Limits on Lorentz Invariance Violation from Gamma-Ray Burst Observations by Fermi Gamma-Ray Space Telescope

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on behalf of the Fermi LAT & GBM Collaborations

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Outline of the Talk:

- Brief motivation & parameterization
- GRB Theoretical framework (a few words on what we know and don't)
- Constraining Lorentz Invariance Violation using GRBs: why use GRBs & how do we set limits
- Limit from the bright long GRB 080916C at z~4.35
- 3 different types of limits from the short bright GRB 090510 at z = 0.903: detailed description & results
- Summary of limits on LIV using Fermi LAT GRBs
- **Conclusions**

Brief Motivation & 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 the speed of light 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:

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

- $s_k = 0, 1$ or -1 stresses the model dependent sign of the effect
- The most natural scale for LIV is the **Planck scale**, where quantum effects on the structure of space-time are expected to become strong: $l_{\rm Planck} = (\hbar G/c^3)^{1/2} \approx 1.62\times10^{-33}$ cm

$$E_{\rm Planck} = M_{\rm Planck}c^2 = (\hbar c^5/G)^{1/2} \approx 1.22\times10^{19} \text{ GeV}$$

Brief Motivation & Parameterization

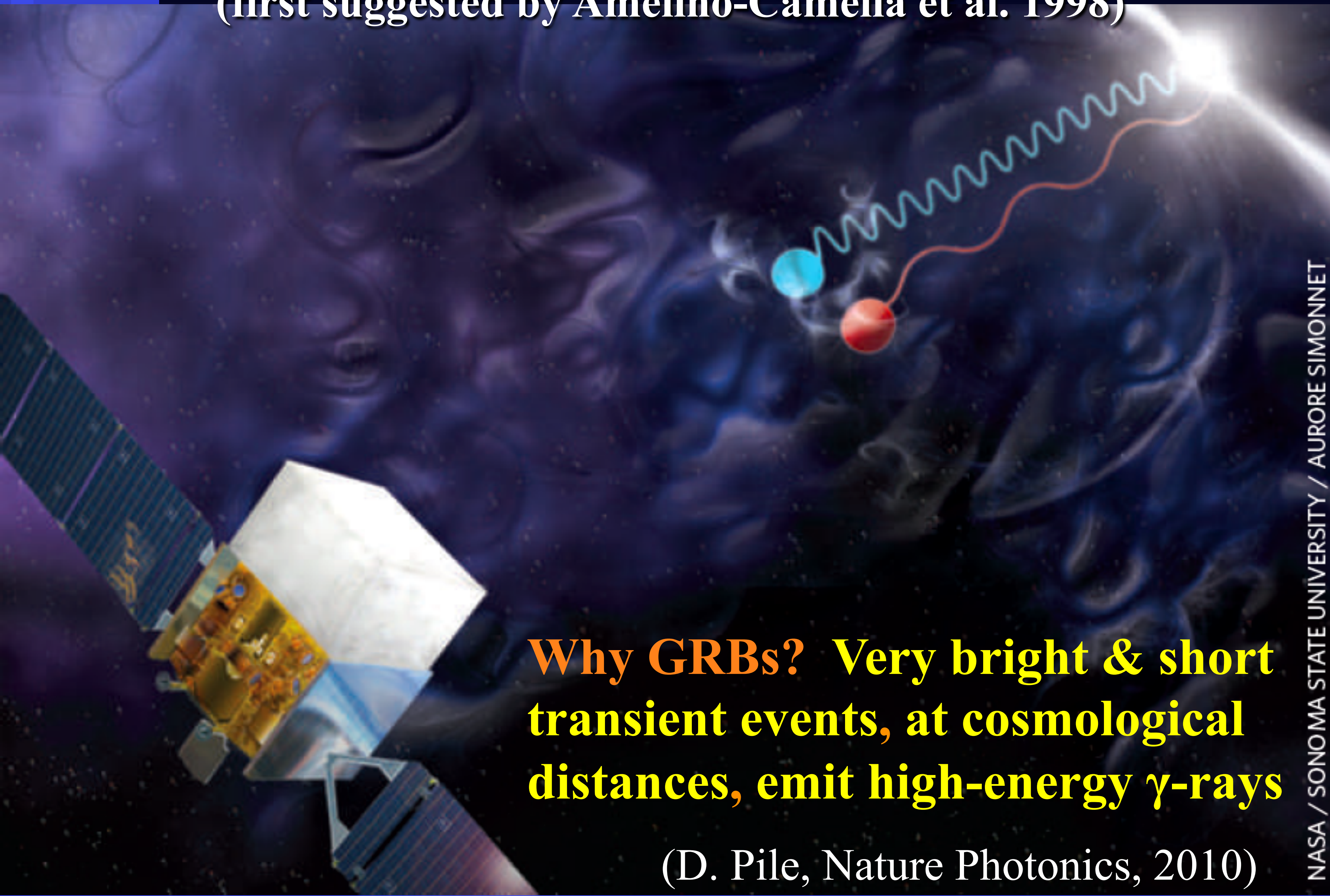
- The photon propagation speed is given by the group velocity:

