Multiwavelength Theory

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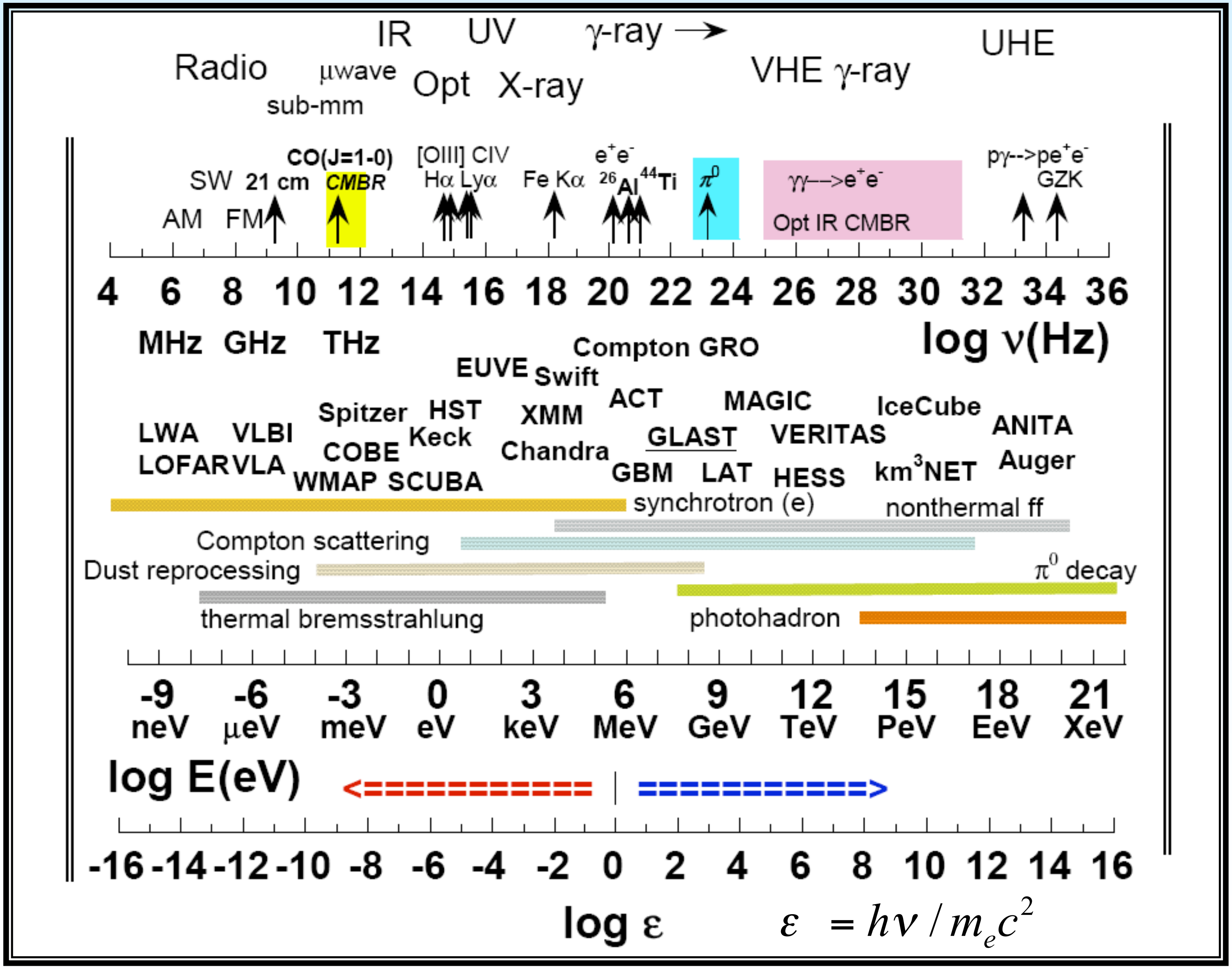
VLBI in the GLAST ERA

Goddard Space Flight Center
Greenbelt, MD
23-24 April 2007

1. γ-Ray and Radio Blazar Theory
2. Magnetic Field and Minimum Jet Power
3. Doppler Factor δ_D
4. Uses of Measurements of B, δ_D

Multiwavelength Perspective



γ-Rays, EGRET, and GLAST

γ Ray flux measured in units of ϕ_{-8} [10^{-8} ph(>100 MeV) cm^{-2} s^{-1}]

($\phi_{-8} = 1 \leftrightarrow \approx 7\times10^{-12}$ ergs cm^{-2} s^{-1} for a flat νF_ν spectrum)

EGRET: $\phi_{-8} = 15$; on-axis 2-week pointing, 1/24th full sky (background limited)

($\approx 10^{-10}$ ergs cm^{-2} s^{-1})

GLAST: $\phi_{-8} = 15$ in 1 – 2 days, full sky (signal limited)

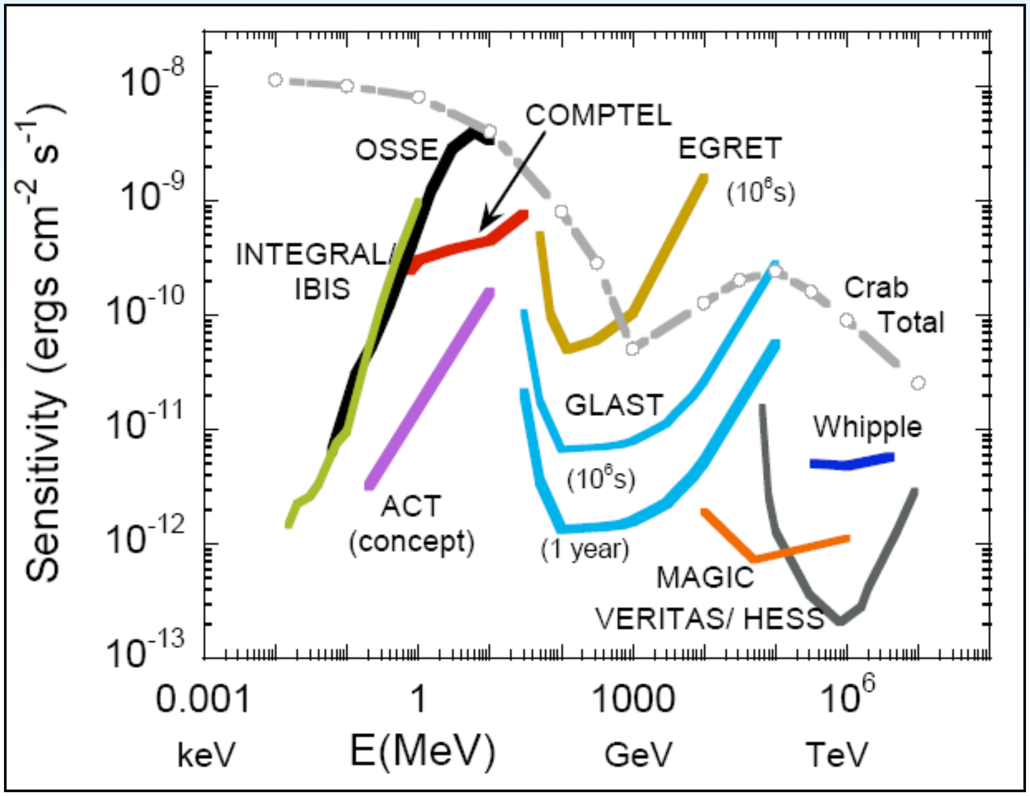
$\phi_{-8} = 0.4$ in 1 year, full sky (background limited)

($\approx 10^{-12}$ ergs cm^{-2} s^{-1})

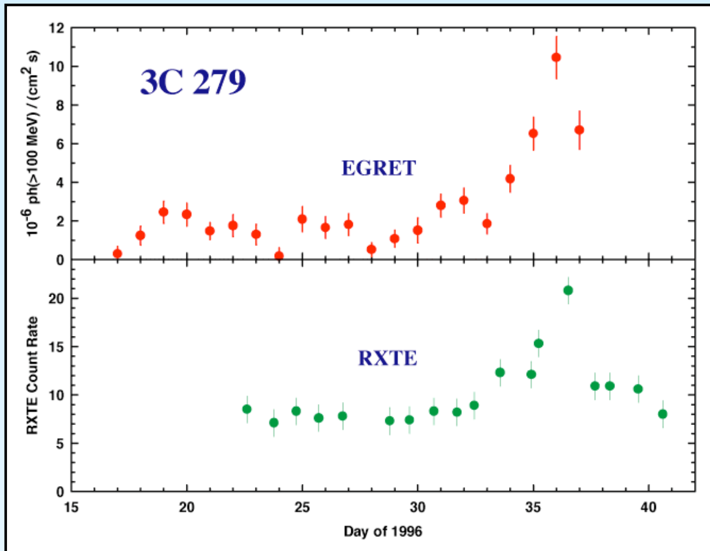
More sensitive to weak hard-spectrum than soft-spectrum sources

Sub-hour scale variability when $\phi_{-8} > 200$ ($>10^{-9}$ ergs cm^{-2} s^{-1})

Rate of flares (Lott, this conf.)



