Emission modelling with stratified jets

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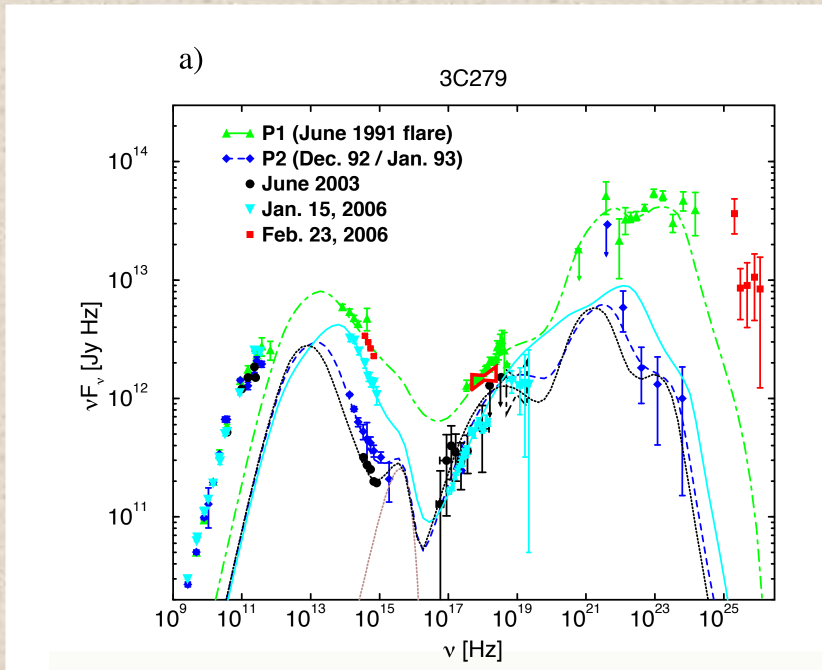
Why stratified jets ?

Non-thermal emission of jets most simply and usally reproduced by one-zone models, assuming a ~ spherical homogeneous emission zone



However, difficulties arise to reproduce correctly :

- Low energy part of the spectrum (opacity effects)
- Non simultaneous variability

No real dynamical model behind the model
-> what do we learn when we fit data ?

Böttcher 2010

From 0-D to N-D

One zone models require a small number of parameters (radius, B field, Lorentz factor …)

Complexity of spectra usually reproduced thanks to *ad hoc* particle energy distribution

- Power law : most often one is not enough -> broken power laws
- More sophisticated PED through acceleration/cooling mechanisms (Fokker-Planck equation)
- Needs also a prescription of ambient photon fields

Stratified models must also specify a full distribution of parameters

- 1 D : B(z), R(z), n(z)…
- 2 D : B(r,z) , n(r,z)
- Full 3D models (numerical simulations)

Complexity reduced by adopting simple ansatz : power-laws ….

Can fit complex spectra with relatively simple particle energy distribution functions.

Not really a new idea !

RELATIVISTIC JETS AS X-RAY AND GAMMA-RAY SOURCES[1]

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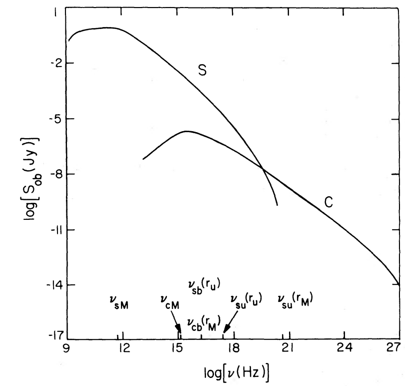

FIG. 2.—The synchrotron and inverse-Compton spectra for an unresolved inhomogeneous jet. This example corresponds to a relativistic conical jet with $D_{19} = 0.5$, $\mathscr{D}_j = \gamma_j = \csc\theta = 5$, $\varphi = 0.1$, and a synchrotron spectrum with $\nu_{sm}(r_u) = 10^9$ Hz, $\nu_{sM} = 5 \times 10^{11}$ Hz, $S_{ob\,s}(\nu_{sM}) = 1.0$ Jy, $\alpha_0 = 0.5$, $\alpha_{s1} = 0$, and $\alpha_{s2} = 0.8$. (All the quantities referred to in the legend or marked in the figure are defined in the text.) Using these observable parameters in eqs. (5), (6), and (12), one obtains $m = 1.25$, $n = 1.65$, $K_1 = 1.7 \times 10^2$ cm^{-3}, $B_1 = 2.9 \times 10^{-2}$G, $r_M = 2.3 \times 10^{-2}$ pc, and $r_u/r_M = 3.7 \times 10^2$. These values, as well as $\gamma_{el} = 50$ and $\gamma_{eu} = 5 \times 10^6$, were used in eqs. (2), (7), (9), and (11) to generate the synchrotron spectrum (labeled S) and the once-scattered inverse-Compton spectrum (labeled C) which are shown here. Note that in this example $\alpha_{s3} = 1.28$, $\alpha_{c1} = 0.62$, and $\alpha_{c2} = 0.75$. The local emission spectra in this jet at a distance of 1 pc from the origin are displayed in Fig. 1.

Inhomogeneous synchrotron-self-Compton models and the problem of relativistic beaming of BL Lac objects

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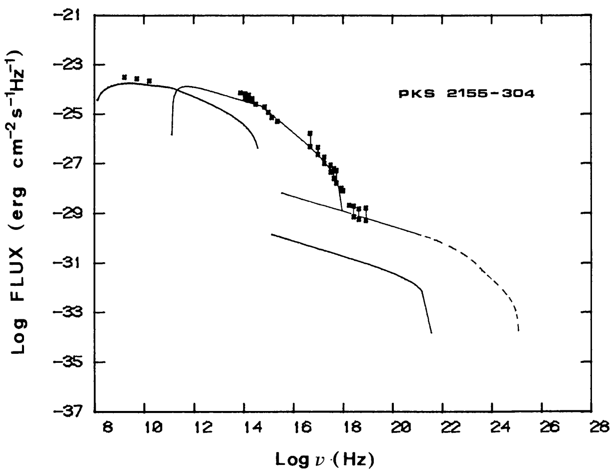


Fig. 4. Observations and calculated spectrum of PKS 2155–304. Data from Maraschi et al. (1983) and references therein. The curve fitting the radio data is synchrotron radiation from the external cone. The IR to soft X-ray flux derives from synchrotron radiation of a paraboloid. At higher energies the self-Compton contribution from the two regions are shown (paraboloid: upper curve, cone: lower curve). The dashed line represent the spectral region which may be affected by photon-photon interaction. The used parameters are specified in Table 3

The « Two flow » model

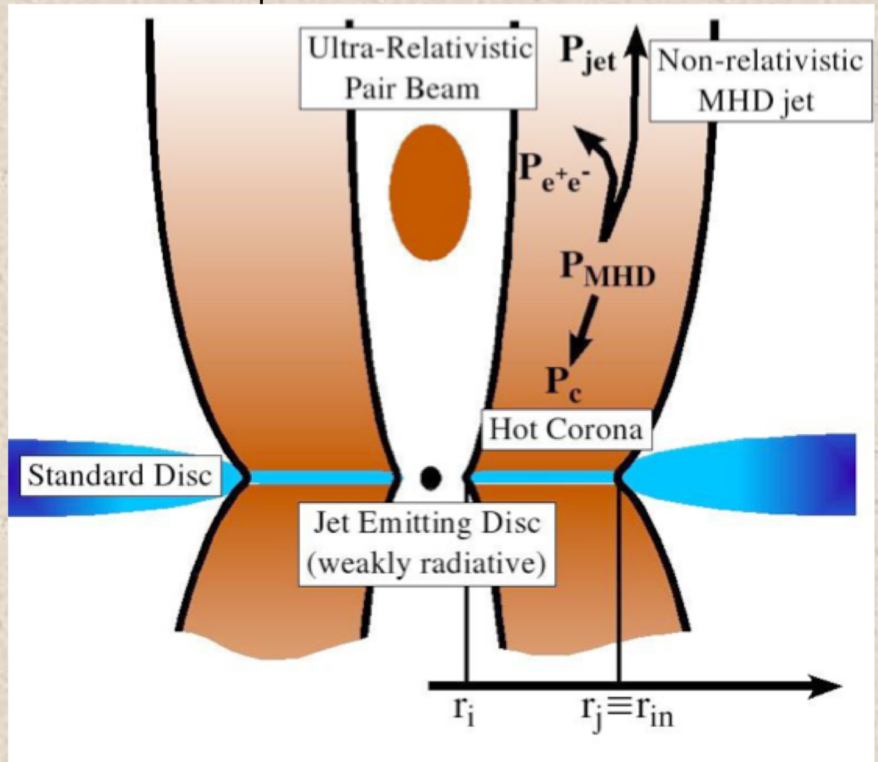
Two flow model : 2 distinct flows (Sol, Pelletier, Asséo '85, H. & Pelletier '91), introduced first for explaining radio observations.
Now more commonly referred as « spine in jet » models !

