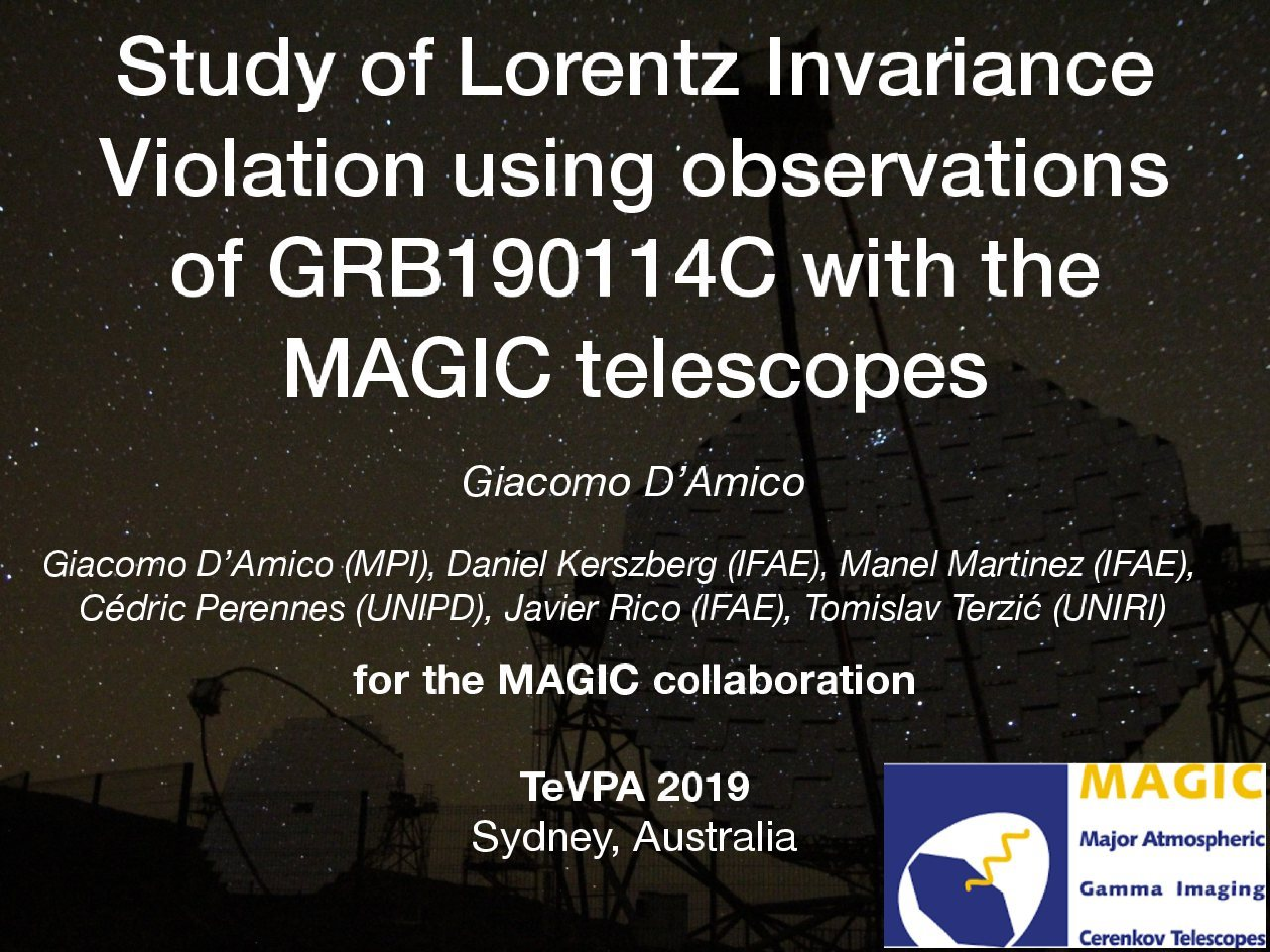

Study of Lorentz Invariance Violation using observations of GRB190114C with the MAGIC telescopes

Giacomo D’Amico

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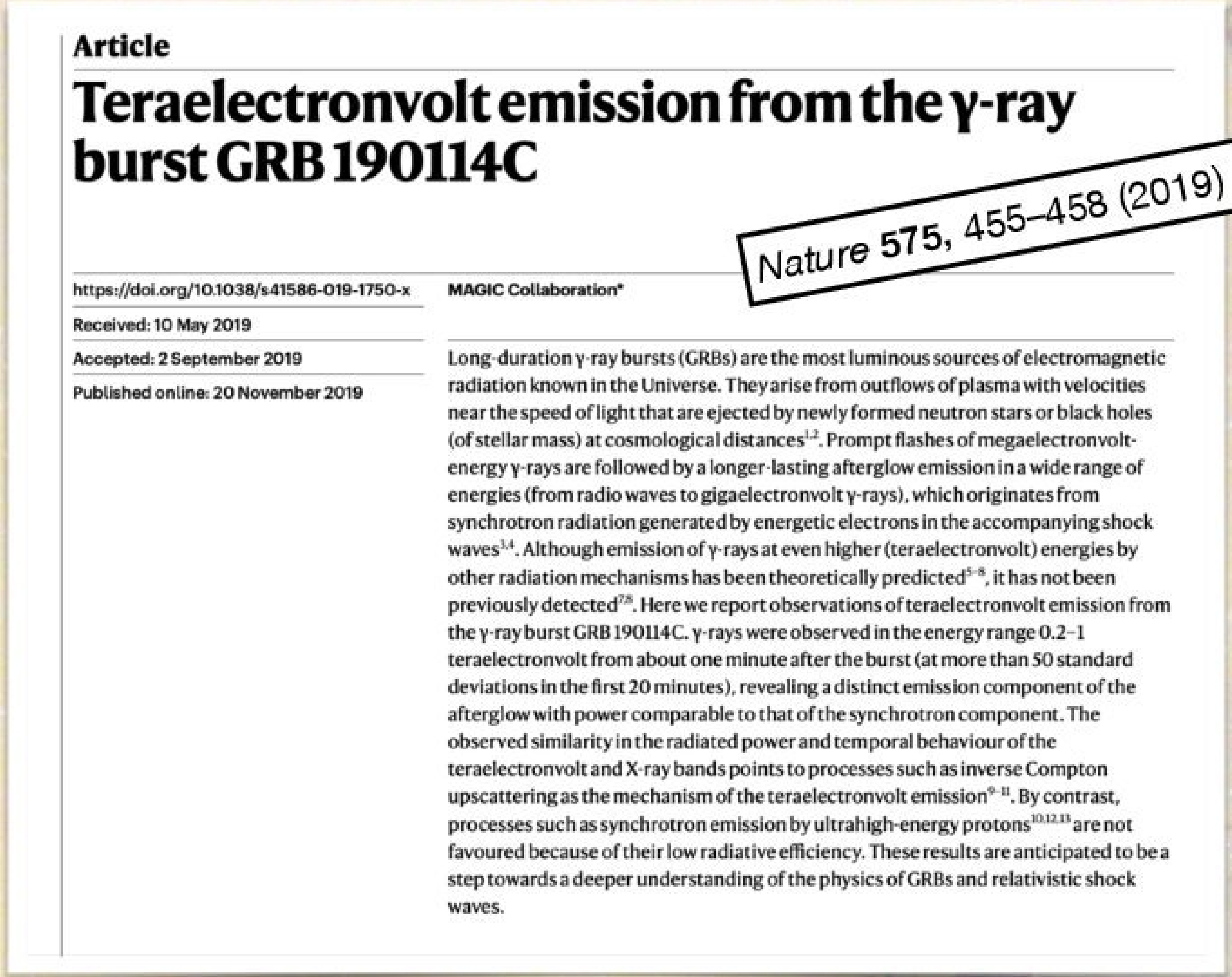
for the MAGIC collaboration

