Pair cascades in AGNs

Juri Poutanen

University of Oulu, Finland

PLAN:

- Classical non-thermal pair models.
  Pair cascades.
- Cascades in AGN jets.
- Modern reincarnations. Self-supporting cascades: photon breeding mechanism.
- Comparison to observations.

Non-thermal pair models

1. No cascade (e.g. synchrotron self-Compton models).
2. Linear electromagnetic cascade (radiation field acting on a cascade is determined by the external conditions, e.g. accretion disk, BLR).
3. Non-linear cascade (the radiation field is determined by the cascade itself).

Bonometto, Rees 1971; Guilbert, Fabian, Rees 1983; Kazanas 1984; Aharonian, Vardanian 1985; Zdziarski & Lightman 1985; Stern 1985; Zdziarski 1986; Zdziarski & Lamb 1986; Fabian et al. 1986; Lightman & Zdziarski 1987; Svensson 1987; Ghisellini 1987; Zdziarski 1988; Done & Fabian 1989; Coppi 1992;

review Svensson 1994

Parameters

Injected compactness (thermal + nonthermal) :

$l_h = l_{th} + l_{nth}$

Ratio of injection rates (particles/soft photons) : l_h / l_s

Soft photon energy : ε_s or kT_s

Lorentz factor of injected electrons : $\gamma_{\max}$

Compactness $$l \equiv \frac{L}{R}\frac{\sigma_T}{m_e c^3} = \frac{2\pi}{3}\frac{m_p}{m_e}\frac{L}{L_{Edd}}\frac{3R_S}{R}$$

Cooling time
(e.g. by Compton) $$t_{cool} = \frac{\gamma}{\dot{\gamma}} = \frac{R}{c}\frac{10}{\gamma l} << \frac{R}{c} = \text{escape}$$

Electron and photon spectra

- Electron kinetic equation

$$\frac{\partial N(\gamma)}{\partial t} + \frac{\partial}{\partial \gamma}\left[\dot{\gamma}\, N(\gamma)\right] = Q(\gamma)$$

- Steady-state

$$\frac{\partial}{\partial t} = 0 \quad \Rightarrow \quad N(\gamma) = \frac{1}{-\dot{\gamma}} \int_{\gamma}^{\infty} Q(\gamma)\, \mathrm{d}\gamma$$

- For monoenergetic or hard injection, electron spectrum

$$Q(\gamma) \propto \delta(\gamma - \gamma_{\max}) \quad \text{or } Q(\gamma) \propto \gamma^{-\Gamma_{inj}}, \quad \Gamma_{inj} < 1$$

$$N(\gamma) \propto \frac{1}{\dot{\gamma}} \propto \gamma^{-2} \quad \text{at } \gamma < \gamma_{\max}$$

- For soft injection

$$Q(\gamma) \propto \gamma^{-\Gamma_{inj}}, \quad \Gamma_{inj} > 1$$

$$N(\gamma) \propto \gamma^{-p}, \quad p = \Gamma_{inj} + 1$$

- Photon spectrum

$$N_{ph}(\varepsilon) \propto \varepsilon^{-\Gamma}, \quad \Gamma = \frac{p+1}{2} = \begin{cases} 3/2 & , \Gamma_{inj} < 1 \\ 1 + \dfrac{\Gamma_{inj}}{2} & , \Gamma_{inj} > 1 \end{cases}$$

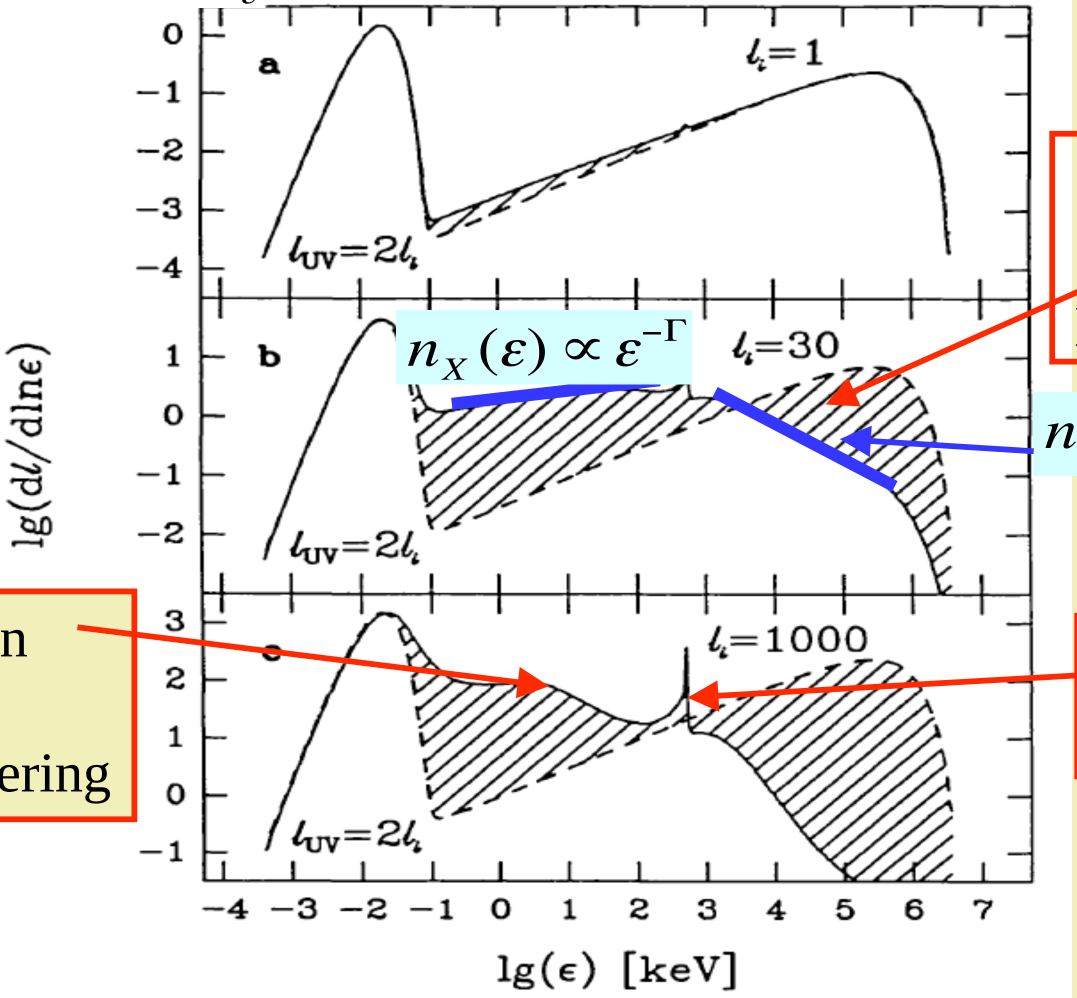
Pair cascade spectra

- The photons from the first generation produce an electron-positron pair. Each high-energy photon of energy $\varepsilon >> 1$ finds a partner $\varepsilon' \geq 1/\varepsilon$
- Lorentz factor of produced pair $\gamma_- + \gamma_+ \approx \varepsilon \Rightarrow \gamma_- \approx \gamma_+ \approx \varepsilon/2$
- The injected spectrum of the next generation pairs = photon spectrum

Generation	1	2	3	4	n
Injected pairs					
$\Gamma_{inj,n} = \Gamma_{ph,n-1}$	<1	$3/2$	$7/4$	$15/8$	$2 - 1/2^{n-1}$
Steady - state pairs					
$p_n = \Gamma_{inj,n} + 1$	2	$5/2$	$11/4$	$23/8$	$3 - 1/2^{n-1}$
Photon distribution					
$\Gamma_{ph,n} = \dfrac{p_n + 1}{2} = 1 + \dfrac{\Gamma_{inj,n}}{2}$	$3/2$	$7/4$	$15/8$	$31/16$	$2 - 1/2^n$

Pair cascade spectra

$\varepsilon^2 n(\varepsilon) = \varepsilon F_\varepsilon$



$n_X(\varepsilon) \propto \varepsilon^{-\Gamma}$

Absorbed by photon-photon pair-production

$n_\gamma(\varepsilon) \propto \varepsilon^{-2\Gamma+1}$

Compton up- or down-scattering

Annihilation line

$$n_X(\varepsilon) \propto \varepsilon^{-\Gamma}, \qquad \Gamma \approx 1.8, \quad \alpha_{\gamma\gamma}(\varepsilon) \approx \frac{\sigma_T}{5}\left[\frac{1}{\varepsilon} n_X(1/\varepsilon)\right] = \frac{\sigma_T}{5 m_e c^3} F_X(1/\varepsilon) \propto \varepsilon^{\Gamma-1}$$

$$n_\gamma(\varepsilon) \propto \frac{\text{emissivity in } \gamma\text{-rays}}{\text{opacity by X-rays}} \propto \frac{\varepsilon^{-\Gamma}}{\varepsilon^{\Gamma-1}} \propto \varepsilon^{-2\Gamma+1}$$

