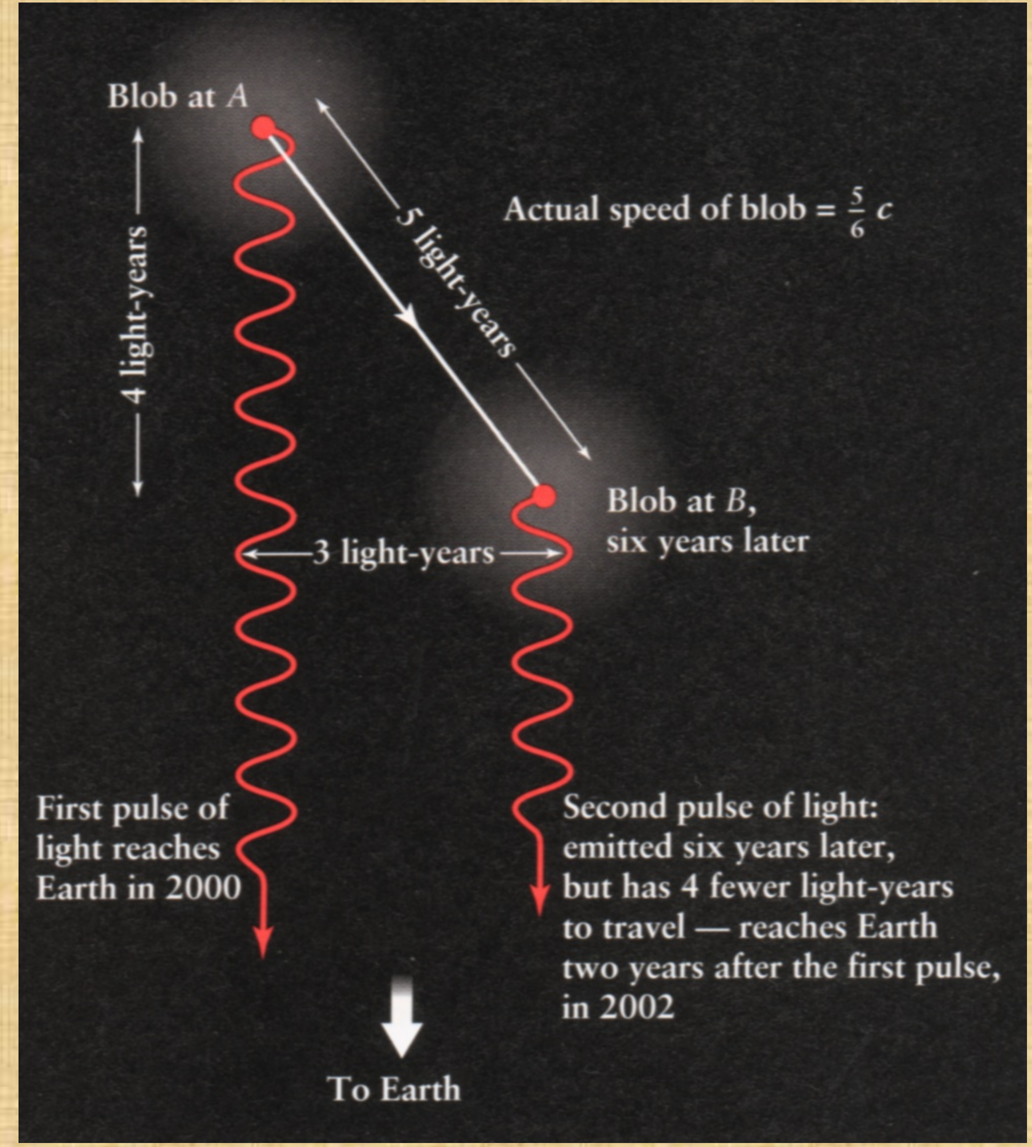
superluminal motion

$$v_{app} = \frac{v_{\rm jet} \sin\theta}{1 - \frac{v_{\rm jet}}{c}\cos\theta}$$



The basic idea is just like in the synchrotron case, the emitting source is chasing it's own emission at a very high speed.

Difference is that now it's the whole bulk of plasma chasing after the radiated photons.

*Requirements:
- Fast
- At small viewing angle

Illustration shows case of apparent velocity being 1.5c!

Relativistic beaming effects

Specific Intensity (Brightness) $I_\nu \equiv dE/dt\, dA\, d\Omega\, d\nu$

$$\delta_{\rm jet} \equiv \gamma_{\rm jet}^{-1} \left(1 - \frac{v_{\rm jet}}{c} \cos\theta\right)^{-1}$$

