Bounds on Lorentz Invariance Violation from Fermi Gamma-Ray Bursts

Jonathan Granot

Open University of Israel

on behalf of the Fermi LAT & GBM Collaborations

17th Lomonosov Conference on Elementary Particle Physics

Moscow State University, Moscow, Russia, August 22, 2015

Outline of the Talk:

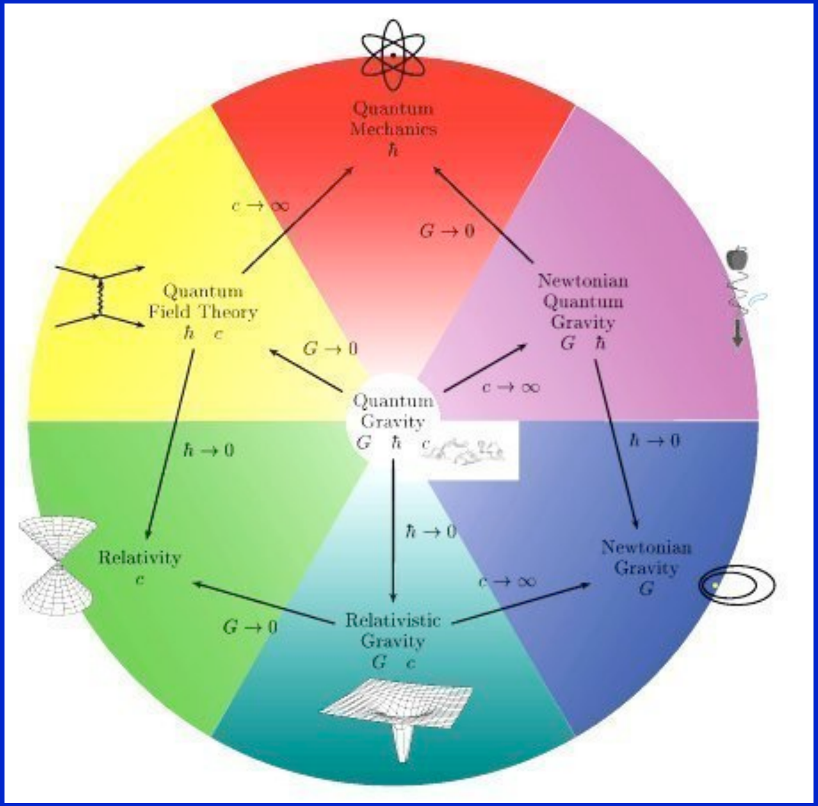
- Brief motivation & parameterization
- Test energy dependence of speed of light in vacuum
- Why use GRBs & how we set limits on such LIV
  - 3 different types of limits from the short bright GRB 090510 at z = 0.903 (Abdo et al. 2009, Nature, 462, 331)
  - Later analysis: 3 methods, 4 GRBs (Vasileiou et al. 2013)
  - Limits on stochastic LIV (Vasileiou+ 15' Nat. Phys. 11, 344)
- **Conclusions**

Quantum Gravity: a physics holy grail

- **Motivation**: to unify in a self-consistent theory Einstein's General Relativity that dominates on large scales & Quantum Theory that dominates on small scales
- Quantum effects on space-time structure expected to become strong near the **Planck scale**:

$l_{Planck} = (\hbar G/c^3)^{1/2} \approx 1.62 \times 10^{-33}$ cm

$E_{planck} = (\hbar c^5/G)^{1/2} \approx 1.22 \times 10^{19}$ GeV



- Many models / ideas out there: **experimental constraints needed**
- Astrophysics as a test bed: large energies and distances; uncontrolled experimental setup

Vacuum energy dispersion: parameterization

- Some quantum-gravity (QG) models allow or even predict (e.g. Ellis et al. 2008) Lorentz Invariance Violation (LIV)
- We directly constrain a simple form of LIV - dependence of speed of light in vacuum on the photon energy: $v_{ph}(E_{ph}) \neq c$
- This may be parameterized through a Taylor expansion of the LIV terms in the dispersion relation:

$$c^2 p_{ph}^2 = E_{\mathrm{ph}}^2 \left[1 + \sum_{k=1}^{\infty} s_k \left(\frac{E_{\mathrm{ph}}}{E_{\mathrm{QG,k}}} \right)^k \right] \quad , \quad \text{where } E_{\mathrm{QG,k}} \leq E_{\mathrm{Planck}} \text{ is naturally expected}$$

- $s_k = -1, 0, 1$ stresses the model dependent sign of the effect
- The most natural scale for LIV is the **Planck scale**