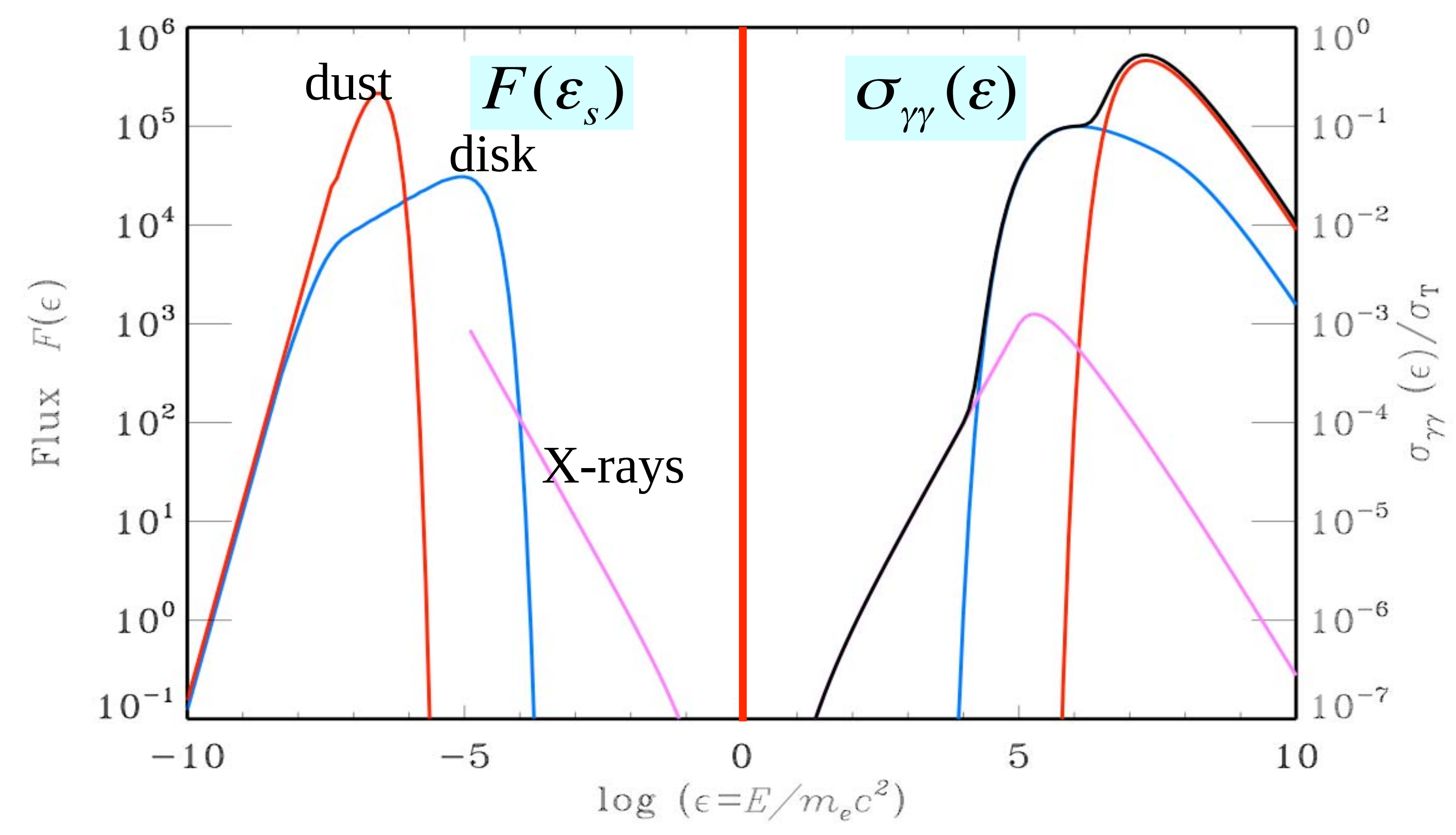
Pair production in AGN

- Optical depth for pair production on radiation from

1. dust (black body T=1000 K)
2. multicolor disk ($T_{\max}$ =10^5K)
3. X-rays (power-law with Γ=2)

$$F(\varepsilon_s) \propto \varepsilon_s^{-\alpha}$$

$$\alpha_{\gamma\gamma}(\varepsilon) \approx \frac{\sigma_T}{5 m_e c^3} F(1/\varepsilon) \propto \varepsilon^{\alpha}$$



Pair production in AGN

Optical depth for pair production on disk photons

$$\tau_{\gamma\gamma} \approx n_{ph}\frac{\sigma_T}{10}R = \frac{L_S}{4\pi R^2 c\left[\varepsilon_S m_e c^2\right]}\frac{\sigma_T}{10}R = \frac{l_S}{40\pi\varepsilon_S}$$

- Typical accretion disk photon energy

$$\varepsilon_S \approx 10^{-5} M_8^{-1/4}\left(\frac{L}{L_{Edd}}\right)^{1/4}$$

- Typical pair production optical depth for photons of energy $\approx 10/\varepsilon_S$ at a distance R

$$\tau_{\gamma\gamma} \approx \frac{10^7 R_S}{R}\left(\frac{L}{L_{Edd}}\right)^{3/4} M_8^{1/4}$$

- γ-sphere for photons $\varepsilon \approx 10/\varepsilon_S \approx 10^6$ (i.e. ≈ 1 TeV) is at

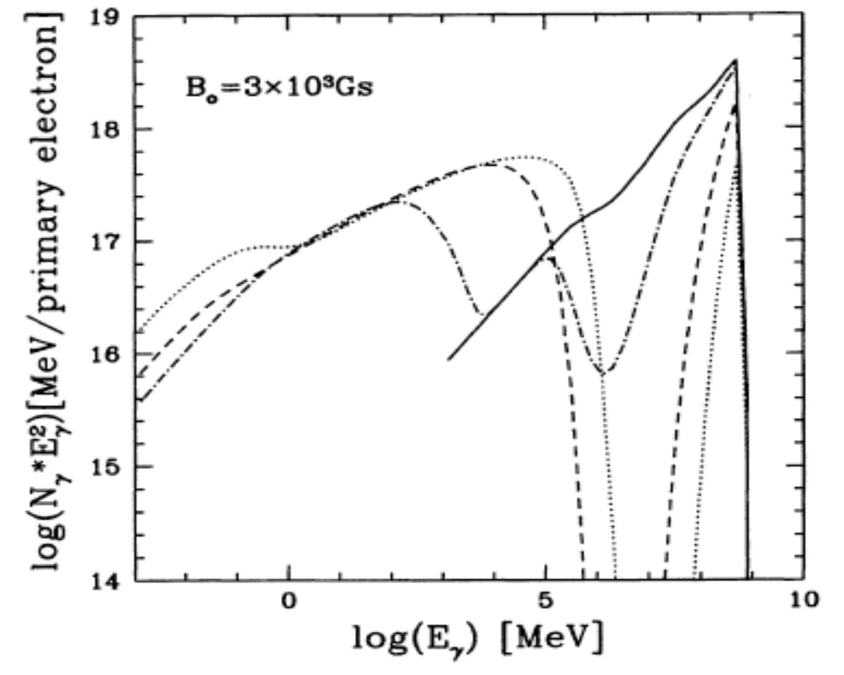
$$\tau_{\gamma\gamma} = 1 \Rightarrow R_\gamma \approx 10^7 R_S\left(\frac{L}{L_{Edd}}\right)^{3/4} M_8^{1/4} = 100\ \mathrm{pc}\left(\frac{L}{L_{Edd}}\right)^{3/4} M_8^{5/4}$$

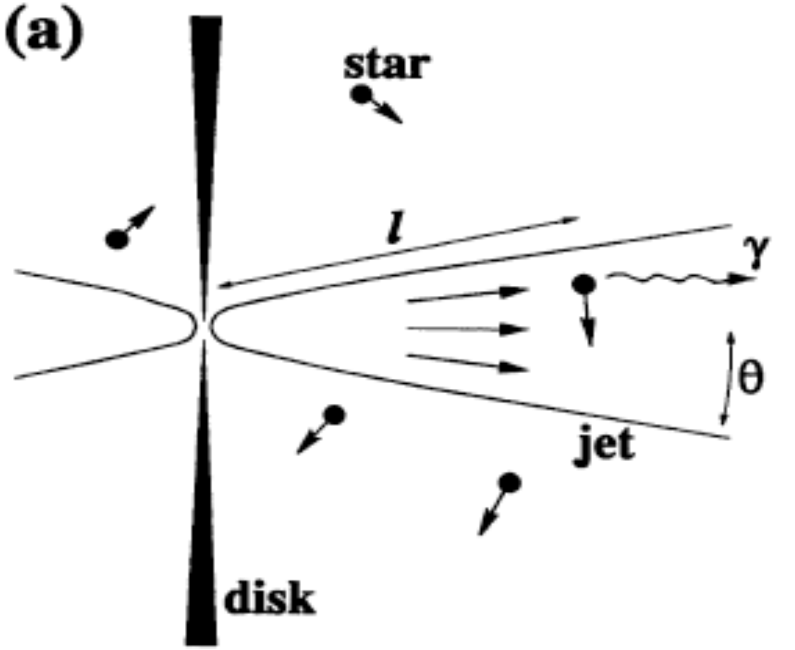
- Of course, at 100 pc disk radiation is beamed and does not interact with the jet radiation.
- An lower γ-ray energies, interaction with the X-rays $F(\varepsilon) \propto \varepsilon^{-1}$ gives

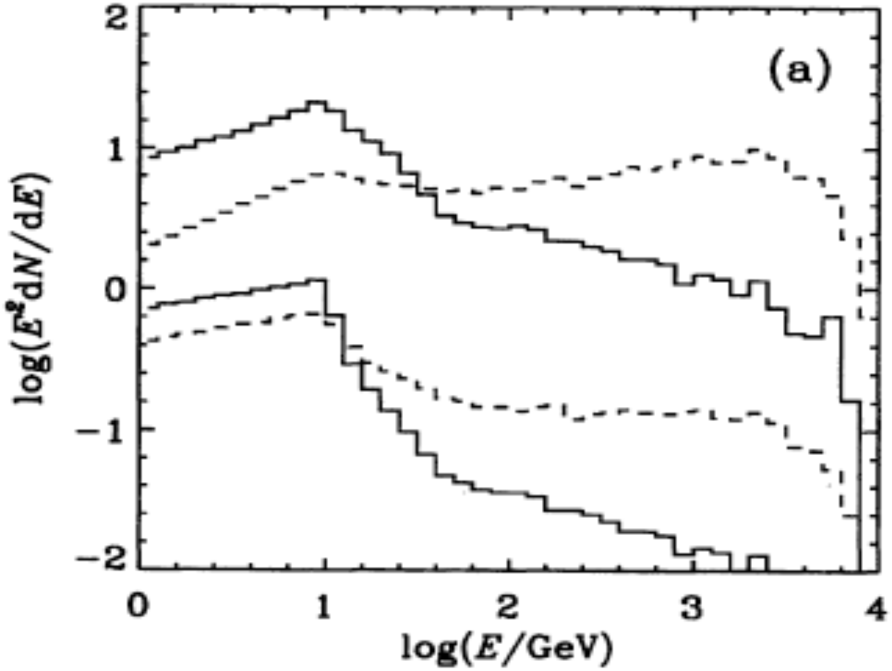
$$R_\gamma \approx 1\ \mathrm{pc}\ \eta_X L_{X,44,}\left(E/1\ \mathrm{GeV}\right)$$