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

- Since $\mathrm{E_{ph}} \ll \mathrm{M_{QG,k}c^2} \lesssim \mathrm{E_{planck}} \sim 10^{19}$ GeV the **lowest order** non-zero term, of order $\mathrm{n} = \min\{\mathrm{k} \mid \mathrm{s_k} \neq 0\}$, **dominates**
- Usually n = 1 (linear) or 2 (quadratic) are considered
- We focus here 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:
  - $\mathrm{s_n} = 1$, $\mathrm{v_{ph}} < \mathrm{c}$: higher energy photons propagate slower
  - $\mathrm{s_n} = -1$, $\mathrm{v_{ph}} > \mathrm{c}$: higher energy photons propagate faster
- We stress: here $\mathrm{c} = \mathrm{v_{ph}}(\mathrm{E_{ph}} \to 0)$ is the low energy limit of $\mathrm{v_{ph}}$

Constraining LIV Using GRBs

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

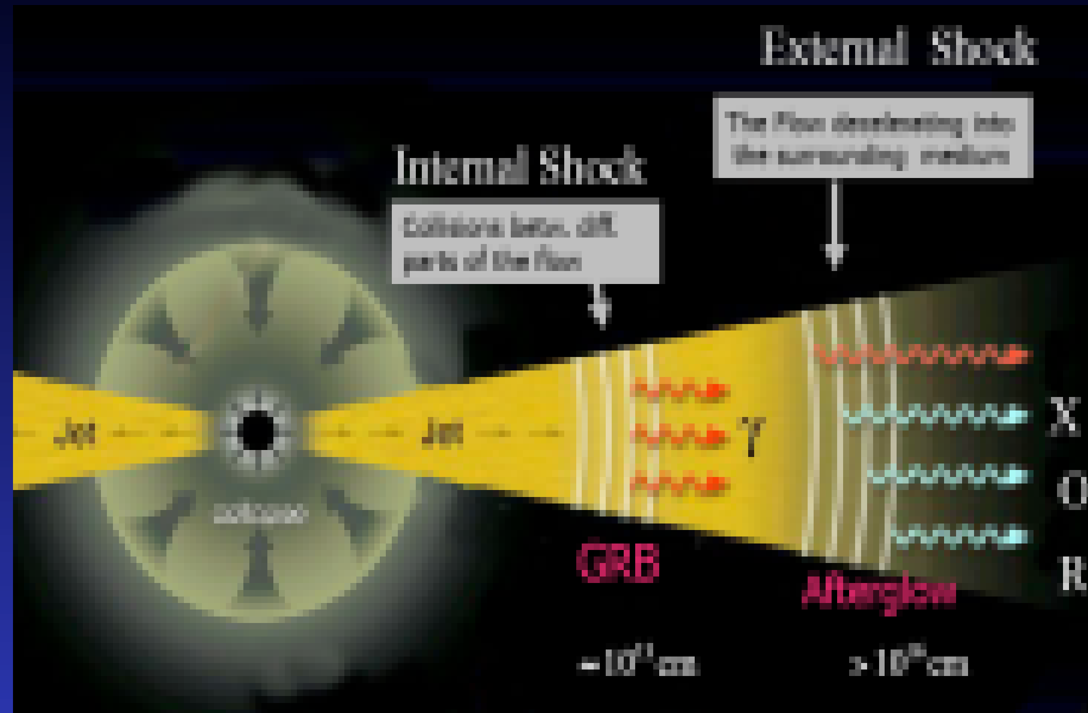


Why GRBs? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays

(D. Pile, Nature Photonics, 2010)

GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Acceleration**:
  fireball or magnetic?
- **Prompt γ-rays**:
  internal shocks?
  emission mechanism?