3C 279



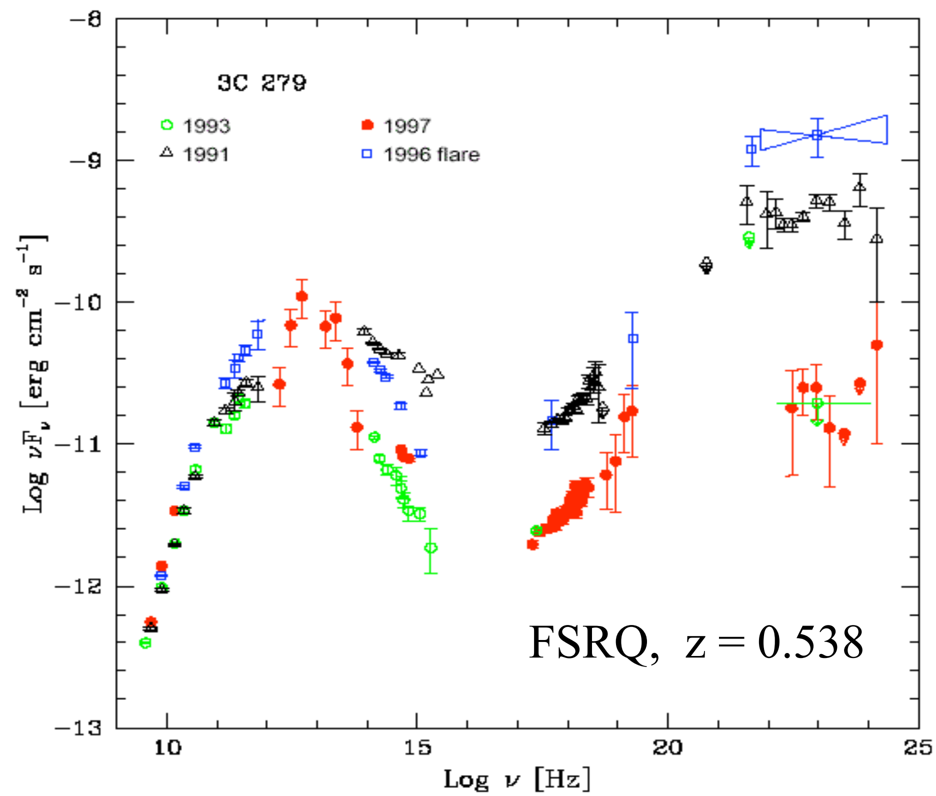


Figure 2. Quasi-simultaneous SEDs of the quasar 3C279 taken in the different epochs. The *BeppoSAX* and EGRET data taken in 1997 are

Sub-day scale variability, well-defined flaring emissions ⇒

γ-ray emission mainly from a single zone

$L \sim 5\times10^{48}$ x $(f/10^{-9}$ ergs cm^{-2} s$^{-1})$ ergs s^{-1}

Variability and Source Size

Source size from direct observations:

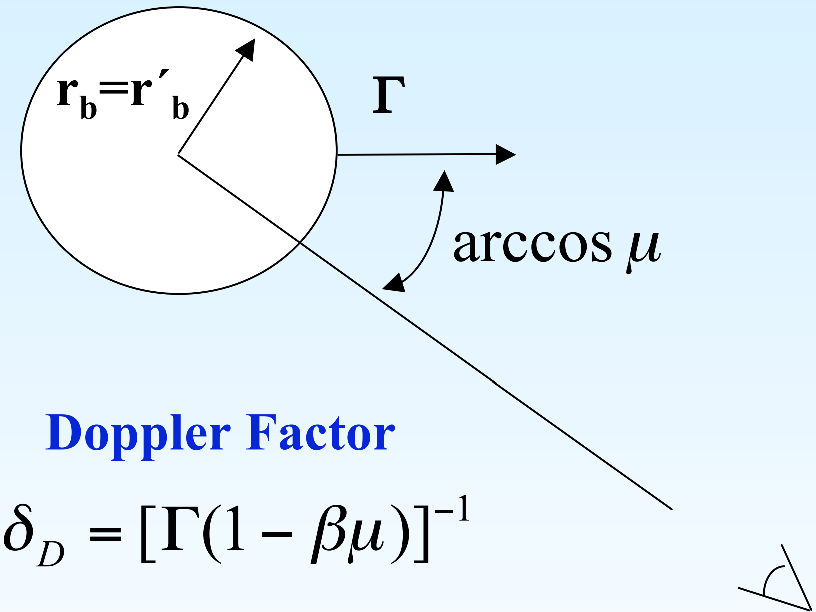
$$r_b' \cong d_A \vartheta \;\cong\; 2\left(\frac{d_A}{10^{27}\,cm}\right)\vartheta(mas)\;pc$$

Source size from temporal variability:

$$r_b' \lesssim ct_{var}' = c\delta_{\mathrm{D}} t_{var}/(1+z)$$

$$r_b'(cm) < \frac{2.5\times 10^{15}\,\delta_D t_{\mathrm{var}}(day)}{(1+z)}$$

Spherical blob in comoving frame

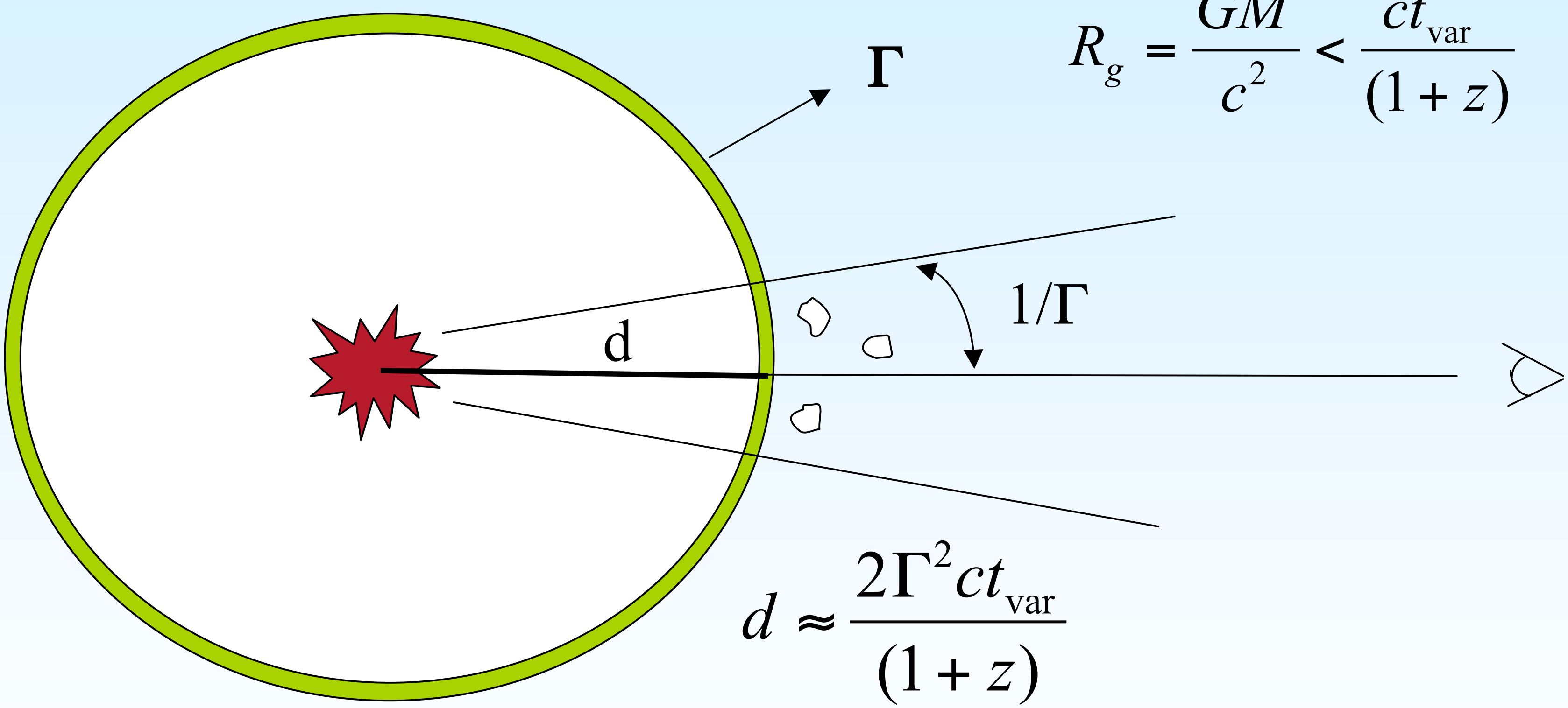


Doppler Factor

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

Variability timescale implies maximum emission region size scale

Variability and Source Location



$$R_g = \frac{GM}{c^2} < \frac{ct_{\rm var}}{(1+z)}$$

$$d \approx \frac{2\Gamma^2 ct_{\rm var}}{(1+z)}$$

Variability timescale implies maximum emission region size scale, maximum engine size scale, but not emission location

