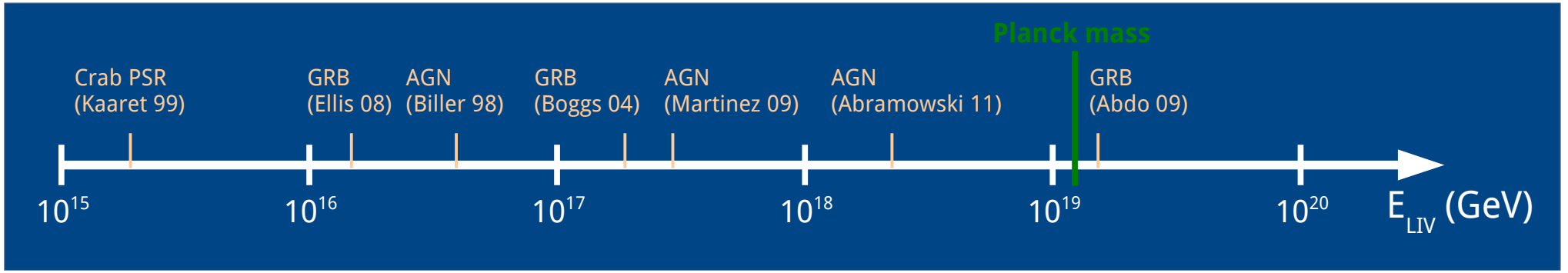
Georgia Tech Physics College of Sciences

Tests of Lorentz Invariance Violation with Gamma-rays



Nepomuk Otte

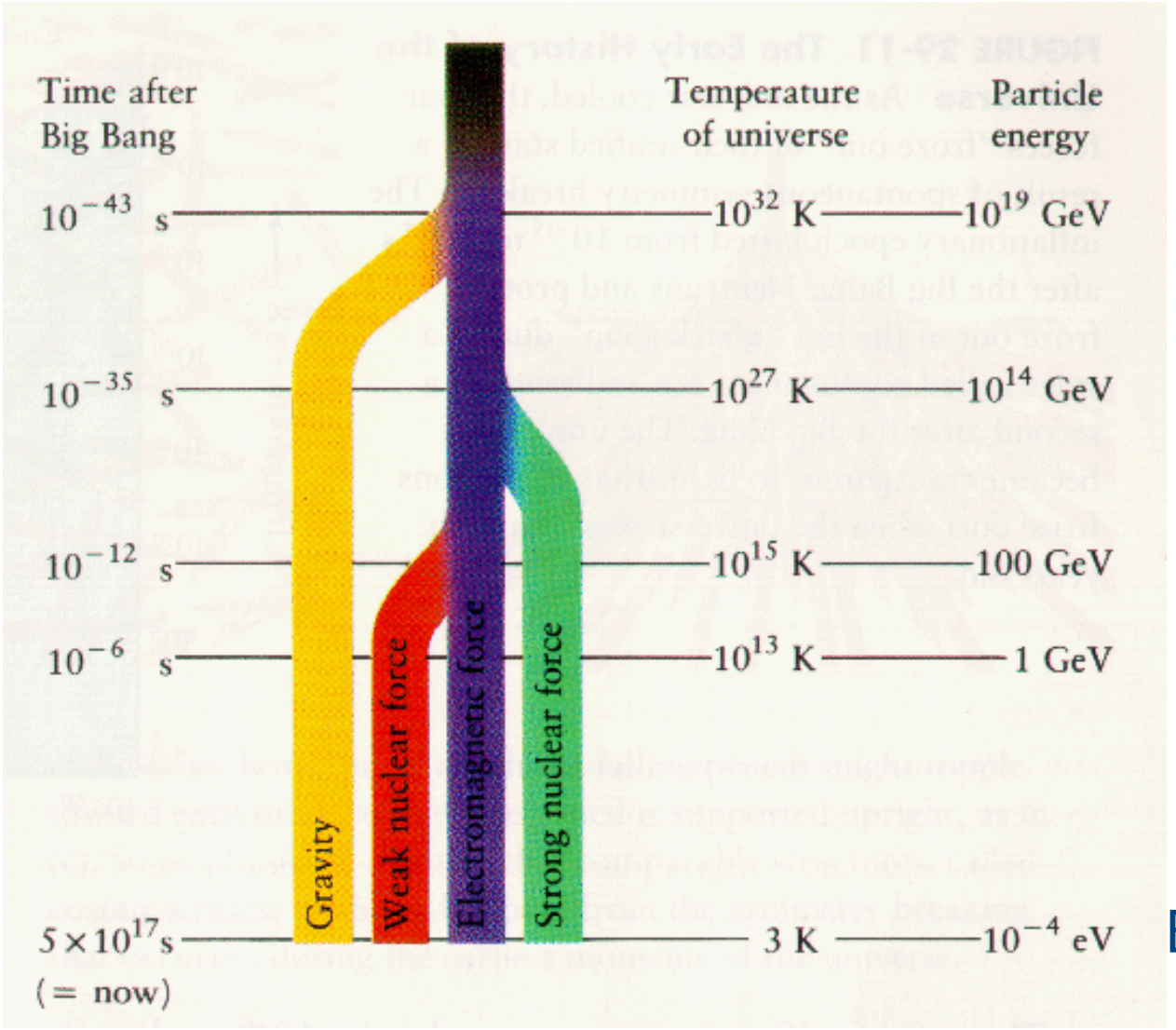
G. Sinnis, M. Errando, B. Zitzer, F. Stecker, V. Vasileiou, P. Kaaret, S. Griffith, I. Taboada, A. McCann

