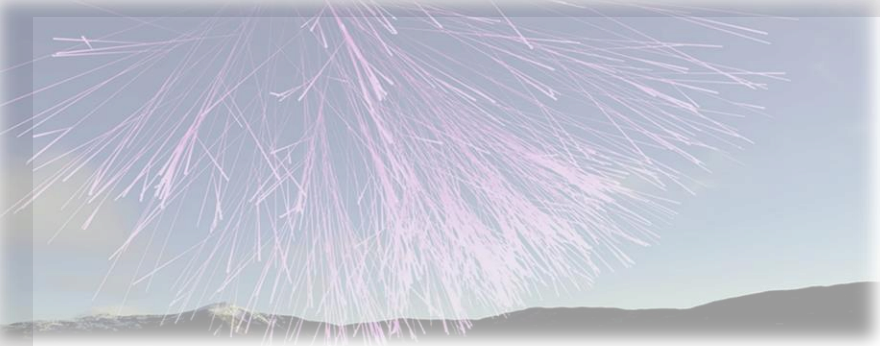


Study of the cosmic muon rate nearby the Advanced Virgo detector at the end of the O3 run

Francesco Di Renzo,[1,2] N.Arnaud,[3,4] T. Avgitas,[4] R.De Rosa,[5] I.Fiori,[4] C.Giunchi,[6] K.Janssens,[7] S.Katsanevas,[4] A.Longo,[8] J.Marteau,[9] M.Olivieri,[10] F.Paoletti,[2,4] P.Ruggi,[4] and M.C.Tringali [4]

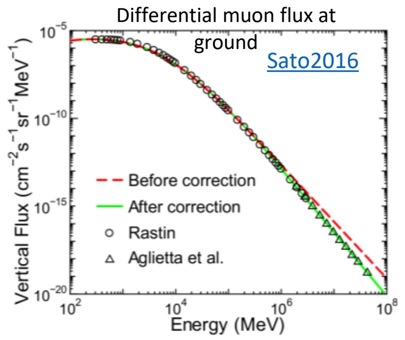
[1] Università di Pisa, Dipartimento di Fisica, I-56127 Pisa, Italy, [2] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy
[3] Universite Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France, [4] European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
[5] Università di Napoli "Federico II", I-80126 Napoli, Italy, [6] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, I-56125 Pisa, Italy
[7] Universiteit Antwerpen, Prinsstraat 13, 2000 Antwerpen, Belgium, [8] Istituto Nazionale di Fisica Nucleare, Sezione di Roma Tre, I-00146 Roma, Italy
[9] Institut de Physique Nucléaire de Lyon, Lyon, France, [10] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, I-40128 Bologna, Italy

EPS-HEP Conference 2021
Online conference, July 26-30, 2021
francesco.direnzo@pi.infn.it

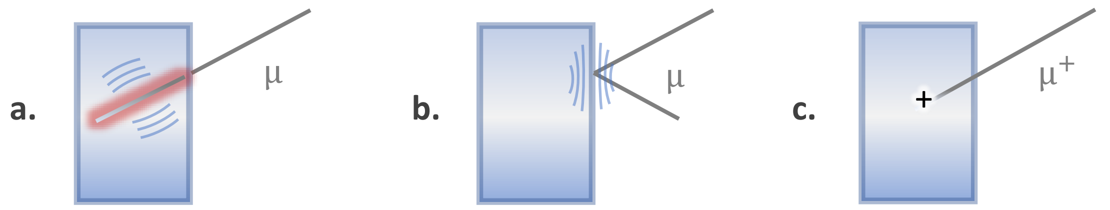
Cosmic rays and Gravitational Wave detectors

Gravitational Wave detectors are constantly passed through by cosmic ray particles:

- 2/3 are secondary muons, from the interactions of primaries with Earth atmosphere;
- Average flux: $1\ \mathrm{min}^{-1}\mathrm{cm}^{-2}$. Constant below ~ 1 GeV, power law with index ~ -3 above;
- Interaction with detector test masses [1,2,3]:
  - **a. Energy transfer**, mainly via ionization losses. Thermal gradient may excite vibrational modes;
  - **b. Momentum transfer**, relevant if in the direction of the laser beam;
  - **c. Charge deposition,** inducing spurious electrostatic coupling to the environment.



Additional continuous noise if the time interval between muon interactions is shorter than the decay time of their effect (depending on mirror quality factor for resonances); otherwise "burst-like" excess of noise (glitch).

