Astrophysical Implications of Photon Breeding Mechanism

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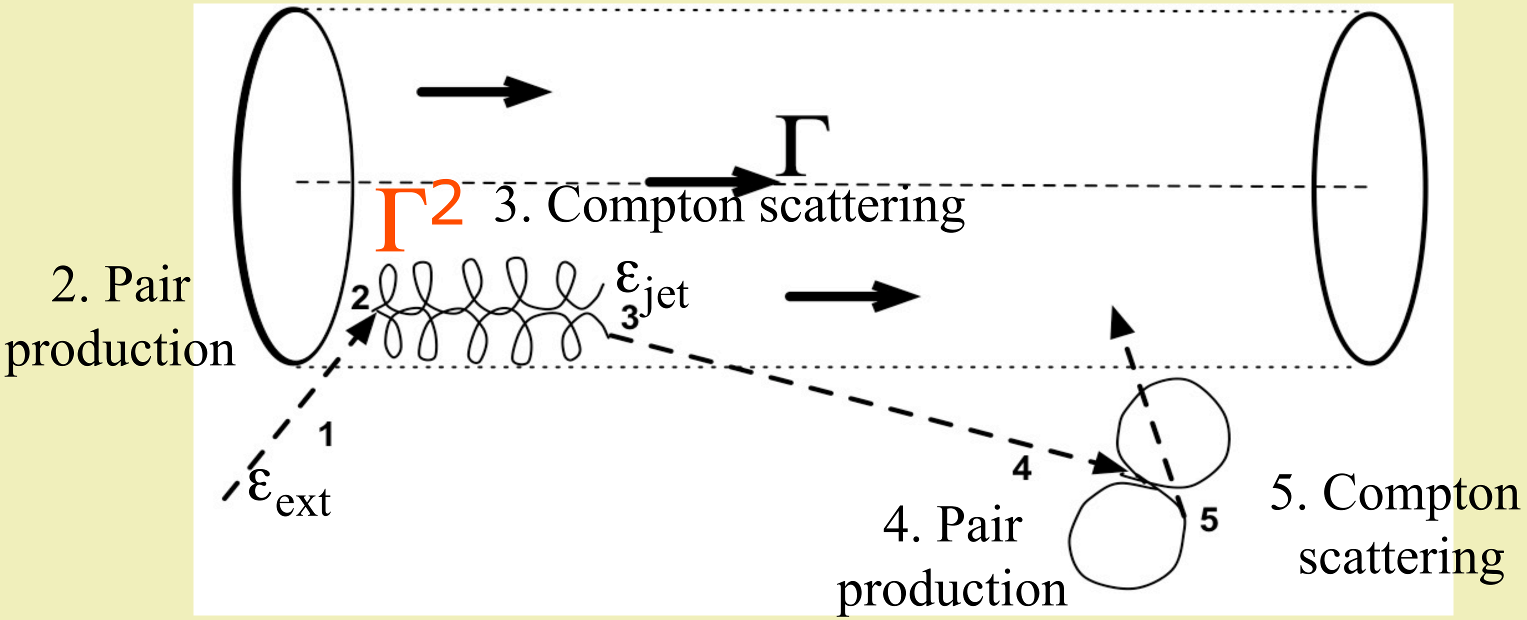
Photon breeding in jet's shear flow



Requirements

1. Some high-energy photons (extragalactic background, shock acceleration)
2. Transversal or chaotic B-field
3. Isotropic radiation field
4. Jet Lorentz factor $\Gamma \geq 4$ (more realistically $\Gamma \geq 10$).

