Modeling AGN Spectral Energy Distributions with Leptonic Models

Justin D. Finke

Space Science Division,

Naval Research Laboratory, Washington, DC, USA

For the *Fermi*-LAT Collaboration

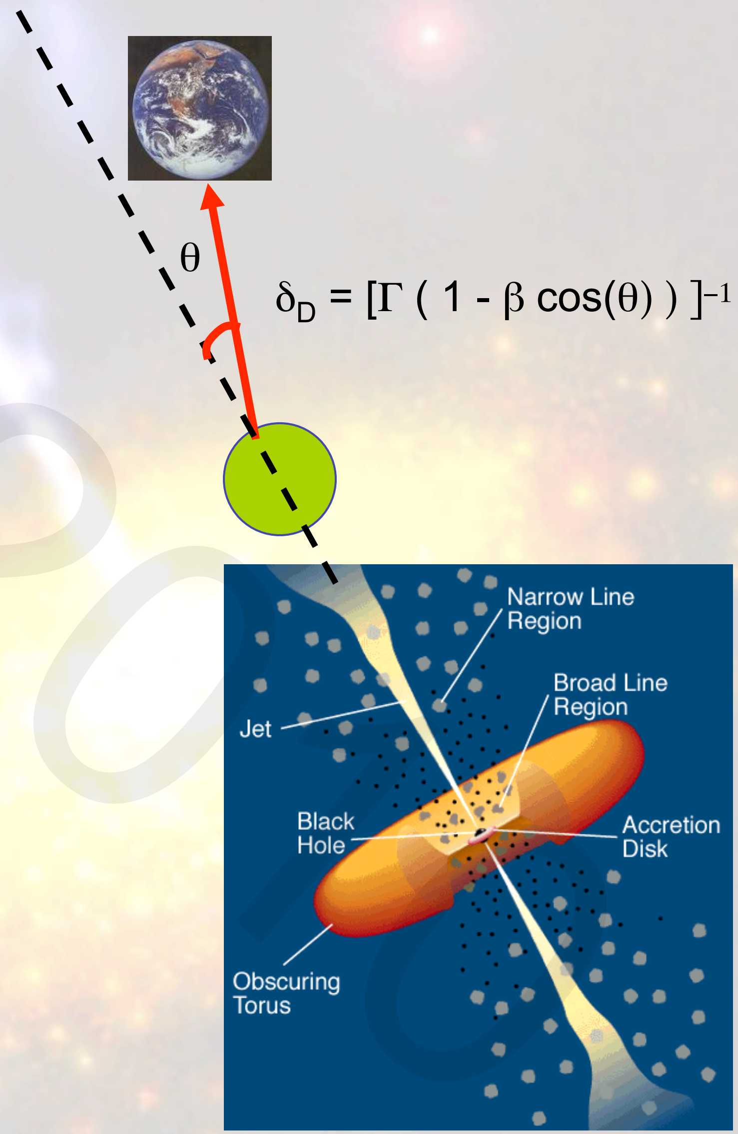
Outline

- Introduction to modeling
  - Synchrotron/SSC models
  - External Compton models

- Modeling 3C 454.3

- Modeling LAT-detected radio galaxies
  - Cen A
  - M87
  - NGC 1275

The One-Zone Time-Independent SSC Model



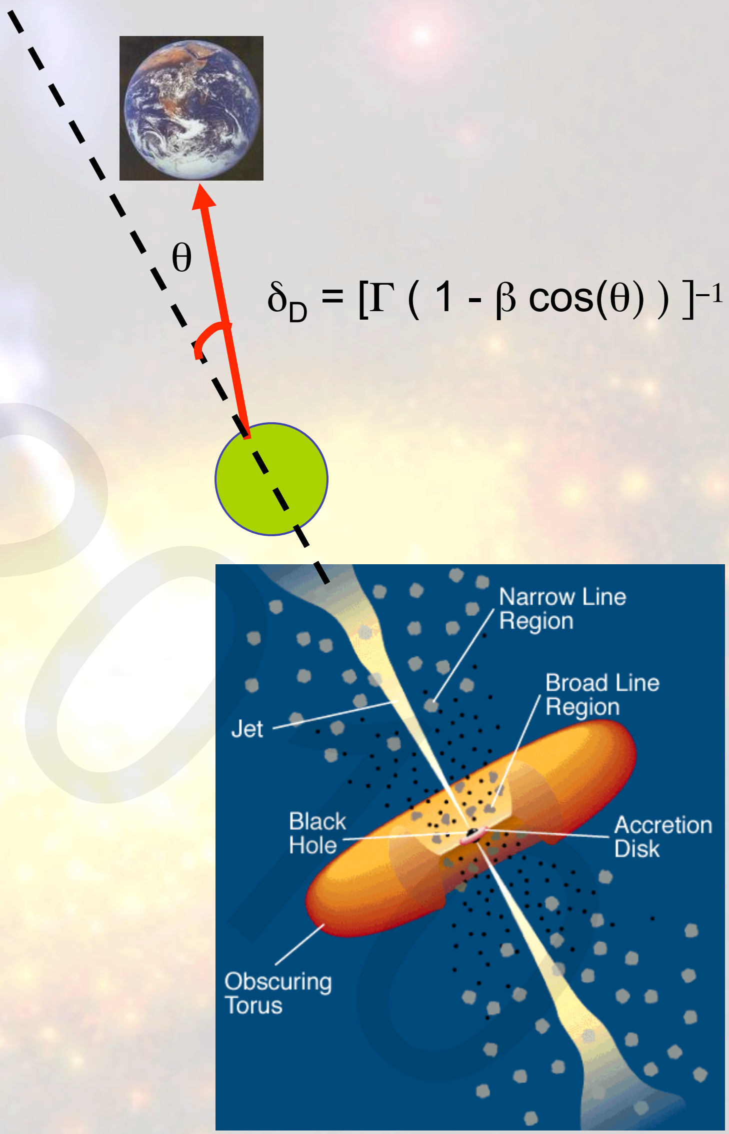
$$\delta_D = [\Gamma (1 - \beta \cos(\theta))]^{-1}$$

The One-Zone Time-Independent SSC Model

In blob frame:
- Tangled, homogeneous B-field
- homogenous, randomly oriented electron distribution

Radiation is Doppler boosted along our line of sight.

Compton scattering synchrotron photons by the same electrons which produce them



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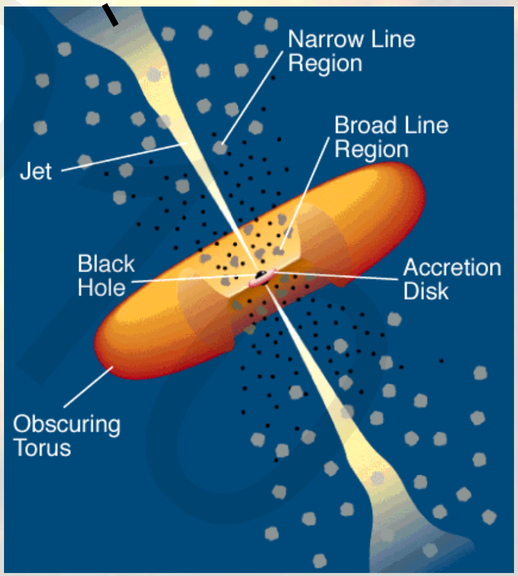


Write SSC as a function of:
δ_D, B, R_b', $N_e(\gamma)$.

Can constrain R_b' based on observations:

$$R_b' \leq \frac{\delta_D c t_{\mathrm{var}}}{(1+z)}$$

Can constrain $N_e(\gamma)$ by relating synch. power-law to electron power-law.

Synchrotron/SSC Model

If scattering is in the Thomson regime, one can derive simple analytic approximations:

$$\delta_D \cong 5.3 \left(\frac{\nu_{SSC,25}}{t_d \nu^2_{syn,16}} \right)^{1/2} \left(\frac{A(\alpha_1, \alpha_2)\, L^2_{SSC,45}}{L_{syn,45}} \right)^{1/4} \quad (1)$$

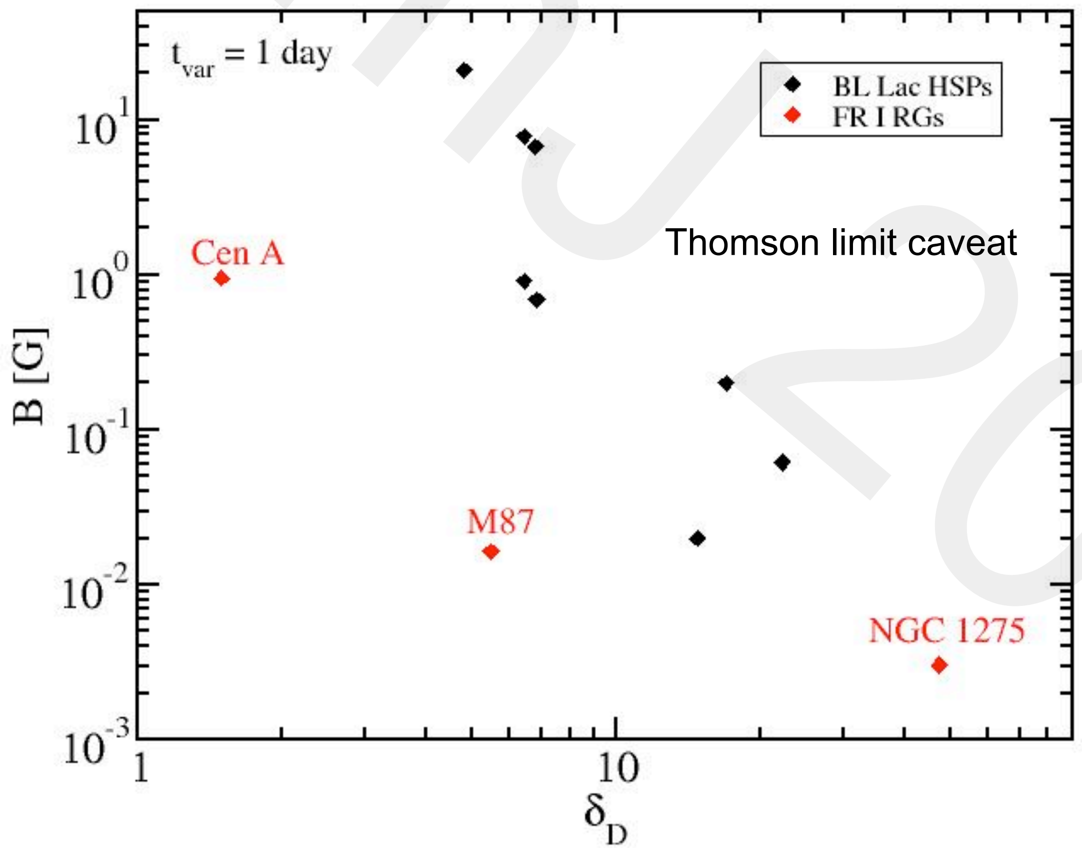
$$B \cong 0.68\, G\, (1+z) \frac{\nu^3_{syn,16} t_d^{1/2}}{\nu^{3/2}_{SSC,25}} \left(\frac{L_{SSC,45}}{A(\alpha_1, \alpha_2)\, L^2_{syn,45}} \right)^{1/4} \quad (2)$$

$$A(\alpha_1, \alpha_2) = (\alpha_1 - 1)^{-1} + (1 - \alpha_2)^{-1}$$

Ghisellini et al. (1996); Tavecchio et al. (1998)

Can observe dependences on observable parameters.

Synchrotron/SSC Model



Used BL Lac SEDs from Abdo et al. (2010), ApJ, 716, 30

RG SEDs from dedicated papers:

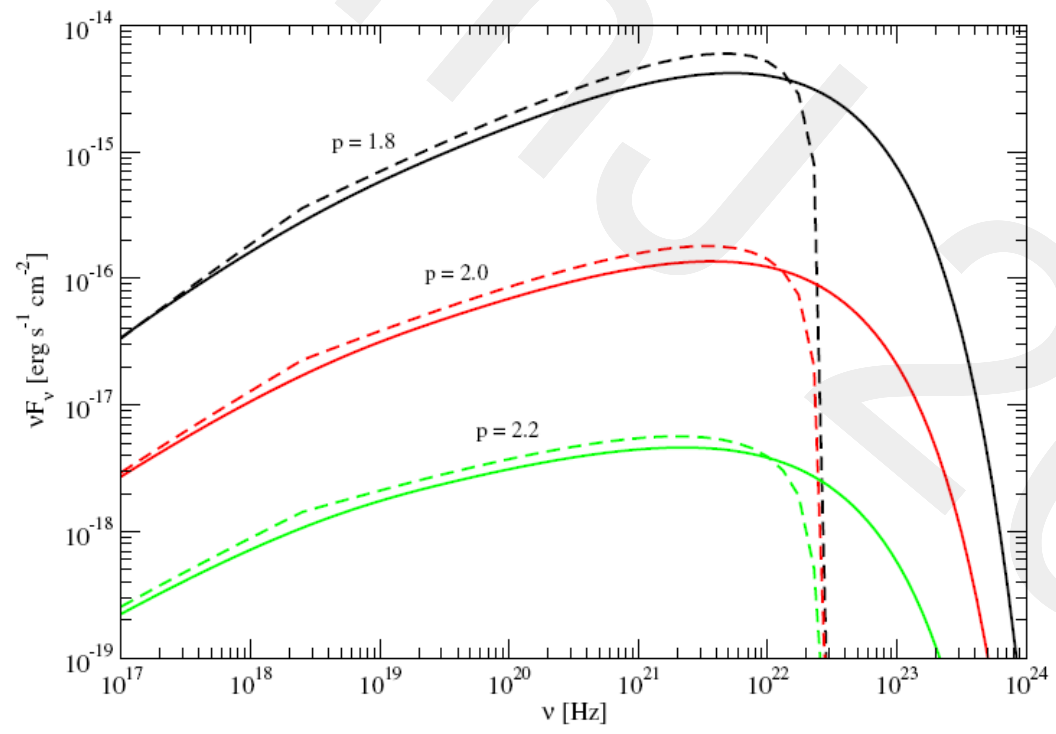
Cen A: Abdo et al. (2010), ApJ, submitted.

M87: Abdo et al. (2010), ApJ, 707, 55

NGC 1275: Abdo et al. (2010), ApJ, 699, 31

Parameters for NGC 1275 not right, probably longer variability timescale.

Thomson and Compton cross-sections



$$N'_e(\gamma') = K_e\ \gamma'^{-p}\ \exp\left(\frac{-\gamma'}{\gamma'_c}\right)\ H(\gamma' - \gamma'_1)$$

Dashed: Thomson + cutoff
Solid: Compton

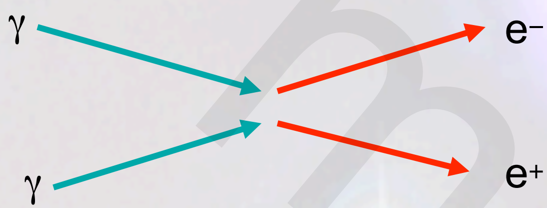
Full Compton expression from Jones (1968).

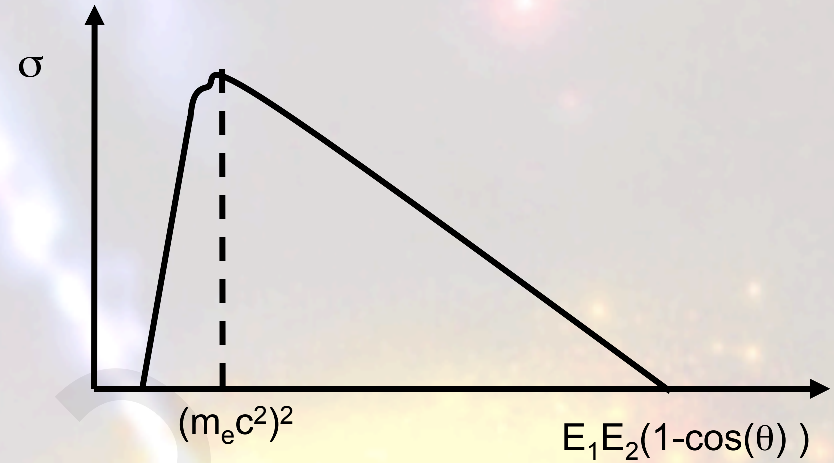
Full Compton expression needed to accurately represent SSC spectrum.

δ_D = 100, B = 10 mG, t_v = 300 s

Finke, Dermer, & Böttcher (2008)

Internal γγ absorption





Leads to constraint on Doppler factor:

$$\delta_{\rm D} \geq \left[\frac{2^{\alpha}(1+z)^{2\alpha}\sigma_T D^2}{m_e c^4 t_{v,min}} \epsilon_\gamma f^{syn}_{\epsilon_\gamma^{-1}}\right]^{\frac{1}{4+2\alpha}}$$

where $\alpha = \alpha_1$ for

$$\epsilon_\gamma^{-1} < \frac{(1+z)^2 \epsilon^{syn}_{pk}}{2\delta_D}$$

and $\alpha = \alpha_2$ for

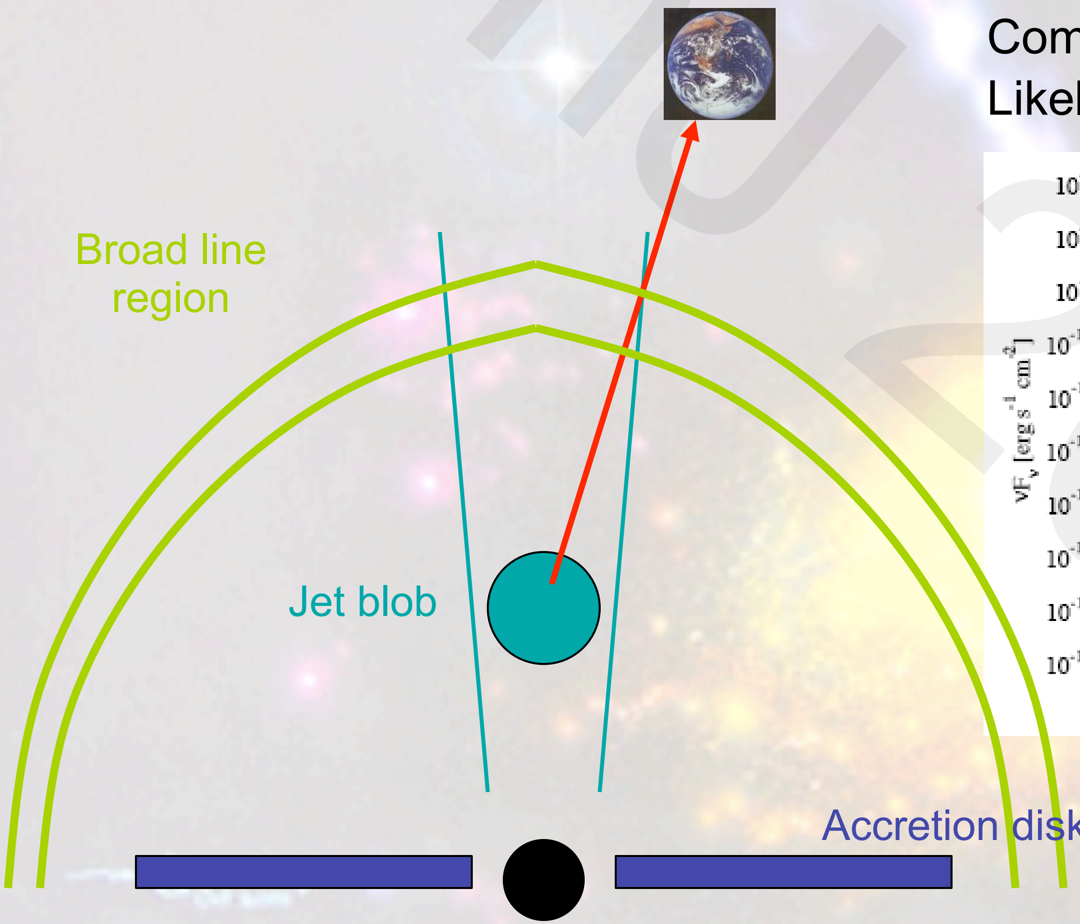
$$\epsilon_\gamma^{-1} > \frac{(1+z)^2 \epsilon^{syn}_{pk}}{2\delta_D}$$

