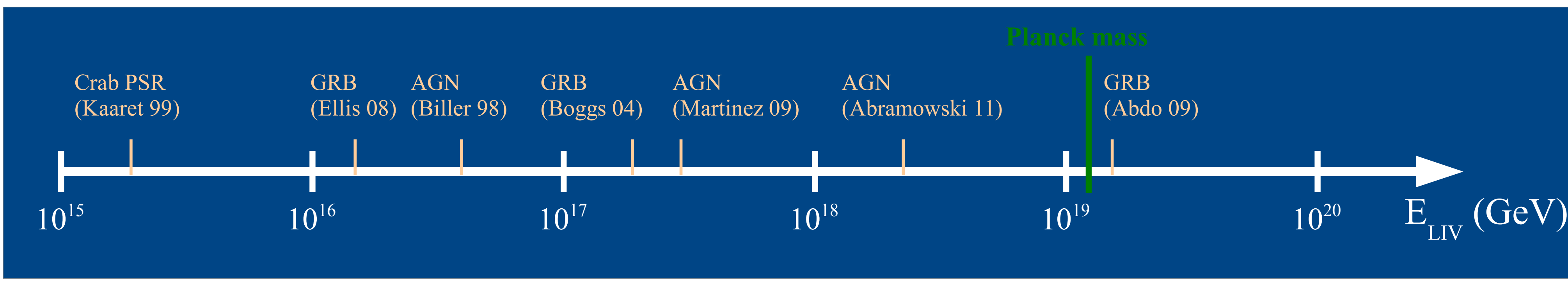
Tests of Lorentz Invariance Violation with Gamma Rays

Based on a white paper for the Snowmass process: arXiv:1305.0264



An overview of present limits

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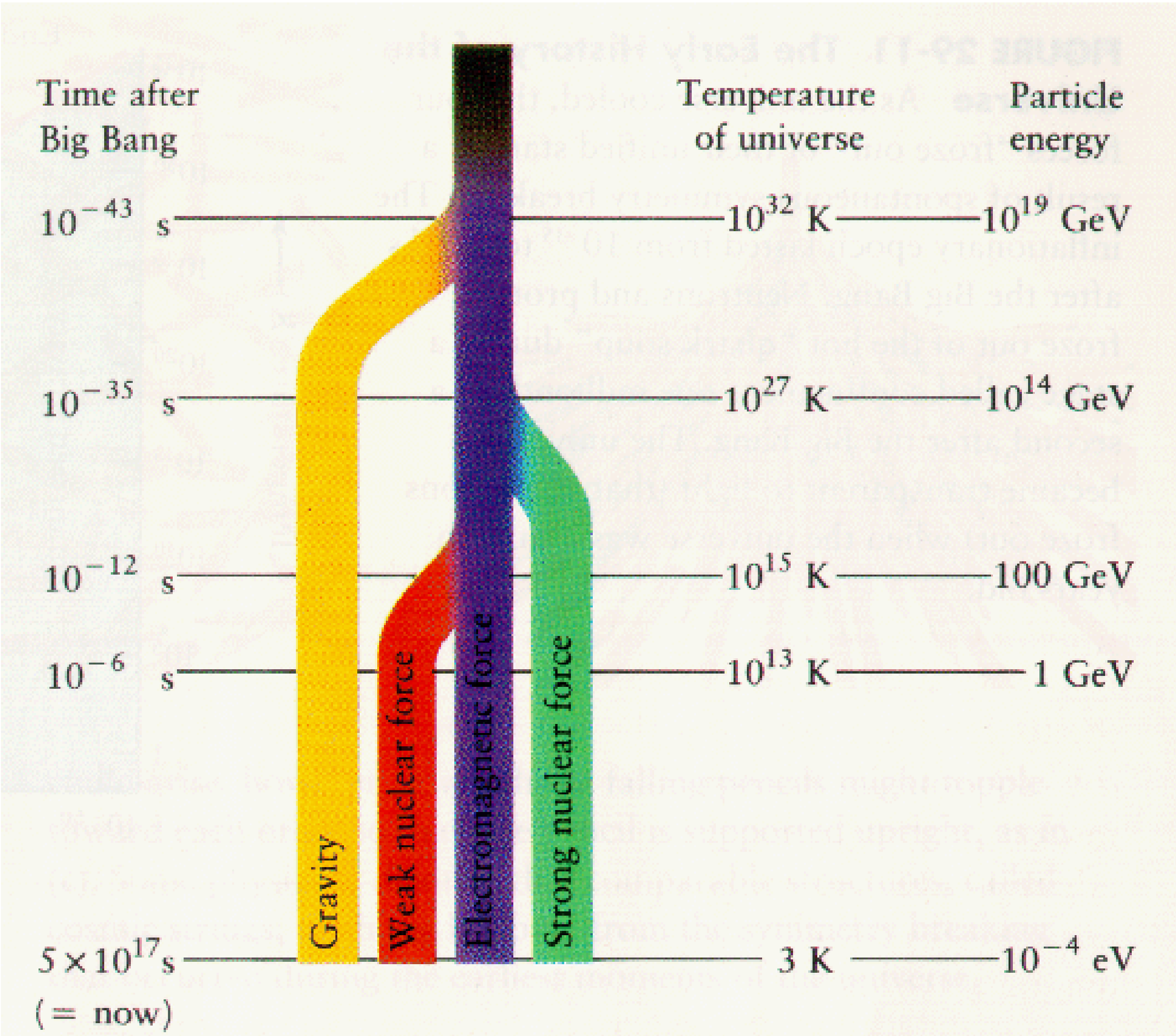
Why test LIV?



