# Challenges to the common-wisdom model for blazar emission from x-ray/TeV simultaneous observations


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# Outline

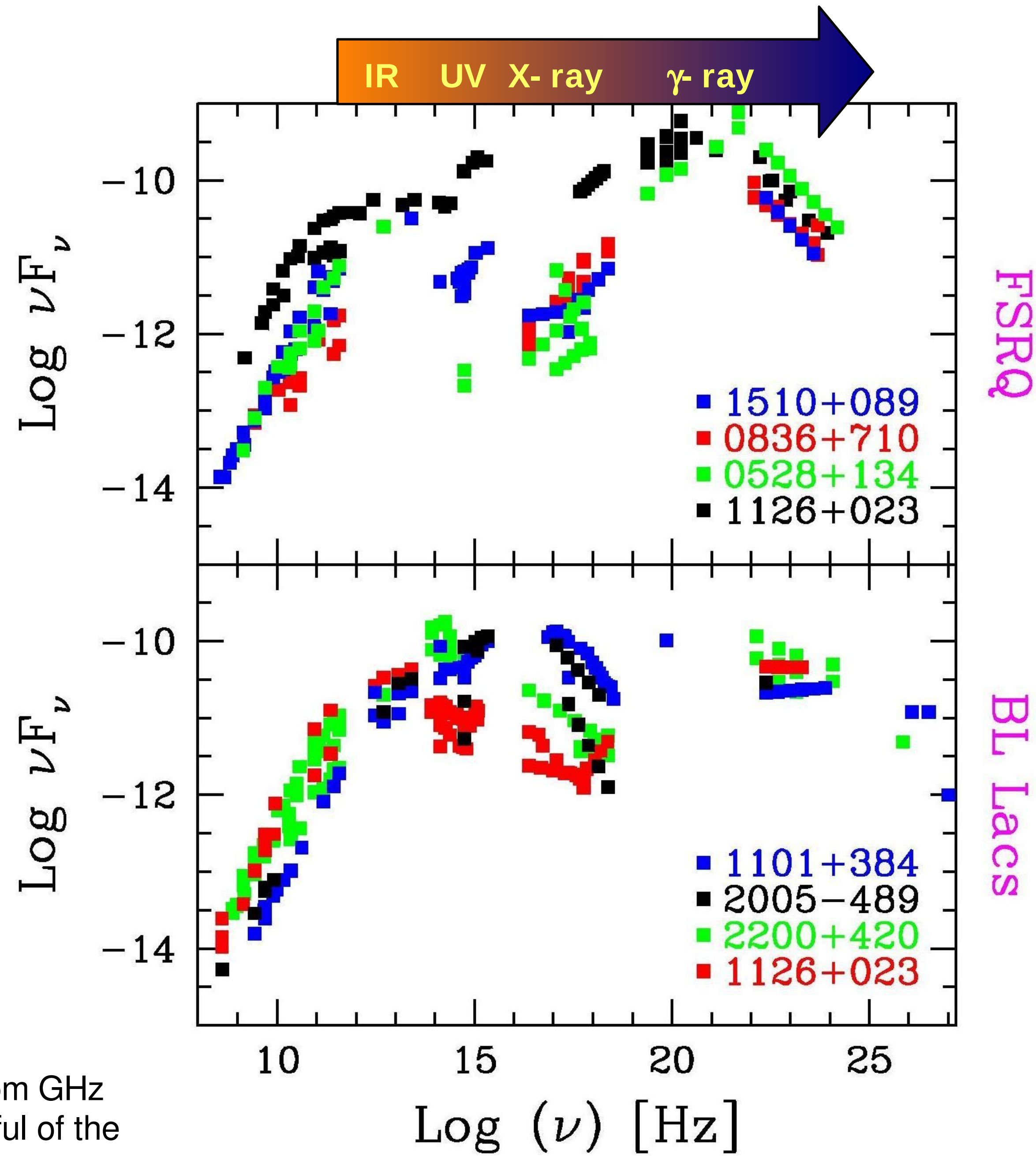
- Blazars, extreme blue blazars and Mkn421, SED and SSC modeling.
- **X-ray (true) spectral variability**:
  - April 2000 x-ray (BeppoSAX) observations.
  - Time resolved (2.5ks) spectra.
  - Flux-Peak correlation.
- **X-ray/TeV correlated variability**:
  - March 2001 multi-$\lambda$ campaign, RossiXTE + Whipple + HEGRA.
  - Flux-Flux correlation.
- Constraints from the observed SEDs and correlated variability
- "Crisis" (?) of the pure synchro-self-Compton (SSC) model

# The universal shape of Blazars SEDs

The blazars' SED are characterized by **two big "humps"** peaking in:

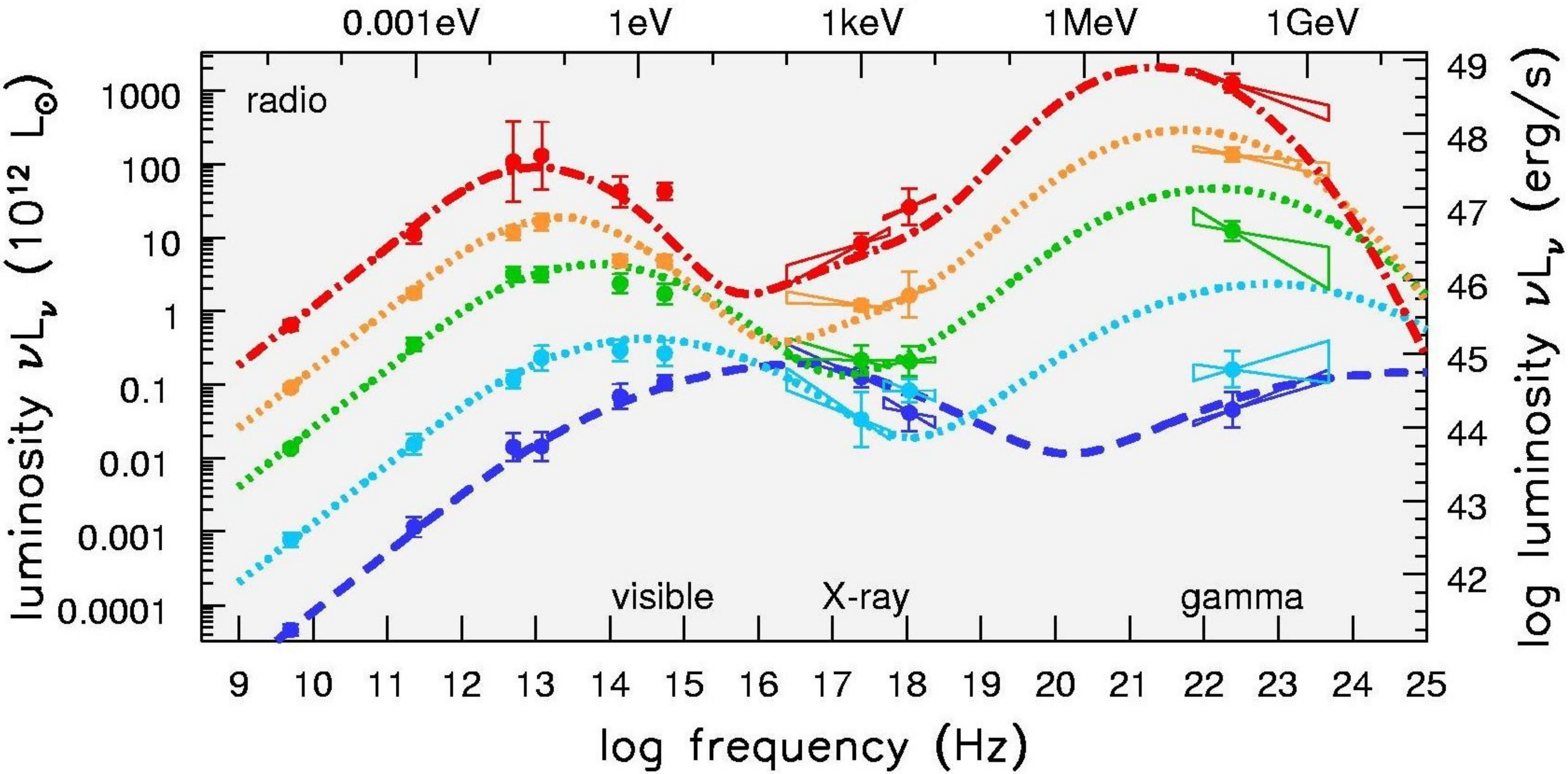
- The IR/X-ray range, and
- The $\gamma$-ray band.

**The total power output is in most cases dominated by the $\gamma$-ray luminosity.**
**(This has been a fundamental contribution brought by the Compton $\gamma$-ray Observatory)**




<u>Examples</u> of blazars SEDs, from GHz radio to TeV -rays, for a handful of the best observed objects.

# The universal shape of Blazars SEDs




Blazar SEDs averaged in bins of source power (Fossati et al. 1998).

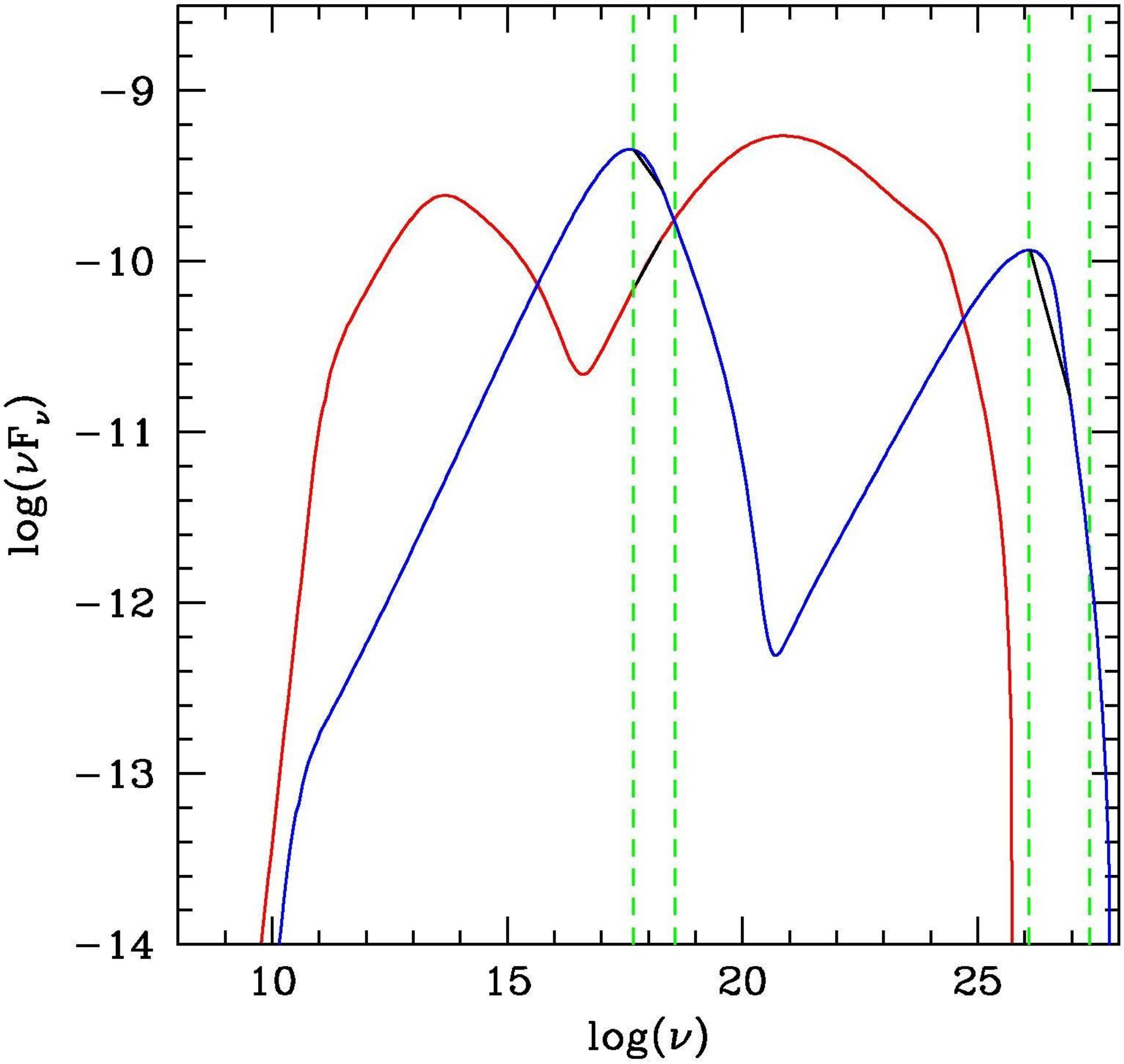
From the phenomenological point of view blazars are coarsely classified on the basis of their synchrotron peak position, into **red** and **blue** SED blazars, or low-peaked (LBL) and high-peaked (HBL).

# SED modeling: synchrotron-self-Compton

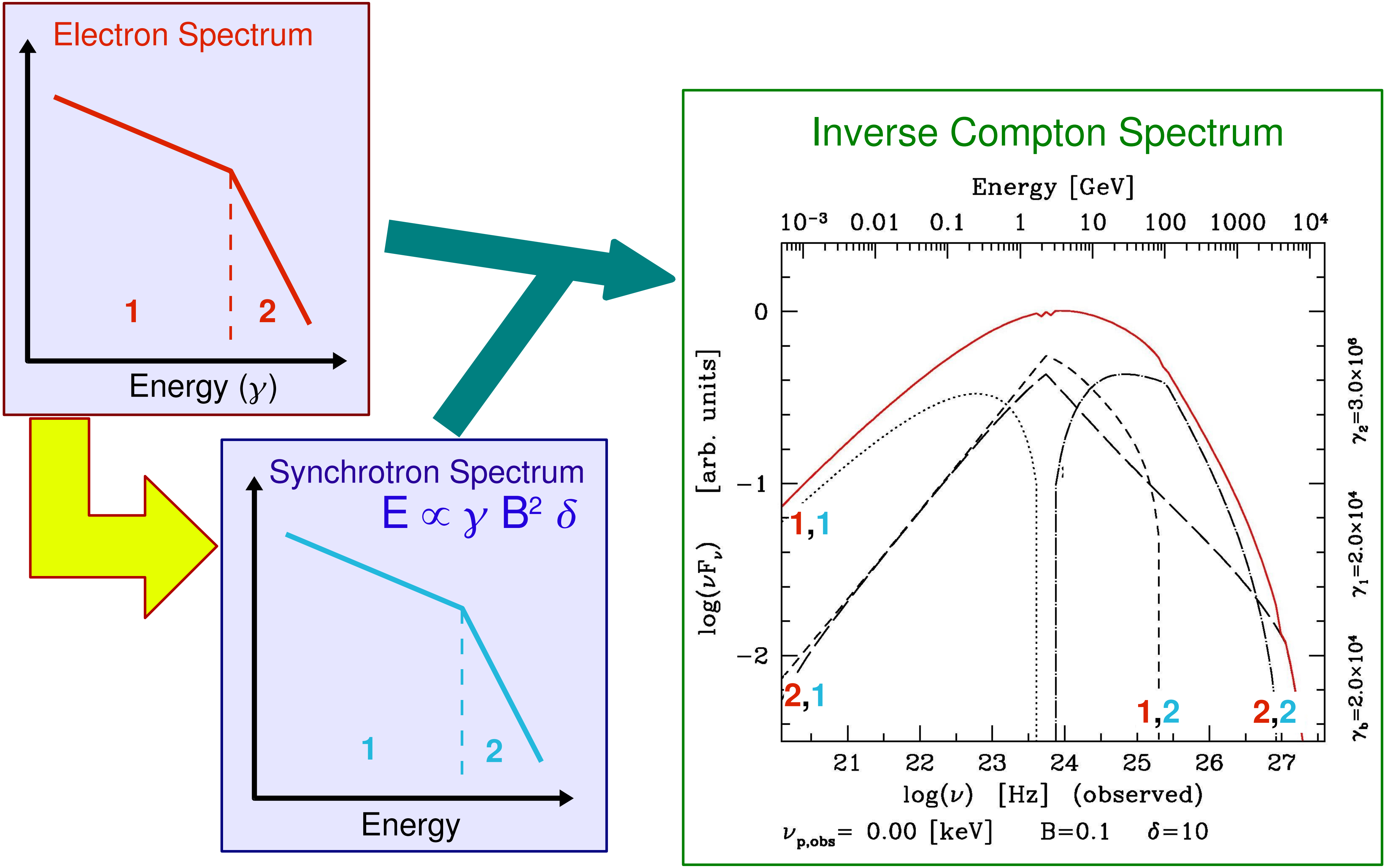
Blazar SEDs snapshots are well modeled by means for a simple one-zone SSC model.

Here are two examples of a "red blazar" and a "blue blazar" SSC SEDs.

The bands delimited by the green dashed lines show the x-ray band around a few keV, and the band observed by ground based TeV telescopes.



