Recent results on LIV studies using MAGIC telescopes from the observation of GRB 190114C

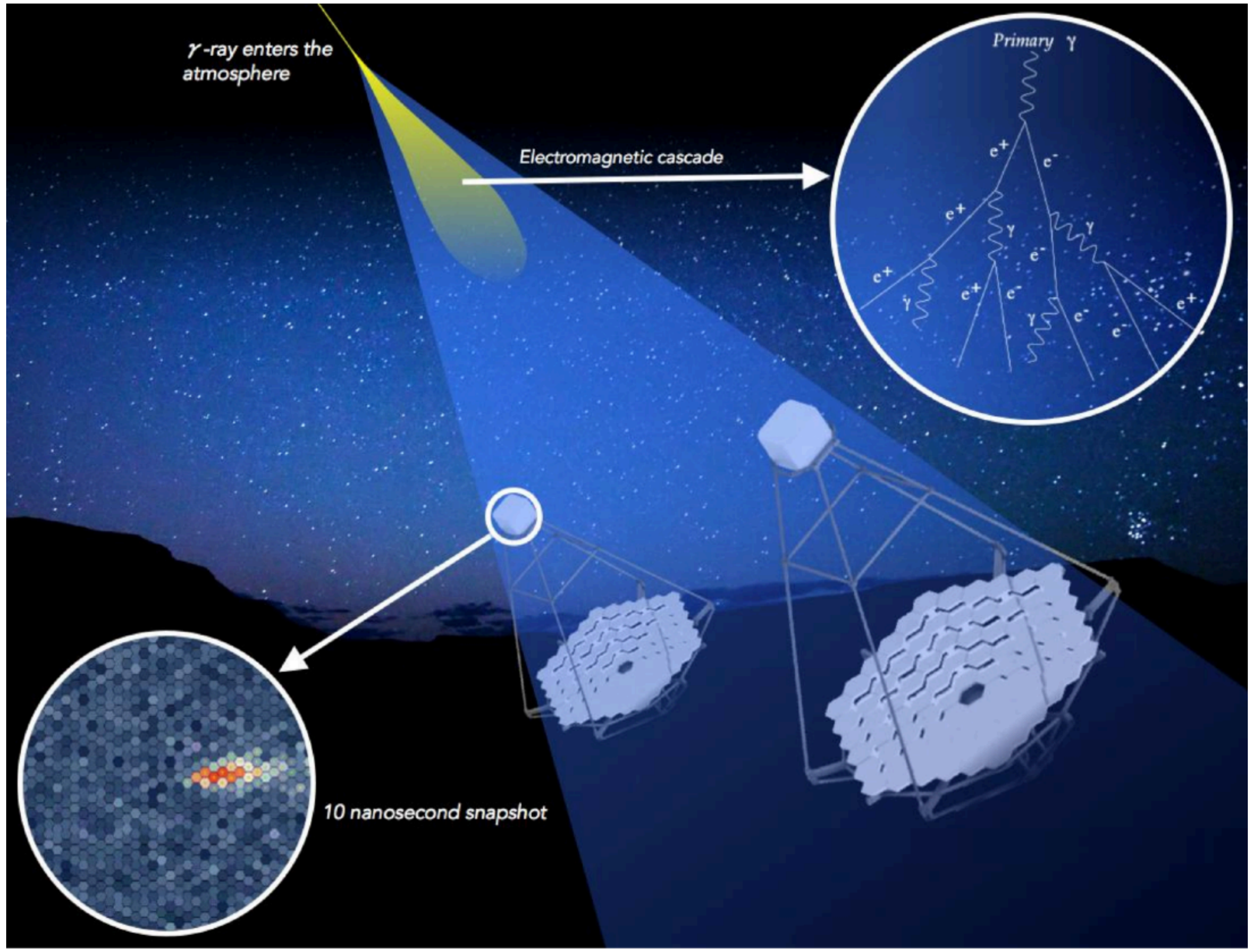
PRL 125, 021301

Giacomo D'Amico
Max Planck Institute for Physics
and
University of Bergen

in collaboration with
Daniel Kerszberg (IFAE), Cédric Perennes (UNIPD), Javier Rico (IFAE), Tomislav Terzić (UNIRI) for the ***MAGIC*** *collaboration*

MG16 5-10 JULY 2021
SIXTEENTH MARCEL GROSSMANN MEETING
ON RECENT DEVELOPMENTS IN THEORETICAL AND EXPERIMENTAL GENERAL RELATIVITY, ASTROPHYSICS AND RELATIVISTIC FIELD THEORIES

How do they work?



Credit: CTA Consortium

They use the earth's **atmosphere** as a **calorimeter**:

1. A gamma or cosmic ray initiates a **particle cascades** in the atmosphere
2. **Secondary charged particles** traveling in the atmosphere will produce **Cherenkov light**
3. This Cherenkov light is ultimately measured by telescope with **fast** and **low-level sensors**

Energy range: 30 GeV – above 50 TeV

GRB 190114C

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Article | Published: 20 November 2019

Teraelectronvolt emission from the γ-ray burst GRB 190114C

MAGIC Collaboration

Nature **575**, 455–458(2019) | Cite this article

Abstract

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[5,6,7,8], 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[9,10,11]. By contrast, processes such as

Artistic rendering of a GRB explosion with one MAGIC telescope

Credits: Gabriel Pérez Díaz

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

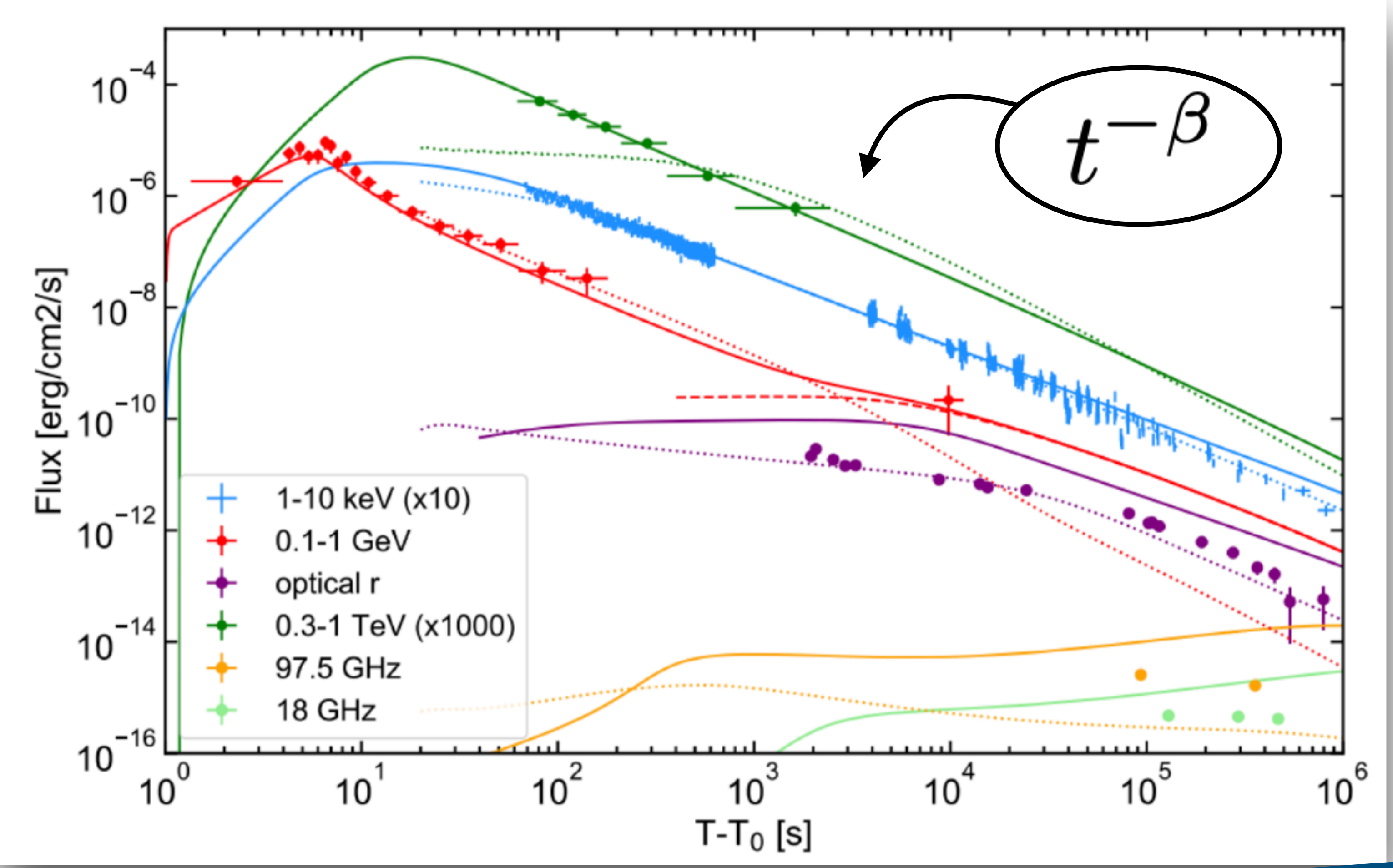
N_{on} = 729

N_{off} ~ 40

GRB 190114C

TEMPORAL EVOLUTION

$$\beta = 1.51 \pm 0.04$$



$(T - T_0)_{min} \sim 62$ s

INTRINSIC SPECTRUM

$$\Phi_1(E) \propto E^{-\alpha}$$

$$\alpha = 2.5 \pm 0.2$$

spectral index time-independent

Check A. Berti's & D. Miceli's talk in the session "GRBs at HE and VHE"!

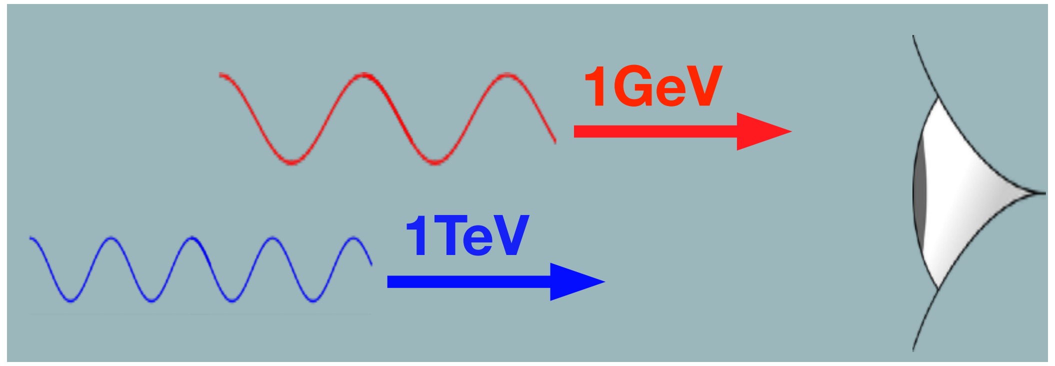
Acciari, V.A., Ansoldi, S., Antonelli, L.A. *et al.* **Teraelectronvolt emission from the γ-ray burst GRB 190114C**. *Nature* **575,** 455–458 (2019)

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)

Q.G. EFFECTS IN GRB 190114C

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

Photon energy at the detector



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

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

$$\Delta t(E,\eta_1) = \eta_1 \cdot 17\ {\rm s/TeV} \cdot E$$

$$\Delta t(E,\eta_2) = \eta_2 \cdot 25\ {\rm s/TeV}^2 \cdot E^2$$

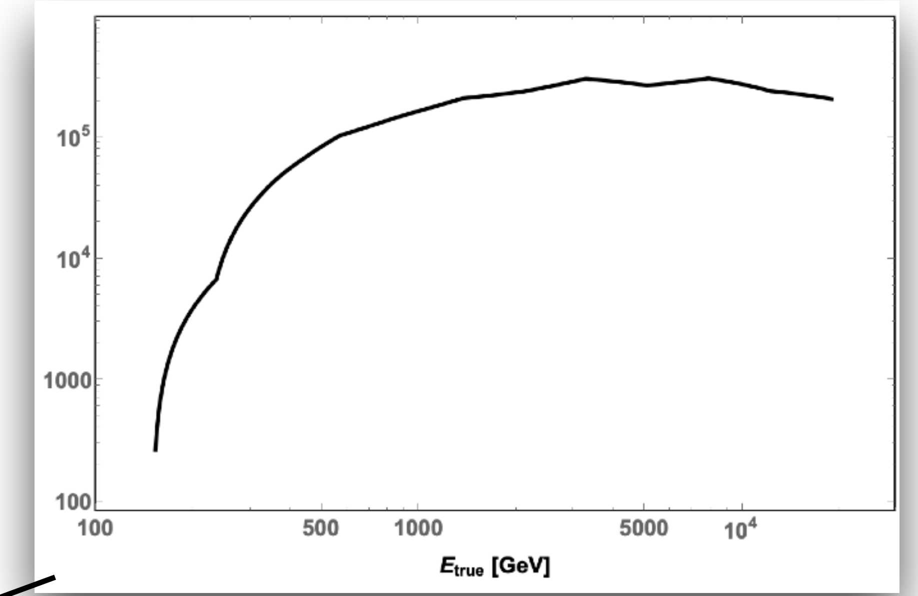
Assuming **η_n = 1** a **1 TeV** gamma should have a **time delay** of

