Time Dependent Multi Zone Modeling of X and γ Variability of Mrk 421

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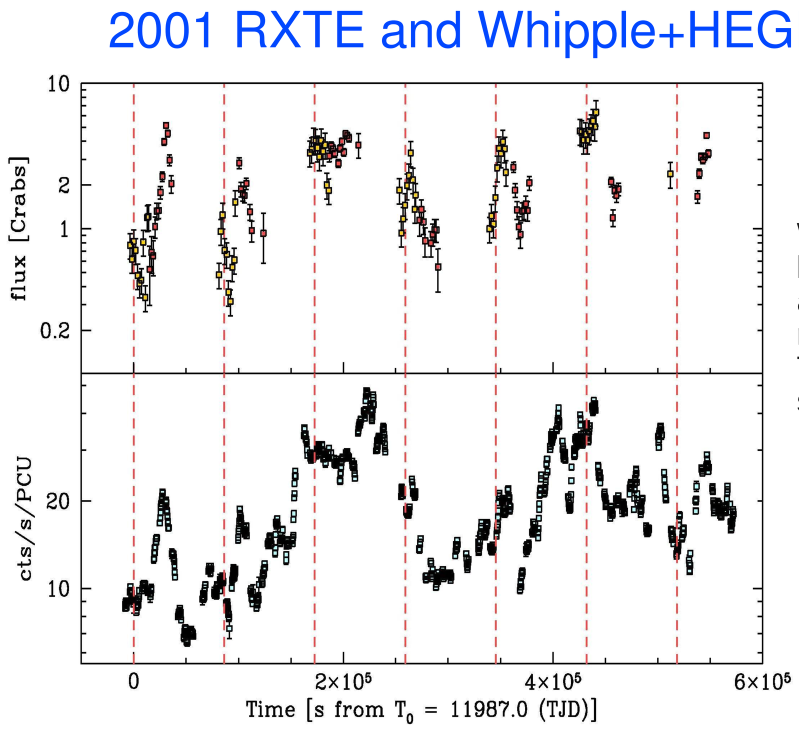
With a powerful new tool we tackle the challenges offered by the complex findings of multiwavelength observations of the archetypical blue blazar, beginning with phase and amplitude X and γ correlation.

We present a time dependent multi zone code to study the SSC emission of Blazar Mrk 421. The code couples the Fokker-Planck equation and the Monte Carlo methods. All the light crossing time effects are fully considered, both *internal* and *external*. It has been built on the solid foundations of the code developed by Liang, Boettcher and Finke and described in Boettcher et al. (2003). A series of important changes have been implemented to make it applicable to blazar jets.
It has long been realized that simple one-zone homogeneous models are not adequate to describe several aspects of the phenomenology, in particular those pertaining to the complex multiwavelength variability. Progress has been made by several groups (Chiaberge & Ghisellini 1999; Kataoka et al. 2000; Graff et al. 2008; Sokolov & Marscher 2004; Katarzinsky et al. 2008) but important trade-offs have always been necessary, such as neglecting internal light travel time or the inclusion of IC losses in the electron evolution.
The code that we briefly introduce here fully accounts for all the relevant effects, and it also affords us significant freedom w.r.t. geometry and "variability". Temporal and spectral results are compared with the observations of Mrk 421 of March 2001. The results shown here represent a very early stage of our work.
In broad terms it seems to be possible to achieve adequate fits to the observations, but a there remain several open issues. Notable features of the simulations include: 1. Systematic soft X-ray intraband lag. 2. The delay of the γ-ray flare with respect to the X-ray flare is model dependent.
The two principal challenges are: 1. The simulated VHE spectrum is always softer than the observed one. 2. The simulated correlation between the TeV gamma-ray and X-ray does not always follow the (super)quadratic relationship that has been observed in multiple occasions. In fact we have not been able to reproduce anything close to it in this first suite of models.

