Searches for Quantum Gravity Signals using Gamma-Ray Bursts

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on behalf of the Fermi LAT & GBM Collaborations

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Outline of the Talk:

- Focus on vacuum energy dispersion (a form of LIV)
- Why do we use GRBs & how do we set the 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
- Future prospects: the Cherenkov Telescope Array
- **Conclusions**

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 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:

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

- $s_k = -1, 0, 1$ stresses the model dependent sign of the effect
- The most natural scale for LIV is the **Planck scale**
  $l_{\mathrm{Planck}} \approx 1.62 \times 10^{-33}$ cm ; $E_{\mathrm{Planck}} = M_{\mathrm{Planck}} c^2 \approx 1.22 \times 10^{19}$ GeV

Vacuum energy dispersion: parameterization

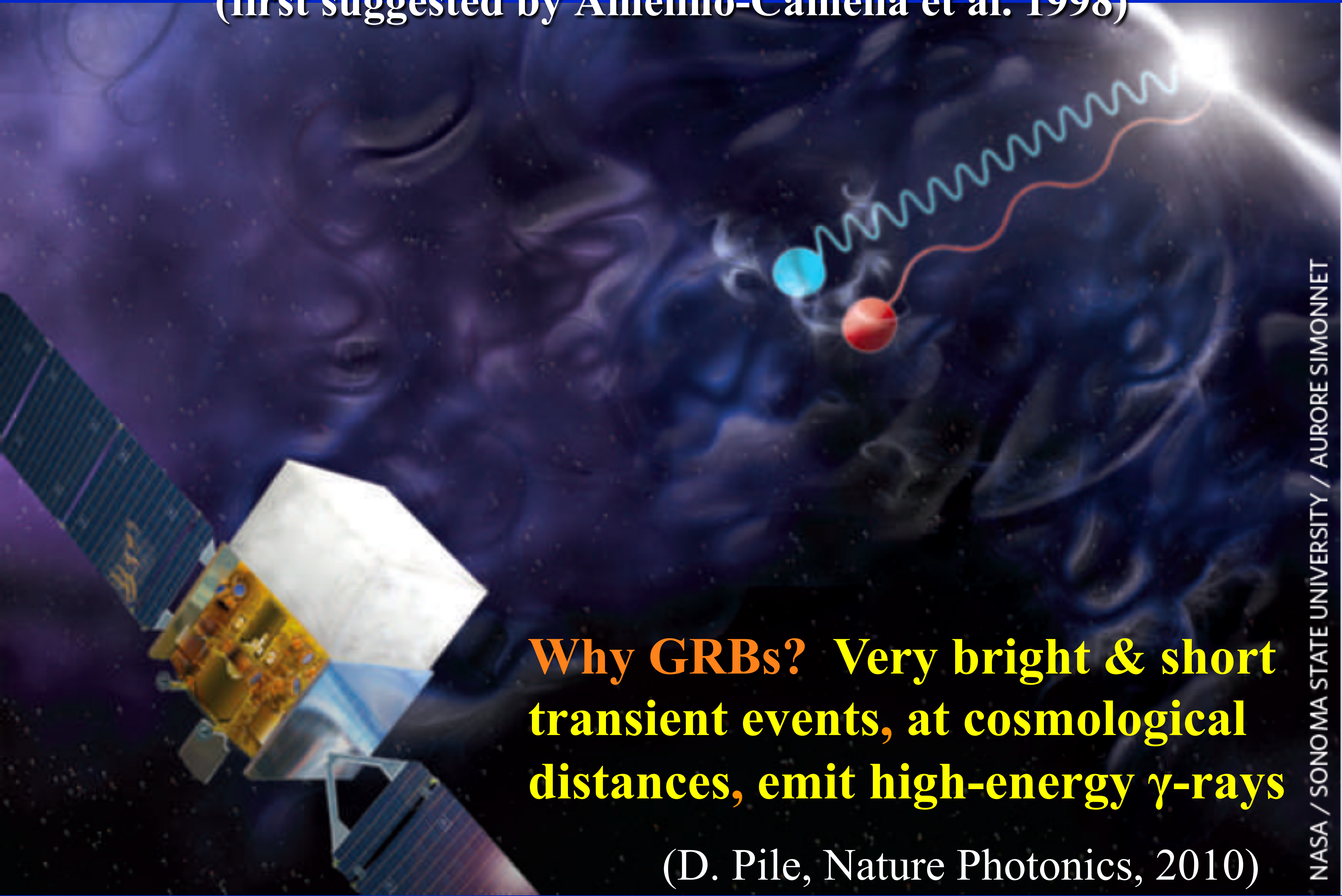
- The photon propagation speed is given by the group velocity:

