SORBONNE UNIVERSITÉ
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J. BOLMONT & C. PERENNES

TESTING LORENTZ INVARIANCE WITH ASTROPHYSICAL SOURCES : REVIEW, ISSUES, AND PROSPECTS

WITH A FOCUS ON AGN

DISCRETE18

November 26-30, 2018

CONTENTS

- Astrophysical sources for MDR searches
  - Modified Dispersion Relations
  - Candidate sources
- Review of published results, focusing on flaring AGNs
- Source-intrinsic effects
  - Understanding the sources
  - Population studies
- Conclusions: issues and prospects

THE LANDSCAPE

THE LANDSCAPE

ASTROPHYSICAL SOURCES FOR MDR SEARCHES

TWO MODELS, A COMMON CONSEQUENCE

STRINGY SPACETIME FOAM

e.g. Amelino-Camelia, Ellis, Mavromatos, Nanopoulos (1999), Ellis, Mavromatos, Nanopoulos (1999), Mavromatos (2010), etc.

LQG SEMI-CLASSICAL FORMALISM

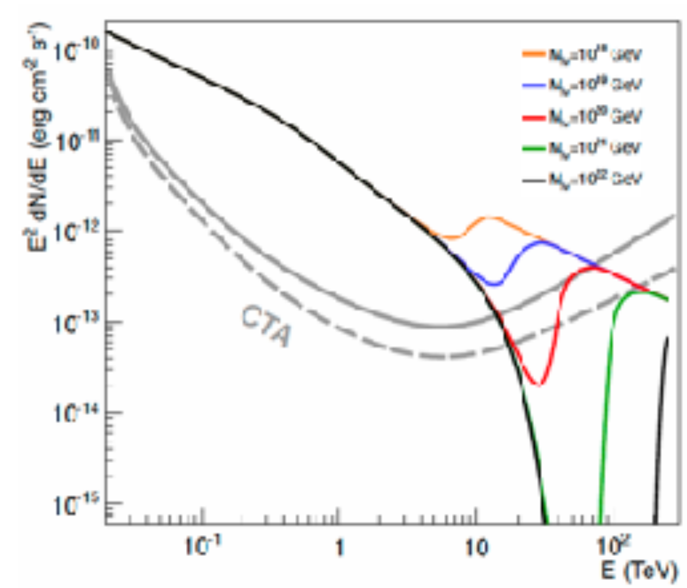
e.g. Gambini & Pullin (1999)

MODIFIED DISPERSION RELATION

GROUP VELOCITY OF PHOTONS BECOMES ENERGY-DEPENDANT

Focus of this talk

MODIFICATION OF GAMMA-GAMMA CROSS-SECTION



Fairbairn et al. (2014)

TWO MODELS, A COMMON CONSEQUENCE

STRINGY SPACETIME FOAM

e.g. Amelino-Camelia, Ellis, Mavromatos, Nanopoulos (1999), Ellis, Mavromatos, Nanopoulos (1999), Mavromatos (2010), etc.

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Focus of this talk

PURELY KINEMATICAL TEST THEORY WHERE

$$E^2 \simeq p^2c^2 \times \left[1 \pm \sum_{n=1}^{\infty} k_n \left(\frac{E}{E_P}\right)^n\right]$$

Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar (1998)

MODIFICATION OF GAMMA-GAMMA CROSS-SECTION

VERY SMALL EFFECT, BUT IT SHOULD CUMULATE ON LARGE DISTANCES

FROM MDR TO TIME-LAG

- Photons from astrophysical sources propagate over large distances
- Universe expansion has to be taken into account when calculating the measured delay (Jacob & Piran, 2008)
- Expression of the time-lag between two photons emitted at the same time at redshift z:

ENERGY LEVER ARM

$$\Delta t_n \simeq s_\pm \frac{n+1}{2} \frac{E_h^n - E_l^n}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$

DISTANCE PARAMETER

- with

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

$$H_0 = 67.74 \pm 0.46 \text{ km/s/Mpc}$$
$$\Omega_m = 0.3089 \pm 0.0062,$$
$$\Omega_\Lambda = 0.6911 \pm 0.0062$$

(Planck, 2015)

DELAYS AT THE SOURCE

$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

- « Source-intrinsic effects »
  - Due to emission mechanisms
  - Differ from one type of source to another
  - Could differ from one flare/burst to another
- Observed for long GRBs
- Only hints for flaring AGNs in the TeV range
  - Details of emission mechanisms are still unknown…

ASTROPHYSICAL SOURCES FOR MDR SEARCHES

- The time-lag Δt_n is proportional to:
  - The distance parameter
  - The energy « lever-arm » $\Delta E^n \equiv E_h^n - E_l^n$
- Need for sources that are
  - Distant
  - Variable or transient
  - Energetic (hard spectra)
- Candidates:
  - Gamma-Ray Bursts (GRBs)
  - Flaring Active Galactic Nuclei (AGNs)
  - Pulsars (PSRs)
- The sensitivity of analyses depends on a combination of factors

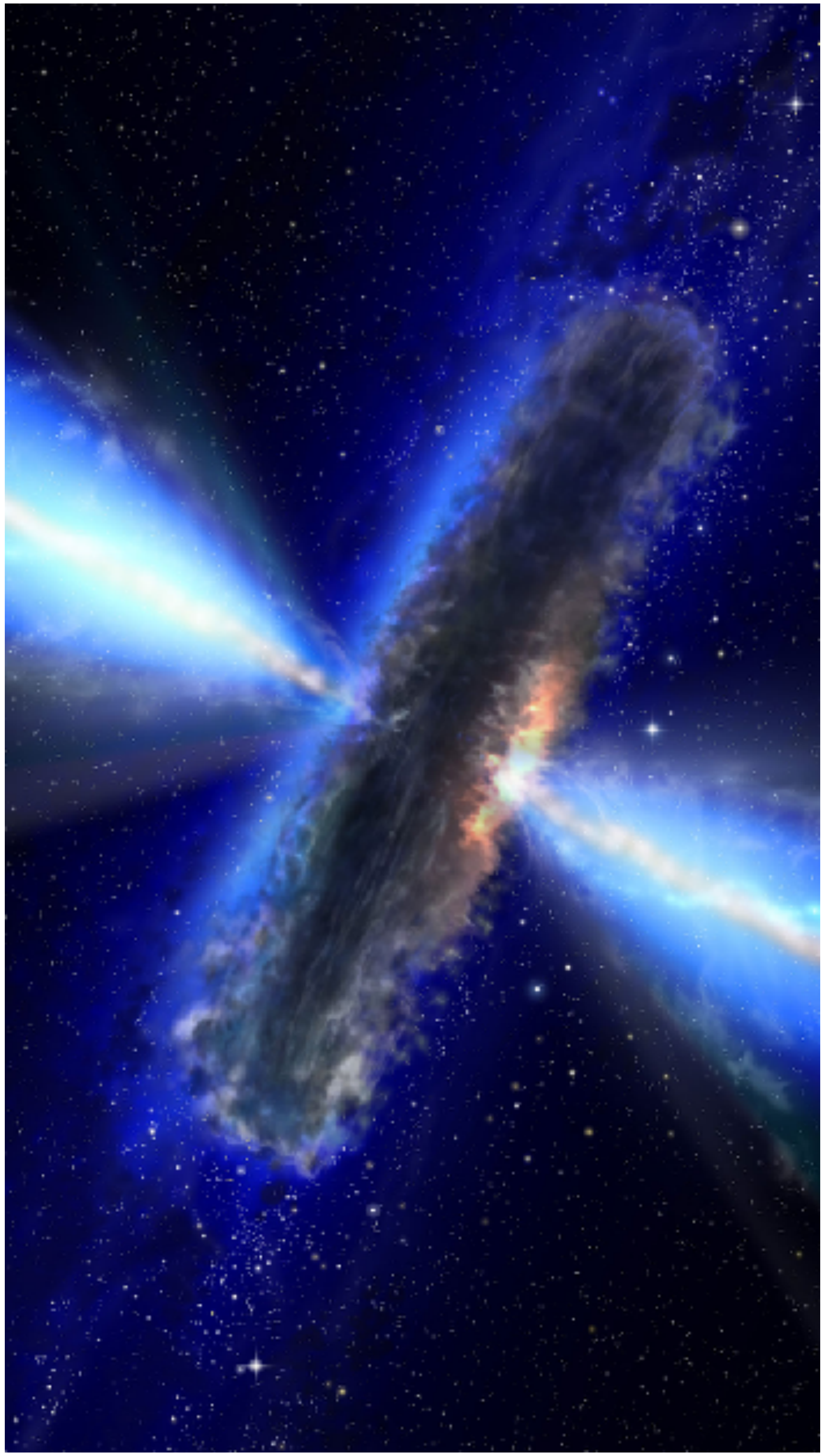
THESE SOURCES HAVE ADVANTAGES AND DRAWBACKS

GRB:
👍 VERY LARGE DISTANCES
👍 SHORT
👎 RANDOM

PSR:
👍 EXTREME VARIABILITY
👍 NOT RANDOM
👎 VERY SMALL DISTANCES

FLARING ACTIVE GALACTIC NUCLEI

- Galaxies with extremely luminous inner region
- Blazars
  - Jet close to the line-of-sight
  - High variability (flares)
- For MDR searches:
  - 👍 Good statistics with IACTs
  - 👍 High variability (O(min))
  - 👍 Distant sources
  - 👎 Flares happen randomly
  - 👎 EBL absorption of TeV photons
  - 👎 Hints of intrinsic temporal effects
  - 👎 Details of emission mechanisms poorly understood