# SED modeling: synchrotron-self-Compton




Krakow CRJA2006: G. Fossati

# The big blue objects

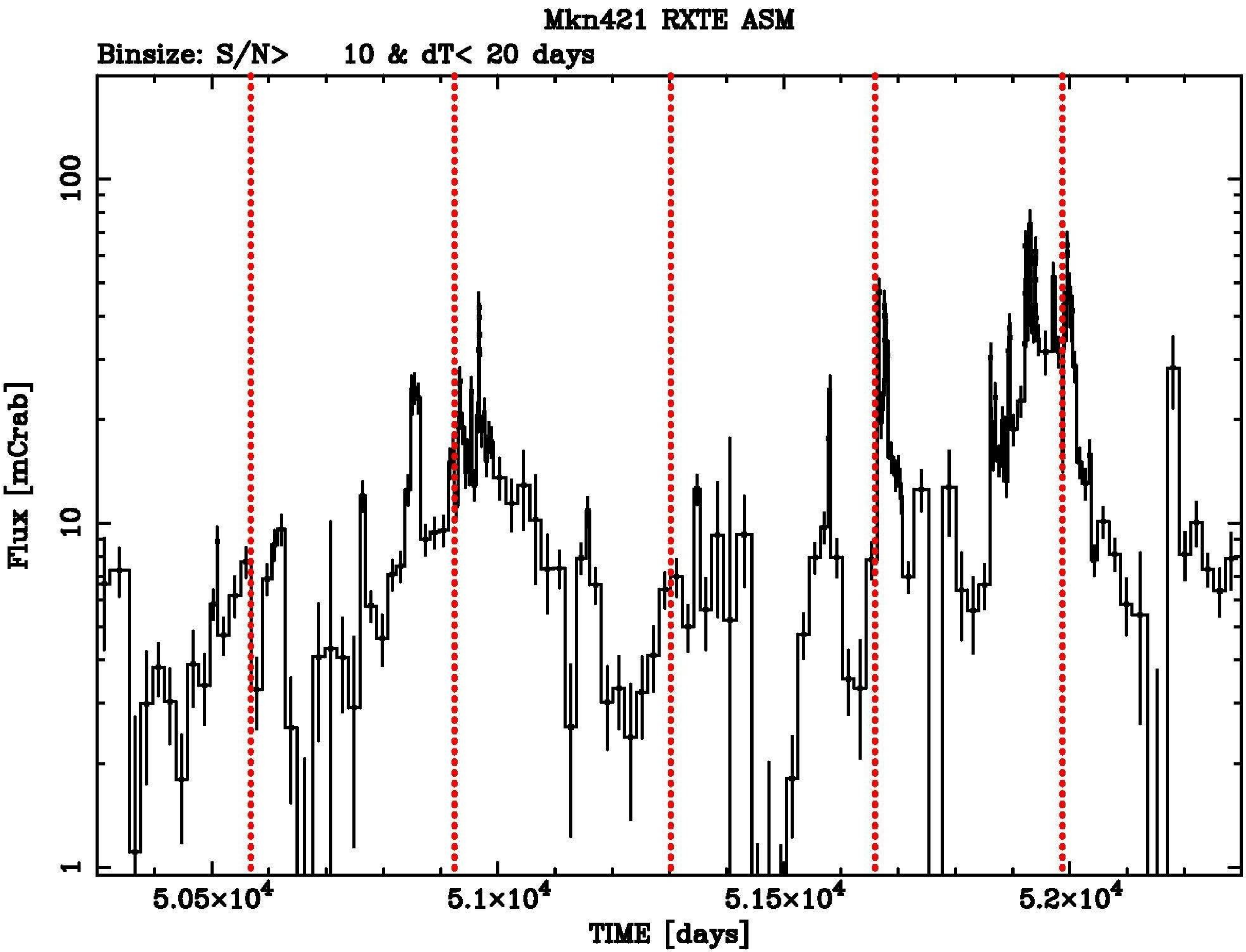
Intensive multiwavelength observations of the brightest, archetypical, blazars are the fundamental means to address questions on the physical conditions in the emission region(s), and the characteristics of the acceleration and energy losses of relativistic electrons.

- The X-ray emission of extreme (big blue) blazars like Mkn 421 is produced by synchrotron by highly relativistic electrons.
- In particular in Mkn 421 in the 0.1–10 keV band we observe the peak of the synchrotron component, and in the TeV band we catch the peak of the inverse Compton component, both supposedly emitted by the highest energy electrons that can be accelerated in the shock.
- We expect the energy of these particles to be determined by the detailed balance between the particle acceleration and the competitive cooling mechanisms.
- We observe the emission from the particles that are most sensitive to the details of the acceleration/cooling mechanisms interplay.

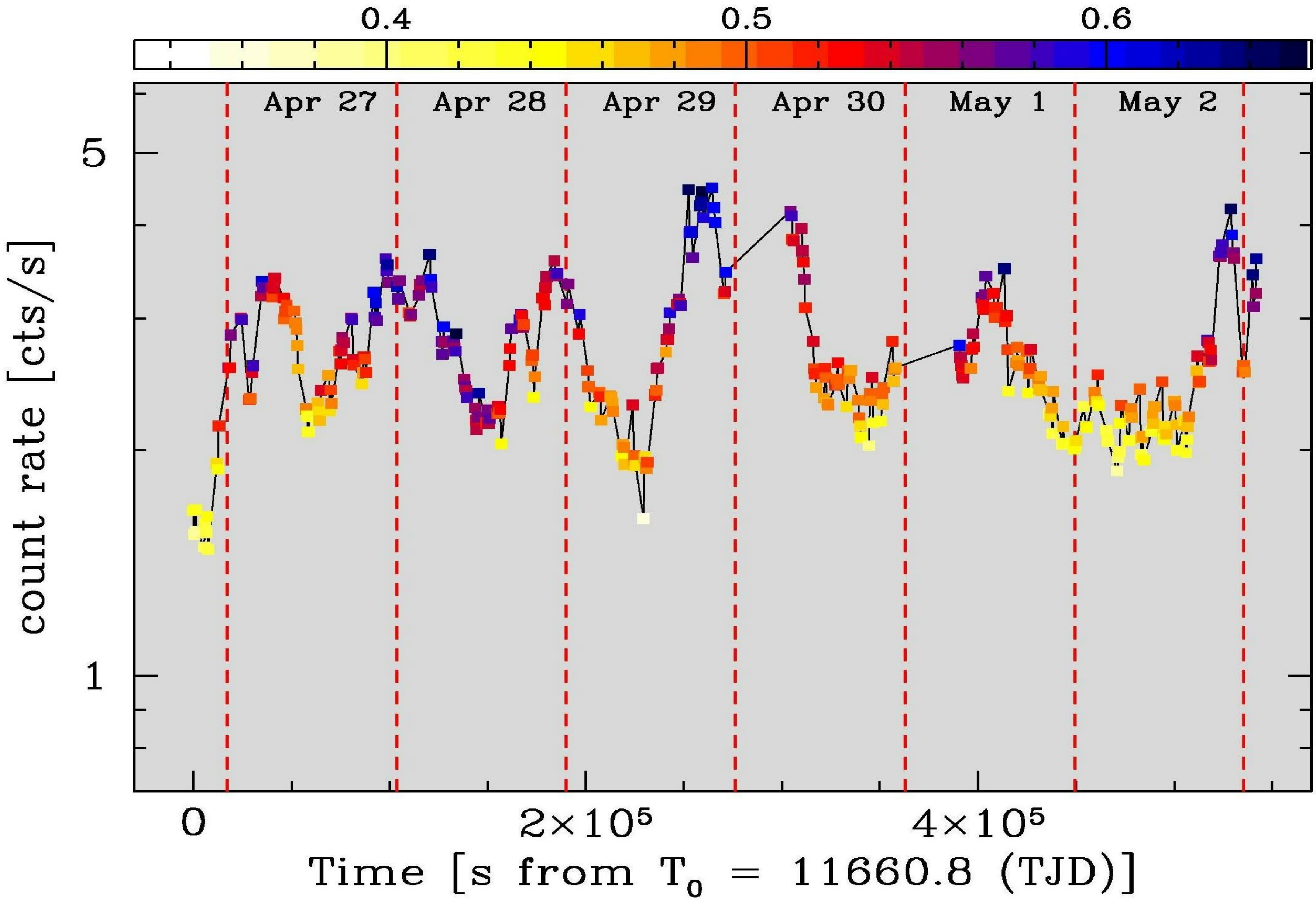
Mkn 421 is one of the best targets to explore the physics of relativistic shocks and particle acceleration and radiation, thanks to the fact that X-ray observations bring us in the core of the action.

# Mkn 421 campaigns: the broad context

RXTE/ASM light curve with marks for the 1997/98/99/00/01 campaigns

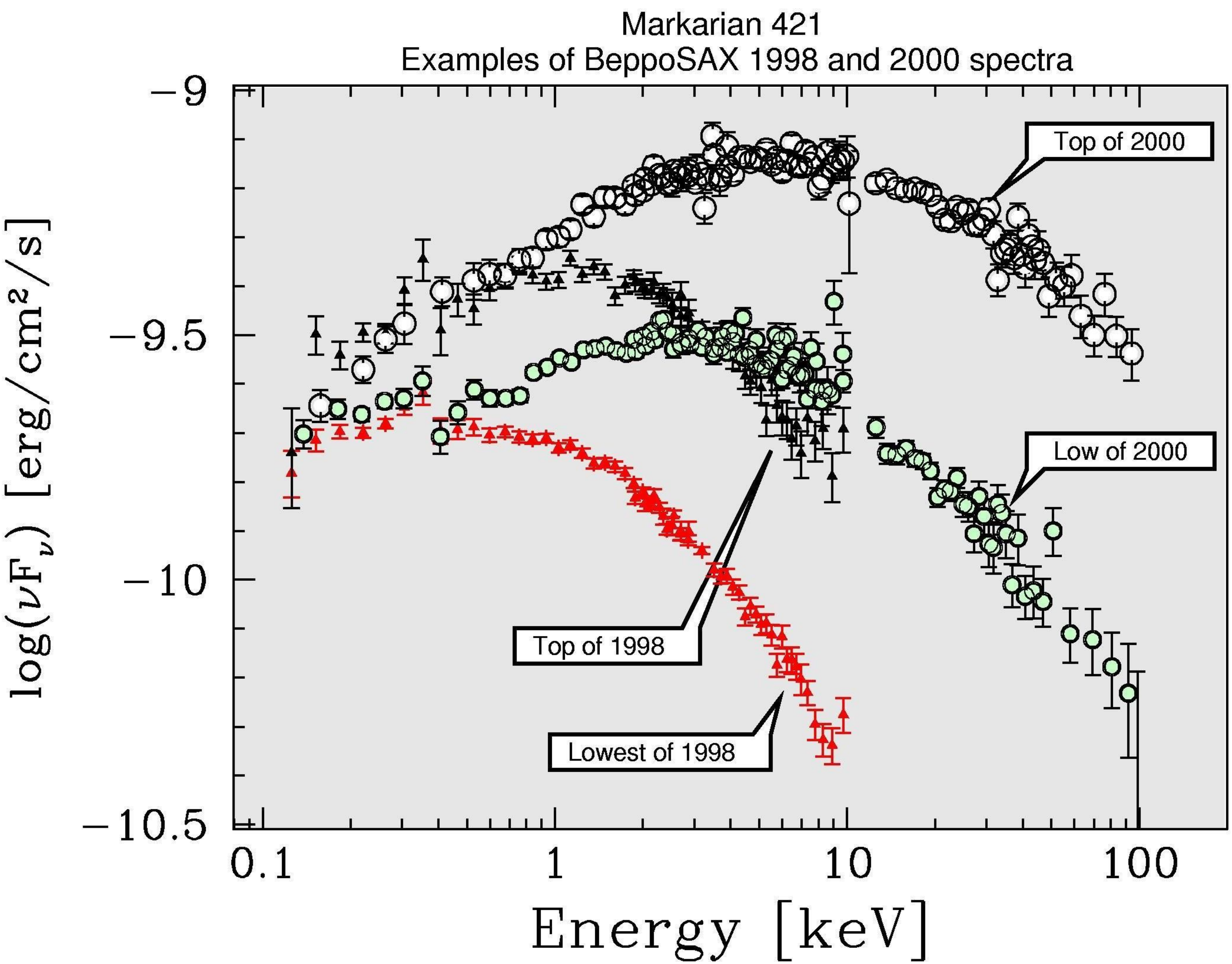


# BeppoSAX 2000: x-ray spectral variability
# HardnessRatio-colored light curve



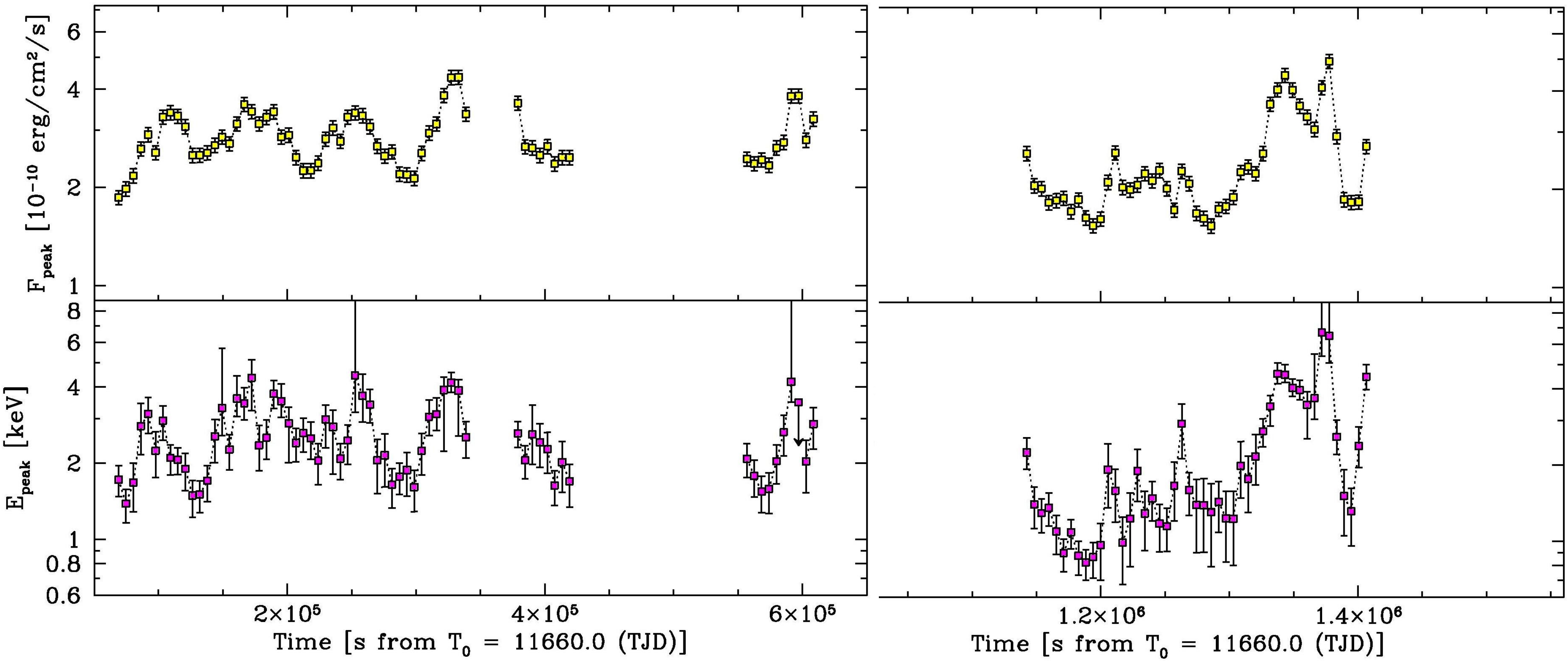
# BeppoSAX strength: broad band x-ray SEDs

BeppoSAX strong point was its broad energy bandpass, providing an unprecedented leverage to study spectral curvature. Despite the relatively small collecting area for Mrk421 it was often possible to sample the spectrum on short (i.e. few ks) timescales.



