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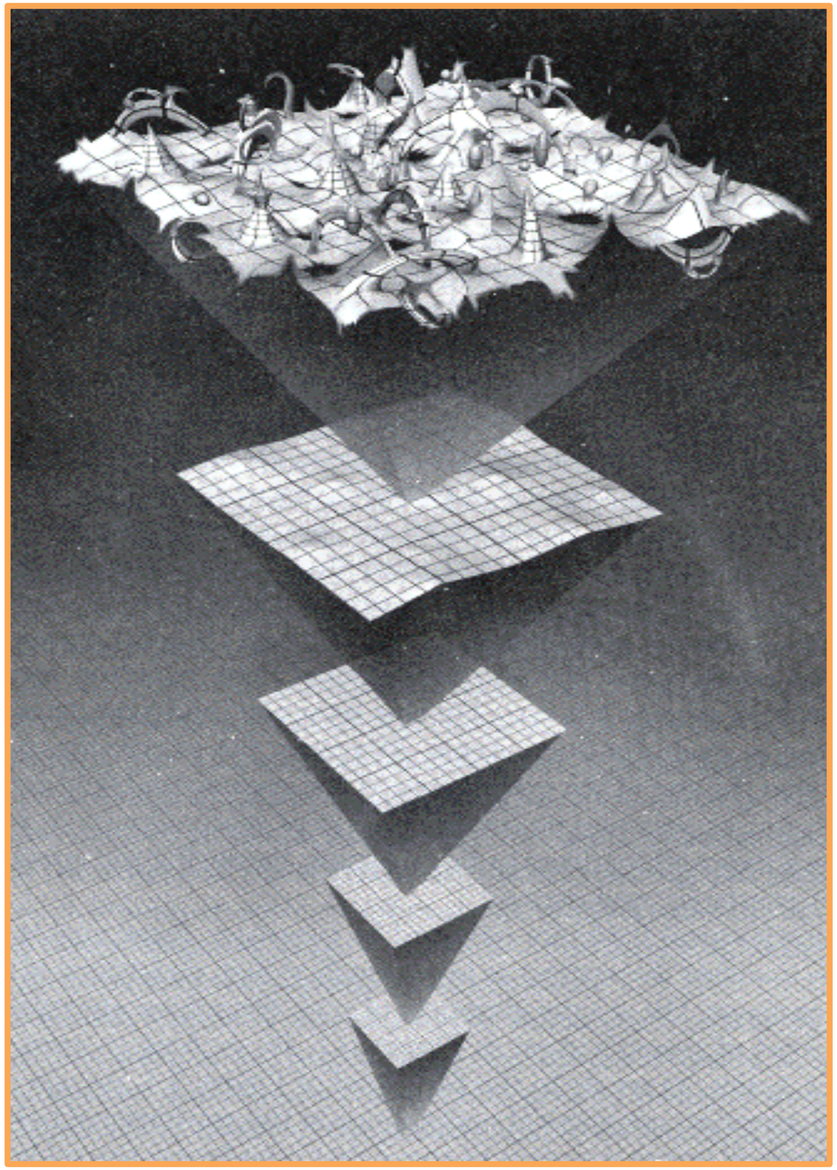


On Bounds on a Possible Energy Dependence of the Speed of Light in Vacuum

Manel Martinez

ICRR Seminar

July 24th 2018

ICRR Institute for Cosmic Ray Research University of Tokyo

Outline

1) Gravitation in the quantum regime ?
2) The measurement of Time of Flight
3) Present situation
4) Multi-messengers ?
5) Summary and Outlook

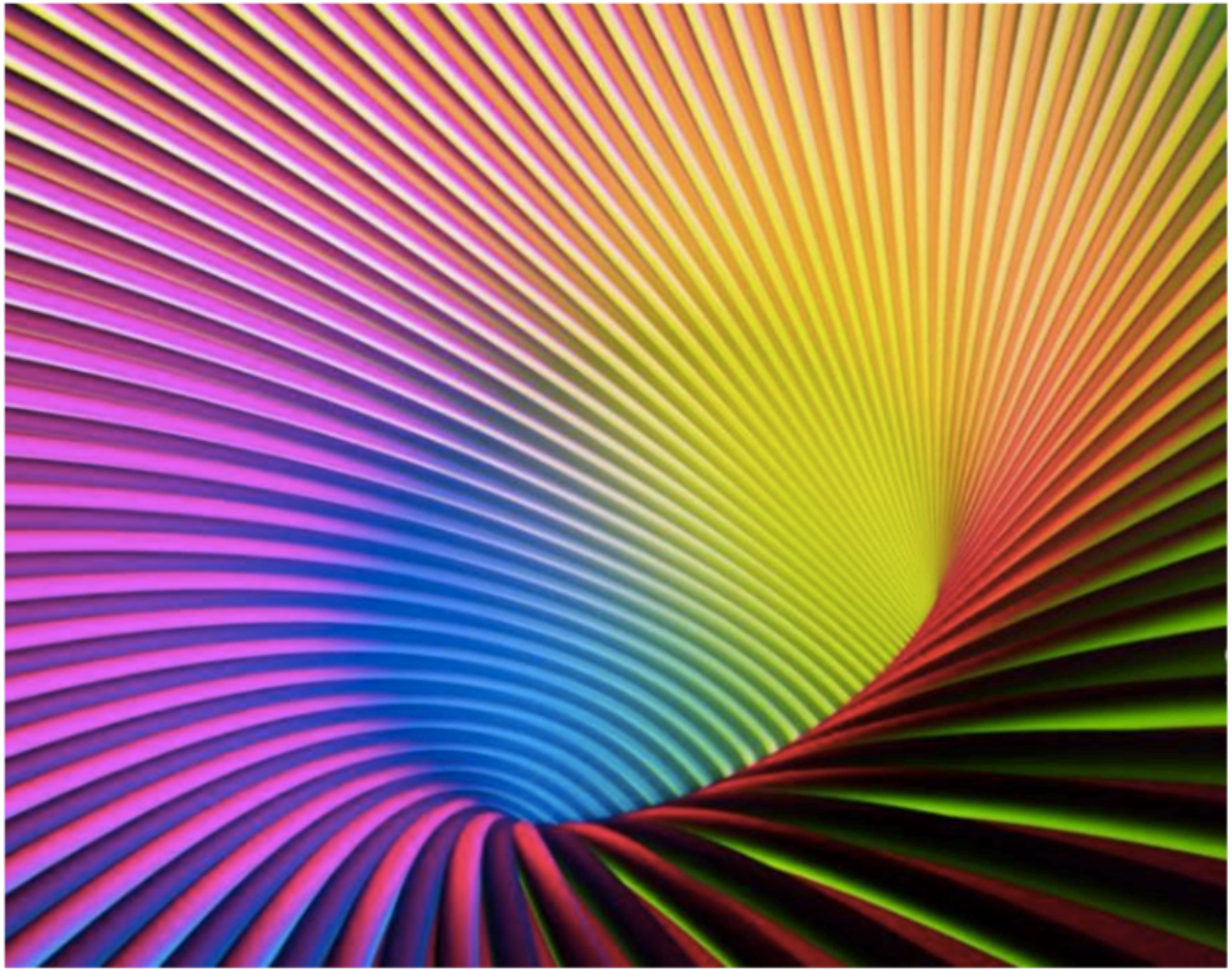
Thanks to G. Amelino-Camelia, M. Gaug, L. Nogues and E. Moretti

1) Gravitation in the quantum regime?

As of today Quantum Gravity is just in our imagination !

giovanni amelino-camelia

MAGIC meeting 28.06.2018



Giovanni Amelino-Camelia, “Quantum Spacetime Phenomenology”, Living Reviews on Relativity 16 (2013) 5

As of today:

No consistent theory describing gravitation in the quantum regime

AND

No direct experimental evidence calling for it…!

ALTHOUGH

Some important observations related to gravity remain unexplained…

(dark matter, dark energy,…)

our “quantum-gravity phenomenological models” will turn out
to be (<u>at best</u>) like the Bohr-Somerfeld quantization…

even the assumption that the quantum-gravity scale should coincide with the Planck scale should be viewed as just a <u>weak</u> guess:

$$E_{QG} \sim E_{Planck} = 1.2 \bullet 10^{19} GeV = \left(\frac{\hbar c^5}{G}\right)^{\frac{1}{2}}$$

i.e. 10^{-35}meters (“Planck length”)

mainly comes from observing that at the Planck scale

$$\lambda_C \sim \lambda_S$$

$$\lambda_c \equiv \frac{1}{M}$$

$$\lambda_s \equiv G_N M$$

Note that this can only be a <u>rough order-of-magnitude estimate</u>
in particular this estimate <u>assumes that G does not run at all</u>!!!!!!!!!
it most likely does run!!!

$$\frac{1}{M} = G_N M \Rightarrow M = E_P$$

$$\frac{1}{M} = G_N(M)\, M \Rightarrow M = ?$$

Giovanni Amelino-Camelia

What is special about the Planck Mass/Length/Time ?

- Introduced in 1906 by Max Planck as a combination of three fundamental constants:

- h -> quantum world
- c -> relativistic world
- G -> gravitation

$$\text{Planck mass, } M_{pl} = \left(\frac{\hbar c}{G}\right)^{1/2} = 2.2\times 10^{-5}\, gm \ \mathbf{= 1.2 \cdot 10^{19} GeV}$$

$$\text{Planck length, } L_{pl} = \left(\frac{\hbar G}{c^3}\right)^{1/2} = 1.6\times 10^{-33}\, cm$$

$$\text{Planck time, } t_{pl} = \left(\frac{\hbar G}{c^5}\right)^{1/2} = 5\times 10^{-44}\ \text{sec}$$

… far, far away from our reach… !

BUT...

- We can write for the dimensionless gravitational coupling (or fine structure constant):

$$\alpha_g \sim Gm^2/\hbar c \sim \left(m/M_{pl}\right)^2$$

showing that for m~M_{pl} gravitation becomes a strong interaction !

- At E_{pl} the **Compton wavelength** of a particle = $\hbar c/E_{pl}$

equals its gravitational radius (**Schwarzschild radius**) = GE_{pl}/c^4
So that the particle is trapped in its own gravitational field.

Gravity meets the Quantum world !

