Testing Quantum Gravity Theories with GLAST

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Thanks: Jay Norris, Johann Cohen-Tanugi, Paul Gazis, Jerry Bonnell, Ron Adler, GLAST Science Teams

- Generic Theory
- Quantum Gravity
- Causal Set Theory
- Doubly Special Relativity
- Observations
- Photon dispersion – data analysis

Unification of General Relativity & Quantum Mechanics

	General Relativity	Quantum Mechanics
Scale	Large	Small
Dynamics	Deterministic	Probabilistic
Space-time	Background Independent	Absolute background

Modify: GR to fit with QM? QM to fit with GR? Both GR and QM?

Seek Observable Effects

Is Lorentz symmetry broken? *Lorentz Invariance Violation*

What about other symmetries (translation and scale invariance, CPT, supersymmetry, Poincaré, …)?

Is space-time discrete/chunky, affecting photon/particle propagation?

Is this quantum foam at the Planck scale (10^{-35} m; 10^{19} GeV)?

QG & the Planck Scale (Adler)

- **$h = 1.054 \times 10^{-27}$ g cm ^{2} / sec** **(Quantum Mechanics)**
- **$c = 2.998 \times 10^{10}$ cm / sec** **(Special Relativity)**
- **$G = 6.670 \times 10^{-8}$ cm ^{3} / g sec ^{2}** **(Gravity/General Relativity)**
- **Only one combination of these variables is a length**

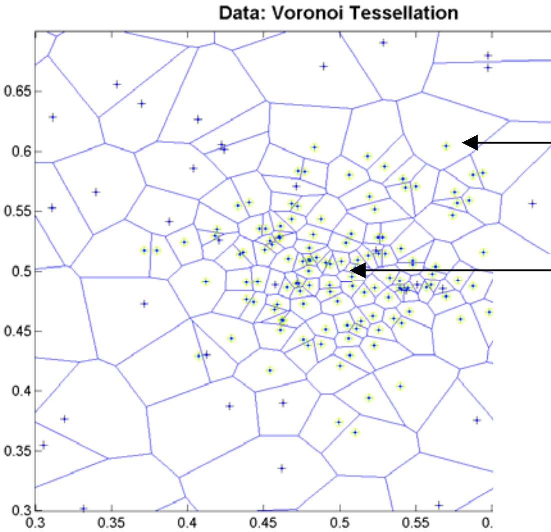
$L_{Planck} = (hG / c^3)^{1/2} = 1.616 \times 10^{-35}$ m (10^{-17} electroweak scale)

Determine the distance L between two points: measure the round-trip transit time of a photon of wavelength λ.

$$\left(\begin{array}{l}\text{Uncertainty in}\\ \text{measured length}\end{array}\right) = \underset{\substack{\uparrow\\ \text{Ordinary}\\ \text{uncertainty}\\ \text{principle}}}{\lambda} + G\,(m_{effective} \underset{\substack{\uparrow\\ \text{Spatial distortion}\\ \text{due to mass/energy}\\ \text{of the photon}}}{=} E_{photon}/c^2)\;/\;L$$

This is $\lambda + \mathbf{L}^2_{\mathbf{planck}} / \lambda$ --- minimum is $2\,\mathbf{L}_{\mathbf{planck}}$ at $\lambda = \mathbf{L}_{\mathbf{planck}}$

Voronoi Tessellations on 3+ Scales



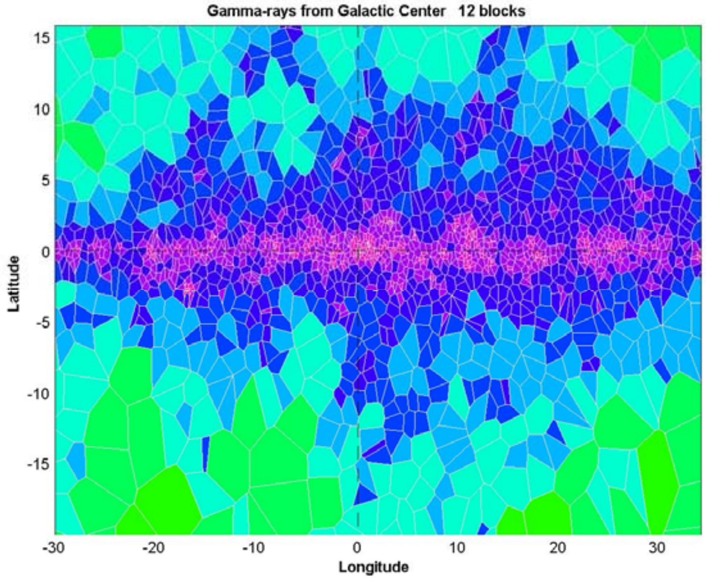
10^{-35} meters

Random space-time lattice (T. D. Lee)

Points: micro-partons?

Cells: Planck length cells

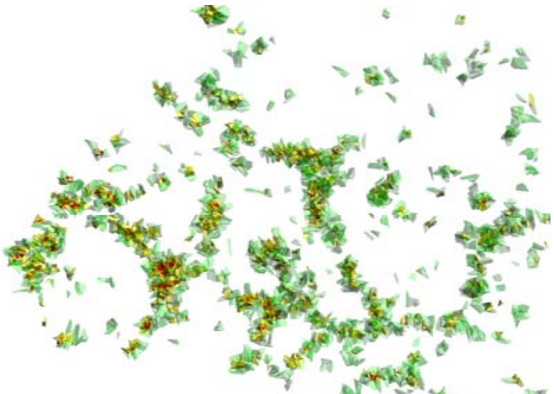
Blocks: Elementary Particles



GLAST Source Detection Algorithm

Points: Photons

Blocks: Point sources



10^{+22} meters

Cluster detection algorithm:

Points: Galaxies

Cells: Galaxy Neighborhoods

Blocks: Clusters, filaments, …

Large Scale Structure

Points: Galaxies

Cells: Voids

Lorentz Invariance: Example from Mattingly

Bimetric action S for two massless scalar fields ϕ and ψ

$\tau^{\alpha\beta}$ is an arbitrary symmetric tensor

$$S = ½\int \sqrt{-g}\ d^4x \left(g^{\alpha\beta}\, \partial_\alpha\phi\, \partial_\beta\phi + (g^{\alpha\beta} + \tau^{\alpha\beta})\, \partial_\alpha\psi\, \partial_\beta\psi \right)$$

Passive (observer) Lorentz Transformation:

$$S = ½\int \sqrt{-g}\ d^4x \left(\boldsymbol{g^{\alpha\beta}\, \partial_\alpha\phi\, \partial_\beta\phi + (g^{\alpha\beta} + \tau^{\alpha\beta})\, \partial_\alpha\psi\, \partial_\beta\psi} \right)$$

Active Lorentz Transformation:

$$S = ½\int \sqrt{-g}\ d^4x \left(g^{\alpha\beta}\, \partial_\alpha\boldsymbol{\phi}\, \partial_\beta\boldsymbol{\phi} + (g^{\alpha\beta} + \tau^{\alpha\beta})\, \partial_\alpha\boldsymbol{\psi}\, \partial_\beta\boldsymbol{\psi} \right)$$

(Only transform the dynamical fields ϕ **and** ψ.)