Vacuum energy dispersion: parameterization

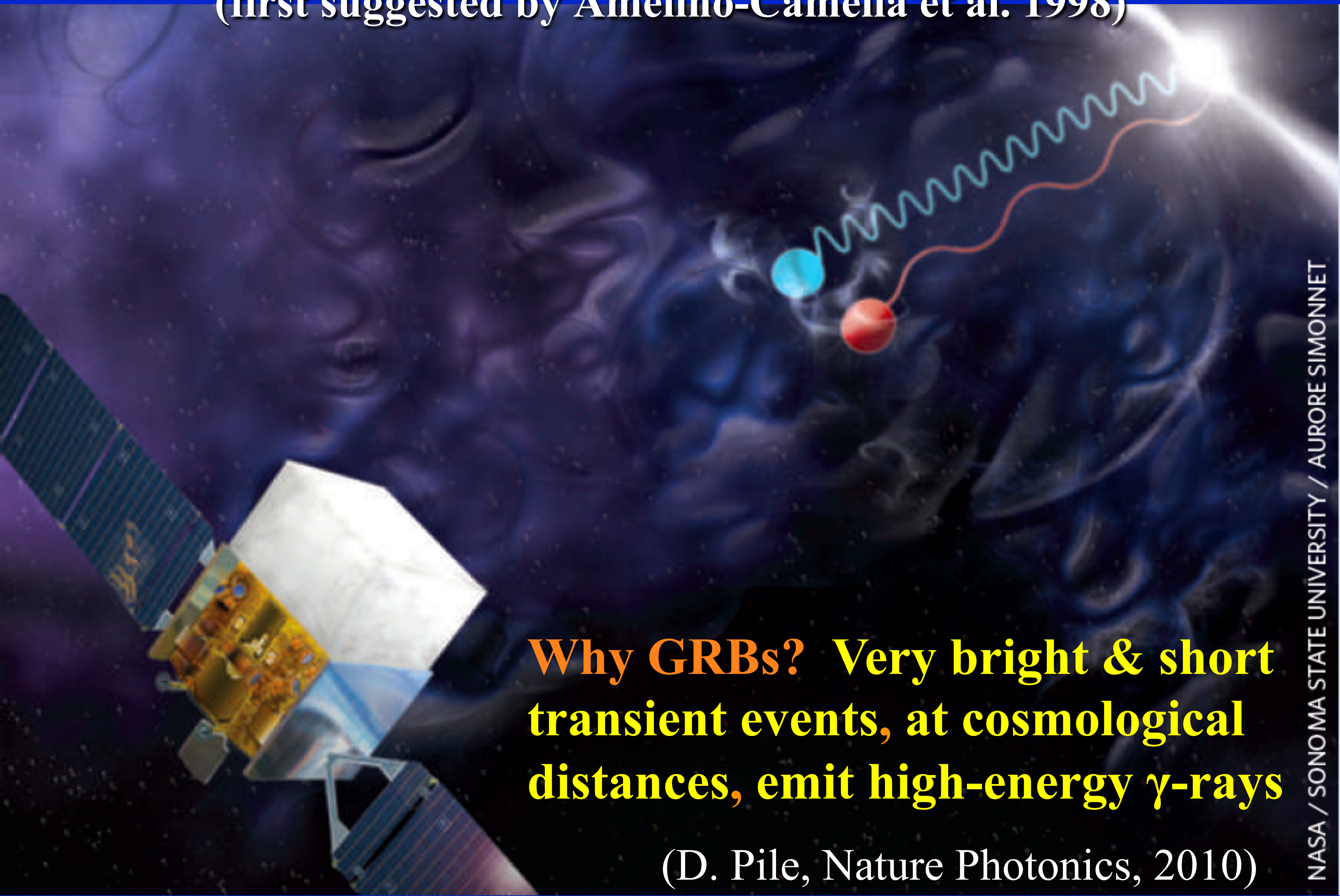
- The photon propagation speed is given by the group velocity:

$$c^2 p_{ph}^2 = E_{\rm ph}^2\left[1+\sum_{k=1}^{\infty} s_k\left(\frac{E_{\rm ph}}{E_{\rm QG,k}}\right)^k\right] \quad , \quad v_{\rm ph}=\frac{\partial E_{\rm ph}}{\partial p_{\rm ph}} \approx c\left[1-s_n\frac{(1+n)}{2}\left(\frac{E_{\rm ph}}{E_{\rm QG,n}}\right)^n\right]$$

- Since $E_{ph} \ll E_{QG,k} \lesssim E_{Planck} \sim 10^{19}$ GeV the **lowest order** non-zero term, of order $n = \min\{k \mid s_k \neq 0\}$, **dominates**
- Usually $n = 1$ (linear) or 2 (quadratic) are considered
- Here we focus on **n = 1**, since only in this case are our limits of the order of the Planck scale
- We try to constrain **both possible signs** of the effect:
  - $s_n = 1$, $v_{ph} < c$: (sub-luminal) higher-E photons are slower
  - $s_n = -1$, $v_{ph} > c$: (super-luminal) higher-E photons are faster
- Notice that here $c = v_{ph}(E_{ph} \to 0)$ is the low energy limit of v_{ph}

Probing Vacuum dispersion Using GRBs

(first suggested by Amelino-Camelia et al. 1998)

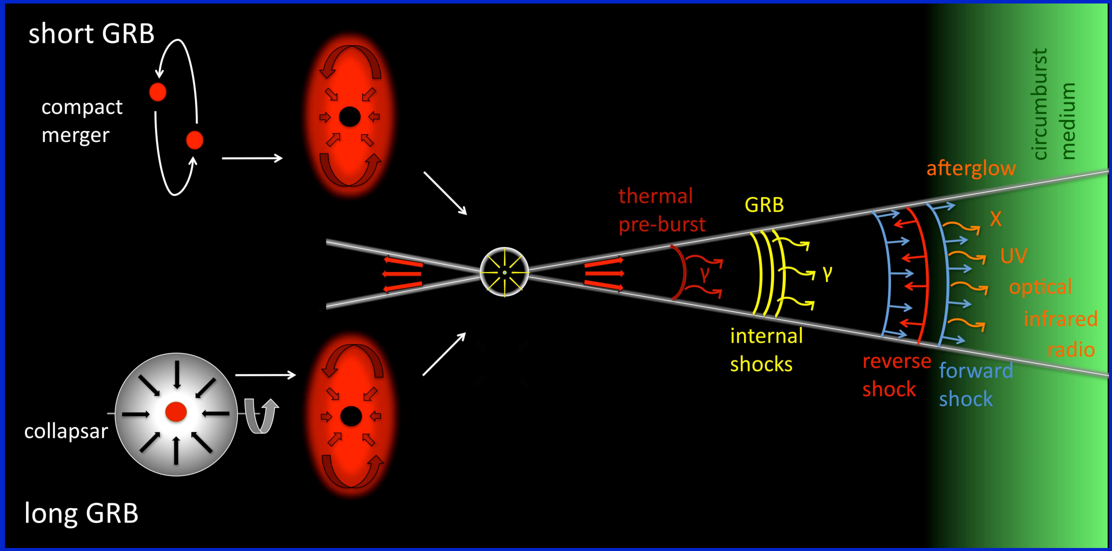


Why GRBs? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays

(D. Pile, Nature Photonics, 2010)

GRB Theor etical Framework:

- **Progenitors**:
  - Short: binary merger?
  - Long: massive stars
- **Jet Acceleration** to $\Gamma > 100$: P_{rad}/B-field?