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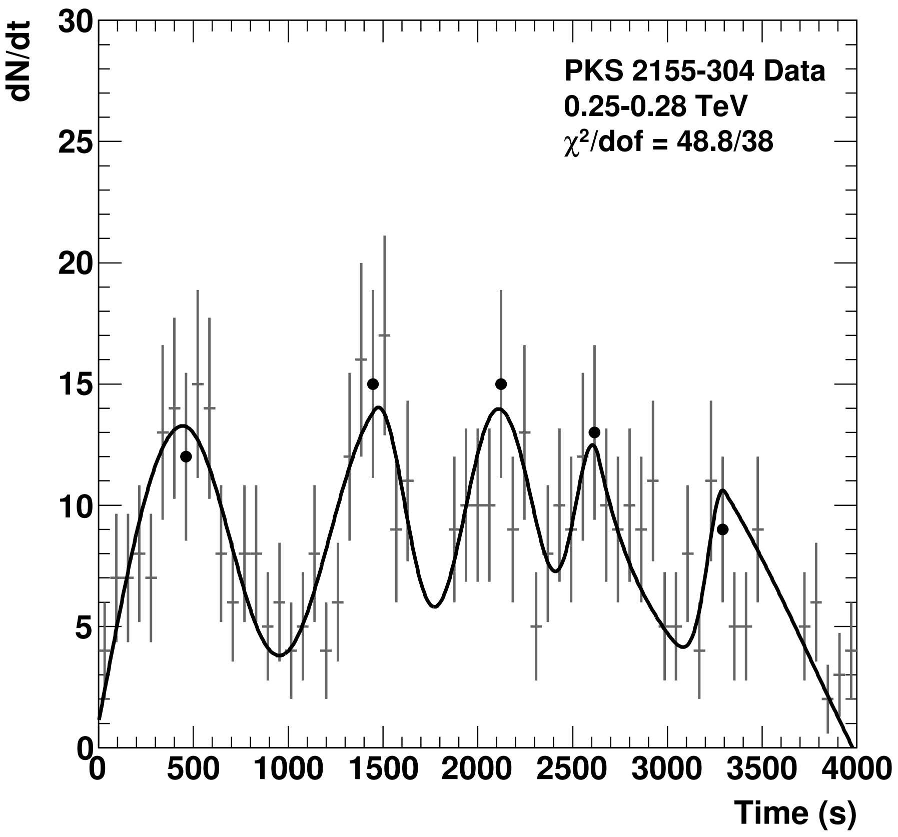
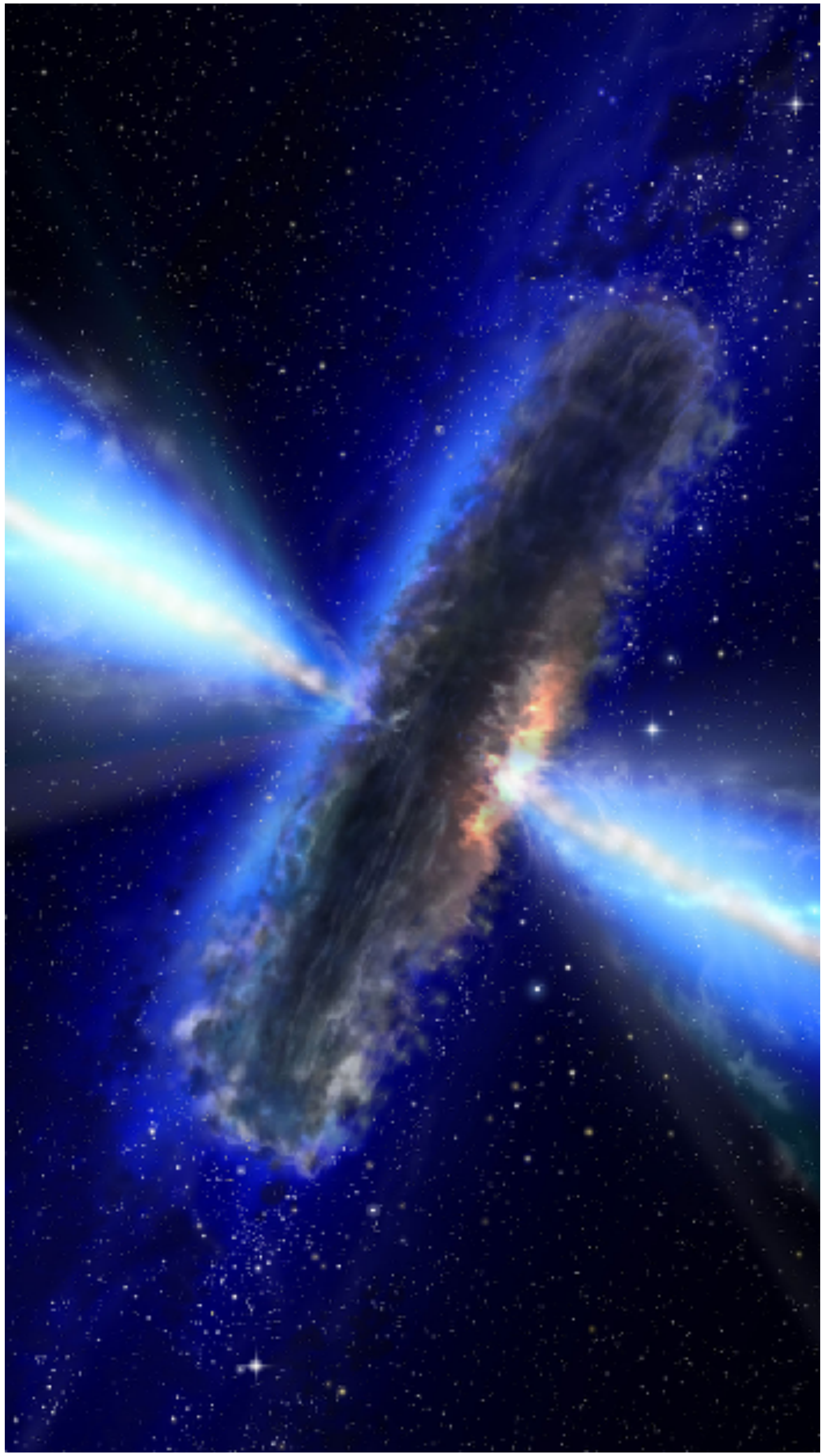


SOME RESULTS



PRELIMINARY COMMENTS

- Results span from the end of 90s to now
- Population studies were done with GRBs (with known z)
- The main result after 25+ years of work:

NO SIGNIFICANT EFFECT WAS FOUND !