Rapid variability by energizing regions within the Doppler cone (e.g., external shocks)

M87, GRBs

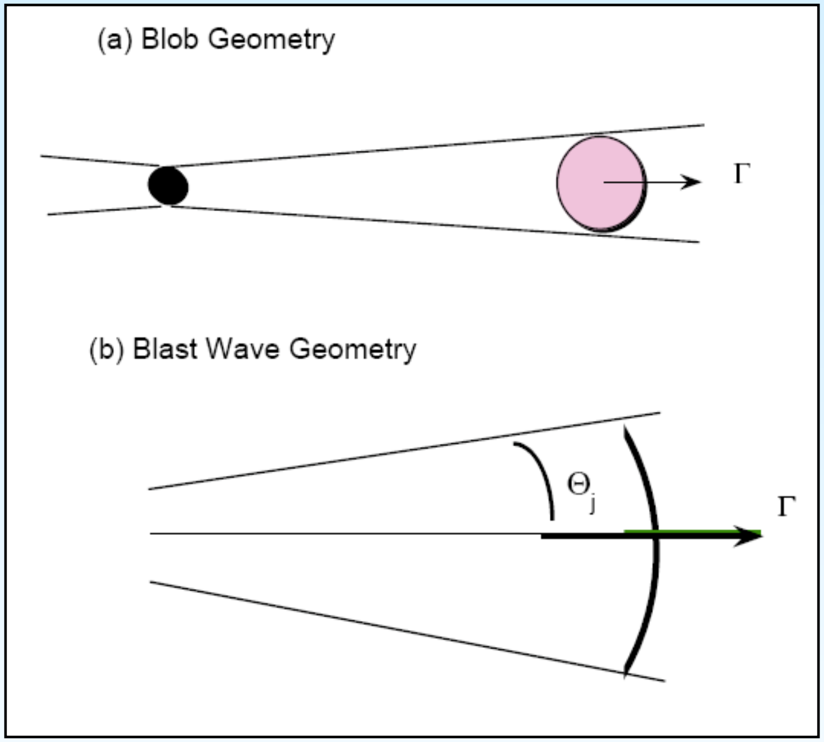
Blobs vs. Blast Waves

One Zone Model

$$\nu F_\nu = f_\varepsilon \; (ergs\ cm^{-2}\ s^{-1})$$

$$f_\epsilon(t) \cong \frac{\delta_D^4 V_b'}{d_L^2}\, \epsilon' j'(\epsilon'\Omega'; t')$$

$$\varepsilon = (h\nu / m_e c^2)$$



$$f_\epsilon(t) \cong \frac{\delta_D^4 V_b'}{4\pi d_L^2}\, \epsilon' j'(\epsilon'; t') \cong \frac{\delta_D^4 \epsilon' L'(\epsilon'; t')}{4\pi d_L^2}$$

Equivalence of blob and blast wave framework for opacity calculations

γ-Ray Blazar Theory

Synchrotron

$$f_\epsilon^s \cong \frac{\delta^4}{6\pi d_L^2} c\sigma_T u_B \gamma_s^3 N_e'(\gamma_s),\ \gamma_s = \sqrt{\frac{\epsilon_z}{\delta\epsilon_B}},$$

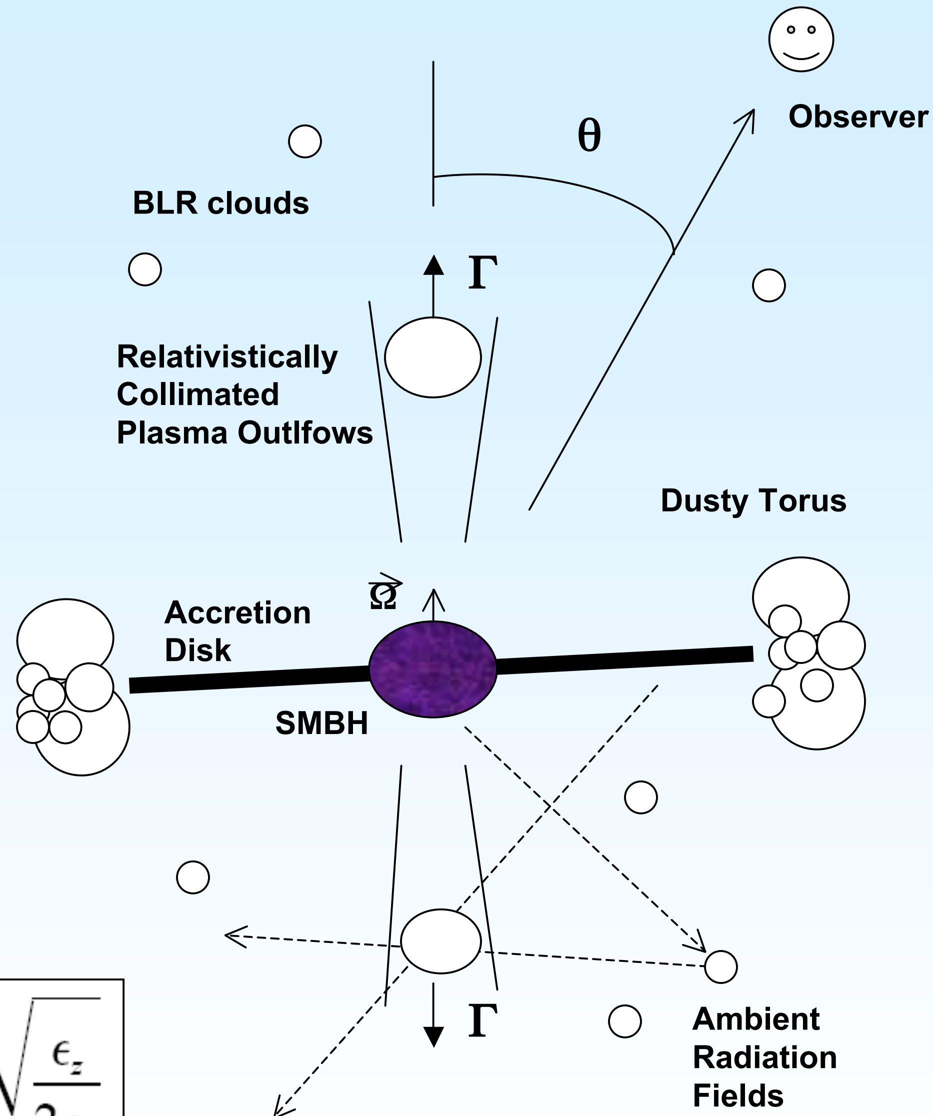
$$\varepsilon_z = (1+z)\varepsilon$$

Synchrotron-self Compton

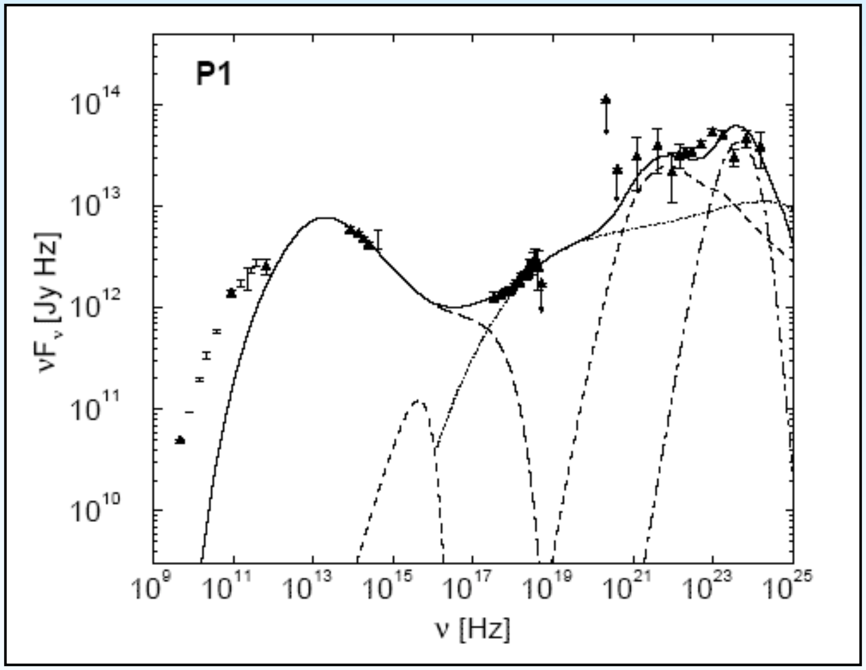
$$f_\epsilon^{SSC} \cong \frac{\delta^4}{9\pi d_L^2} \frac{c\sigma_T^2 r_b u_B K^2}{V_b'} \gamma_s^{3-p} \Sigma_C$$