Pair cascades in AGN

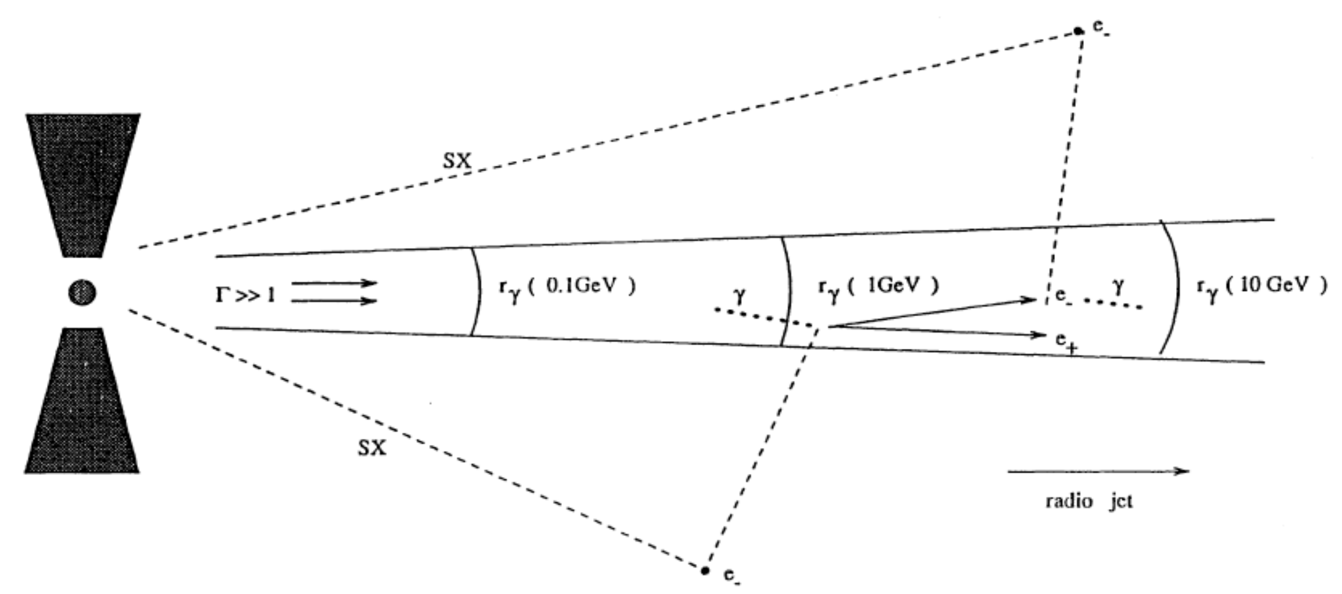
- Bednarek 1997: Synchrotron cascades by extremely high-energy gamma-rays.
- Bednarek & Protheroe 1997: cascade from the jet-star interaction





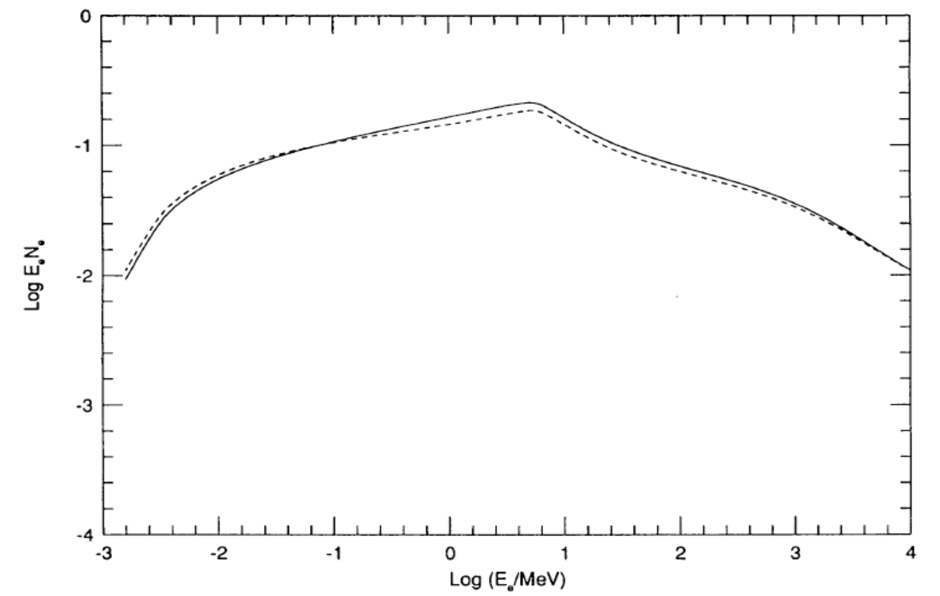


Pair cascades in AGN



Blandford & Levinson 1995

Levinson & Blandford 1995



- Electrons are accelerated over the length of the jet.
- X-ray photons provide opacity for photon-photon pair production.
- γ-sphere grows with photon energy.
- Higher energy γ-rays escape from larger distances and are less variable.
- Produces too many X-rays?

Self-supporting cascades

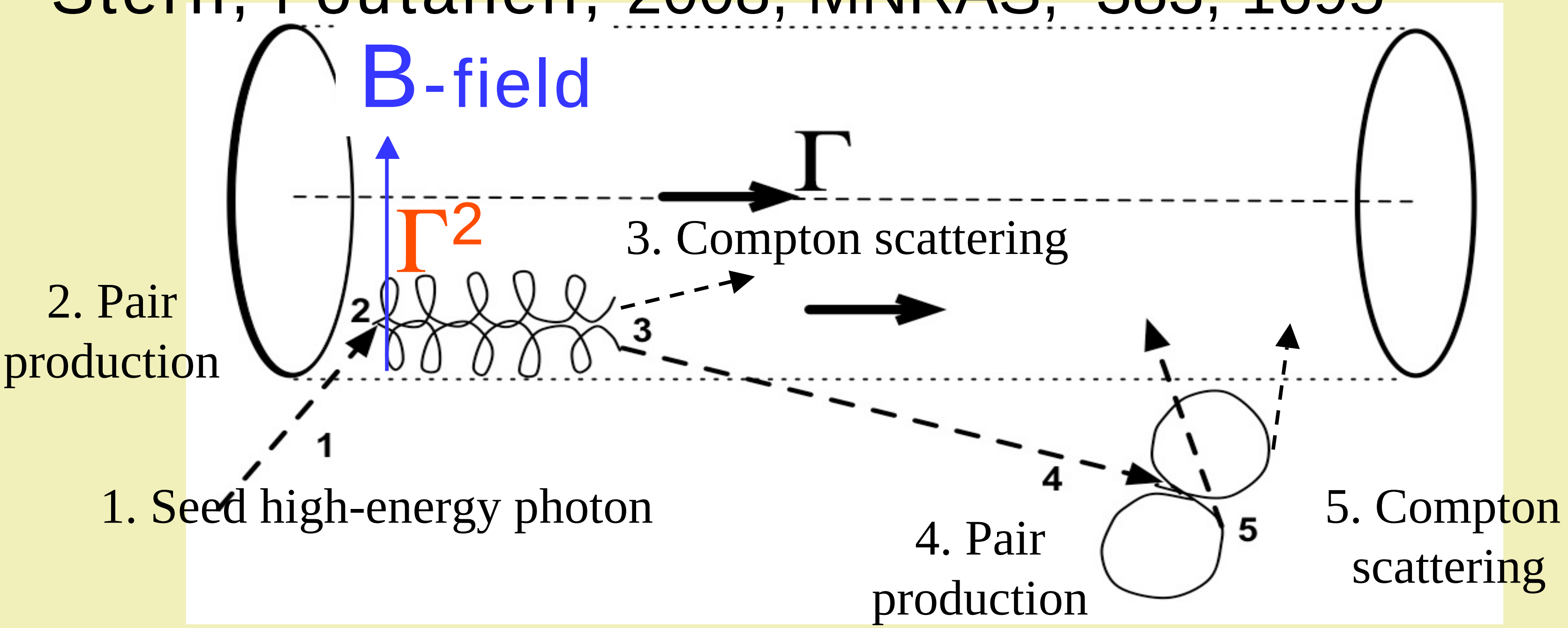
- All models assume ad hoc particle injection/acceleration.
- Too many parameters make prediction almost impossible.
- Most of the models consider no feedback from the external environment (except of the injection of external soft photons).

- The interaction between the jet and the external medium might be important and can produce strongly non-linear effects.

Photon breeding mechanism

Stern, Poutanen, 2006, MNRAS, 372, 1217

Stern, Poutanen, 2008, MNRAS, 383, 1695



B-field

Γ

Γ^2

1. Seed high-energy photon

2. Pair production

3. Compton scattering

4. Pair production

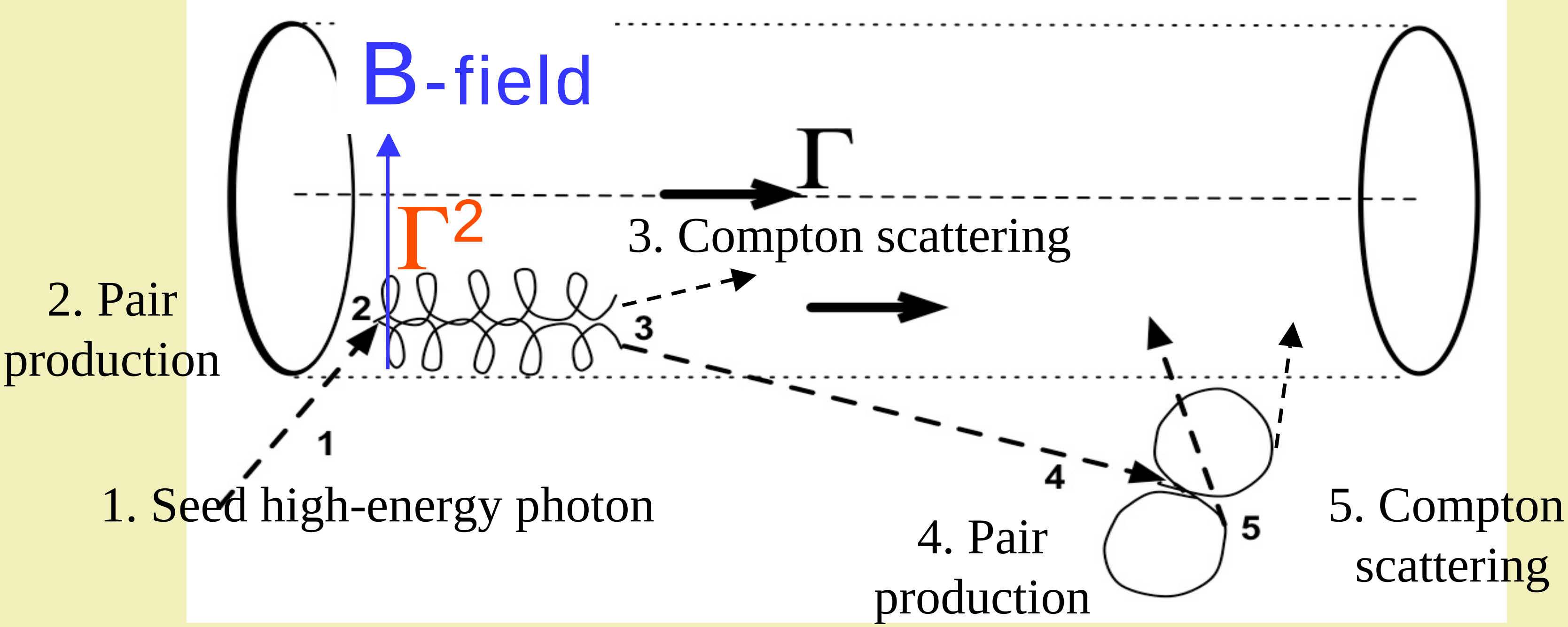
5. Compton scattering

The mechanism is supercritical if the total amplification factor through all the steps is larger than unity:

$$A = C_1 C_2 C_3 C_4 C_5 > 1$$

where C_n denote the energy transmission coefficient for a given step.

