Title: Lorentz Invariance Violation searches with HESS

Date: Oct 22, 2012 03:00 PM

URL: http://pirsa.org/12100084

Abstract: The high flux and variability of the blazar PKS 2155-304 as observed by H.E.S.S. during the night of 28 July 2006 allowed a very high precision search for Quantum Gravity-induced energy-dependent time lags. In this talk, I will review the results published by the H.E.S.S. collaboration on this topic. In particular, I will emphasize the latest results obtained using a likelihood fit to study individual photon data. With this method and a proper error calibration procedure, a very high precision measurement was achieved leading to the best constraints on linear and quadratic terms of the dispersion relations obtained with an AGN so far.

Content

- Introduction: what we try to do
  - The formalism in use
  - Propagation vs. intrinsic lags
  - What we try to do
- Ground-based gamma-ray astronomy
  - Principles of ground-based gamma-ray astronomy
  - H.E.S.S.-I
- The H.E.S.S. results
  - The data: PKS 2155-304 flare of july 2006
  - Aharonian et al. (H.E.S.S. Collaboration) 2008, Phys. Rev. Lett., 101, 170402
  - Abramowski et al. (H.E.S.S. Collaboration) 2011, Astropart. Phys., 34, 738
- Conclusions
- Discussion on future developments

Introduction:
what we try to do

See also the talk by J. Granot on wednesday.

The formalism in use

- Lorentz Invariance Violation effects should appear at E ~ O($E_P = 1.2 \times 10^{19}$ GeV)
- For E << E_P, a series expansion is expected to be possible, giving:

$$c' = c\left(1 \pm \xi \frac{E}{E_{\mathrm{P}}} \pm \zeta^2 \frac{E^2}{E_{\mathrm{P}}^2}\right) \quad \text{at the 2}^{\text{nd}} \text{ order}$$

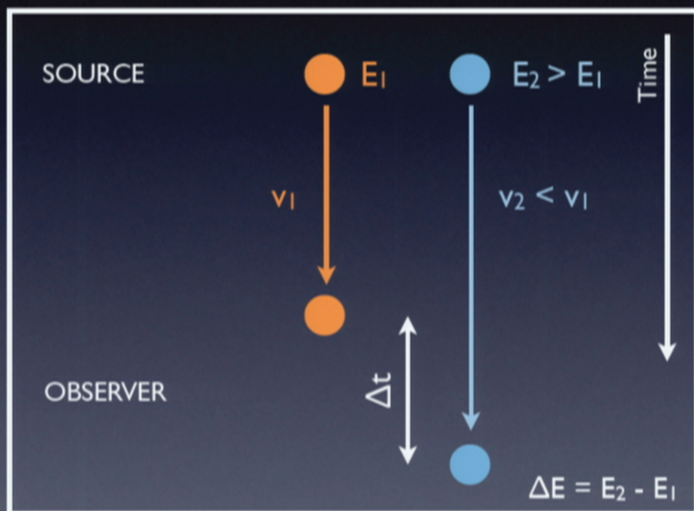
- Depending on their energies, photons travel at different speeds
- Tiny modifications can add-up over very large propagation distances and lead to measurable delays ➔ use of variable and distant sources (GRBs, AGN flares)
- We consider two photons with energie E_1 and E_2 emitted at the same time and detected at times t_1 and t_2.
  - At the first order : $$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_{\mathrm{P}} H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$
  - At the second order: $$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2E_{\mathrm{P}}^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$\Delta t = t_1 - t_2 \qquad \Delta E = E_1 - E_2 \qquad \Delta E^2 = E_1^2 - E_2^2 \qquad \Omega_\Lambda = 0.7 \qquad \Omega_m = 0.3$$

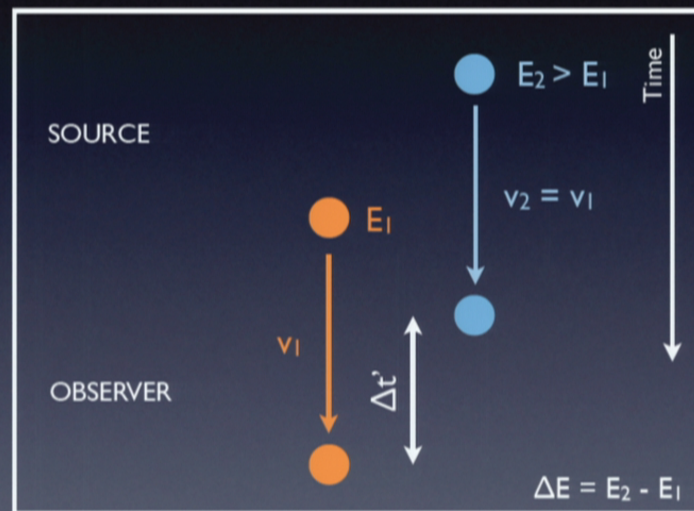
G. Amelino-Camelia et al., Nat. 395, 525 (1998) - U. Jacob & T. Piran, J. of Cosmology and Astropart. Phys. 1, 31 (2008)

QG Effects vs. Source Effects

- BUT : Emission processes or the structure of the source can introduce a time lag too !
- It is necessary to separate the two effects → population studies



Quantum Gravity effect



Possible source effect

Propagation → LIV Effect

Emission → Source Effect

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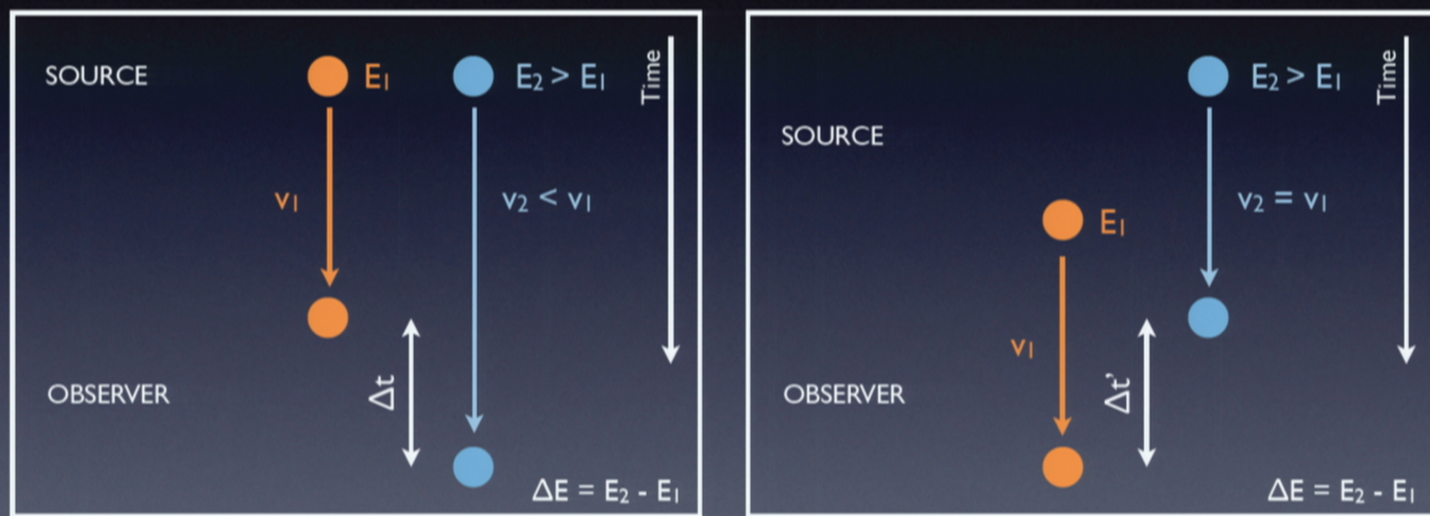
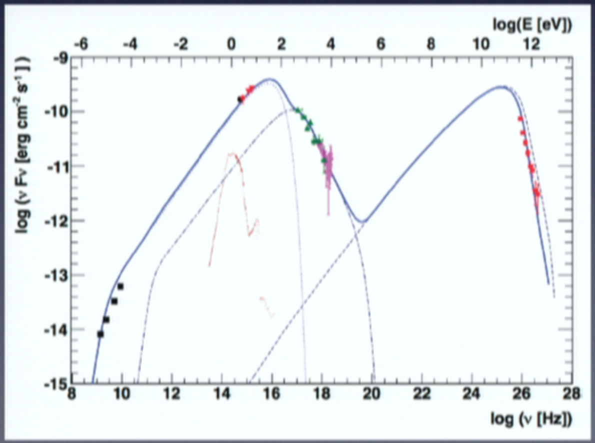


Quantum Gravity effect | Possible source effect

Propagation → LIV Effect | **Emission → Source Effect**

QG Effects vs. Source Effects (2)

- Assumption:
  - ➡ Source effect are neglected !
- To reduce the impact of this assumption,
  - ➡ We consider only one source of data (H.E.S.S.)
  - ➡ Photons are emitted by the same physical process (IC)
- It will be crucial to understand source effect if a significant lag is measured...



A. Abramowski et al. (H.E.S.S. Collaboration), A&A 539, A149 (2012)

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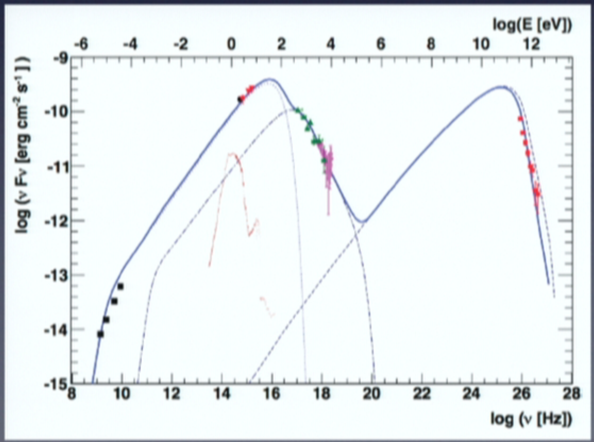

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Summary: what we try to do

- We consider sources that are
  - Variable → Because we need to measure time lags
  - Distant → Because lags will be larger if the propagation distance is larger
- We consider an energy domain where only one emission process is thought to dominate
  - Inverse Compton regime for H.E.S.S.

