EEE data analysis and coalescence of two Neutron Stars

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CENTRO FERMI
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Extreme Energy Events
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DATA CENTRE FOR ASTROPHYSICS

Speakers
Mario Lauriano
Andrea Castagna

Introduction

This work, included in the EEE Project (Extreme Energy Events), is aimed at the development of concepts and methods of experimental research, in particular about cosmic rays. The working hypothesis was to look for a correlation between the coalescence event of two neutron stars, which took place in the galaxy NGC 4993 on 17th August 2017, and the flow of muons produced as a result of the interaction of the primary cosmic rays, emitted by the kilonova, with the atmosphere.

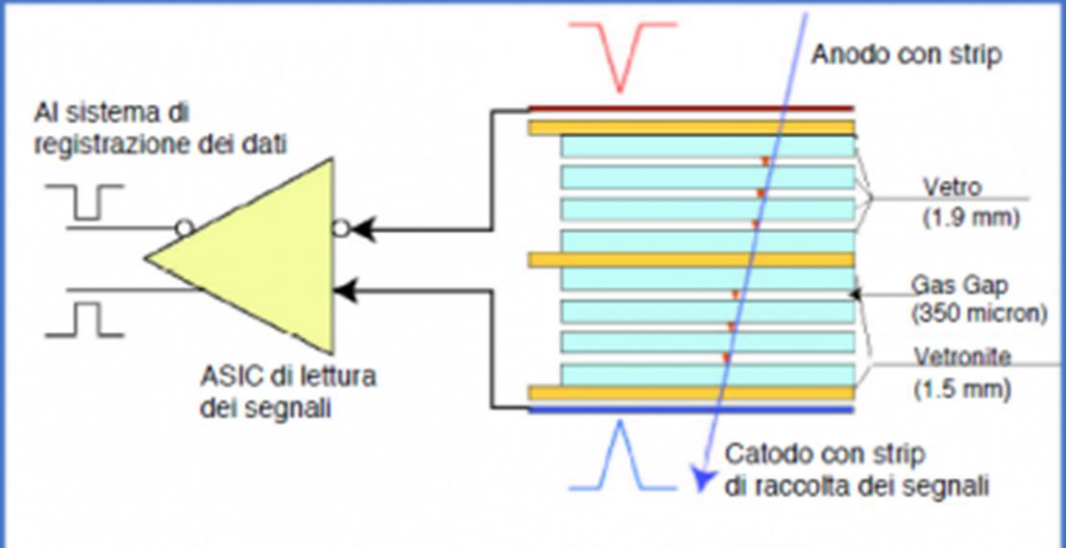
The activity focused on the distant correlations of events: detections of muons occurred at the same time in different observatories. In particular, we focused on the study of the events of 17th August 2017, the date in which a gamma-ray was detected by the two space satellites FERMI (NASA) and INTEGRAL (ESA). The burst was generated by a kilonova: a very energetic explosion caused by the coalescence of the two neutron stars. The work was conducted with the clear awareness that, if there was a correlation, it would already have been published by the experts of the sector with data of a superior quality.

Targets

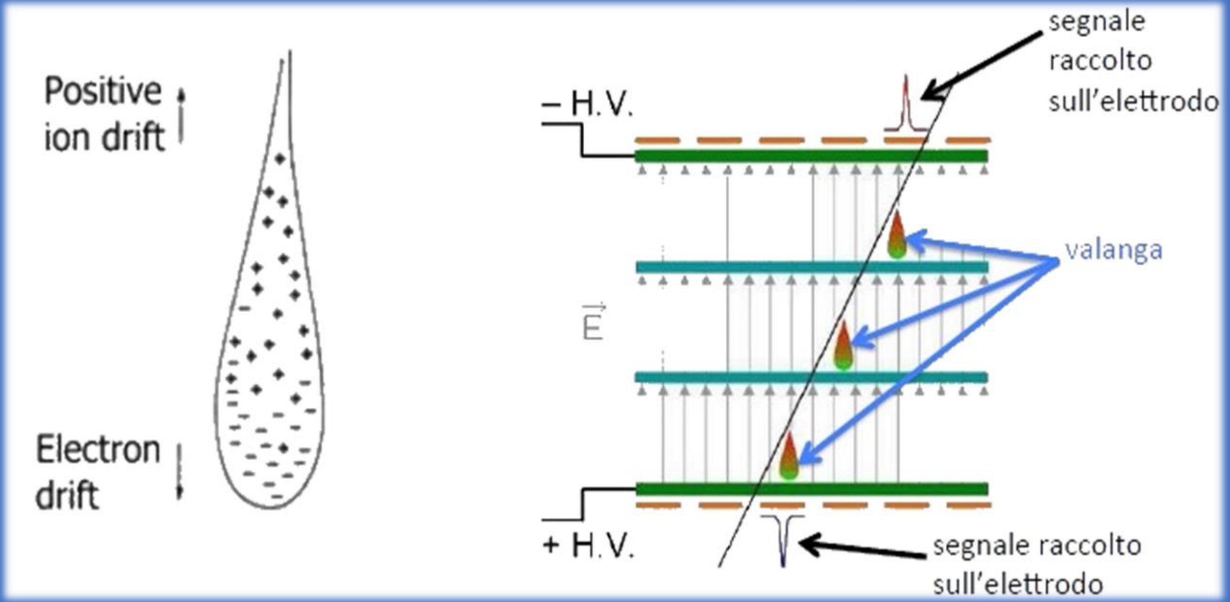
The targets were the development of a valid method for the analysis of distance correlations and the search for a significant event on 17th August 2017 in the EEE network, able to prove the theoretical link that should exist between cosmic rays and coalescence events of two neutron stars.

[1] Video: European Southern Observatory (ESO), «Neutron star merger animation ending with kilonova explosion»

Detectors: composition

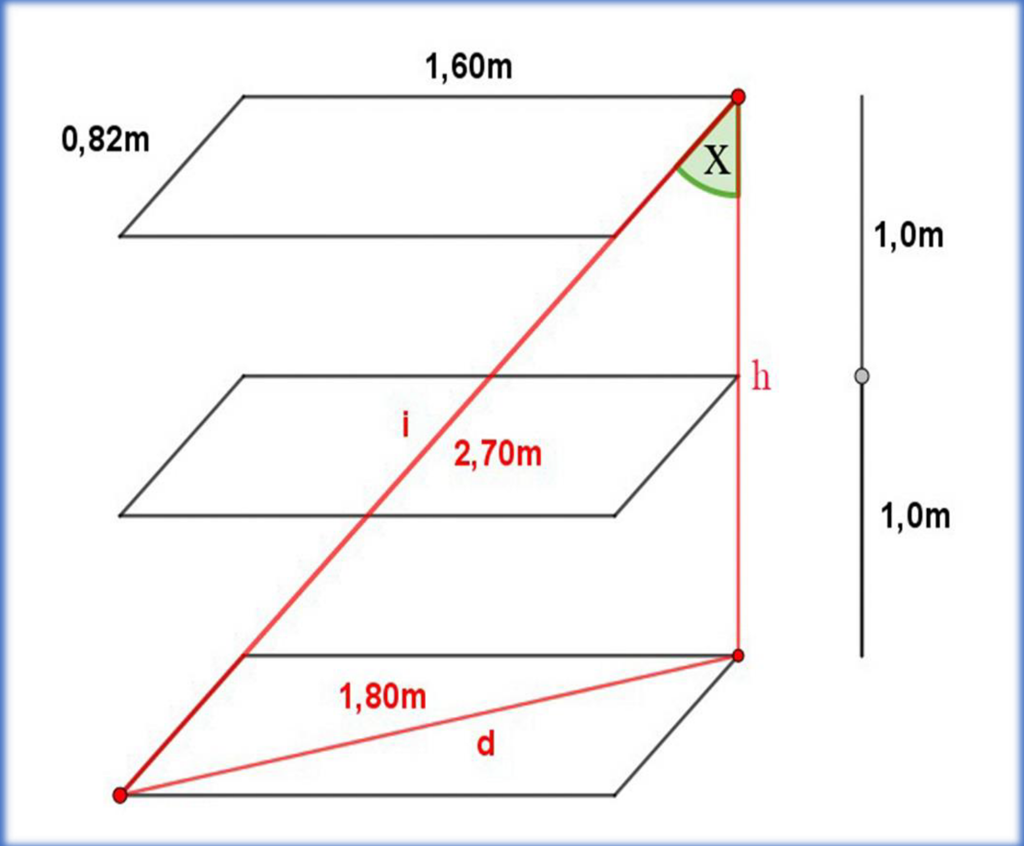


Rappresentazione schematica del rivelatore MRPC e del suo sistema di lettura e acquisizione dei dati.