Photon breeding mechanism



Requirements

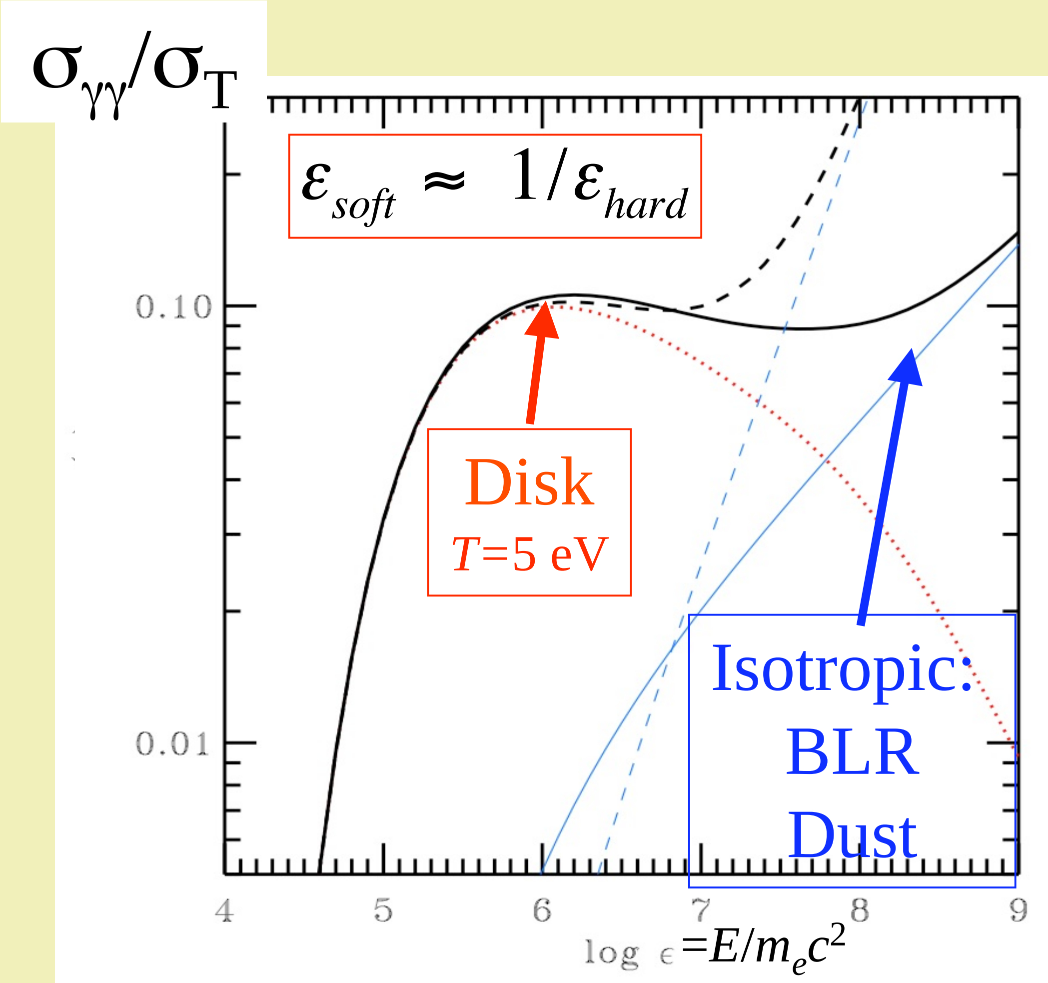
1. Some seed high-energy photons
2. Transversal or chaotic B-field
3. Isotropic radiation field (broad emission line region at 10^{17} cm)
4. Jet Lorentz factor $\Gamma \geq 4$

   (more realistically $\Gamma \geq 10$).

Opacities in AGN jets

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

$$\tau_{\gamma\gamma}(\varepsilon) = n_{ph}\sigma_{\gamma\gamma}R\theta_{\rm jet} = 60\ \frac{L_{\rm disk,45}}{R_{17}}(10\theta_{\rm jet})$$



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

$\gamma_{\rm min} \approx 10^5$ -mirrors the disk spectrum, $\gamma_{\rm max} \approx 10^8$ -depends on the magnetic field and the soft photon field.

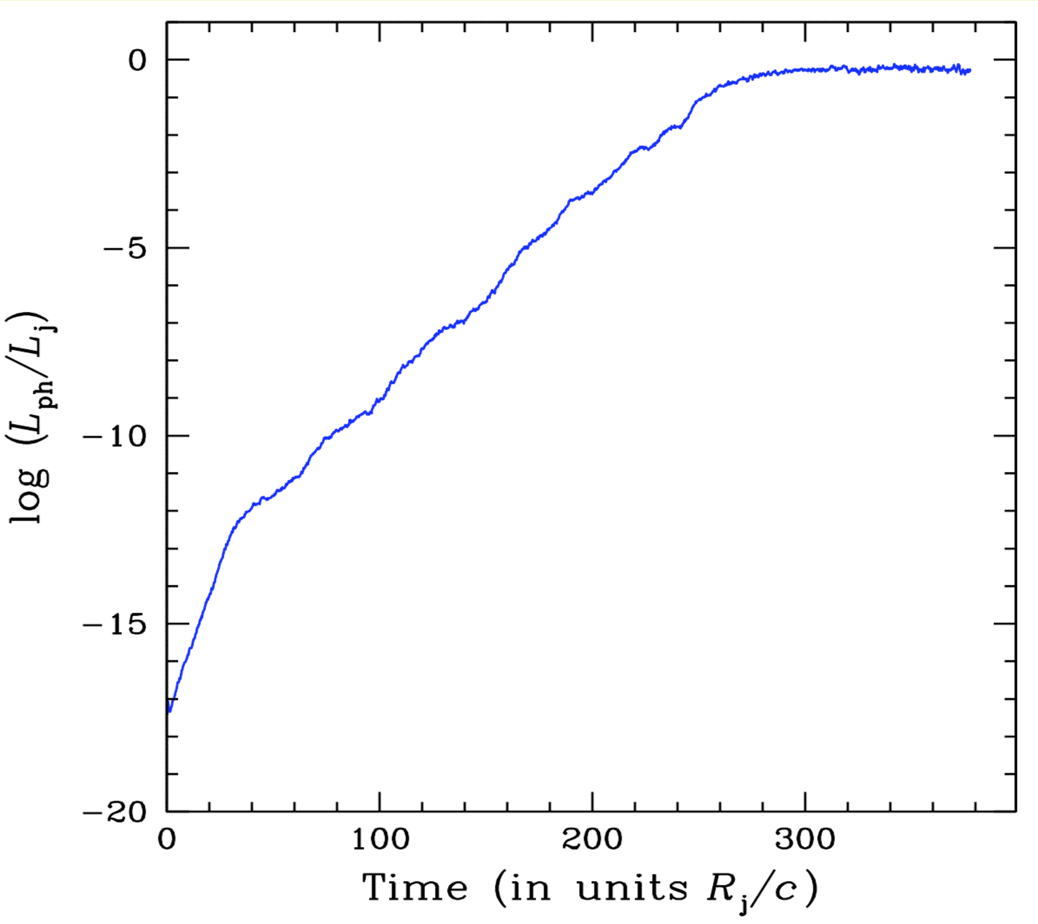
Gamma-ray emission sites

- 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 $\Gamma \geq 10$).

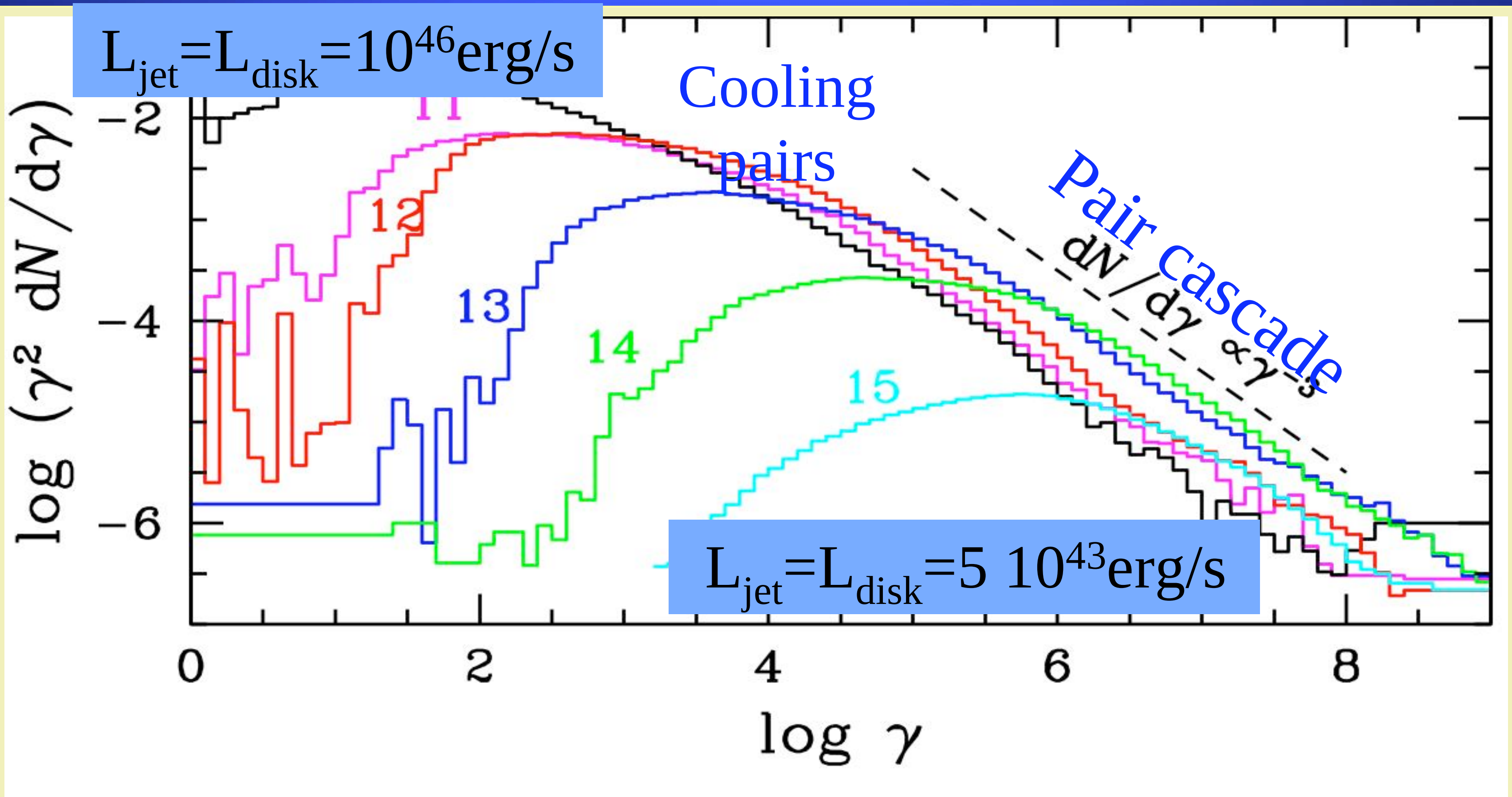
Origin of seed high-energy photons

- Particle acceleration in shocks, shear layers?
- Secondary particles from cosmic ray interaction?
- Gamma-ray background?