- Lower limits on $E_{QG,1}$ and $E_{QG,2}$ are derived
  - Error evaluation is essential
- The only known exception:
  - Flare of Mkn 501 in July 2006, Albert et al. (2008)

LIMITS ON $E_{QG,1}$ AND $E_{QG,2}$ FOR THE SUBLIMINAL CASE (95%CL)

	Source(s)	Experiment	Method	Results	
Individual GRB	GRB 021206	RHESSI	Fit + mean arrival time in a spike	$E_{QG,1} > 1.8 \times 10^{17}$ GeV	
	GRB 080916C	Fermi GBM + LAT	associating a 13 GeV photon with the trigger time	$E_{QG,1} > 1.3 \times 10^{18}$ GeV	$E_{QG,2} > 0.8 \times 10^{10}$ GeV
	GRB 090510	Fermi GBM + LAT	associating a 31 GeV photon with the start of any observed emission, DisCan	$E_{QG,1} > 1.5 \times 10^{19}$ GeV	$E_{QG,2} > 3.0 \times 10^{10}$ GeV
		Fermi LAT	PairView, SMM, likelihood	$E_{QG,1} > 9.3 \times 10^{19}$ GeV	$E_{QG,2} > 1.3 \times 10^{11}$ GeV
Several GRB	9 GRBs	BATSE + OSSE	Fit	$E_{QG,1} > 10^{15}$ GeV	
	9 GRBs	BATSE + OSSE	wavelets	$E_{QG,1} > 0.7 \times 10^{16}$ GeV	$E_{QG,2} > 2.9 \times 10^{6}$ GeV
	15 GRBs	HETE-2	wavelets	$E_{QG,1} > 0.4 \times 10^{16}$ GeV	
	17 GRBs	INTEGRAL	likelihood	$E_{QG,1} > 3.2 \times 10^{11}$ GeV	
	35 GRBs	BATSE + HETE-2 + Swift	wavelets	$E_{QG,1} > 1.4 \times 10^{16}$ GeV	
	15 GRBs	SWIFT	CCF (50-100 keV, 150-200 keV)	$E_{QG,1} > 1.48 \times 10^{16}$ GeV	
Individual PSR	Crab pulsar	EGRET	average time of the main pulse in different energy bands, fit of main pulse	$E_{QG,1} > 0.2 \times 10^{15}$ GeV	
		VERITAS	DisCan	$E_{QG,1} > 1.9 \times 10^{17}$ GeV	
		MAGIC	likelihood	$E_{QG,1} > 7 \times 10^{17}$ GeV	$E_{QG,2} > 4.6 \times 10^{10}$ GeV
	Vela pulsar	H.E.S.S.	likelihood	$E_{QG,1} > 3.5 \times 10^{15}$ GeV	$E_{QG,2} > 6.4 \times 10^{8}$ GeV

- Best limit so far: $E_{QG,1} > 9.3 \times 10^{19}$ GeV with GRB 090510
- Population studies lead to $E_{QG,1} > 1.5 \times 10^{16}$ GeV
- Competitive results possible for pulsars on $E_{QG,2}$

Boggs et al. (2004)
Abdo et al. (2009b)
Abdo et al. (2009a)
Vasileiou et al. (2013)
Ellis et al. (2000)
Ellis et al. (2003)
Bolmont et al. (2008)
Lamon et al. (2008)
Ellis et al. (2006, 2008)
Bernardini et al. (2017)
Kaaret (1999)
Zitzer and the VERITAS Collaboration (2013)
Terrats (2015)
Chretien (2015)

LIMITS ON $E_{QG,1}$ AND $E_{QG,2}$ FOR THE SUBLIMINAL CASE (AGN)

* Accepted ApJ
** Preliminary

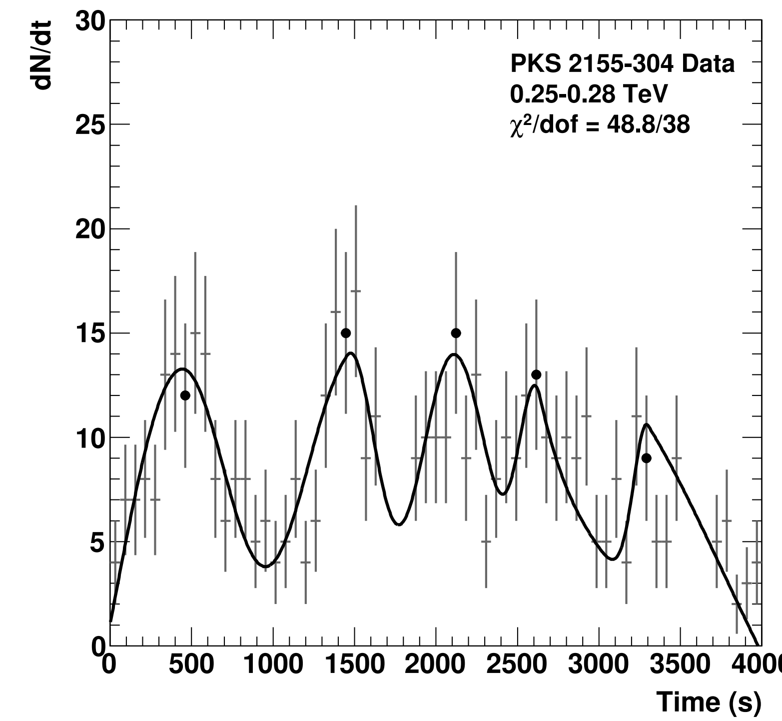
Source(s)	Experiment	Method	Results		
Mrk 421	Whipple	average time of the main pulse in different energy bands	$E_{QG,1} > 0.4 \times 10^{17}$ GeV		
Mrk 501	MAGIC	ECF, likelihood	$E_{QG,1} > 0.2 \times 10^{18}$ GeV	$E_{QG,2} > 2.6 \times 10^{10}$ GeV	
		likelihood	$E_{QG,1} > 0.3 \times 10^{18}$ GeV	$E_{QG,2} > 5.7 \times 10^{10}$ GeV	
	H.E.S.S.	likelihood	$E_{QG,1} > 8.5 \times 10^{17}$ GeV	$E_{QG,2} > 1.1 \times 10^{11}$ GeV	*
PKS 2155-304	H.E.S.S.	MCCF	$E_{QG,1} > 7.2 \times 10^{17}$ GeV	$E_{QG,2} > 0.1 \times 10^{10}$ GeV	
		wavelets	$E_{QG,1} > 5.2 \times 10^{17}$ GeV		
		likelihood	$E_{QG,1} > 2.1 \times 10^{18}$ GeV	$E_{QG,2} > 6.4 \times 10^{10}$ GeV	
PG 1553+113	H.E.S.S.	likelihood	$E_{QG,1} > 4.1 \times 10^{17}$ GeV	$E_{QG,2} > 2.1 \times 10^{10}$ GeV	
3C279	H.E.S.S.	likelihood	$E_{QG,1} > 1.7 \times 10^{17}$ GeV	$E_{QG,2} > 2.0 \times 10^{10}$ GeV	**

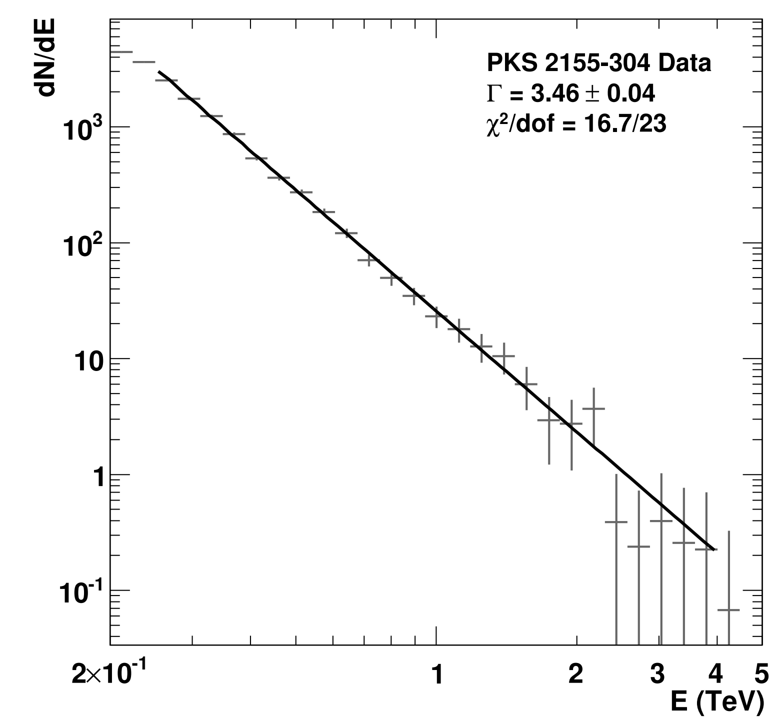
Reference
Biller et al. (1999)
Albert et al. (2008)
Martínez and Errando (2009)
Cologna and the H.E.S.S. Collaboration (2015)
Aharonian et al. (2008)
Abramowski et al. (2011)
Abramowski et al. (2015)
Romoli and the H.E.S.S. Collaboration (2017)

