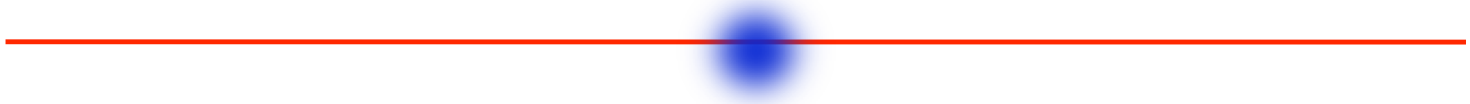
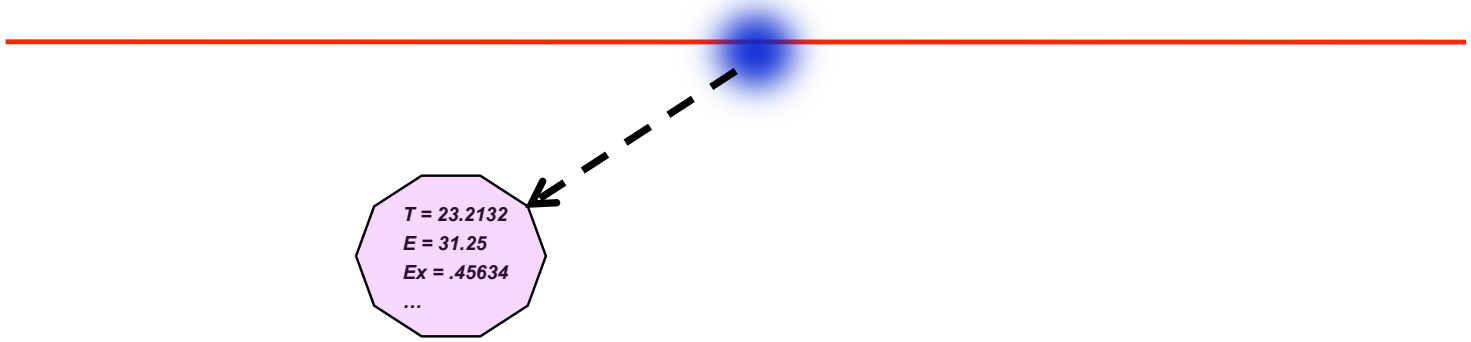
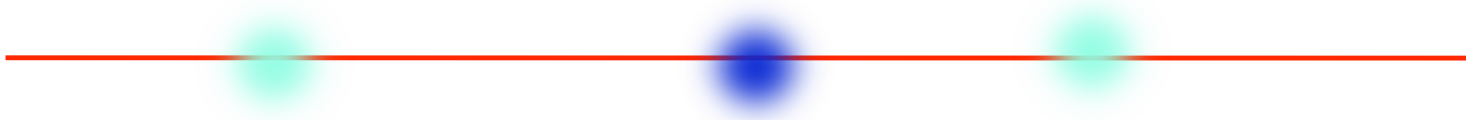
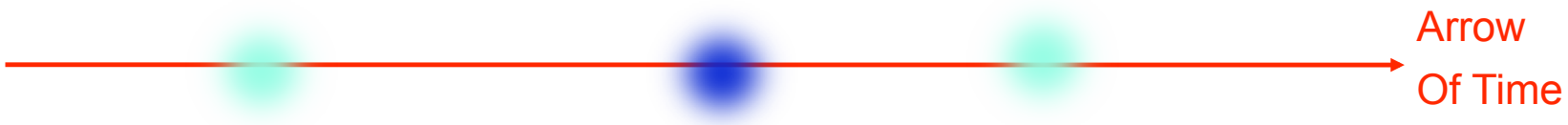
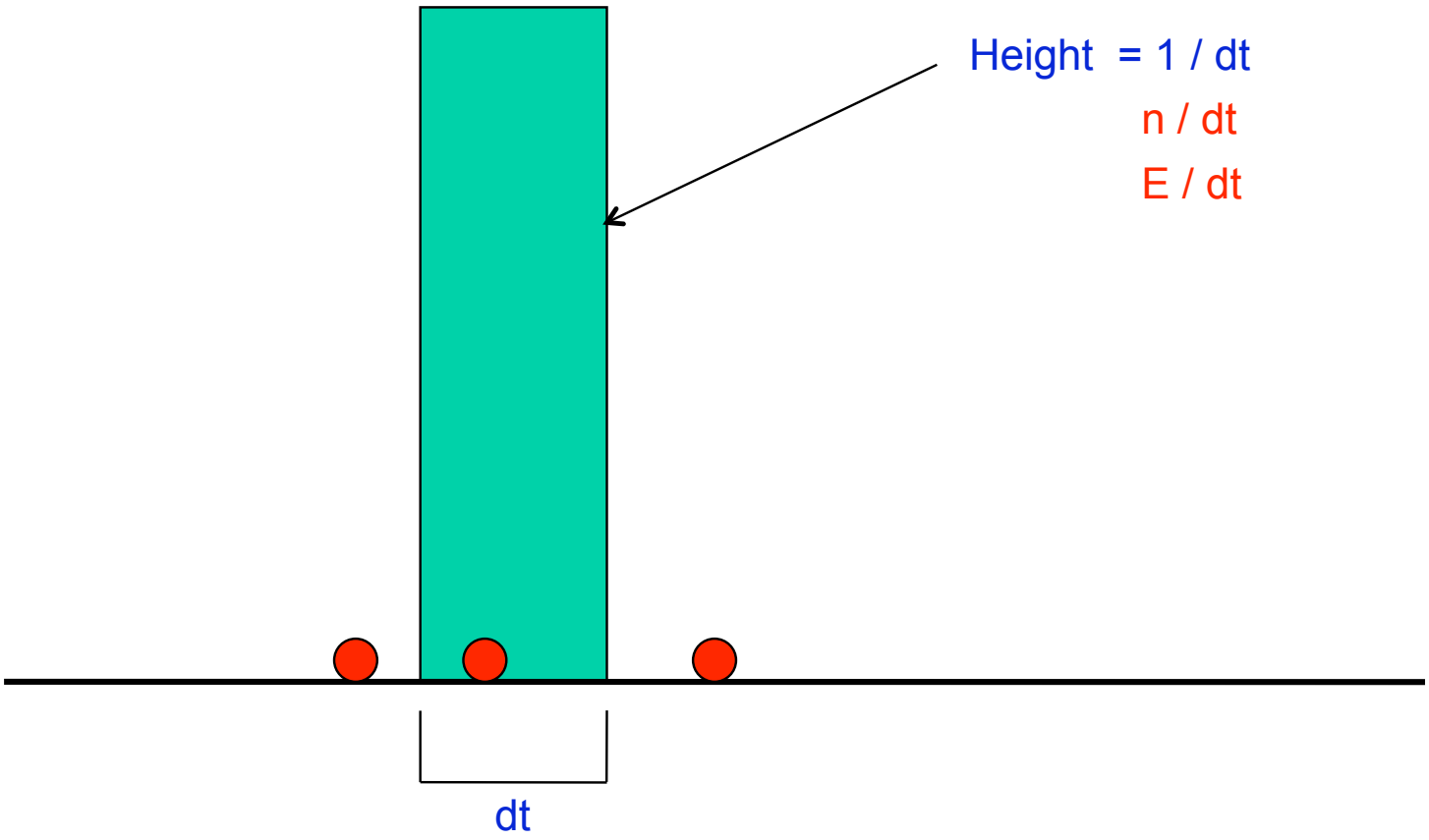
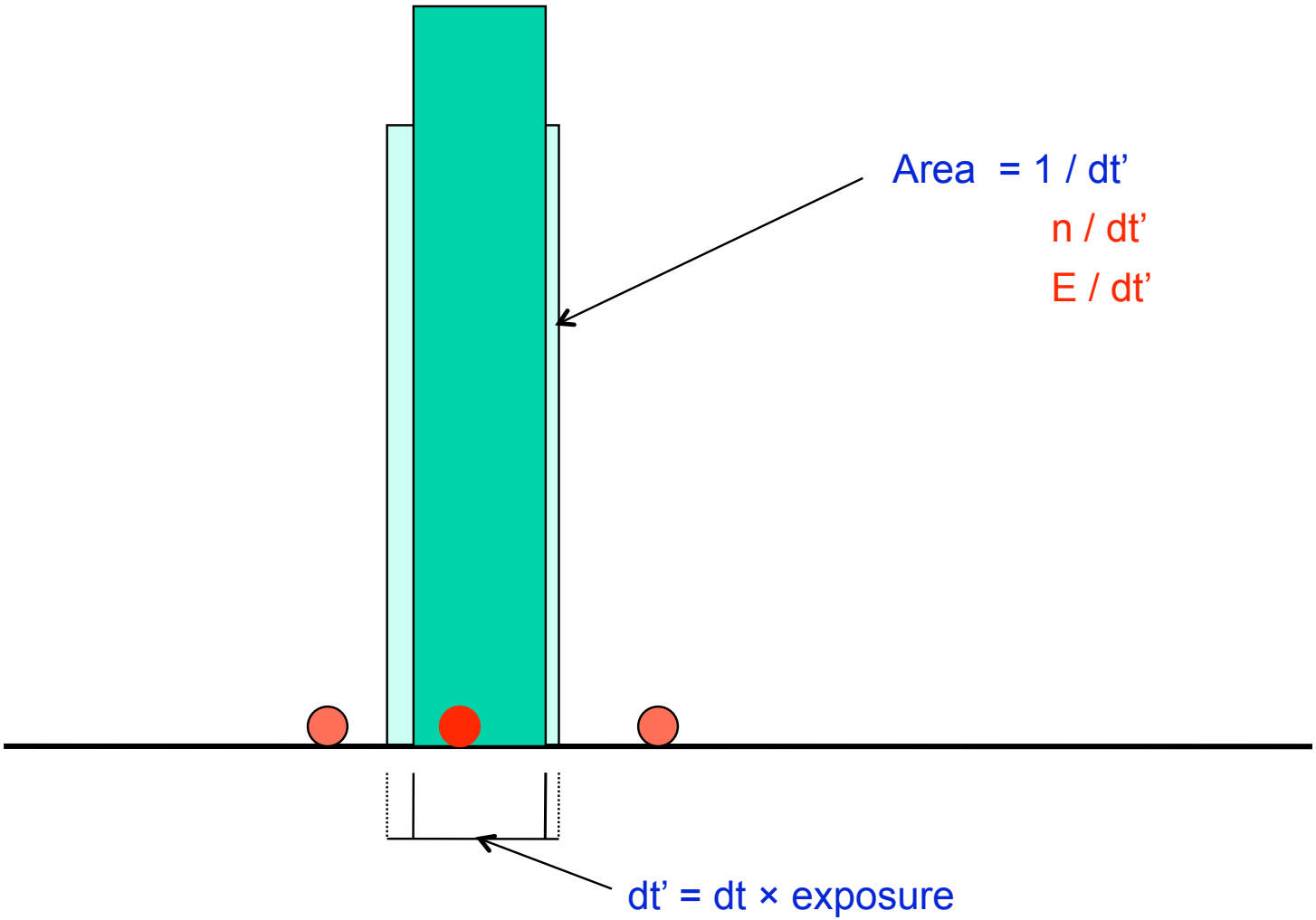