Let us start from the extragalactic gamma-ray background observed at Earth. Photon breeding increases energy density of high-energy photons by 20 orders of magnitude in 3 years.

Electron distribution (in the jet)



$L_{jet}=L_{disk}=10^{46}$erg/s

Cooling pairs

Pair cascade

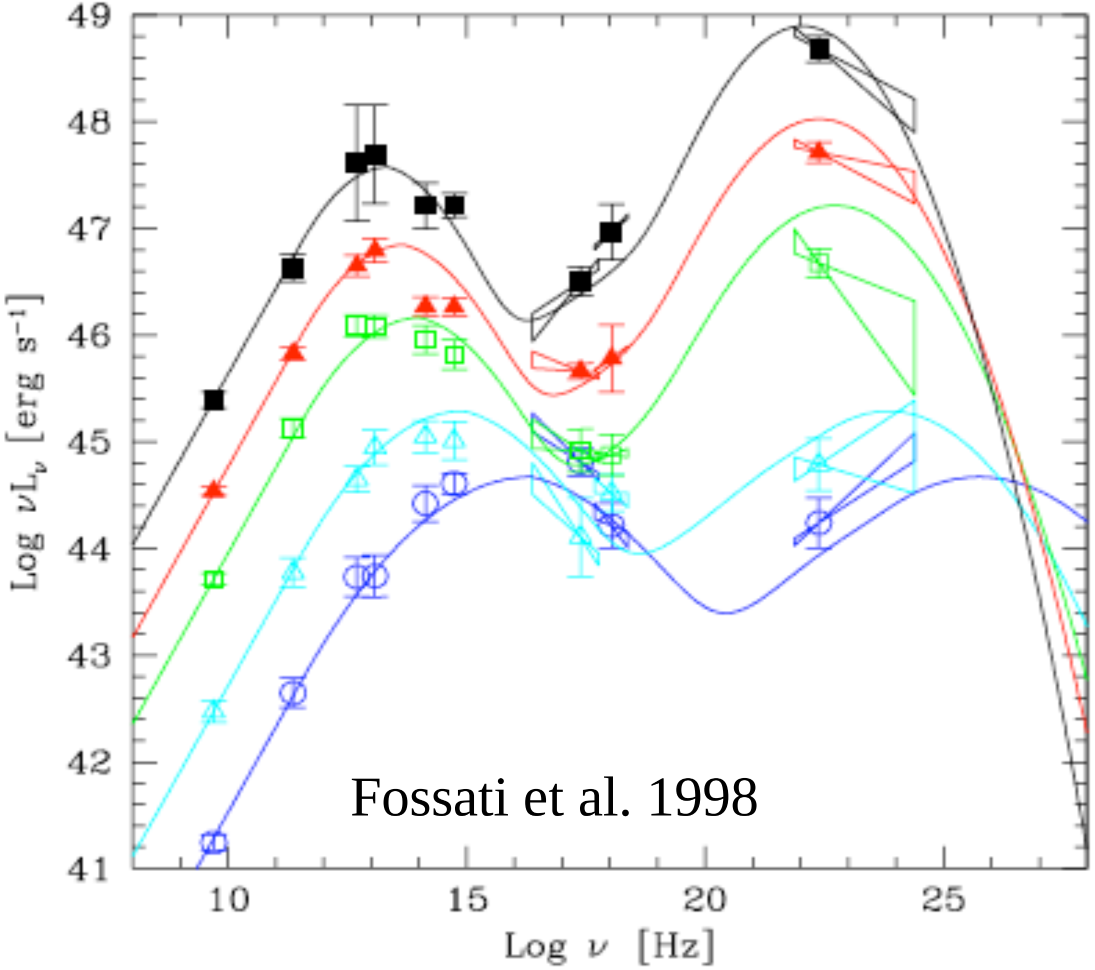
$L_{jet}=L_{disk}=5\ 10^{43}$erg/s

Photon breeding: electrons are “injected” at $\gamma>10^5$

Observations: the electron “injection” peaks between $\gamma_{min}=10^4$-10^5 and $\gamma_{max}=10^6$-10^7 in low-luminosity objects (Ghisellini et al. 2002, Krawczynski et al. 2002, Konopelko et al. 2003, Giebels et al. 2007).