- **17 seconds** (n=1)
- **25 seconds** (n=2)

Where we have defined **η** as the **ratio** between the **Planck energy** and the **Q.G. energy scale**

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

Taking into account the instrument response function of the telescope



P.D.F. for time and estimated energy

$$f_s(t, E_{est} \,|\, \eta_n, I) \propto$$

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

Intrinsic LC

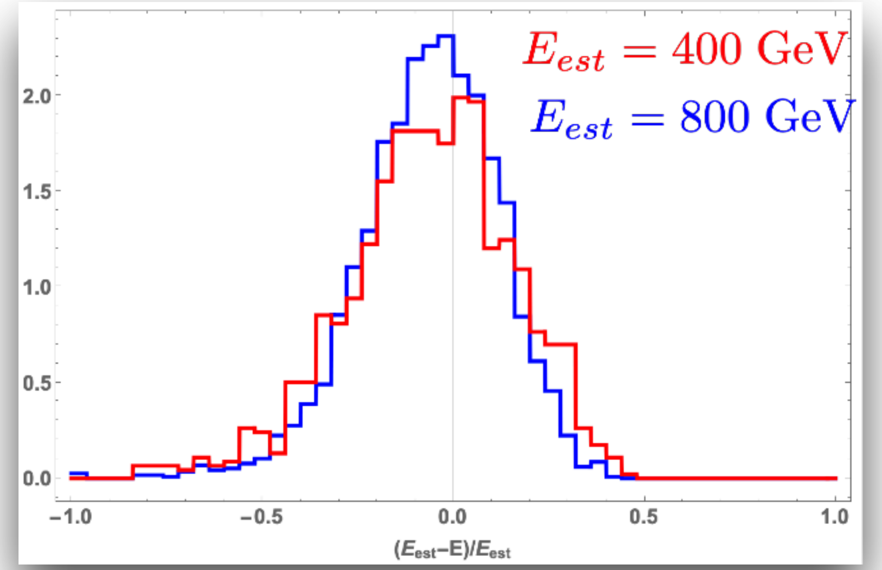
Intrinsic spectrum

delay

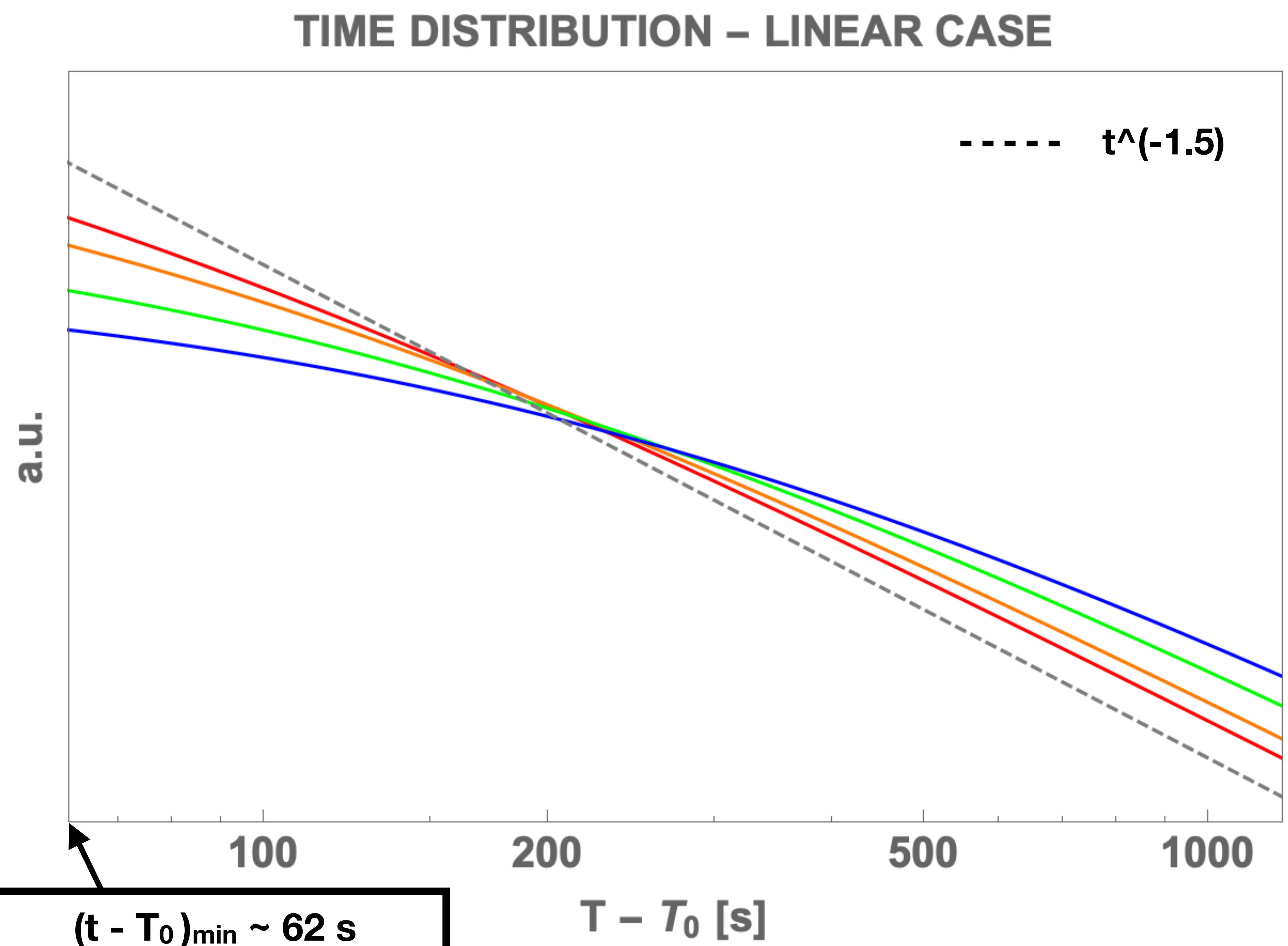
EBL attenuation

$$\Delta t(E, \eta_1) = \eta_1 \;\cdot\; 17\ \mathrm{s/TeV} \;\cdot\; E$$

$$\Delta t(E, \eta_2) = \eta_2 \;\cdot\; 25\ \mathrm{s/TeV^2} \;\cdot\; E^2$$



Q.G. EFFECTS IN THE TIME DISTRIBUTION

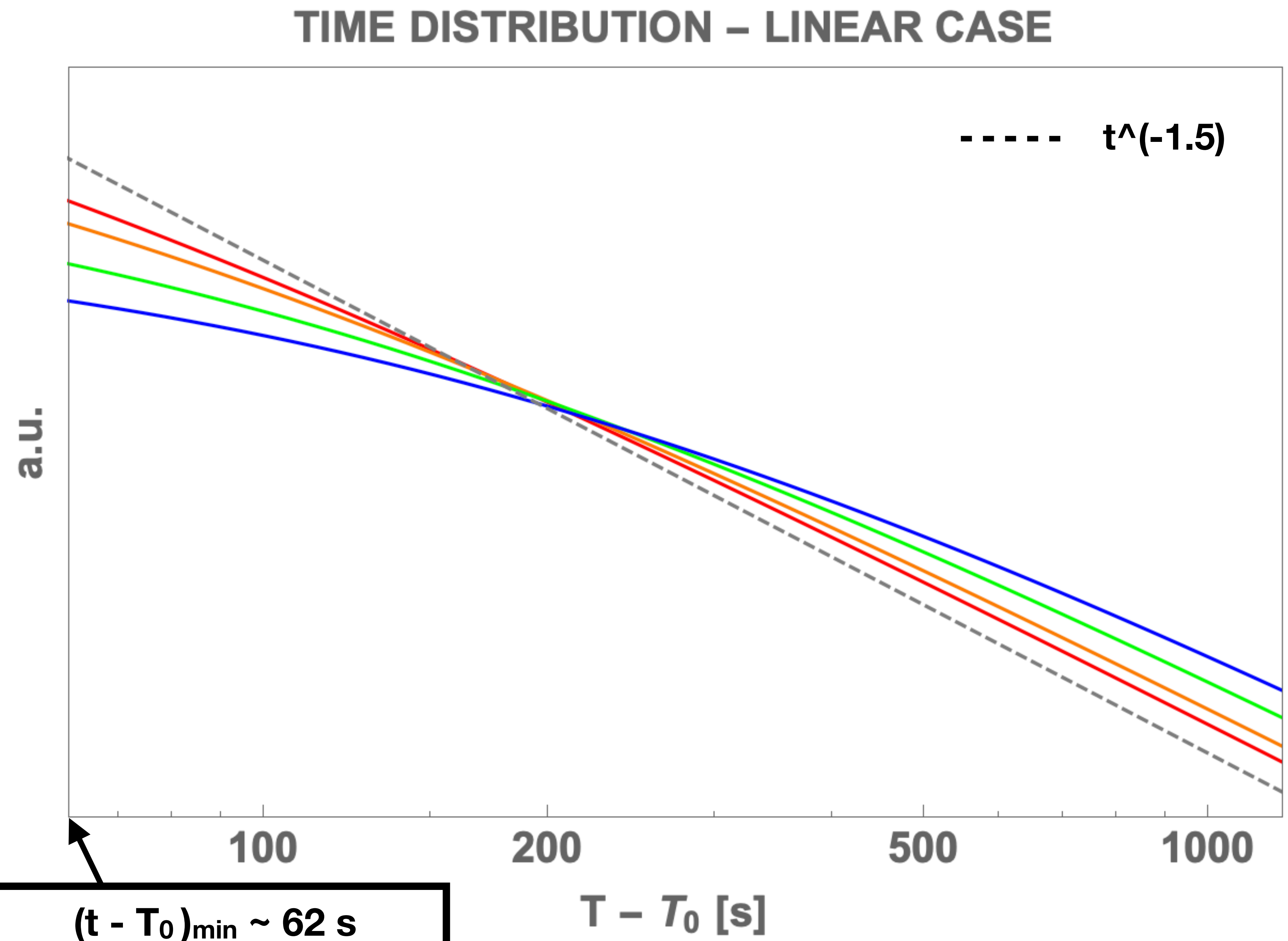


(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -7$$

$$\Delta t = \eta_1 \cdot \ 17 \text{ s} \cdot \frac{E}{\text{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV



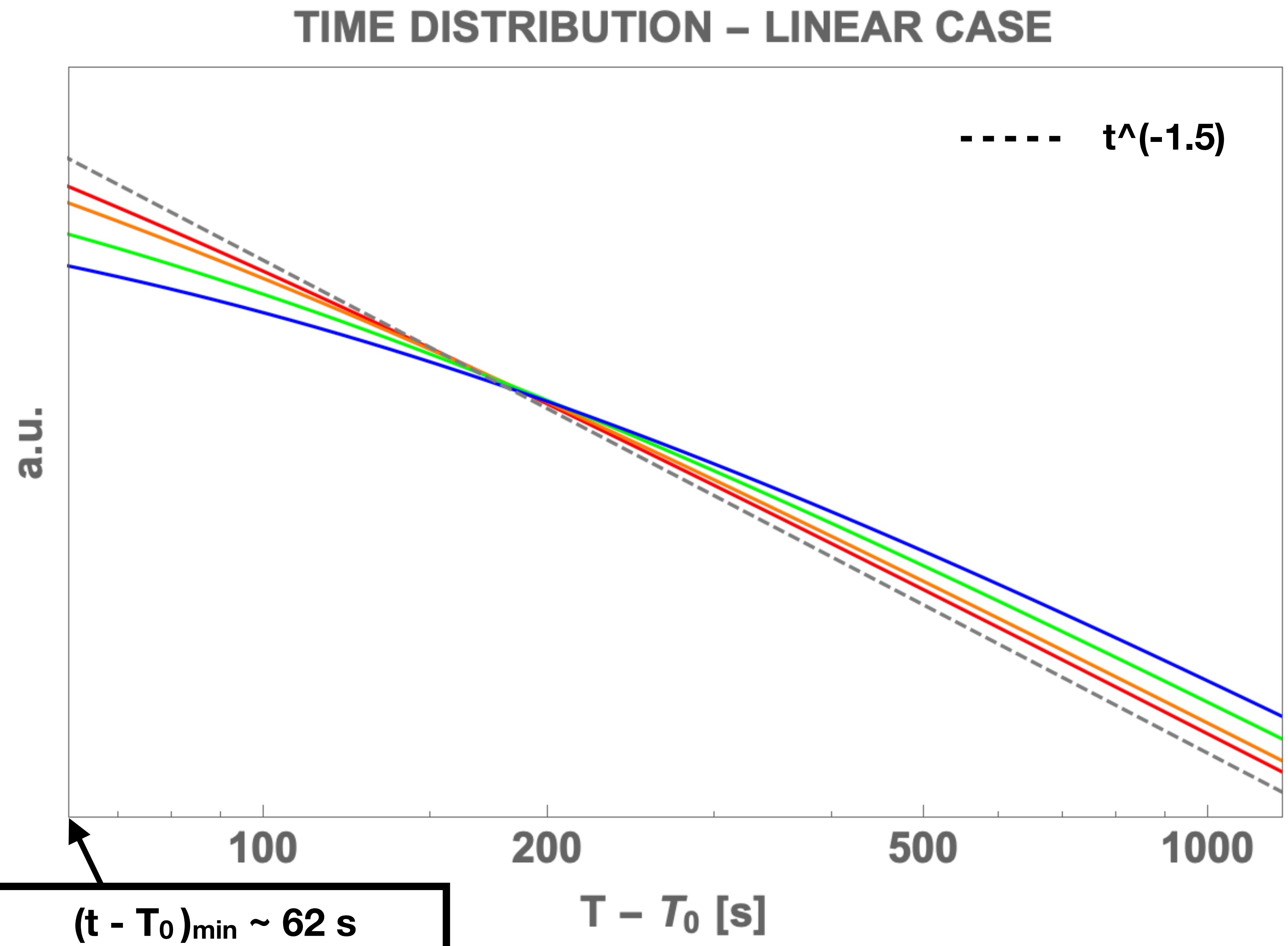
(t - T_0)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -5$$

$$\Delta t = \eta_1 \cdot 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



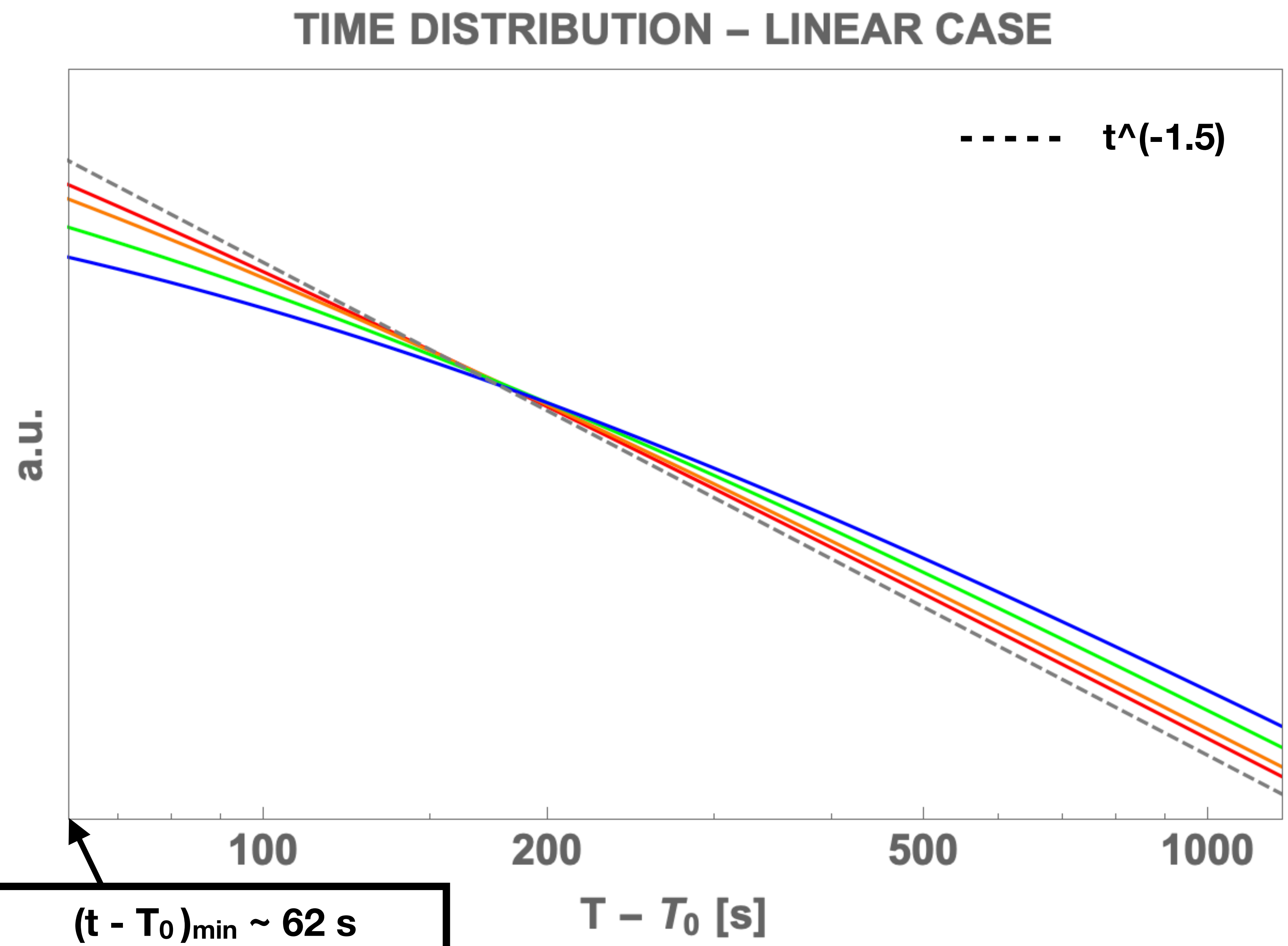
(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -3$$

$$\Delta t = \eta_1 \cdot 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



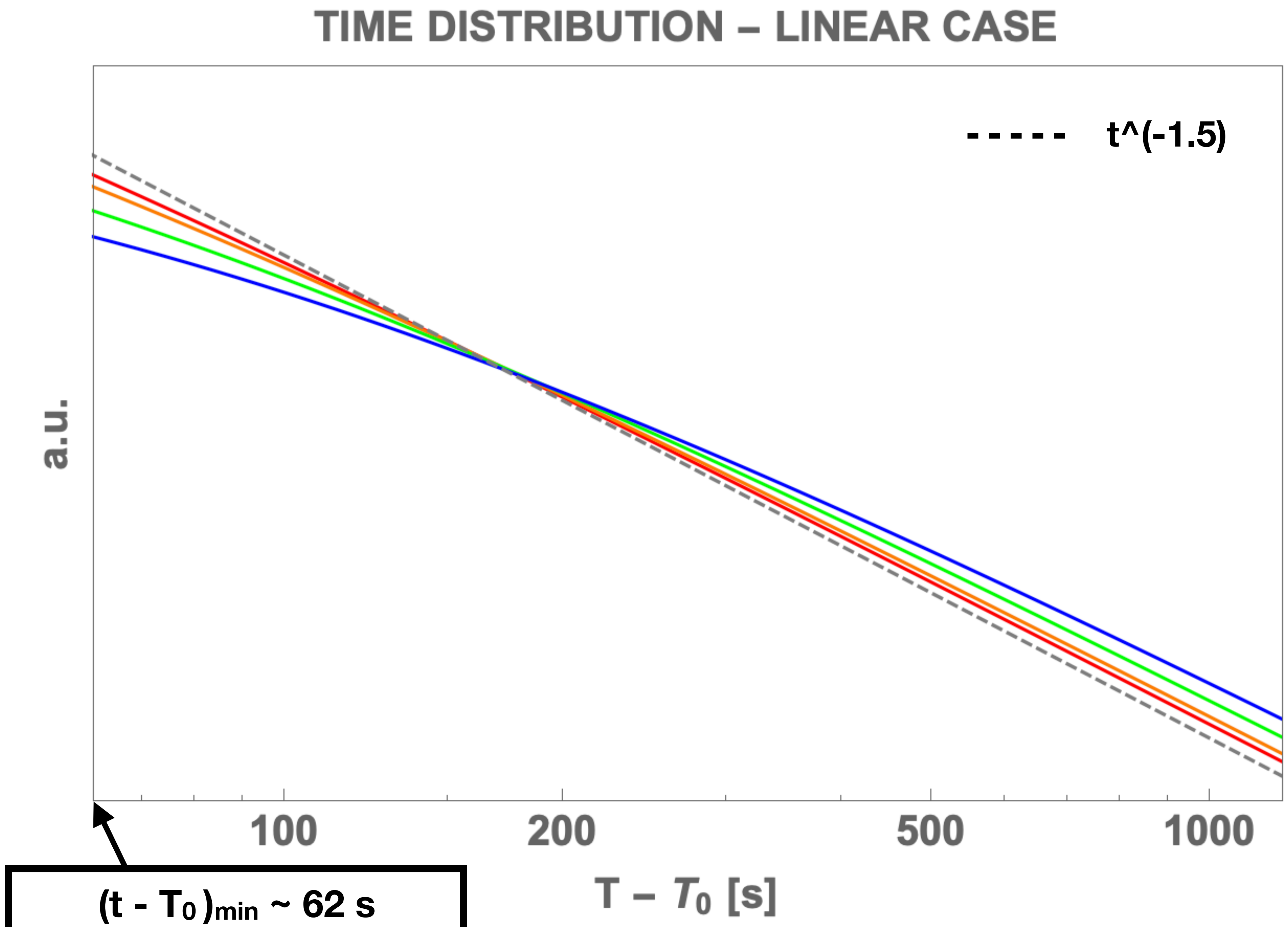
(t - T_0)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -2.5$$

$$\Delta t = \eta_1 \cdot\ 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



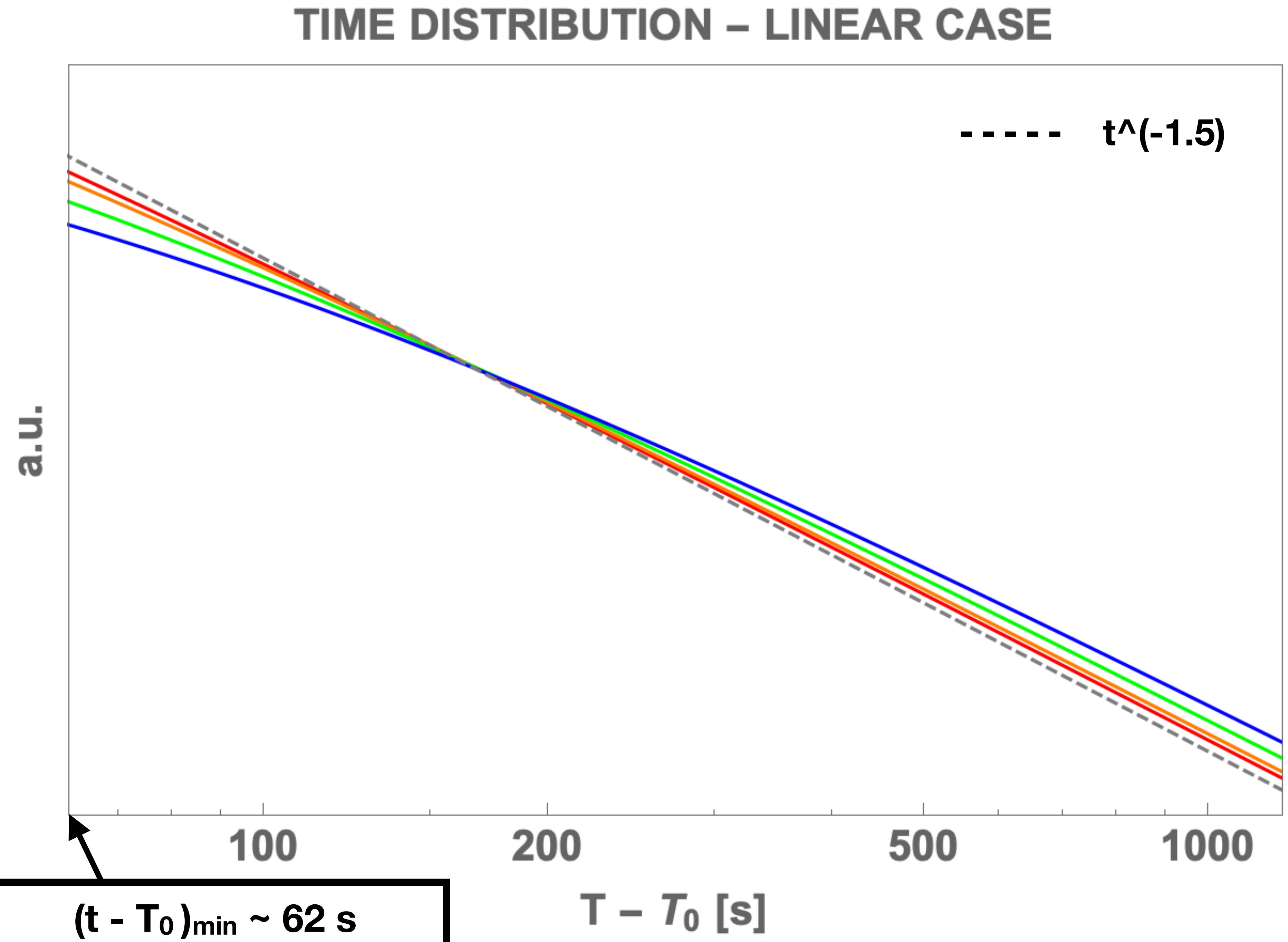
(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -2$$

$$\Delta t = \eta_1 \cdot \; 17 \text{ s} \cdot \frac{E}{\text{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