Opacities in AGN jets

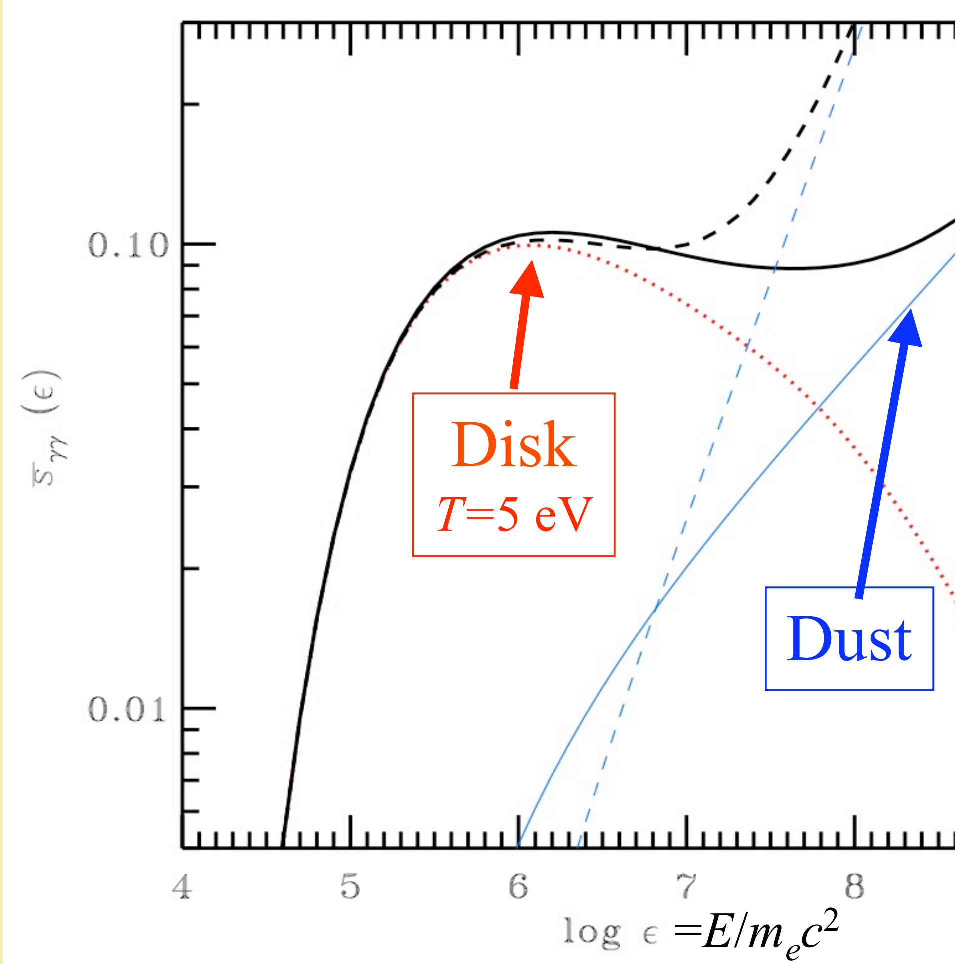
Thomson depth across the jet is

$$\tau_T = n_e \sigma_T R \theta_{\rm jet} = 2.3\ 10^{-5} \frac{L_{\rm kin,45}}{R_{17}\theta_{\rm jet}\Gamma}$$

High-energy photons are converted to electron- positron pairs because the optical depth is large

$$\tau_{\gamma\gamma}(\varepsilon) = \frac{1}{5} n_{ph} \sigma_T R \theta_{\rm jet} =$$

$$= 60 \frac{L_{\rm disk,45}}{R_{17} T_5} (10\theta_{\rm jet})$$



Pairs in the jet are produced with $\gamma = \varepsilon\Gamma$

$\gamma_{min} = 10^{4.5}$ -mirrors the disk spectrum

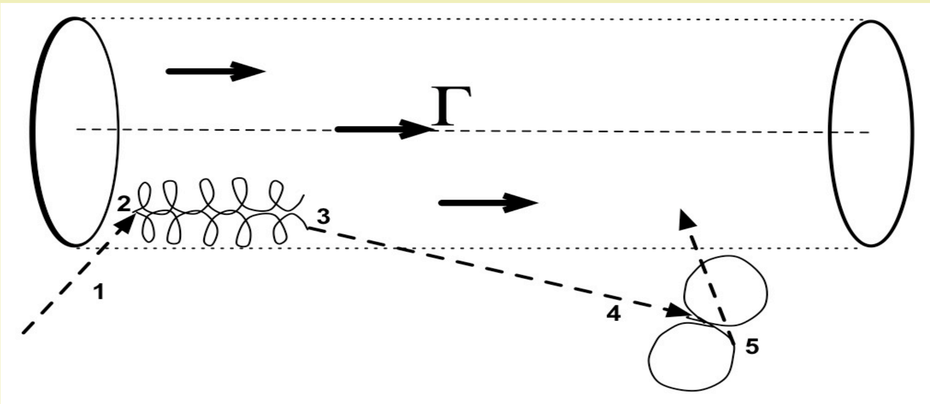
$\gamma_{max} = 10^{6-8}$ -depends on the magnetic fie

Transmission coefficients

$$C_1(\varepsilon_e \to \varepsilon_j) = \int_0^\infty \exp(-\alpha_j x) \frac{\exp(-\alpha_e x)\alpha_e dx}{2} = \frac{1}{2}\frac{b}{1+b}$$

$$C_4(\varepsilon_j \to \varepsilon_e) = \frac{1}{2}\frac{1}{1+b}$$

$$\boxed{b = \frac{\alpha_e}{\alpha_j}}$$



Note that $C_1(\varepsilon_e \to \varepsilon_j) + C_4(\varepsilon_j \to \varepsilon_e) = 1/2$