# $F_{peak}$ and $E_{peak}$ light curves, 2000a

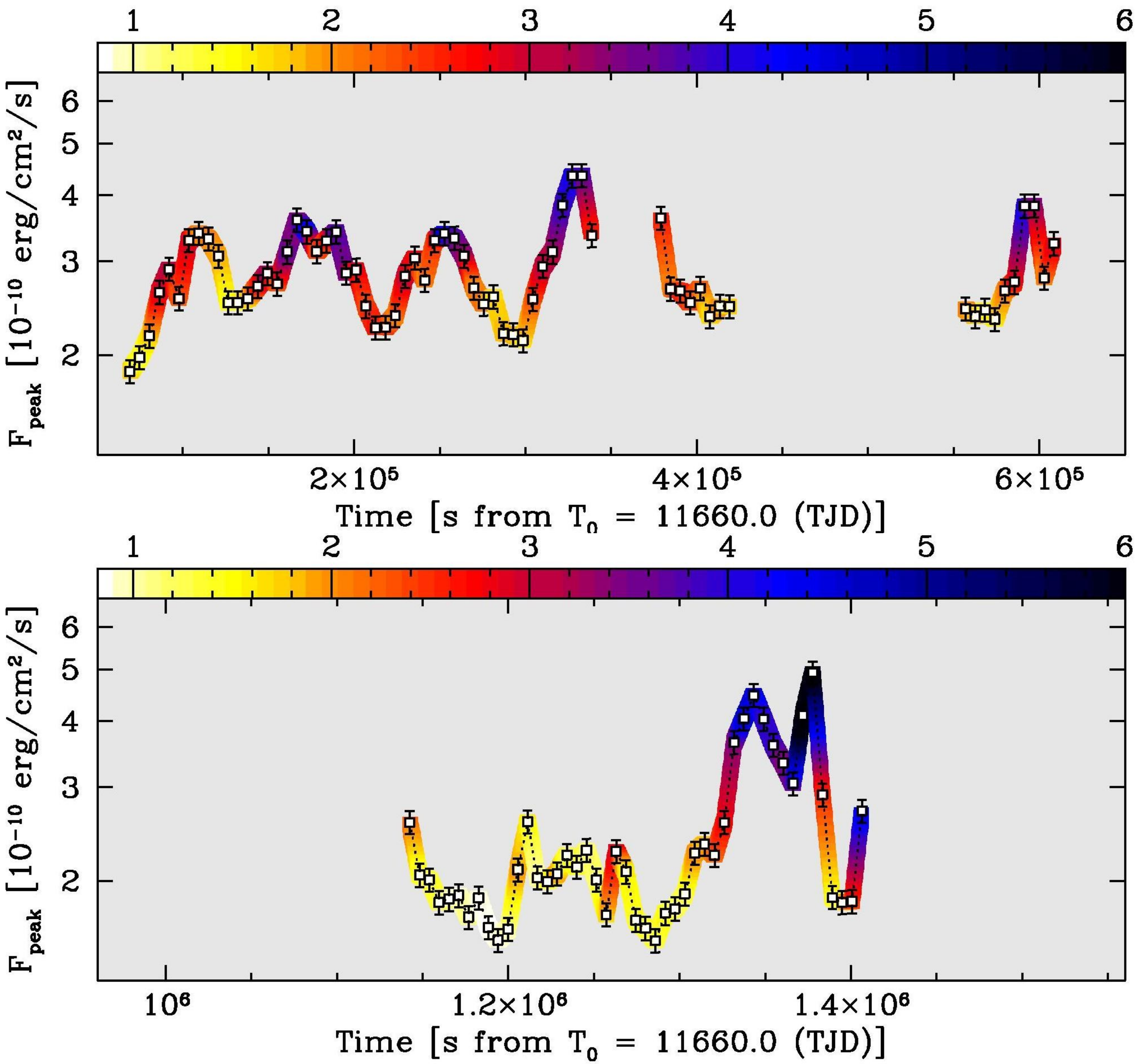
LECS+MECS (0.2—10 keV) spectra for 113 orbits, also with PDS data/upper limits. Each spectrum is integrated over ≈2.5 ks. Epeak is determined with unprecedented accuracy.






(Fossati et al. in preparation)

# $E_{peak}$-colored light curve



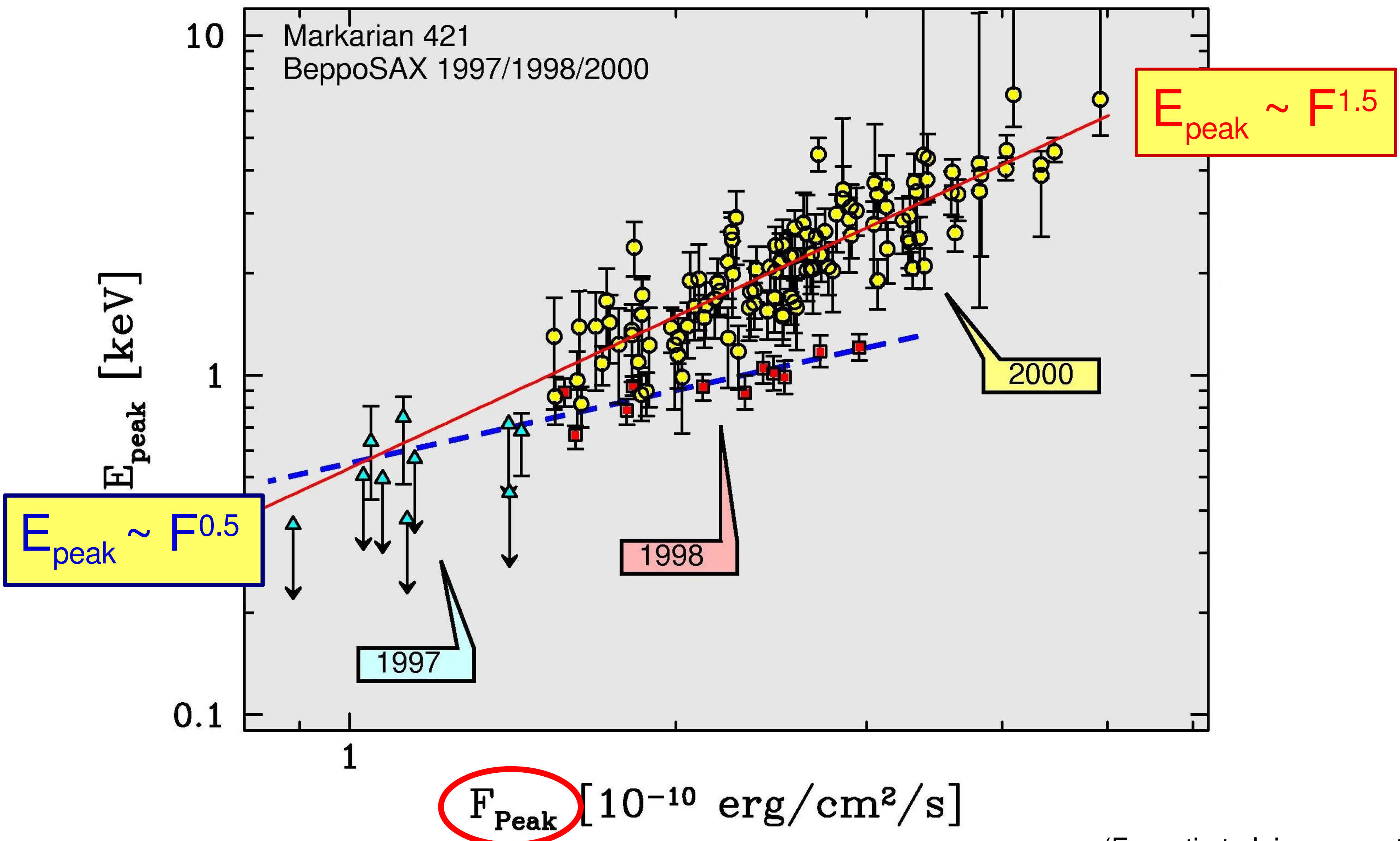

Light curves color coded on the synchrotron peak position (data are interpolated to fill the orbital gaps). The vertical and horizontal scales are the same for the two panels.



(Fossati et al. in preparation)

# $E_{peak}$ vs. $F_{peak}$

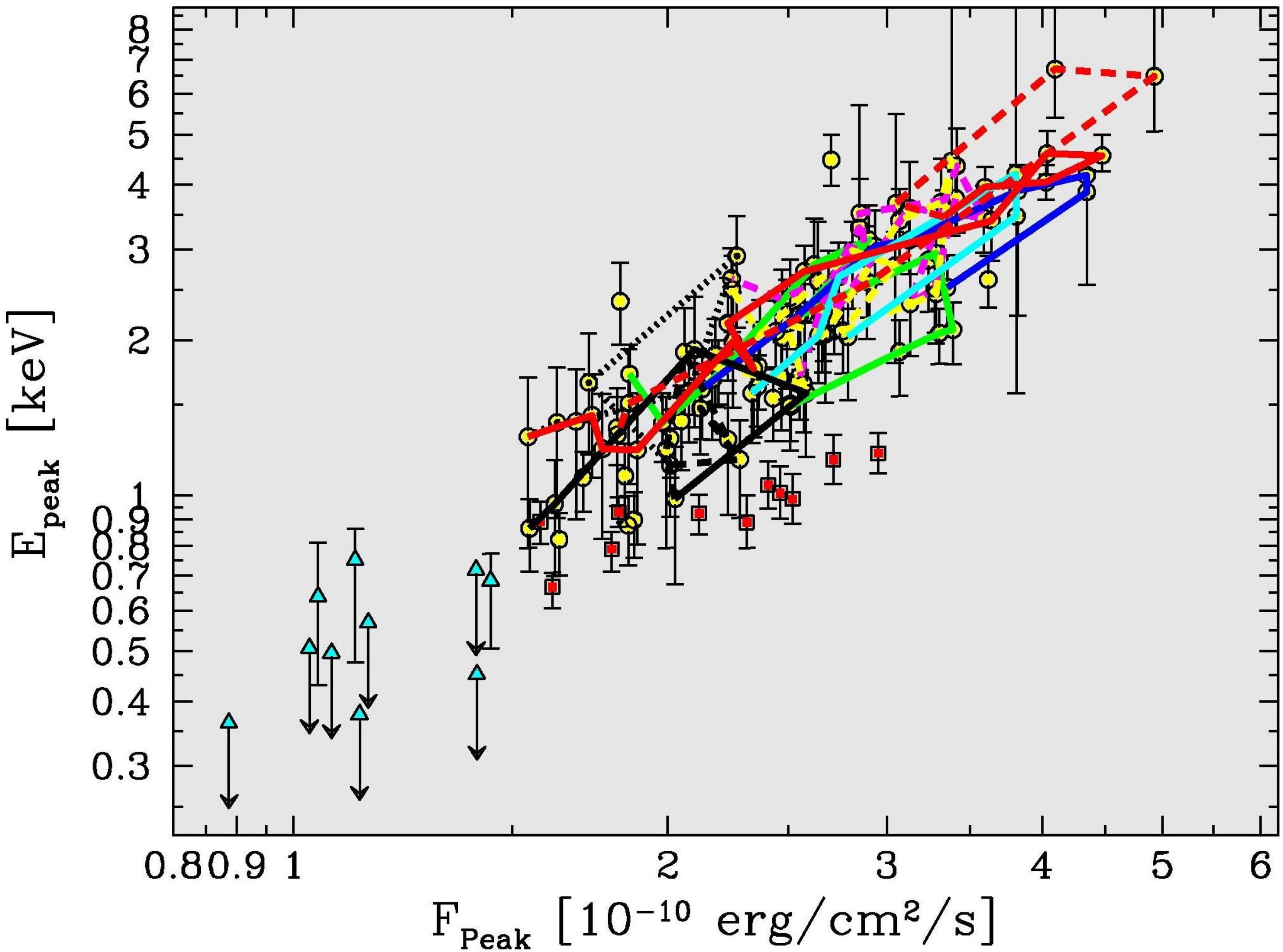
We extended the correlation between flux/**luminosity** and **synchrotron peak energy**.
It seems that it might be variable, by comparison with the sparser '97+'98 data.




(Fossati et al. in preparation)

# $E_{peak}$ vs. $F_{peak}$

In the 2000 dataset the same overall correlation is *obeyed* by all individual flares, represented here by tracks of different color.
Hence, the different (w.r.t. previous campaigns) correlation slope does not seem to result from the *"stacking"* of offset tracks all sharing the "old correlation slope".




(Fossati et al. in preparation)

# RXTE/TeV March 2001 observations summary

Summary of the simultaneous x-ray/TeV coverage for March 2001.
The *detailed* fraction refers to short (256s) time intervals with both x-ray and TeV data.
The *run-by-run* statistics are instead computed by using whole TeV *runs* as the reference interval.

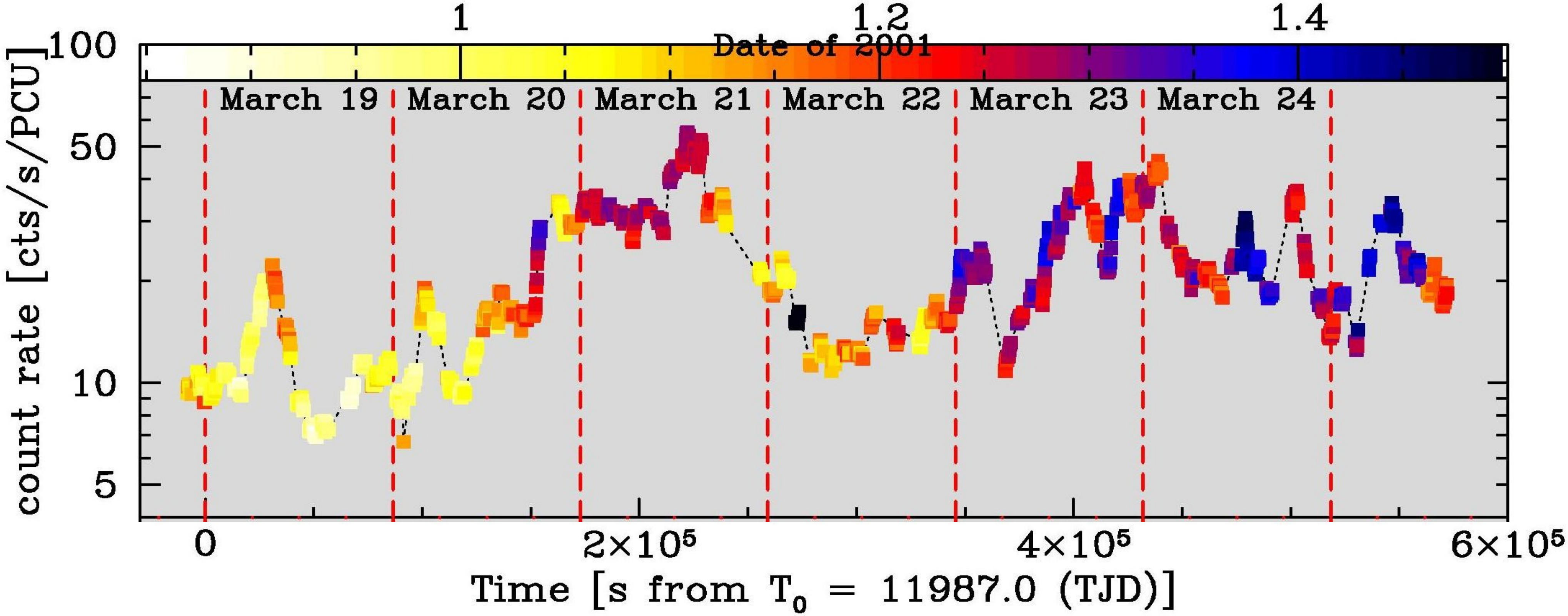
*Rossi*XTE/PCA AND WHIPPLE+HEGRA OVERLAP STATISTICS

| Night # | Date[a] | Date (MJD) | TeV Exp. Time | Overlap Fraction detailed[b] | Overlap Fraction run-by-run[c] |
|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) |
| All | March 18–25 | 51986/51993 | $62^h06^m$ | 49 % | 104/ 133 (78 %) |
| 1 | March 18/19 | 51986/51987 | $11^h18^m$ | 48 % | 22/ 24 (92 %) |
| 2 | March 19/20 | 51987/51988 | $8^h17^m$ | 63 % | 15/ 18 (83 %) |
| 3 | March 20/21 | 51988/51989 | $11^h06^m$ | 48 % | 18/ 23 (78 %) |
| 4 | March 21/22 | 51989/51990 | $8^h44^m$ | 49 % | 14/ 19 (74 %) |
| 5 | March 22/23 | 51990/51991 | $9^h17^m$ | 43 % | 13/ 20 (65 %) |
| 6 | March 23/24 | 51991/51992 | $6^h55^m$ | 57 % | 13/ 15 (87 %) |
| 7 | March 24/25 | 51992/51993 | $6^h26^m$ | 34 % | 9/ 14 (64 %) |