Using synch/SSC expressions:

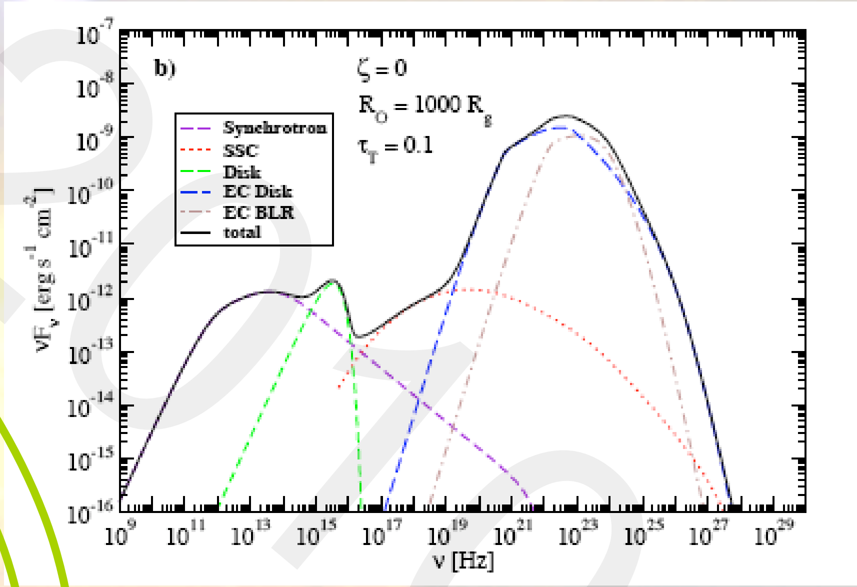
$$\delta_D \geq 4.4 \left[2^{-\alpha}(1+z)^{2\alpha}\ \epsilon_{\gamma,7}\ D_{25}\ f^{syn}_{\epsilon_\gamma^{-1},-10} \times \frac{\epsilon^{syn}_{pk,-7}}{\epsilon^{SSC}_{pk}} \frac{\sqrt{f^{syn}_{pk,-10}}}{f^{SSC}_{pk,-10}} \frac{1}{\sqrt{A(\alpha_1,\alpha_2)}} \right]^{1/4}$$

e.g., Dondi & Ghisellini (1995), MNRAS, 273, 583; Ackerman et al. (2010), arXiv:1005.2141

External Sources for Compton Scattering and $\gamma\gamma$ Absorption



Various radiation components can Compton scatter and absorb γ-rays. Likely found in FSRQs.



Dermer, Finke, Krug, & Böttcher (2009), ApJ, 692, 32

External Sources for Compton Scattering and $\gamma\gamma$ Absorption

Compton scattering

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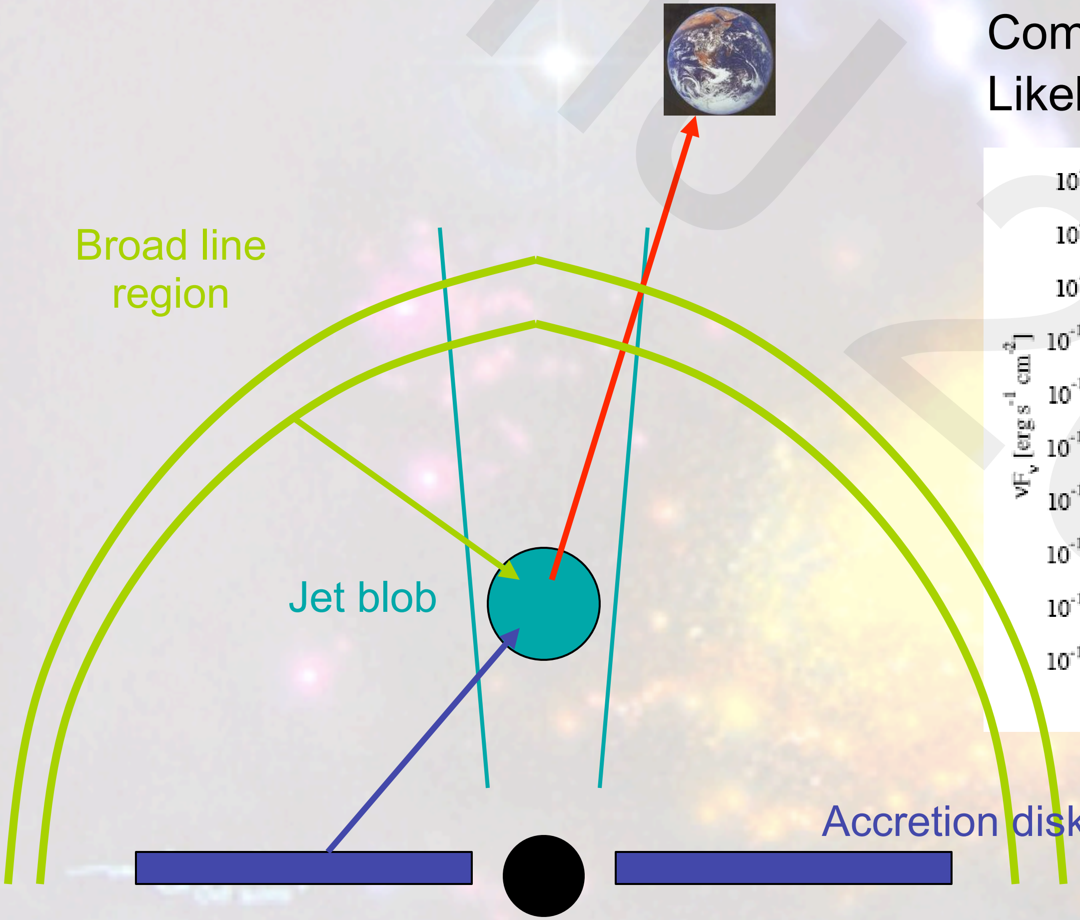

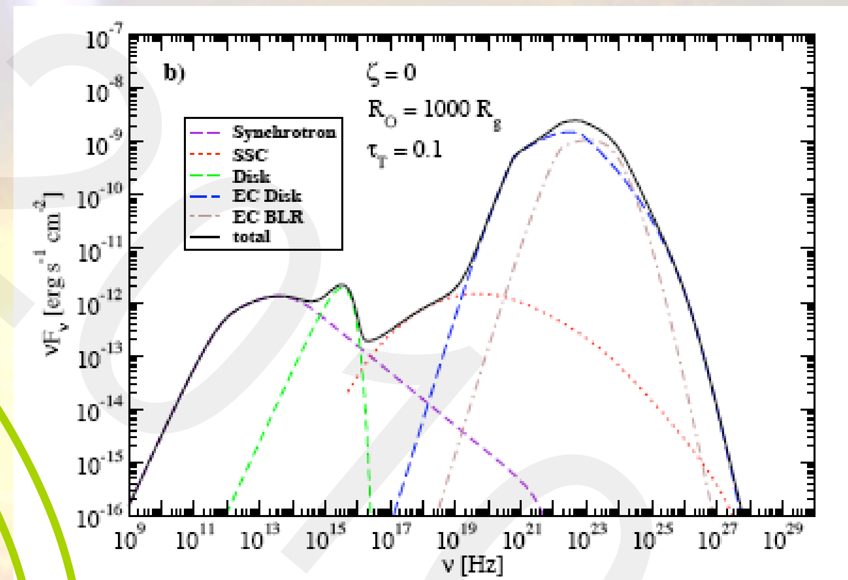

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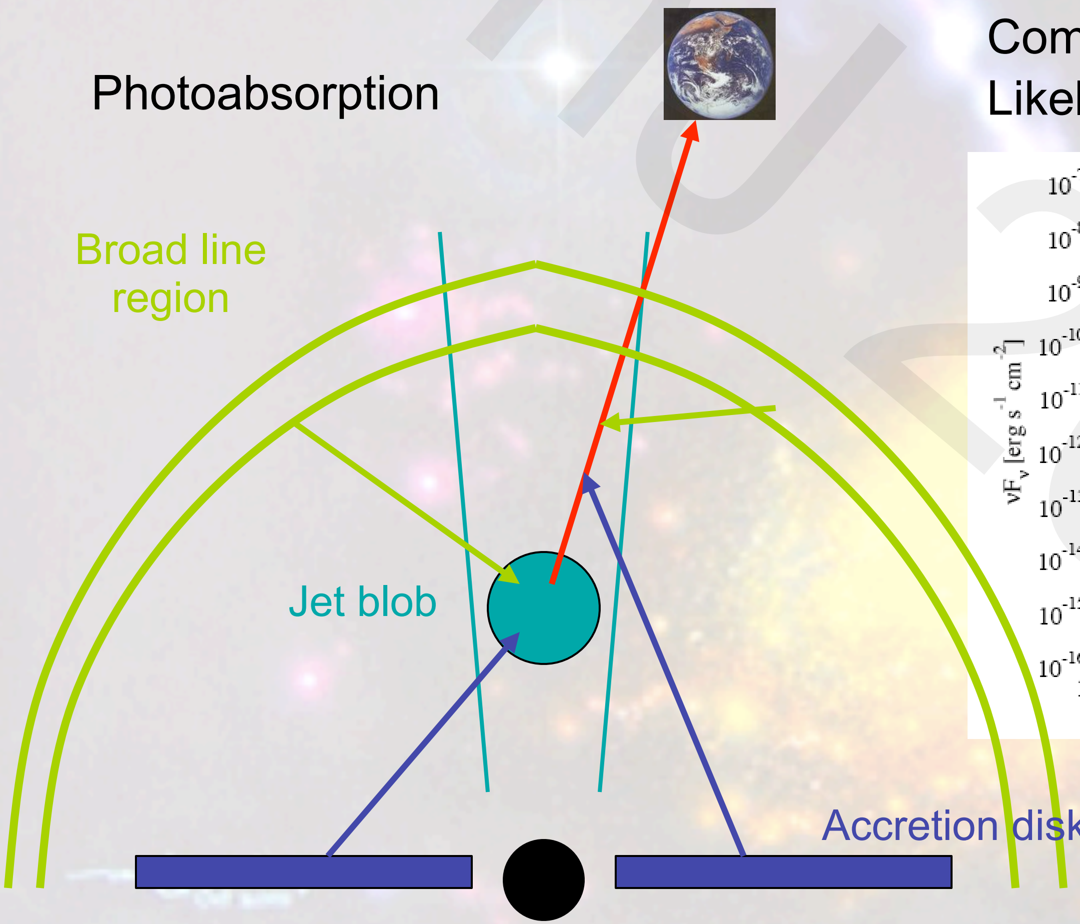
External Sources for Compton Scattering and $\gamma\gamma$ Absorption

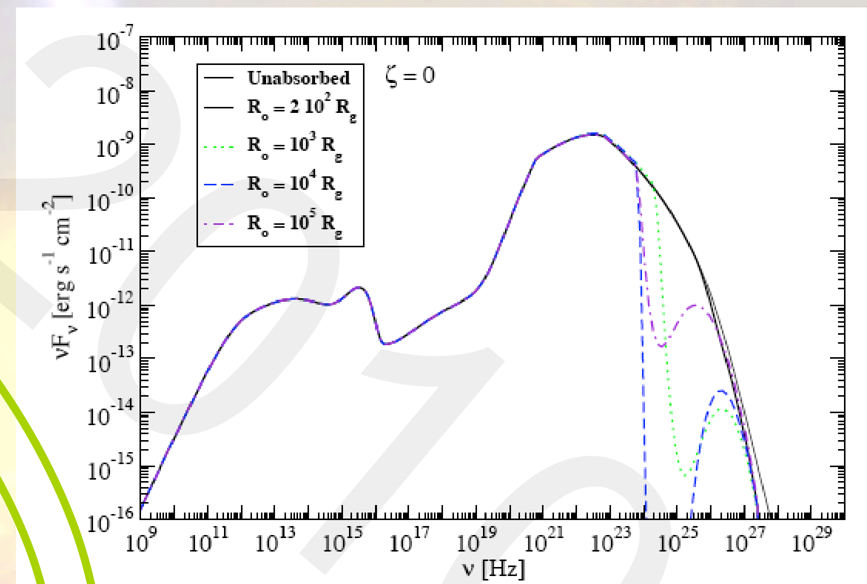
Compton scattering

Photoabsorption



Various radiation components can Compton scatter and absorb γ-rays.

Likely found in FSRQs.



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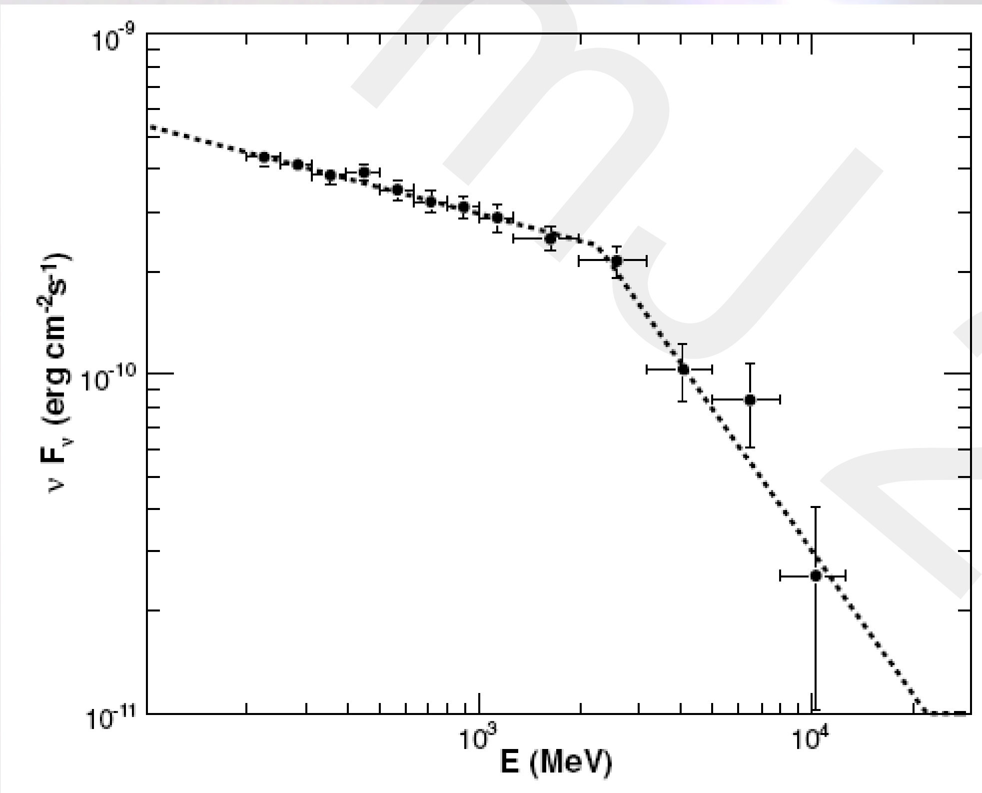
The Quasar

Fermi-LAT Spectrum of the FSRQ 3C 454.3



Abdo et al. (2009), ApJ, 699, 817

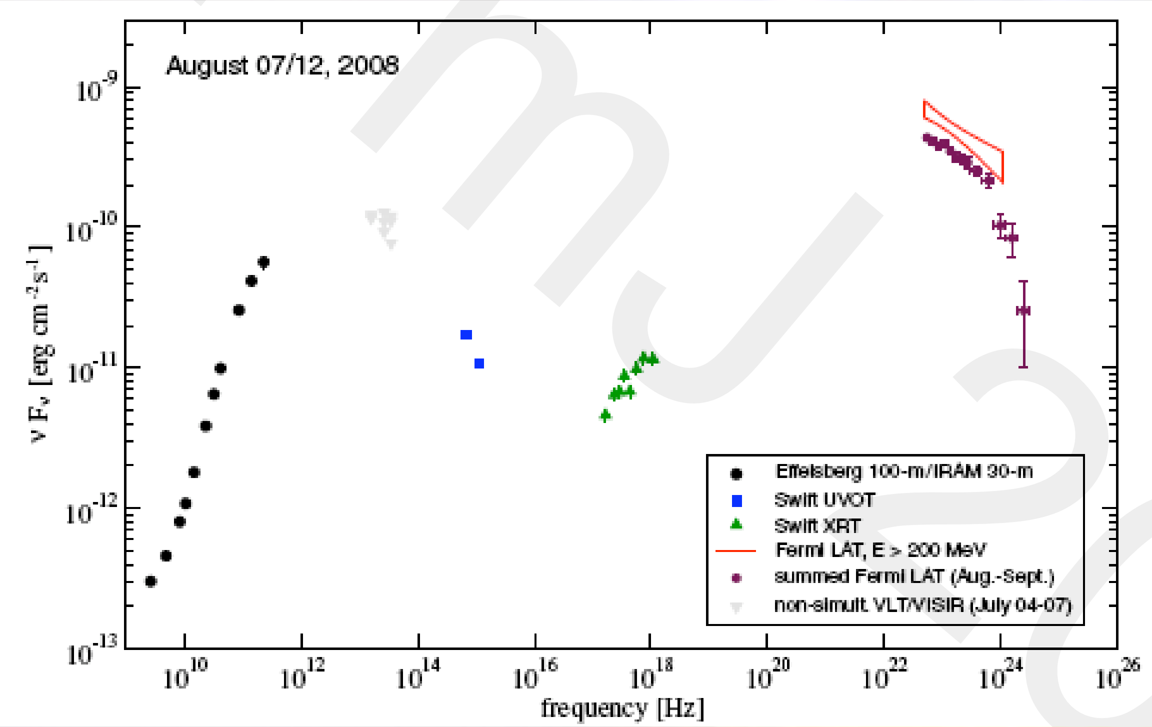
- Data taken from July -- October 2008

- Exhibits spectral break:
  - Γ_1 = 2.3 +/- 0.1
  - Γ_2 = 3.5 +/- 0.25
  - E_{brk} = 2.4 GeV

- Variable on timescales ~ few days

- Optical (SMARTS, *Swift*-UVOT), γ-rays (*Fermi*-LAT) have well-correlated variability while X-rays (*Swift*-XRT) do not (Bonning et al. 2009, ApJ, 697, L81).