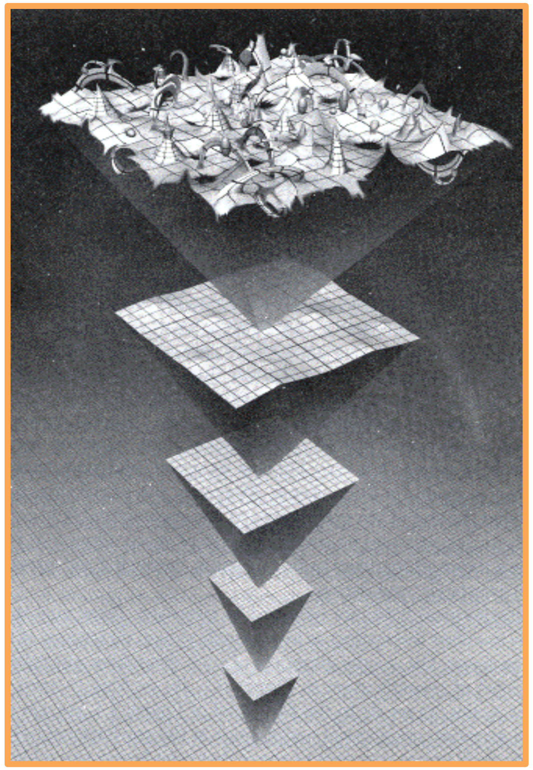
expected many new structures for the quantum gravity realm…

of particular interest for phenomenology the possible implications for relativistic symmetries (Lorentz, Poincarè,…)

Planck length as the minimum allowed value for wavelengths:

- suggested by several indirect arguments combining quantum mechanics and GR
- found in some detailed analyses of formalisms in use in the study of the QG problem

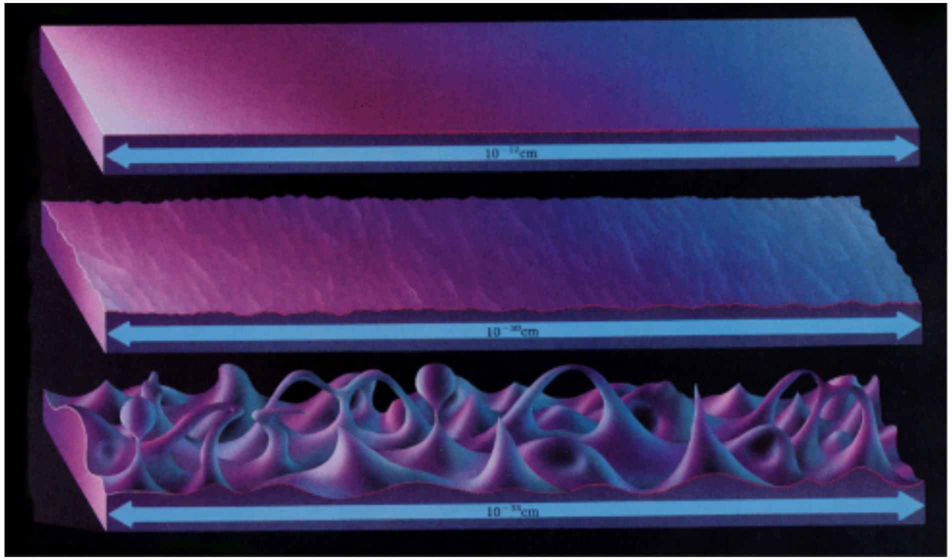
Giovanni Amelino-Camelia



When approaching the Planck Scale the fabric of space-time may become foamy and relativistic symmetries may be deformed or distorted ("violated")

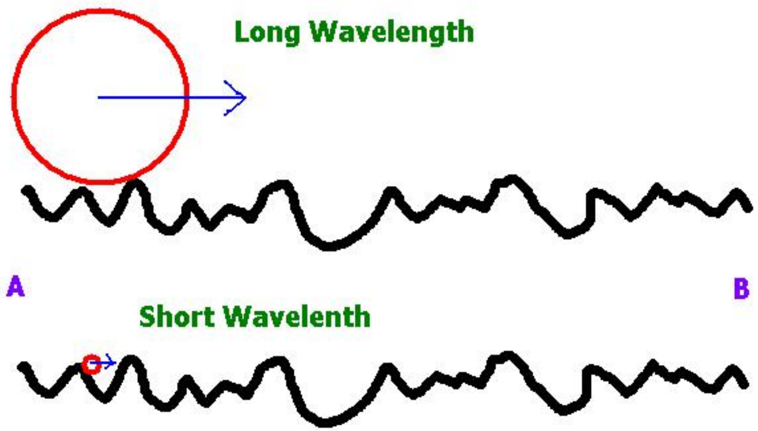
John Wheeler - 1955

Let me fly mi imagination…



Spacetime structure in vacuum does carry energy (for instance Gravitational Waves)

Energy fluctuations in the quantum vacuum in gravitation may create and annihilate spacetime topological structures (blackholes, wormholes,..)



The speed of light in vacuum may depend on its wavelength ?

=> That will break Lorenz Invariance !

What is Lorenz Invariance ?

- Lorentz transformations arise necessarily under the assumptions of:
  - **Spatial and temporal homogeneity**
  - **Spatial isotropy**
  - **Equivalence principle (equivalence of inertial frames)**
  - **Pre-causality (time-ordering of two events along an observer worldline does not change in different systems of reference).**

(see e.g. S. Sonego and M. Pin. J.Math.Phys. , 50:042902, 2009, arXiv:gr-qc/08121294)

- Have to give up at least one of these axioms to obtain violation of LI.

- Lorentz invariance is a cornerstone of **both the Standard Model and General Relativity**!

- Lorentz Invariance has been **tested** to extreme precision so far and no hint for LI violation has been found.

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Shall we really want to give all this up ???

Lorenz Invariance Violation and Quantum Gravity

Direct quantization of General Relativity (GR) leads to non-renormalizable Quantum Field Theory (QFT)

- High energy LIV can regularize field theories

- Some QG models with LIV:
  - **Wraped brane worlds**. One model in P.Horawa (arXiv:0812.4287)
  - **Loop quantum gravity** . C.Rovelli (arXiv:gr-qc/9710008)
  - **Effective Field Theories**. Overview in R.Bluhm (arXiv:hep-ph/0506054)

- Some QG models without LIV:
  - **String theory with Lorentz-covariant dynamics**. A.Kostelecky (Phys. Rev. Lett. 63)
  - **Doubly Special Relativity (DSR)** G.Amelino-Camelia (arXiv:hep-th/0012238)

Lorenz Invariance Violation and Quantum Gravity

- Other hints:
  - Discretization of space-time destroys spatial and temporal homogeneity (through appearance of **virtual black holes**).
  - There exists a (non-local, cosmological) distinguished reference frame: the **Cosmic Microwave Background**.
  - **Analogue frameworks** within Bose-Einstein Condensates display effective (acoustic) LI at low energies which “break” at higher energies.

Knowing (from experiment) whether GQ is Lorentz invariant or not, is a fundamental ingredient to select theories.

see e.g. S. Liberati, *Tests of Lorentz invariance: a 2013 update*. Classical and Quantum Gravity, 30(13):133001, 2013 (arXiv: 1304.5795v3)

and D. Mattingly. *Modern Tests of Lorentz Invariance*. Living Reviews in Relativity, 8:5, 2005 (arXiv:gr-qc/0502097)

How to test it ?

- LIV extensions of the standard model (SME) lead to a modified dispersion relation:

$$E^2 = p^2 + m^2 + f\left(p; \xi / M_{Pl}\right)$$

where

* $f\left(p; \xi / M_{Pl}\right)$ is a function of dimension $(\text{mass})^2$,

* M_{Pl} the Planck mass ($1.2 \cdot 10^{19}$ GeV) and

* **ξ** a coupling parameter (naturally of order 1).

Modified dispersion relations

- In low-energy limit, $f\left(p;\xi/M_{Pl}\right)$ can be expanded:

$$f\left(p;\xi/M_{Pl}\right) \approx E_{Pl}\xi_i^{(1)}p^i + \xi_{ij}^{(2)}p^i p^j + \frac{\xi_{ijk}^{(3)}}{E_{Pl}}p^i p^j p^k + \dots$$

- Assuming non-violation of rotational symmetry:

$$f\left(p;\xi/M_{Pl}\right) \approx \underbrace{E_{Pl}\xi^{(1)}\left|p\right| + \xi^{(2)}\left|p^2\right|}_{\substack{\text{affect}\\ \text{low-energy physics}}} + \underbrace{\frac{\xi^{(3)}}{E_{Pl}}\left|p^3\right| + \frac{\xi^{(4)}}{E_{Pl}^2}\left|p^{(4)}\right|}_{\substack{\text{affect}\\ \text{high-energy physics}}} + \dots$$

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violate CPT

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birefringence

(R. C. Myers and M. Pospelov, Phys. Rev. Lett. 90, 211601 (2003), arXiv:hep-ph/0301124)

Terrestrial experiments: LE tests

It is well tested that nature is Lorentz Invariant well below the Planck scale. For this reason, looking for LIV deviation at low energy ($\xi^{(1)}$ and $\xi^{(2)}$ terms) require experiments with very high precision.

- **Penning traps:** Change in cyclotron motion and Larmor precession of a charged particle confined for long time. Limits in R.K. Mittleman et al (Phys. Rev. Lett. 83, 2116)
- **Clock comparison:** Differences in the frequencies of clocks (co-local atomic transitions) over long periods of time. O.Bertolami et al (arXiv:hep-ph/0412289)
- **Cavity experiments**: Variation of the cavity resonance frequency with space orientation. Some limits in G. Amelino-Camelia (arXiv:gr-qc/0501053)
- **Neutral mesons:** Test sidereal variations and other orientation effects on mass diference of K_0 eigen-states. Some limits in De Angelis et al. (Nuovo Cim., C034N3:323, 2011)
- **Spin polarized torsion balances:** Orientation dependence of a spin polarization generated by a specific pattern of magnets. Time-like limits on $\xi^{(2)}$ of $O(10^{-29})$. M.Smiciklas et al (arXiv:1106.0738)

A detailed review on these experiments and more can be found at: D.Mattingly (arXiv:gr-qc/0502097)

Astrophysical experiments: HE tests

To constrain the $\xi^{(3)}$ and $\xi^{(4)}$ terms, much higher energy is required, not reachable by experiments at Earth. High and Very High Energy astrophysics are playing an important role in this field.

- **Vacuum birefringence:** Change in polarization angles with energy and distance provoking decrease in polarization degree. L.Maccione et al (arXiv:0809.0220)
- **Threshold reactions:** LIV-allowed and LIV-modified reactions. T.Jacobson et al (arXiv:hep-ph/0209264)
  - Photon-pair creation.
  - Gamma-ray decays.
- **Synchrotron radiation:** changes in the expected frequency for Synchrotron emission due to LIV presence. Study for Crab Nebula in T.Jacobson et al (arXiv:astro-ph/0212190).
- **Photon Time of Flight:** Energy and distance dependence of the photon speed. Kinematical approach.

