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TESTING LIV WITH VHE GAMMA-RAYS
CTA Perspectives

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Sections

- **Quantum Gravity: Lorentz Invariance Violation**
- **Vacuum Refractive Index: Time-of-Flight Experiments**
  - Current Results from AGNs and GRBs
  - Methodology of the tests
- **Unbinned Algorithms: Optimising LIV Searches**
- **Kolmogorov Metric**
- **Sensitivity & Data Analysis: PKS 2155-304**
- **Search by-products:**
  - Magnetic Fields
  - Particle Acceleration in Jets
- **CTA Discussion**

Lorentz Invariance

Lorentz Invariance is one of the fundamental symmetries of nature, describing how the laws of physics transform between inertial frames.

Lorentz invariance is preserved both by General Relativity (in its local form) and Quantum Mechanics (Jordan-Pauli, 1928)

- Landau & Lifshitz (Field Theory; Ellis+00)

$$G_{00} \equiv -h\,, \quad \mathscr{G}_i = -\frac{G_{0i}}{G_{00}}\,, \quad i = 1, 2, 3\,.$$

static (diagonal) gravitational field, h

\+ non-diagonal comp's g_{0i}

$$\nabla \cdot \boldsymbol{B} = 0\,, \quad \nabla \times \boldsymbol{H} = \frac{1}{c}\frac{\partial}{\partial t}\boldsymbol{D} = 0\,,$$

$$\nabla \cdot \boldsymbol{D} = 0\,, \quad \nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial}{\partial t}\boldsymbol{B} = 0\,,$$

, where

$$\boldsymbol{D} = \frac{\boldsymbol{E}}{\sqrt{h}} + \boldsymbol{H} \times \mathscr{G}\,, \quad \boldsymbol{B} = \frac{\boldsymbol{H}}{\sqrt{h}} + \mathscr{G} \times \boldsymbol{E}\,.$$

Thus:

$$k^2 - \omega^2 - 2\overline{U}k\omega = 0$$

dispersion relation

$$c(E) = c(1 - \overline{U}) + \mathcal{O}(\overline{U}^2)$$

non-trivial refractive index

LIV in Quantum Gravity

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Uncertainty Principle:

$$\Delta x . \Delta p \approx \hbar$$

But Heisenberg's description do not take into account the mass(-energy) content of the electron m/c^2, and in the e^- - γ interaction gravity will introduce an acceleration that will correspond to further position uncertainty for e^-.

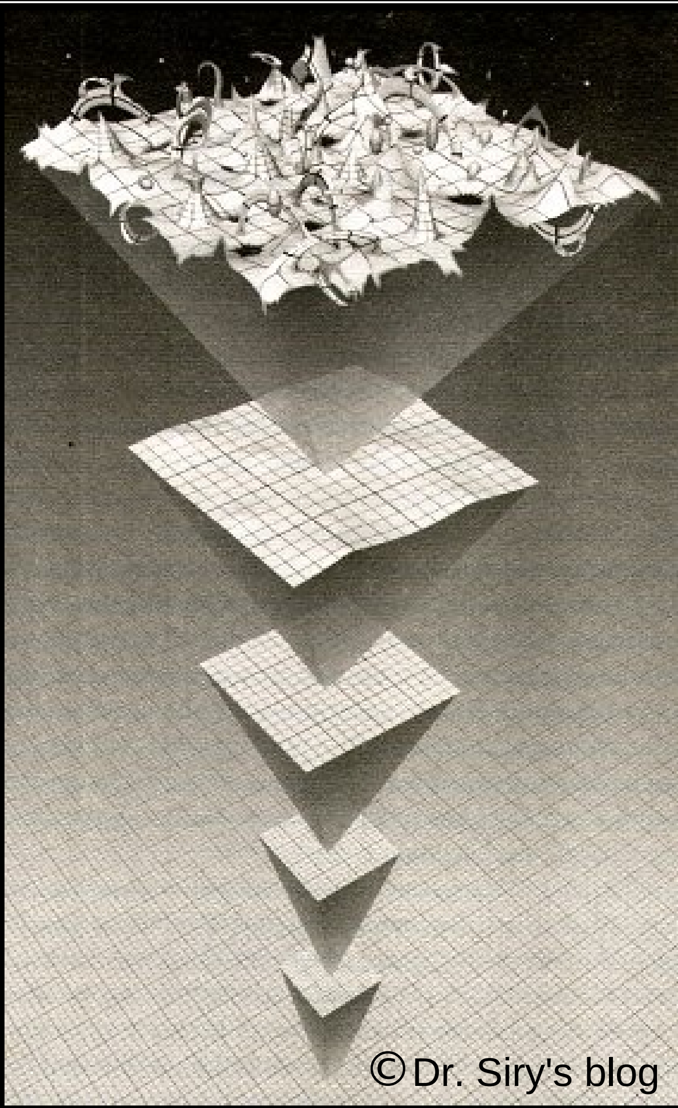
Modified Uncertainty Principle:

$$\Delta x \approx \frac{\hbar}{\Delta p} + L_p^2 \frac{\Delta p}{\hbar} .$$

(Adler+Santiago '99)

Here, the new term corresponds to a fluctuation in the metric δg that will give out the picture of foamy space-time. The scale in which this happens is

$$\Delta x_{\min} \approx 2\sqrt{\frac{G\hbar}{c^3}} = 2L_p$$



Wheeler, 1950's
quantum foam

Time-of-Flight Experiments

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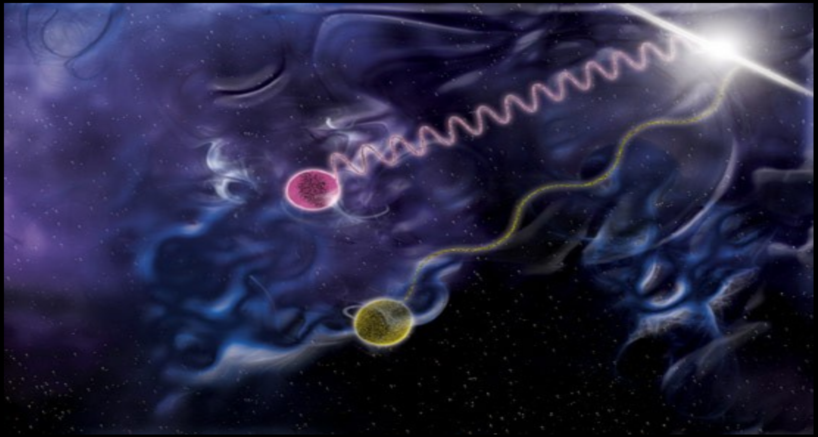

- Magnitude of the energy-dependent variation in c is very small for typical VHE photons (1TeV)

$$\delta c \sim E/E_P \sim \lambda/L_P \approx 10^{-15} c$$

- But propagation over cosmological distances will magnify the effect and a difference on the arrival time of photons E_1 and E_2 will be:

$$\Delta t \approx \xi \frac{E}{E_{QG}} \frac{L}{c}$$

(Amelino-Camelia+98)

Where $\xi = E_{QG}/E_P$ determines the energy-scale for break of Lorentz Invariance and is the quantity to be tested by experiments ($E \ll E_{QG}$)

$$c^2\mathbf{p}^2 = E^2[1 + \xi E/E_{QG} + O(E^2/E_{QG}^2)]$$,to second order terms only.

Time-of-Flight Experiments

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- An appropriate estimate of the energy-scale parameter ξ must take into account cosmological expansion and the right expression to be used is:

$$\Delta t = \frac{\Delta z}{H_0} = \frac{1+n}{2H_0}\left(\frac{E_0}{\xi E_{pl}}\right)^n \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

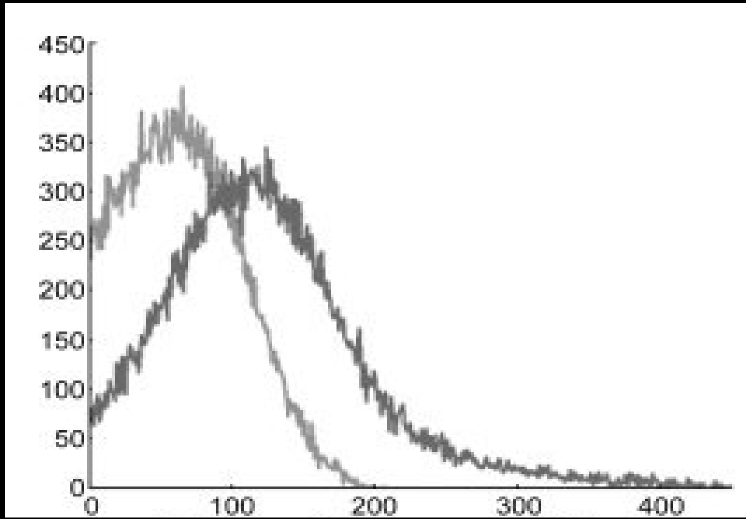
, to the n[th] order of the perturbation