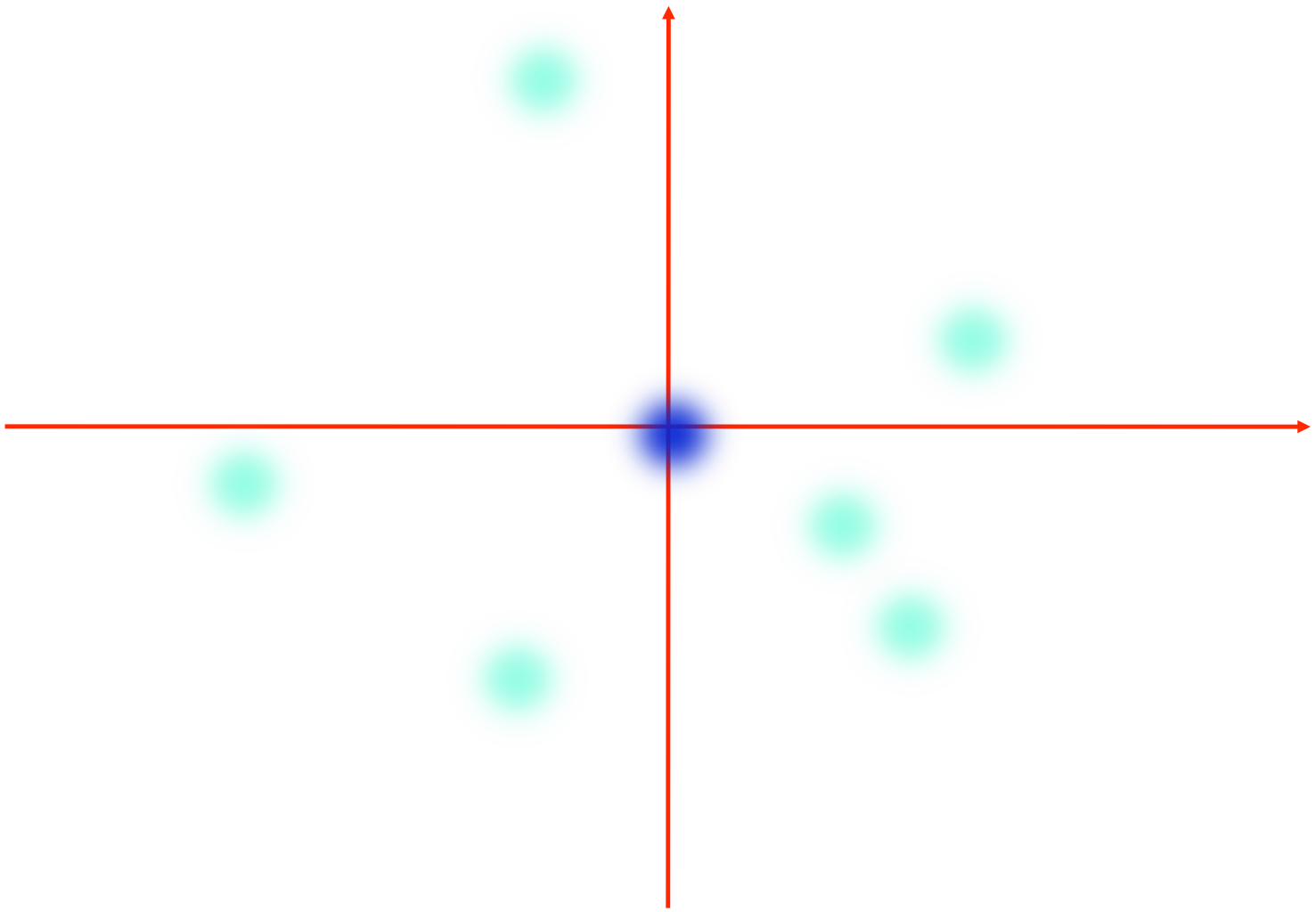

T = 23.2132
E = 31.25
Ex = .45634
...