2) The measurement of Time of Flight

Photon Time of Flight

From the modified photon dispersion relation, we can derive a velocity

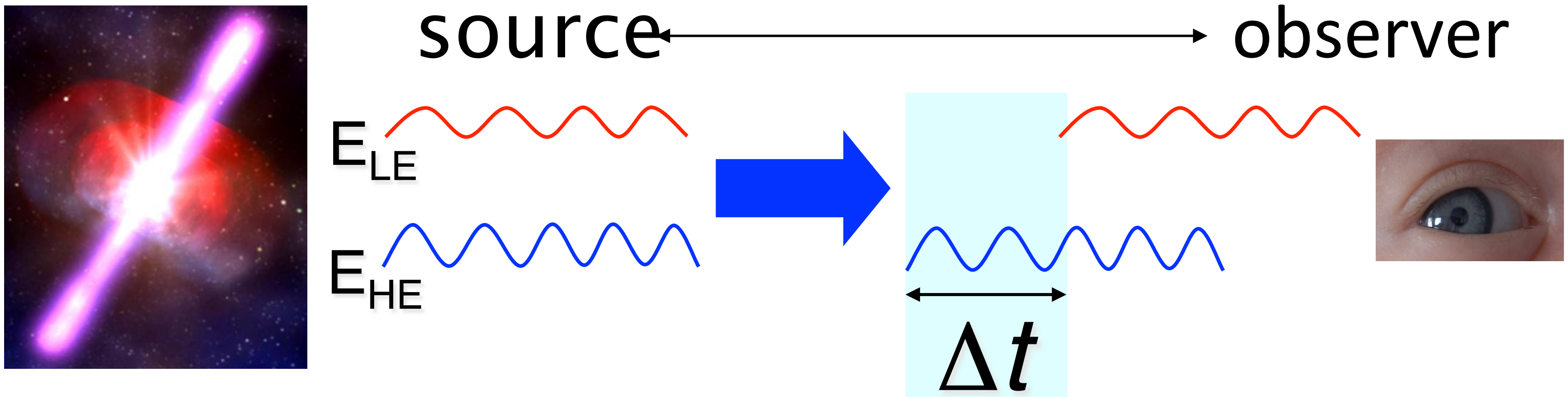
$$v = \partial E / \partial p \quad \longrightarrow \quad v_\gamma = 1 + \frac{(n-1) f_\gamma^{(n)} E^{n-2}}{2E_{Pl}^{n-2}}$$

If $n > 2$, the velocity is energy dependent and the difference of arrival times (ΔT) of 2 photons (E_1 and E_2)can be expressed, as function of their travelling time (T) as

$$\Delta T = \Delta v T = \frac{(n-1) f_\gamma^{(n)} (E_1^{n-2} - E_2^{n-2})}{2E_{Pl}^{n-2}} T$$

If the traveling time is larger, that is, the source is distant, the LIV effect is amplified. So we should focus on ***n*=3** and ***n*=4**.

Photon Time of Flight



Ingredients needed

- Fast flaring source (clock tick)
- At the highest possible distance (cumulative delay effect)
- With the highest possible energy (energy scale determines Effective QG scale tested)

$$\Delta T = \Delta v T = \frac{(n-1) f_\gamma^{(n)} (E_1^{n-2} - E_2^{n-2})}{2 E_{Pl}^{n-2}} T$$

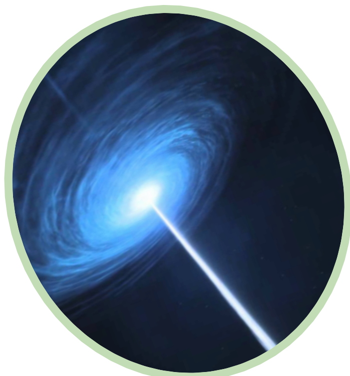
Which tool ?: Cherenkov telescopes !

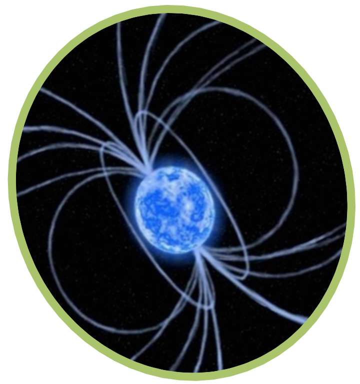
- **Very good time resolution**
- **Distant sources**.
- **Very high energy**
- Highest energies gamma-ray detectors:
  - MAGIC (2 telescopes, Spain)
  - H.E.S.S. (5 telescopes, Namibia)
  - VERITAS (4 telescopes, Arizona)
  - Upcoming CTA (2 arrays of telescopes, Spain and Chile) More info in M.Actis et al (arXiv:1008.3703)

Image of MAGIC-I

Sensitivities for different sources

Source family	d [pc]	E [GeV]	δt [s]	Expected limits E_{QG1} [GeV]	E_{QG2} [GeV]
GRB	10^{10}	10^{1}	$10^{0} - 10^{2}$	$10^{17} - 10^{19}$	$10^{9} - 10^{10}$
AGN	10^{8}	10^{4}	$10^{2} - 10^{5}$	$10^{15} - 10^{18}$	$10^{9} - 10^{11}$
Pulsar	10^{3}	10^{2}	$10^{-2} - 10^{-4}$	$10^{17} - 10^{19}$	$10^{10} - 10^{11}$





Caveats

- VHE gamma rays are absorbed by pair production with the EBL photons -> trade-off between d and E.

- Acceleration mechanisms may produce source-dependent intrinsic delays -> combine different source types and at different distances.

- No light-curve model -> complex flares that require cumbersome statistics treatment

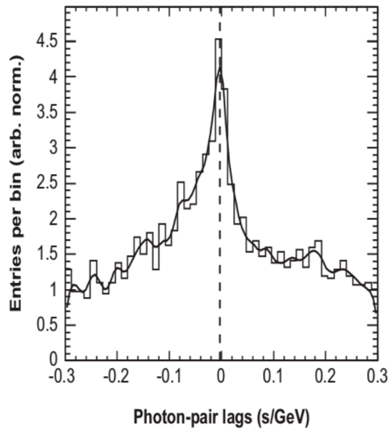
ToF: Extracting LIV from data

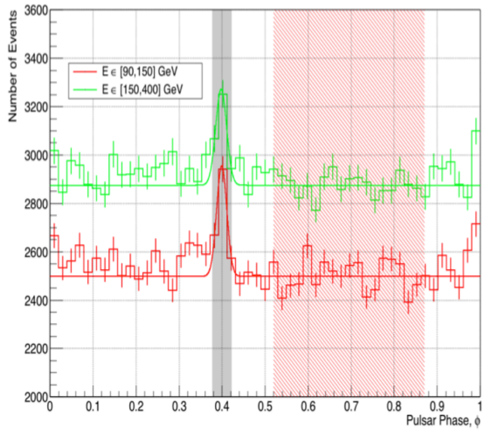
Pair View

Computation of spectral lags between pairs of photons in a data set. The distribution of the spectral lags is used to estimate the LIV parameter.

- Application of the method to GRBs in V.Vasileiou et al (arXiv:1305.3463)

$$l_{i,j} \equiv \frac{t_i - t_j}{E_i^n - E_j^n}$$





Peak comparison

Comparison of the time distribution peaks of subsets of a same data set with different energy ranges.

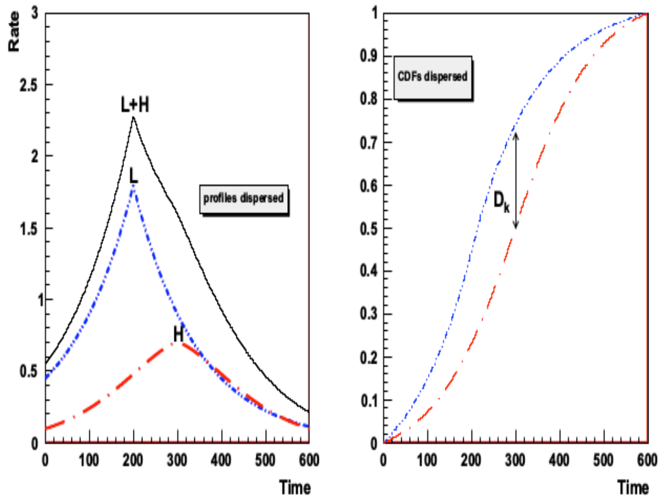
- Whipple, Fermi, H.E.S.S. and application of the method to Crab Pulsar in M.Gaug et al (arXiv:1709.00346)

ToF: Extracting LIV from data

Dispersion cancellation

LIV makes the time distribution smoother, injecting inverse LIV effect, we try to recover the sharpness of the time distribution. Several ways of applying this idea.

- One version of the method in M.Daniel et al (arXiv:1204.2205)



Maximum Likelihood

Maximization of the Likelihood function, created by the PDFs of every events. The PDFs is created by a model that makes maximum use of the information and contains several parameter, the LIV one among them.

- Explanation of the method in M.Martinez et al (arXiv:0803.2120), application to Pulsar in M.Gaug et al (arXiv:1709.00346)

Method: time-lag maximum likelihood analysis

$$\mathcal{L} = \prod_{1}^{N_\gamma} \frac{\mathrm{dP}}{\mathrm{dE_i dt_i}}$$

reconstructed energy

true energy (unknown)

$$\frac{\mathrm{dP}}{\mathrm{dE_i dt_i}} = N \int_0^\infty \Gamma(E_s) C(E_s, t) G(E - E_s, \sigma_E(E_s)) F(t - D(E_s, E_{QGn}, z)) \mathrm{dE_s}$$

True energy distribution (No absorption, no experiment effects)

Detector efficiency in time and energy (Collection Area)

Relation between E_s and E. Detector effect.