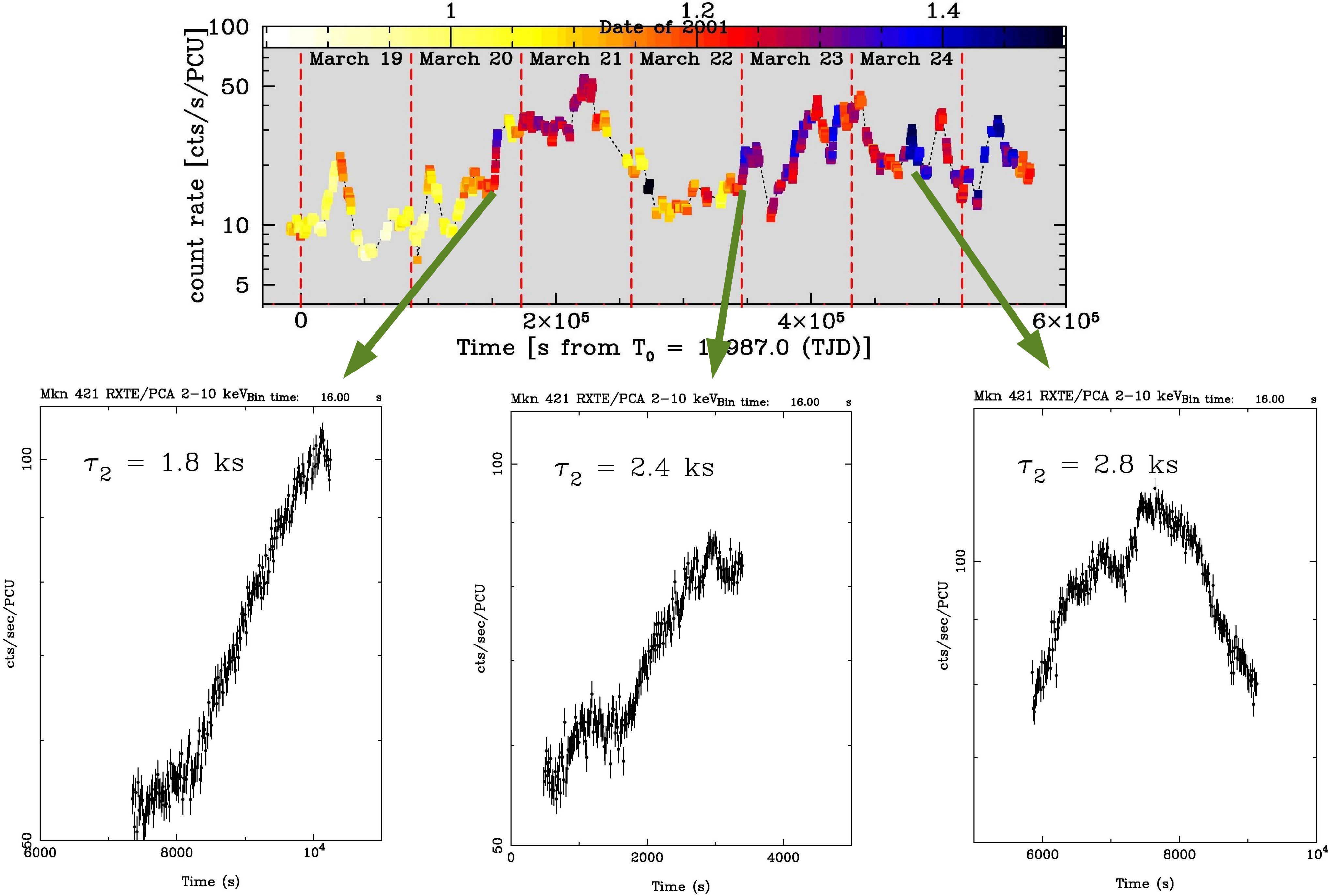
(Fossati et al. in preparation)

# RXTE 2001: x-ray spectral variability
# HardnessRatio-colored light curve

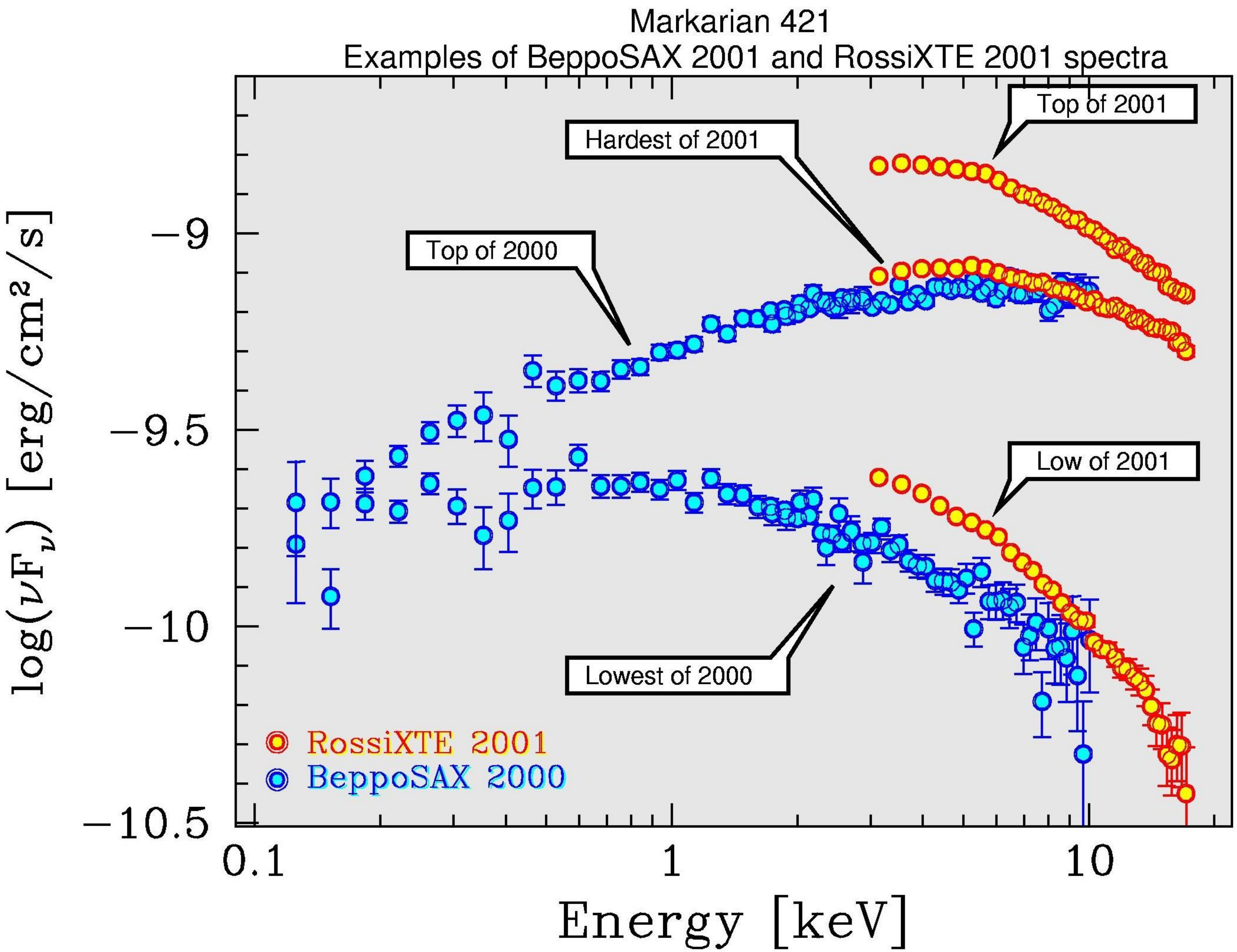



Hardness ratio and rates over 128s time bins.
Please note that the color coding is not directly comparable with the similar light curve shown for the BeppoSAX 2000 campaign.

# RXTE strength: high throughput



# X-ray SEDs: BeppoSAX vs. RXTE

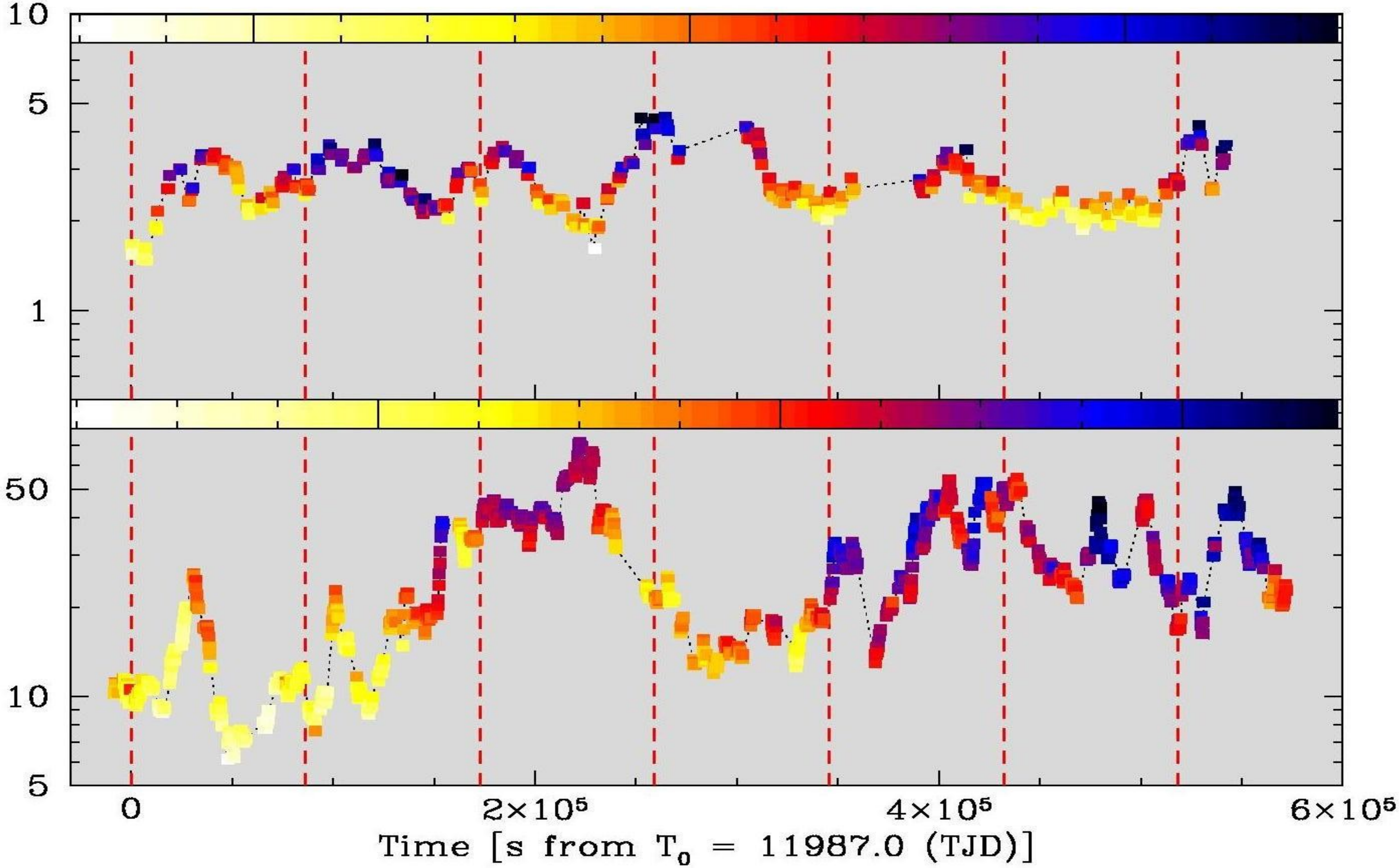



This figure shows clearly that because of the limited energy leverage, with RXTE it is not possible (at least for this campaign) to carefully constrain the synchrotron peak position.

More interestingly it also shows that, despite the higher luminosity, in 2001 the synchrotron peak position did not seem to shift to higher energies. In fact, the constraints obtained by broken power law fits, and the few directly observed peaks, suggest that the peak never exceeded several keV.

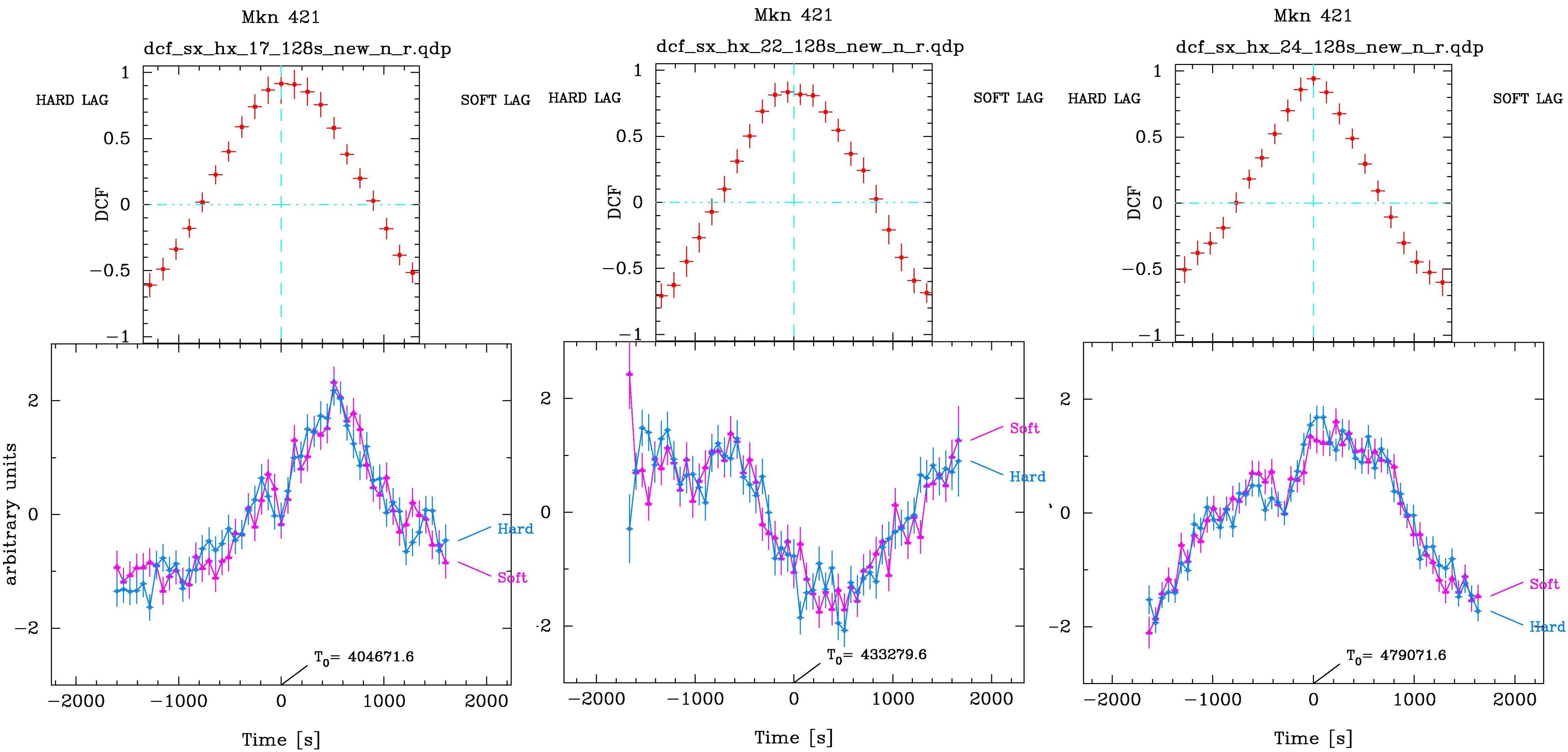
# RXTE 2001 vs. BeppoSAX 2000

Light curves are color coded on hardness ratio, but the scales (HR and brightness) are not necessarily directly comparable. The plot X/Y scales are however identical and so the comparison of variability amplitude and timescales is fair.



# Discrete Correlation Function: x-ray

Intra-orbit cross correlation between different RXTE/PCA energy bands does not yield any measurable lag (within the accuracy afforded by the dataset, i.e. 128 seconds).



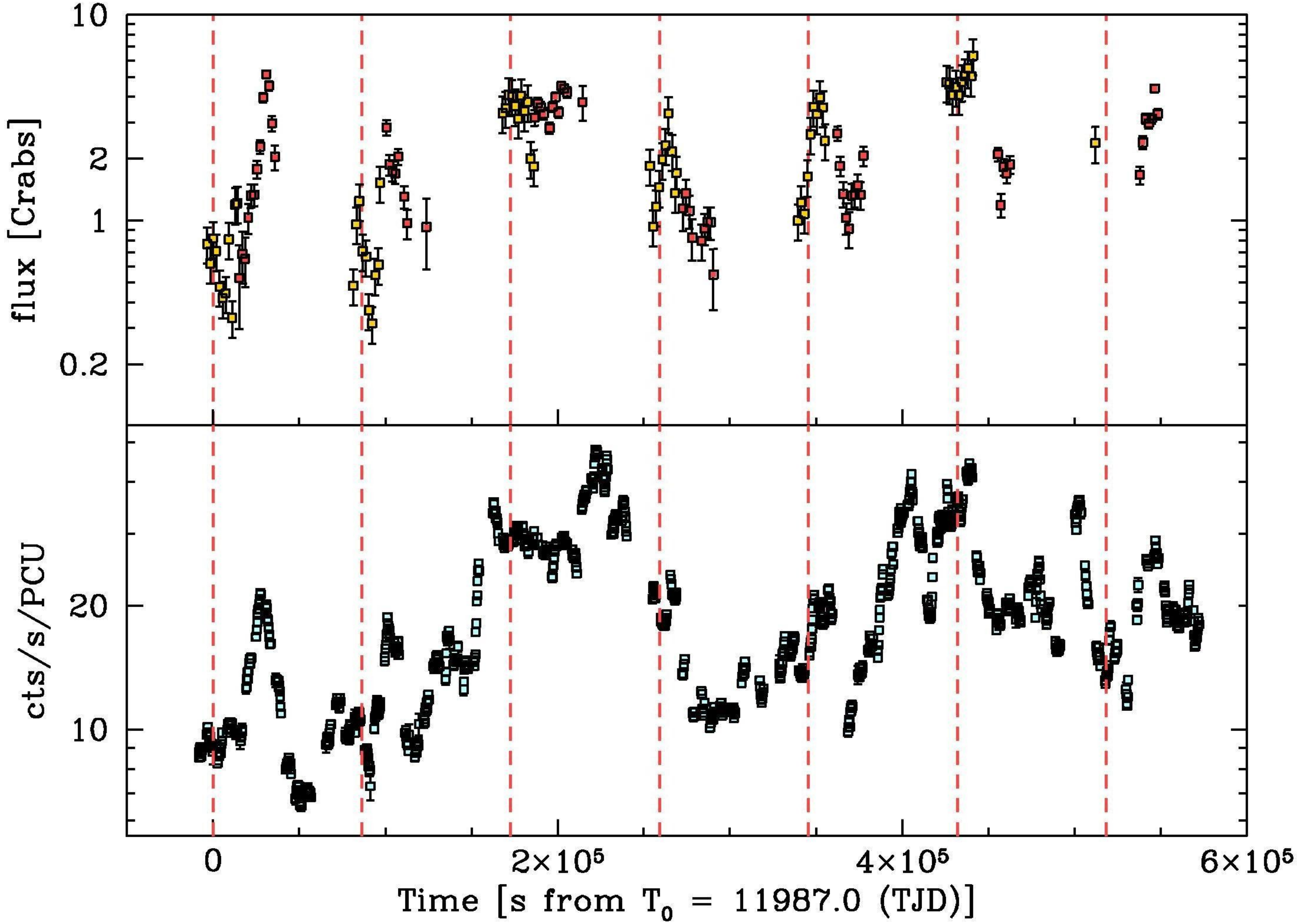



(Fossati et al. in preparation)

# RXTE and Whipple+HEGRA light curves (2001)

In all following 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.