    → In principle, minimize source effects
  - Remaining intrinsic effects are neglected
- We compare
  - Light curves in two energy domains (CCF, CWT)
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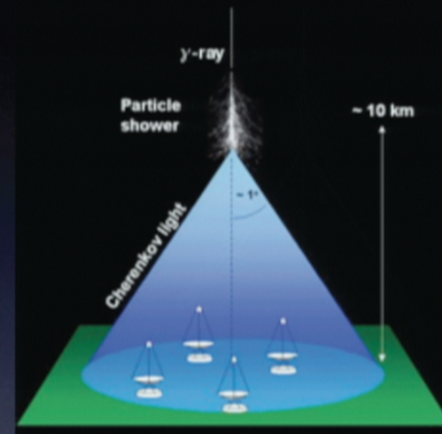
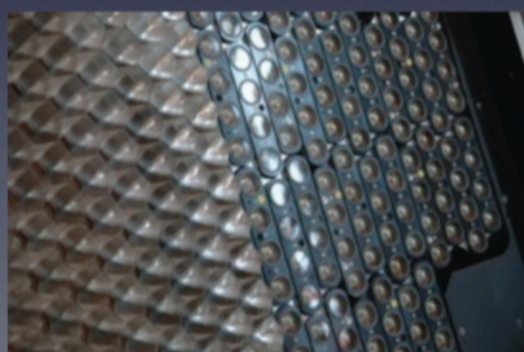
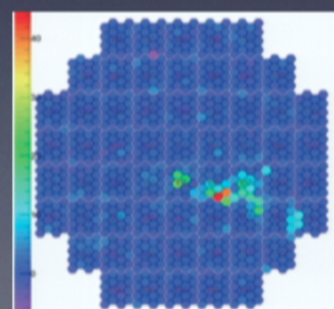
Principles

- Production of a shower of particles
- Faint and short flash of Cherenkov light
- Image of the shower on a fast camera in the focal plane
- Analysis of the image:
    - Shape → Type of the particle
    - Intensity → Energy
    - Orientation → Direction
- Stereoscopy: direct measurement of the origin of the γ, multiplicity of the images

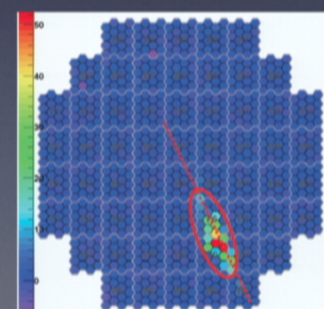




Hadron



Gamma



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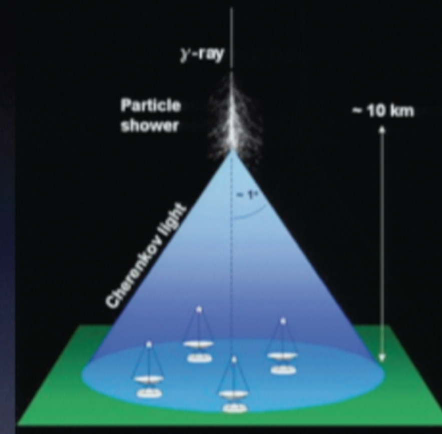

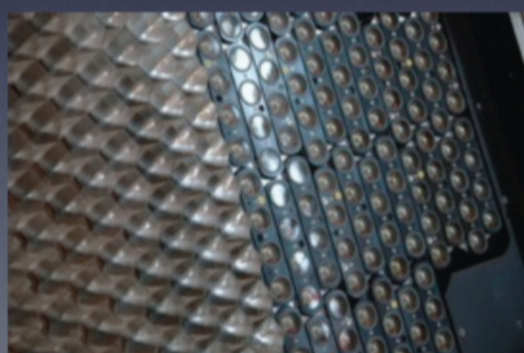

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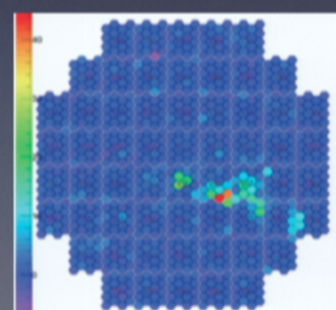

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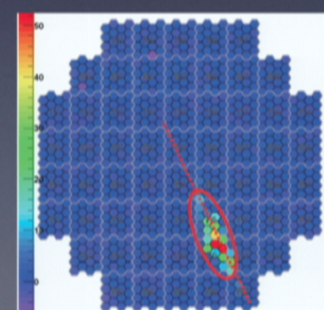
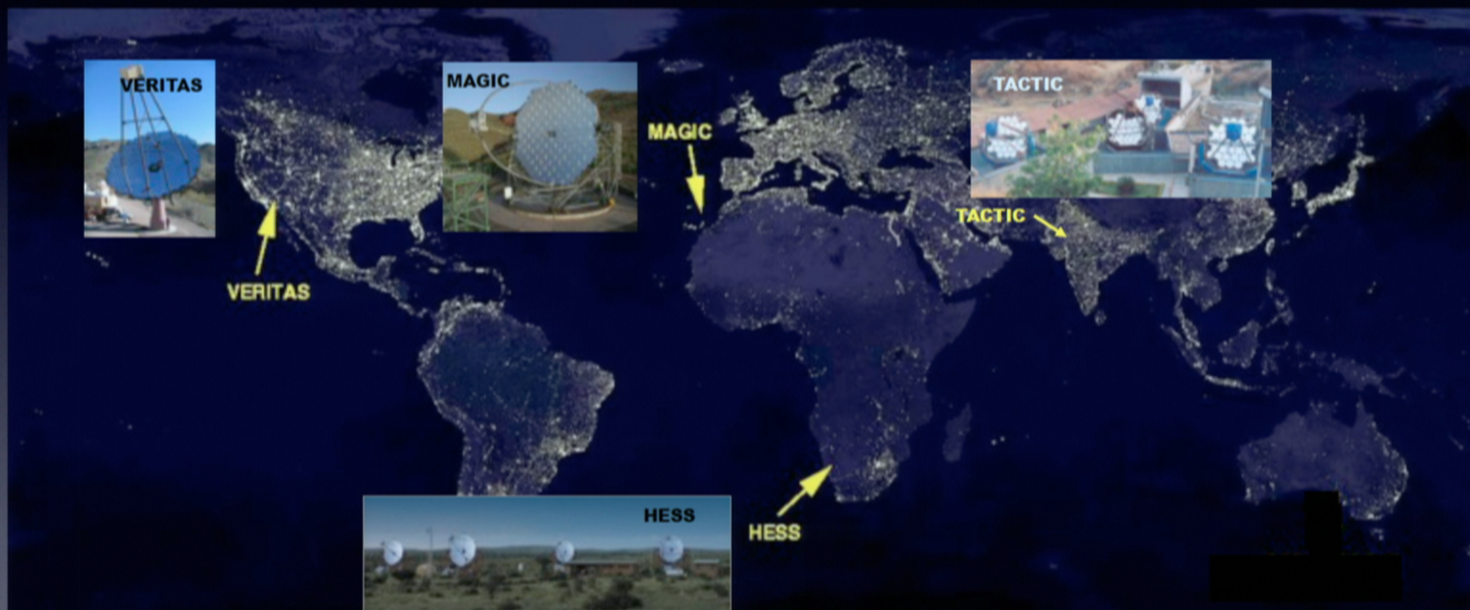
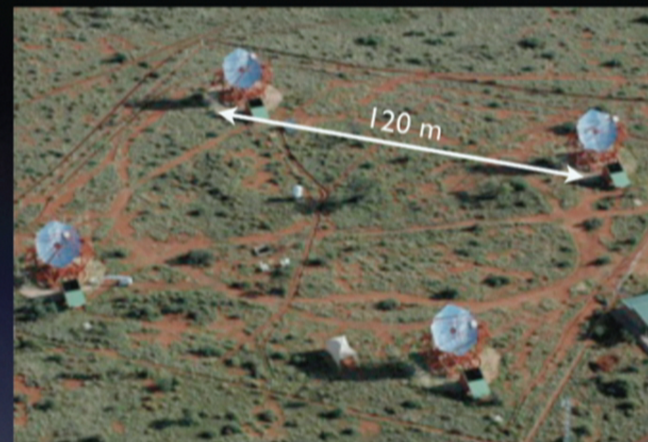


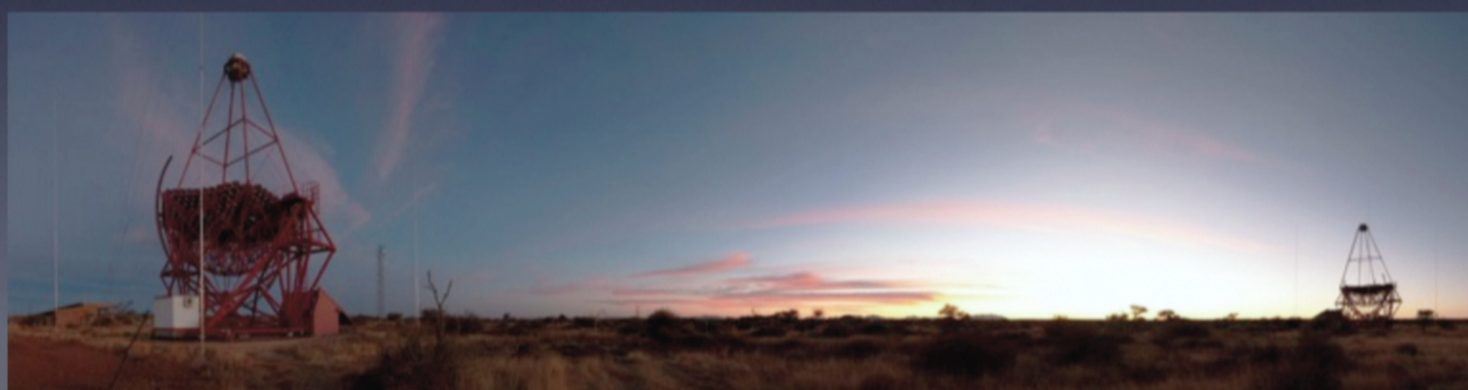
In the world...



H.E.S.S.-I

- High Energy Stereoscopic System
- 4 telescopes located in Namibia
- 12 m diameter, 15 m focal length
- Field of view ~5°
- Angular resolution < 0.1°
- Energy resolution ~15%
- Energy range from ~100 GeV to ~100 TeV
- More than 60 sources discovered





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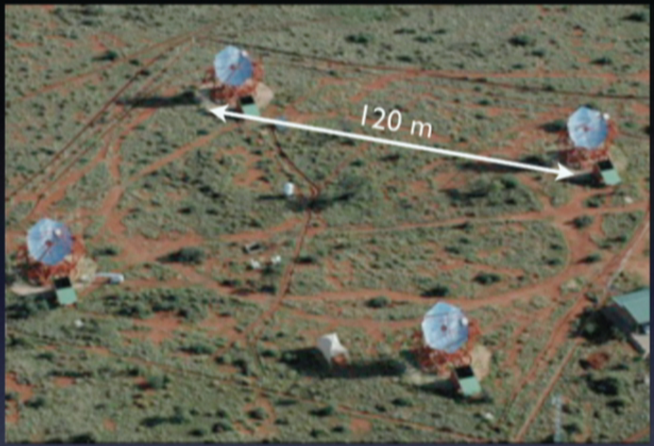