$\nu' = \delta\, \nu \rightarrow d\nu' = \delta\, d\nu$

$dA = \delta^2\, dA'$

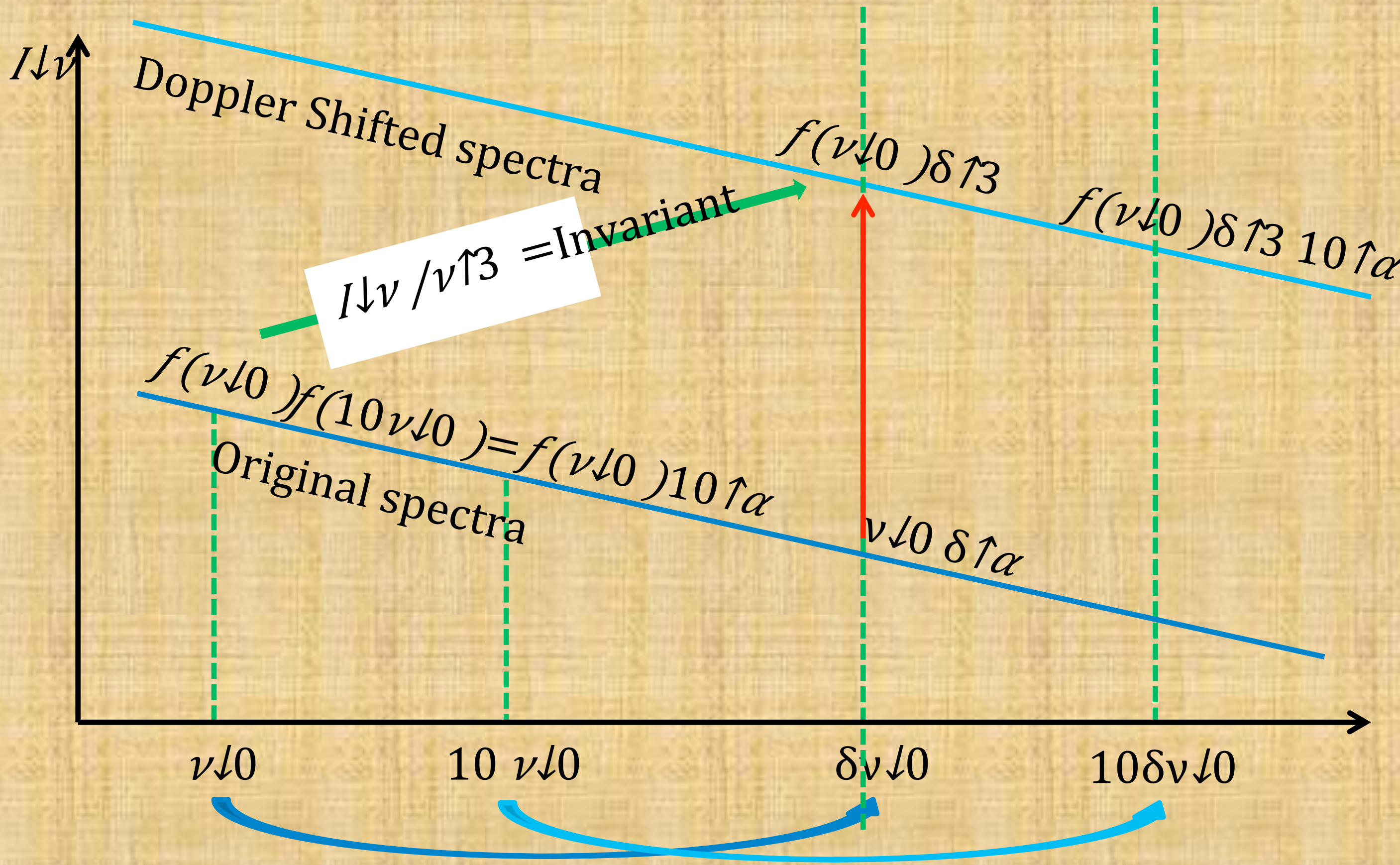
By essence of angle narrowing effect, $d\Omega = \delta^2\, d\Omega'$

$I_\nu \equiv dE/dt\, dA\, d\Omega\, d\nu = dE'/dt'\, \delta^2\, dA'\, \delta^2\, d\Omega' \, 1/\delta\, d\nu' = I_{\nu'}/\delta^3 = I_{\nu'} (\nu/\nu')$
$\rightarrow I_\nu/\nu^3 = I_{\nu'}/\nu'^3 = \textit{Lorentz Invariant}$

Beaming effects on PL spectra

Again, given a power law spectra, $f_\nu \propto \nu^\alpha$

$$\delta_{\rm jet} \equiv \gamma_{\rm jet}^{-1} \left(1 - \frac{v_{\rm jet}}{c} \cos\theta\right)^{-1}$$



The apparent spectra will be $f_{\nu,app} = f_\nu \, \delta_{\rm jet}^{3-\alpha}$

Jet-counterjet ratio

The apparent spectra will be $f_{\nu,app} = f_\nu \, \delta_{\text{jet}}^{3-\alpha}$

So the ratio of jet-counter jet is $R \approx \left(\frac{1 + \frac{v_{\text{jet}}}{c} \cos \theta}{1 - \frac{v_{\text{jet}}}{c} \cos \theta} \right)^{3-\alpha}$

Plugging in some numbers, $\gamma \sim 10$, $\beta \sim 0.995$, $\alpha \sim 0$
Then…R is in millions!

It's no wonder the counter-jet vanishes in cases where we see the jet head-on!

Unification of compact and extended QSRs (by viewing angle)

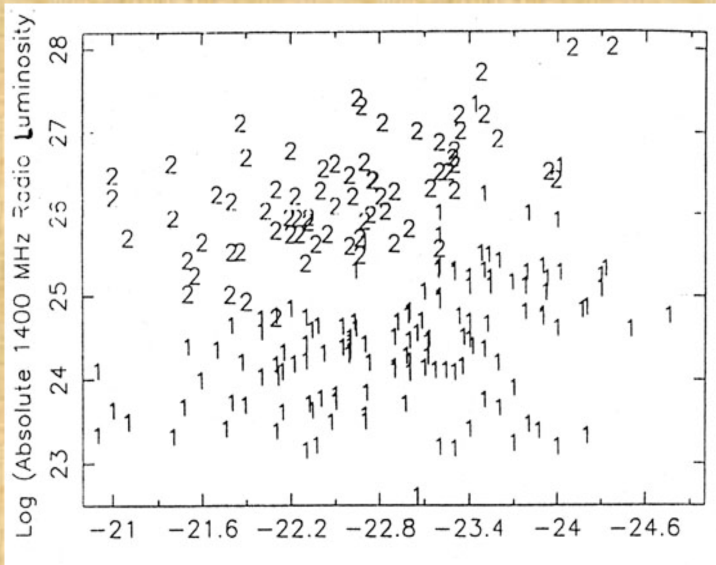
*Resolved missing jet problem!

