

# Experimental Challenges for Lorentz Invariance:

GLAST's Role in the *Search for Quantum Gravity*

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Thanks: Jay Norris, Ron Adler, Johann Cohen-Tanugi

## LV = Lorentz Violation

“... no quantum gravity model predicts LV conclusively ...”<sup>1</sup>

“... no current suggestion of LV is firm enough to be considered a prediction ...”<sup>2</sup>

“To date no LV phenomena have been observed ...”<sup>2</sup>

<sup>1</sup> Mattingly, “Modern Tests of Lorentz Invariance,” gr-qc/0502097

<sup>2</sup> Jacobson, Liberati, Mattingly, and Stecker, “New limits on Planck scale Lorentz violation in QED,” 2004, astro-ph/0309681

$$\tau(E) \approx 10 \text{ msec} \left( \frac{d_{\text{Gpc}}}{1} \right)^{-1} E_{\text{GeV}}$$

$$\tau = E_{\text{QG}} / E_{\text{Planck}}$$

dimensionless, but not necessarily  $\approx 1$

## Time-of-Flight Measurements (Mattingly, gr-qc/0502097)

Is the speed of light a function of photon energy? **Postulate:**

$$\begin{array}{lll} E^2 = m^2 + p^2 & \Rightarrow E^2 = F(p, m) & \text{particles} \\ E^2 = p^2 & \Rightarrow E^2 = F(p) & \text{photons} \end{array}$$

“Since we live in an almost Lorentz invariant world (and are nearly at rest with respect to the CMBR), in the preferred frame  $F(p,m)$  must reduce to the Lorentz invariant dispersion at small energies and momenta. It is therefore **natural to expand  $F(p,m)$  about  $p = 0$  ...**”

$$E^2 = m^2 + p^2 + E_{\text{planck}} f^{(1)} |p| + f^{(2)} |p|^2 + f^{(3)} |p|^3 / E_{\text{planck}} + \dots \text{ (particles)}$$

$$\Delta t / T = 0.5 (n - 1) f^{(n)} (\Delta E / E_{\text{planck}})^{n-2} \text{ (photons)}$$

where  $n$  is the order of the first non-zero term in the expansion.

# There is no Quantum Gravity dispersion!

(argument due to Ron Adler)

Simple treatment of wave equation in time and 1 space dimension.

All coordinates continuous:

\_ phase velocity = group velocity =  $\omega / k$

\_ No dispersion

Spatial coordinate granular:

\_ Dispersion: group velocity depends on energy

\_ For  $k \rightarrow 0$ , recover continuous case

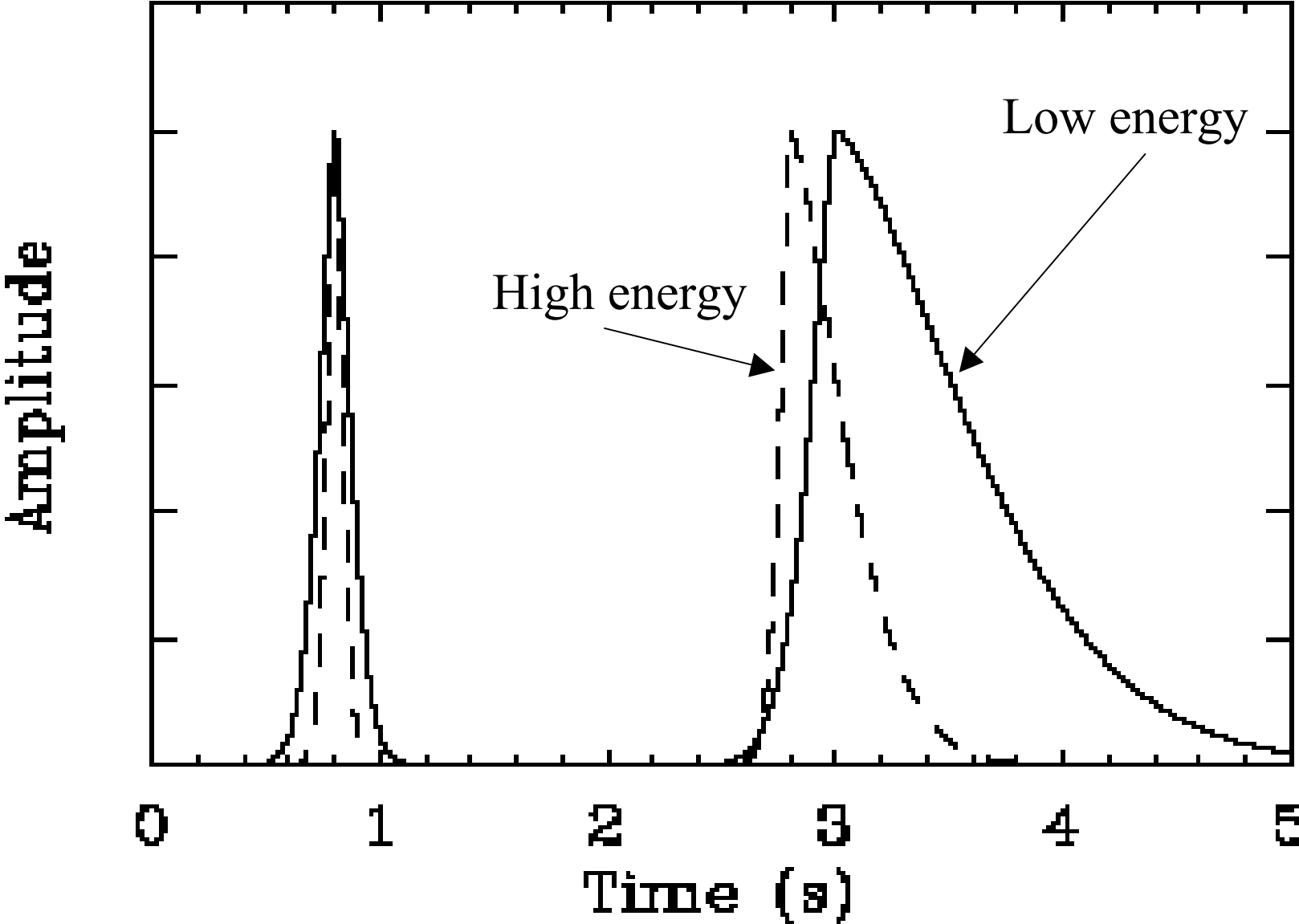
Both time and spatial coordinate granular:

\_  $\omega = k$

\_ Wave velocity is unity

\_ No dispersion

Even if there is dispersion, it may be masked by the Pulse Asymmetry / Energy-shift Paradigm, Norris, Marani, and Bonnell, astro-ph/9903233



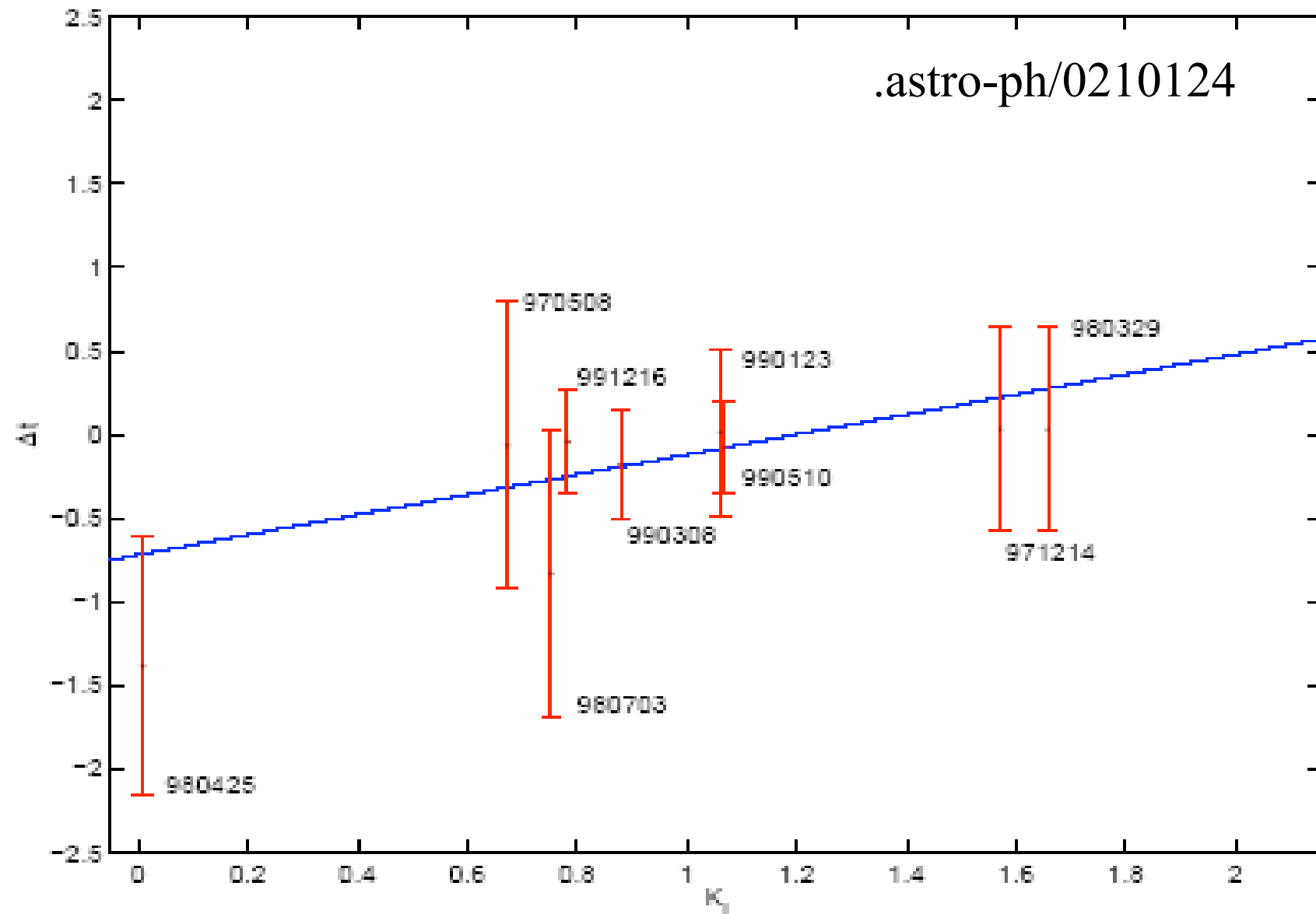


Fig. 6. Spectral time lags between the arrival times of pairs of genuine variation points detected in the third and first BATSE spectral bands. The analysis has been done for 9 GRB light curves collected with time resolution 64 ms. The solid line shows the best linear fit to the data.