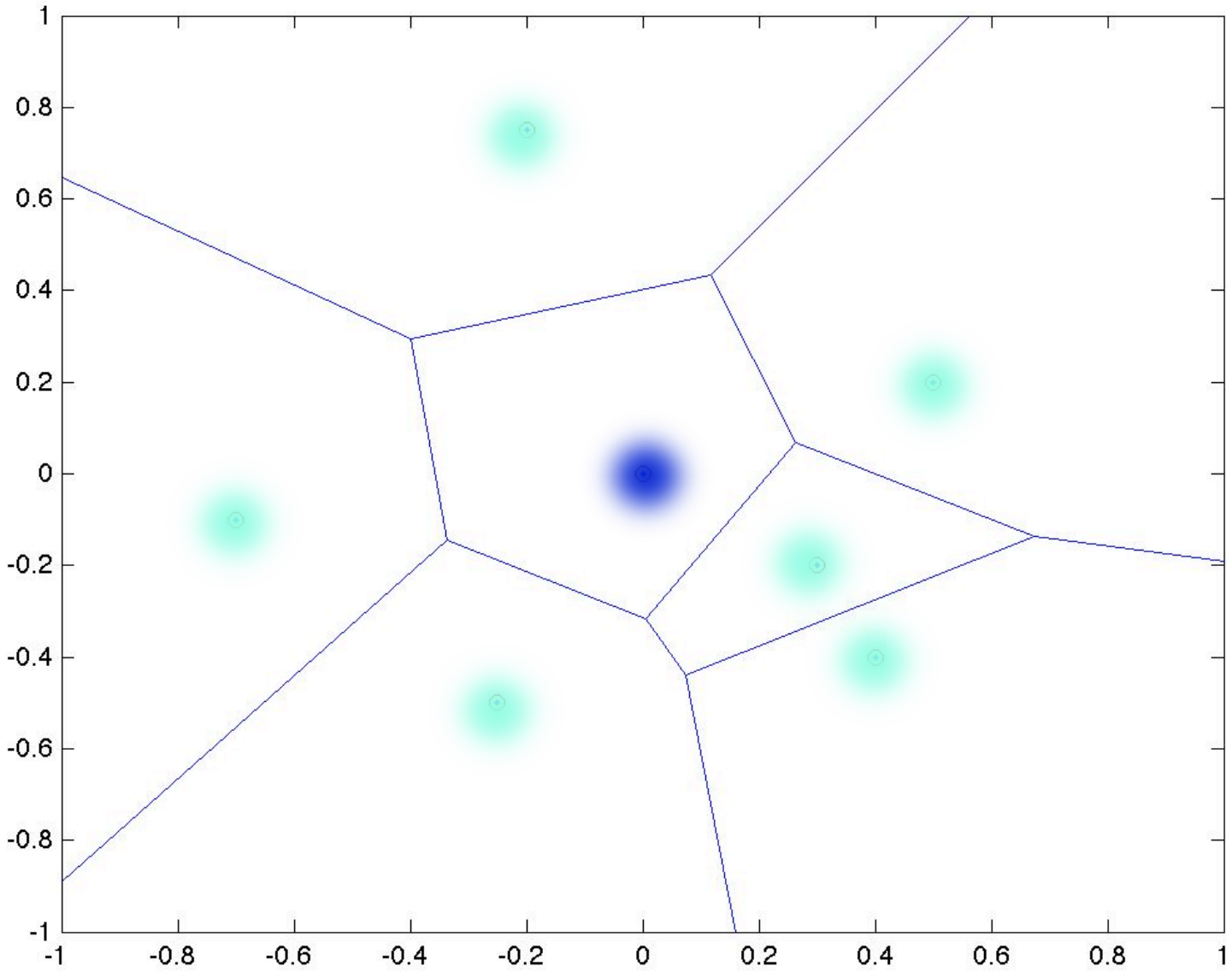


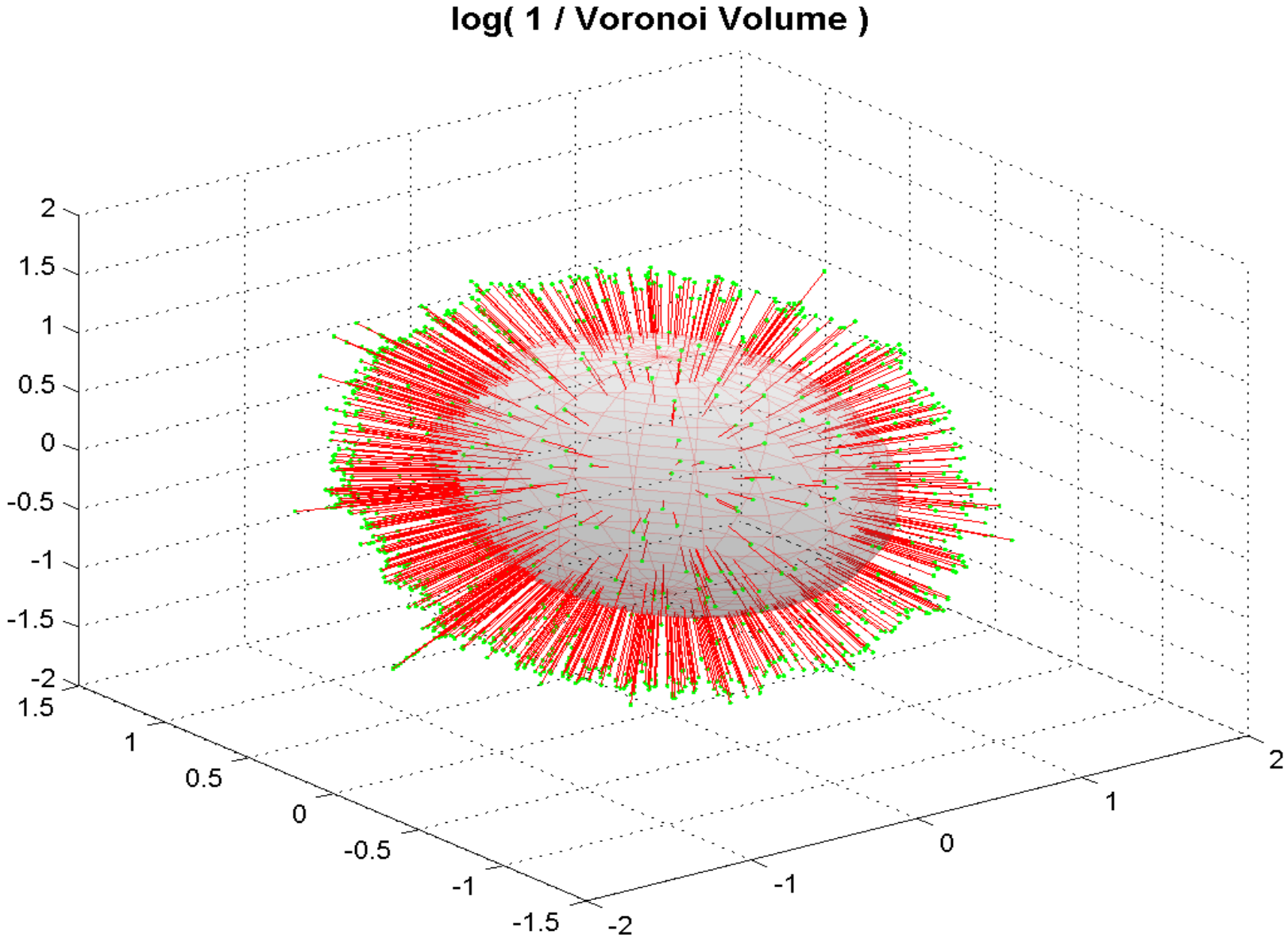

Arrow
Of Time

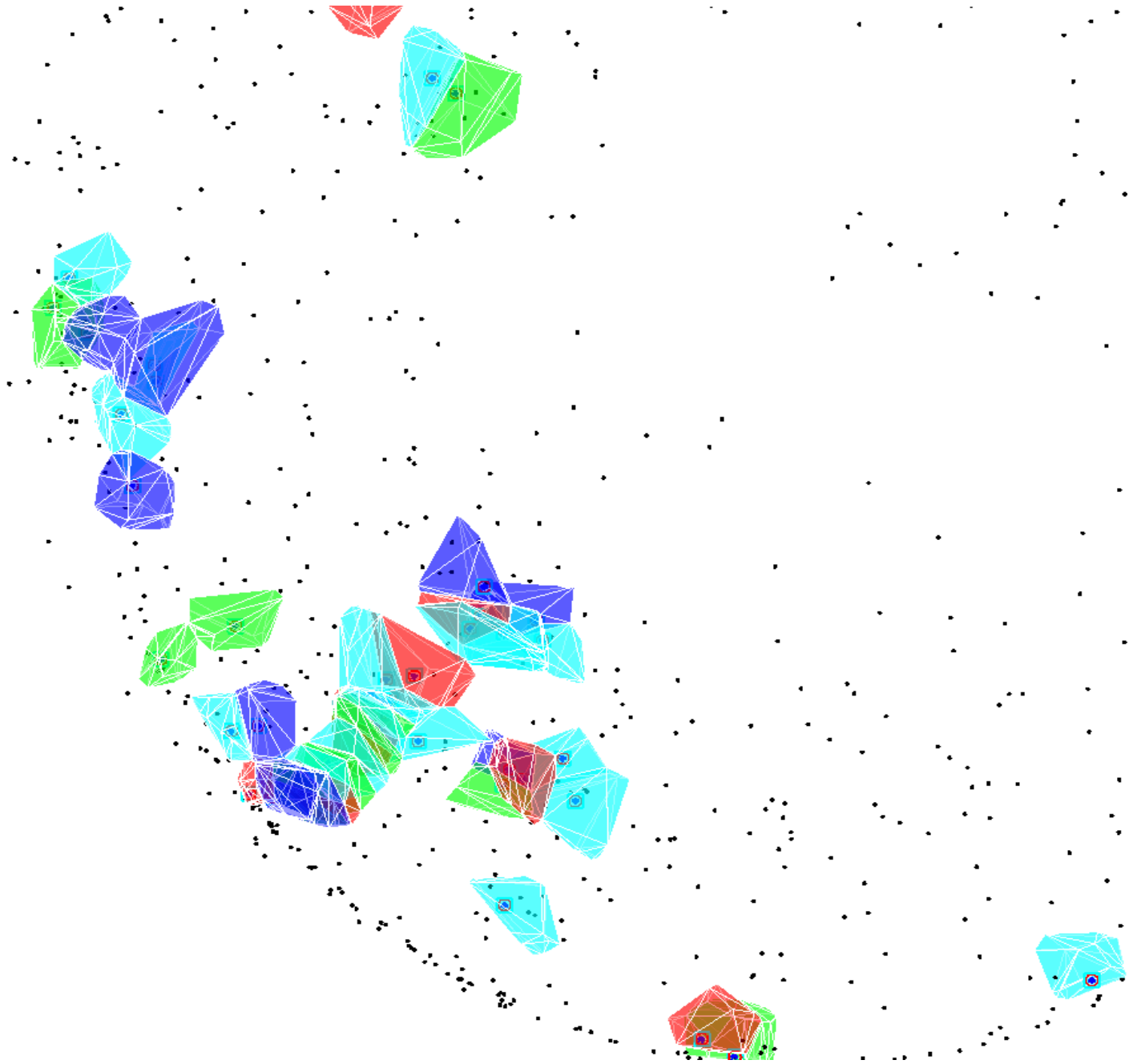

Height = 1 / dt
n / dt
E / dt
dt

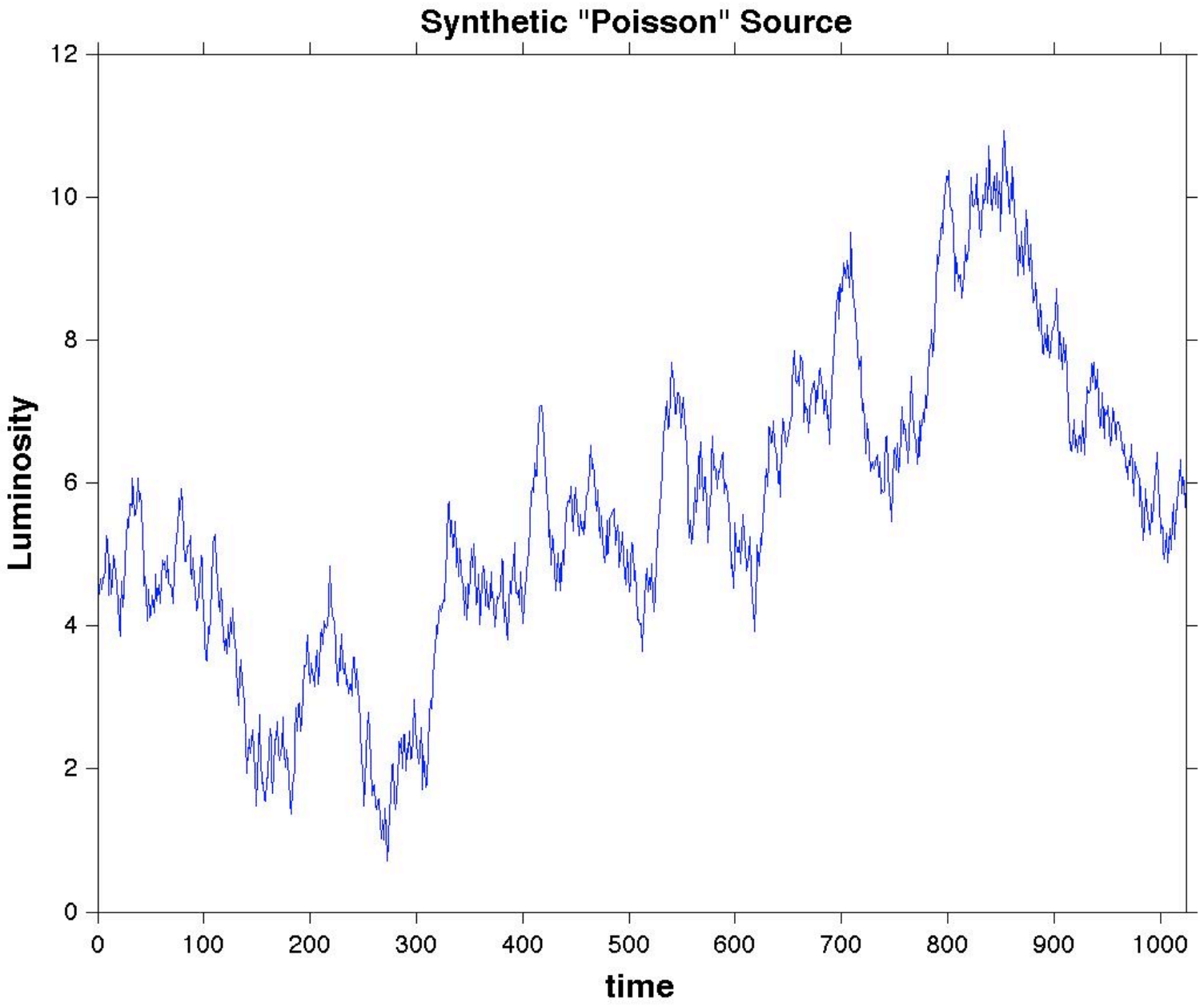

Area = 1 / dt'
n / dt'
E / dt'
dt' = dt × exposure

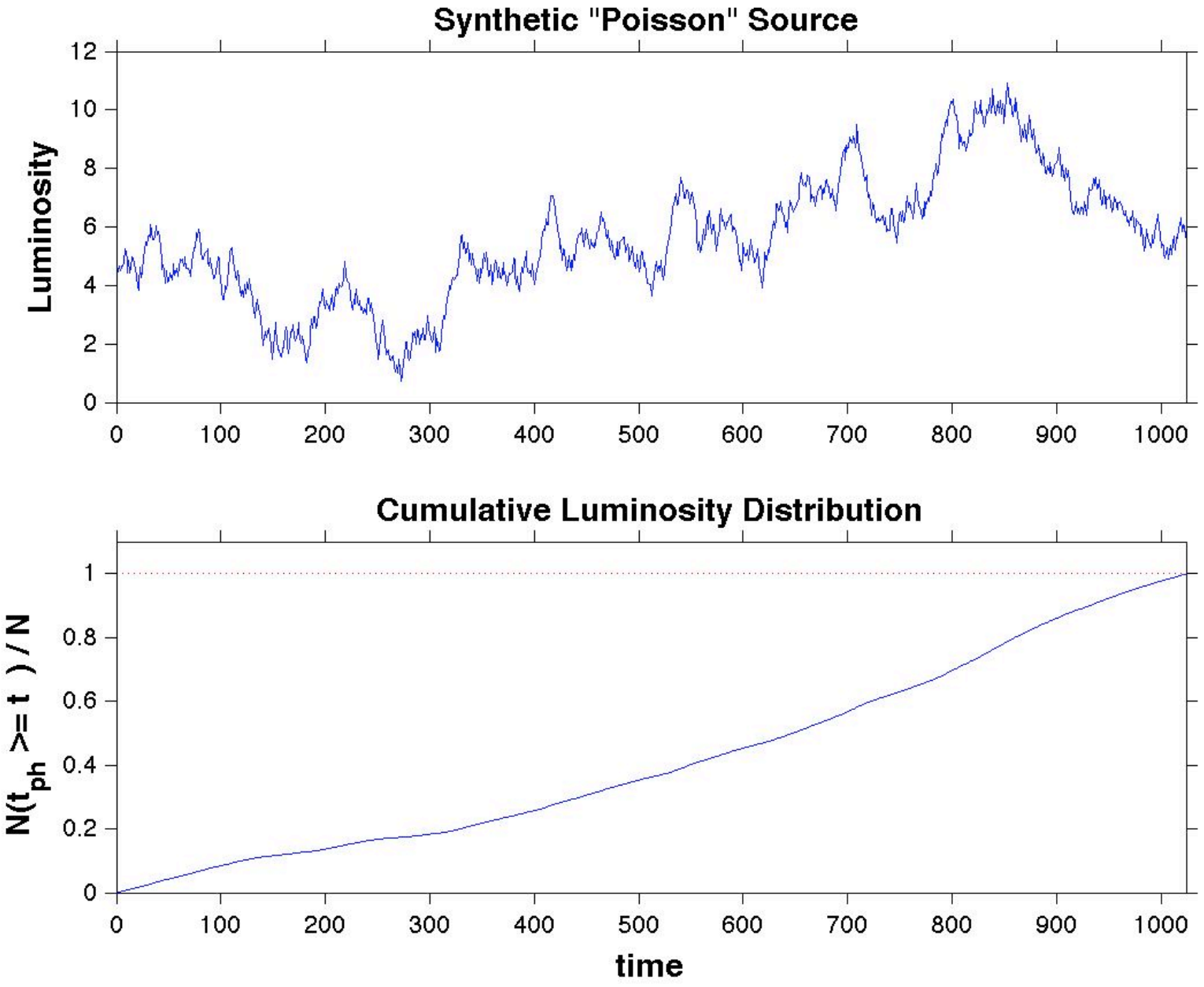


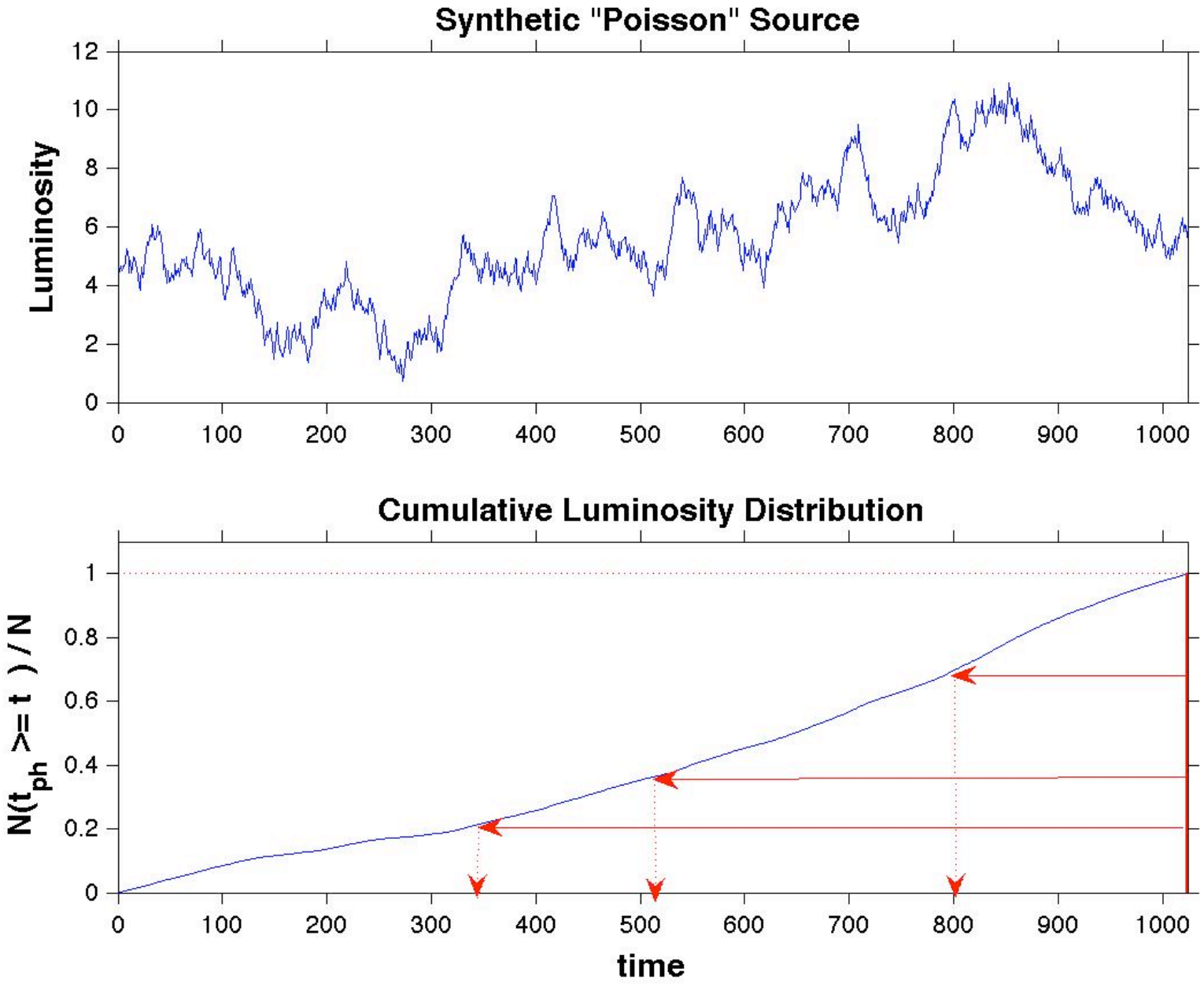

1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

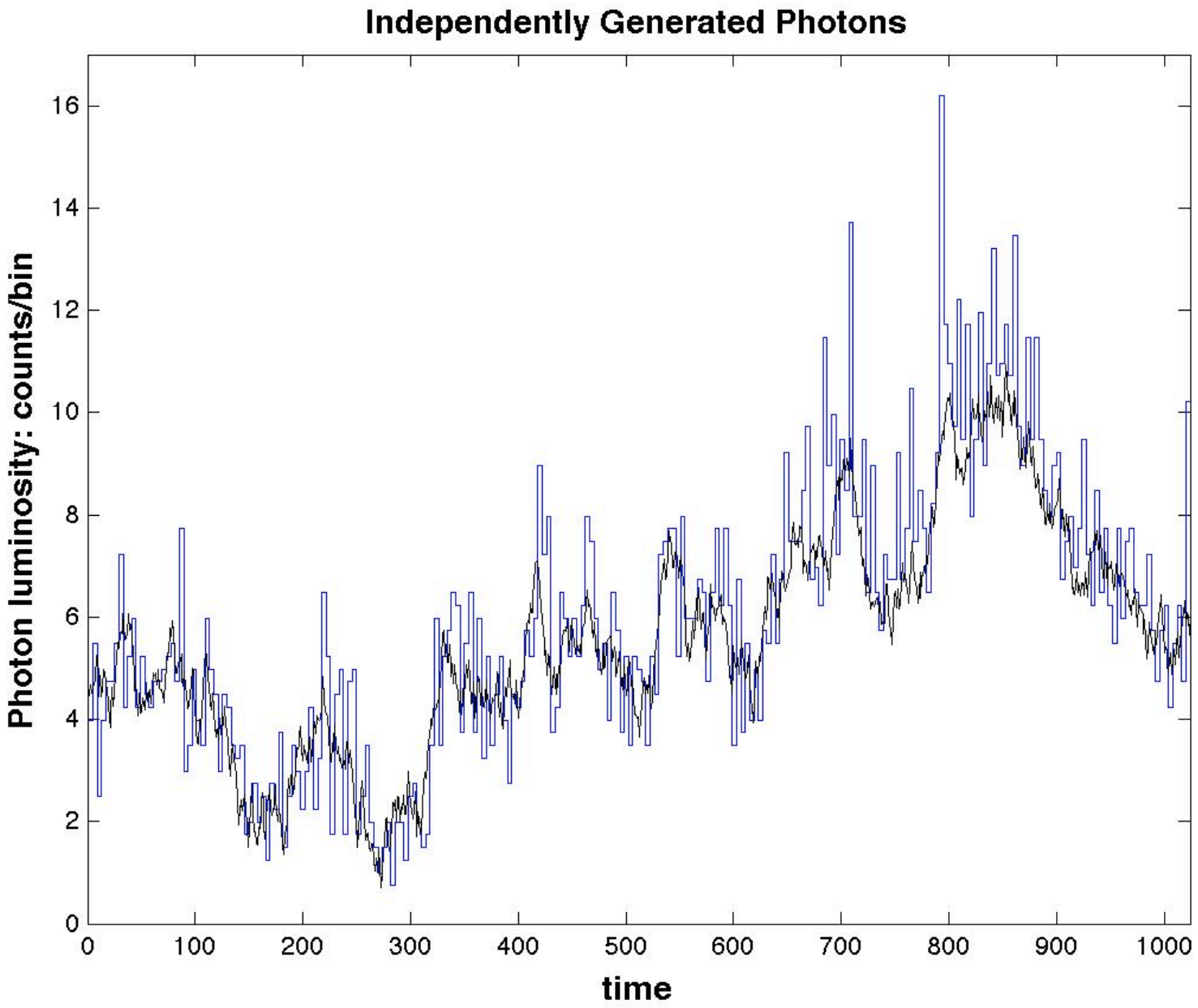

log(1 / Voronoi Volume)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-1
0
1
2




Synthetic "Poisson" Source
Luminosity
time
0
2
4
6
8
10
12
0
100
200
300
400
500
600
700
800
900
1000


Synthetic "Poisson" Source
Luminosity
0
2
4
6
8
10
12
0
100
200
300
400
500
600
700
800
900
1000
Cumulative Luminosity Distribution
N(t_ph >= t) / N
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
700