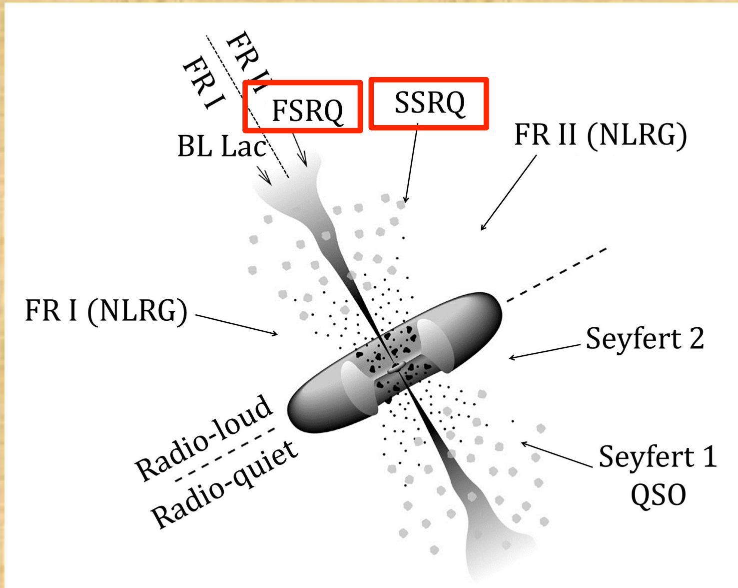
*interesting fact:

FSRQs are probably FR II seen end-on, but tend to be ones somewhat above the FR I-FR II divide

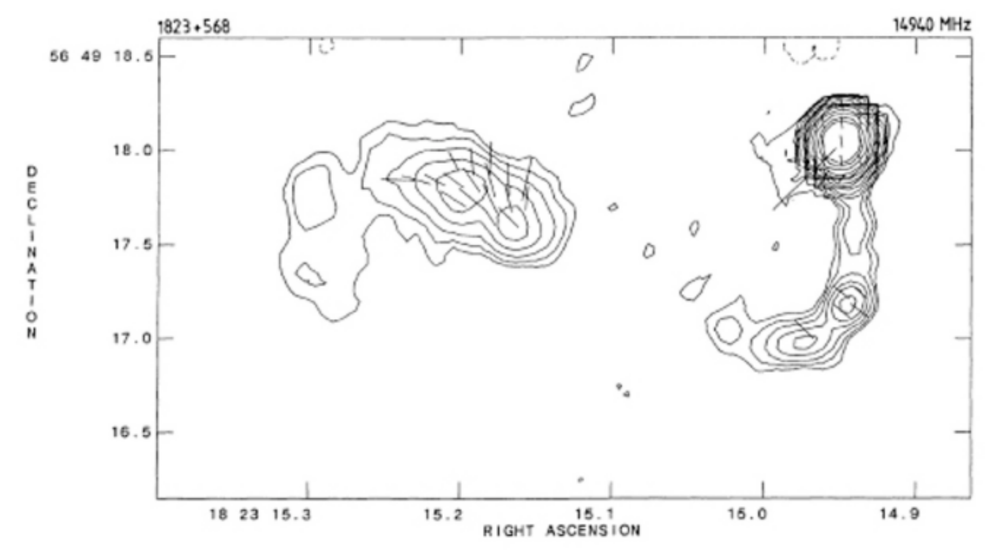
How do we explain?

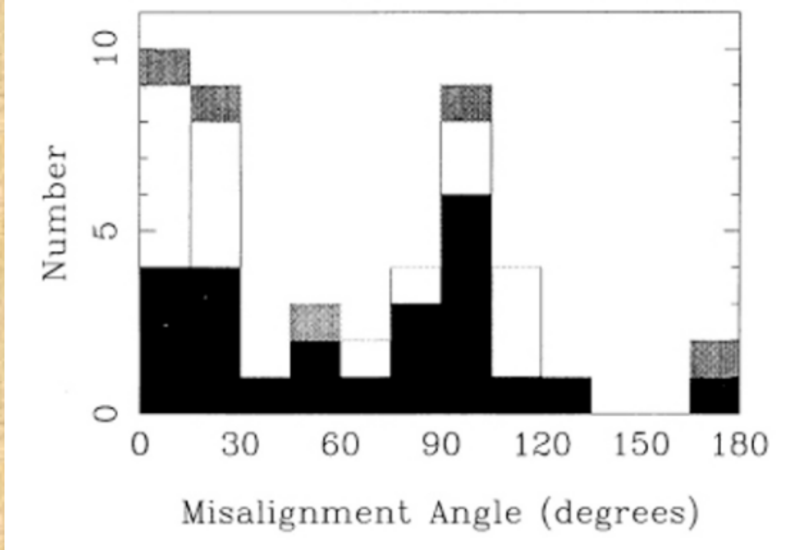
As will see later in cosmic evolution section, FR I are more uniformly distributed throughout time. So it's much more likely to find a beamed FR I than FR II… <u>*but then what does it mean to be at the divide…*</u>

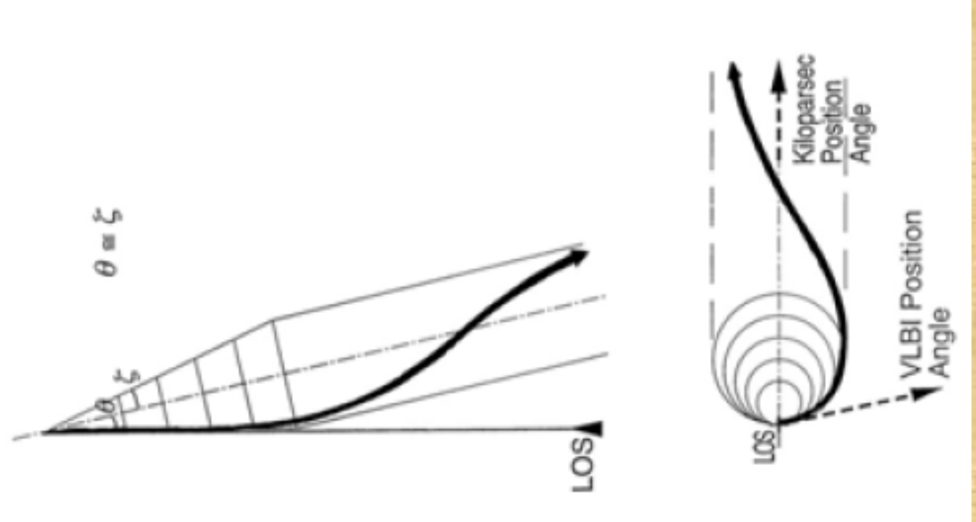




Helical jets







Outline

Ch1.