Event time distribution at the source (Before propagation effects)

M. Martinez and M.Errando Astropart.Phys.31:226,2009

3) Present situation

Main ToF measurements

- First astrophysical limit on $\xi^{(3)}$ was obtained from the Crab Pulsar (**optical data**)! (Warner & Nather, Nature, 222 (1969) 157)

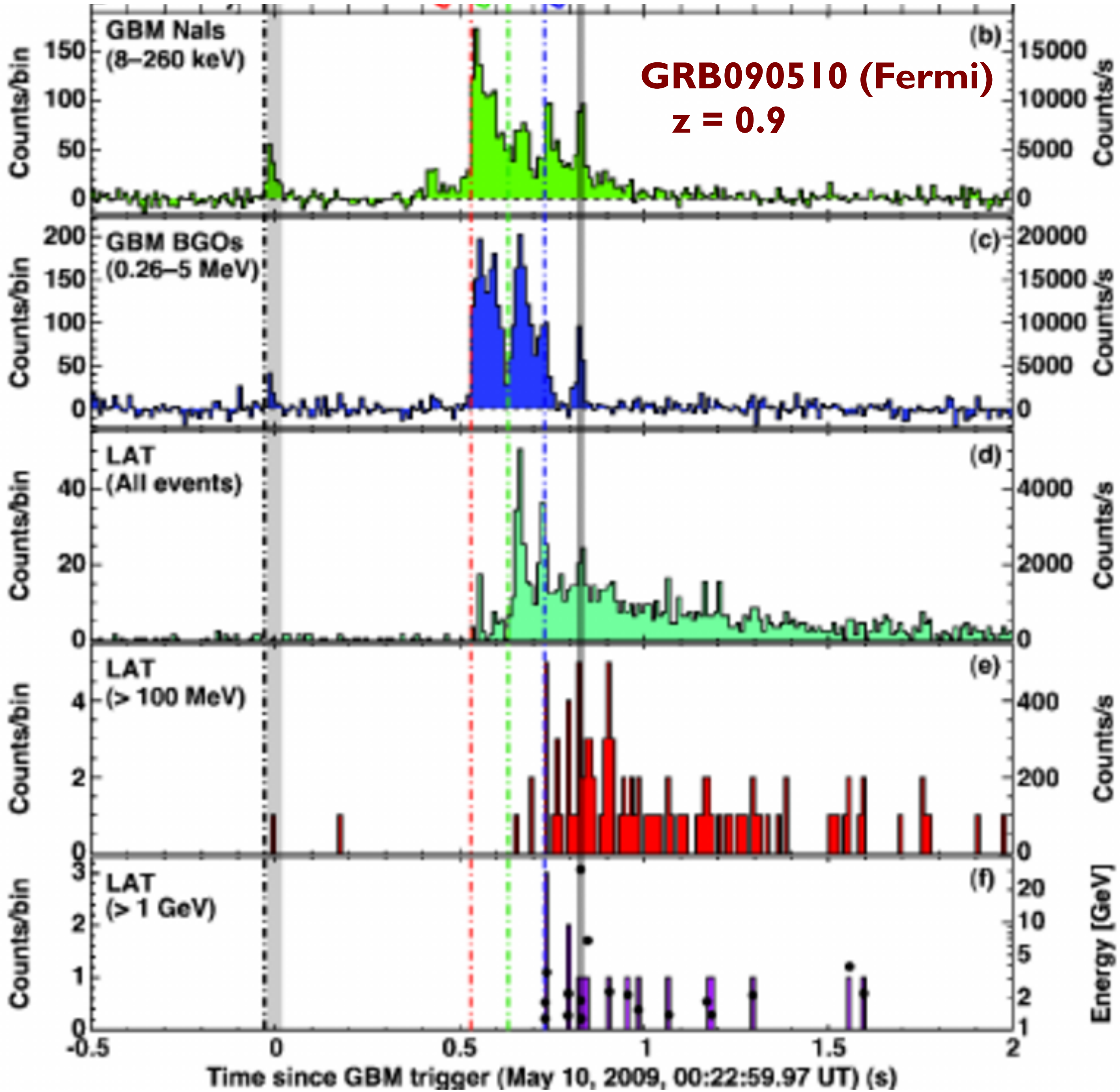
- Greatly improved with **EGRET** data from the Crab Pulsar (up to 2 GeV) (Kaaret, A&A 345 (1999) L32)

- Simple limit from **WHIPPLE** using a Mrk421 flare (Biller et al.,Phys Rev.Lett 89 (1999) 2108)

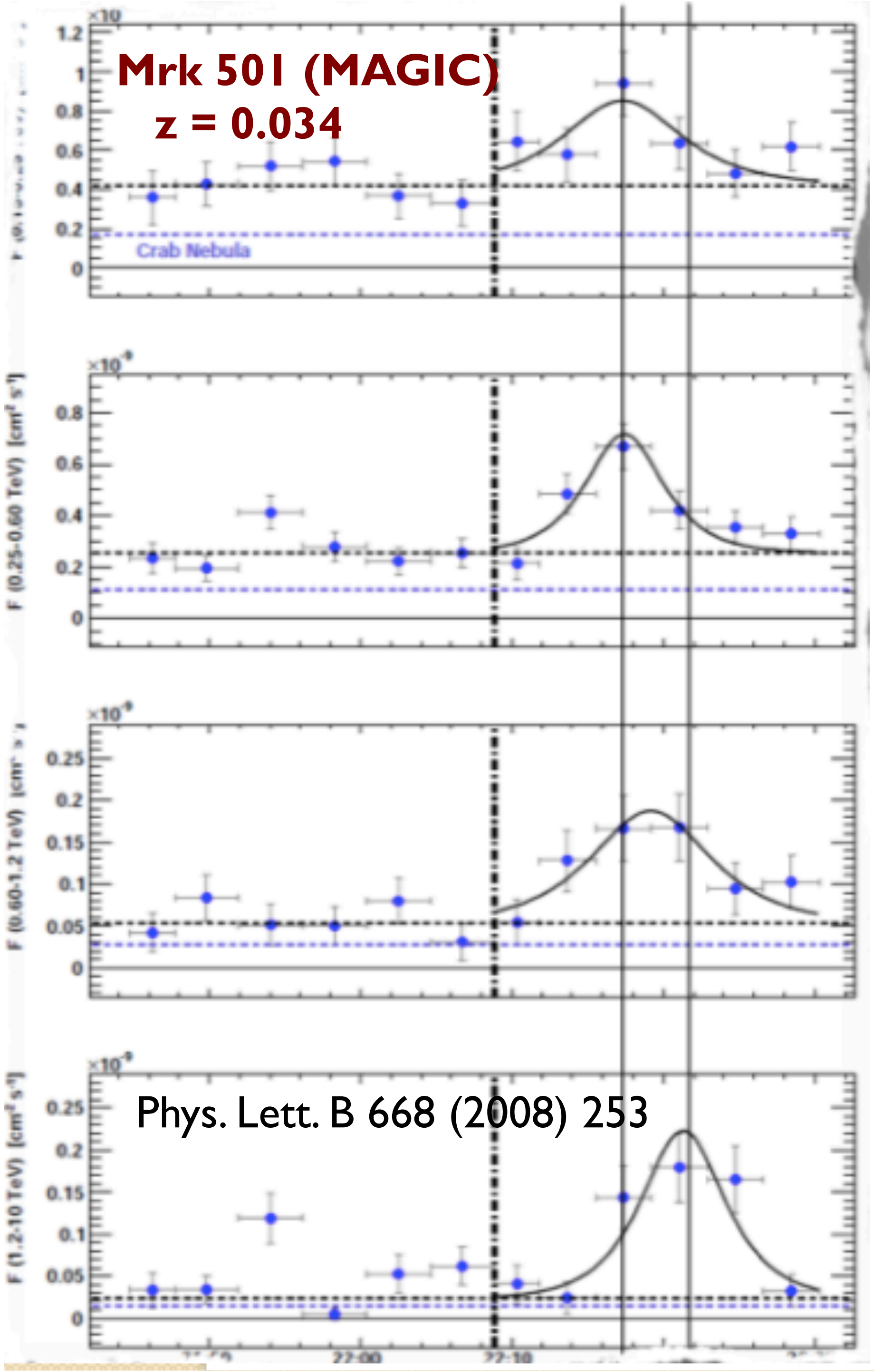
- Rapid flares of Mrk501 detected with **MAGIC** (Albert et al., PhLB 668 (2008) 253) and PKS2155 detected by **H.E.S.S.** (Abramowski et al., Aph 34 (2011) 738)

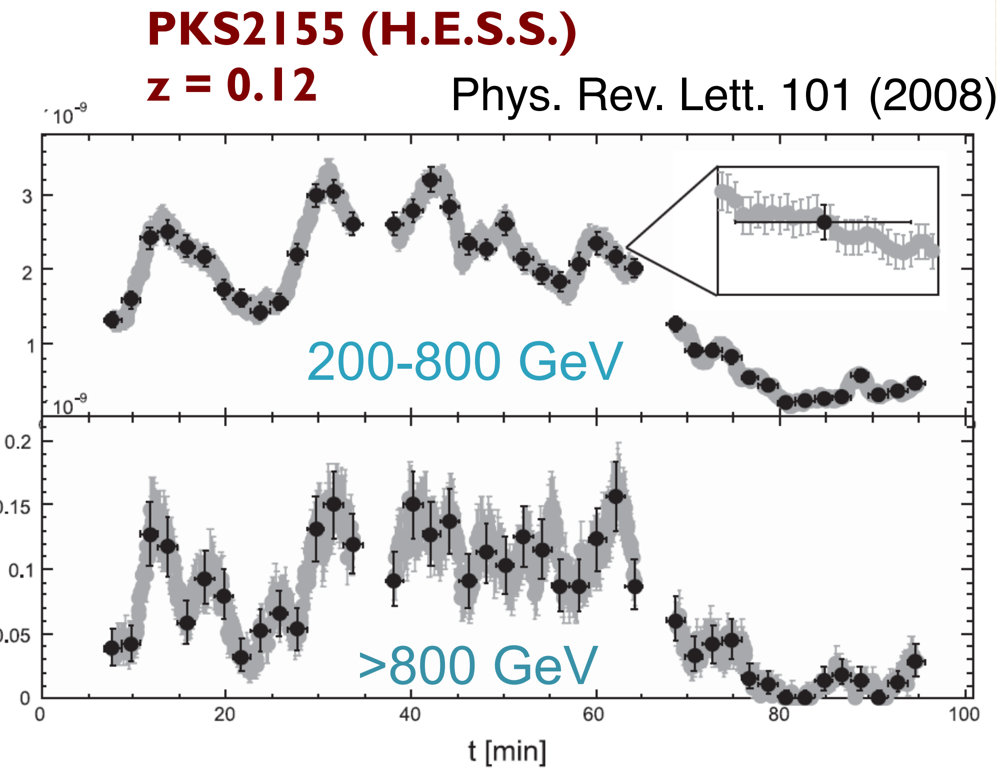
- Current best limits from **Fermi-LAT** using GRBs (specially GRB090510) (Vasileiou et al. Phys. Rev. D 87 (2013) 122001)