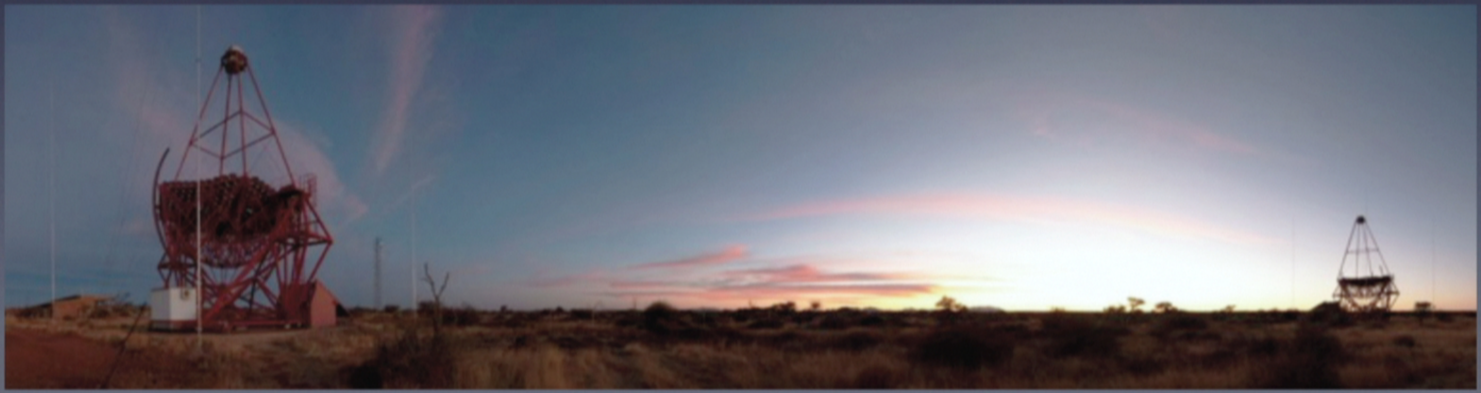

The data : PKS 2155-304

- BL Lac object
- z = 0.116 (~490 Mpc)
- Flare in july 2006
  - High flux → ~14 Crab
  - High statistics → ~10000 photons after cuts
  - Broken power-law spectrum
  - High variability:
    - Minute time-scale variability
    - Rise and fall-times of ~200s
- «Ideal» data:
  - Low zenith angle
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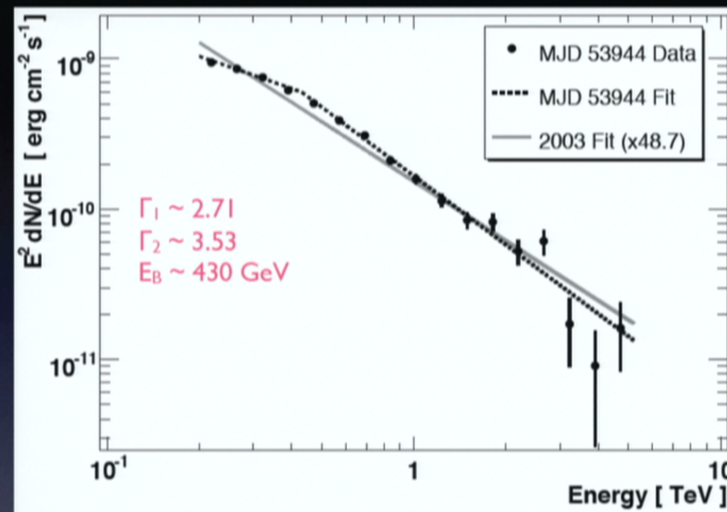
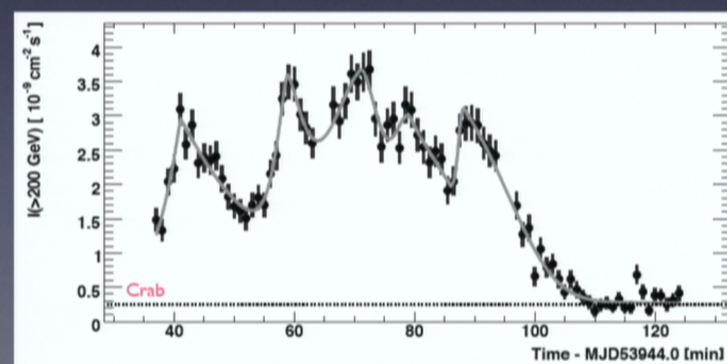
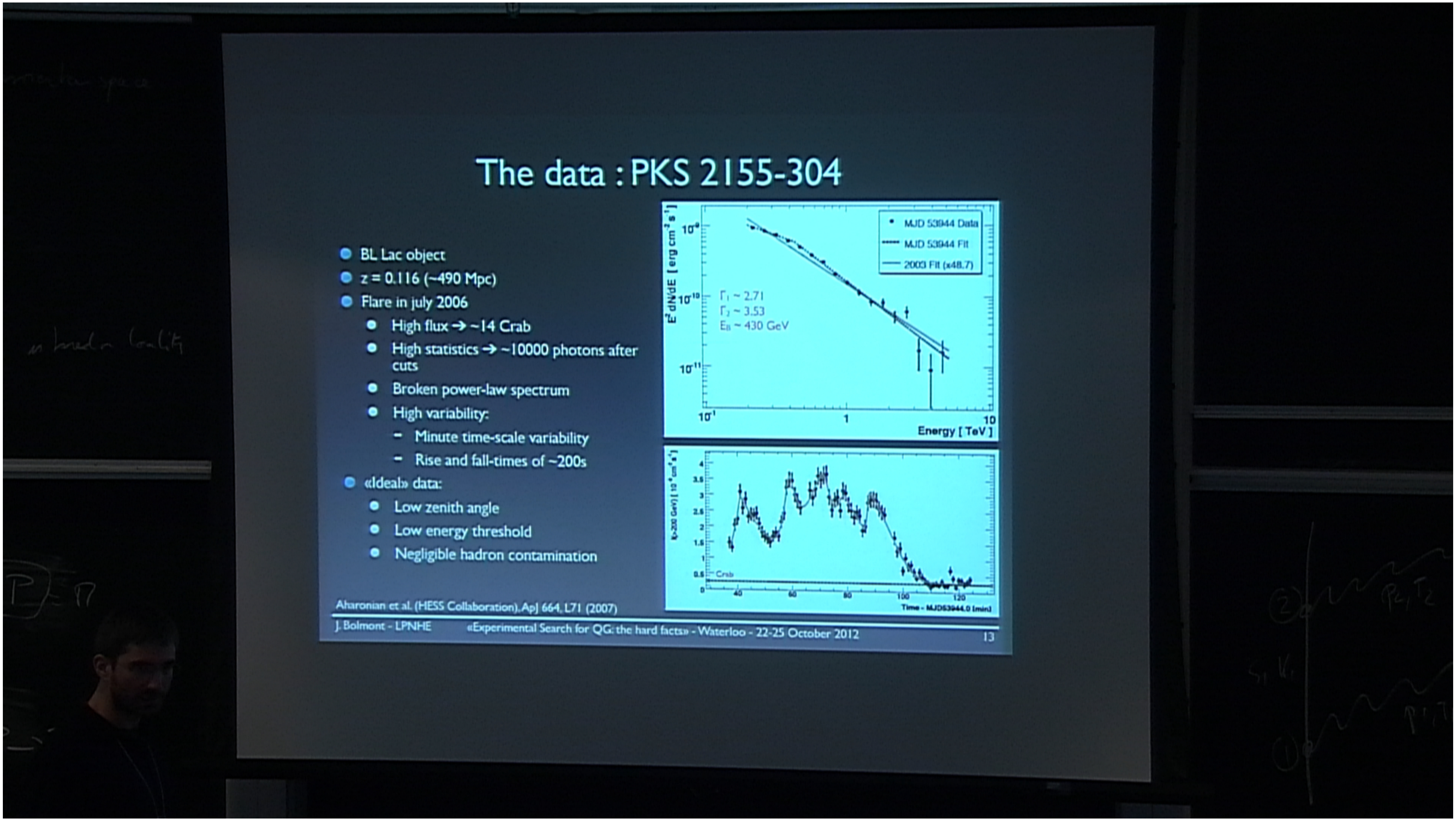




Aharonian et al. (HESS Collaboration), ApJ 664, L71 (2007)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MJD 53944 Data
MJD 53944 Fit
2003 Fit (x48.7)
Γ1 ~ 2.71
Γ2 ~ 3.53
EB ~ 430 GeV
Energy [TeV]
Crab
Aharonian et al. (HESS Collaboration), ApJ 664, L71 (2007)
J. Bolmont - LPNHE
«Experimental Search for QG: the hard facts» - Waterloo - 22-25 October 2012
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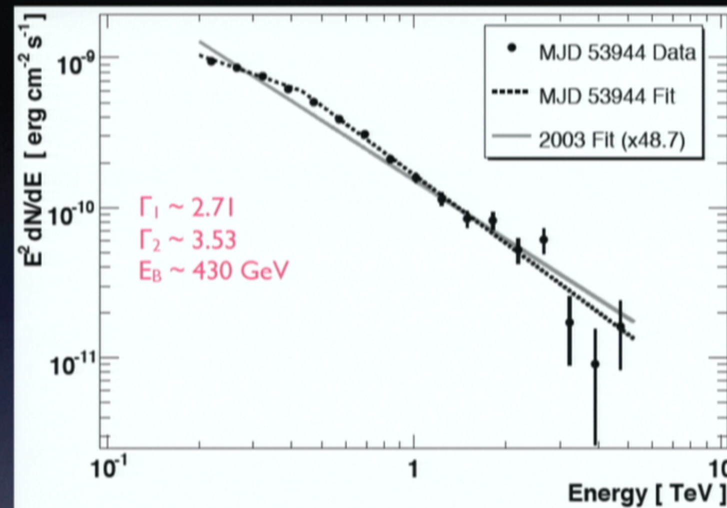

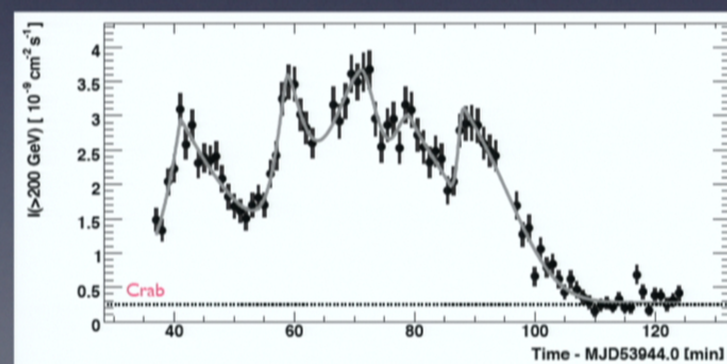

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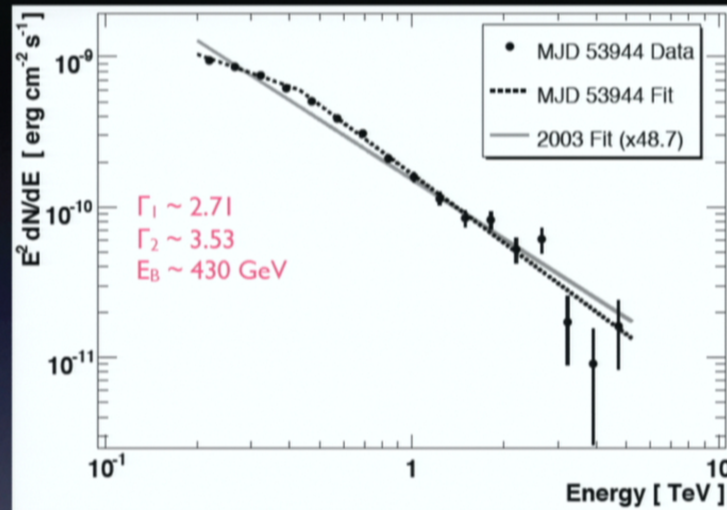