1st flow : MHD jet e^- p+ mildly relativistic (BP type)
*carries most of the power
*fuelled by accretion disk
*large scale structures, hotspots

+

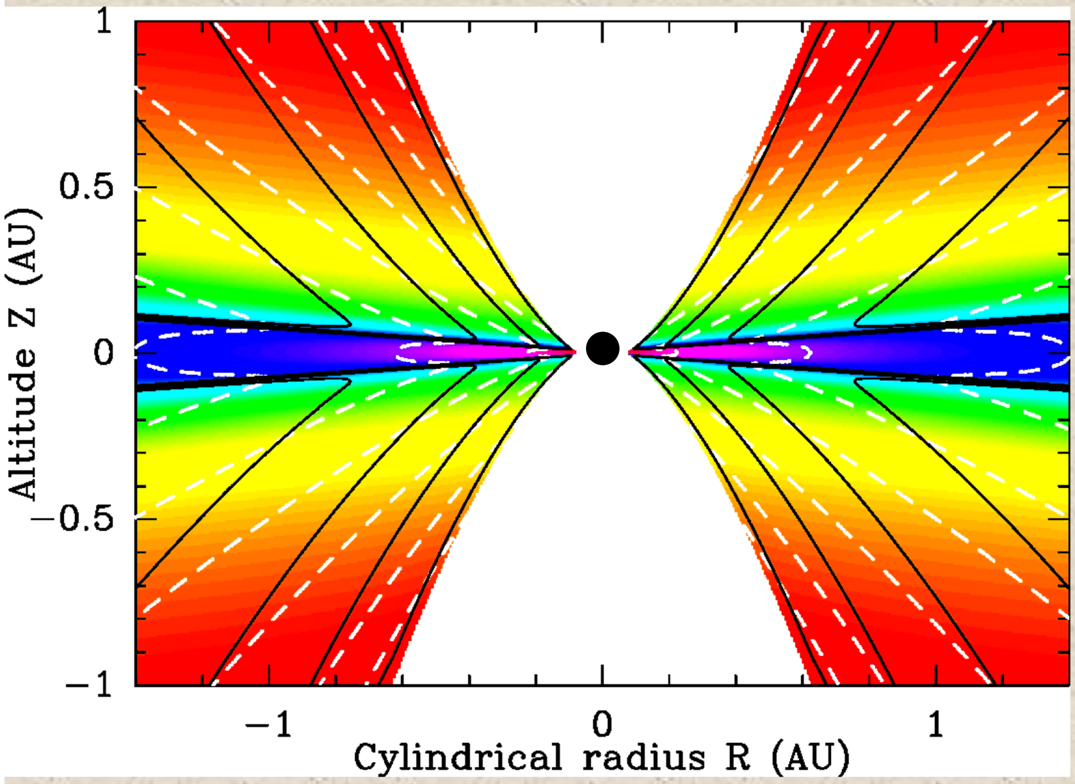
2^{nd} flow :Ultra relativistic e^+-e^-pair plasma

* Generated in the « empty » funnel (no baryon load).
* Produces high energy photons and relativistic motions
* Energetically minor component
* Confined by external MHD flow



The « slow » MHD component

Baryonic jet can be emitted from the accretion disk through MHD mechanism (a la Blandford-Payne) (Ferreira et al., '97, '04)



B field extract angular momentum and power from the JED (Jet Emitting Disk)
Disk can be weakly radiative (like ADAF)

Jet only mildly relativistic under self consistent accretion-ejection conditions
$\mu = p_B/(p_g+p_{rad}) \sim 0.1$ to 1

NB :curvature of B field lines can be achieved because
$v_r/v_{Kepl} \sim h/r$

(SS disk : $v_r/v_{Kepl} = (h/r)^2$)

Formation of the « fast » pair plasma

In situ generation of pair plasma in the MHD funnel (H.& Pelletier 91, Marcowith et al. '95)

Produced through gamma-ray emission

- Injection of some relativistic particles
- X-ray and gamma-ray emission by IC and/or SSC
- γ–γ annihilation forms new pairs
- Continuous reacceleration by MHD turbulence necessary for a pair runaway to develop.
- Limited by the free energy available: saturation must occur at some point.

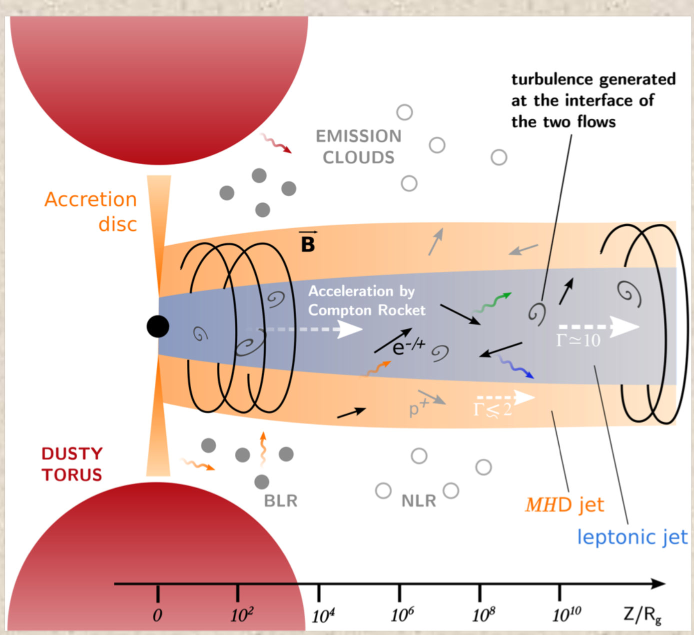


Fig. 1. Schematic view of the model developed in the two-flow paradigm.

Vuillaume et al. 2018

Simulation of spectra :Recipe for a stratified (possibly variable) jet

To describe a continuous jet, one needs

1) A geometry R(z,t) -> parametrized

2) A B-field distribution B(z,t) -> parametrized

3) A Lorentz factor distribution $\Gamma_b(z,t)$ -> deduced from anisotropic Compton equilibrium velocity, or parametrized

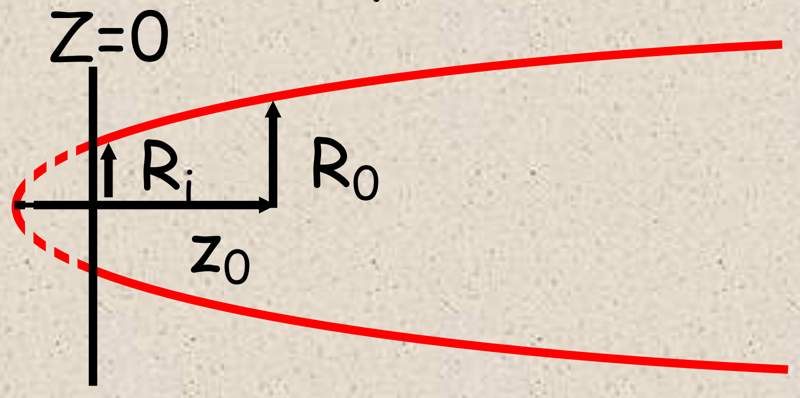
4) A Particle distribution $n(\gamma,z,t)$ -> computed from parametrized acceleration rate and cooling processes, assuming a quasi-Maxwellian shape

Jet geometry

Determined by MHD solutions (inner funnel)

