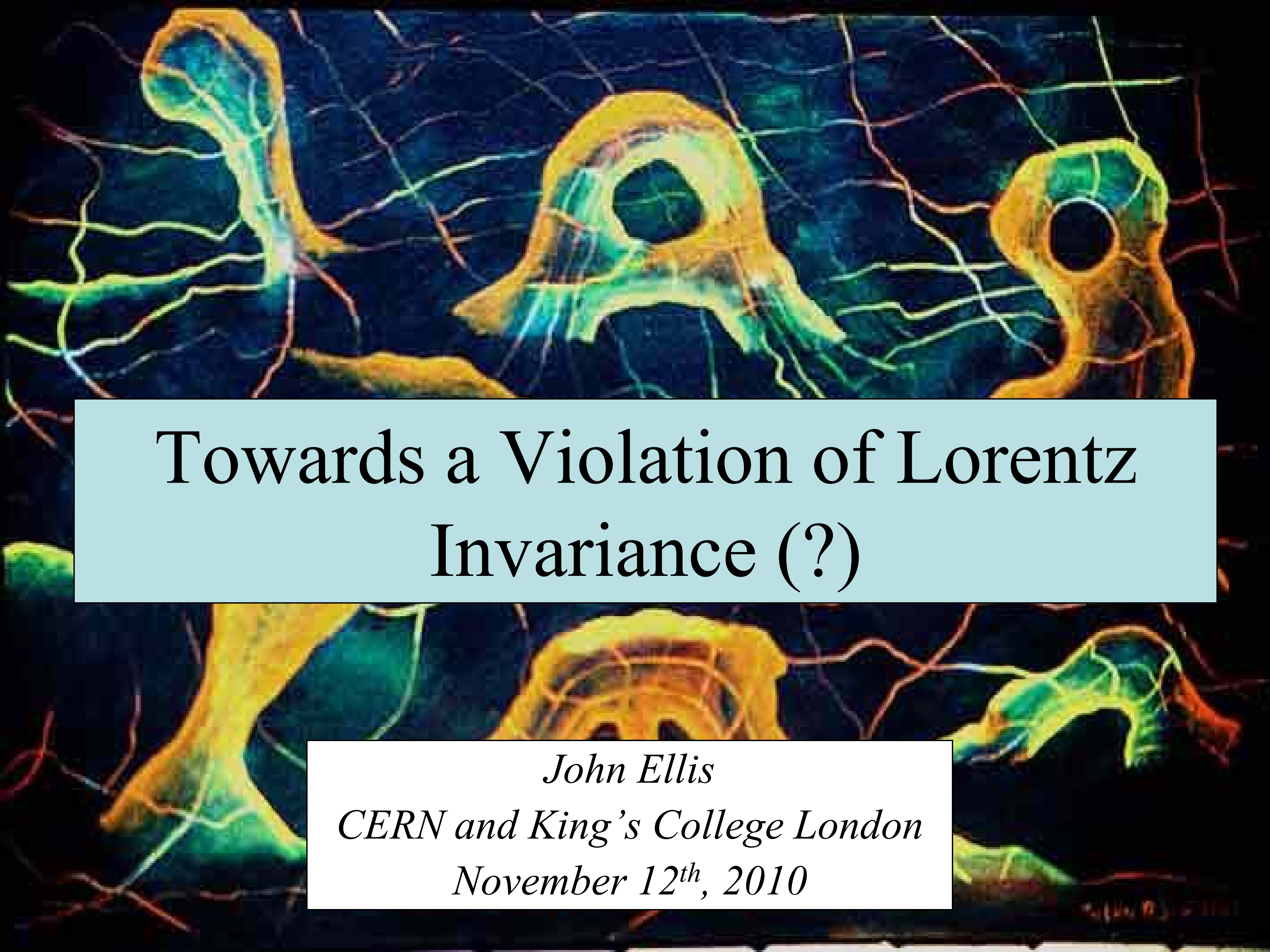


Towards a Violation of Lorentz Invariance (?)

John Ellis
CERN and King’s College London
November 12th, 2010

Work in Collaboration with:

Nick Mavromatos, Dimitri Nanopoulos & Giovanni Amelino-Camelia, Ignatios Antoniadis, Costas Bachas, CPLEAR Collaboration (Erwin Gabathuler, Noulis Pavlopoulos, Maria Fidecaro, Thomas Ruf, …), Kostas Farakos, John Hagelin, Jorge Lopez, Vasou Mitsou, Sasha Sakharov, Subir Sarkar, Edward Sarkisyan, Mark Srednicki, Michael Westmuckett, MAGIC Collaboration (Adrian Biland, Rudy Bock, Robert Wagner, Mannel Martinez, ….)

Is anything sacred?

- Quantum mechanics and gravity not combined
- Will their combination require modifying either or both?
- Issues in quantum gravity
- Modification of quantum mechanics?

  experimental probes with kaons
- Violation of CPT?
- **Modification of Lorentz invariance?**

  astrophysical probes with GRBs, AGNs
- Violation of equivalence principle?
- ….

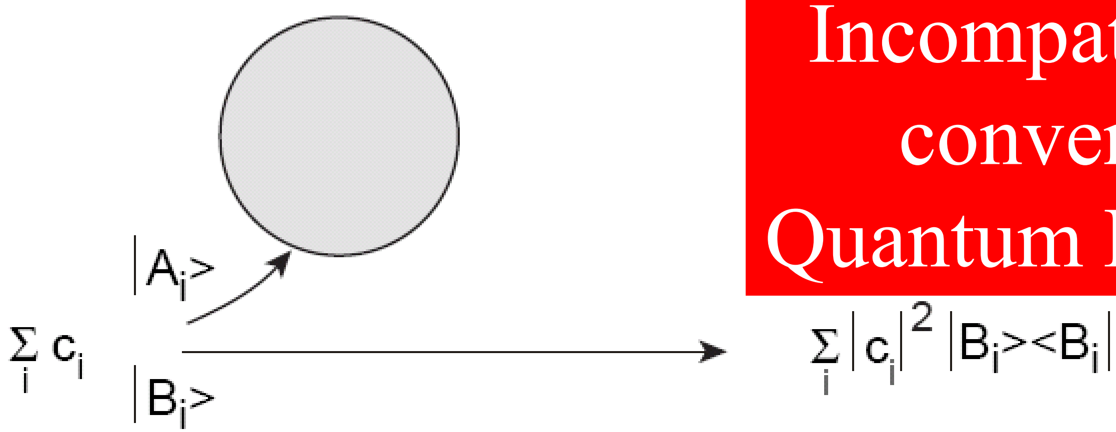
Problems of Quantum Gravity

- Gravity grows with energy: $\sigma_G \sim E^2/m_P^4$
- Two-graviton exchange is infinite:

$$\int^{\Lambda\to\infty} d^4k \left(\frac{1}{k^2}\right) \leftrightarrow \int_{1/\Lambda\to 0} d^4x \left(\frac{1}{x^6}\right) \sim \Lambda^2 \to \infty$$

- **Gravity is a non-renormalizable theory**
- Pure states evolve to mixed states?

Incompatible with conventional Quantum Mechanics

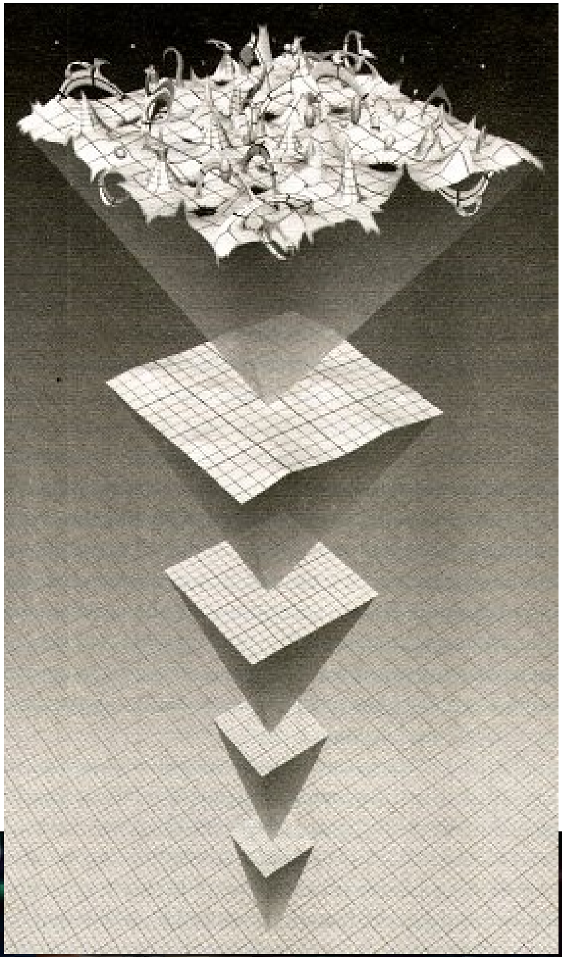


Nature of QG Vacuum

- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $\Delta E, \Delta x, \Delta t, \Delta \chi \sim 1$
- Fluctuations in energy, space, time, topology of order unity
- **Space-time foam**