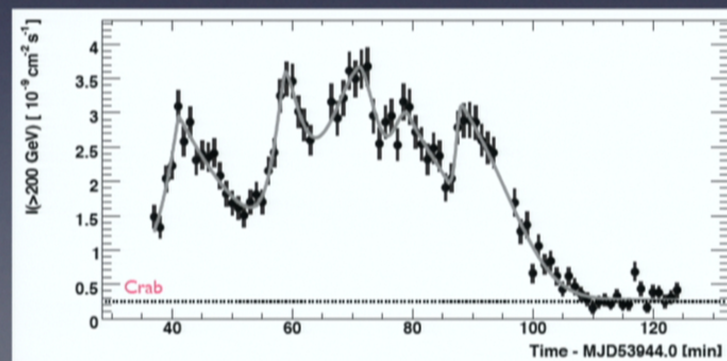

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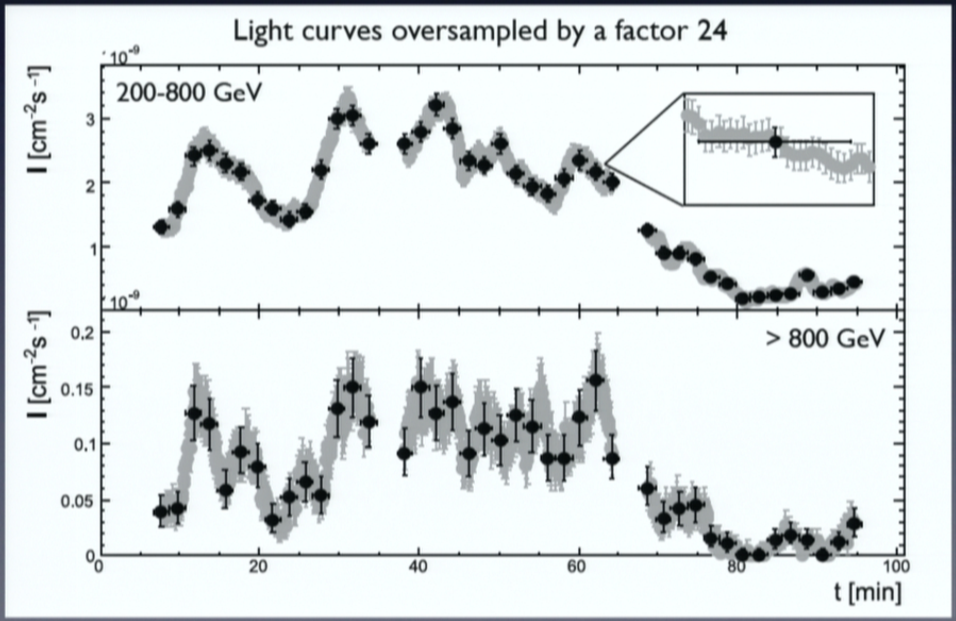
Methods

- Use of two analyses techniques on binned light curves
  - Cross Correlation Function (CCF)
  - Wavelet analysis (CWT: Continuous Wavelet Transform)



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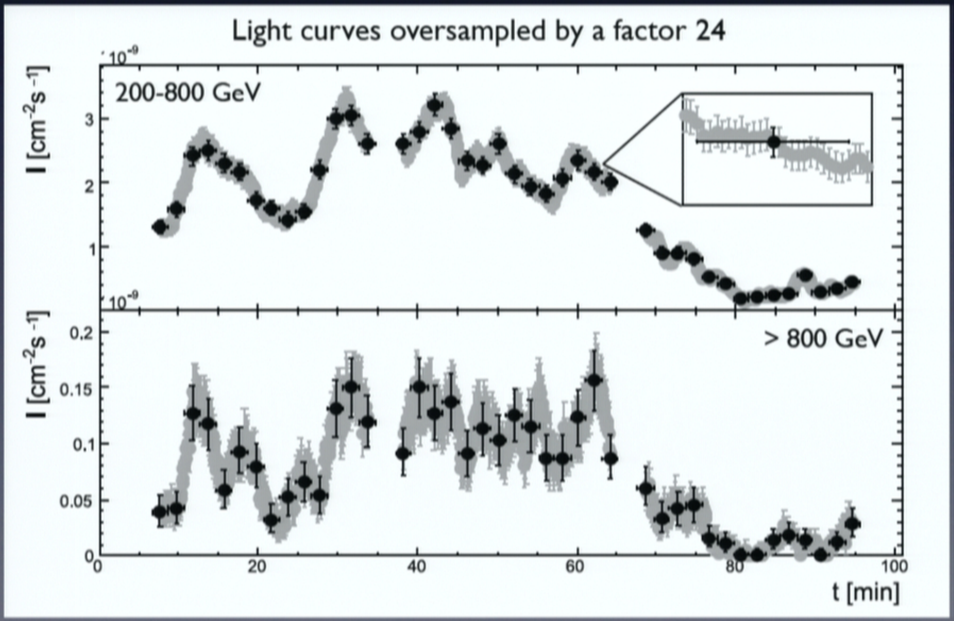
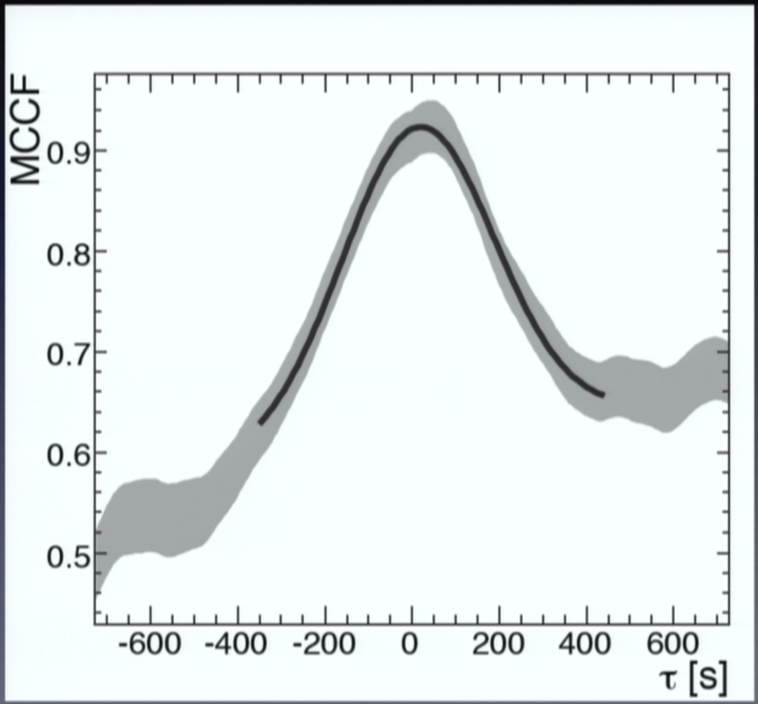


Measuring the time lag

- MCCF :
  - 200 < E < 800 GeV & E > 800 GeV
  - ΔE = 1 TeV
  - Fit with a gaussian + polynomial
  - τ_{peak} = 20 s
- CWT :
  - 210 < E < 250 GeV & E > 600 GeV
  - ΔE = 0.92 TeV
  - Two pairs of extrema identified
  - $<\tau>$ = 27 s



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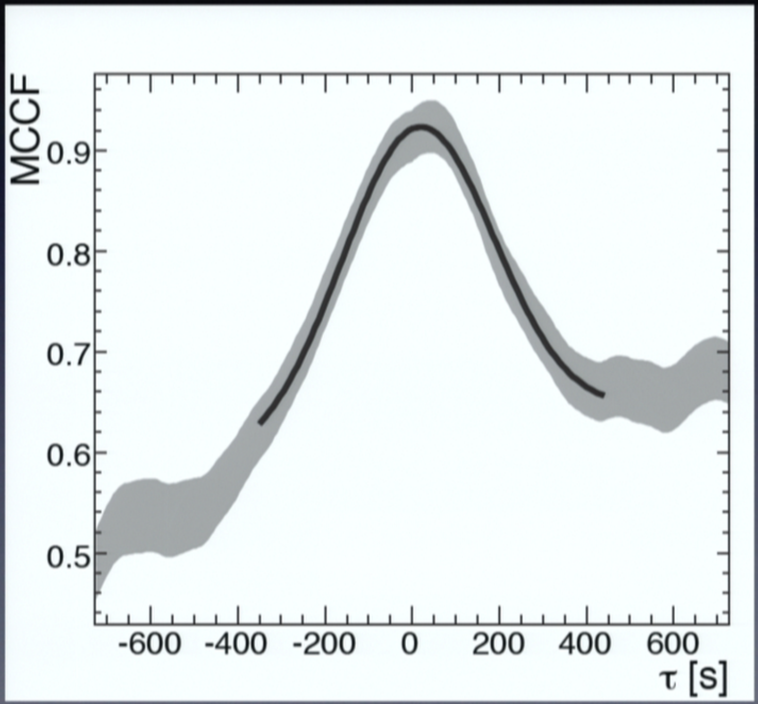

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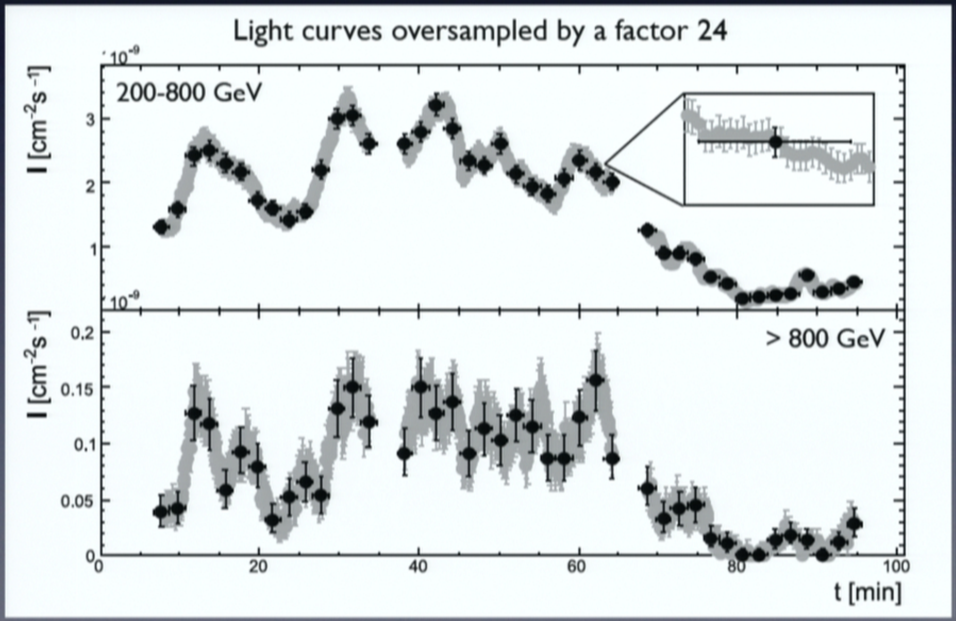
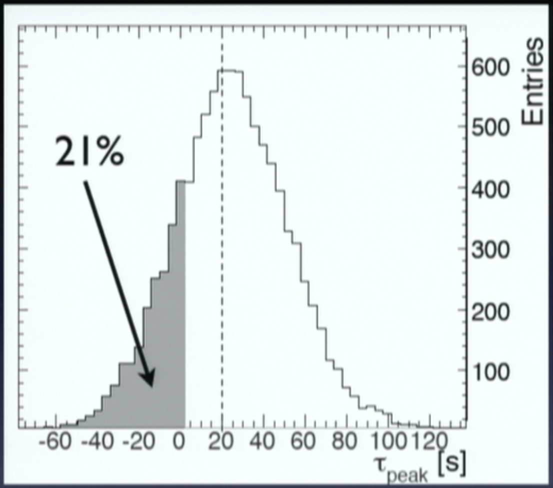
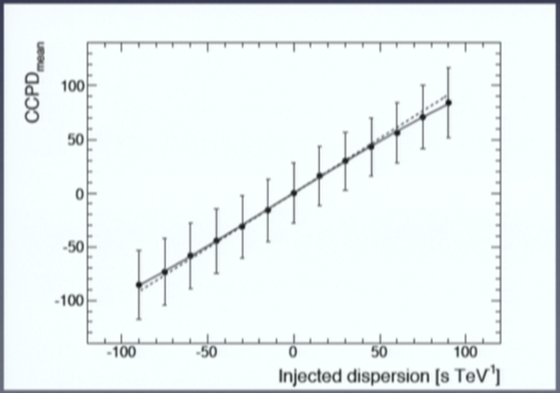