2001 RXTE and Whipple+HEGRA light curves



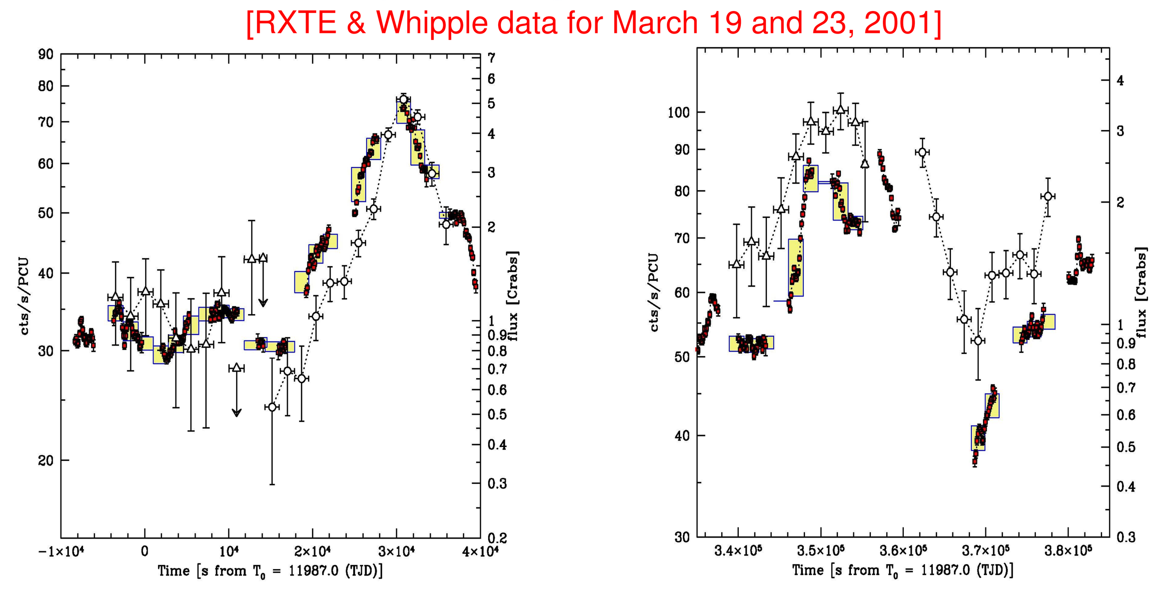
Red is Whipple,
Yellow is HEGRA

Whipple and HEGRA visibilities were optimal and allowed a continuous coverage for up to 11 hours. This enabled us to follow several flares in their entirety.

In all light curve plots the vertical scales for x-ray and TeV are such that an equal variation in the plot corresponds to a quadratic change in the TeV w.r.t. the x-ray.

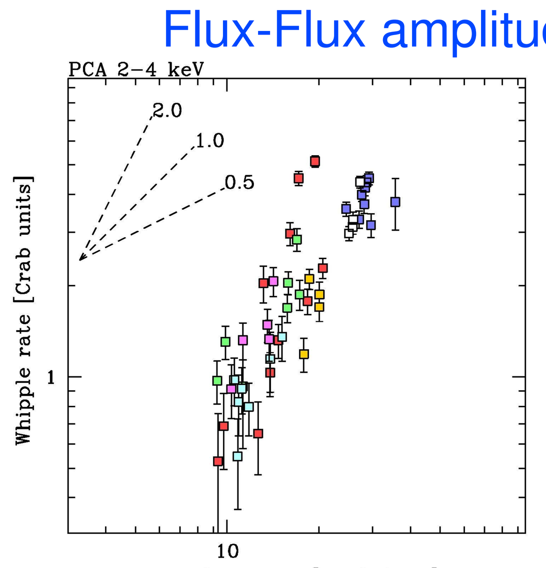
X-ray/TeV light curves details

[RXTE & Whipple data for March 19 and 23, 2001]