[2] D. De Gruttola, Presentation «Il telescopio EEE»

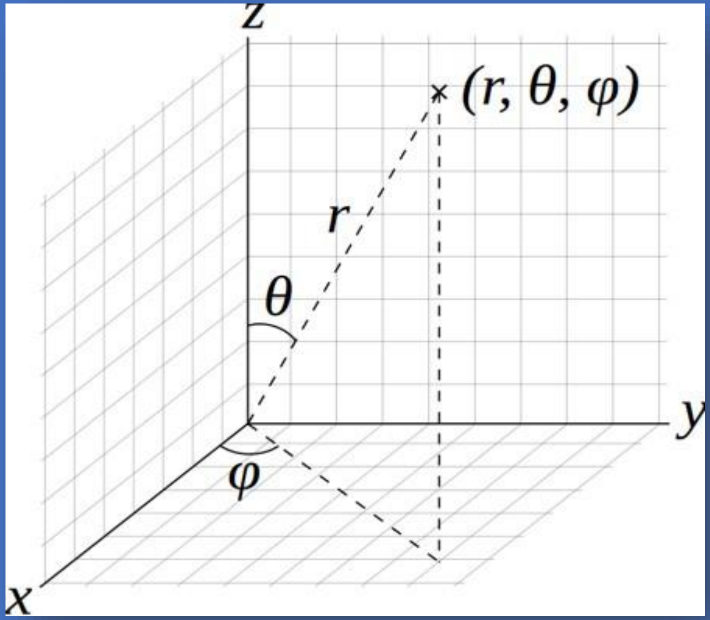
Detectors: sensibility



$$\frac{\sin 90°}{2{,}7} = \frac{\sin \theta}{1{,}8}$$

$$\sin \theta \approx 0{,}67$$

$$\arcsin 0{,}67 \approx 42°\, 4'\, 1{,}43''$$



A ltitude of galaxy NGC 4993

Detector	Altitude NGC 4993
AREZ-01	17° 50’ 37’’
BOLO-04	16° 45’ 17’’
CERN-01	13° 22’ 30’’
CERN-02	13° 22’ 30’’
SALE-02	21° 17’ 43’’
TORI-03	14° 57’ 43’’
TORI-04	14° 57’ 43’’

E mitted protons per m^2 from the kilonova

Running detectors
AREZ-01
BOLO-04
CERN-01
CERN-02
SALE-02
TORI-03
TORI-04

$$m_1 \in [1.36 - 2.26]M_\odot \rightarrow \overline{m_1} = 1.81M_\odot \quad [3]$$

$$m_2 \in [0.86 - 1.36]M_\odot \rightarrow \overline{m_2} = 1.11M_\odot \quad [3]$$

$$\boldsymbol{E} = (\overline{m_1} + \overline{m_2}) - m_{tot} = 0.1M_\odot$$

$$\mathbf{E(eV) = 1.116 \times 10^{65} eV} \quad \textit{emitted energy from the coalescence}$$

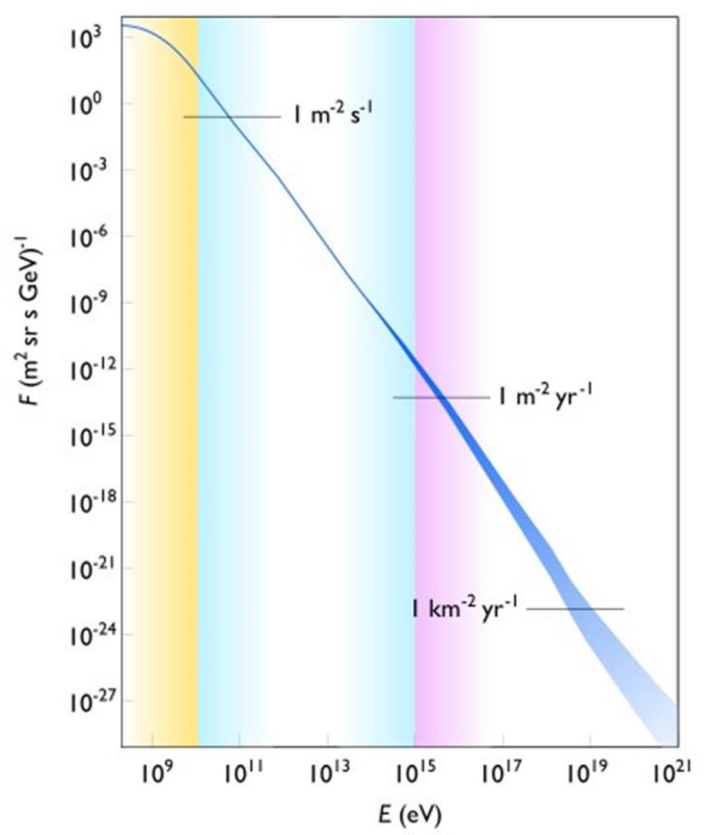
$$\mathbf{n_{p^+} = \frac{E}{m_{p_+}} = 0.118 \times 10^{57}}$$

$$\boldsymbol{d} = 130\ M\ a.l. = 1.3 \times 10^8\ a.l. \ [3]$$

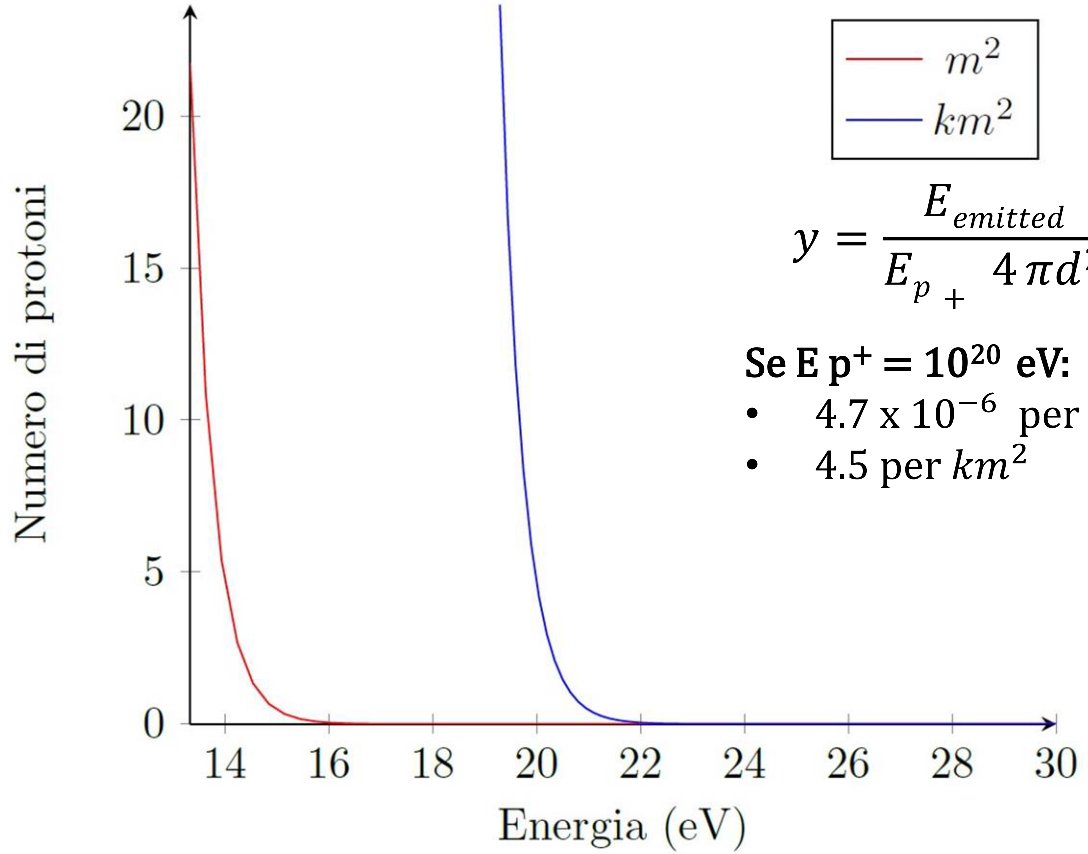
$$\boldsymbol{\frac{n_{p^+}}{m^2} = \frac{n_{p^+}}{4\pi d^2} = 6.2 \times 10^6 \frac{n_{p^+}}{m^2}} \quad \textit{numbers of protons per } m^2 \textit{ on the Earth}$$