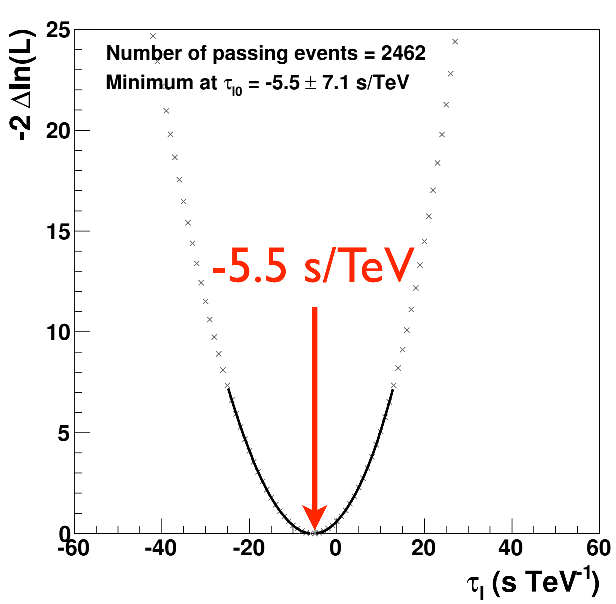
- 5 different objects
- Redshift ranging from 0.03 (Mrk 421) to 0.54 (3C279)
- Best limit for $E_{QG,1}$: PKS 2155 and for $E_{QG,2}$: Mrk 501

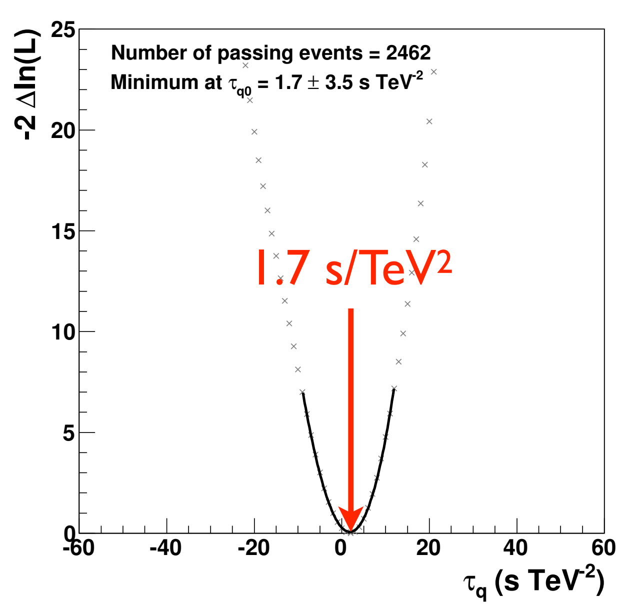
PKS 2155-304 FLARE SEEN BY H.E.S.S. IN 2006

- z = 0.116
- Flare in July 2006:
  - Ideal observation conditions
  - ~10000 photons in ~90 min
  - High variability (O(min))
  - Negligible background
- Use of a likelihood procedure (Martinez & Errando, 2009)
- Toy Monte Carlo technique:
  error calibration and systematics studies









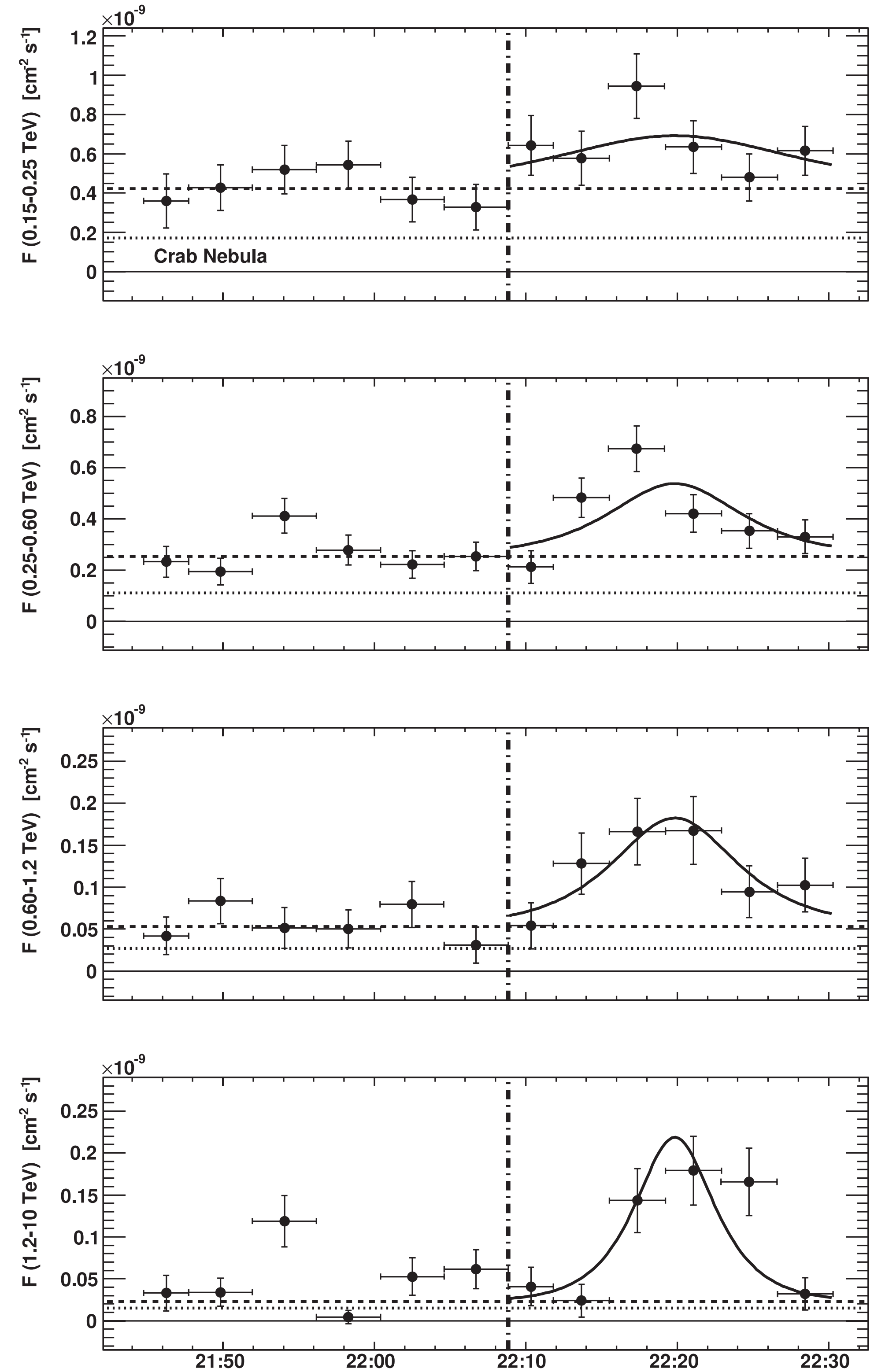
$\tau_l = -5.5 \pm 10.9_{(stat)} \pm 10.3_{(sys)}$ s/TeV