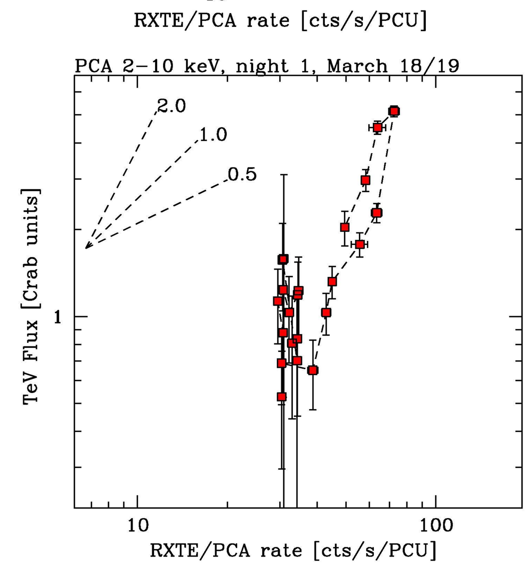


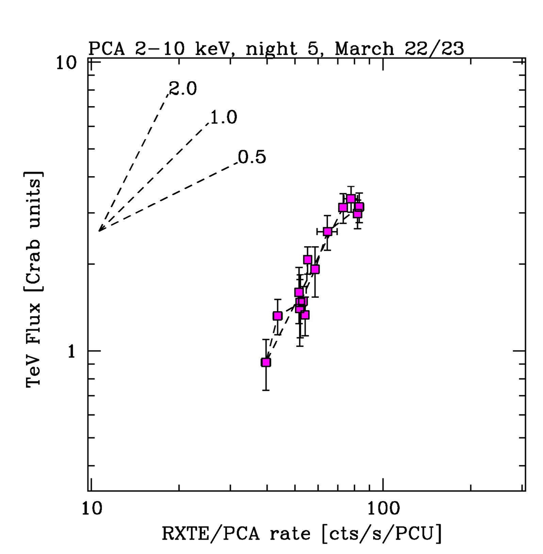
- The white symbols are the Whipple/HEGRA (TeV)28 min. runs data.
- Dark/red colored points are RXTE/PCA (x-ray) 2-10 keV in 128 sec bins.
- Yellow boxes are the RXTE/PCA x-ray data binned over the TeV light curve bins.

Flux-Flux amplitude correlation: quadratic!



- Fluxes are highly correlated.
- The slope of the correlation seems to change with energy (not discussed here) but overall the relationship is quadratic.
- The Flux-Flux plots for the best two "nights" (below) confirm the correlation.
- With one important additional piece of information: the source traces the same (quadratic) track on the rise and decay phases of the flares.



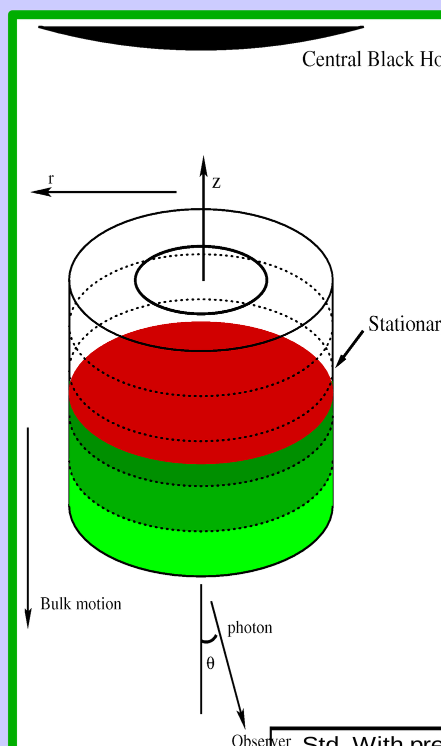


Observational Summary

The 2000 and 2001 week-long datasets provide us with a wealth of new challenging observational findings, possibly forcing us to give up some of our favorite prejudices about the properties of the emission region (processes?) in blazar jets.

- X-ray (true) spectral variability:
- Time resolved (2.5ks) spectra measure accurately synchrotron peak.
- (new) tight Flux-Peak correlation.
- No intraband x-ray lags (<128 seconds)
- X-ray/TeV correlated variability:
- X-ray and TeV light curves correlated with lag shorter than 2 ks.
- Flux-Flux x-ray/TeV correlation is quadratic going up and down flares.