- **γ-rays**: dissipation: shocks/B? emission mechanism?
- The jet **decelerates** by sweeping-up external medium

⇒ **afterglow** emission from the long lived shock going into the external medium: X-ray ➔ optical ➔ radio

- Allows measuring the source's cosmological redshift

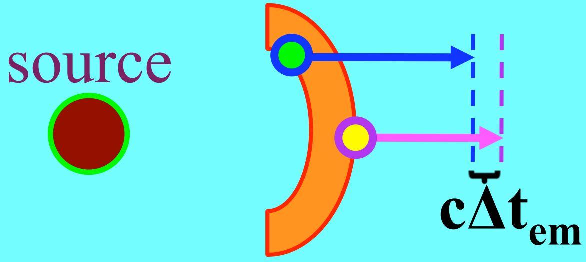
Constraining LIV Using GRBs

- A high-energy photon E_h would arrive after (in the sub-luminal case: $v_{ph} < c$, $s_n = 1$), or possibly before (in the super-luminal case, $v_{ph} > c$, $s_n = -1$) a low-energy photon E_l emitted together
- The time delay in the arrival of the high-energy photon is:

$$\Delta t_{\mathrm{LIV}} = s_n \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{E_{\mathrm{QG,n}}^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

(Jacob & Piran 2008)

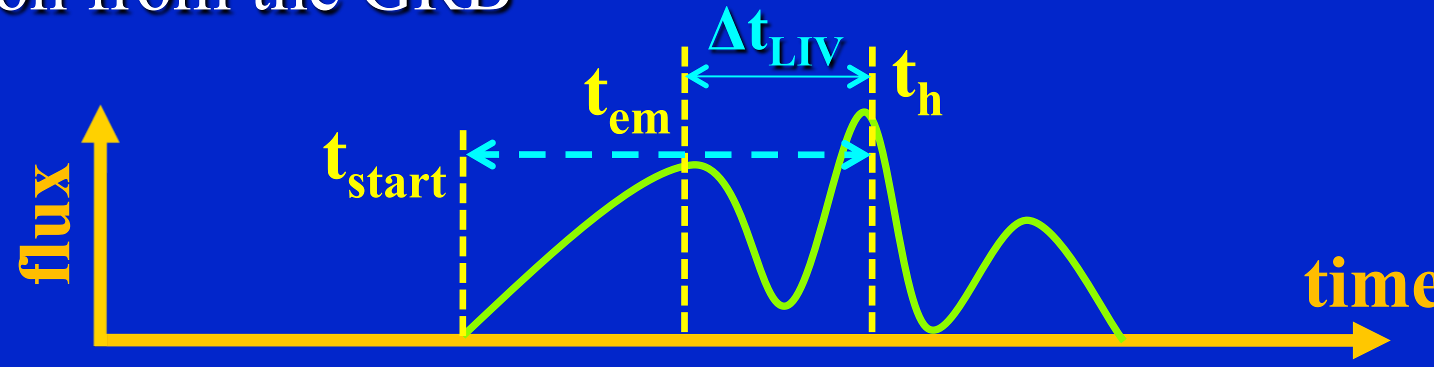
- The photons E_h & E_l do not have to be emitted at exactly the same time & place in the source, but we must be able to limit the difference in their effective emission times (i.e. arrival times for $v_{ph} = c$) using our knowledge about GRB emission



$$\Delta t_{\mathrm{obs}} = \Delta t_{\mathrm{em}} + \Delta t_{\mathrm{LIV}}$$

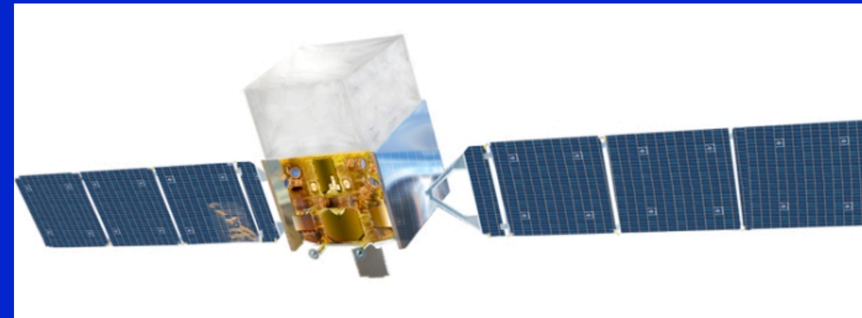
Method 1

- Limits only $s_n = 1$ - the sub-luminal case: $v_{ph} < c$, & positive time delay, $\Delta t_{LIV} = t_h - t_{em} > 0$ (here t_h is the actual measured arrival time, while t_{em} would be the arrival time if $v_{ph} = c$)
- We consider a single high-energy photon of energy E_h and assume that it was emitted after the onset time (t_{start}) of the relevant low-energy (E_l) emission episode: $t_{em} > t_{start}$
- ➔ $\Delta t_{LIV} = t_h - t_{em} < t_h - t_{start}$
- A conservative assumption: t_{start} = the onset of any observed emission from the GRB

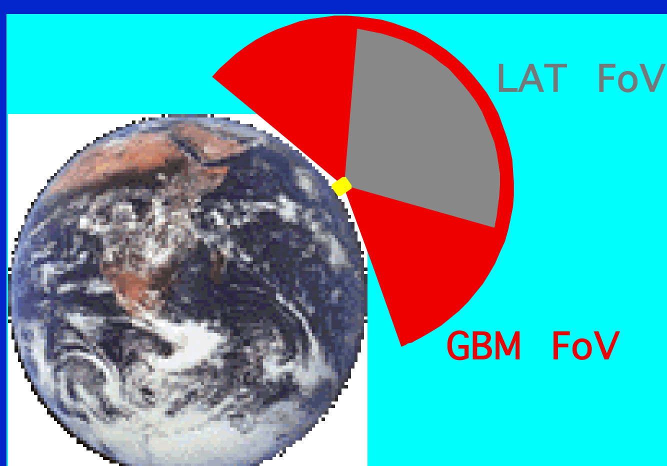


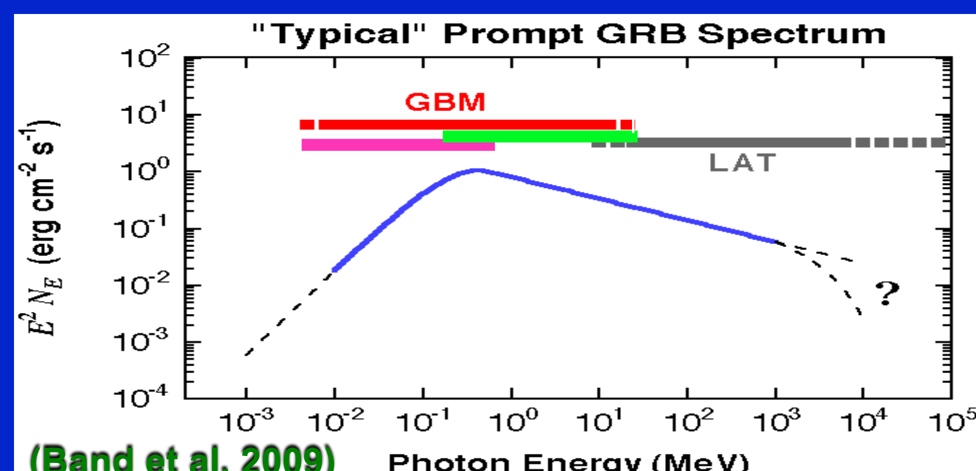
Fermi Gamma-ray Space Telescope

(launched on June 11, 2008)