$\tau_2 = 1.7 \pm 6.3_{(stat)} \pm 6.6_{(sys)}$ s/TeV^2

MKN 501 FLARE SEEN BY MAGIC IN 2005

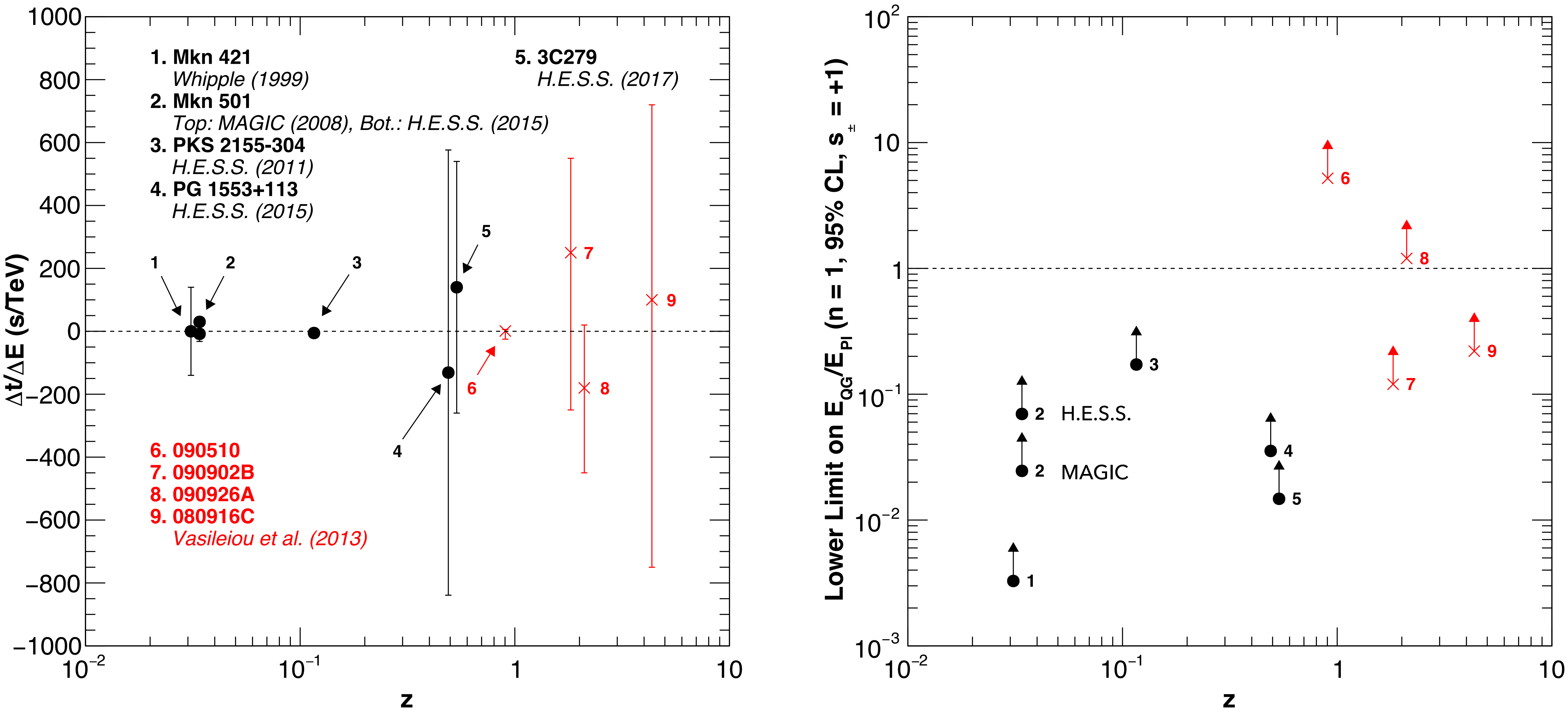
- z = 0.034
- ~20 minute long flare on July 9
- ~1500 photons
- Negligible background
- Lag of 4±1 min measured between < 250 GeV and >1.2 TeV
  - Confirmed with 2 methods
    - Albert et al. (2008)
    - Martinez & Errando (2009)
- τ_1 = (0.030±0.012) s/GeV, and $E_{QG,1} = 0.30^{+0.24}_{-0.10} \times 10^{18}$ GeV
  - Finally interpreted as a source intrinsic effect

Flare of Mkn 501 (MAGIC), Albert et al. (2007)

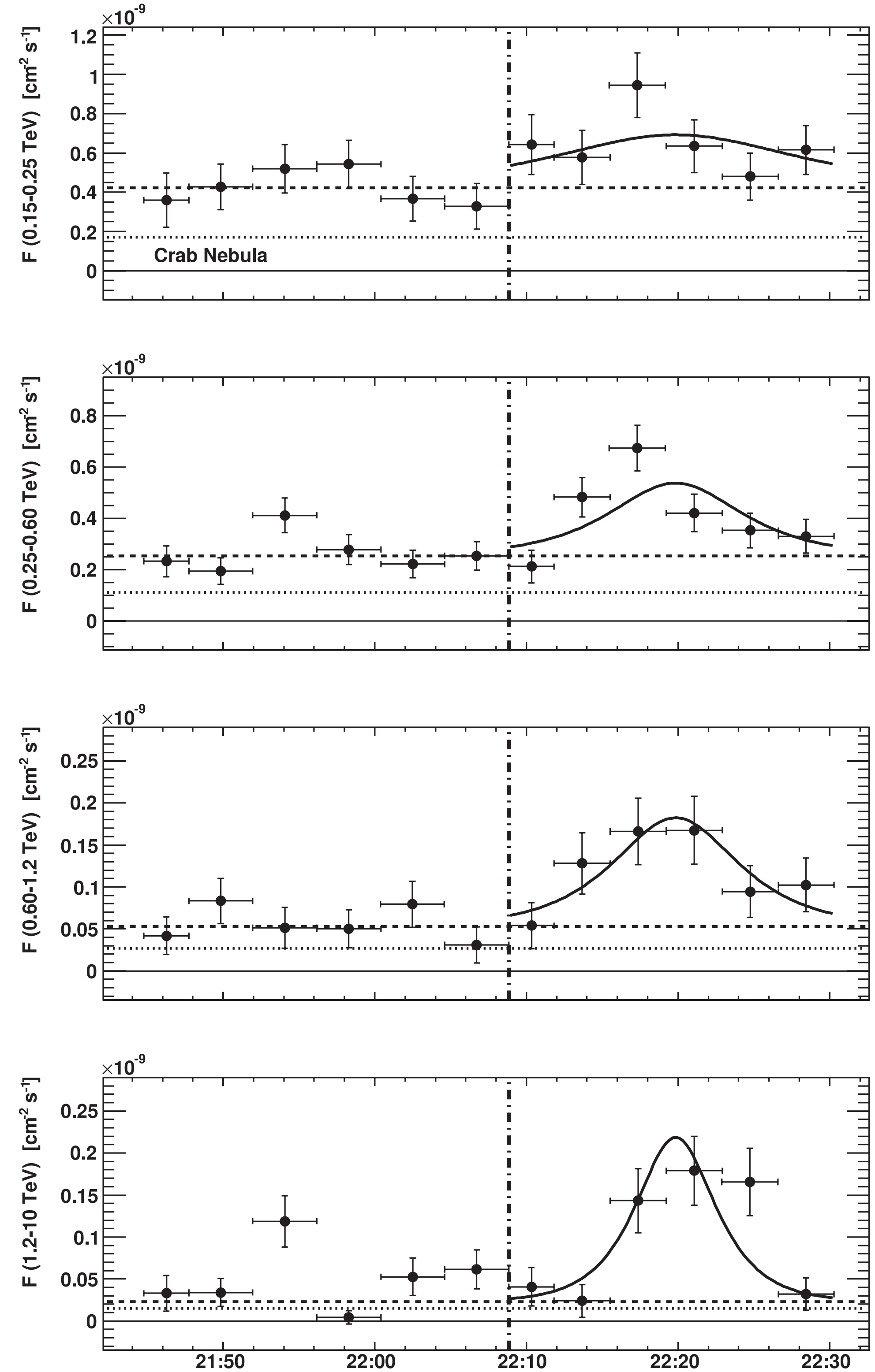


Lag of 4±1 min (< 250 GeV, >1.2 TeV)

SUMMARY



- Results for linear and subluminal effect, obtained with a likelihood method
- 4 Fermi-LAT GRBs included (Vasileiou et al., 2013)



SOURCE-INTRINSIC EFFECTS

HOW TO DEAL WITH SOURCE INTRINSIC EFFECTS ?

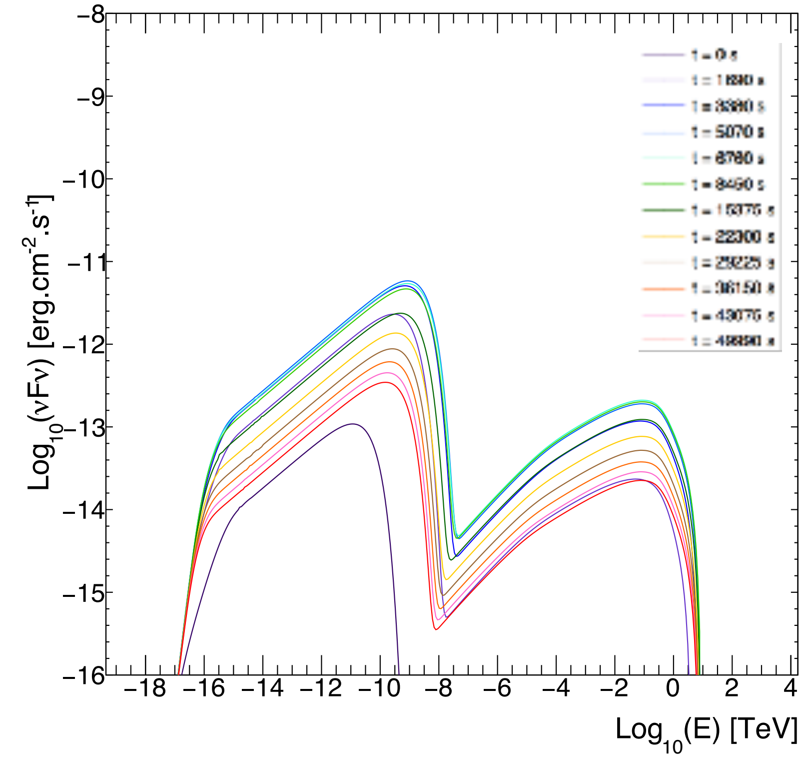
$$\Delta t_{n\,\mathrm{total}} = \Delta t_{n\,\mathrm{LIV}} + (1+z)\,\Delta t_{\mathrm{source}}$$