TeVPA 2019
Sydney, Australia

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

GRB 190114C



Article

Teraelectronvolt emission from the γ-ray burst GRB 190114C

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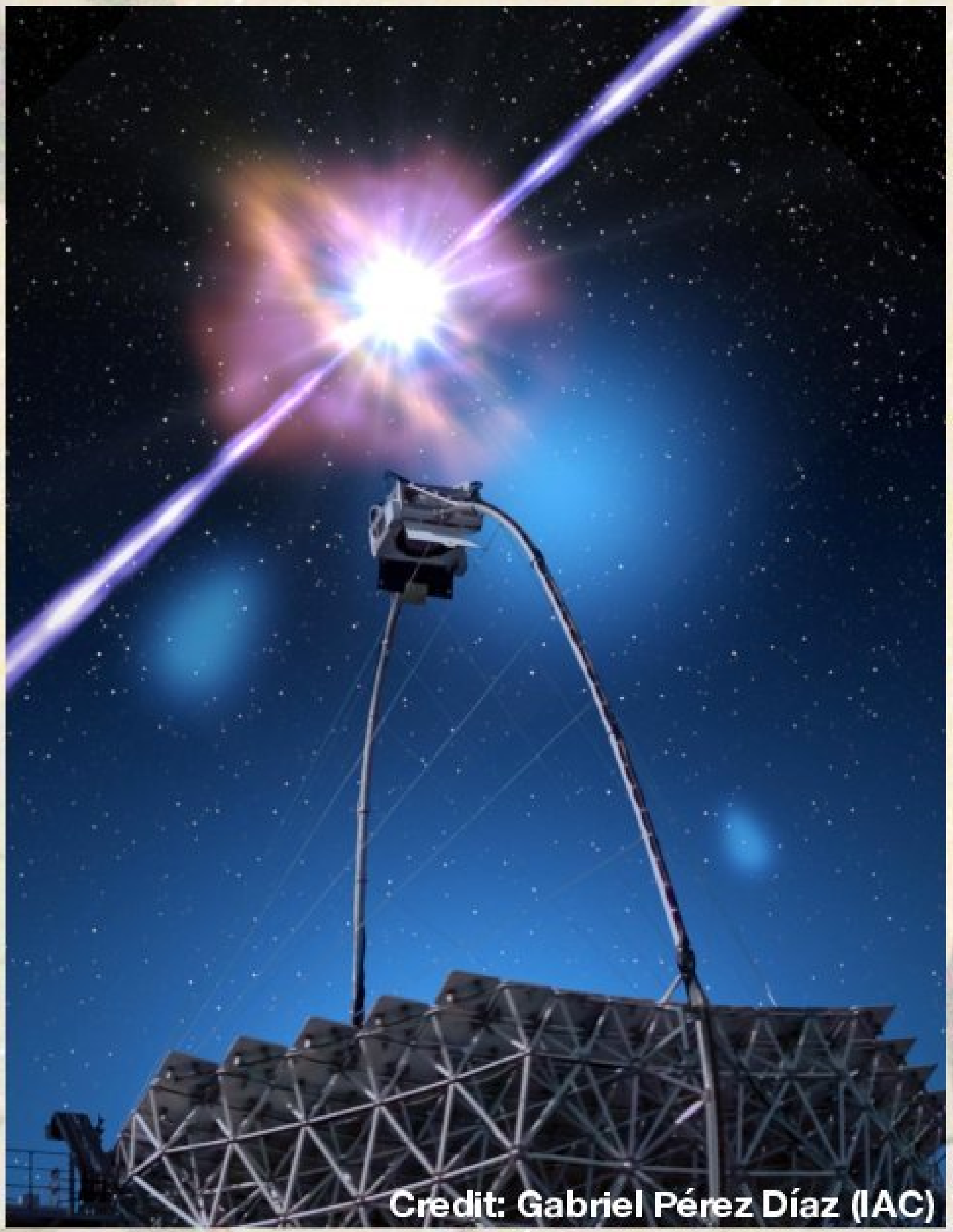
MAGIC Collaboration*

Long-duration γ-ray bursts (GRBs) are the most luminous sources of electromagnetic radiation known in the Universe. They arise from outflows of plasma with velocities near the speed of light that are ejected by newly formed neutron stars or black holes (of stellar mass) at cosmological distances[1,2]. Prompt flashes of megaelectronvolt-energy γ-rays are followed by a longer-lasting afterglow emission in a wide range of energies (from radio waves to gigaelectronvolt γ-rays), which originates from synchrotron radiation generated by energetic electrons in the accompanying shock waves[3,4]. Although emission of γ-rays at even higher (teraelectronvolt) energies by other radiation mechanisms has been theoretically predicted[5–8], it has not been previously detected[7,8]. Here we report observations of teraelectronvolt emission from the γ-ray burst GRB 190114C. γ-rays were observed in the energy range 0.2–1 teraelectronvolt from about one minute after the burst (at more than 50 standard deviations in the first 20 minutes), revealing a distinct emission component of the afterglow with power comparable to that of the synchrotron component. The observed similarity in the radiated power and temporal behaviour of the teraelectronvolt and X-ray bands points to processes such as inverse Compton upscattering as the mechanism of the teraelectronvolt emission[9–11]. By contrast, processes such as synchrotron emission by ultrahigh-energy protons[10,12,13] are not favoured because of their low radiative efficiency. These results are anticipated to be a step towards a deeper understanding of the physics of GRBs and relativistic shock waves.



Credit: Gabriel Pérez Díaz (IAC)

T_0 = 20:57:03.19 UT

E_{min} ~ 300 GeV ⟷ E_{max} ~ 2 TeV

$(t - T_0)_{min}$ ~ 62 s ⟷ $(t - T_0)_{max}$ ~ 1200 s

See talk by Elena Moretti

LORENTZ INVARIANCE VIOLATION

$$E = p \longrightarrow \Delta t = 0$$

LORENTZ INVARIANCE VIOLATION

$$E = p \longrightarrow \Delta t = 0$$

Loop Quantum Gravity

Double Special Relativity

Quantum Gravity in 3 dimensional space-time

Heuristic arguments

According to above mentioned QG models at the **Planck scale (E_{Pl} = 1.2 10^{19} GeV)**
Lorentz symmetries are expected to be **broken** or **deformed**

$$E^2 \simeq p^2 \left[1 - s_\pm \left(\frac{E}{E_{QG,n}}\right)^n\right] \longrightarrow \Delta t \simeq s_\pm \frac{n+1}{2} \left(\frac{E}{E_{QG,n}}\right)^n \cdot D$$

LORENTZ INVARIANCE VIOLATION

- **Time of arrival for a gamma emitted at redshift z:**

Photon energy at the detector

$$\Delta t = t_{off}(1+z) + s_{\pm}\frac{n+1}{2}D_n(z)\left(\frac{E}{E_{\mathrm{QG,n}}}\right)^n$$

offset at the **source** between the time of emission of the **low-energy particles** used as reference and the time of emission of the **higher-energy particle** of interest

$$D_n(z) = \frac{1}{H_0}\int_0^z \frac{(1+\zeta)^n}{\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}d\zeta$$

- **Taking** $z = 0.42, \quad H_0 = 70\,\mathrm{km}\,s^{-1}\,\mathrm{Mpc}^{-1}, \quad \Omega_\Lambda = 0.7, \quad \Omega_m = 0.3$

We should expect a **LIV time delay Δt(E; η_n)** from the GRB19014C gammas:

$$\Delta t(E;\eta_1,z) = \left(1.7\cdot 10^{-2}\,\mathrm{s/GeV}\right)\;E\cdot\eta_1$$
$$\Delta t(E;\eta_2,z) = \left(2.5\cdot 10^{-5}\,\mathrm{s/GeV^2}\right)\;E^2\cdot\eta_2$$

Where we have defined the parameters →

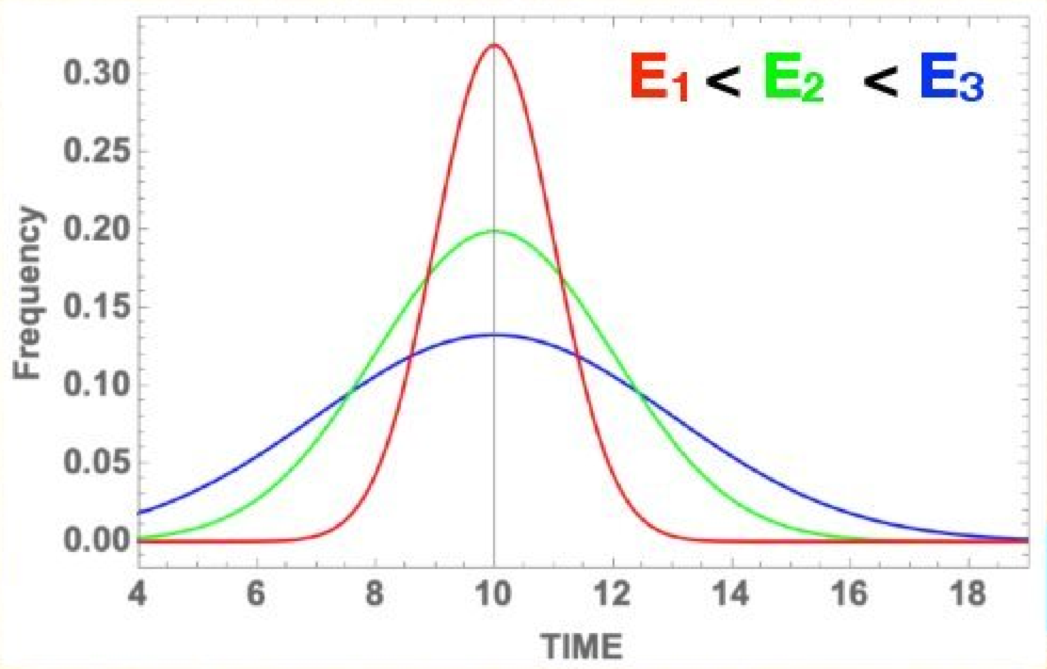
$$\eta_1 = s_{\pm}\cdot E_{\mathrm{Pl}}/E_{\mathrm{QG,1}}$$
$$\eta_2 = 10^{-16}\cdot s_{\pm}\cdot E_{\mathrm{Pl}}^2/E_{\mathrm{QG,2}}^2$$