(Jacob+Piran'08)

- For a TeV source like PKS 2155-304 (~ 500 Mpc), for example, the first order effect expected is of ~ 5s, since the first order term, of the delay is estimated to be:

$$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_P H_0}\int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

$\approx$ **10ξ s/Gpc.TeV**



Thus the need to observe sharp transient features in the light curve of distant sources to detect the expected dispersion

The sub-Planckian Fermi limit: GRB 090510

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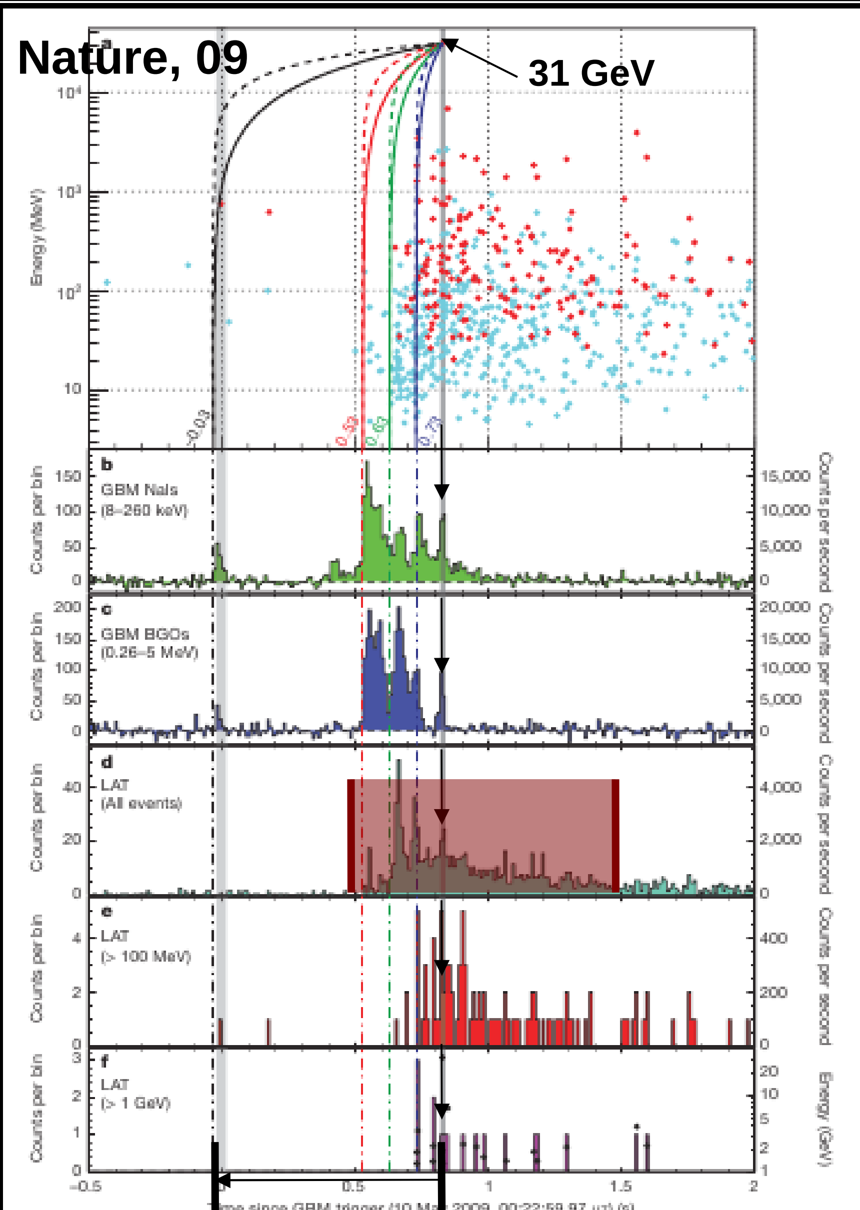


This was a distant, short GRB (z ~ 0.9; $d_L \approx 5$ Gpc) observed by Fermi with a maximum photon energy of ~ 31 ± 5 GeV.

Using a *dispersion cancellation* algorithm (Scargle+ '08) a negative result on energy-dependent dispersion was obtained:

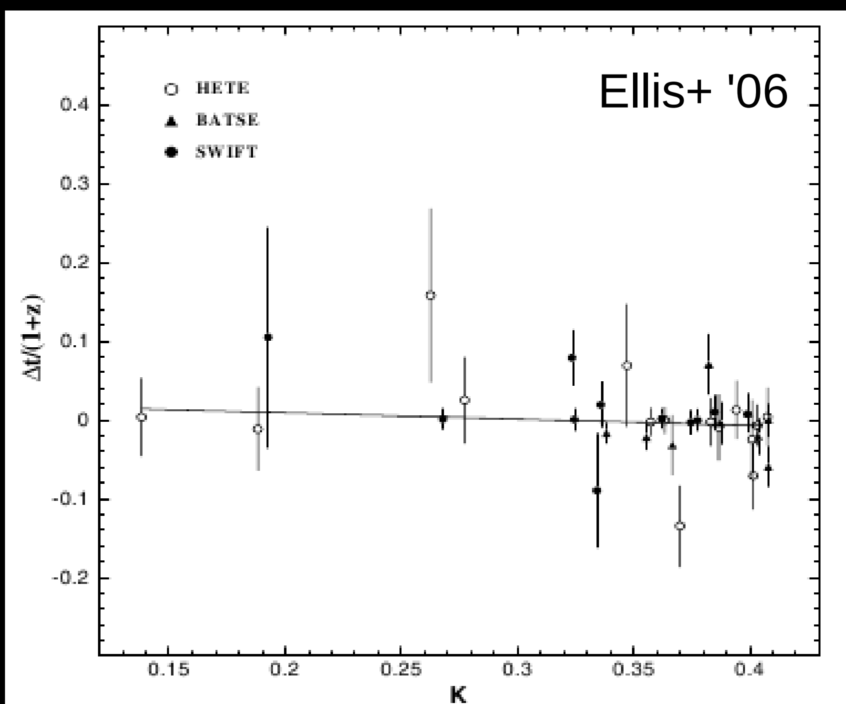
Δt/ΔE < 30 ms/Gev, and
ξ > 1.22

- Intrinsic lags for short bursts at keV-MeV energies are very small (~ 10 ms), which is of the order of the spike widths.
- The measurements strongly disfavour any model of Planck-scale physics which cause a linear (n=1) variation of the speed of light with energy.

But n > 1 effects are still to be tested and this still only one measurment

Robust LIV Limits from GRBS: population sampling

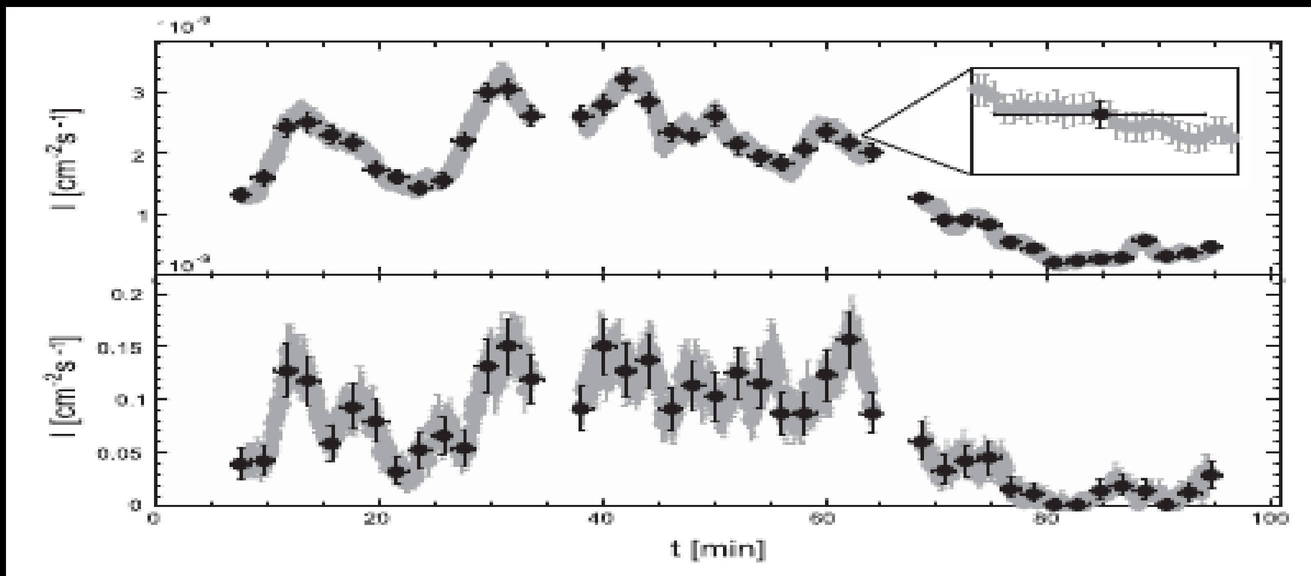
- **A propagation-dispersion model make specific predictions on the dependence between the magnitude of the lags and the distance to the source**
- **This fact can be used to separate extrinsic from intrinsic effects and account for “spurious” non-systematic contributions to a single measurement that the observer could be unaware of or could fall out of his control.**