- Because of its fundamental nature
- Probe physics at Planck energy (10^{19} GeV):
  - Microscopic structure of space time
  - Physics beyond the standard model

Finding LIV is evidence for new physics

A whole Zoo of Possibilities where LIV could manifest

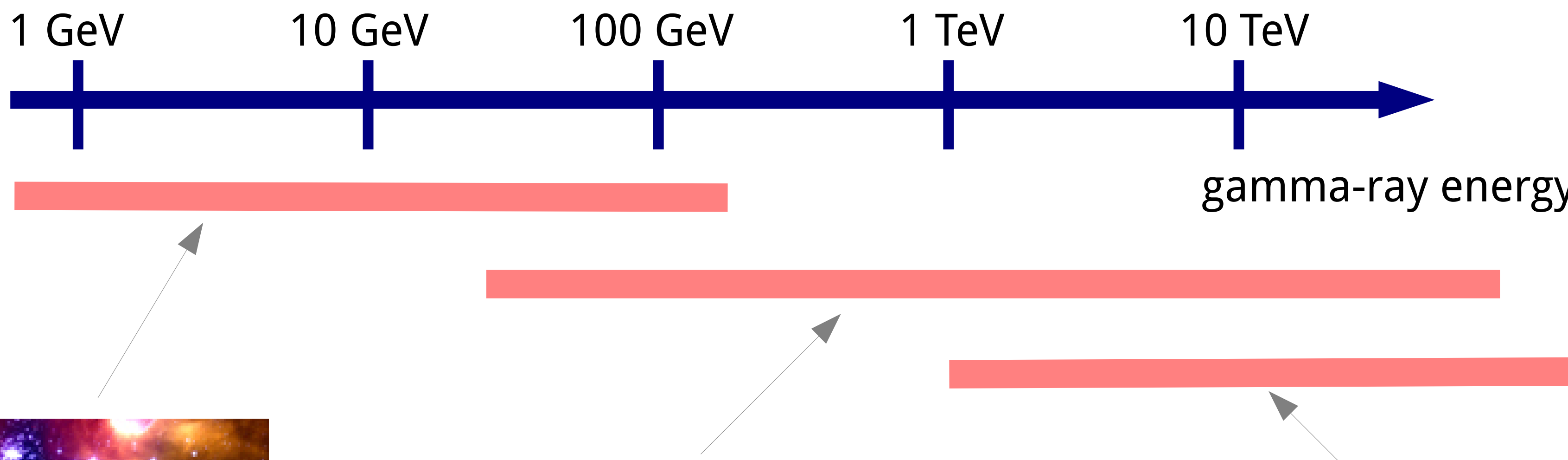
- Energy dependent dispersion of speed of light
- Polarization measurements
- Accelerator experiments
- Time of flight
- Birefringence
- Threshold Effects

Many complementary approaches

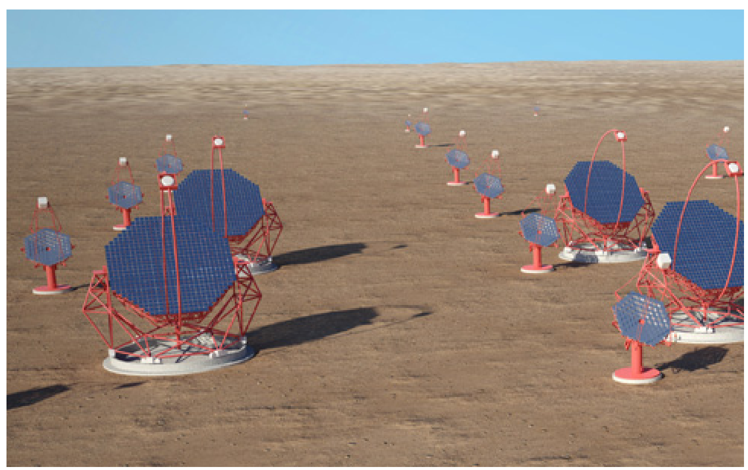
Here:

How astrophysics observations in the very-high-energy gamma-ray band constrain LIV.