→ Assuming $\eta_n = 1$ a 1 TeV gamma should have a **time delay** of
- 17 seconds (n=1)
- 25 seconds (n=2)

LORENTZ INVARIANCE VIOLATION

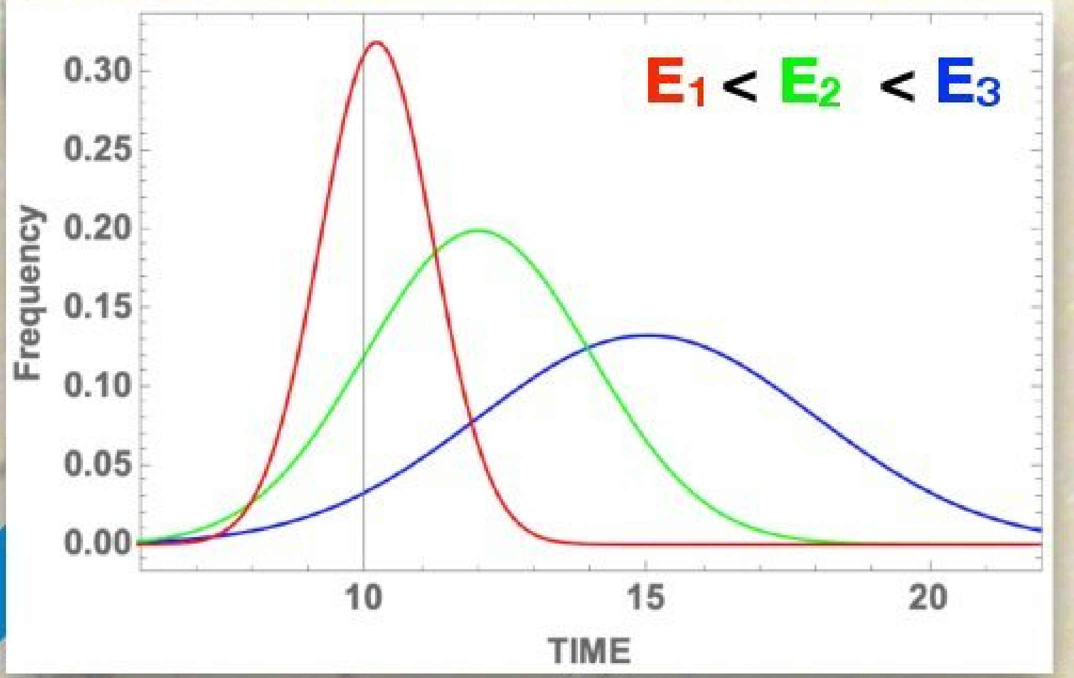
HOW TO SPOT LIV EFFECTS FROM DATA?

Intrinsic LC at the source



LIV effects

Observed LC at the detector



REAL DATA

Statistical analysis

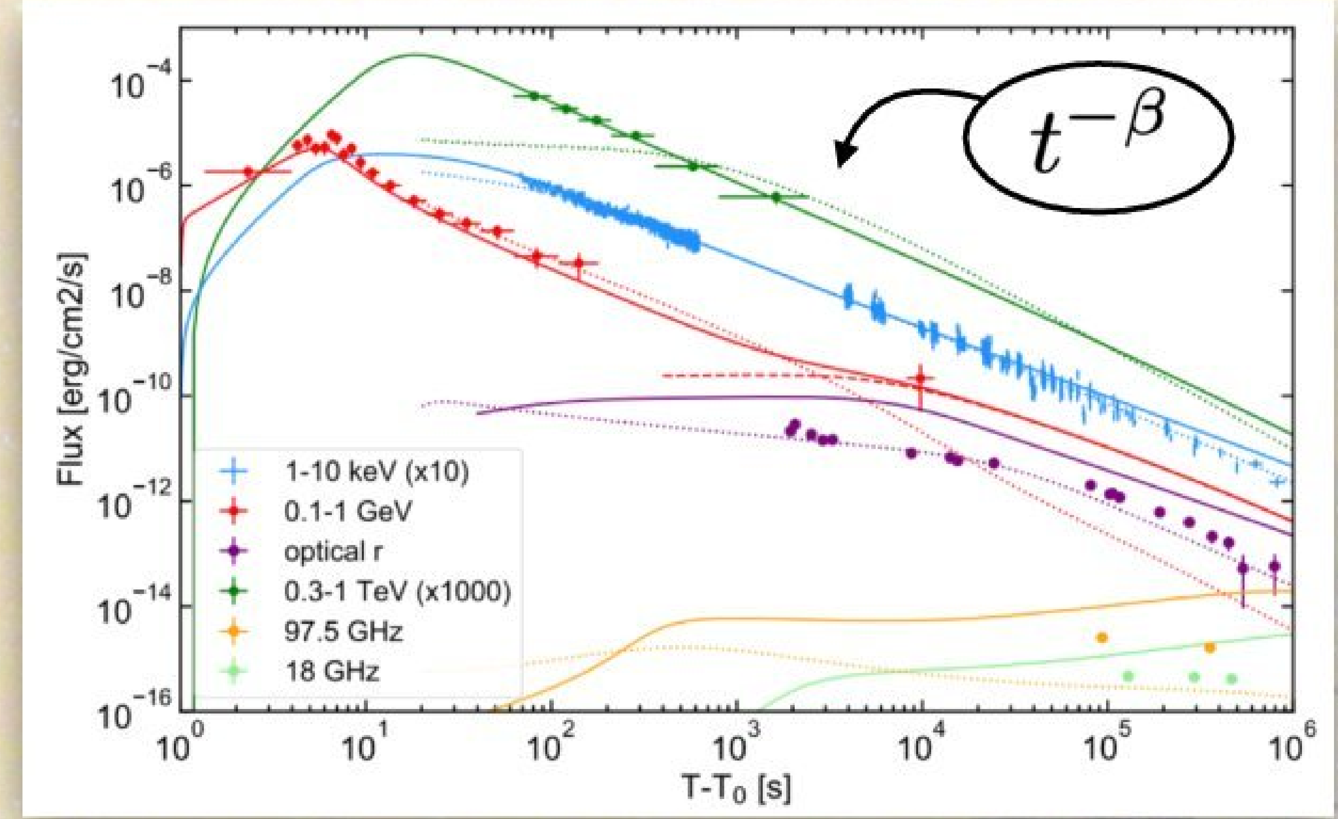
MC SIMULUATIONS

CONSTRAINTS ON THE ENERGY SCALE
OR
DISCOVERY!

ASSUMPTION FOR THE INTRINSIC LIGHT CURVE AND SPECTRUM

$$\Phi(t, E) = \Phi_1(E) \cdot \Phi_2(t)$$

- We are going to use the **LC** derived from **theoretical model** in the **0.3-1 TeV band**



$$\beta = 1.51 \pm 0.04$$

Acciari, V.A., Ansoldi, S., Antonelli, L.A. *et al.*
Teraelectronvolt emission from the γ-ray burst GRB 190114C.
Nature **575,** 455–458 (2019)

Acciari, V.A., Ansoldi, S., Antonelli, L.A. *et al.*
Observation of inverse Compton emission from a long γ-ray burst.
Nature 575, 459–463 (2019)