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

- Since $E_{\mathrm{ph}} \ll E_{\mathrm{QG,k}} \lesssim E_{\mathrm{planck}} \sim 10^{19}$ 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
- 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:
    - $s_n = 1$, $v_{\mathrm{ph}} < c$: higher energy photons propagate slower
    - $s_n = -1$, $v_{\mathrm{ph}} > c$: higher energy photons propagate faster
- We stress: here $c = v_{\mathrm{ph}}(E_{\mathrm{ph}} \rightarrow 0)$ is the low energy limit of v_{ph}

Probing Vacuum dispersion Using GRBs

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



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

(D. Pile, Nature Photonics, 2010)

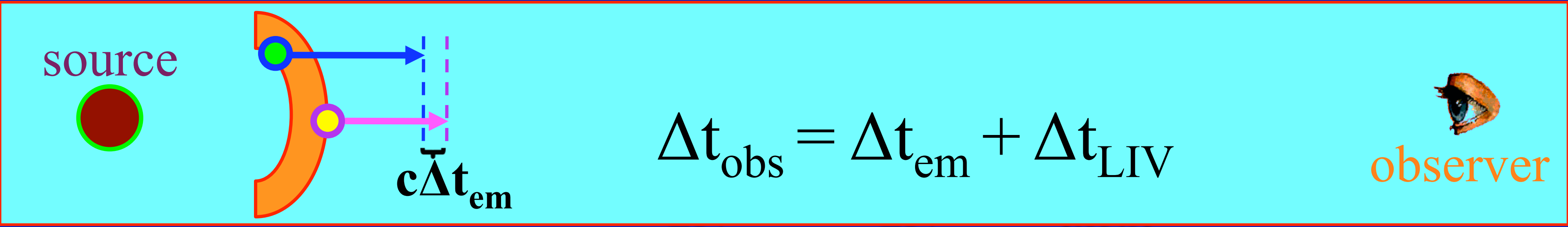
Constraining LIV Using GRBs

- 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:

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

(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. in their arrival times to an observer near the GRB along our L.O.S



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

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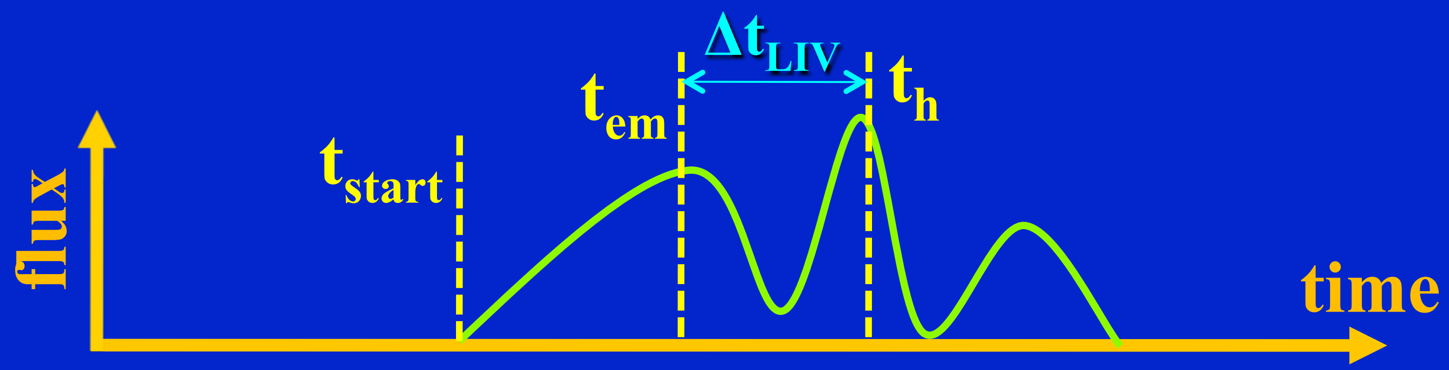
- Our limits apply to any source of energy dispersion on the way from the source to us, and may constrain some (even more) exotic physics ($\Delta t_{\mathrm{LIV}} \rightarrow \Delta t_{\mathrm{LIV}} + \Delta t_{\mathrm{exotic}}$)