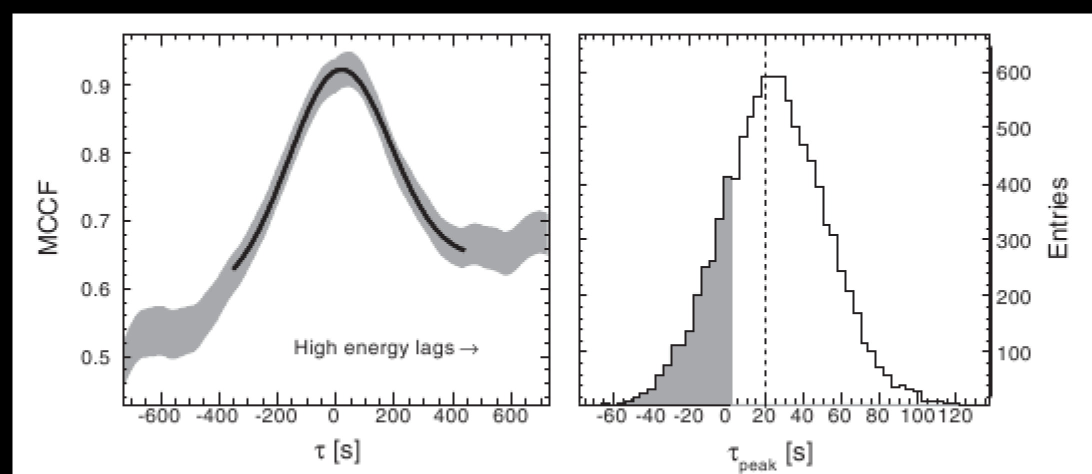
A combination of different types of sources, such as AGNs and GRBs, or a long vs. short GRB analysis is clearly an important addition to the tests, still to be conducted.

VHE Astronomy: The situation with AGNS

HESS '08 (PKS 2155-304):



$$|\xi|^{-1} E_p > 7.2 \times 10^{17}\ \mathrm{GeV}$$



A few notes on methodology

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- The detection of an energy-dependent dispersion is limited mainly by the **'sensitivity factor'** pointed out by Amelino-Camelia+98

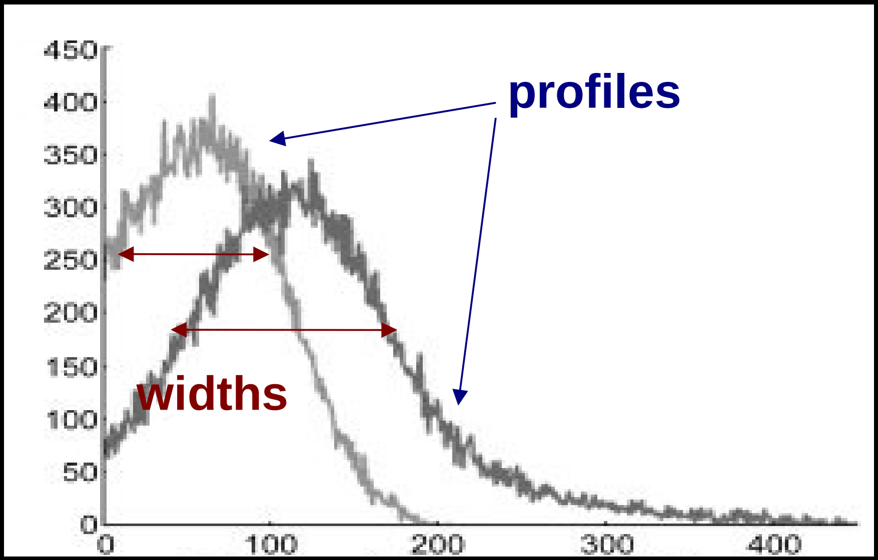
$$\eta \equiv \Delta t/\delta t = \frac{\text{delay}}{\text{burst width}}$$

- Since usually is the case that delay << burst width (by over an order of magnitude!) one wants to probe the maximum temporal resolution of the light-curve by using **unbinned methods**.

- The great limitation in these methods come from **energy resolution**, and an optimal method is one that is least dependent on this factor.

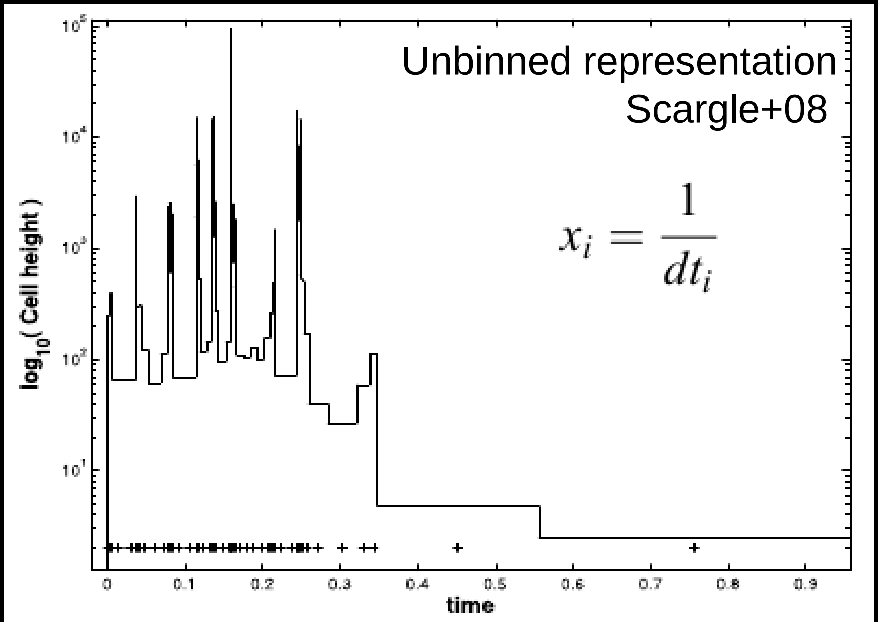
- Usually, the emission mechanisms at the source are poorly known, and even observational parameters such as emission spectrum can contain many systematics and model dependencies and we prefer to concentrate on **non-parametric tests** (i.e. not likelihood methods based on a “model” to the light curve – Martinez+Errando 2009)

The how-to of non-parametric approaches



→ The delay is always an assymetric effect in time, whose result will be to **disperse the light-curve, broadening** it.

→ This assymetry will have another systematic effect which is to change the **shape of the profile, skewing** it, and this skewing will be larger at higher-energy bands.



Optimal unbinned methods use *dispersion cancelation* algorithms (Scargle+08, Ellis+08)

$$t_i' = t_i^{\mathrm{obs}} - \theta E_i^{\mathrm{obs}}$$

Choice of Cost function

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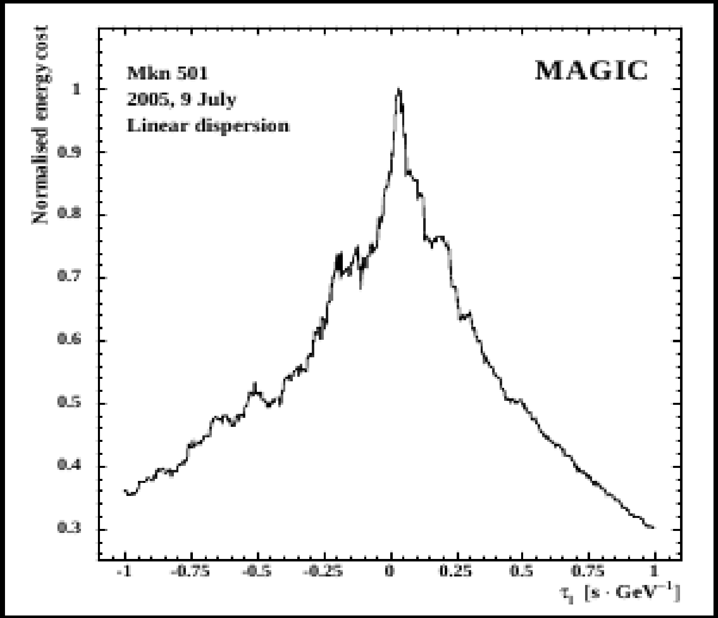
The cost-function is a choice of measure to describe the undispersed state of the light-curve