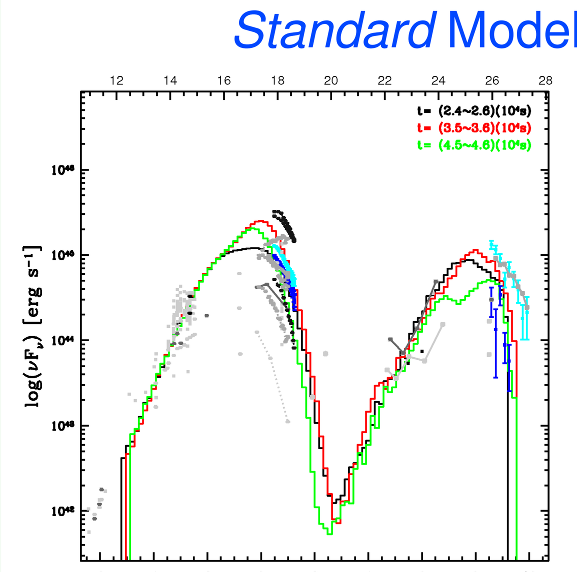
Code and Model



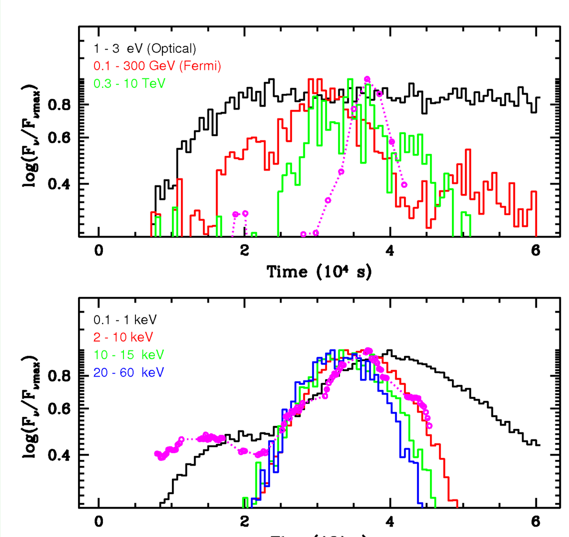
The code couples Fokker-Planck (FP) equa-tion governing the evolution of the electron spectrum and a Monte Carlo treatment of photons, tracking production and propagation, scattering. The geometry of the code is illustrated in this diagram. It has cylindrical symmetry and the volume is divided radially and vertically in different zones.
The variability is assumed to be produced by injection of fresh particles by a shock encounte-red by the volume under study.
The underlying physical mechanism responsible for the injection is not speci-fied, and this latter is treated empirically. In the cases discussed here, we inject a power law component.

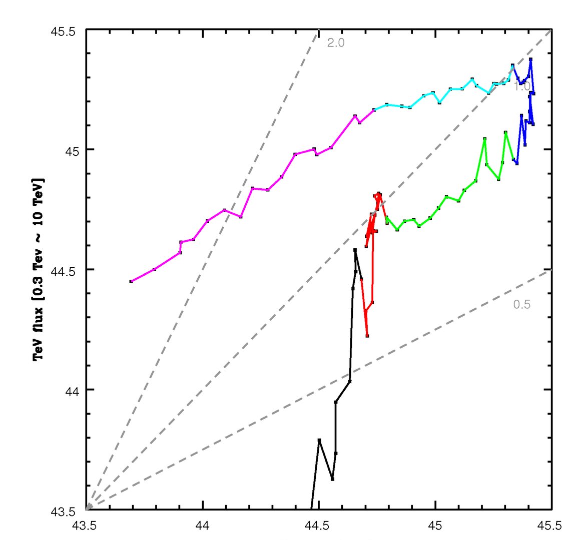
	B	R	delta	T inj	g_{min}	g_{max}
		(10^{15} cm)		(s)		
Std. With pre-filling	0.1	10	33	5×10^5	8×10^4	1.5×10^5
Std. With foreground	0.1	10	33	5×10^5	50	1.5×10^5
Better SED	0.03	15	46	8×10^5	2×10^4	1.5×10^5
red blazar	0.1	20	16	1×10^6	5×10^2	5×10^3
extreme delta	0.1	2	100	2×10^5	1×10^3	7×10^4