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: $t_{em} > t_{start}$



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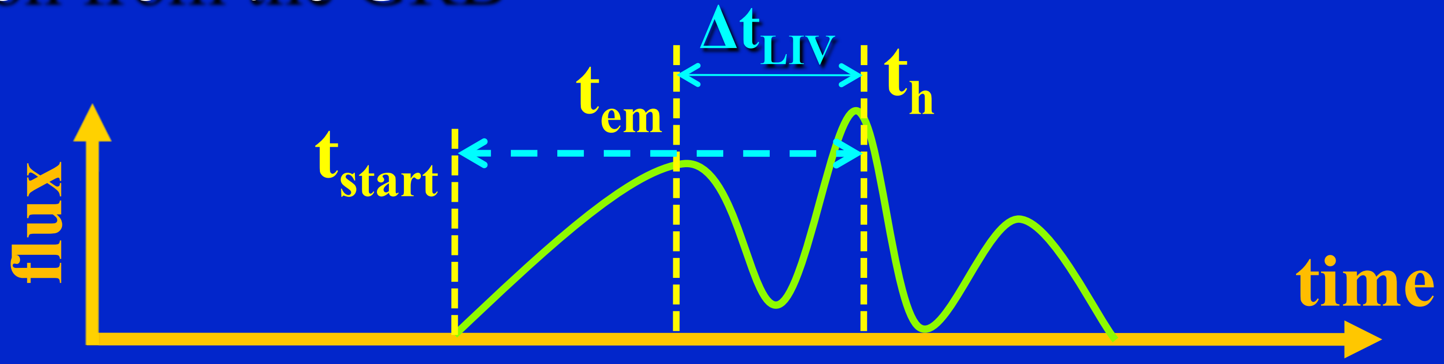
- ➔ $\Delta t_{LIV} = t_h - t_{em} < t_h - t_{start}$
- A conservative assumption: t_{start} = the onset of any observed emission from the GRB



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

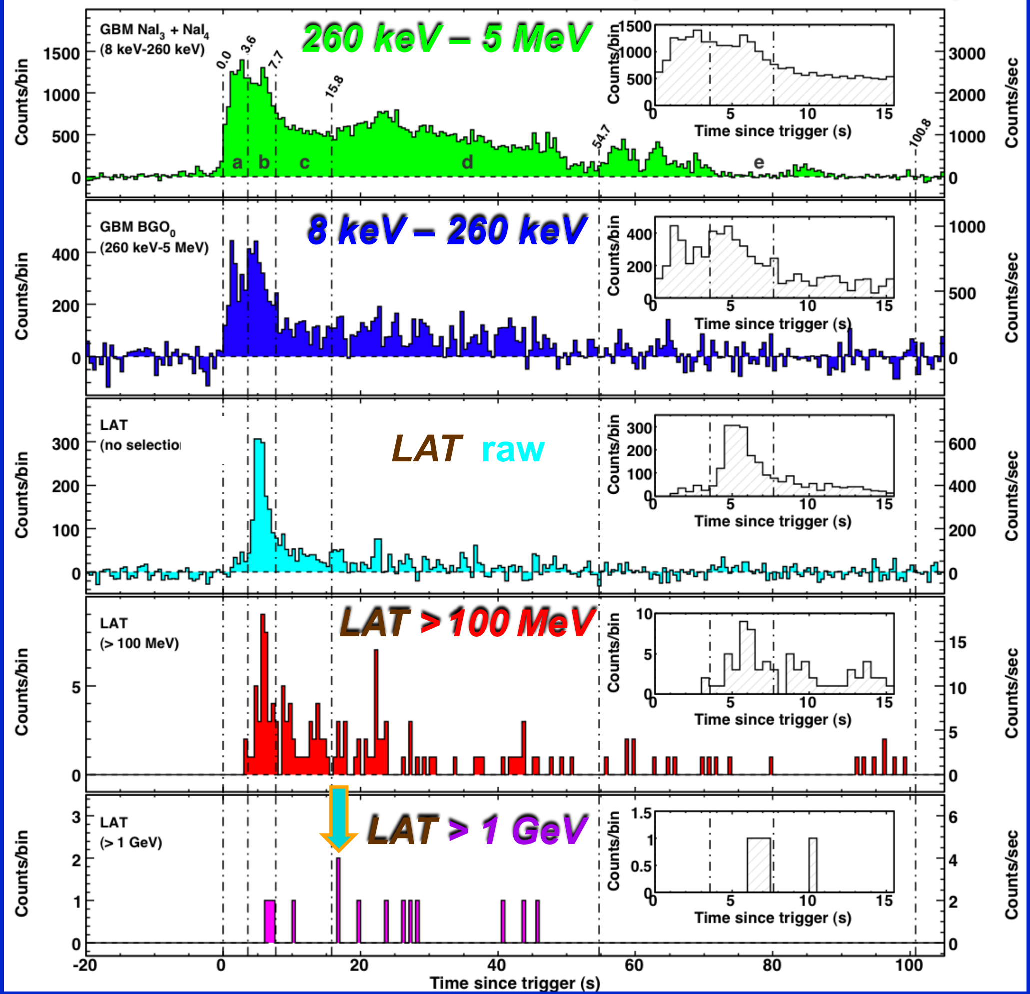
- GRB080916C: highest energy photon (13 GeV) arrived 16.5 s after low-energy photons started arriving (=the GRB trigger)

  ➔ **conservative lower limit:**

  $E_{QG,1} > 1.3\times10^{18}$ **GeV**

  $\approx 0.11 E_{Planck}$

- This improved upon the previous limits of this type, reaching 11% of E_{Planck}



