Measuring space-time fuzziness with high energy γ-ray detectors

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Abstract. There are several suggestions to probe space-time fuzziness (also known as space-time foam) due to the quantum mechanics nature of space-time. These effects are predicted to be very small, being related to the Planck length, so that the only hope to experimentally detect them is to look at particles propagating along cosmological distances. Some phenomenological approaches suggest that photons originating from point-like sources at cosmological distance experience path length fluctuation that could be detected. Also the direction of flight of such photons may be subject to a dispersion such that the image of a point-like source is blurred and detected as a disk. An experimentally accessible signature may be images of point-like sources larger that the size due to the Point Spread Function of the instrument. This additional broadening should increase with distance and photon energy. Some concrete examples that can be studied with the AGILE and FERMI-LAT γ-ray satellite experiments are discussed.

1 Theoretical framework

The theoretical framework used as reference is presented in [1] and references therein [2–6].
A highly simplified view is the following: a unified point of view of general relativity and quantum mechanics implies that at the the Planck scale, $\ell_P = \sqrt{\frac{\hbar G}{c^3}}$, space-time cannot be treated as smooth and structureless. It would rather appear like *quantum foam*, whose features are unknown both at the theoretical and experimental levels.
Even if a quantitative experimental prediction of the influence of this quantum foam is beyond the existing theoretical framework, some phenomenological approaches are attempting qualitative predictions that are potentially subject to experimental measurements.
Following [1, 7], we assume that the accuracy with which a length ℓ can be measured due to fluctuation of the space-time is

$$\delta\ell \sim N\ell^{(1-\alpha)}\ell_P^{\alpha} \qquad (1)$$

where $N \sim 1$ and $\alpha \leq 1$ is a parameter defining different space-time models. The models discussed in [1] suggest values $\alpha \in (\frac{1}{2}, \frac{2}{3})$ depending on the assumptions.
The goal would be to study variation of a fraction of wave length over astronomical scale. That seems

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an impossible task at first sight; it is so if we interpret Eq.1 in term of variation of time of arrival of the different photons

$$\delta t \sim \delta\ell/c \sim N t^{(1-\alpha)} t_P^{\alpha} \tag{2}$$

where $t_P = \sqrt{\frac{\hbar G}{c^5}} \sim 5.4 \times 10^{-44}$ s is the Planck time.
The best result in this line of thought is due to FERMI-LAT [8] that sets limits on the spread of time arrival due to quantum effect $\delta t \leq 1$ s for a propagation time $t \sim 7 \times 10^9$ y. This result sets a limit $\alpha > 0.3$ that is not very significant.
A much more powerful approach relies on the fact that different parts of the photon wave front traverse different parts of the space-time foam and experience different path length fluctuations. That results in different phases on the spherical front of the wave that, at the time of interaction with the detector, results in the direction perpendicular to the front (the photon direction) fluctuating randomly. That translates in an angular uncertainty

$$\delta\psi \sim N(\ell/\lambda)^{(1-\alpha)}(\ell_P/\lambda)^{\alpha} \tag{3}$$

This angular uncertainty can be measured at wave lengths from optical to radio and, at some extent, in the soft X-ray, using interference techniques (see [1] for discussion). Figure 1 shows the angular resolutions of several telescopes versus the wave length.
A complementary approach relies on making use of high energy γ-rays, that permit the measurement of the photon direction on an event by event basis. Existing detectors, based on conversion in $e^+ - e^-$ pairs provide resolutions $O(1^\circ)$ or less in the energy range $E_\gamma \geq 100$ MeV (see [9] for AGILE, [10] for FERMI-LAT).
Figure 1 reports approximate estimations of the angular resolutions for such experiments. It demonstrates that high energy γ-ray detectors offer the opportunity of exploring a region of the parameter space otherwise inaccessible.

2 Experimental search

The search of space-time foam could make use of AGILE and FERMI-LAT data looking at extra-galactic sources far away such that their transverse size is small in comparison to the detector resolution. Being the γ-ray detector resolutions much worse than those of optical telescopes, that is easier. The images from these sources should be carefully reconstructed and compared with the PSF of the detectors. The detector resolutions must therefore be carefully measured and simulated on ground and in flight.
If the measured sizes exceed the expected angular resolutions and if this trend increases (linearly) with the distance and with the energy, it would be a strong sign of quantum mechanical effects on the propagation of photons through space-time foam.
The dependency on the distance can be studied measuring the spot sizes for different extra-galactic sources at different distances while the dependency on the energy can be studied separately for each source as long as the spot sizes can be determined with sufficient statistics.
In Fig. 2 the angular resolution of the FERMI-LAT and AGILE detectors are shown versus the energy compared with the blurring due to space-time foam for $\alpha = 0.75$ and z = 1. The effect should be detectable above a few GeVs.