Some Approaches to QG Theory

Loop Quantum Gravity	hep-th/0601129
String theory	many
Effective Field Theory	hep-th/0407370
The World as a Hologram	hep-th/9409089
Quantum Computation	quant-ph/0501135
Extra Dimensions	hep-ph/9811291
Statistical Geometry	Myrheim, TH.2538-CERN
Categorical Geometry ?	gr-qc/0602120
Self-organized criticality	hep-th/0412307
Random Lattice Field Theory	T. D. Lee
Dynamic Probabilistic Causal Structure ?	gr-qc/0509120
Causal Sets	gr-qc/06 01 069/121
Random Walk	gr-qc/0403085
Regge Calculus	gr-qc/0012035
Quantum State Diffusion	I. Percival

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

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

$$E^2 = m^2 + p^2 \quad \Rightarrow E^2 = F(p, m) \qquad \text{particles}$$
$$E^2 = p^2 \quad \Rightarrow E^2 = F(\ p) \qquad \text{photons}$$

“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 ...”

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

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

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

More complete and cogent analysis in “High-energy Tests of Lorentz Invariance, Coleman and Glashow, hep-ph/9812418.

Doubly (or Deformed) Special Relativity

Instead of a single observer-independent scale (velocity of light),
DSR postulates an additional such scale (energy/momentum).

Lorentz invariance is deformed, not broken: changes in transformations of energy/momentum yield modified dispersion relations such as

$$E^2 - p^2 = \mu^2 \, [\, 1 + \sigma \, (E / E_{Planck})^n \,]^2$$

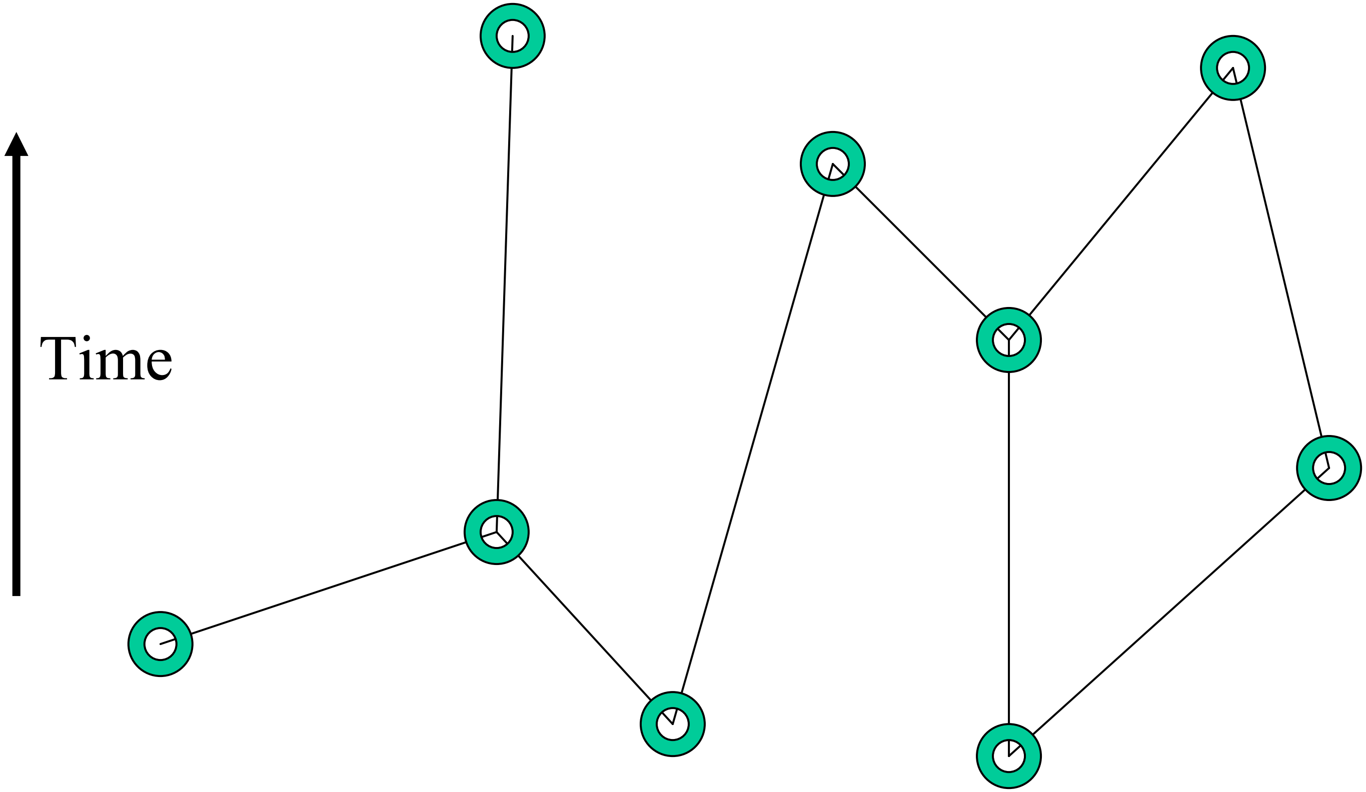
May predict photon dispersion, but no birefringence, Goldstone bosons , new particle reactions or significantly modified thresholds, and …

- **DSR is not a complete theory**
- **DSR has no dynamics**
- **DSR has problems when applied to macroscopic objects**
- **The physical object that carries the second scale is unknown**

Amelino-Camelia et al., gr-qc/0312124
Kowalski-Glikman, gr-qc/0603022, gr-qc/0405273

Causal (Partially Ordered) Sets

Ordered: time-like intervals Not ordered: space-like intervals



Hasse Diagrams (Helmut Hasse 1898–1979)) portray partially ordered sets.

- **A line goes *upward* from x to y if $x < y$ and there is no z such that $x < z < y$.**
- **Each line meets exactly two vertices.**
- **Any diagram uniquely determines a partial order, but not vice versa.**

Construction of Causal Sets

- **Define continuum space-time S (flat, curved, …)**
- **Sprinkle points p_i randomly in S (*Poisson distribution*)**
- **Establish *causal connections*: Is p_n in p_m's causal future? If so, $p_n >= p_m$ (partially ordered set)**
- **Throw away all above except causal connections**
- **Two classes of causal connections:**
  - **Direct: no intermediate points p_k**
  - **Indirect: at least one intermediate point: $p_n >= p_k >= p_m$**

Causal Set Physics

Translation invariance not respected except statistically.

Quantum mechanics! Three assumptions:

- Time reversible evolution
- Current velocity is irrotational
- Particles undergo Brownian motion with diffusion coefficient ~ h/m