The 3C 454.3 SED



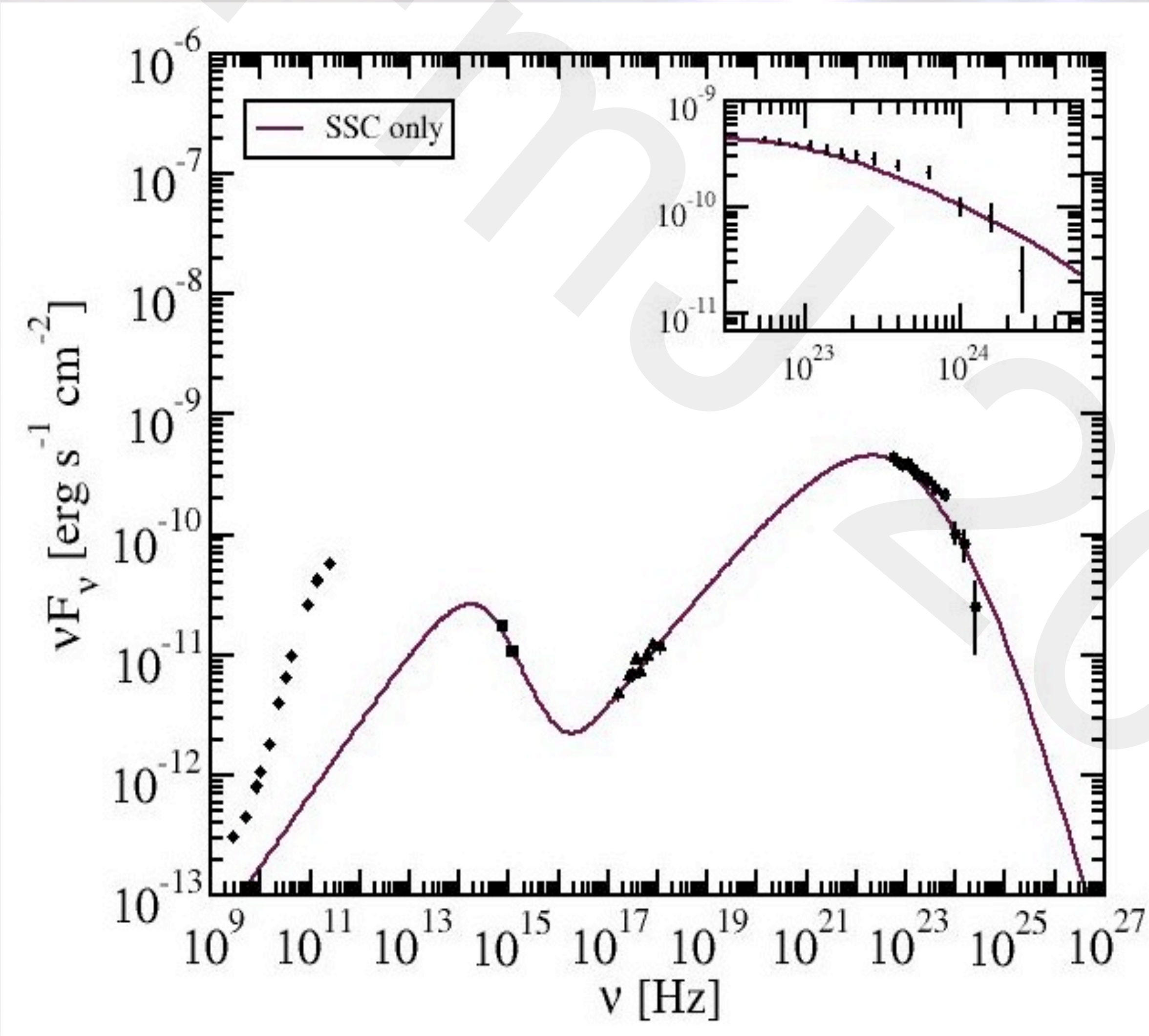
Abdo et al. (2009), ApJ, 699, 817

- Optical & X-ray constrain p_1~1.8, p_2~4.8 ($n_e \sim \gamma^{-p}$).
- Approximately consistent with synchrotron & Compton scattering in fast cooling regime.
- This is not consistent with the LAT spectrum spectral indices if this component is from Compton scattering of a single photon source.

LAT spectrum could be explained by:

- broad Compton scattering component
- Compton scattering of multiple photon sources.

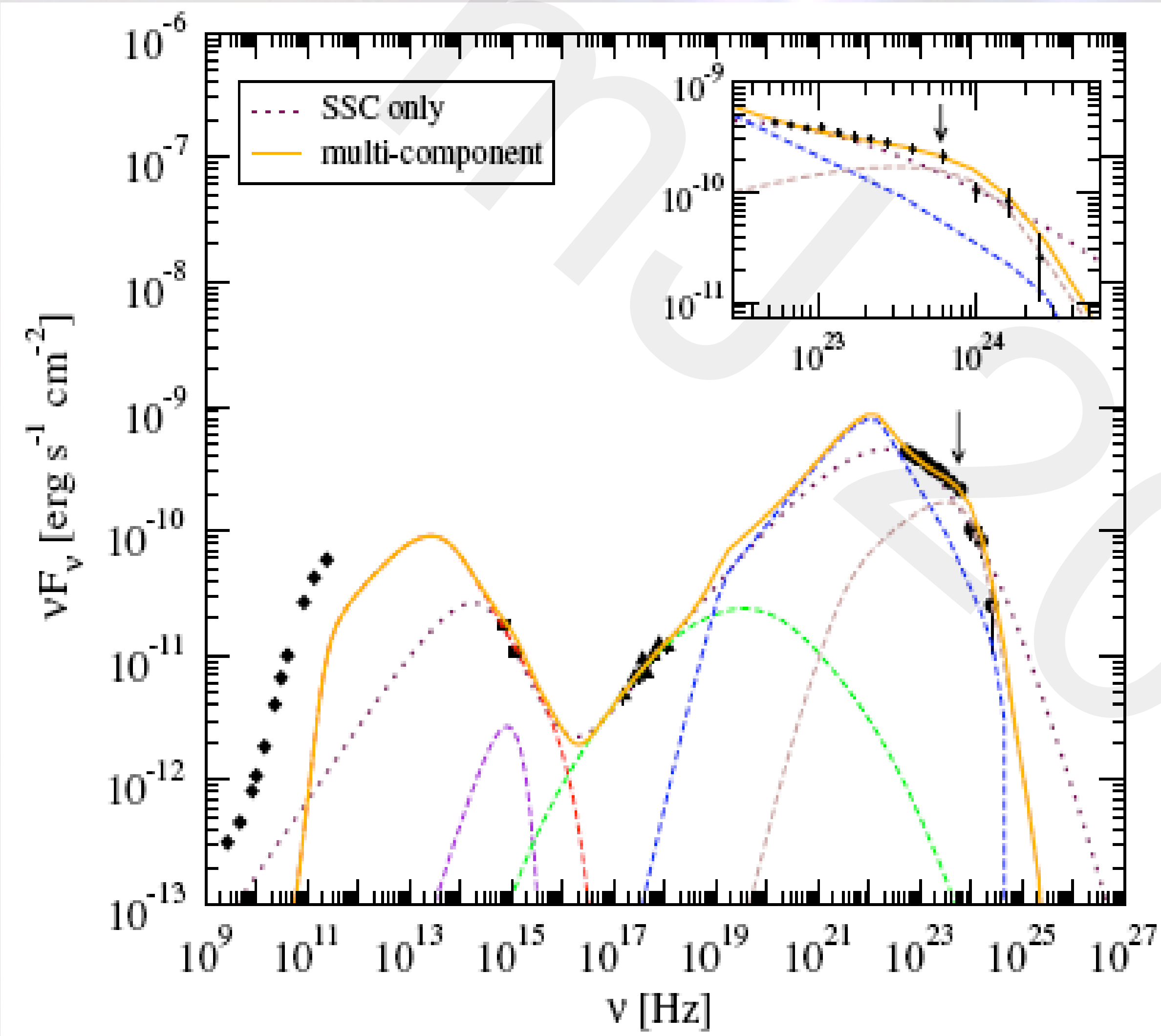
SSC Model Fit



- synch/SSC fit explains SED ok but problems:
  - Doesn't fit γ-rays so great.
  - Ignores BLR which must be present due to optical spectrum.
  - Far from equipartition.
  - $B / B_{eq} = 0.06$

Finke & Dermer (2010) ApJ, 714, L303

Model Fit

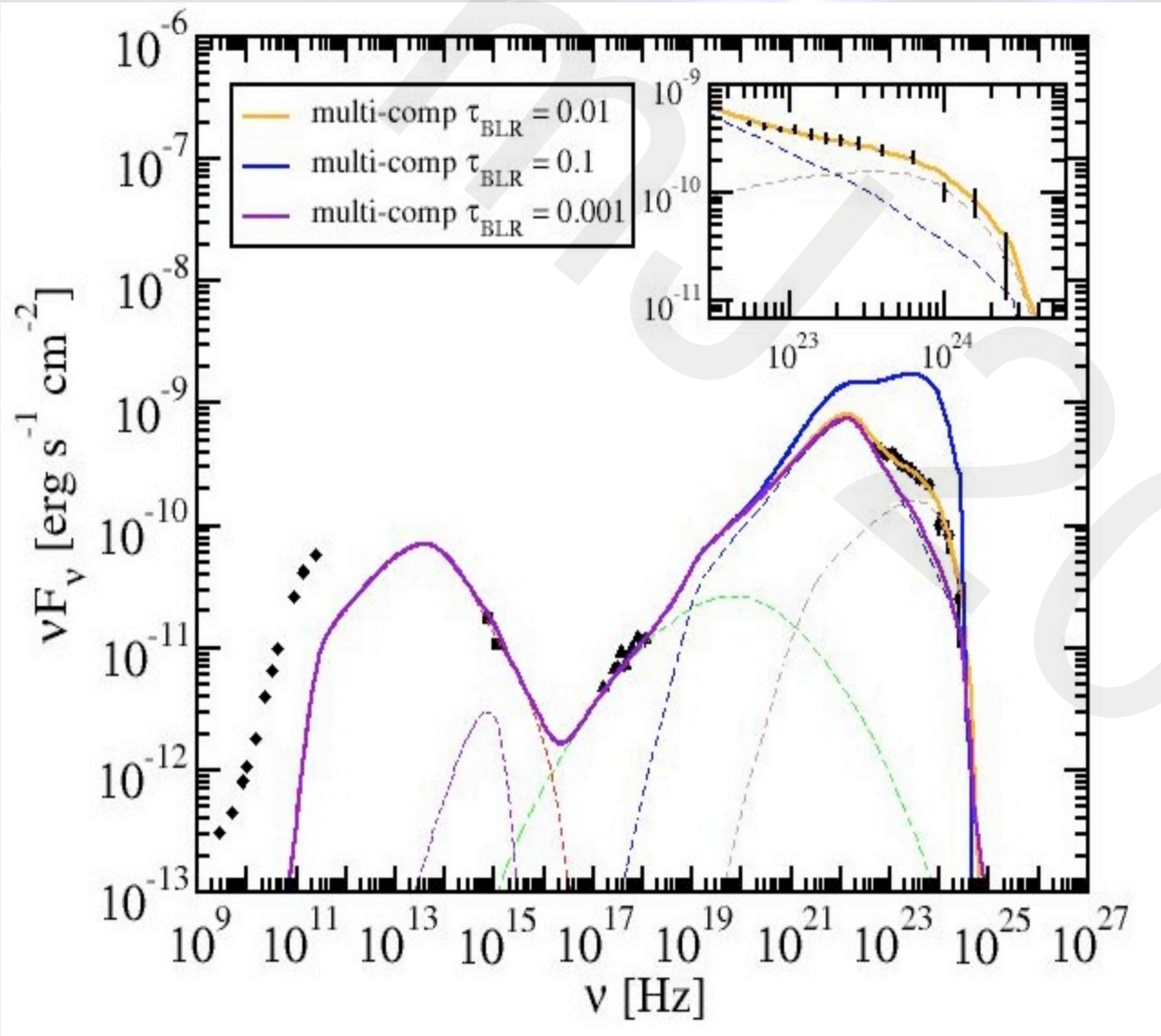


- Combination of EC-disk (lower energy) and EC-BLR (higher energy) fits well.

- This model:
  - Agrees with all observations including variability.
  - Includes BLR.
  - Close to equipartition.
  - $B / B_{eq} = 0.6$

Finke & Dermer (2010) ApJ, 714, L303

Model Fit



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IC-disk and IC-BLR model

- BLR e^- number density ~ r^{-2} gives u_{BLR} ~ r^{-3}, similar to u_{disk}.
- For this combination to explain break, u_{disk} ~ u_{BLR}.
- The spectral break will exist independent of r.
- Requires τ_{BLR} ~ $R_g/R_{BLR,i}$
- This BLR density is consistent with a wind model for the BLR (Murray & Chiang 1995, ApJ, 454, L105).
- Can spectral breaks in other sources be attributed to this model? Could breaks be from internal $\gamma\gamma$ absorption (e.g., Reimer 2007)?

3C 454.3 Model Params

Symbol	Multi-component Model	SSC Model
z	0.859	0.859
$\Gamma_{\rm bulk}$	15	15
$\delta_{\rm D}$	30	28
B	0.4 G	0.032 G
t_v	1.7×10^5 s	1.7×10^5 s
p_1	2.0	1.8
p_2	4.4	4.8
$\gamma'_{\rm min}$	3×10^1	10
$\gamma'_{\rm max}$	2×10^4	2×10^9
$\gamma'_{\rm brk}$	1.1×10^3	10^4
M_9	2.0	
$l_{\rm Edd}$	0.04	
η	1/12	
r	$1.5 \times 10^3 R_g$	
$\tau_{\rm BLR}$	0.01	
R_i	$5.0 \times 10^2 R_g$	
R_o	$5.0 \times 10^5 R_g$	
ζ	-2	
$B/B_{\rm eq}$	0.6	0.06
$P_{j,B}$	1.8×10^{45} erg s^{-1}	10^{43} erg s^{-1}
$P_{j,{\rm par}}$	2.7×10^{46} erg s^{-1}	2.3×10^{47} erg s^{-1}

Finke & Dermer (2010) ApJ, 714, L303

Radio Galaxies

Jet emission from radio galaxies

- The viewing angle gives a significant constraint for radio galaxies (Urry & Padovani 1995; Abdo et al. 2010, submitted):

$$\delta_D \leq \csc \theta_j$$

- So Doppler factors (and hence Lorentz factors) must be small for off-axis RG emission.

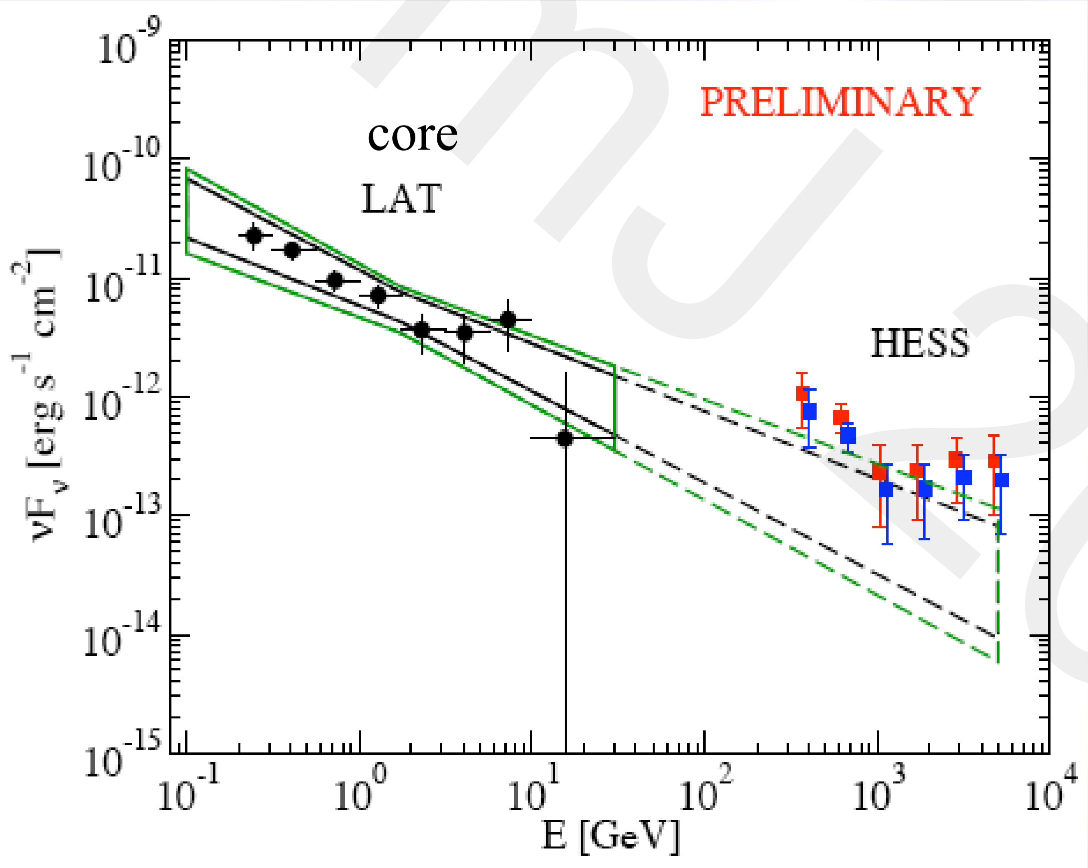
- Modeling SEDs of radio galaxies gives typically lower δ_D than blazars.

- But they are still brighter than one would expect from de-beamed blazar emission.
  - Does this imply that RG emission is from a slower region than blazars (e.g., Chiaberge 2000)?

Cen A

- An FR I radio galaxy 3.7 Mpc from Earth
- Has been detected with EGRET (Hartman 1999) and HESS (Aharonian et al. 2009).
- Giant (10 deg) radio lobes, detected in γ-rays by the LAT (Abdo et al. 2010, Science, 328, 725; Cheung, Wed.)
- LAT core spectrum is consistent with EGRET.
- The LAT, HESS and EGRET showed no evidence for variability.
- From radio observations, θ_j >~ 15 deg (Hardcastle et al. 2003).