Topics addressed in this Talk

(not necessarily on this order)

- Why testing LIV?
- How to test LIV with gamma rays?
  - Energy dependent dispersion
    - AGN, GRB, pulsar
  - Threshold effects
    - Vacuum Cherenkov Radiation
    - Shift in threshold energy for pair production
- What limits tests for LIV in gamma-rays?
  - Source effects
- How to improve beyond systematic limits?
- What are prospects of testing LIV in gamma-rays?

Why test LIV?



- Because of its fundamental nature
- Probe physics at Planck energy (10^{19} GeV): Microscopic structure of space time
  - Quantum Gravity?
  - String Theory?
- Energy scale not possible to access directly
- Use theoretical predictions to search for effects:

Lorentz Invariance Violation

Energy dependent dispersion
Threshold effects

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)
- Threshold for pair production increased -> lower gamma-ray opacity from EBL absorption
  Constrained from AGN observations in TeV (20 TeV, Mkn 501)
  $\delta < 2(m_e/E_\gamma)^2 = 1.3 \times 10^{-15}$

Expect only modest improvements of these constraints in the future (~ factor 5)

Energy dependent Dispersion in Photon Sector

$$c'(E) = c + \underbrace{a \cdot \frac{E}{E_{\mathrm{LIV}}}}_{\text{Linear term}} + \underbrace{b \cdot \left(\frac{E}{E_{\mathrm{LIV}}}\right)^2}_{\text{Quadratic term}}$$