[3] The Astrophysical Journal Letters, Volume 848, Number 2. Published 2017 October 16

E nergy of emitted protons



[4]



$$y = \frac{E_{emitted}}{E_{p^+} \; 4\pi d^2}$$

Se E $p^+ = 10^{20}$ eV:

- 4.7×10^{-6} per m^2
- 4.5 per km^2

[4] S. Swordy, «The energy spectra and anisotropies of cosmic rays», 2001, Space Science Reviews 99, pp85–94

T Ime delay of protons respect to photons

Grandezze: $m = 10^{20}$ eV
$d = 1.30 \times 10^8$ a.l. [5]
$m_0 = 10^9$ eV

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = 10^{11} \rightarrow v = c(1 - \gamma^{-2})^{\frac{1}{2}}$$

$$\Delta t = \frac{d}{v} - \frac{d}{c} = \frac{d}{c(1-\gamma^{-2})^{\frac{1}{2}}} - \frac{d}{c} = \frac{d}{c}[(1-\gamma^{-2})^{-\frac{1}{2}}] \approx \frac{d}{c}[1 - (-\frac{1}{2})\gamma^{-2} - 1] = \frac{d}{c}\frac{1}{2}\gamma^{-2}$$

$$\frac{d}{c} = 1.3 \times 10^8 yr = 4.03 \times 10^{15} s$$

$$\Delta t = \left(\frac{4.03 \times 10^{15}}{2} s\right) \gamma^{-2} = (2.02 \times 10^{15} s)\gamma^{-2}$$

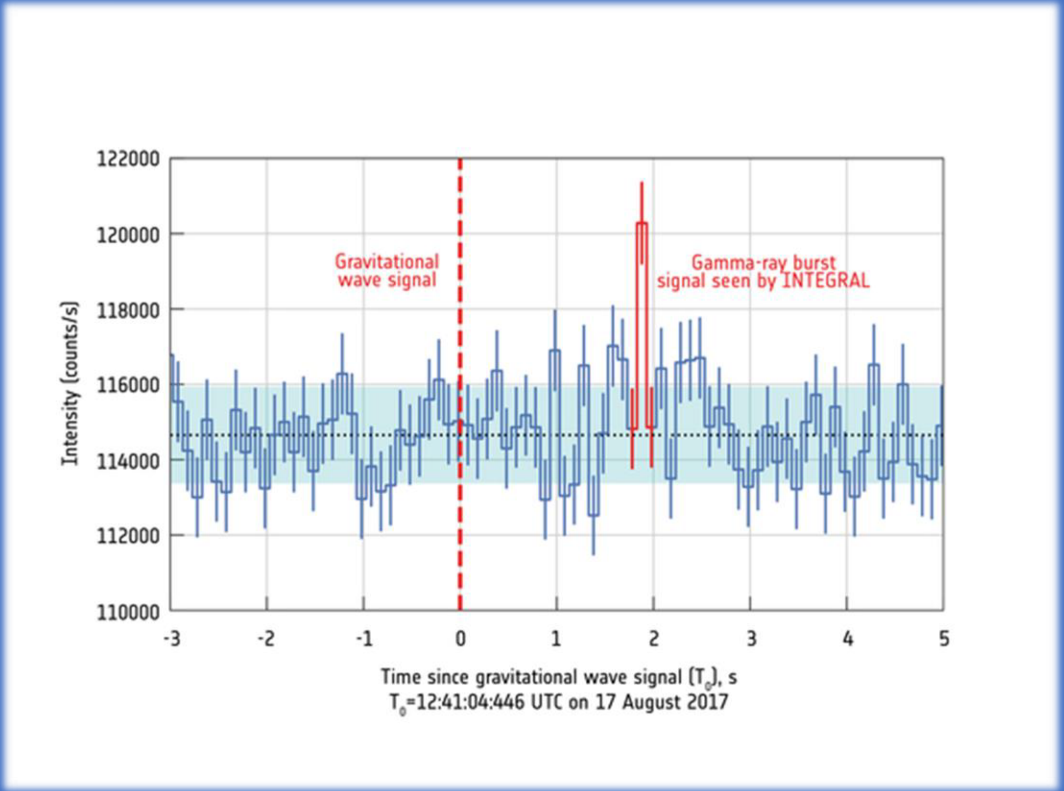
E p^+ [eV]	γ	Δt [s]
10^{20}	10^{11}	2.02×10^{-7}
10^{17}	10^{8}	0.202
10^{16}	10^{7}	20.02
10^{15}	10^{6}	2.02×10^{3}
10^{14}	10^{5}	2.02×10^{5}

[6]

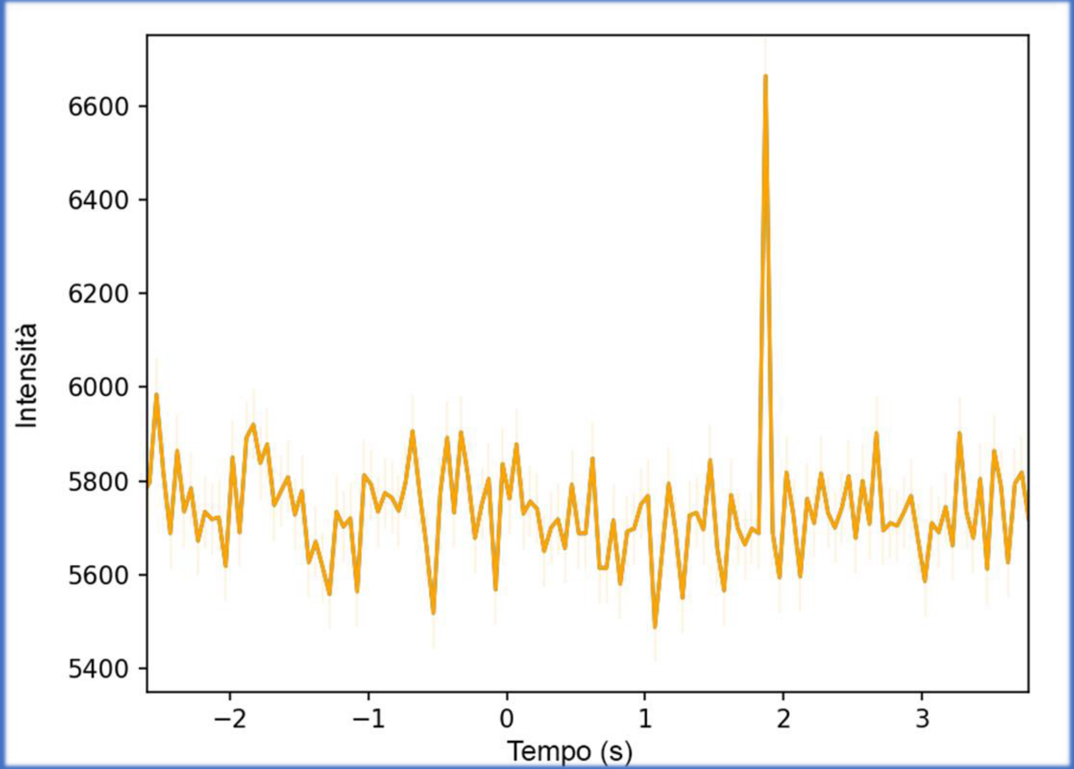
[5] The Astrophysical Journal Letters, Volume 848, Number 2. Published 2017 October 16

[6] Prof. Giovanni Peres, Professor of Astronomy and General Relativity at the University of Palermo

I NTEGRAL gamma ray burst analysis



[7]