Cen A γ-ray Spectrum



Statistical-only errors
Statistical + systematic errors

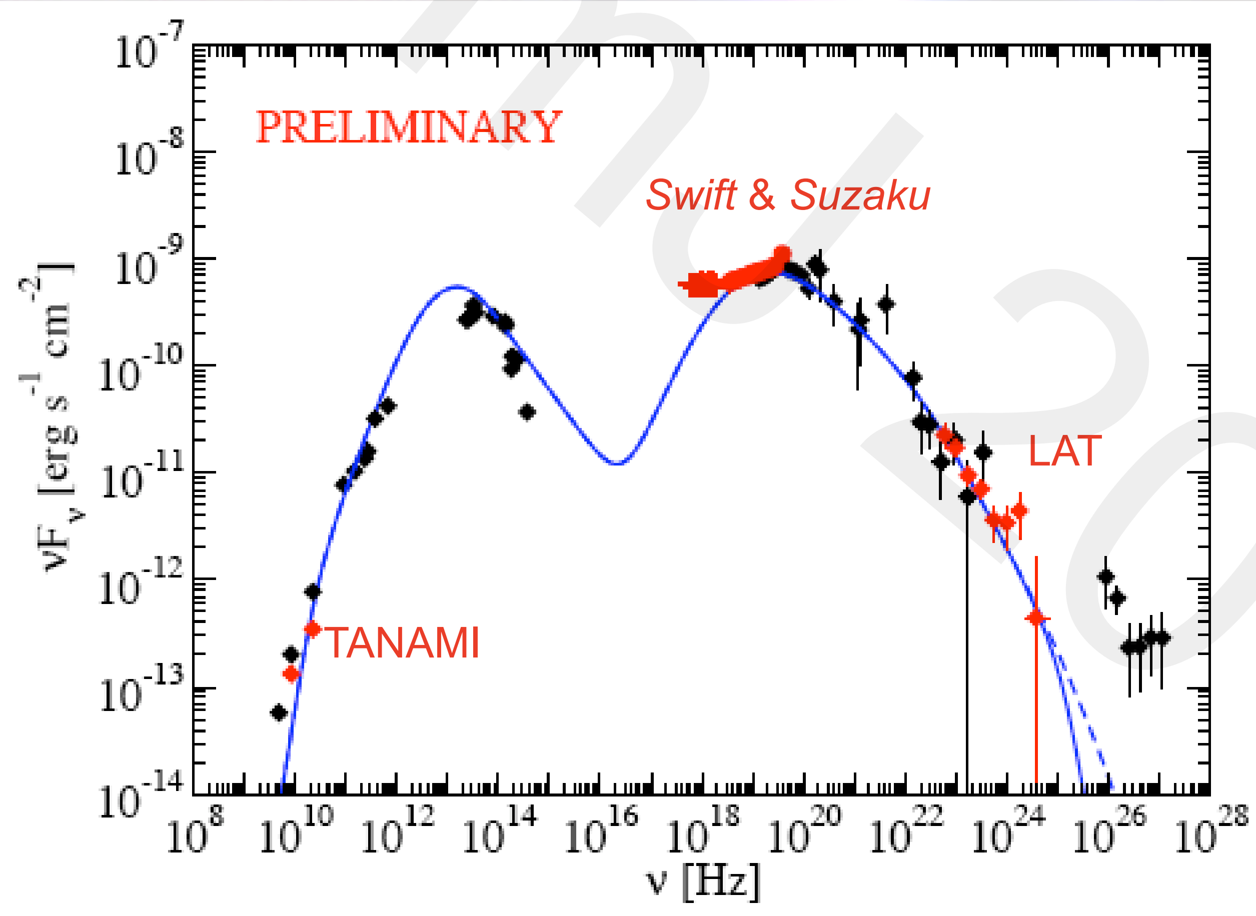
Non-simultaneous HESS spectrum from 2008

If HESS spectrum is scaled down by its normalization uncertainty, it is barely consistent with extrapolated LAT spectrum.

Neither LAT nor HESS show any variability.

Abdo et al. 2010, ApJ, submitted

Cen A SED

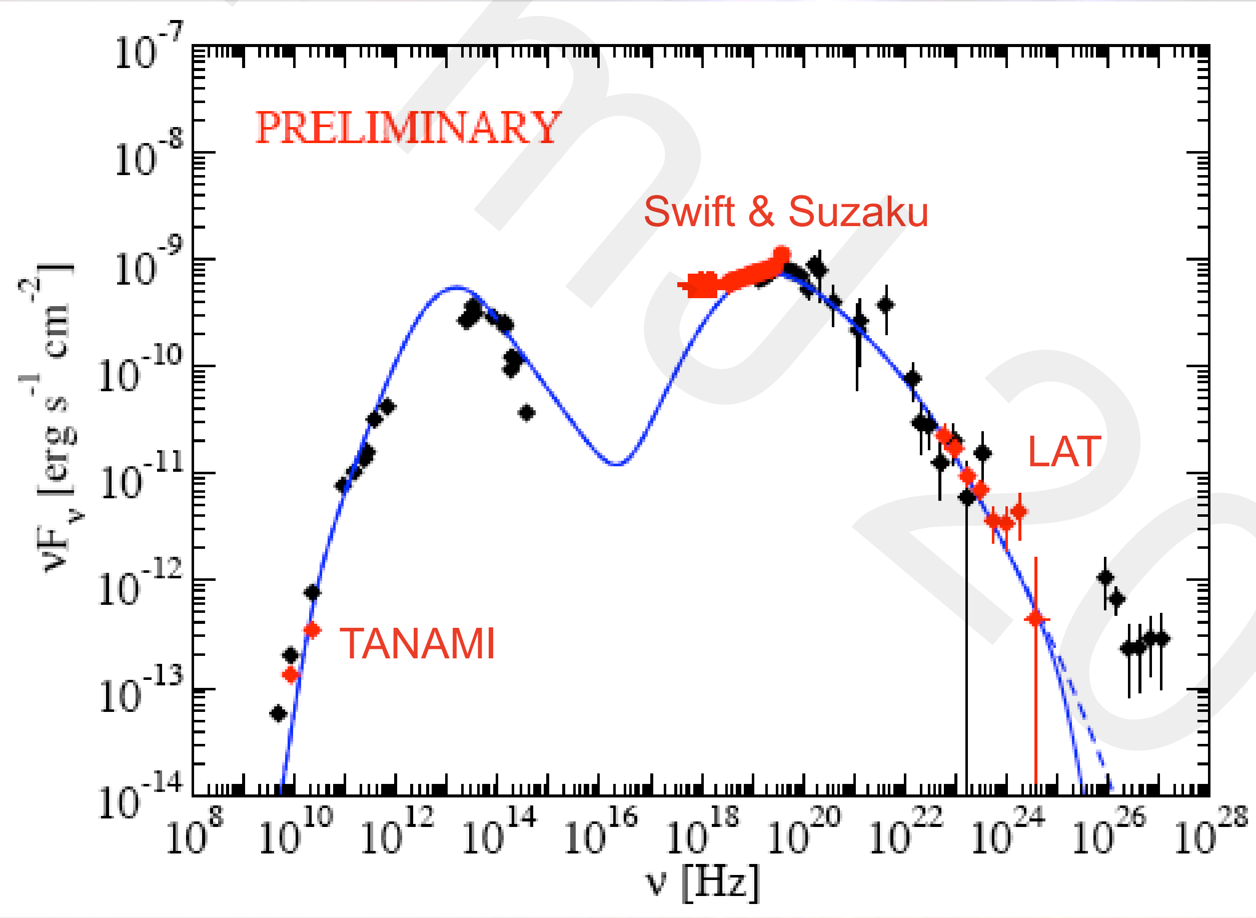


Red: simultaneous
Black: archival

Photoabsorption implies SSC cannot explain LAT and HESS γ-rays.

Abdo et al. 2010, ApJ, submitted

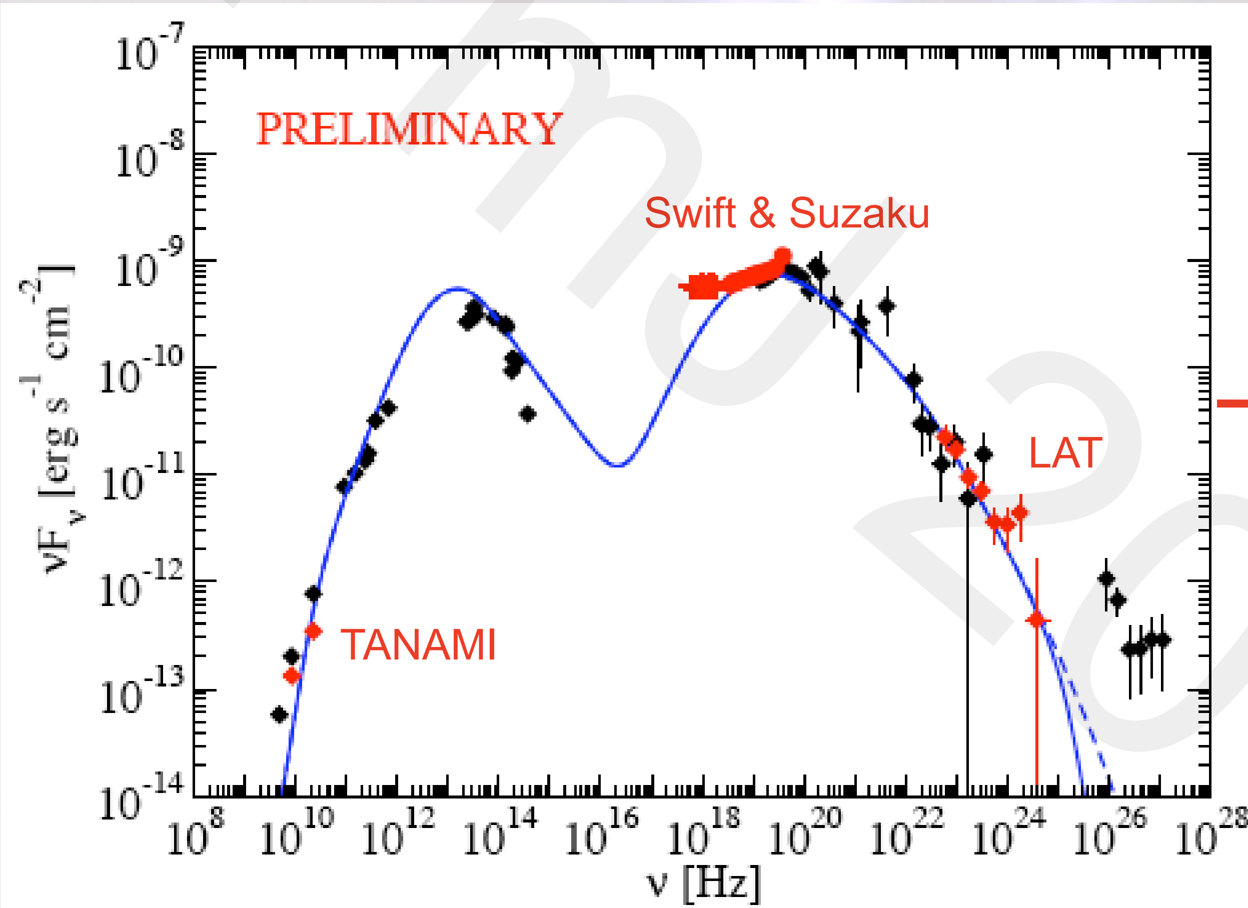
Cen A SED



Γ_j	7.0
δ_D	1.0
θ_j	30 deg
B	6.2 G
t_{var}	1.0×10^5 s
R_b	3.0×10^{15} cm
p_1	1.8
p_2	4.3
γ_{min}	3×10^2
γ_{max}	1×10^8
γ_{brk}	8×10^2
$P_{j,B}$	6.5×10^{43} erg s^{-1}
$P_{j,e}$	3.1×10^{43} erg s^{-1}

Abdo et al. 2010, ApJ, submitted

Cen A SED



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Size scale limited by TANAMI observations (Mueller, Ojha, Kadler, Ploetz, Hase). Talk by Ojha Tuesday, poster P18 by Mueller.

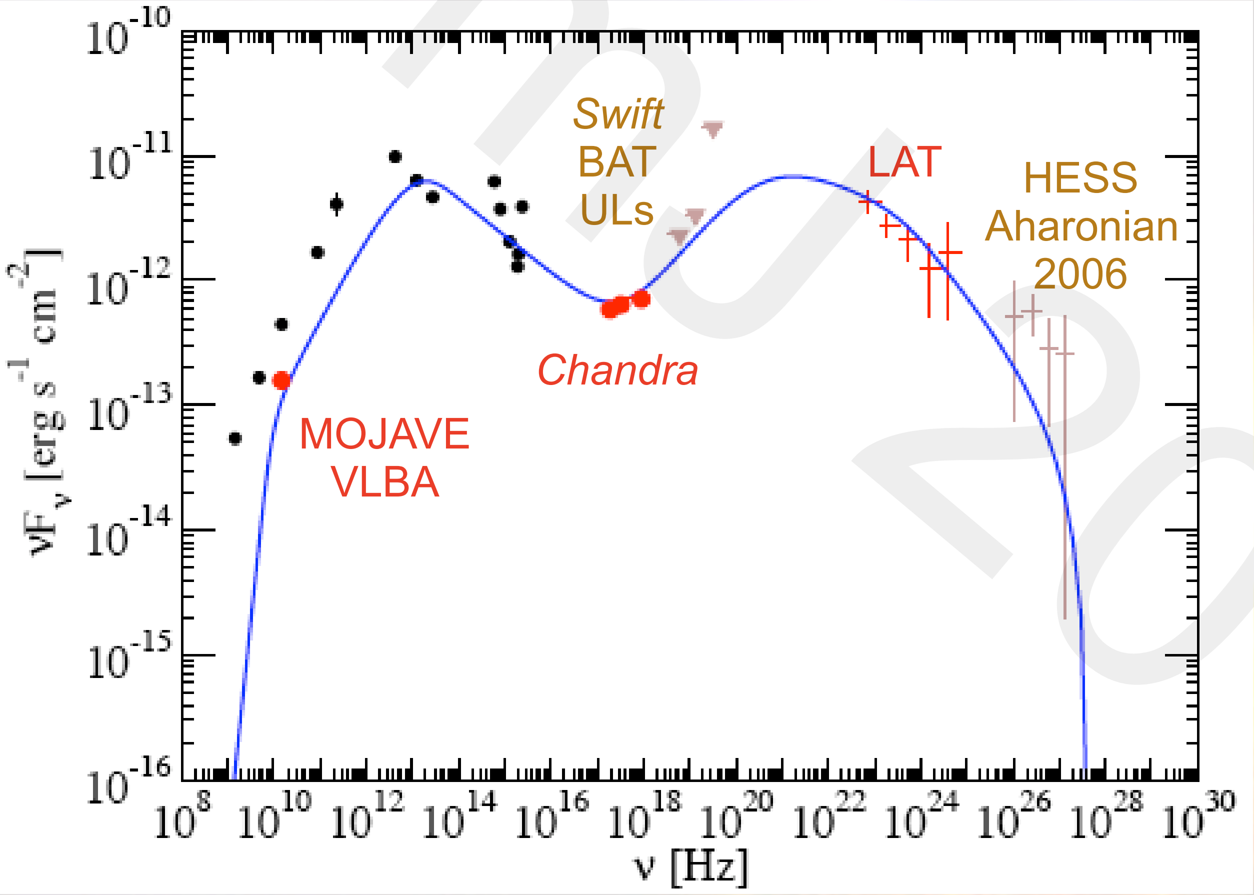
Abdo et al. 2010, ApJ, submitted

The Radio Galaxy
M 87

M87

- FRI at D = 16 Mpc
- Regular detections by TeV telescopes (e.g., Aharonian 2006, Acciari 2008, 2009). Some controversy over origin of TeV γ-rays, whether from core or farther out (HST-1).
- Angle θ_j < 19 deg (Biretta et al. 1999, ApJ, 520, 621). Smaller angles than Cen A means larger δ_D, and $\gamma\gamma$ absorption constraint can be avoided.
- No LAT variability in 10 month data. LAT spectrum consistent with EGRET.

M87



Γ_j	2.3
δ_D	3.9
θ_j	10 deg
B	0.055 G
t_{var}	1.2×10^5 s
R_b	1.4×10^{16} cm
p_1	1.6
p_2	3.6
γ_{min}	1
γ_{max}	1×10^7
γ_{brk}	4×10^3
$P_{j,B}$	2.0×10^{40} erg s^{-1}
$P_{j,e}$	7.0×10^{42} erg s^{-1}

TeV from a non-simultaneous low state

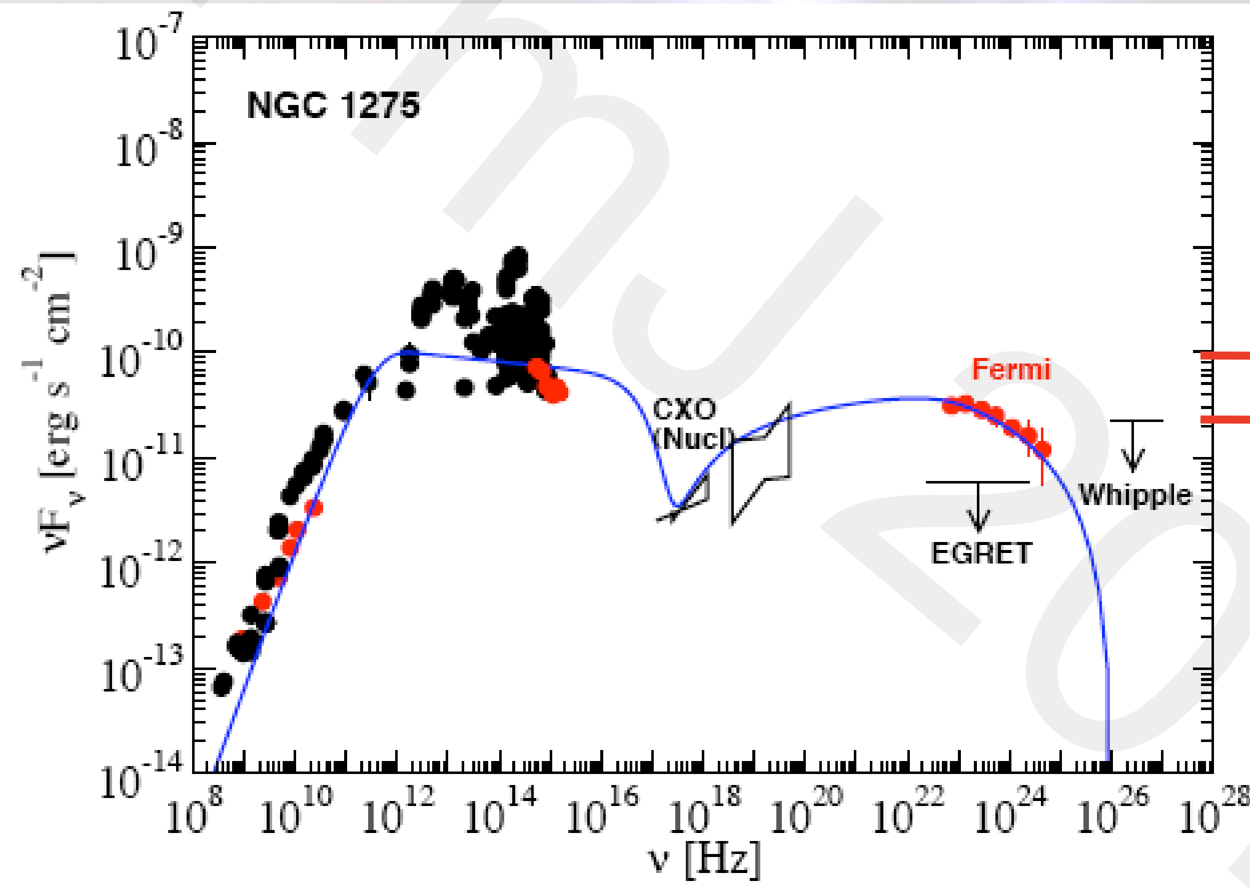
Abdo et al. 2009, ApJ, 707, 55

The Radio Galaxy NGC 1275

NGC 1275

- Per A, 3C 84
- $z = 0.018$ ($d_L = 75$ Mpc)
- Seyfert 1.5 (Veron-Cetty & Veron 2006)
- In initial LAT detection (4 months of data), it was unclear location of γ-rays, whether from Perseus Cluster or Per A (Abdo et al. 2009, ApJ, 699, 31), and no γ-ray variability found.
- With additional 8 months of data, Per A origin and variability on month timescales was found (Kataoka et al. 2010, ApJ, 715, 554).

