Title: Astrophysical Searches for Quantum Gravity Signals

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Abstract: Some recent searches for quantum gravity signatures using observations of distant astrophysical sources will be discussed, focusing on the search for Lorentz invariance violation (LIV) in the form of a dependence of the photon propagation speed on its energy. Fermi gamma-ray space telescope observations of ~8 keV to ~30 GeV photons from a short (< 1 s) gamma-ray burst (GRB 090510) at a cosmological distance (z = 0.903), enabled for the first time to put a direct time of flight limit on a possible linear variation of the speed of light with photon energy that is beyond the Planck scale. Parameterizing

|v/c-1| = E/E_{QG} our most conservative limits are
E_{QG}/E_{Planck}

> 1.2, while less conservative limits are up to 1-2
orders of

magnitude stricter. Other types of astrophysical searches
for LIV will be briefly outlined, along with some prospects for the future.

Astrophysical Searches for Quantum Gravity Signals

Jonathan Granot
Open University of Israel

on behalf of the Fermi LAT & GBM Collaborations

Experimental search for quantum gravity: the hard facts
Perimeter Institute (Colloquium), October 24, 2012

Outline of the Talk:

- Brief motivation & narrowing down the scope
- Vacuum birefringence: helicity dependence of $v_{ph}(E)$
- Vacuum dispersion: energy dependence $v_{ph}(E)$
- Using TeV flares from AGN
- Using GRBs: why, and how we set the limits
- Limit from the bright long GRB 080916C at $z \sim 4.35$
- 3 different types of limits from the short bright GRB 090510 at $z = 0.903$: detailed description & results
- Summary of Fermi GRB limits & future prospects
- **Conclusions**

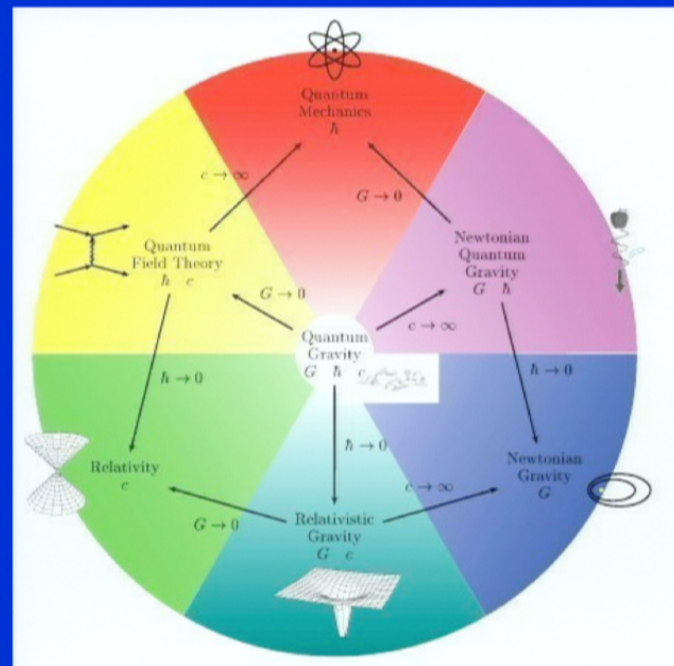
Quantum Gravity: a physics holey grail

- **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:

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

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

- Many models / ideas out there: experimental constraints needed



Astrophysics as a test bed:

- **Advantage**: large energies and distances available for free
- **Disadvantage**: uncontrolled experimental setup / conditions
  - Vacuum birefringence: constrained by polarization
  - Vacuum dispersion: by short timescale variability
  - Pair production threshold: attenuation on the EBL
  - Electron LIV: synchrotron radiation from the Crab nebula
  - Space-time fuzziness: blur sources, broaden spectral lines
  - UHECR / ν LIV: energy spectrum / arrival time from GRBs
  - Massive gravitons: supernovae cooling
  - Cosmic string: gravitational lensing, gravity waves
  - Early universe: CMB polarization, 21 cm HI line surveys…

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Vacuum energy dispersion / birefringence

- Some quantum-gravity (QG) models (e.g. odd n SME) tie between vacuum dispersion & birefringence ⇒ makes life easier as birefringence is easier to constrain observationally
- Some models allow vacuum dispersion without birefringence
- 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:

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

- $s_k = -1\ ,0,\ 1$ = model (helicity) 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 / birefringence

- 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 $E_{ph} \ll M_{QG,k}c^2 \lesssim E_{planck} \sim 10^{19}$ 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
- 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:
  - $s_n = 1$, $v_{ph} < c$: higher energy photons propagate slower
  - $s_n = -1$, $v_{ph} > c$: higher energy photons propagate faster
- We stress: here $c = v_{ph}(E_{ph} \to 0)$ is the low energy limit of v_{ph}

Vacuum Birefringence: Polarization

- Helicity (left or right circular polarization) dependence of the photon propagation speed: $c - v_{ph,L}(E) \approx v_{ph,R}(E) - c$
- Rotates the position angle θ of linearly polarized radiation:
  $\Delta\varphi_{R,L} = 2\Delta\theta = \omega\Delta t_{R,L} \approx \omega\Delta v_{R,L} D/c^2 \approx E^{n+1}D(1+n)/\hbar c(E_{QG*,n})^n$
- $\Delta E/E \gtrsim 0.2\text{-}1 \Rightarrow \Delta\theta(E_2) \sim 2\Delta\theta(E_1)$
  $\Delta\theta(E_1) \gtrsim 1 \Rightarrow$ depolarization

- $\Rightarrow$ linear pol. constrains $E_{QG*,n} = \xi_{1*}E_{planck}$:

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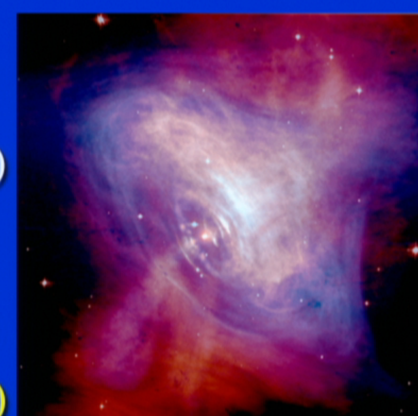
◆ Galaxy at $D \sim 0.3$ Gpc, optical: 

$P \sim 10\% \Rightarrow \xi_{1*} > 5\times10^3$ (Gleizer & Nozameh 01)

◆ Crab nebula (Galactic SNR; $D \approx 2$ kpc)

X/γ-rays: $P \sim 46\%$ (INTEGRAL 150-300 keV)

$\Rightarrow \xi_{1*} > 1.1\times10^9$ (99% CL; Maccione et al. 2008)



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- $\Rightarrow$ linear pol. constrains $E_{QG*,n} = \xi_{1*} E_{planck}$:

◆ Gamma-Ray Bursts: ($z \sim 1$; $D \sim$ several Gpc):

- ◆ Optical: $P \sim 10\% \Rightarrow \xi_{1*} > 5\times10^6$ (Fan et al. 2007)
- ◆ X/γ-ray: $P \sim 50\text{-}80\%$ (IKAROS/GAP; 70-300 keV)

  $\Rightarrow \xi_{1*} > 10^{15}$

  (Toma et al. 2012)

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- ◆ Optical: $P \sim 10\% \Rightarrow \xi_{1*} > 5\times10^6$ (Fan et al
- ◆ X/γ-ray: $P \sim 5$[illegible]-8[illegible]% (IKAROS/GAP; 70-300

  $\Rightarrow \xi_{1*} > 1$[illegible] **Unreliable**

  (Toma et al. 2012)

Vacuum dispersion: time variability

- Relevant models without leading order vacuum birefringence
- Good candidate sources: **TeV flares** from AGN

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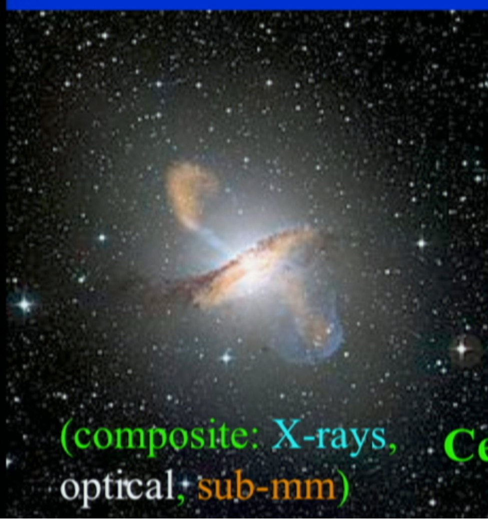
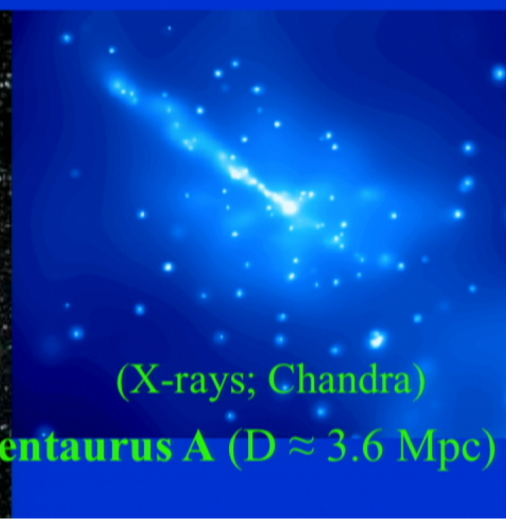
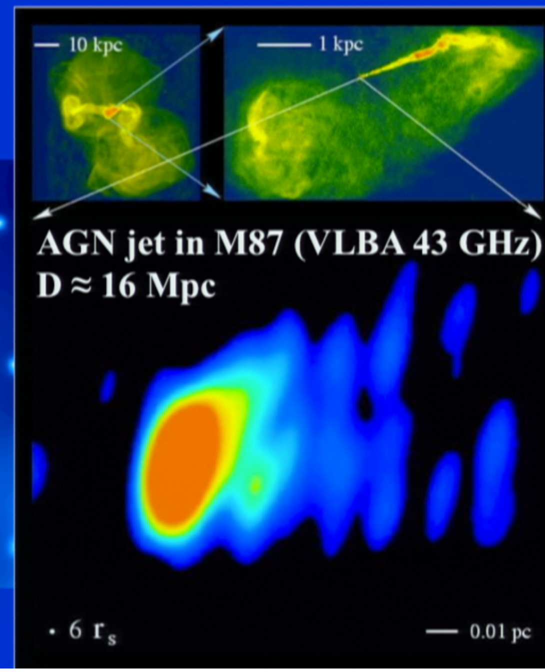
- Relevant models without leading order vacuum birefringence
- Good candidate sources: **TeV flares** from AGN
- **AGN**: accreting super-massive black holes galaxy centers
  - Mass: $M_{BH} \sim 10^6 - 10^9\, M_\odot$ Jet Lorentz factor: $\Gamma \sim 5 - 30$
- Active for millions of years
- Sometimes emit short bight flares