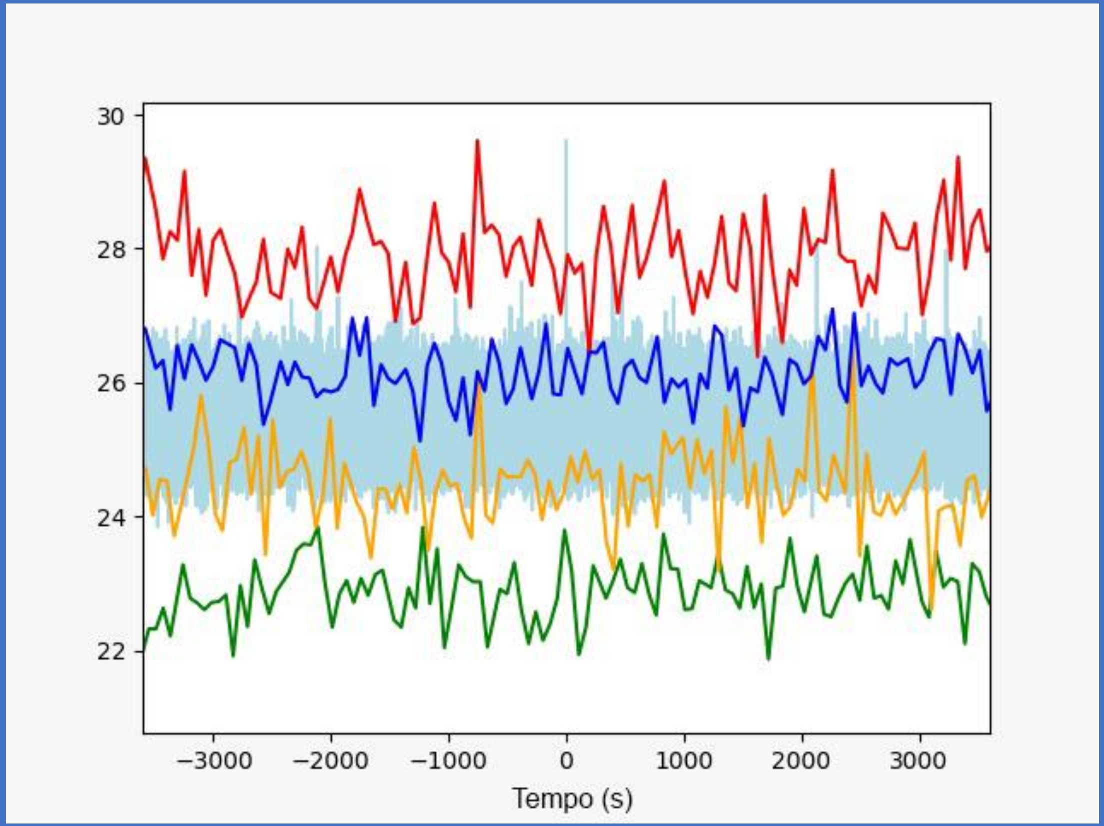


[8]

[7] ESA/INTEGRAL/SPI/ISDC, "INTEGRAL: Gamma ray burst after gravitational waves“, 16 October 2017

[8] Team EEE ‘’B. Croce’’. Thanks to Dr. Carlo Ferrigno, P.I. of INTEGRAL Science Data Centre (University of Geneva)

Comparison EEE-INTEGRAL



t_0 = gamma burst

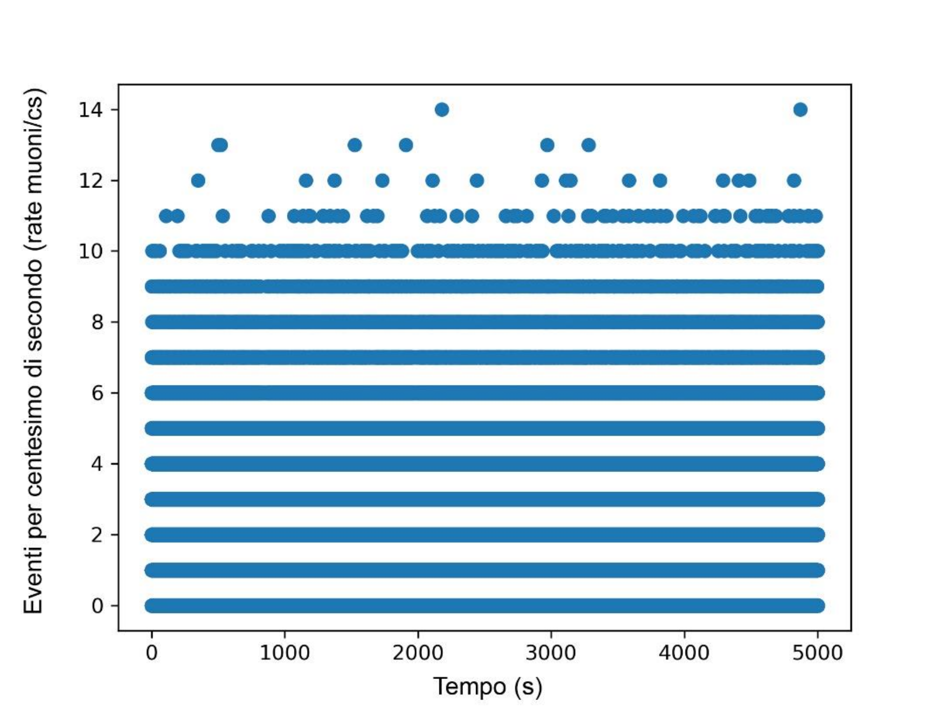
Overlap of: INTEGRAL (background), CERN-02 (red), TORI-04 (green) and SALE-02 (yellow).

The average of the muon flow recorded by the three telescopes of the EEE network is reported in **blue.**