External Compton

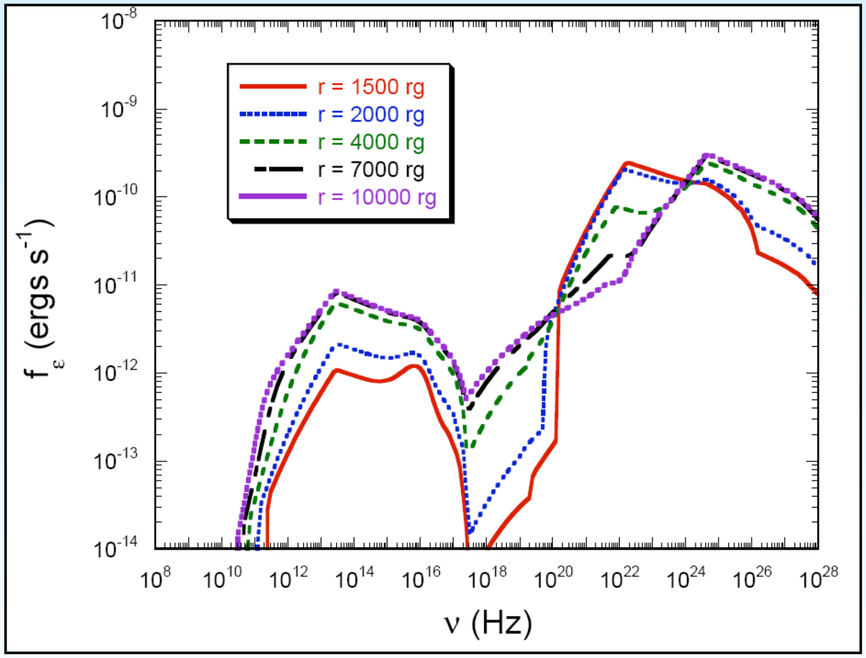
$$f_\epsilon^{EC} \cong \frac{\delta^6}{6\pi d_L^2} c\sigma_T u_* \gamma_{EC}^3 N_e'(\gamma_{EC}),\ \gamma_{EC} = \frac{1}{\delta}\sqrt{\frac{\epsilon_z}{2\epsilon_*}}$$



Blazar Modeling



Hartman, Böttcher, et al. (2001)



Dermer and Schlickeiser (2002)

Predicts soft-to-hard evolution of the γ-rays as the blob moves away from the black hole (highly idealized)

(assumes γ-rays made within Broad Line Region)

Radio Physics and VLBI

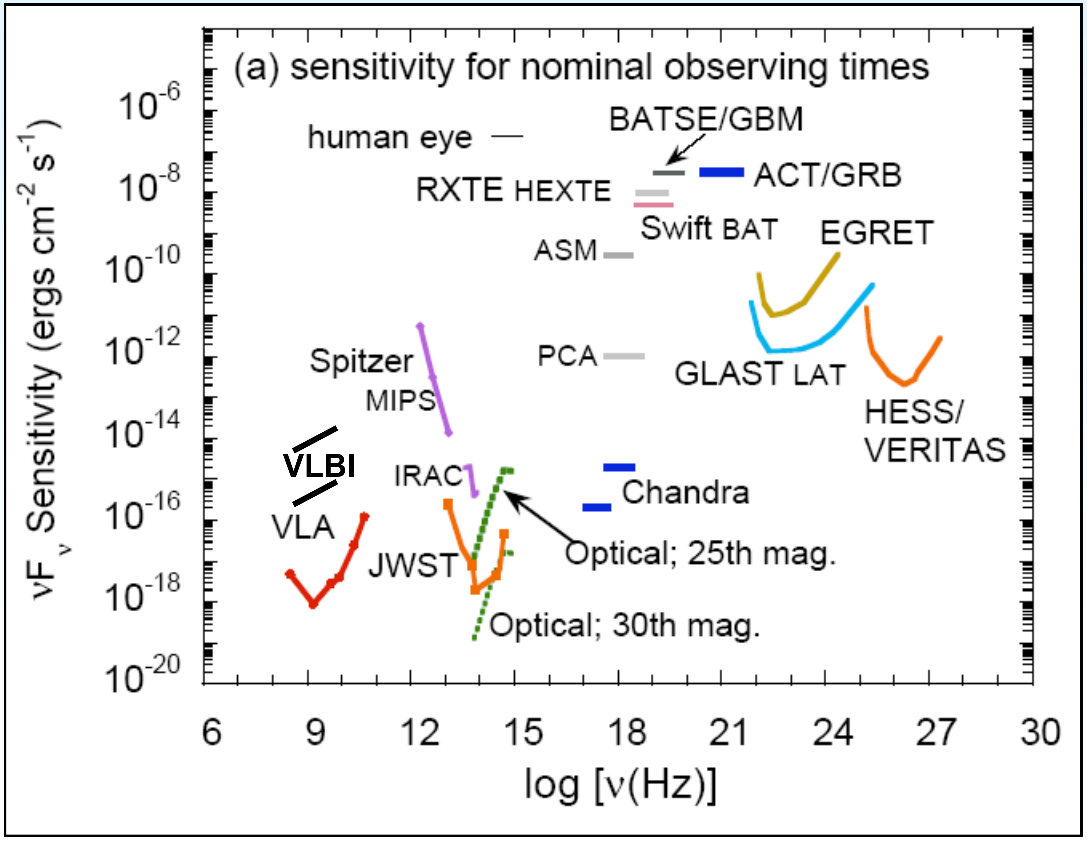
Radio flux measured in Jy (10^{-23} ergs cm^{-2} s^{-1}Hz^{-1})

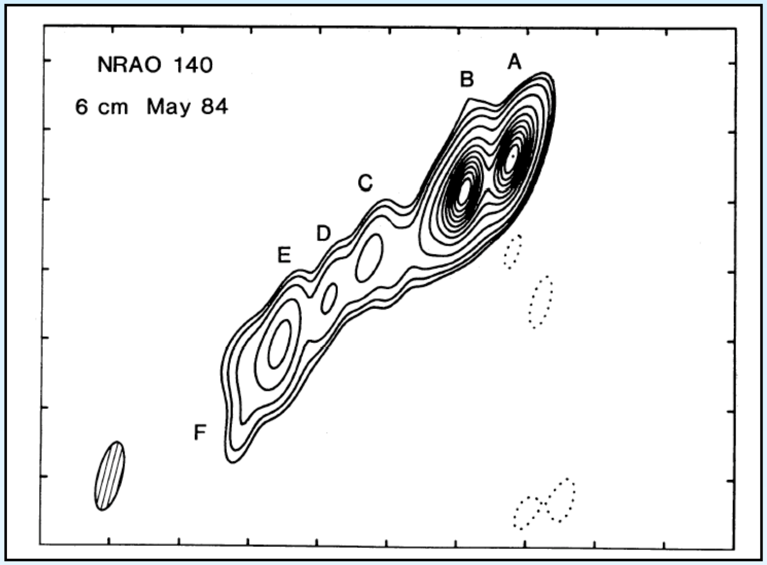
Nominal observing frequencies: 0.3 GHz – 90 GHz