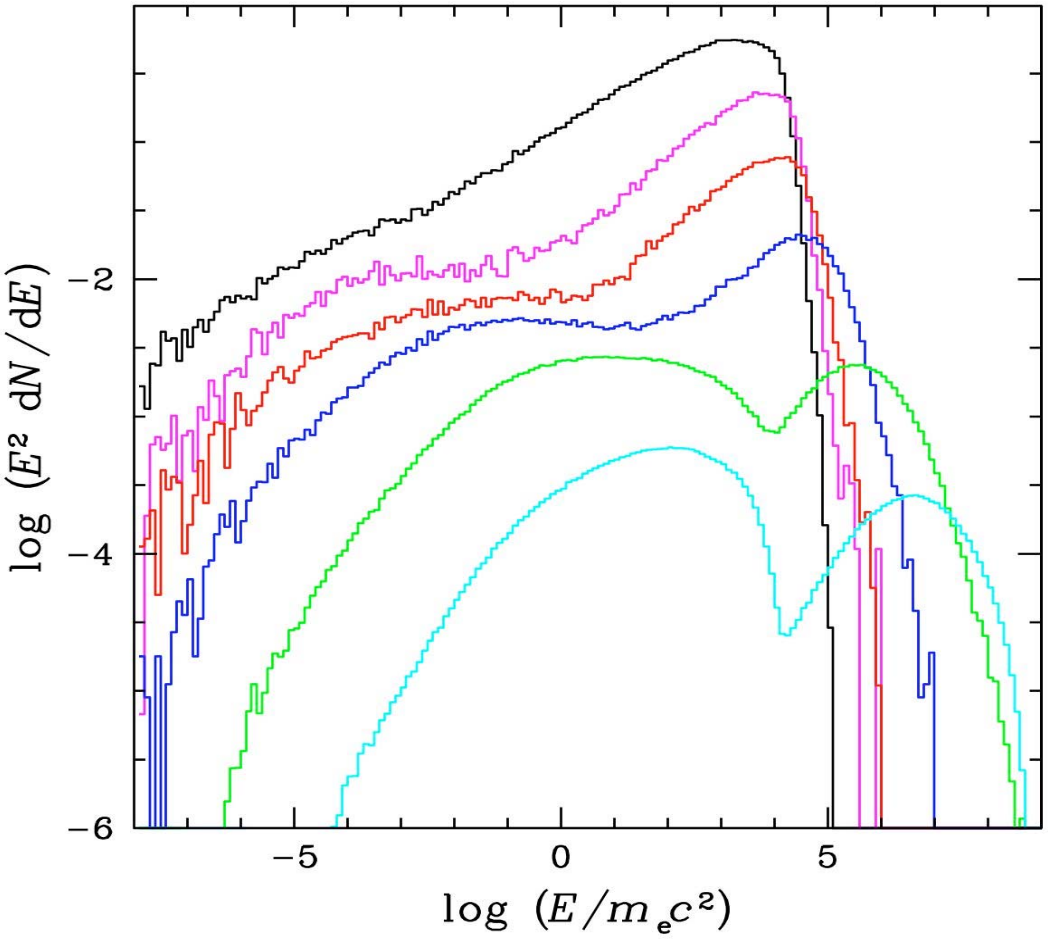
Blazar sequence

Observed



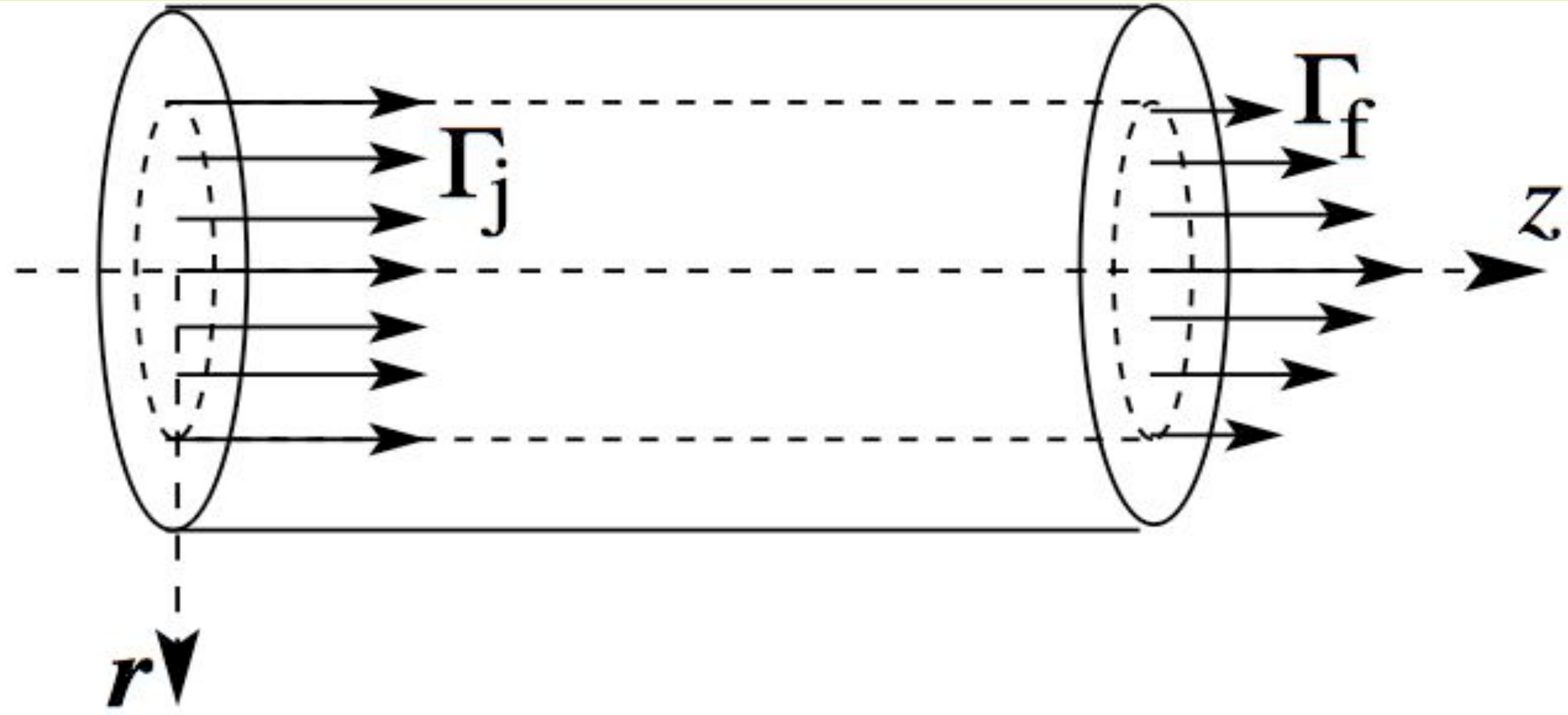
Fossati et al. 1998

Modeled



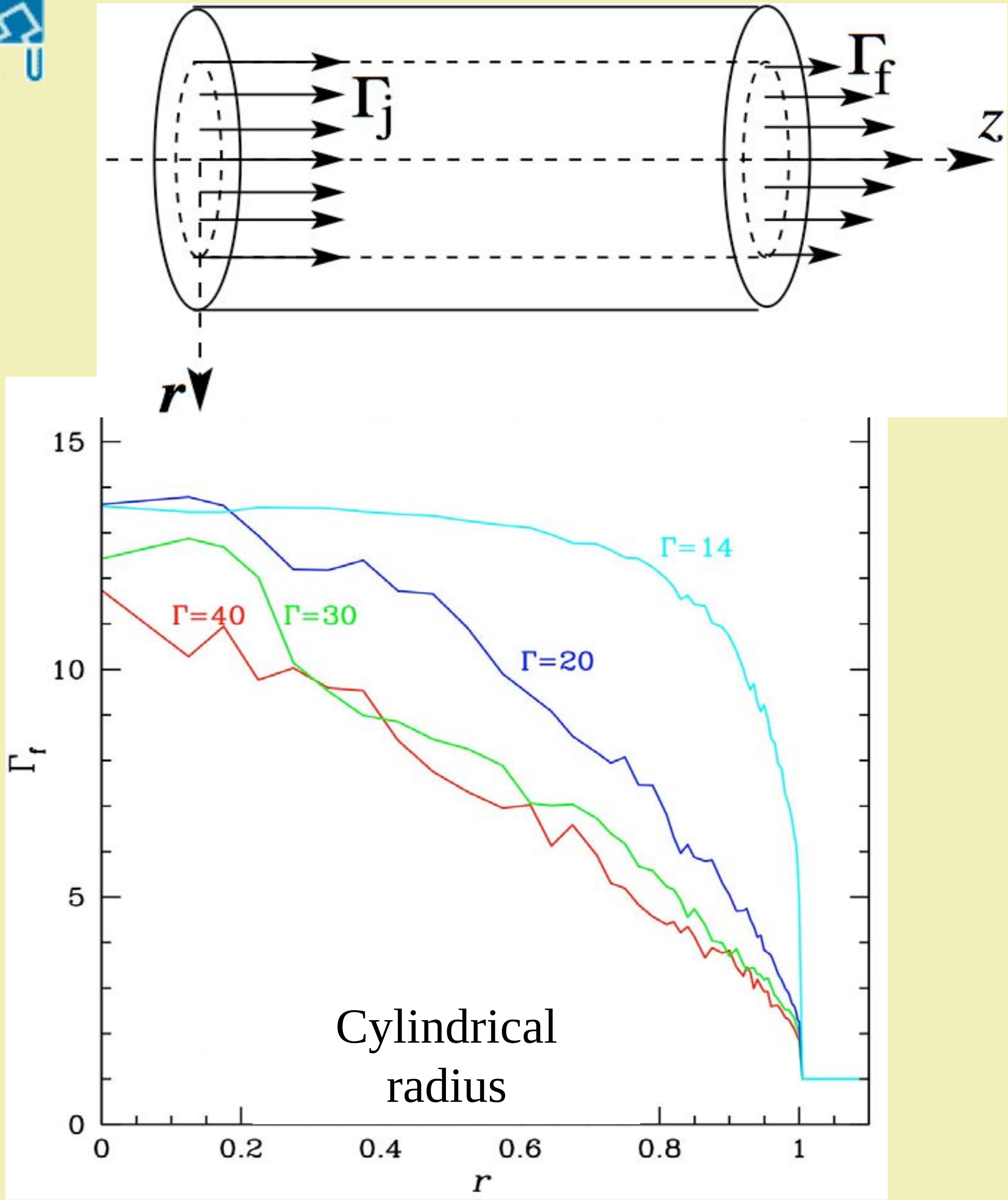
Low-energy component in high-luminosity sources might be produced at larger distances.

Decelerating & structured jet



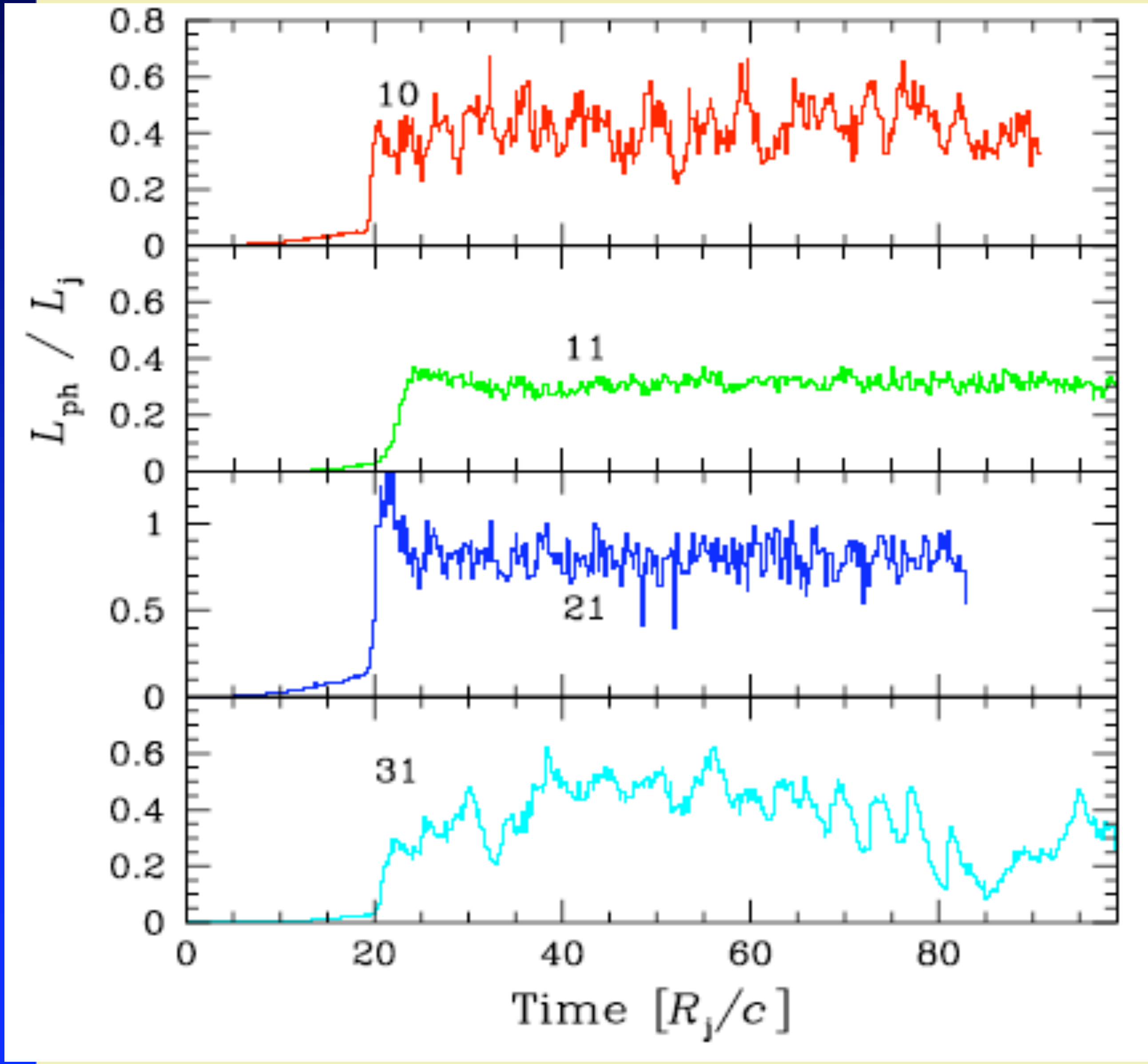
1. Photon breeding provides friction between the jet and the external medium.
2. Produces a decelerating and “structured” jet.

Terminal jet Lorentz factor



1. Terminal Lorentz factor is smaller for larger initial Γ_j
2. High radiative efficiency 10-80%.
3. Gradient of Γ implies broad emission pattern.
4. Predicts high gamma-luminosity in radio galaxies (e.g. M87).
5. Solves the Doppler factor-crisis.

Temporal variability



The system is super-critical.

Shows chaotic behaviour.

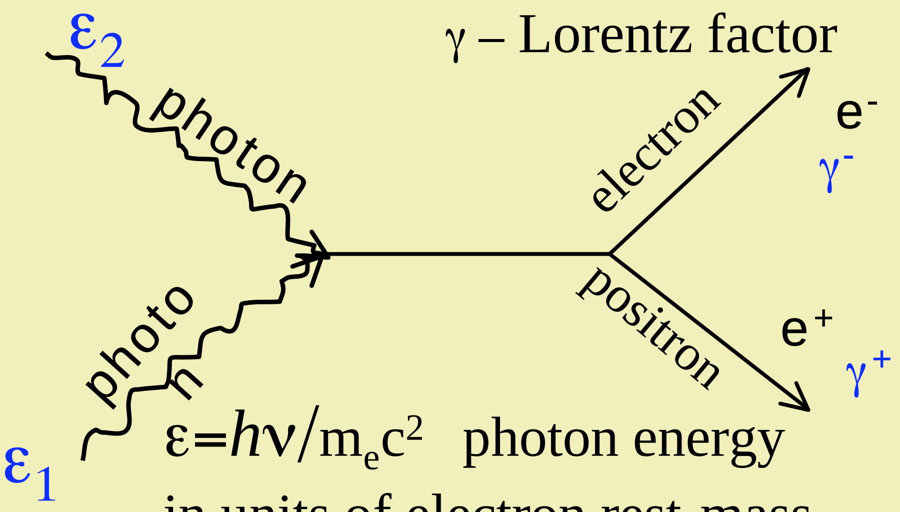
Flux doubling at time-scales $< R_j/c\Gamma^2$.