Parametrized by a « shifted » power-law

$$R(z) = R_0 \left[\frac{Z}{Z_0} + \left(\frac{R_i}{R_0} \right)^{1/\omega} \right]^{\omega}$$



Conservation of poloidal flux Bp α $R(z)^{-2}$
Conservation of current Bφ α $R(z)^{-1}$ ∝

Assuming some interconversion process

$$B(z) = B_0 \left[\frac{R(z)}{R_0} \right]^{-\lambda}$$

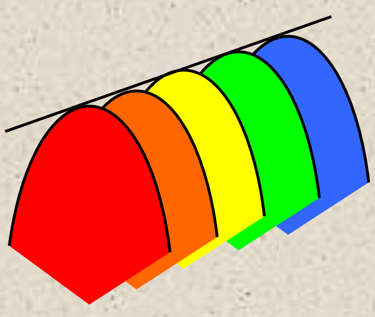
$1 < \lambda < 2$

Particle energy distribution

Acceleration processes can produce power-law (shock accel.) or quasi-Maxwellian, « pile-up » distributions

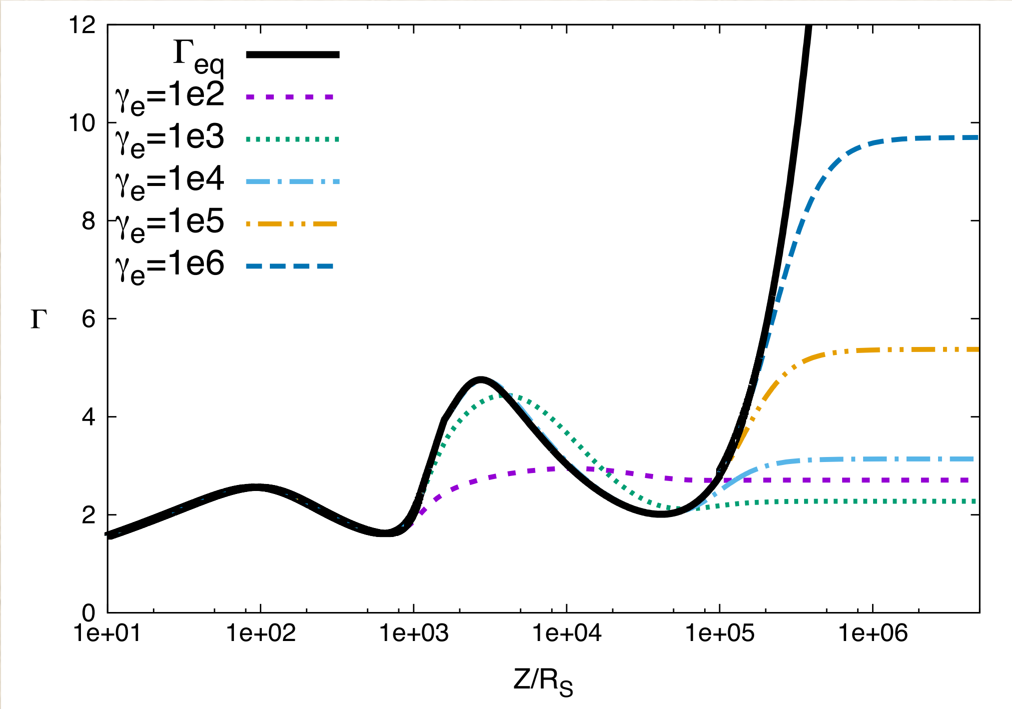
$$n(\gamma;z;t) = n_0(z;t)\gamma^2 \exp\left(-\frac{\gamma}{\gamma_0(z;t)}\right)$$

Apparent power-law can be reproduced by a spatial convolution of peaked functions (e.g. like a standard accretion « multicolor » disk model)



Seems more adapted for TeV blazars with peaked γ-ray emission
NB : the exact shape of the distribution is not very important as long as it is a good representation of a Dirac-distribution.

Bulk Lorentz factor



Controlled by soft photon field anisotropy for an e+e- plasma

Final Lorentz factor depends on local acceleration process

Evolution of particle distribution along the jet

Reacceleration necessary (short cooling time)

Relativistic temperature γ_0 evolves following acceleration vs cooling

$$\frac{d\gamma_0}{d\tau} = Q_{acc} - P_{sync} - P_{IC}$$

Acceleration rate is assumed to follow a power-law with a spatial damping

$$Q_{acc} = Q_0 \left(\frac{z}{z_0}\right)^{-\eta} \exp(-\frac{z}{z_c})$$

Evolution of particle density

Computation of radiative processes :
- Synchrotron
- Synchrotron Self-Compton
- External Compton : accretion disk, BLR, IR- torus
- Anisotropy taken into account
- Pair production and annihilation

Freshly produced pairs are assumed to be instantaneously reaccelerated and reinjected in the relativistic distribution.

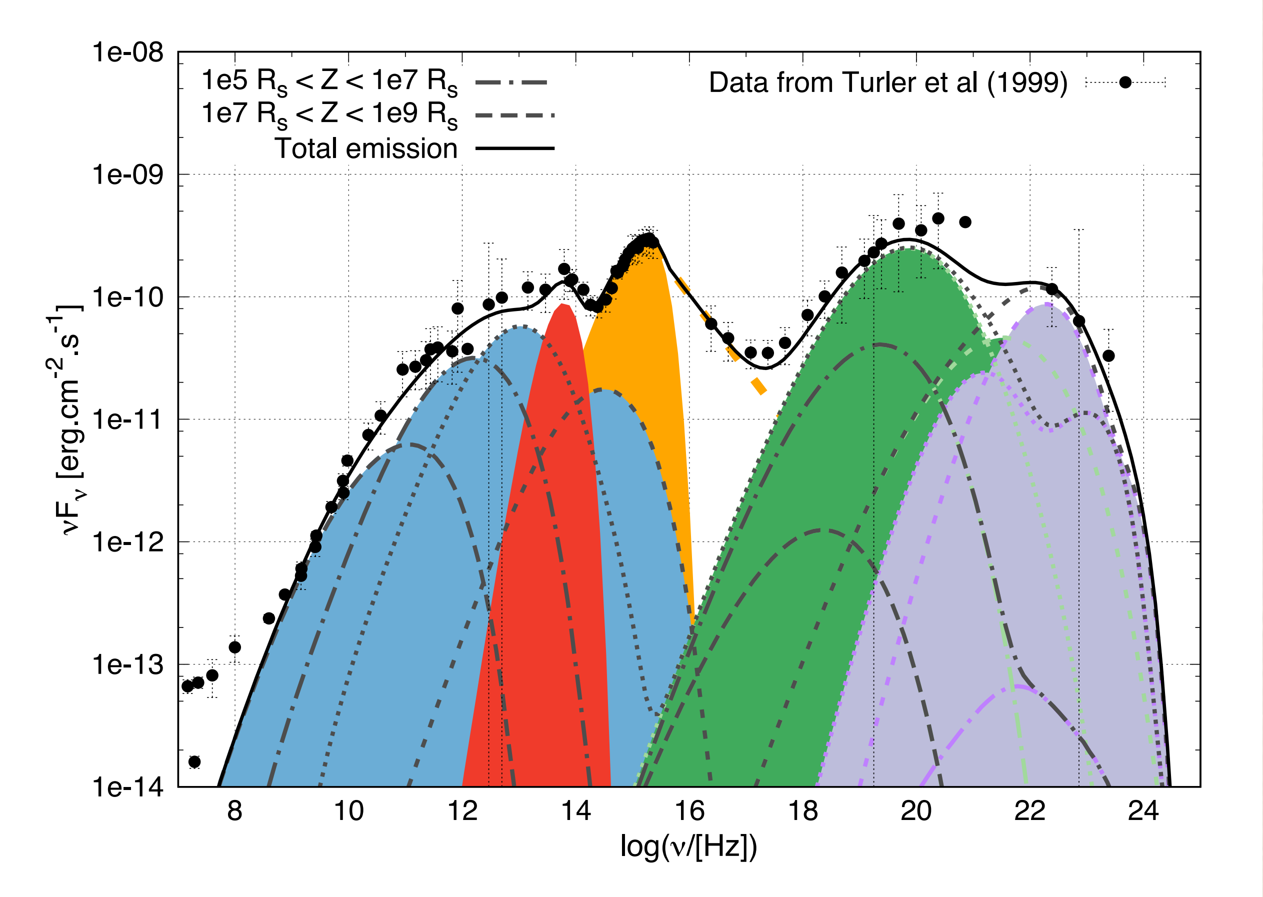
Needs an initial pair injection !