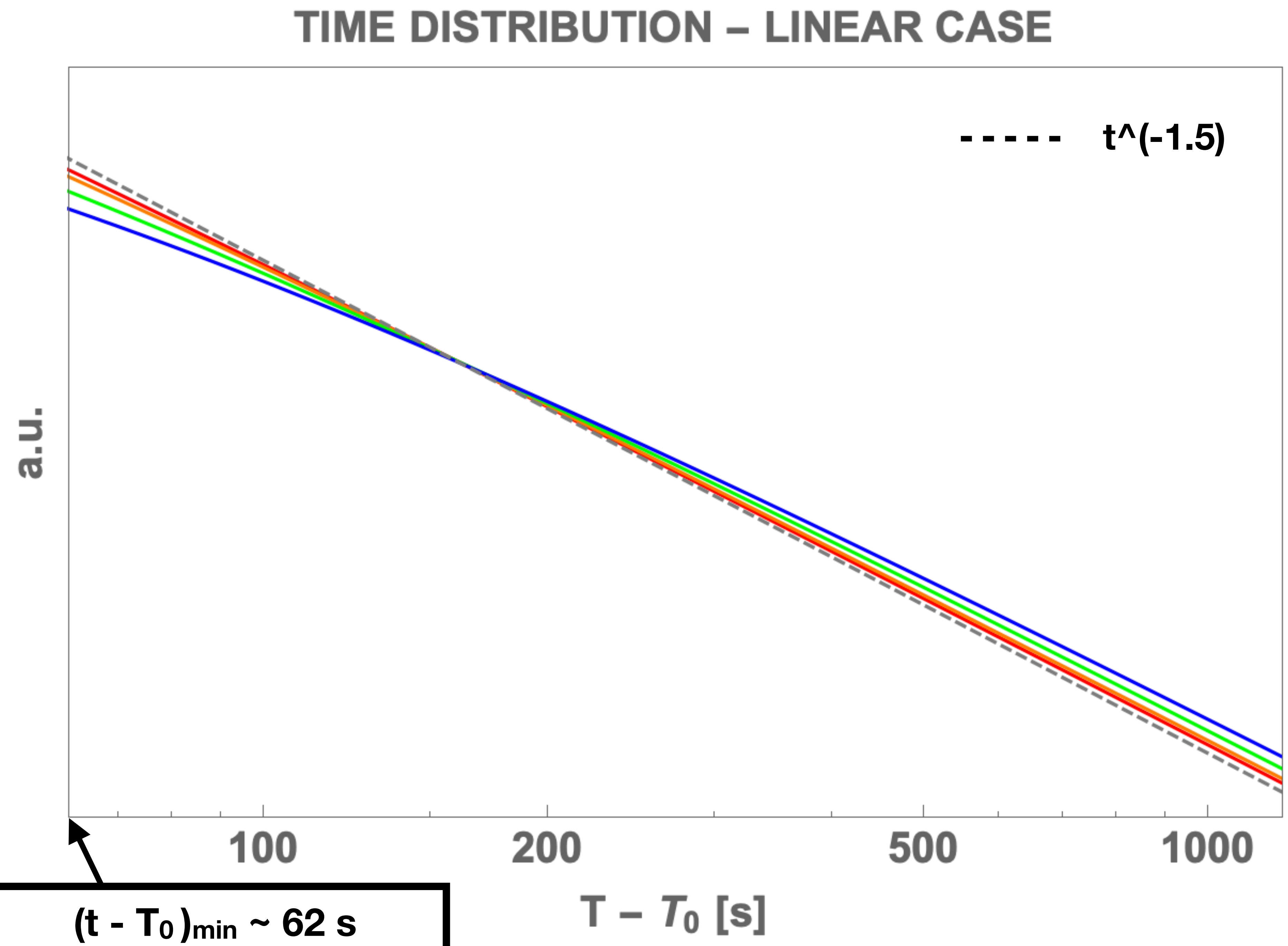
(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -1.5$$

$$\Delta t = \eta_1 \cdot\ 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



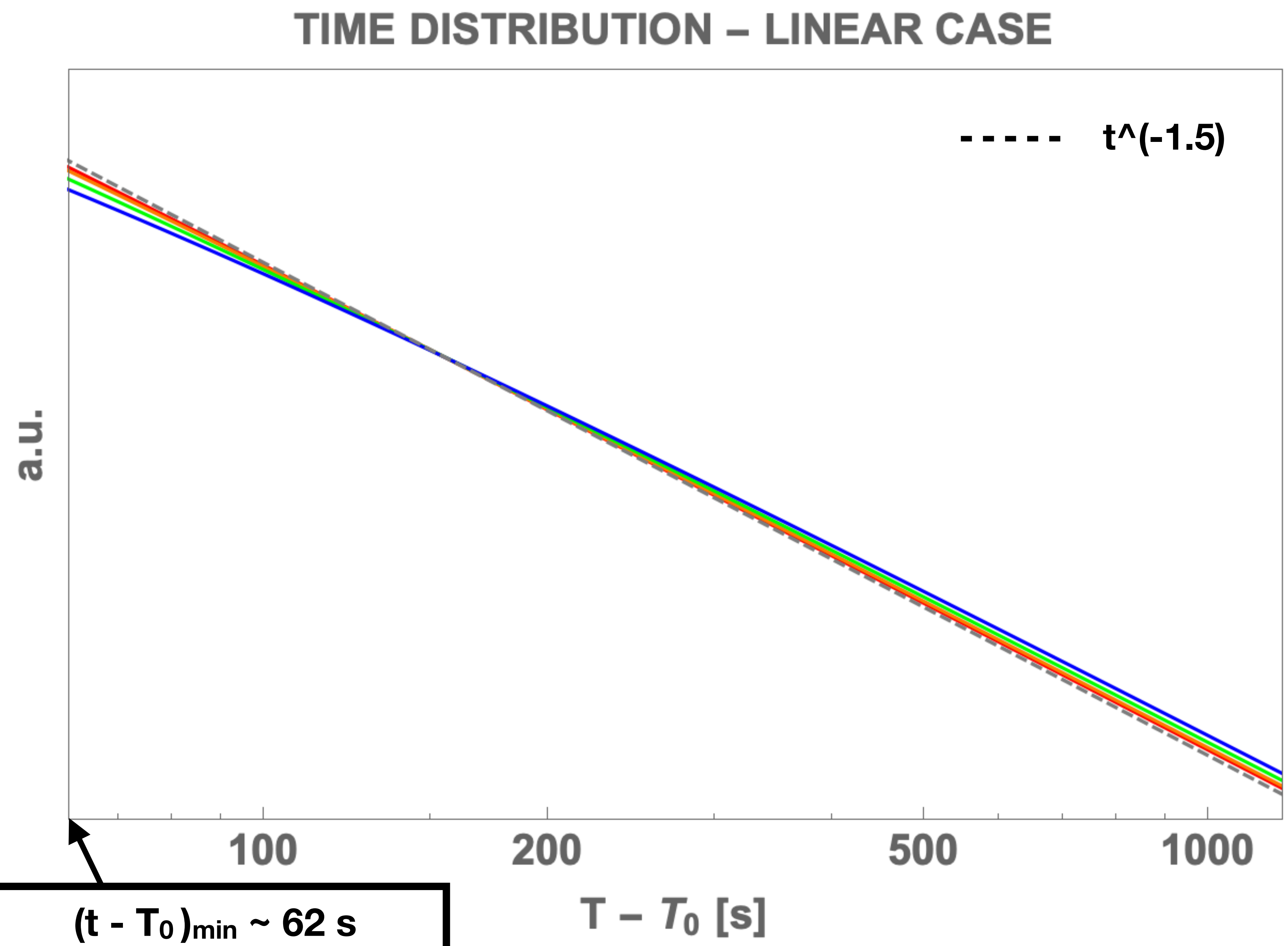
(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -1$$

$$\Delta t = \eta_1 \cdot \ 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



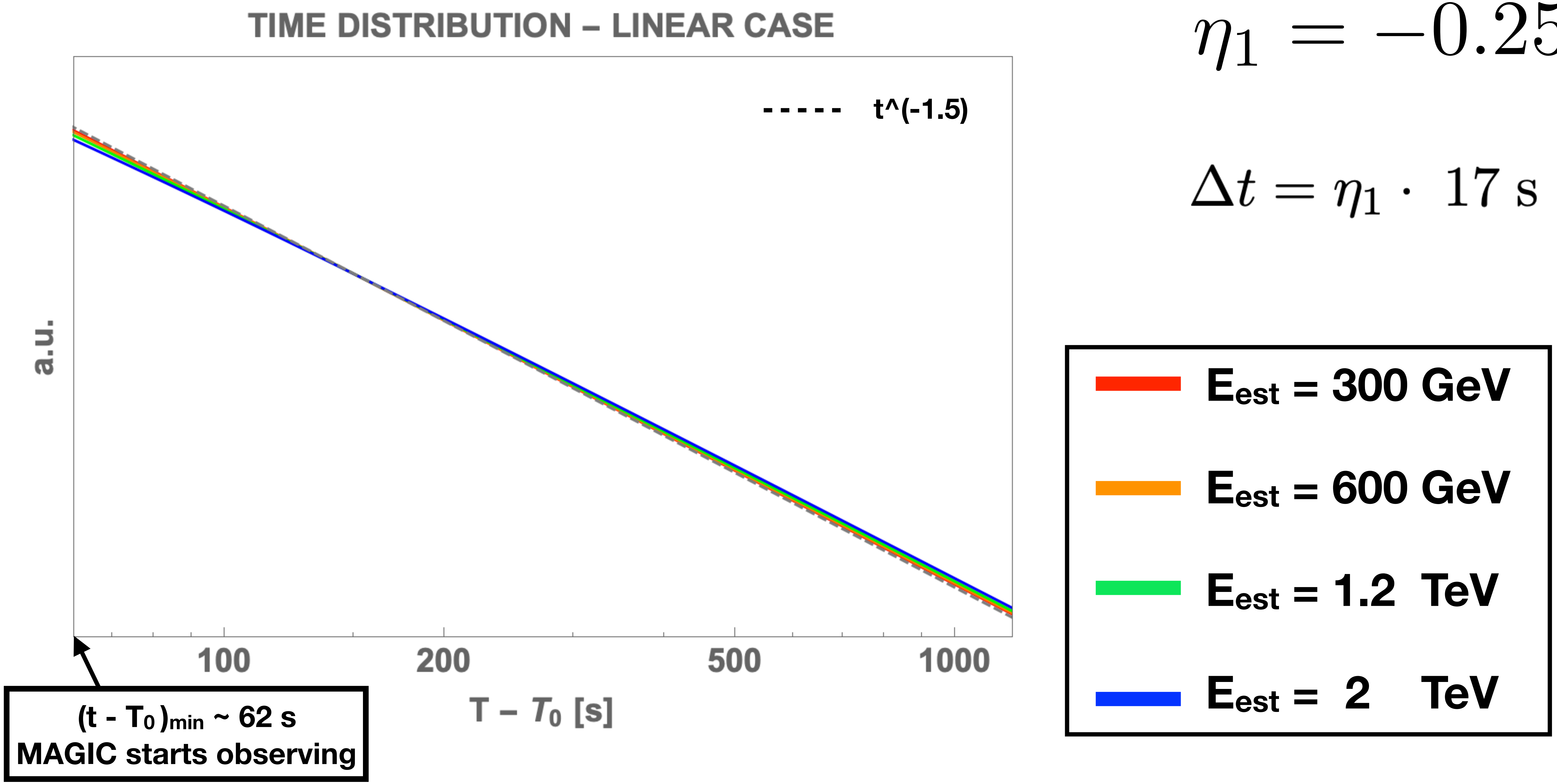
(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = -0.5$$