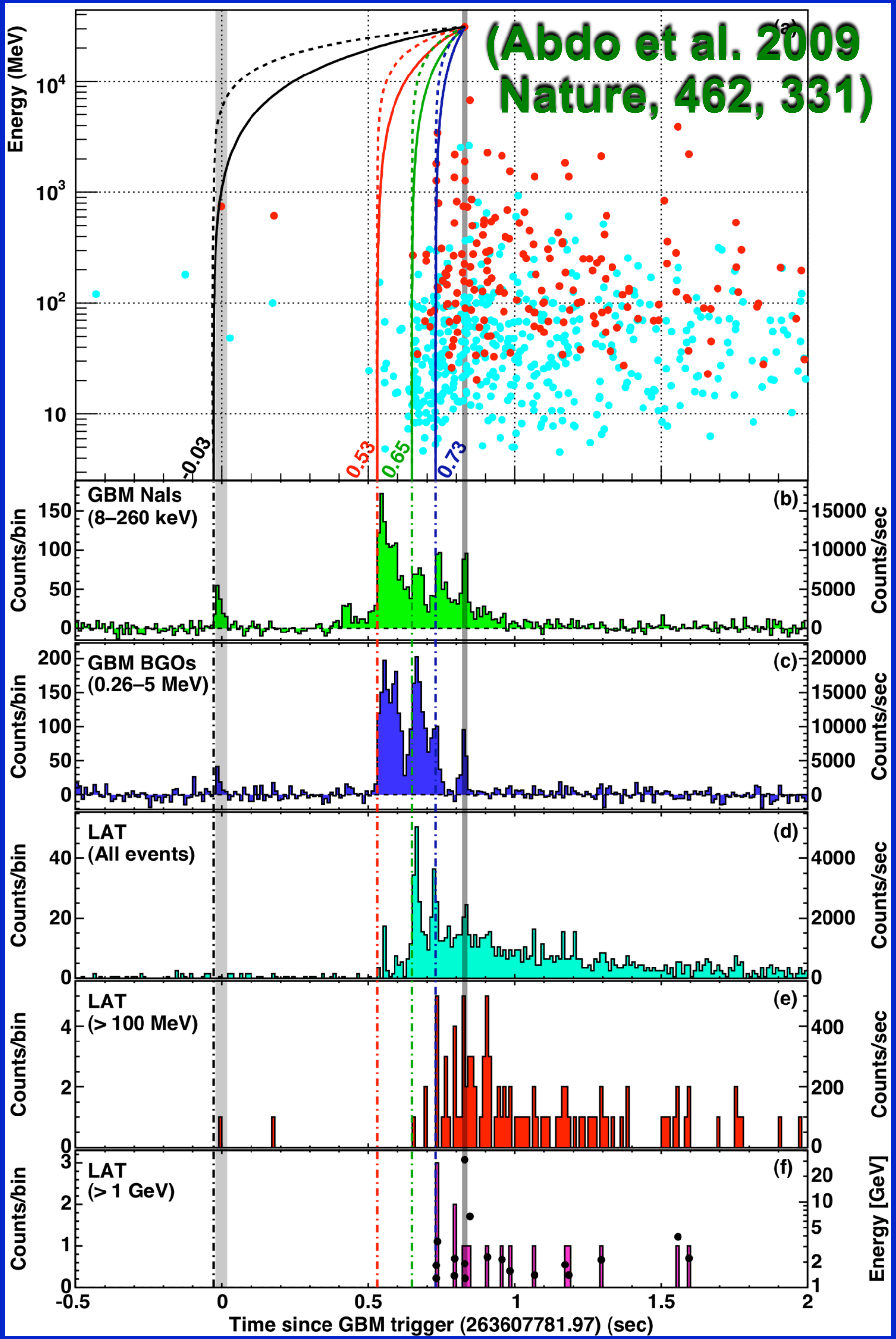
- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10^3 keV, 2×BGO 0.15 – 40 MeV), full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime





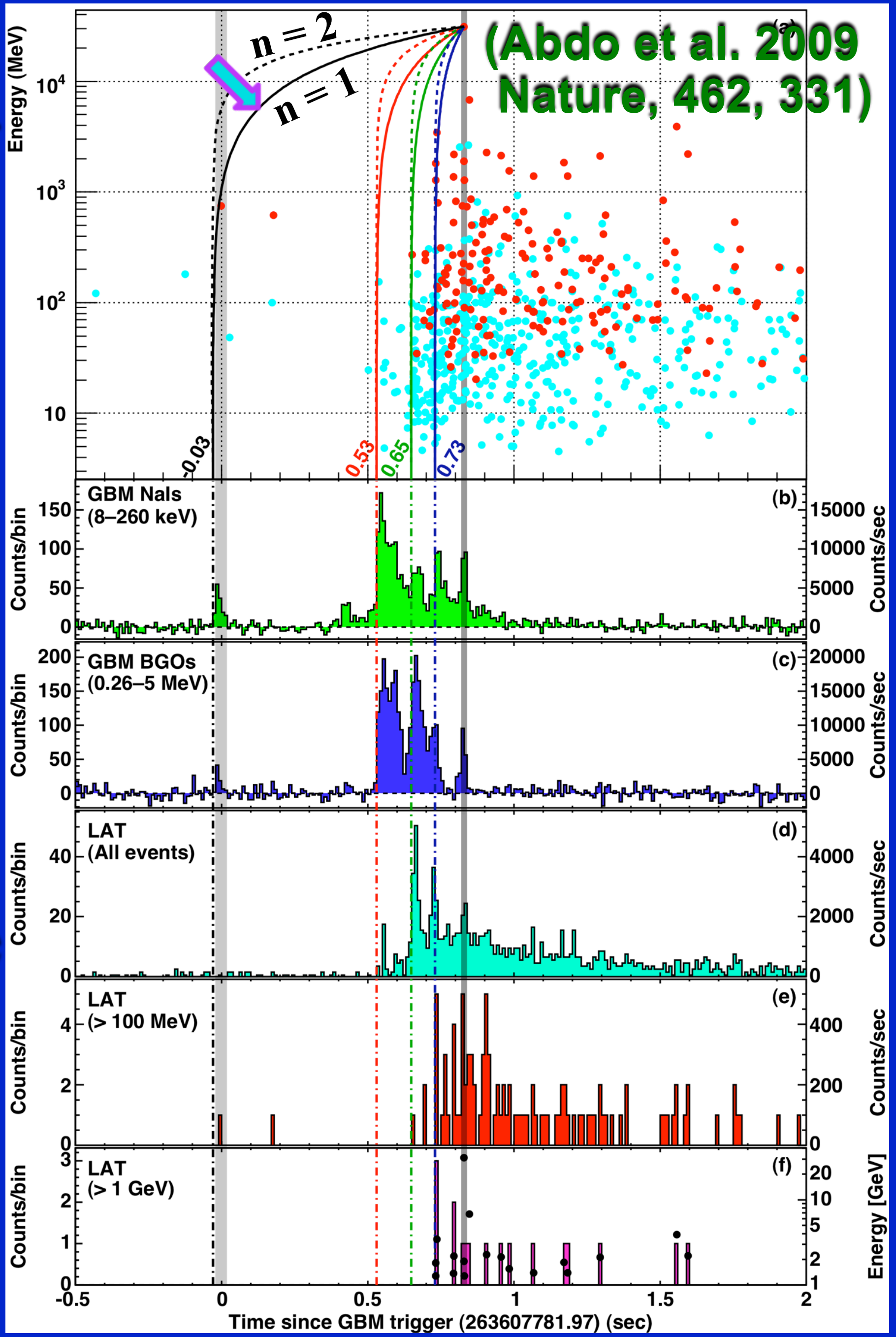
GRB090510: L.I.V

- A short GRB (duration ~1 s)
- Redshift: $z = 0.903 \pm 0.001$
- A ~31 GeV photon arrived at $t_h = 0.829$ s after the trigger
- We carefully verified it is a photon+from the GRB at $>5\sigma$
- Intrinsic spectral lags known on timescale of individual pulses: weak effect expected



GRB090510: L.I.V

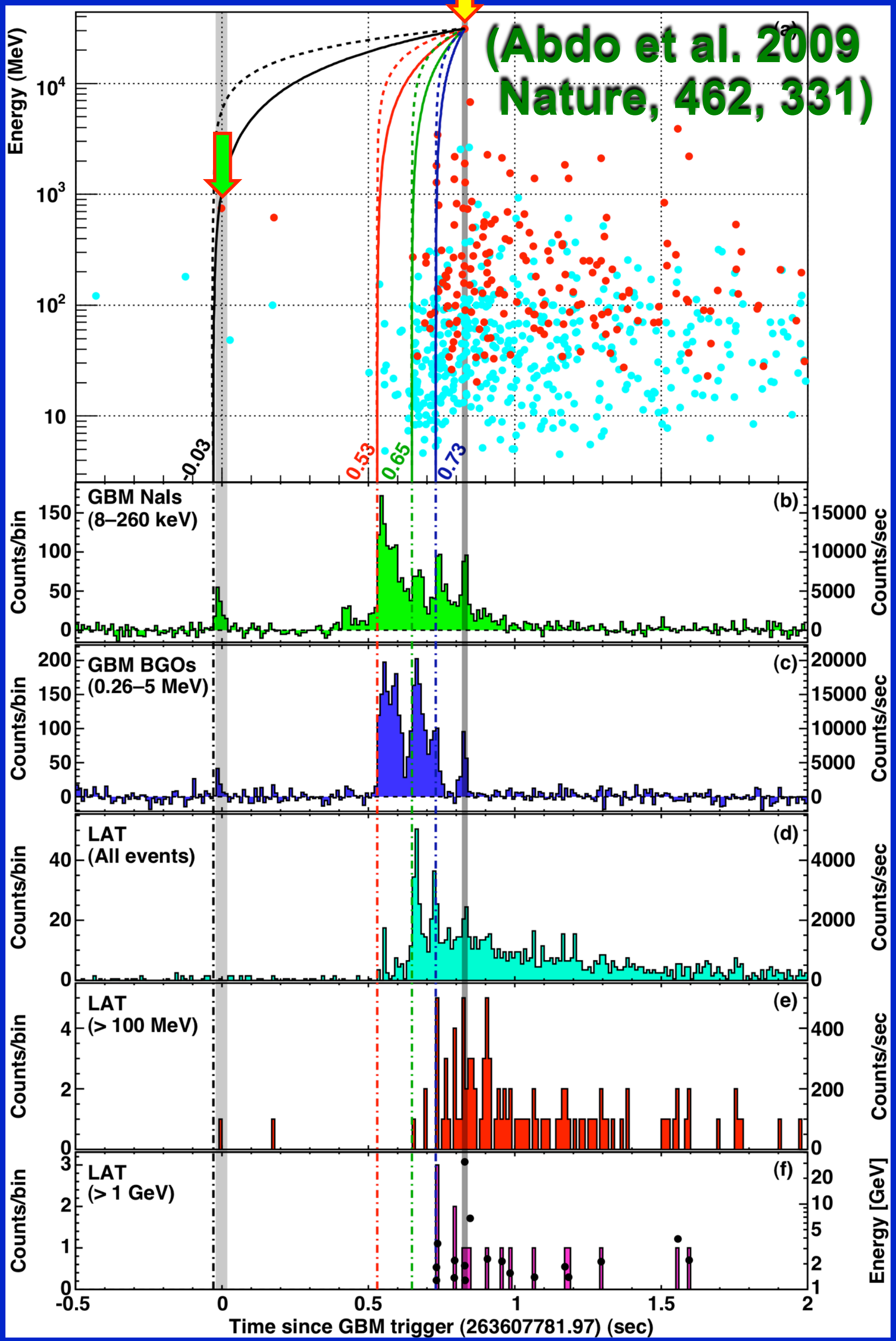
- Method 1: different choices of t_{start} from the most conservative to the least conservative
- $t_{start} = -0.03$ s precursor onset
  ➔ $\xi_1 = E_{QG,1}/E_{Planck} > 1.19$
- $t_{start} = 0.53$ s onset of main emission episode ➔ $\xi_1 > 3.42$
- For any reasonable emission spectrum a ~31 GeV photon is accompanied by many γ's above 0.1 or 1 GeV that "mark" its t_{em}
- $t_{start} = 0.63$ s, 0.73 s onset of emission above 0.1, 1 GeV
  ➔ $\xi_1 > 5.12$, $\xi_1 > 10.0$