NGC 1275



Γ_j	1.8
δ_D	2.3
θ_j	25 deg
B	0.05 G
t_{var}	3.0×10^7 s
R_b	2.0×10^{18} cm
p_1	2.1
p_2	3.1
γ_{min}	8×10^2
γ_{max}	4×10^5
γ_{brk}	1×10^3
$P_{j,B}$	2.3×10^{44} erg s^{-1}
$P_{j,e}$	2.3×10^{43} erg s^{-1}

Original modeling used large var. time, consistent with obs. at that time.

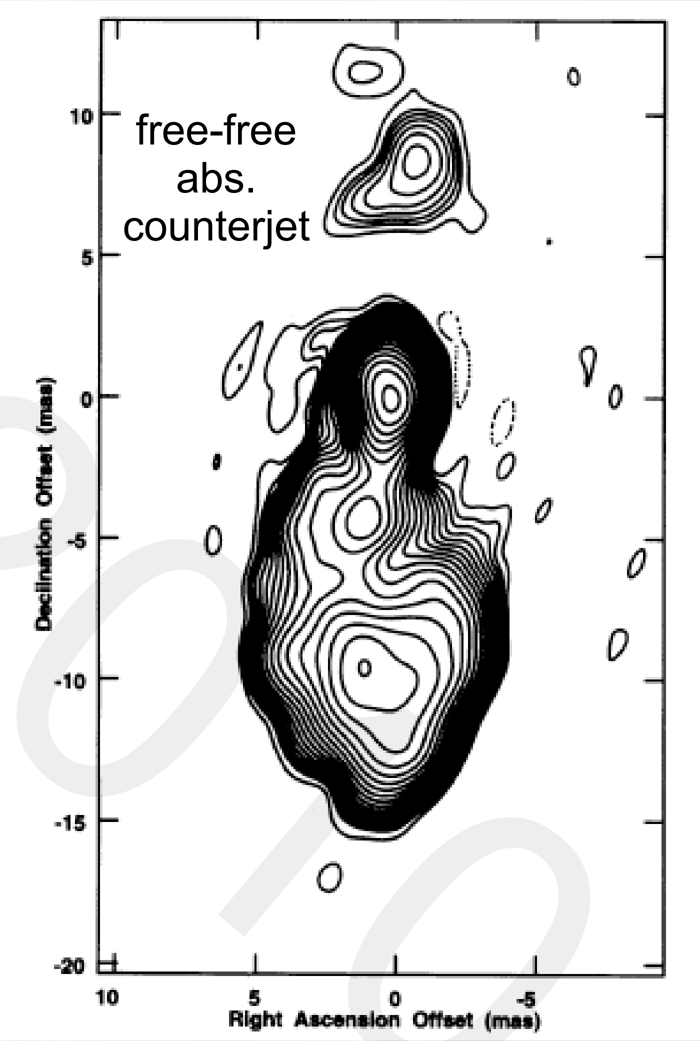
Abdo et al. 2009, ApJ, 699, 31

NGC 1275

- Using t_{var} = 1 month, Thomson limit equations give B = 0.016 G and δ_D = 8.6. This implies θ_j < 6.6 deg.

- Radio morphology, location of the core, somewhat ambiguous (e.g., Vermeulen et al. 1994; Nesterov et al. 1995; Walker et al. 2000; Nagai et al. 2010)

- Also see talks on Wednesday, by Hiroshi Nagai & Kenneth Kellerman.



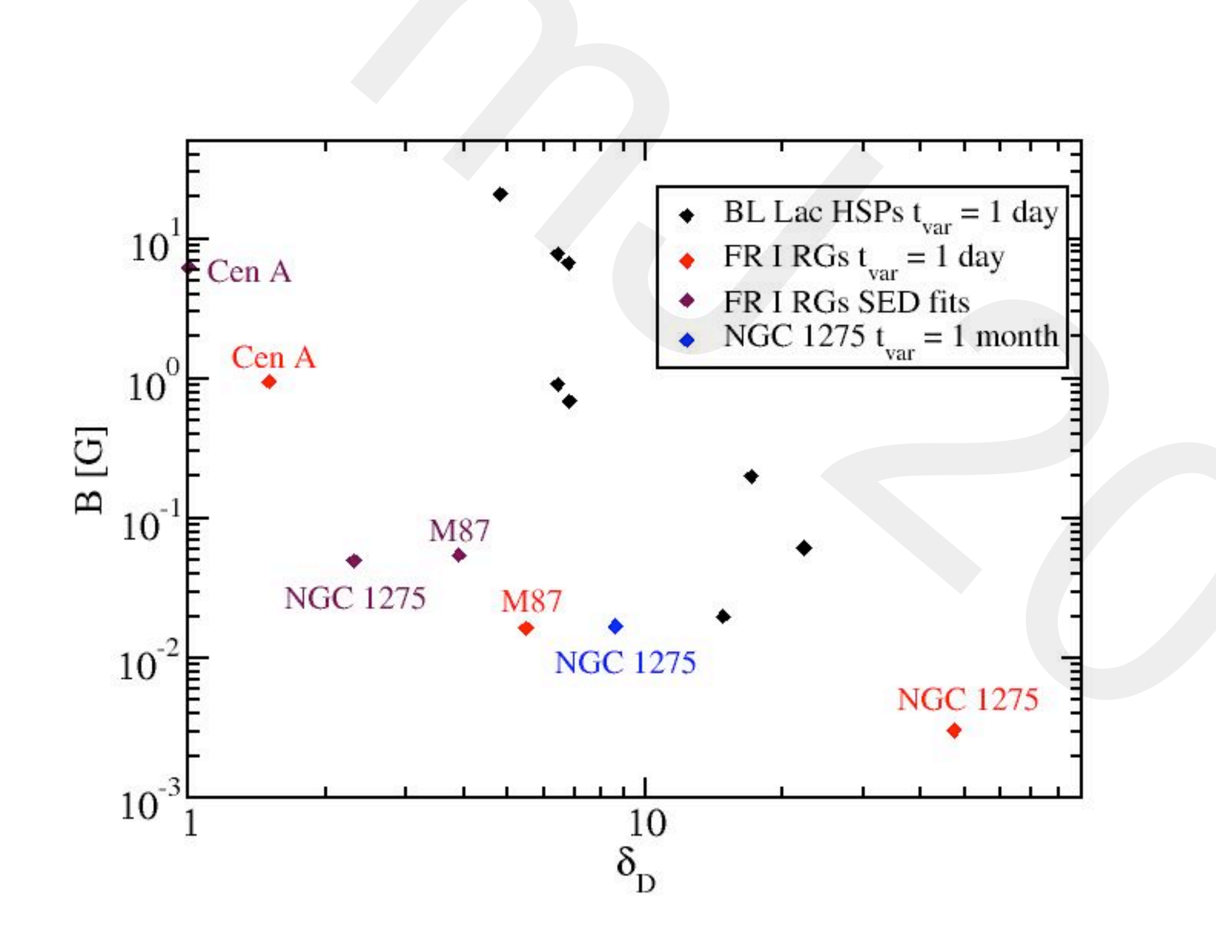
8.4 GHz.
Walker et al. 1994, ApJ, 430, L45

Radio Galaxy Modeling Results

Parameter	Symbol	Cen A	M87	NGC 1275
Bulk Lorentz Factor	Γ_j	7.0	2.3	1.8
Doppler Factor	δ_D	1.0	3.9	2.3
Jet Angle	θ_j	$30°$	$10°$	$25°$
Magnetic Field [G]	B	6.2	0.055	0.05
Variability Timescale [sec]	t_v	1.0×10^5	1.2×10^5	3.0×10^7
Comoving blob size scale [cm]	R'_b	3.0×10^{15}	1.4×10^{16}	2.0×10^{18}
Low-Energy Electron Spectral Index	p_1	1.8	1.6	2.1
High-Energy Electron Spectral Index	p_2	4.3	3.6	3.1
Minimum Electron Lorentz Factor	γ_{min}	3×10^2	1.0	8.0×10^2
Maximum Electron Lorentz Factor	γ_{max}	1×10^8	1.0×10^7	4.0×10^5
Break Electron Lorentz Factor	γ_{brk}	8×10^2	4×10^3	9.6×10^2
Jet Power in Magnetic Field [erg s^{-1}]	$P_{j,B}$	6.5×10^{43}	2.0×10^{40}	2.3×10^{44}
Jet Power in Electrons [erg s^{-1}]	$P_{j,e}$	3.1×10^{43}	7.0×10^{42}	2.3×10^{43}

$L_{edd} = 1.2 \times 10^{47}\ M_9$ erg s^{-1}

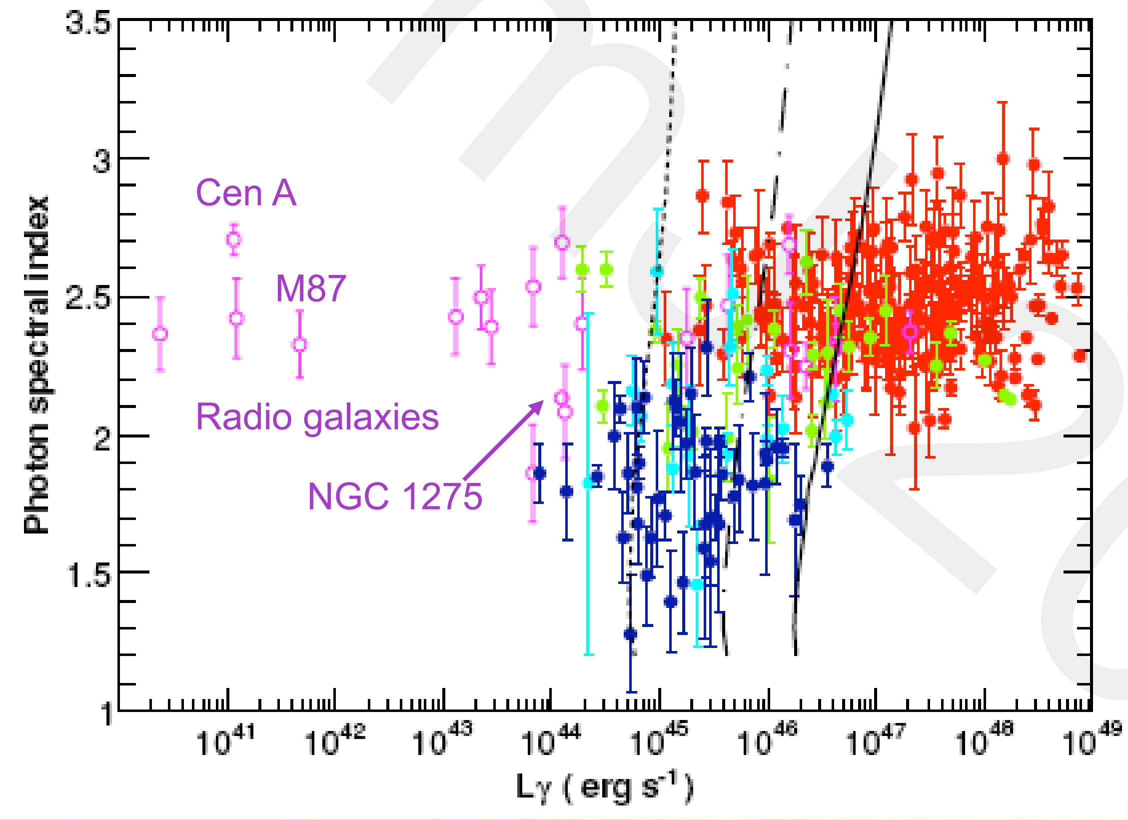
Synchrotron/SSC Model



How accurate are approximate expressions?

NGC 1275 used different variability time

Blazar Unification



1LAC blazars and RGs. Abdo et al. (2010), ApJ, 715, 429

Are radio galaxies populating a new region of this plot? Evidence for emission from a different region region of the jet?

The cores of RGs are brighter than one would expect from de-beamed BL Lacs (Chiaberge et al. 2000). Explained by slower flow in sheath or slower flow closer to jet (Georganopoulos & Kazanas 2003).

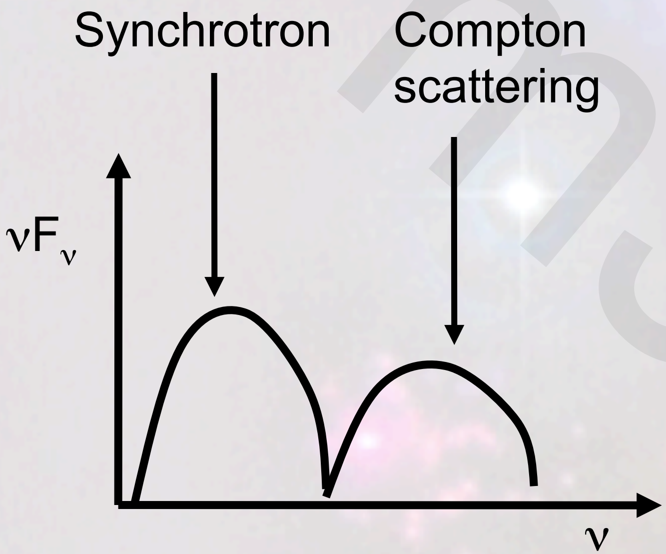
Is NGC 1275 a blazar?

Summary

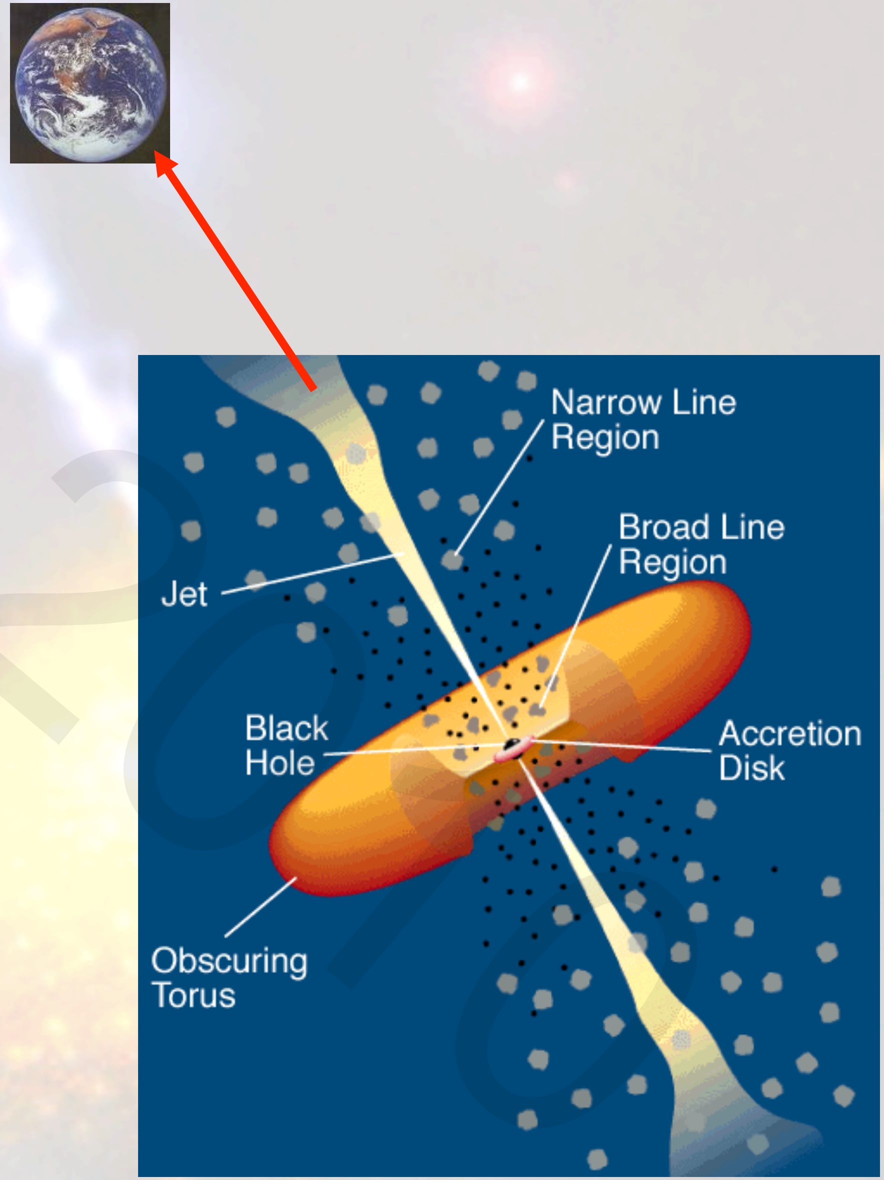
- 3C 454.3
  - SED and γ-ray spectrum can be modeled as a combination of to EC components, including wind BLR.
- Cen A
  - Synch/SSC can explain all emission except non-simultaneous TeV HESS emission.
- M87
  - Synch SSC can explain all emission including non-simultaneous low state HESS emission.
- NGC 1275 / Per A
  - Synch/SSC can only explain latest emission if angle to line of sight is small (<~ 7 deg).