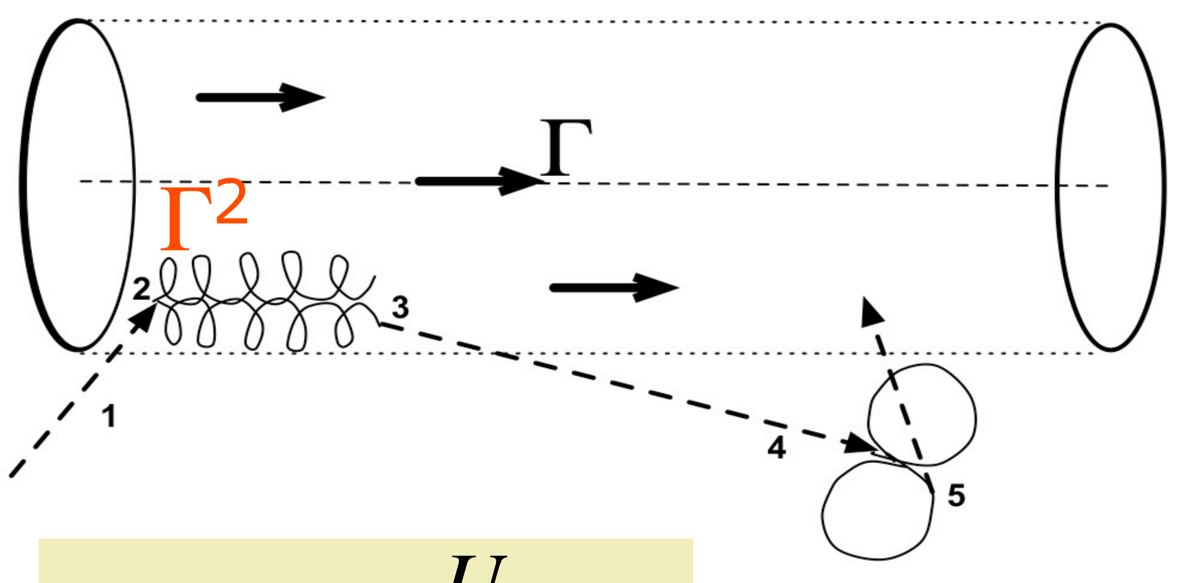
Maximum of their product is reached when $b=1$:

max $(C_1\ C_4) = 1/16$ (1D approximation)

Transmission coefficients (cont.)

$$C_2(\varepsilon_{iso}) \approx \Gamma^2$$

Consequence of two Lorentz transformations



U_T - soft photon field energy density in the Thomson regim

U_{cycle} - photon field which can be transformed to photons of sufficiently high energy

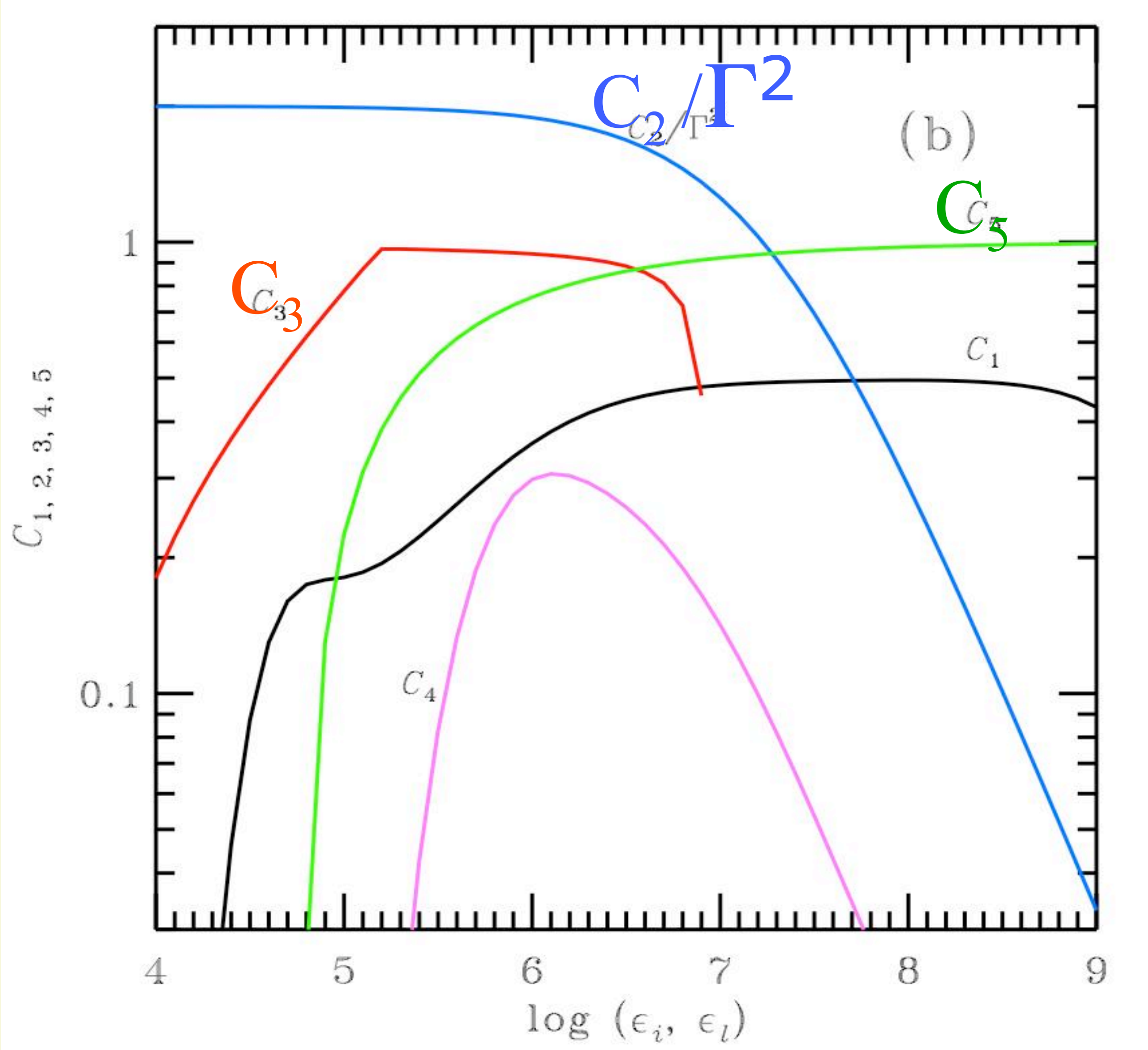
U_B =$B^2/8\pi$- magnetic field energy density.