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

Pulsar (Kaaret 99)

GRB (Ellis 06)

AGN (Biller 98)

GRB (Boggs 04)

AGN (Albert 08)

GRB080916C

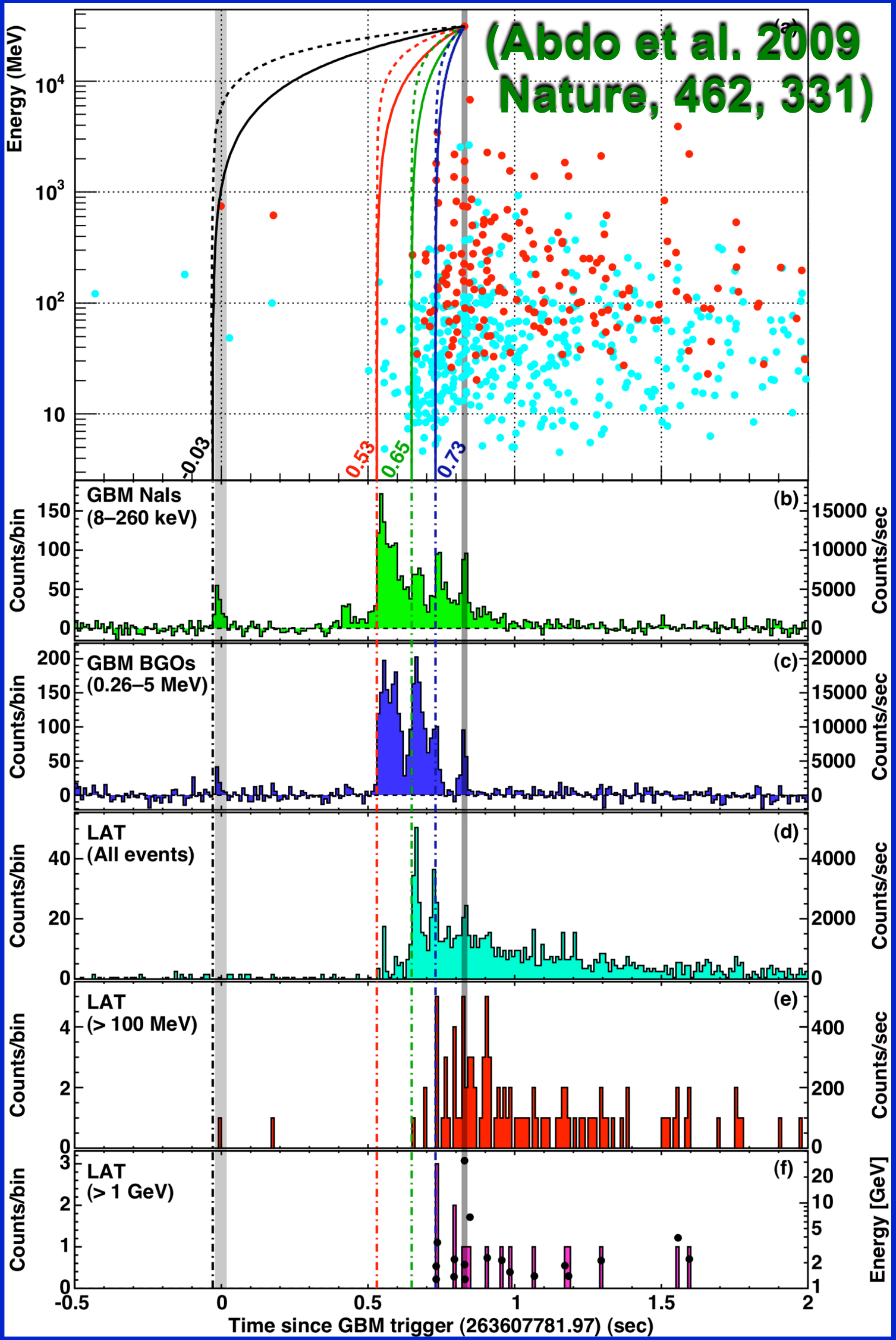
Planck mass

min $E_{QG,1}$ (GeV)

10^{15} — 1.8×10^{15} — 0.9×10^{16} — 10^{16} — 4×10^{16} — 10^{17} — 1.8×10^{17} — 0.2×10^{18} — 10^{18} — 1.3×10^{18} — 10^{19} — 1.2×10^{19}