Backup Slides

Blazar SED

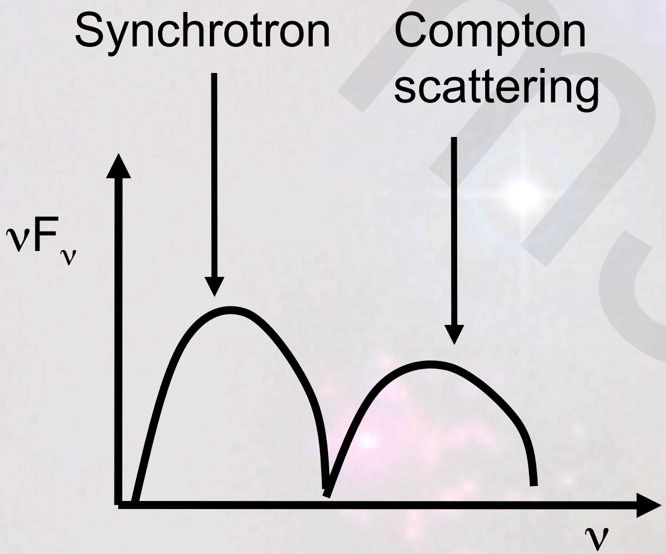


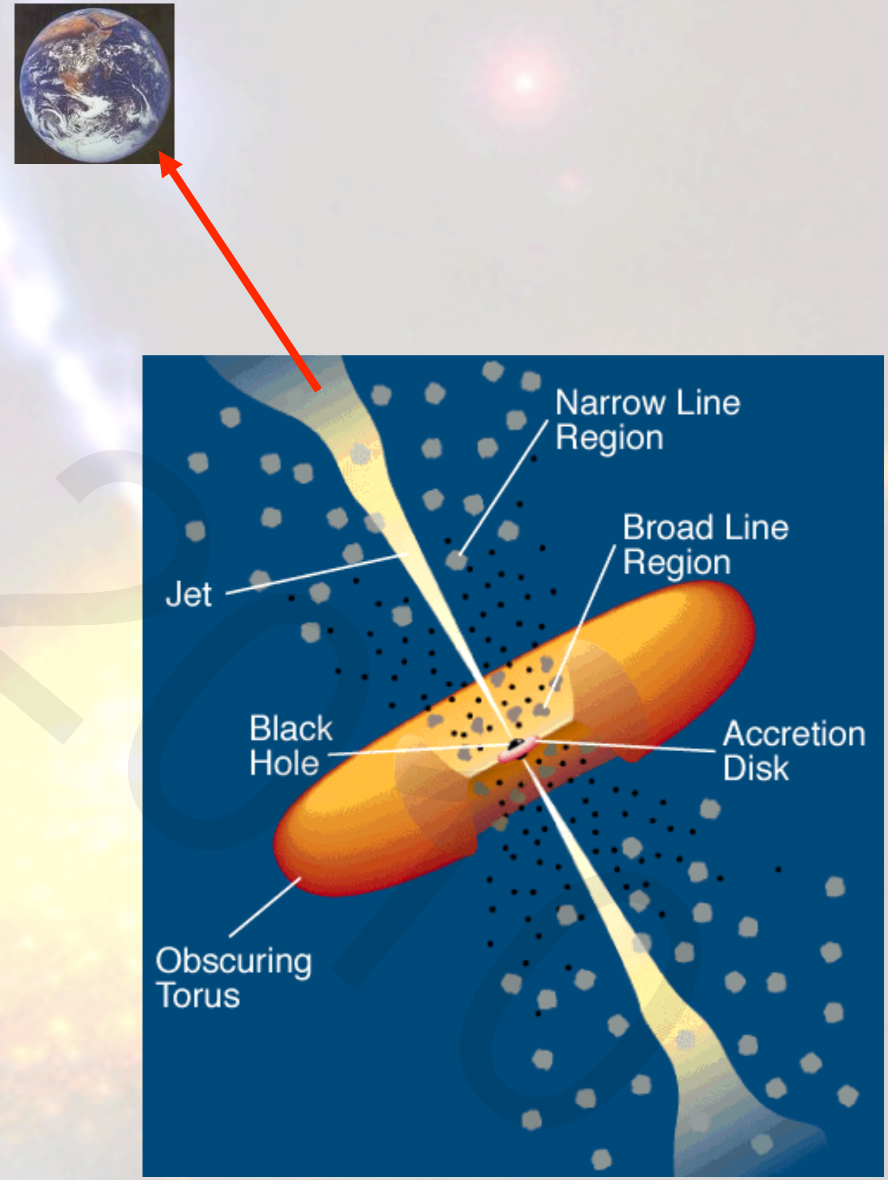
Synchrotron
Compton scattering
νF_ν
ν



Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus

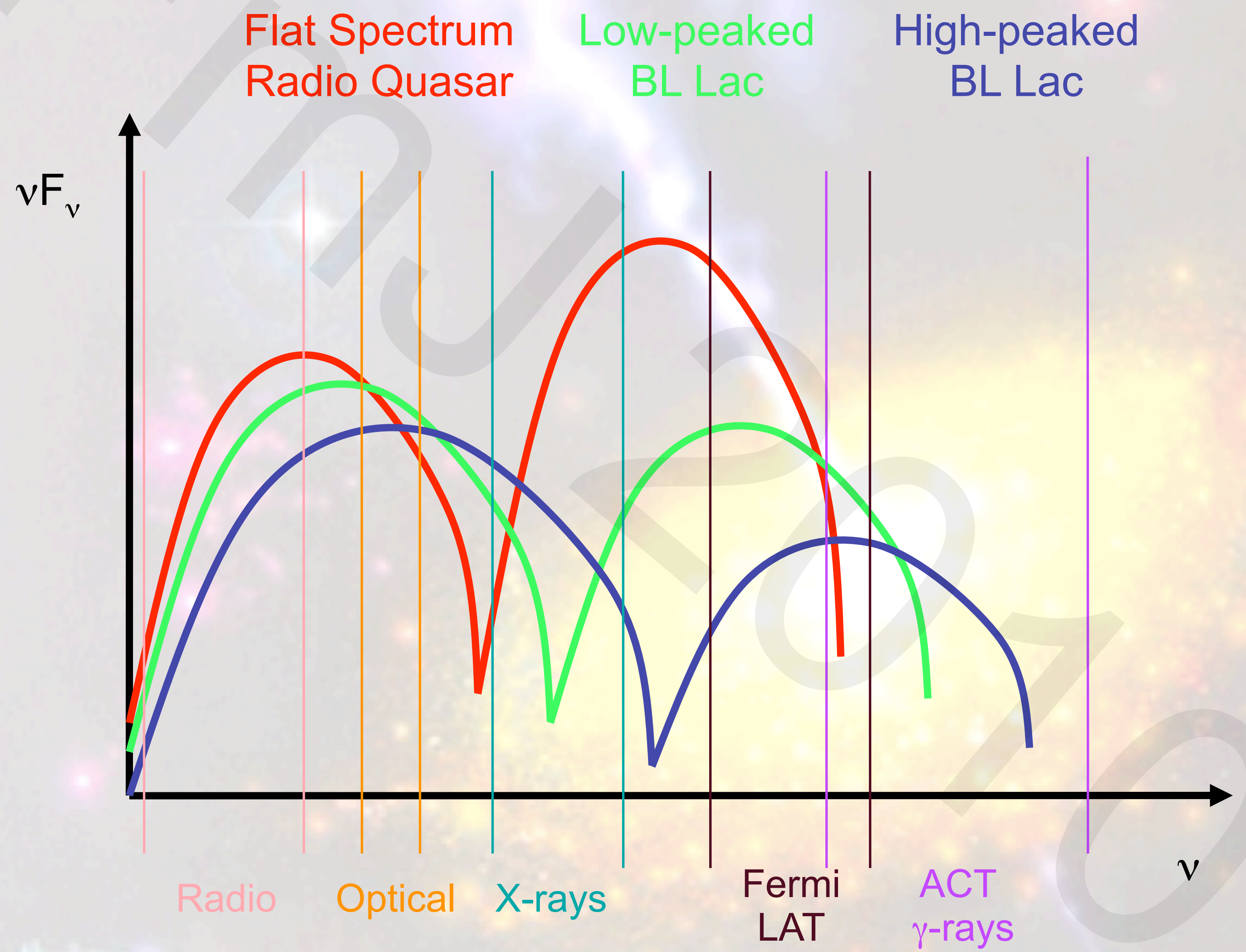
Blazar SED





Compton scattering of:
- synchrotron (SSC)
- disk radiation
- broad line regions
- torus radiation
- slow sheath surrounding blob (Ghisellini et al. 2005)

Blazar Sequence

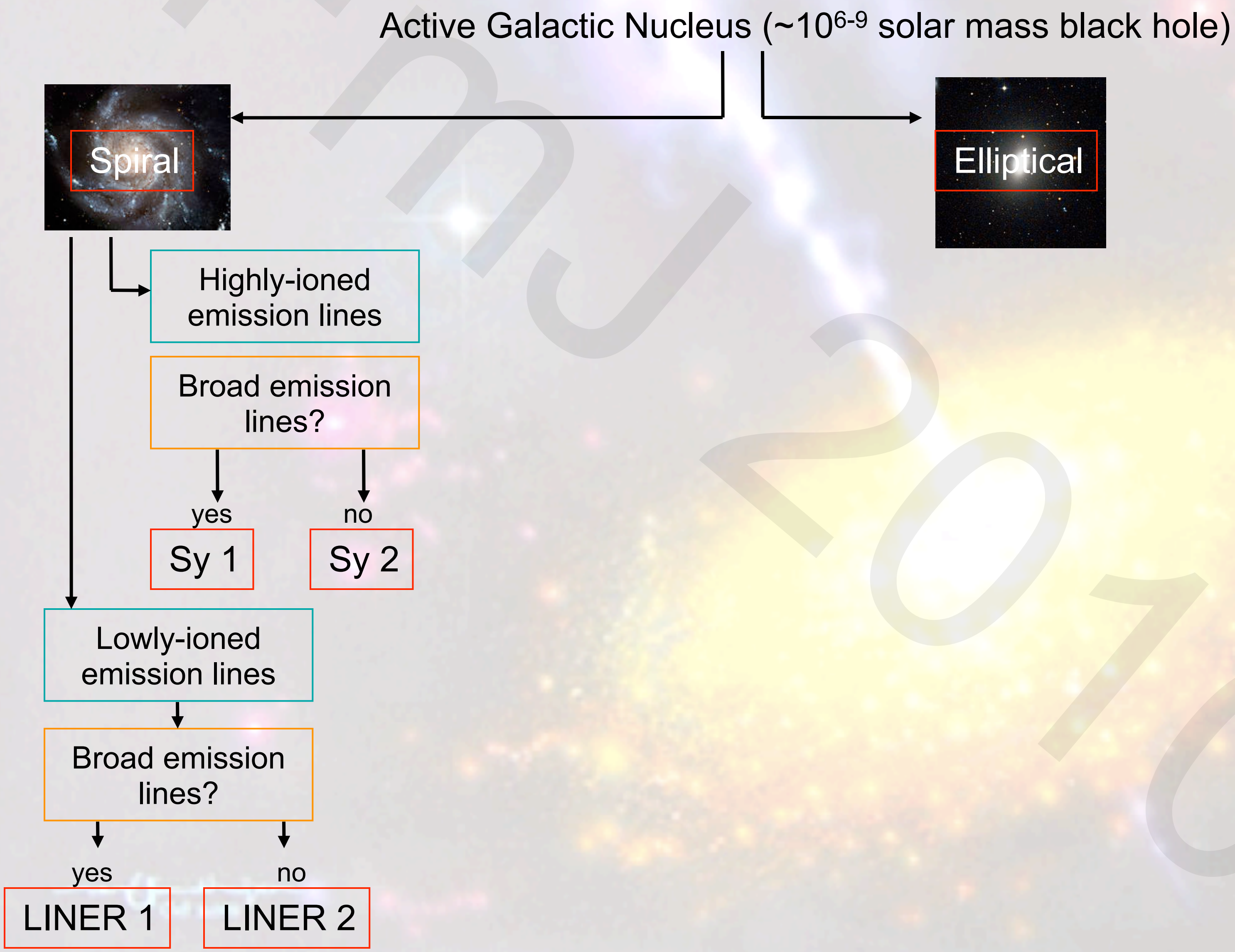


e.g., Ghisellini et al. 1998, MNRAS, 301, 451

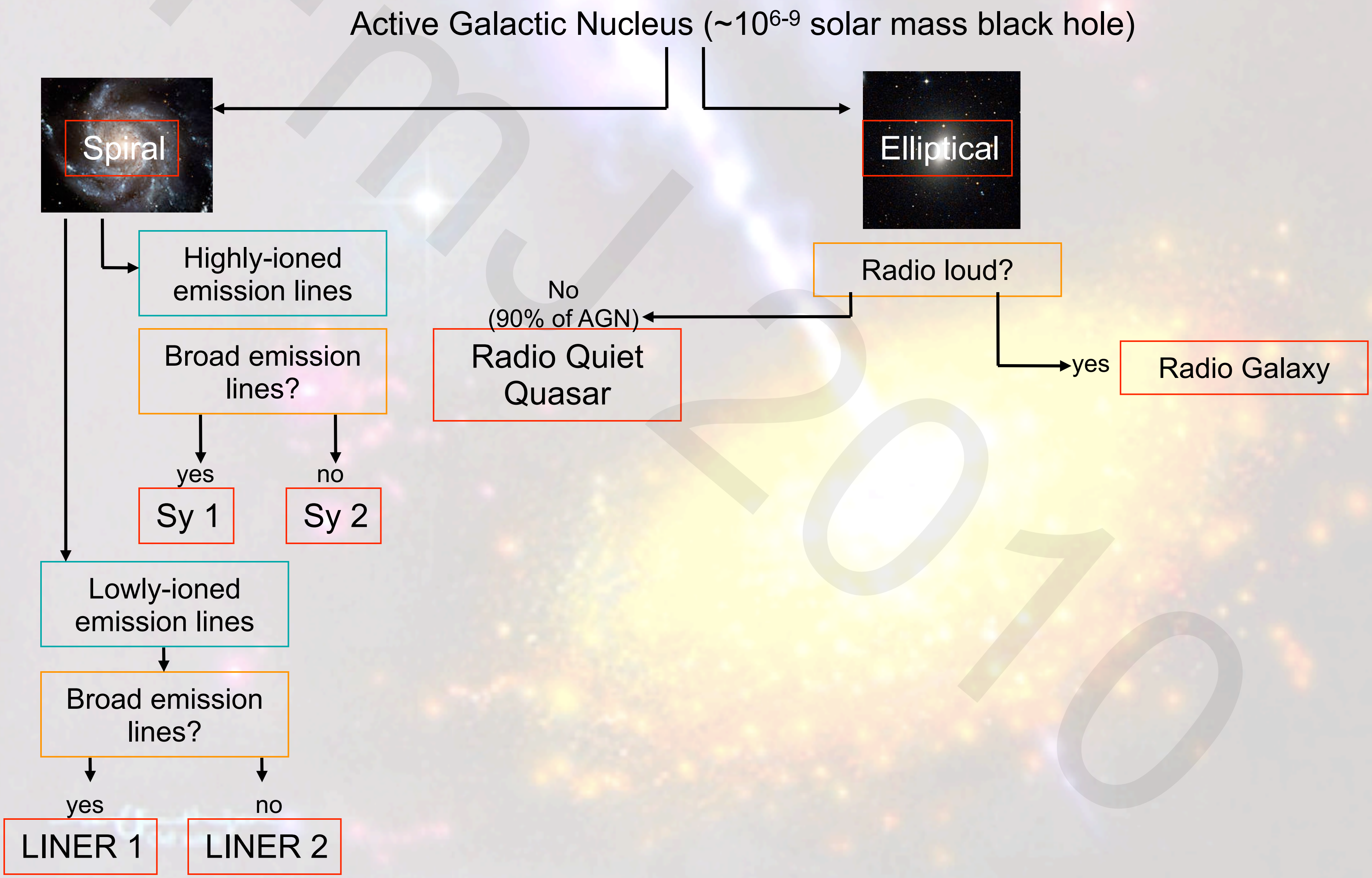
Unified Model of AGN

Active Galactic Nucleus (~10^{6-9} solar mass black hole)