Typical cost functions try to maximise a sharpness-related quantity, such as:

1. The total photon-energy inside a window around the peak of the transient feature:



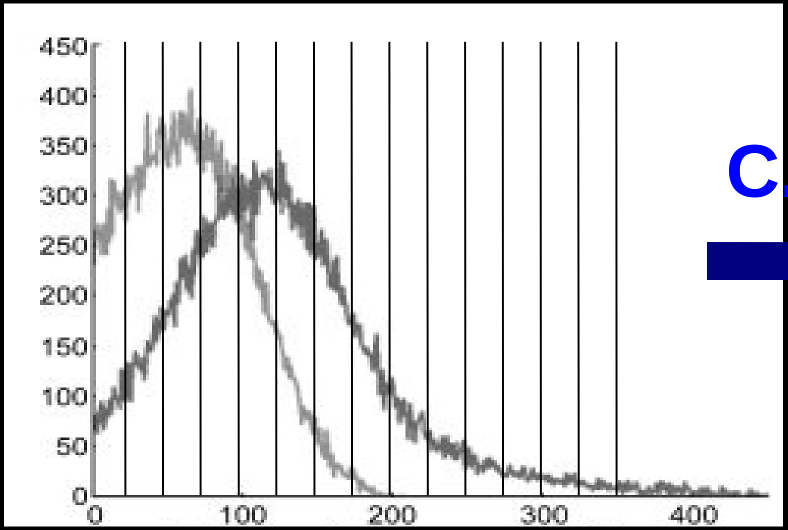
2. The total entropy of the distribution, which decreases for sharper distributions (Scargle+08)

$$p_n = \frac{x_n}{\sum x_n}$$

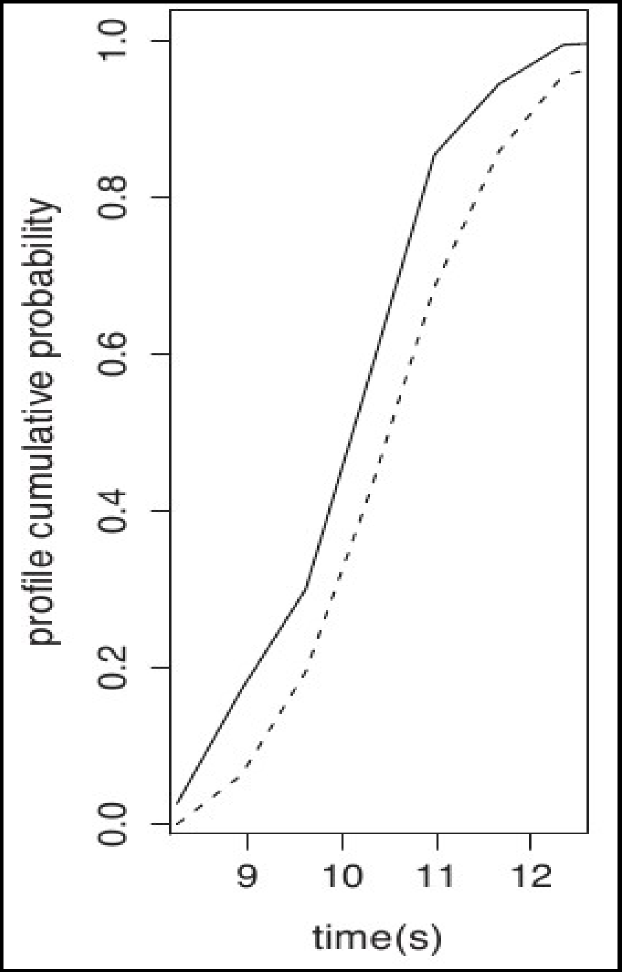
$$I(\text{Shannon}) = \sum p_n \log p_n$$

Kolmogorov Metric

- **A new approach to a choice of cost function, which looks into the discrepancy between the high and low-energy burst profiles.**



C.D.F.



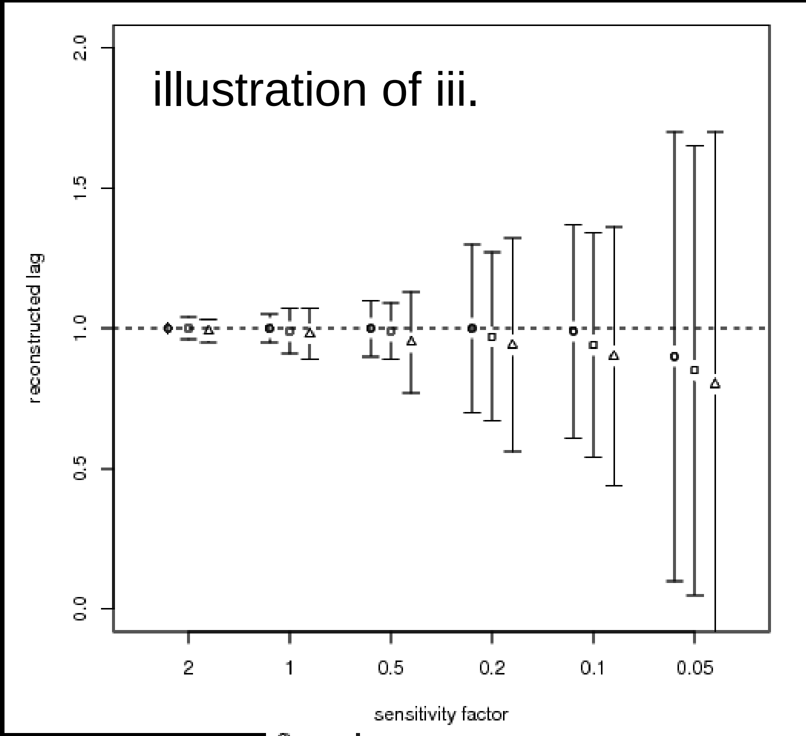
$$D_K \equiv \sup_{x \in \Re} |F_X(x) - F_Y(x)|,$$

$$\tau^* : D_{K,\tau^*} = \min_{\tau} \sup_{x \in \Re} |F_X(x) - F_Y(x)|$$

Kolmogorov Metric

- **The advantages of a metric-minimisation approach are three-fold:**

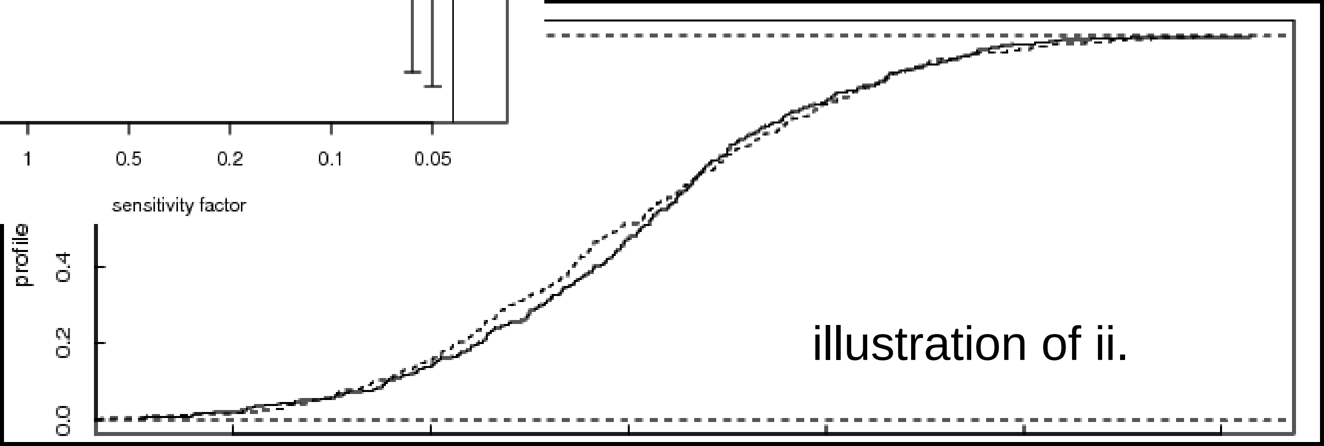
the minimisation of the CDF discrepancy is



i. a <u>fit to the entire profile</u> with a <u>natural weight</u> towards the most transient part of the profile;

ii. because it <u>"averages over"</u> the data set twice min(sup(X-Y)) it suffers less from statistical fluctuations and works with very small number of events;

iii. It turned out to be very little sensitive to the limitations on the <u>energy resolution</u>.