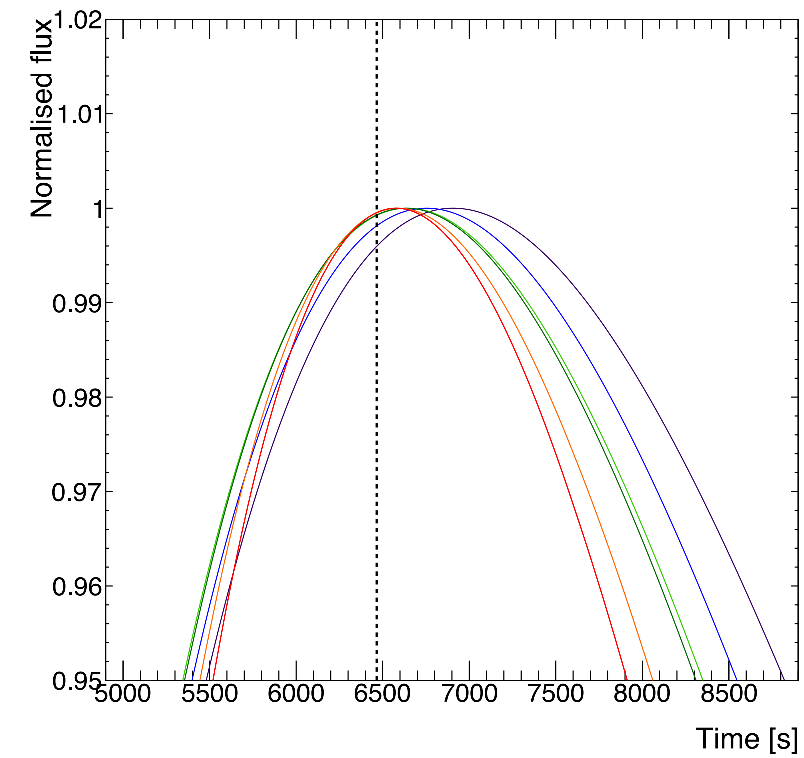
- Neglect intrinsic effects → Restrict the energy range; Restrict the time domain
- Understanding the sources → A task for the future
  - Full modeling
- Use population studies to separate intrinsic and propagation effects → A task for the future
  - Intrinsic effects do not depend on distance

C. Perennes, H. Sol, JB
Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Need for a time-dependent model of AGN flare emission
- First attempt to characterize intrinsic effects in AGN flares in connexion to LIV searches
    - PhD thesis by C. Perennes, LPNHE
    - Paper coming soon
- Leptonic model
  - Temporal evolution due to
    - Electron acceleration (flux increase)
    - Electron energy losses and decrease of magnetic field (flux decrease)
  - SED and light curves produced from a simple SSC model (Katarzyński et al. 2001)
- Δt computed from a reference light curve (lowest energy)

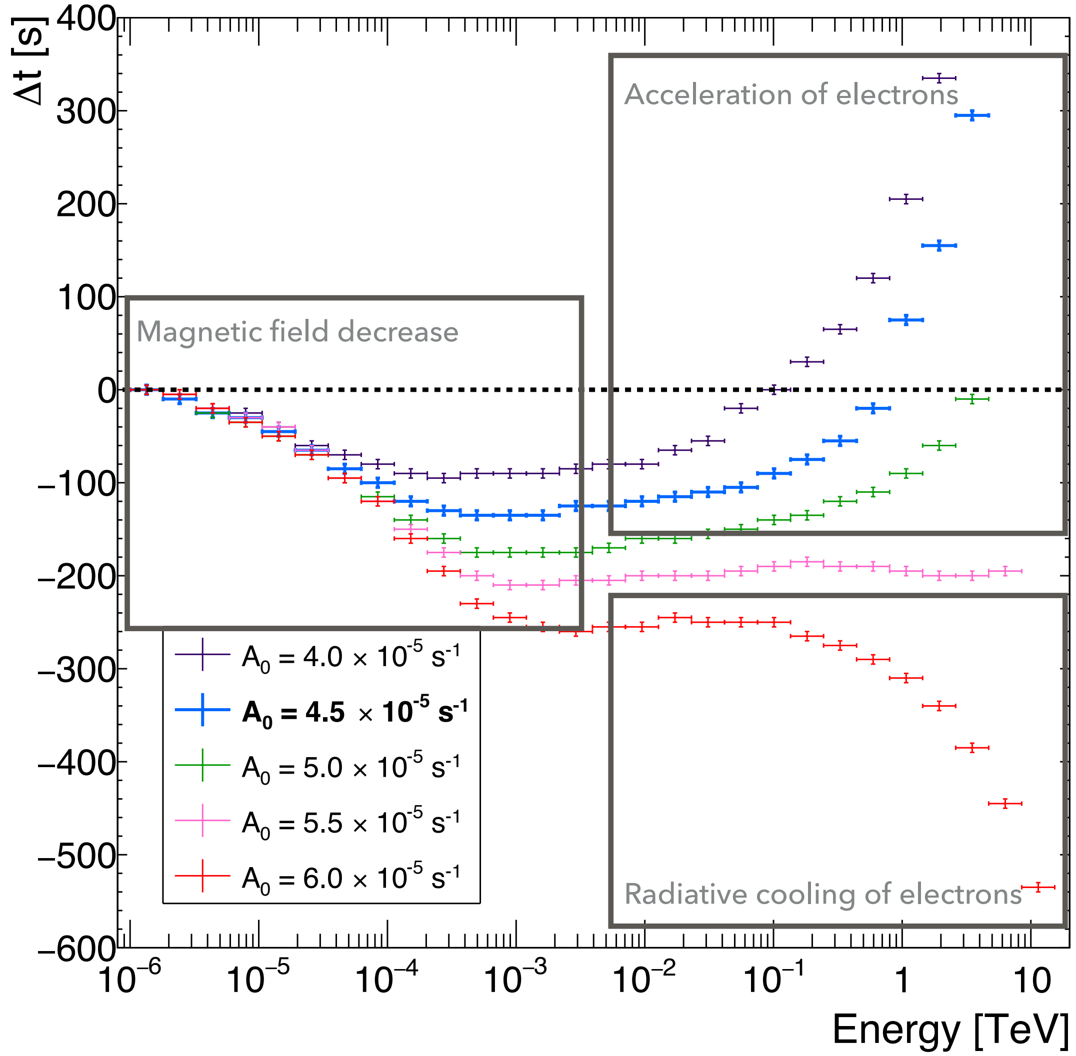




Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Time delays are found to be driven by
  - Acceleration:
    - e- are still accelerating when light curves starts to decay
    - e- need more time to emit the highest energy photons than e- emitting low energy photons
    - LE light curves reach their maximum first
  - Radiative cooling:
    - e- have started to cool down when light curves starts to decay
    - e- emitting the highest energy photons lose their energy faster than e- emitting low energy photons
    - HE light curves reach their maximum first