# How best to measure Energy-Dependent Lags?

The data: time and energy tagged --  $t_i, E_i, i = 1, 2, \dots, N$

Usual approach: - bin the data in both time and energy  
- find peak in cross-correlation function  
(across E bands)

## Entropy approach

define transformation of time:  $t'_i = f(t_i) = t_i + L(c, E_i)$   
(lag L is a function of a parameter c)

If c is other than the correct value, the light curve for the transformed times will be smeared out. Hence the entropy of the light curve will be minimum for the correct value:

$$c_{\text{optimum}} = \text{argmin} [ \text{Entropy} ( \text{histogram}( t_i + L(c, E_i) ) ) ]$$

lag estimate is then just  $L(c_{\text{optimum}}, E)$

# How best to measure Energy-Dependent Lags?

Entropy method:

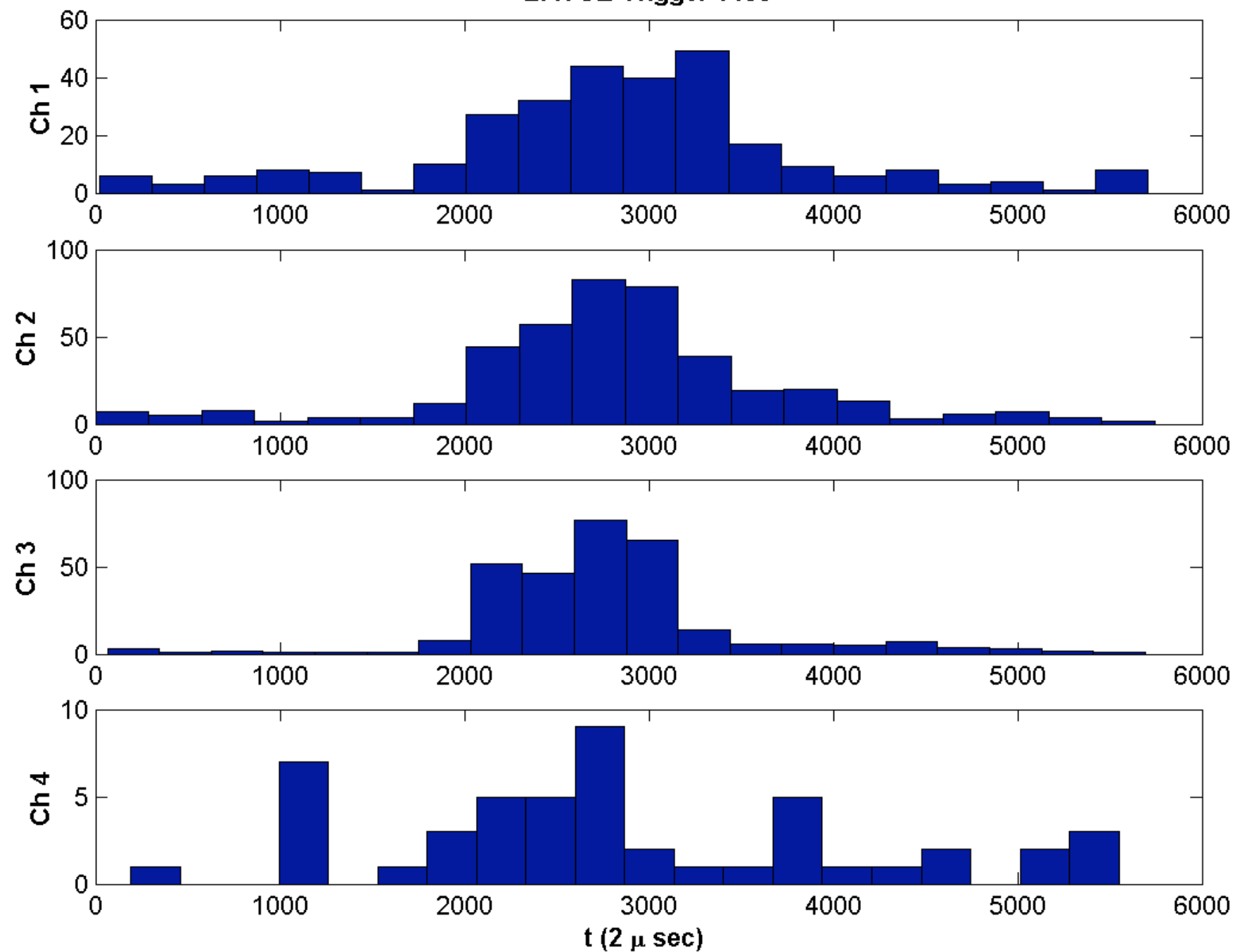
1. Make histogram  $n_k =$  number of transformed times  $t'_i$  in bin  $k$
2. Convert to a probability distribution:  $p_k = n_k / \sum n_k$
3. Compute entropy:  $S(c) = \sum p_k \log( p_k )$
4. Minimize  $S(c)$  with respect to  $c$

Examples:

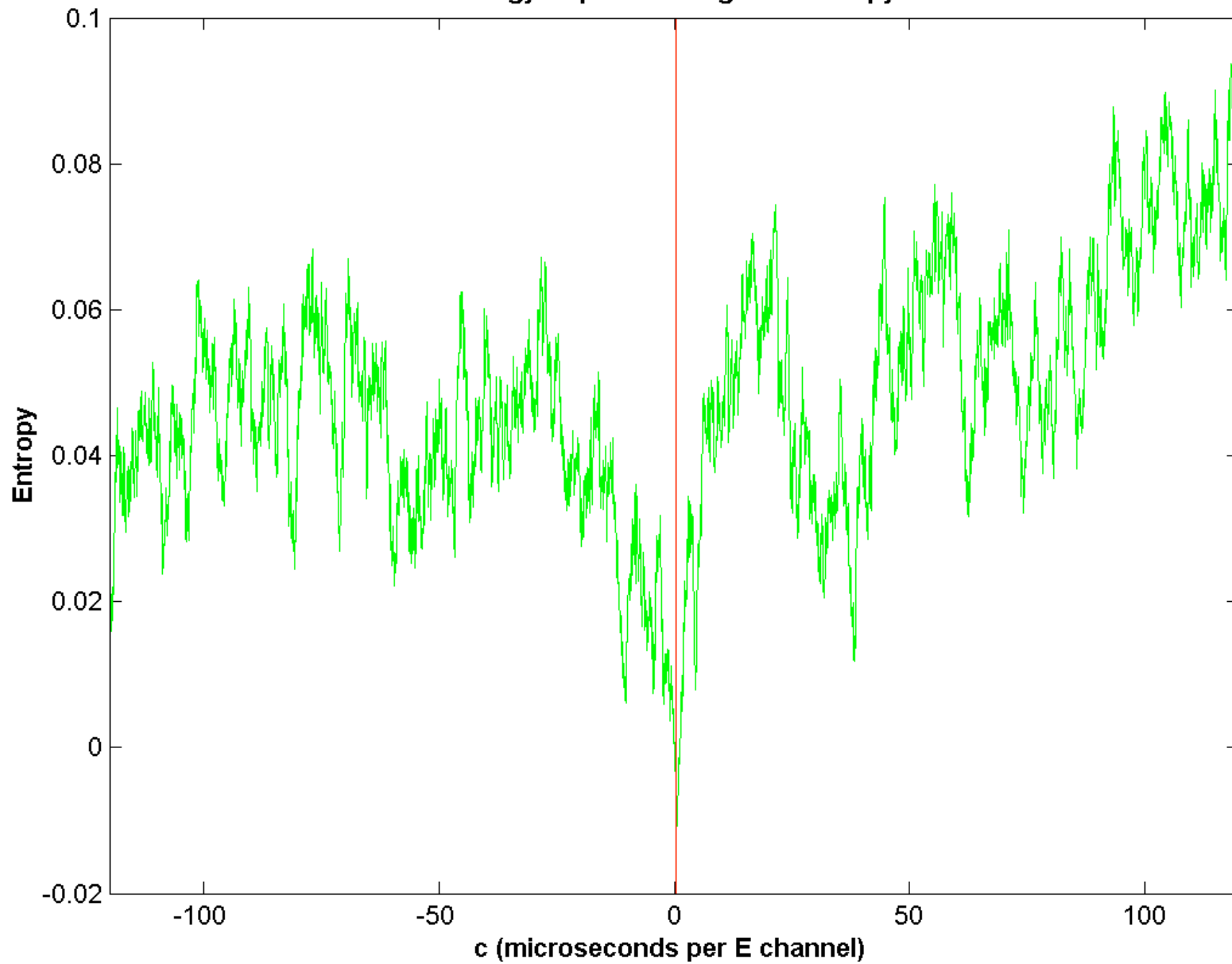
$$t'_i = f( t_i ) = t_i + c E_i \quad (\text{first term in Taylor expansion})$$

$$t'_i = f( t_i ) = t_i + c / E_i^2 \quad (\text{finite photon mass dispersion relation})$$