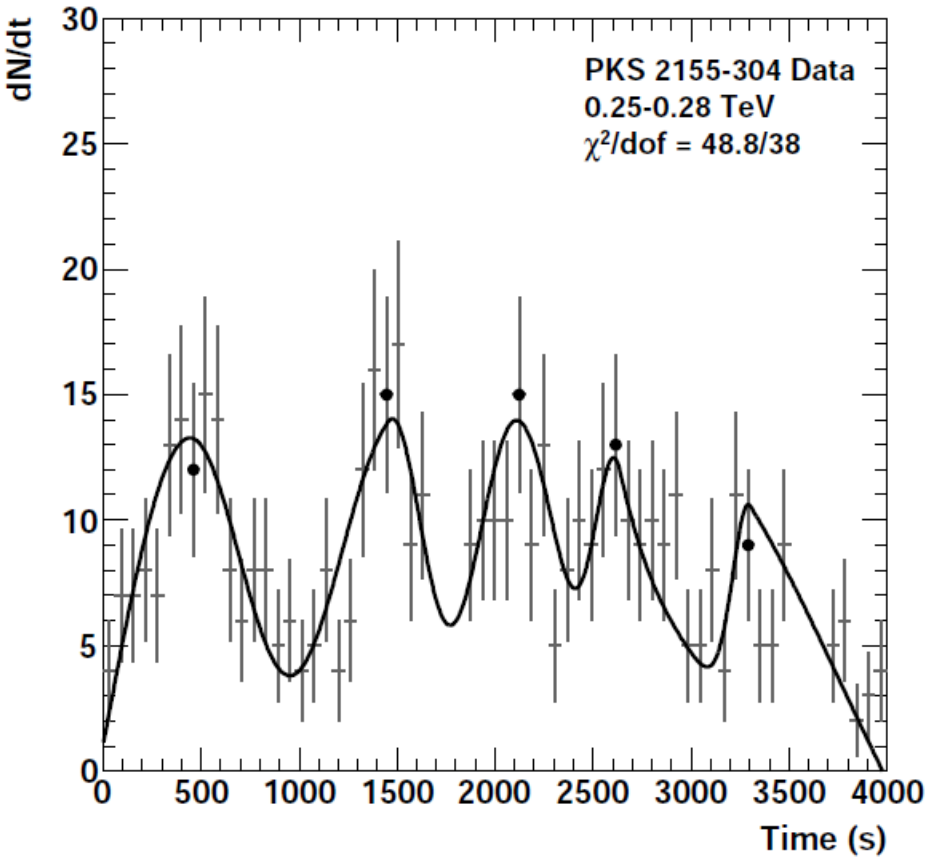
$$\Delta t_1 = \frac{d}{c} \cdot \frac{E_{\mathrm{h}} - E_{\mathrm{l}}}{E_{\mathrm{LIV}}} \qquad \Delta t_2 = \frac{d}{c} \cdot \frac{3}{2} \cdot \frac{E_{\mathrm{h}}^2 - E_{\mathrm{l}}^2}{E_{\mathrm{LIV}}^2}$$

-> Photon energy dependent propagation times

Macroscopic effect if large distances **d** and high photon energies **E**

only possible with gamma-ray astroparticle physics

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: $E_{LIV} > 2.1 \times 10^{18}$ GeV
- Quadratic: $E_{LIV} > 6.4 \times 10^{10}$ GeV