J.A.Wheeler



- **Manifestations?**

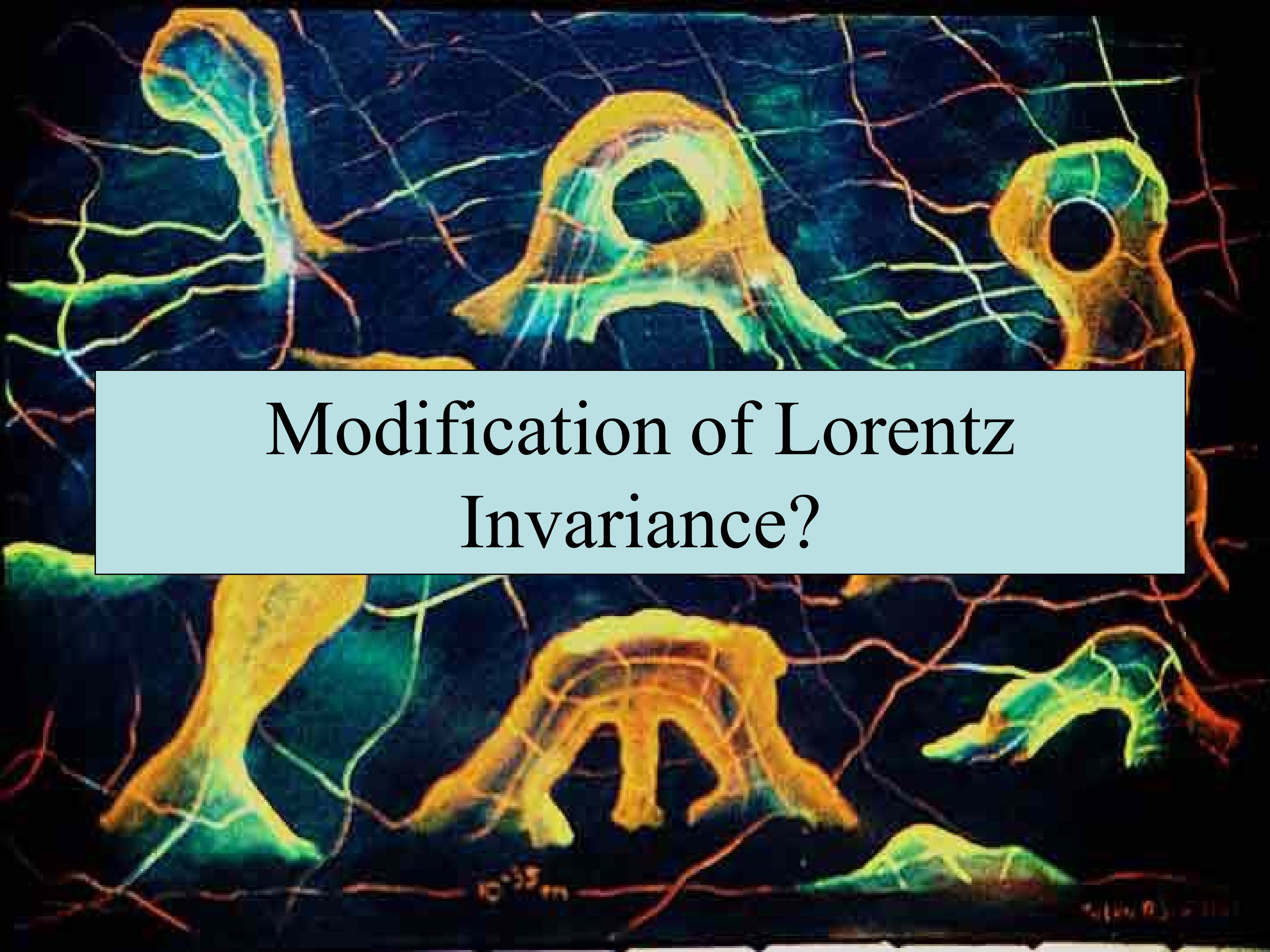
Reconciling General Relativity and Quantum Mechanics

- Unfinished business of 20^{th}-century physics
- Primary task of 21^{st}-century physics
- One or the other – or both – must be modified?
- Modification of quantum mechanics?
- Violation of CPT?
- Modification of Lorentz invariance?
- Breakdown of equivalence principle?
- Search for distinctive signature not allowed in quantum field theory

String Theory

- Point-like particles → extended objects
- Simplest possibility: lengths of string
  - no divergences in perturbation theory
- Quantum consistency fixes critical # dimensions:
  - bosonic string: 26, superstring: 10
- Non-perturbative configurations: D-branes
  - black-hole entropy = # of D-brane states
- Is critical string theory the whole story?

Modification of Lorentz Invariance?



Space-Time Foam as a Non-Trivial Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index
- Effect on propagation that increases with energy:

$$c^2\mathrm{p}^2 = E^2\left[1+\xi E/E_{\mathrm{QG}}+\mathcal{O}(E^2/E_{\mathrm{QG}}^2)\right] \qquad v=\frac{\partial E}{\partial p}\sim c\left(1-\xi\frac{E}{E_{\mathrm{QG}}}\right)$$

- Non-critical string model: ξ = -1
- ξ = -1 needed: avoid Čerenkov radiation *in vacuo*
- Expect: $E_{QG} = O(M_P)$
- Related to $1/M_D$ in non-critical string model

Amelino-Camelia, JE, Mavromatos, Nanopoulos: 1996

Non-Critical String Description

- Consider energetic particle propagating through foam of D0-particles
- Interactions → D0-particle recoil
- Recoil motion modifies flat-space metric:

$$G_{ij} = \delta_{ij},\ G_{00} = -1,\ G_{0i} = \epsilon^2 (Y_i + \overline{U}_i t)\Theta_\epsilon(t)$$

- Where $U_i \sim E/m_D$ is the recoil velocity
  - Modified Maxwell equations:

$$\frac{1}{c^2}\frac{\partial^2}{\partial^2 t}B - \nabla^2 B - 2\left(\overline{U}.\nabla\right)\frac{1}{c}\frac{\partial}{\partial t}B = 0$$

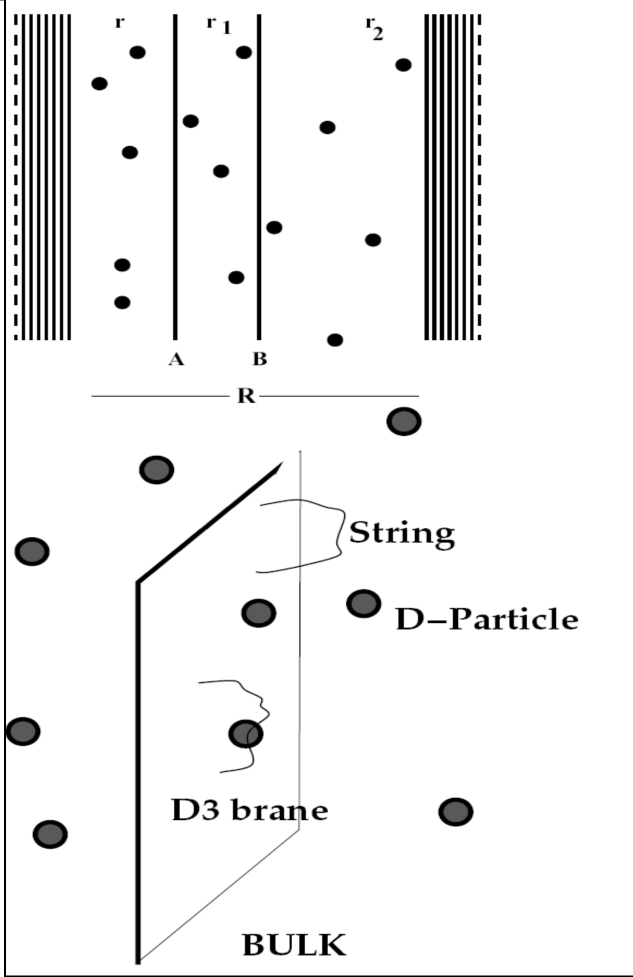
$$\frac{1}{c^2}\frac{\partial^2}{\partial^2 t}E - \nabla^2 E - 2\left(\overline{U}.\nabla\right)\frac{1}{c}\frac{\partial}{\partial t}E = 0$$

- Modified dispersion relation: $k^2 - \omega^2 - 2\overline{U}k\omega = 0$
- Subluminal propagation: $c(E) = c\left(1 - \overline{U}\right) + \mathcal{O}\left(\overline{U}^2\right)$

JE, Farakos, Mavromatos, Mitsou + Nanopoulos

D-Brane Model of Space-Time Foam

- The Universe as (3+1)-dimensional subspace moving through higher-dimensional space
- D-particles in bulk space
- Observer on D-brane sees them as 0-dimensional defects in space-time
- Particles (photons, gravitons) interact the defects, experience delays ~ E



Astrophysical Probes of Lorentz Violation

- Time delay from distant object:

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

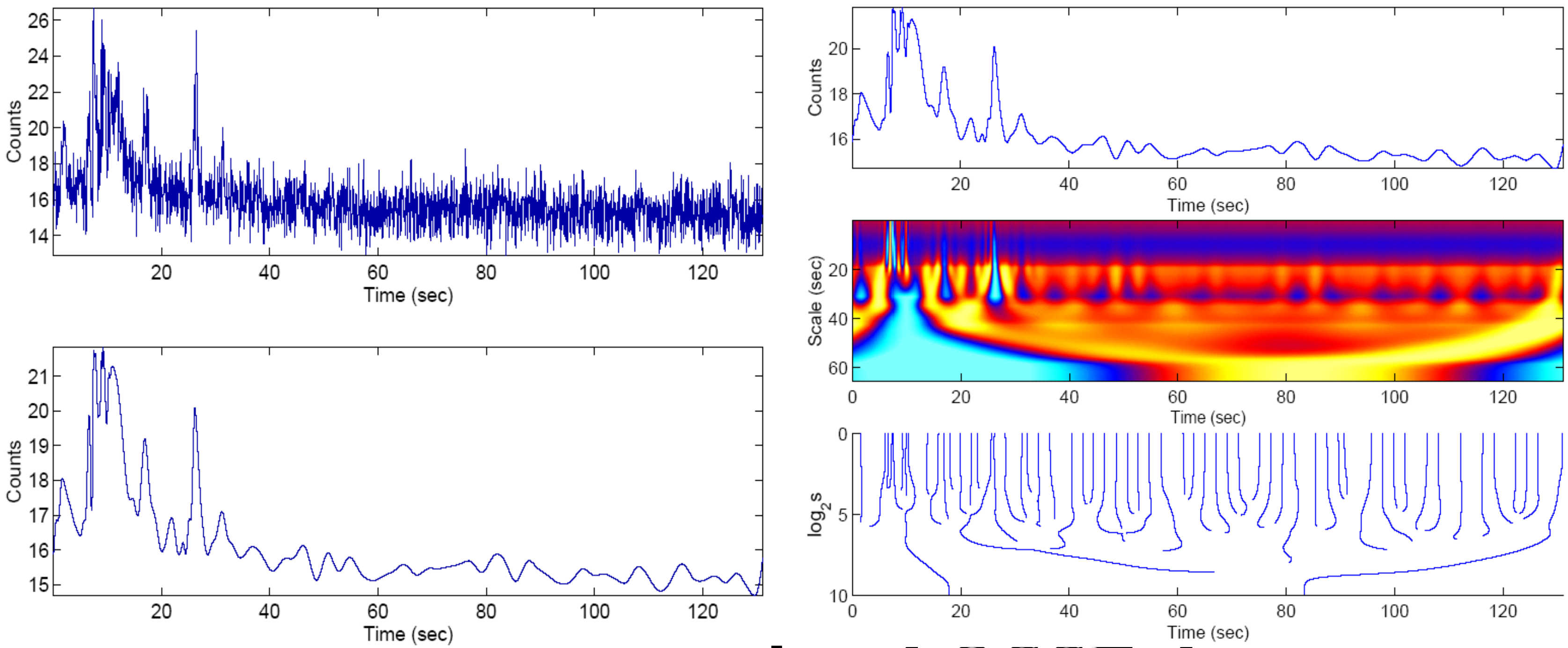
Amelino-Camelia, JE, Mavromatos, Nanopoulos + Sarkar: 1997

- Compare arrivals of photons of different energies from astrophysical source with small intrinsic δt
- Gamma-Ray Bursters, pulsars, active galaxies, …
- Typical sensitivities:

Source	Distance	E	Δt	Sensitivity to M
GRB 920229 [a]	3000 Mpc (?)	200 keV	10^{-2} s	0.6×10^{16} GeV (?)
GRB 980425 [a]	40 Mpc	1.8 MeV	10^{-3} s (?)	0.7×10^{16} GeV (?)
GRB 920925c [a]	40 Mpc (?)	200 TeV (?)	200 s	0.4×10^{19} GeV (?)
Mrk 421 [b]	100 Mpc	2 TeV	280 s	$> 7 \times 10^{16}$ GeV
Crab pulsar [c]	2.2 kpc	2 GeV	0.35 ms	$> 1.3 \times 10^{15}$ GeV
GRB 990123	5000 Mpc	4 MeV	1 s (?)	2×10^{15} GeV (?)