GRB090510: L.I.V

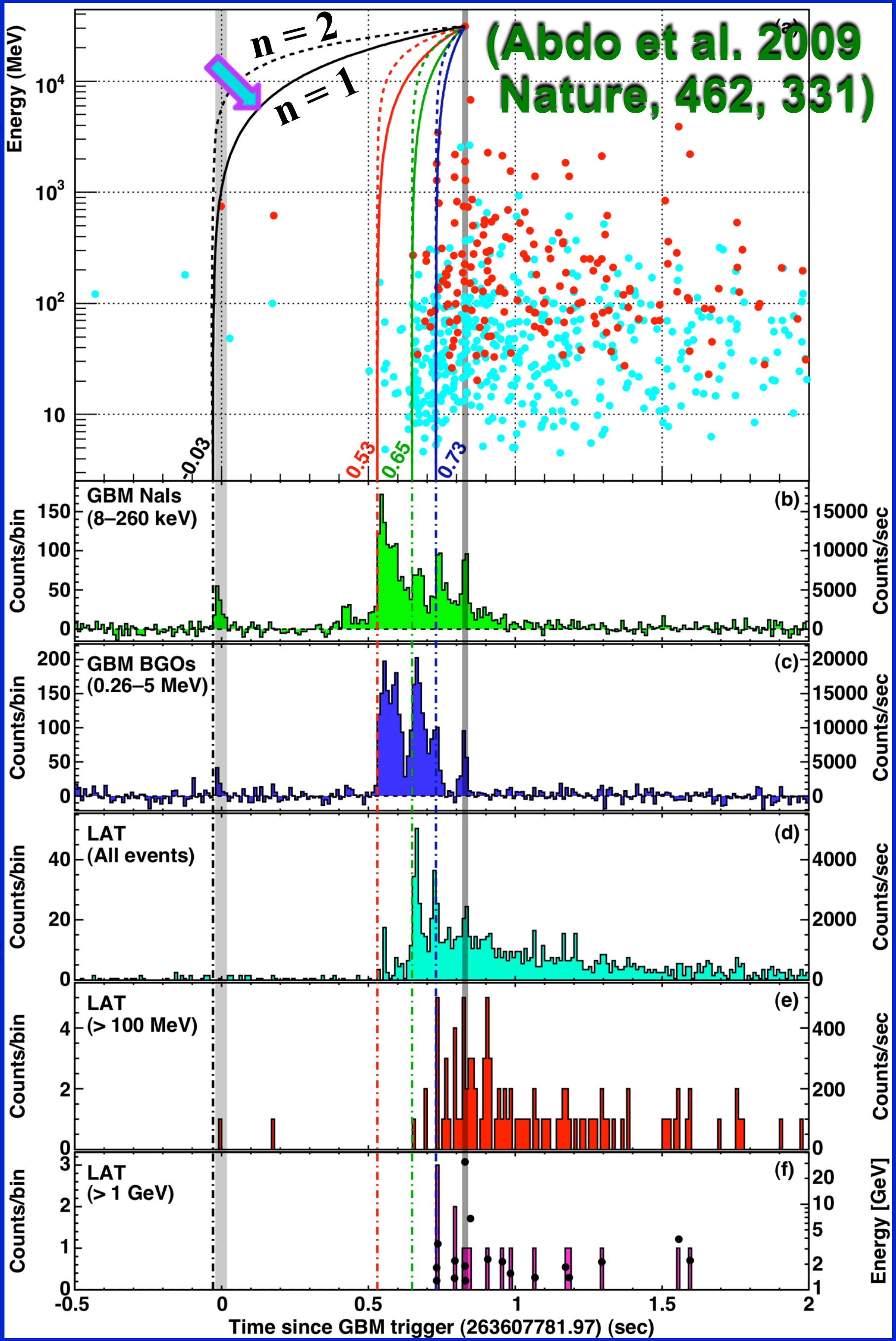
- A short GRB (duration ~1 s)
- Redshift: $z = 0.903 \pm 0.003$
- A ~31 GeV photon arrived at $t_h = 0.829$ s after the trigger
- We carefully verified it is a photon; from the GRB at $>5\sigma$
- We use the 1-σ lower bounds on the measured values of E_h (28 GeV) and z (0.900)
- Intrinsic spectral lags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