-Crab pulsar analysis beyond 400 GeV by **MAGIC** (Ahnen et al., ApJS 232 (2017) 9)

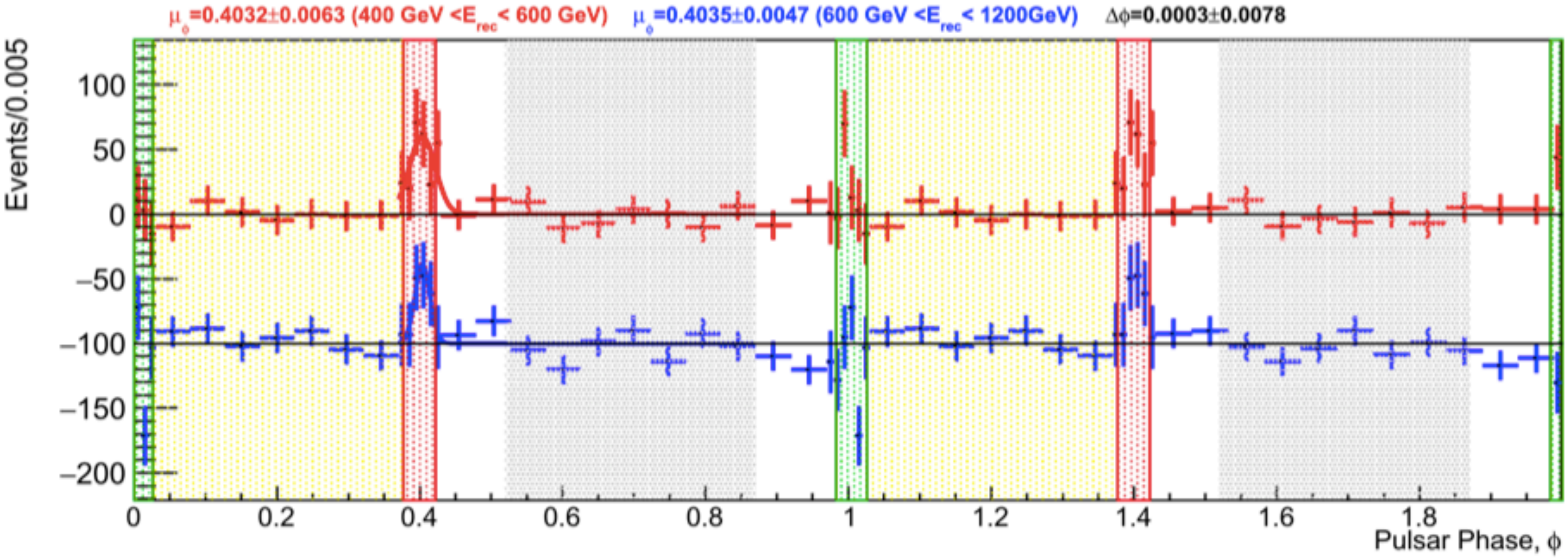


Fermi Collaboration Nature 462 (2009) 331-334


Mrk 501 (MAGIC)
z = 0.034
Crab Nebula
F (0.25-0.60 TeV) [cm⁻² s⁻¹]
F (1.2-10 TeV) [cm⁻² s⁻¹]
22:00
22:10
Phys. Lett. B 668 (2008) 253

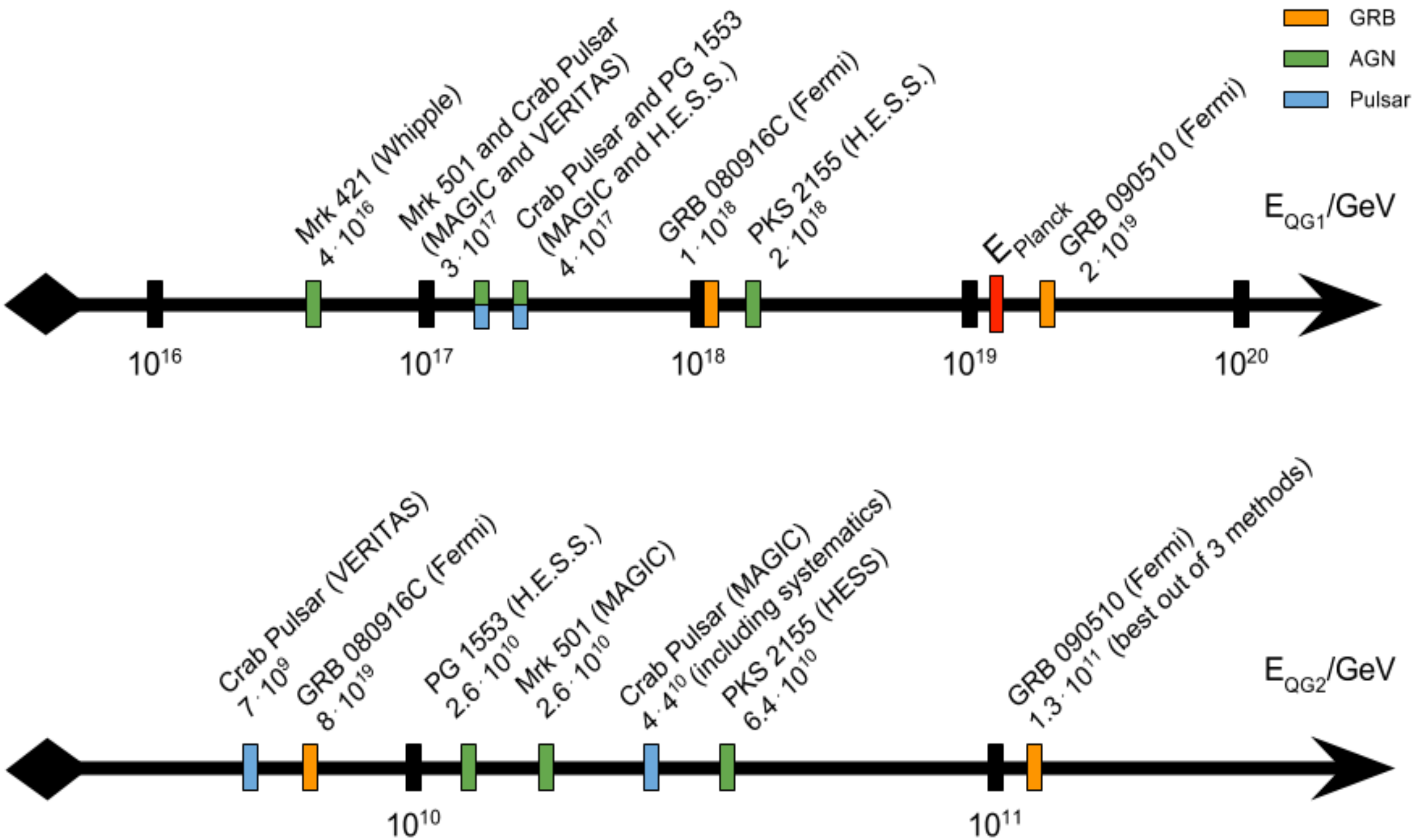

PKS2155 (H.E.S.S.)
z = 0.12
Phys. Rev. Lett. 101 (2008)
200-800 GeV
>800 GeV
t [min]

Crab Pulsar (MAGIC)
d = 2.2 Kpc



MAGIC Coll, ApJS 232 (2017) 9)

Current ToF limits



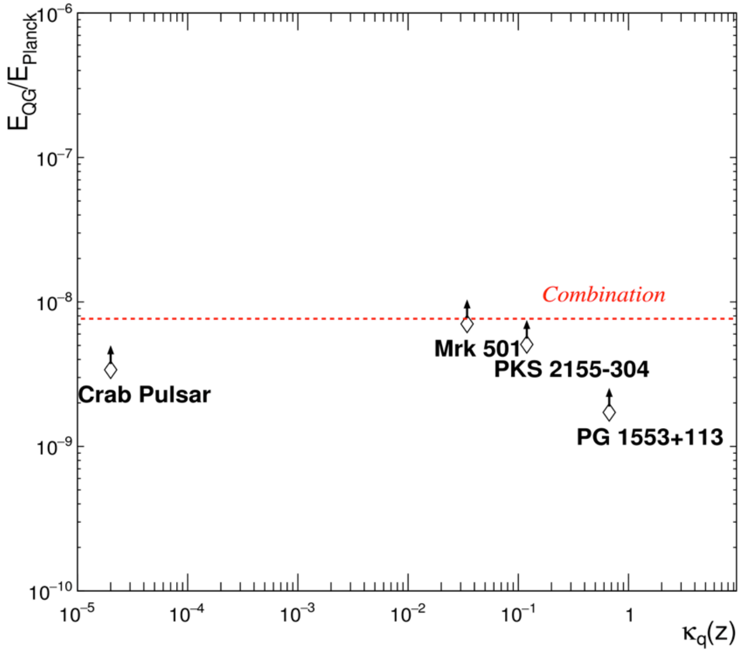
Next steps for IACTs

Until not long ago:

- Every experiment working individually.
- Data is private.
- Getting LIV bound with only the source observed by the instrument.

Now: the LIV Consortium (H.E.S.S. + MAGIC + VERITAS)

- Joined efforts to study LIV.
- MoU agreement to share published data and Instrument Response Functions.
- LIV ToF analysis with a combination of different types of sources from different experiments.
- First results presented at ICRC 2017, in Korea. L.Nogués et al (arXiv:1710.08342)
- List of sources growing with publications.
- Redshift study.
- Combined Likelihood method.
- Preparations and predictions for CTA.