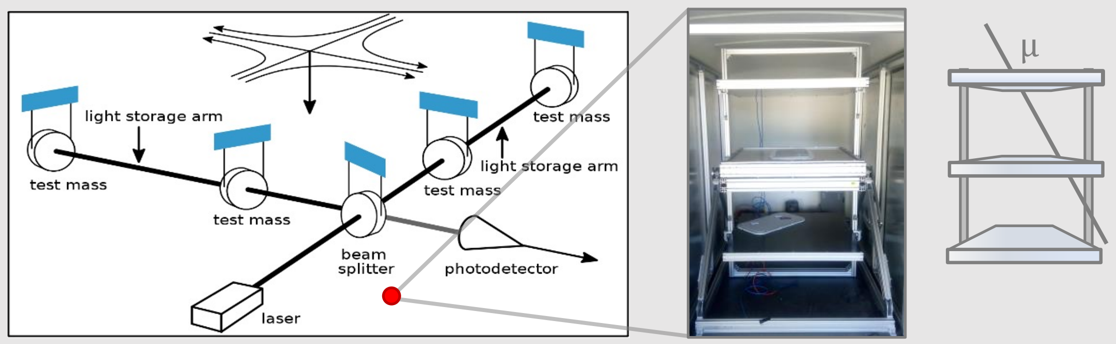


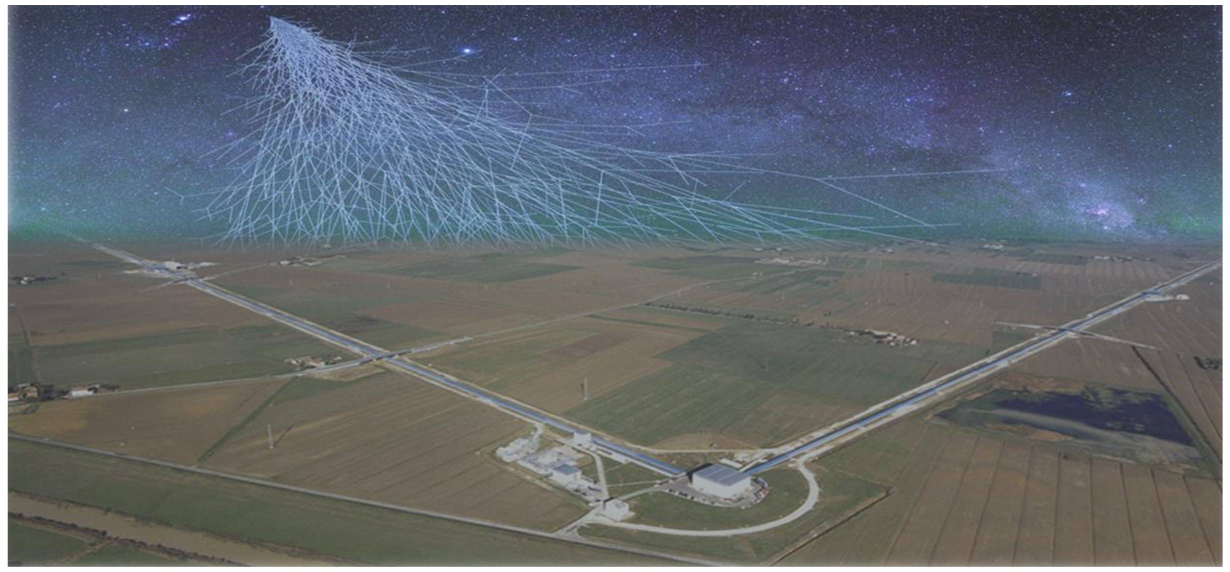
To evaluate this effect, we present here the first joint analysis of gravitational wave data and muon counts from a muon telescope near the Virgo Central Building.

The IPI2 muon telescope

Scintillator-based muon tracking detector [4], installed in close distance to the Virgo Beam Splitter mirror. Three layers of 80x80 cm^2, measuring double and triple coincidences with time accuracy of 10 ns.

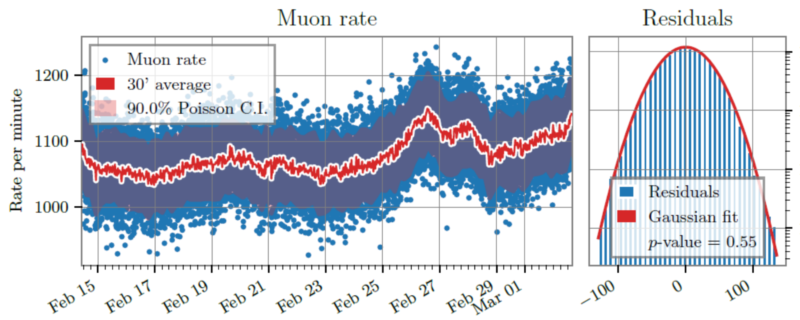
Feb 14 - Mar 2, 2020: joint data acquisition. **4 public alerts** of GW candidates [4].