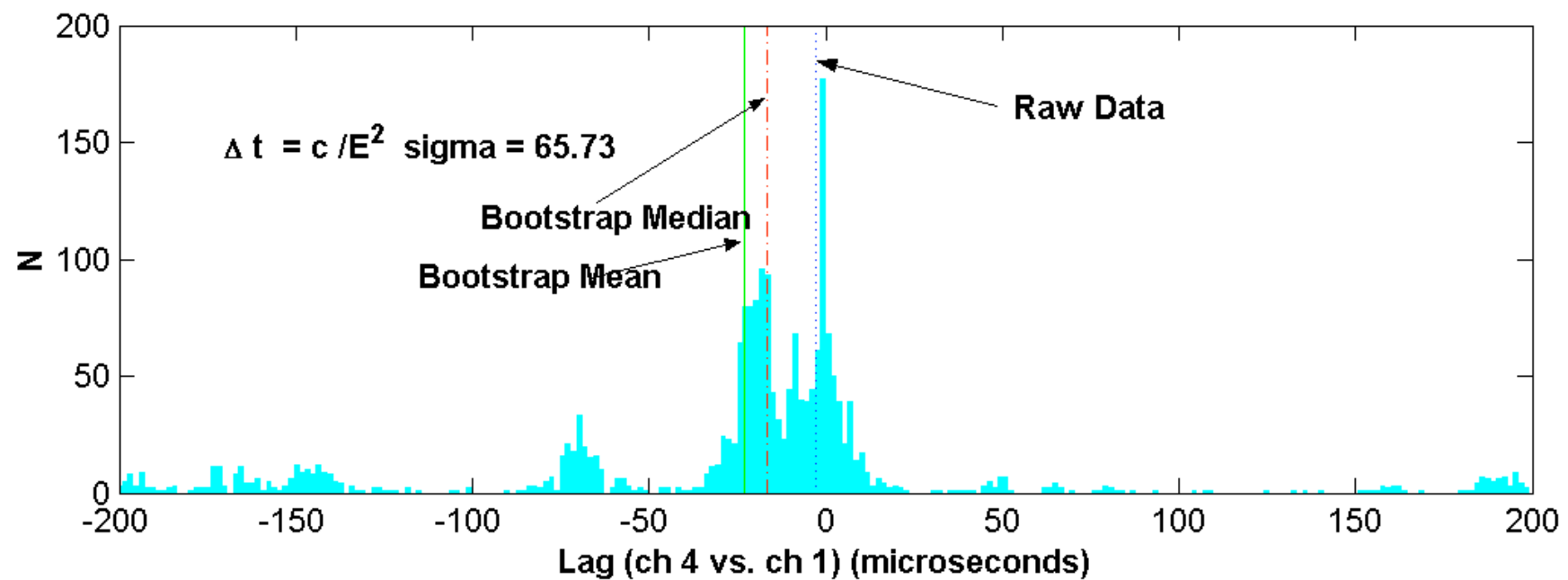
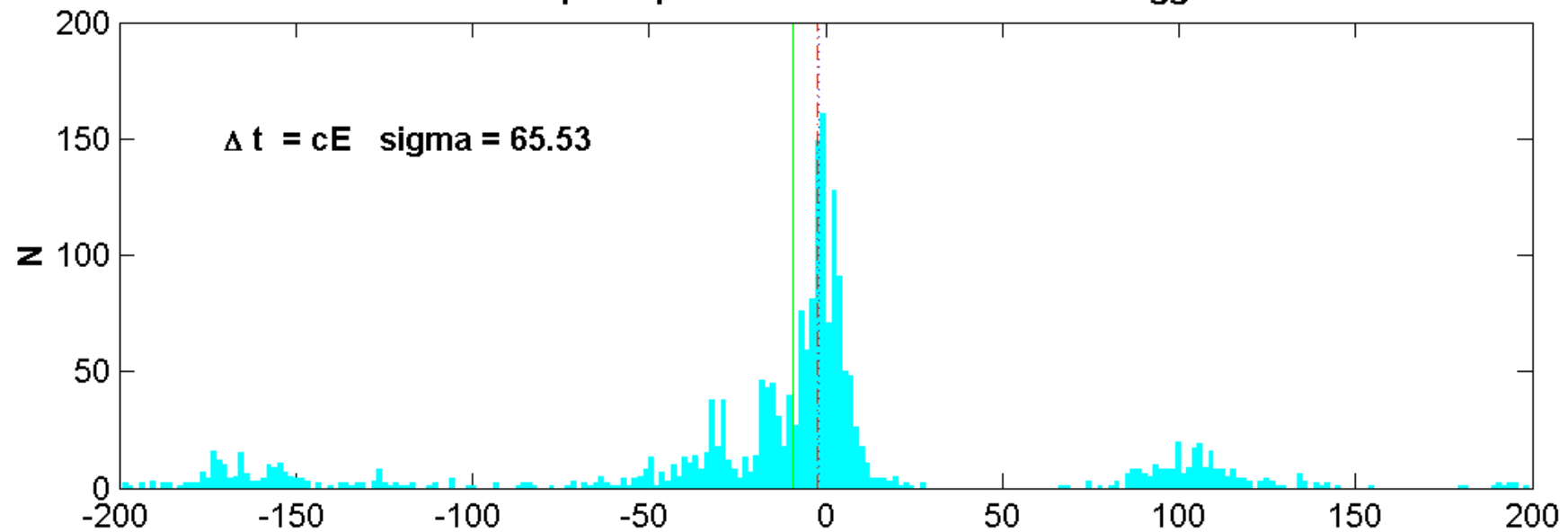
### BATSE Trigger 1453