Error calibration (MCCF)

- Using a toy Monte Carlo
  - 10000 simulated light curves for each energy band
  - Flux varied within the measurement errors
  - MCCF computed and τ_{peak} measured
- Cross Correlation Peak Distribution
  - Mean = 25 s
  - RMS = 28 s
  - $\tau_{peak} < 0$ for 21% of the simulations
  - $\tau_{peak} = 0$ cannot be excluded
- Response to energy dispersion
  - Injecting a dispersion in the data
  - $|\Delta t/\Delta E| < 90$ s/TeV by steps of 15 s/TeV
- Same kind of procedure for the WT-based method





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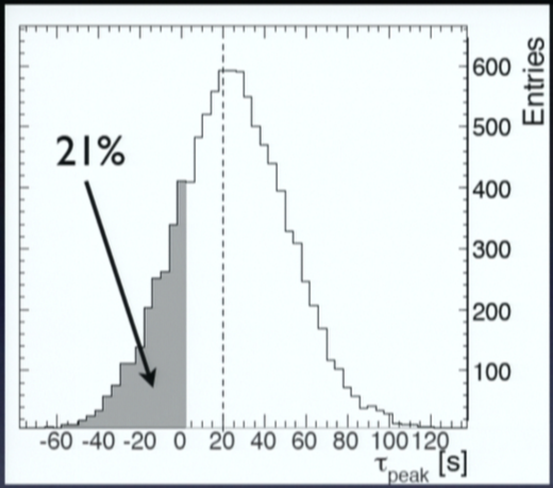

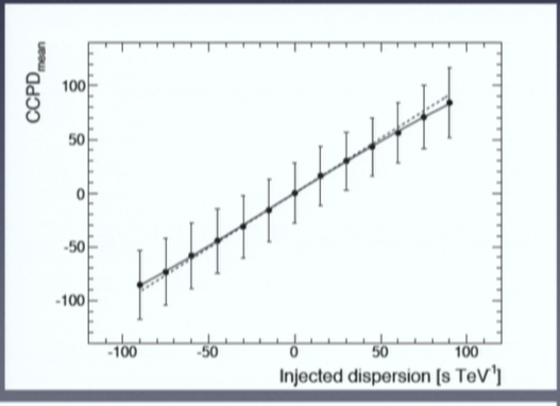

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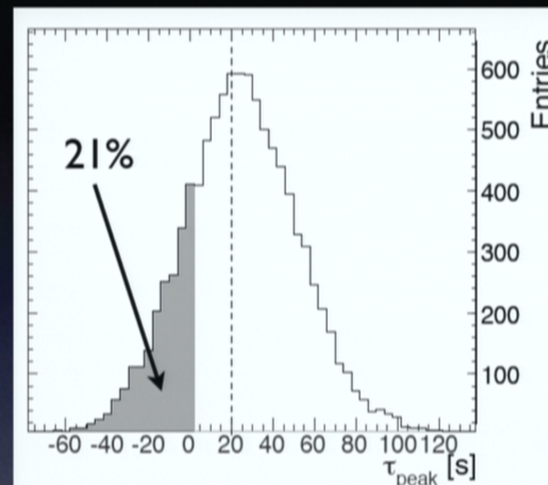

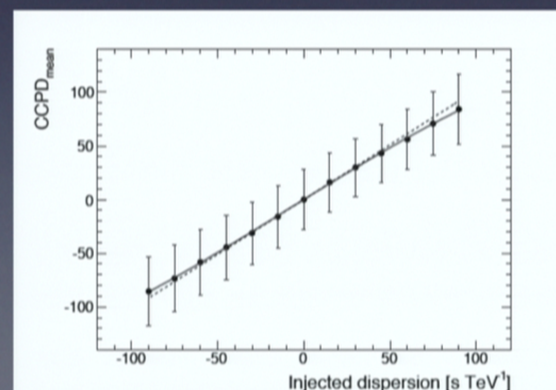

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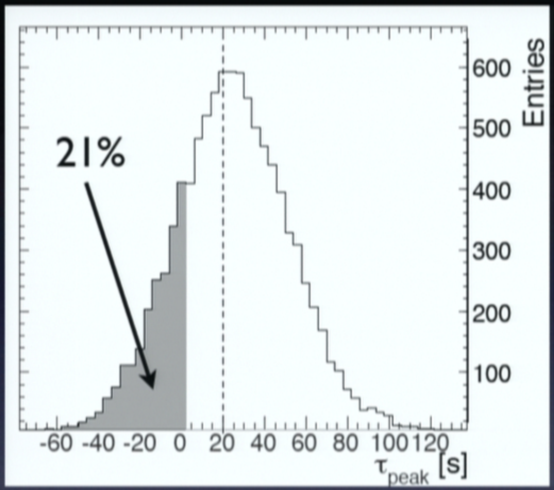

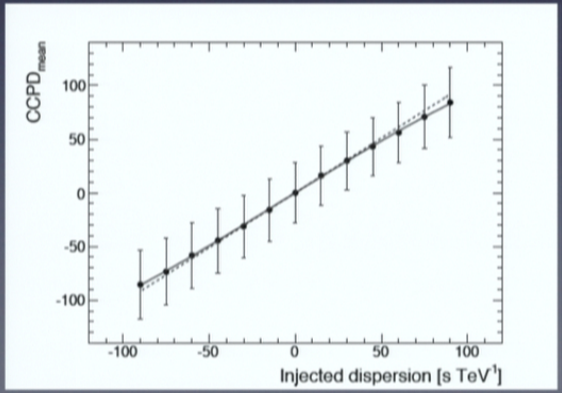

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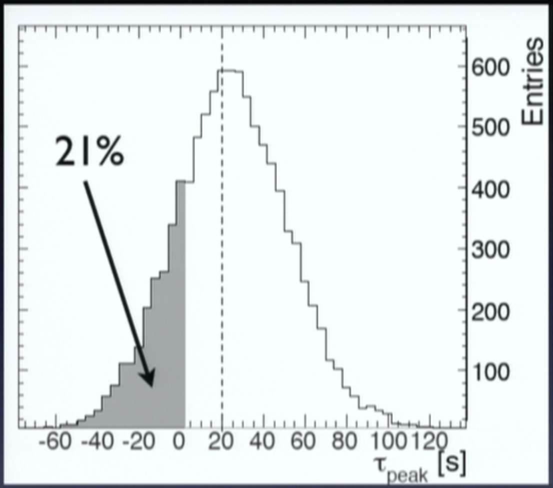
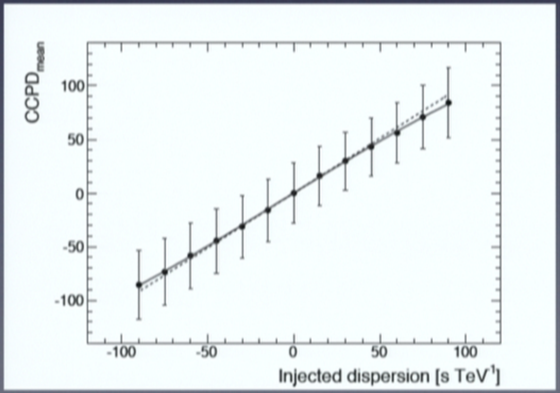
  - $\tau_{peak} < 0$ for 21% of the simulations
  - $\tau_{peak} = 0$ cannot be excluded
- Response to energy dispersion
  - Injecting a dispersion in the data
  - $|\Delta t/\Delta E| < 90$ s/TeV by steps of 15 s/TeV
- Same kind of procedure for the WT-based method





Error calibration (MCCF)

- Using a toy Monte Carlo
  - 10000 simulated light curves for each energy band
  - Flux varied within the measurement errors
  - MCCF computed and τ_{peak} measured
- Cross Correlation Peak Distribution
  - Mean = 25 s
  - RMS = 28 s
  - $\tau_{peak} < 0$ for 21% of the simulations
  - $\tau_{peak} = 0$ cannot be excluded
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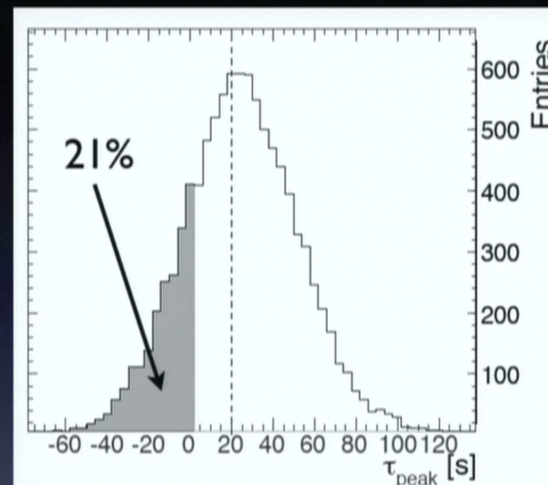

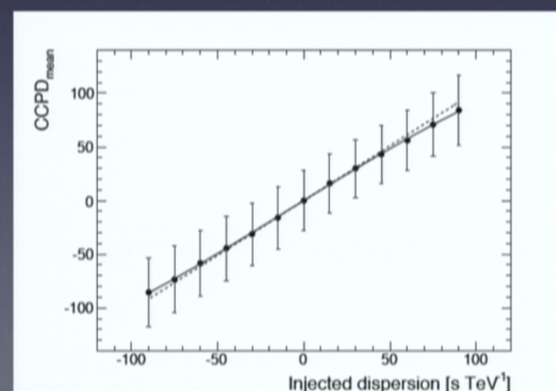

Results

Method	<ΔE> (TeV)	Δt/ΔE 95% CL (s/TeV)	E^l_{QG} 95% CL (GeV)	$\Delta t/\Delta E^2$ (s/TeV^2)	E^q_{QG} 95% CL (GeV)
MCCF	1.02	< 73	$> 7.2\times10^{17}$	< 41	$> 1.4\times10^{9}$
CWT	0.92	< 100	$> 5.2\times10^{17}$	-	-