Construction of solutions

Physical parameters (densities, « thermal » Lorentz factors, luminosities) computed all along the jet

Depends on some initial conditions and distribution of physical parameters (especially the ill-known acceleration rate …) -> large set of possible solutions !

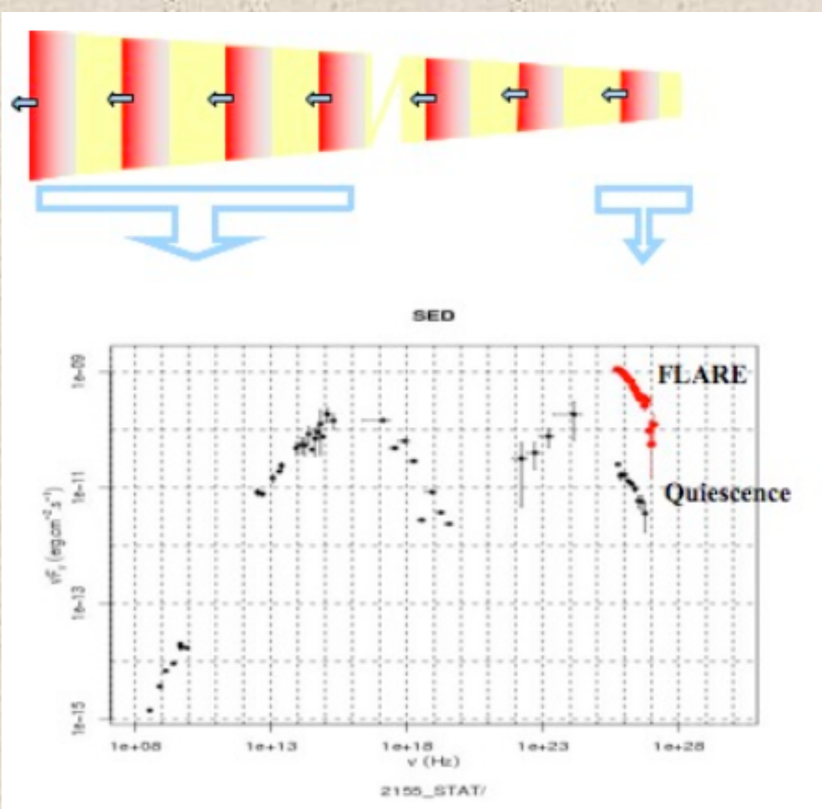
Example on 3C 273



Vuillaume et al. 2018

Time dependent solutions

Due to variability, instantaneous SED is a complicated convolution of the whole history of the jet, integrated all over the length.



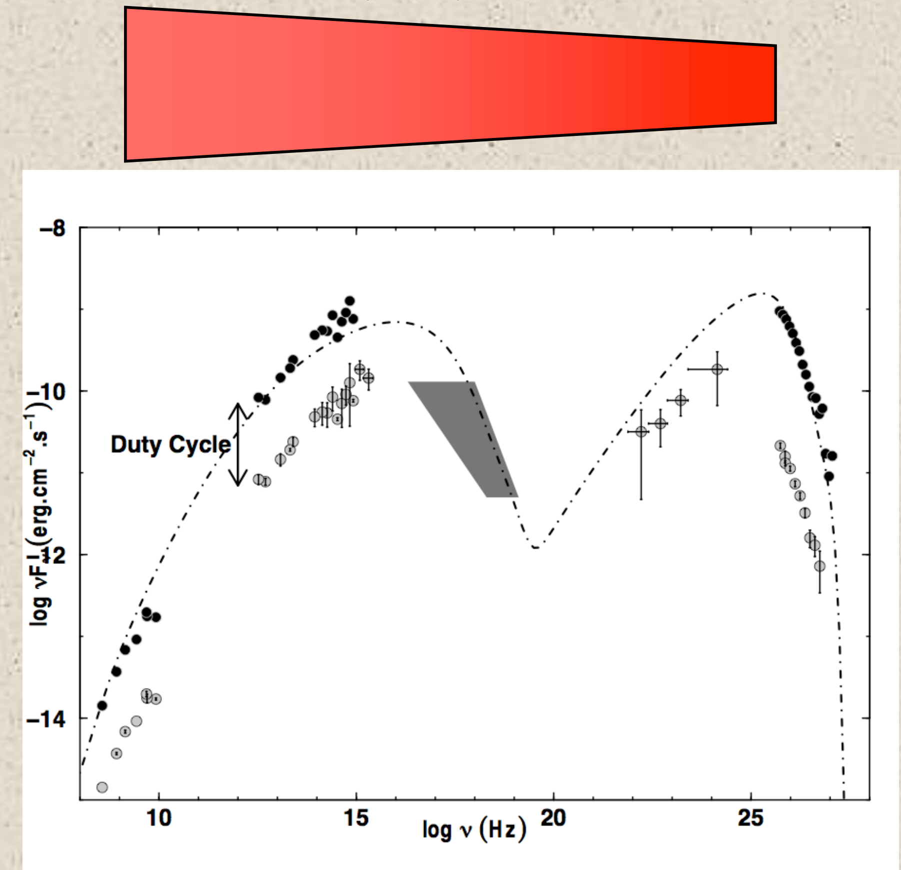
High energy data can be dominated by a single, or a few flares

Low energy data averaged over numerous flares, with a duty cycle *f*

Boutelier et al., 2008

Steady state solutions

Construction of a « fake constant flaring state » by multiplying low energy points by f^{-1} (estimated from flaring duty cycle)