800
900
1000
time


Synthetic "Poisson" Source
Luminosity
0
2
4
6
8
10
12
0
100
200
300
400
500
600
700
800
900
1000
Cumulative Luminosity Distribution
N(t_ph >= t) / N
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
600
700
800
900
1000
time


Independently Generated Photons
Photon luminosity: counts/bin
time
0
2
4
6
8
10
12
14
16
0
100
200
300
400
500
600
700
800
900
1000

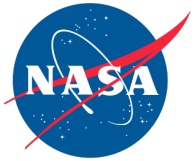
Novel Methods for Analysis Of Event/Point Data

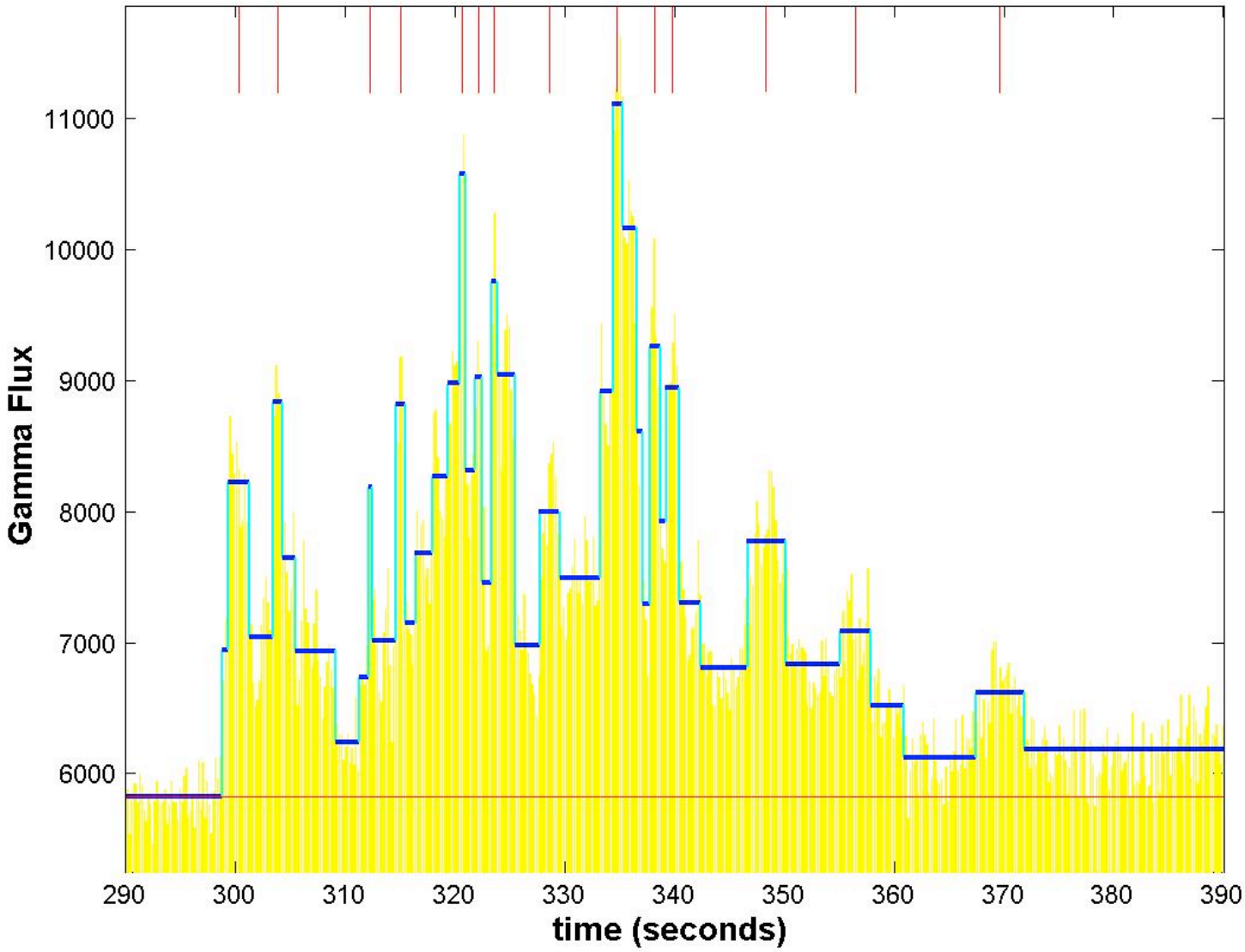
- Luminosity: random or deterministic
- Photon Emission Independent Random Process (Poisson)

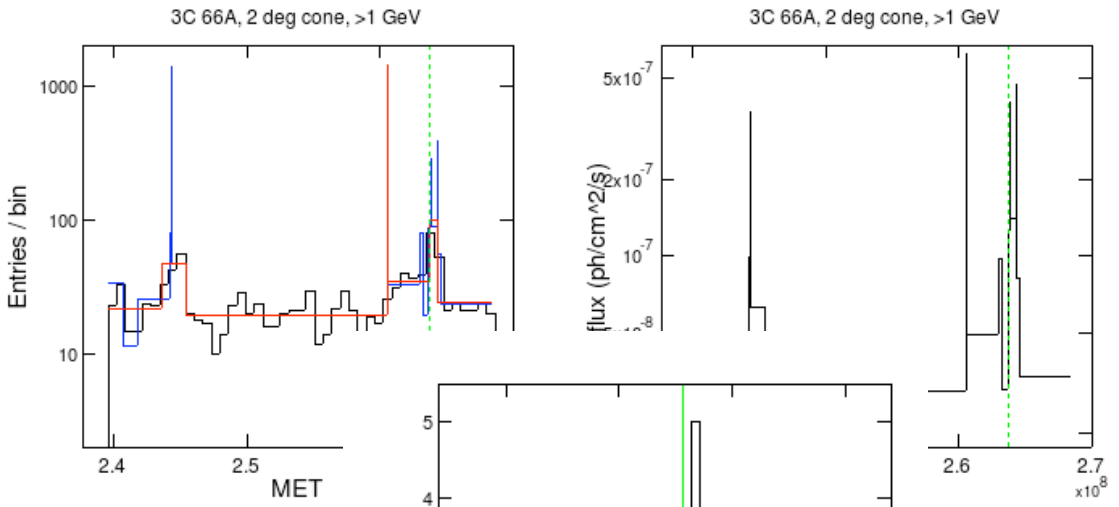
- Random Scintillation, Dispersion, etc.?

- Random Detection of Photons (Poisson)

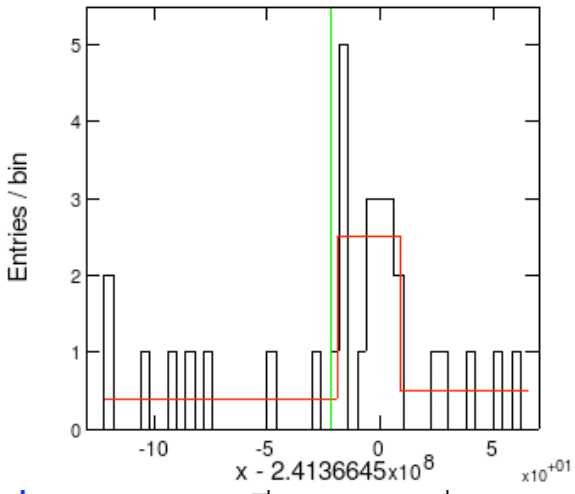
Correlations in source luminosity do not imply correlations in time series data!