**Red is Whipple,**
**Yellow is HEGRA**

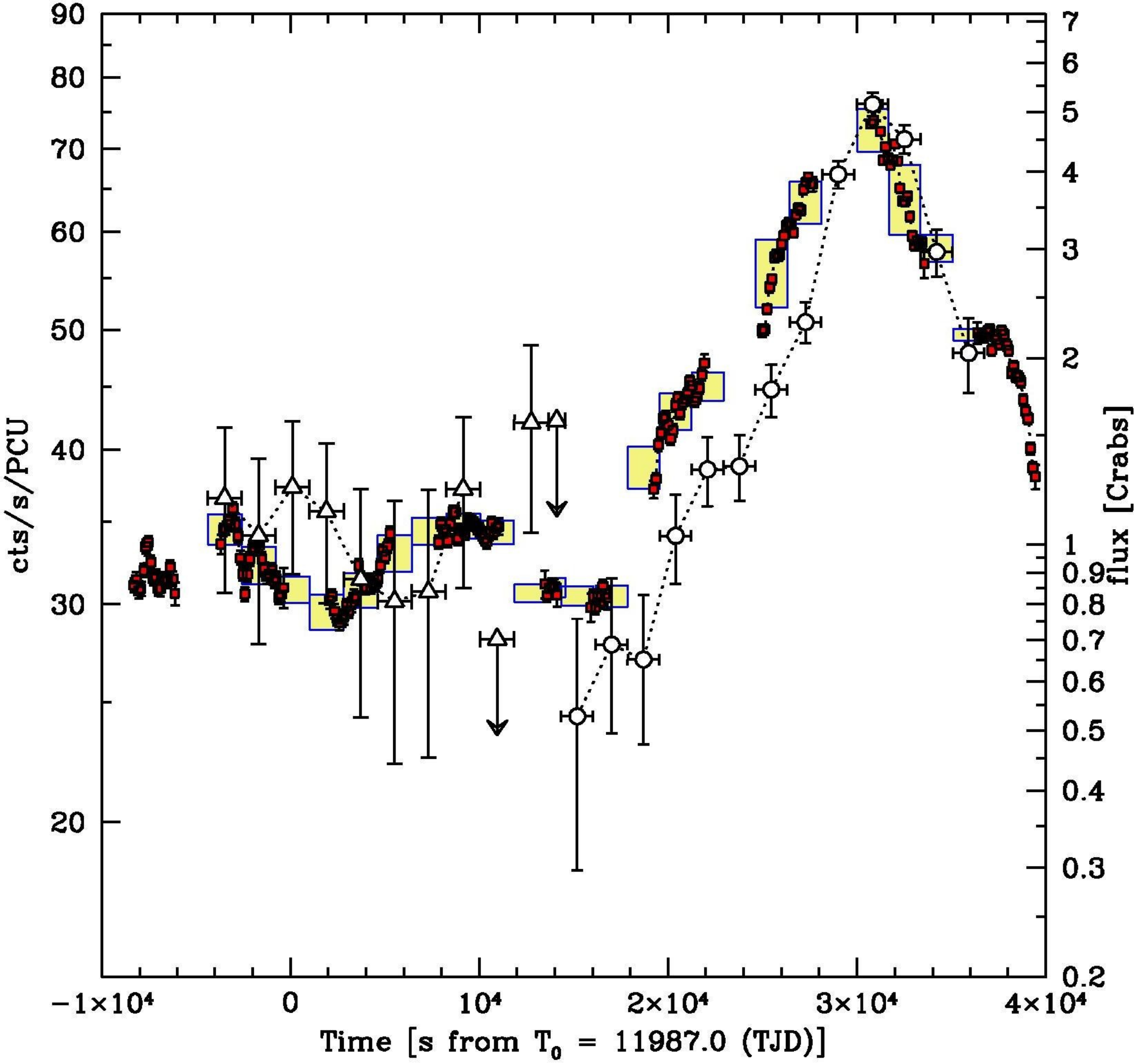



(Fossati et al. in preparation)

# X-ray/TeV light curves gallery: *excellent*

[RXTE & Whipple data for March 19, 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.




(Fossati et al. in preparation)

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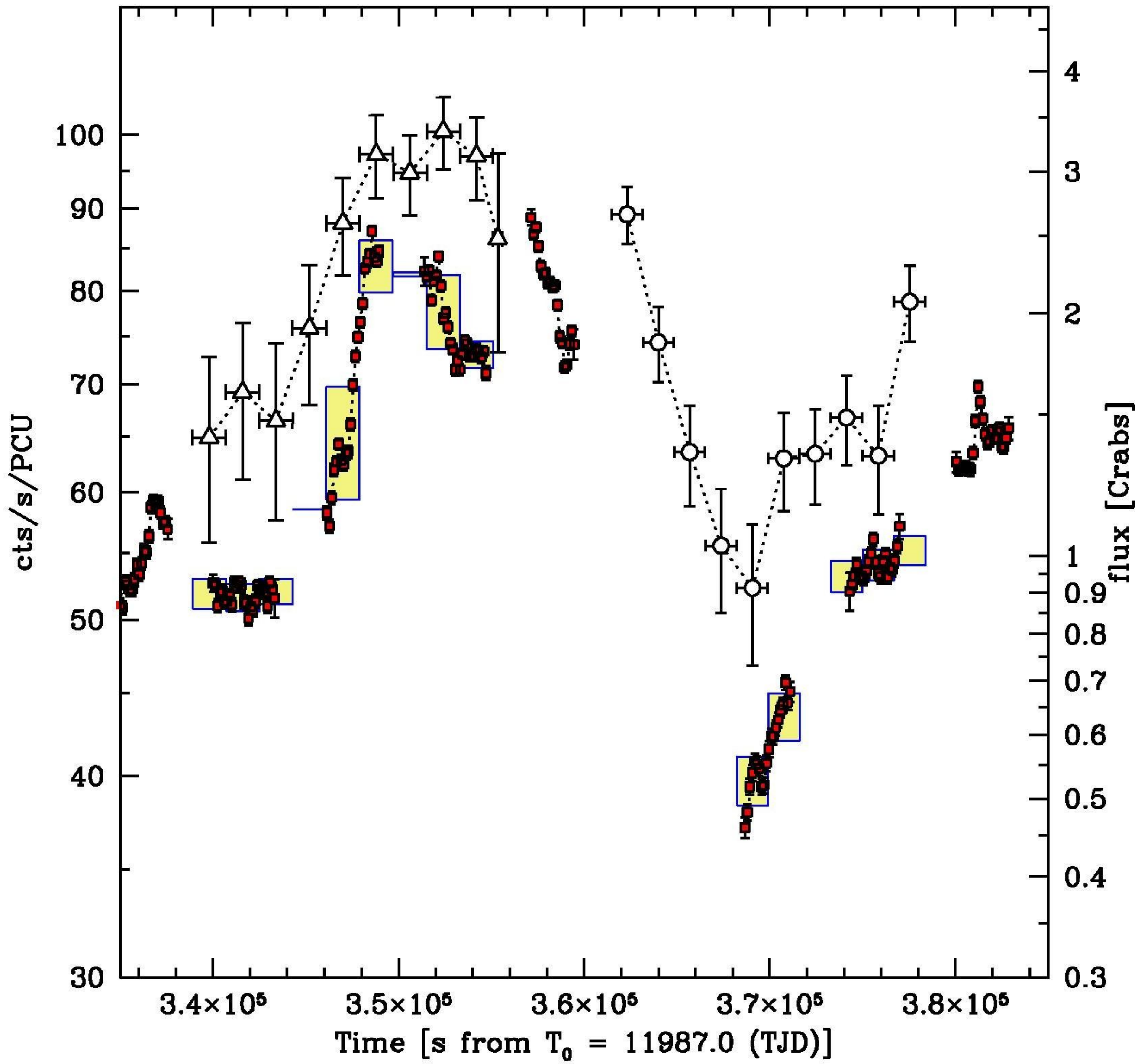
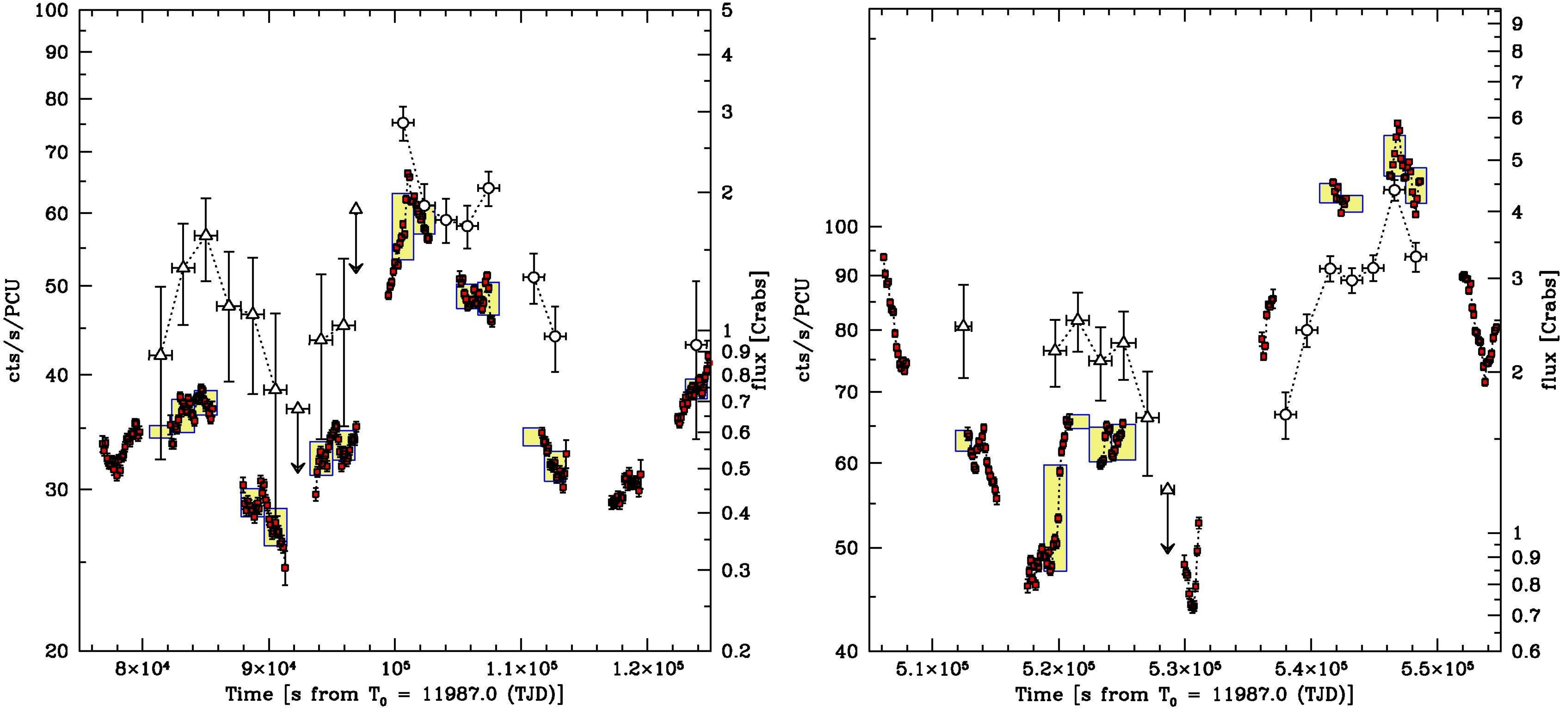



(Fossati et al. in preparation)

# X-ray/TeV light curves gallery: *good*

[RXTE & Whipple data for March 20 and 25, 2001]



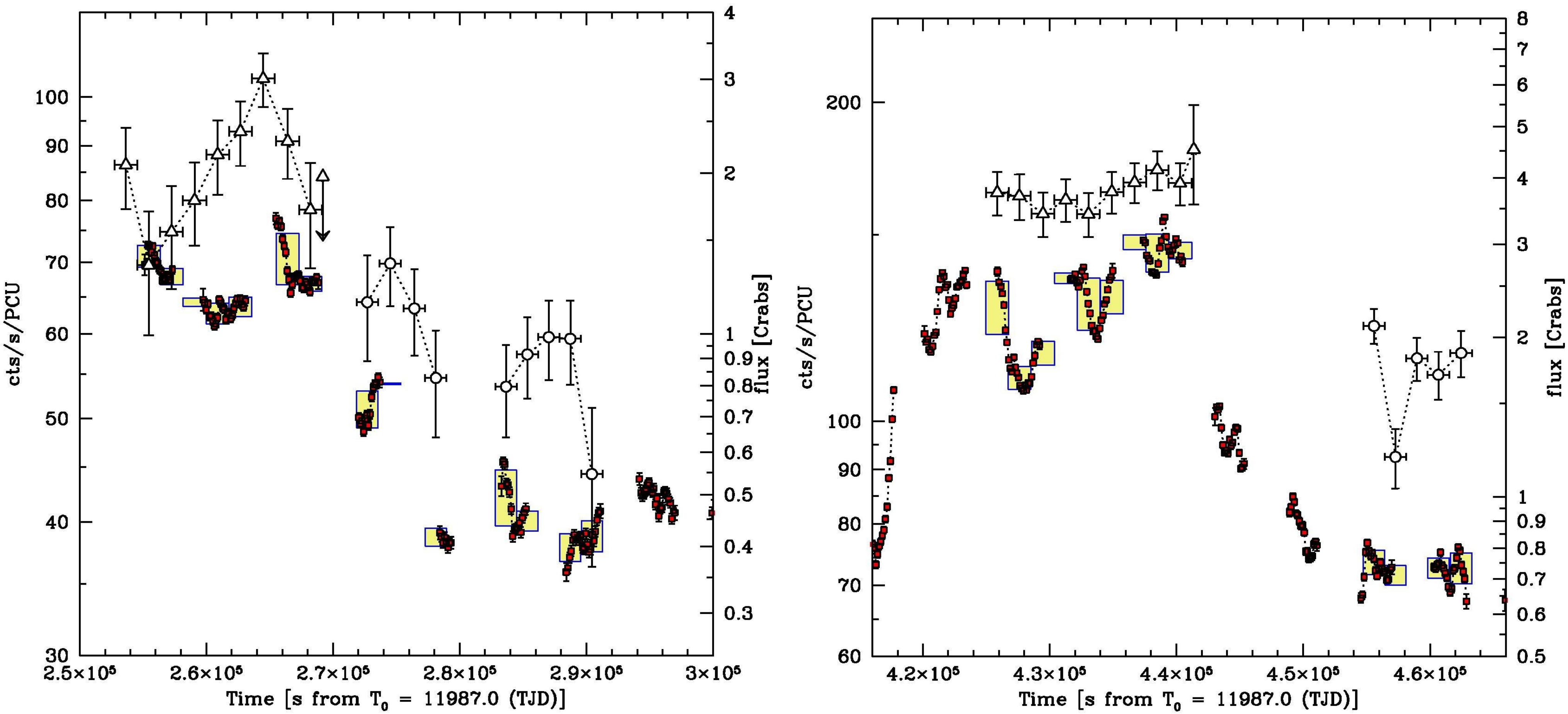

- The <u>white symbols</u> are the Whipple/HEGRA (TeV)28 min. runs data.
- Dark/red colored points are RXTE/PCA (x-ray) 2-10 keV in 128 sec bins.
- <u>Yellow boxes</u> are the RXTE/PCA x-ray data binned over the TeV light curve bins.