- **Deceleration**: the outflow decelerates (by a **reverse** shock for $\sigma \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

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:

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

(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. in their arrival times to an observer near the GRB along our L.O.S
- Our limits apply to any source of energy dispersion on the way from the source to us, and may constrain some (even more) exotic physics ($\Delta t_{\mathrm{LIV}} \to \Delta t_{\mathrm{LIV}} + \Delta t_{\mathrm{exotic}}$)

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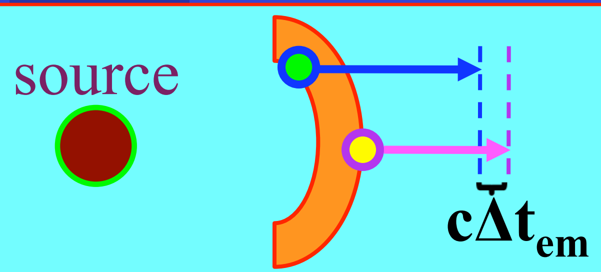


$$\Delta t_{obs} = \Delta t_{em} + \Delta t_{\mathrm{LIV}}$$

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: $t_{em} > t_{start}$
- $\Rightarrow \Delta t_{LIV} = t_h - t_{em} < t_h - t_{start}$
- A conservative assumption: t_{start} = the onset of any observed emission from the GRB

Limits on LIV: GRB080916C ($z \approx 4.35$)

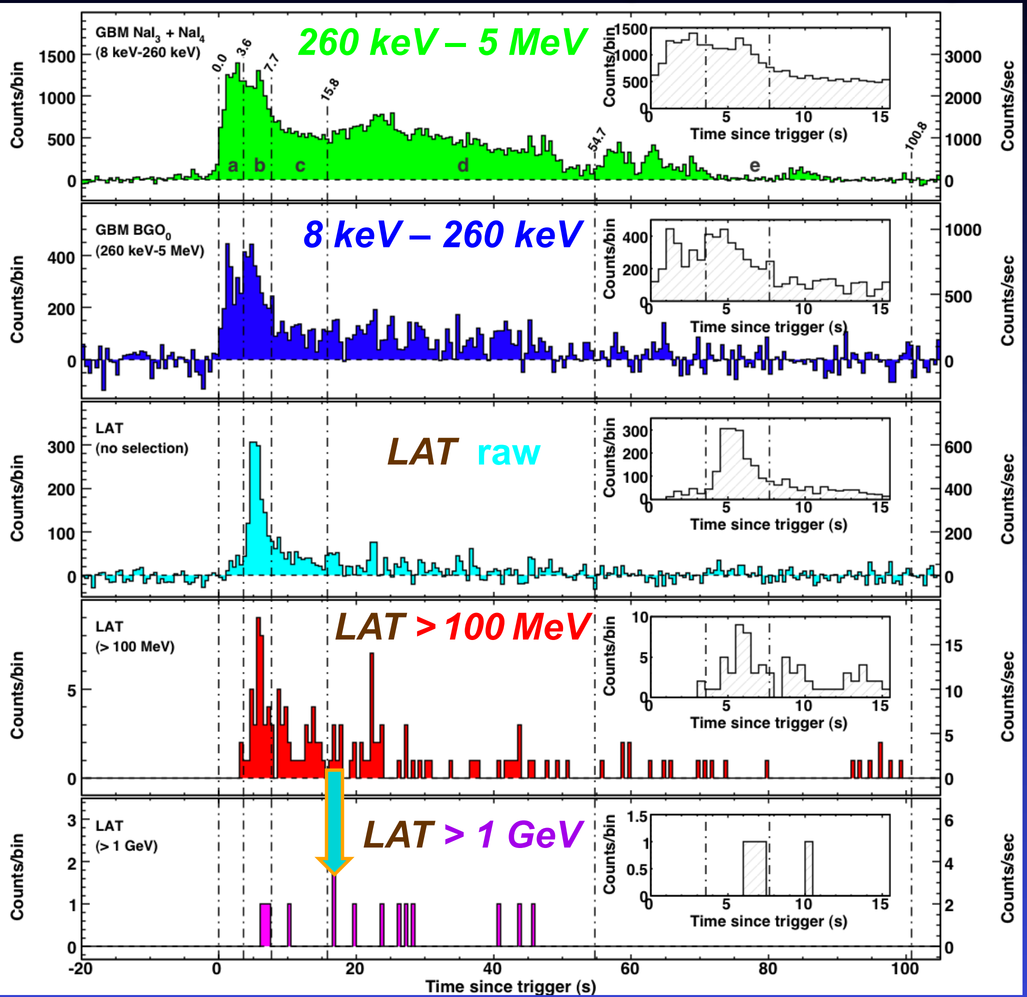
- GRB080916C: highest energy photon (13 GeV) arrived 16.5 s after low-energy photons started arriving (=the GRB trigger)