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

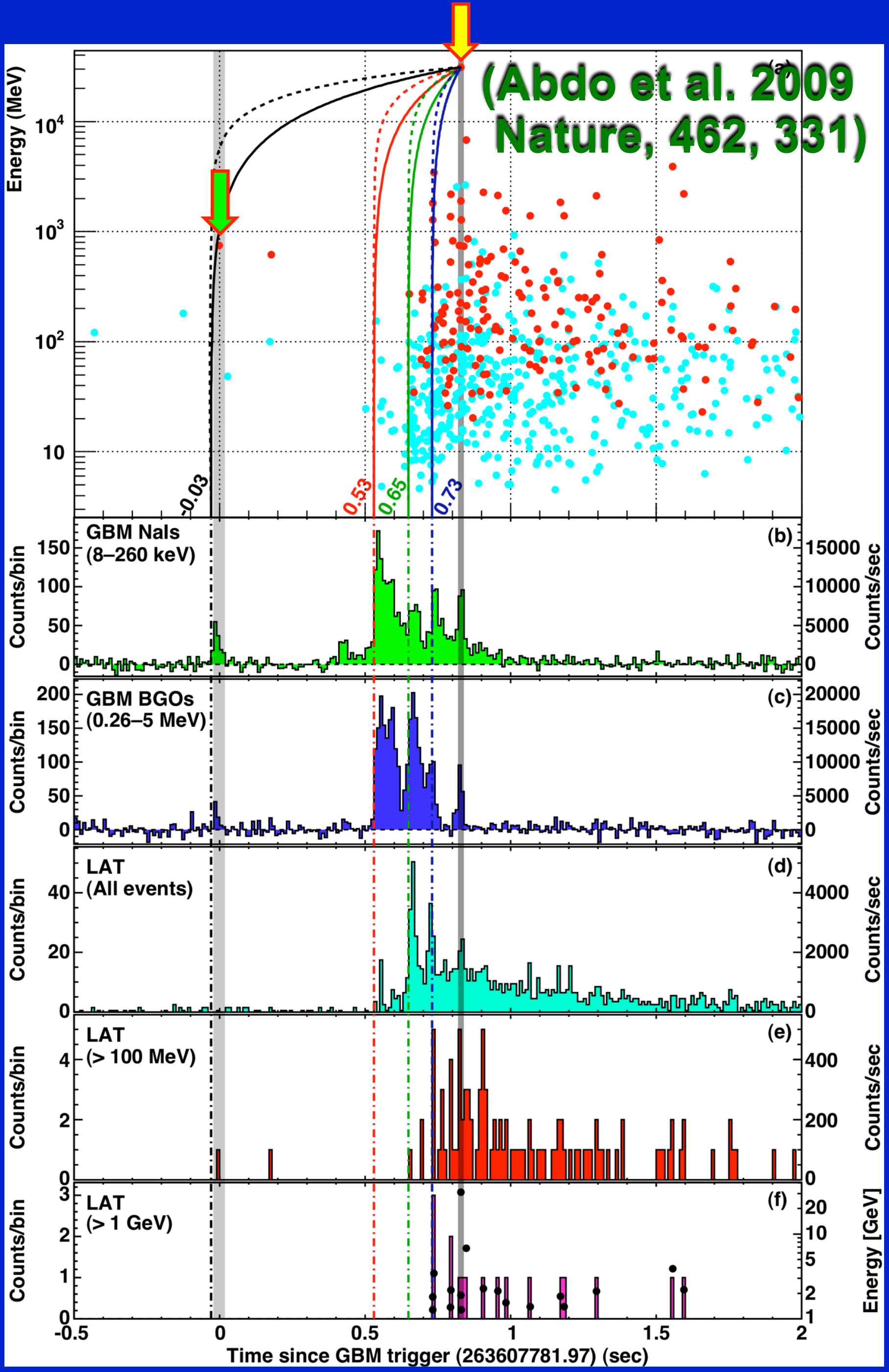
GRB090510: L.I.V

- 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 ➔ $\xi_1 > 5.12$, $\xi_1 > 10.0$


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

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)