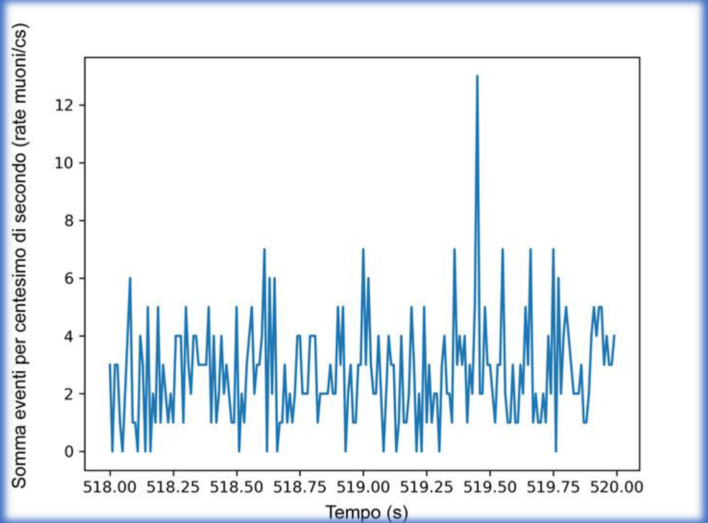
The ordinate value is not respected

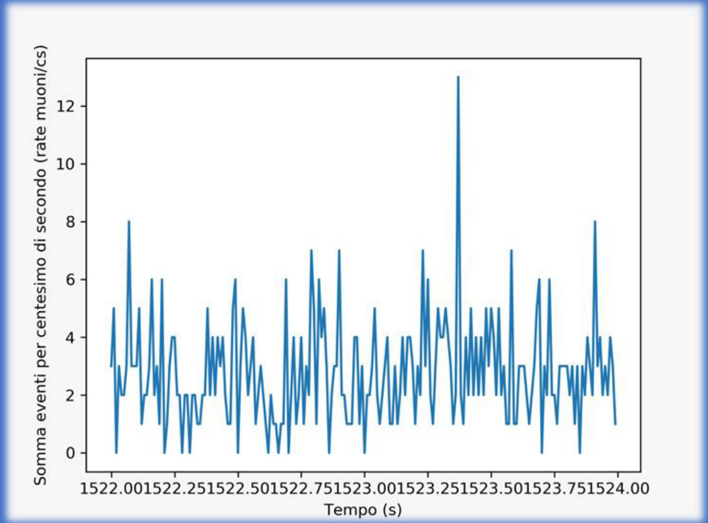
Scintillations per unit of time

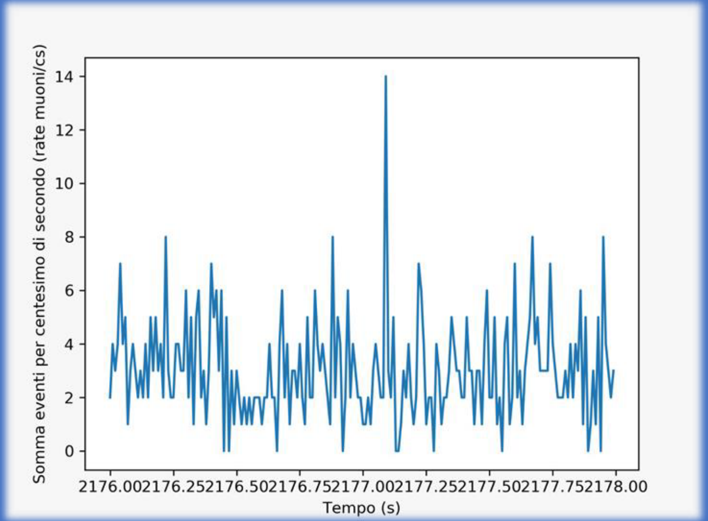
```
import numpy as np
import matplotlib.pyplot as plt
bolo 04=np.genfromtxt ( "BOLO-04from2017-08-17to2017-08-17. csv " , delimiter=" , " )
cern 01=np.genfromtxt ( "CERN-01from2017-08-17to2017-08-17. csv " , delimiter=" , " )
cern 02=np.genfromtxt ( "CERN-02from2017-08-17to2017-08-18. csv " , delimiter=" , " )
sale 02=np.genfromtxt ( "SALE-02from2017-08-17to2017-08-17. csv " , delimiter=" , " )
tori 03=np.genfromtxt ( "TORI-03from2017-08-17to2017-08-17. csv " , delimiter=" , " )
tori 04=np.genfromtxt ( "TORI-04from2017-08-17to2017-08-17. csv " , delimiter=" , " )
t0=1167609600 #1 Gennaio 1970 in UTC, timestamp
tgb=1502973664 #1502973664 il secondo del gamma burst
def grafico(tel,m1,m2):
x=(tel[1:,0]+tel[1:,1]10*(-9)+t0-tgb)
i0,=np.where(np.trunc(x)==0)
imin,=np.where(np.trunc(x)==m1)
imax,=np.where(np.trunc(x)==m2)
x=x[imin[0]:imax[len(imax)-1]]
tot_s=m2-m1
print(tot_s)
Nc = tot_s*n
pdf, bins = np.histogram( x, bins=np.linspace(m1,m2,Nc+1), density = False )
return pdf
m1=0 #secondo di inizio (rispetto al tgb)
m2=5000 #secondo di fine (rispetto al tgb)
n=10**2 #al centesimo
y_s=grafico(cern_02,m1,m2)+grafico(tori_04,m1,m2)+
grafico(bolo_04,m1,m2)+grafico(cern_01,m1,m2)+grafico(tori_03,m1,m2)+
grafico(sale_02,m1,m2)
x=np.linspace(m1,m2-1/n,(m2-m1)*n)
plt.xlabel('Secondi')
plt.ylabel('Scintillazioni al centesimo di secondo')
plt.scatter(x,y_s)
plt.show()
```

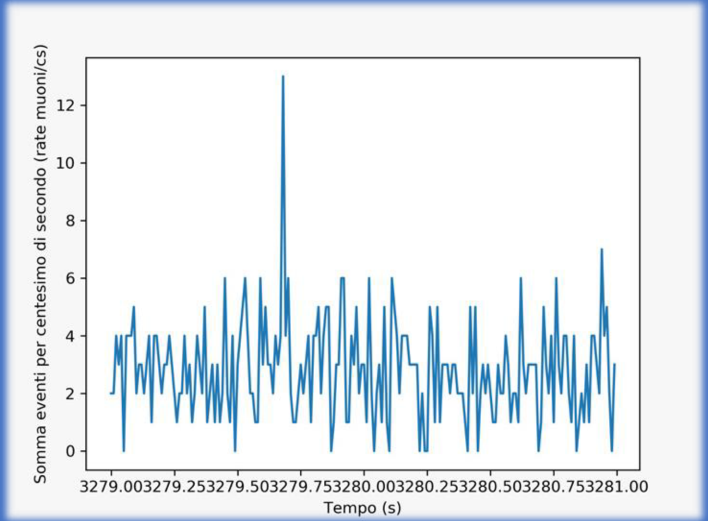


Analysis of the four most significant peaks of the previous graph, respectively at 518s, 1522s, 2176s, 3279s after the Gamma Ray Burst