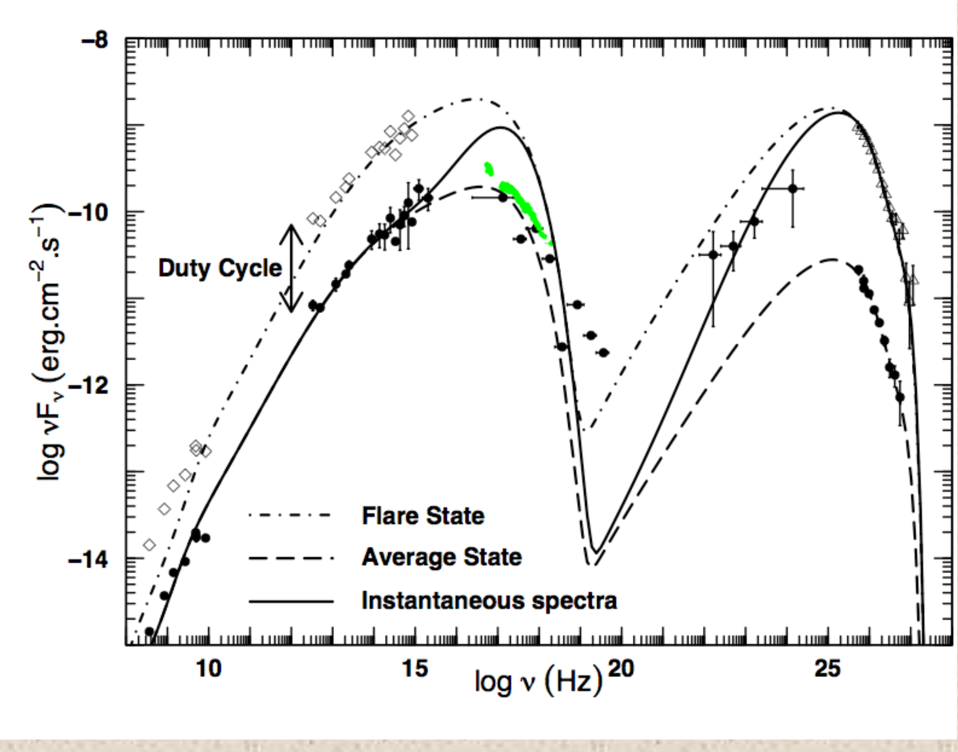


Time dependent solutions

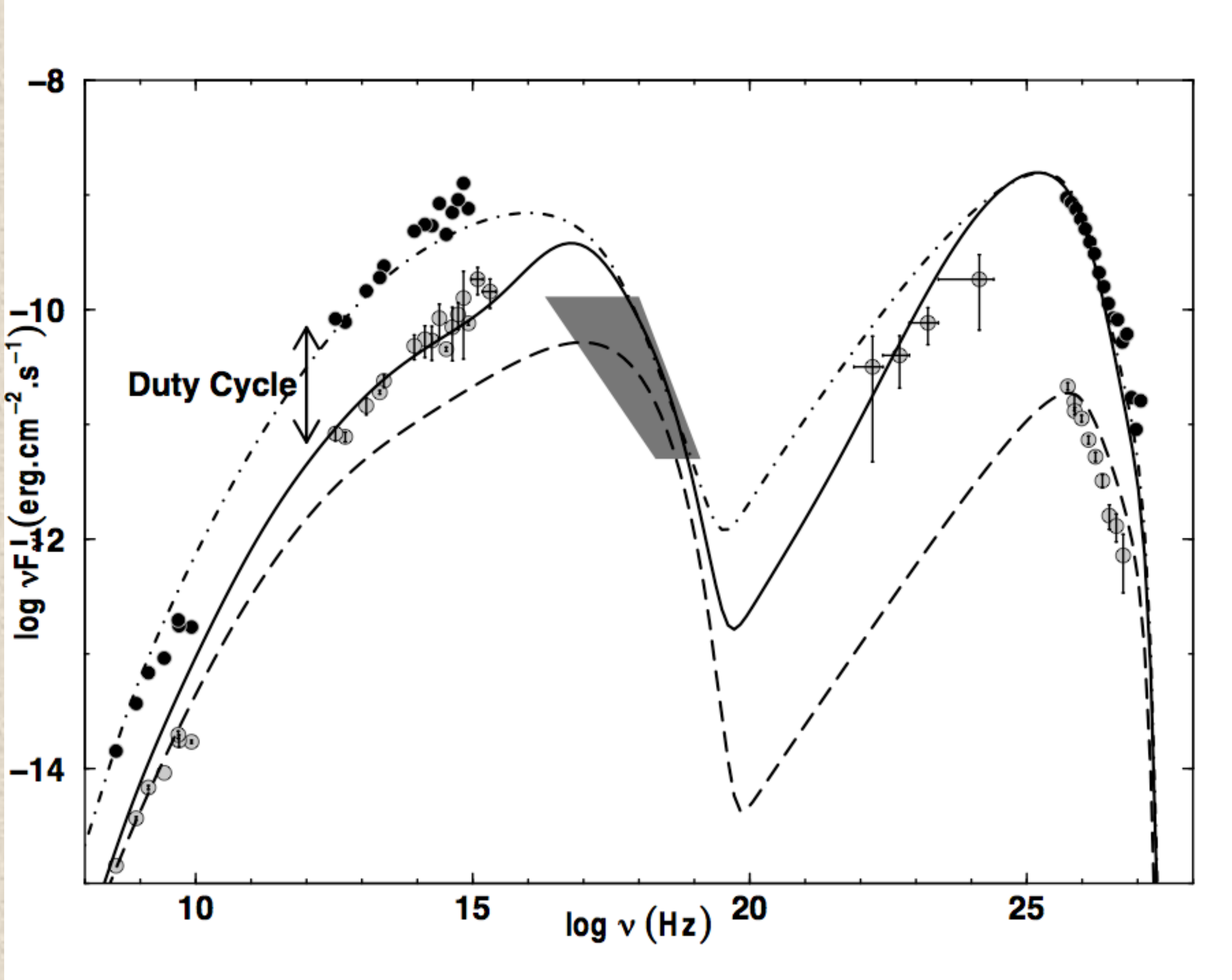
From a « fake flaring state, we can construct a set of theoretical «constant quiescent/intermediate » states (varying density and/or acceleration rate) .

•Prescribe a history of injections

•Add the retarded solutions at each altitude

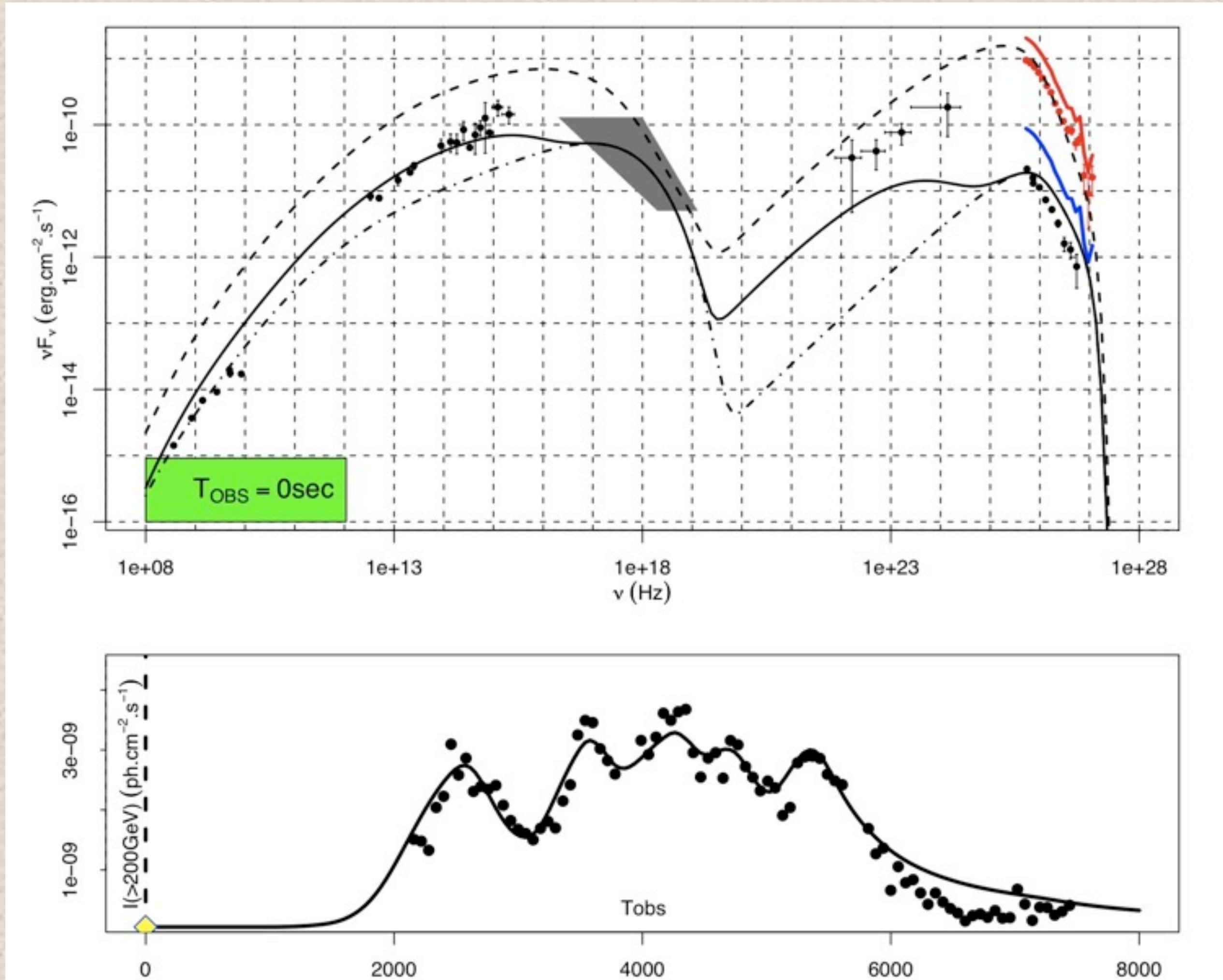


PKS 2155-304 flare



$\Gamma_{b\infty}$:15
cosi:1
R_i: 1.1e+14 cm
R_0: 1.78e+14 cm
Z_0: 2e+15 cm
Z_{max}: 5e+19 m
B_0: 5 G
Q_0: 6.5
$N_{tot}(z_0)$:
40 cm-3 (quiesc.)
600 cm-3 (flare)
ω: 0.2
λ : 1.9
ζ : 1.27