Gamma-Ray Instruments



Fermi-LAT



Cherenkov telescopes
e.g. VERITAS and CTA

Water Cherenkov detectors
HAWC

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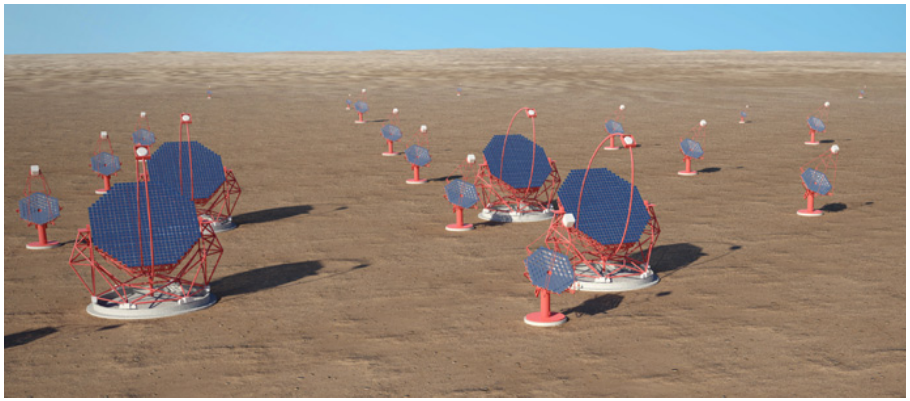
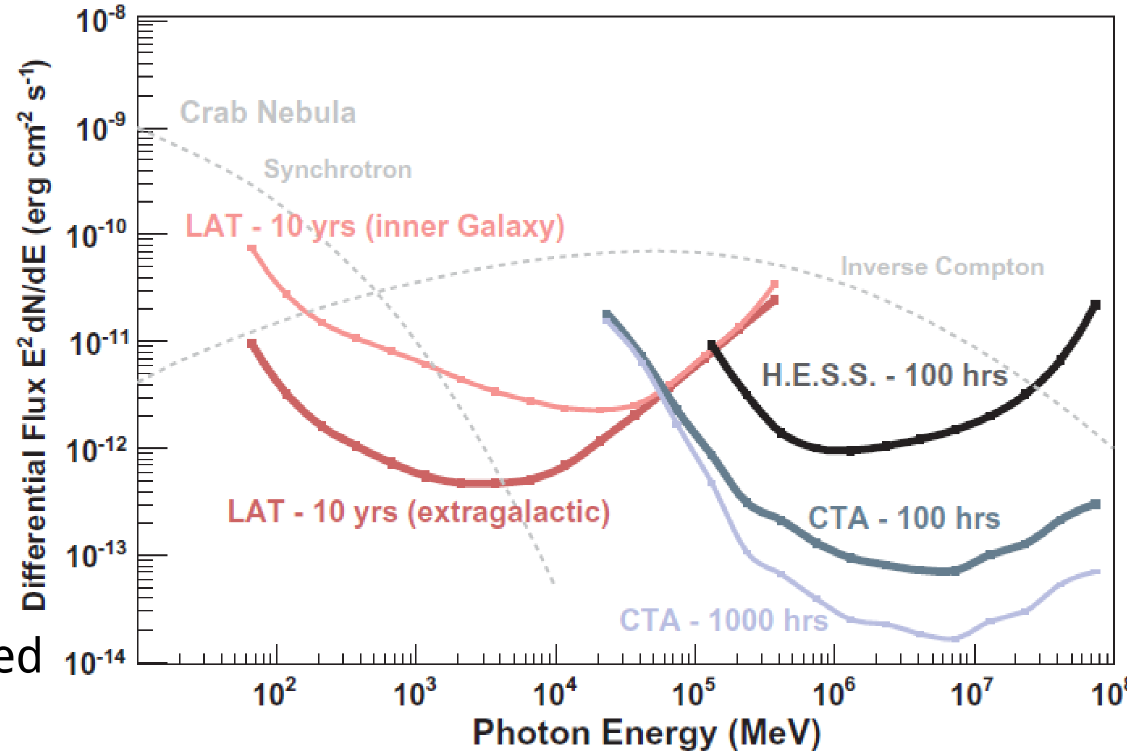
VERITAS

- **Operating since Fall 2007**
- **Energy range**: ~100 GeV to several 10 TeV (~75 GeV after PMT upgrade in 2012)
- **Angular resolution:** ~0.1° (energy dependent)
- **Energy resolution:** 15% (energy dependent)
- **Systematic uncertainties:** Energy ~20%; Spectral index ~0.2
- **Sensitivity:** **1% Crab Nebula flux in <30 hours**

The Cherenkov Telescope Array





~50 Cherenkov telescopes
- three different telescope sizes
- one northern one southern site planned

Energy range: ~20 GeV to ~100 TeV

Expected performance @ 1 TeV:

Tenfold better sensitivity than VERITAS
Angular resolution: 0.05 degrees
Energy resolution: 10%
Field of View: 8 degrees
Repointing: 60 s (goal)