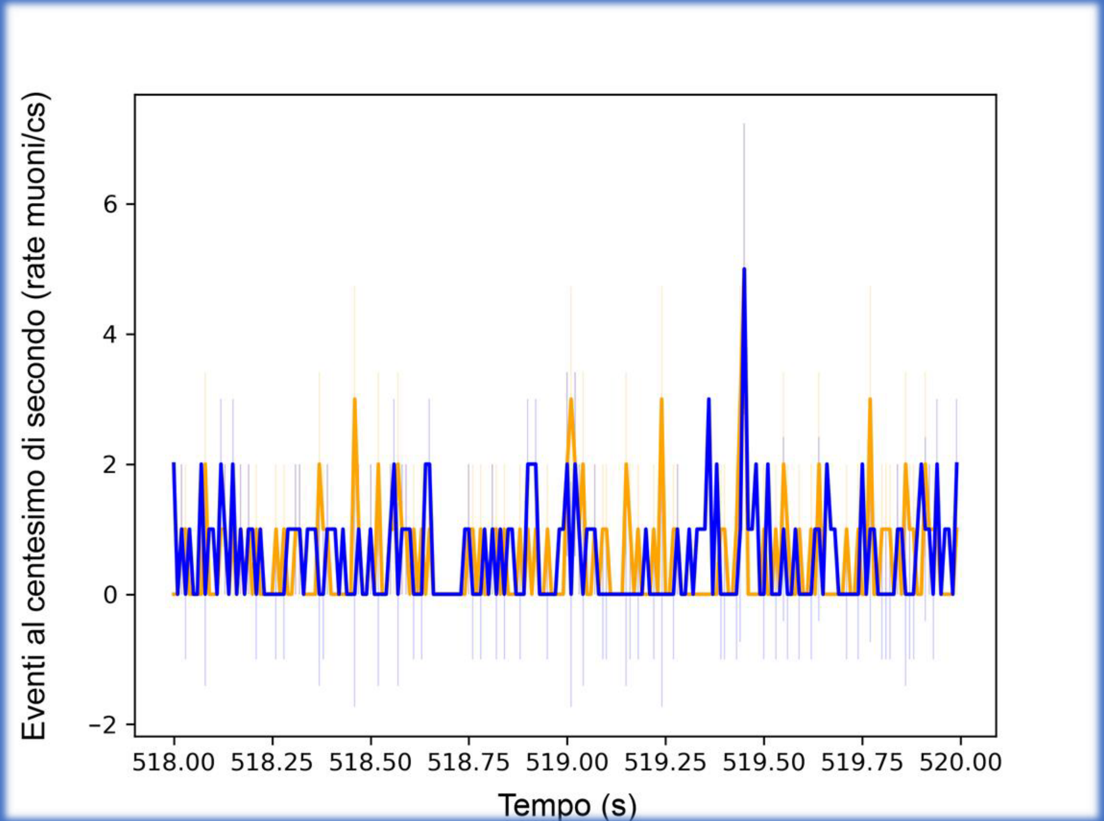


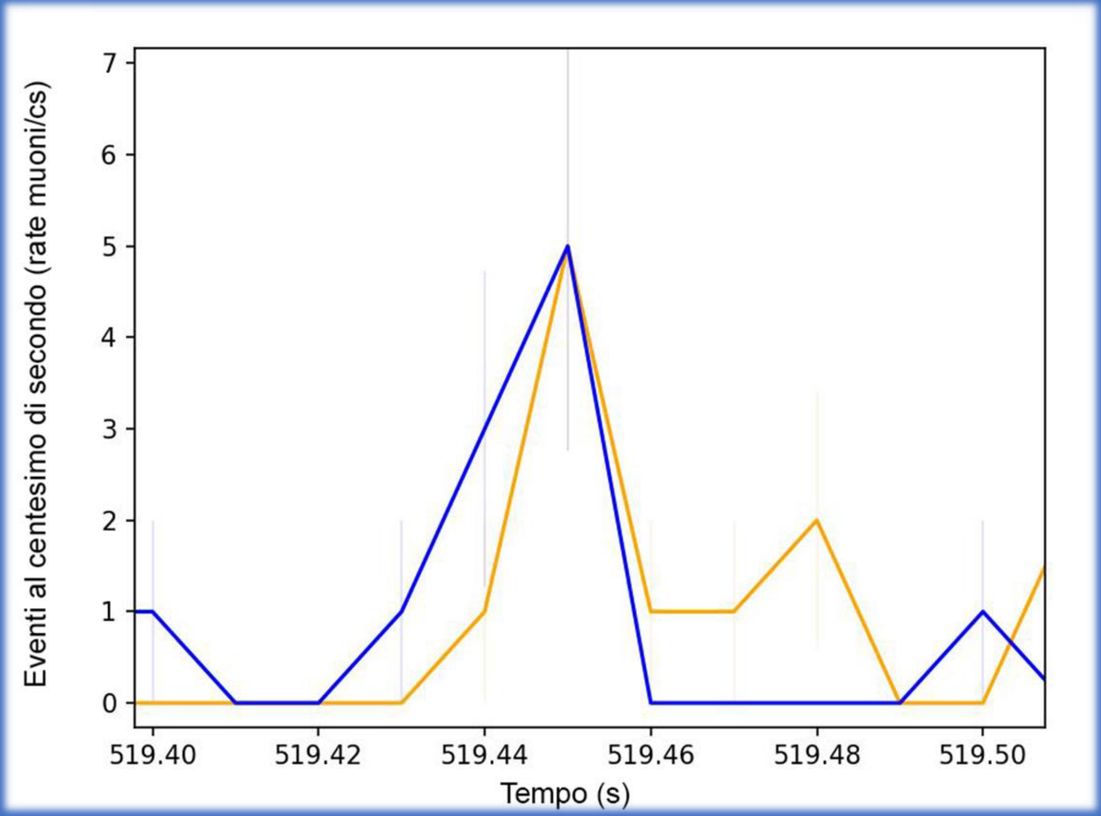




S earch for significant events

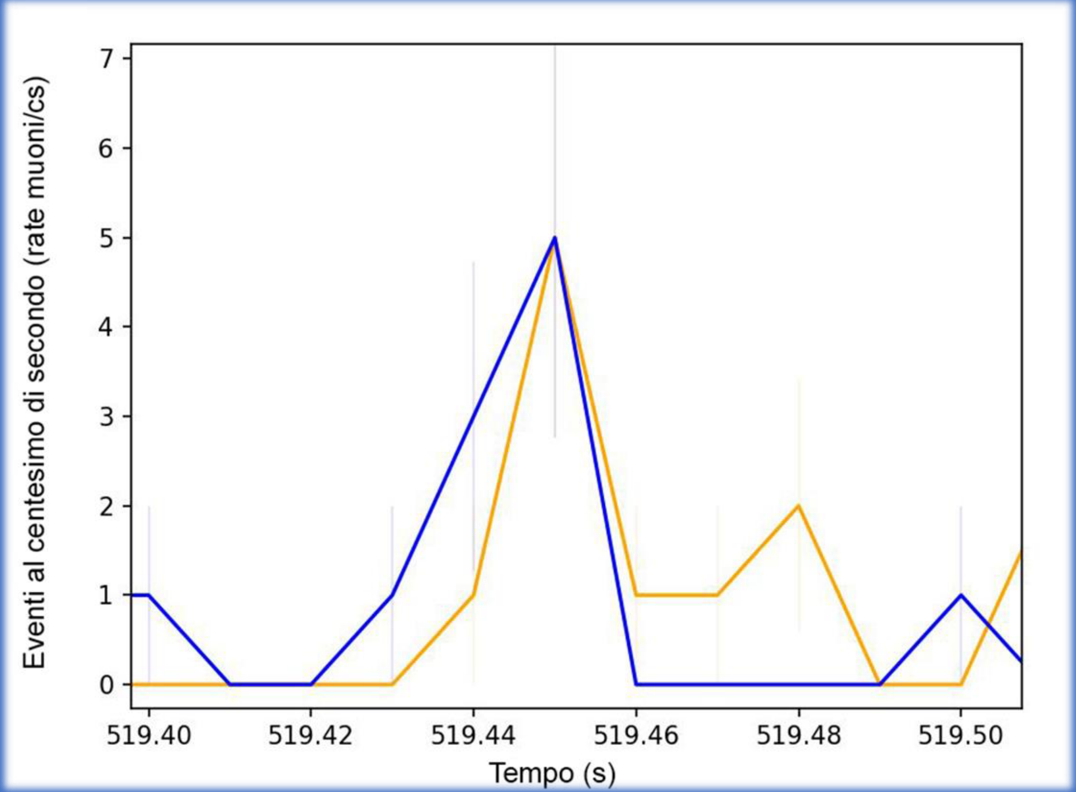
Of the four peaks examined, the first (519.45s from the GRB) has a coincidence of 5 muons in the same hundredth of a second [cs] from both Cern-01 and Tori-04

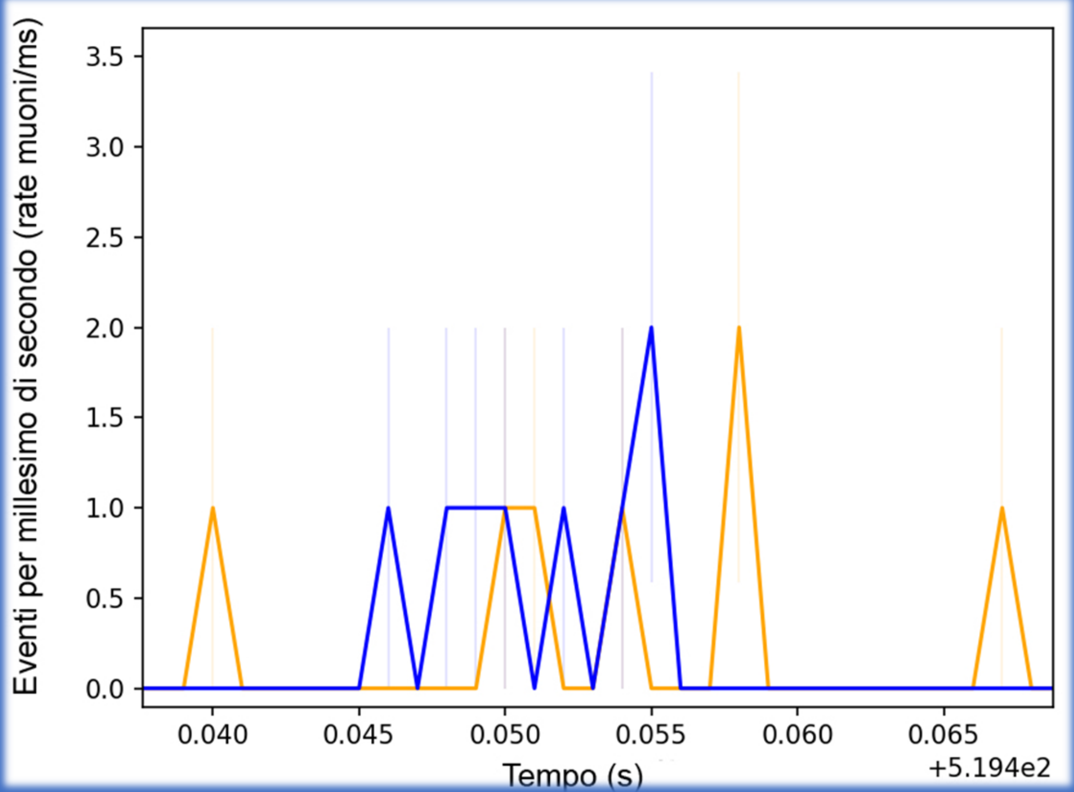




Search for significant events

The same coincidence observed at thousandths of a second [ms]. The new highlighted time delay may be due either to a different sensitivity of the electronic components of the two detectors or to an uncorrelation between the two primary cosmic beams