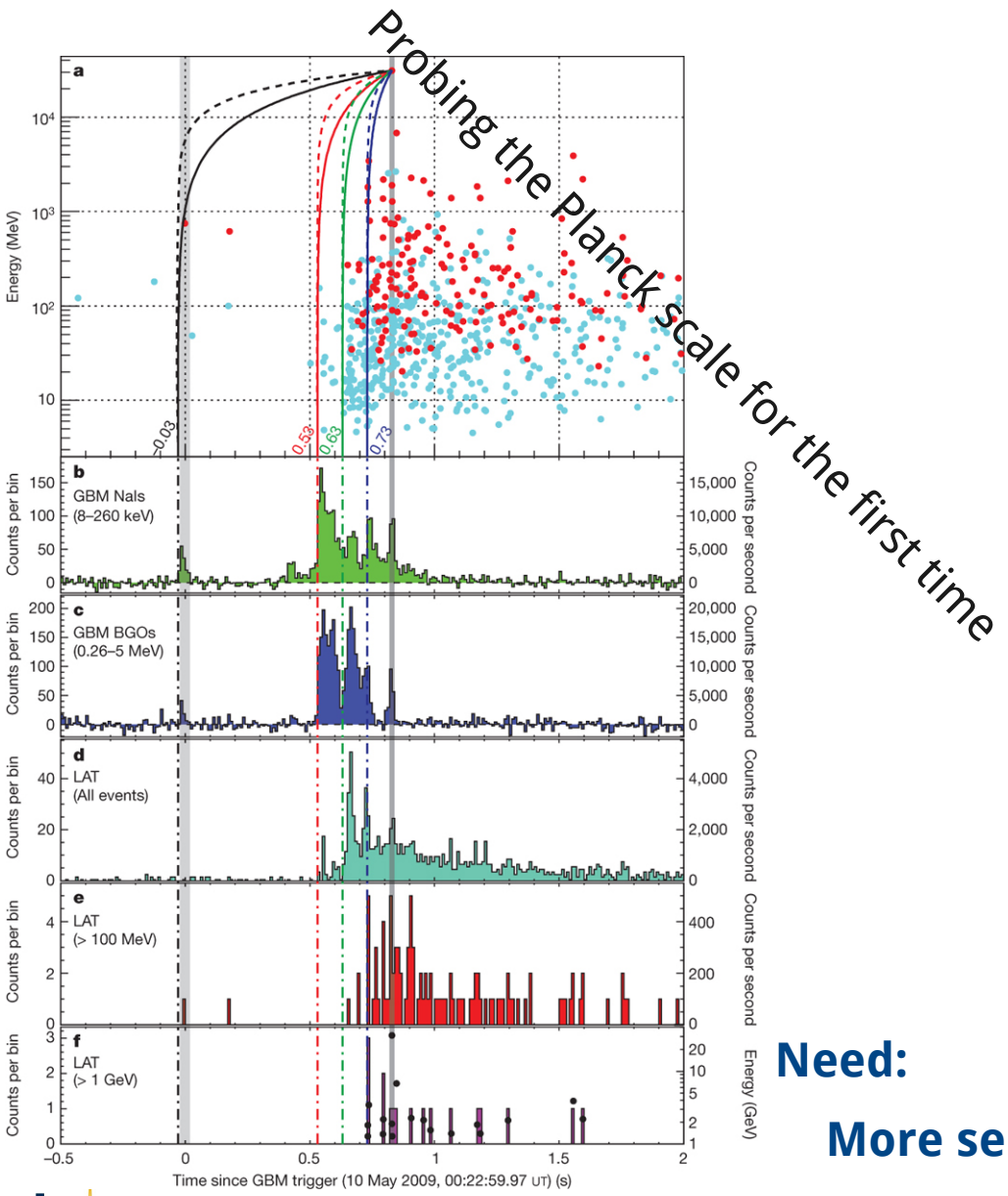
Short time scale TeV gamma-ray window opened with recent generation of IACT: H.E.S.S., **VERITAS**, and MAGIC

Shorter timescales possible? -> need CTA

More statistics (detections) -> VERITAS, CTA

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

LIV Tests with GRBs



- 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

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 100 GeV (GRB 090510)
- Big improvement with CTA/HAWC -> Upper limit on detection rate is a few per year (uncertain due to unkown source physics)

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)