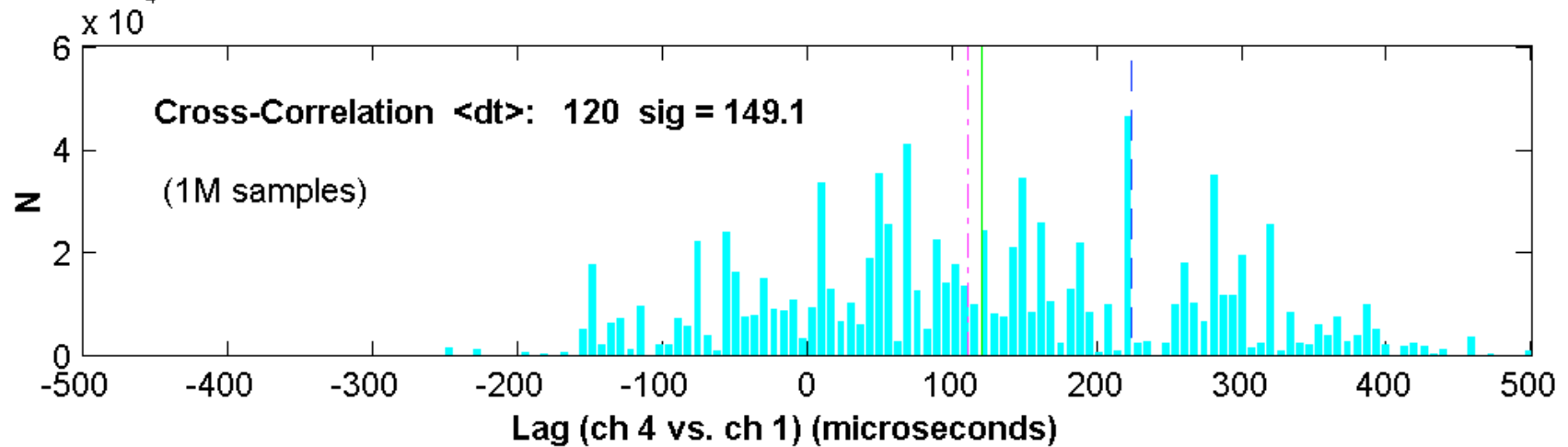
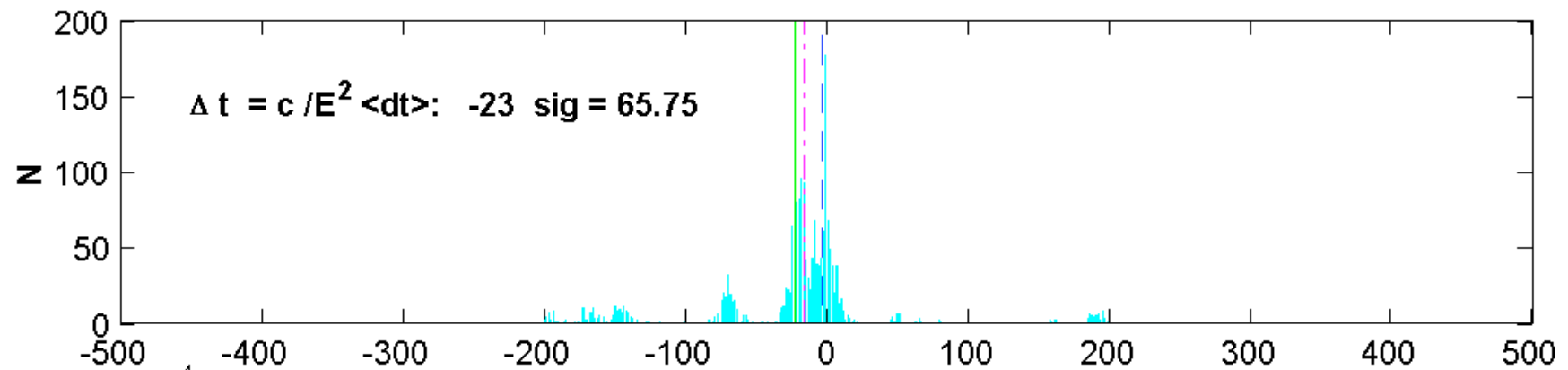
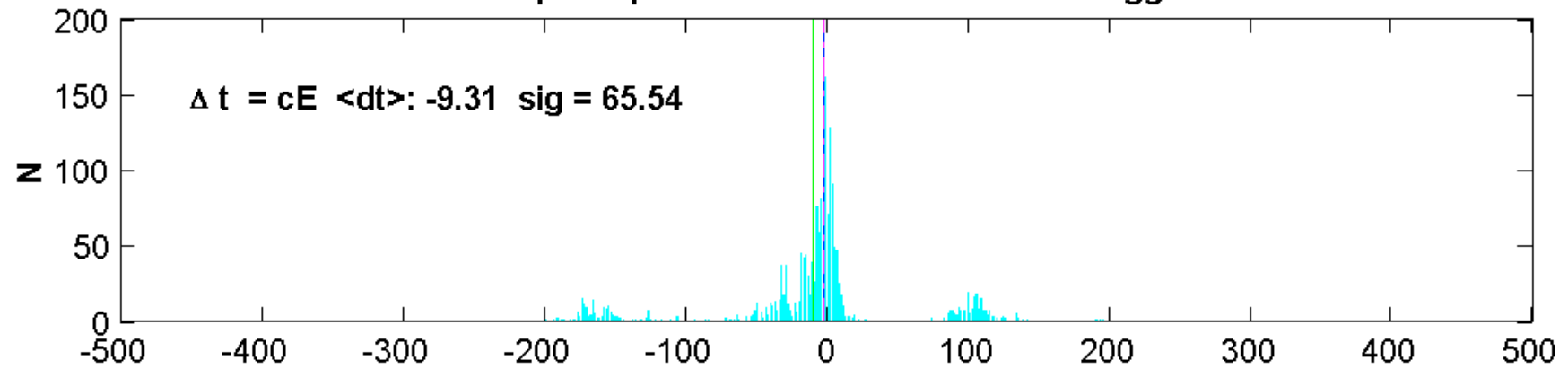
Energy-Dependent Lags via Entropy