1. Why do we think they are Black Holes?(1.1-1.2)
2. How heavy are they?(1.3)

Ch2.

1. Overview of the unification
2. Early understanding of seyferts (2.1)
3. Radio Galaxies, Quasars and their unification(2.2-2.2.3.2)
   * Basics of synchrotron emission and spectra
   * Beaming and superluminal motion
4. Blazars(2.2.3.4-2.2.3.5)
5. Cosmic Evolution of RGs and QSRs (2.2.4)

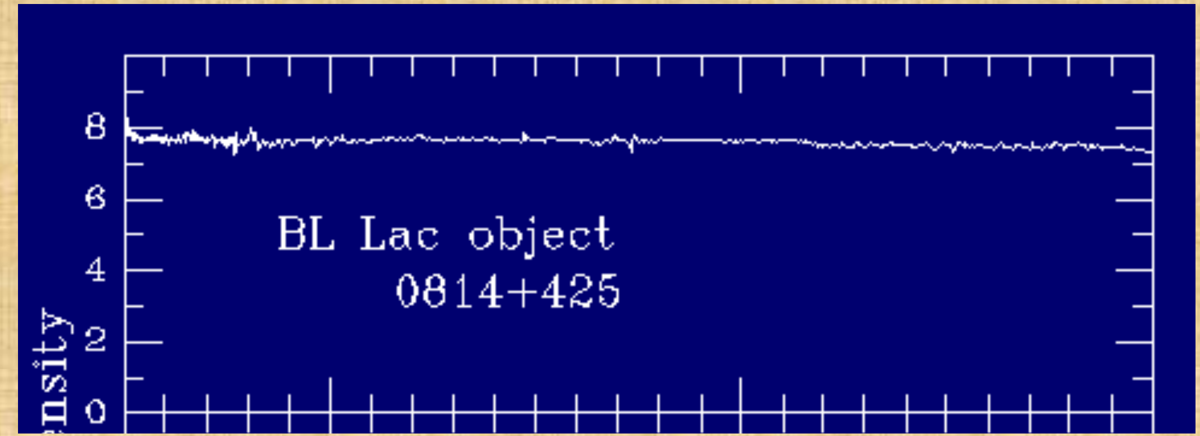
Blazars

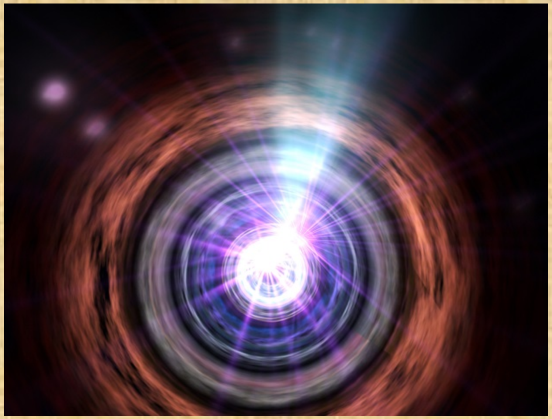
1968

Originally of variable star class, BL Lacertae was found to be consistent with flat spectrum, compact radio source at z=0.069.

*Variations of the jet flow make it appear like a variable star. (optical synchrotron)

*Like QSRs but with very red polarized optical continuum spectrum and weak or no lines. Make them hard to distinguish from red stars.

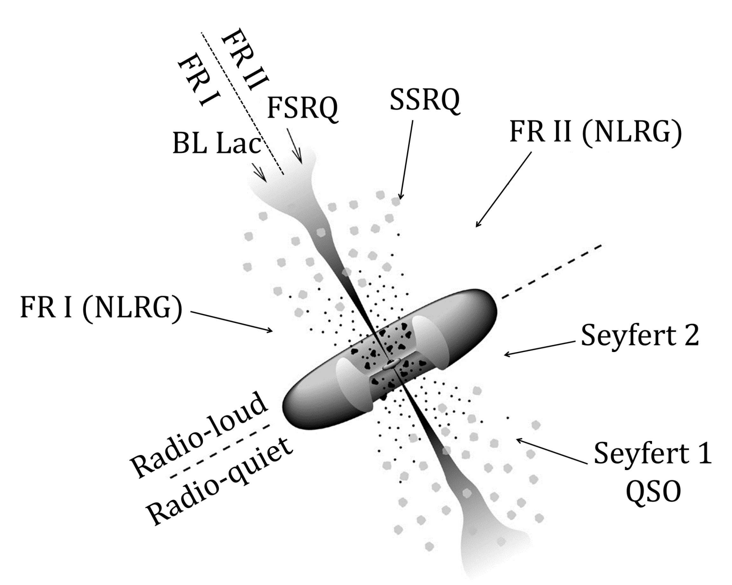




Blazars in place of unification

*These objects seem to behave like quasars seen head on thus named Blazar (BL Lac +Quasar)

*Because of their orientation, they are 1/10,000 of all active galaxies with jets (which are only 10% of all AGNs)



*Often need to find them in radio or X-ray, but radio or X-ray selected objects seem to be of different class.