… imply existence of a wave function satisfying Schrödinger equation

Nelson, Phy. Rev.1969, 150, p. 1079
Markopoulou and Smolin, gr-qc/0311059

Photon Propagation in Causal Sets

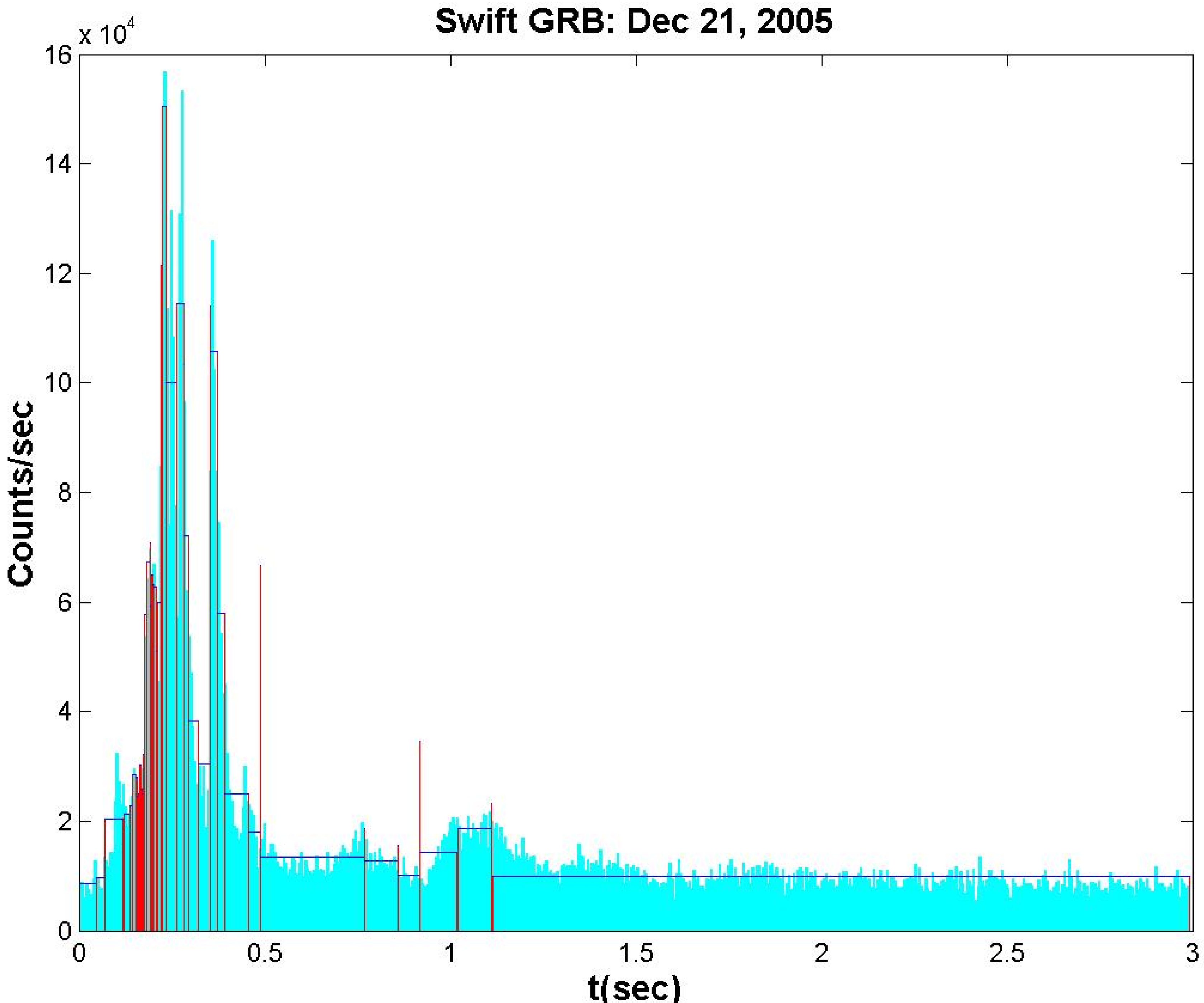
- Start with purely discrete causal set
- Use algorithms for:
  - Determining the dimension
  - Constructing discrete metric consistent with continuous metric
  - Measure density, curvature, etc.
- Define a photon propagator (probability amplitude, energy dependent phase factor, … ?)
- Forward causal connections trace photon paths
  - energy dependent propagator amplitude
  - energy dependent propagator phase
  - deterministic

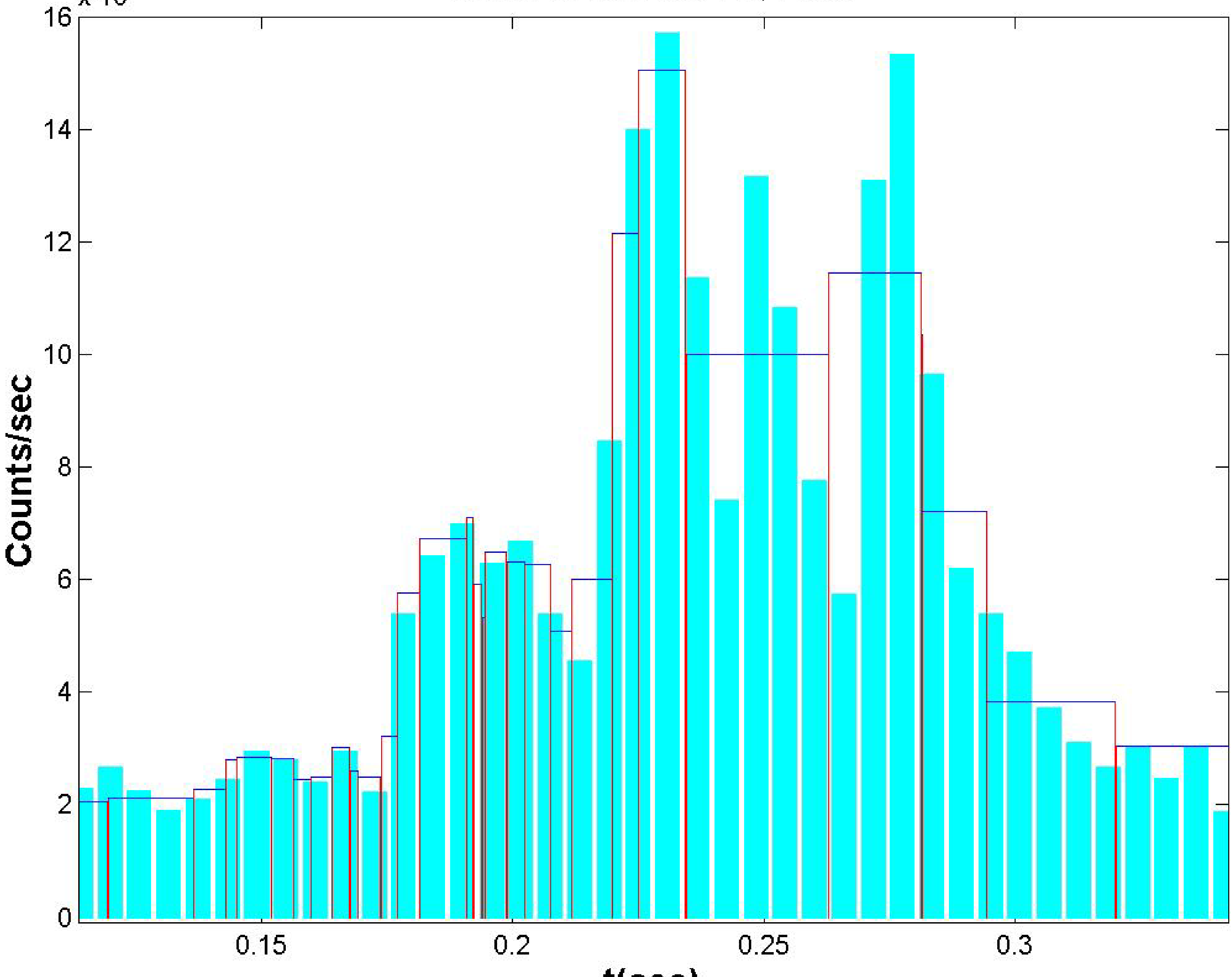
Observational Improvements

- **By increasing detector size, or going into space, or using technological improvement, or technique refinement, observations are probing…**
  - **Higher energies**
  - **Weaker interactions**
  - **Lower fluxes**
  - **Lower temperatures**
  - **Shorter time resolution**
  - **Longer distances**
  - **Gravitational waves**