GRB090510: L.I.V

- Method 2: least conservative
- Associating a high energy photon with a sharp spike in the low energy lightcurve, which it falls on top of
- Limits both signs: $s_n = \pm 1$
- Non-negligible chance probability (~5-10%), but still provides useful information
- For a 0.75 GeV photon during precursor: $|\Delta t| < 19\,\mathrm{ms}$, $\xi_1 > 1.33$
- For the 31 GeV photon (*shaded vertical region*) ➔ $|\Delta t| < 10\,\mathrm{ms}$ and $\xi_1 = E_{QG,1}/E_{Planck} > 102$

(Abdo et al. 2009 Nature, 462, 331)



Method 3: DisCan (Scargle et al. 2008)

- Based on lack of smearing of the fine time structure (sharp narrow spikes in the lightcurve) due to energy dispersion
- Constrains both possible signs of the effect: $s_n = \pm 1$
- Uses all LAT photons during the brightest emission episode (obs. range 35 MeV – 31 GeV); no binning in time or energy
- Shifts the arrival time of photons according to a trail energy dispersion (linear in our case), finding the coefficient that maximizes a measure of the resulting lightcurve variability
- We found a symmetric upper limit on a linear dispersion: $|\Delta t/\Delta E| < 30$ ms/GeV (99% CL) ➔ $E_{QG,1} > 1.22\,E_{Planck}$
- Remains unchanged when using only photons < 1 or 3 GeV (a very robust limit)

Newer Analysis of brightest LAT GRBs

(Vasileiou, Jacholkowska, Piron, Bolmont, Couturier, Granot, Stecker, Cohen-Tanugi & Longo 2013, PRD, 87, 122001)

- Use 3 different analysis methods: complimentary in sensitivity & improves reliability of results
  - **PairView (PV)**: distribution of spectral lags $\Delta t/\Delta(E^n)$ for all photon pairs used to estimate τ_n; CI from simulations

$$\tau_n \equiv \frac{\Delta t}{(E_h^n - E_l^n)} \simeq s_\pm \frac{(1+n)}{2H_0} \frac{1}{E_{QG}^n} \times k_n$$

$$k_n \equiv \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_\Lambda + \Omega_{\rm M}(1+z')^3}} dz'$$

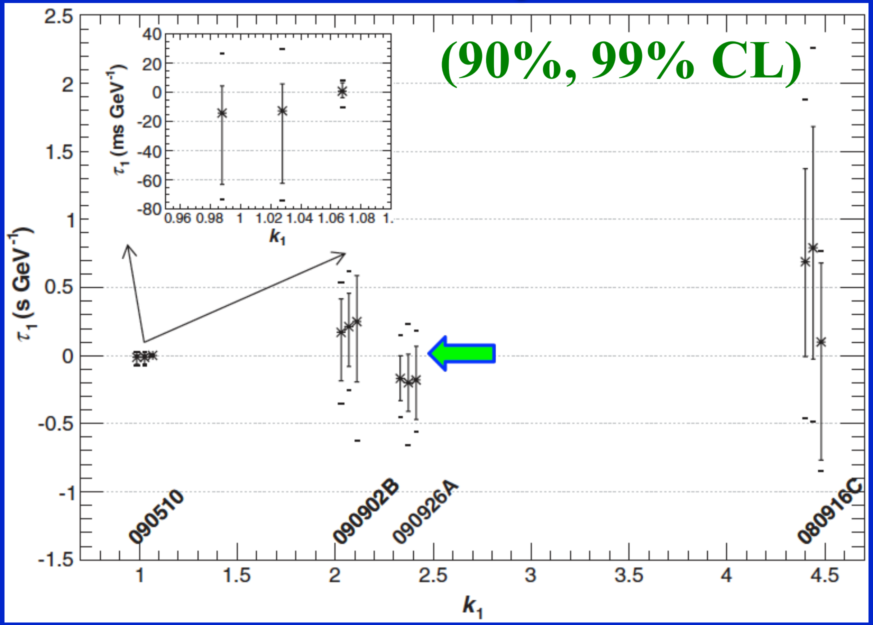
Newer Analysis of brightest LAT GRBs

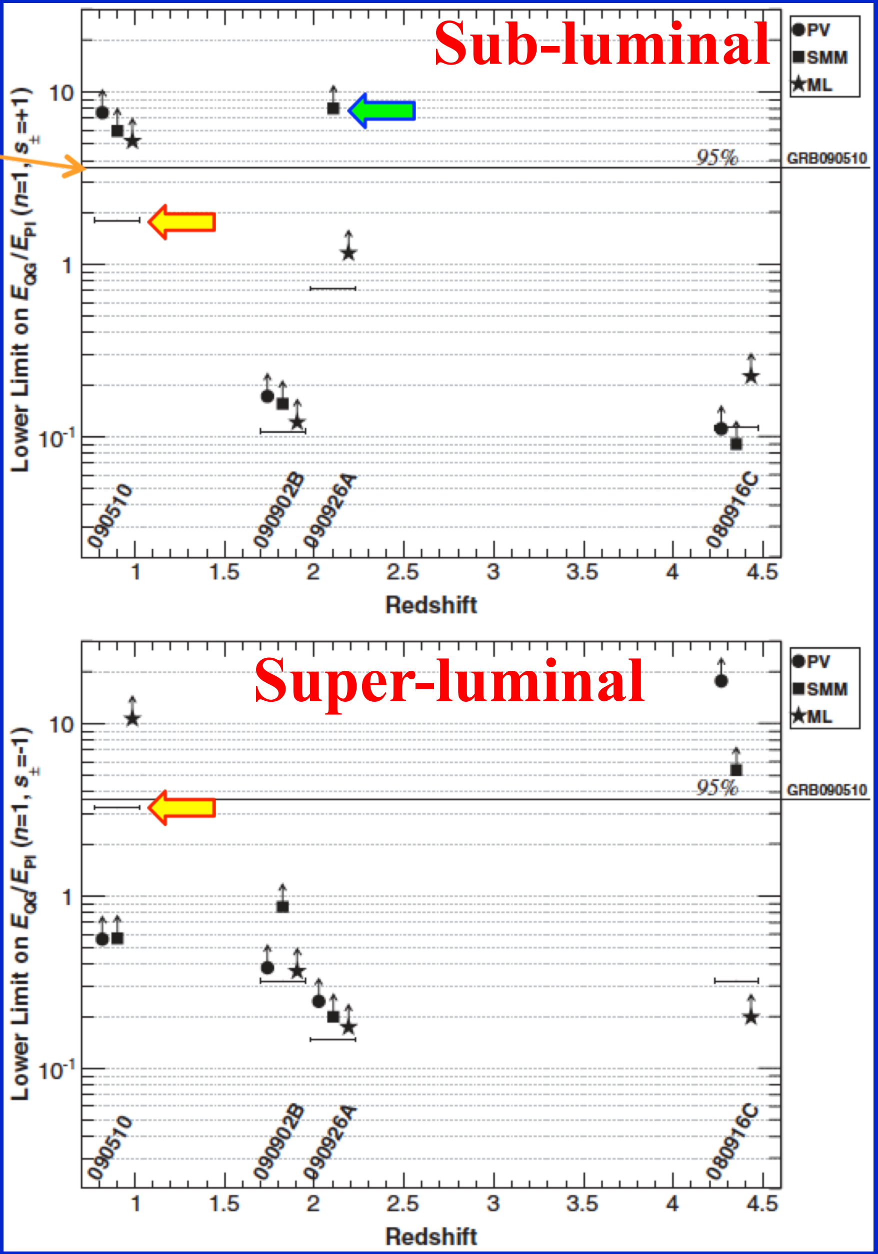
(Vasileiou, Jacholkowska, Piron, Bolmont, Couturier, Granot, Stecker, Cohen-Tanugi & Longo 2013, PRD, 87, 122001)