Evolution of the SED



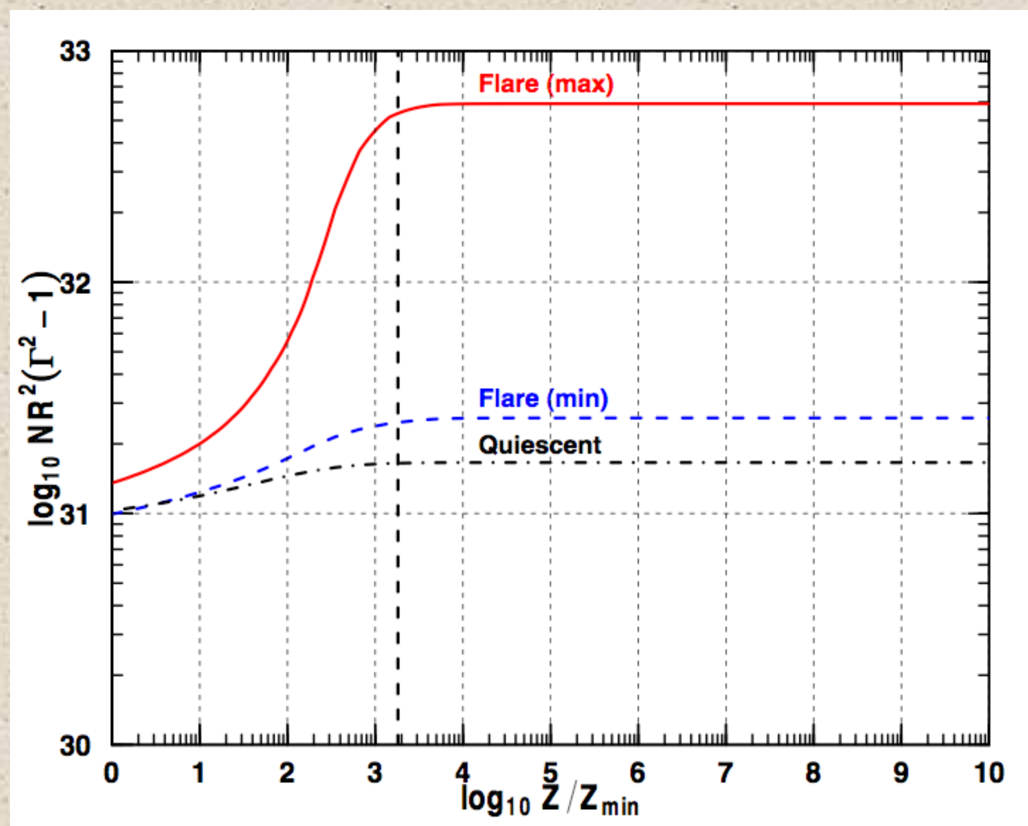
F(>200Gev)

Pair production flare

With the chosen parameters, intense pair production occurs during a flare.

Strongly non linear behavior, overdensity will propagate along the jet

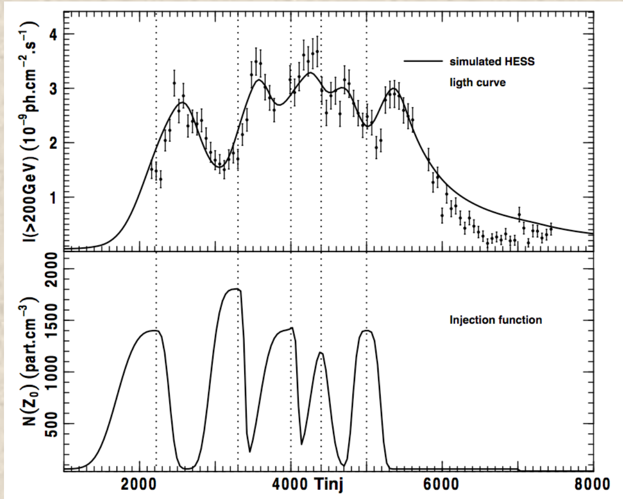
($\tau_{\gamma\gamma}$ reaches a few %)



Delayed variability

TeV

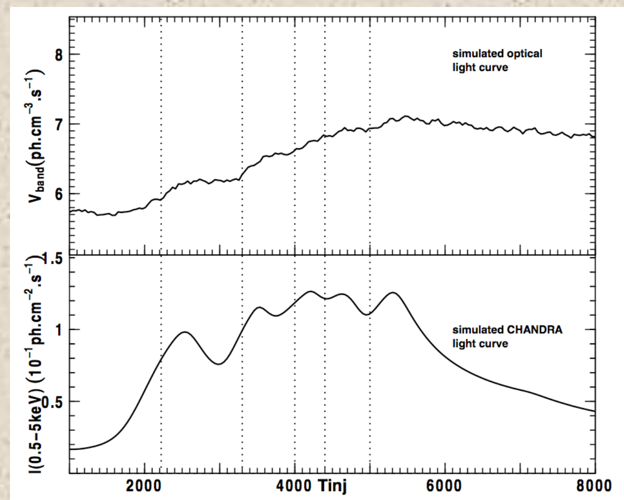
injection



Larger wavelengths variability is delayed and smoothed -> low band pass filter

optical

X-ray



Conclusions and further thoughts

- Observations show that the emission is much likely distributed all along the jet, although active regions are probably localized and 1-zone models can fit correctly the most variable part of the spectrum
- Pair production can be important and explain rapid flares. Injection of pairs -> ergosphere ? (Benjamin's talk)
- Very short time variability probably involve small active sites (reconnexion sites, « mini-jets »), more to be expected with CTA.
- Difficult to construct models with a fine description of reality while reproducing particular observations (light curves …), undersconstrained → what do we learn from our models ?

Dynamics of pair plasmas

If baryonic jet is dominated by MHD, a relativistic pair plasma will be dominated by radiative effects
Inverse Compton effect

$$t_{IC} = -\gamma/\dot{\gamma} = 3m_e c^2/(4c\sigma_T \gamma U_{ph})$$

Where the energy density is $U_{ph} = L/(4\pi R^2 c)$

Introducing the soft photon compactness

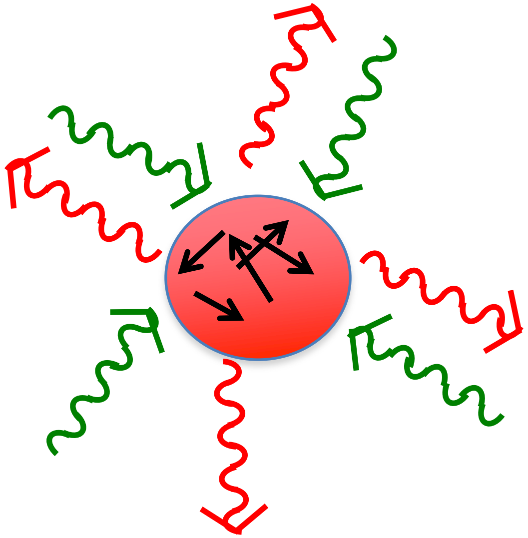
$$l_s = \frac{L\sigma_T}{4\pi m_e c^3 R} = \frac{m_p}{m_e}\frac{L}{L_{edd}}\frac{R_g}{R} \simeq 10^2 - 10^3$$

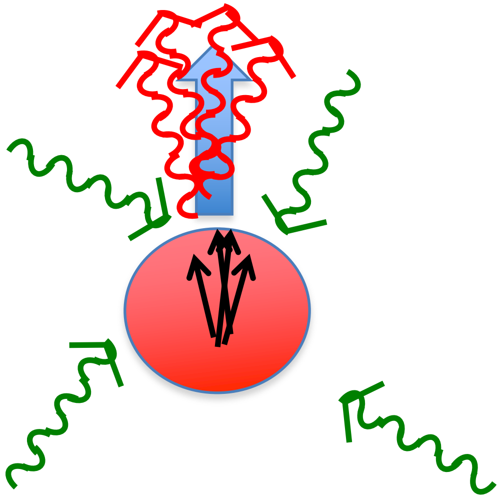
For a near Eddington accreting BH

One gets $t_{IC} = \frac{1}{\gamma l_s}\frac{R}{c} \ll \frac{R}{c}$

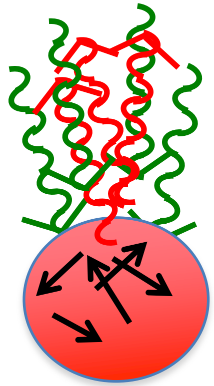
« Compton Drag »

Compton drag : « braking » effect due to the anisotropy of ambient isotropic photon field aberrated through a relativistic motion.