$$C_3(\varepsilon_{iso}) = \frac{U_{cycle}}{U_B + U_T}$$

depend on the soft photon spectrum and the magnetic field

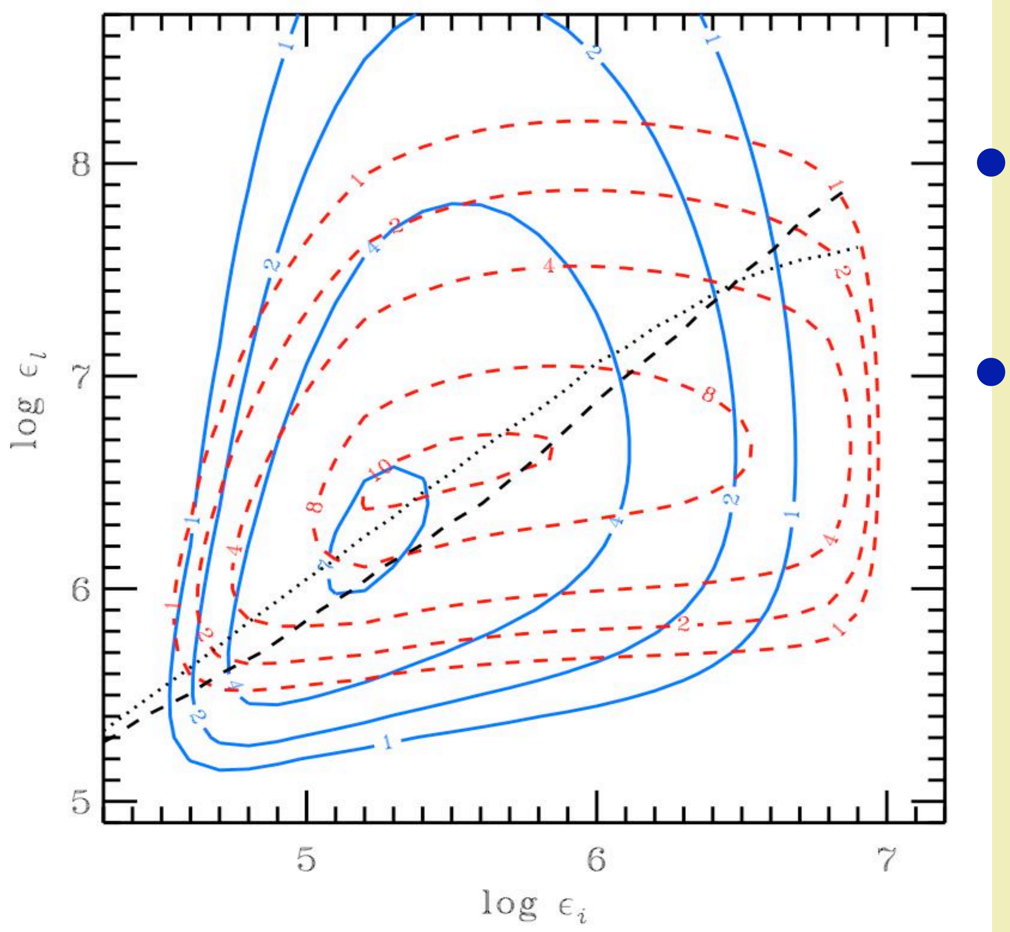
$$C_5(\varepsilon_{jet}) = \frac{U_{cycle}}{U}$$

Transmission coefficients (cont.)



Product of transmission coefficients

$\Gamma=10$



- Absolute maximum of the amplification factor is

  $A \approx \Gamma^2 / 10.$
- $\Gamma \geq$ 3-4 is required for photon breeding to operate.
- Amplification is maximal for

  1) weak magnetic field,

  2) dense soft photon field,

  3) large jet Lorentz factor Γ

  as these conditions reduce the synchrotron losses.

Gamma-ray emission sites

Photon breeding needs soft (isotropic) photon background.