- Use 3 different analysis methods: complimentary in sensitivity & improves reliability of results
  - **PairView (PV)**: distribution of spectral lags $\Delta t/\Delta(E^n)$ for all photon pairs used to estimate τ_n; CI from simulations
  - **S**harpness **M**aximization **M**ethod (SMM): **improved** DisCan
  - **M**aximum **L**ikelihood (ML): low-E data → lightcurve template for high-E data → maximize L for trial τ_n values
- Use the 4 brightest Fermi/LAT GRBs with known redshifts
- The new analysis methods improve the sensitivity/LIV limits
- Conservatively account for Intrinsic Effects: $\boldsymbol{\tau_n = \tau_{GRB} + \tau_{LIV}}$

All 3 Methods: Results (95% CL, n = 1)

- ~2 times stricter than the best previous limits (horizontal lines)
- Horizontal bars: mean limits over the 3 methods, accounting for GRB intrinsic effects
- Neglecting intrinsic effects can lead to unrealistically strict limits

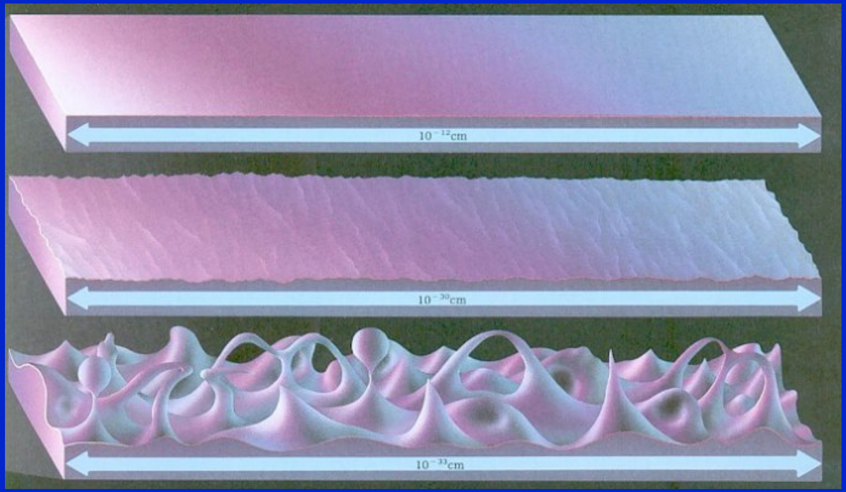




Very New: Limits on Stochastic LIV

(Vasileiou, Granot, Piran & Amelino-Camelia 2015; Nat. Phys. 11, 344)

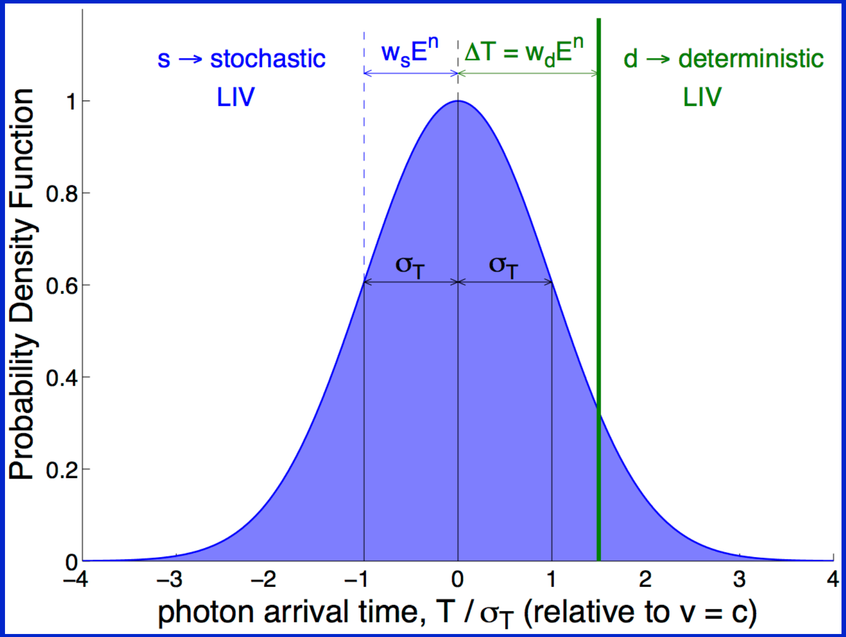
- The concept of spacetime foam: suggests LIV may be stochastic
- Photons of same energy emitted together arrive at different times according to some PDF



- Differs from deterministic LIV where E_{ph} uniquely determines v_{ph} & $v_{ph} - c$ has the same sign:
- We considered a Gaussian PDF:

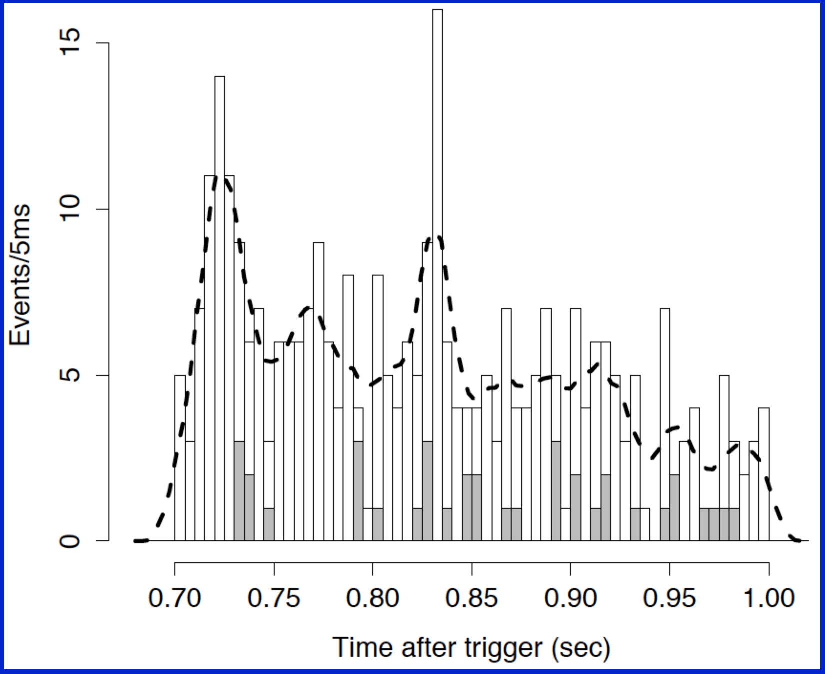
$$v(E) = c + \delta v(E)\,,\ \ \delta v = \mathrm{G}(0,\sigma_v)$$

$$\sigma_v(E) = (E/\xi_{s,n_s} E_{\mathrm{Planck}})^{n_s} c$$



Data Analysis: Maximum Likelihood

- We generalized this existing method to stochastic LIV
- $E < E_{th}$ used for emission template; $E > E_{th}$ used for likelihood
- We chose $E_{th} = 300$ MeV (negligible LIV $< E_{th}$ + enough γ's $> E_{th}$)
- Time interval: 0.7-1.0 s (brightest, most variable, highest E_{ph} & relatively stable emission spectrum; 316 γ's $< E_{th}$, 37 γ's $> E_{th}$)
- Optimized lightcurve reconstruction method with simulations
  - ◆ KDE with fixed 6 ms bandwidth
  - ⇒ Reconstructed L.C. template: *f(t)*



Data Analysis: Maximum Likelihood

- $\sigma_T(E) = T_c\sigma_v(E)/c = \boldsymbol{w}E$, $\boldsymbol{w(z)} = \sigma_T(E)/E = T_c/\xi_{s,1}E_{\text{Planck}}$
  stochastic LIV parameter (measured in s/GeV):

$$w(z) = \frac{1}{\xi_{s,1}E_{\text{Pl}}H_0}\int_0^z \frac{(1+z')}{\sqrt{\Omega_\Lambda + \Omega_M(1+z')^3}}dz'$$

- Likelihood: product of probabilities for all high-energy photons ($E > E_{th}$):

$$\mathcal{L}(w) = \prod_{i=1}^{N} P(E_i, t_i|w, f)$$

- For each photon, a convolution is done to account for all possible emission times with the appropriate probability

$$P_{\text{LIV}}(\Delta t, E|w) = G(\Delta t|0, \sigma_{LIV} = wE_i)$$

$$P(E_i, t_i|w, f) = \int_{-\infty}^{\infty} G(t_i' - t_i|0, wE_i)\ f(t_i')dt_i'$$

- Altogether:

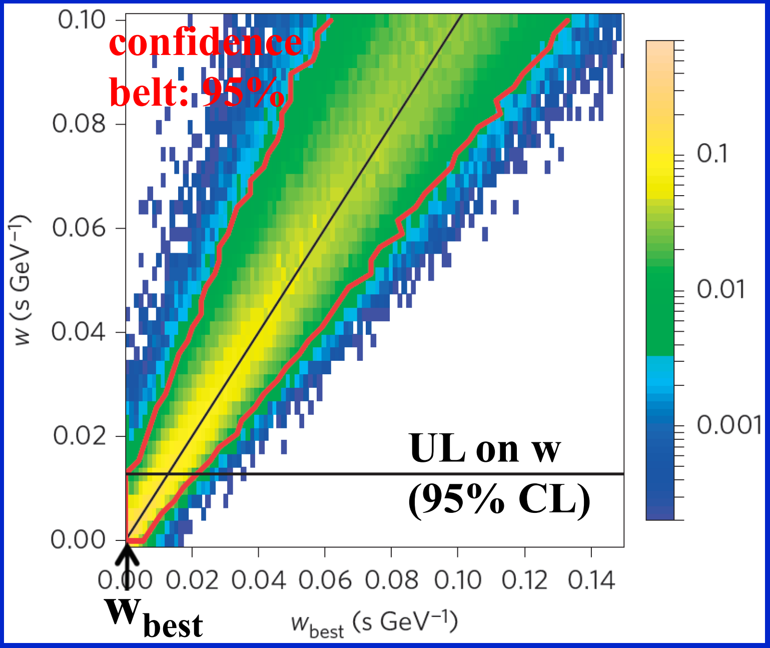
$$\mathcal{L}(w) = \prod_{i=1}^{N} P_i(w) \propto \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi}wE_i}\int_{-\infty}^{\infty} f(t_i - \tau)\exp\left[-\frac{1}{2}\left(\frac{\tau}{wE_i}\right)^2\right]d\tau$$

Results & Confidence Intervals:

- Our best estimate for w that maximizes $L(\mathrm{w})$: $\mathrm{w_{best}} = 0$ s/GeV
- Confidence Interval: Feldman-Cousin method (computationally expensive, but provides proper coverage & is less sensitive to biases)
  - Use artificial lightcurve close to detected one + inject a known w
  - Many simulations (random realizations) for each trial value of w
  - ML applied to each realization $\Rightarrow \mathrm{w_{best}}(\mathrm{w}) \Rightarrow$ global confidence belt
  - $\Rightarrow$ derive Confidence Interval for w using $\mathrm{w_{best}}$ from the actual data
- CI on w $\Rightarrow$ CI on $\xi_{s,1} = E_{QG,s,1}/E_{Planck}$
- We obtain a Planck-scale limit (the 1st for stochastic or fuzzy LIV):

$\xi_{s,1} > 2.8$ at 95% confidence

$\xi_{s,1} > 1.6$ at 99% confidence



Conclusions:

- Astrophysical tests of QG can help – look for them
- GRBs are very useful for constraining LIV
- Bright **short** GRBs are more useful than long ones
- **$E_{QG,1}/E_{Planck}$ ≥ a few** even when conservatively accounting for possible intrinsic source effects
- New Planck scale limits on stochastic / fuzzy LIV
- Quantum-Gravity Models with linear ($n = 1$) photon energy dispersion are disfavored