Obs. frame



Plasma frame

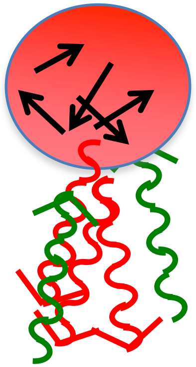
Static source

Relativistic motion -> Net negative force

Case of an isotropic photon field

What is the real effect of « Compton Drag » ?

If the initial photon field is *anisotropic*, the effect is more complicated



The force is > 0 for $\Gamma < \Gamma_{eq}$ (Compton « rocket » effect , O'Dell '81)

= 0 for $\Gamma = \Gamma_{eq}$

< 0 for $\Gamma > \Gamma_{eq}$ (Compton Drag)

Sets up an « equilibrium » Lorentz factor Γ_{eq}
for which the aberrated net flux vanishes -> « speed limiter »

On the axis of a standard accretion disk

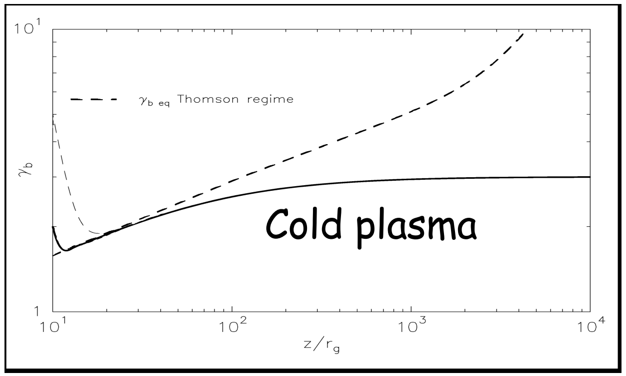
$$\Gamma_{eq} \sim (z/Ri)^{1/4}$$

Predicts a progressive acceleration along the axis, but saturates quickly (~100 rg) at

$$\Gamma_{b\infty} \sim l_s^{1/7} \sim 3$$

(ls = soft photon compactness)

Γ_b

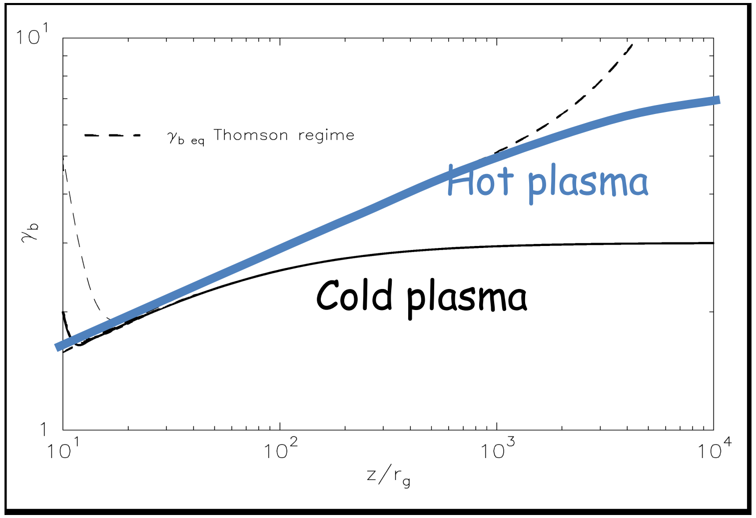


z/rg

For a *cold* plasma (or single test particle) : ordinary radiation pressure

Getting relativistic: Bulk acceleration of relativistic pair plasma

Efficiency of radiative acceleration much higher for ***hot*** relativistic plasma (Compton « rocket » effect, O'Dell '81)



$\Gamma_{b\infty} \sim (l_s \langle\gamma^2\rangle/\langle\gamma\rangle)^{1/7} \sim 10\text{-}20$

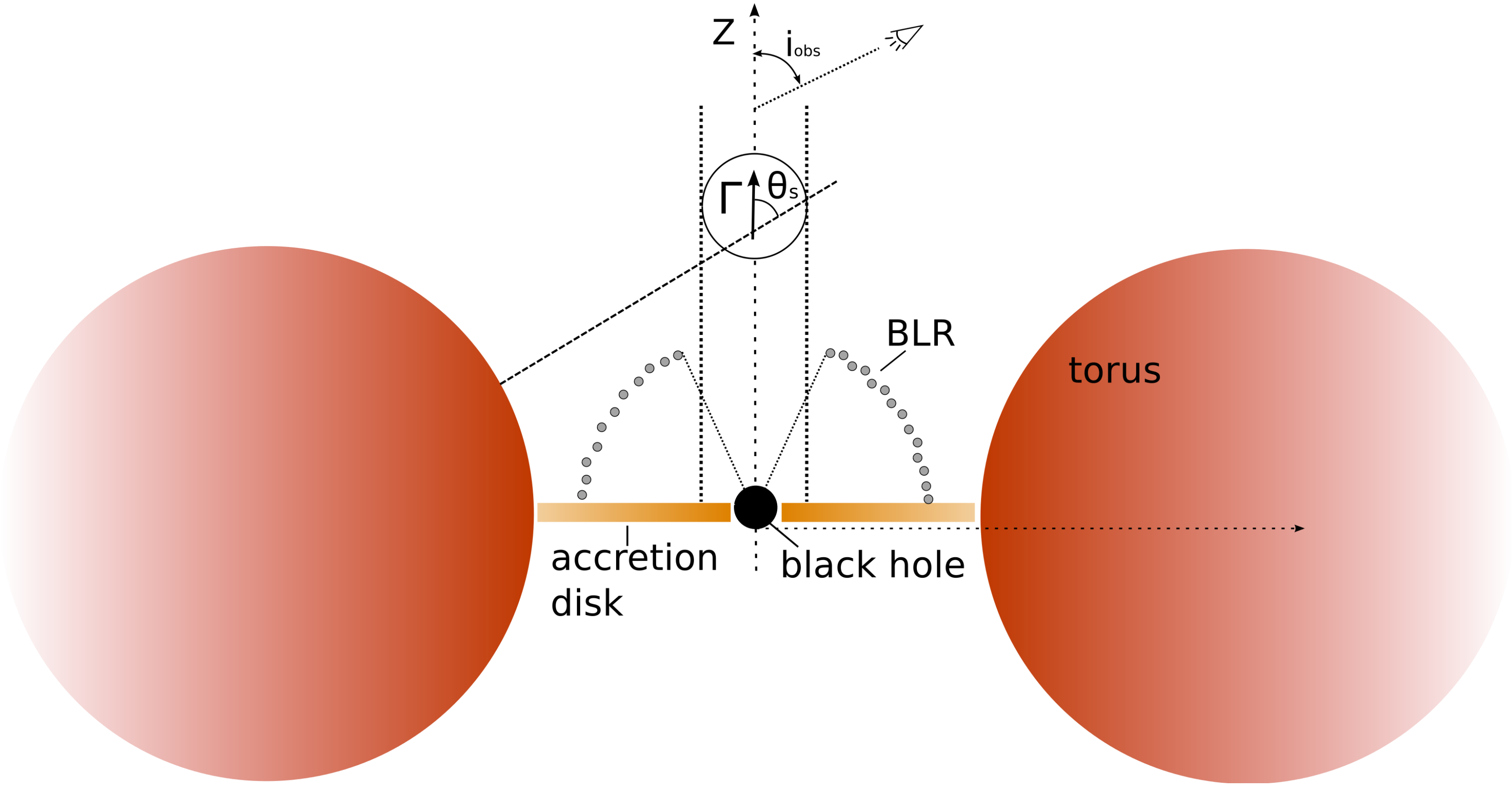
$\Gamma_{b\infty} \sim l_s^{1/7} \sim 3$

For a standard accretion disc radiation field

but cooling is as fast as acceleration (Phinney, '82) -> inefficient if no heating-> relaxes quickly to the « cold » case.