  $\Rightarrow$ **conservative lower limit:**

  $M_{QG,1} > 1.3\times10^{18}$ GeV/c^2

  $\approx 0.11 M_{Planck}$

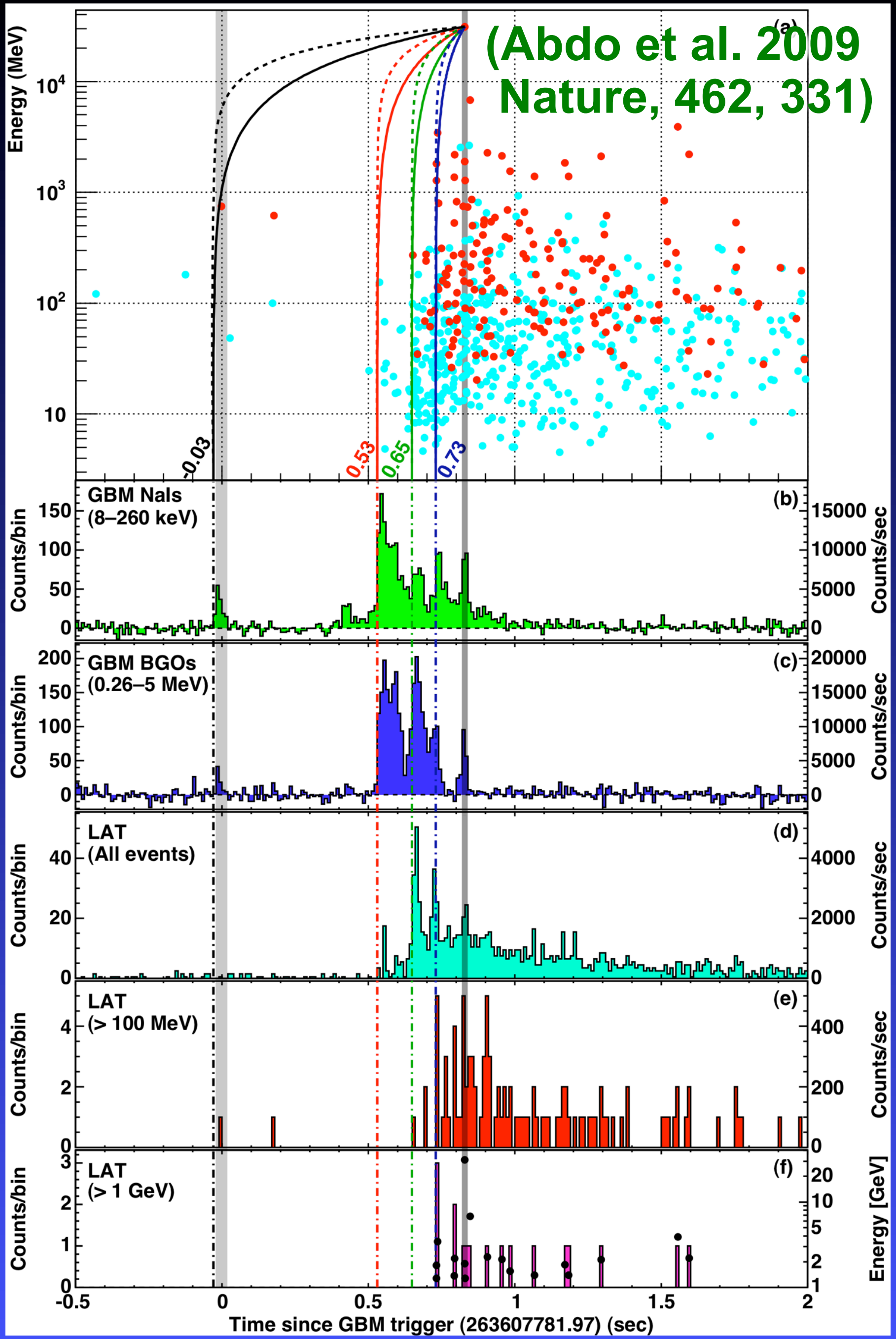
- This improved upon the previous limits of this type, reaching 10% of M_{Planck}



(Abdo et al. 2009, Science, 323, 1688)