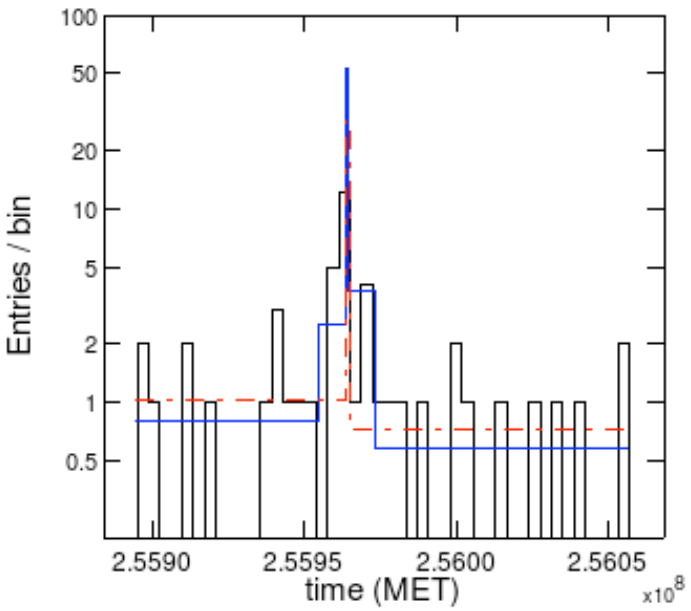


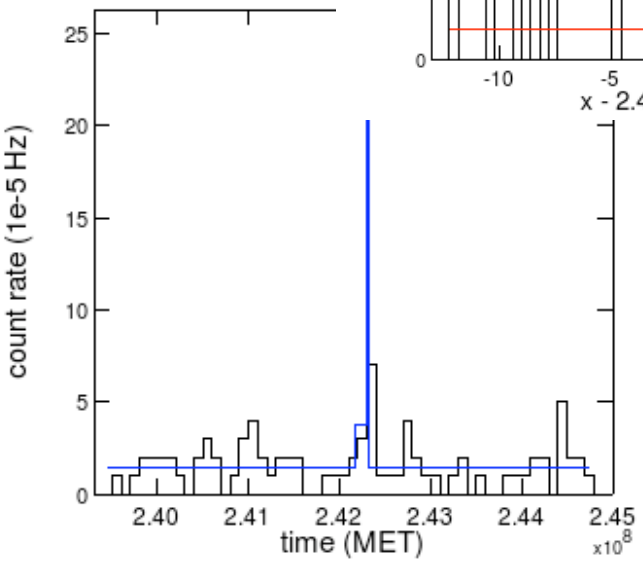

Gamma Flux
11000
10000
9000
8000
7000
6000
290
300
310
320
330
340
350
360
370
380
390
time (seconds)

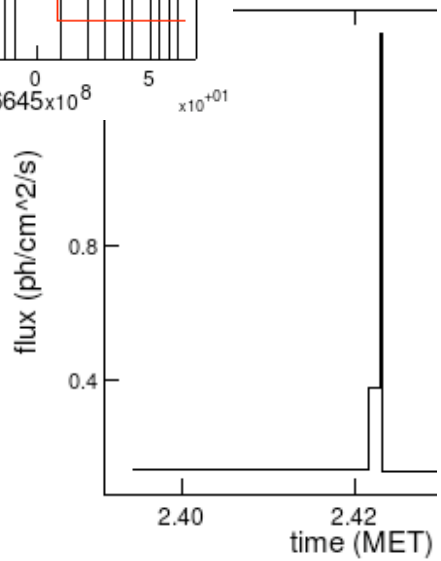

3C 66A, 2 deg cone, >1 GeV
Entries / bin
MET

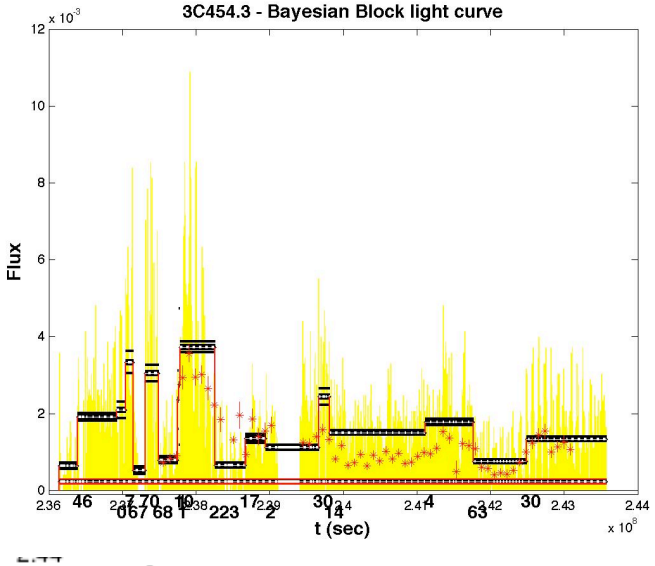
3C 66A, 2 deg cone, >1 GeV
flux (ph/cm^2/s)

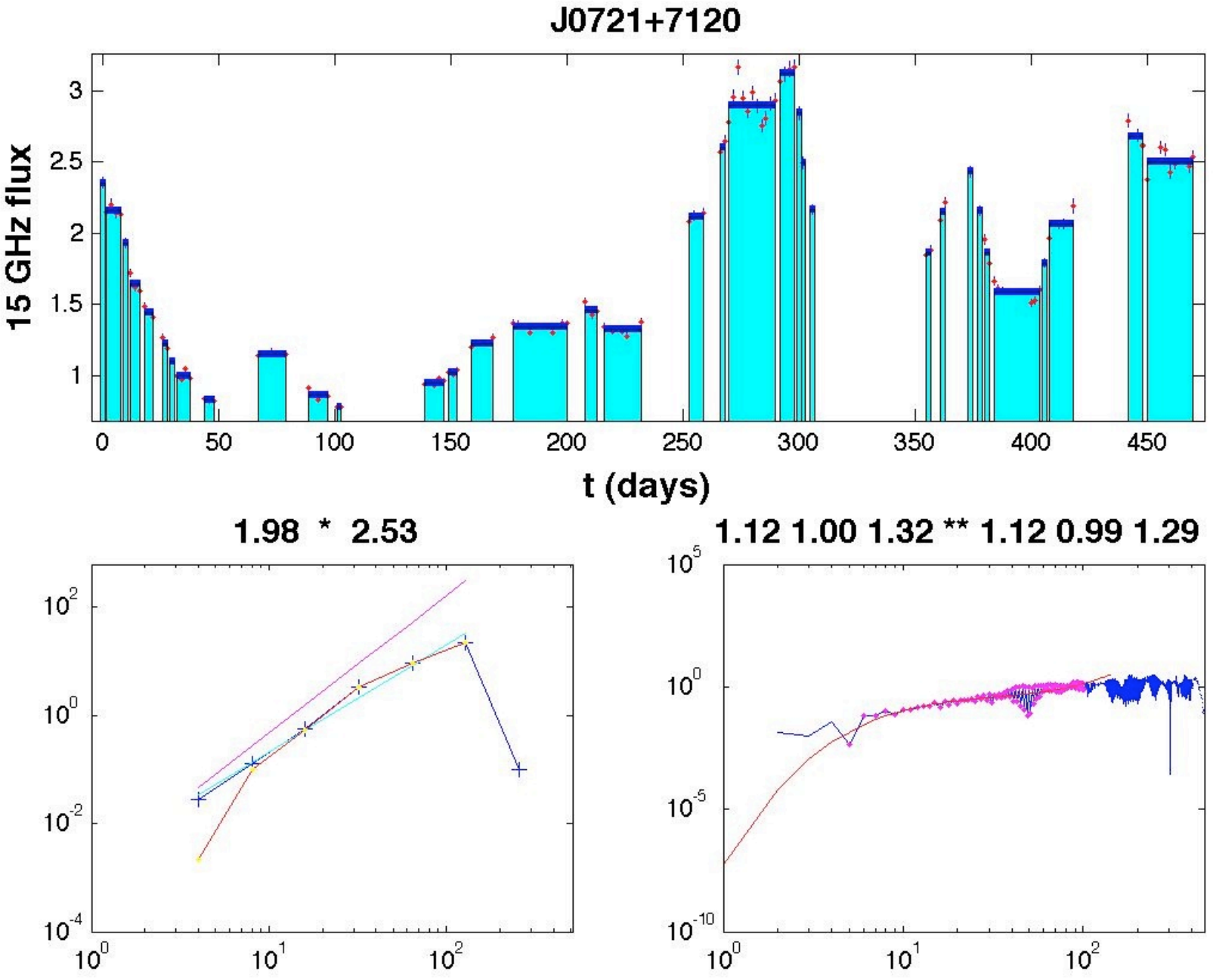

Entries / bin
x - 2.4136645

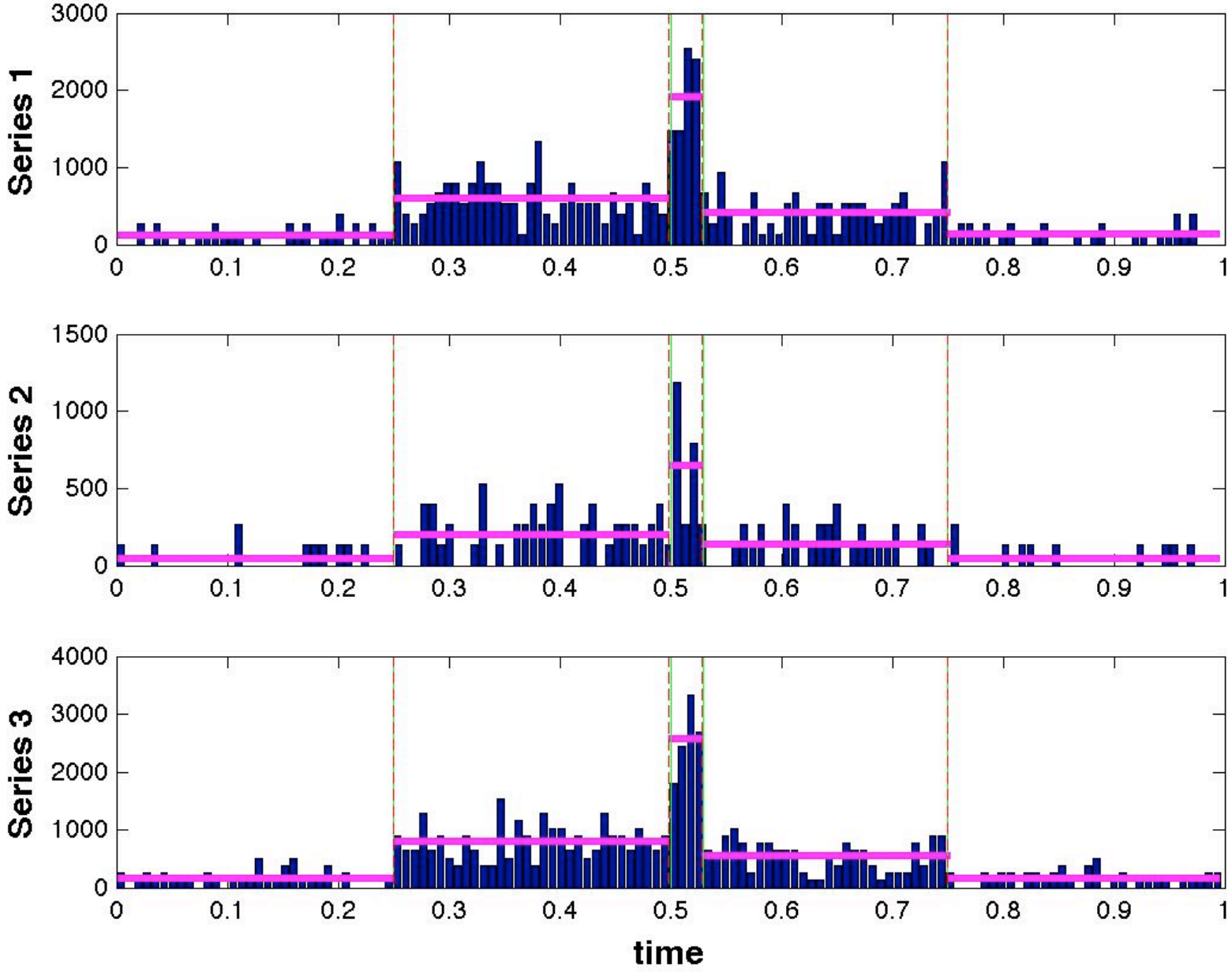

Entries / bin
time (MET)


count rate (1e-5 Hz)
time (MET)


flux (ph/cm^2/s)
time (MET)