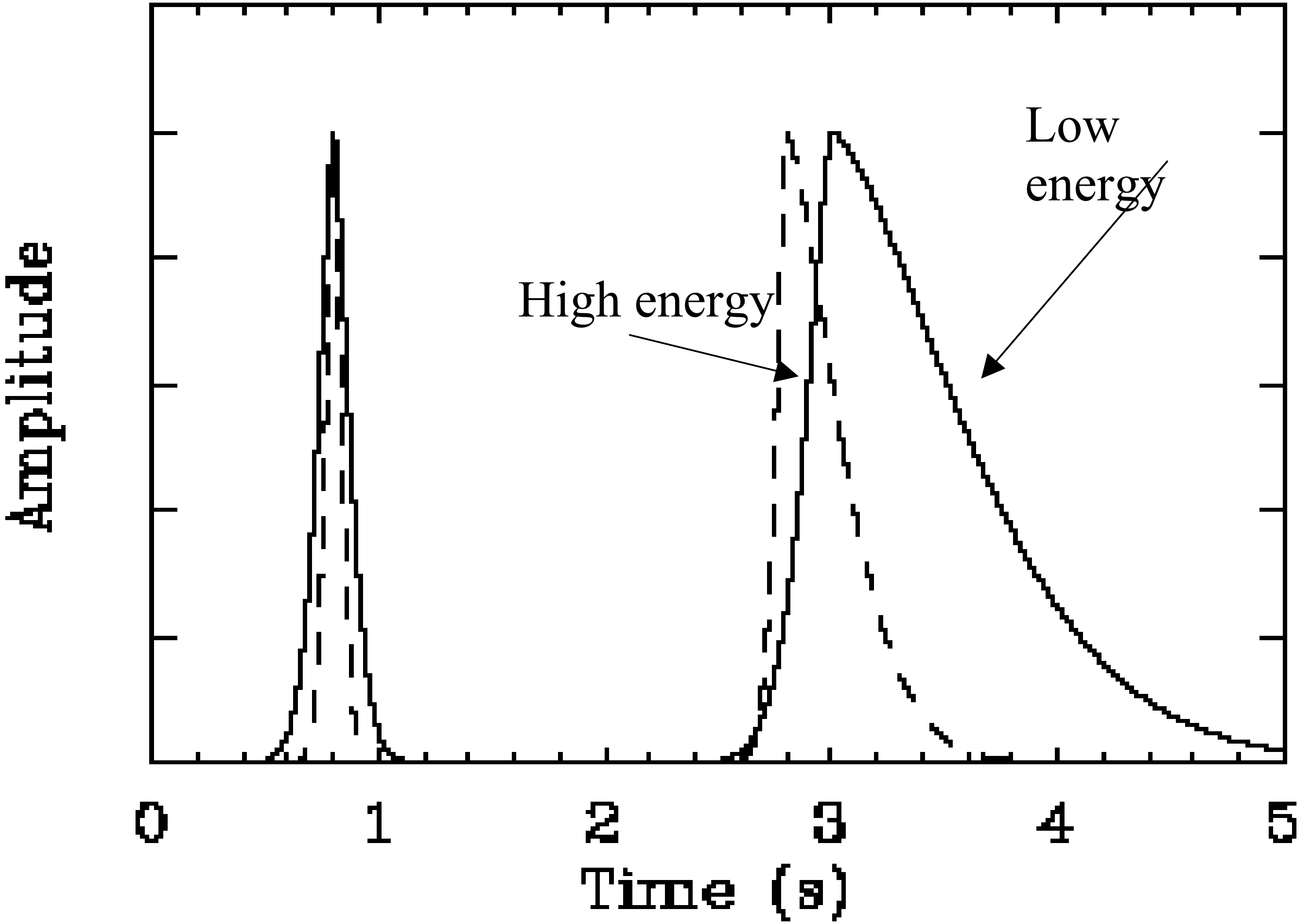
High Energy Astrophysics Tests of Lorentz Invariance Violation

- Dispersion in γ-rays from GRBs & AGN
- Photon decay (Coleman & Glashow 1999, Stecker & Glashow 2001)
- Vacuum Cherenkov radiation (Coleman & Glashow 1999; Stecker & Glashow 2001)
- Shifted pair production threshold constraints from AGN γ-rays (Stecker & Glashow 2001).
- Long baseline vacuum birefringence (GRB polarization)
- Electron velocity (Crab Nebula γ-ray spectrum;Jacobson, Liberati & Mattingly 2003).
- Ultrahigh energy cosmic ray spectrum GZK effect (Coleman & Glashow 1999; Stecker & Scully 2005).
- Photon phase coherence (diffraction patterns of distant point sources)
- Dispersion in neutrinos from GRBs (Jacob and Piran, hep-ph/0607145)
- Modified dispersion relation
  - white dwarf Fermi temperatures
  - neutrino oscillations and pulsar kicks
  - Pulsar rotation periods


Swift GRB: Dec 21, 2005
x 10^4
16
14
12
10
8
6
4
2
0
Counts/sec
0
0.5
1
1.5
2
2.5
3
t(sec)


16
14
12
10
8
6
4
2
0
Counts/sec
0.15
0.2
0.25
0.3

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



How best to measure Energy-Dependent Lags?

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

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: $t'_i = f(t_i) = t_i + L(\theta, E_i)$
(lag L is a function of a parameter θ)

If θ 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:

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

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

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: $p_k = n_k / \Sigma n_k$
3. Compute entropy: $S(\theta) = \Sigma p_k \log(p_k)$
4. Minimize $S(\theta)$ with respect to θ

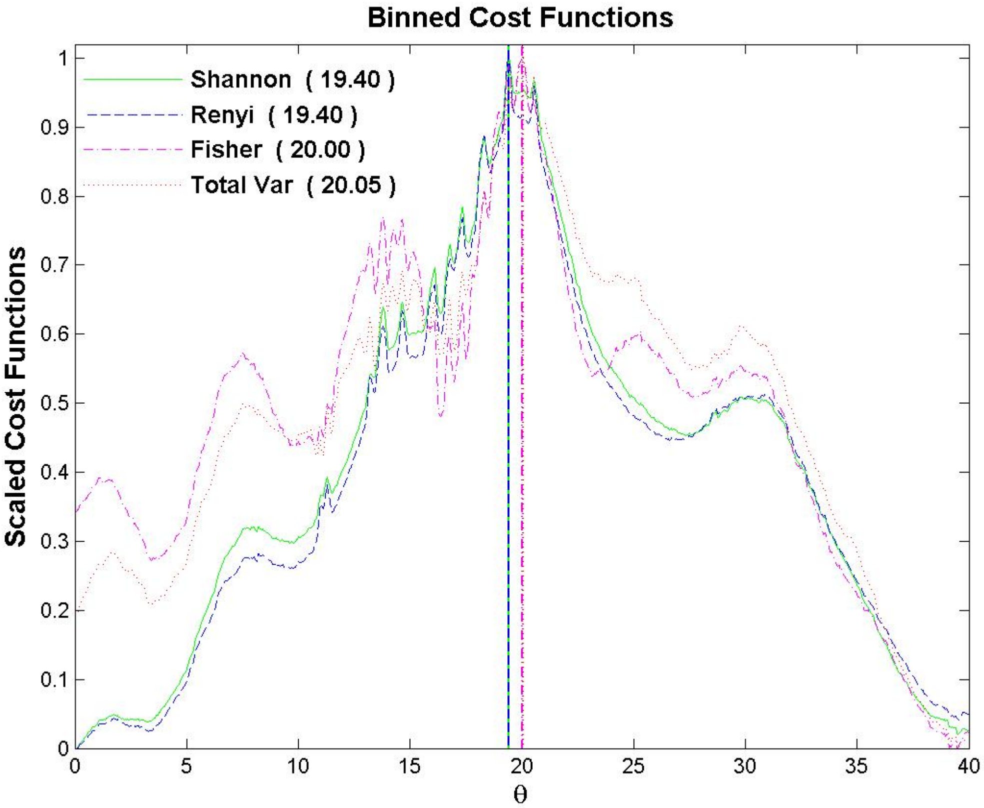
Examples:

$t'_i = f(t_i) = t_i + \theta E_i$ (first term in Taylor expansion)

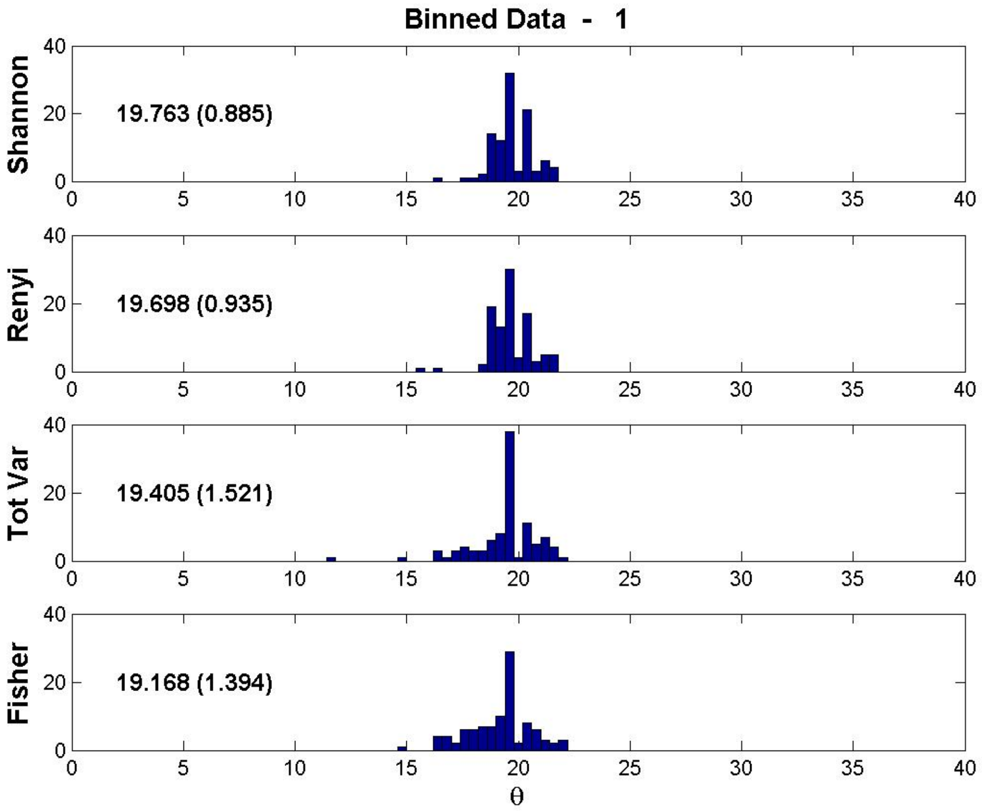
$t'_i = f(t_i) = t_i + \theta / E_i^2$ (finite photon mass dispersion rel.)

Matlab code

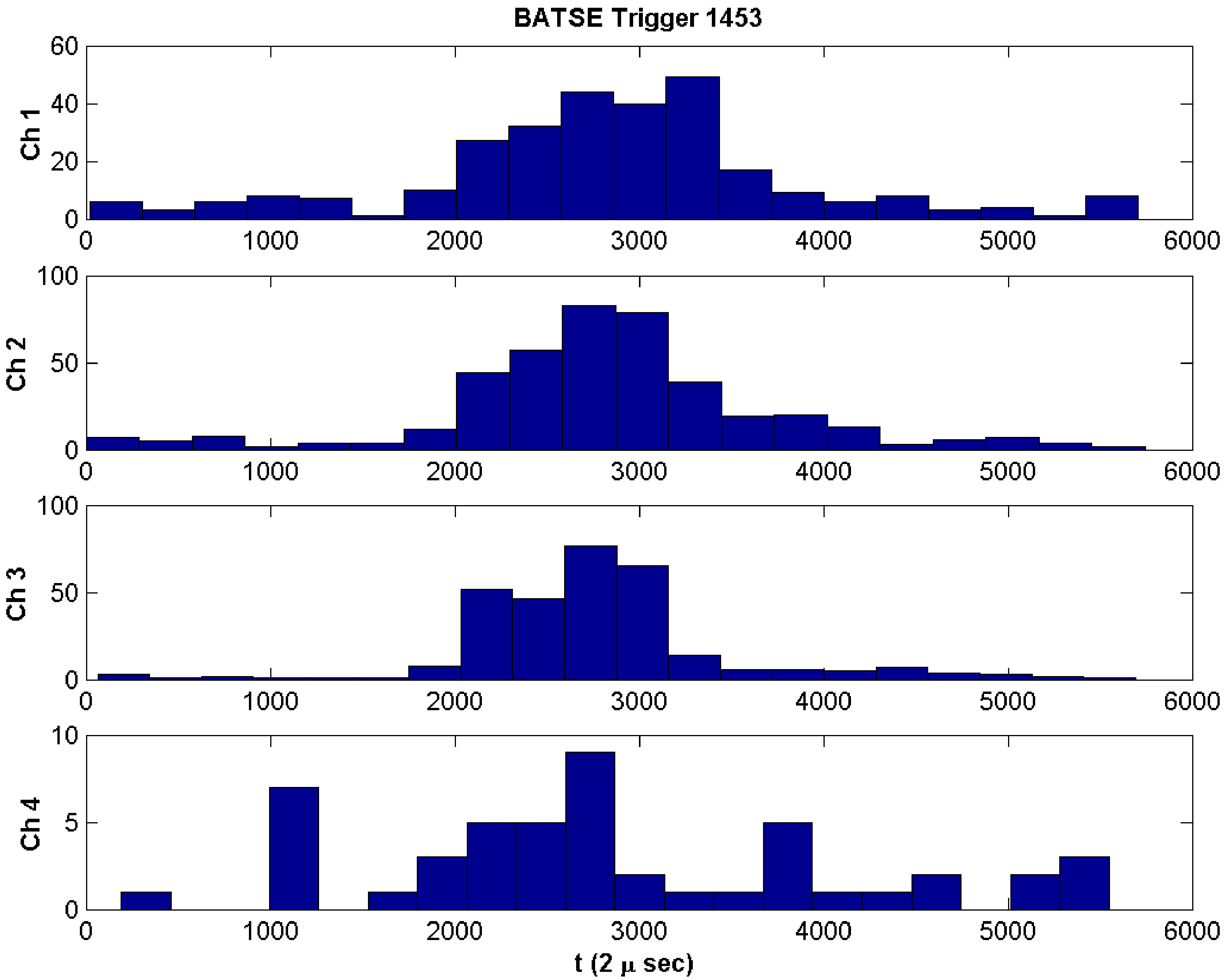
```
pp = hist( times, bins );
iu = find( pp > 0 );

% Shannon information
cost = - sum( pp(iu) .* log( pp(iu) ) ) * dd_xx;

% Renyi information: Cover and Thomas, (16.83)
cost = log( sum( pp(iu) .^ alpha  ) * dd_xx ) / ( 1 - alpha );

% total variation
cost = sum( abs( diff( pp ) ) );

% Fisher information; eq. (1.24) of Frieden
cost = 4 * sum( ( diff( sqrt( pp ) ) ) .^ 2  );

% Interval Distribution Curvature:
hh = hist( diff( sort( times) ), bins );
pp = polyfit( bins, hh, 2 );
cost = - pp(3) - pp(2);
```