GRB090510: L.I.V

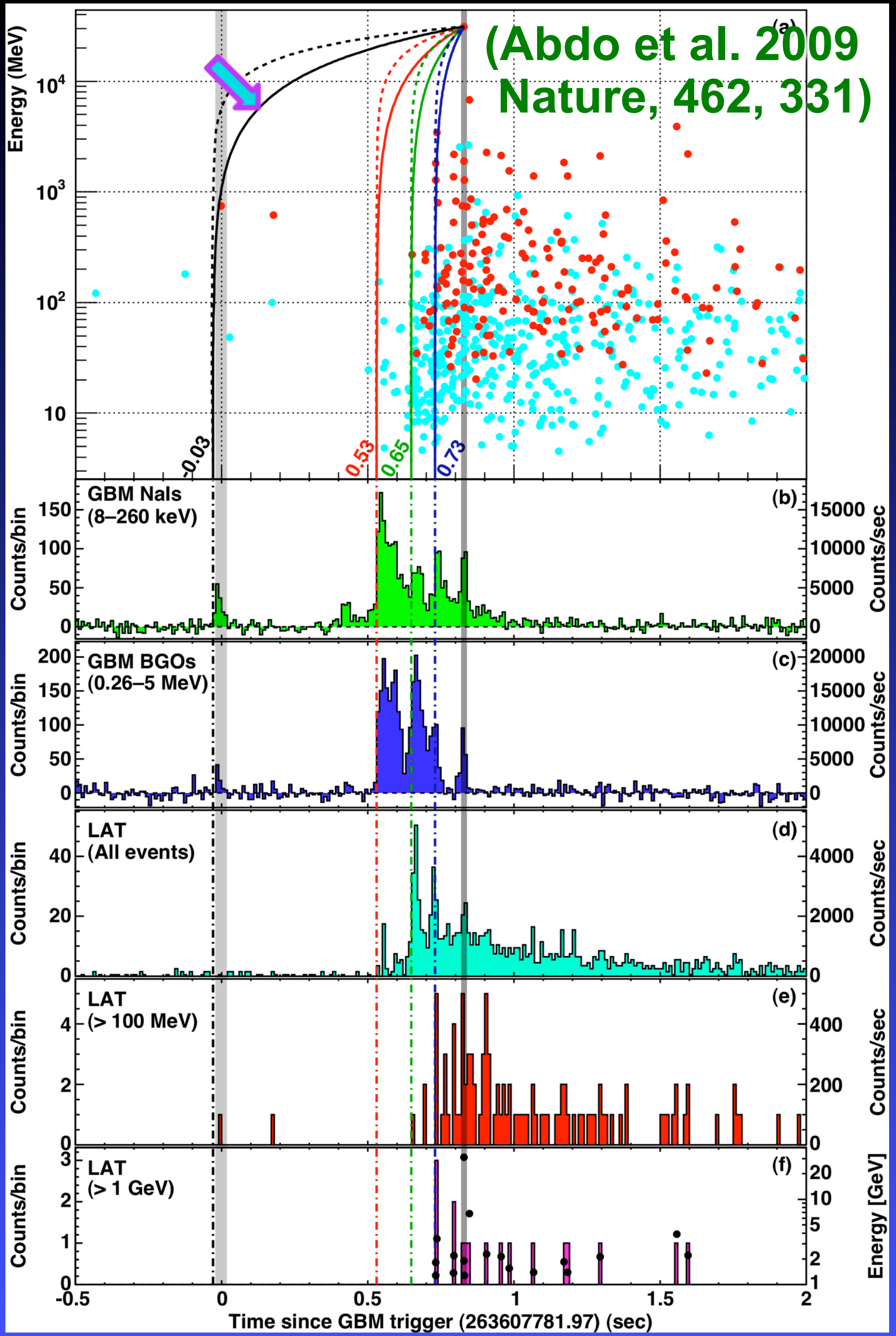
- A short GRB (duration ~1 s)
- Redshift: $z = 0.903 \pm 0.003$
- A ~31 GeV photon arrived at $t_h = 0.829$ s after the trigger
- We carefully verified it is a photon; from the GRB at >5σ
- We use the 1-σ lower bounds on the measured values of E_h (28 GeV) and z (0.900)
- Intrinsic spectral lags known on timescale of individual pulses: weak effect expected