### 2000 Bootstrap samples: "microburst" in BATSE Trigger 1453

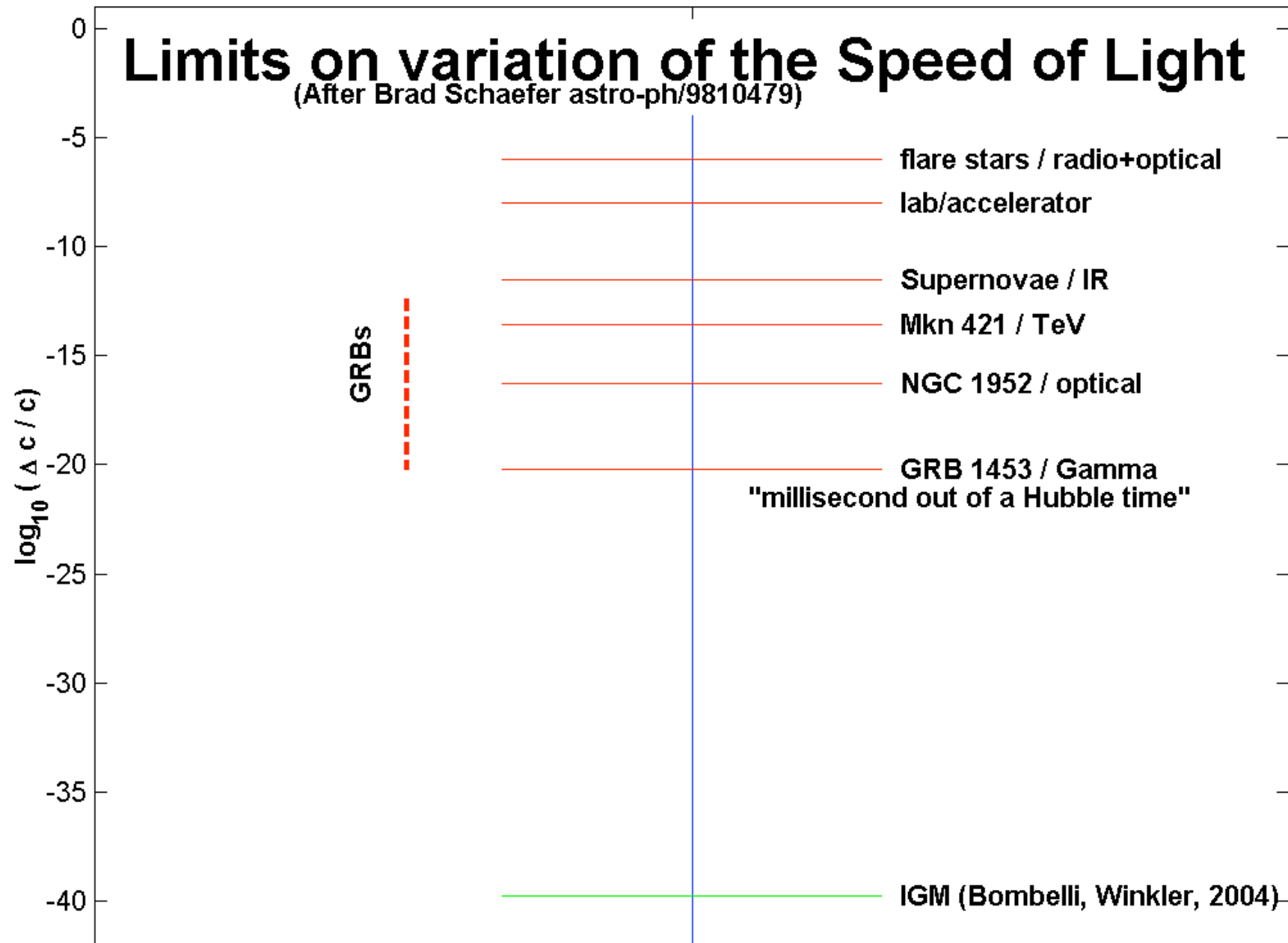


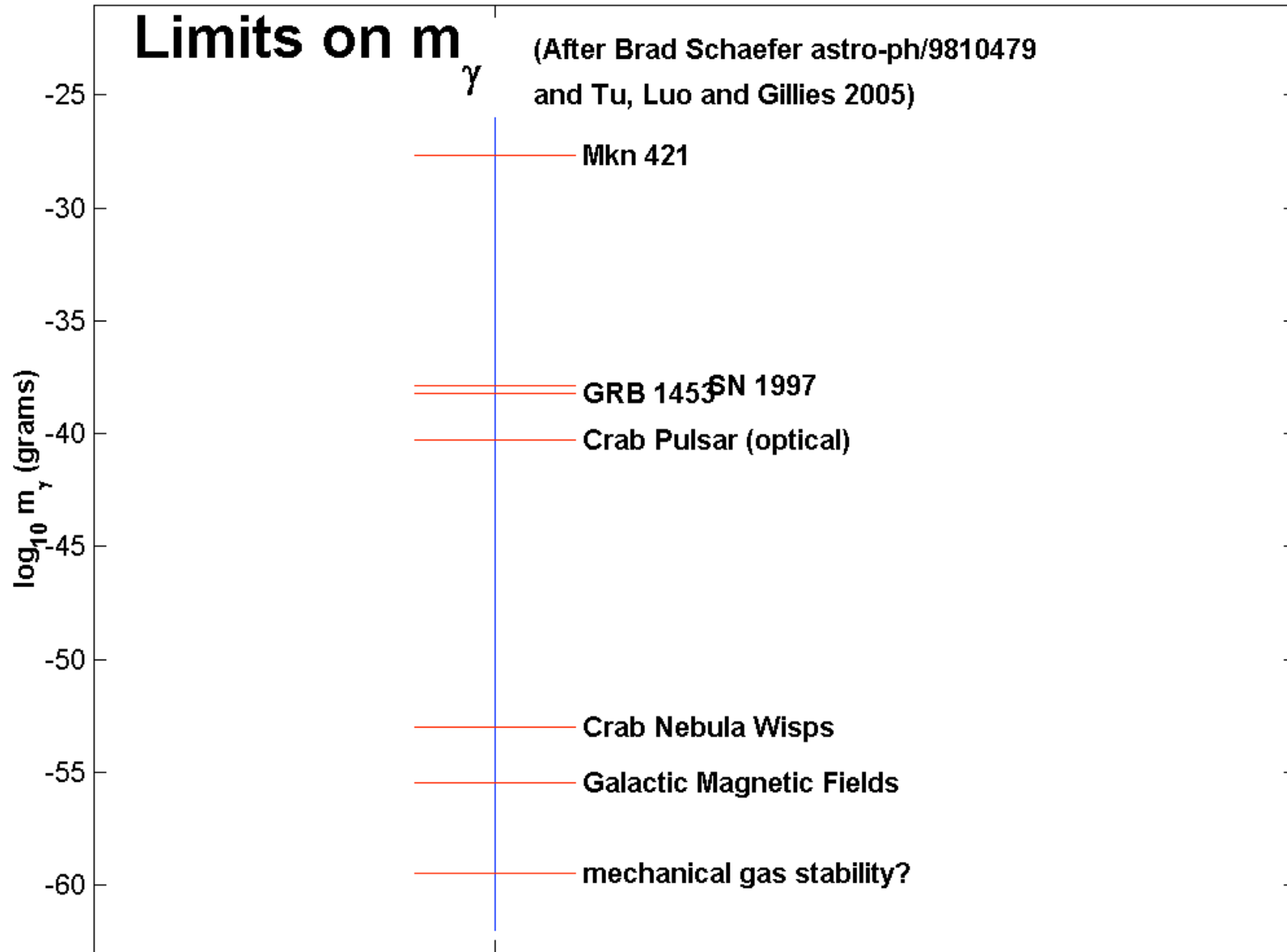
### 2000 Bootstrap samples: "microburst" in BATSE Trigger 1453