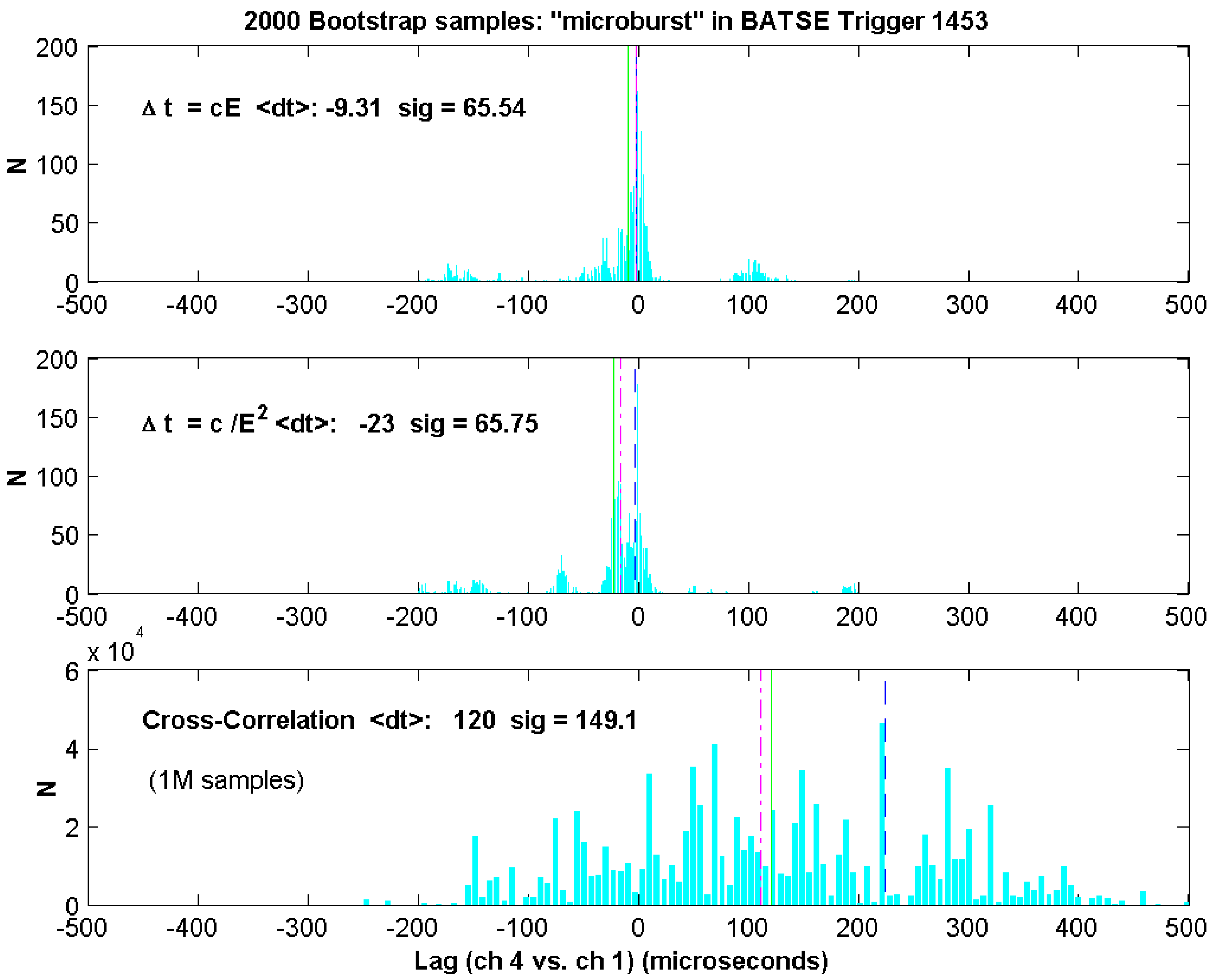


Cost function vs θ (ms/GeV) for binned data from a synthetic GRB (imposed dispersion of 20 ms/GeV) as will be seen by GLAST.