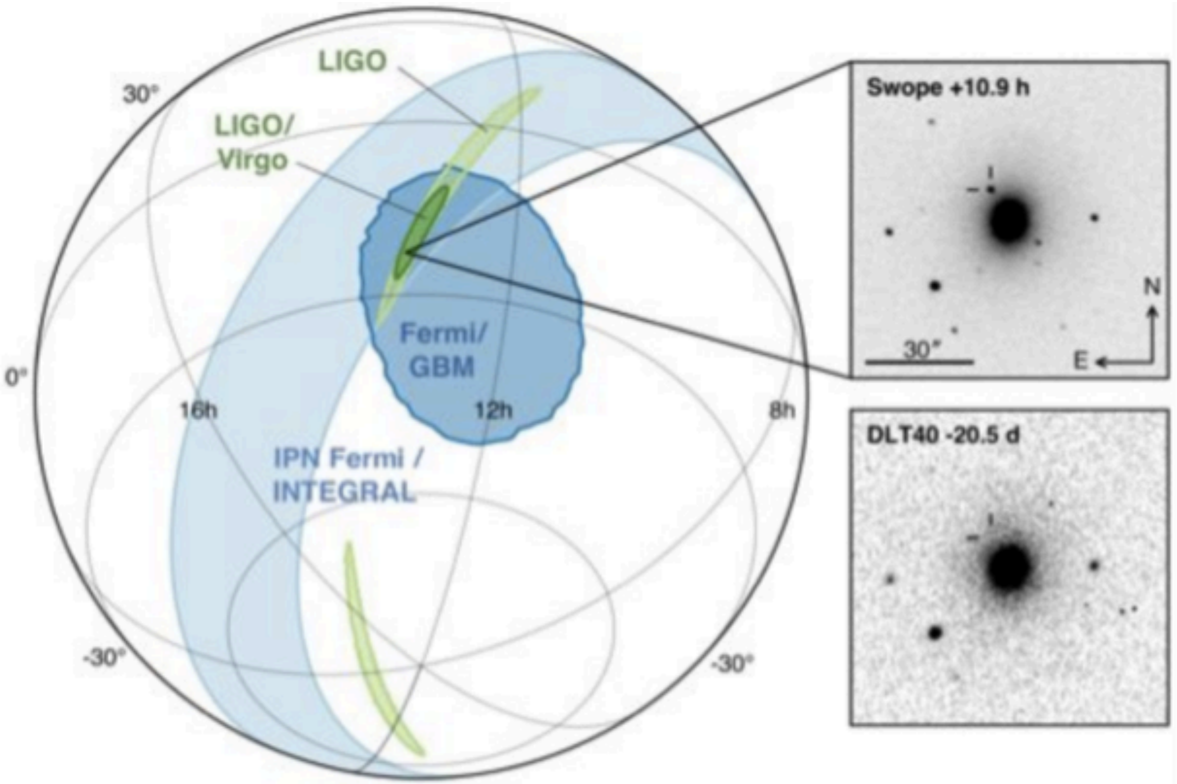
$$L_{Comb}(\lambda) = \prod_{i=1}^{Nsource} L_i(\lambda)$$

4) Multi-messenger ?

GW170817/
GRB170817A

GW170817/GRB170817A

- Binary Neutron Star merger detected by LIGO-Virgo.
- Follow up by ~70 ground- and space- based observatories.



PRL.119 161101 (2017)
ApJL 848: L12 (2017)

Follow up

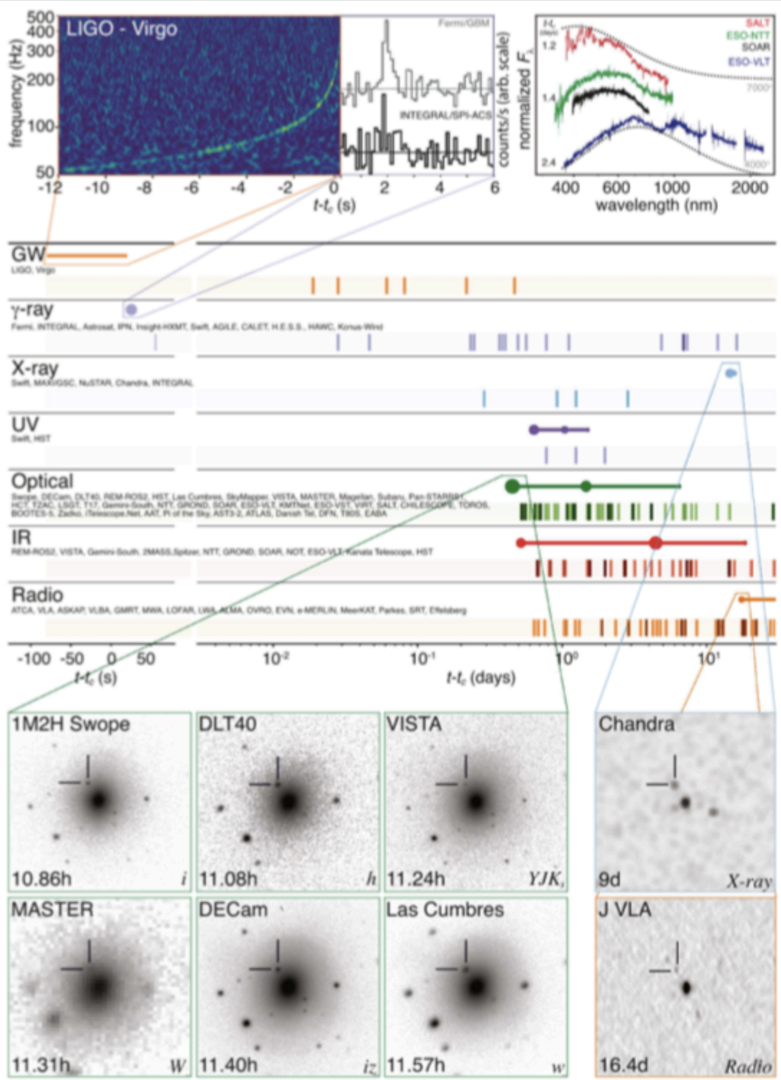
Observation time line

Very extensive multi-messenger and multi-wavelength campaign for days and weeks after the event!

Discovered the host galaxy: NGC 4993 and the faiding kilonova.

No detection above few MeV and no neutrinos associated to the event.

B. P. Abbott et al., Multi-messenger Observations of a Binary Neutron Star Merger, ApJL, (2017)

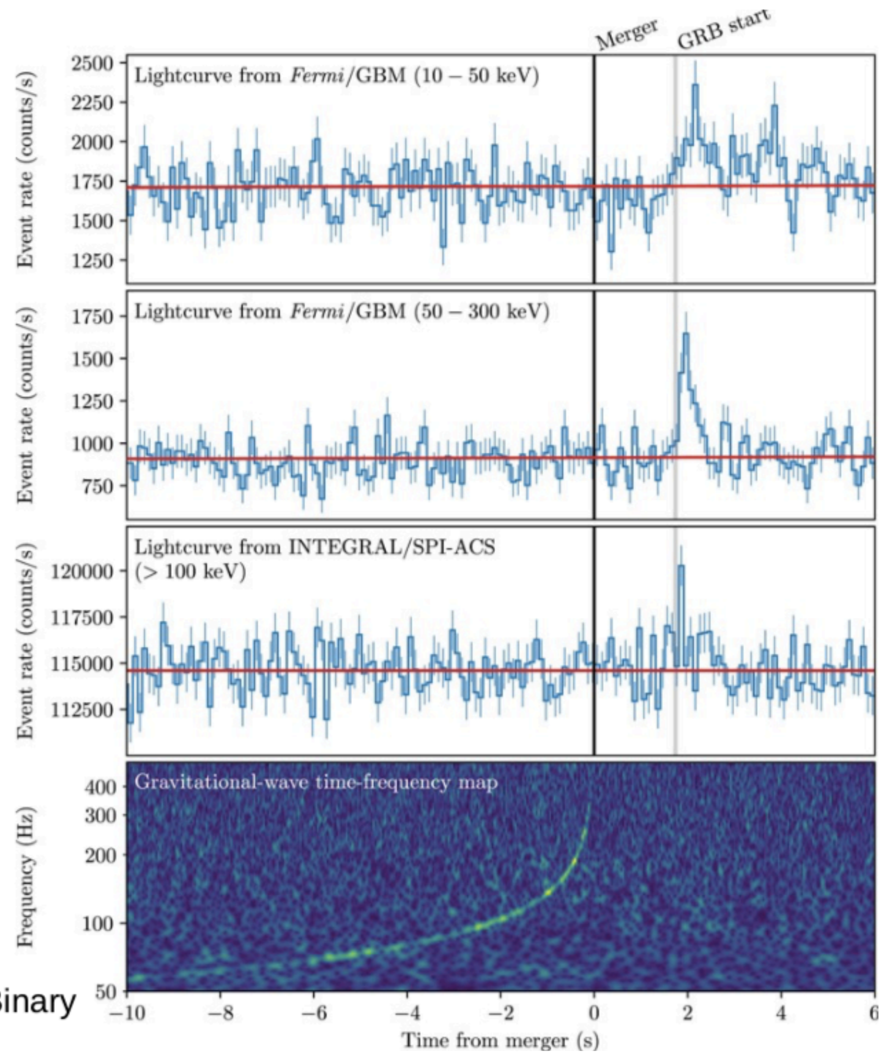


Gamma ray

GRB170817A occurs (1.74 ± 0.05) seconds after GW170817

Independently detected in-orbit by Fermi-GBM and in the routine untargeted search for short transients by INTEGRAL SPI-ACS

Probability that GW170817 and GRB170817A occurred this close in time and with location agreement by chance is 5.0×10^{-8} (Gaussian equivalent significance of 5.3σ)



B. P. Abbott et al., Gravitational Waves and Gamma Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A, ApJL, (2017)

Binary properties from GW detection

The GW signal duration was about 100s with combined SNR of 32.4

The properties of gravitational-wave sources are inferred by matching the data with predicted waveforms

Localisation region from the 3 detectors: 28 deg²

Luminosity distance: 40^{+8}_{-14} Mpc (about 130 Mly)

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–$1.60\ M_\odot$	1.36–$2.26\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$	0.86–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$

Quantum regime ?

- Extremelly high energy > 0.025 M_{Sun}

BUT

- Max Frequency ~ 500 Hz

$\Rightarrow$ **Wavelength ~ 600 Km**

Macroscopic (classical) World !

Constraint on the GW speed

If the difference (~2s) of the GW and EM signal is due to different velocities of the 2 types of waves, we obtain an Upper bound on the difference between the velocities.

To obtain a lower bound we can assume that the EM signal was emitted 10s after the GW one.