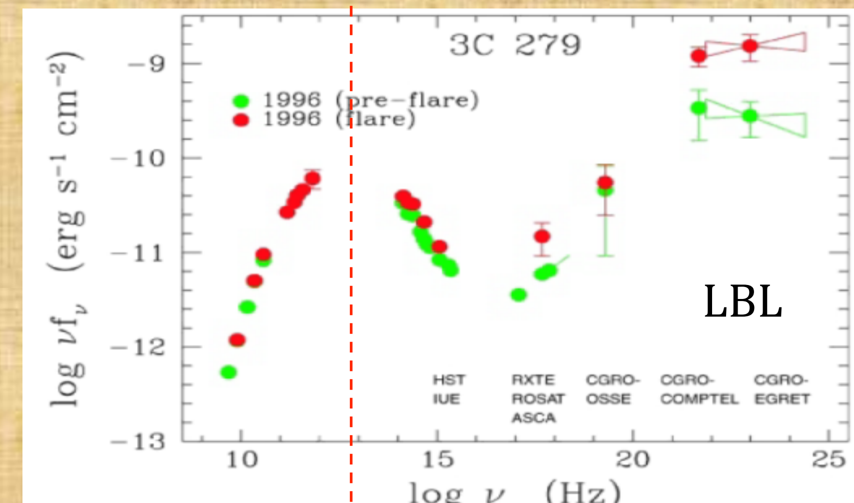
- X-ray selected: higher power, lower peak frequency (LBL, FSRQ)
- Radio selected: lower power, higher peak frequency (HBL)

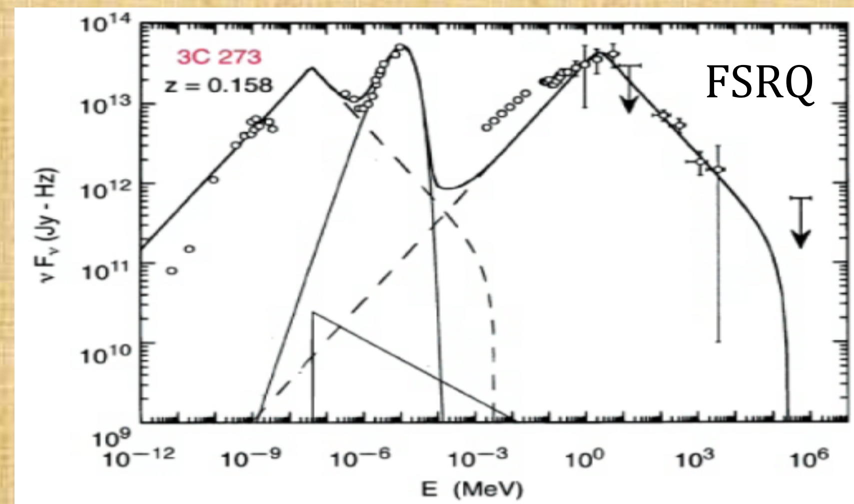
The spectra of Blazars (Synchrotron+SSC)

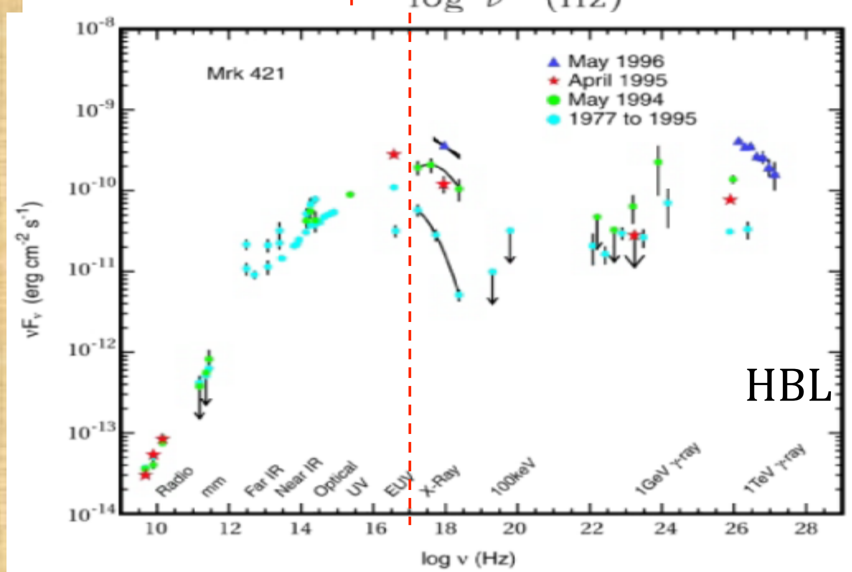
*Often need to find them in radio or X-ray, but radio or X-ray selected objects seem to be of different class.

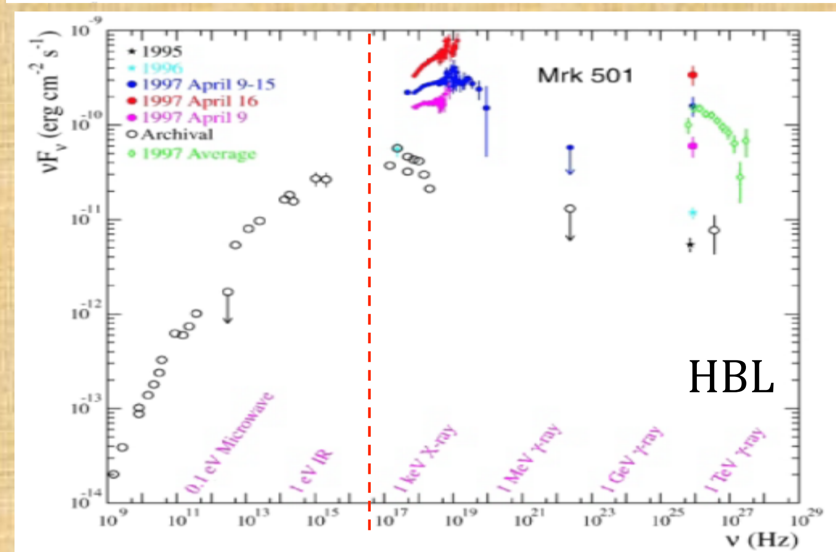
- X-ray selected: higher power, lower peak frequency (LBL, FSRQ)

-Radio selected: lower power, higher peak frequency (HBL)