- No lag measured → 95% CL limits derived on E_{QG} for linear and quadratic effects
- Differences between the two methods:
  - mean energy gaps <ΔE>
  - larger Δt measured with CWT
- Low sensitivity to the quadratic term

$M^l_{QG} > 7.2\times10^{17}$ GeV

$M^q_{QG} > 1.4\times10^{9}$ GeV

The Method

- Study of the correlation between the arrival time and the energy of the photons
- Method used by Lamon *et al.* for INTEGRAL and by Martinez and Errando for MAGIC
- We use the following form for the probability density function:

$$P(t,E) = N \int_0^\infty A(E_S)\,\Gamma(E_S)\,G(E-E_S,\sigma(E_S))\,F_S(t-\tau E_S)\,dE_S$$

where $\Gamma(E_S)$ is the emitted spectrum, $G(E-E_S, \sigma(E_S))$ is the smearing function in energy, $A(E_S)$ is the acceptance of H.E.S.S. and F_S is the emission time distribution at the source

- Here we assume linear and quadratic effects with a time-lag parameter τ expressed in s/TeV (s/TeV^2)
- The likelihood function is then given by the product

$$L = \prod_i P_i(t,E)$$

over all photons in the studied sample

- The maximum of the likelihood gives the time-lag τ_l (τ_q) in s/TeV (s/TeV^2)

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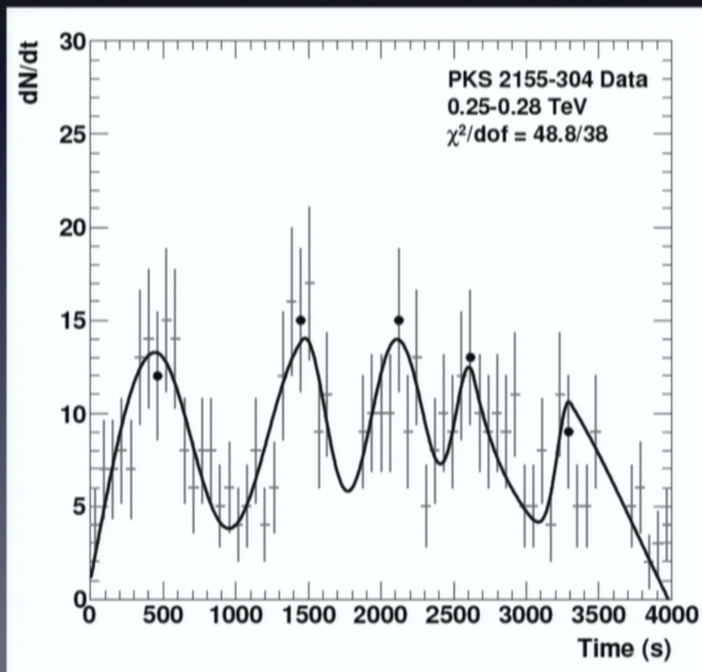
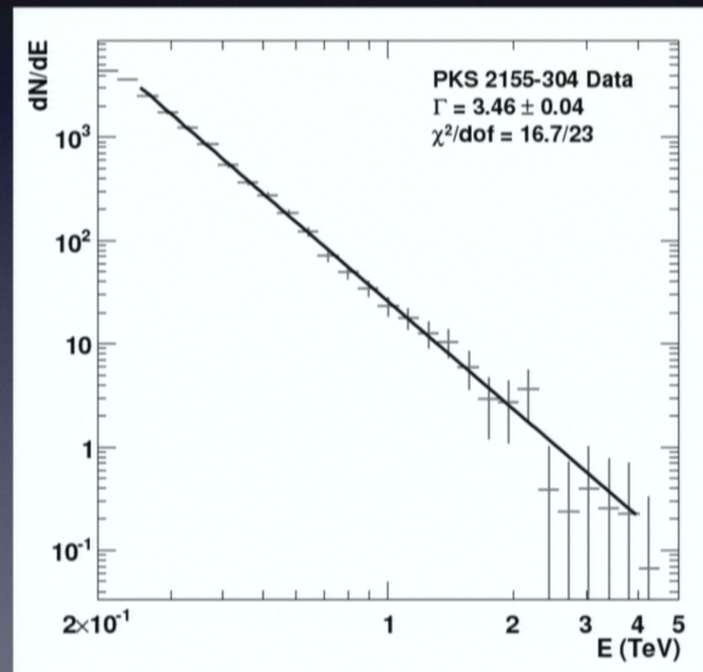
Application on PKS 2155 data

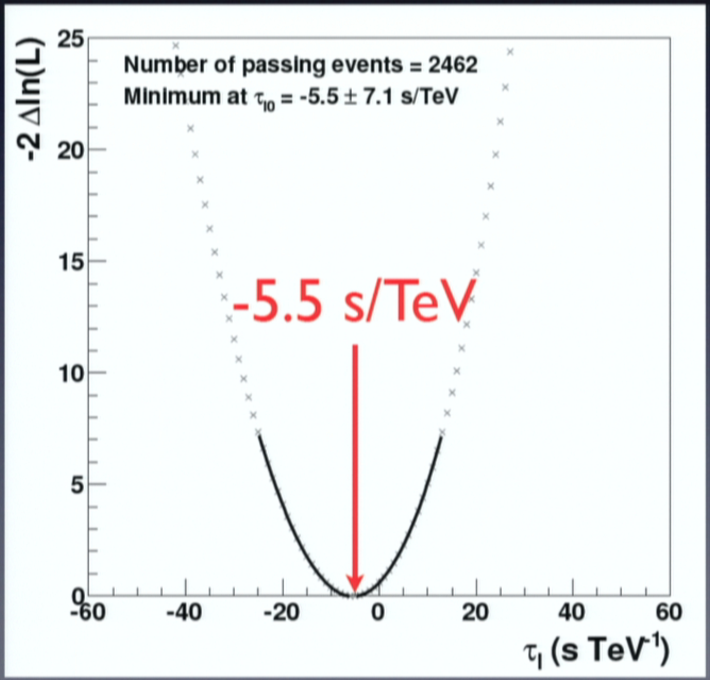
- The light curve and spectrum have to be parameterized
- F_S is approximated by the «template» light curve at low energies (0.25-0.28 TeV)

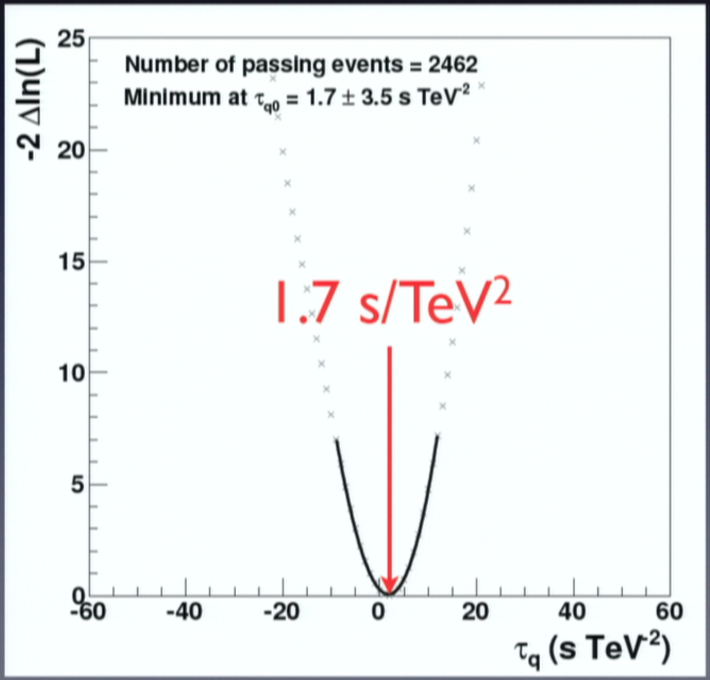




Application on PKS 2155 data

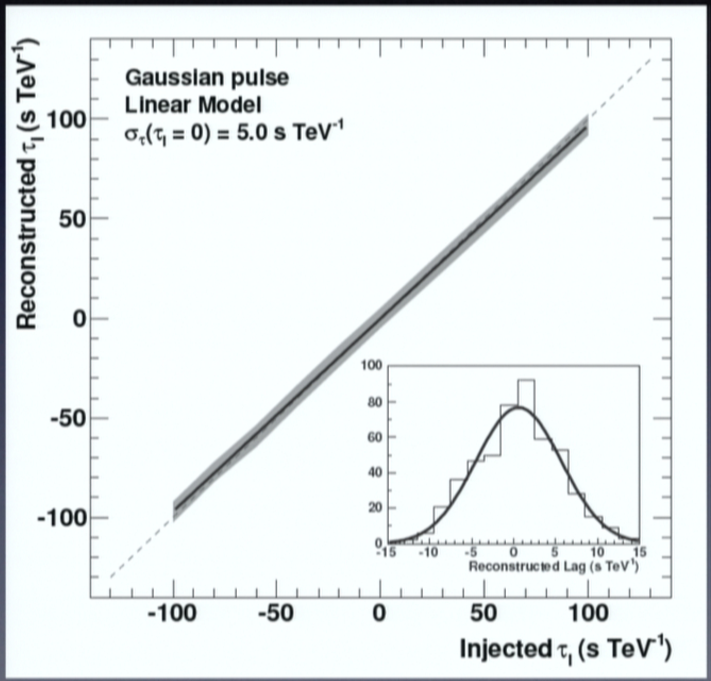
- Maximization of likelihood for the linear and quadratic cases
- Errors are obtained for $-2\Delta\ln(L) = 1$