- We are going to use for the **intrinsic spectrum** a **power-law** with **spectral index alpha** which is then **EBL attenuated**

$$\Phi_1(E) \propto E^{-\alpha} \qquad \alpha = 2.5 \pm 0.2$$

PROBABILITY DISTRIBUTION FUNCTION

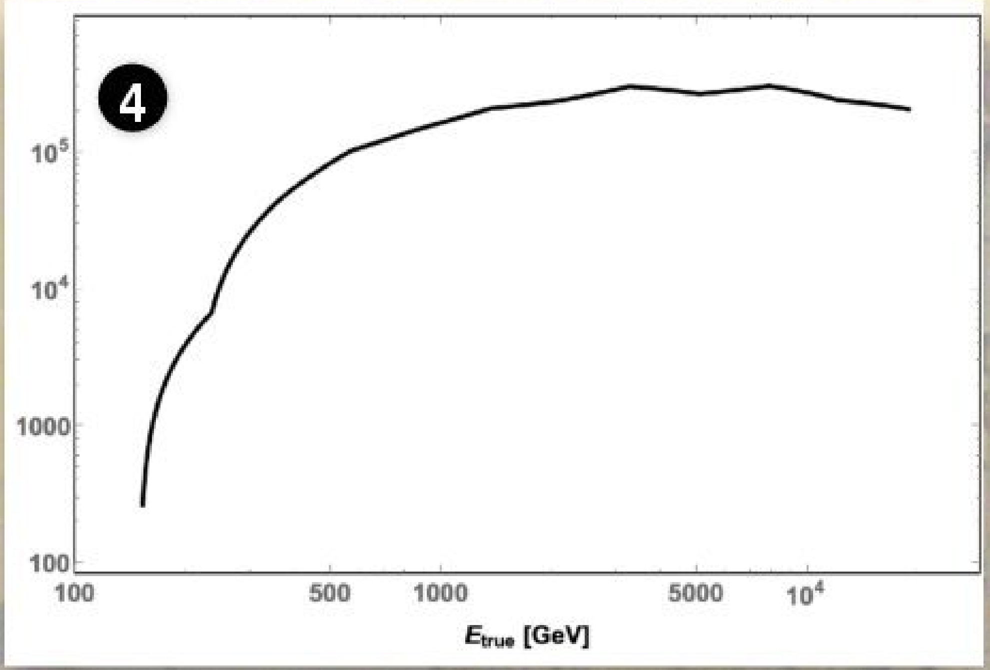
What's the **probability** to observe a **gamma** at a given **time t** and with **estimated energy $\mathbf{E_{est}}$**?

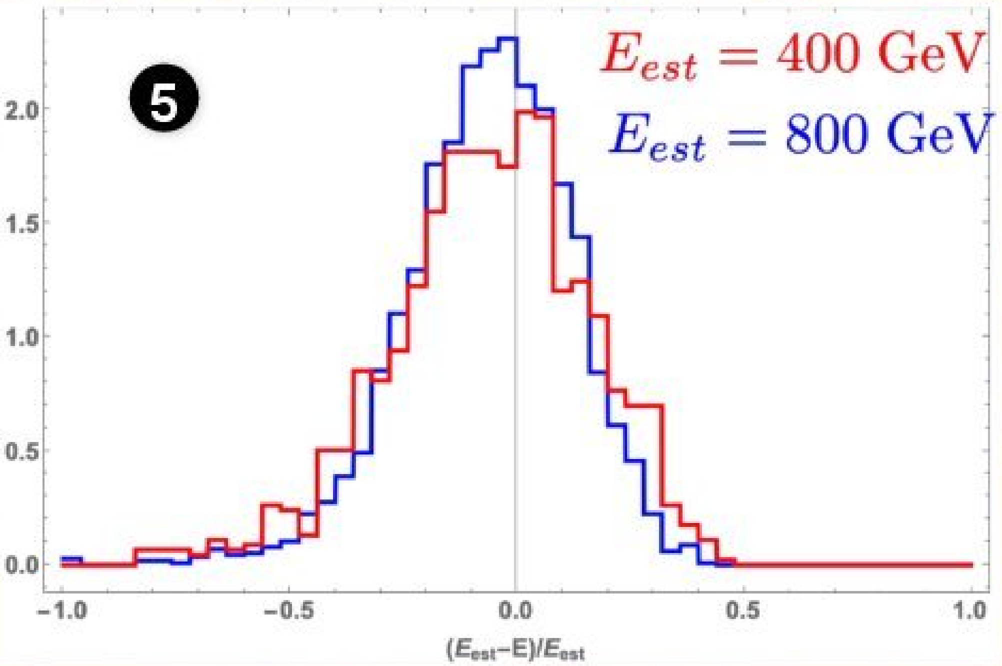
Intrinsic parameters for LC and spectrum

LIV delay

$$f_s(t, E_{est} \,|\, \eta_n, I) \propto \int_0^\infty dE \; \underset{①}{\Phi_1(E)} \cdot \underset{②}{\Phi_2(t - \Delta t(E; \eta_n, z))} \cdot \underset{③}{F(E)} \cdot \underset{④}{A_{eff}(E)} \cdot \underset{⑤}{G(E_{est}, E)}$$

① **Intrinsic spectrum** ② **Intrinsic Light Curve** ③ **EBL attenuation**



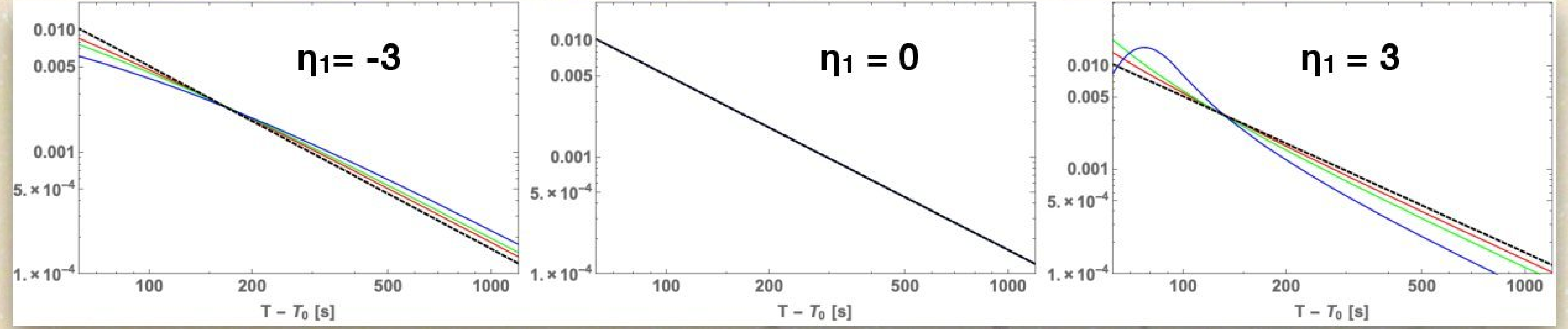


PROBABILITY DISTRIBUTION FUNCTION - LINEAR CASE

$$f_s(t, E_{est} \mid \eta_n, I) \propto \int_0^{\infty} dE\ \Phi_1(E) \cdot \Phi_2(t - \Delta t(E; \eta_n, z)) \cdot F(E) \cdot A_{eff}(E) \cdot G\,(E_{est}, E)$$

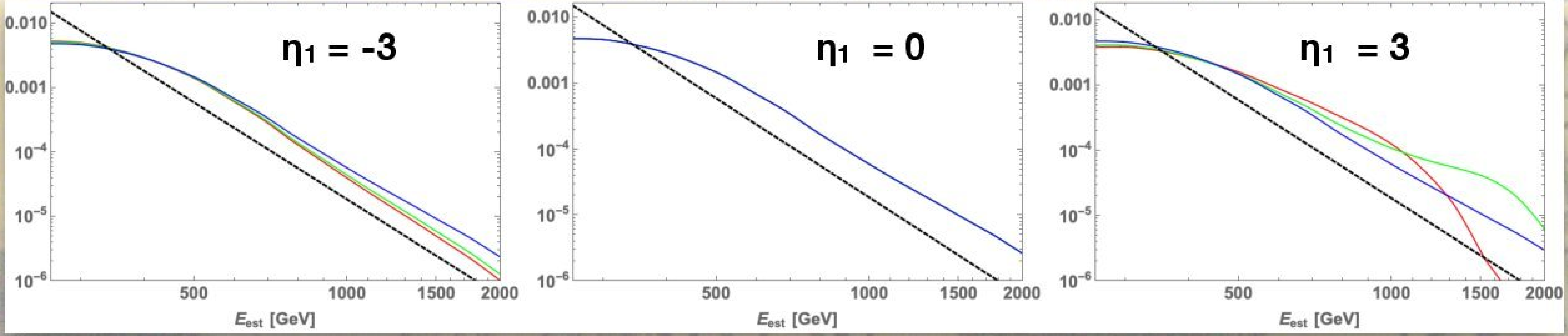
Evolution in **time** assuming different values of **η_1**

🟥 **Eest = 300 GeV** 🟩 **Eest = 600 GeV** 🟦 **Eest = 1.2 TeV** ----- **t^(-1.5)**