(Fossati et al. in preparation)

# X-ray/TeV light curves gallery: *poor*

[RXTE & Whipple data for March 22 and 24, 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.
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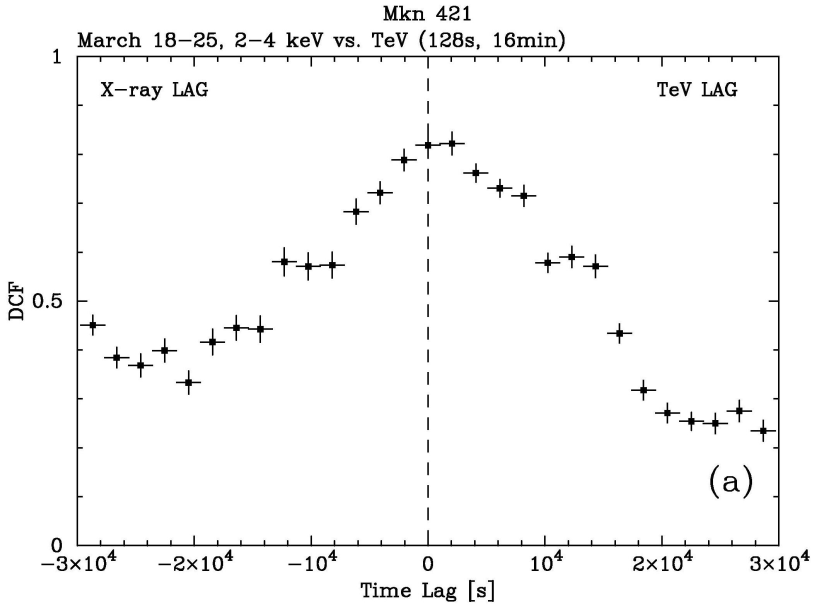
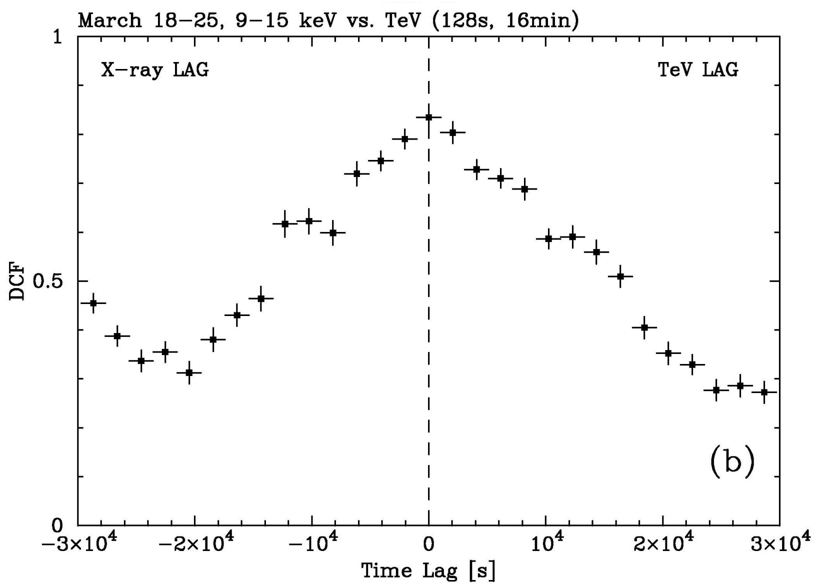
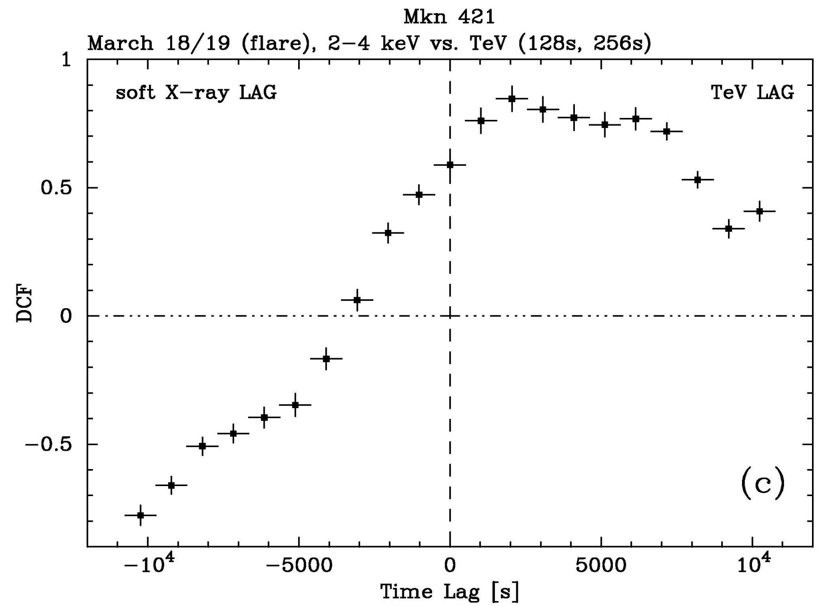
(Fossati et al. in preparation)

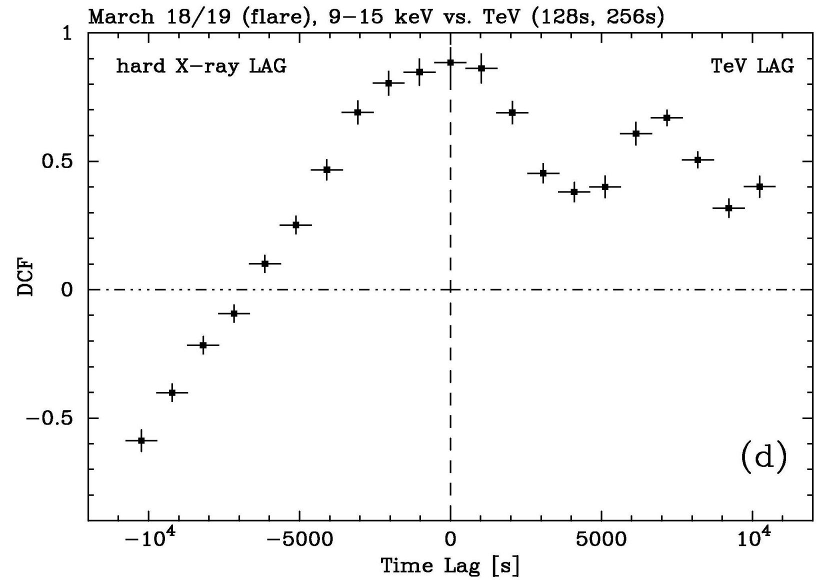
# Discrete Correlation Function: x-ray/TeV




*These are DCF in 2ks bins for two different x-ray bands: top, 2-4 keV, bottom, 9-15 keV*



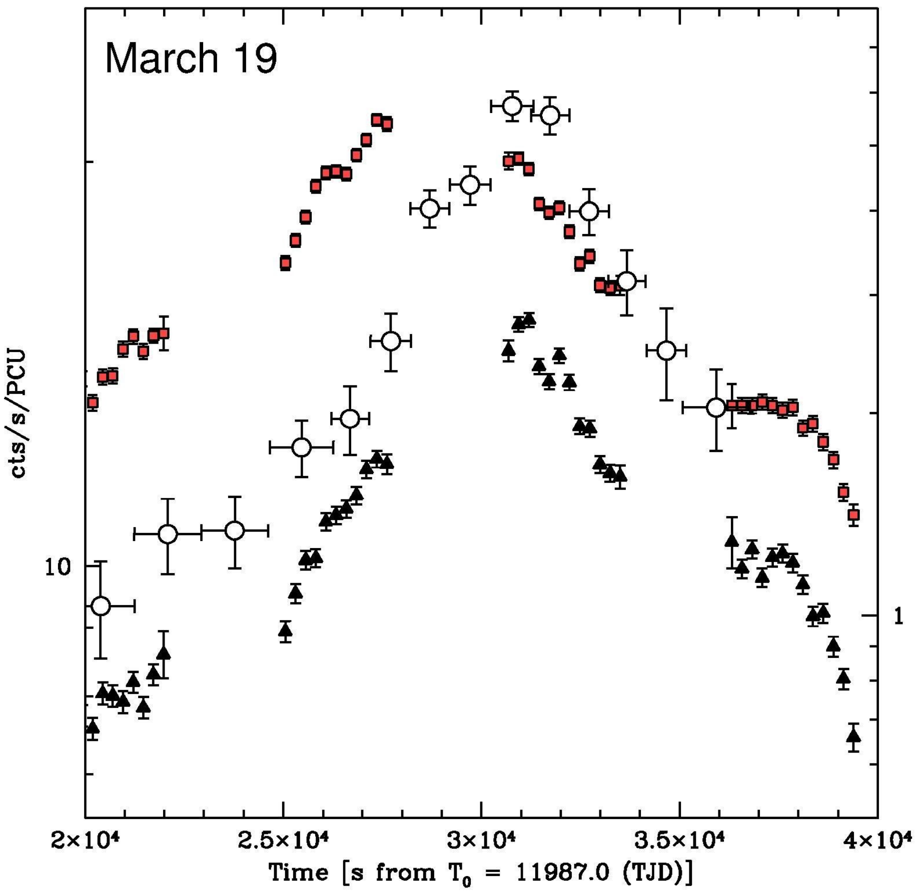

Cross-correlation of the full week-long TeV and x-ray light curves also does not yield any lag-detection.

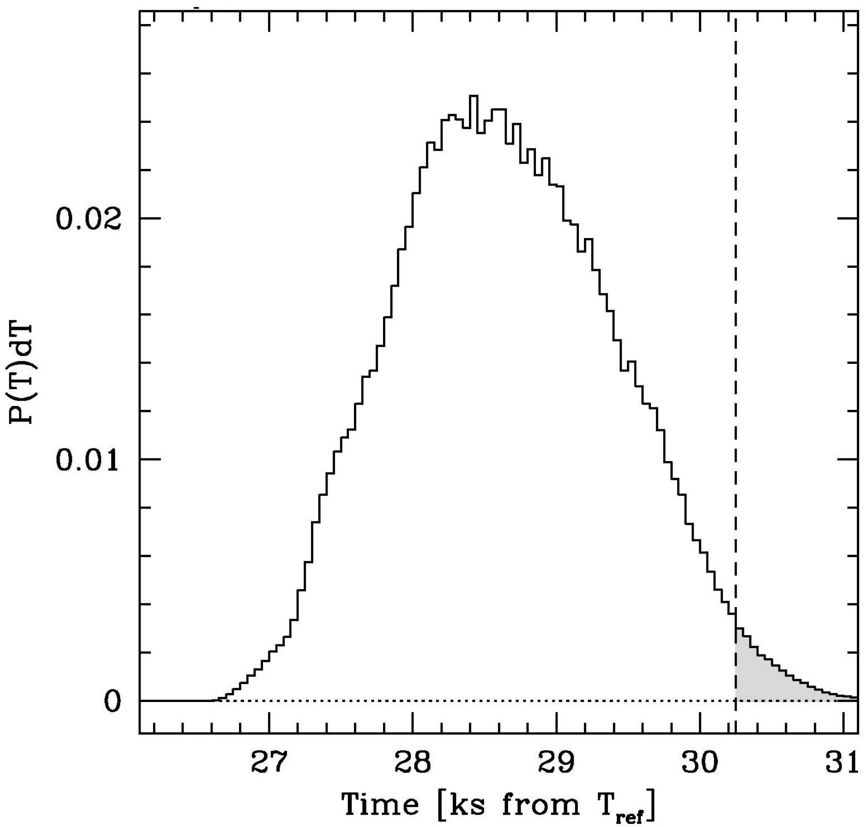
Focusing on the March 19$^{th}$ flare there is a hint that there could in fact be a lag between the TeV and (softer) x-ray variations.

(Fossati et al. in preparation)

# TeV lagging soft x-ray on March 19th ?

We have tried to look at the March 19th event in depth, applying a novel technique based on the general statistical properties of the x-ray data (and a good deal of –reasonable-- assumptions). The result is that the data are consistent at 98% level with the TeV flare peak lagging the soft x-ray variation (but fully consistent with simultaneity with the harder x-ray band).



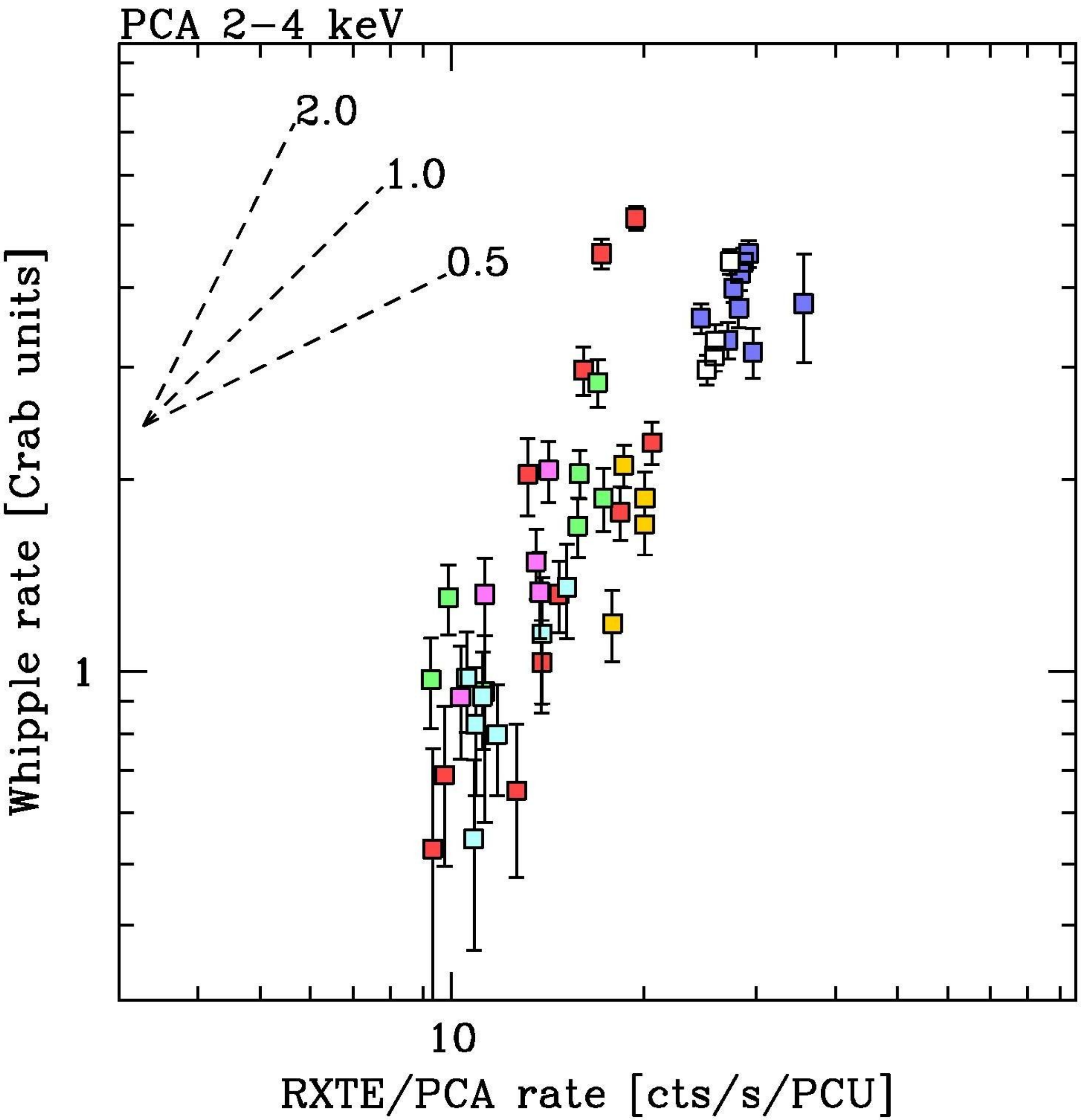






(Fossati et al. in preparation)

# Flux-Flux amplitude correlation (I)

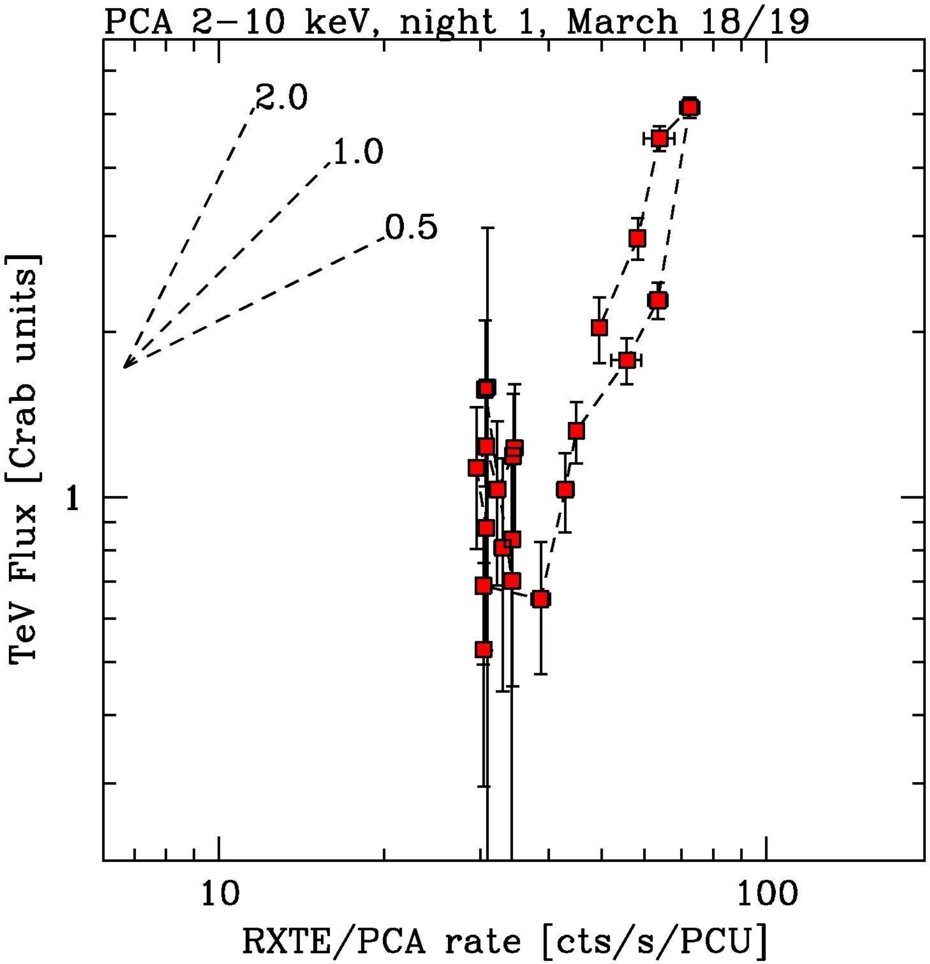
[all March 2001 Whipple data]