3 Conclusions

The quantum mechanics nature of space-time is possibly subject to experimental investigation studying the path length fluctuations due to the space-time foam. The smallness of these effects require

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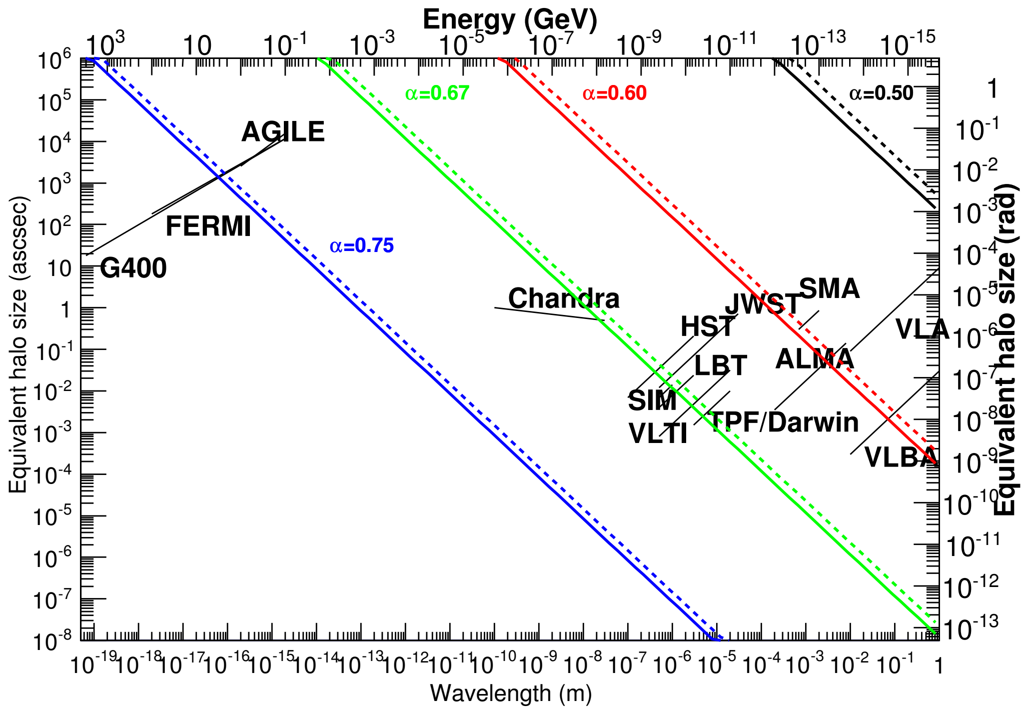

Figure 1. The detectability of various models of foamy space-time with existing and planned telescope/detectors. Diagonal tracks are shown for four models of foamy space-time, namely α= 0.5, 0.6, 2/3, 0.75 for z = 1 and 4 (respectively the lower and upper tracks for each model) and N = 1.9. Also shown are the observing ranges and resolution limits (i.e., PSF size) for a wide variety of telescopes/detectors, both current and planned.

measurements on astronomical scale. The size of a point-like source is expected to increase with distance and energy. That makes attractive high energy γ-ray detectors with good angular resolution to study so far unexplored regions of the parameter spaces. An approximated estimation of the capability of investigating space-time foam with AGILE and FERMI-LAT detectors is provided.

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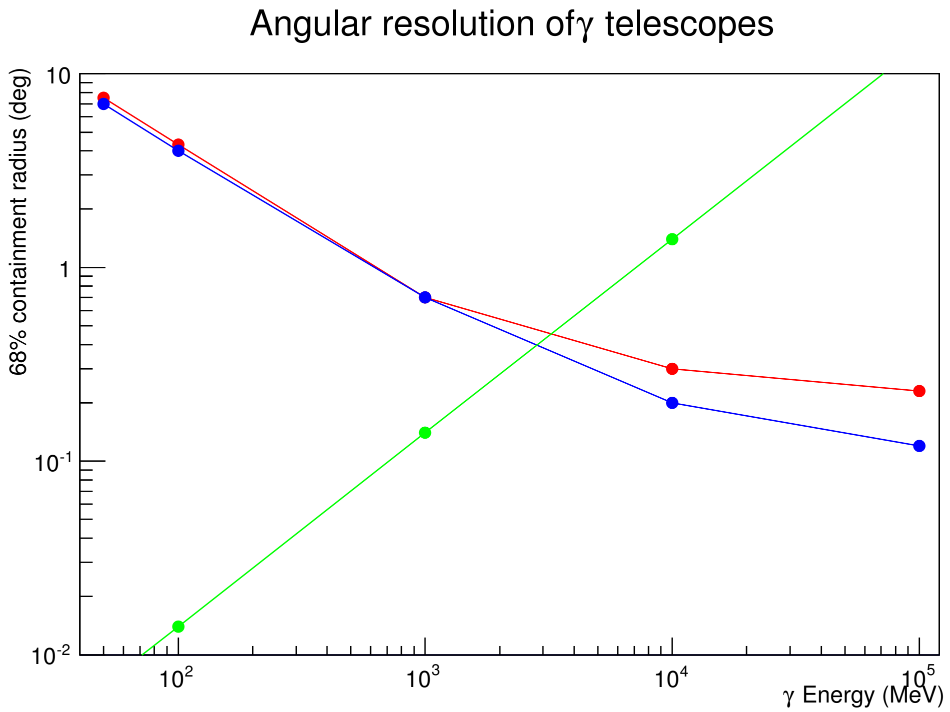

Figure 2. Angular resolution of the FERMI-LAT detector (blue) and of AGILE-GRID detector (red) and the blurring of the source due to the foam for $\alpha = 0.75$ and z = 1.

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