$$\Delta t = \eta_1 \cdot 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

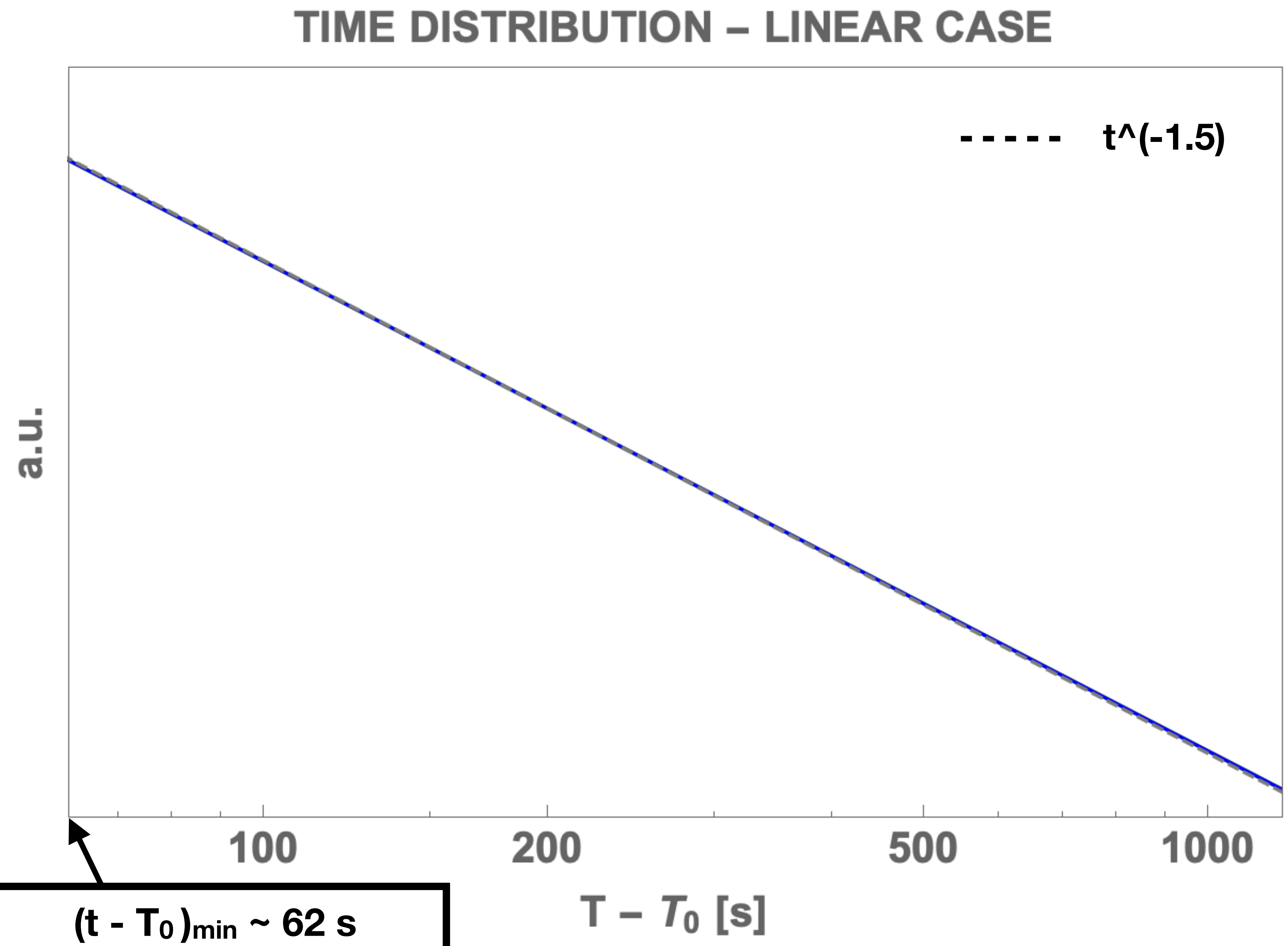
Q.G. EFFECTS IN THE TIME DISTRIBUTION



$$\eta_1 = -0.25$$

$$\Delta t = \eta_1 \cdot \; 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

Q.G. EFFECTS IN THE TIME DISTRIBUTION



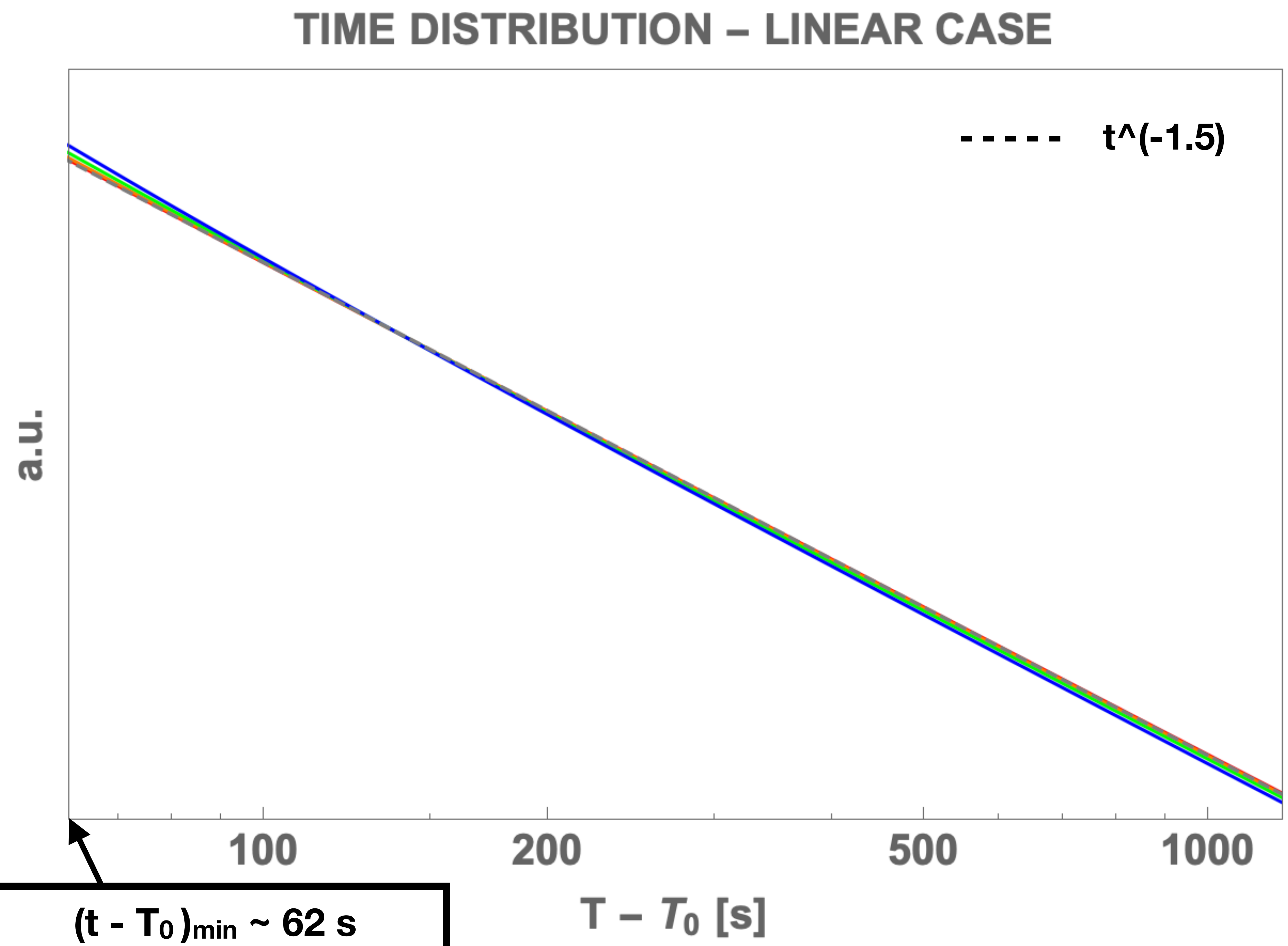
(t - T$_0$)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = 0$$

$$\Delta t = \eta_1 \cdot \; 17 \text{ s} \cdot \frac{E}{\text{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



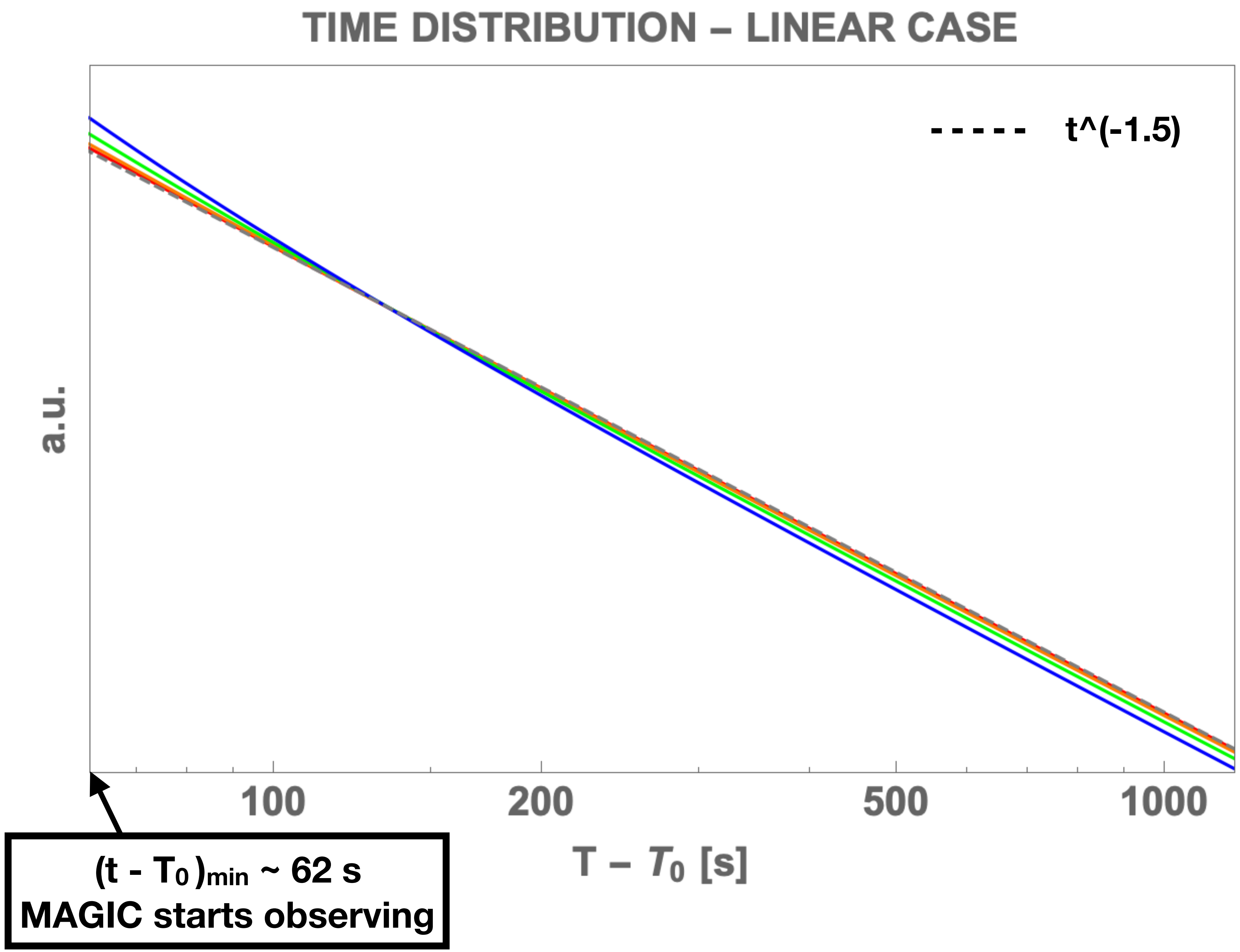
(t - T_0)$_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = 0.25$$

$$\Delta t = \eta_1 \cdot 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION

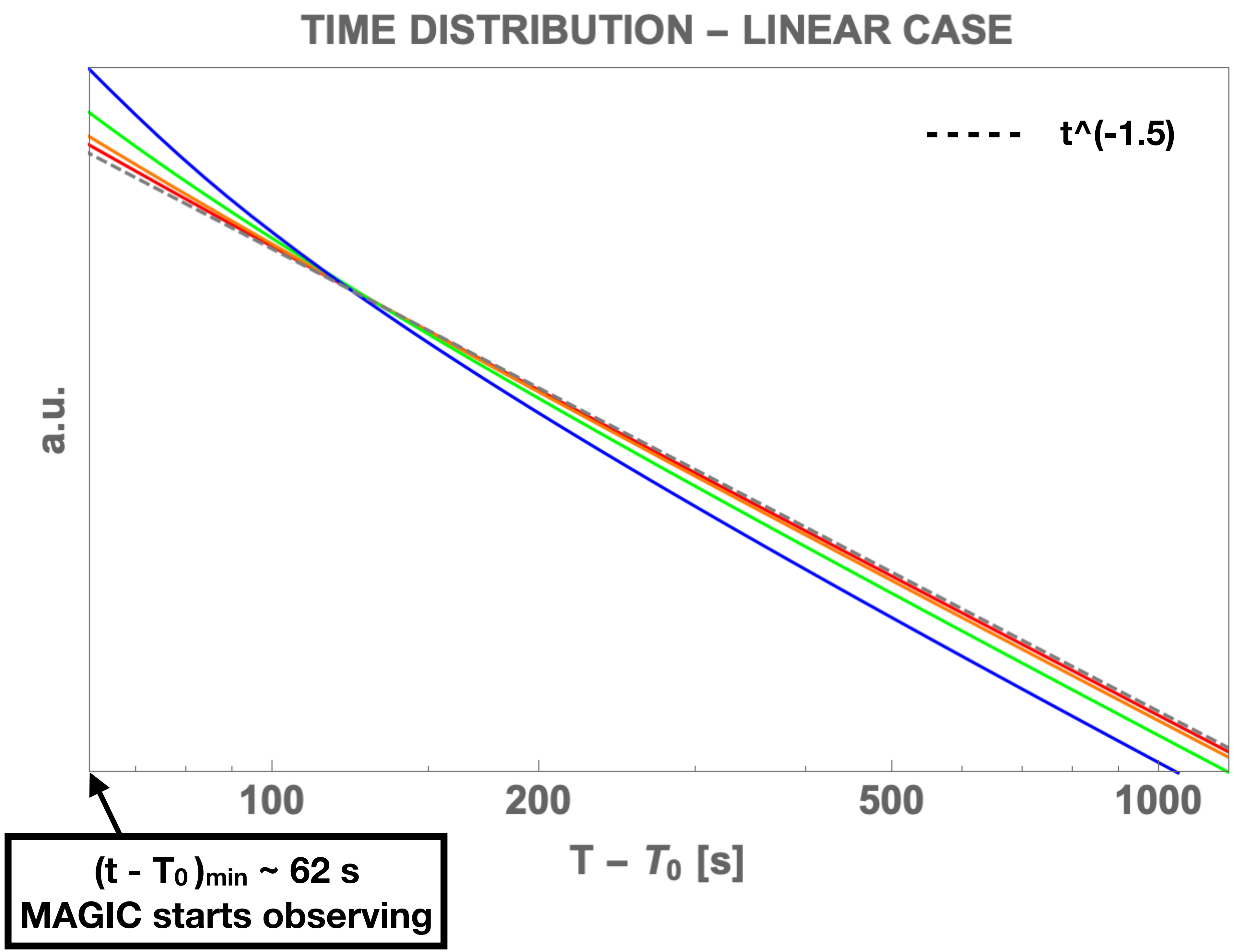


$$\eta_1 = 0.5$$

$$\Delta t = \eta_1 \cdot \; 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION

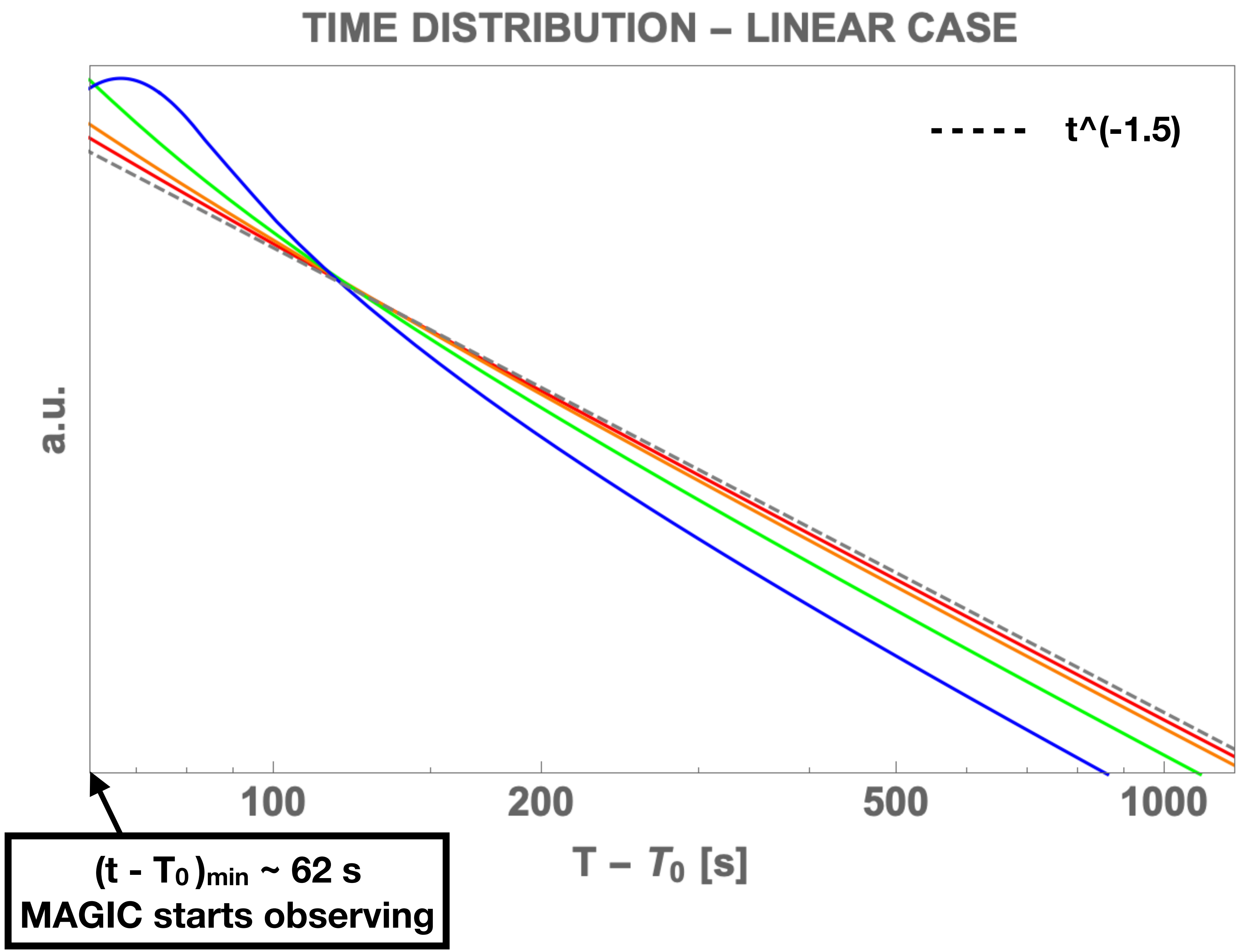


$$\eta_1 = 1$$

$$\Delta t = \eta_1 \cdot 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION

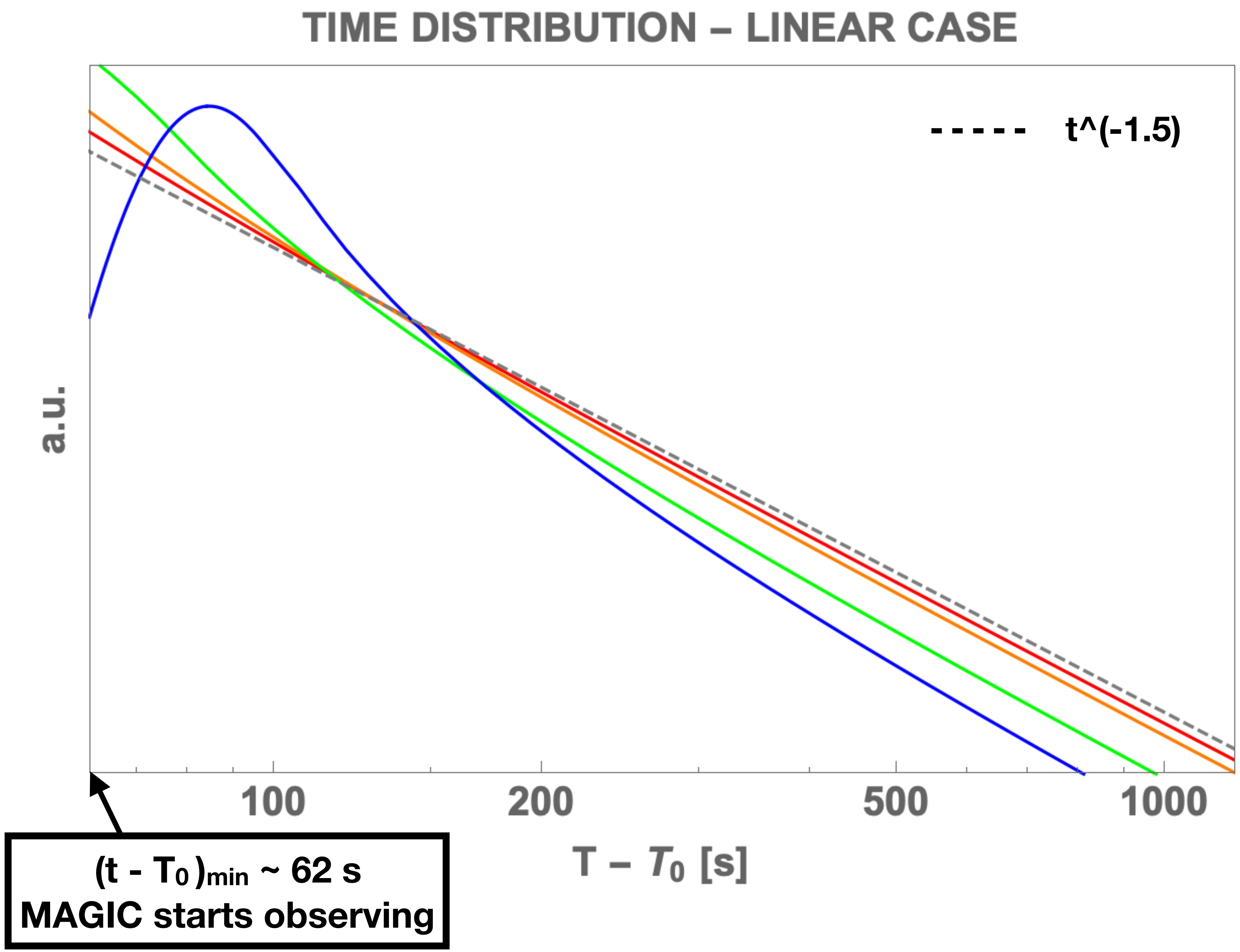


$$\eta_1 = 1.5$$

$$\Delta t = \eta_1 \cdot 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

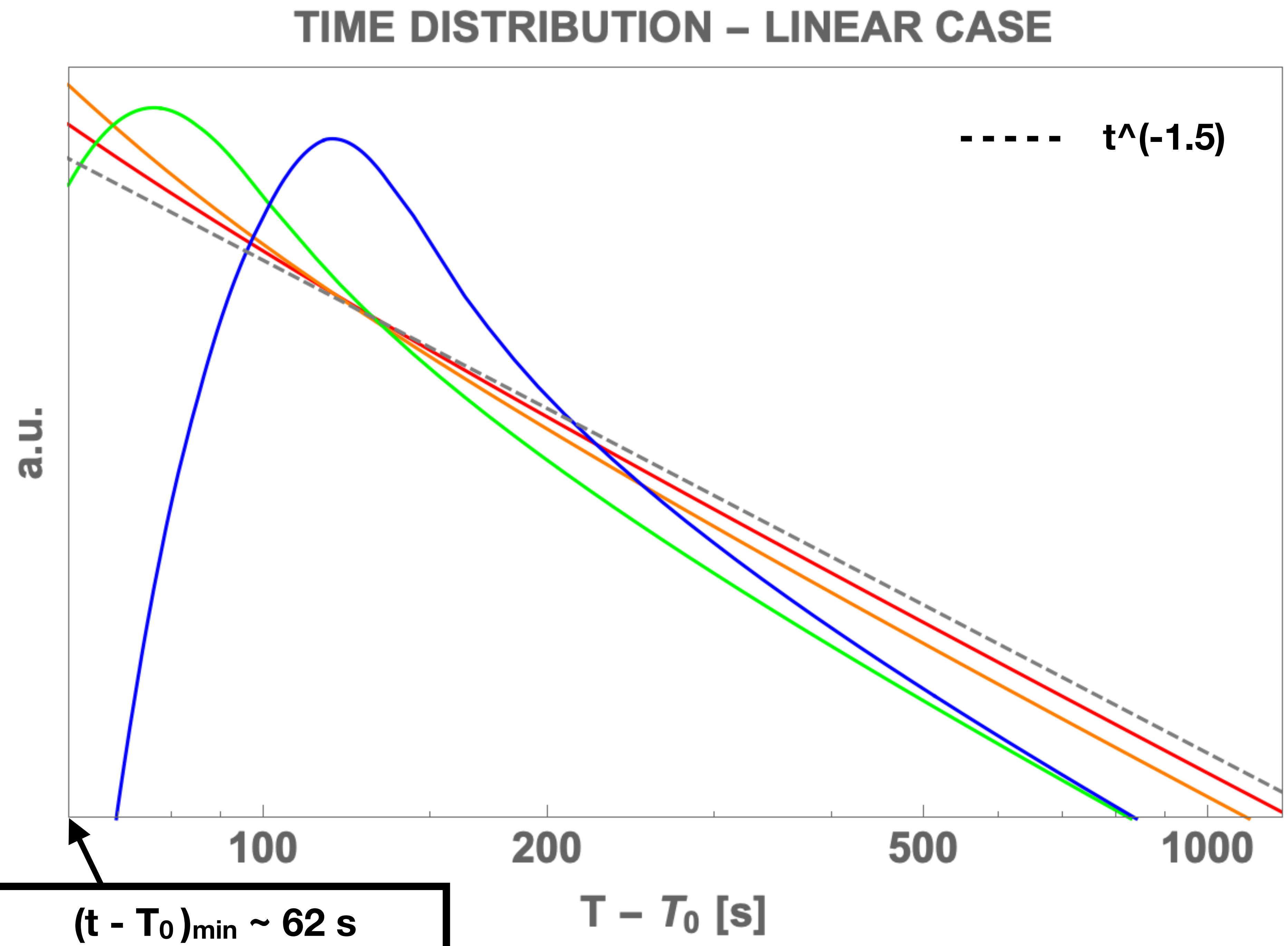
Q.G. EFFECTS IN THE TIME DISTRIBUTION



$$\eta_1 = 2$$

$$\Delta t = \eta_1 \cdot \ 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV



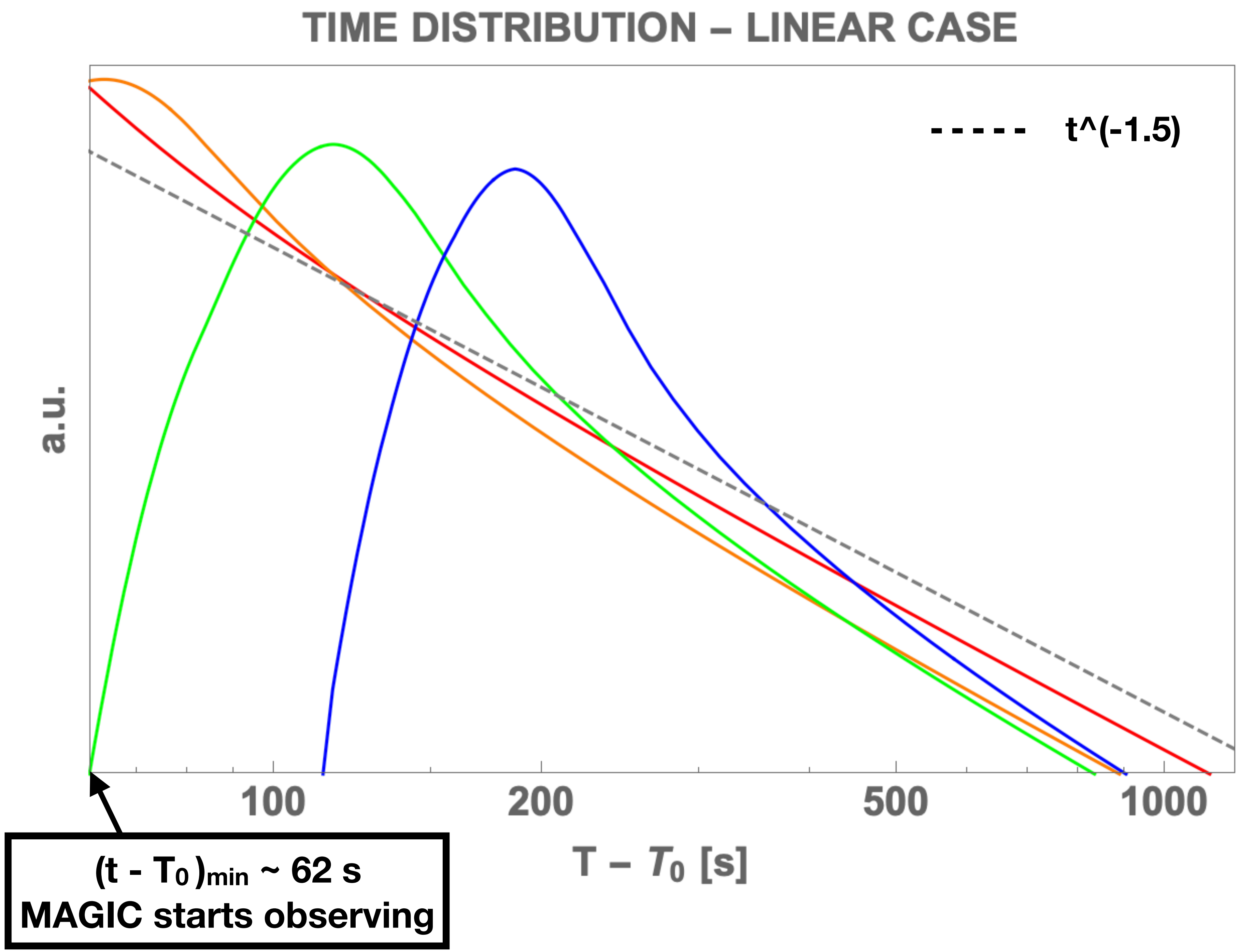
$(t - T_0)_{min}$ ~ 62 s
MAGIC starts observing

$$\eta_1 = 3$$

$$\Delta t = \eta_1 \cdot \ 17\ \mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$

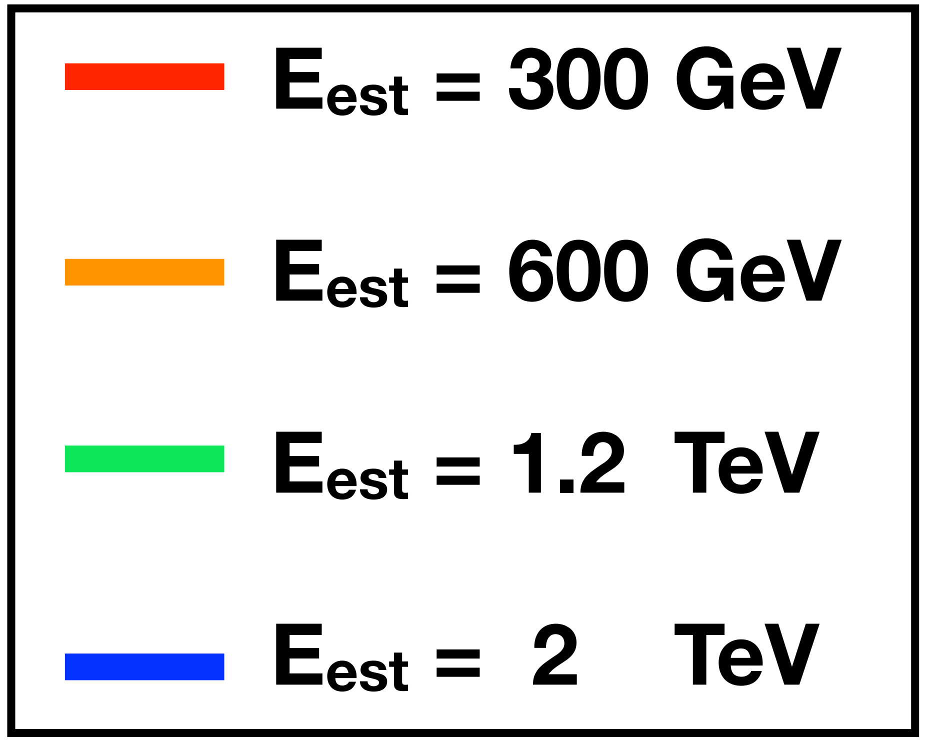
- E_{est} = 300 GeV
- E_{est} = 600 GeV
- E_{est} = 1.2 TeV
- E_{est} = 2 TeV

Q.G. EFFECTS IN THE TIME DISTRIBUTION



$$\eta_1 = 5$$

$$\Delta t = \eta_1 \cdot \, 17\,\mathrm{s} \cdot \frac{E}{\mathrm{TeV}}$$



LIKELIHOOD ANALYSIS

Likelihood

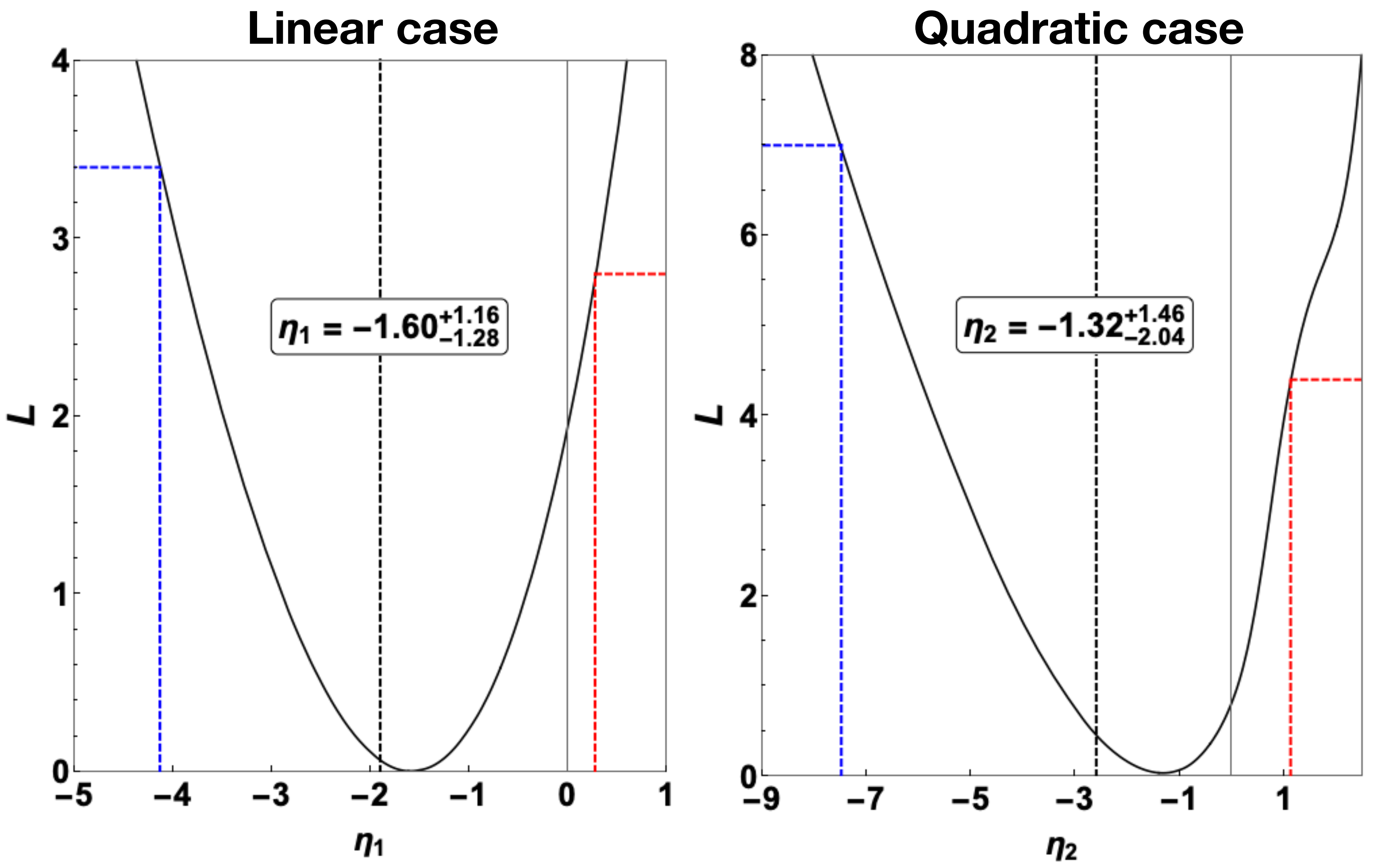
P.D.F. of detecting a **signal** event with a given estimated **energy** and arrival **time**

$$\mathcal{L}(\eta_n, I) = \prod_i^{N_{on}} \left(\frac{N_{on} - N_{off}}{N_{on}} \cdot f_s(t_i, E_i \,|\, \eta_n, I) \; + \; + \frac{N_{off}}{N_{on}} \cdot f_b(t_i, E_i) \right) \cdot P(I)$$