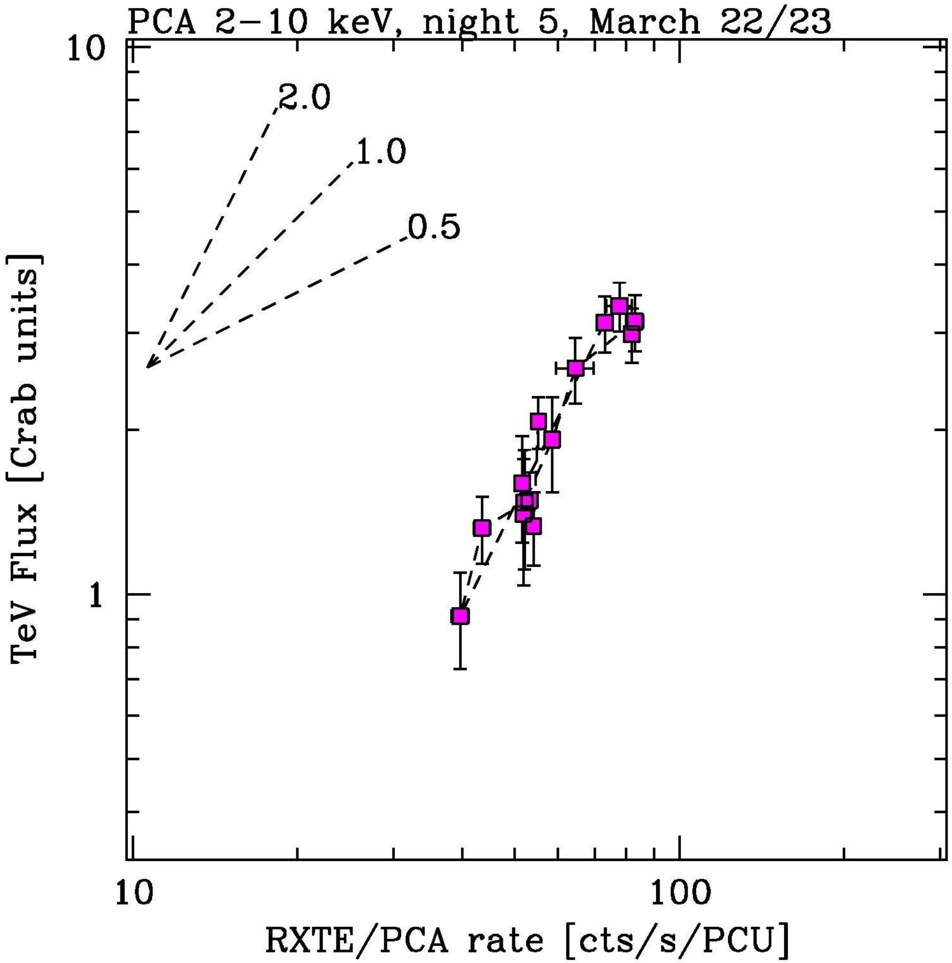



- Fluxes are highly correlated.
- The slope of the correlation seems to change with energy (not discussed here) but overall the **relationship is QUADRATIC.**

# Flux-Flux amplitude correlation (II): best cases

[Whipple & HEGRA data]



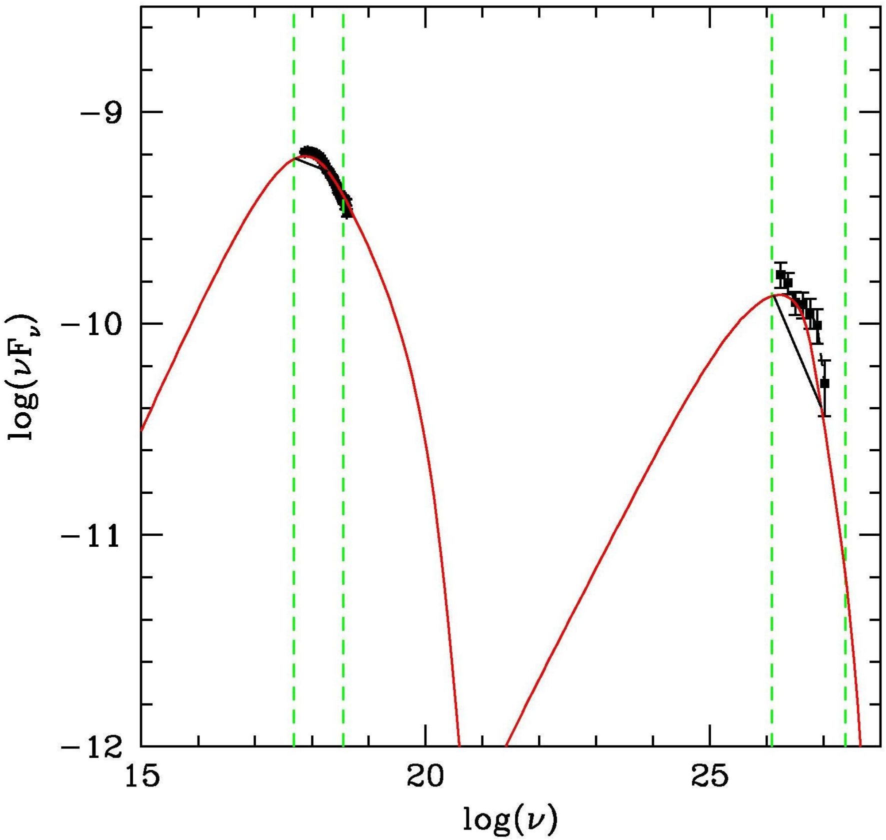



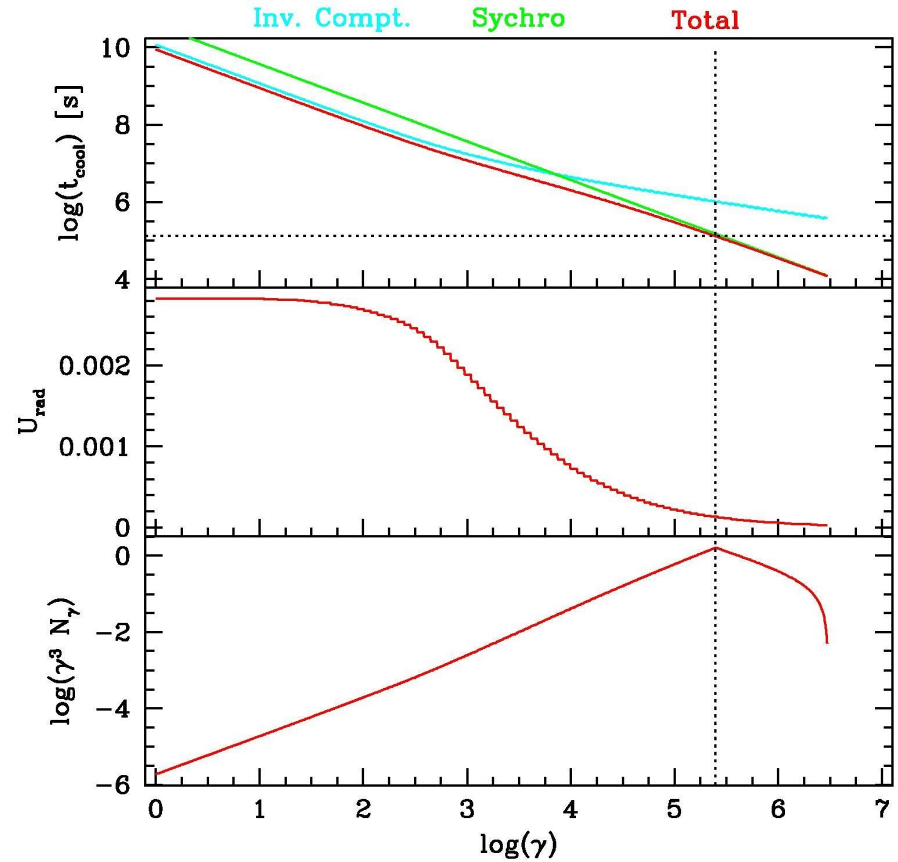

- The Flux-Flux plots for the best two “nights” confirm the correlation.
- With one important additional piece of information: the source traces the **same** (quadratic) **track on the rise and decay phases** of the flares.



(Fossati et al. in preparation)

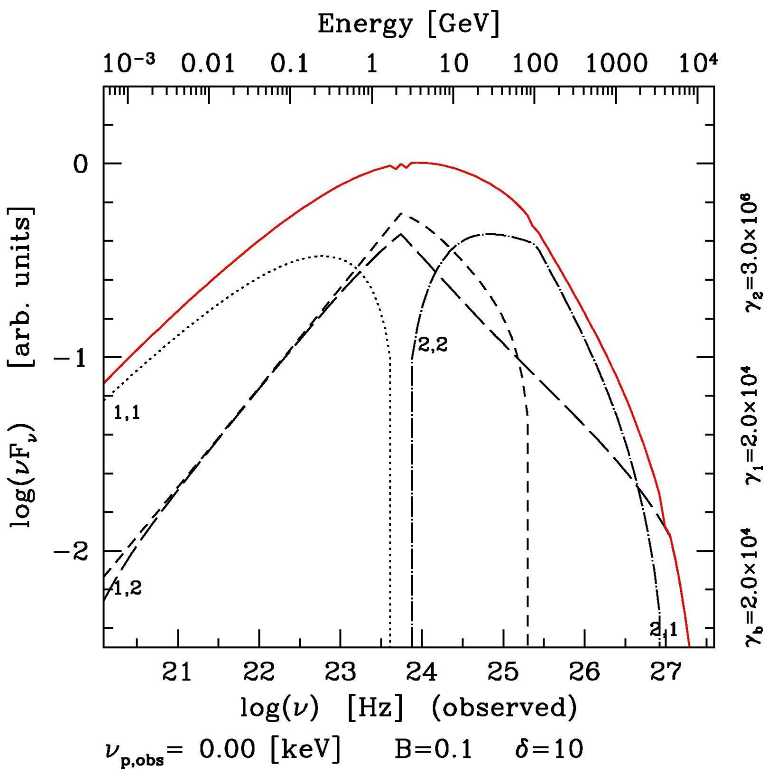
# Modeling: plain SSC and "the comfort zone"



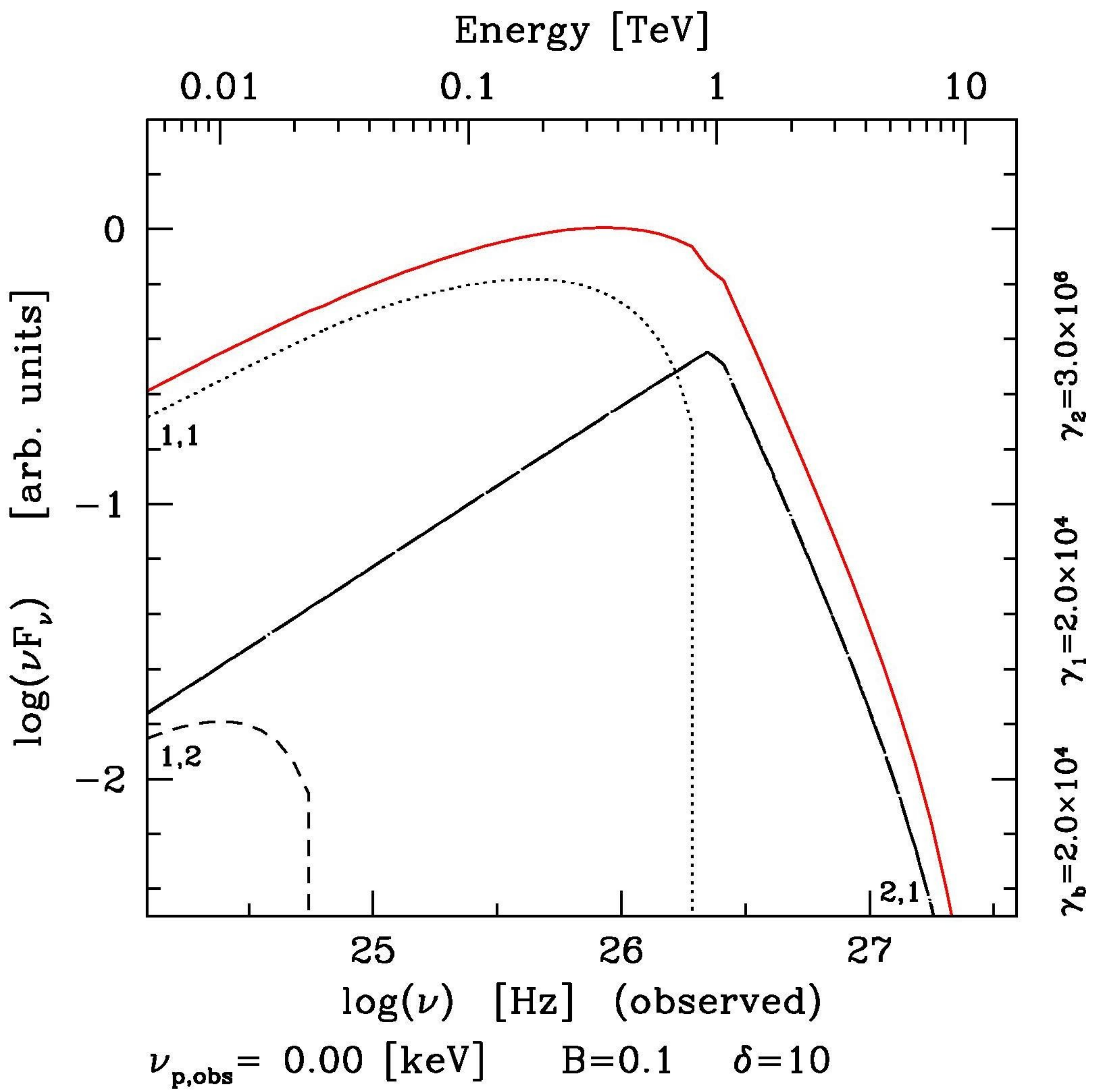




- SSC blob-in-jet model, applied to the data of the March 22-23 night, HEGRA spectrum (Aharonian et al. 2002).
- In the right panel <u>bottom</u> to <u>top:</u>
  - Electron distribution (multiplied by energy$^3$) to show its features more clearly.
  - Radiation energy density "available" for each electron energy (shaped by the K-N cross-section cutoff).
  - Electrons cooling times are consistent with the observations.

# The SSC “de-composition” and the Klein-Nishina regime

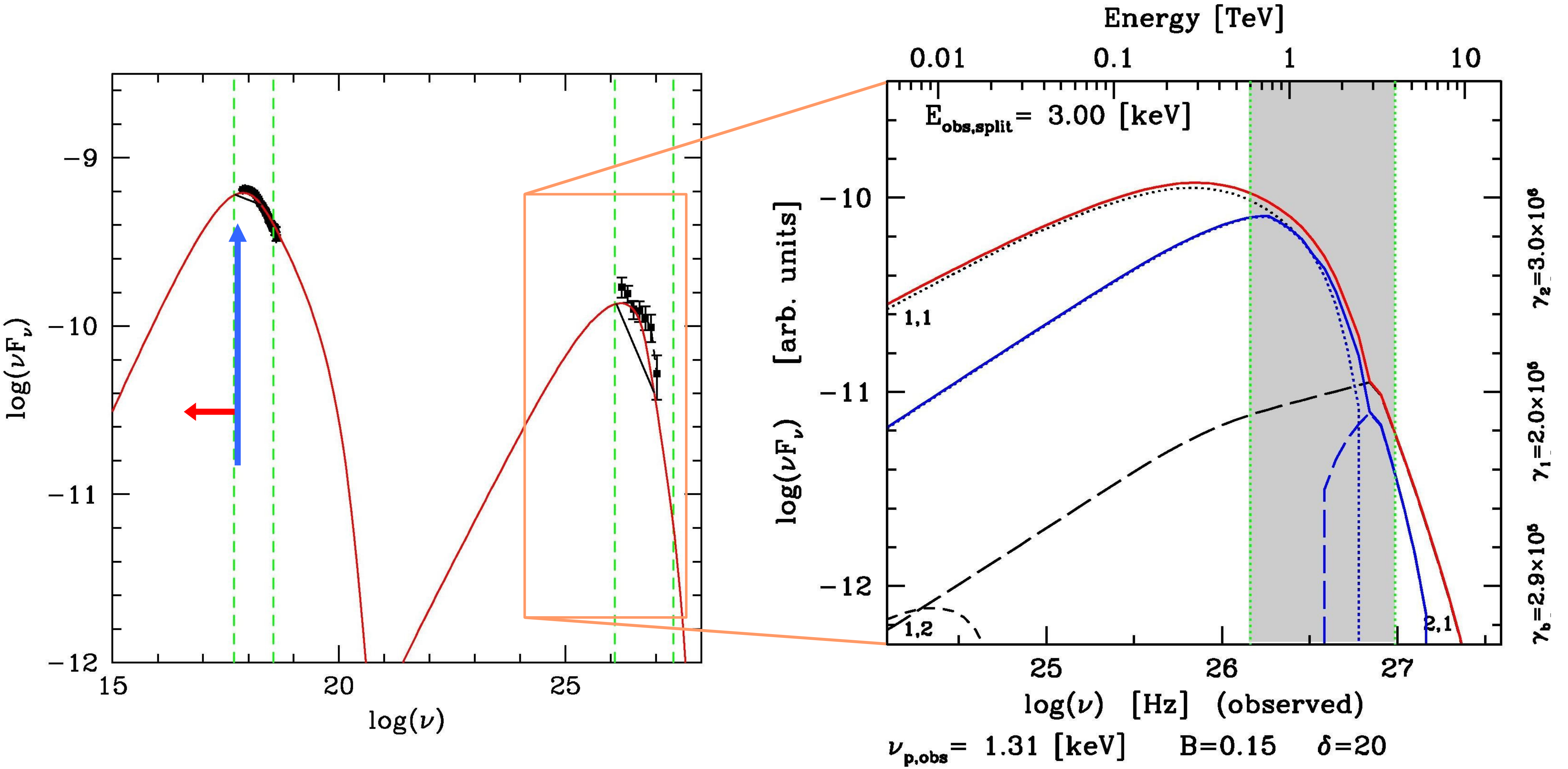



- Example of inverse Compton peak without any Klein-Nishina effect.