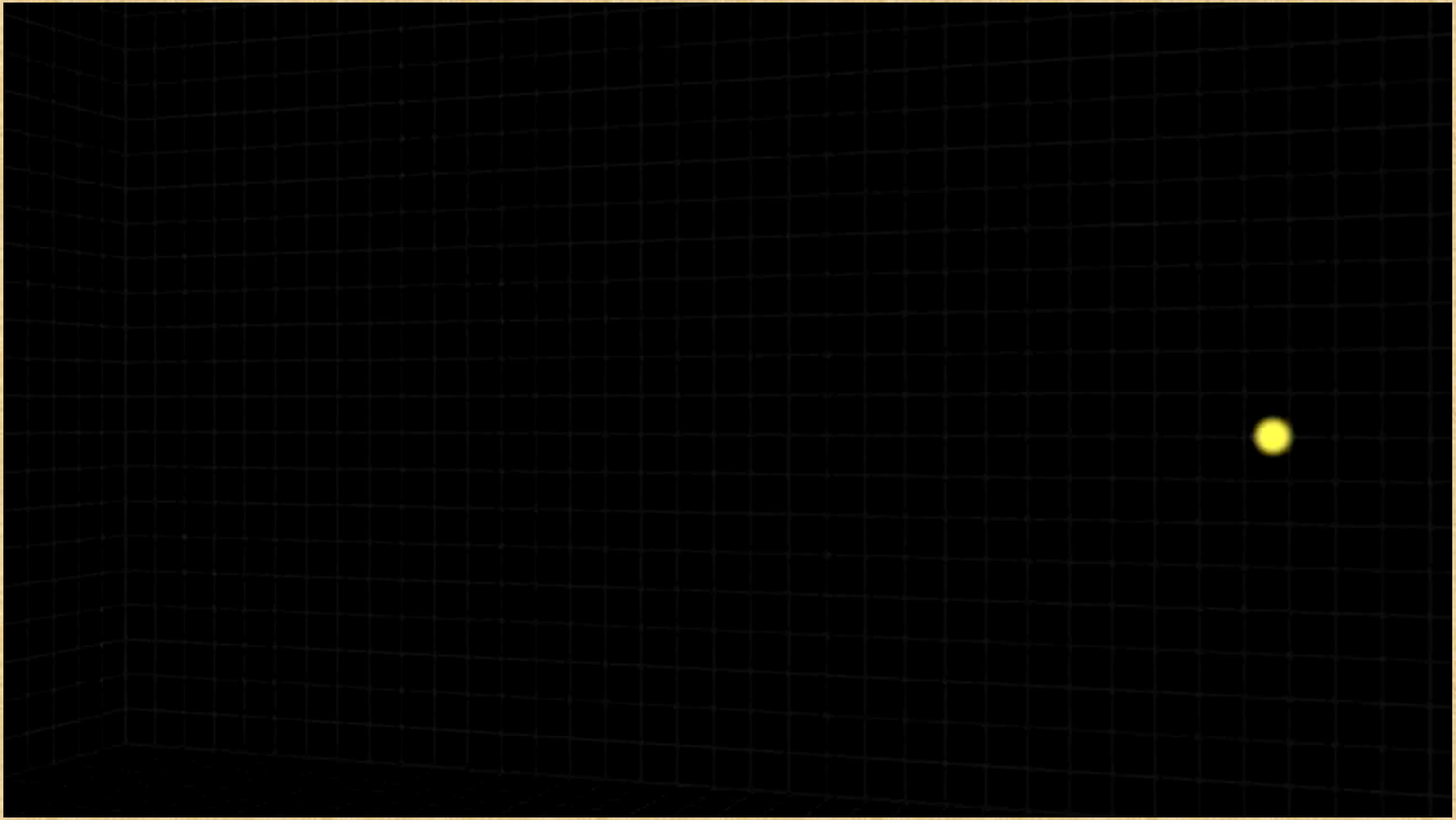




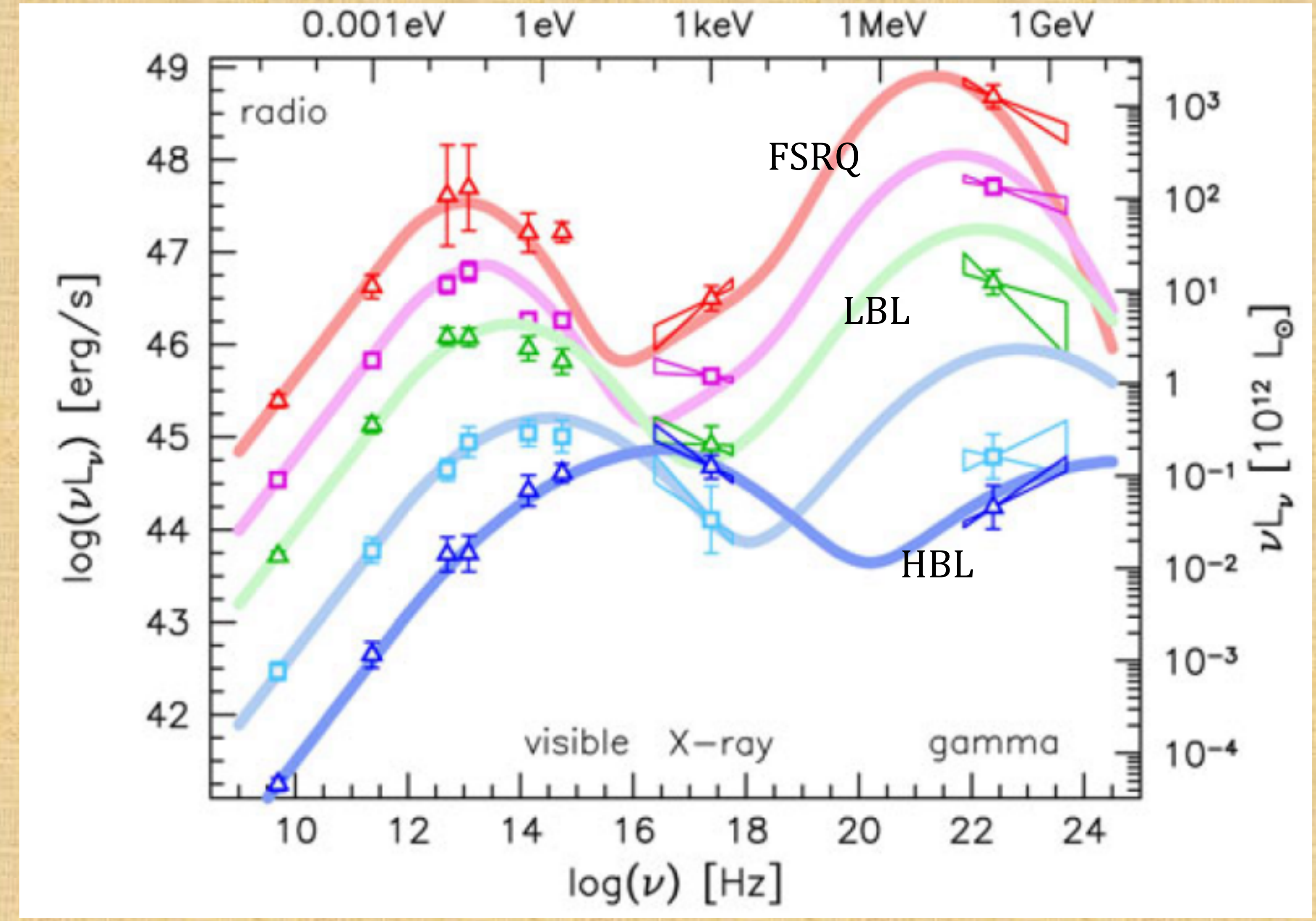




Synchrotron Self Compton



LBL, HBL, FSRQ evolution sequence?



IDV Blazars-The extreme of beaming ?

IDV- Intra-day variable

1. Beaming effect

Estimated Brightness Temperature ~ $10^{18-21}\ K$

intrinsic should be $<10^{12}\ K$

$$T_{b,app} = \delta_{\text{jet}}^{3-\alpha}\, T_{b,intr}$$

Gives Lorentz factor of hundreds, way faster than any other observed jet source.

2. Scintillation(like twinkling stars)

Estimated Brightness Temperature ~ $10^{13-14}\ K$