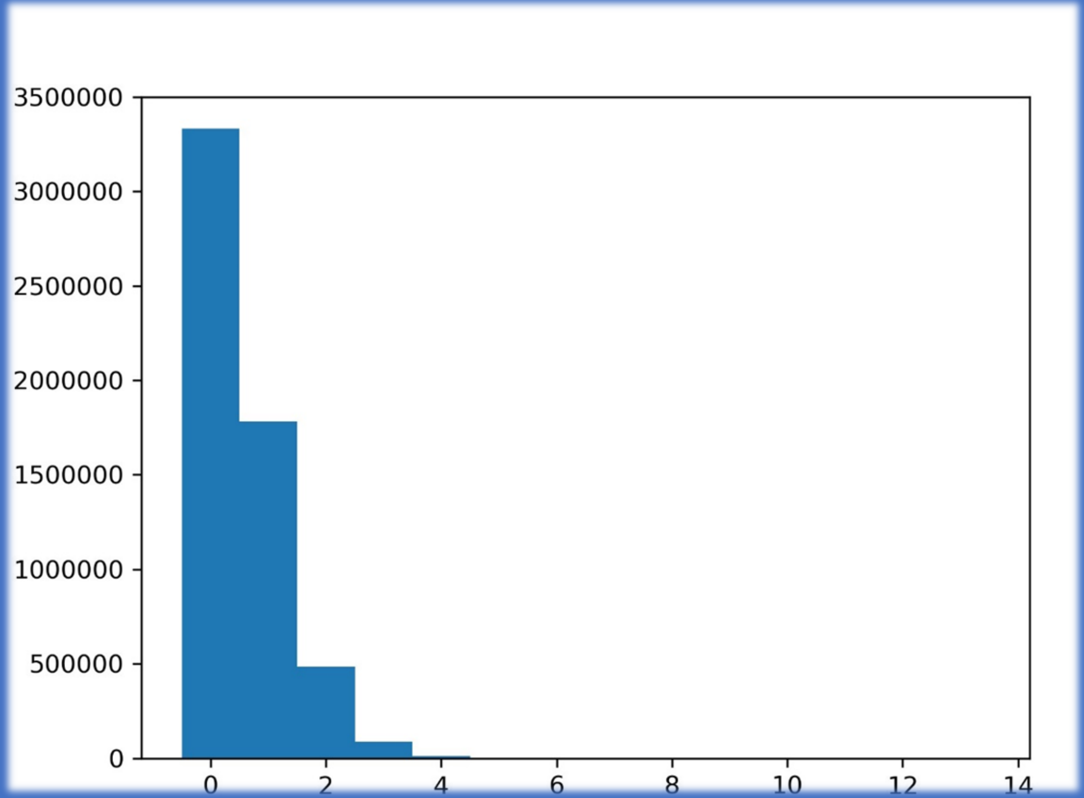




Statistical evaluations

```
m1=-52000 #inizio del file
m2=5000 #fine del file
n=100 #risoluzione al centesimo
y_s=grafico(cern_01,m1,m2)

#Raccolta dei risultati per numero di eventi
pdf, bins = np.histogram(y_s, bins=np.arange(0,15),
density=False)
plt.xlabel('Numero di eventi')
plt.ylabel('Scintillazioni al centesimo di secondo')
plt.bar(bins, pdf)
plt.show()
```



Statistical evaluations

To evaluate how often a coincidence occurred such as that identified between CERN-01 and TORI-04, we have graphically represented the number of coincidence events at the hundredths of a second [cs] of *x* muons. This was represented as a function of the number of muons (per detector) that compose coincidence itself. The analysis was conducted on Cern-01 for 16.3 hours on 17th August 2017.

Then, we looked for a mathematical model that generalized the distribution obtained from the data. This looked as a **Poisson distribution**.

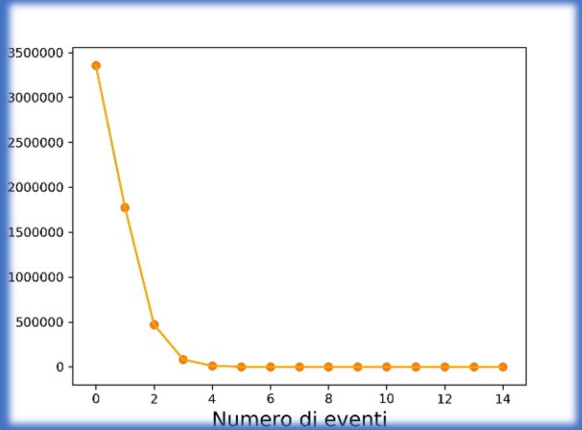
$$P(n) = \frac{e^{-\frac{N_e}{T}}\left(\frac{N_e}{T}\right)^n}{n!}$$

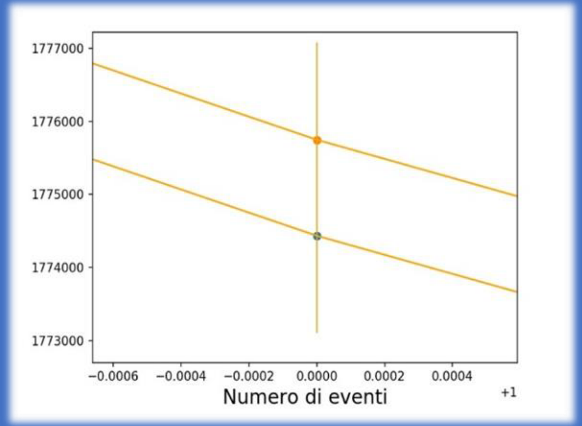
$\frac{N_e}{T}$ = average rate of events recorded by the telescope in the time interval **T**

$$P_{tot}(5) = P_{cern\text{-}01} \cdot P_{tori\text{-}04} = 4.62 \times 10^{-6}\ \%$$

$$rate_{event} = \frac{cs}{giorno} \cdot P_{tot} = 8.64 \times 10^{6} \cdot 4.62 \times 10^{-8} = 3.99 \times 10^{-1}\ \frac{eventi}{giorno}$$