Wavelet Analysis of GRB Data

- Optimal for finding significant time structures:

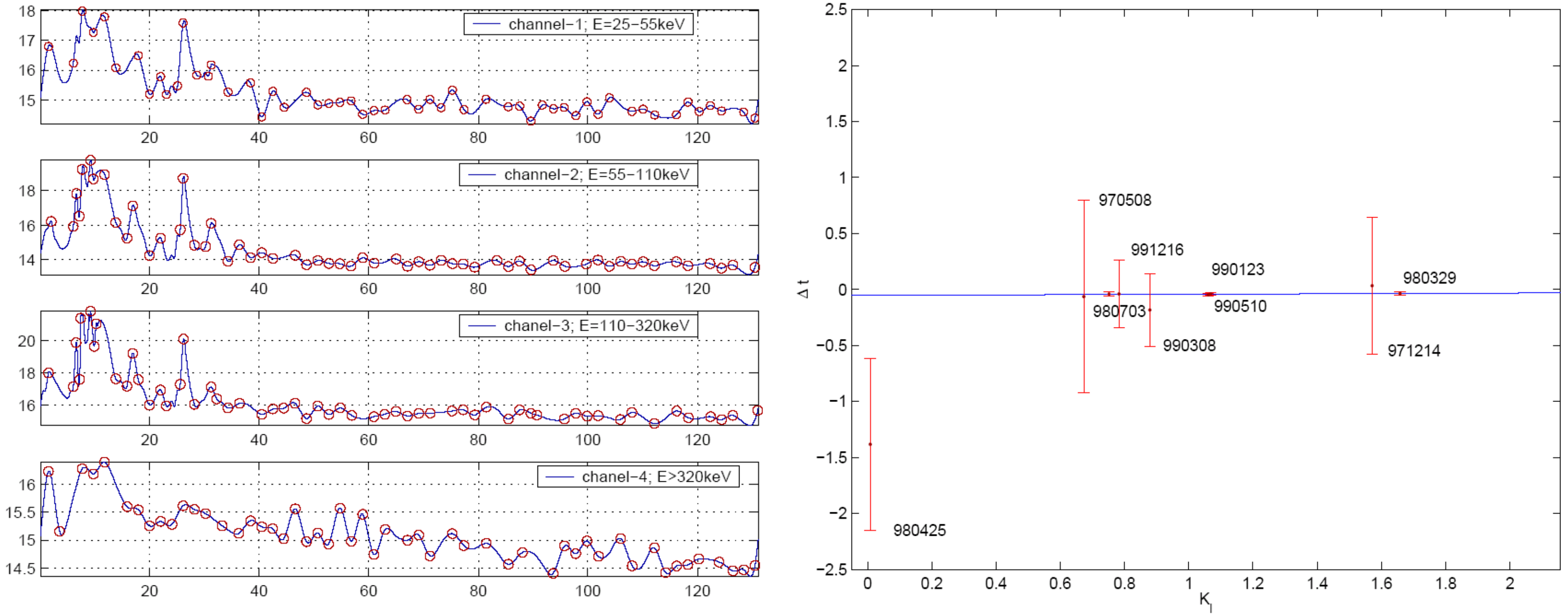


- Use data from BATSE and OSSE detectors on Compton Gamma-Ray Observatory satellite

JE, Mavromatos, Nanopoulos + Sakharov: 2002

Wavelet Analysis of GRB Data

- Compare time structures in different energy bands:

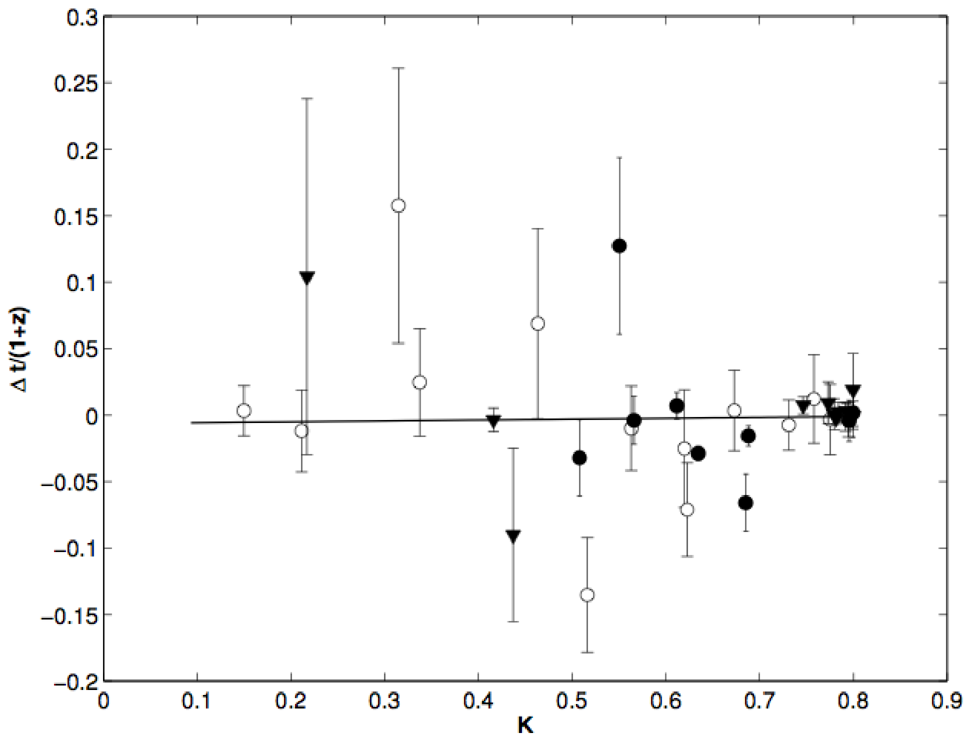


- No significant correlation of time-lags with redshift distance

JE, Mavromatos, Nanopoulos + Sakharov: 2002

Updated Analysis including HETE Data

- Corrected treatment of redshift



- Improved lower limit:

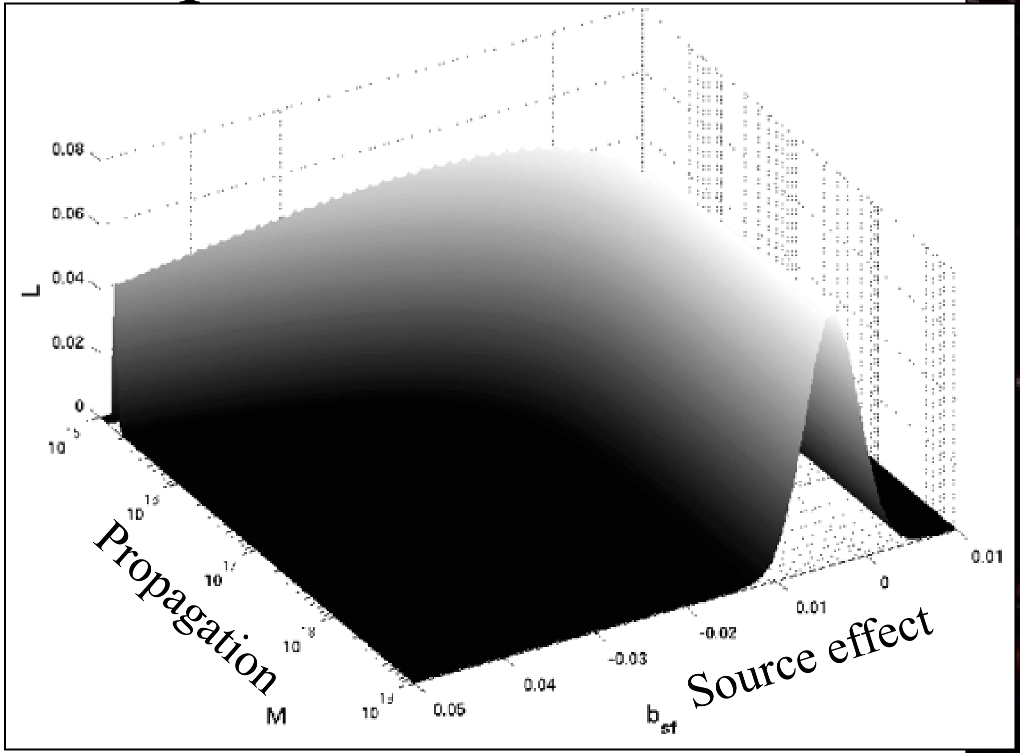
$$M \geq 1.4 \times 10^{16} \text{ GeV}$$

GRB	z	z Refs.	$\Delta t_{\rm total}^{(E_{\rm high}-E_{\rm low})}$(s)
BATSE (64 ms)			
970508	0.835	[24]	-0.059±0.044
971214	3.418	[25]	-0.098±0.045
980329	3.9	[23]	-0.084±0.036
980703	0.966	[26]	0.138±0.053
990123	1.600	[27]	-0.155±0.041
990308	1.2	[28]	0.0188±0.0138
990510	1.619	[29]	-0.0017±0.0143
991216	1.020	[30]	-0.0091±0.0012
990506	1.3060	[31]	-0.0503±0.0075
HETE (164 ms)			
010921	0.45	[32]	0.0357±0.0585
020124	3.198	[33]	-0.0046±0.0455
020903	0.25	[34]	-0.0150±0.0386
020813	1.25	[35]	-0.1602±0.0794
020819	0.41	[36]	0.222±0.145
021004	2.33	[37]	-0.0402±0.1109
021211	1.01	[23]	-0.0202±0.0639
030226	1.99	[23]	-0.0227±0.0568
030323	3.372	[38]	-0.0148±0.0570
030328	1.52	[23]	0.00825±0.07661
030329	0.168	[39, 23]	0.0037±0.0219
030429	2.66	[40]	-0.0123±0.0965
040924	0.859	[23]	-0.2516±0.0801
041006	0.716	[23]	0.1179±0.1228
050408	1.2357	[23]	-0.0562±0.0989
SWIFT (64 ms)			
050319	3.24	[41]	0.0054±0.0109
050401	2.9	[23]	-0.0135±0.0285
050416	0.653	[23]	-0.1491±0.1075
050505	4.3	[23]	-0.0012±0.0561
050525	0.606	[23, 42]	0.1261±0.0159
050603	2.821	[23]	-0.0032±0.0047
050724	0.258	[43]	0.131±0.1681
050730	3.968	[44]	0.094±0.1361
050820	2.612	[23]	0.033±0.0569
050904	6.29	[45]	0.004±0.0852
050922	2.17	[23]	0.0231±0.0208

JE, Mavromatos, Nanopoulos, Sakharov + Sarkisyan: astro-ph/0510172

Source Effect vs Propagation Effect?