GRB090510: L.I.V

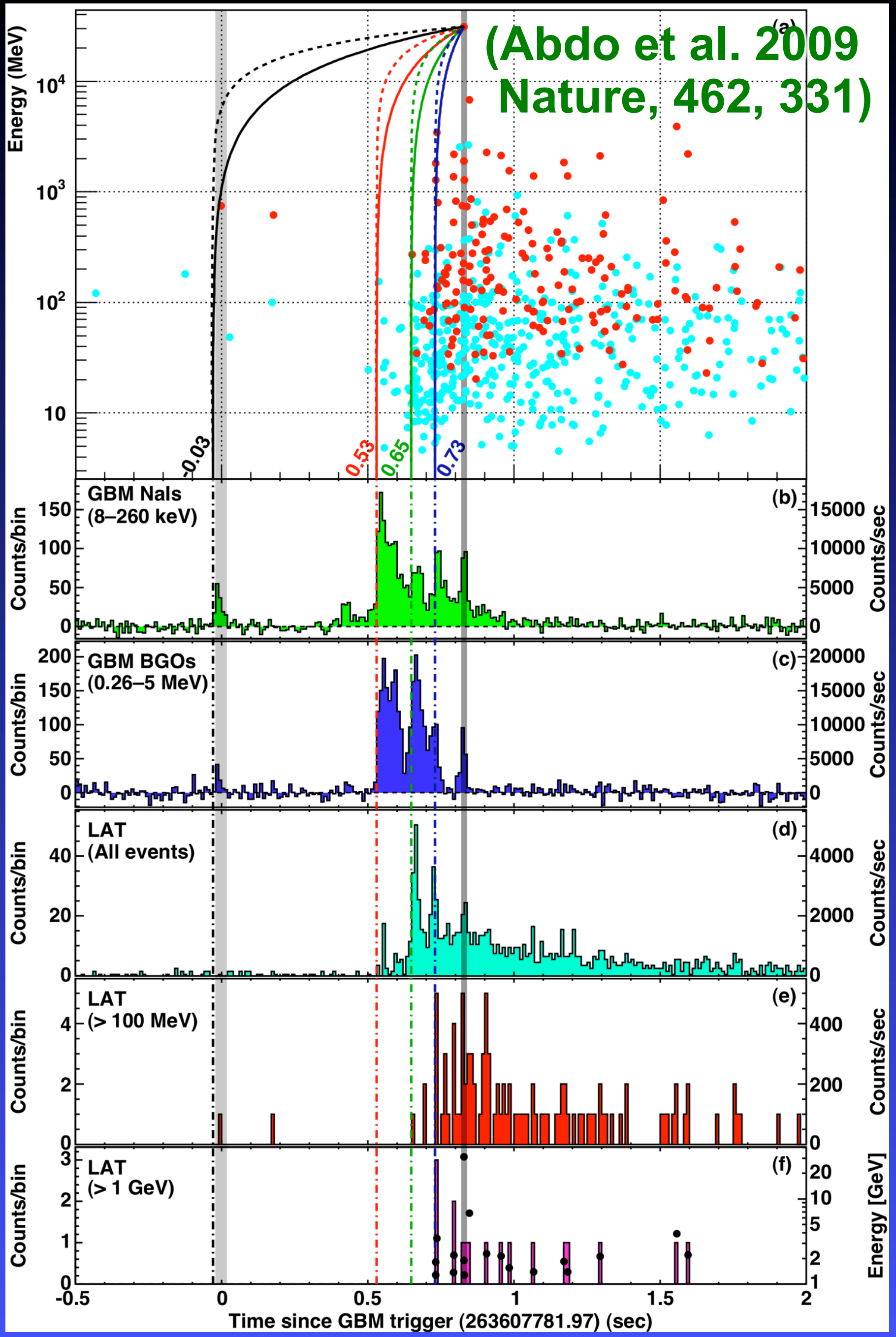
- Method 1: different choices of t_{start} from the most conservative to the least conservative
- $t_{start} = -0.03$ s precursor onset $\Rightarrow$ $\xi_1 = M_{QG,1}/M_{Planck} > 1.19$
- $t_{start} = 0.53$ s onset of main emission episode $\Rightarrow \xi_1 > 3.42$
- For any reasonable emission spectrum 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