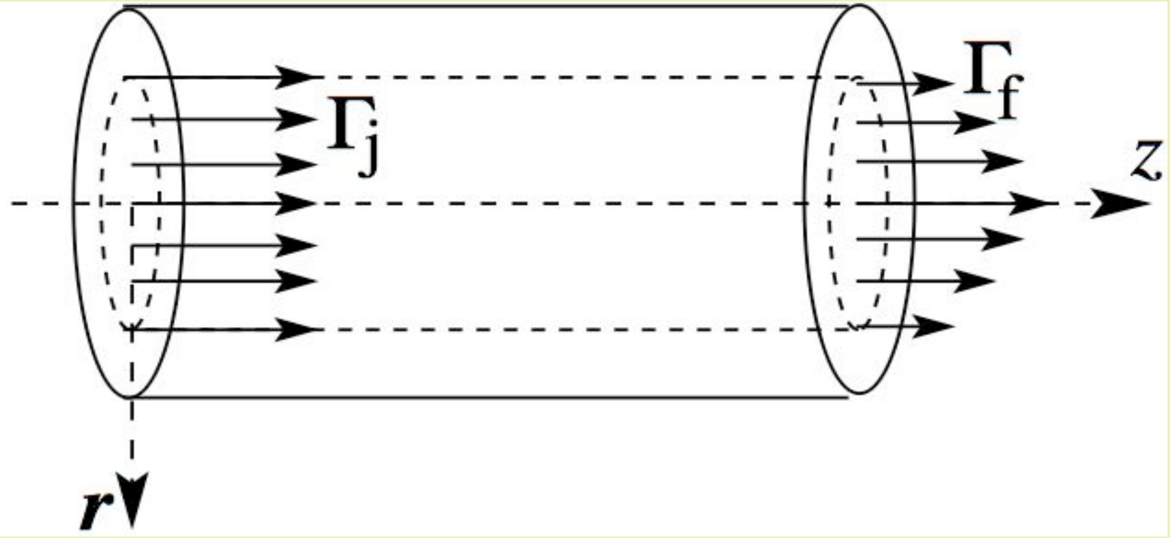
1. Near the accretion disk (if the jet is already accelerated with $\Gamma \geq 10$)
2. Broad emission line region at 10^{17} cm.
3. Dusty torus at parsec scale (if still $\Gamma \geq 10$).
4. Stellar radiation at kpc scale (if $\Gamma \geq 10$).
5. Cosmic microwave background at 100 kpc scale (if $\Gamma \geq 10$).

Doppler factor (Delta)-crisis

- Doppler factors determined from TeV blazars δ~20-50.
- Apparent velocities at parsec scales in Mrk 421, Mrk 501 are other TeV blazars are mildly relativistic (Marscher 1999; Piner & Edwards 2004, 2005).
- Unification (source statistics and luminosity ratio) of FR I with BL Lacs requires Γ~4÷6 (for the blob and steady jet, respectively).
- TeV emission observed in (off-axis) radio galaxy M87 contradicts strong beaming models (predicts huge beamed luminosity).
- SOLUTIONS:

1. *Assume* decelerating jet (Georganopoulos & Kazanas 2003)
2. *Assume* structured jet (fast spine - slow sheath) (Chiaberge et al. 2000, Ghisellini et al. 2005)
3. Large opening angle jet (Gopal-Krishna et al. 2004)

Jet structure as a result of photon breeding decelerating (due to ERC) and "structured"