200 mJy source at 5 GHz ↔ 10^{-14} ergs cm^{-2} s^{-1}

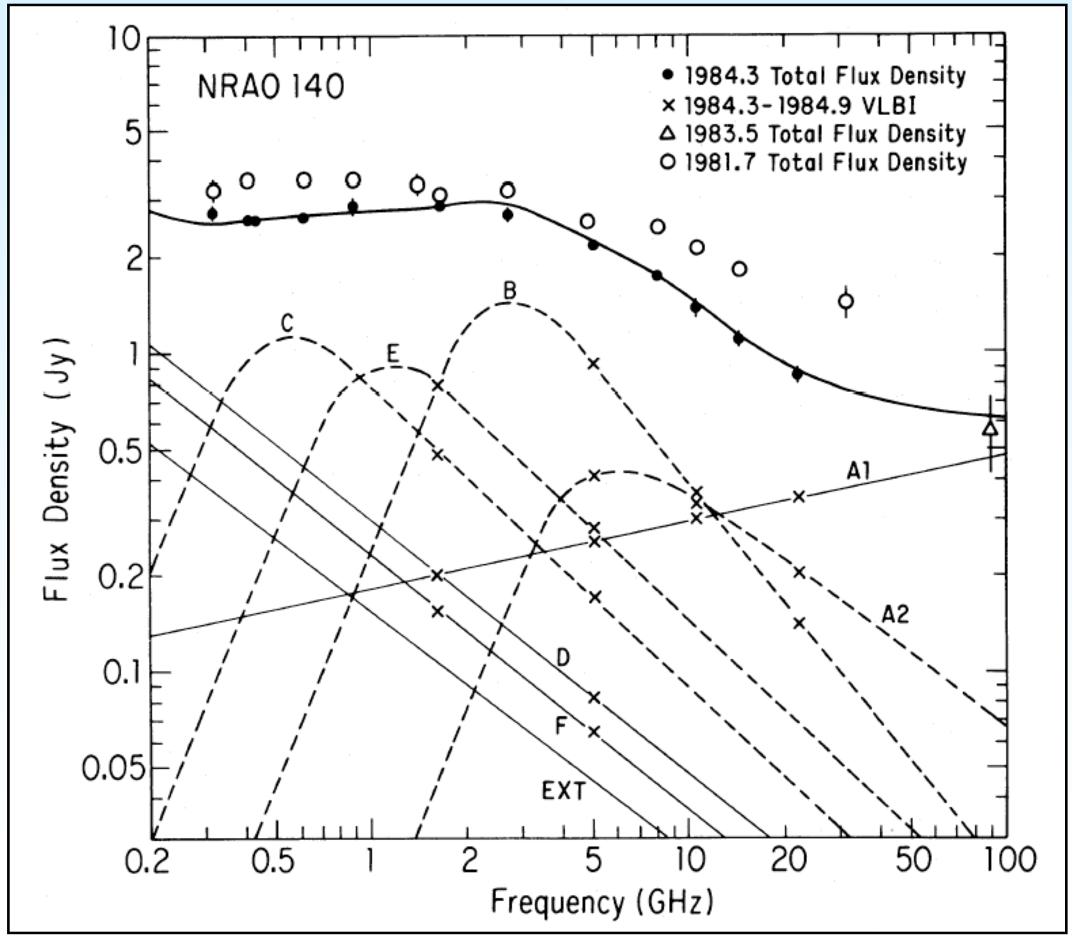
Better resolution at
higher frequency

Sub milliarcsecond
source at z = 0.1 ↔ 2 pc





NRAO 140



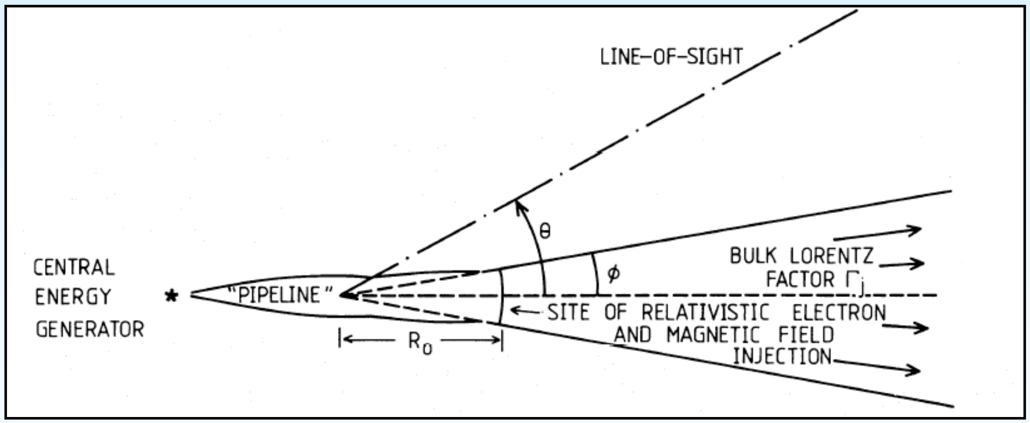
Resolved core, extended emission components ⇒ multizone model with mutiple self-absorbed components

Complicated magnetic field structure

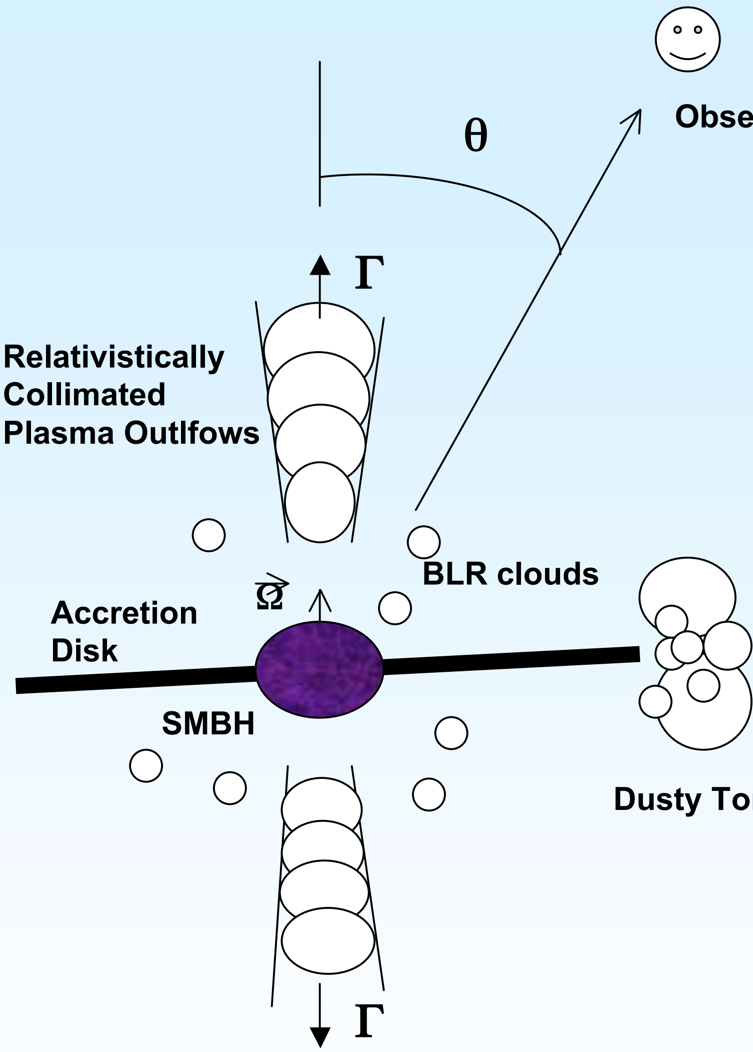
Marscher (1988)

Radio Blazar Model

Shock-in-Jet Model
Multizone Jet Model



Marscher & Gear (1985)

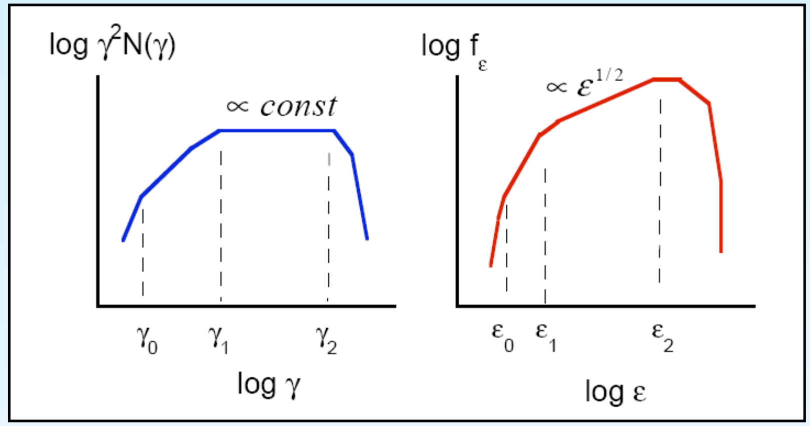


1. **Polarization obs. ⇒ ordered magnetic field**
2. **Bent jet ⇒non-ballistic motions**