Requires continuous reacceleration.,only possible with an external energy reservoir -> surrounding MHD jet or Poynting flux from BZ process (BZ actually not necessary, applies also without ergosphere)

More realistic photon field



Emitted power

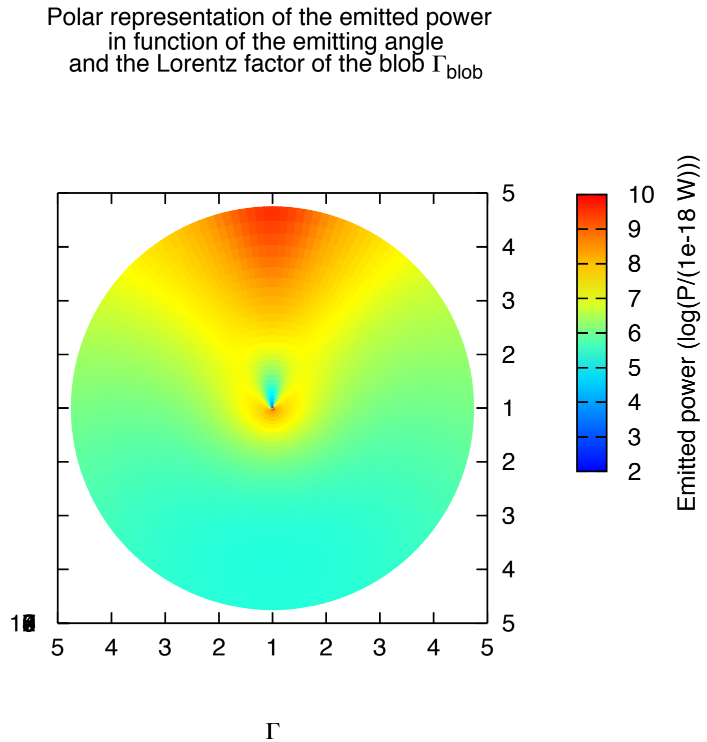
FSRQ dominated by external Compton component

Effect of anisotropy must be carefully taken into account)

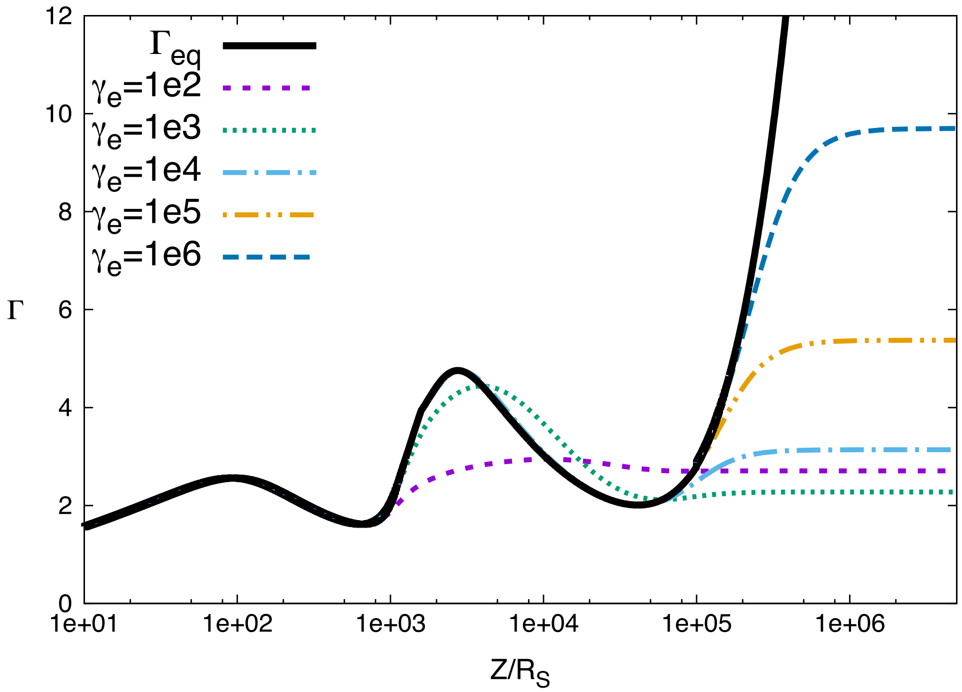
Isotropic component EC (BLR, IR torus) « boosted »

By a factor $\Gamma_b{}^6$ but disk photon « deboosted »

However close to the black hole, Γ_b can be much lower and EC from disk photons can dominate



Results on equilibrium velocity

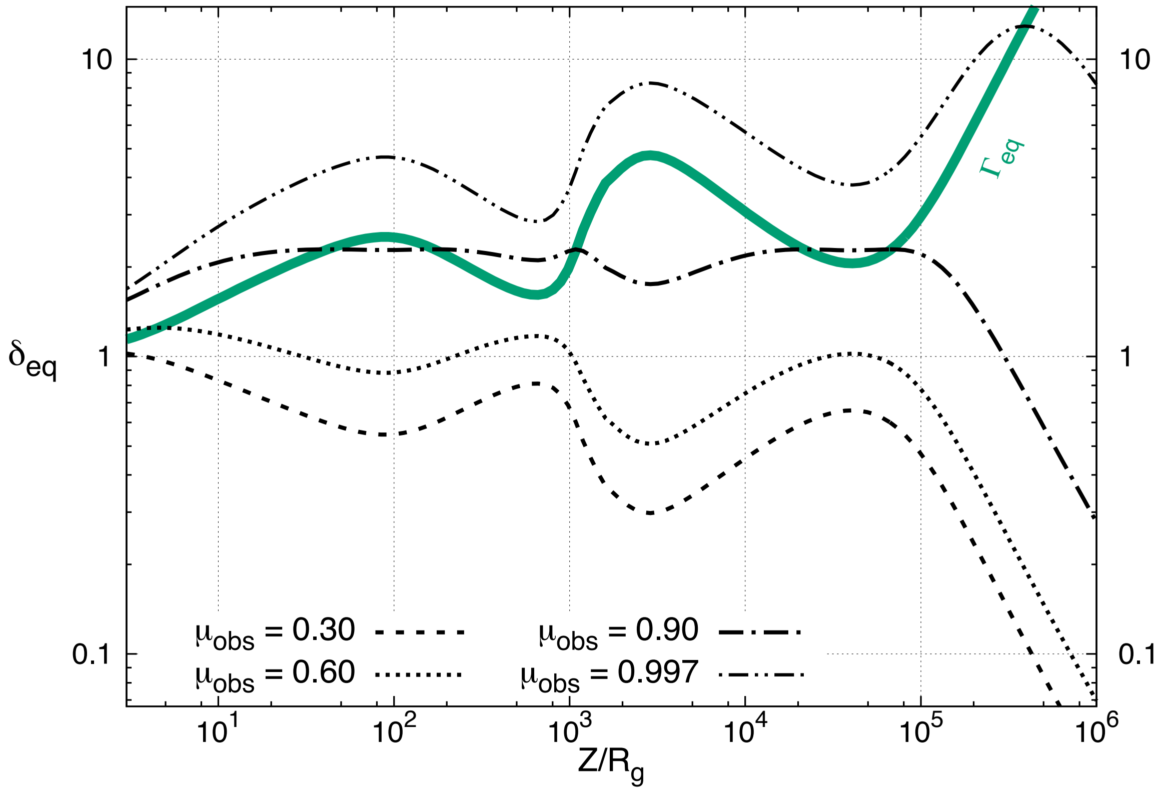


T. Vuillaume, G.H., P.O Petrucci, A&A, accepted

Complex pattern of acceleration and deceleration

Final velocity can depend strongly on the relativistic « temperature » of the plasma

Consequences on the Doppler factor



-> Complex variability pattern expected …