Relation to other cost functions

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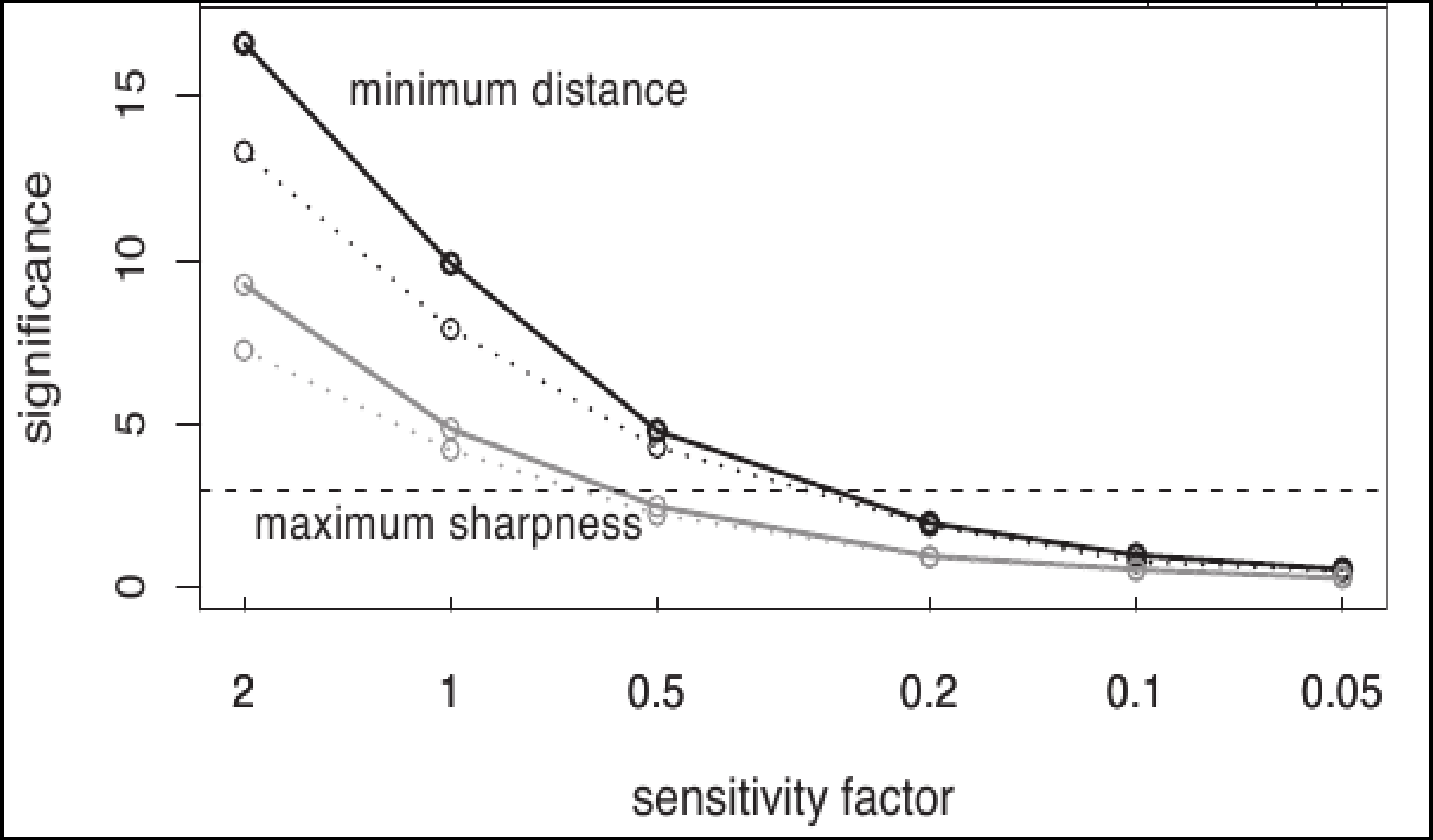

Application to HESS data: Analysis of PKS 2155-304 large flare

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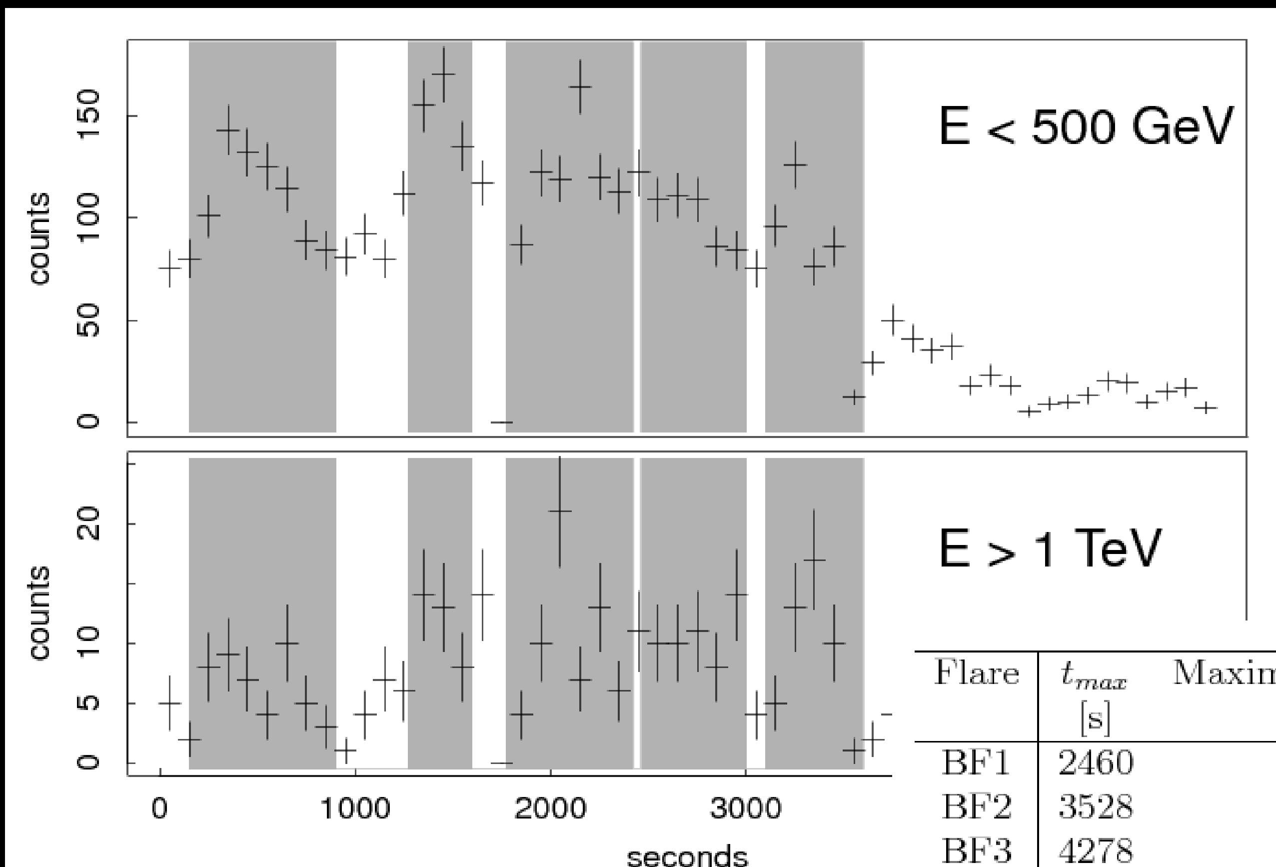
- **Over 10,000 events registered in ~ 90 min, and time-resolved transient features down to a 200-300s width: η ~ 0.1**



$$I(t) = I_{max} \exp\left[-\frac{|t - t_{max}|}{\sigma_{r,d}}^{\kappa}\right]$$

Flare	t_{max} [s]	Maximum Count Rate [Hz]	σ_r [s]	σ_d [s]	κ
BF1	2460	1.33	173	610	1.07
BF2	3528	1.04	116	178	1.43
BF3	4278	1.53	404	269	1.59
BF4	4770	0.99	178	657	2.01
BF5	5298	0.74	67	620	2.44