Muon rate model

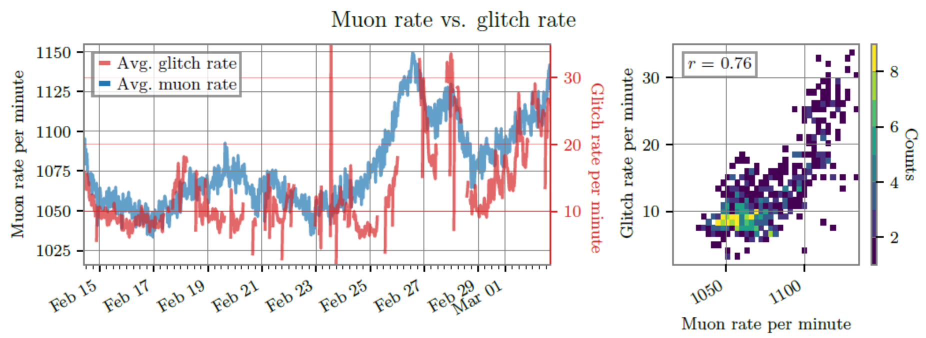
The muon rate is not constant with time; it can be modelled with a Poisson process with mean varying on time scales $\gtrsim$ 1 hour.



Correlation of muon and glitch rate

Glitches are transient excesses of noise in GW detectors, typically of duration $\lesssim$ 1 sec.

We measured the correlation between (average) muon rate and glitch rate.



There is indeed a high correlation: Pearson's $r \simeq 76\%$. This implies **no causation** though.

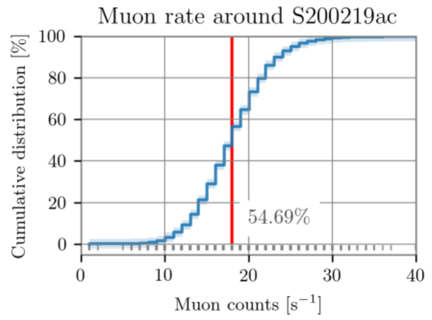
⇨ **Both are influenced by atmospheric conditions** [6].

E.g.: for muons, the less the pressure (the matter above the detector), the less the interaction of primaries and the atmosphere, hence their rate. Moreover, low pressure is often associated to bad weather conditions, which are a known cause of glitches in Virgo [7].

Muon rate around candidate events at the end of O3b

We tested whether the rate of muons in correspondence of candidate events at the end of O3b was larger than what was expected for that period.

1. Estimate the *empirical cumulative distribution* of the muon counts per second in one hour around the time of each candidate;
2. Obtain the p- value of the counts in the second around the event and compare it with a test significance α;
3. **Fisher's combined test** for all the candidate events.

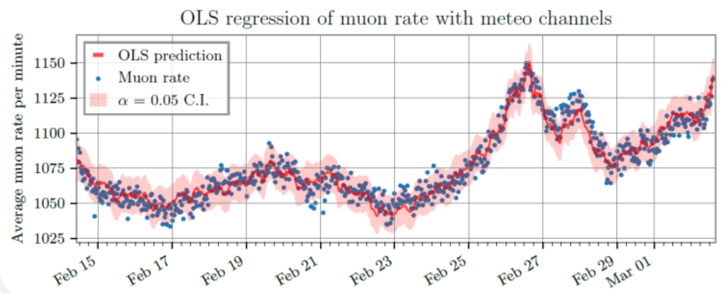


Example: S200219ac

Results: for NO candidate event, nor collectively, the rate was found larger than expected. This seems to exclude abnormal muon influences in correspondence with them.

Regression of muon rate with weather sensors

Many weather parameters, like atmospheric pressure and temperature, are known to influence the rate of muons [6]. We performed the Ordinary Least Square (OLS) regression of the measured rate with the signals from some sensors of the meteo station outside the Virgo Central Building.



The resulting R^2 coefficient, representing the explained variability, is **92%.**
The correlation of the residual and the glitch rate is now just **15%.**

Conclusions

We studied the possible effect of cosmic muons on the Virgo GW detector at the end of O3b. We have found no evidence of additional noise from them. The observed correlation with the glitch rate is an example of "correlation ⇏ causation". Indeed, the common cause of their variability are variations of atmospheric conditions.

[1] Giazotto A 1988 Physics Letters A 128 241-244
[2] Clay R, et al. 1997 Pub. of the Astro. Soc. of Australia **14** 195-199
[3] Braginsky V et al. 2006 Physics Letters A 350 1-4
[4] Lesparre N, et al. 2012 Geo. Instr., Methods and Data Systems **1** 33-42
[5] GraceDB O3 Public Alerts, https://gracedb.ligo.org/
[6] Maghrabi A, et al. 2018 Advances in Space Research **62** 3267-3277
[7] The Virgo Collab. 2021 The Virgo O3 run and the impact of the environment. To be submitted to CQG.