3C454.3 - Bayesian Block light curve
Flux
t (sec)


J0721+7120
15 GHz flux
t (days)
1.98 * 2.53
1.12 1.00 1.32 ** 1.12 0.99 1.29


Series 1
3000
2000
1000
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Series 2
1500
1000
500
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Series 3
4000
3000
2000
1000
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
time

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)

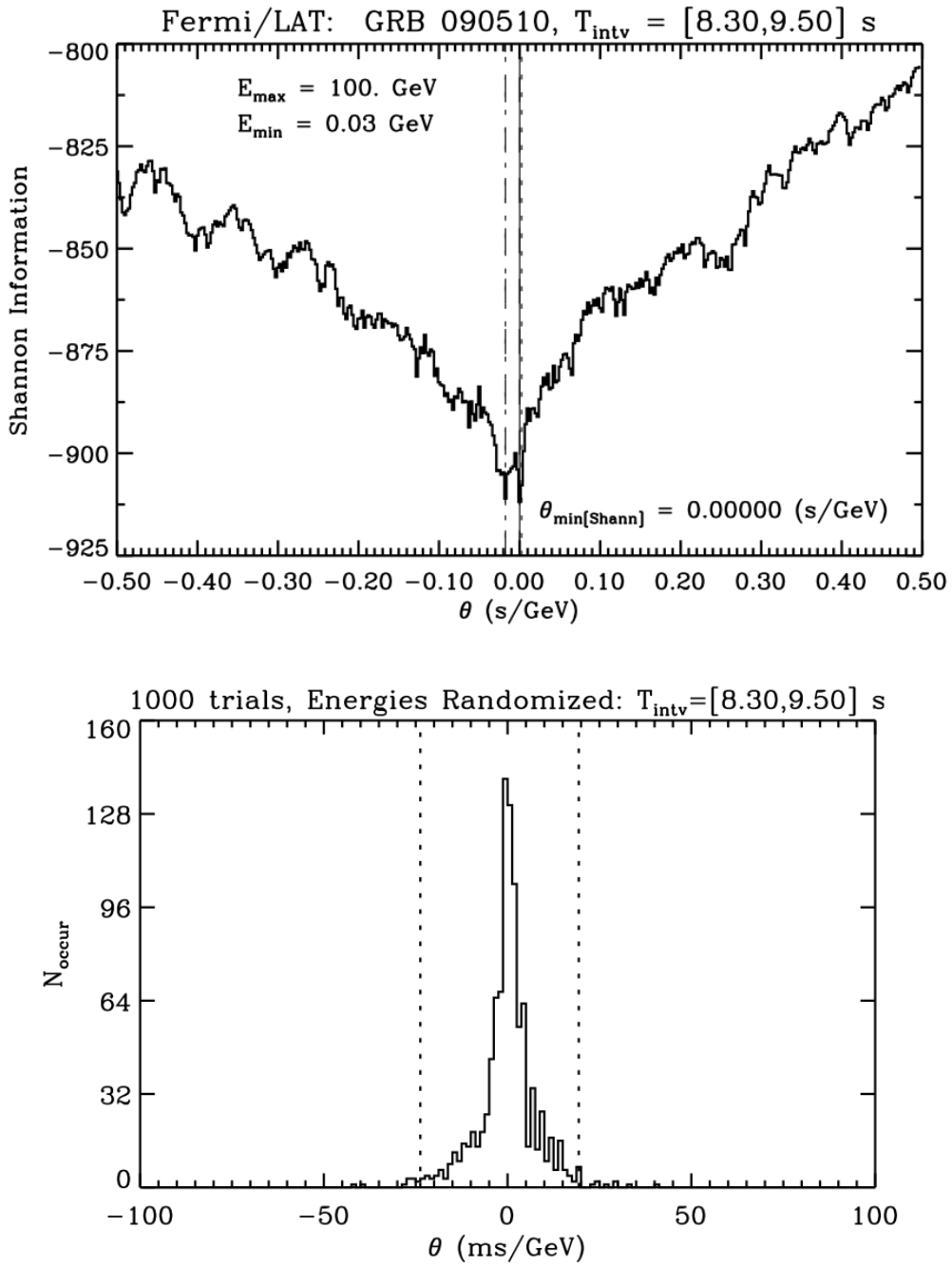
Entropy approach

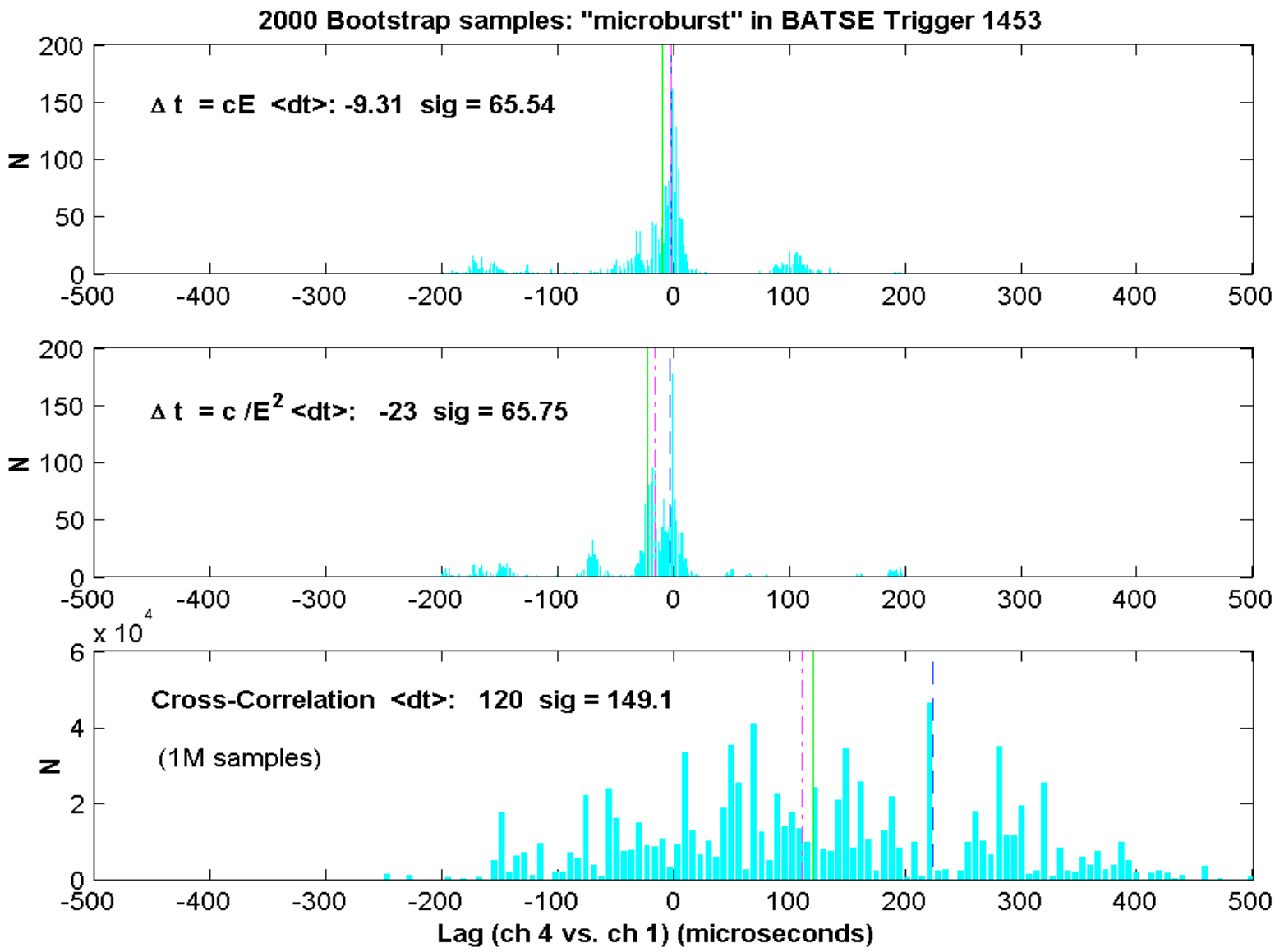
define transformation of time: $t'_i = f(t_i) = t_i + L(\theta, E_i)$
(lag L is a function of a parameter θ)

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:

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

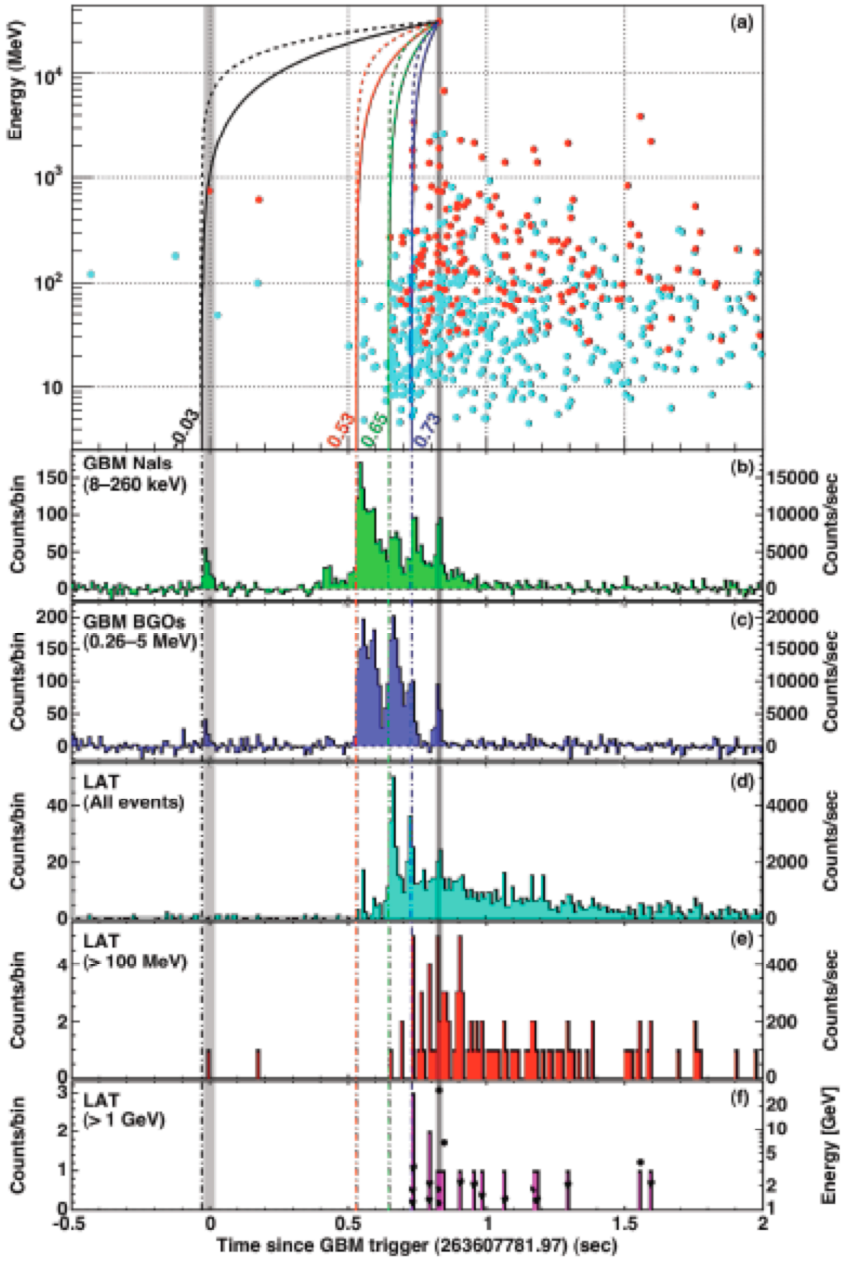
lag estimate is then just $L(\theta_{optimum}, E)$


Fermi/LAT: GRB 090510, T_intv = [8.30,9.50] s
E_max = 100. GeV
E_min = 0.03 GeV
θ_min[Shann] = 0.00000 (s/GeV)
Shannon Information
θ (s/GeV)
1000 trials, Energies Randomized: T_intv=[8.30,9.50] s
N_occur
θ (ms/GeV)


2000 Bootstrap samples: "microburst" in BATSE Trigger 1453
Δ t = cE <dt>: -9.31 sig = 65.54
Δ t = c /E^2 <dt>: -23 sig = 65.75
Cross-Correlation <dt>: 120 sig = 149.1
(1M samples)
x 10^4
N
Lag (ch 4 vs. ch 1) (microseconds)