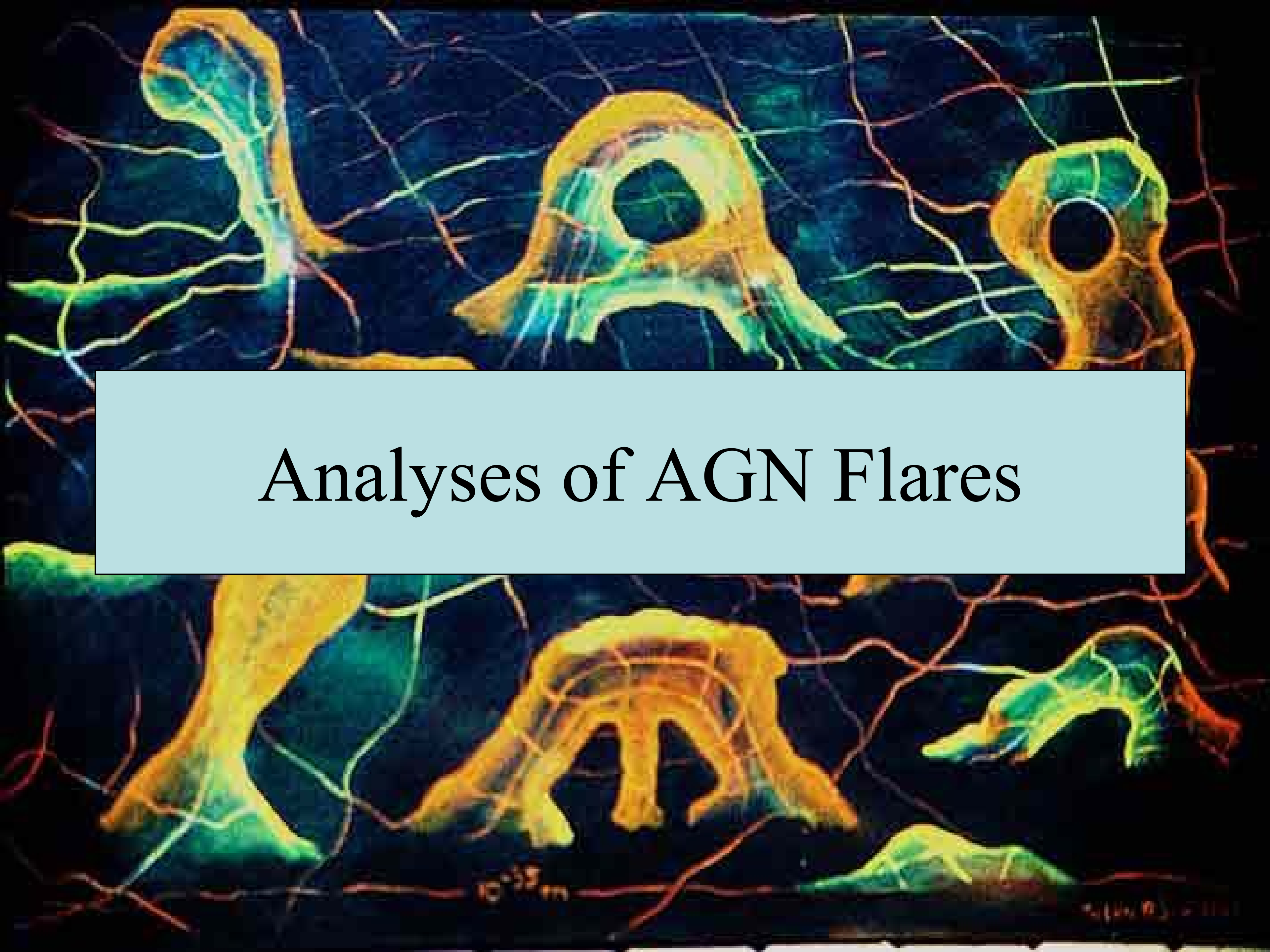
- Evidence for stochastic spread in intrinsic delays at sources
- Cannot distinguish with single source
- Need statistical techniques for multiple sources



- Correlation between source and propagation effects: Need better understanding of GRBs!

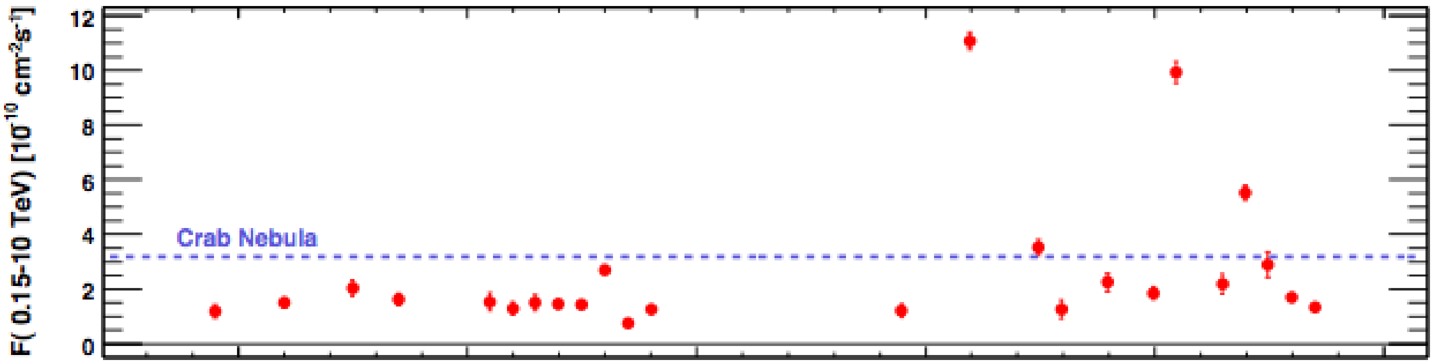
JE, Mavromatos, Nanopoulos, Sakharov + Sarkisyan: astro-ph/0510172

Analyses of AGN Flares



Flaring of AGN Markarian 501

- AGN at redshift z = 0.034
- Flare on July 9th, 2005 with short rise/fall time

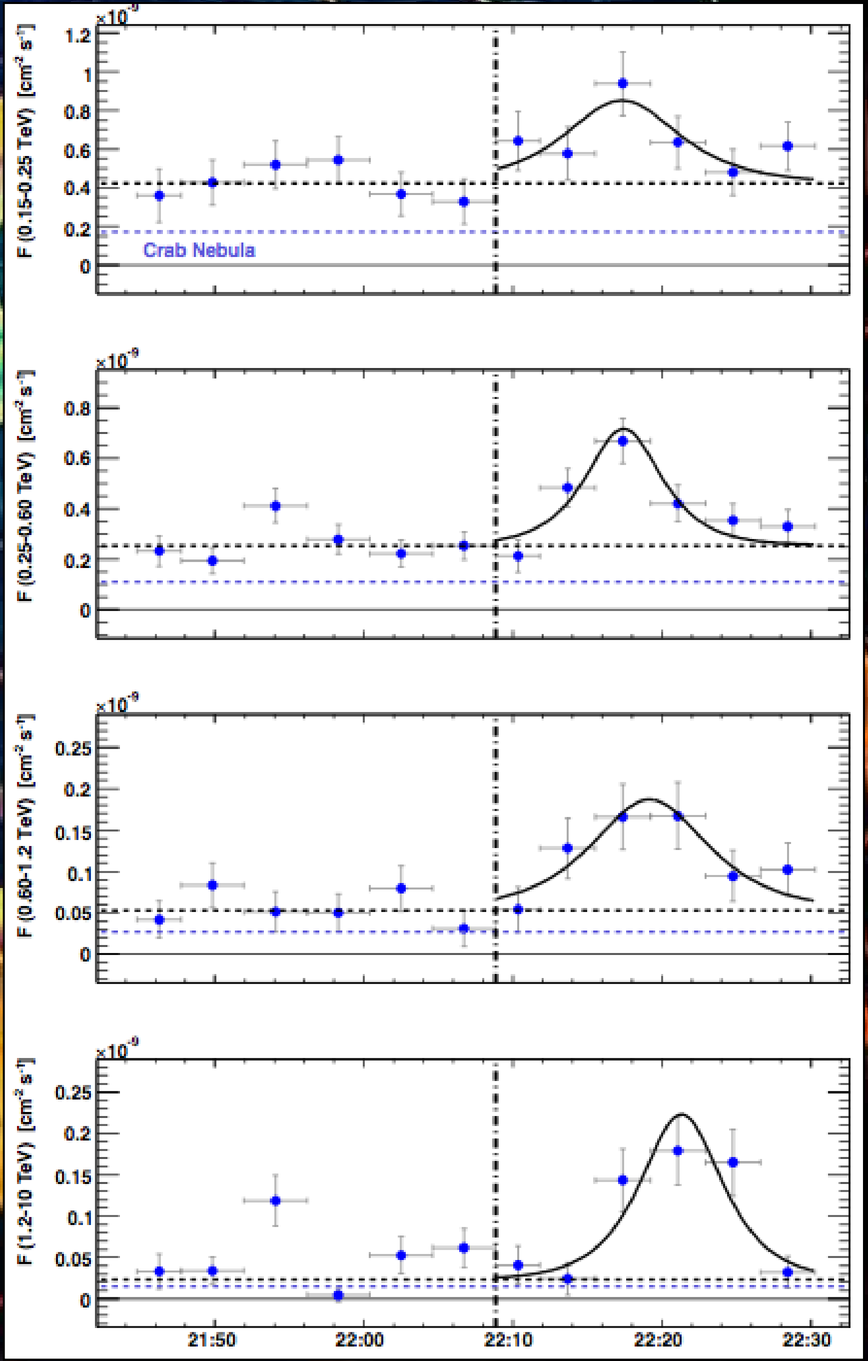


- Observed at energies from 150 GeV to ~ 10 TeV
- Earlier flare on June 30th not significant at high energies

MAGIC Collaboration: astro-ph/0702008

Time Delay from Markarian 501?