$\rightarrow \gamma \sim 5-50$

IDVs, therefore, may represent the extremes of viewing angle close to the line of sight or, alternatively, the extremes of jet speed in extragalactic radio sources.

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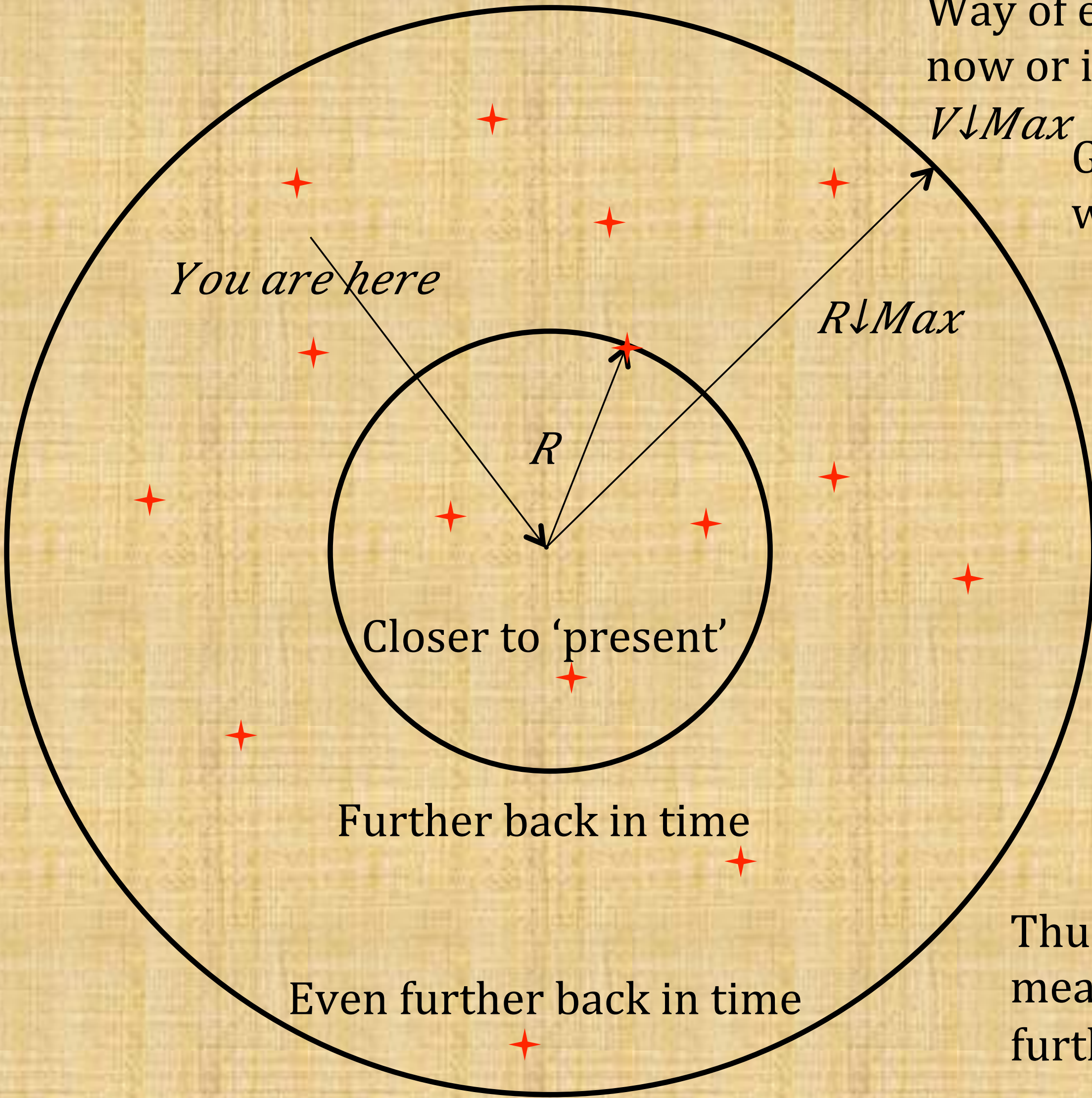
Examining the cosmic evolution



Way of estimate whether there are more now or in the past is to take the ratio V/V_{Max}

Given an even distribution, one would expect $\langle V/V_{Max} \rangle \sim 0.5$

For example,
assume the observation flux limit is 1Jy, and we have a bunch of 4Jy sources.