Equipartition (Minimum Energy) Magnetic Field

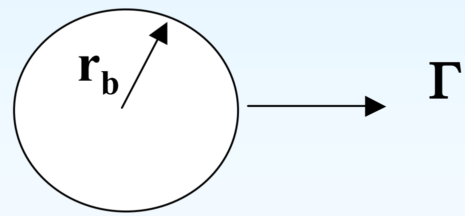
$$W'_e = \hat{k}_{eq} V'_b U_B \ , \ \text{where } \hat{k}_{eq} \equiv \frac{k_{eq}}{(1+k_{pe})}$$

$U_B = B^2/8\pi$ $\qquad V'_b = 4\pi r_b^3/3$



Relate observables to comoving quantities:

$$f_\epsilon^{syn} \cong \frac{\delta_{\rm D}^4}{6\pi d_L^2}\, c\sigma_{\rm T} U_B \frac{(p-2)W'_e}{m_e c^2 \gamma_1^{2-p}} \left(\frac{\epsilon_z}{\delta_{\rm D}\varepsilon_B}\right)^{(3-p)/2}$$

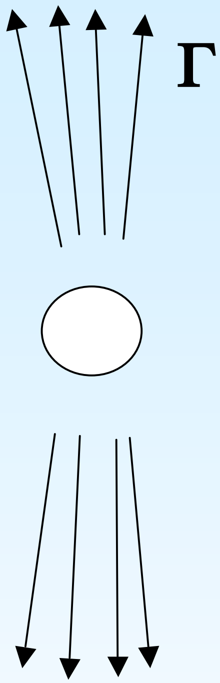


$$\delta_{\rm D}\varepsilon_B \equiv y_{eq} = \left[\frac{9 m_e c^2 d_L^2 f_\epsilon^{syn} \gamma_1^{2-p} \epsilon_z^{(p-3)/2}}{2c\sigma_{\rm T} U_{cr}^2 (p-2)\hat{k}_{eq} r_b^3}\right]^{2/(5+p)}$$

p = 2

$$B(\text{Gauss}) \cong 130\ \frac{d_{28}^{4/7} f_{-10}^{2/7} [(1+k_{pe})\ln(\nu_2/\nu_1)]^{2/7} (1+z)^{5/7}}{k_{eq}^{2/7} [t_{\rm var}({\rm d})]^{6/7} \delta_{\rm D}^{13/7} \nu_{13}^{1/7}}$$

Strongest dependence on Doppler Factor; then on variability time scale



Minimum Jet Power

$$n_* = \frac{L^*_{j,ke}}{2\Omega_j R^2 (\Gamma m_e c^2)\beta c} = n'(\langle\gamma\rangle + \chi m_p/m_e)$$

$$L^*_B = 2\Omega_j c R^2 \beta \Gamma^2 (\frac{B^2}{8\pi})$$

Total jet power = sum of particle kinetic and magnetic field

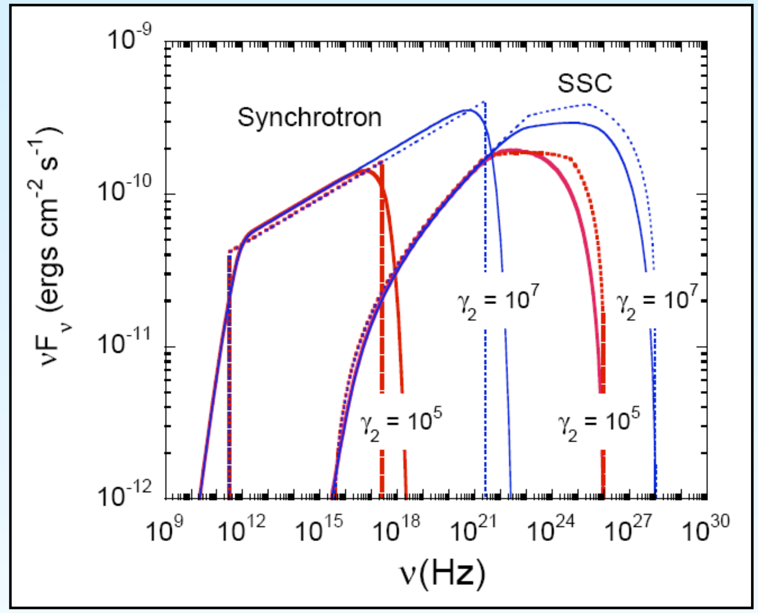
Minimize jet power for measured synchrotron flux

$$L^*_{j,min} = 8.7\times10^{44}\,\frac{d_{28}^{10/7}\vartheta_{mas}^{2/7}}{(1+z)^{6/7}\epsilon_{-10}^{2/7}}\,\left[(1+k_{pe})\lambda_5 f_{-14}\right]^{4/7}\ \text{ergs s}^{-1}$$

Minimum jet power for equipartition (minimum energy) magnetic field

Magnetic Field from Ratio of SSC/Synchrotron Flux

$$\frac{f_{\varepsilon^{SSC}}^{SSC}}{f_{\varepsilon^{syn}}^{syn}} \equiv \Pi = \frac{U'_{syn}}{U'_B}$$



Synchrotron energy density from synchrotron flux

$$f_{\varepsilon^{syn}}^{syn} = \frac{\delta_D^4}{4\pi d_L^2}\frac{V_b' U_{syn}'}{(r_b / c)}\ , V_b' = \frac{4\pi}{3} r_b^3$$

$$\Rightarrow B = \frac{4\sqrt{\pi}(1+z)d_L}{c^{3/2}\delta_D^3 t_{\rm var}}\sqrt{\frac{f_{\varepsilon^{syn}}^{syn}}{\Pi}}$$

Difficulty: identifying SSC component

Minimum energy B + SSC/Syn B implies (minimum energy) Doppler factor

$$\delta_D \cong 9\ \frac{d_{28}^{3/8}(1+z)^{1/4} f_{-10}^{3/16}\Pi^{-7/16}\nu_{13}^{1/8}}{[(1+k_{pe})\ln(\nu_2/\nu_1)]^{1/4}[t_{\rm var}(day)]^{1/8}}$$

Magnetic Field and Doppler Factor from Self-Absorbed Flux

Measured intensity at self-absorption frequency relates B, δ_D

$$I_T \equiv I_{\nu_T} \cong \sqrt{\frac{\delta_{\rm D}}{1+z}}\, d(p)\, m_e c^2\, \frac{\nu_T^2}{c^2} \sqrt{\frac{\nu_T}{\nu_B}}$$

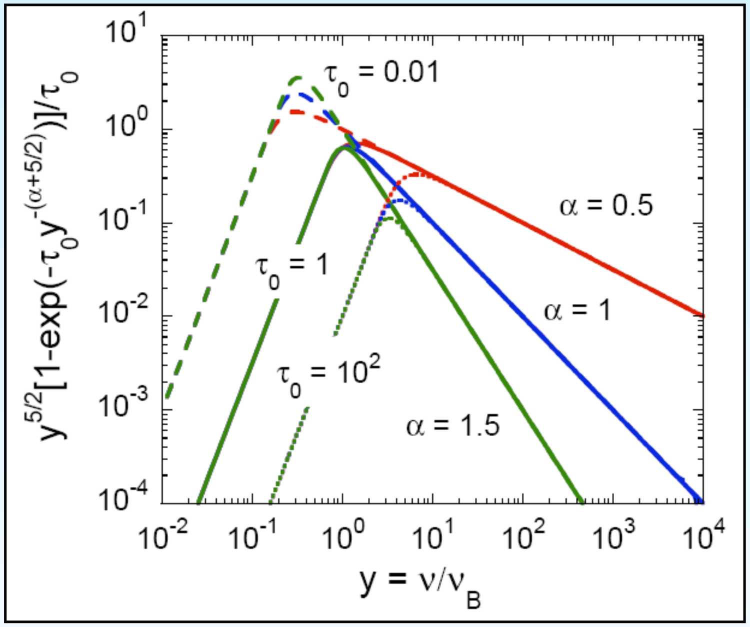
Combine with ratio Π of SSC to synchrotron fluxes to give brightness temperature

$$T_b \cong 1.2 \times 10^{12} \left(\frac{\delta_{\rm D}}{1+z}\right)^{6/5} \sqrt{\frac{\Pi(1-\alpha)d^4(p)}{\bar{\nu}({\rm GHz})}}\ {\rm K}$$

(Internal) Compton catastrophe

(External) Compton catastrophe from broad line region radiation field

Where are the γ-rays made?