Evolution in **estimated energy** assuming different values of **η_1**

🟥 **t = 65 s + T0** 🟩 **t = 100 s + T0** 🟦 **t = 1000 s + T0** ----- **E^(-5)**

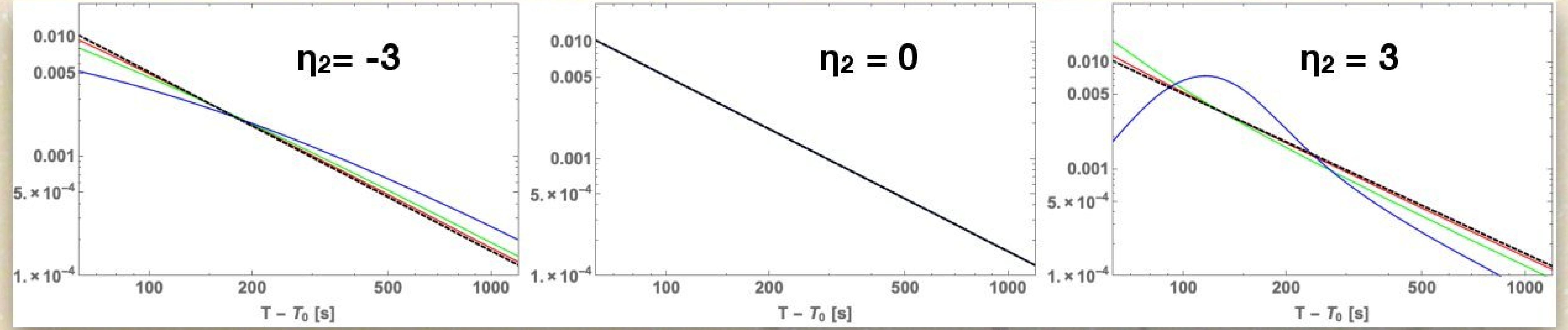


PROBABILITY DISTRIBUTION FUNCTION - QUADRATIC CASE

$$f_s(t, E_{est}\,|\,\eta_n, I) \propto \int_0^\infty dE\; \Phi_1(E)\cdot\Phi_2(t-\Delta t(E;\eta_n,z))\cdot F(E)\cdot A_{eff}(E)\cdot G\,(E_{est},E)$$

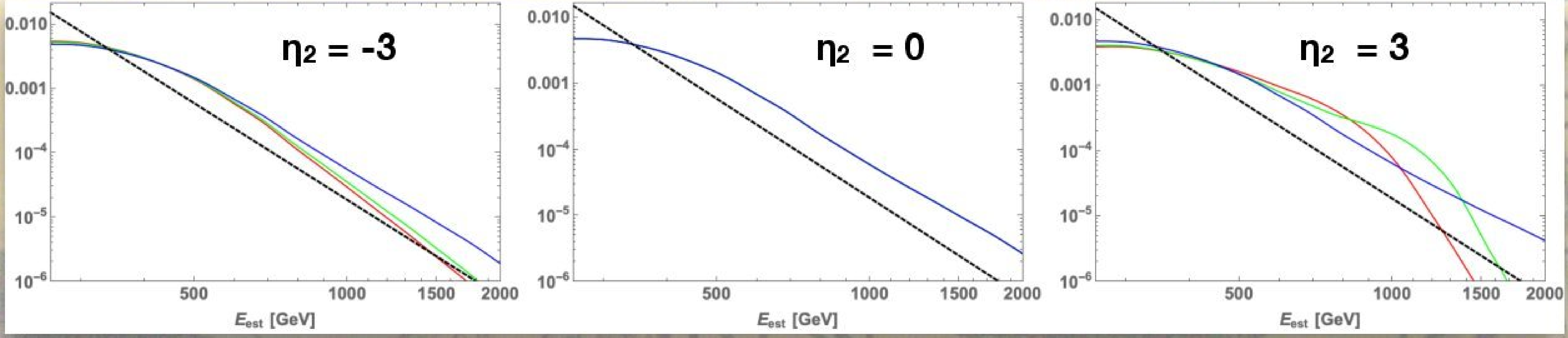
Evolution in **time** assuming different values of η_2

🟥 **Eest = 300 GeV** 🟩 **Eest = 600 GeV** 🟦 **Eest = 1.2 TeV** - - - - - **t^(-1.5)**



Evolution in **estimated energy** assuming different values of η_2

🟥 **t = 65 s + T0** 🟩 **t = 100 s + T0** 🟦 **t = 1000 s + T0** - - - - - **E^(-5)**



Likelihood maximization analysis

Among the **infinite** set of **two-dimensional pdf**, which one better **describes** our **data**? And how **confident** can we be on **excluding** some of them?

- **Likelihood** definition:

$$\mathcal{L}\left(\overbrace{\eta_n\,;}^{\text{nuisance parameters}}\ \overbrace{\alpha,\ \beta\,|\,\{t^{(i)},E_{est}^{(i)}\}_{i=1,\ldots,N_{on}}\ ,\ N_{on},N_{off}}^{\text{observed variables}}\right) = \overset{❶}{\mathcal{N}(\beta\,|\,1.51,0.04)} \cdot \overset{❷}{\mathcal{N}(\alpha\,|\,2.5,0.2)} \cdot$$

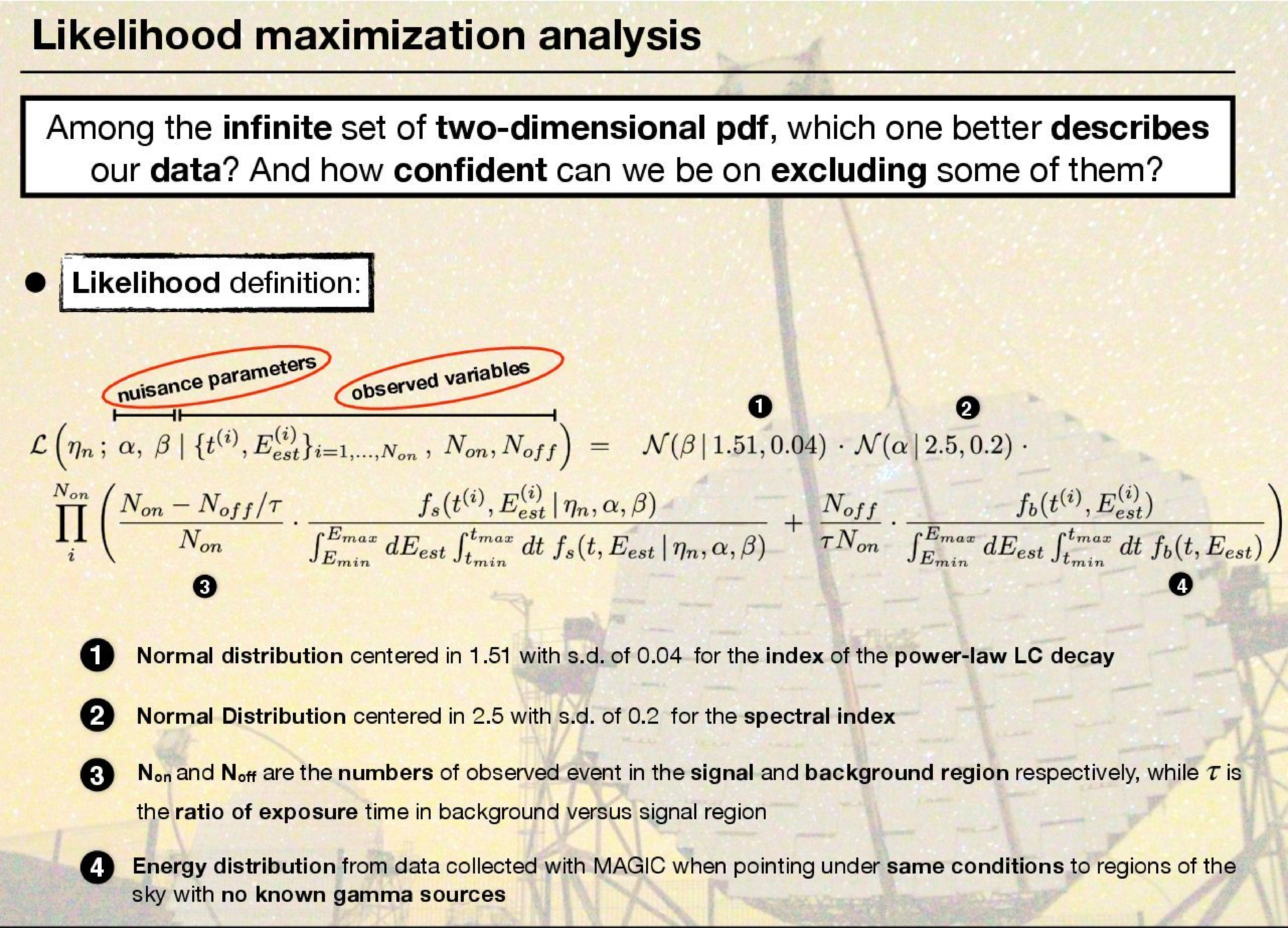
$$\prod_{i}^{N_{on}}\left(\underset{❸}{\frac{N_{on}-N_{off}/\tau}{N_{on}}}\cdot\frac{f_s(t^{(i)},E_{est}^{(i)}\,|\,\eta_n,\alpha,\beta)}{\int_{E_{min}}^{E_{max}}dE_{est}\int_{t_{min}}^{t_{max}}dt\ f_s(t,E_{est}\,|\,\eta_n,\alpha,\beta)}+\frac{N_{off}}{\tau N_{on}}\cdot\underset{❹}{\frac{f_b(t^{(i)},E_{est}^{(i)})}{\int_{E_{min}}^{E_{max}}dE_{est}\int_{t_{min}}^{t_{max}}dt\ f_b(t,E_{est})}}\right)$$