P.D.F. of detecting a **background** event with a given estimated **energy** and arrival **time**

$$P(I) = \mathcal{N}(\beta|1.51, 0.04) \cdot \mathcal{N}(\alpha|2.5, 0.2)$$

Likelihood profile

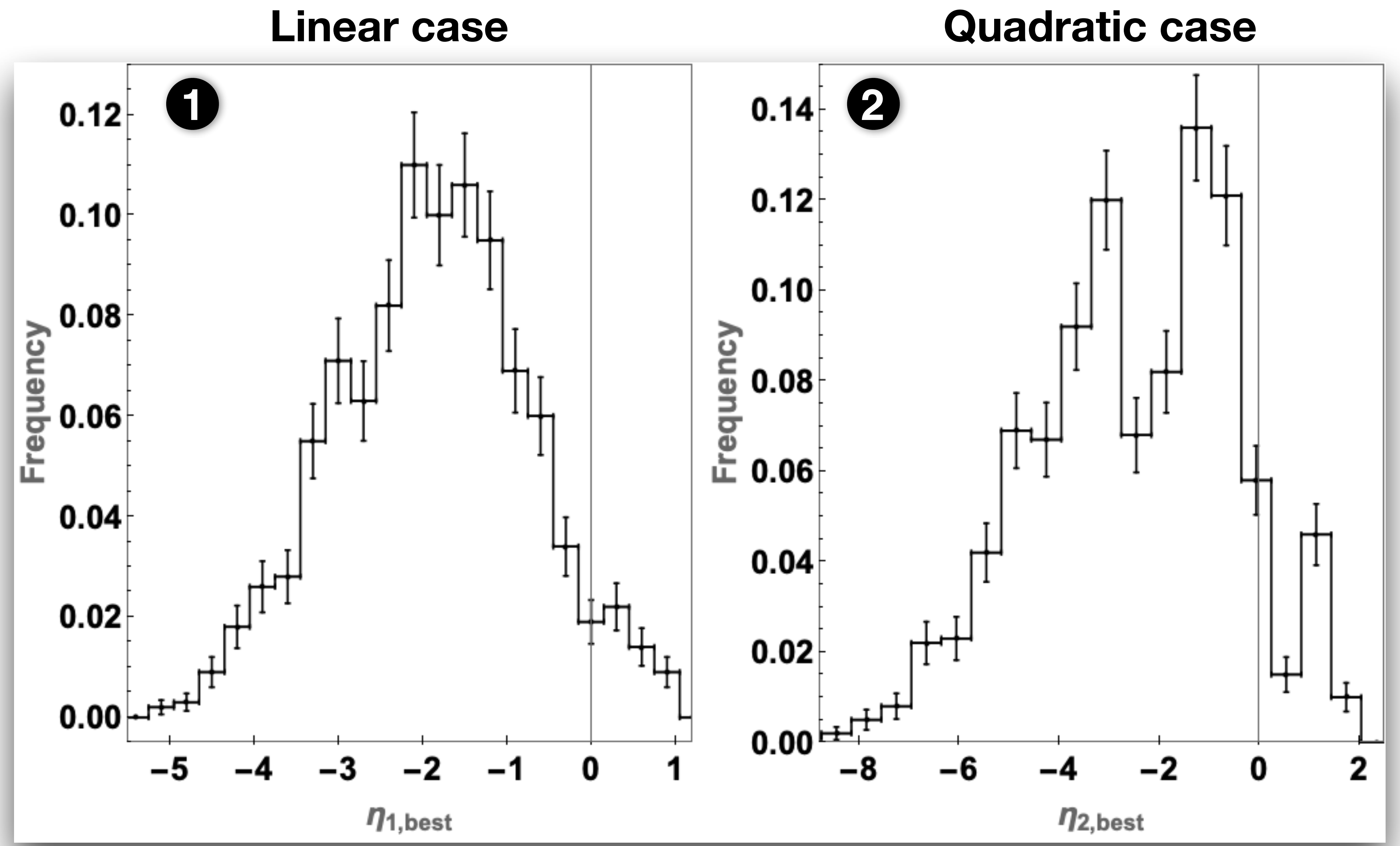


95% LL and UL thresholds are obtained from MCs

LIKELIHOOD ANALYSIS

Is our **intrinsic** model compatible with the **null hypothesis**?

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



1. $\text{BIAS} = -1.9$
2. $\text{BIAS} = -2.6$

- The **likelihood** is slightly shifted toward negative values (**superluminal scenario**)
- This also shows that our data are **compatible** with the null hypothesis

RESULTS

From the GRB 190114C data we got the following 95% lower limits on the Q.G. energy scale

	superl.	subl.
$E_{QG,1}$ [10^{19} GeV]	0.55	0.58
$E_{QG,2}$ [10^{10} GeV]	5.6	6.3

95% lower limit on the Q.G. energy scale for
← linear scenario
← quadratic scenario

$$E_{Pl} \sim 1.2 \cdot 10^{19}\ \text{GeV}$$

COMPARISON WITH PREVIOUS LIMITS

Source	Source type	Redshift	$E_{QG,1}$ [10^{19} GeV]	$E_{QG,2}$ [10^{10} GeV]	Instrument
GRB 090510	GRB	0.9	9.3	13	*Fermi*-LAT[1]
GRB 140119C	GRB	0.42	**0.58**	**6.3**	MAGIC
PKS 2155-304	AGN	0.116	0.21	6.4	H.E.S.S.[2]
Mrk 501	AGN	0.034	0.036	8.5	H.E.S.S.[3]
Mrk 501	AGN	0.034	0.021	2.6	MAGIC[4]
Mrk 421	AGN	0.031	pending	pending	MAGIC
Crab Pulsar	Pulsar	2.0 kpc	0.055	5.9	MAGIC[5]

← **this work**

1 Vasileiou+ (2013)
2 Abramowski+ (2011)
3 Abdalla+ (2019)
4 Albert+ (2008)
5 Ahnen+ (2017)

CONCLUSIONS

- From the **300 GeV - 2 TeV** gamma-ray photons observed from GRB 190114C, we performed a **likelihood 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
  - **Q.G.** effects described by a **model with 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 Q.G. effect**

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

	superluminal	subluminal
$E_{\mathrm{QG},1}$ [GeV]	$> 0.55 \cdot 10^{19}$	$> 0.58 \cdot 10^{19}$
$E_{\mathrm{QG},2}$ [GeV]	$> 5.6 \cdot 10^{10}$	$> 6.3 \cdot 10^{10}$

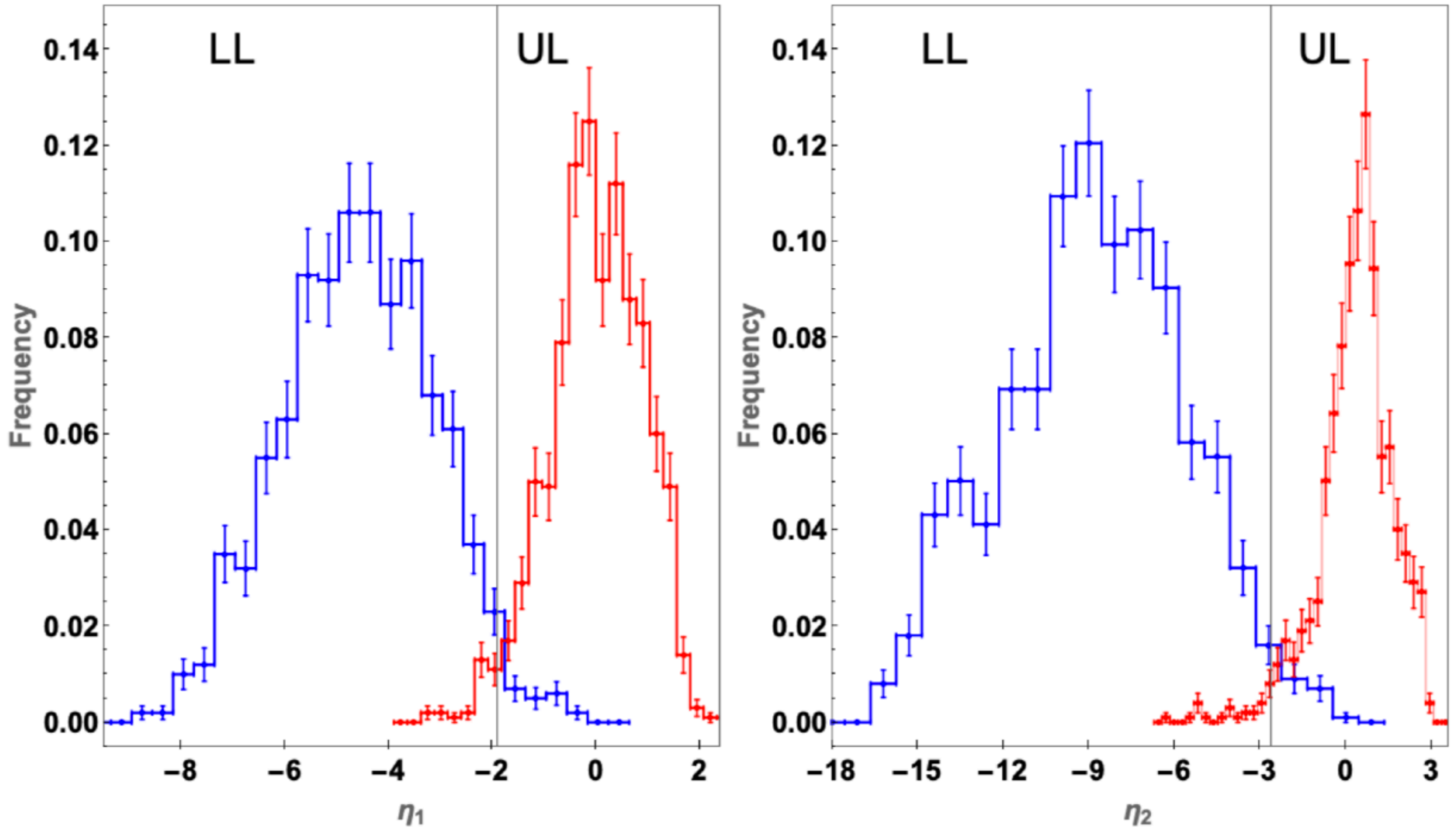
THANK YOU FOR YOUR ATTENTION!

Calibration of 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

Linear case ❶ Quadratic case ❷



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:

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

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

BACKUP SILDE 2

We also investigated systematic effects:

- Possible change of spectral index of GRB190114C → Systematics < 5 %
- Cherenkov light collected by the telescopes overestimated by 15% in our analysis → Systematics ~ 18 % (29%) for subluminal (superluminal) case