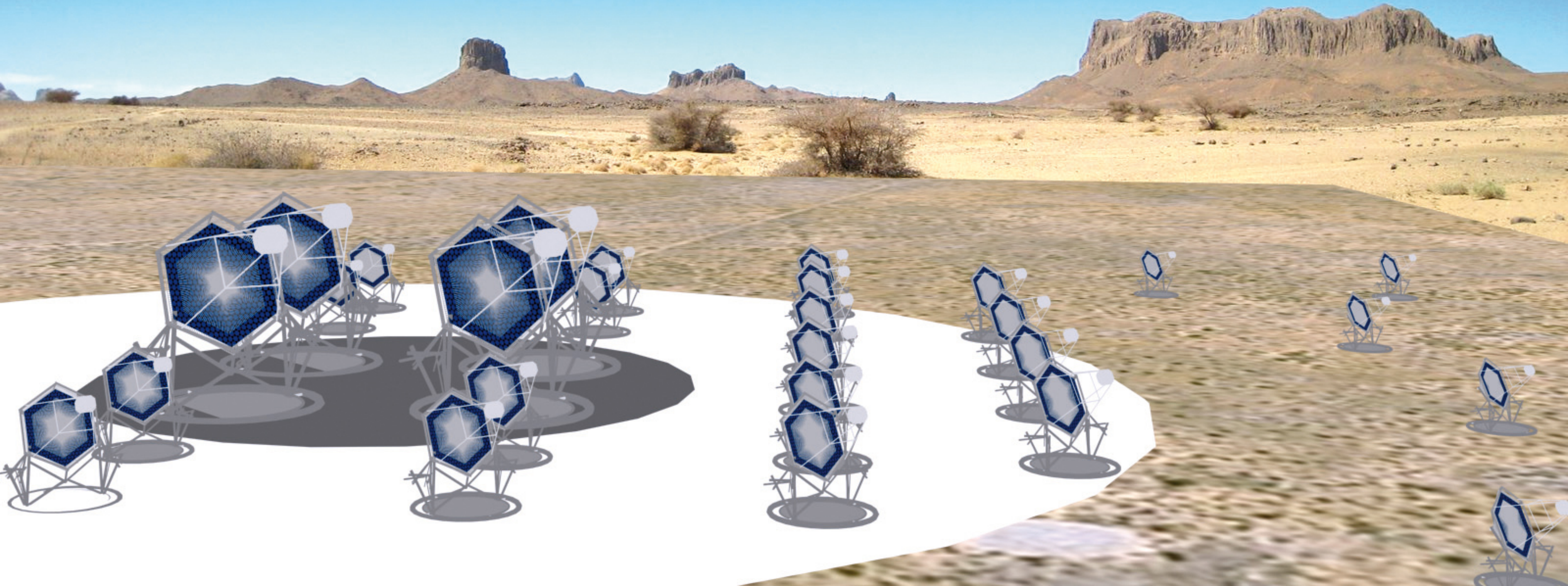
Limits on LIV from Fermi GRBs

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

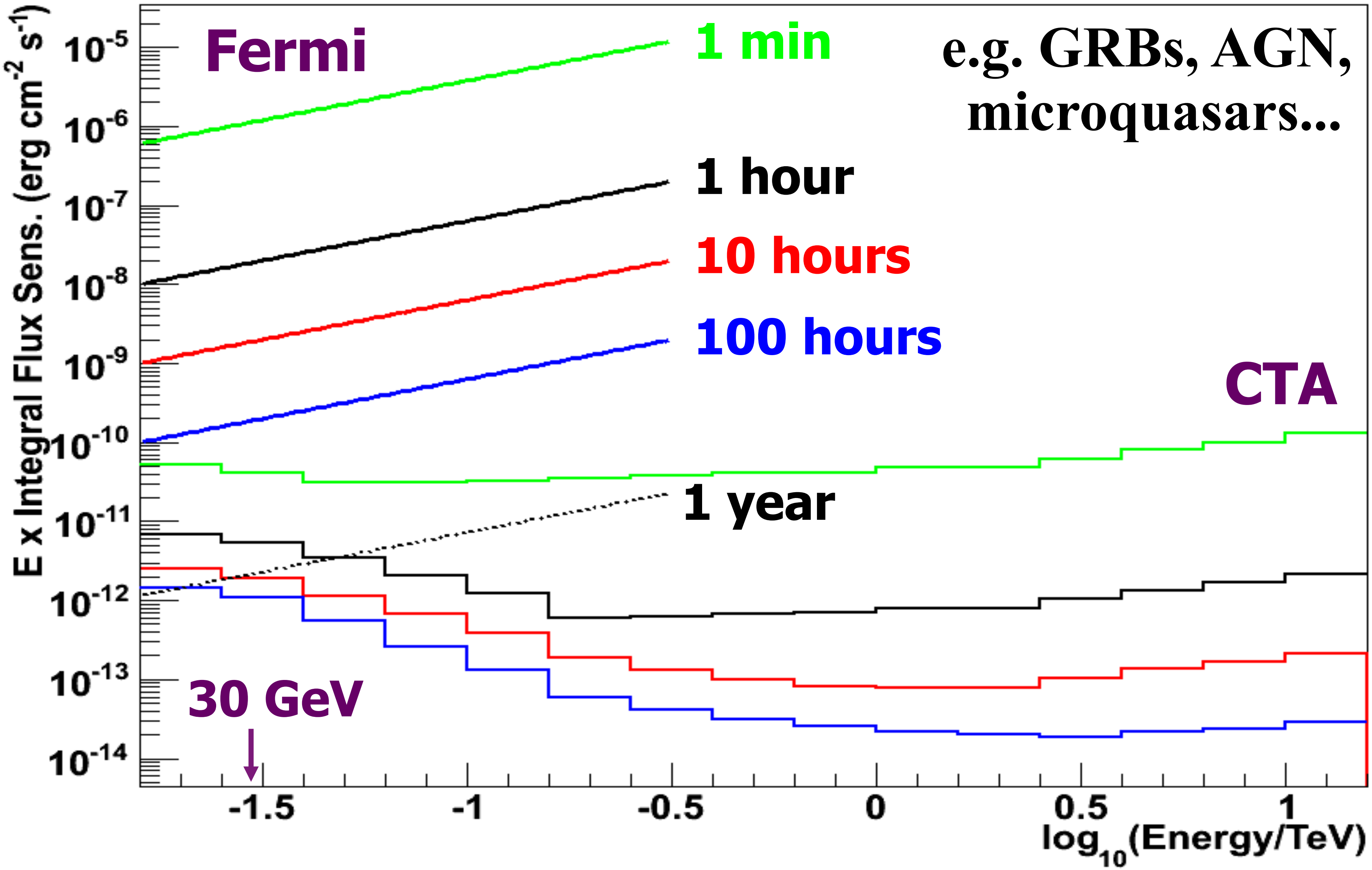
- Method 1: assuming a high-energy photon is not emitted before the onset of the relevant low-energy emission episode
- Method 2: associating a high-energy photon with a spike in the low-energy light-curve that it coincides with
- Method 3: DisCan (dispersion cancelation; very robust) – lack of smearing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