- Arrival time delay of ~ 4 minutes reported for photons in highest-energy bin
- Sensitive to M_{QG1} ~ 10^{16} GeV



MAGIC Collaboration: astro-ph/0702008

Analysis of AGN Markarian 501

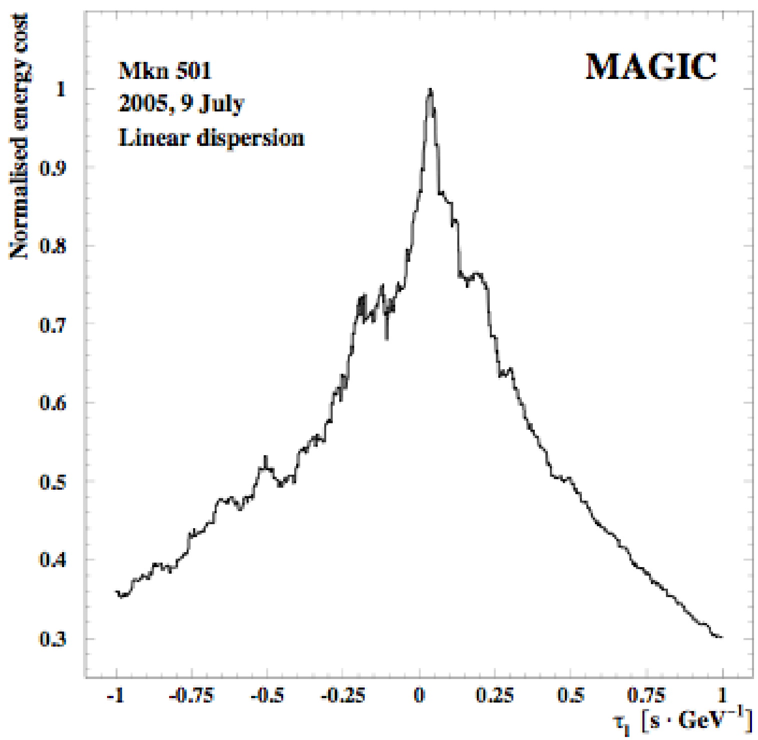
- Non-trivial energy-dependent dispersion relation would tend to spread out any sharp structure
- Analyze individual photons, using measured energies E and arrival times t
- Use 1000 Monte Carlo samples to allow for ΔE
- Track back using many values of M_{QG}
- Determine value of M_{QG} that maximizes peaking of energy flow

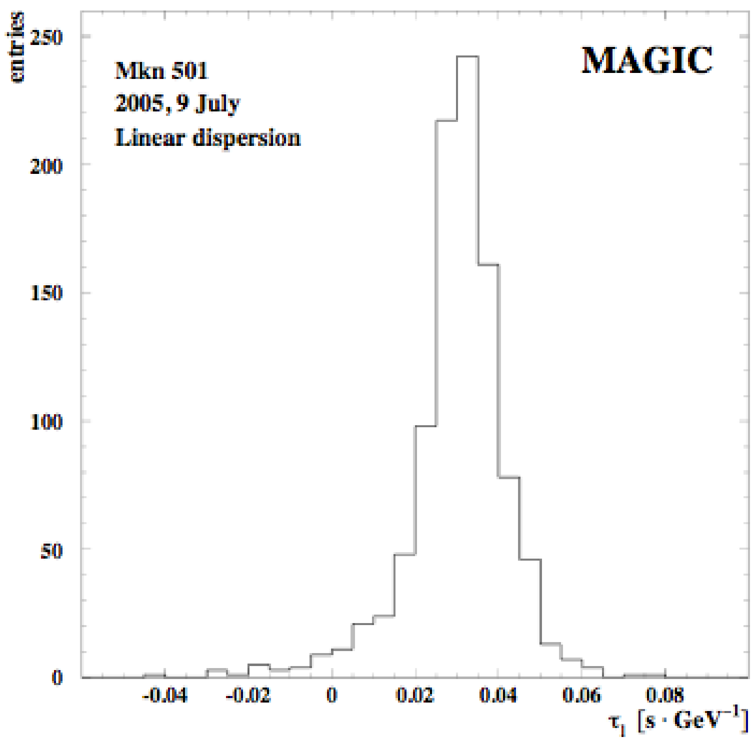
MAGIC Collaboration +
JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan:
arXiv:0708:2889 [astro-ph]

QG Analysis of AGN Markarian 501

Energy peaking for one Monte Carlo realization

Distribution of time delays for different realizations





MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

QG Results for AGN Markarian 501

- Significance of time delay < 95%
- Linear dispersion: (E/M_{QG1})
  - One-σ range: $M_{QG1} = (0.34 \text{ to } 0.78) \times 10^{18}$ GeV
  - 95% CL lower limit: $M_{QG1} > 0.26 \times 10^{18}$ GeV
- Quadratic dispersion: $(E/M_{QG2})^2$
  - One-σ range: $M_{QG2} = (0.47 \text{ to } 1.1) \times 10^{11}$ GeV
  - 95% CL lower limit: $M_{QG2} > 0.27 \times 10^{11}$ GeV
- Cannot exclude initial time delay at source

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Possible Source Effects?

- Cannot exclude emission mechanism that delays higher-energy photons
- Can exclude conventional thermodynamic plasma effects:

$$\Delta t = D(\alpha^2 T^2/6q^2)\ln^2(qT/m_e^2)$$

T = temperature, D = size of emission region, q = photon momentum

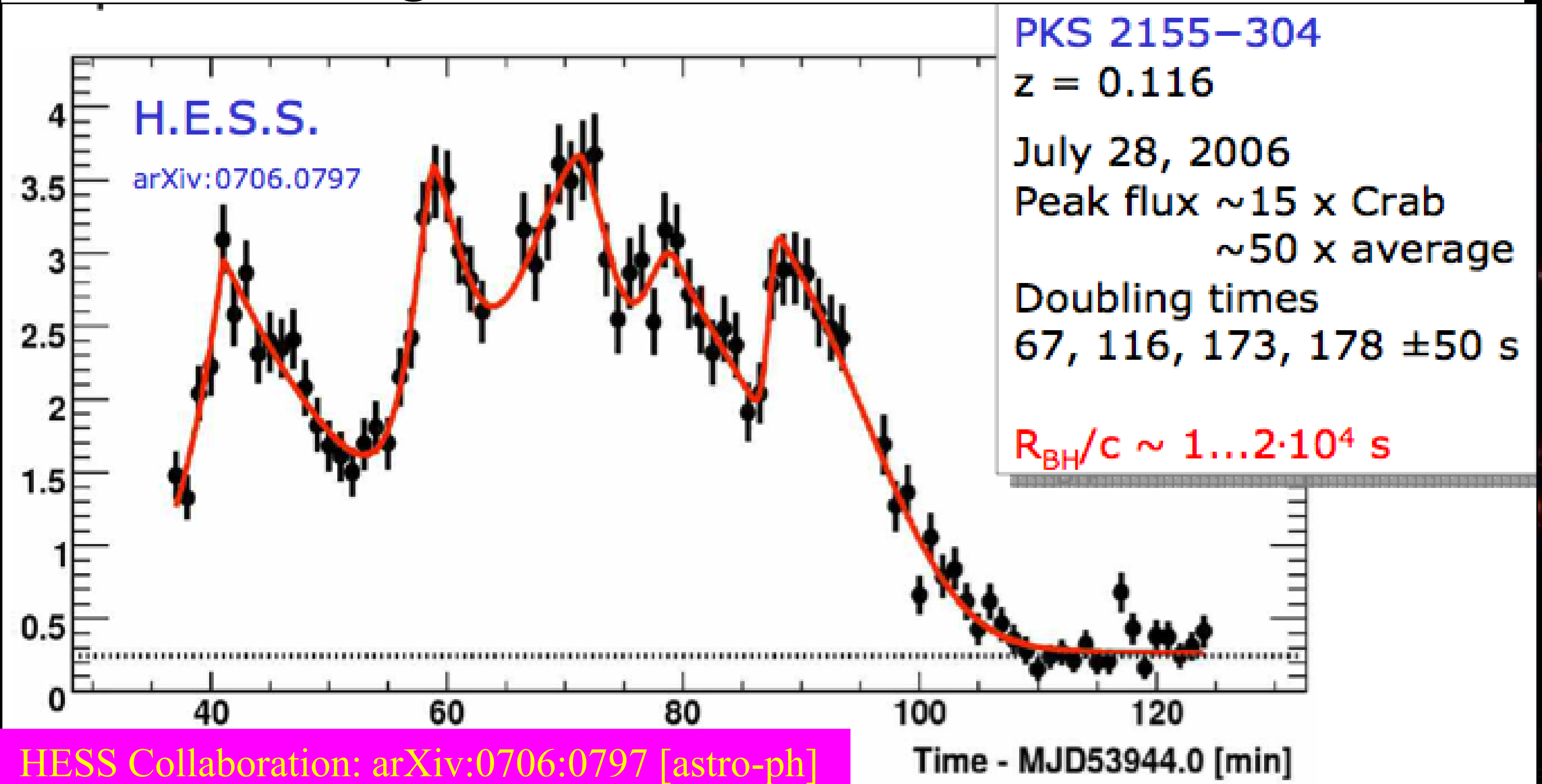
Orders of magnitude too small for T $\sim 10^{-2}$ MeV, D $\sim 10^9$ km, q ~ 1 TeV

- Test with other AGNs (cf GRB analysis)

MAGIC Collaboration + JE, Mavromatos, Nanopoulos, Sakharov, Sarkisyan: arXiv:0708:2889 [astro-ph]

Analysis of AGN PKS 2155-304

- Observation by HESS of multiple flaring of AGN at larger redshift with more statistics