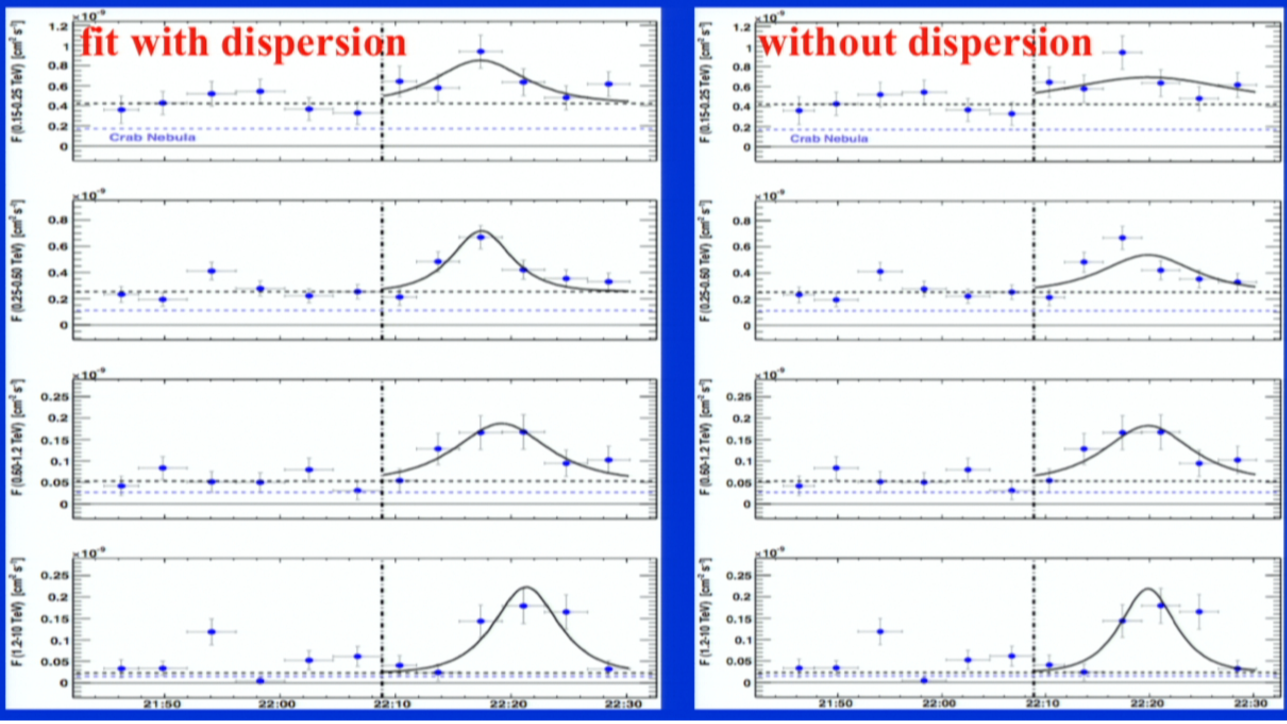
Centaurus A (D ≈ 3.6 Mpc)



Vacuum dispersion: time variability

- **MAGIC** (07,08): Mkn 501, $D \approx 140$ Mpc; 0.17-10 TeV; $t_{var} \sim 120$ s
  $\Delta t_{LIV} \approx t\Delta v_{LIV}/c \approx \frac{1}{2}(1+n)\,[\Delta E^n/(E_{QG,n})^n]\,D/c$
  claimed a possible detection: $\xi_1 \sim 0.03$, $E_{QG,2} \sim 6\times10^{10}$ GeV
  or alternatively lower limits: $\xi_1 > 0.02$, $E_{QG,2} > 4\times10^{10}$ GeV

2005
July 9
flare



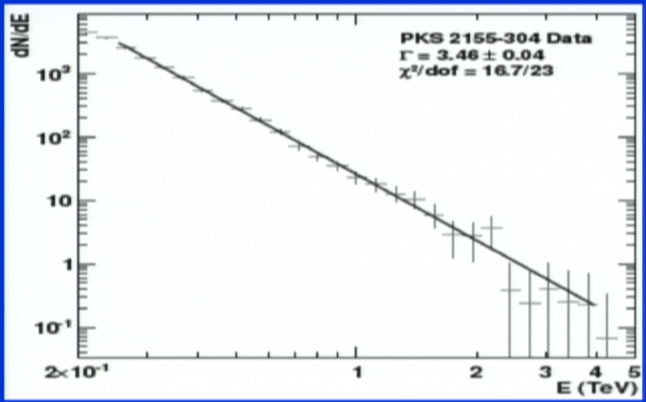
Vacuum dispersion: time variability

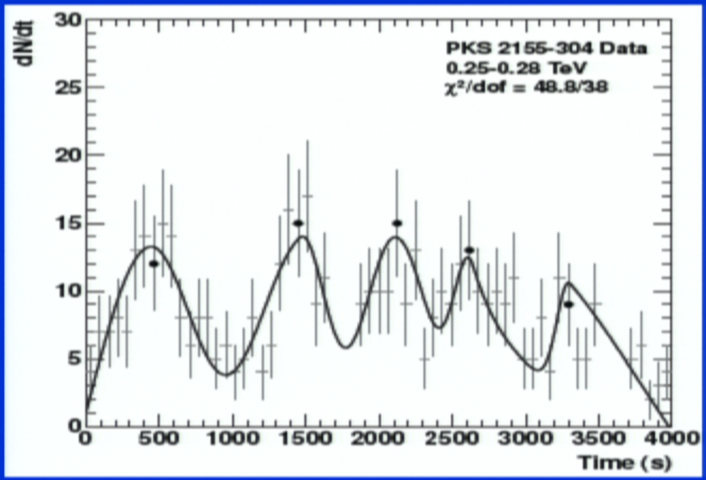
◆ **HESS** (08,11): PKS 2155-304, $D \approx 480$ Mpc; 0.2-5 TeV

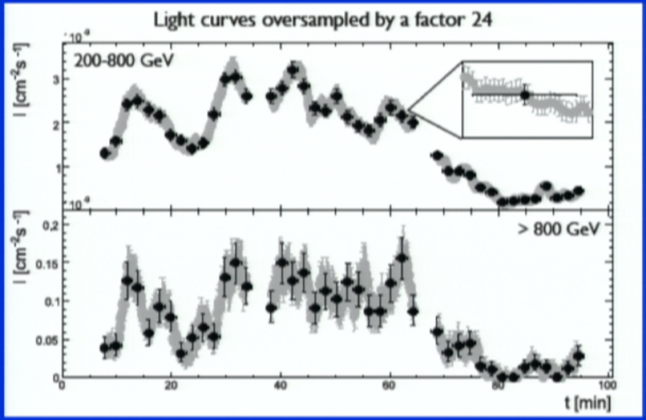
⇒ $\xi_1 > 0.06$, $E_{QG,2} > 1.4\times10^9$ GeV (95% CL; 2008)

Better analysis methods (2011):