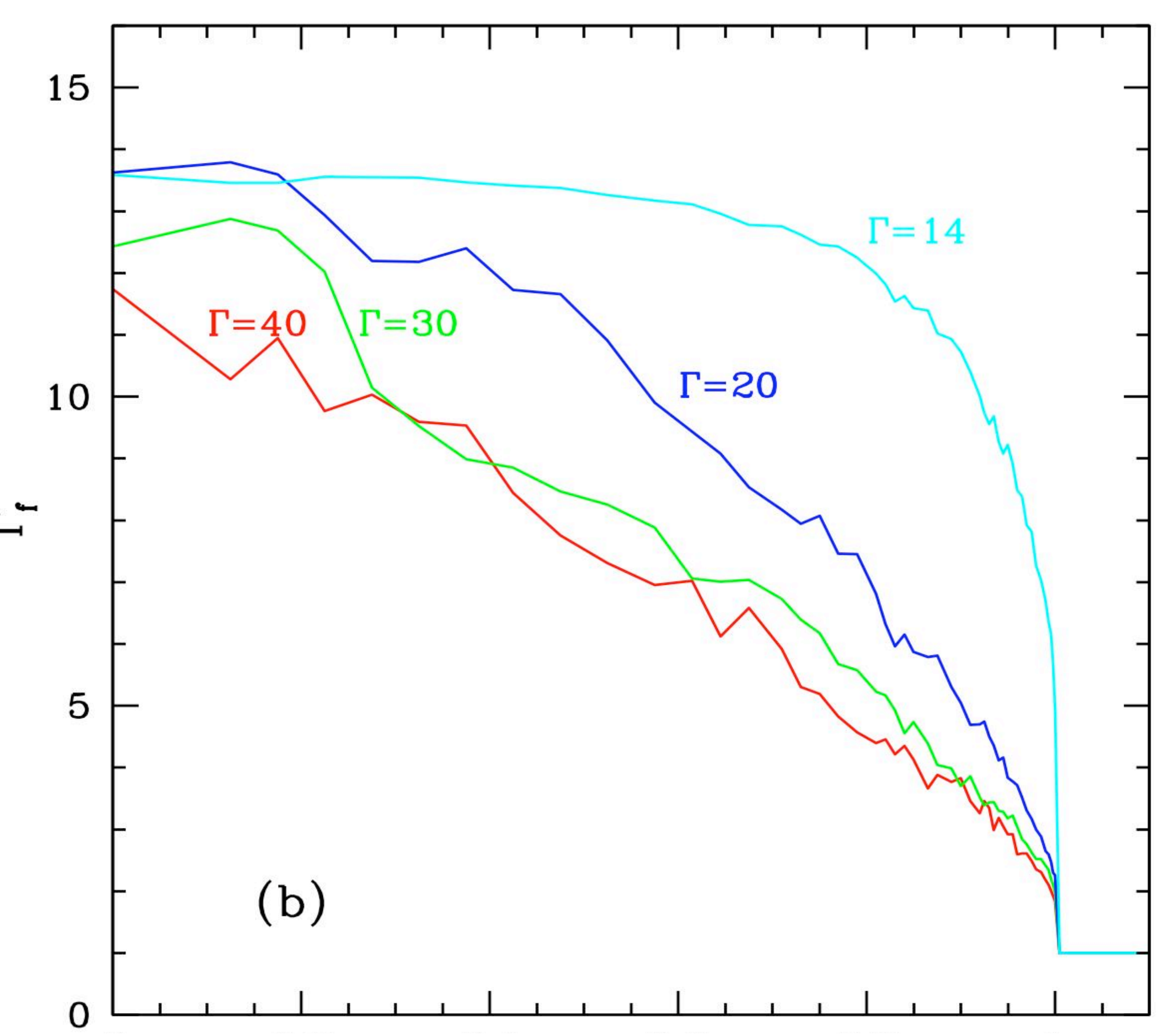
Decelerating jet

$$\beta_{app} = \frac{\beta\cos\theta}{1-\beta\sin\theta} \approx \frac{2\theta\Gamma^2}{1+(\theta\Gamma)^2}$$

$$\beta_{app} \approx 2\theta\Gamma_f^2 \le 2\frac{\Gamma_f^2}{\Gamma_0} \quad \text{for } \theta \le \frac{1}{\Gamma_0} << \frac{1}{\Gamma_f}$$

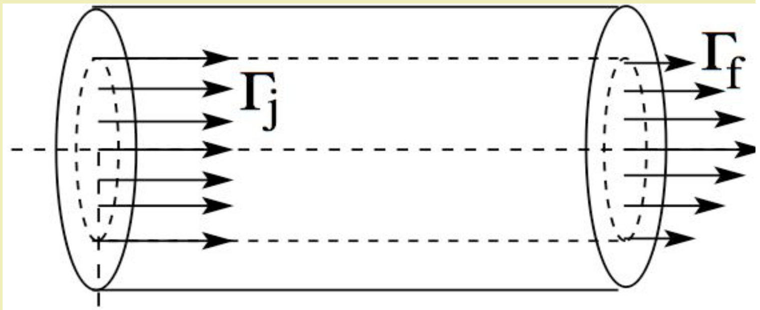
$$\beta_{app} < 1 \quad \text{for } \Gamma_f < \sqrt{\Gamma_0/2}$$