  $\Rightarrow \xi_1 > 5.12$, $\xi_1 > 10.0$



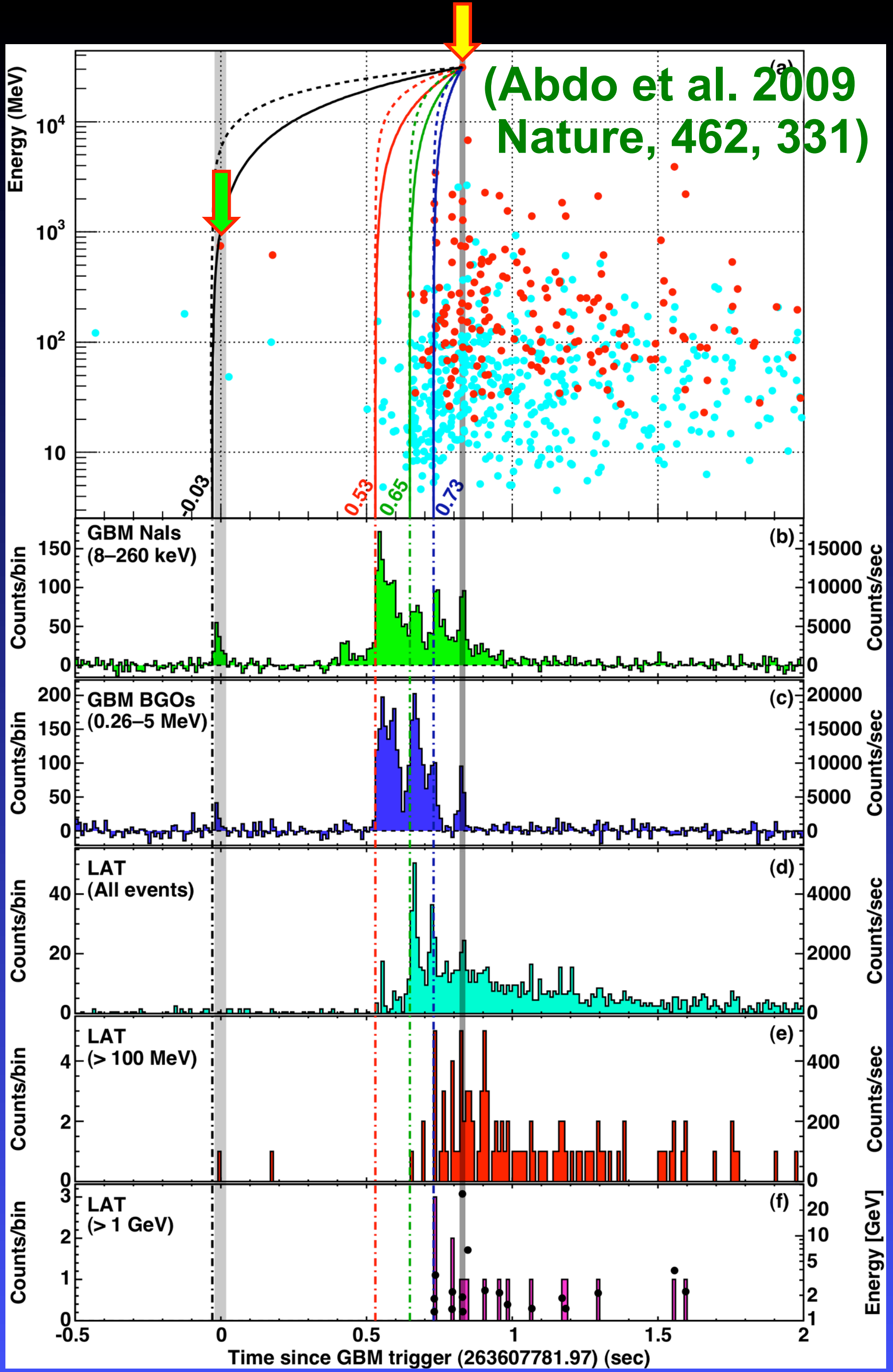
GRB090510: L.I.V

- New claim: Swift detected some low level emission ~13 s before the GRB090510 trigger
- Still to be verified (never seen before in any short GRB)
- Even if this detection is real:
  - Highly unlikely that no other LAT photons were emitted together with the ~31 GeV photon (none were observed)
  - Fine tuning is required for the ~31 GeV photon to arrive on top of brightest emission episode (+on a narrow spike)



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 the 31 GeV photon (*shaded vertical region*) $\Rightarrow |\Delta t| < 10$ ms and $\xi_1 = M_{QG,1}/M_{Planck} > 102$
- For a 0.75 GeV photon during precursor: $|\Delta t| < 19$ ms, $\xi_1 > 1.33$



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) $\Rightarrow$ $M_{QG,1} > 1.22 M_{Planck}$
- Remains unchanged when using only photons < 1 or 3 GeV (a very robust limit)