NB: Adiabatic losses neglected

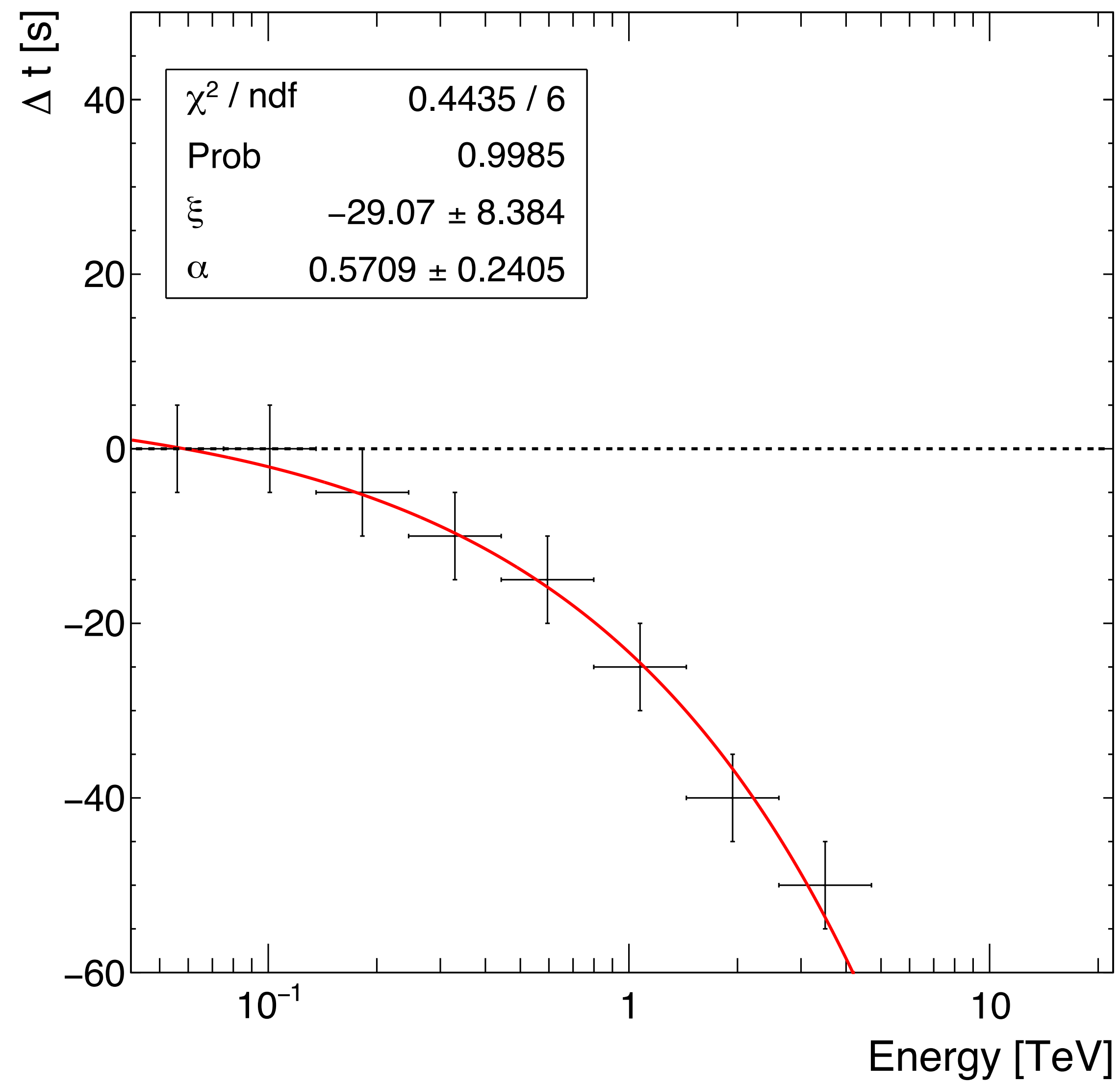
Plots from C. Perennes

UNDERSTANDING INTRINSIC EFFECTS

- Focusing on TeV energies
- Lags can be parameterized by a power law

$$\Delta t = \xi \times (E^{\alpha} - E_0^{\alpha})$$

  - α is found in the range 0.4 - 0.9
  - ξ can be positive (mimicking a subluminal LIV) or negative (superluminal LIV)



PAPER COMING SOON

- Except for Mkn 501, no lag was measured
  - Constraints on emission, using multi-λ observations
  - From these constraints, get robust constraints on MDR

PREPARING POPULATION STUDIES

L. Nogués, T. Lin, C. Perennes, A. E. Gent, M. Gaug, A. Jacholkowska, M. Martinez, A.N. Otte, R.M. Wagner, J. E. Ward, B. Zitzer, JB

- Joint effort initiated in a working group gathering MAGIC, VERITAS and H.E.S.S. members
- Goal :
  - Combining existing data for AGNs and Pulsars from the three experiments
  - Get combined limits on LIV as a legacy before CTA
  - Redshift dependence study
  - Prepare CTA
- Combine likelihoods to estimate a redshift-independent parameter λ

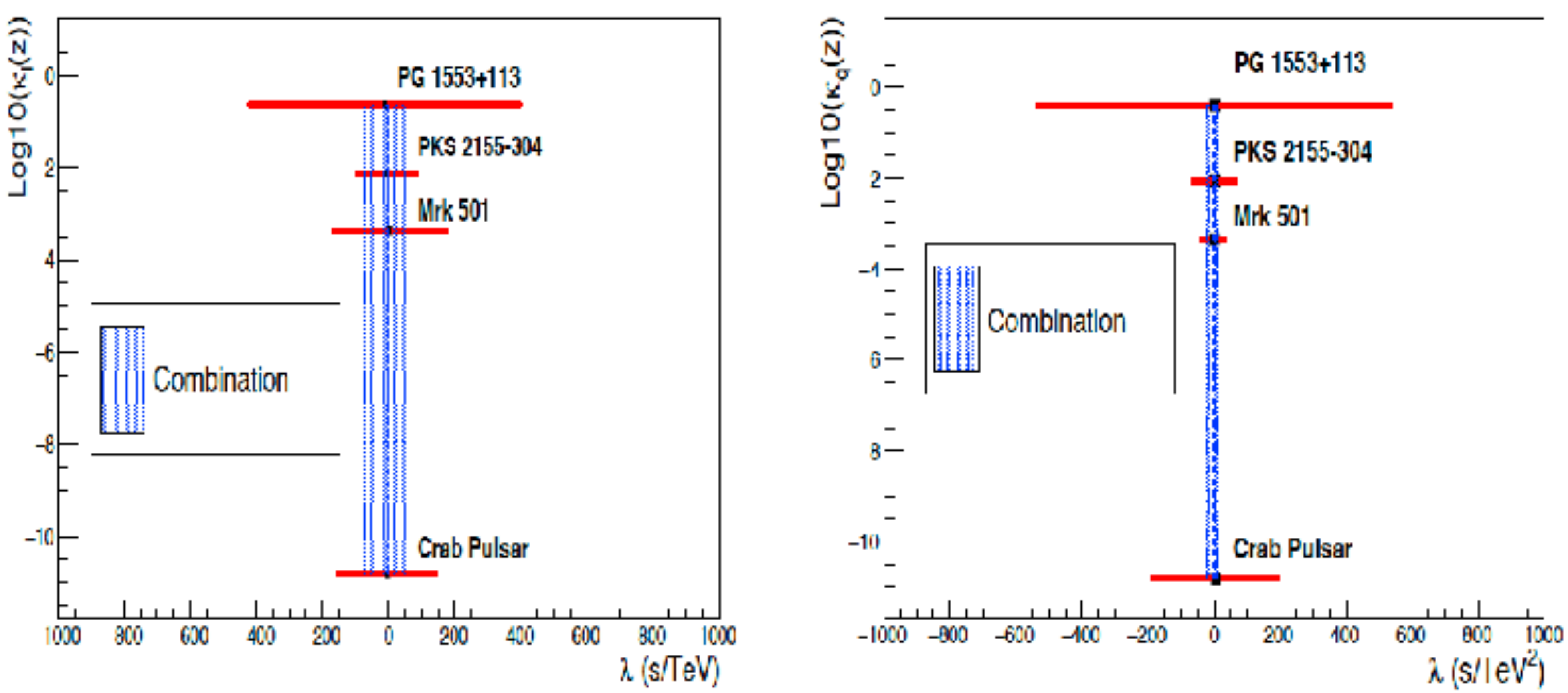
$$L_{Comb}(\lambda) = \prod_{i=1}^{Nsource} L_i(\lambda) \longrightarrow -2log(L_{Comb}(\lambda)) = -2 \sum_{i=1}^{Nsource} log(L_i(\lambda))$$