Terminal jet Lorentz factor

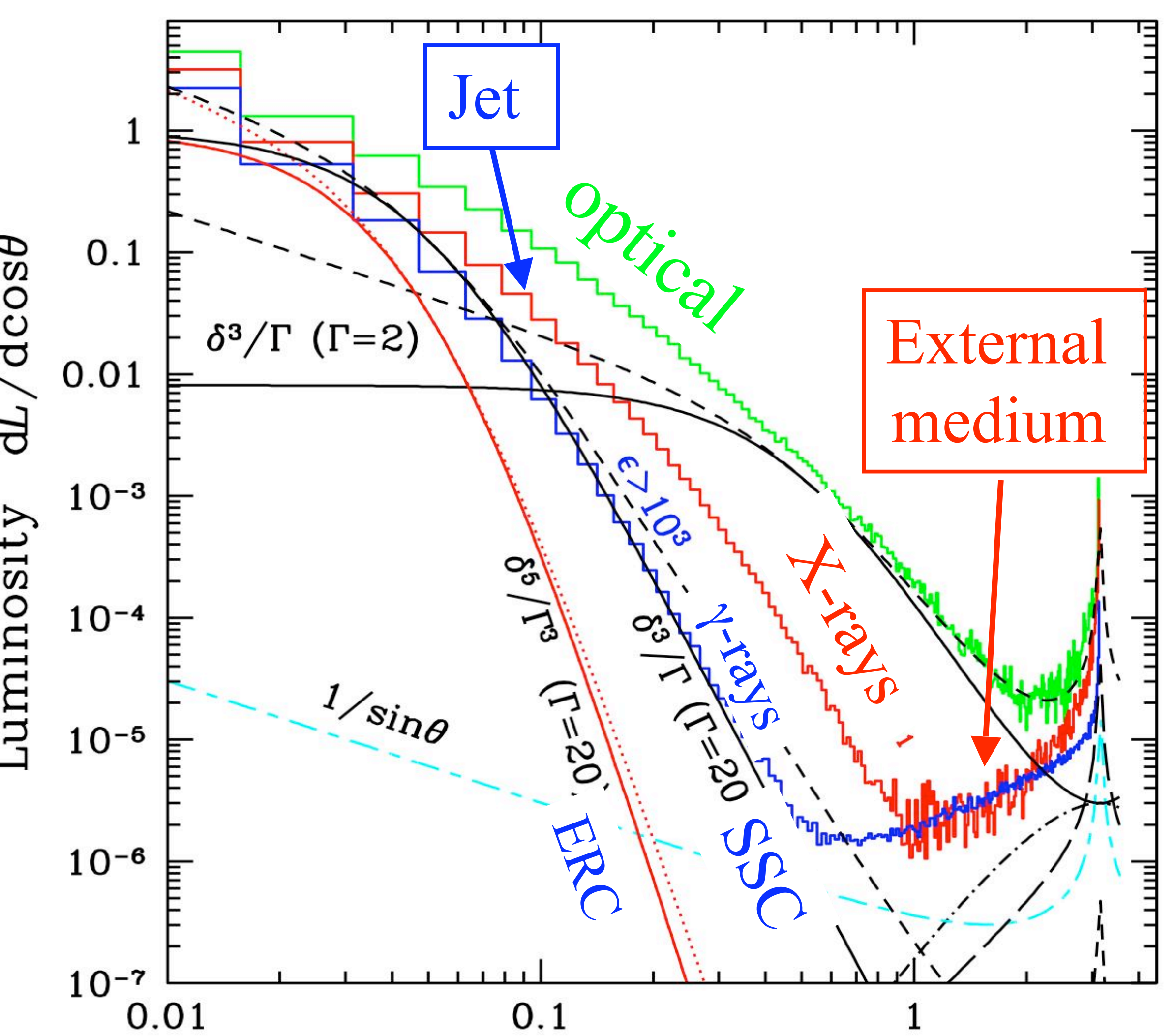


$L_{jet}=L_{disk}=3\ 10^{44}$ erg/s
$L_B=0.2\ L_{jet}$
$L_{iso}=0.05\ L_{disk}$
$R=2\ 10^{17}$ cm

1. Terminal Lorentz factor is smaller for larger initial Γ_j
2. $\Gamma(r)$ saturates at $d\Gamma(r)/dr=const$



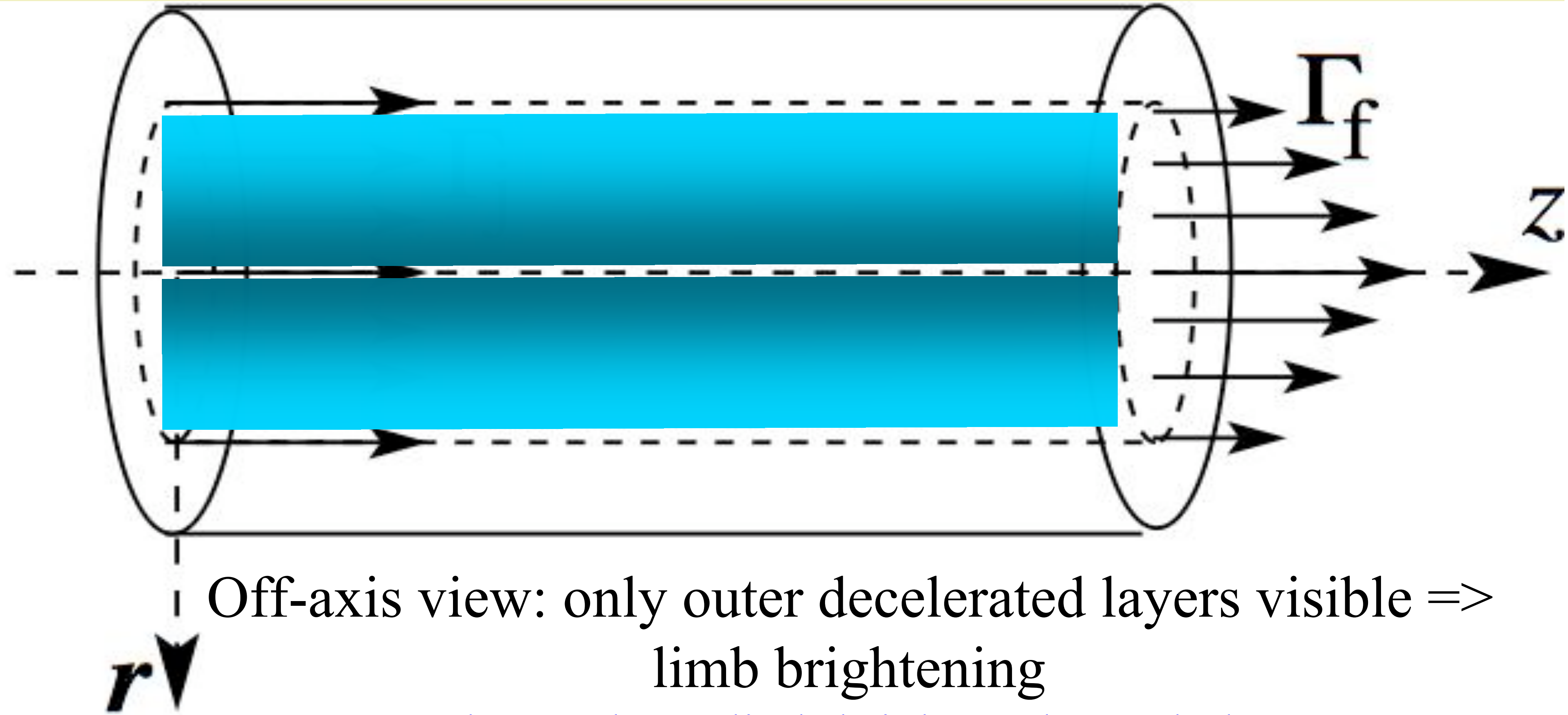
Angular distribution of radiation from the decelerating structured jet



1. Gamma-ray radiation is coming from the fast spine.
2. Optical is synchrotron from the slow sheath.
3. X-rays are the mixture.
4. Gamma-ray at large angles by pairs in external medium have luminosity Γ_j^4 smaller than that at angle $1/\Gamma_j$ (Γ_j^2 - amplification, Γ_j^2 - beaming). Compare to δ^3 ratio for $\theta = 1/\Gamma_j$ and $\theta \approx 1$ which is Γ_j^6
5. Photon breeding predicts high gamma luminosity in radio galaxies (e.g. M87
6. Solves the delta-crisis.