$\xi_1 > 0.17$, $E_{QG,2} > 6\times10^{10}$ GeV







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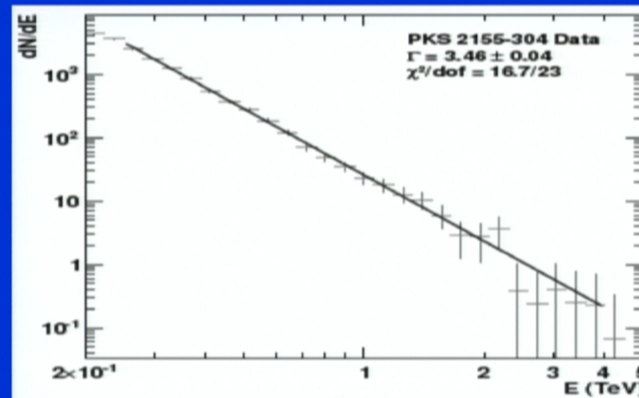
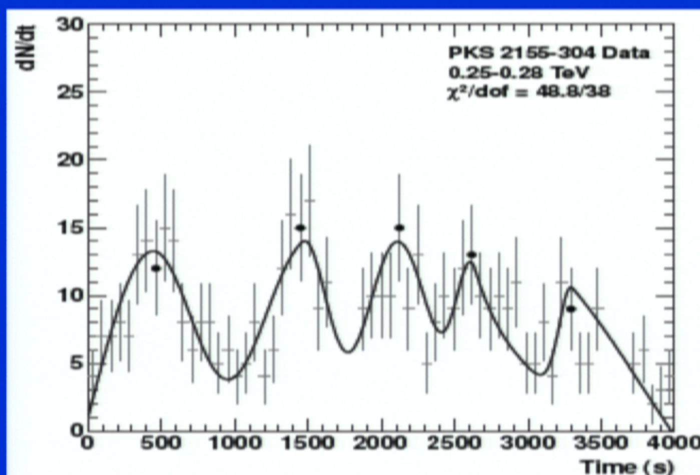
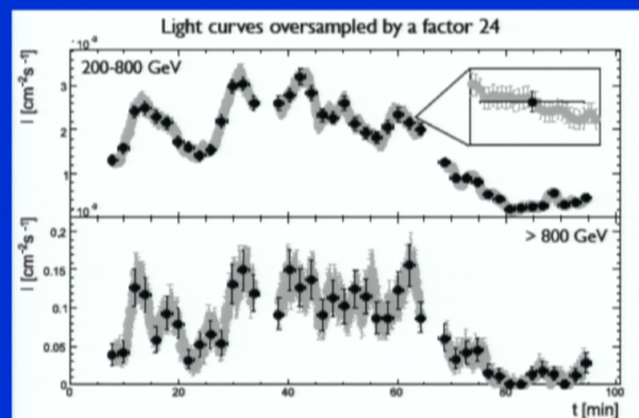
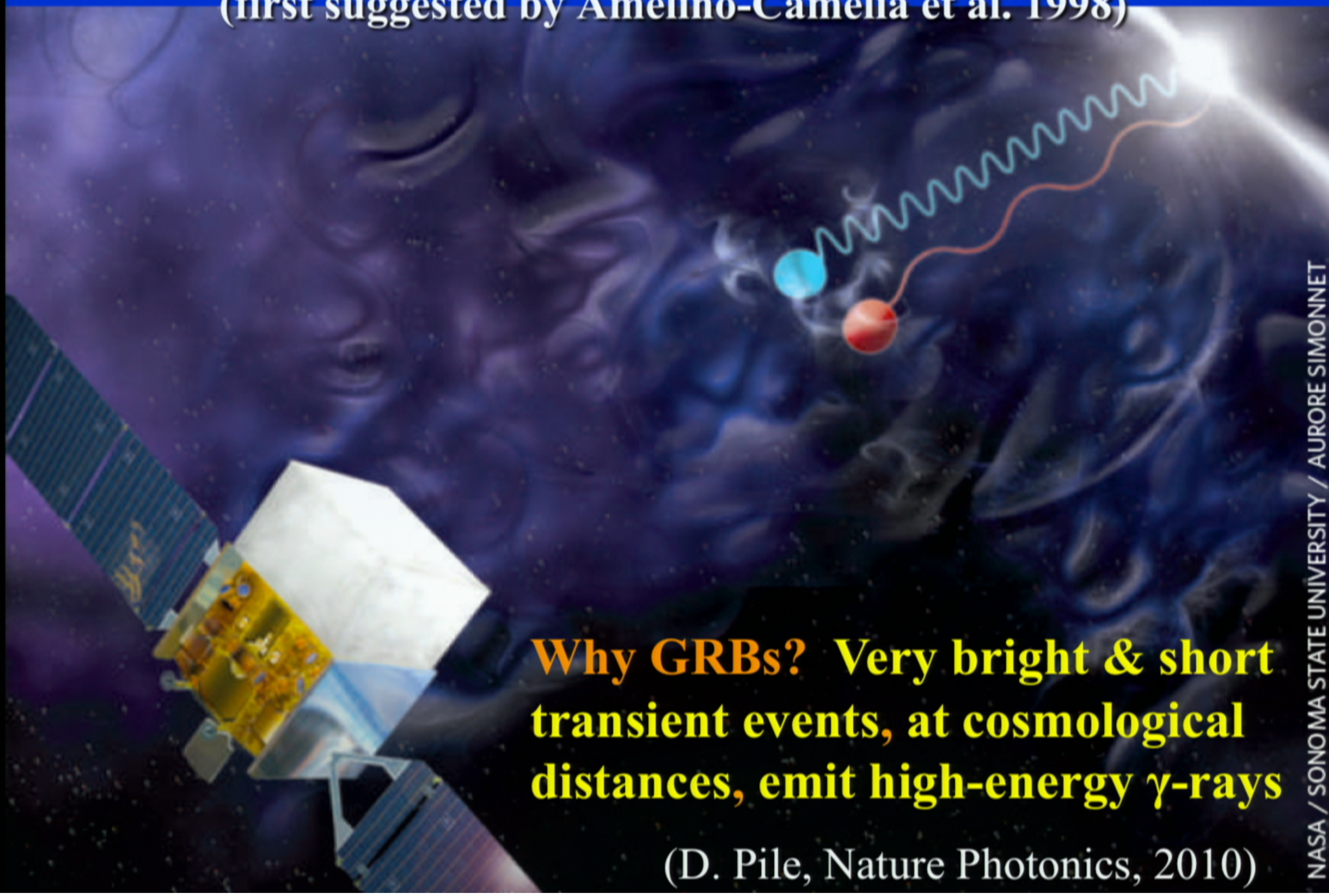






Probing Vacuum dispersion Using GRBs

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

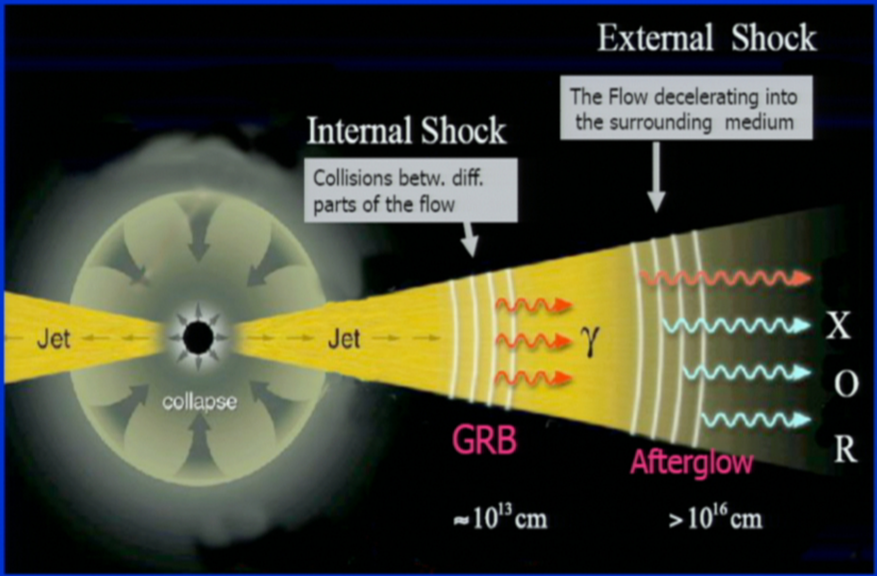


Why GRBs? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays

(D. Pile, Nature Photonics, 2010)

GRB 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

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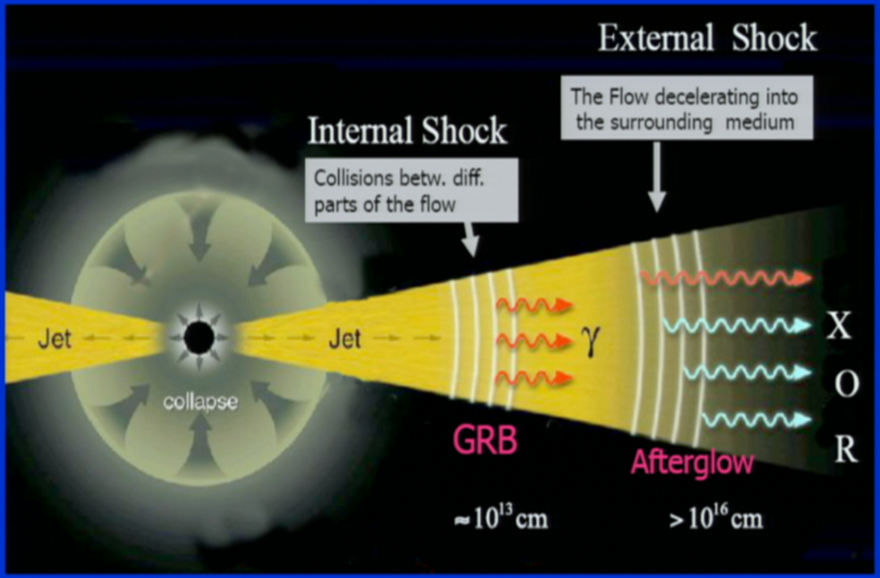

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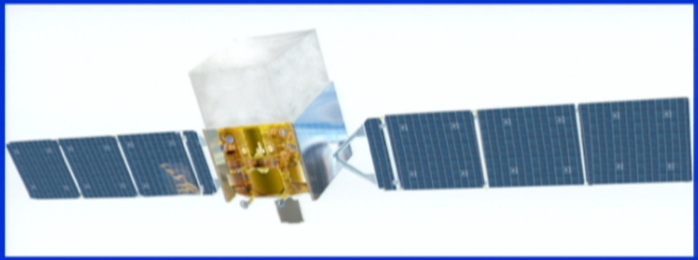
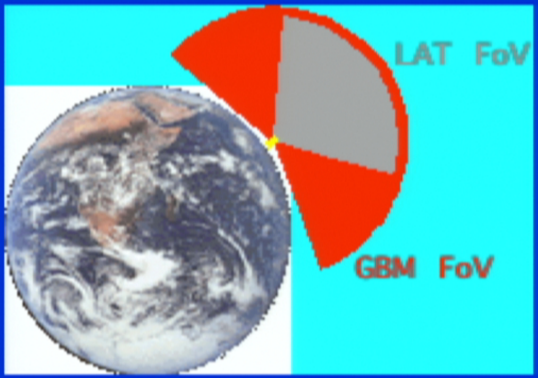
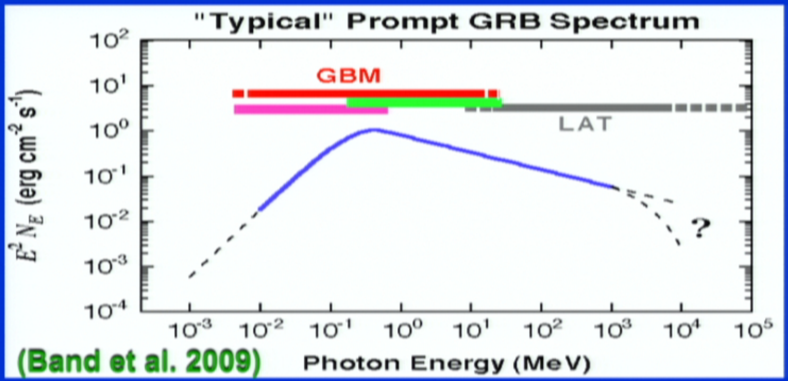
Fermi Gamma-ray Space Telescope
(launched on June 11, 2008)