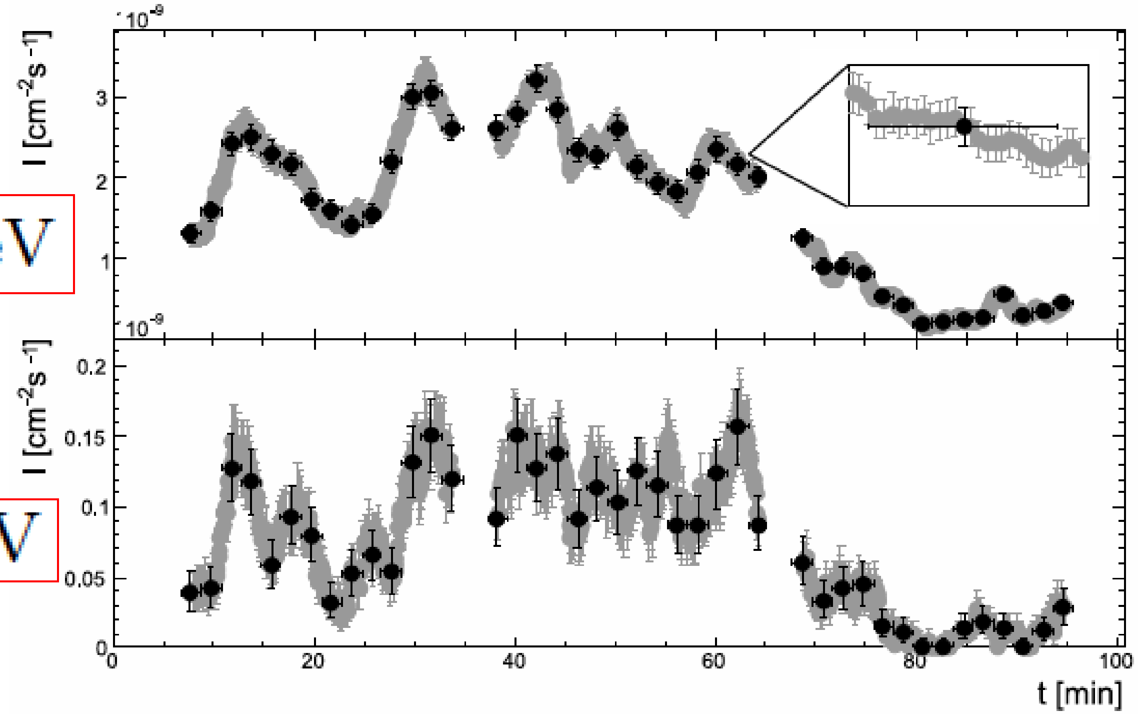
HESS Collaboration: arXiv:0706:0797 [astro-ph]

Analysis of AGN PKS 2155-304

- Comparison between HESS data in different energy bins

200-800 GeV

>800 GeV

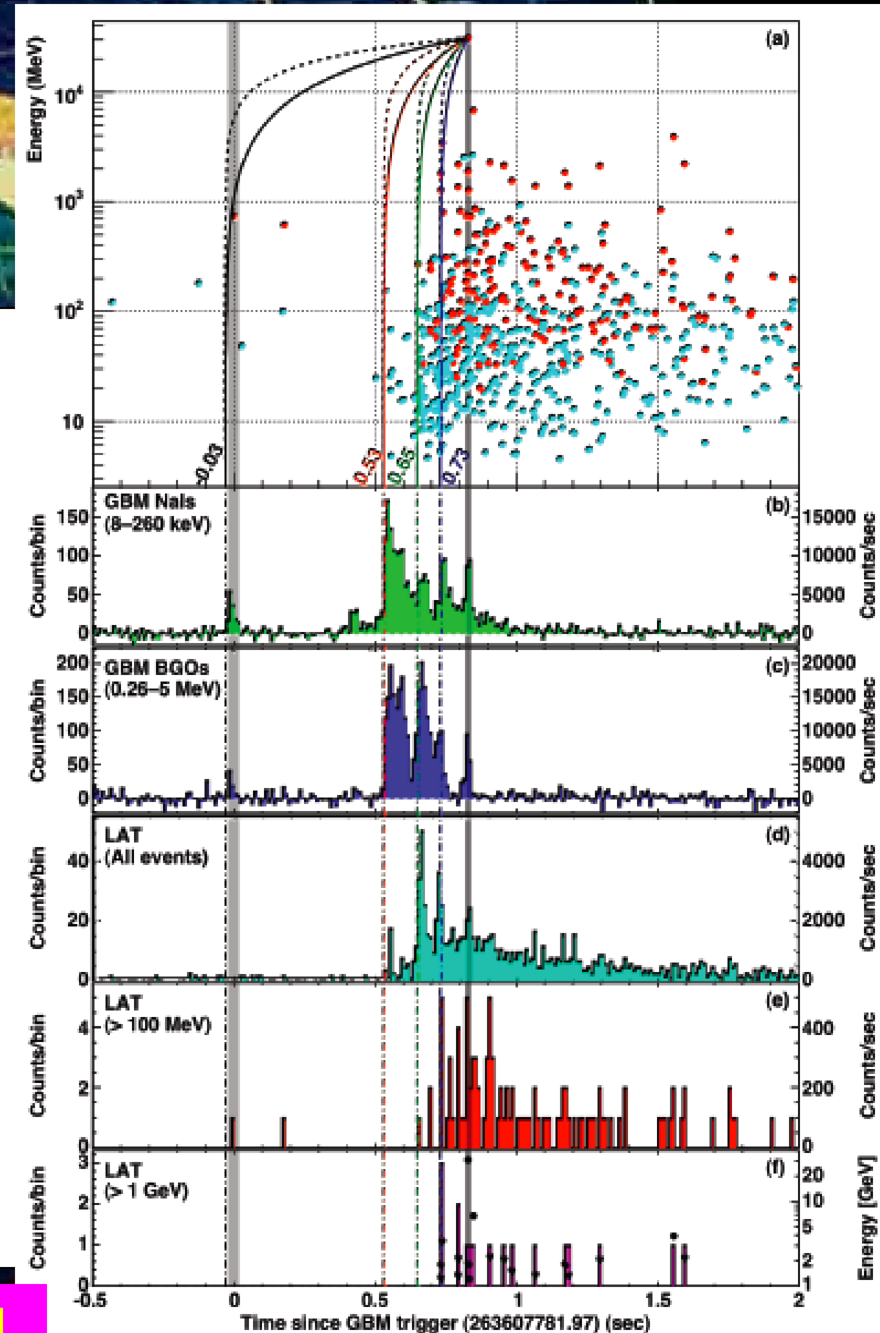


- No significant differences in arrival times
- Lower limit on $m_{QG} > 7.2 \times 10^{17}$ GeV

HESS Collaboration: arXiv:0810:3475 [astro-ph]

Fermi Analysis of GRB 090510

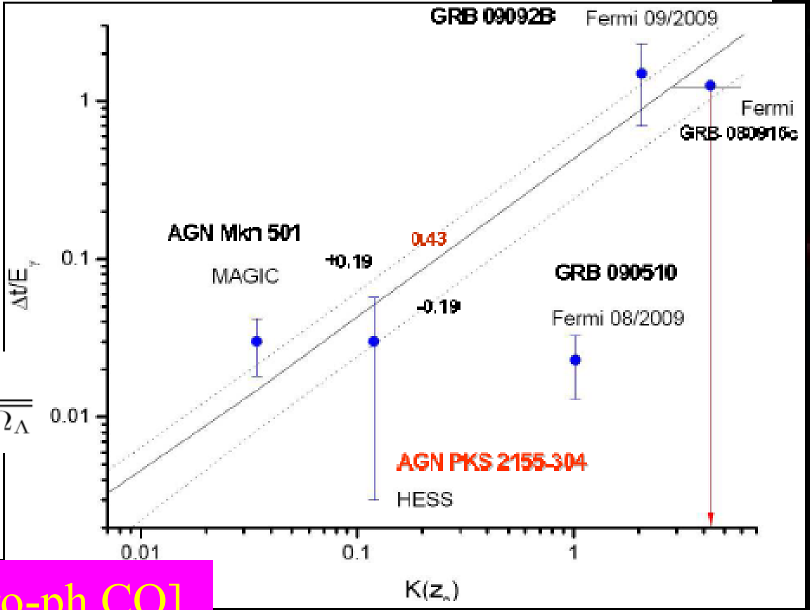
- Redshift z = 0.903 ± 0.003
- γ energies up to 31 GeV
- No hint of energy-dependent time delay
- Lower limit on m_{QG} depends sensitively on assumptions
- m > 1.2 to 102 m



Fermi Collaboration: arXiv:0908.1832 [astro-ph]