- Inverse Compton peak WITH signature of Klein-Nishina effect.

# Modeling: finding the seed photons




- SSC blob-in-jet model, applied to the data of the March 22-23 night, HEGRA spectrum (Aharonian et al. 2002).
- In the right panel the IC peak split in its “components”:
  - The **blue lines** are the IC with the **10-100 eV** synchrotron photons.
  - Electrons are split at 3 keV.



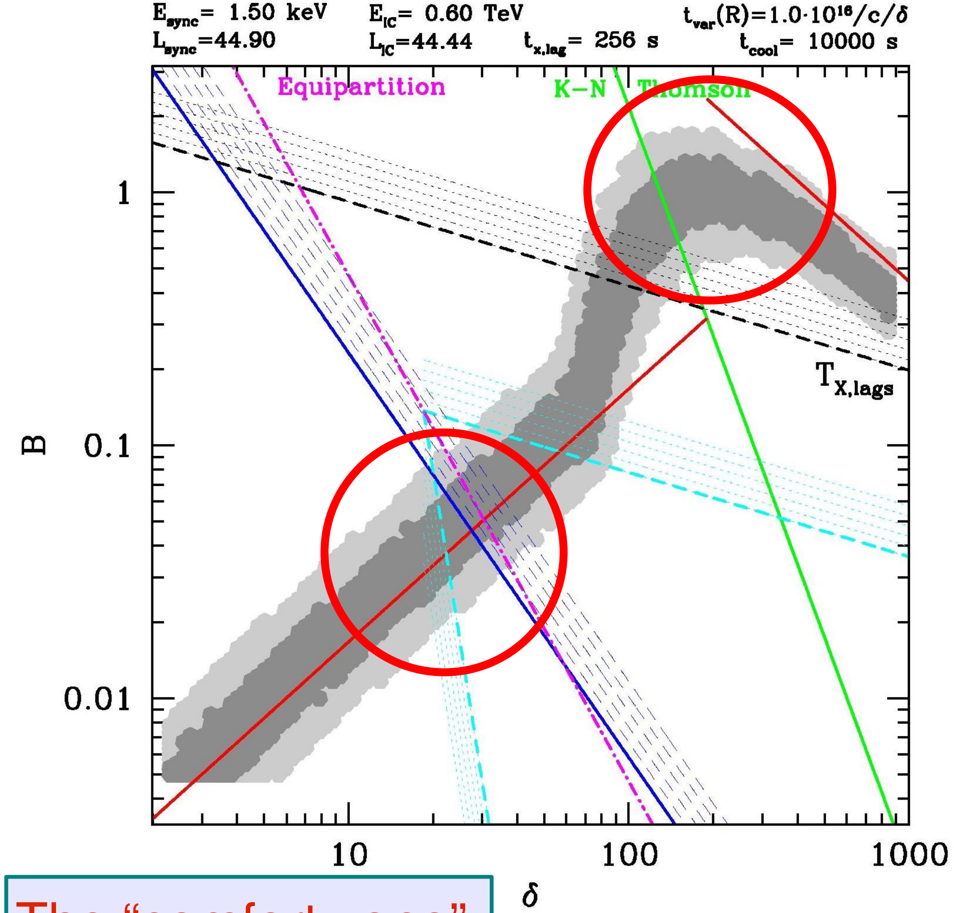
(Fossati et al. in preparation)

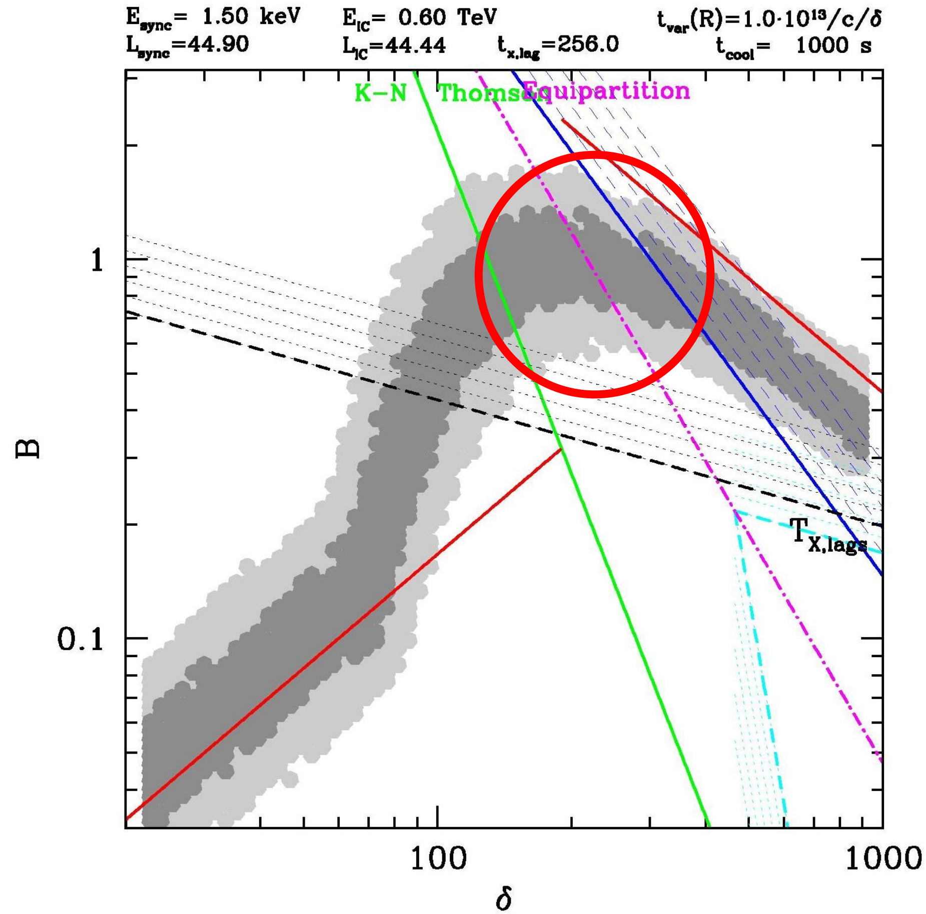
# Exploiting the observational findings

- We can "measure" the position of the synchrotron and Compton peaks.
- We can do it in a time resolved fashion.
- SSC models have been very successful at reproducing "snapshot", or average SEDs, but the addition of detailed flux-flux, phase and amplitude correlations, brings a tough challenge to the table.
- The most important *apparent* requirement to satisfy is to have the TeV peak emitted in **Thomson regime**.

# Exploiting the SSC built-in constraints

In the SSC framework, the measurements of the synchrotron and IC peak energies and luminosities determine a locus for a given SED in the $\delta$-B plane.
Additional constraints (preferences?) can be expressed as a function of $\delta$-B and drawn in this diagram.



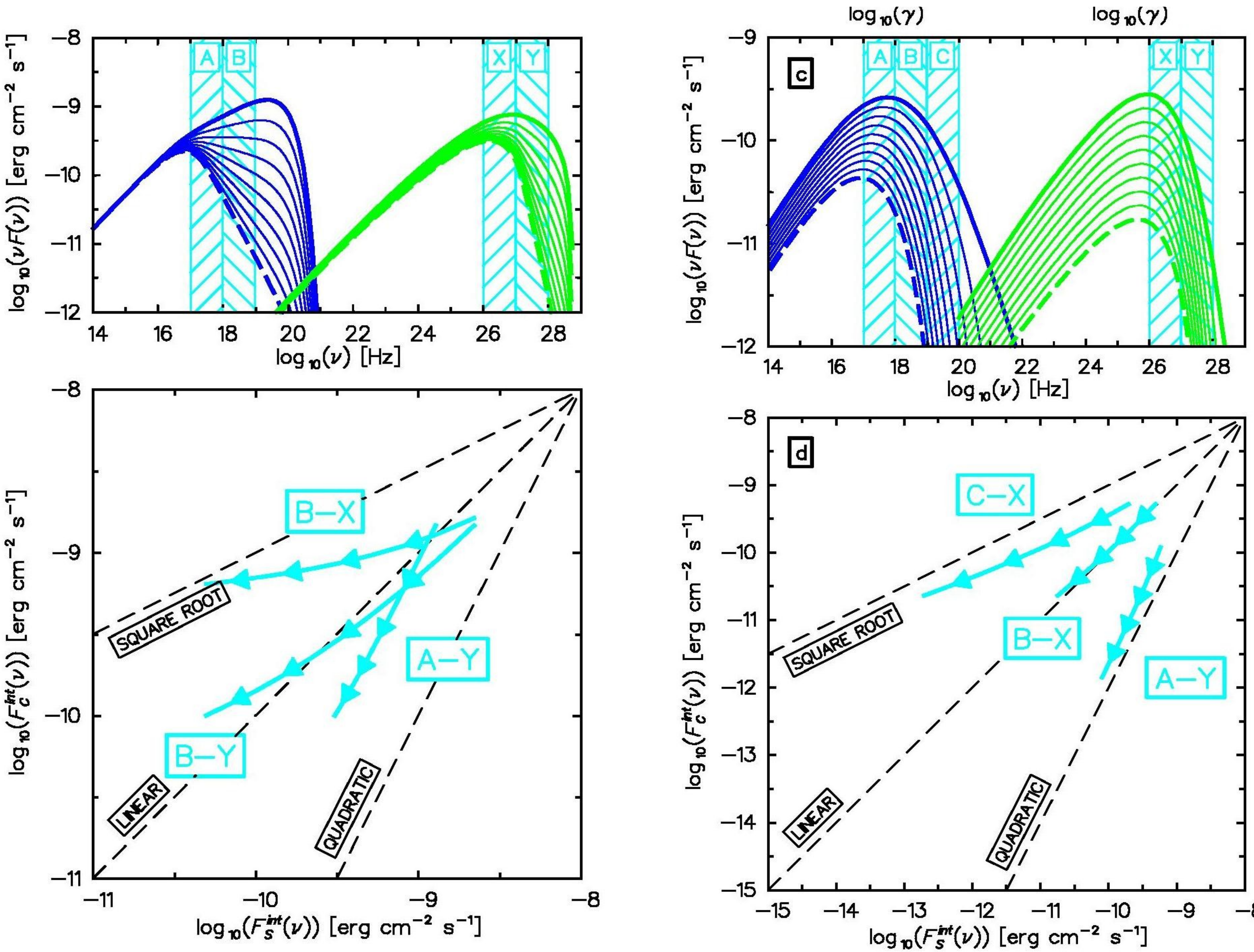

The "comfort zone":
B~0.1 $\delta$~20

**Small blob** and **very large Doppler** factor would shift all constraints into the Thomson regime region.

(Fossati et al. in preparation)

# Modeling the flux-flux correlation

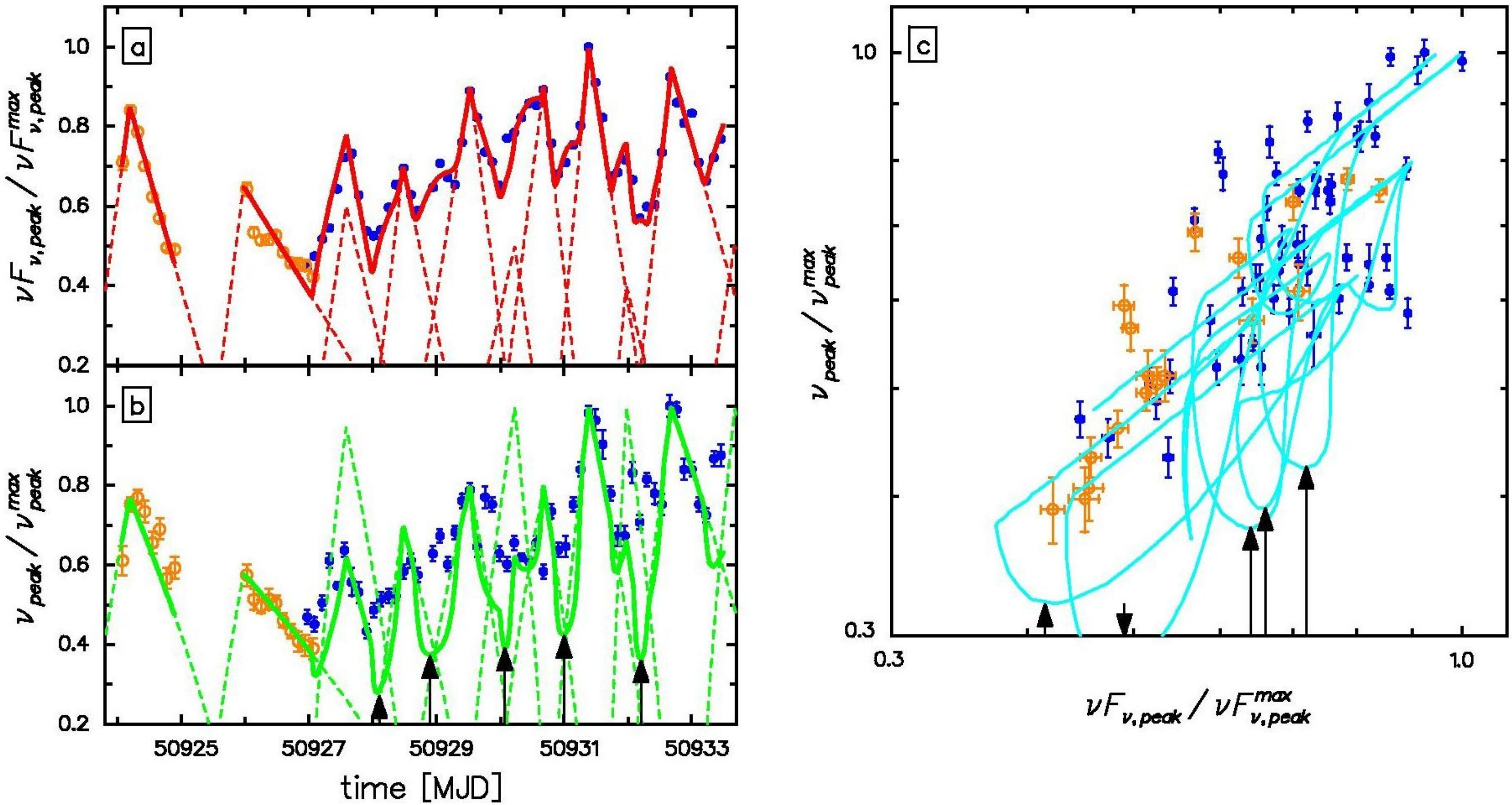
Katarzynski et al. (2005) performed an in-depth analysis of what conditions (physical and observational) would combine to produce the observed quadratic correlation during the decaying phase of a flare.  It requires very contrived assumptions.




(Katarzynski et al. 2005)

# Modeling the peak-flux correlation

Katarzynski et al. also addressed the $E_{peak}$-$F_{peak}$ correlation with the simplest possible scenario, often discussed in the context of blazar variability studies, namely that the light curve is comprised of several random "shots". The spectral data would seem to rule out a basic *implementation* of this scenario. It would fail to produce the observed correlation across multiple flares.




(Katarzynski et al. in 2006)

# 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.
  - Hard to reproduce this correlation in a “shot” scenario for variability.
- **X-ray/TeV correlated variability**:
  - No intraband x-ray lags (<128 seconds)
  - X-ray and TeV light curves correlated with lag shorter and 2 ks.
  - Flux-Flux x-ray/TeV correlation is quadratic going up and down flares.
  - Challenging for standard one-zone model conditions, which would require substantial fine tuning in order to produce this correlation throughout a flare.
- “Crisis” (?) of the pure synchro-self-Compton (SSC) model