Conclusions

- Copious production of pairs seem to be unavoidable in relativistic jets
- Photon breeding

1. is based on well-known physics
2. is the self-consistent mechanism for acceleration of high-energy electrons (pairs)
3. has high radiative efficiency
4. shows fast variability and chaotic behaviour
5. produces decelerating, structured jet with a broad emission pattern. Predicts strong GeV-TeV emission for off-axis objects (radio galaxies)
6. is very promising in explaining high luminosities of relativistic jets in quasars

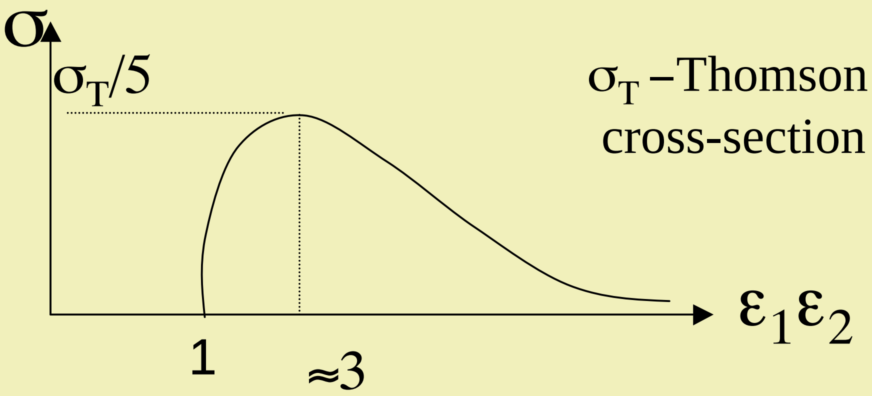
Photon-photon pair production



γ – Lorentz factor

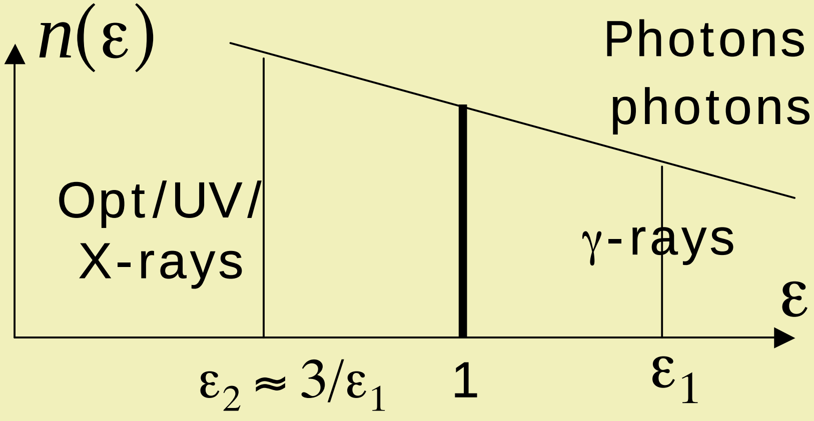
$\varepsilon = h\nu / m_e c^2$ photon energy in units of electron rest-mass

Cross-section for pair production



σ_T –Thomson cross-section

PAIR PRODUCTION in a power-law radiation field



Photons at ε_1 interact mainly with target photons just above threshold at $\varepsilon_2 \approx 2/\varepsilon_1$

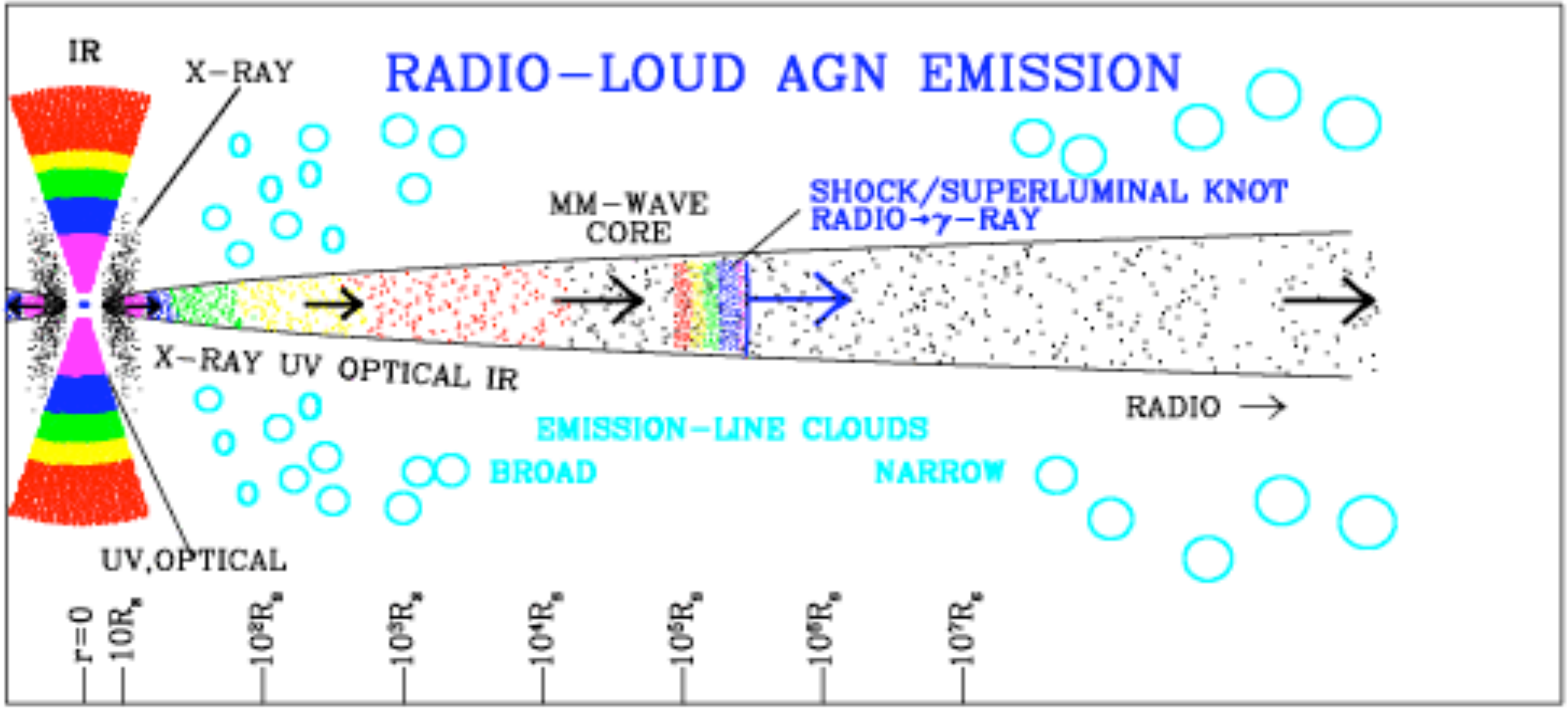
Produced pairs

Energy conservation $\gamma^+ + \gamma^- = \varepsilon_2 + \varepsilon_1 \approx \varepsilon_1$

As $\gamma^+ \approx \gamma^- \Rightarrow \gamma^+ \approx \gamma^- \approx \varepsilon_1/2$

Each particle has approximately half of the hard photon energy.

Model for a quasar



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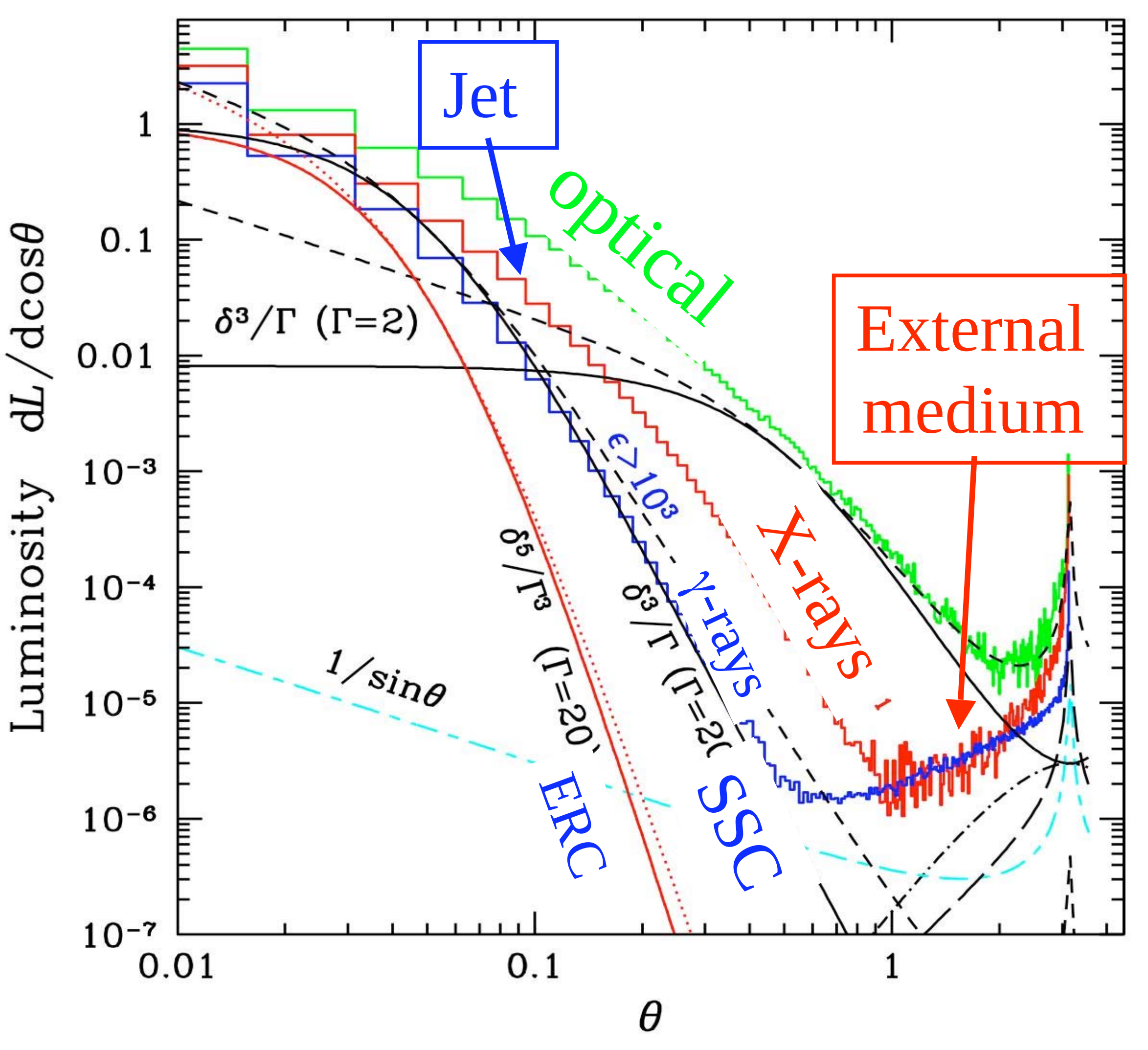
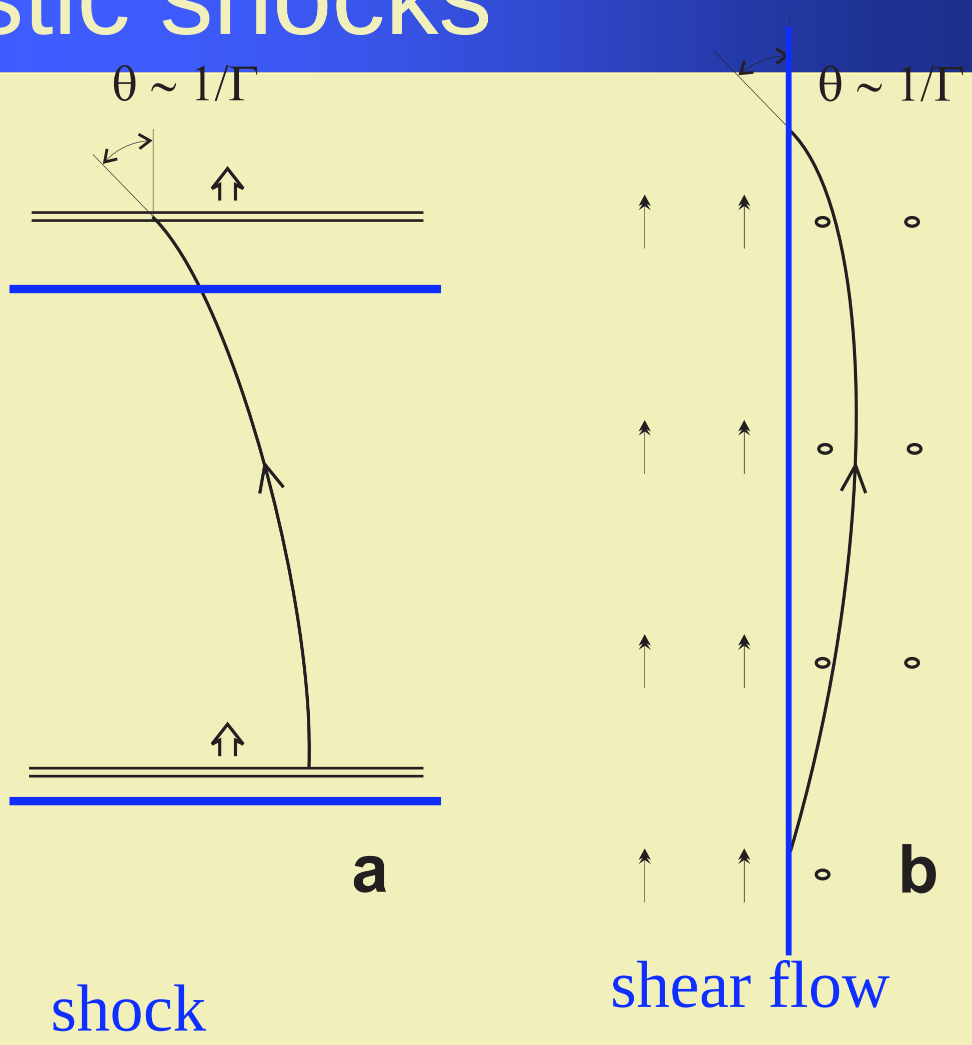
Angular distribution of radiation from the decelerating structured jet