Standard Model with region *pre-filled*



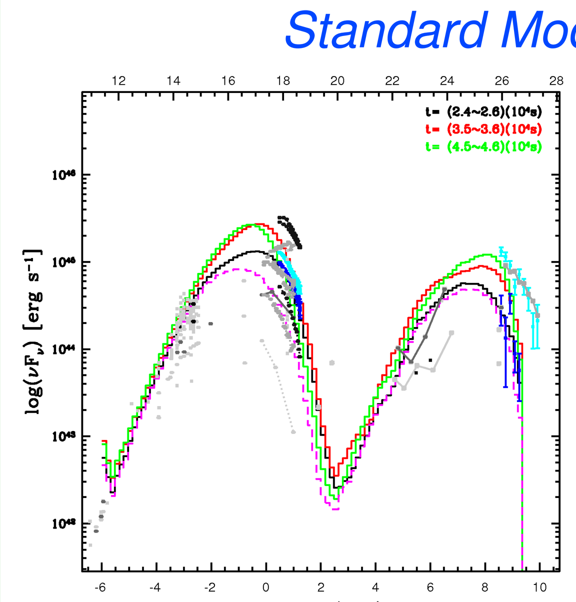
In this first case we assume that in the active region there is a pre-existing electron population, with lower energy, thus evolving slowly.
This component provides a substantial contribution to the photon field in the *blob* that can be Compton scattered by the fresh particles.
The idea is to allow the IC component to respond rapidly to the injection avoiding the delay due to the build up of the synchrotron component.





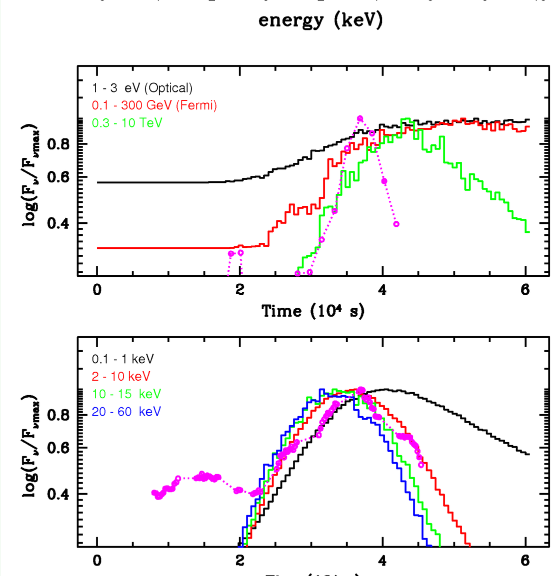
Observed light curves in multiple energy bands. Please note that the initial ramp-up (T<20ks) is not significant because it represents the pre-filling of the active region. The irregular points connected with the dotted line are the 2-10 keV and TeV light curves for March 19 2001.
In the F-F plot colors highlight 10ks-long sections of the light curve, with the black being 0-10ks.