- 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

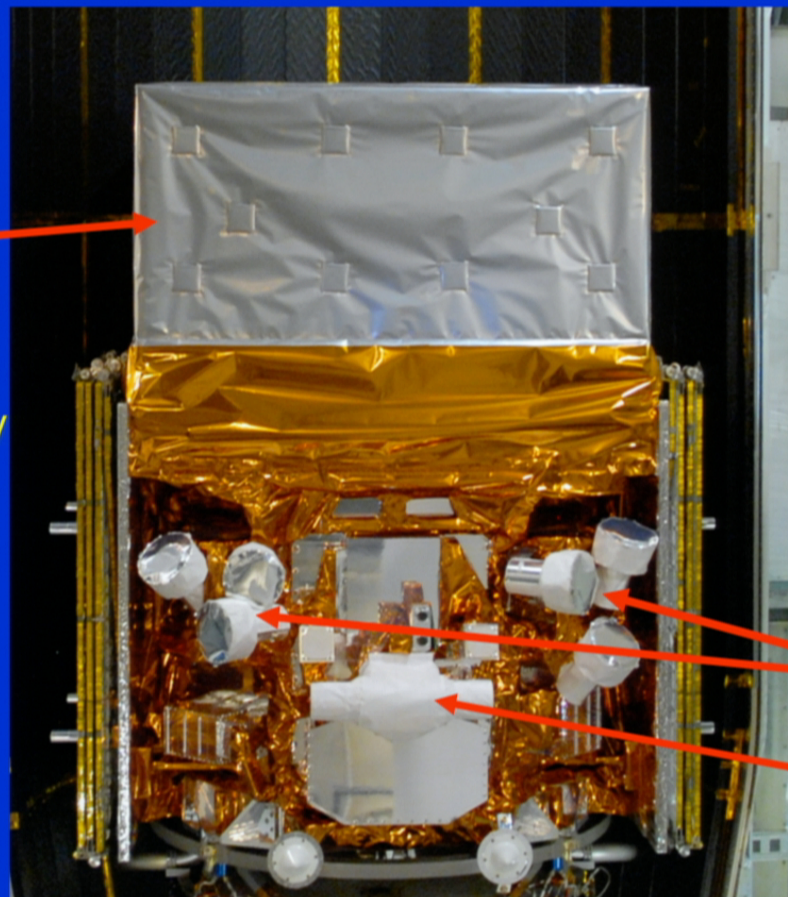




The Fermi Observatory

Large Area Telescope (LAT)

- Large Field of View (>2.4 sr)
- views entire sky every 3 hrs
- 20 MeV - 300 GeV



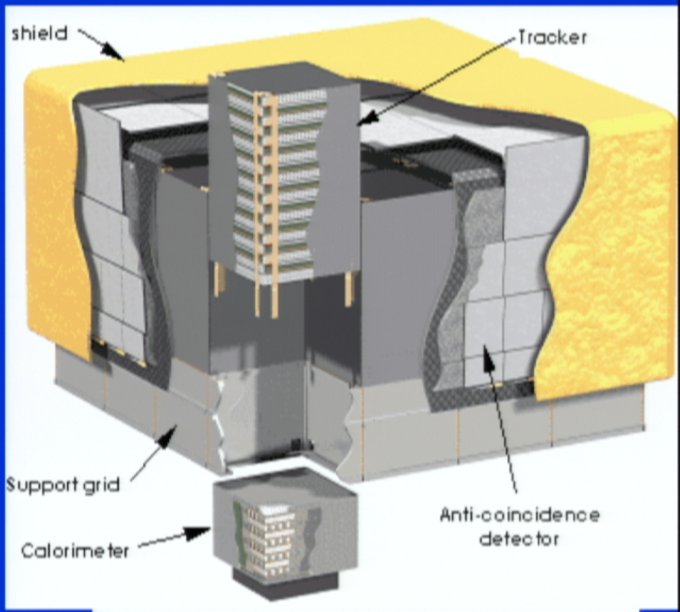
Gamma-ray Burst Monitor (GBM)

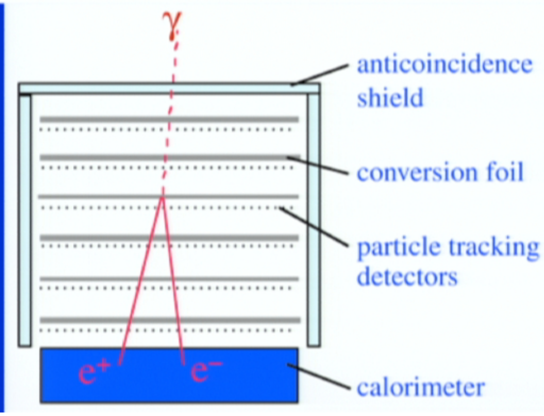
- Views entire unocculted sky
- **NaI:** 8 keV - 1 MeV
- **BGO:** 0.15 - 30 MeV

The Large Area Telescope

Pair-conversion γ-ray detector

- Energy range: 20MeV – >300GeV
- ✔ GeV photons useful for LIV studies with GRBs
- Wide field of view (~±70°); large effective area
- ✔ Helps with detecting many GRBs with ample photon statistics per detection
- Good angular (~0.2° at 1GeV) and energy resolution (~10% over 1GeV), low bkg rate (<1Hz in ROI over 20MeV)
- ✔ Provides high-quality data for LIV studies
- In first 3 years:
  - Detected 10 GRBs with a measured redshift
  - 21 GRBs with emission over 1 GeV
  - Range of redshifts extends from 0.74 to 4.35





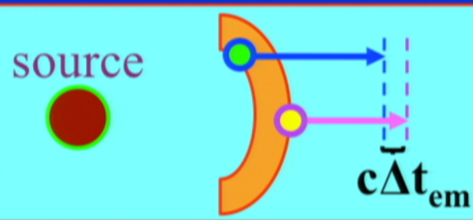
Constraining LIV Using GRBs

- 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



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

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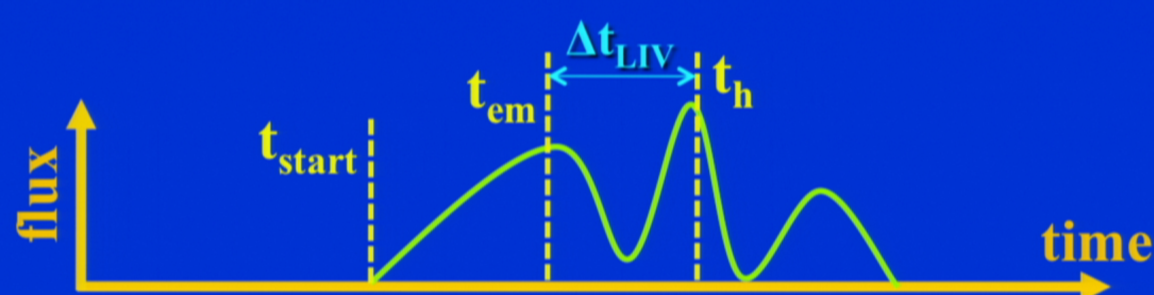
- Our limits apply to any source of energy dispersion on the way from the source to us, and may constrain some (even more) exotic physics ($\Delta t_{\rm LIV} \rightarrow \Delta t_{\rm LIV} + \Delta t_{\rm exotic}$)

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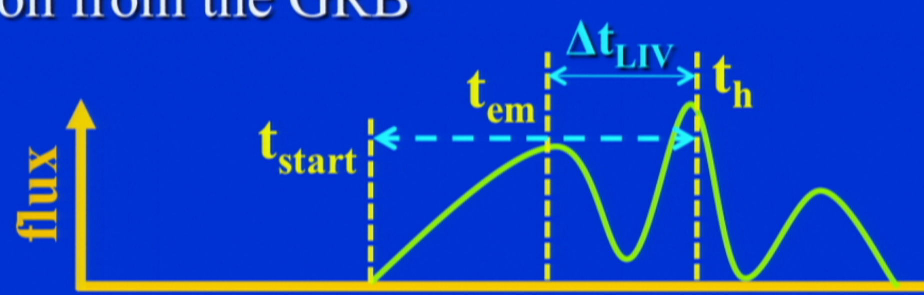
- $\Rightarrow \Delta t_{LIV} = t_h - t_{em} < t_h - t_{start}$
- A conservative assumption: t_{start} = the onset of any observed emission from the GRB