Fermi Gamma-Ray Burst GRB090510 observations limit variation of speed of light with energy

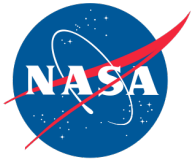
Nature, In Press



Novel Methods for Analysis Of Event/Point Data

✔

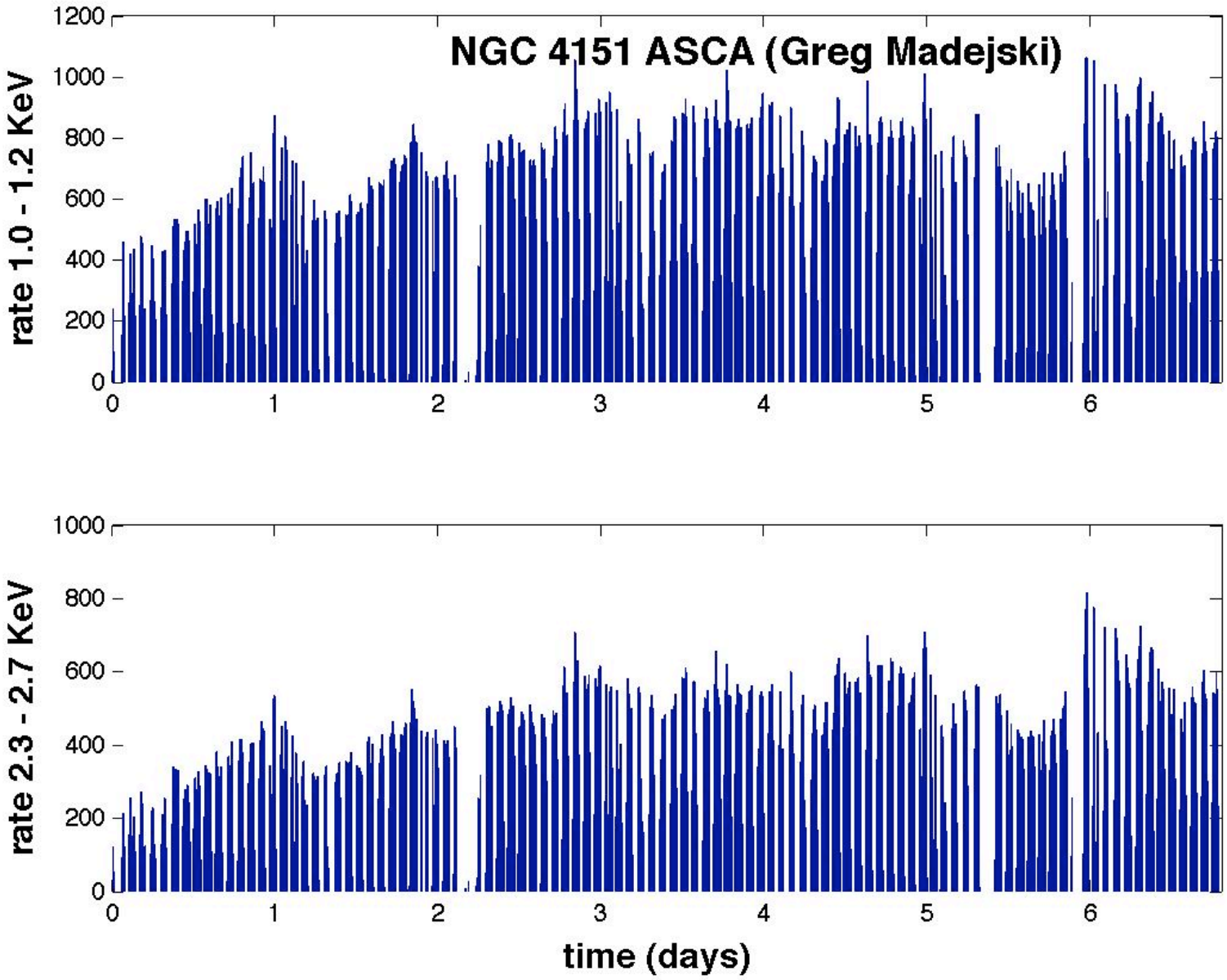
	Correlation Function	Fourier Power	Wavelet Power	Structure Function
Auto	✔	✔	✔	✔
Cross	✔	✔	✔	✔

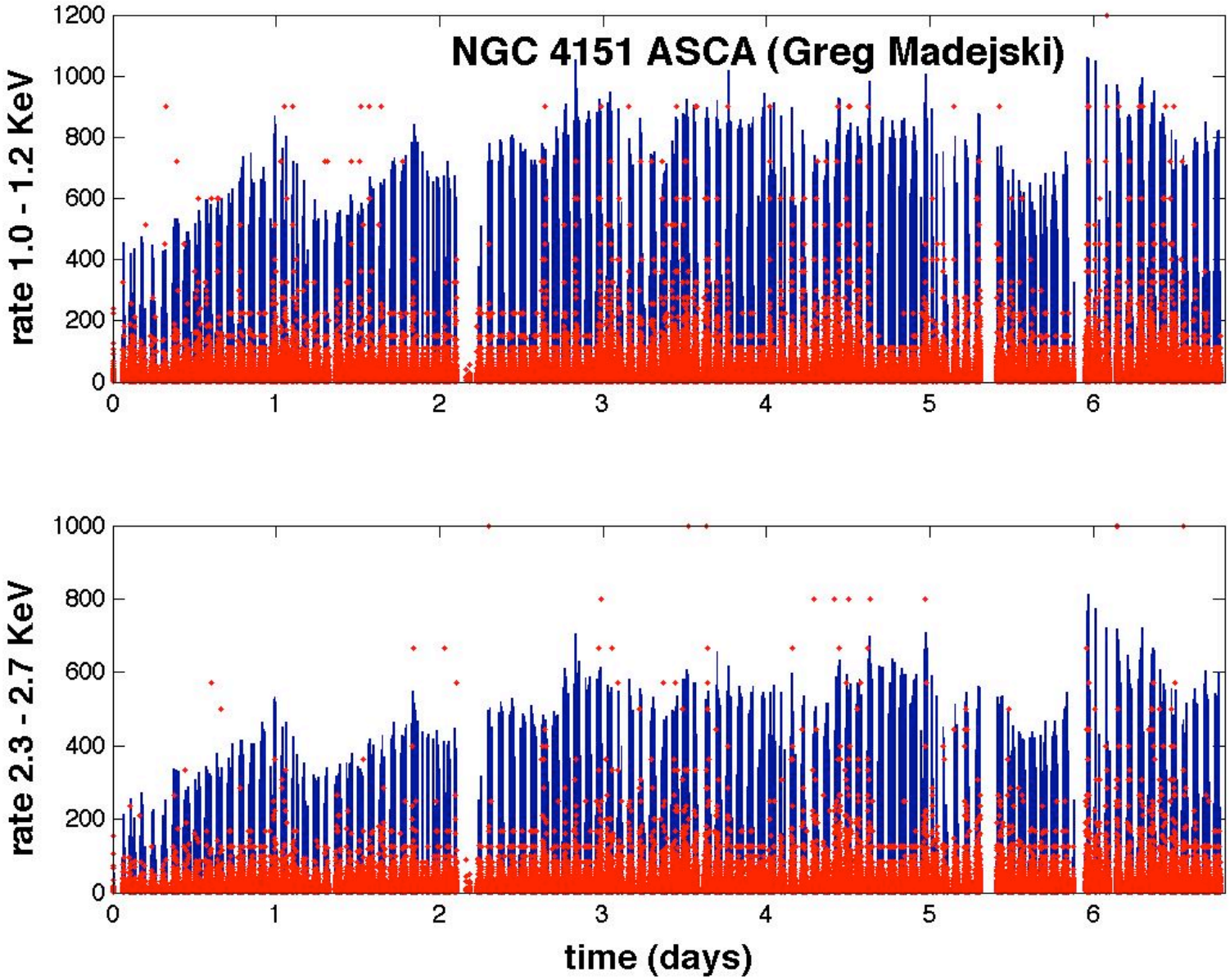


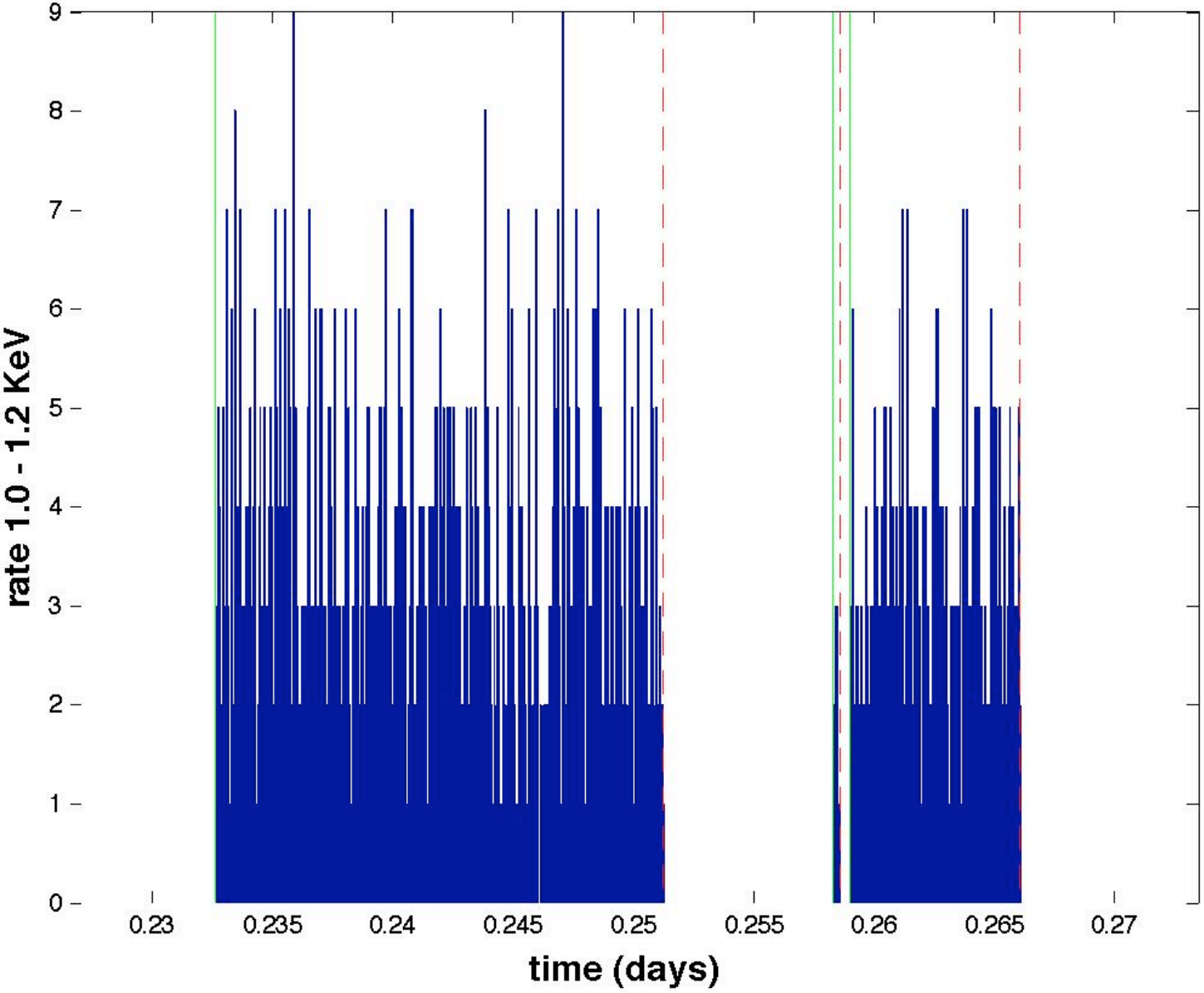
Cross- and Auto- Correlation Functions for unevenly spaced data