with $\lambda = \dfrac{\Delta t_n}{\Delta E^n \ \kappa(z)}$

Plots from Nogués et al., ICRC 2017

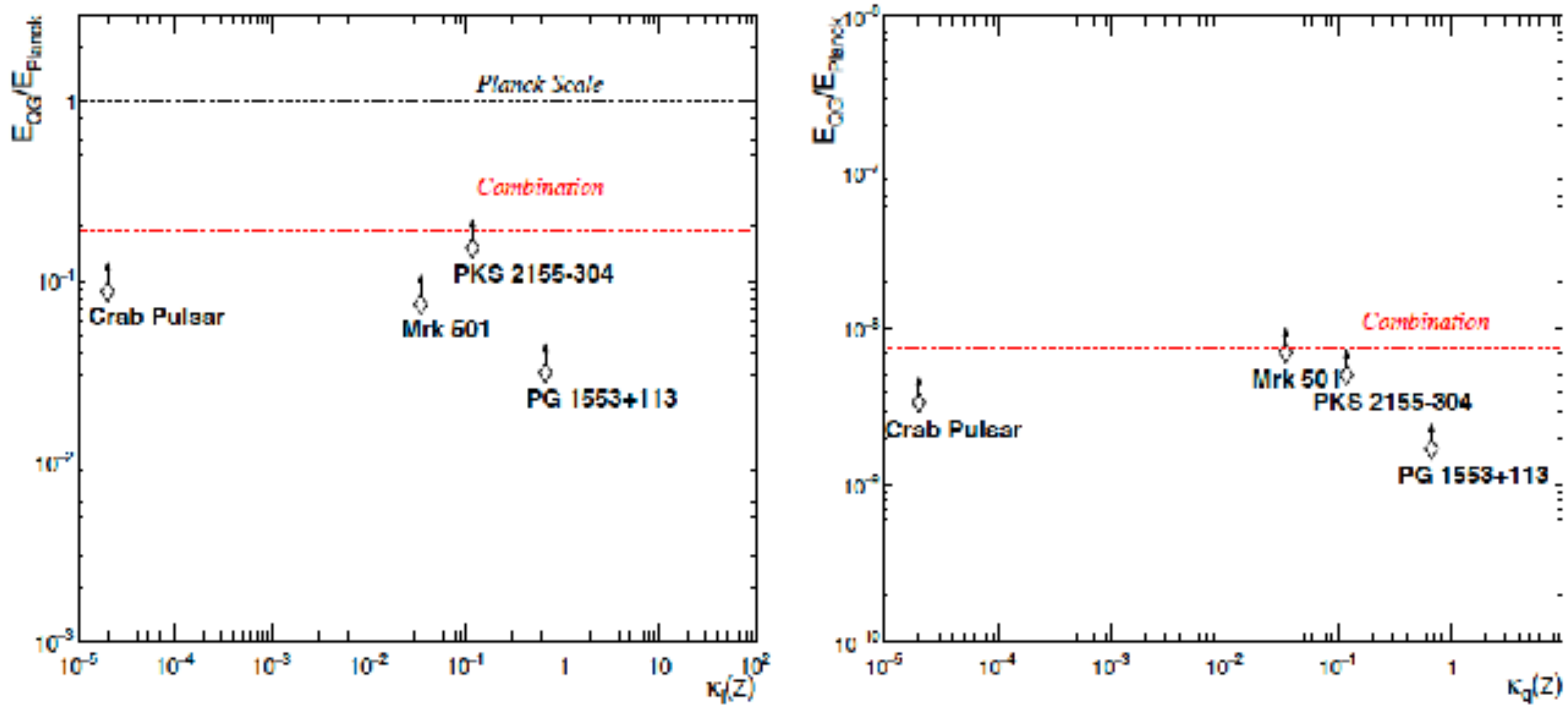
PREPARING POPULATION STUDIES

- For now, only simulations
- 990 sets of simulated data from published spectra and light curves
  - Mrk 501 2005 flare detected by MAGIC
  - PG 1553+113 2012 flare detected by H.E.S.S.
  - PKS 2155-304 2006 flare detected by H.E.S.S.
  - VHE Crab Pulsar detected by VERITAS



Plots from Nogués et al., ICRC 2017

PREPARING POPULATION STUDIES



- Combination dominated by
  - PKS 2155 for the linear term
    - 24% improvement w.r.t. the best individual case
  - Mrk 501 for the quadratic term
    - 10% improvement
- Technical paper on the method to appear in 2019
- Final paper with all available sources to follow

A CRUCIAL STEP BEFORE CTA !

SUMMARY, ISSUES & PROSPECTS

Artist's view of CTA Northern site

SUMMARY

- LIV in the form of MDR for photons in vacuum is predicted by different QG approaches
  - Stringy spacetime foam, Semi-classical treatment in Loop QG, but also Causal sets, Non-commutative spacetime…
- Astrophysical sources are good tools to probe MDR
  - Complementarity of PSR, GRBs, flaring AGNs
- After 20 years of work on that topic
  - No propagation effect was discovered
  - Limits were set on $E_{QG,1}$ and $E_{QG,2}$
  - Planck scale sensitivity reached for the linear effect
- A number of problems remain

OPEN ISSUES (THEORY SIDE)

- MDR are obtained from « simplified » models
  - Full theory of QG could lead to a neither linear nor quadratic MDR
- The « distance parameter » $\int_0^z \frac{(1+z')^n}{H(z')} dz'$ from Jacob & Piran (2008) is obtained assuming that translations are not affected by Planck scale effects (Rosati et al. 2015)
  - A more thorough study of this question is needed and could lead to a re-evaluation of all published limits
- …

OPEN ISSUES (OBSERVATION SIDE)

- MDR « Time of Flight » searches are limited by our limited understanding of astrophysical sources
  - Source-intrinsic effects involve complex processes, difficult to model
- Population studies are still lacking for VHE data
  - Done with GRBs at low energies, leading to $E_{QG,1} \sim 10^{16}$ GeV
- Methods for lag measurements have all their drawbacks
  - Likelihood procedure is very precise, but requires a fit of the (binned) light curve at low energies
  - Correlation methods give only a lag between two fixed energy bands, etc.
  - New methods coud still be proposed
- …

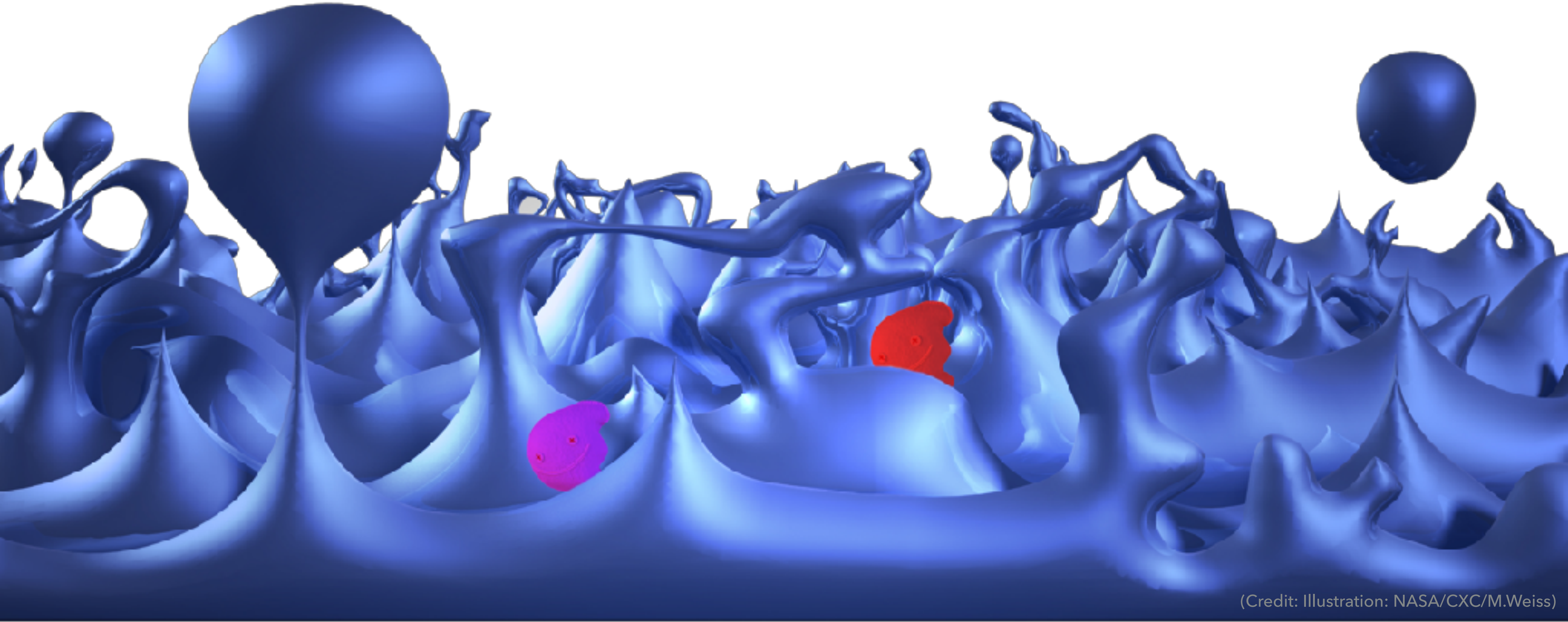
PROSPECTS (FOR THE EXPERIMENTAL SIDE)

- Population studies are a main goal for the future
  - With all possible sources (AGNs, GRBs, PSRs)
  - They will help for
    - Searching for a dependance with redshift
    - Understanding the sources
    - Confirm linear effect exclusion
- Modeling sources with the goal to
  - Constrain (or predict ?) source-intrinsic effects
  - Get more robust constraints on propagation effects
- Multi-λ, multi-messenger and TO observations will have an important role to play
- A lot remains to be done !

MERCI !

THANKS !

DANKE !



(Credit: Illustration: NASA/CXC/M.Weiss)