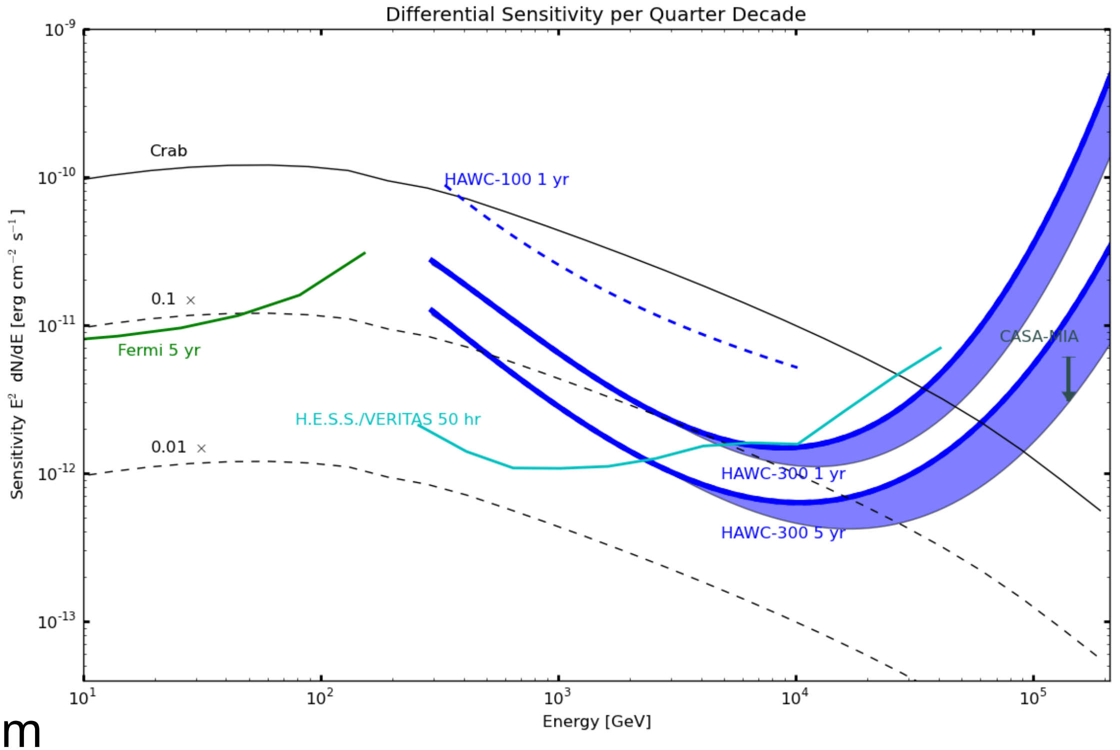
CTA is in its prototype stage

Planned US contribution:
36 Schwarzschild-Couder Telescopes

-> Factor three improvement in sensitivity

HAWC

Water Cherenkov Detector



Under construction in Mexico @ 4,100 m

1/3 complete, completion in 2014

15 times more sensitive than Milagro

Threshold Effects

Stecker, Glashow (2001)

Result from max velocity for electrons c_e being different from photons c

$$c_e \equiv c_\gamma(1+\delta), \quad 0 < |\delta| \ll 1$$

c_e<c

- Decay of photon into e+/e- pair possible

-> stringent constraints from 50 TeV gamma rays observed from Crab Nebula

$$E_{\max} = m_e \sqrt{2/|\delta|} \quad \Rightarrow \quad \delta < 2 \times 10^{-16}$$

c_e>c

- Maximum electron energy limited by vacuum Cherenkov radiation
  - $\delta < 1.3 \times 10^{-13}$ (from max observed electron energies in CR spectrum)
  - $\delta < 6 \times 10^{-20}$ (from April 2011 Crab flare at 400 MeV, Stecker (2013))
- Threshold for pair production increased -> lower gamma-ray opacity from EBL absorption
  - Constrained from AGN observations in TeV (20 TeV, Mkn 501)
  - $\delta < 2(m_e/E_\gamma)^2 = 1.3 \times 10^{-15}$

Energy dependent Dispersion in Photon Sector

$$c'(E) = c + a \cdot \frac{E}{E_{\mathrm{LIV}}} + b \cdot \left(\frac{E}{E_{\mathrm{LIV}}}\right)^2$$

$$\Delta t_1 = \frac{d}{c} \cdot \frac{E_{\mathrm{h}} - E_{\mathrm{l}}}{E_{\mathrm{LIV}}}$$

Linear term

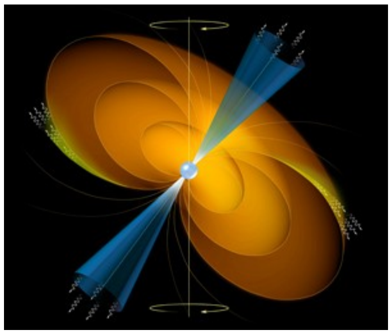
$$\Delta t_2 = \frac{d}{c} \cdot \frac{3}{2} \cdot \frac{E_{\mathrm{h}}^2 - E_{\mathrm{l}}^2}{E_{\mathrm{LIV}}^2}$$

Quadratic term

Arrival time differences (**Δt**) become noticeable for large distances **d** and high photon energies **E**

Testing the Speed of Light in Gamma Rays

Pulsars



z=0

Flaring AGN

z=0.01 … ~1

GRB

z > 1

Distance

Advantages:
- Photons with the highest possible energies
- Astronomical, cosmological distances

Challenges:
- Limited sample
- Not reproducible (AGN, GRB)
- Unknown source physics

Different ways of testing and possibly detecting LIV
is the way to go to overcome challenges

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LIV Test with Pulsars

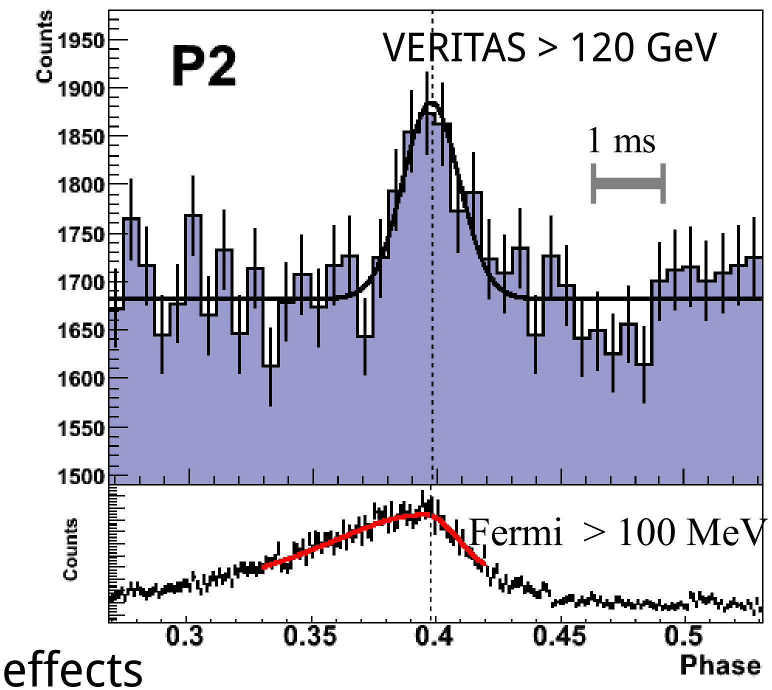
A.N.O. ICRC (2011) arXiv:1208.2033
B. Zitzer ICRC (2013) arXiv:1307.8382