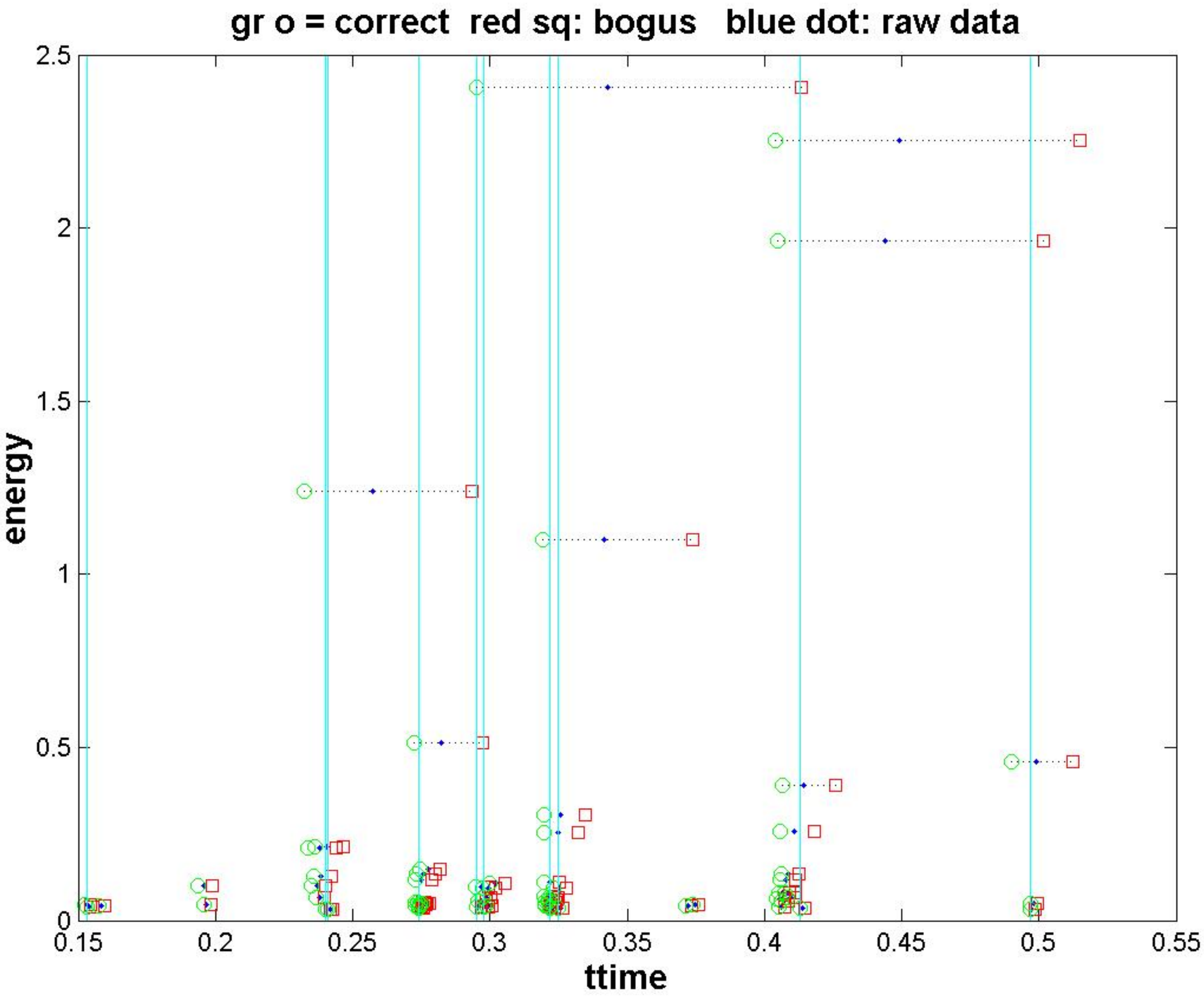


Distribution of estimated dispersion (ms/GeV) for 100 synthetic GRBs with true value θ = 20. Means (variances) are indicated for each cost function.

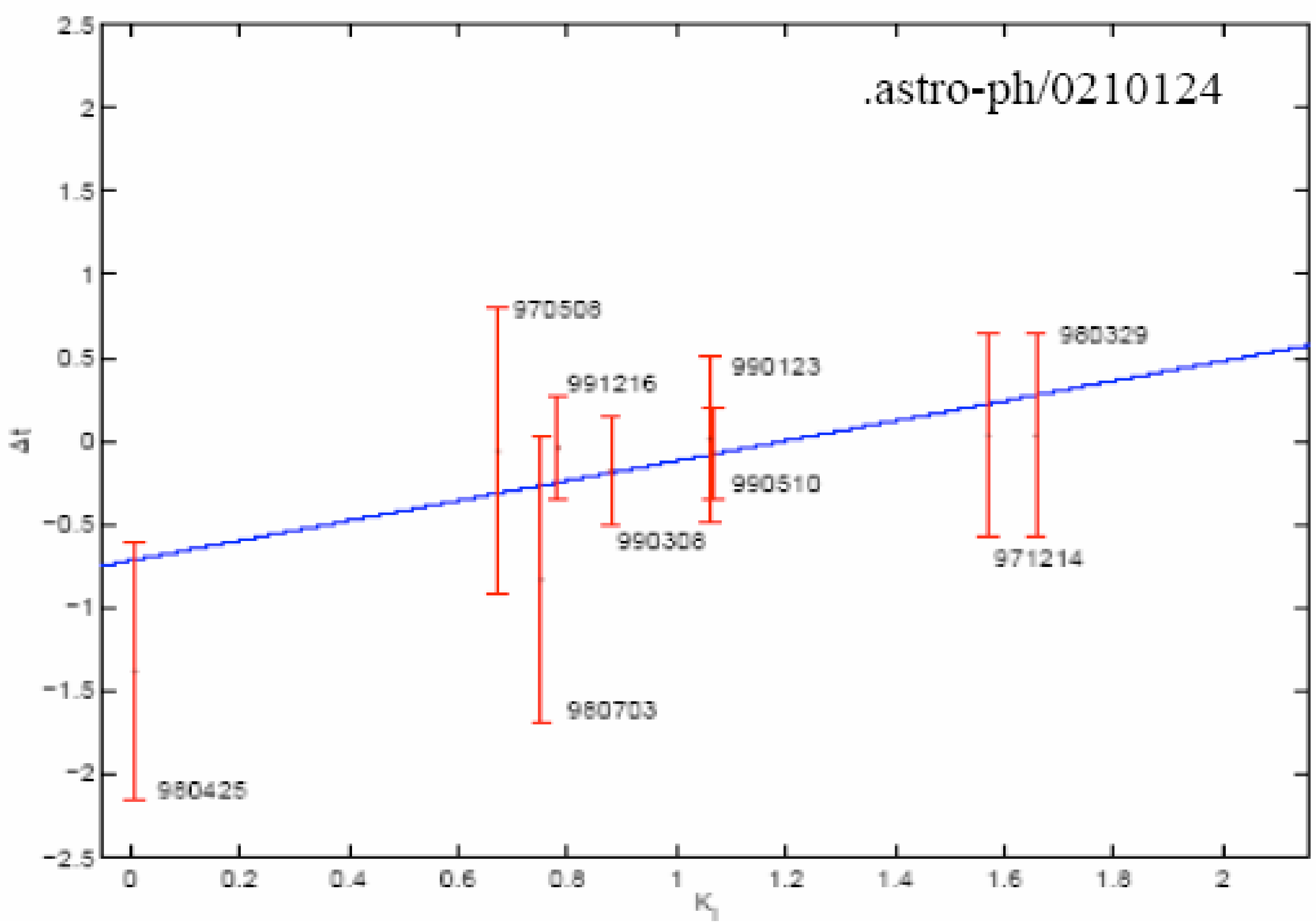

BATSE Trigger 1453
Ch 1
Ch 2
Ch 3
Ch 4
60
40
20
0
100
50
0
100
50
0
10
5
0
0
1000
2000
3000
4000
5000
6000
t (2 μ sec)


2000 Bootstrap samples: "microburst" in BATSE Trigger 1453
Δ t = cE <dt>: -9.31 sig = 65.54
Δ t = c /E² <dt>: -23 sig = 65.75
Cross-Correlation <dt>: 120 sig = 149.1
(1M samples)
N
N
N
200
150
100
50
0
x 10⁴
6
4
2
0
-500
-400
-300
-200
-100
0
100
200
300
400
500
Lag (ch 4 vs. ch 1) (microseconds)