Then since the total number scales with volume (given even distribution), the average would be 0.5

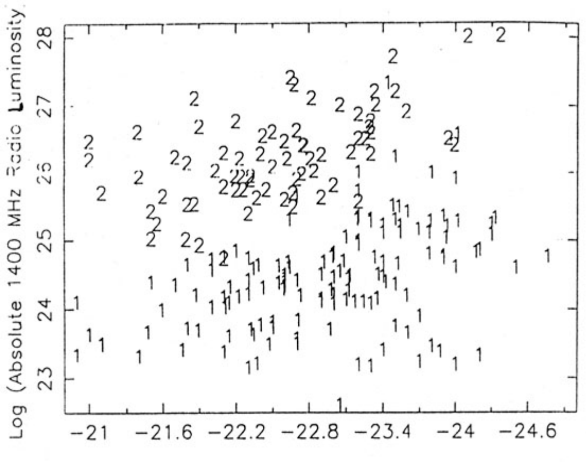
Thus, if $\langle V/V_{Max} \rangle > 0.5$, it would mean that there are more of them further to us.

Cosmic evolution radio loud sources

FRI : almost no evolution τ>34Gyr

FRII : rapid evolution τ~1.7Gyr

FSRQs evolve slower than steep spectrum extended sources(possibly due to selection effects, we only see the bottom line of FR IIs)

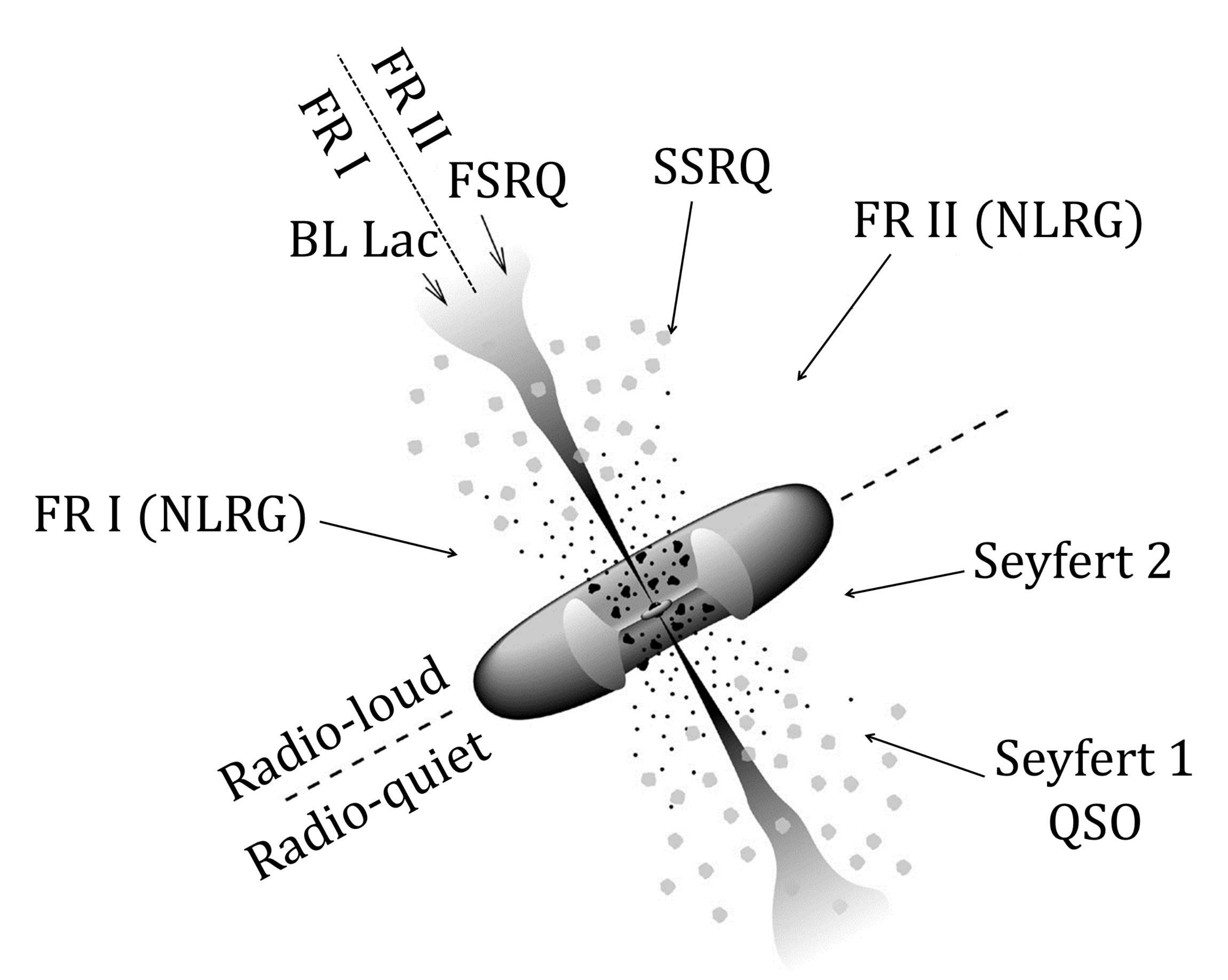


BL Lac：don't evolve much, much like FRIs

*Understanding by beaming effect

FRI have slower evolution thus have higher total probability of having one beamed at us.

Final summary



TO BE STARTED!!