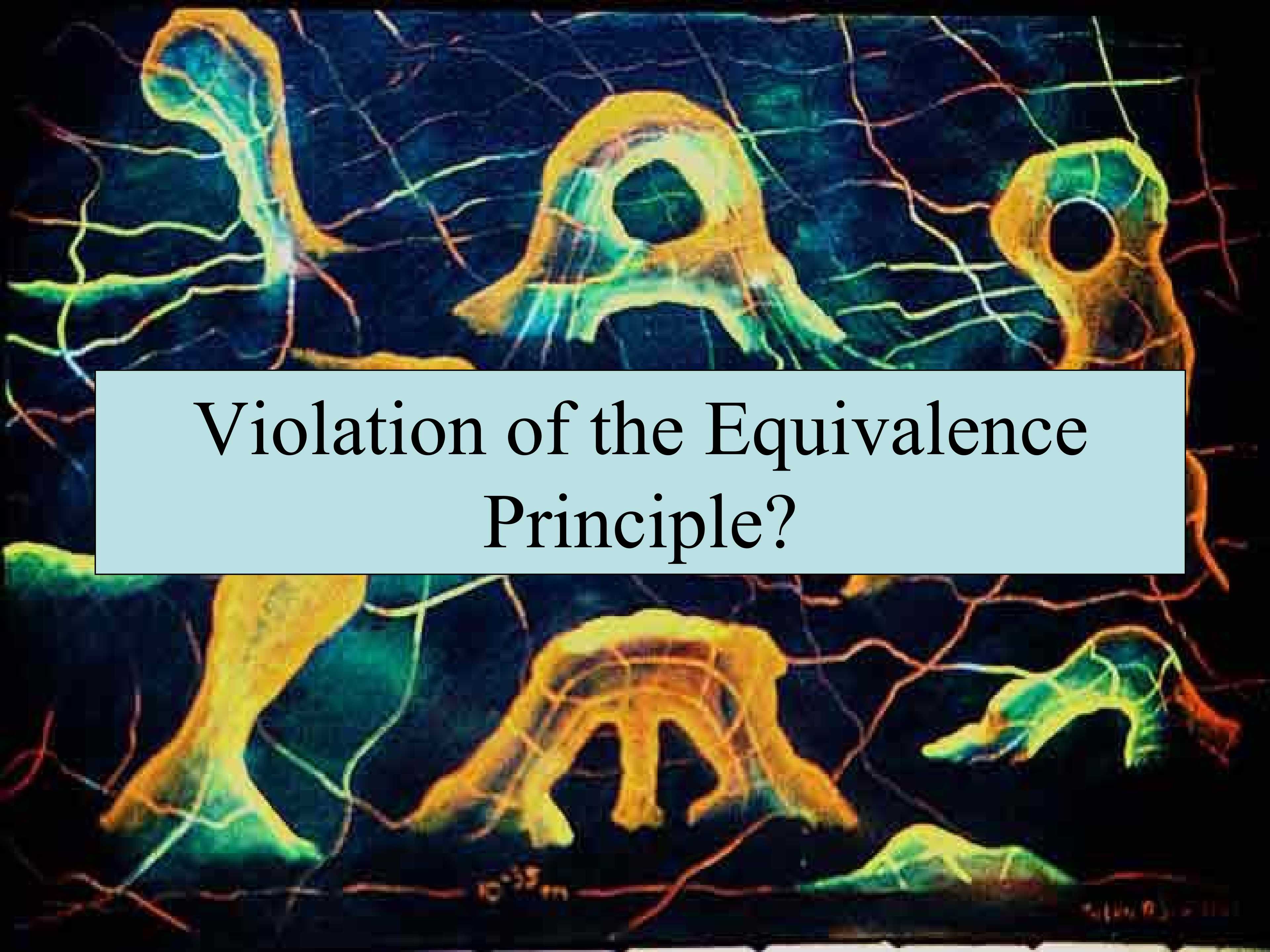
Compilation of Time Delay Limits

- Hint from Mkn 501 compatible with PKS 2155-304, GRBs 080915c, 09092b
- PKS 2155-304, GRBs 090510, 080915c compatible with null effects
- Could the effect on light propagation be redshift dependent?
- Lower density n(z) of space-time defects for $0.2 < z < 1$?
- 'D-void'? $\Delta t_{\rm obs} = \int_0^z dz \frac{n(z) E_{\rm obs}}{M_s H_0} \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$
- Correlate with dark energy?



JE, Mavromatos, Nanopoulos: arXiv:0912:3428 [astro-ph.CO]

Violation of the Equivalence Principle?



Non-Universality of Lorentz Violation?

- Do all relativistic particles have same velocity?
- Not necessarily, if particle interactions with space-time foam are non-universal
- (Relativistic) departure from Principle of Equivalence
- Suggested by astrophysics: limits on Lorentz violation for electrons >> m_P
- Expected in non-critical string model of foam

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

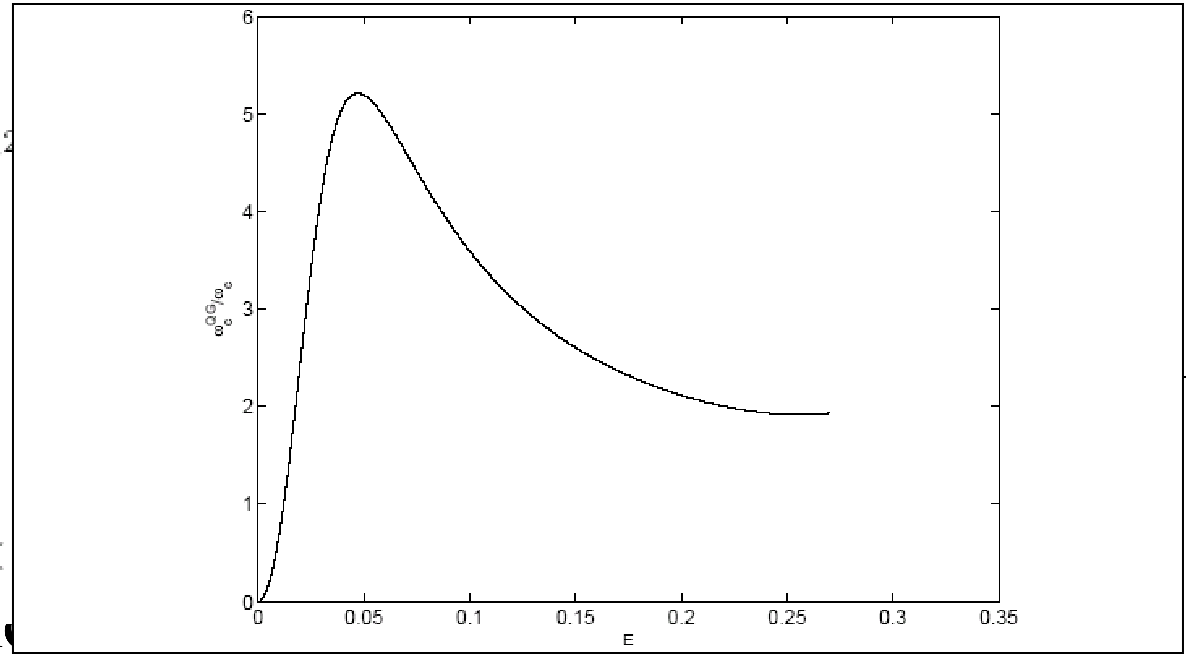
- See 0.5 GeV γ: inverse Compton by > 50 TeV *e*
- Consider modified dispersion relations for both electrons *e* and photons γ:

$$\omega^2(k) = k^2$$

- Lorentz-invariant:
- QG modification:
- For $\xi_e = (E/m_P)^\alpha$
  data →

$$|\xi_e| <$$

- Lower bound on m
- If $\alpha = 1$: $m_{QG} > 10^{26}$ GeV

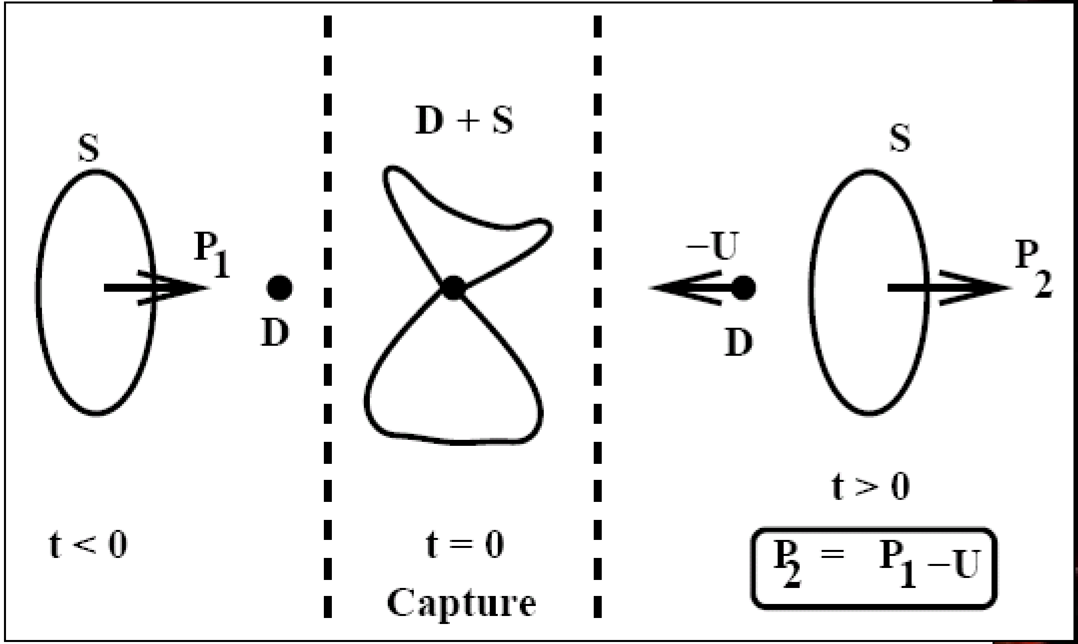


No constraint on dispersion relation for photon

tos + Nanopoulos

Non-Universality in D-Brane Model

- D-branes carry only vacuum quantum numbers
- Only particles without conserved gauge charges interact with D particles,
  e.g., photons

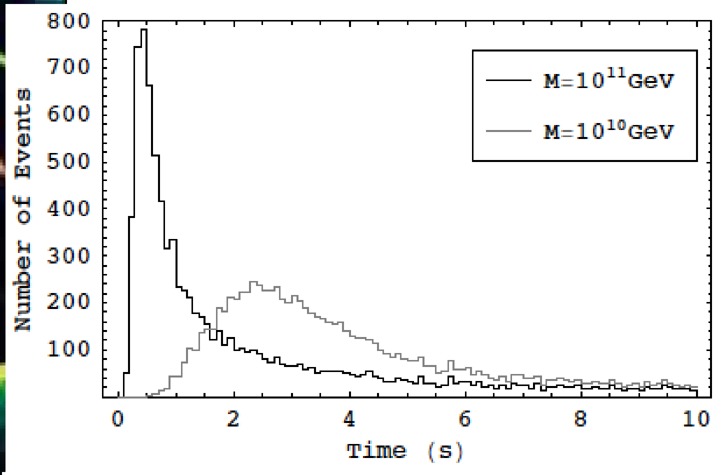


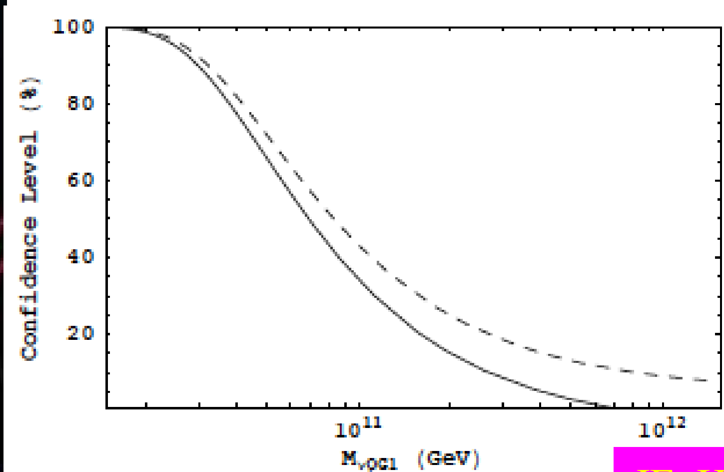
- Charged particles such as electrons do not 'see' D-particle foam → propagate normally

JE, Mavromatos + Nanopoulos

Limits on Neutrino Velocities

- Best present limit from SN 1987a





IMB

t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	38	7
0.412	37	7
0.650	28	6
1.141	39	7
1.562	36	9
2.684	36	6
5.010	19	5
5.582	22	5