❶ **Normal distribution** centered in 1.51 with s.d. of 0.04 for the **index** of the **power-law LC decay**

❷ **Normal Distribution** centered in 2.5 with s.d. of 0.2 for the **spectral index**

❸ **N_{on}** and **N_{off}** are the **numbers** of observed event in the **signal** and **background region** respectively, while τ is the **ratio of exposure** time in background versus signal region

❹ **Energy distribution** from data collected with MAGIC when pointing under **same conditions** to regions of the sky with **no known gamma sources**



Likelihood maximization analysis

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$$\prod_i^{N_{on}}\left(\frac{N_{on}-N_{off}/\tau}{N_{on}}\cdot\frac{f_s(t^{(i)}, E_{est}^{(i)}\,|\,\eta_n,\alpha,\beta)}{\int_{E_{min}}^{E_{max}} dE_{est}\int_{t_{min}}^{t_{max}} dt\ f_s(t, E_{est}\,|\,\eta_n,\alpha,\beta)} + \frac{N_{off}}{\tau N_{on}}\cdot\frac{f_b(t^{(i)}, E_{est}^{(i)})}{\int_{E_{min}}^{E_{max}} dE_{est}\int_{t_{min}}^{t_{max}} dt\ f_b(t, E_{est})}\right)$$

- We define the following variable:

$$-2\Delta\ln\left(\mathcal{L}\right) = -2\ln\left(\frac{\max(\mathcal{L})_{\alpha,\beta}}{\max(\mathcal{L})_{\eta_n,\alpha,\beta}}\right)$$

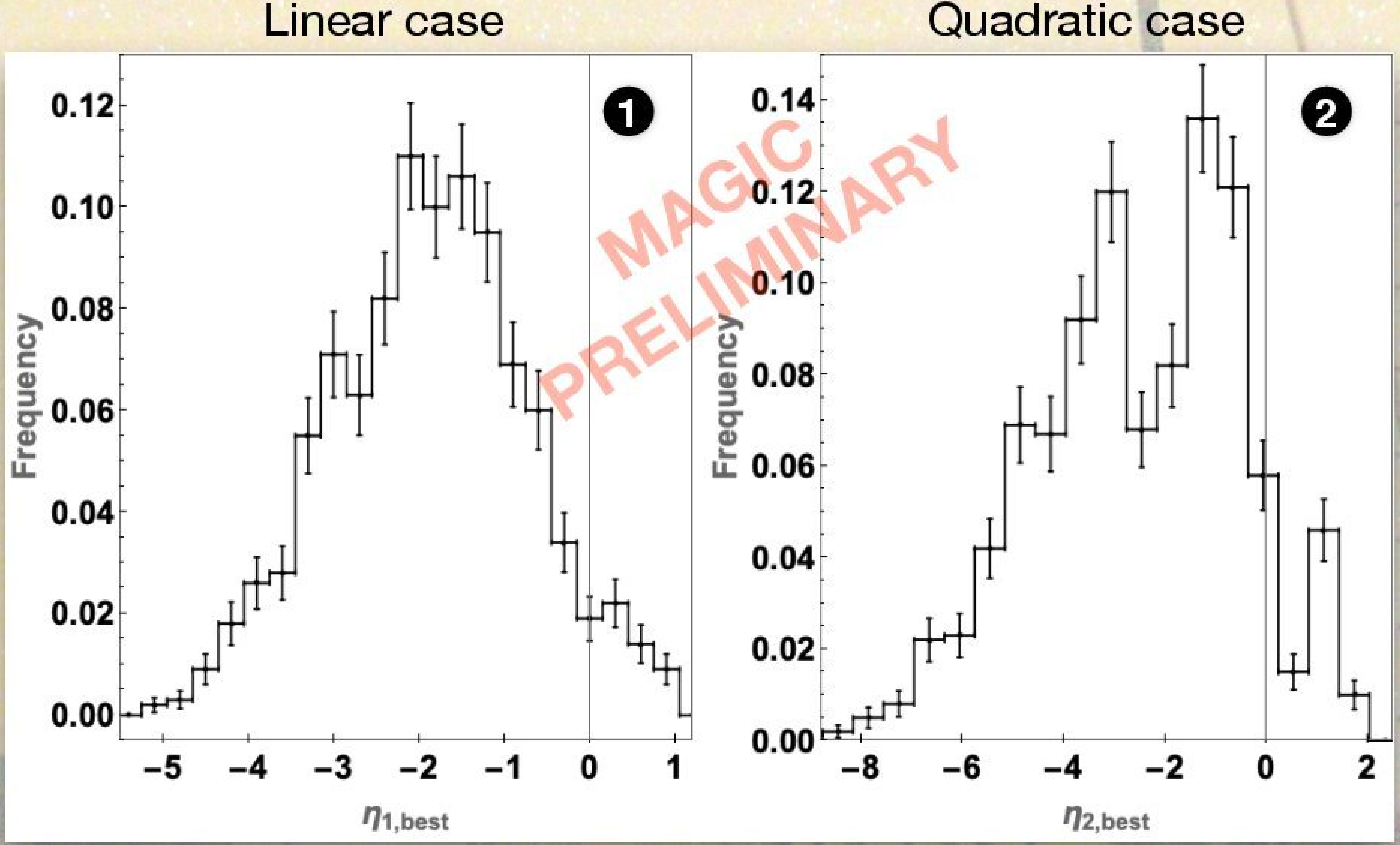
$$\max\{f\}_y \equiv f(x,\bar{y}) \ \ \text{where } \bar{y} \text{ maximizes } f \text{ for a given value of } x$$

MC SIMULATIONS

Is our **LC and spectral model** a good **description** of the observed data?
We estimate **biases** arising from our model using **MC simulations:**

MC data sets is generated by **reshuffling + bootstrapping** the **real data set**, so that any **LIV effect**, if presents, is **destroyed** but **temporal** and **energy distribution** are **preserved**