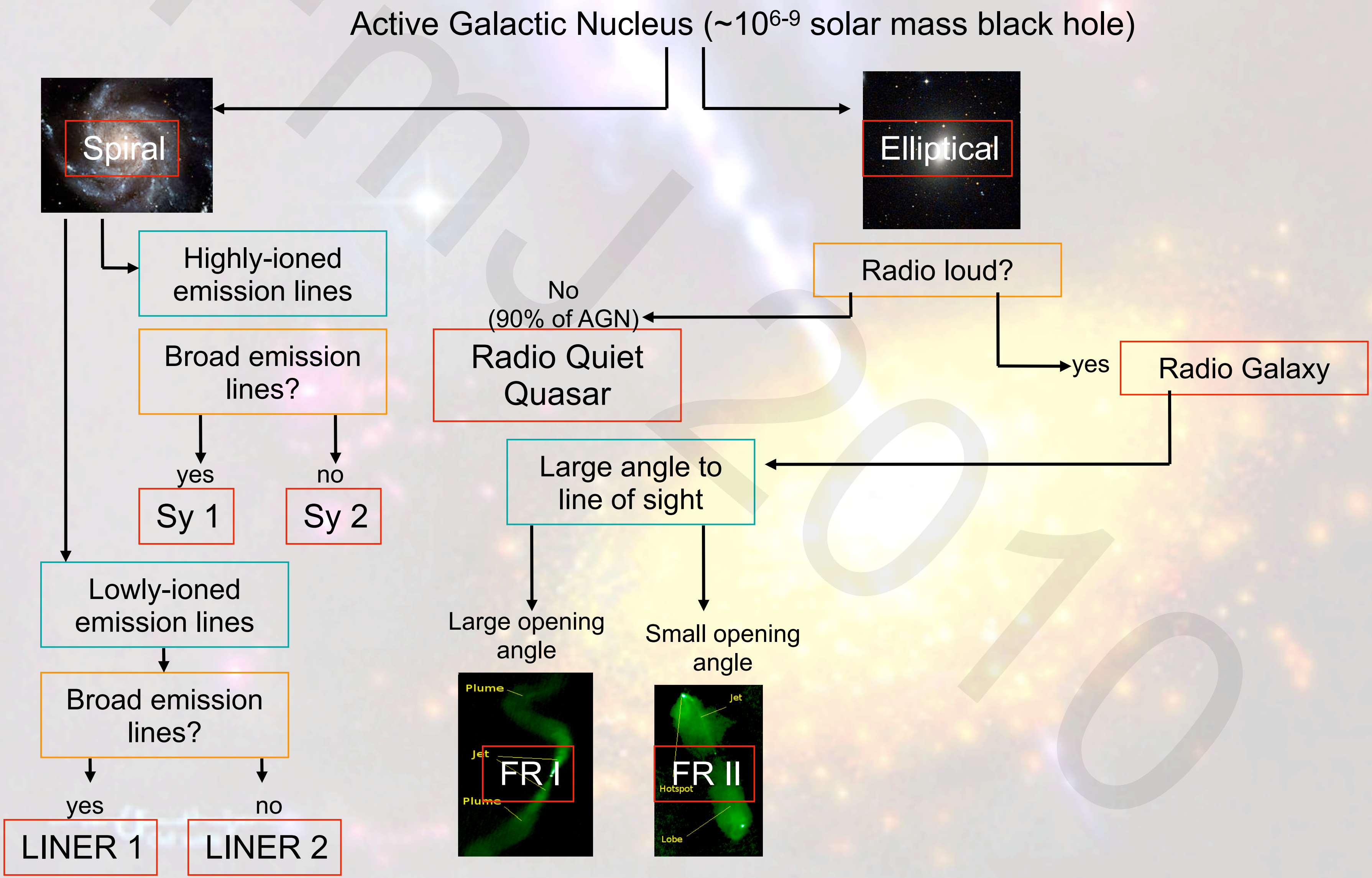
Unified Model of AGN



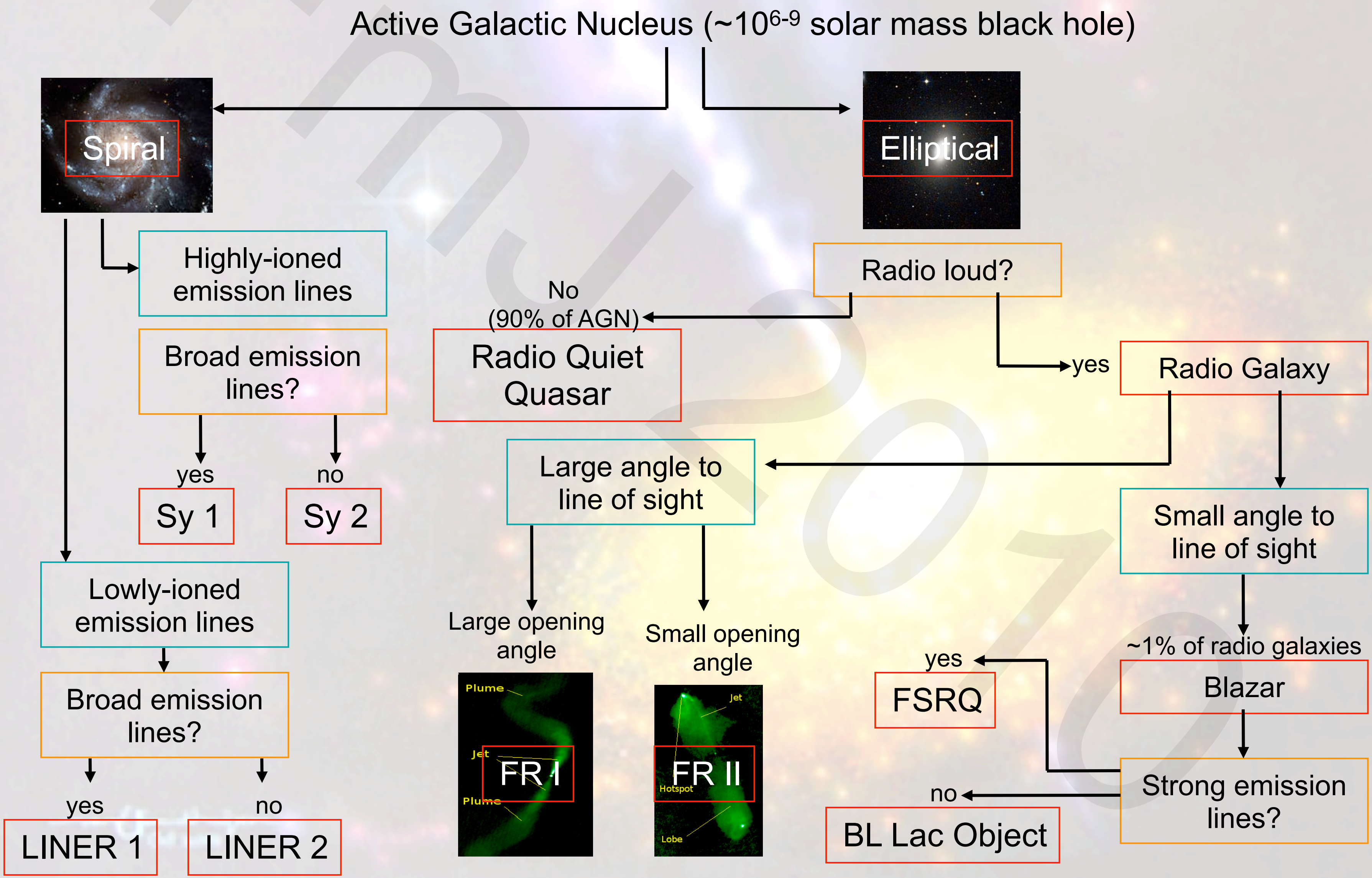
Unified Model of AGN



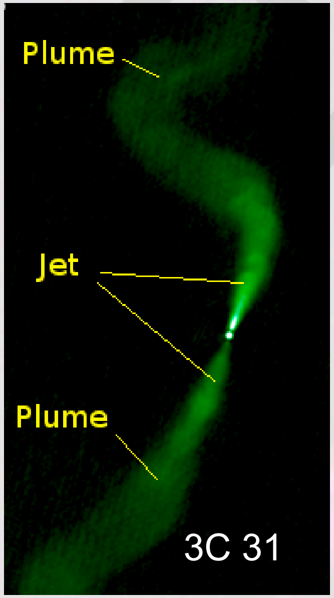
Unified Model of AGN

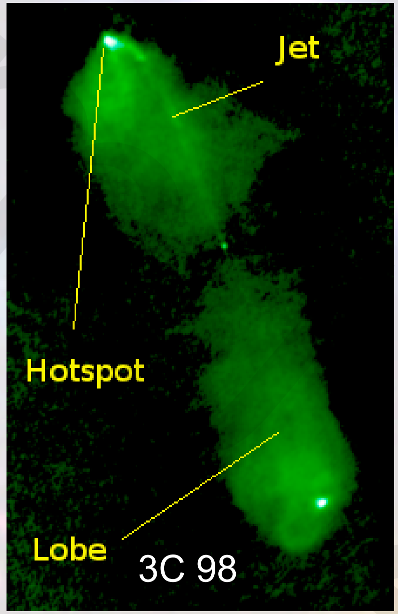


Unified Model of AGN



Radio Loud AGN



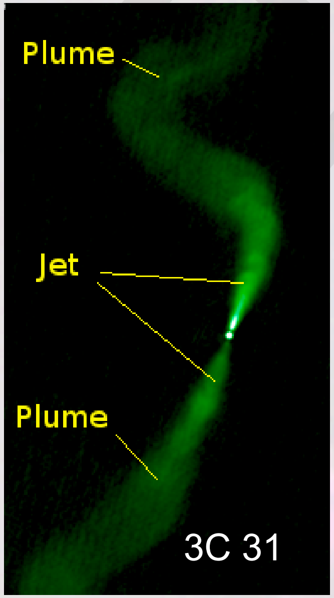


Fanaroff-Riley I

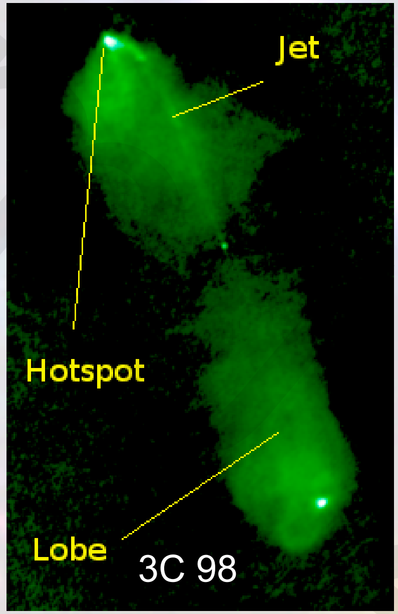
Fanaroff-Riley II

Urry & Padovani (1995)

Radio Loud AGN



Fanaroff-Riley I

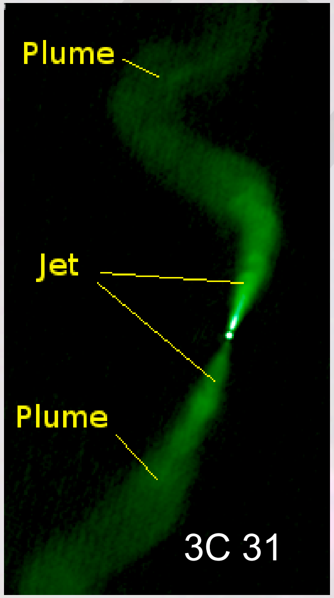


Fanaroff-Riley II

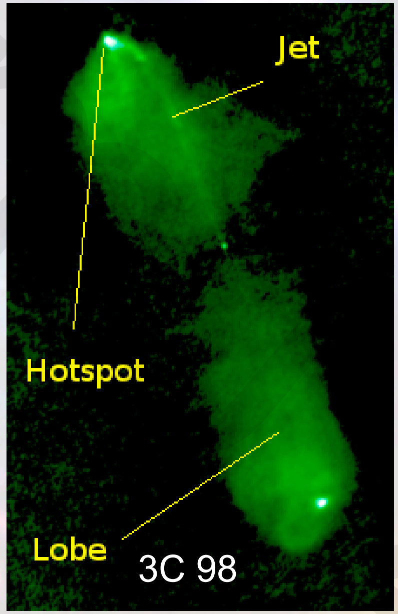
	Low power, wide opening angle	High power, narrow angle
Jet pointed away from us	FR I	FR II
Jet pointed towards us	BL Lac	FSRQ

Urry & Padovani (1995)

Radio Loud AGN



Fanaroff-Riley I



Fanaroff-Riley II

Evidence:

Diffuse radio lobes in BL Lacs

Statistics of blazars

Apparent Superluminal motion

	Low power, wide opening angle	High power, narrow angle
Jet pointed away from us	FR I	FR II
Jet pointed towards us	BL Lac	FSRQ

Urry & Padovani (1995)

Beaming Physics

Rest Frame

e.g., Rybicki & Lightman (1979)

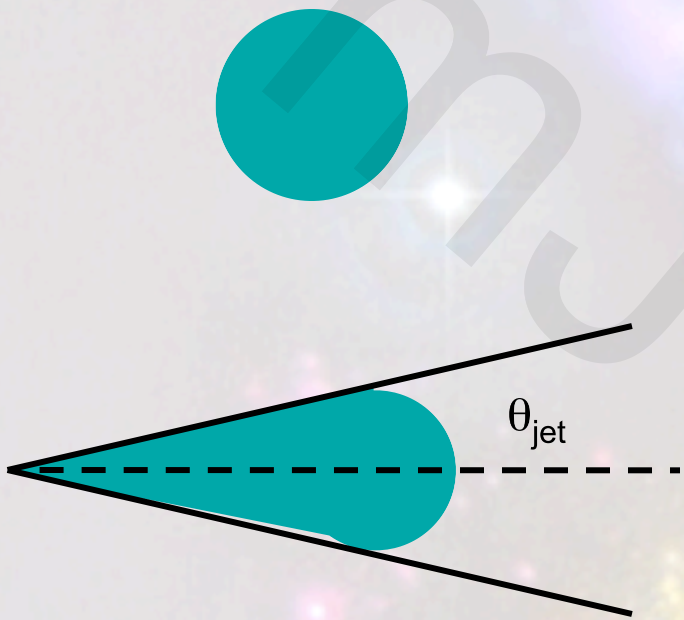
Beaming Physics

Rest Frame

$\Gamma = (1 - \beta^2)^{-1/2}$

e.g., Rybicki & Lightman (1979)

Beaming Physics



Rest Frame

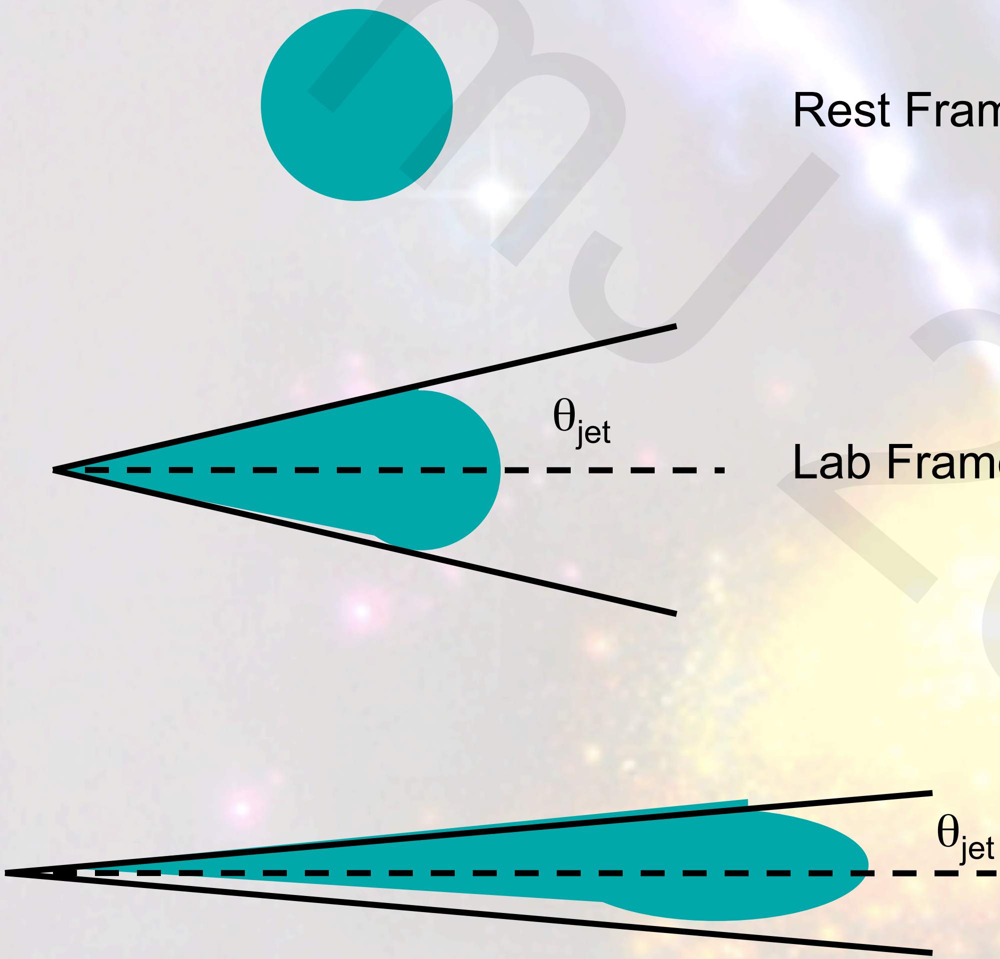
$\Gamma = (1 - \beta^2)^{-1/2}$

Lab Frame

$\theta_{jet} = 1/\Gamma$

e.g., Rybicki & Lightman (1979)

Beaming Physics



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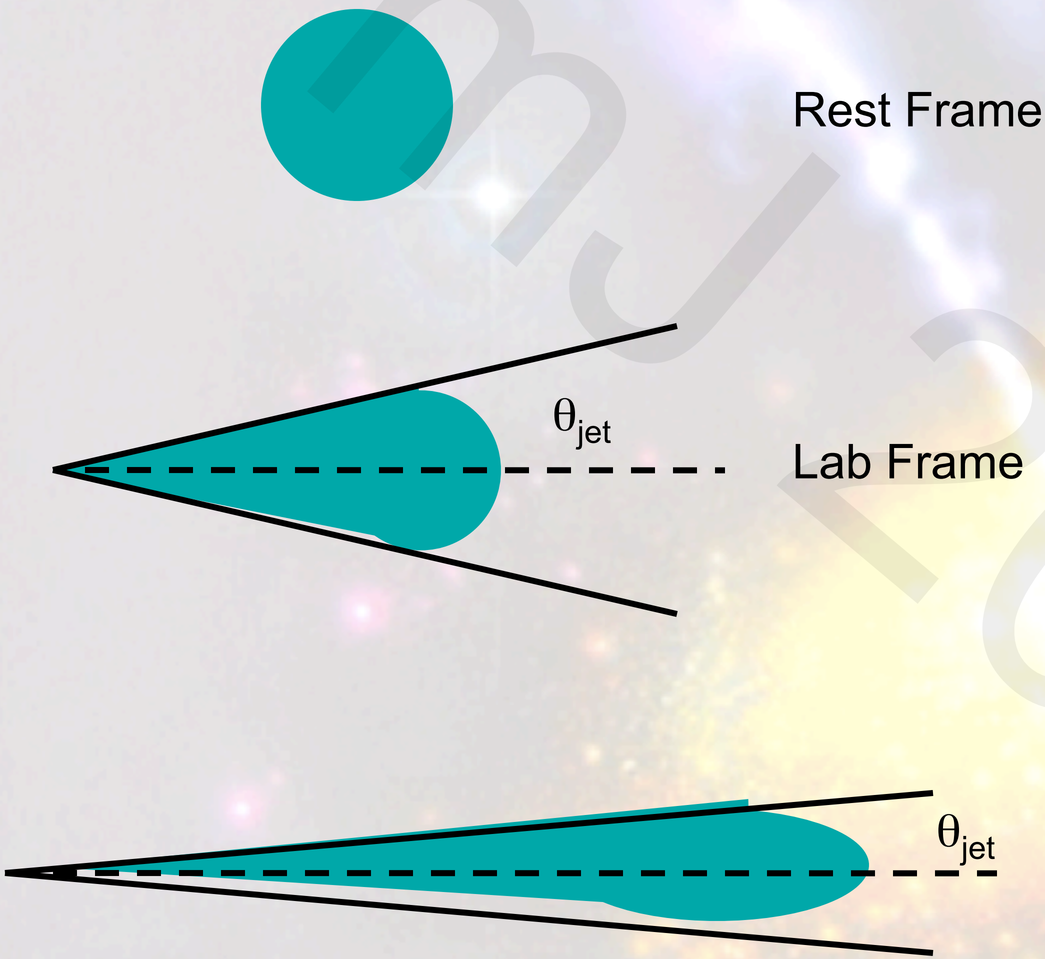
Beaming Physics



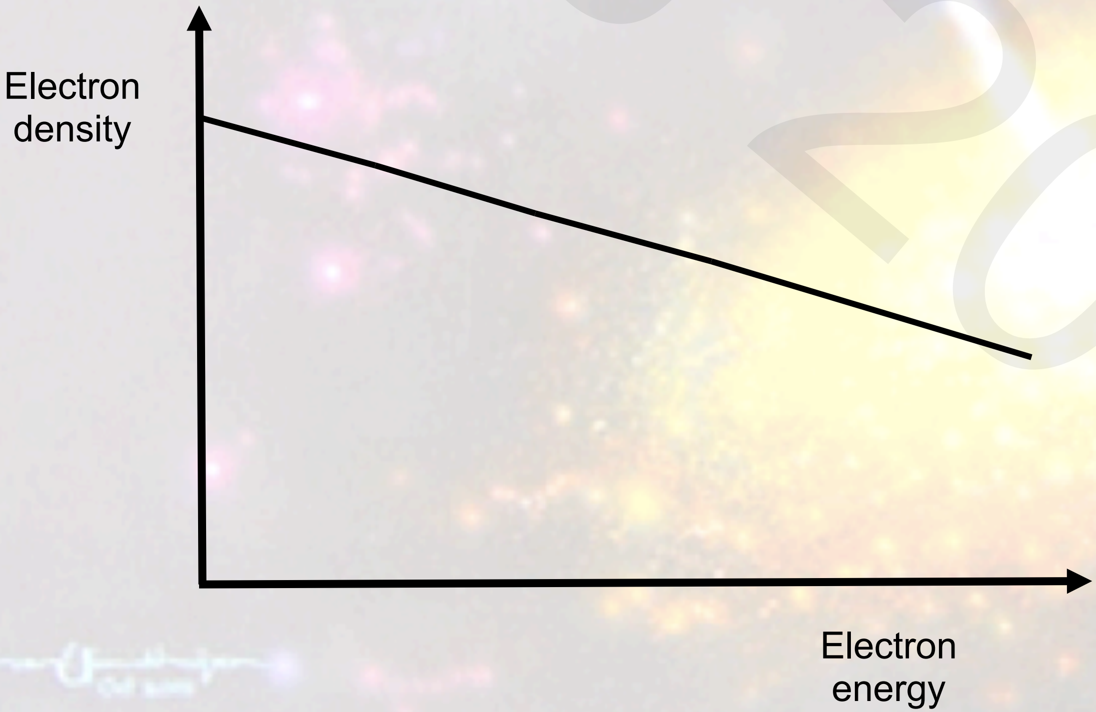
$\Gamma = (1 - \beta^2)^{-1/2}$

$\theta_{jet} = 1/\Gamma$

Radio galaxy statistics imply that on average, $\Gamma \sim 15$ ($\beta \sim 0.998$)

e.g., Rybicki & Lightman (1979)

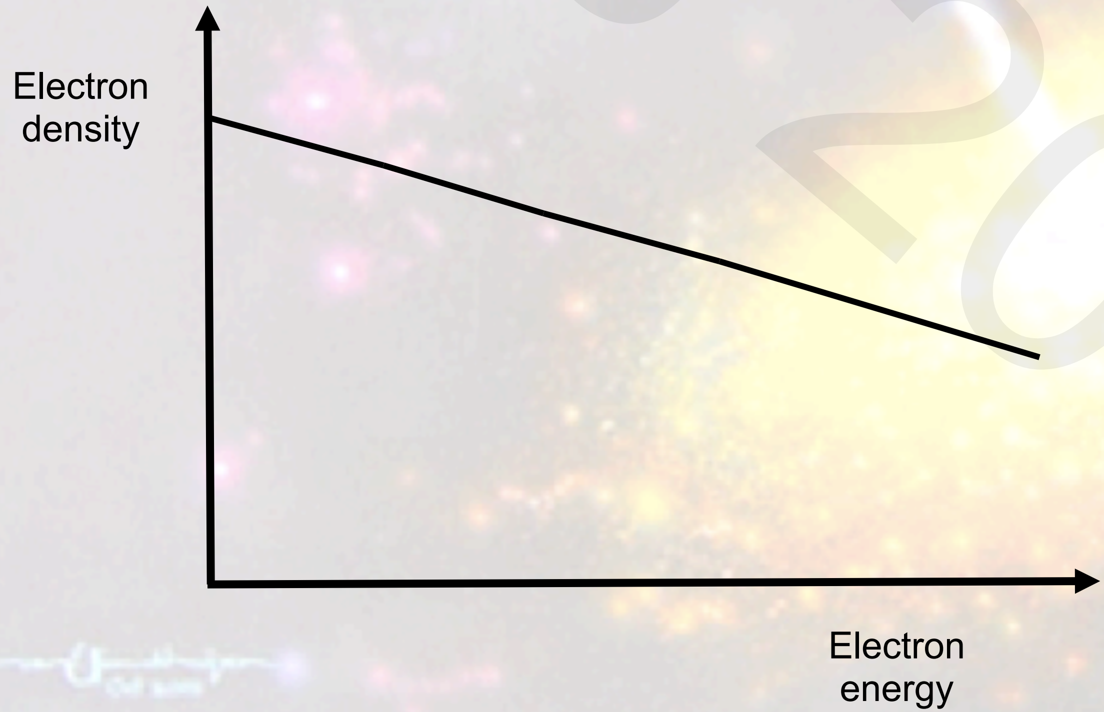
Modeling Blazars: electron distribution



Electron distribution:
$n_e(\gamma) \sim \gamma^{-p}$

Modeling Blazars: electron distribution

Fermi mechanism accelerate electrons to nonthermal power-law distribution.