# Limits on variation of the Speed of Light

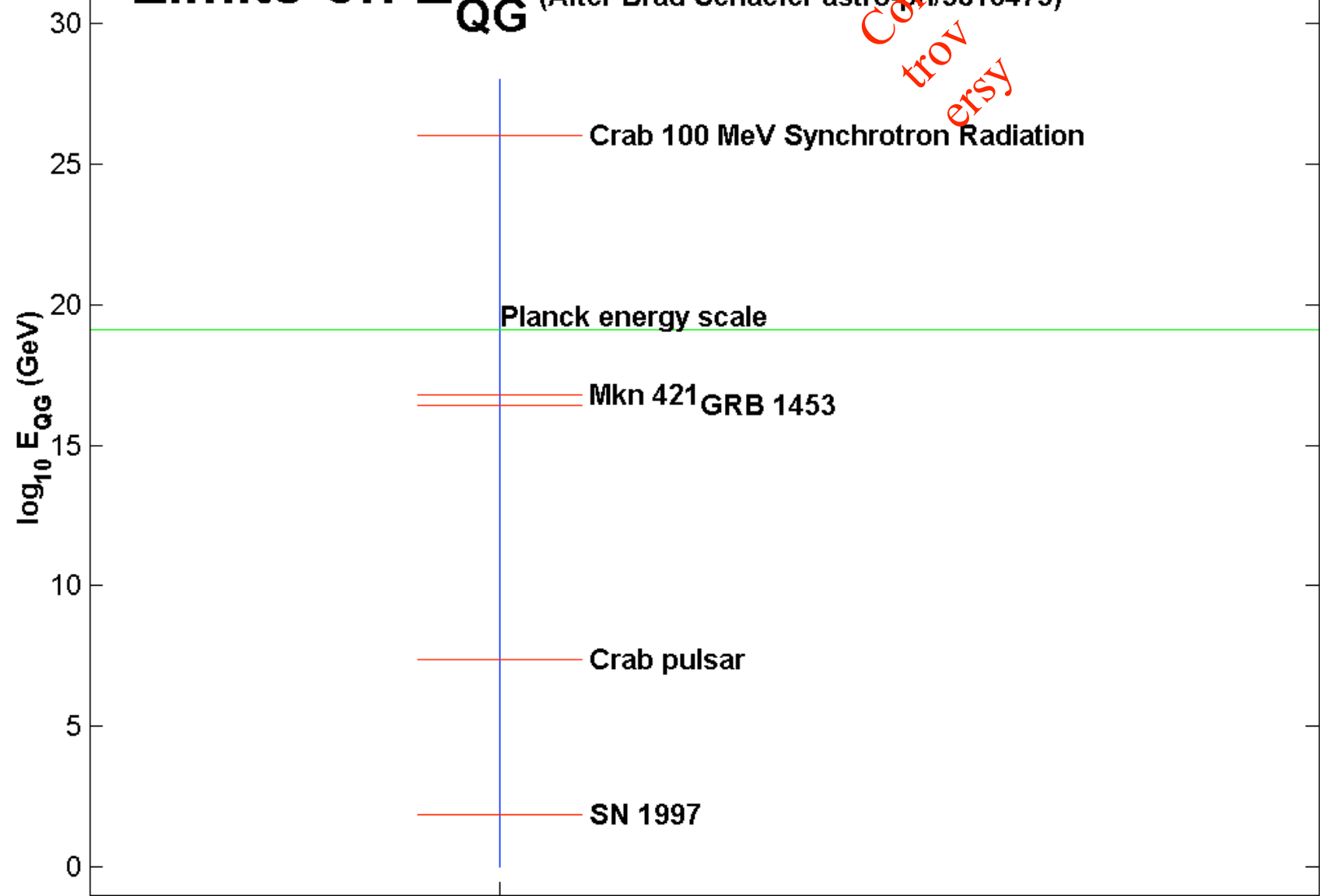
(After Brad Schaefer astro-ph/9810479)





Carroll, Field, Jackiw 1990

# Limits on $E_{QG}$ (After Brad Schaefer astro-ph/9810479)



Modern Tests of Lorentz Invariance, David Mattingly, gr-qc/0502097 – an extensive review

Quantum-Gravity Analysis of Gamma-Ray Bursts using Wavelets  
Ellis, Mavromatos, Nanopoulos, and Sakharov, astro-ph/0210124

New limits on Planck scale Lorentz violation in QED, Jacobson, Liberati, Mattingly,  
and Stecker, astro-ph/0309681

The Search for Quantum Gravity Signals, G. Amelino-Camelia, C. Lammerzahl,  
A. Macias and H. Muller, gr-qc/0501053

G. Amelino-Camelia et al., Nature 393, 763 (1998) and many others

Severe Limits on Variations of the Speed of Light with Frequency, Brad Schaefer,  
astro-ph/9810479

A strong astrophysical constraint on the violation of special relativity by quantum gravity  
T. Jacobson, S. Liberati, and D. Mattingly, astro-ph/0212190

Effects of CPT and Lorentz Invariance Violation on Pulsar Kicks, Lambiase, astro-ph/0503002 ????

Is there any evidence for extra-dimensions or quantum gravity effects from the delayed MeV-  
GeV photons in GRB 940217? Cheng and Harko, astro-ph/0407416

Possible Astrophysical Probes of Quantum Gravity, Sarkar, gr-qc/0204092

Gamma-Ray Bursts as Probes for Quantum Gravity, Piran, astro-ph/0407462