GRB090510

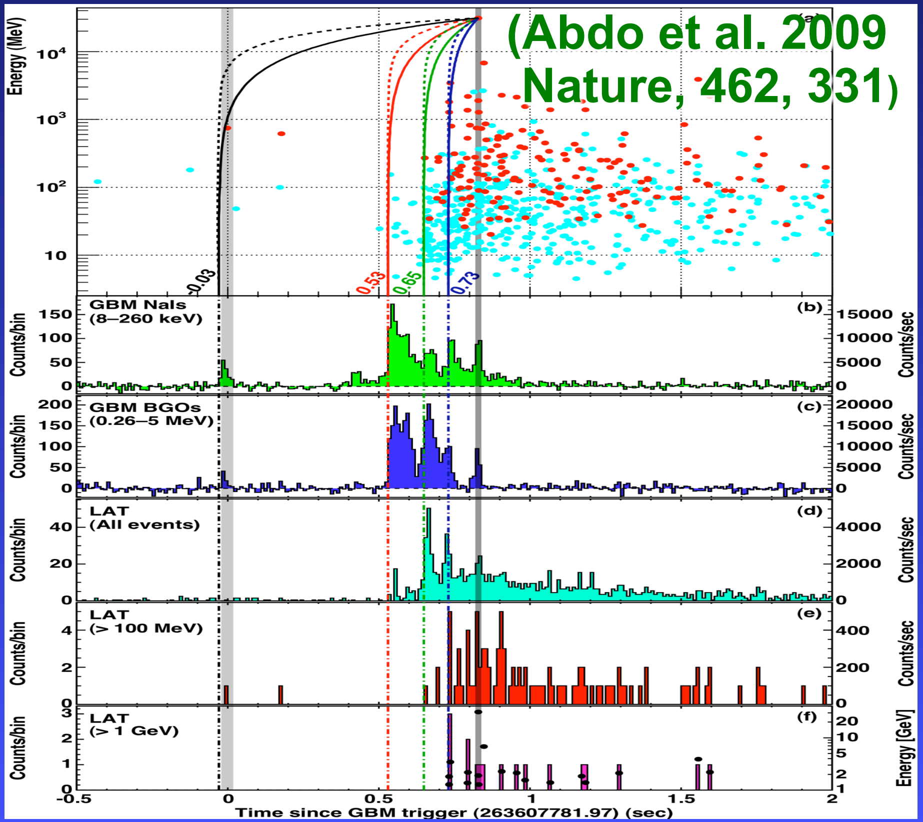
limits on LIV

Summary:

	t_{start} (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of t_{start} or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{QG,1}/M_{Planck}$	limit on $M_{QG,2}$ in 10^{10} GeV/c^2
a	-30	< 859	start of any observed emission	0.1	1	> 1.19	> 2.99
b	530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42	> 5.06
c	630	< 199	start of > 100 MeV emission	100	1	> 5.12	> 6.20
d	730	< 99	start of > 1 GeV emission	1000	1	> 10.0	> 8.79
e	—	< 10	association with < 1 MeV spike	0.1	± 1	> 102	> 27.7
f	—	< 19	if 0.75 GeV γ is from 1st spike	0.1	-1	> 1.33	> 0.54
g	$\lvert\Delta t/\Delta E\rvert < 30$ ms/GeV		lag analysis of all LAT events	—	± 1	> 1.22	—

Our results disfavor QG models with linear LIV (n = 1)

- a-e based on 31 GeV γ-ray
- a-d method 1: $t_{em} \geq t_{strat}$
- e,f: method 2: association with a low-energy spike
- g: method 3: DisCan sharpness of HE spikes
- All of our lower limits on $M_{QG,1}$ are above M_{Planck}



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

Limits on LIV from Fermi GRBs

GRB	duration or class	# of events > 0.1 GeV	# of events > 1 GeV	method	Lower Limit on $M_{QG,1}/M_{Planck}$	Valid for S_n =	Highest photon Energy	redshift
080916C	long	145	14	1	0.11	+1	~ 13 GeV	~ 4.35
090510	short	> 150	> 20	1	1.2, 3.4, 5.1, 10	+1	~ 31 GeV	0.903
				2	102	±1		
				3	1.2	±1		
090902B	long	> 200	> 30	1	0.068	+1	~ 33 GeV	1.822
090926	long	> 150	> 50	1 , 3	0.066, 0.082	+1	~ 20 GeV	2.1062

- Method 1: assuming a high-energy photon is not emitted before the onset of the relevant low-energy emission episode
- Method 2: associating a high-energy photon with a spike in the low-energy light-curve that it coincides with
- Method 3: DisCan (dispersion cancelation; very robust) – lack of smearing of narrow spikes in high-energy light-curve

Conclusions:

- GRBs are very useful for constraining LIV
- Bright **short** GRBs are more useful than long ones
- A very robust and conservative limit on a linear energy dispersion of either sign: $\mathbf{M_{QG,1} > 1.22 M_{Planck}}$
- Still conservative but somewhat less robust limits: $M_{QG,1}/M_{Planck} > 5.1,\ 10$ (onset of emission >0.1, 1 GeV)
- "Intuition builder": $M_{QG,1} / M_{planck} > 102$
- Quantum-Gravity Models with linear energy dispersion ($n = 1$) are disfavored