Future: Cherenkov Telescope Array (CTA)

- **Energy range: ~20 GeV to ~300 TeV**
  - an **order of magnitude more sensitive** than current instruments around 1 TeV (~150M€ price tag), better angular/energy resolution
  - >1000 members in 27 countries
  - Should become operational around ~2018
- **2 sites (southern + northern hemispheres)**
- **Hundreds of telescopes of 3 different sizes**



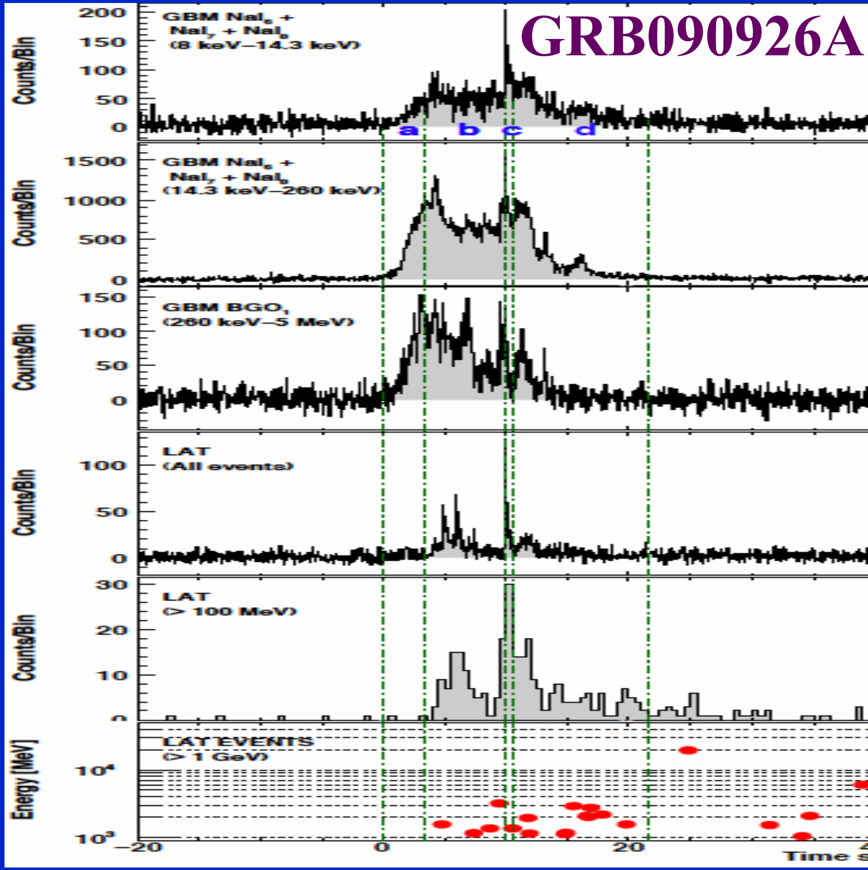
A bigger difference for transient sources



Prospects for LIV studies with CTA GRBs

- Method 1: it may be difficult to do much better
  - Our current limit $|\Delta t/\Delta E| < 30$ ms/GeV would require $E_h > 1$ TeV for a **response time** of 30 s
  - at > 1 TeV intrinsically fewer photons + EBL
- Method 3: might work best
  - Sharp bright spikes up to high energies exist also well within long GRBs
  - $t_{var} \sim 0.1$ s & $E_h \sim 0.1$ TeV could do ~30 times better
- A short GRB in CTA FoV (survey mode) would be great

10 ms, 1 TeV: $>10^3$ times better



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: $\mathbf{E_{QG,1} > 1.2E_{Planck}}$
- Still conservative but somewhat less robust limits: $E_{QG,1}/E_{Planck} > 5.1$, 10 (onset of emission >0.1, 1 GeV)
- "Intuition builder" liberal limit: $E_{QG,1} / E_{planck} > 102$
- Quantum-Gravity Models with linear ($n = 1$) photon energy dispersion are disfavored