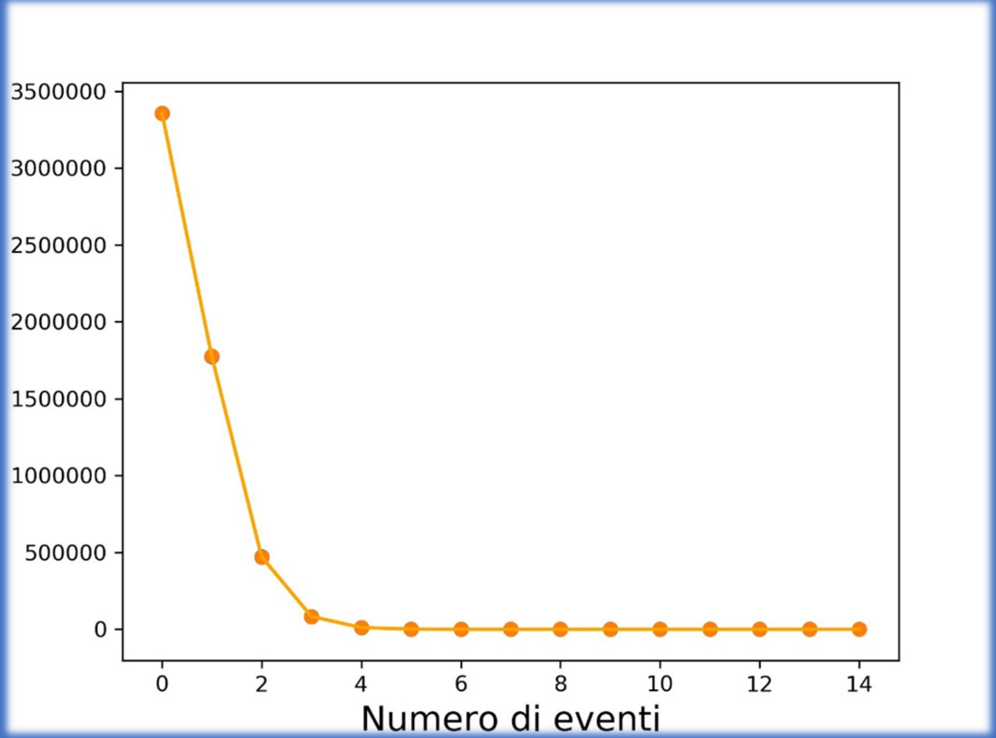
2gg 12h 7min 30s

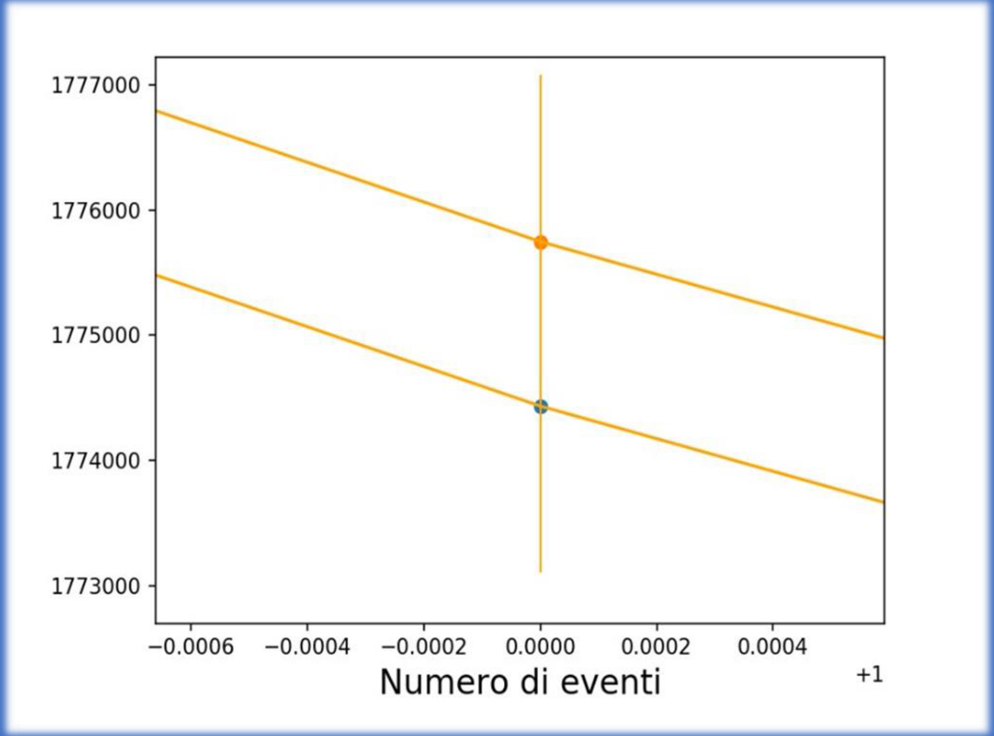




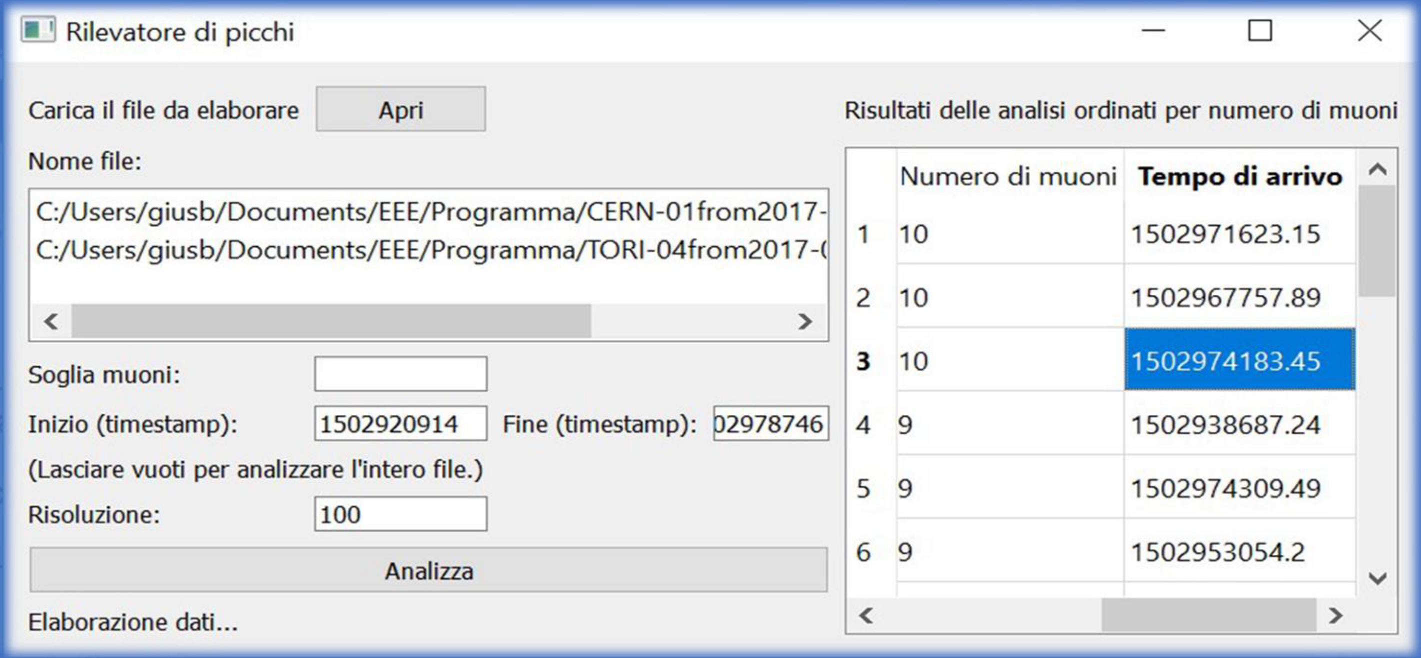
S tatistical evaluations

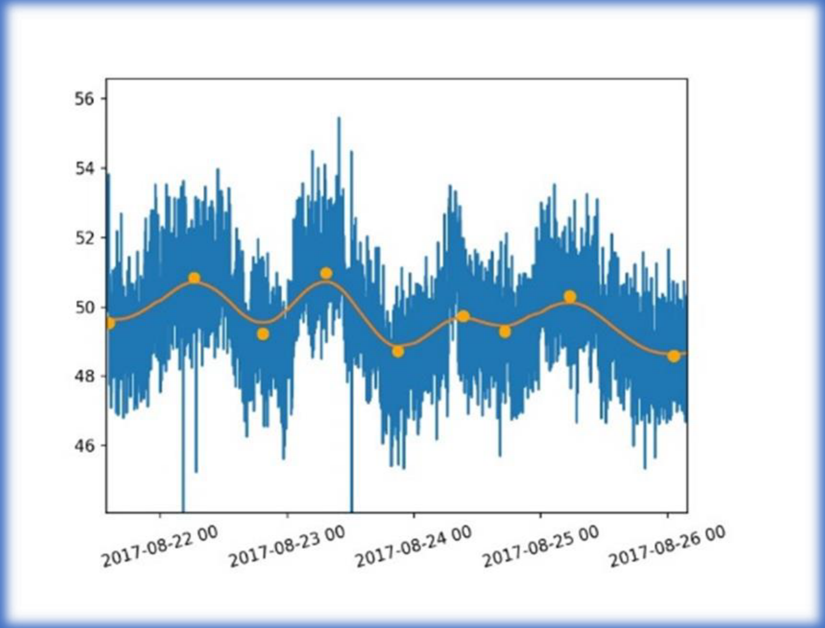
Graphical comparison between model and data (Poisson distribution-EEE data)





Analysis automation





Thanks

- **Prof. Vincenzo Di Matteo** – Liceo ''B. Croce'' Palermo
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- **EEE Collaboration, Dr. Marta Pepe, Dr. Silvia Pisano** – Centro Fermi
- **Prof. Giovanni Peres** – Dipartimento di Fisica Palermo (DIFC-UNIPA)
- **Dr. Carlo Ferrigno** – INTEGRAL Science Data Centre (University of Geneva)