LIV Test with Pulsars

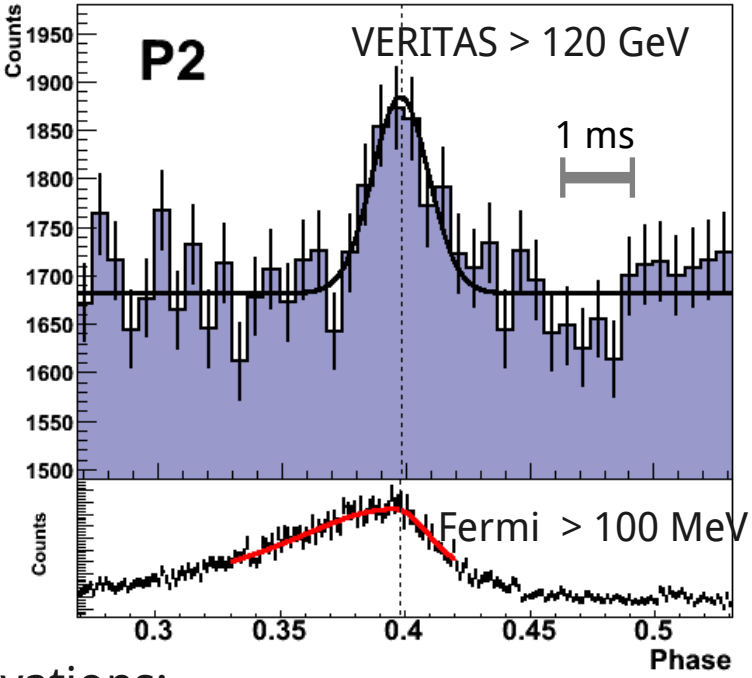
A.N.O. ICRC (2011). http://arxiv.org/abs/1208.2033

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

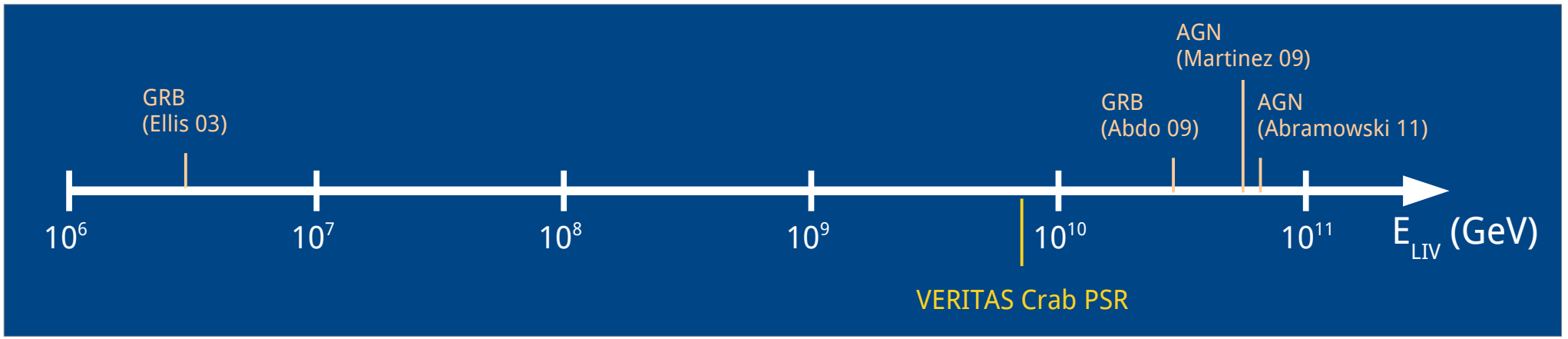


Improved limits (factor 10) with more sensitive observations:

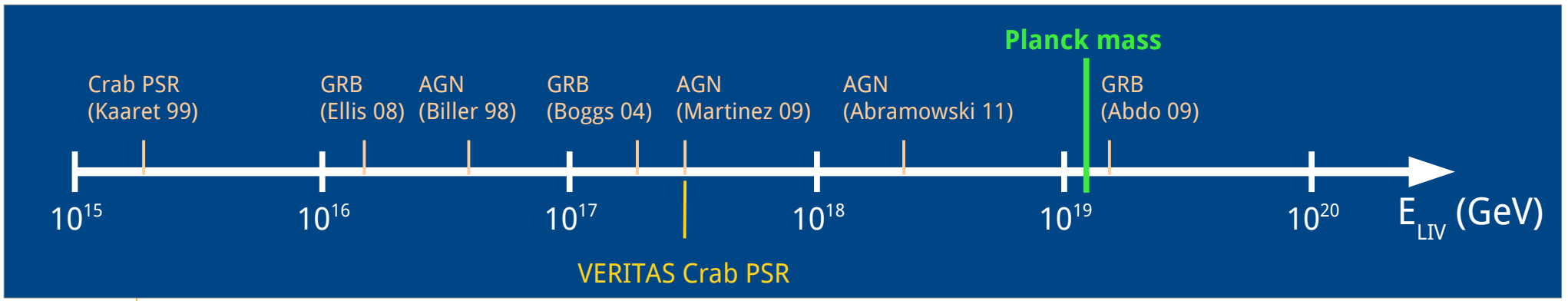
- Deeper observations: **VERITAS**
- Higher sensitivity instruments: **CTA**
- Detection of other pulsars in the VHE band: **VERITAS**, **CTA**