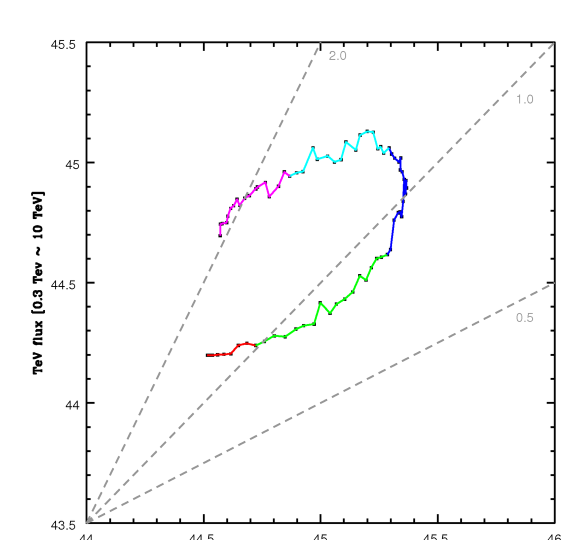
Standard Model with foreground



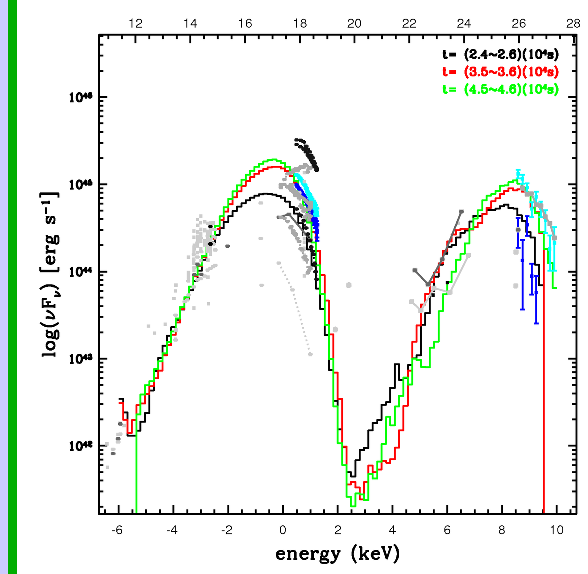
In this second case, the active region starts off "empty", but its flux, SED, etc are observed together with a steady foreground component, assumed to be emitted in a different region of the jet, non interfering with each other.

Since at the beginning there are not enough soft photons to produce a bright IC component, the VHE luminosity lags the X-ray variation.