Time-Energy Representation

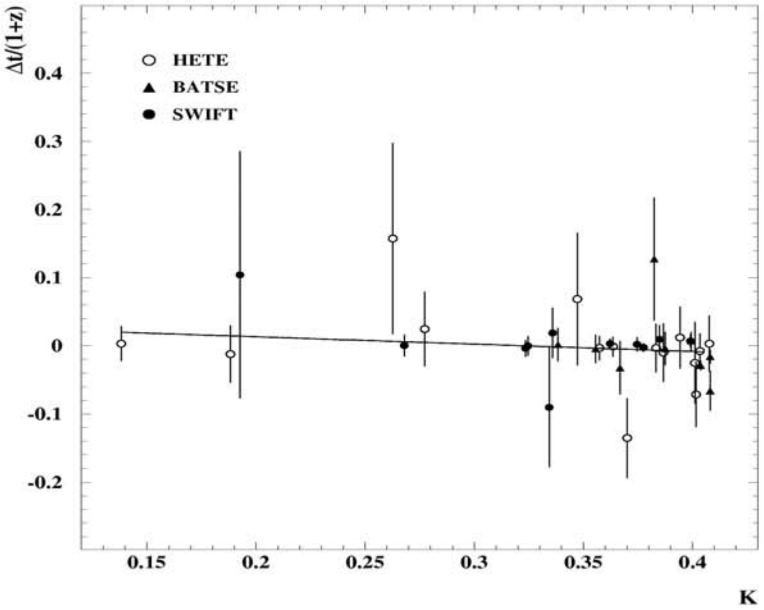


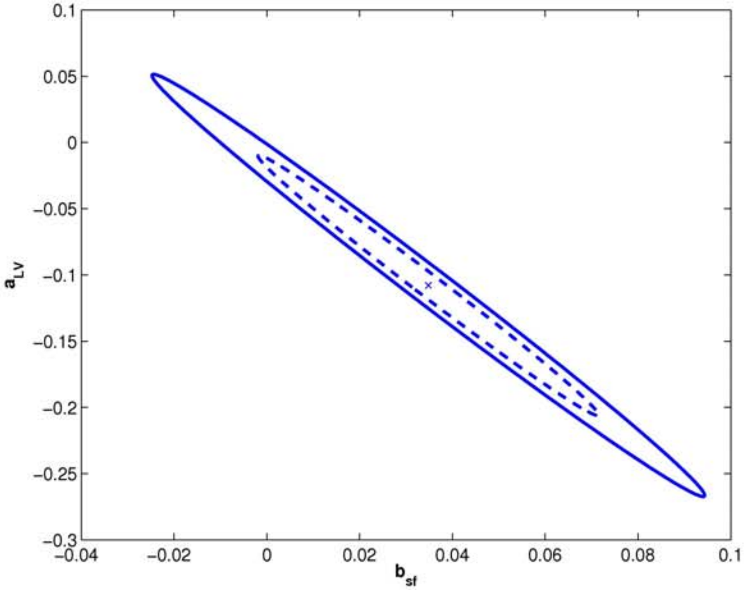
Previous estimate from Cross-correlations

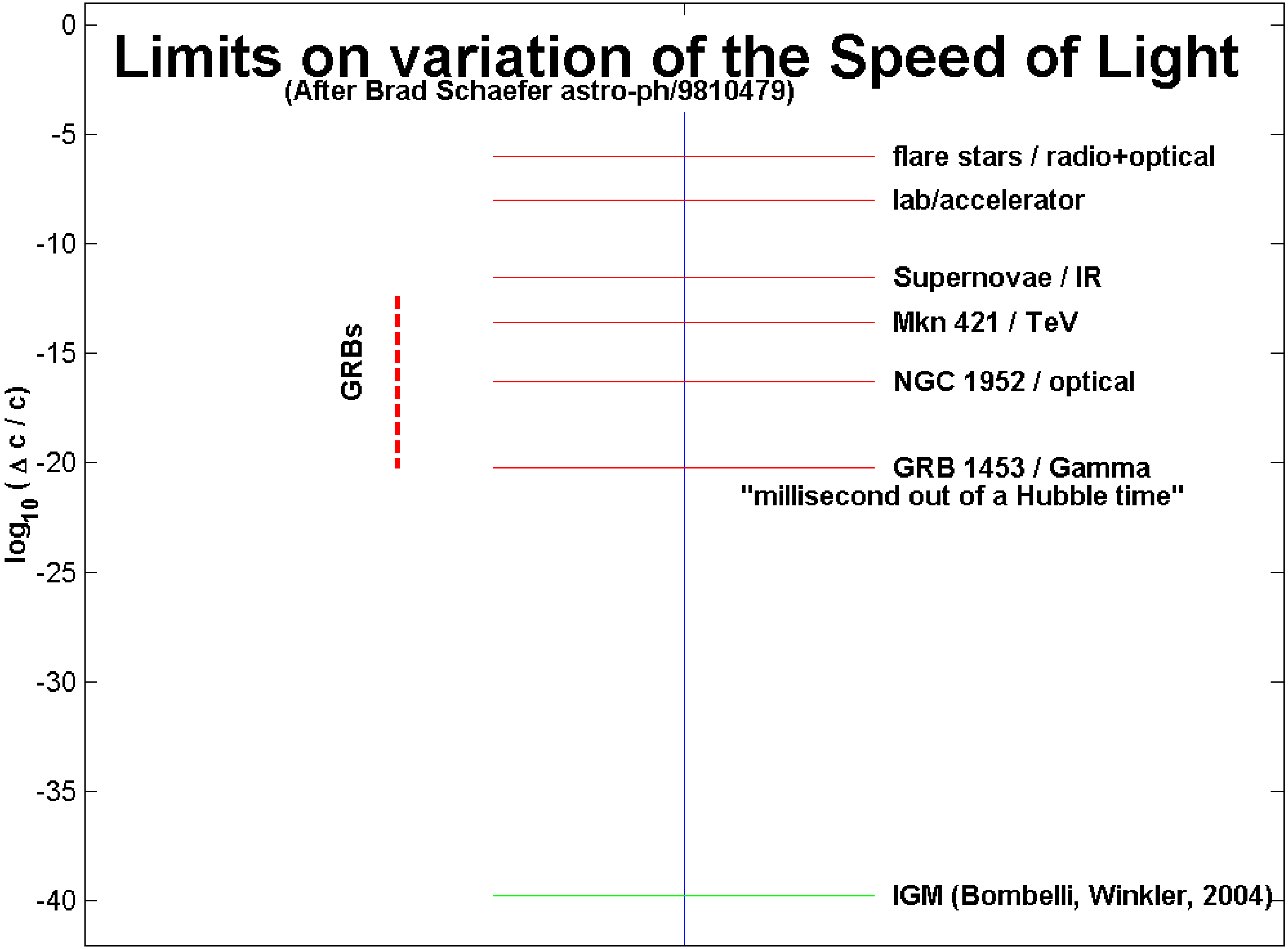


Ellis et al 2002
Wavelet method

From Ellis et al.
Astro-ph/0510172







Limits on variation of the Speed of Light

(After Brad Schaefer astro-ph/9810479)

High-Energy Tests of Lorentz Invariance, Sidney Coleman and Sheldon Glashow, (1999) hep-ph/9812418; systematic development of perturbation of the Standard Model and discussion of astrophysical tests.

Modern Tests of Lorentz Invariance, David Mattingly, (2005) gr-qc/0502097; review of both theory and observation

Quantum-Gravity Analysis of Gamma-RayBursts 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

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

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

If you look at the Catalan version of Wikipedia (yes, such thing exists), and you look for "GLAST“ http://ca.wikipedia.org/wiki/GLAST You will find that it says something like "an observatory to be put in orbit to verify predictions of loop quantum gravity". I don't know who posted that entry... it wasn't us...

GLAST

De Viquipèdia

Dreceres ràpides: navegació, cerca

GLAST és un observatori en òrbita previst per l'any 2006. Aquest observatori tindria la precisió necessària per comprovar els càlculs dels estudiosos de la gravetat quàntica de bucles (Teoria de la xarxa d'espín) Rodolfo Gambini, de la Universidad de la República (Uruguay), Jorge Pullin, de la Universitat estatal de Louisiana, i d'altres. Segons aquests càlculs els fotons de diferent energies podrien viatjar a diferent velocitat.

Aquesta verificació només es pot fer amb els raigs gamma, calen fotons d'energies molt elevades per que la magnitud d'aquests efectes és proporcional al quocient entre la longitud de Planck, i la longitud d'ona.

Bibliografia:

Investigación i Ciencia (Scientific American), Átomos del Espacio y del Tiempo, plana 58, per Lee Smolin, març 2004, Prensa Científica, S. A., Muntaner, 339 pral 1ª, 08021, Barcelona