An Overview over various Limits

Quadratic term:



Linear term:



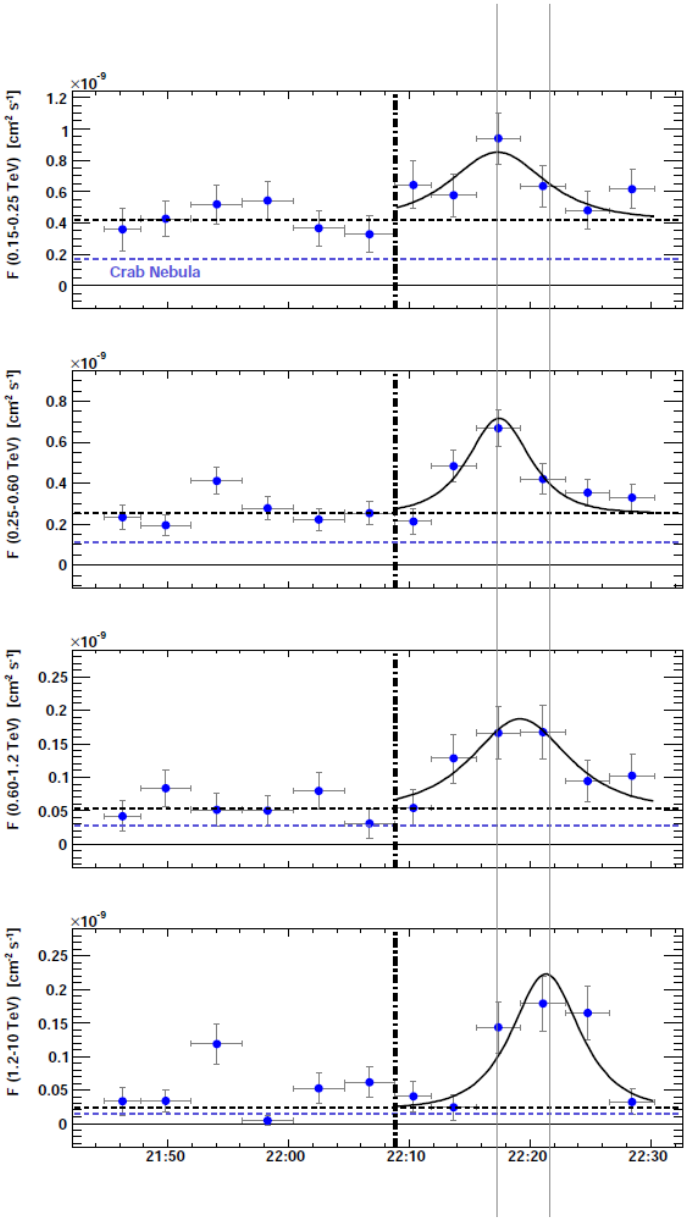
Source intrinsic effects the ultimate hurdle?

- 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

How to distinguish between source and propagation effects?

Answer: Search for redshift dependence

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



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

Prospects of doing LIV Tests with gamma-rays

- Only a handful of constraining observations so far
  - Source effects could hide LIV effects
  - Ten times more sources will have a significant impact but needs ten times more sensitive instruments (VERITAS -> CTA, HAWC)
- 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