Baksan

t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	12.0	2.4
0.435	17.9	3.6
1.710	23.5	4.7
7.687	17.6	3.5
9.099	10.3	4.1

Kamiokande II

t (s)	E (MeV)	σ_E (MeV)
$t \equiv 0.0$	20.0	2.9
0.107	13.5	3.2
0.303	7.5	2.0
0.324	9.2	2.7
0.507	12.8	2.9
1.541	35.4	8.0
1.728	21.0	4.2
1.915	19.8	3.2
9.219	8.6	2.7
10.433	13.0	2.6
12.439	8.9	1.9

$$M_{\nu QG1} > 2.7 \times 10^{10} \text{ GeV}$$

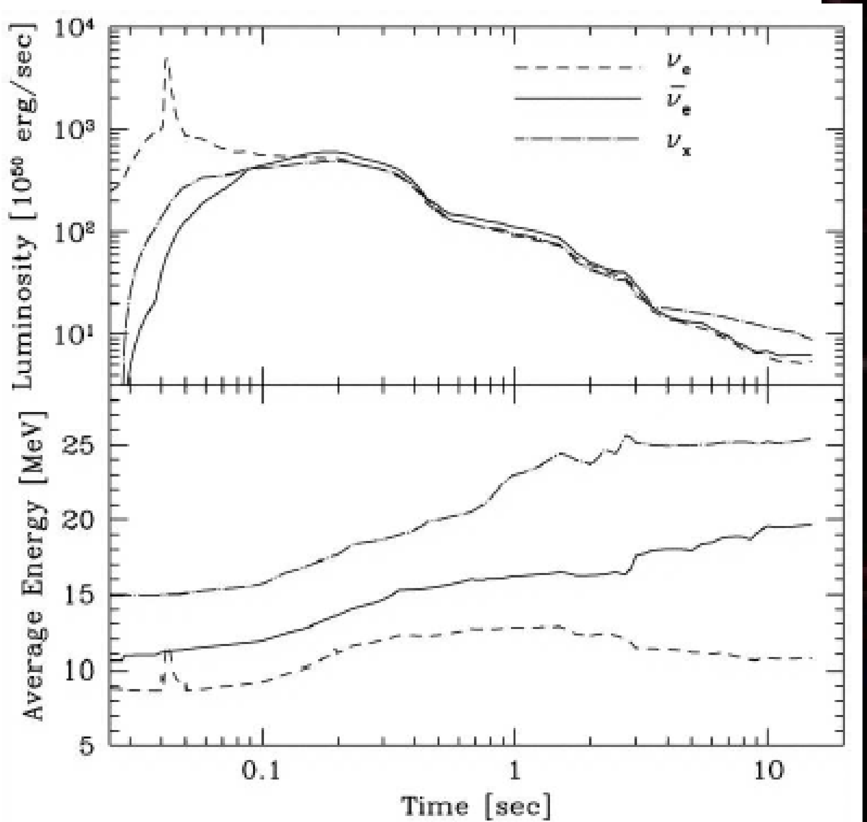
JE, Harries, Meregaglia, Rubbia + Sakharov: arXiv:0805.0253 [hep-ph]

Prospective Future SN Limit

- Use Livermore simulation of galactic supernova
- Monte Carlo simulation of SuperKamiokande
- Expect ~ 10,000 events
- Estimated lower limit

$$M_{\nu QG1} > 2.2 \times 10^{11} GeV$$

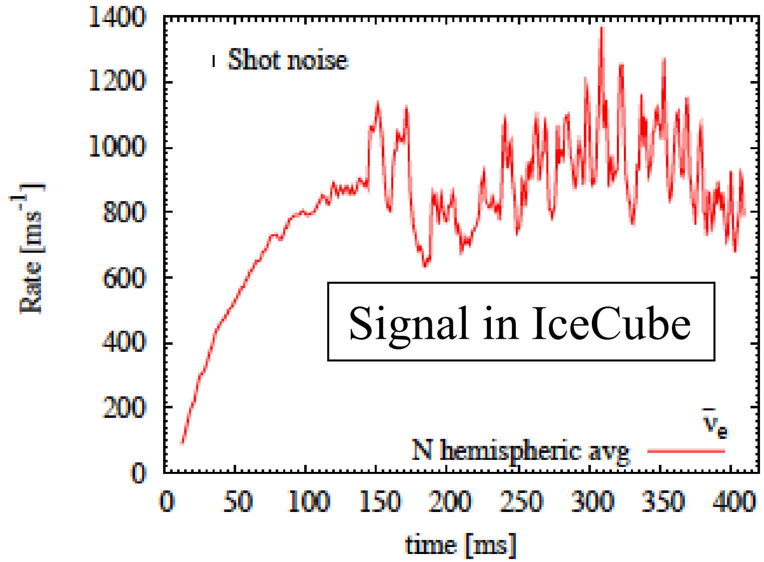
- For subluminal effect



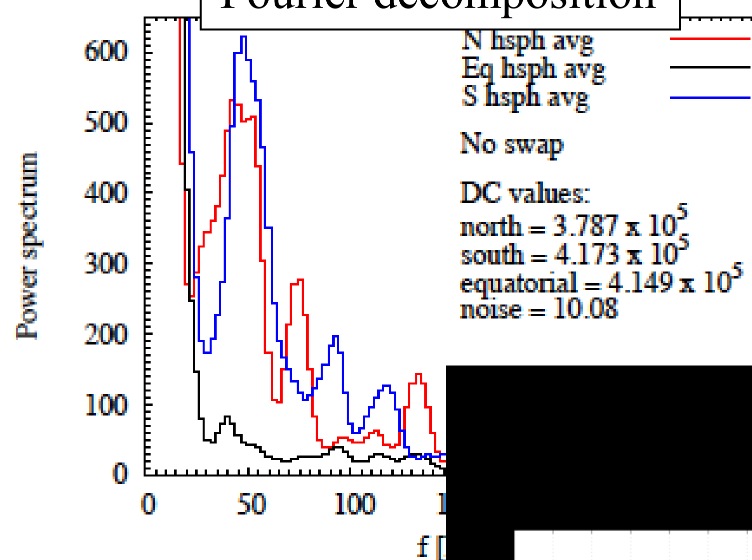
JE, Harries, Meregaglia, Rubbia + Sakharov: arXiv:0805.0253 [hep-ph]

Possible Enhancement of SN Sensitivity

- New 2-dimensional simulation indicates time structure in ν emission

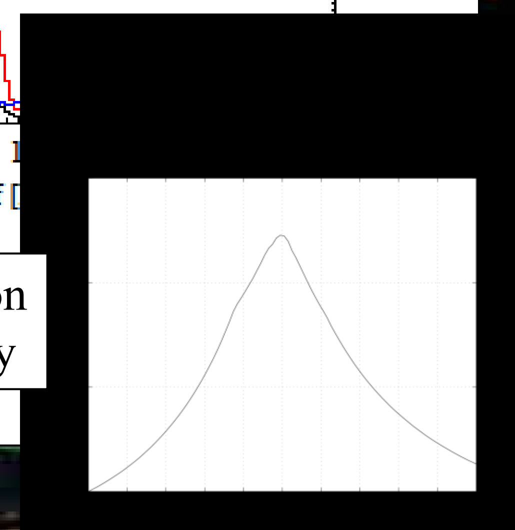


Fourier decomposition



- May increase sensitivity by 2 – 3 orders of magnitude

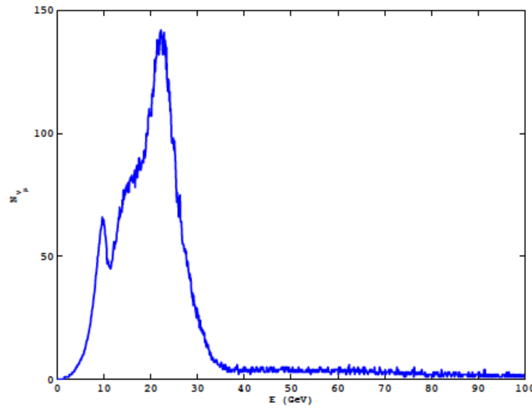
Shannon entropy

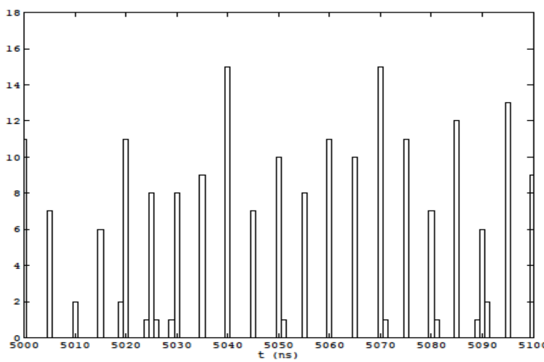


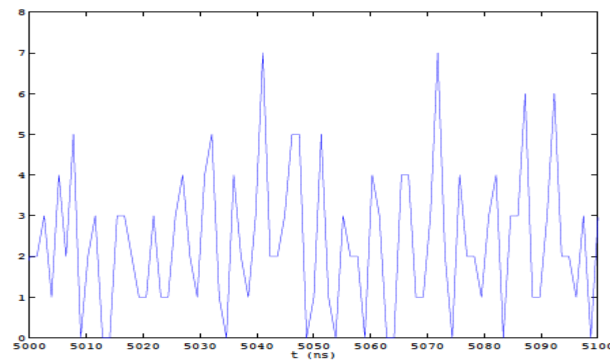
JE, Janka, Mavromatos + Sakharov: in preparation

Sensitivity with OPERA in CNGS Beam

- Average energy ~ 17 GeV
- Complicated time structure:
  - Spill length 10.5 μs, 2100 bunches 5ns, each with 4-σ width 2 ns







- Using only spill structure: $M_{\nu QG1} \sim 7 \times 10^5$ GeV
- Using bunch structure: $M_{\nu QG1} \sim 5 \times 10^7$ GeV
- Using events in rock: $M_{\nu QG1} \simeq 4 \times 10^8$ GeV

JE, Harries, Meregaglia, Rubbia + Sakharov: arXiv:0805.0253 [hep-ph]

Summary & Prospects

- Think about possible experimental signatures of quantum gravity
- Consider distinctive effects not allowed in usual quantum field theory
- Only heuristic discussion yet possible
- ‘Violation’ of quantum mechanics?
- Breakdown of Lorentz invariance?
- Astrophysical γ rays best opportunity?
- Violation of equivalence principle?
- Neutrino experiments independent, less sensitive