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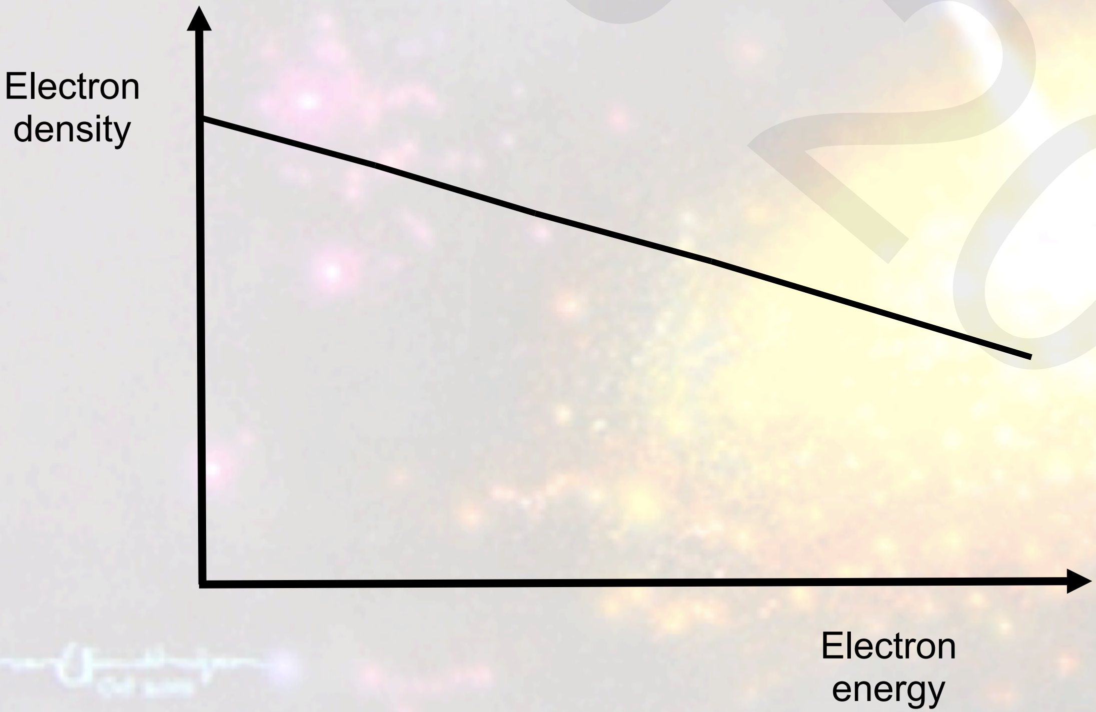
Electrons radiative energy by synchrotron and Compton processes. $d\gamma/dt \sim \gamma^3 n_e(\gamma)$



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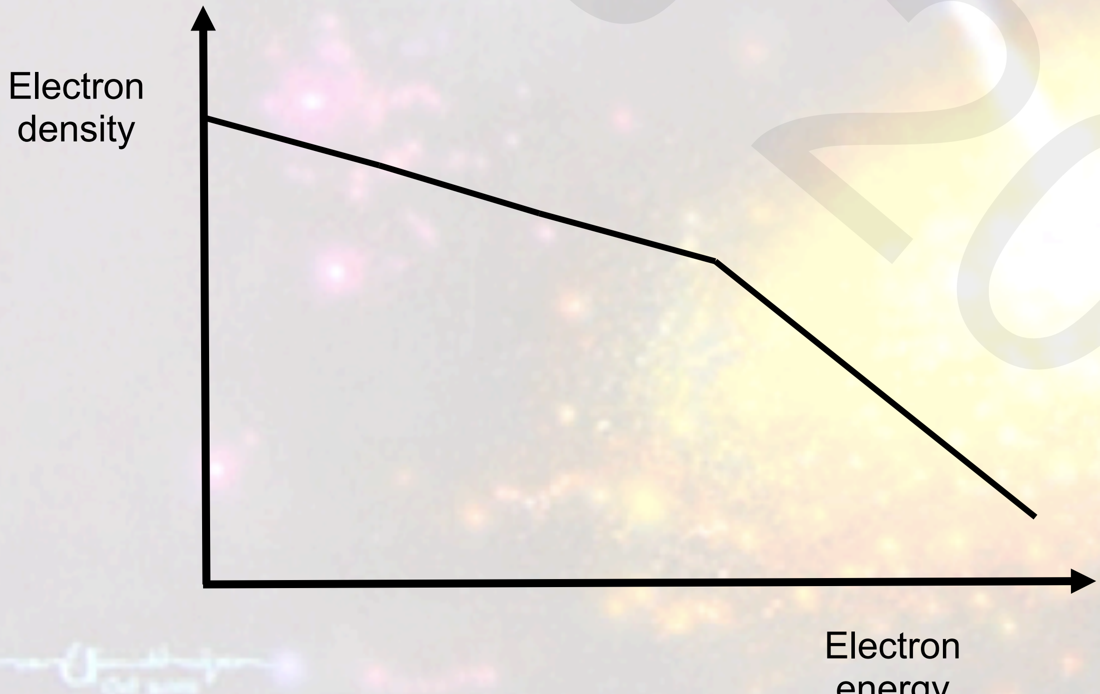

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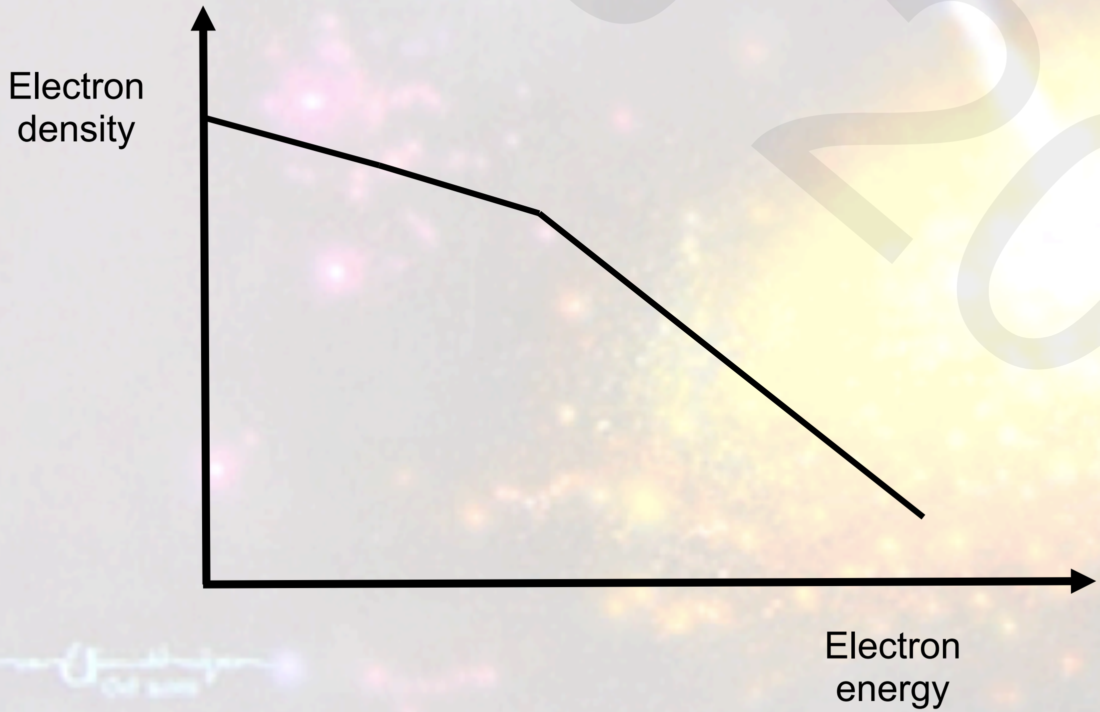

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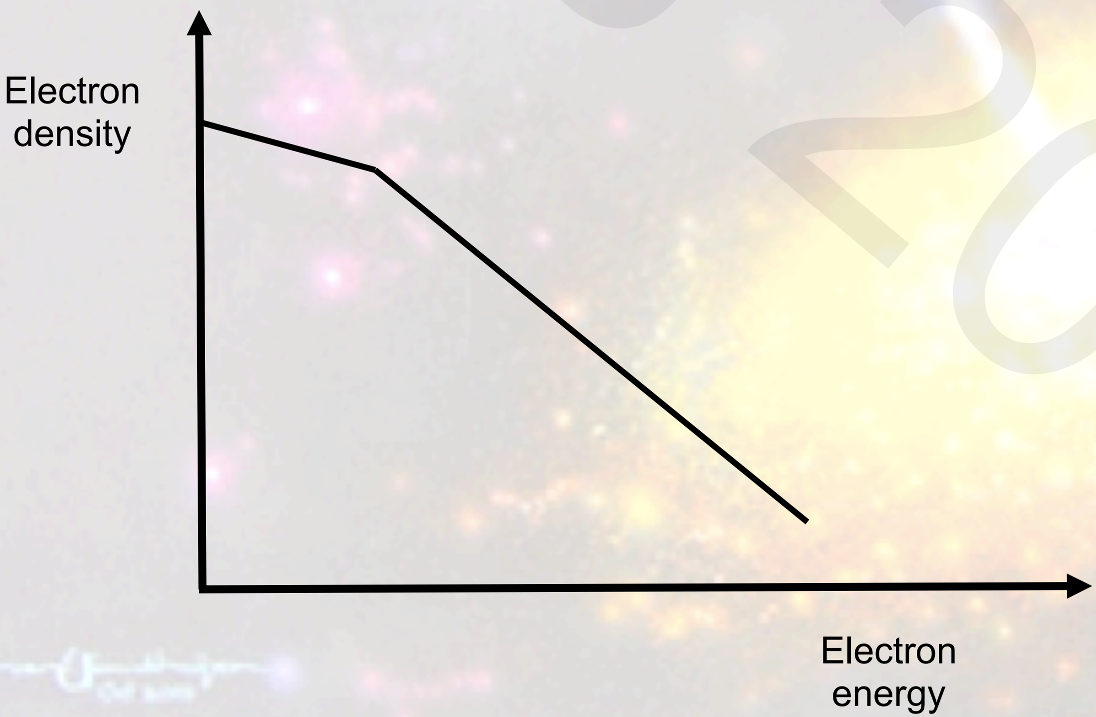

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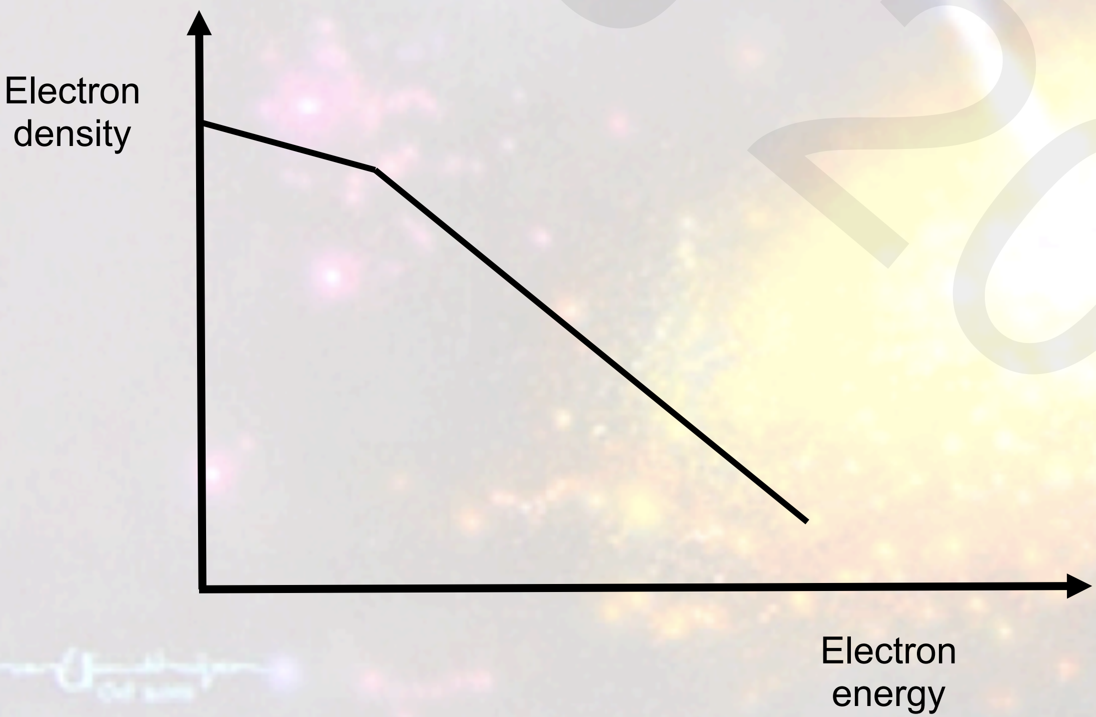
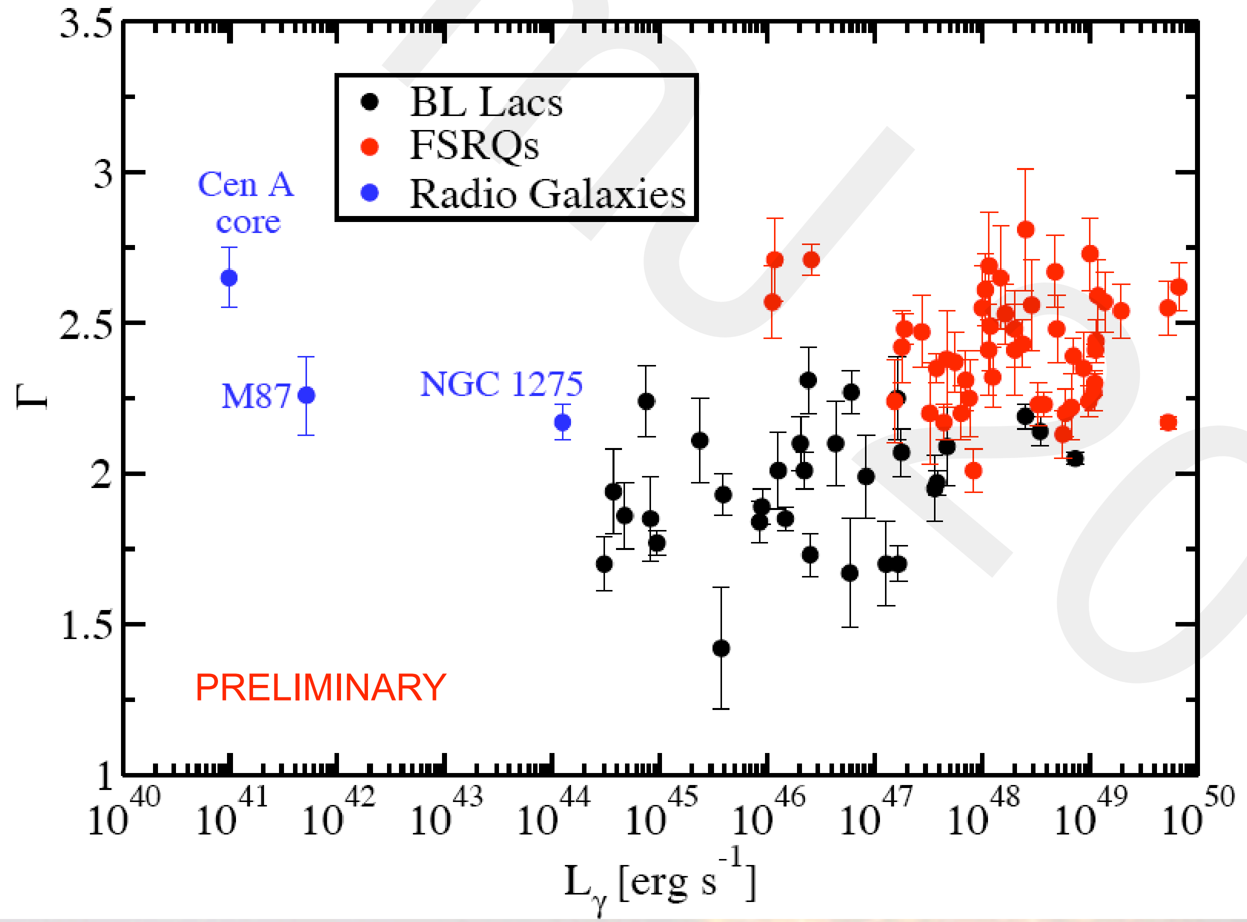


Electron distribution:
$n_e(\gamma) \sim \gamma^{-p}$

Synchrotron/Compton cooling break:
$\Delta p = 1$

Blazar Unification



LBAS blazars with RGs.

Are radio galaxies populating a new region of this plot?

Or is there a selection effect?

The cores of RGs are brighter than one would expect from de-beamed BL Lacs (Chiaberge et al. 2000). Explained by slower flow in sheath or slower flow closer to jet (Georganopoulos & Kazanas 2003).