Detection of the Crab pulsar above 100 GeV with VERITAS

- Peaks at 100 MeV (Fermi) and 120 GeV (VERITAS) line up

$$\Delta t_{95\%} < 1.65 \cdot \delta \cdot P/\sqrt{2} < 100\,\mu s$$

- Linear: $E_{LIV} > 3\text{x}10^{17}$ GeV
- Quadratic: $E_{LIV} > 7\text{x}10^{9}$ GeV



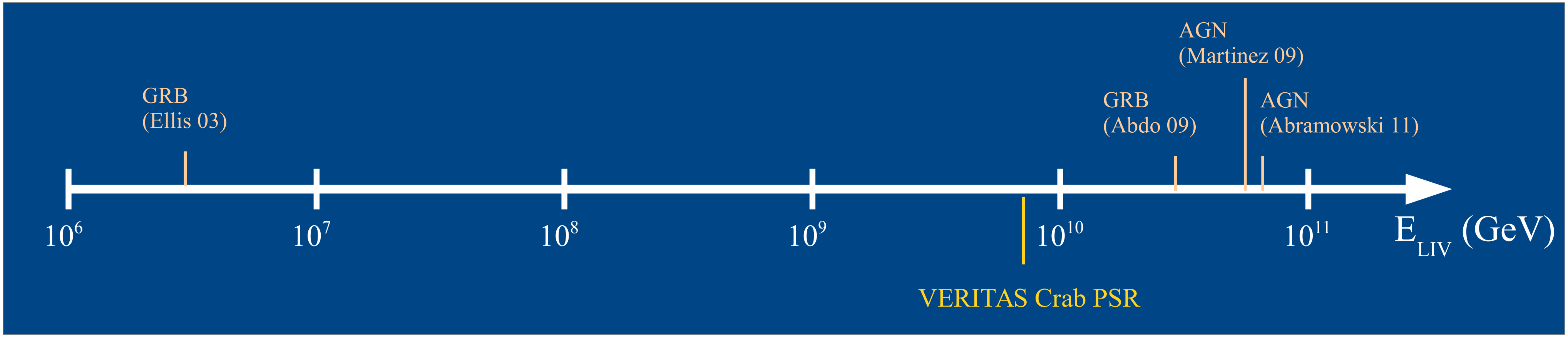
LIV tests with pulsars are reproducible and source effects can be disentangled from propagation effects

Improved limits (factor 10) with more sensitive observations:

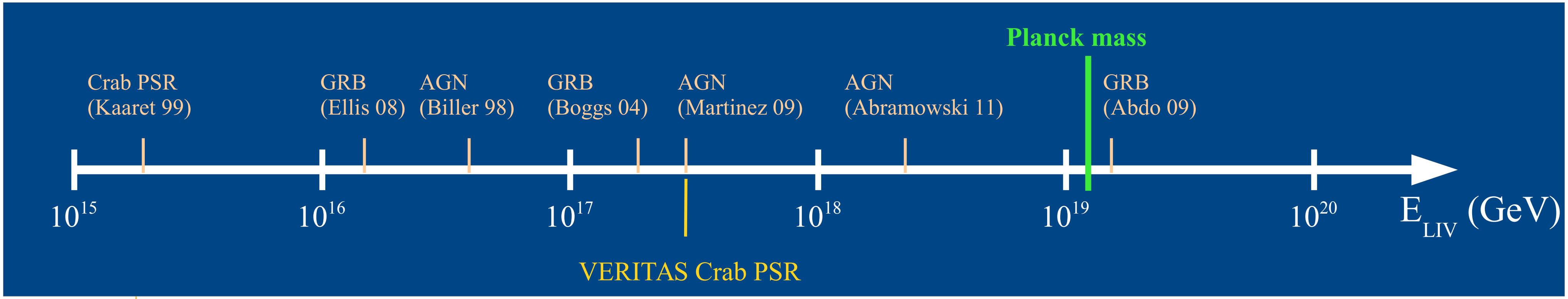
- Deeper observations: **VERITAS**
- Higher sensitivity instruments: **CTA**
- Detection of other pulsars in the VHE band: **VERITAS**, **CTA**

An Overview over various Limits

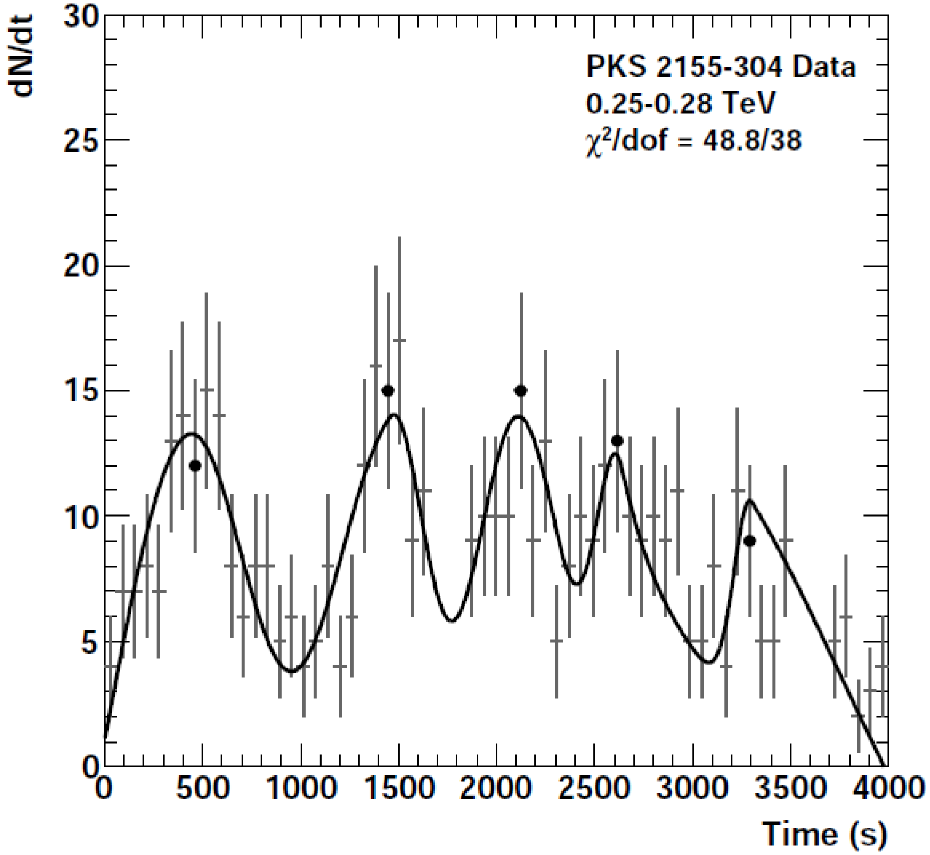
Quadratic term:



Linear term:



LIV Tests with AGNs



H.E.S.S. Collaboration Astropart.Phys.34:738-747,2011

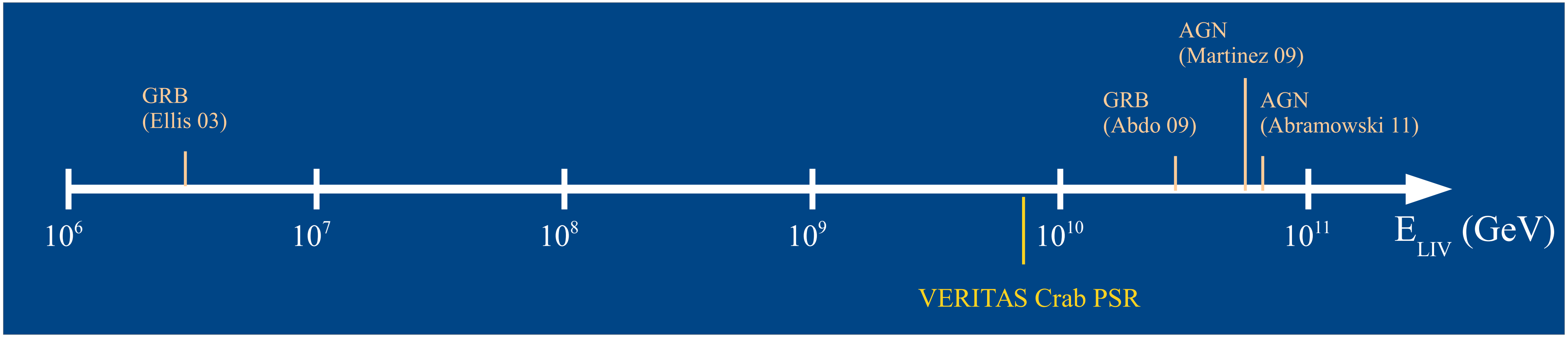
- PKS 2155-304
- z = 0.116
- July 28, 2006 flare
- **Flaring timescale ~min**
- Linear: $E_{LIV} > 2.1\times10^{18}$ GeV
- Quadratic: $E_{LIV} > 6.4\times10^{10}$ GeV

Short time scale TeV gamma-ray window opened with recent generation of IACT: H.E.S.S., **VERITAS**, and MAGIC
Shorter timescales possible? -> need CTA
More statistics (detections) -> VERITAS, CTA

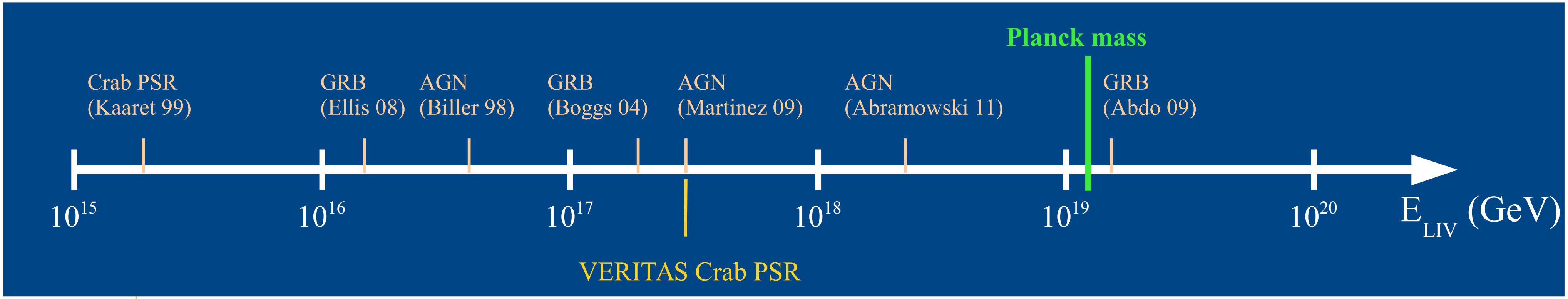
The most constraining limits on the quadratic term will come from future AGN observations (> factor 50)

An Overview over various Limits

Quadratic term:



Linear term:



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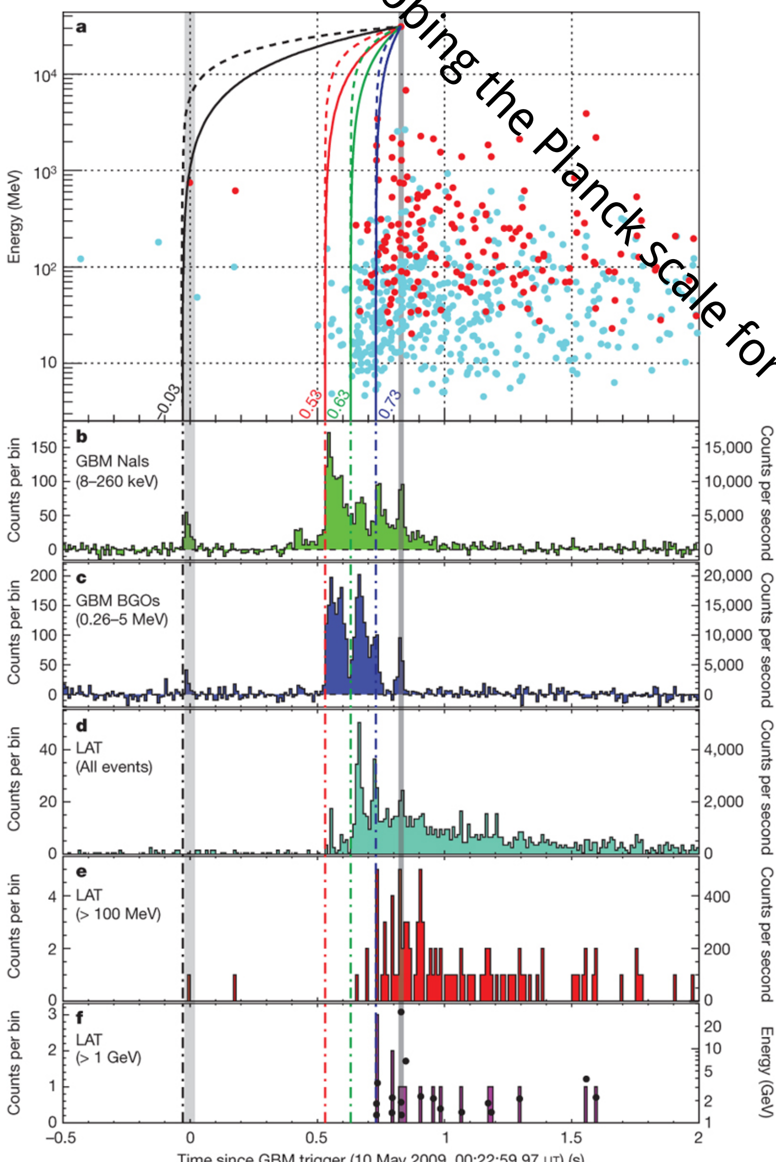
LIV Tests with GRBs

Probing the Planck scale for the first time



- GRB 090510
- **z = 0.903**
- Limits derived from one 31 GeV photon
- **Timescale ~seconds**
- **Linear: $E_{LIV} > 1.5 \times 10^{19}$ GeV**
- Quadratic: $E_{LIV} > 3.0 \times 10^{10}$ GeV

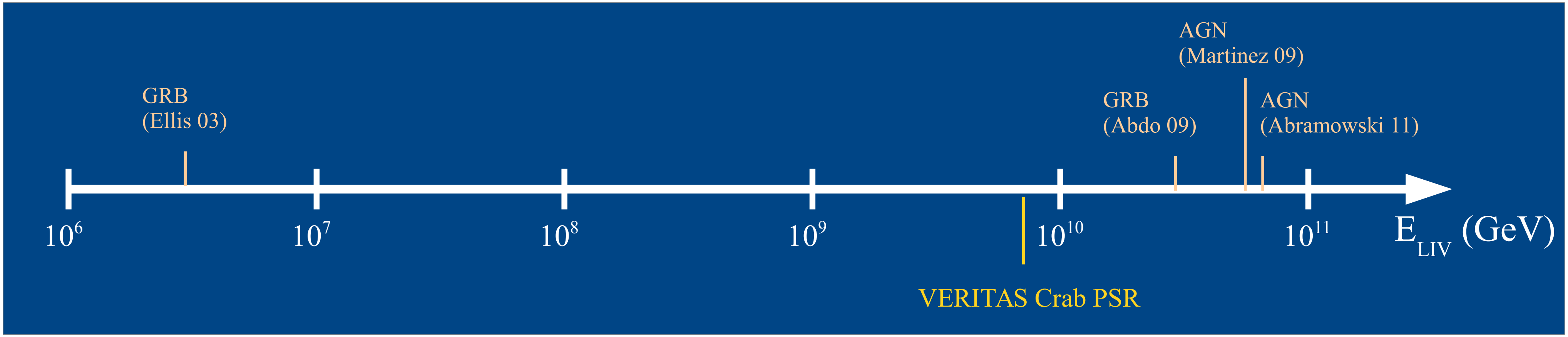
Need:

More sensitivity at highest gamma-ray energies

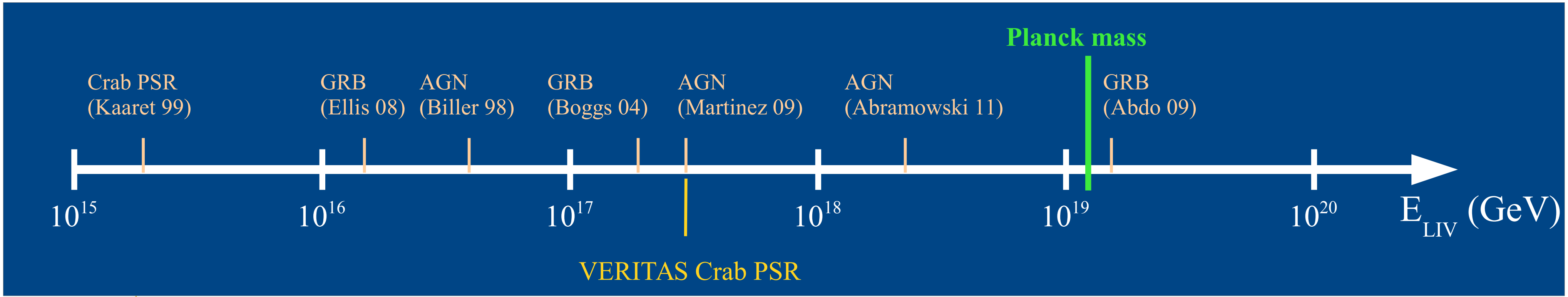
Fermi Collaboration Nature 462, 331-334

An Overview over various Limits

Quadratic term:



Linear term:



GRB Observations with CTA and HAWC

- No GRB detected in gamma-rays > 100 GeV
  - H.E.S.S., MAGIC, and **VERITAS** have active GRB groups
  - But we know that GRB emit up to 126 GeV (GRB 130427A)
- Big improvement with CTA/HAWC -> Upper limit on detection rate is a few per year (uncertain due to unkown source physics)
  - HAWC Collaboration. Astropart.Phys. 35. (2012) 641 Taboada & Gilmore arXiv:1306.1127
  - CTA Consortium Astropart. Phys. 43. (2013) 252-275; Exp. Astr. 35, 3, 413-457

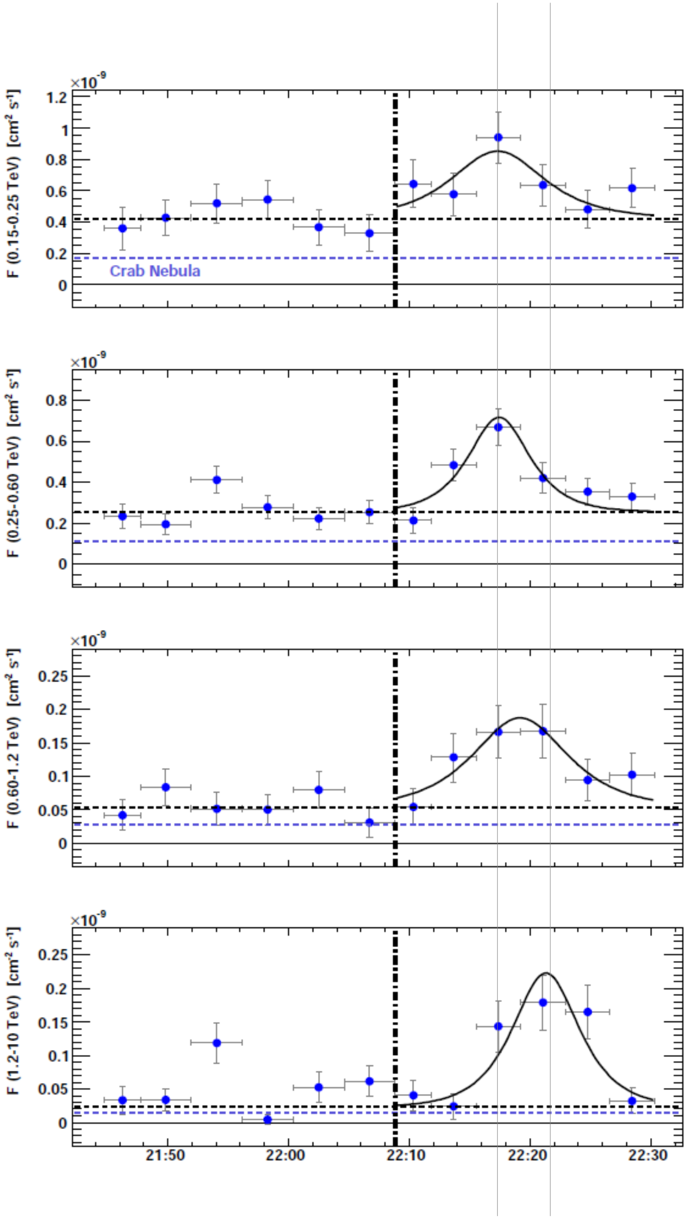
A complementary approach to VHE GRB observations

CTA	**HAWC**
Long GRB	Short GRB
afterglow	prompt emission

CTA and HAWC will probe LIV with GRB detections far beyond the Planck scale (linear term)

Source intrinsic effects the ultimate hurdle?

- Mrk 501
- July 9, 2005 flare
- z = 0.034
- Delay observed between 150 GeV and 1 TeV (2.5 sigma)
- Linear: $E_{LIV} > 2.1 \times 10^{17}$ GeV
- Quadratic: $E_{LIV} > 2.6 \times 10^{10}$ GeV



MAGIC Collaboration, Astrophys.J.669:862-883,2007

How to distinguish between source and propagation effects?

Answer: Search for redshift dependence

-> requires large number of detected flaring AGN, GRB, pulsars

Prospects of doing LIV Tests with gamma-rays

- Only a handful of constraining observations so far
  - Ten times more sources will have a significant impact but needs ten times more sensitive instruments (VERITAS -> CTA, HAWC)
  - Source effects could hide LIV effects
- Quadratic term not well constrained but could be dominating term in LIV
  - Reaching higher energy is more important than distance -> ground based gamma-ray instruments preferred: VERITAS, CTA, HAWC
  - Best available limits already come from IACT like VERITAS
- For the upper end of predicted range expect similar rate of detecting GRB with CTA/HAWC than with Fermi-LAT but at higher energies (factor 10 or more)

CTA, HAWC:
Transitioning from individual source studies to population studies for LIV