Application to HESS data: Analysis of PKS 2155-304 large flare

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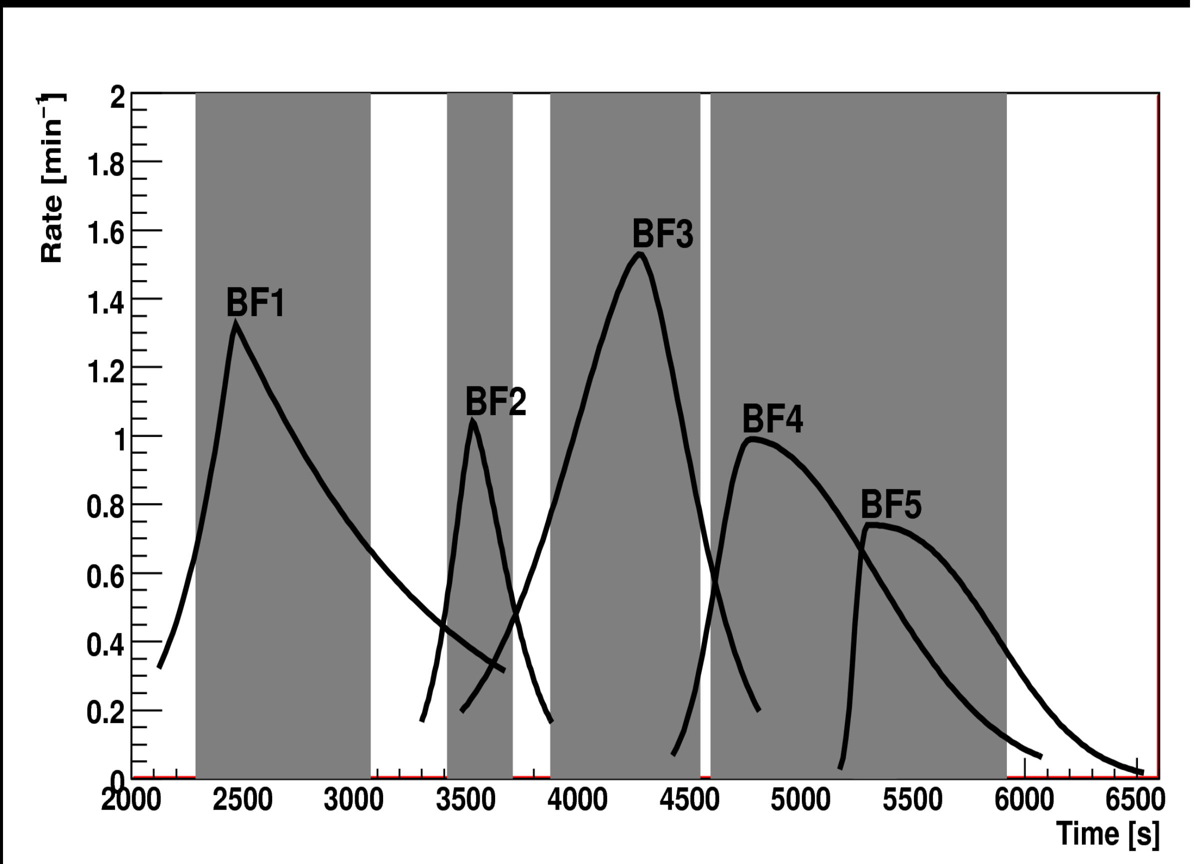
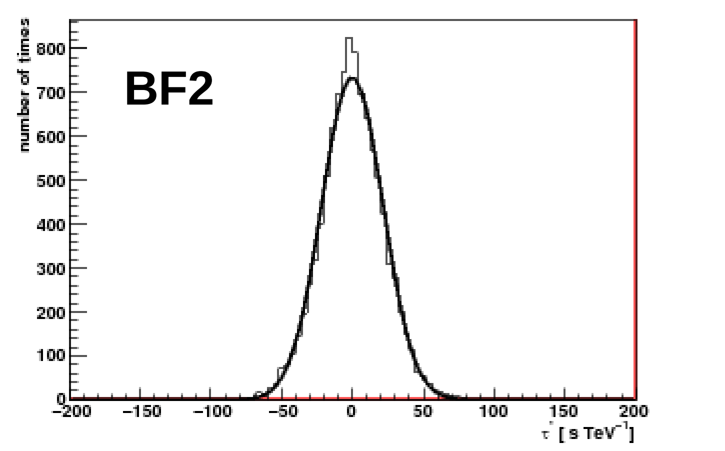
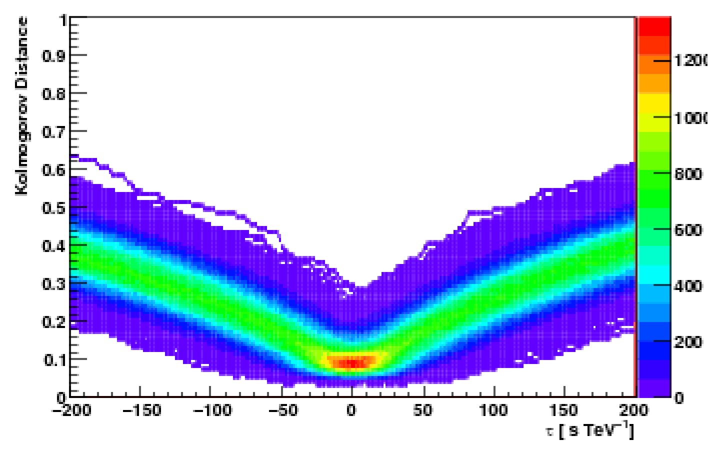
- To assess the significance of our tests we parameterised the five individual bursts BF1-5 following the original fits by HESS original paper, for consistency