Distribution of the LIV parameter η_n that maximize the likelihood



❶

$$\mathrm{BIAS} = -1.9$$

$$\sigma = 1.2$$

❷

$$\mathrm{BIAS} = -2.6$$

$$\sigma = 2.2$$

MC SIMULATIONS

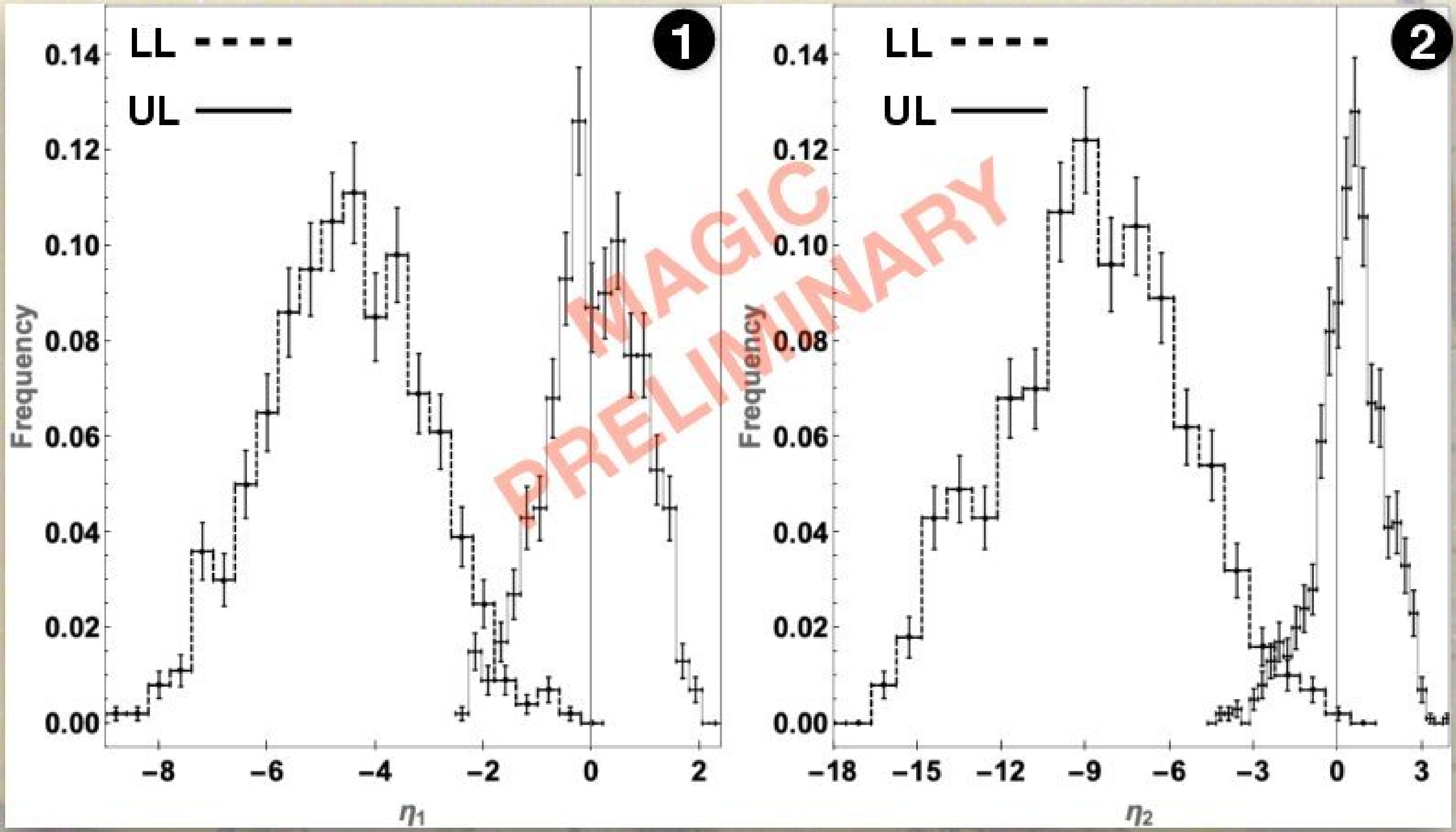
We then **calibrate** lower (**LLs**) and upper (**ULs**) **limits** using **MC simulations:**

For each **MC simulation** we compute the **LLs** and **ULs** using a pair of **thresholds** common to all the simulation. This pair of **thresholds** is chosen so that:

- only **2.5%** of the simulated **LLs** is **bigger** than the **bias** previous computed
- only **2.5%** of the simulated **ULs** is **smaller** than the **bias** previous computed

Distribution of lower (LLs) and upper (ULs) limits

Linear case Quadratic case



❶

Pair of **thresholds** for **linear** case:

$$-2\Delta \ln \mathcal{L} = 3.4$$

$$-2\Delta \ln \mathcal{L} = 2.8$$

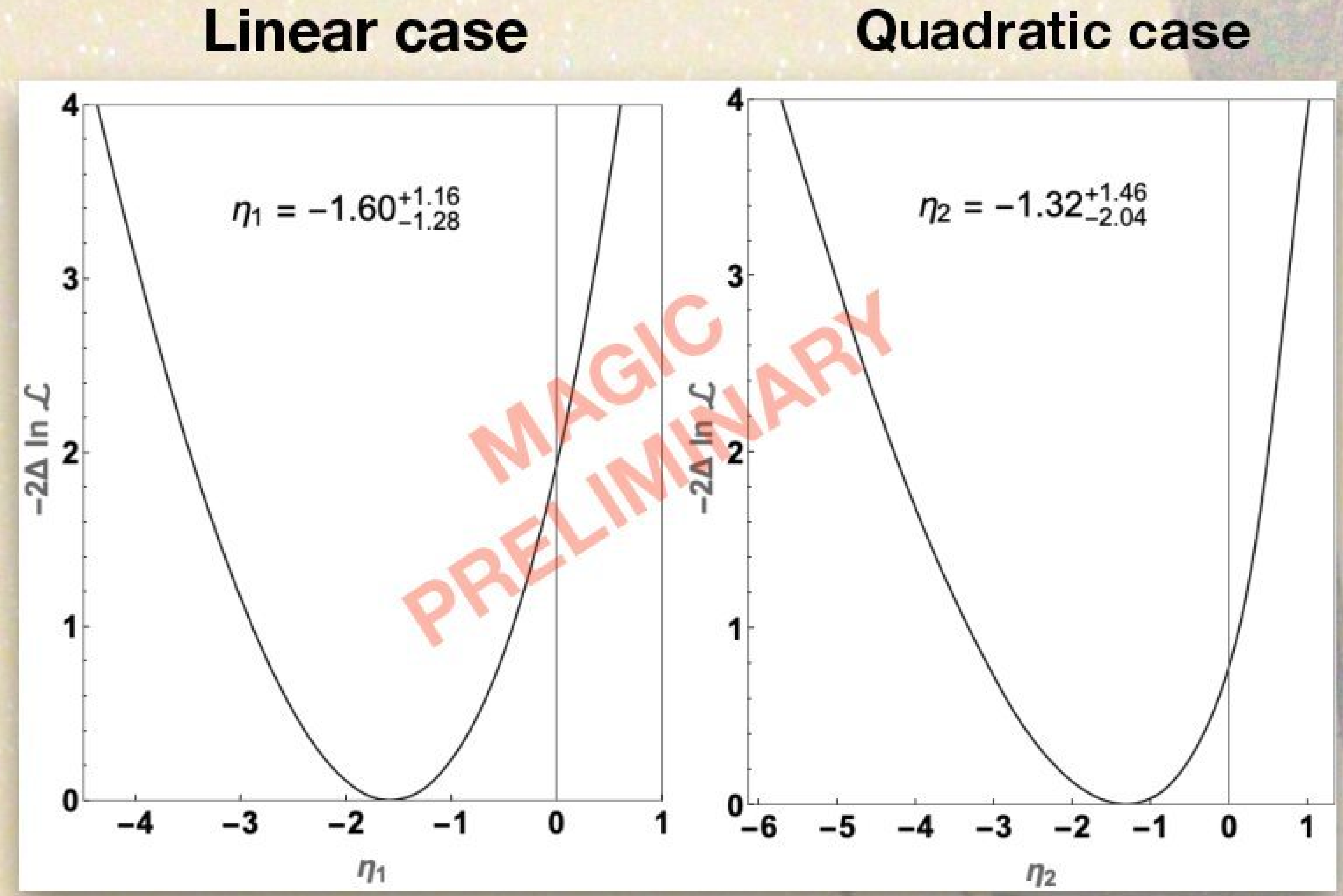
❷

Pair of **thresholds** for **quadratic** case:

$$-2\Delta \ln \mathcal{L} = 7.0$$

$$-2\Delta \ln \mathcal{L} = 4.4$$

RESULTS FOR LINEAR AND QUADRATIC CASE



Linear case

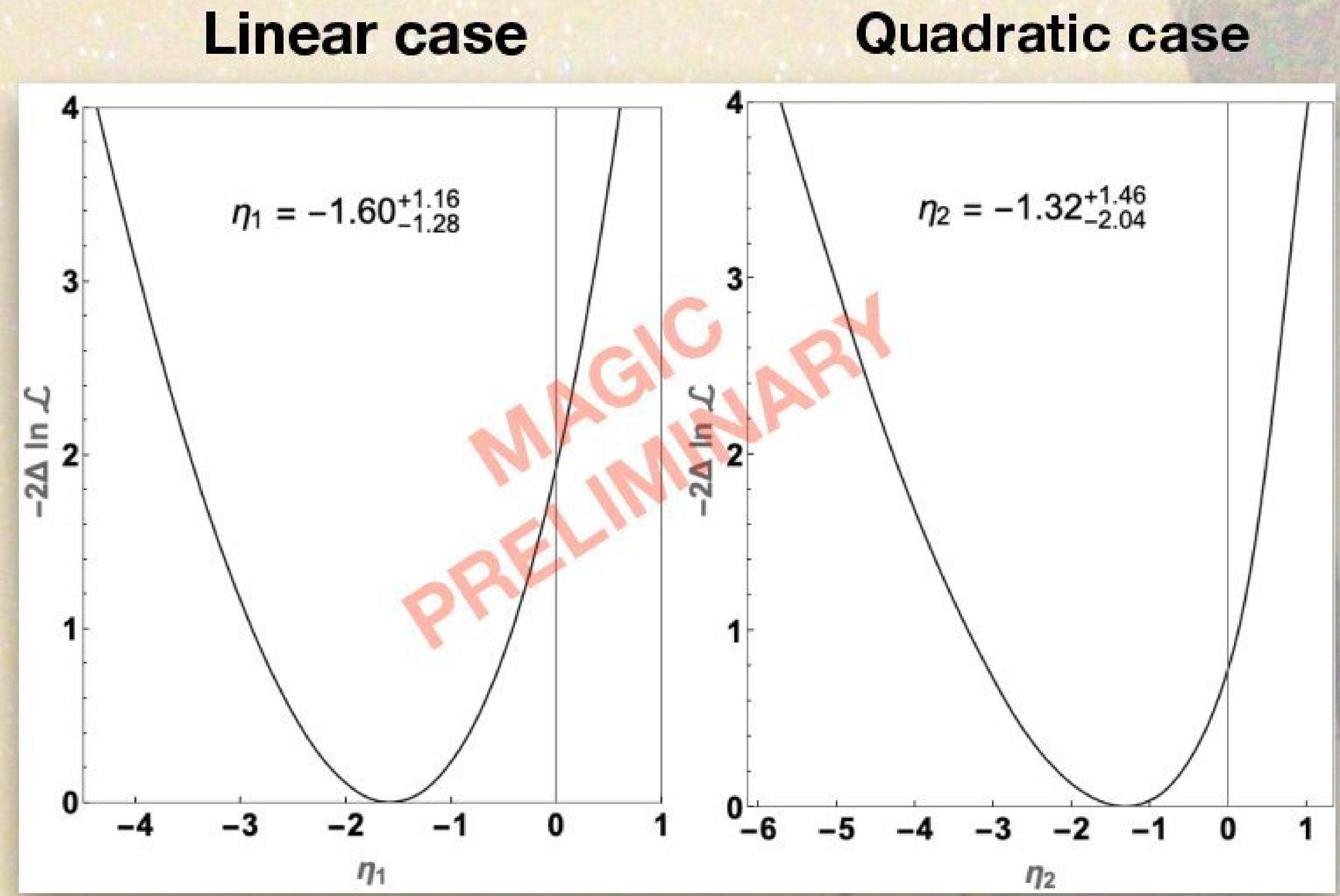
Quadratic case

- The **likelihood** is slightly shifted toward negative values (**subluminal scenario**)
- Although the **value** that **maximizes** the likelihood is **compatible** with the null hypothesis: **no LIV effect**
  n=1 —> p-value = 0.78
  n=2 —> p-value = 0.59

- Taking into account the **bias** and the **calibrated thresholds** for the **95% CI** previously obtained

	Lower Limit	Upper Limit
η_1	-2.2	2.1
η_2	-4.8	3.7

RESULTS FOR LINEAR AND QUADRATIC CASE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  n=1 —> p-value = 0.78
  n=2 —> p-value = 0.59

From the definitions of the parameter η_n

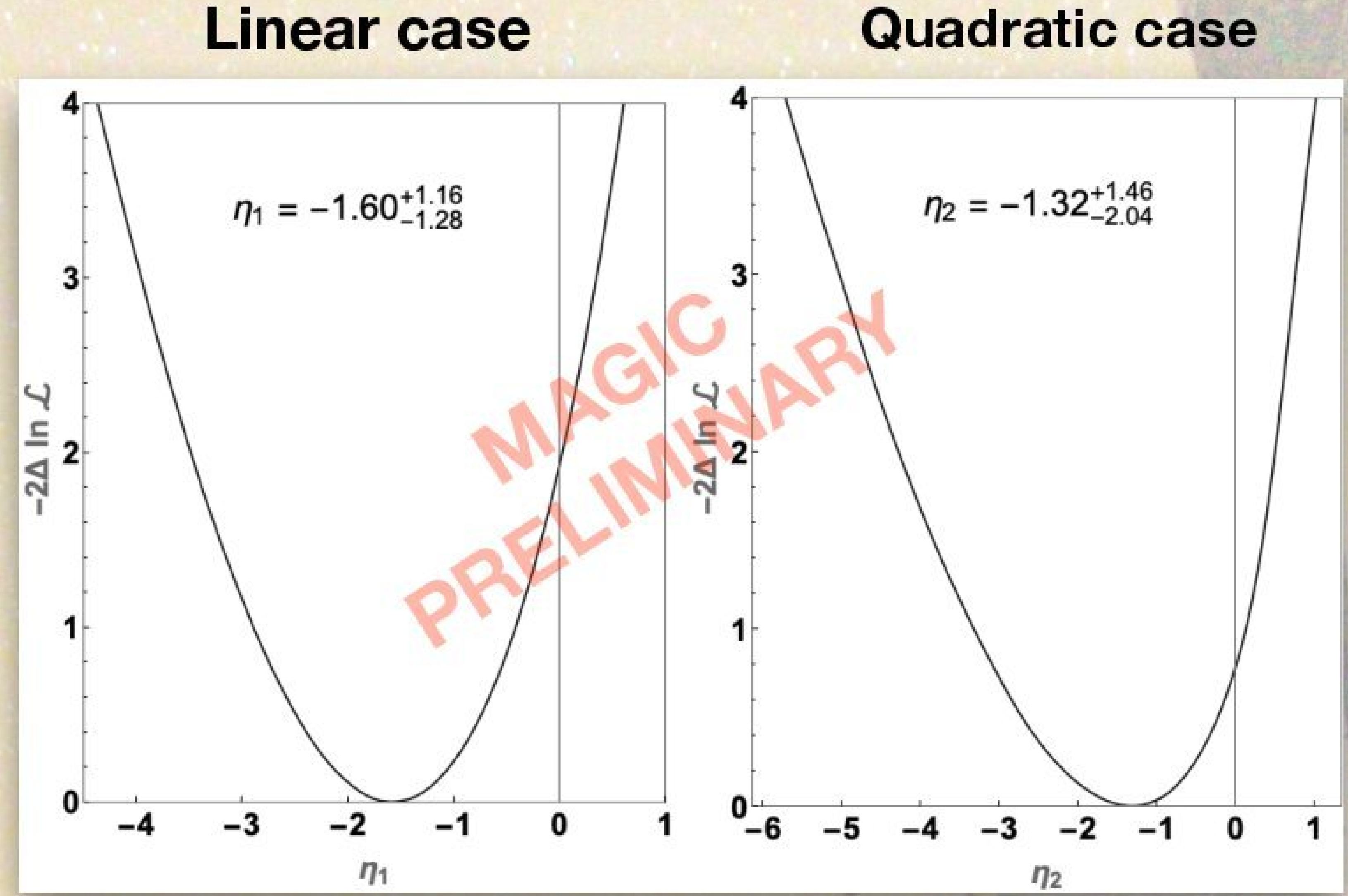
$$\eta_1 = s_\pm \cdot E_{\rm Pl}/E_{\rm QG,1}$$
$$\eta_2 = 10^{-16} \cdot s_\pm \cdot E^2_{\rm Pl}/E^2_{\rm QG,2}$$

$\longrightarrow$

superluminal case

$$E_{QG,1} > 0.45 \cdot E_{Pl}$$
$$E_{QG,2} > 5.6 \cdot 10^{10}\ \text{GeV}$$

RESULTS FOR LINEAR AND QUADRATIC CASE



- The **likelihood** is slightly shifted toward negative values (**subluminal scenario**)
- Although the **value** that **maximizes** the likelihood is **compatible** with the null hypothesis: **no LIV effect**
  n=1 —> p-value = 0.78
  n=2 —> p-value = 0.59

Most stringent limits:

$$E_{QG,1} > 7.6 \cdot E_{Pl}$$
$$E_{QG,2} > 1.3 \cdot 10^{11} \text{ GeV}$$

V. Vasileiou at al. Phys. Rev. D **87**, 122001 – 2013

From the definitions of the parameter ηn

$$\eta_1 = s_\pm \cdot E_{\mathrm{Pl}}/E_{\mathrm{QG},1}$$
$$\eta_2 = 10^{-16} \cdot s_\pm \cdot E_{\mathrm{Pl}}^2/E_{\mathrm{QG},2}^2$$

→

subluminal case

$$E_{QG,1} > 0.48 \cdot E_{Pl}$$
$$E_{QG,2} > 6.3 \cdot 10^{10} \text{ GeV}$$

CONCLUSIONS

- We performed a **likelihood maximization analysis** making a set of **conservative assumptions**:
  - Intrinsic **Light Curve** derived from **data** and from **theoretical models**
  - Intrinsic smooth **power-law spectrum** independent from time
  - **LIV** effects described by a **single parameter η_n**

- The values of η_1 and η_2 obtained from the **likelihood maximization** are **compatible** at **1 sigma** with the null hypothesis: **no LIV effect**

- We derived at **95%** confidence level the following **lower limits** for the **quantum-gravity energy scale:**

	superluminal case	subluminal case
n=1	$E_{QG,1} > 0.45 \cdot E_{Pl}$	$E_{QG,1} > 0.48 \cdot E_{Pl}$
n=2	$E_{QG,2} > 5.6 \cdot 10^{10}$ GeV	$E_{QG,2} > 6.3 \cdot 10^{10}$ GeV

THANK YOU FOR YOUR ATTENTION

AND

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