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

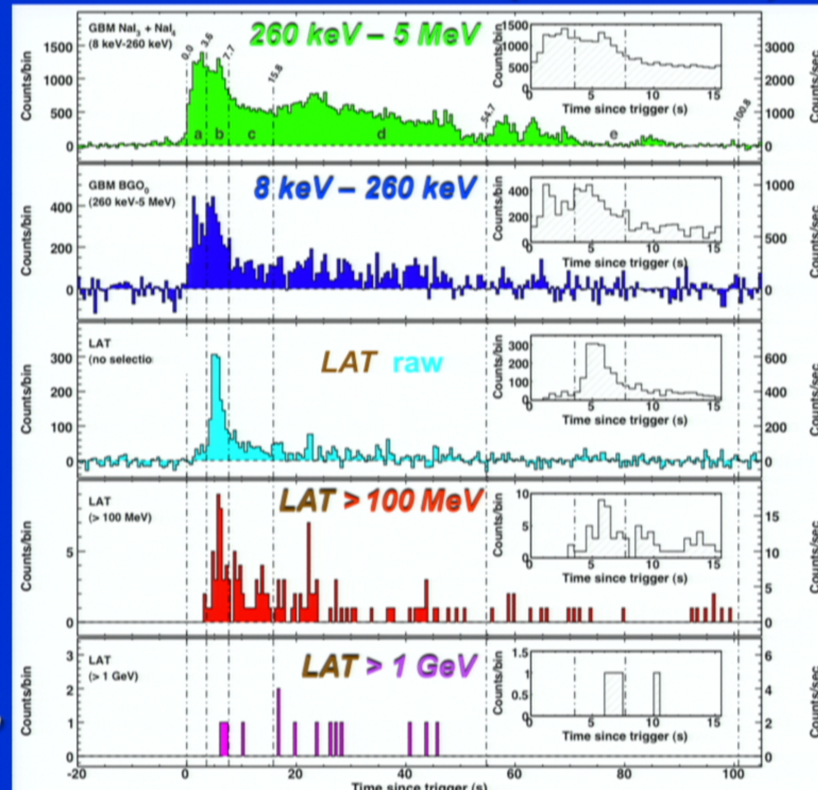
- GRB080916C: highest energy photon (13 GeV) arrived 16.5 s after low-energy photons started arriving (=the GRB trigger)

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

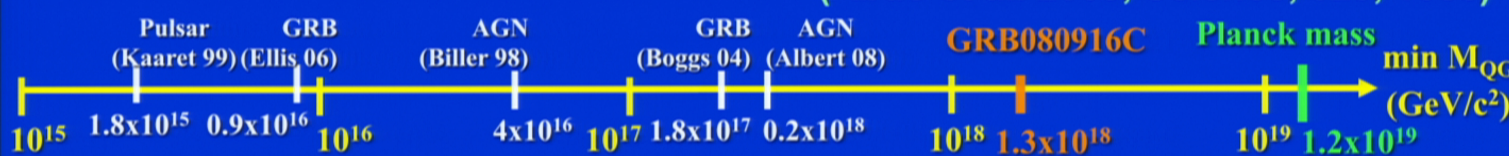
  $M_{QG,1} > 1.3\times10^{18}\ \mathrm{GeV}/c^2$

  $\approx 0.11 M_{Planck}$

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

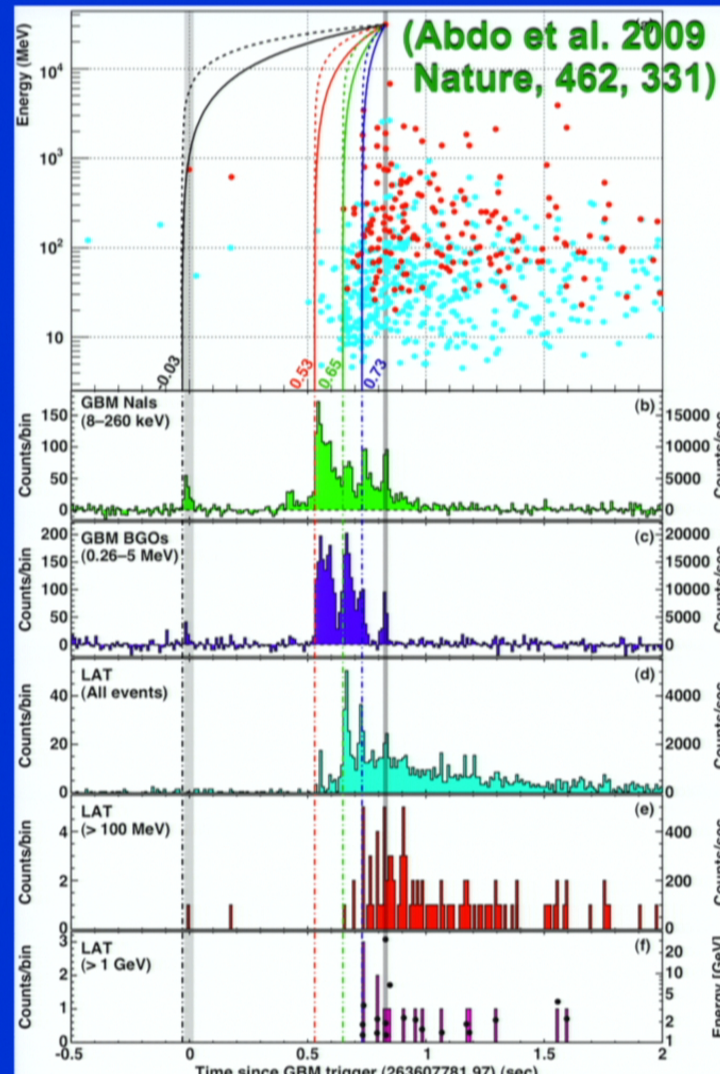


(Abdo et al. 2009, Science, 323, 1688)



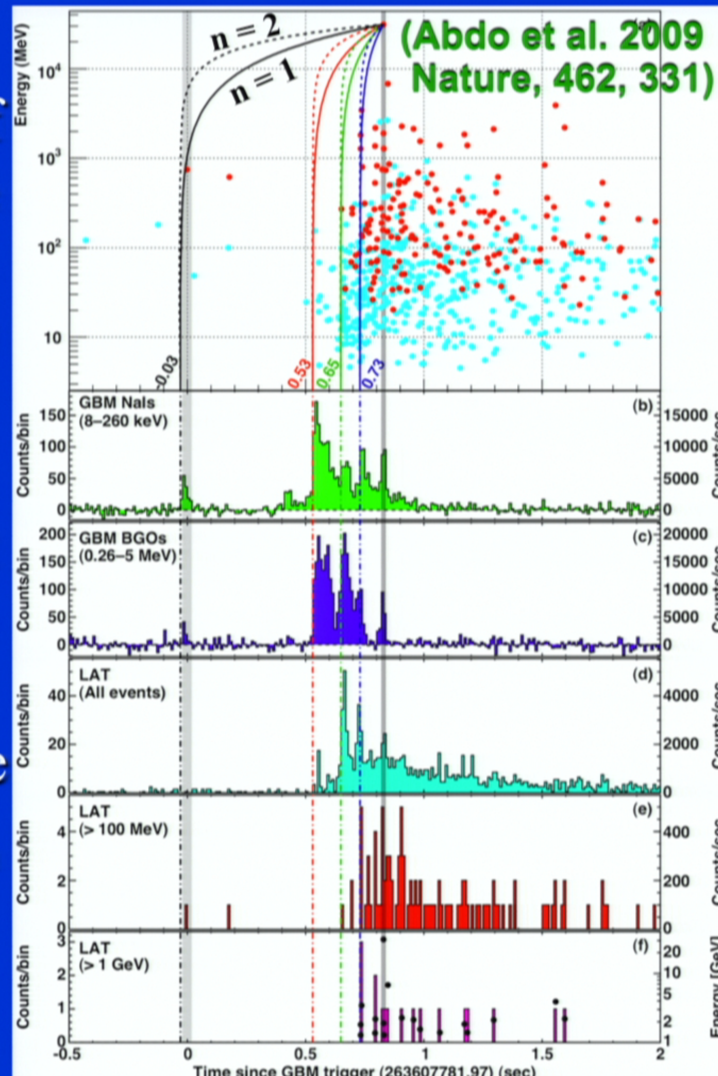
GRB090510: L.I.V

- 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 $>5\sigma$
- 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