Performance of the Method: number of events

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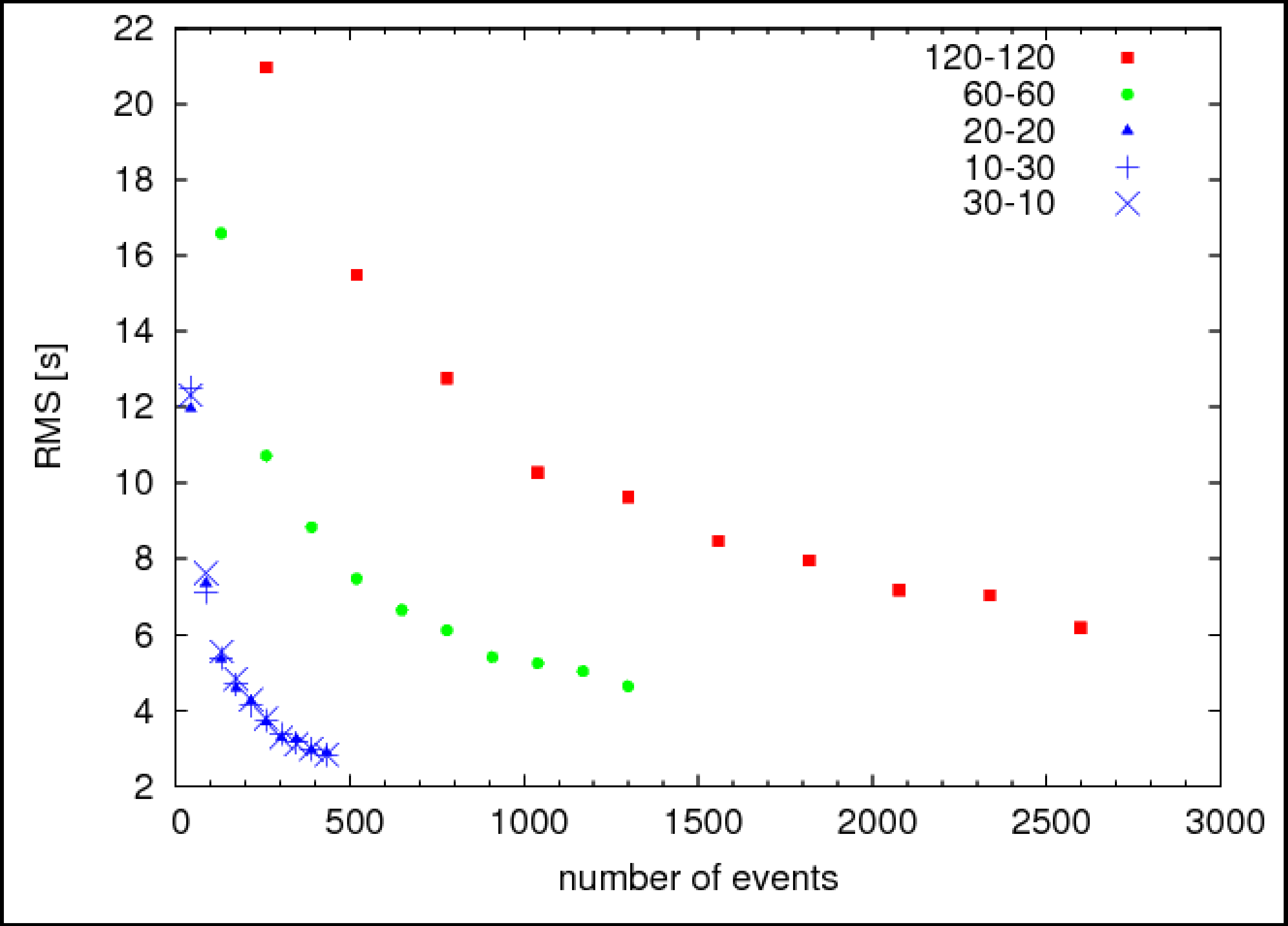
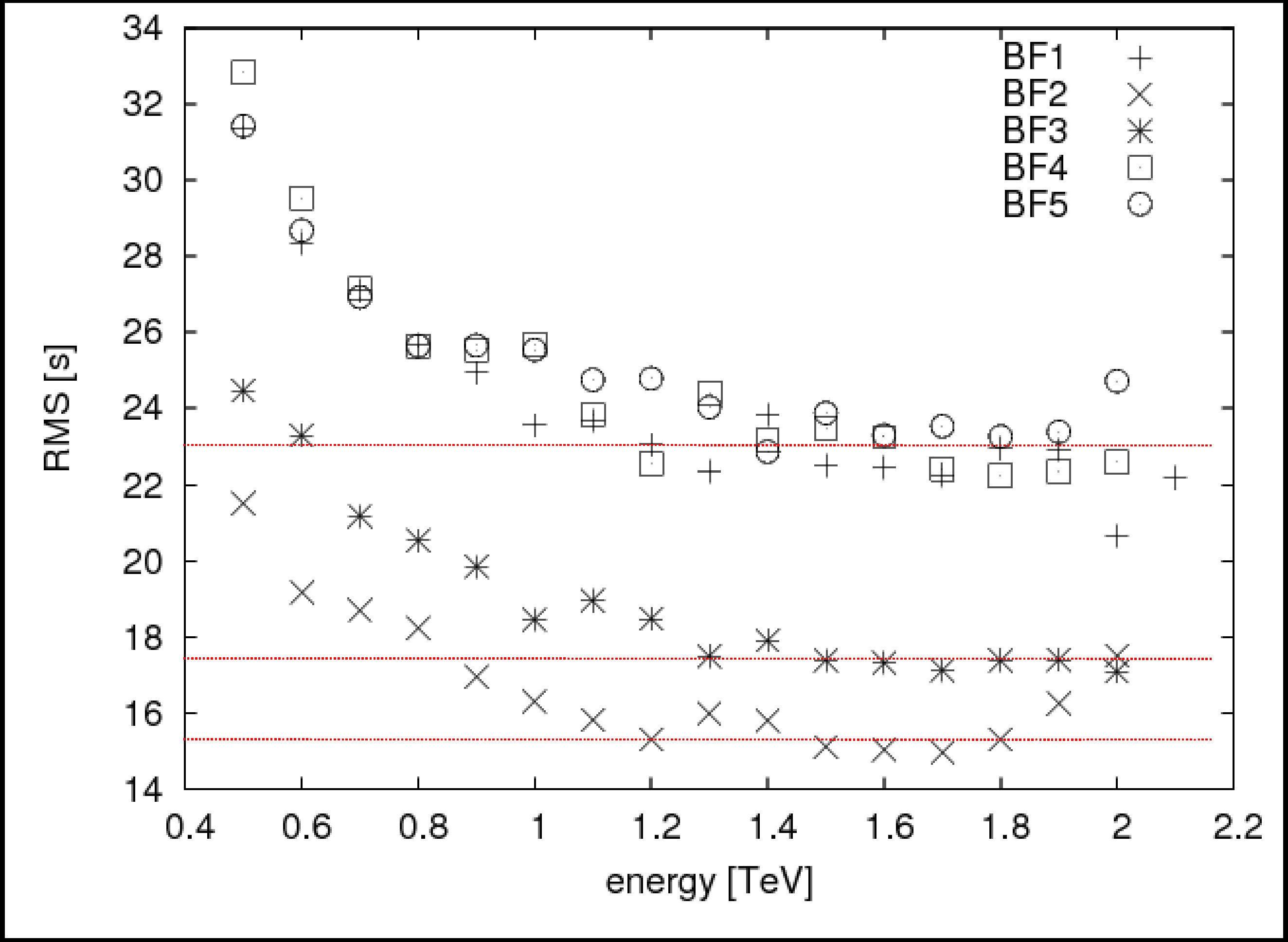


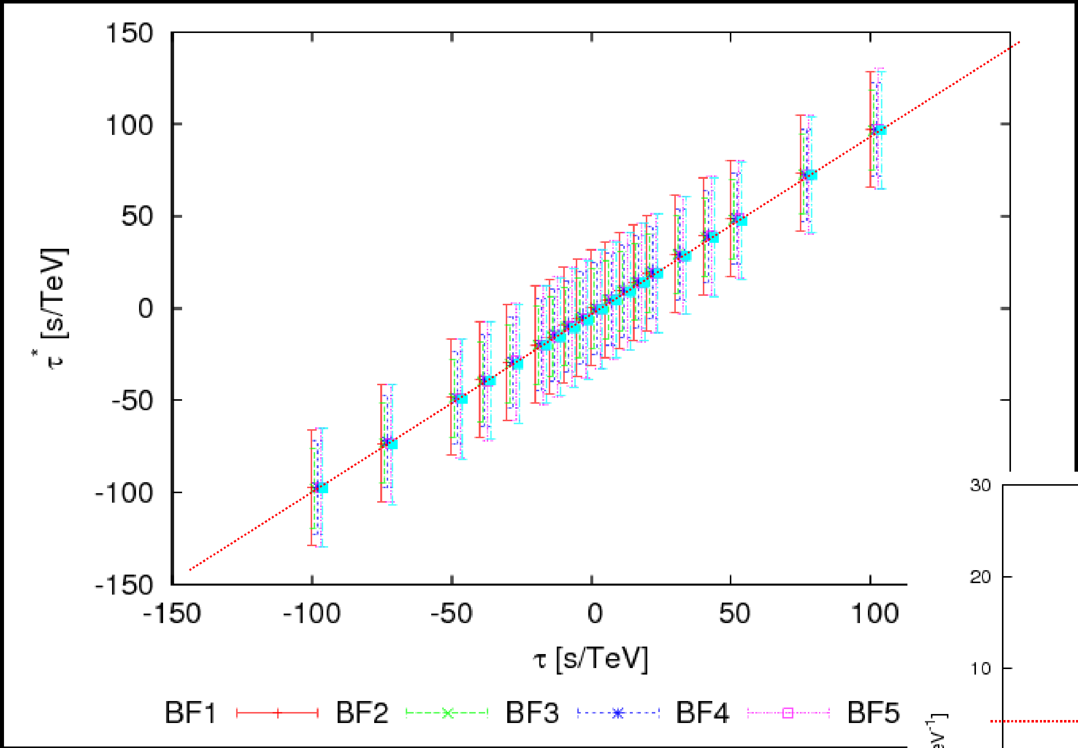
For CTA: an increase in the sensitivity by an order of magnitude around 1 TeV is likely to improve significantly the RMS for otherwise not very well sampled features (likely to be the shortest ones) – and has also the potential to viabilise the test on broader features.

Performance of the Method: energy cuts



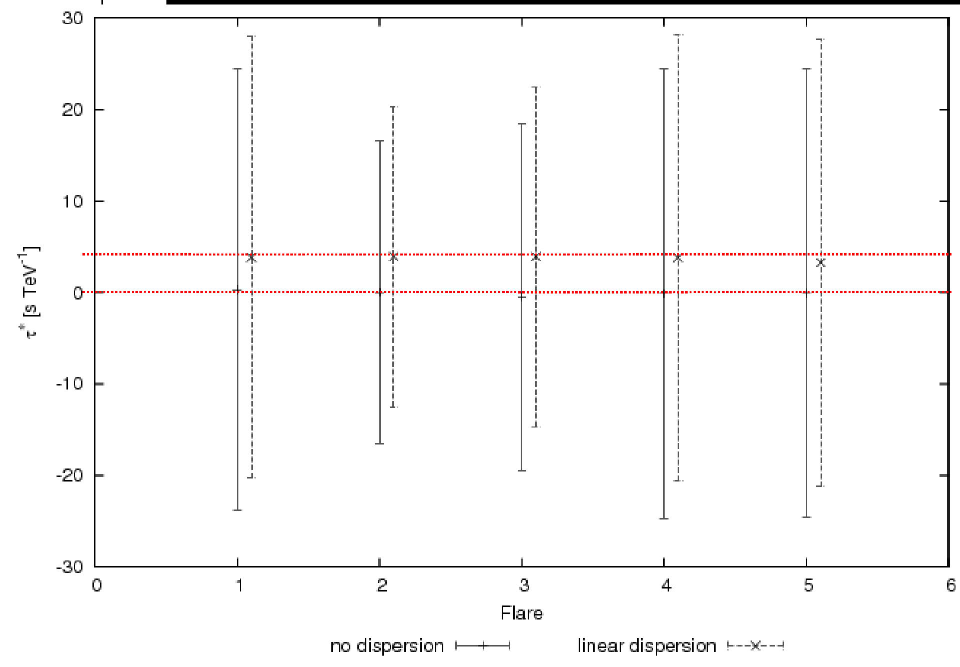
For CTA: by increasing the low energy boundary by lowering the energy threshold, and accumulating more statistics towards highest energies, we will decrease the overall rms level of the curves, maybe extending the low plateau to higher energies.