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.

Fermi I acceleration in relativistic shocks

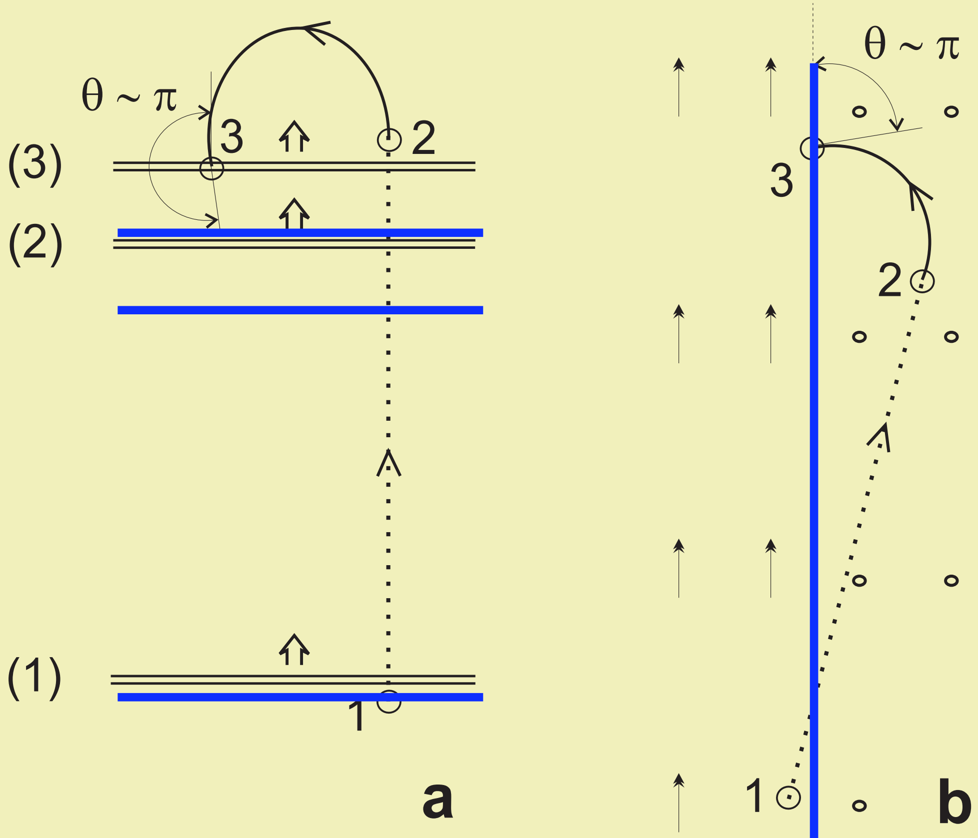
- Relativistic shock with Lorentz factor Γ
- Particles crossing the shock can, in principle, gain Γ^2 in energy for every cycle.
- However, since shock is relativistic, for already a very small deflection angle $\theta \sim 1/\Gamma$, the shock catches up the particle.
- Thus, the gain is only factor of 2.
- Injection problem



Conversion mechanism

Discovered independently by Boris E. Stern (astro-ph/0301384), MNRAS, 345, 590 (2003) and Derishev E. et al. (astro-ph/0301263), Phys. Rev. D 68, 043003 (2003)

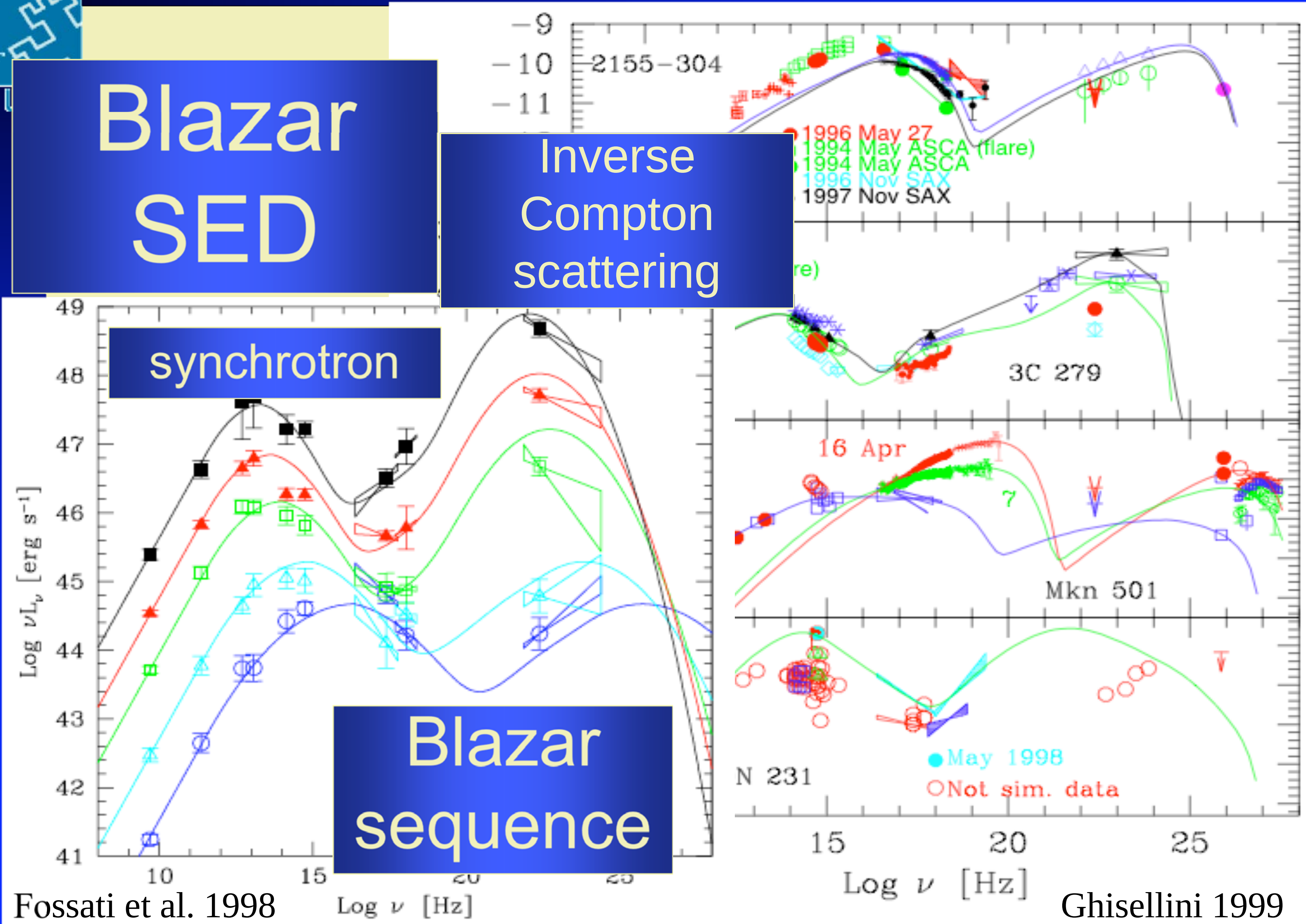
- Instead of charged particles, energy is transported through the shock by neutral particles, e.g. photons.
- A hard photon is born downstream (1). Then it is converted in the upstream region to an e^{+-} pair (2) (by $\gamma\gamma$ interaction with a soft photon).
- Pair turns around (3) and is advected back to the downstream flow where it Comptonizes a soft photon and produces another hard photon (1), thus closing the cycle.



shock

shear flow

Blazar SED



Inverse Compton scattering

synchrotron

Blazar sequence

Fossati et al. 1998

Ghisellini 1999