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



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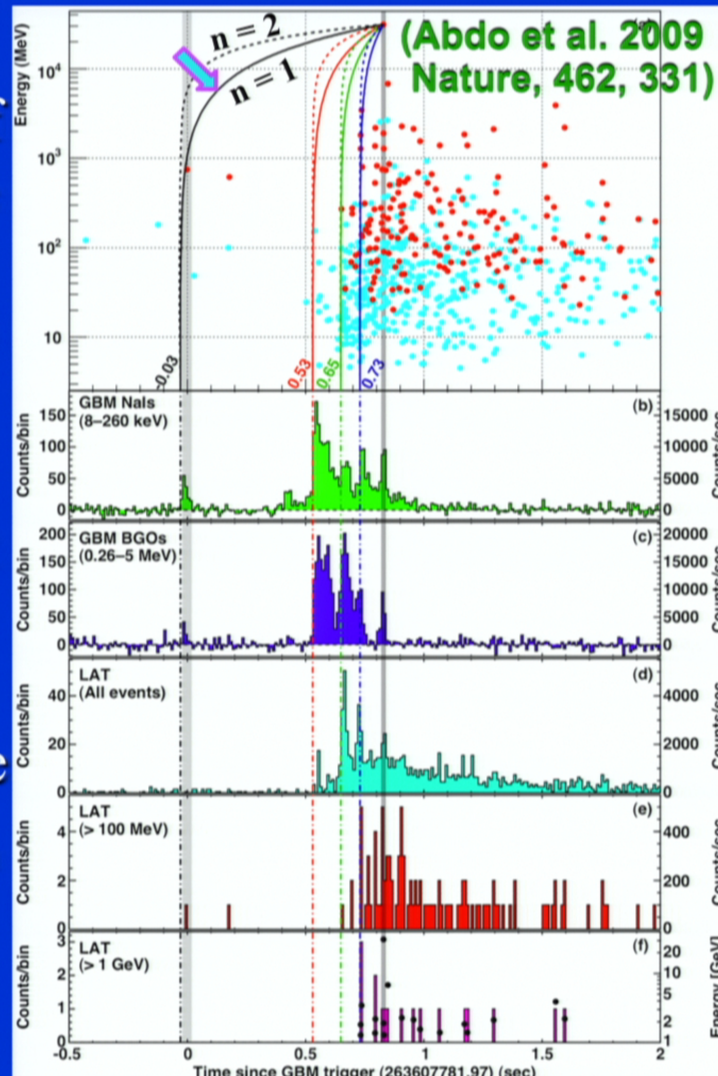
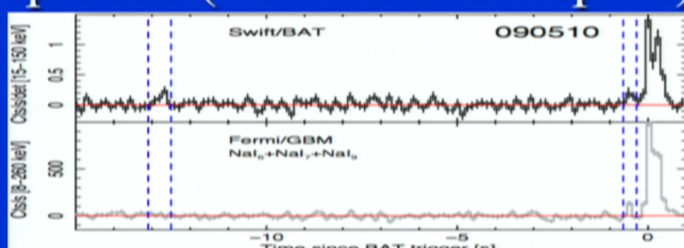
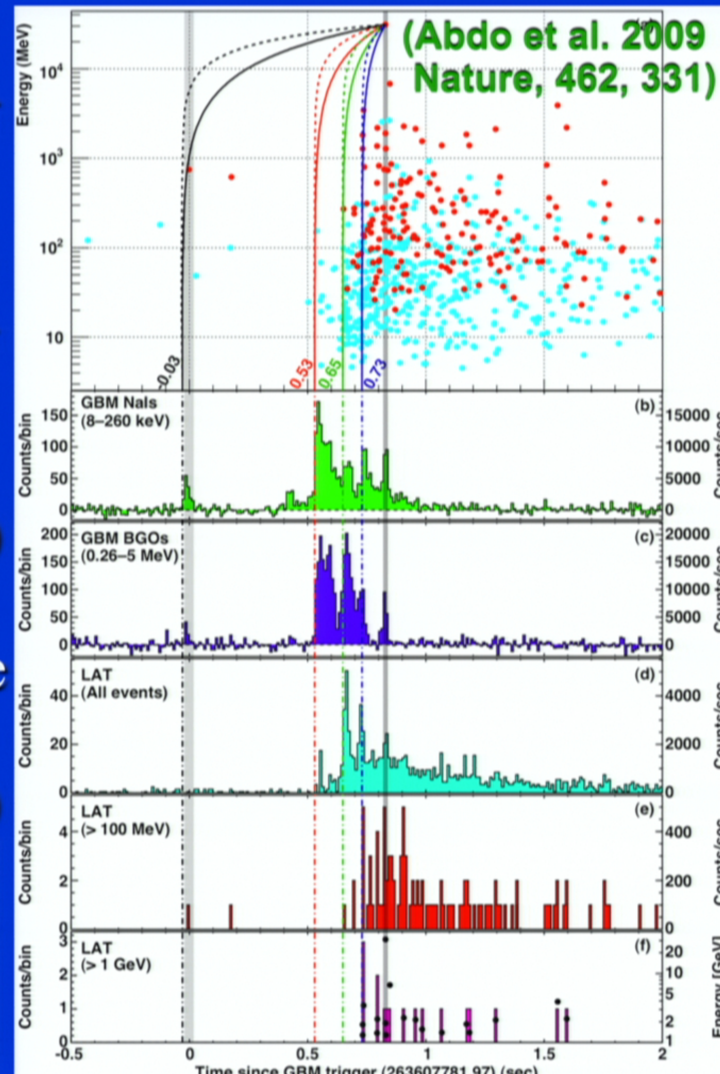


GRB090510: L.I.V

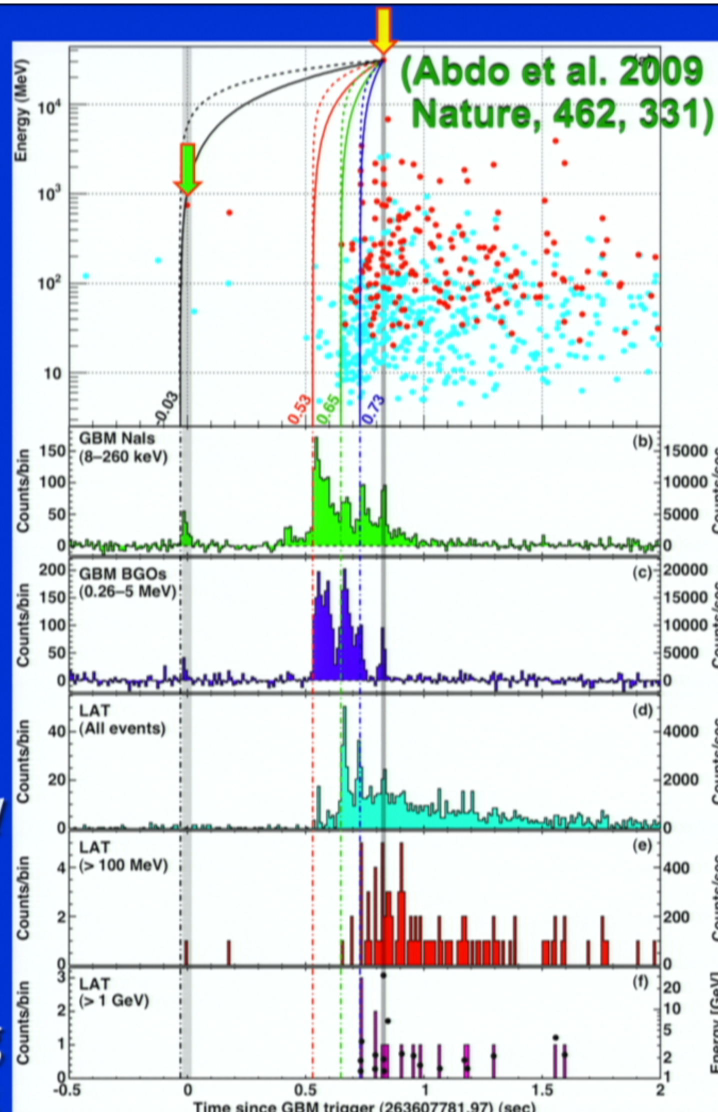
- Troja et al. 2010: detection of low level emission ~13 s before the GRB090510 trigger
  - Highly unlikely that no other LAT photons were emitted together with the ~31 GeV photon (none were observed)
  - Fine tuning is required for the ~31 GeV photon to arrive on top of brightest emission episode (+on 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)

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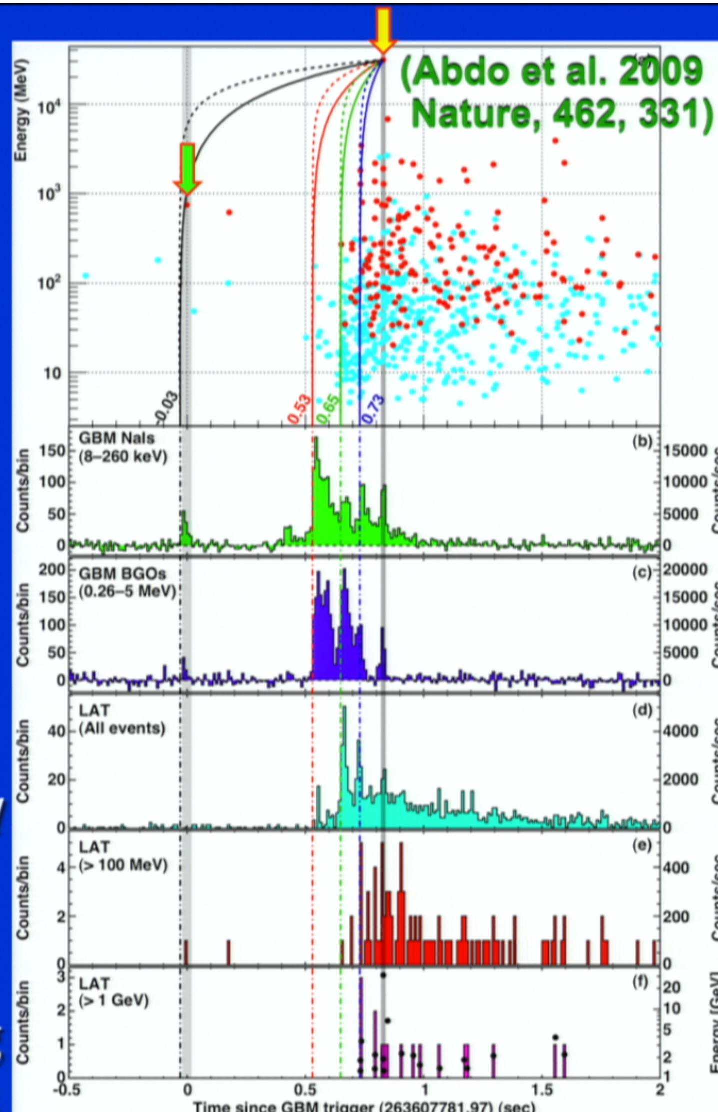