Kellerman & Pauliny-Toth
Burbidge
Marscher
Jones, O'Dell, & Stein

Measuring the Doppler Factor: γγ Transparency Arguments

In comoving frame, avoiding threshold condition for γγ interactions requires

$$\varepsilon'\varepsilon_1' < 1;$$ Target Photon Flux: $10^{-10} f_{-10}\ ergs\ cm^{-2} s^{-1}$

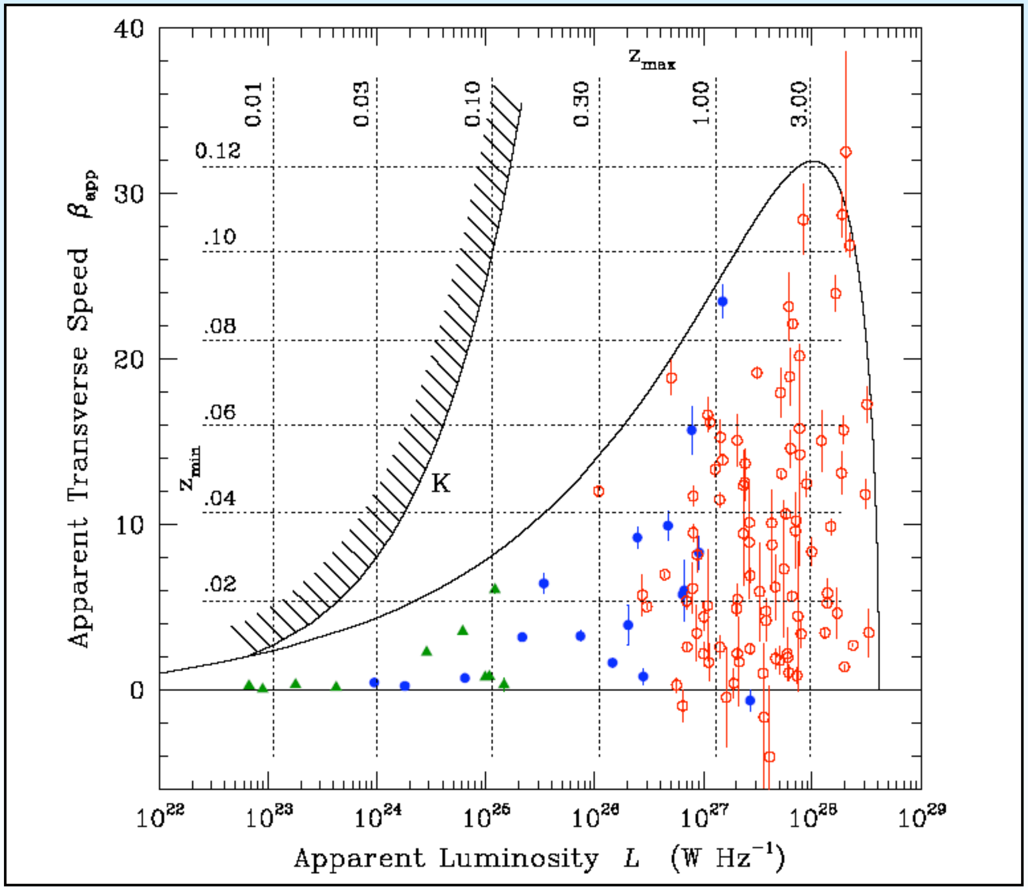
Requirement that γγ optical depth be less than unity:

$$\tau_{\gamma\gamma} \approx \frac{\sigma_T}{3}\left(\frac{2}{\varepsilon_1'}\right) n'_{ph}\left(\frac{2}{\varepsilon_1'}\right) r_b\ ,\ r_b \leq \frac{c t_{\rm var}\delta_D}{(1+z)} \Rightarrow$$

$$\delta_{\rm D} \gtrsim 6.8\ \left[\frac{d_{28}^2 f_{-10}}{t_4}\ \left(\frac{1+z}{2}\right)\right]^{1/5}\ \left(\frac{E_{GeV}}{\epsilon_{pk}}\right)^{1/10}$$

$$\delta_{\rm D} \gtrsim 10.9\ \left[\left(\frac{d_L}{140\ \rm Mpc}\right)^2 \frac{f_{-10} E_{TeV}}{t_4}\right]^{1/6}$$

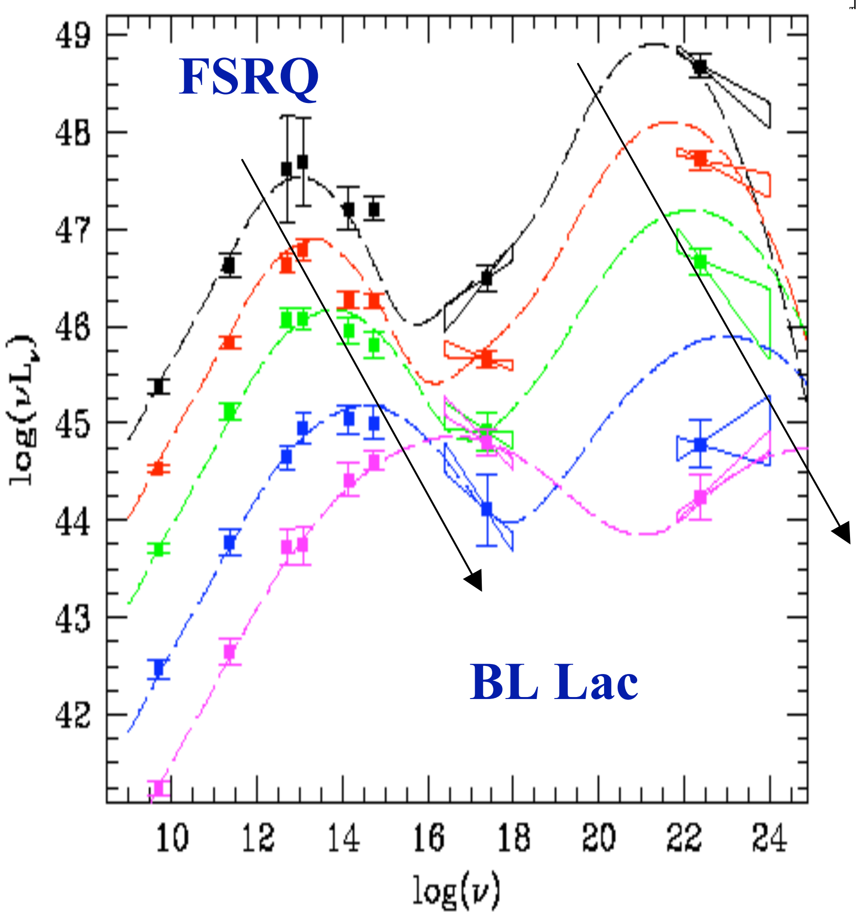
Statistical Limits on Γ



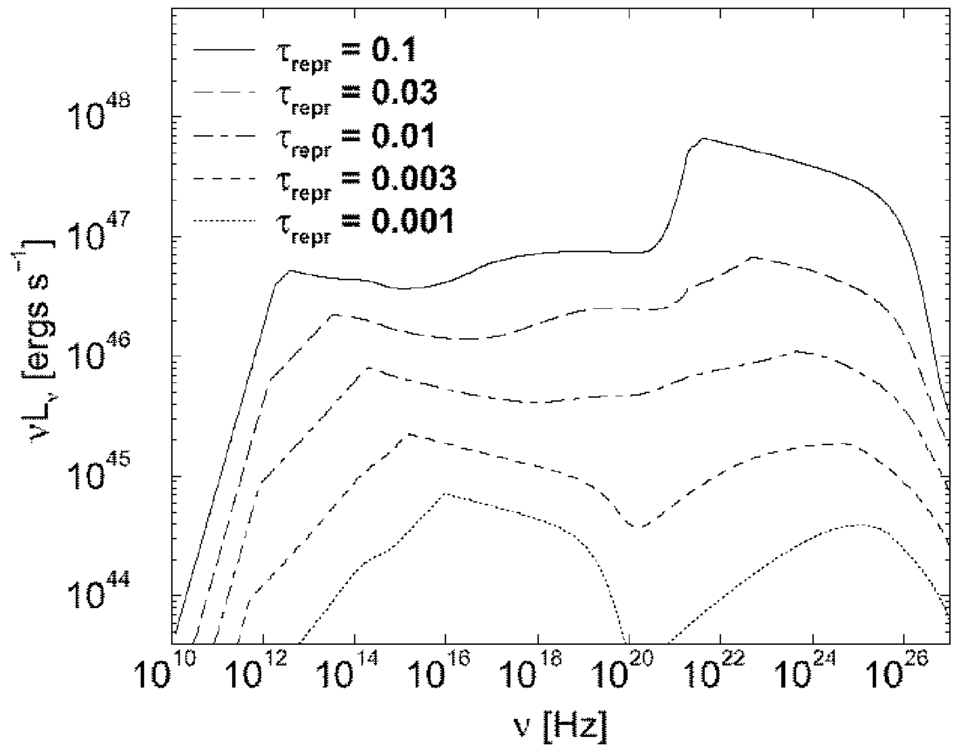
Cohen et al. (2007)