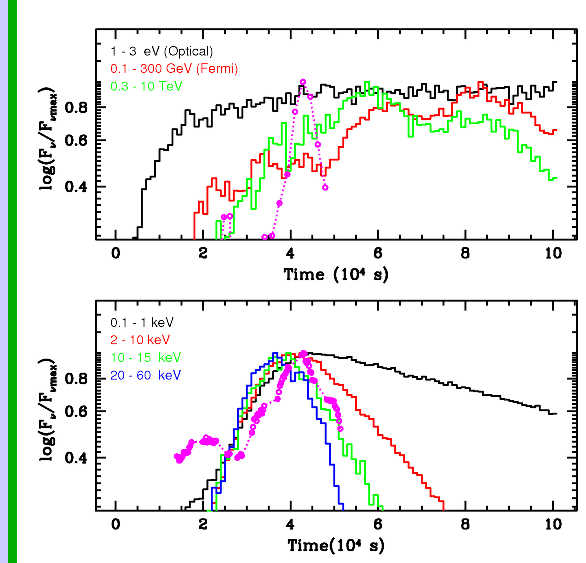


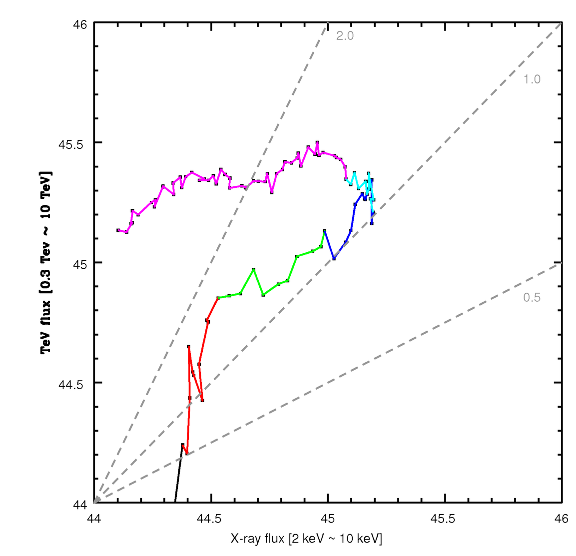


Better SED case

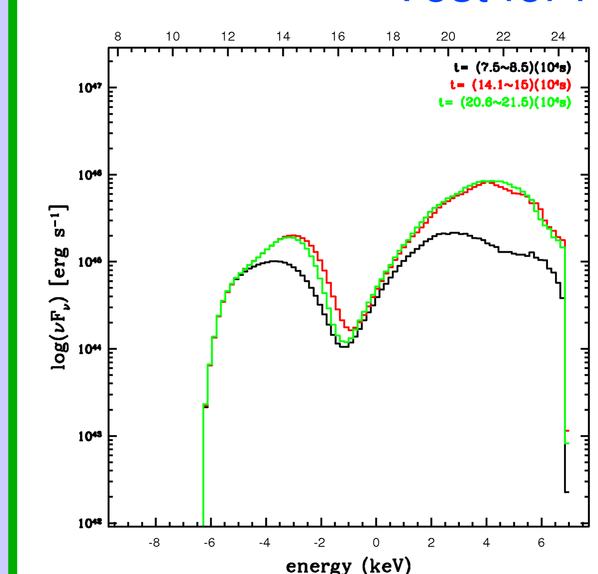


In order to obtain a better match of the VHE spectrum, we can try to increase the Doppler factor and decrease the magnetic field, aiming at pushing the IC peak to higher energy.
Larger Doppler factors help improve the SED fit, as it has been shown by several authors when fitting snapshot "static" SEDs.
We can indeed obtain a good match with the TeV spectrum, but we "pay" a significant price in terms of light curves.