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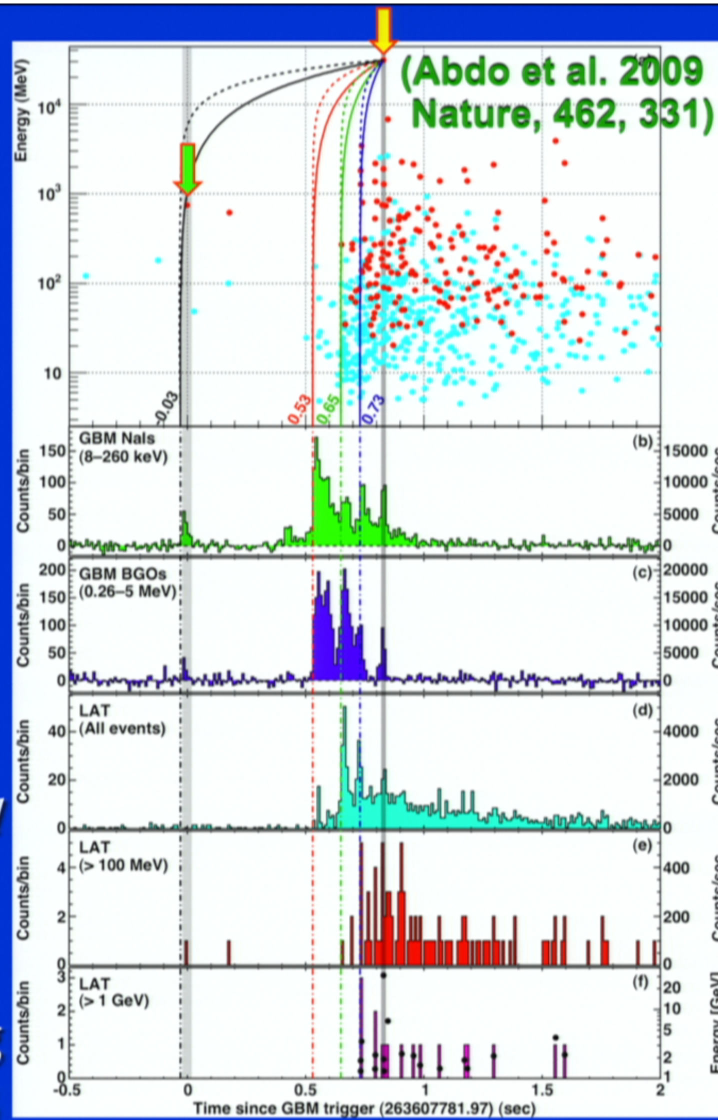

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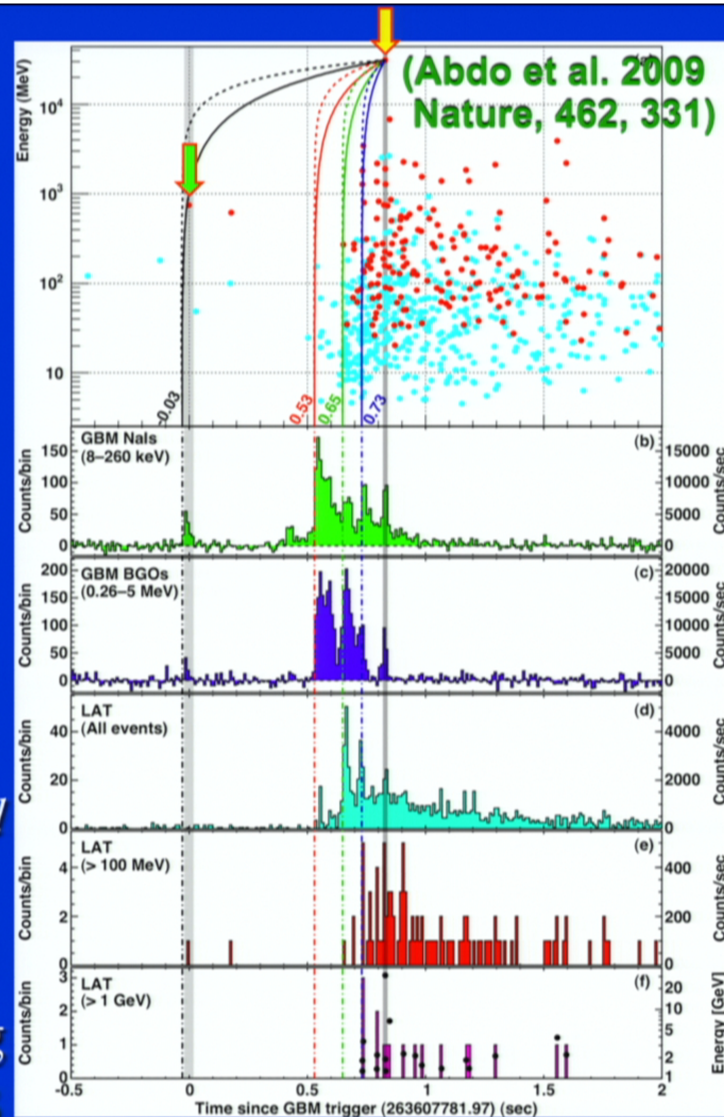

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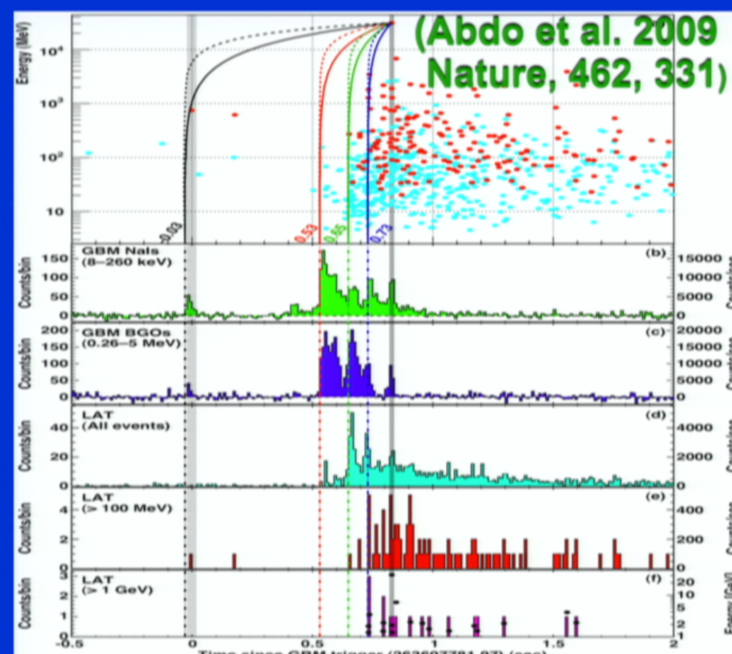
GRB090510 limits on LIV Summary:

	$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$	limit on $M_{\rm QG,2}$ 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	—

- 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}



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Our results disfavor QG models with linear (n = 1) $v_{ph}(E)$

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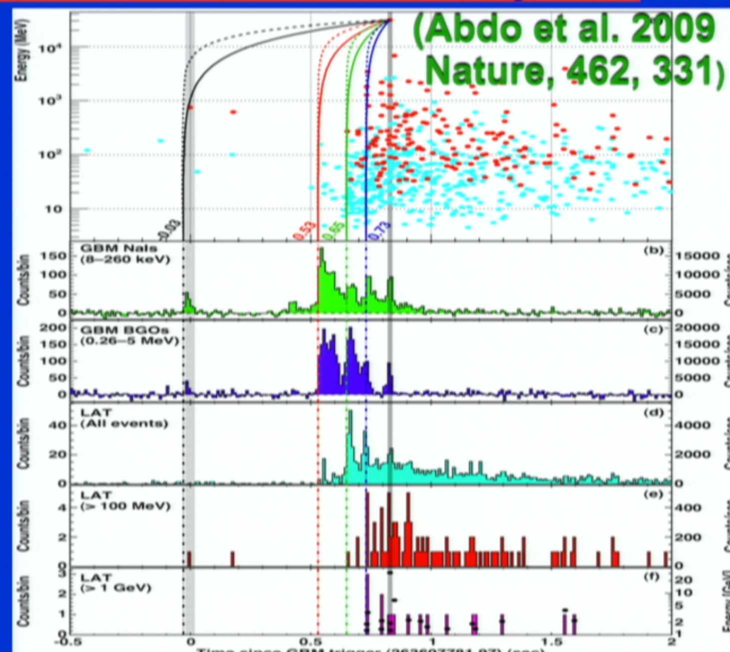


(Abdo et al. 2009 Nature, 462, 331)

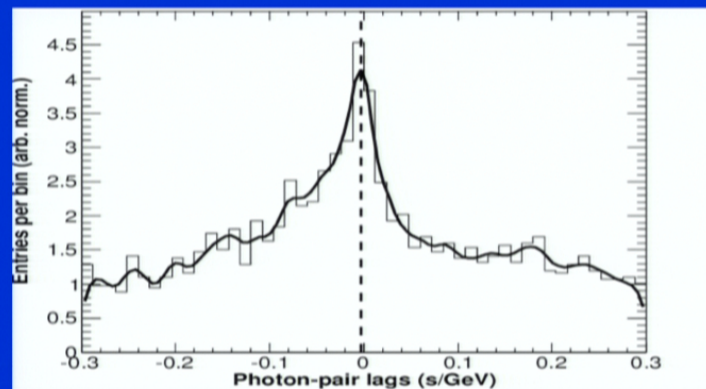
Limits on LIV from Fermi GRBs

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

Limits on LIV from Fermi GRBs

- A. PairView: calculates spectral lags $l_{i,j}$ between all pairs of photons in a dataset and identifies the most prominent value of $l_{i,j}$ as the best estimate of the LIV parameter $\underset{i>j}{l_{i,j}} \equiv \frac{t_i - t_j}{E_i^n - E_j^n}$
- The distribution of $l_{i,j}$ will have a peak approximately centered at the true value τ_n
  - If data has no lag, there will still be a peak but at zero
  - Peak width/height depend on statistical strength of the dataset: many GeV photons in a bright pulse will give the strongest signal



- B. Sharpness Maximization: based on idea similar to DisCan
- C. Likelihood analysis: used before on AGN – low-energy lightcurve + spectrum template used to claculate unbinned likelihood for high-energy data as a function of $\tau_n = \Delta t/\Delta E^n$

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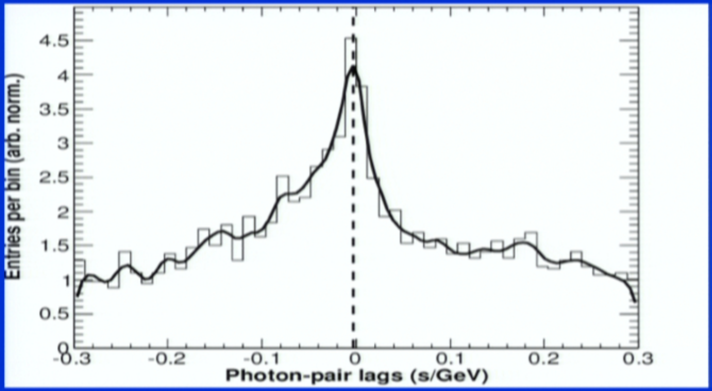