Analogous figure for GLAST using different measures of Doppler factor
Comparison of Doppler factors using γγ and VLBI

Blazar Main Sequence



Sambruna et al. (1996); Fossati et al. (1998)

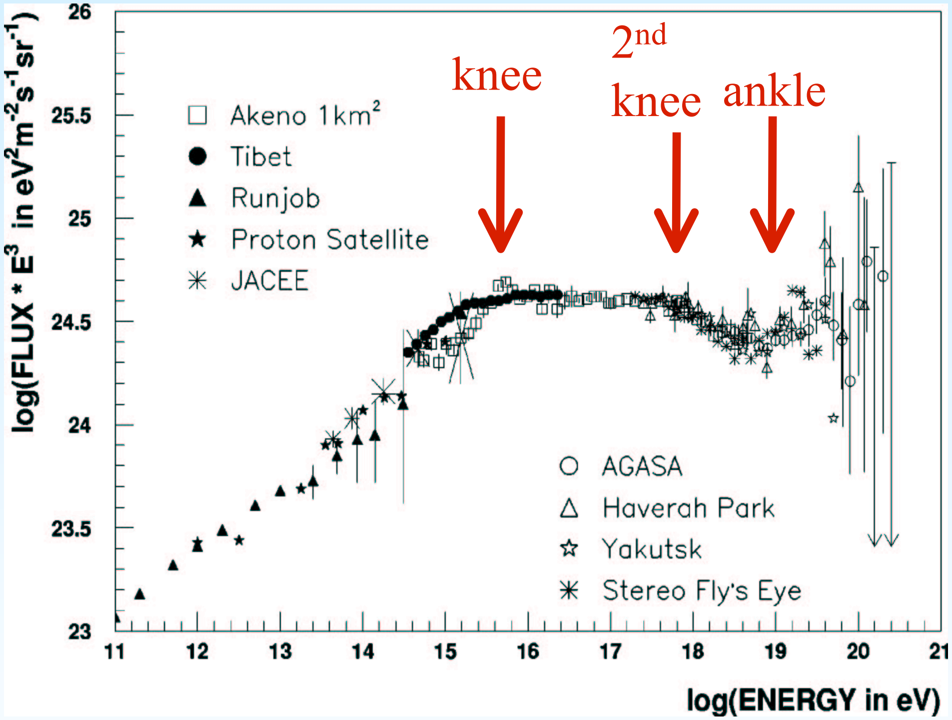


Evolution from FSRQ to BL Lac Objects in terms of a reduction of fuel from surrounding gas and dust

Böttcher and Dermer (2000)
Cavaliere and d'Elia (2000)

Improved modeling given specific or statistical mean values of B and δ_D for various classes

Ultra-high EnergyCosmic Ray Origin



Blazars have been proposed as a model for UHECR origin (e.g., Berezinsky and coworkers; Atoyan)

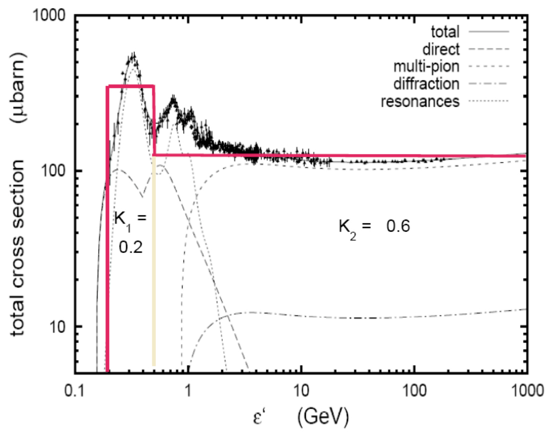
Hadronic acceleration in relativistic shocks of blazars

Detection of PeV neutrinos from blazars will confirm the model

Neutrinos produced in conditions of high-internal photon energy density, i.e., large flux and low Doppler factors, when photohadronic production rate

$$t'_{\phi\pi} \equiv \rho_{\phi\pi}^{-1} < t'_{\rm var} = \delta_D t_{\rm var}/(1+z)$$

Guaranteed Strong Photohadronic Losses

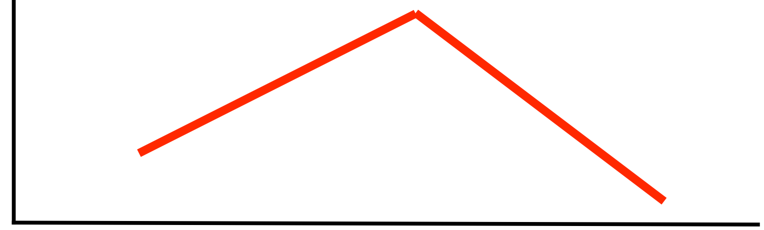


When are blazars neutrino-bright?

$$\rho_{\phi\pi} = \frac{3\hat{\sigma} d_L^2 f_{\epsilon_{pk}} (1+z)}{m_e c^4 \delta_D^5 t_v^2 \epsilon_{pk}}$$

$$\boxed{\delta_D < \delta_{\phi\pi} \equiv \left(\frac{3\hat{\sigma} d_L^2 f_{\epsilon_{pk}}}{m_e c^4 t_v \epsilon_{pk}}\right)^{1/4}}$$

$$S(x) = x^a H(x; x_a, 1) + x^b H(x; 1, x_b)$$



$$x = \epsilon/\epsilon_{pk} = \epsilon'/\epsilon'_{pk}$$

$$E_p^{\phi\pi} = \frac{m_p c^2 \delta_{\phi\pi}^2 \epsilon'_{thr}}{2(1+z)\epsilon_{pk}}$$

$$\tau_{\gamma\gamma}^{\phi\pi} = \frac{\sigma_T}{12\hat{\sigma}} \cong 800$$

$$E_\gamma^{\gamma\gamma} = \frac{2 m_e c^2 \delta_{\phi\pi}^2}{(1+z)^2 \epsilon_{pk}}$$

w/ Truong Le **(NRL),**
Enrico Ramirez-Ruiz **(IAS)**

Table of Requirements for Photopion Losses

TABLE I: Doppler factor $\delta_{\phi\pi}$ for guaranteed photopion losses, γ-ray photon energy $E_\gamma^{\gamma\gamma}$ for $\gamma\gamma$ attenuation with photons at the peak of the target photon SED, and cosmic ray energy $E_p^{\phi\pi}$ for photopion interactions with peak target photons (sources at $z = 2$ except for XBL, at $z \approx 0.08$, $d_L = 10^{27}$ cm).

	ℓ	η	τ	j	$\delta_{\phi\pi}$	$E_\gamma^{\gamma\gamma}$(GeV)	$E_p^{\phi\pi}$(eV)
FSRQ	28.7	-11	5	-5 (5 eV)	9	92	5×10^{17}
IR/optical				-6 (0.5 eV)	16	30×10^3	1.6×10^{19}
FSRQ	28.7	-11	5	-2 (5 keV)	1.6	0.03	1.6×10^{13}
X−ray				-3 (0.5 keV)	2.8	0.92	5×10^{14}
XBL	27	-10	3	-2 (5 keV)	1.3	0.14	3×10^{13}
X−ray				-3 (0.5 keV)	2.3	4.7	9×10^{14}
GRB	28.7	-6	0	0 (511 keV)	160	2.9	2×10^{15}
γ ray				-1 (51 keV)	280	92	5×10^{16}
X−ray flare		-9	2	-3 (0.5 keV)	50	290	1.6×10^{17}

Summary

- GLAST and VLBI give B and δ_D
  - Comparison of values obtained by different methods
  - Derive minimum jet powers
  - Use for comparing blazar populations, extended radio power
  - Use for studying blazar demographics

- Measurements of Doppler factor imply when blazars should be neutrino bright

- Blazar modeling hangs on question of where γ-rays are made