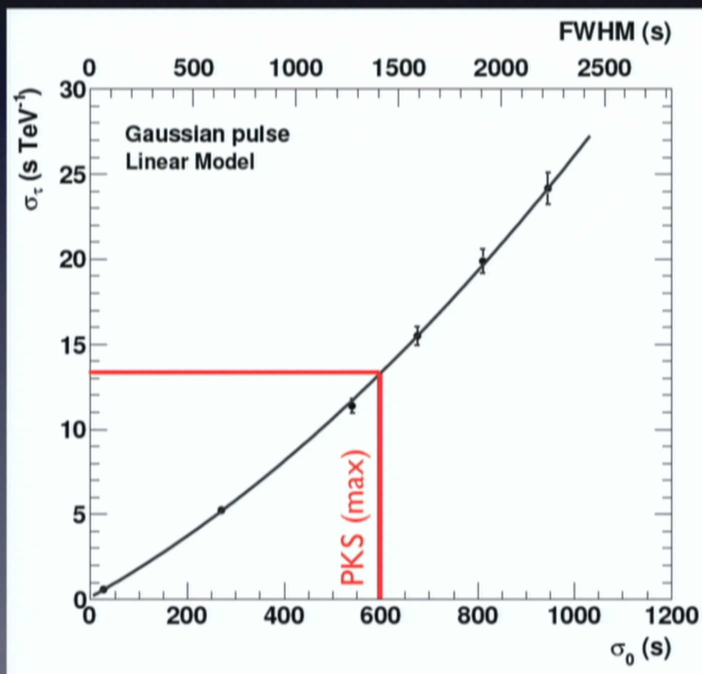
Error Calibration and Systematics

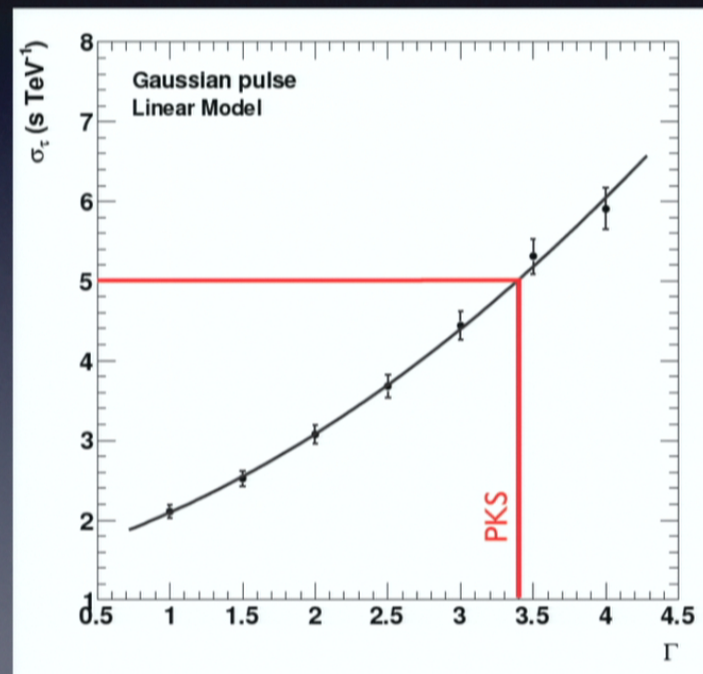
- A toy Monte Carlo was used to evaluate systematics and to calibrate the errors
- Generation of a set of photons
  - Same statistics as in data
  - Energy distribution according to the measured spectrum of PKS
  - Time distribution following a gaussian distribution or following the measured LC of PKS
  - Time lag injected in the range -100 s/TeV (s/TeV^2) to 100 s/TeV (s/TeV^2)
  - Lag reconstructed with the likelihood fit
- Important parameters:
  - The slope of the calibration curve
  - The width of the distribution of reconstructed lags σ_τ



Error Calibration and Systematics (2)

- Pulse shape: width and symmetry/asymmetry of the pulse
- Variation of the error with the spectral index





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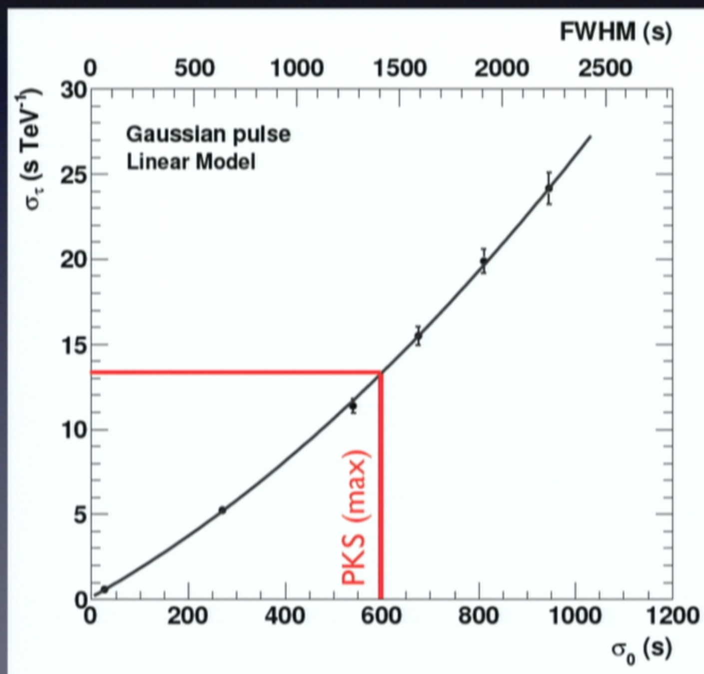
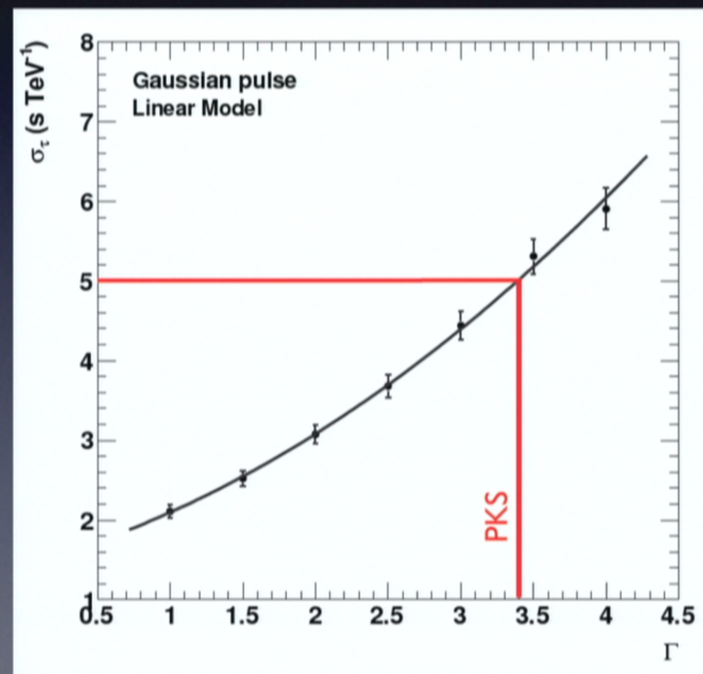
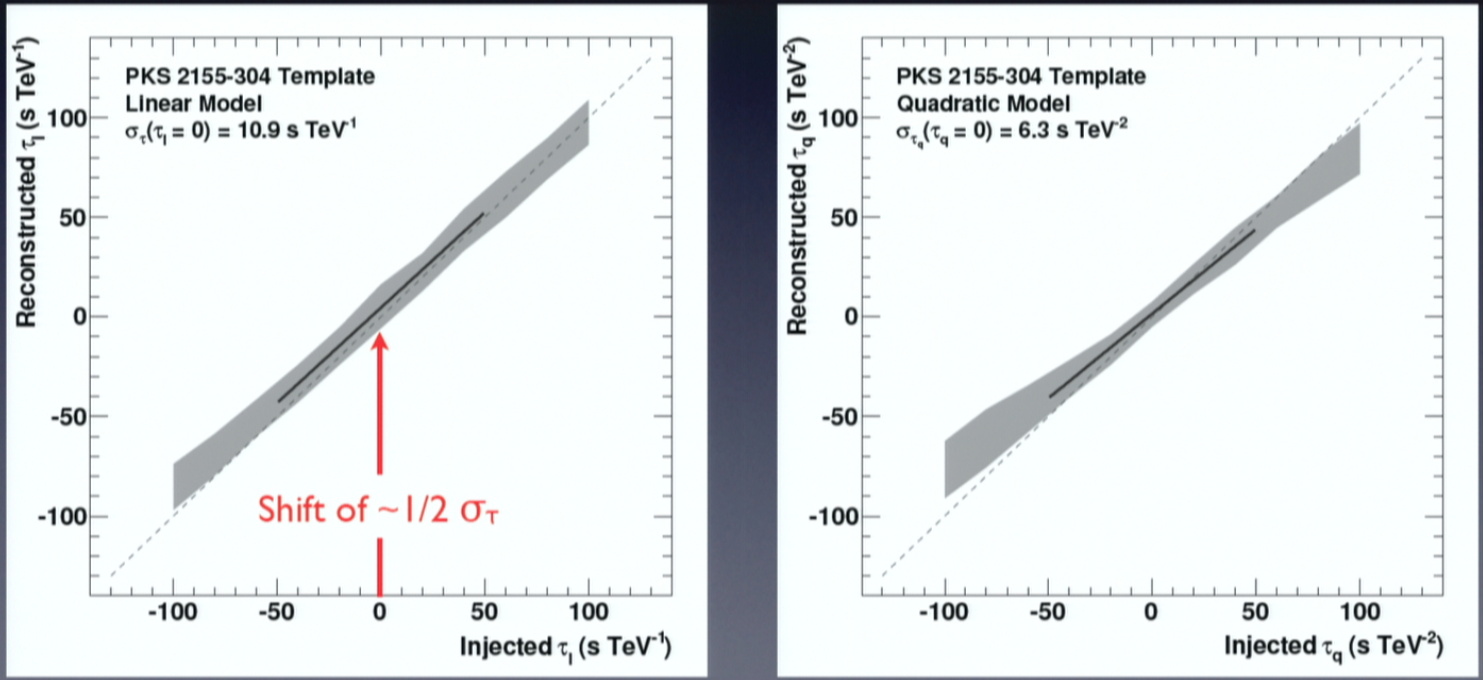




Error Calibration and Systematics (3)

- The time distribution of photons is generated from the measured light curve at low energies
  → Statistical error



Summary of systematic studies

	Change in estimated τ_l (s/TeV)	Change in estimated τ_q (s/TeV^2)
Selection cuts	< 5	
Background contribution	< 1	
Acceptance factors	< 1	
Energy resolution	< 1	
Energy calibration	< 2	
Spectral index	< 1	
Calibration systematics (constant, shift)	< 5	< 1
$F_S(t)$ parameterization	≈ 7	≈3
Total	< 10.3	< 6.6

Results

- Considering the results from data and taking into account systematics:

$$\tau'_{0l} = -5.5 \pm 10.9_{(stat)} \pm 10.3_{(sys)}\ \mathrm{s/TeV}$$

$$\tau'_{0q} = 1.7 \pm 6.3_{(stat)} \pm 6.6_{(sys)}\ \mathrm{s/TeV^2}$$

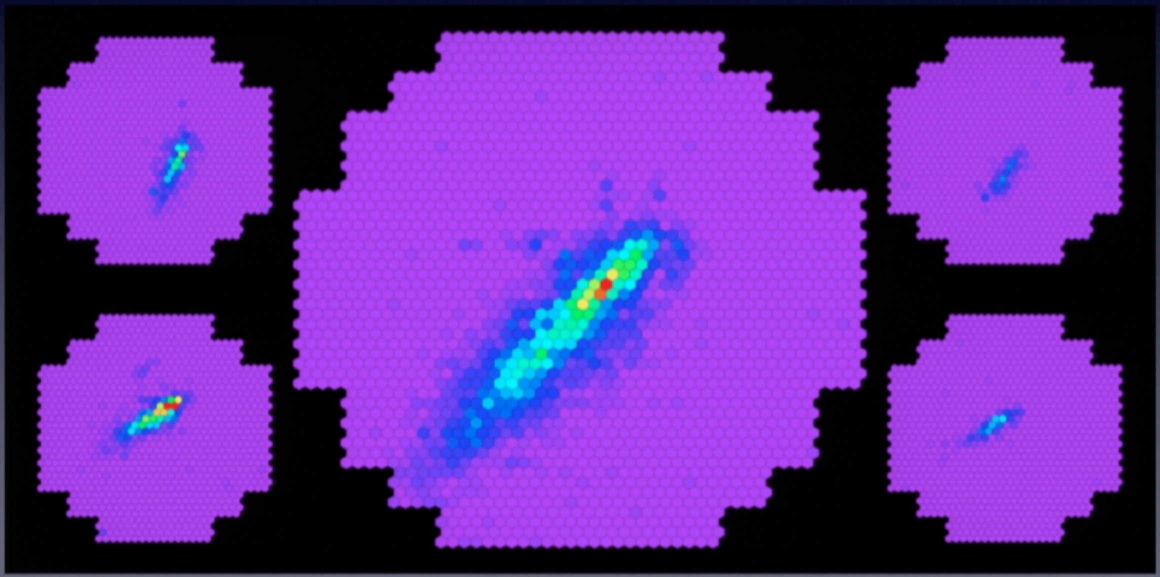
- The corresponding limits are

$$E^{l}_{QG} > 2.1\times10^{18}\ \mathrm{GeV}\ (\xi < 5.7)$$

$$E^{q}_{QG} > 0.6\times10^{11}\ \mathrm{GeV}\ (\zeta < 3.6\times10^{16})$$

- A factor 3 higher than the CWT/CCF result
- The best limits obtained with an AGN so far