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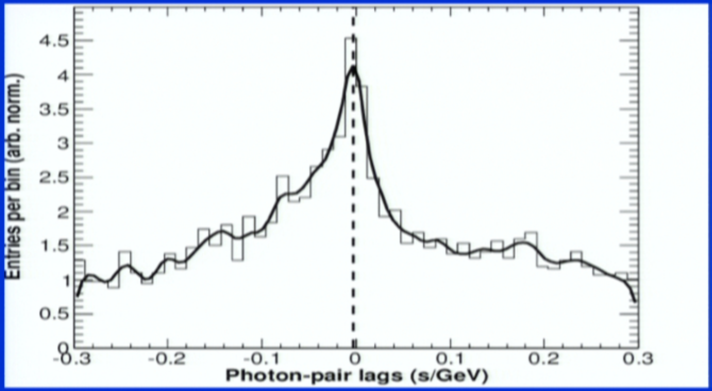

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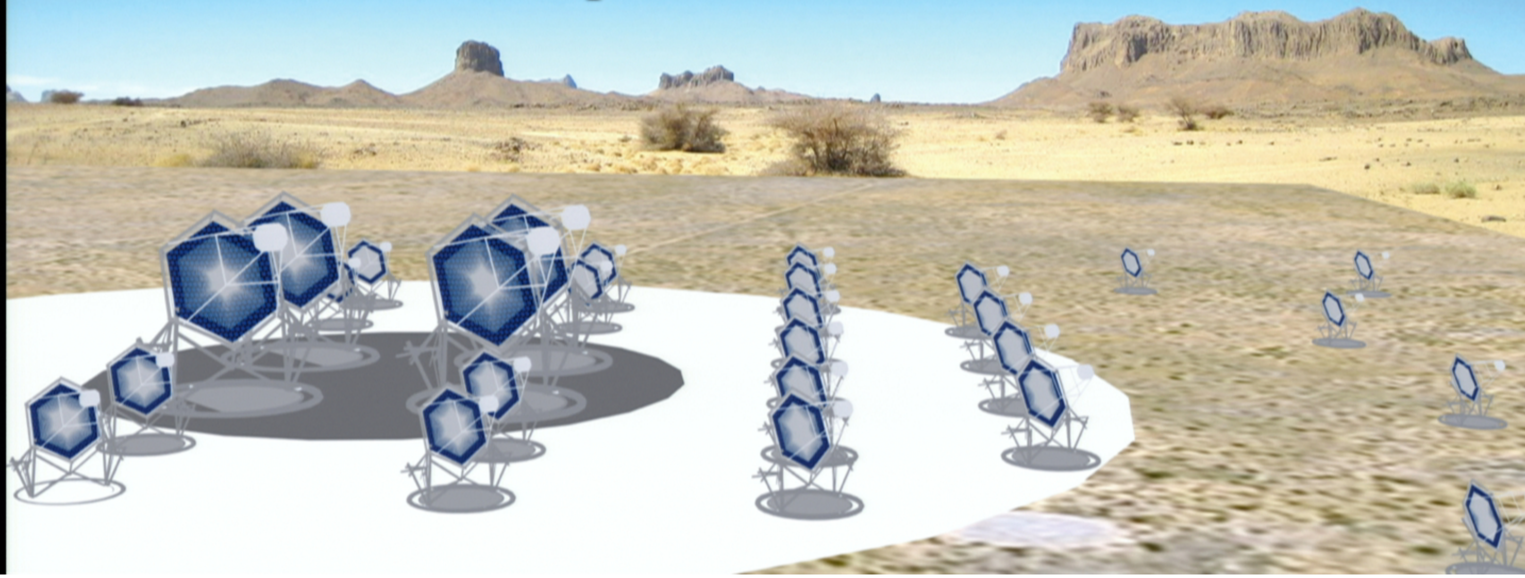
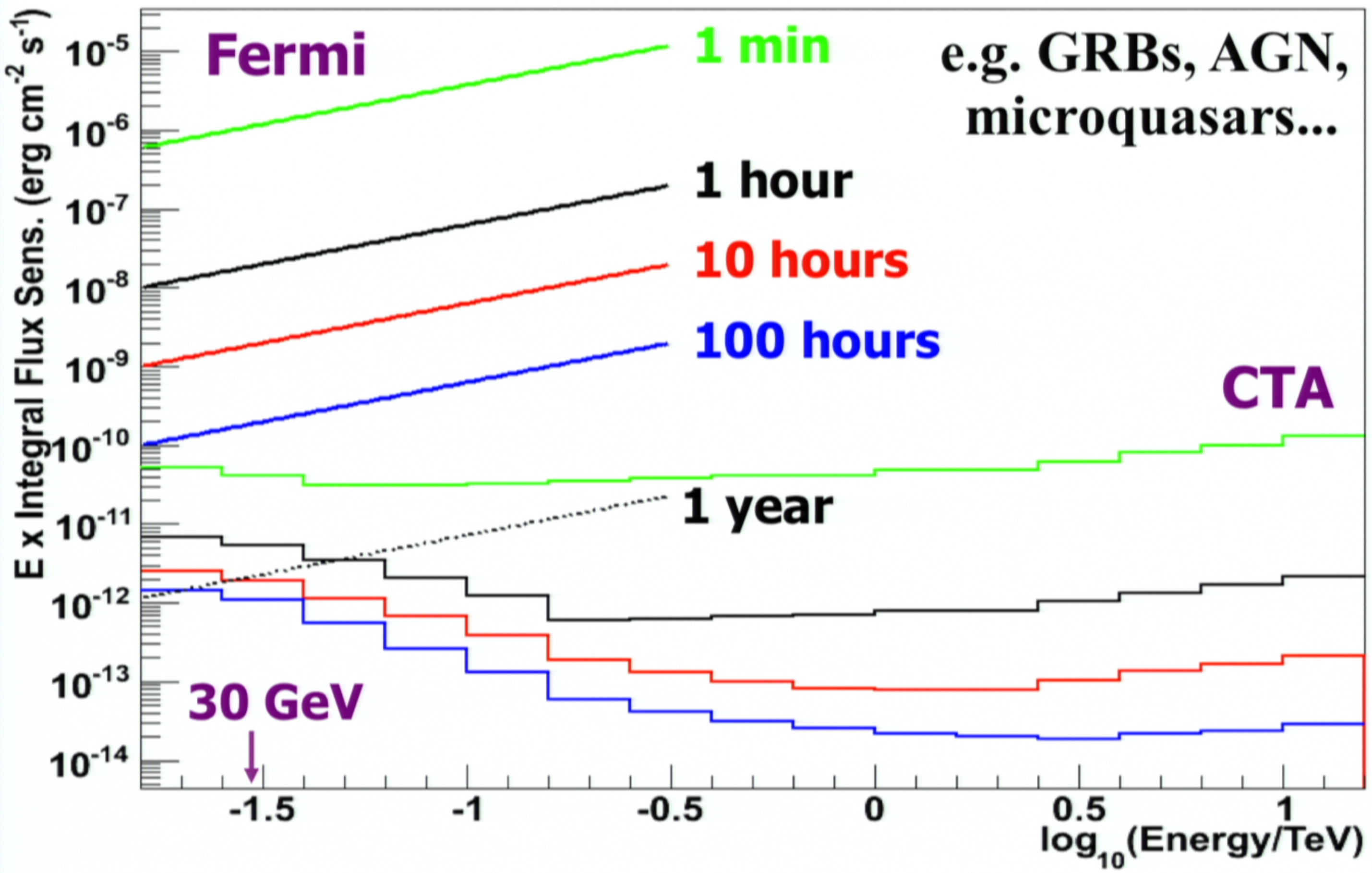
The Future - CTA

- **Energy range: ~20 GeV to ~500 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
  - Preparatory Phase 2010-2013, construction 2013-2018
- **2 sites (southern + northern hemispheres)**
- **Hundreds of telescopes of 3 different sizes**



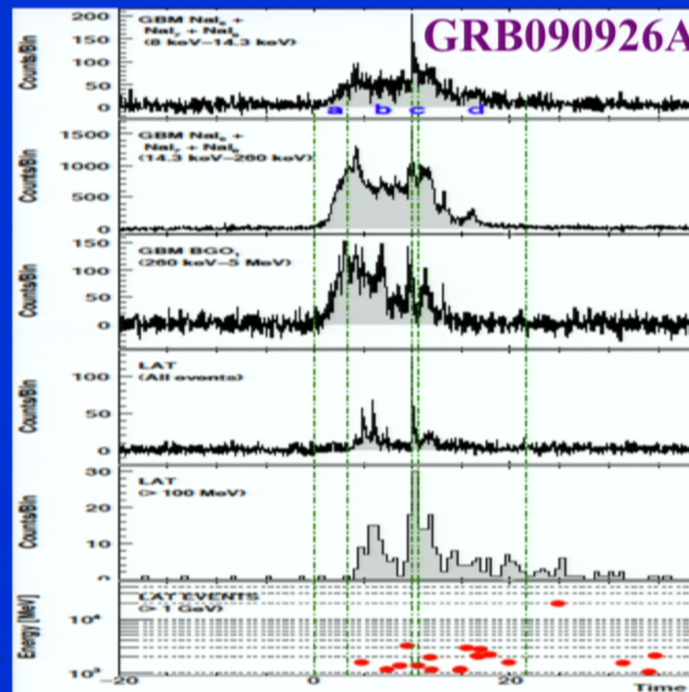
A bigger difference for transient sources



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:

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

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