(at the consevative distance of 26Mpc**)**

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

… and LIV (EM sector)

- Given the long wavelength of GW, in spite of the huge energy released, it is not really exploring the quantum regime => assume $v_{GW} = c$

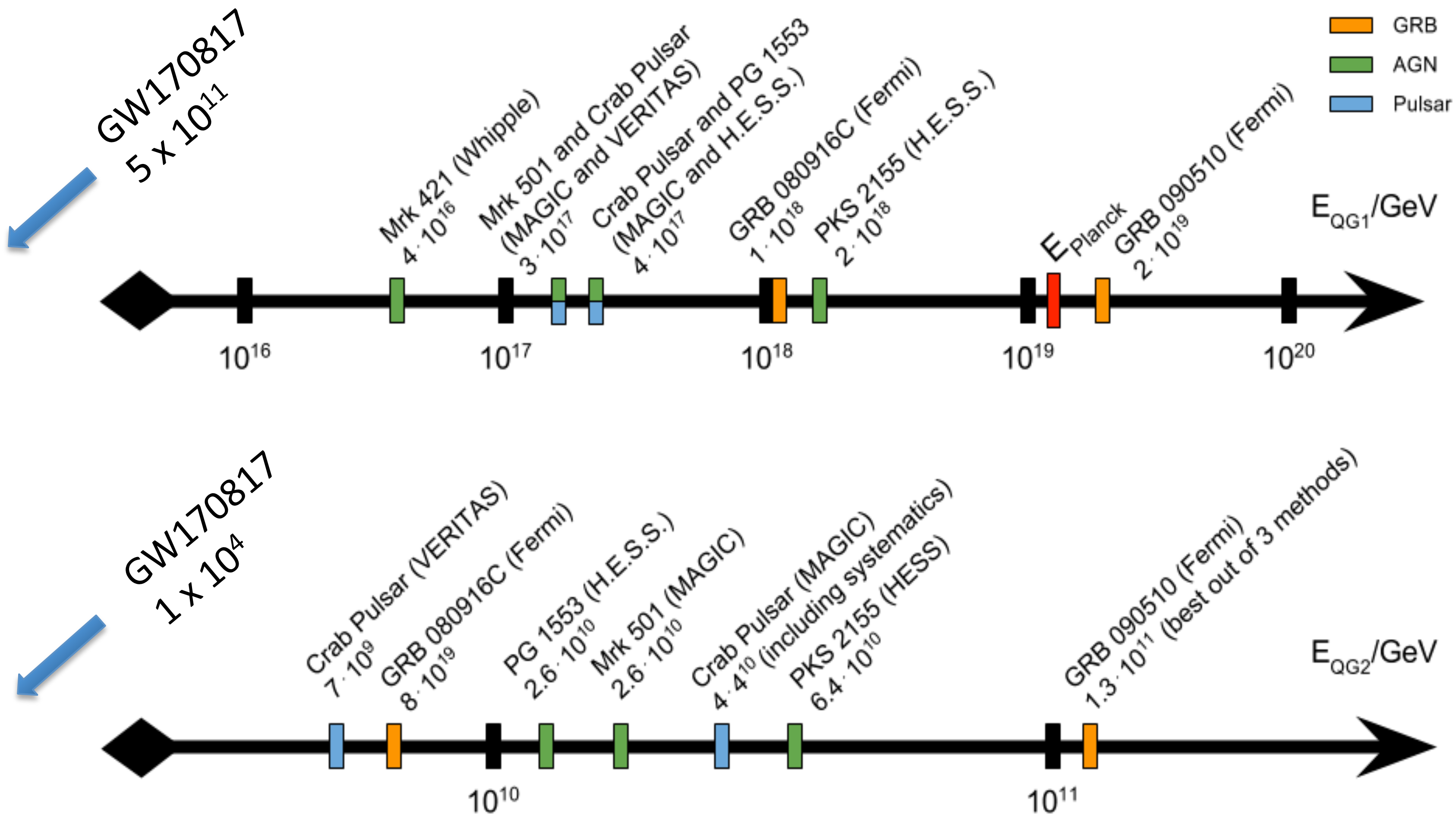
- LIV test sensitivity limited by:

  * Relatively short distance (~ 40 Mpc => z ~0.01)
  * Relatively low energy (~ 200 KeV) -> Fermi GBM

  => not competitive at all with current bounds:

  E_{QG1} ~ 5 x 10^{11} GeV
  E_{QG2} ~ 1 x 10^{4} GeV

Current ToF limits

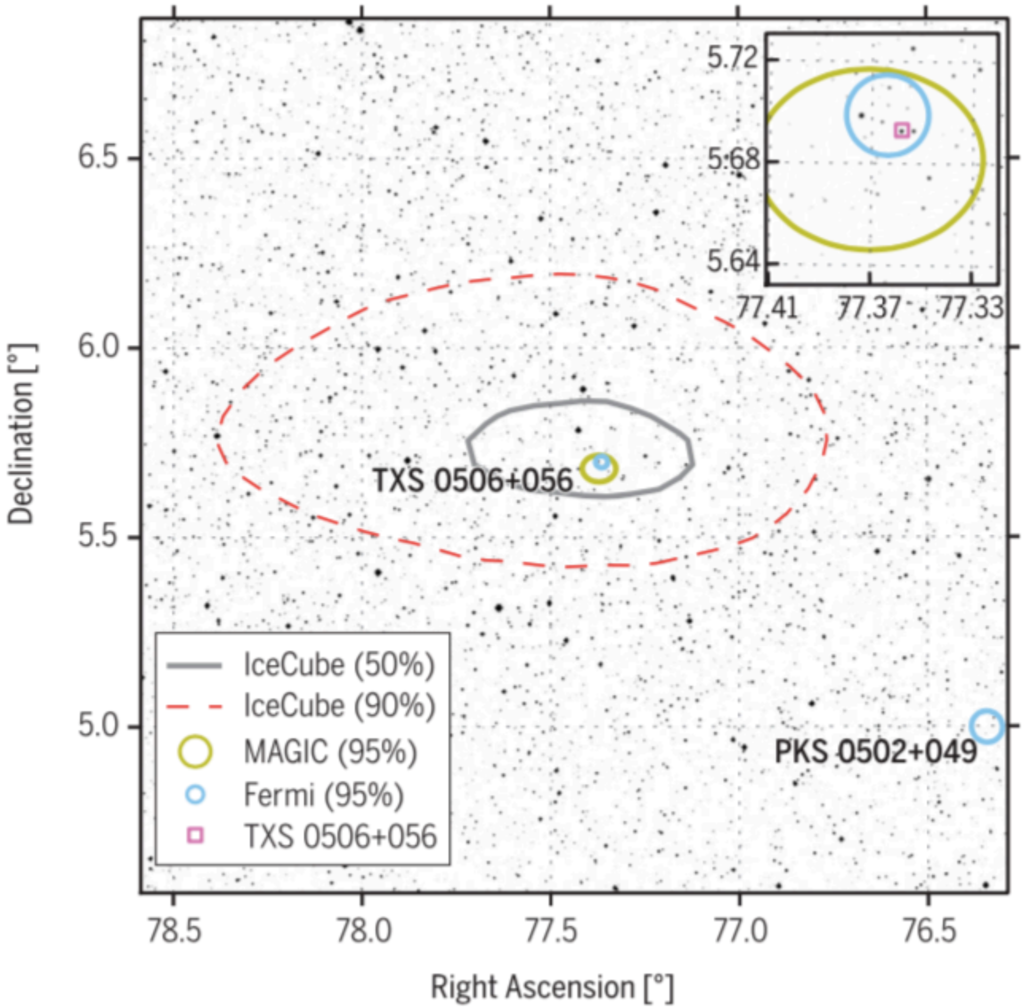


IceCube-170922A/ TXS0506+056

IceCube-170922A/TXS0506+056

- HE neutrino associated (3 sigma) with Blazar.
- Follow up by ~ 15 ground- and space-based observatories

Science 361, eaat1378 (2018)



IceCube-170922A/TXS0506+056

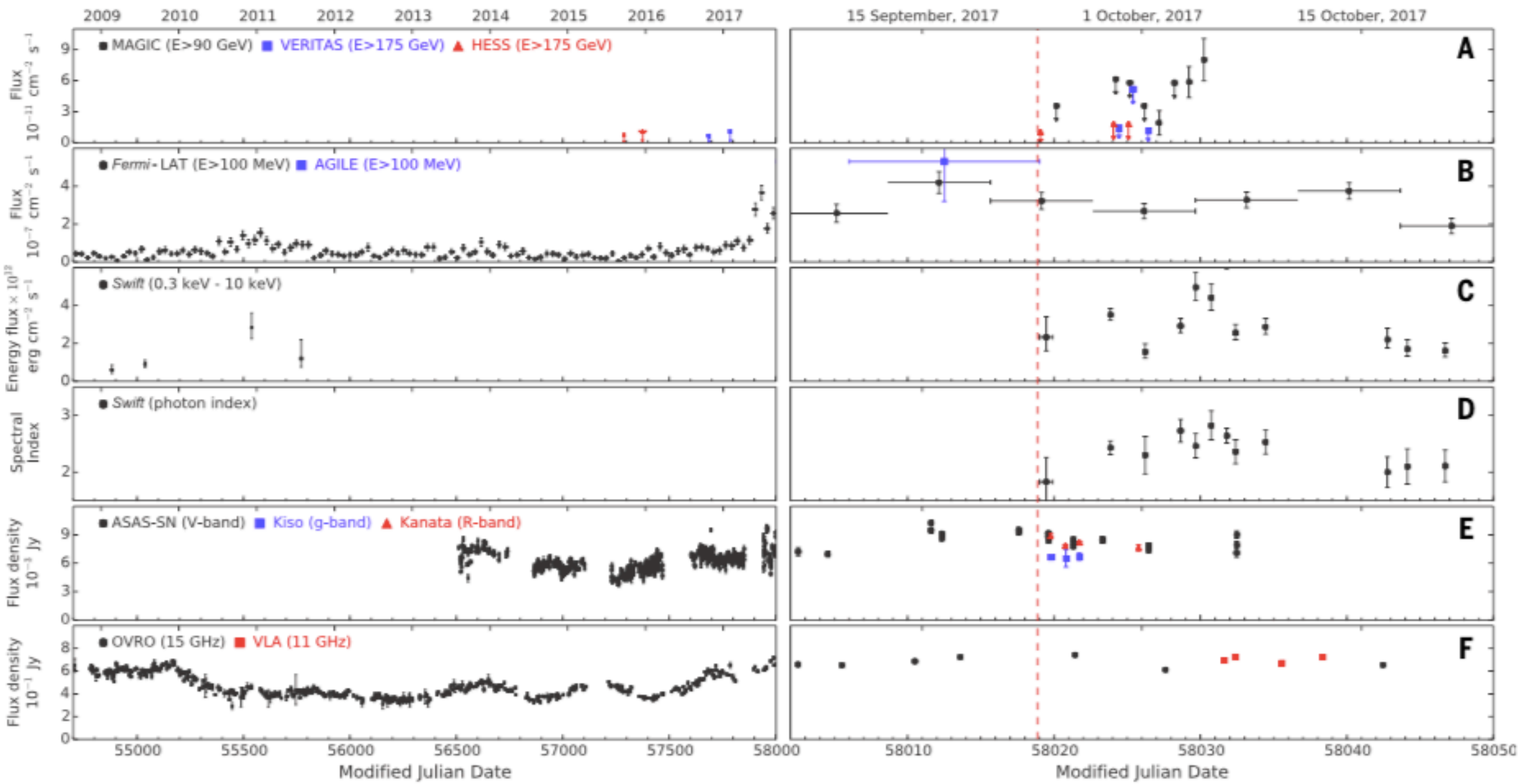
- Very Large neutrino energy ~290 TeV
  neutrinos have mass but at that energy -> $v/c \sim 1 - 0.5 \times 10^{-31}$
- Large gamma energy, up to ~ 500 GeV
- Large source distance z=0.3365 +- 0.0010