Conclusions



Comparison with other results from AGNs

Mkn 501	MAGIC	ECF, Likelihood	$E^{l}_{QG} > 3\times10^{17}$ GeV	Albert et al., Phys. Lett. B 668 (2008) 253 + Martinez & Erando, Astropart. Phys. 31, 226 (2009)
PKS 2155 -304	HESS	CCF, Wavelets	$E^{l}_{QG} > 7\times10^{17}$ GeV $E^{q}_{QG} > 1.4\times10^{9}$ GeV	Aharonian et al., Phys. Rev. Lett. 101 (2008) 170402
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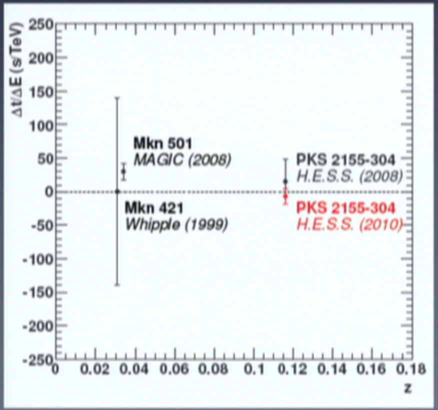
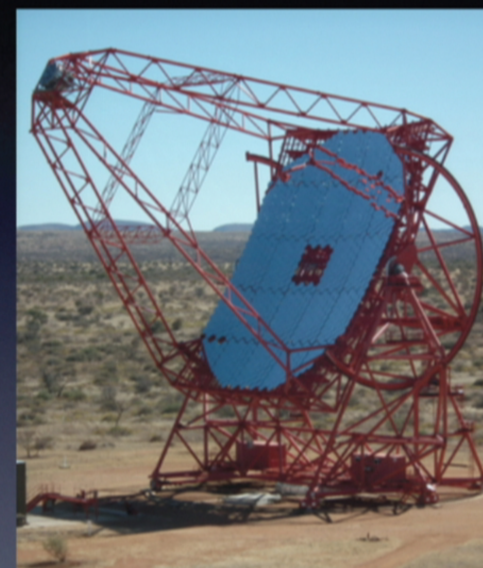
- The last HESS result is
  - A factor of ~10 higher than MAGIC result for the linear correction
  - A factor of ~2 higher than the MAGIC result for the quadratic correction
- Essentially due to higher statistics and greater distance



The near future: H.E.S.S.-II

- Inaugurated on september 28th
- A new telescope
  - Total mirror area: 600 m^2
  - Focal Length: 36 m
- A new camera
  - 2048 pixels
  - FOV: 3.2 deg
  - Weight: 2.8 tons
  - Energy threshold: ~30 GeV
- Currently being comissionned

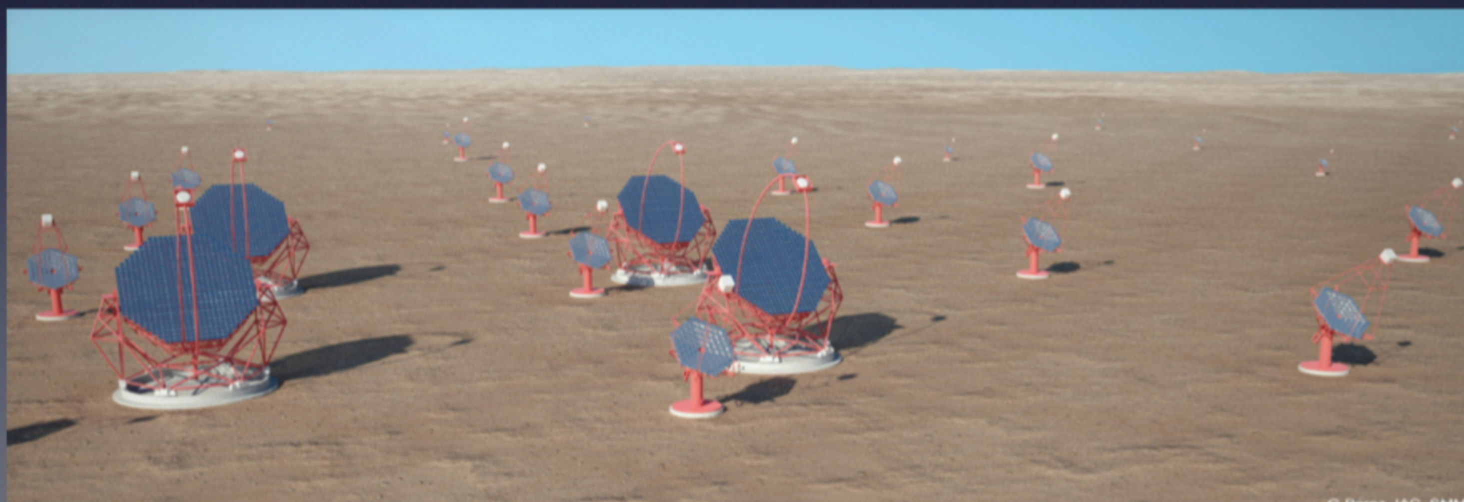


The extension of the energy range to low energies will allow to observe more transient sources...

Further in the future: CTA

- 100s of telescopes on two sites
- Three sizes of telescopes for wide energy coverage from ~10 GeV to 100 TeV
- A sensitivity 10 times higher than the current generation of telescopes
- Pointing modes dedicated to transient sources detection

→ A great step towards population studies with AGN !




Merci !

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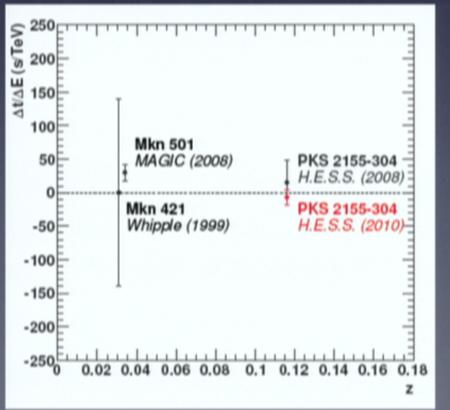
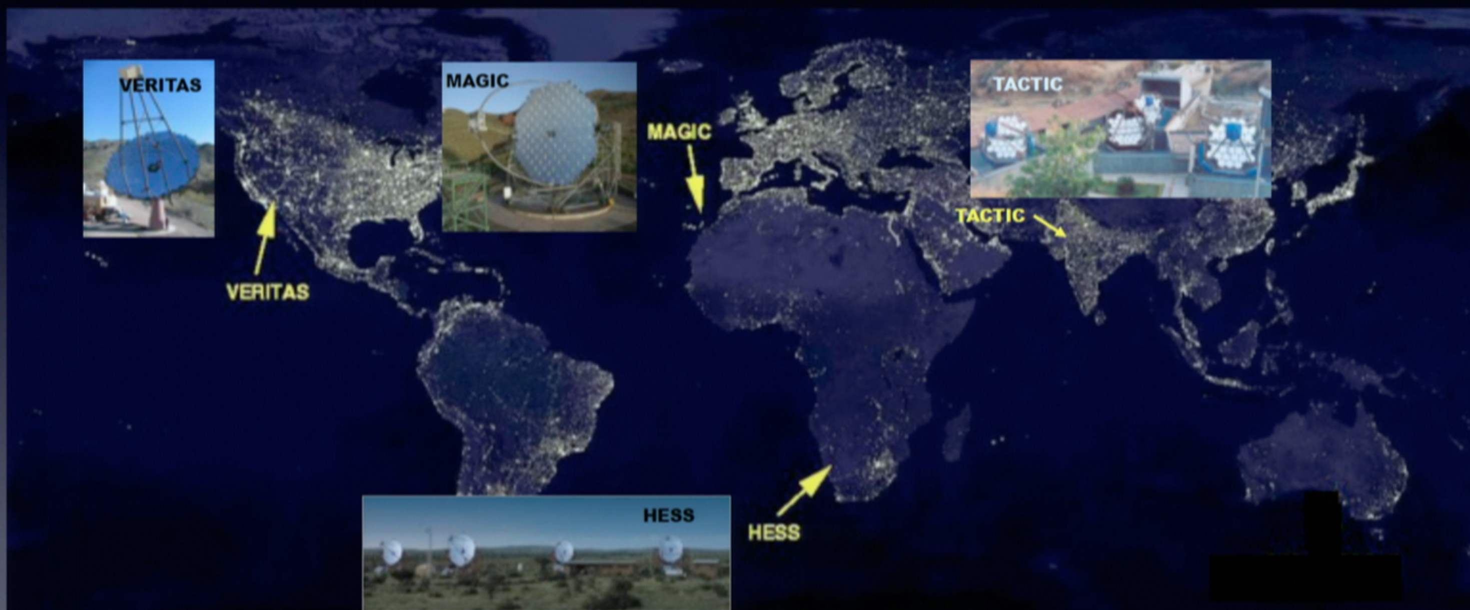


In the world...



The formalism in use

- Lorentz Invariance Violation effects should appear at E ~ O(E_P = 1.2x10[19] GeV)
- For E << E_P, a series expansion is expected to be possible, giving:

$$c' = c\left(1 \pm \xi \frac{E}{E_\mathrm{P}} \pm \zeta^2 \frac{E^2}{E_\mathrm{P}^2}\right)$$ at the 2nd order

- Depending on their energies, photons travel at different speeds
- Tiny modifications can add-up over very large propagation distances and lead to measurable delays
  → use of variable and distant sources (GRBs, AGN flares)
- We consider two photons with energie E_1 and E_2 emitted at the same time and detected at times t_1 and t_2.
  - At the first order : $$\frac{\Delta t}{\Delta E} \approx \frac{\xi}{E_\mathrm{P} H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$
  - At the second order: $$\frac{\Delta t}{\Delta E^2} \approx \frac{3\zeta}{2 E_\mathrm{P}^2 H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$\Delta t = t_1 - t_2$ $\quad \Delta E = E_1 - E_2$ $\quad \Delta E^2 = E_1^2 - E_2^2$ $\quad \Omega_\Lambda = 0.7$ $\quad \Omega_m = 0.3$

G. Amelino-Camelia et al., Nat. 395, 525 (1998) - U. Jacob & T. Piran, J. of Cosmology and Astropart. Phys. 1, 31 (2008)