Observational appearance

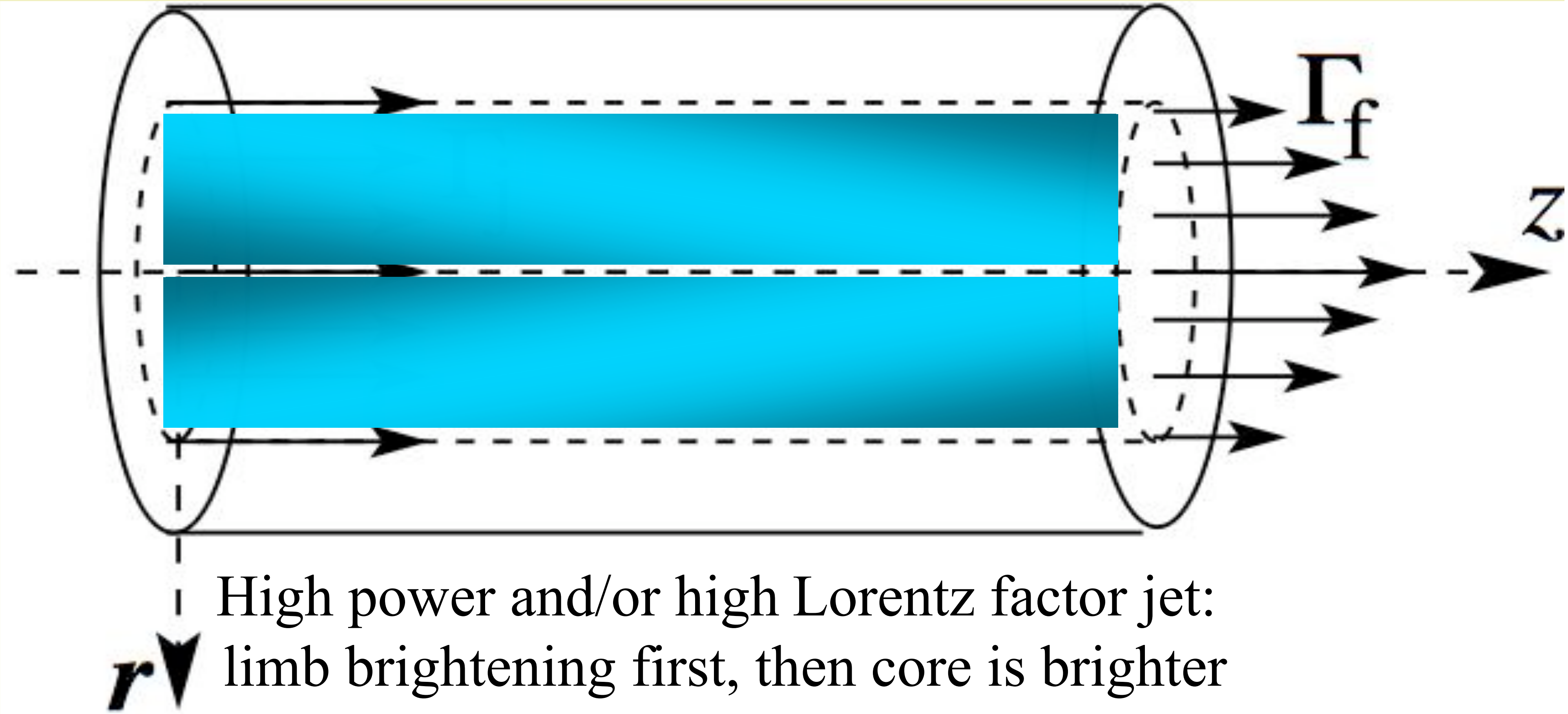
Low power or low Lorentz factor jets:
only outer layers decelerate => limb brightening



Off-axis view: only outer decelerated layers visible =>
limb brightening

Mrk 501 shows limb-brightened morphology

Observational appearance



High power and/or high Lorentz factor jet:
limb brightening first, then core is brighter

Conclusions

- Photon breeding mechanism is based on well-known physi
- Photon breeding is an efficient accelerator of high-energy pairs. Any other mechanism of particle acceleration can provide high-energy electrons (and therefore photons) for photon breeding, which takes over.
- Spectra consistent with blazar-sequence.
- High radiative efficiency of photon breeding reduces the power budget.
- Photon breeding produces decelerating, structured jet.
  This results in a broad emission pattern.
  This resolves the delta-crisis.
- Produces strong GeV-TeV emission for off-axis objects (radio galaxies).
- Fill outer layers of the jet with pairs. Limb-brightening morphology.
- The process is very promising in explaining high luminosities of relativistic jets in AGNs