Dispersion Recovery



Same test, for fixed dispersion, for each flare BF1-5, showing that despite the lack of sensitivity (large RMS) the method re-constructs very well the true dispersion parameter

Accuracy on the recovery of true dispersion parameter as function of its value for each BF1-5



Analysis Results

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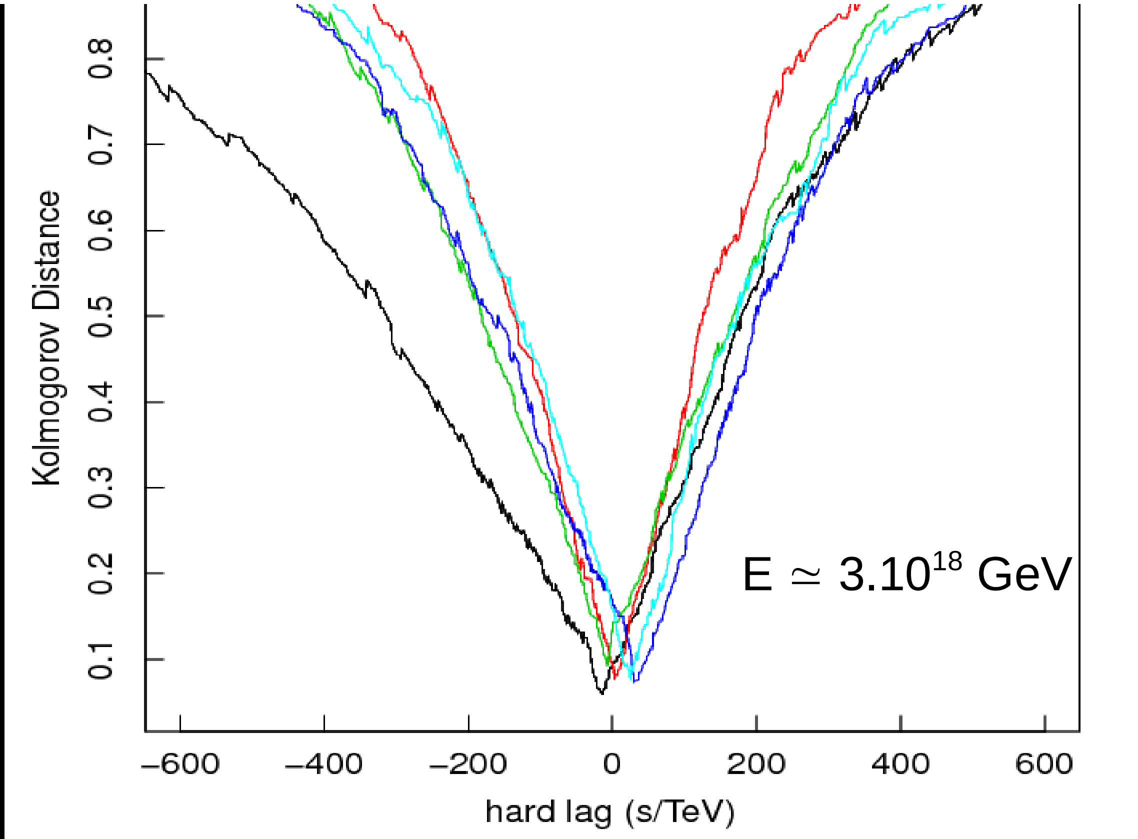
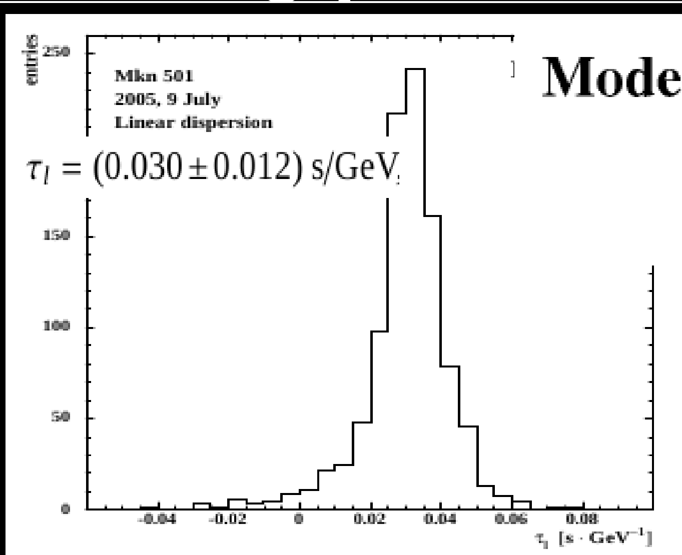
Flare	Time Window [s]	events $E_1 < 500$ GeV	events $E_2 > 1$ TeV	$<\Delta E>$ [TeV]	lag [s/TeV]
BF1	800	868	48	1.42	-14 ±25
BF2	380	562	46	1.23	3 ±16
BF3	600	725	61	1.40	-7 ±19
BF4	490	501	53	1.25	30 ±23
BF5	510	424	50	1.29	25 ±24

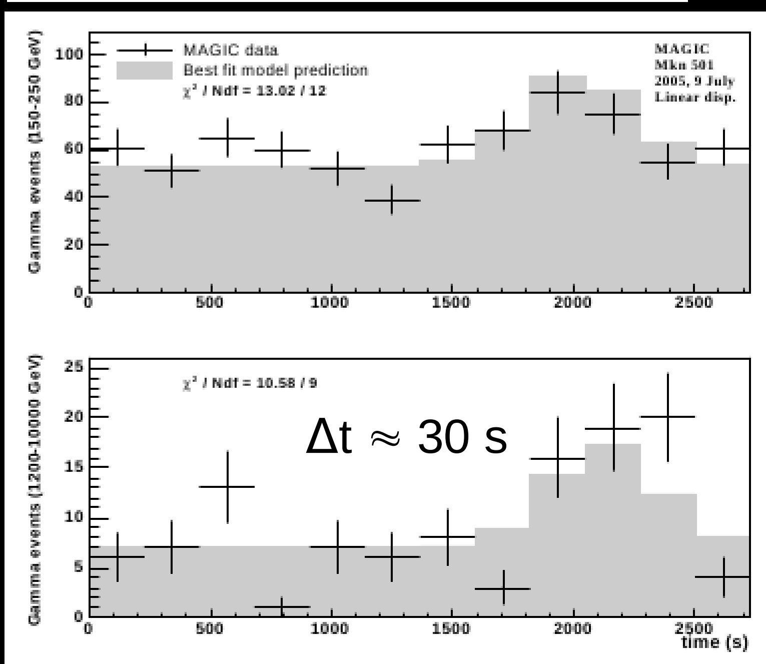


LIV search by-products: Probing particle acceleration in jets



Modeling the Delayed Emission in the 2005 Mkn 501 Very-High-Energy Gamma-Ray Flare

Włodek Bednarek* and Robert Wagner†



Photon energy: $E_\gamma \simeq m_e \gamma_e D_b.$

Time delay:

$$\Delta\tau = \int_{t_{\min}}^{t_{\max}} (1-\beta(t))\,dt \cong \int_{\gamma_b^{\min}}^{\gamma_b^{\max}} \frac{dt}{2\gamma_b^2},$$

$$\Delta\tau \cong \frac{1}{2A}\int_{\gamma_b^{\min}}^{\gamma_b^{\max}} \frac{d\gamma_b}{\gamma_b^2} = \frac{1}{2A}\left(\frac{1}{\gamma_b^{\min}} - \frac{1}{\gamma_b^{\max}}\right) \approx \frac{1}{2A\gamma_b^{\min}},$$

Acceleration distance:

$$X_{acc} = c\Delta\tau\left(2\gamma_b^{\max}\gamma_b^{\min} - 1\right).$$

LIV search by-products: Magnetic field around Xgal sources

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Sensitivity of γ-ray telescopes for detection of magnetic fields in the intergalactic medium

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$$T_{\text{delay,limit}} \simeq 10^6 \frac{\kappa(1-\tau_\theta^{-1})}{(1+z)}\left[\frac{E_\gamma}{0.1\ \text{GeV}}\right]^{-3/2}\ \text{s}$$

$$F_{\text{delay}} \sim \frac{T_{\text{flare}}}{T_{\text{delay}} + T_{\text{flare}}} F_0((1+z)E_{\gamma_0}).$$