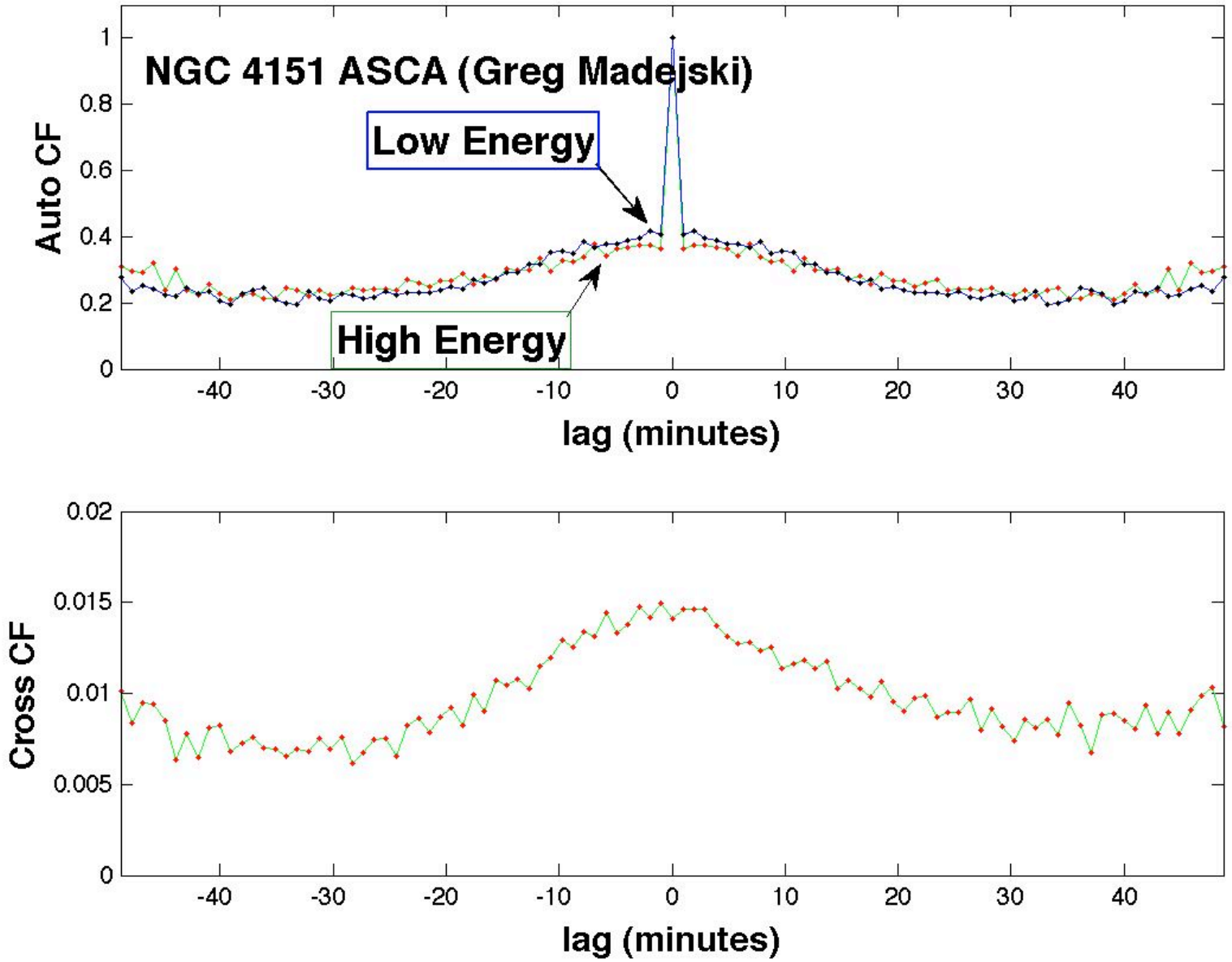
Edelson and Krolik:

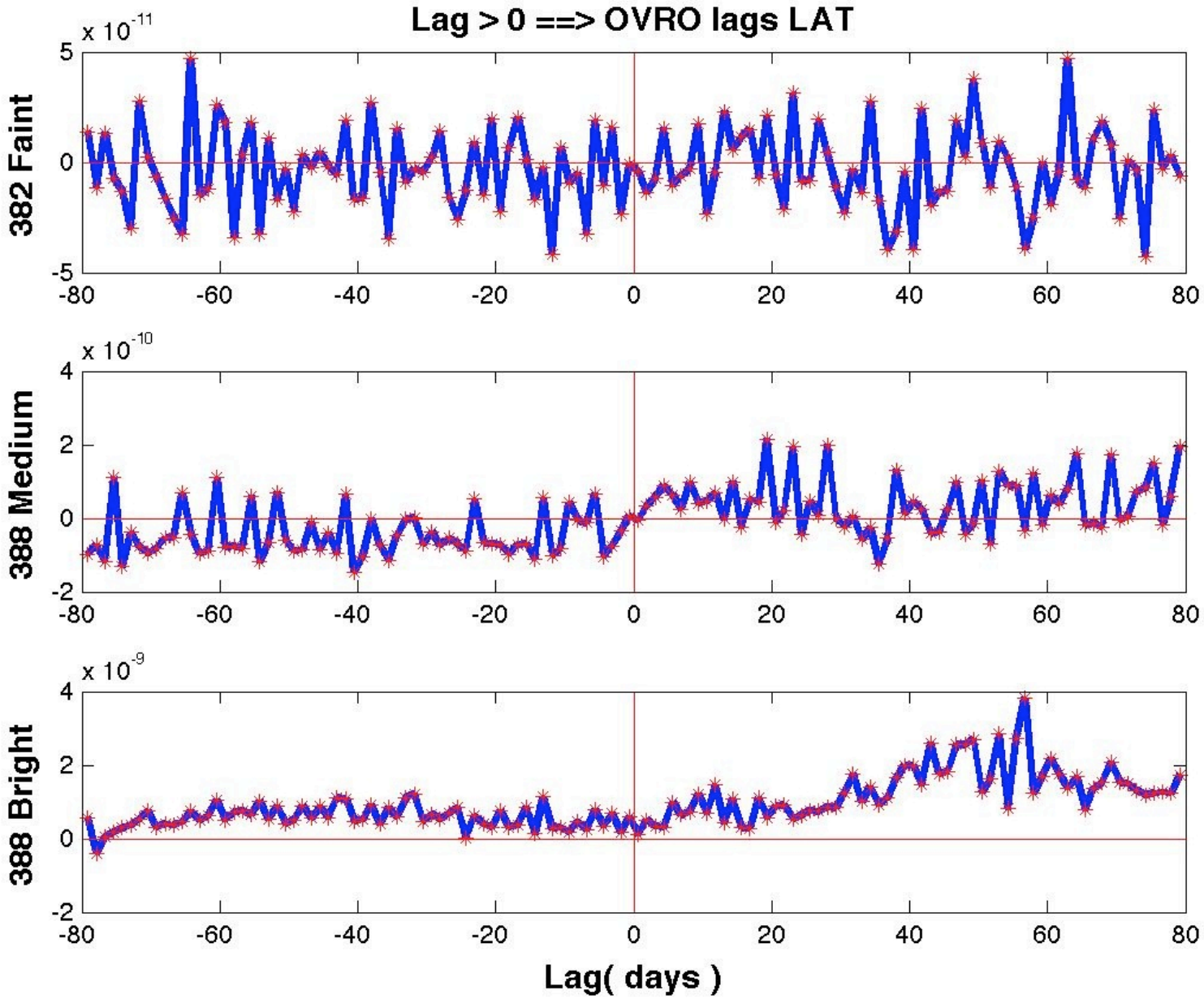
The Discrete Correlation Function: a New Method
for Analyzing Unevenly Sampled Variability Data
Ap. J. 333 (1988) 646


NGC 4151 ASCA (Greg Madejski)
rate 1.0 - 1.2 KeV
rate 2.3 - 2.7 KeV
time (days)
0
200
400
600
800
1000
1200
0
1
2
3
4
5
6


NGC 4151 ASCA (Greg Madejski)
rate 1.0 - 1.2 KeV
rate 2.3 - 2.7 KeV
time (days)
0
200
400
600
800
1000
1200
0
1
2
3
4
5
6


rate 1.0 - 1.2 KeV
time (days)
0
1
2
3
4
5
6
7
8
9
0.23
0.235
0.24
0.245
0.25
0.255
0.26
0.265
0.27


NGC 4151 ASCA (Greg Madejski)
Low Energy
High Energy
Auto CF
lag (minutes)
Cross CF
lag (minutes)


Lag > 0 ==> OVRO lags LAT
382 Faint
x 10^-11
5
0
-5
388 Medium
x 10^-10
4
2
0
-2
388 Bright
x 10^-9
4
2
0
-2
-80
-60
-40
-20
0
20
40
60
80
Lag(days)

All of this will be in the

Handbook of Statistical Analysis of Event Data

… funded by the NASA AISR Program

MatLab Code

Documentation

Examples

Tutorial

Contributions welcome!

A. A. Abdo, M. Ackermann, M. Ajello, K. Asano, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet, G. Barbiellini, M. G. Baring, D. Bastieri, K. Bechtol, R. Bellazzini, B. Berenji, P. N. Bhat, E. Bissaldi, E. D. Bloom, E. Bonamente, J. Bonnell, A. W. Borgland, A. Bouvier, J. Bregeon, A. Brez, M. S. Briggs, M. Brigida, P. Bruel, J. M. Burgess, T. H. Burnett, G. A. Caliandro, R. A. Cameron, P. A. Caraveo, J. M. Casandjian, C. Cecchi, Ö. Çelik, V. Chaplin, E. Charles, C. C. Cheung, J. Chiang, S. Ciprini, R. Claus, J. Cohen-Tanugi, L. R. Cominsky, V. Connaughton, J. Conrad, S. Cutini, C. D. Dermer, A. de Angelis, F. de Palma, S. W. Digel, B. L. Dingus, E. do Couto e Silva, P. S. Drell, R. Dubois, D. Dumora, C. Farnier, C. Favuzzi, S. J. Fegan, J. Finke, G. Fishman, W. B. Focke, L. Foschini, Y. Fukazawa, S. Funk, P. Fusco, F. Gargano, D. Gasparrini, N. Gehrels, S. Germani, L. Gibby, B. Giebels, N. Giglietto, F. Giordano, T. Glanzman, G. Godfrey, J. Granot, J. Greiner, I. A. Grenier, M.-H. Grondin, J. E. Grove, D. Grupe, L. Guillemot, S. Guiriec, Y. Hanabata, A. K. Harding, M. Hayashida, E. Hays, E. A. Hoversten, R. E. Hughes, G. Jóhannesson, A. S. Johnson, R. P. Johnson, W. N. Johnson, T. Kamae, H. Katagiri, J. Kataoka, N. Kawai, M. Kerr, R. M. Kippen, J. Knödlseder, D. Kocevski, C. Kouveliotou, F. Kuehn, M. Kuss, J. Lande, L. Latronico, M. Lemoine-Goumard, F. Longo, F. Loparco, B. Lott, M. N. Lovellette, P. Lubrano, G. M. Madejski, A. Makeev, M. N. Mazziotta, S. McBreen, J. E. McEnery, S. McGlynn, P. Mészáros, C. Meurer, P. F. Michelson, W. Mitthumsiri, T. Mizuno, A. A. Moiseev, C. Monte, M. E. Monzani, E. Moretti, A. Morselli, I. V. Moskalenko, S. Murgia, T. Nakamori, P. L. Nolan, J. P. Norris, E. Nuss, M. Ohno, T. Ohsugi, N. Omodei, E. Orlando, J. F. Ormes, M. Ozaki, W. S. Paciesas, D. Paneque, J. H. Panetta, D. Parent, V. Pelassa, M. Pepe, M. Pesce-Rollins, V. Petrosian, F. Piron, T. A. Porter, R. Preece, S. Rainò, E. Ramirez-Ruiz, R. Rando, M. Razzano, S. Razzaque, A. Reimer, O. Reimer, T. Reposeur, S. Ritz, L. S. Rochester, A. Y. Rodriguez, M. Roth, F. Ryde, H. F.-W. Sadrozinski, D. Sanchez, A. Sander, P. M. Saz Parkinson, J. D. Scargle, T. L. Schalk, C. Sgrò, E. J. Siskind, D. A. Smith, P. D. Smith, G. Spandre, P. Spinelli, M. Stamatikos, F. W. Stecker, M. S. Strickman, D. J. Suson, H. Tajima, H. Takahashi, T. Takahashi, T. Tanaka, J. B. Thayer, J. G. Thayer, D. J. Thompson, L. Tibaldo, K. Toma, D. F. Torres, G. Tosti, E. Troja, Y. Uchiyama, T. Uehara, T. L. Usher, A. J. van der Horst, V. Vasileiou, N. Vilchez, V. Vitale, A. von Kienlin, A. P. Waite, P. Wang, C. Wilson-Hodge, B. L. Winer, K. S. Wood, X. F. Wu, R. Yamazaki, T. Ylinen, M. Ziegler