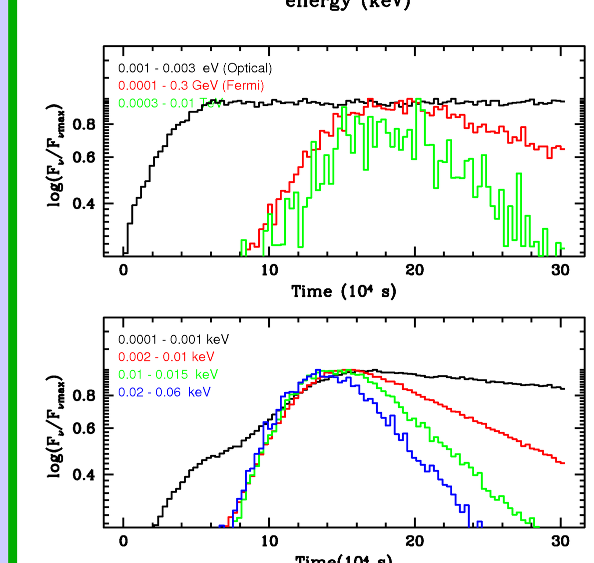


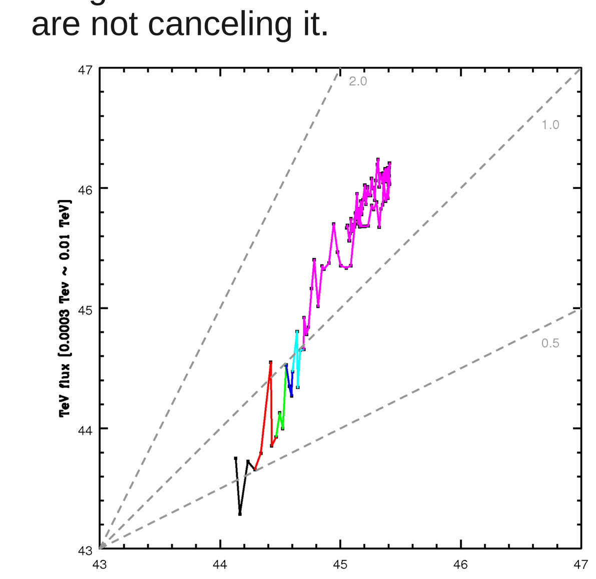


Test for *red blazar* case

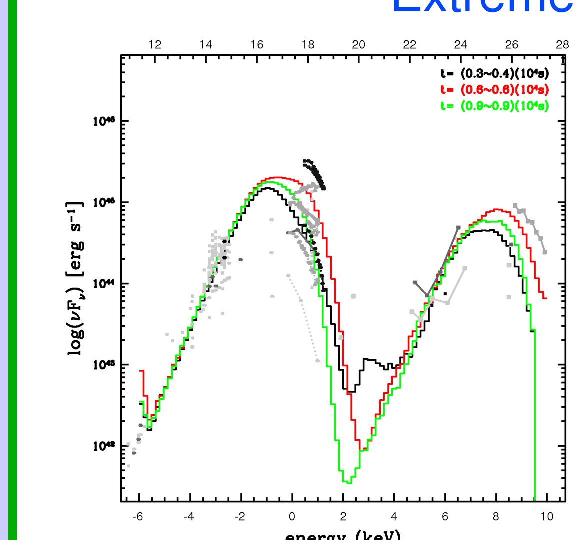


As a control we simulated also cases in which the IC would occur mostly in the Thomson regime, to try to reproduce the quadratic relationship which is certainly affected by the reduced Klein-Nishina cross section.
In order to make a meaningful comparison, we focus on wavelength that are *equivalent* to the X and TeV for the blue blazar case, i.e. around the two peaks.
The fluxes in the chosen bands show indeed a quadratic correlation, hence the geometric and travel time effects are not canceling it.

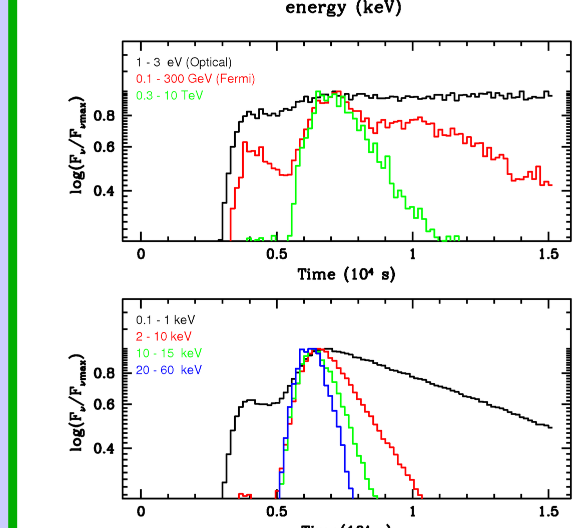


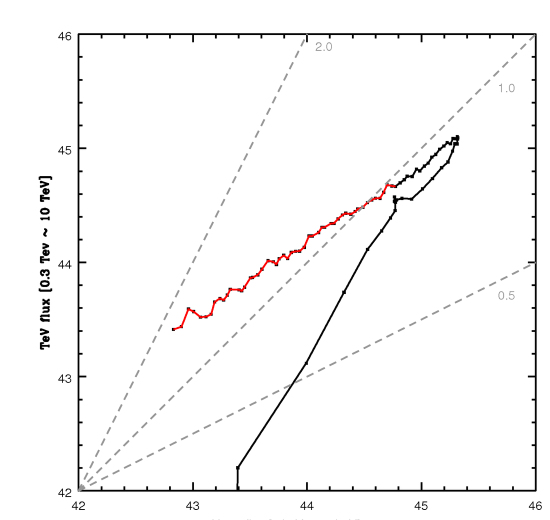


Extreme Doppler factor



Final case concerns the (now) often discussed possibility of an extreme value for the Doppler factor. This in principle should alleviate some of the problems with IC scattering in the blob frame, namely increase its "efficiency". One effect that is sought to achieve is to recover the quadratic relationship between X and γ emission.
Our current results are not very comforting on this respect, as the correlation, while improved, remains approximately linear.





We have just started to apply the code to model real observations in a very basic form. We will begin soon to include in the analysis the actual time-resolved spectra, first in X-ray. The current simple recipe for acceleration will be replaced with more sophisticated and physics-based approach to gain insight on the shock processes. The difficulty of producing the quadratic relationship between X and g seems to remain a tough challenge, and we will bring into consideration non-radiative cooling (e.g. adiabatic). We are working on the inclusion of external radiation field and looking forward to study the most powerful red blazars.

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