but

- The neutrino emission was not "simultaneous" with the emission of gammas

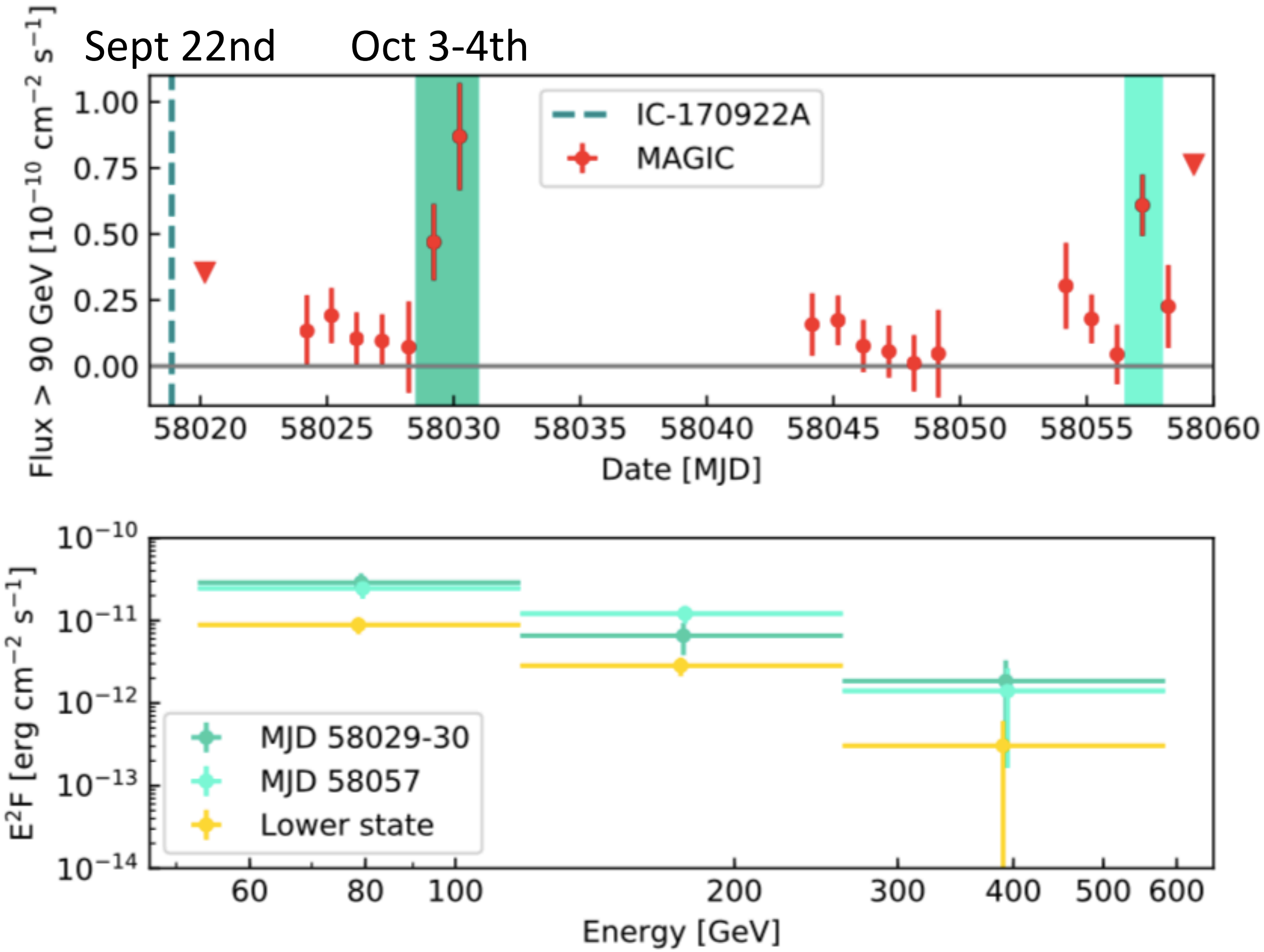
=> no useful LIV constraint

Follow up



MAGIC (E>90 GeV)
VERITAS (E>175 GeV)
HESS (E>175 GeV)
Fermi-LAT (E>100 MeV)
AGILE (E>100 MeV)
Swift (0.3 keV - 10 keV)
Swift (photon index)
ASAS-SN (V-band)
Kiso (g-band)
Kanata (R-band)
OVRO (15 GHz)
VLA (11 GHz)
15 September, 2017
1 October, 2017
15 October, 2017
Modified Julian Date
Modified Julian Date
A
B
C
D
E
F

Lightcurve and spectrum



5) Summary and Outlook

- Measuring **a possible Energy Dependence of the Speed of Light in Vacuum** is important because it may pinpoint LIV due to the quantum structure of spacetime (Quantum Gravity).

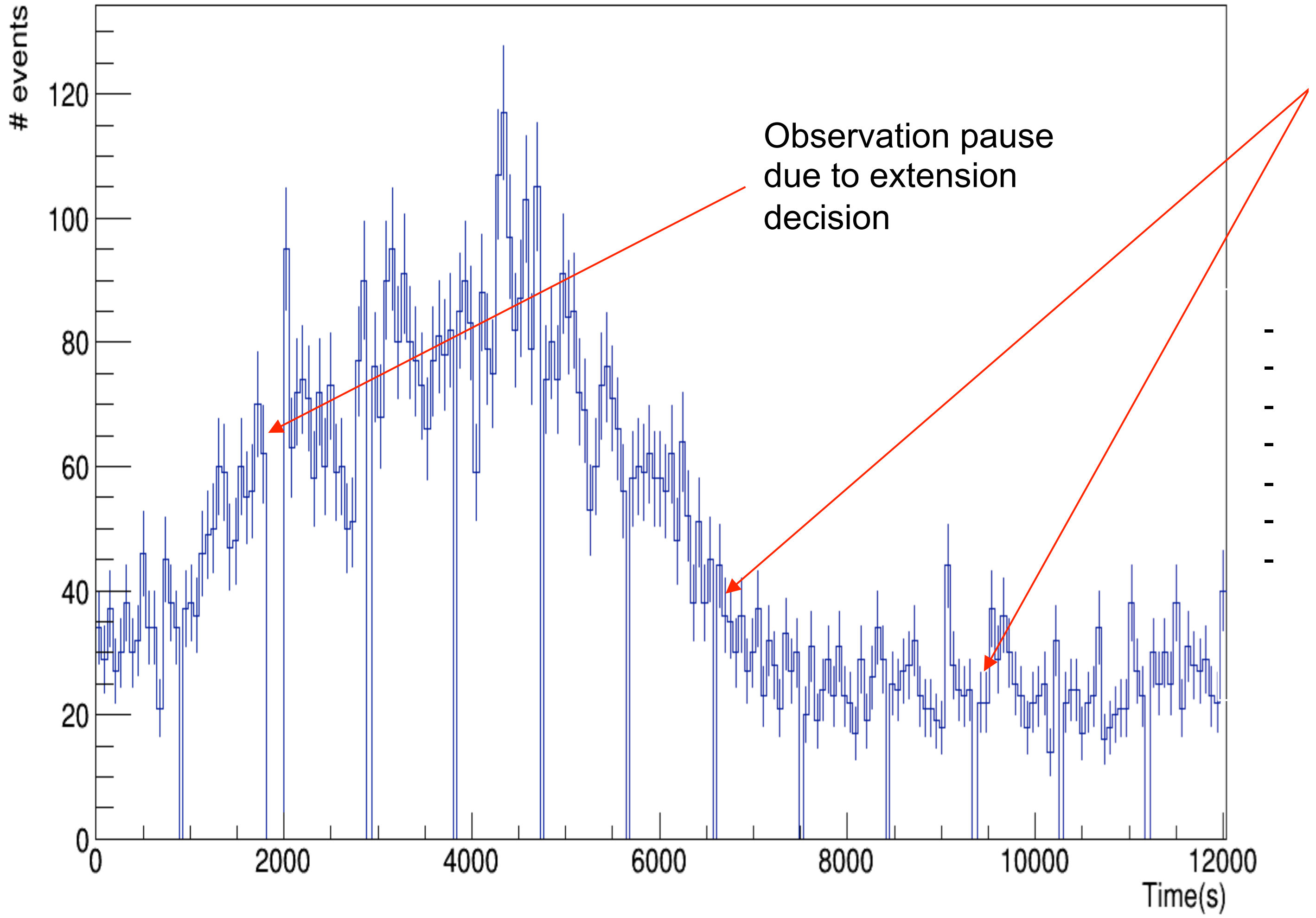
- Effects are expected to be tiny $O(E/E_{PL})$ but at our reach with gamma ray detectors (satellites + ground-based)
  => We can measure delays of seconds in distances of hundreds of millions light years
  => huge step forward !

- Present bound on a **linear realisation** of LIV already above E_{PL} but measurements should continue.

- Bounds on a (more theoretically favoured) **quadratic realisation** of LIV still far away from E_{PL} but…

flares keep coming and sensitivity keeps growing !

Long “monster” Mrk421 2014 MAGIC flare



- **ON events:** 12994
- **ON above 4 TeV:** 122
- **OFF events:** 1550
- **Energy:** 100 - 51000 GeV
- **Number of wobbles:** 13
- **Original analysis:** Mireia
- **Extension:** 3.5h

- Analysis rather complex and still ongoing (Leyre Nogues PhD Thesis – Nov 2018), but bounds may sizably improve current ones (linear and quadratic).

- And if PeV gammas detected (in CTA or, for instance, using Very-Large Zenith Angle observations) bounds in quadratic term could improve by up to 4 orders of magnitude.

STAY tuned !