Voyage 2050 - long term plan in the ESA science programme

GrailQuest: hunting for Atoms of Space and Time hidden in the wrinkle of Space–Time

A swarm of nano/micro/small–satellites to probe the ultimate structure of Space-Time and an all-sky monitor to study high energy astrophysics phenomena

Prof. Luciano Burderi

Dipartimento di Fisica, Università degli Studi di Cagliari

SP Monserrato-Sestu km 0.7, 09042 Monserrato, Italy

Tel.: +39-070-6754854

Fax: +39-070-510171

E-mail: burderi@dsf.unica.it

Author list:

Prof. Tiziana Di Salvo
Università degli Studi di Palermo, Dipartimento di Fisica e Chimica, via Archirafi 36, 90123 Palermo, Italy

Dr. Andrea Sanna
Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu km 0.7, 09042 Monserrato, Italy

Prof. Filippo Frontera
Department of Physics and Earth Science, University of Ferrara, via Saragat 1, I-44122, Ferrara, Italy

Prof. Silvia Zane
Mullard Space Science Laboratory, University College London. Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK

Dr. Fabrizio Fiore
INAF-OATs Via G.B. Tiepolo, 11, I-34143 Trieste

Dr. Enrico Costa
INAF-IAPS,Via del Fosso del Cavaliere 100, I-00133 Rome, Italy

Prof. Giovanni Amelino-Camelia
Dipartimento di Fisica Ettore Pancini, Università di Napoli "Federico II", and INFN, Sezione di Napoli, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy

Prof. Mariafelicia De Laurentis
Dipartimento di Fisica E. Pancini, Universit di Napoli "Federico II", Compl. Univ. di Monte S. Angelo, Edificio G, Via Cinthia, I-80126, Napoli, Italy

Prof. Andrea Santangelo
University of Tubingen-IAAT, Sand 1, D-72076 Tbingen, Germany

Dr. Gabriele Ghisellini
INAF - Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807, Merate, Italy

Dr. Marco Feroci
INAF-IAPS,Via del Fosso del Cavaliere 100, I-00133 Rome, Italy

Dr. Cluadio Labanti
INAF-OAS Bologna, Via Gobetti 101, I-40129 Bologna, Italy

Dr. Massimo Della Valle
Capodimonte Observatory, INAF-Naples , Salita Moiariello 16, 80131-Naples, Italy

Prof. Salvatore Capozziello
Dipartimento di Fisica, Universit di Napoli "Federico II", Complesso Universitario di Monte SantAngelo, Via Cinthia, 21, I-80126 Napoli, Italy

Prof. Dhiren Kataria
Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Surrey, RH5 6NT, UK

Prof. Paolo De Bernardis
Physics Department, Universit di Roma Sapienza, Ple. Aldo Moro 2, 00185, Rome, Italy

Dr. Lorenzo Amati
INAFOsservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, I-40129 Bologna, Italy

Prof. Eugenio Coccia
INFN, Gran Sasso Science Institute, I-67100 L'Aquila, Italy

Prof. Francesca Vidotto
Department of Applied Mathematics, University of Western Ontario, London, ON N6A 5B7, Canada

Prof. Heino Falcke
Department of Astrophysics/IMAPP, Radboud University, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands

Prof. Luciano Rezzolla
Institut für Theoretische Physik, Goethe Universita t Frankfurt am Main, Germany

Prof. Thibault Damour
Institut des Hautes Etudes Scientifiques, 91440 Bures-sur-Yvette, France

Prof. Carlo Rovelli
CPT, Aix-Marseille Universitè, Universitè de Toulon, CNRS, Marseille, Francey

Prof. Monica Colpi
Dipartimento di Fisica "G. Occhialini", Universitá degli Studi Milano - Bicocca, Piazza della Scienza 3, Milano, Italy

Prof. Tsvi Piran
Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel

Prof. Kevin C. Hurley
University of California, Berkeley, Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94720-7450, USA

Prof. Marica Branchesi
INFN, Gran Sasso Science Institute, I-67100 L'Aquila, Italy

Dr. Barbara Negri
Italian Space Agency - ASI, Via del Politecnico, 00133 Roma, Italy

Prof. Alessandro Riggio
Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu km 0.7, 09042 Monserrato, Italy

Prof. Rosario Iaria
Università degli Studi di Palermo, Dipartimento di Fisica e Chimica, via Archirafi 36, 90123 Palermo, Italy

Abstract *Context:* The planning of the ESA Science Programme Voyage 2050 relies on the public discussion of open scientific questions, of paramount importance for an advance of our understanding of the Laws of Nature, that can be addressed by a scientific space mission within the Voyage 2050 planning cycle, covering the period 2035 to 2050. As a part of the ESA Science Programme Voyage 2050, a new concept of high–energy mission named ***GrailQuest*** (Gamma Ray Astronomy International Laboratory for QUantum Exploration of Space–Time) is investigated.
Aims: The three main scientific objectives that ***GrailQuest*** wants to pursue are: *i)* to probe space-time structure down to the Planck-scale by measuring the delays between photons of different energies in the prompt emission of Gamma Ray Bursts; *ii)* to localise Gamma Ray Bursts prompt emission with an accuracy of few arc-seconds. This capability is particularly relevant in light of the recent discovery that fast high energy transients are the electromagnetic counterparts of at least some gravitational wave events recently discovered by Advanced LIGO/Virgo; *iii)* to fully exploit timing capabilities down to micro-seconds or below at X/Gamma-ray energies, by means of an adequate combination of temporal resolution and collecting area. This will allow to effectively investigate, for the first time, the micro-second structure of Gamma Ray Bursts and other transient phenomena in the X/Gamma-ray energy window.
Methods: ***GrailQuest*** is a mission concept based on a constellation of nano/micro/small–satellites in low (or near) Earth orbits, hosting fast scintillators to probe the X/gamma–ray emission of bright high–energy transients. The main features of this proposed experiment are: temporal resolution $\leq$ 100 nanosecond, huge overall collecting area, $\sim$ 100 square meters, very broad energy band coverage, $\sim$ 1 keV–10 MeV. ***GrailQuest*** is conceived as a all-sky monitor for fast localisation of high signal-to-noise ratio transients in the broad keV–MeV band by robust temporal triangulation techniques with accuracies at micro–second level, and baselines of several thousand of km. These features allow unprecedented localisation capabilities, in the keV–MeV band, of few arc-seconds or below, depending on the temporal structure of the transient event. Despite the huge collecting area, hundred(s) of square meters, and the consequent number of nano/micro/small–satellites utilised (from thousand(s) down to ten(s), respectively), orbiting all–around Earth in uniformly distributed orbits, the technical capabilities and subsequent design of each nano/micro/small–satellite of the constellation are extremely simple and robust. This allow for mass–production of the base unit of this experiment, namely a nano/micro/small–satellite equipped with a non–collimated (half–sky field of view) detector (effective area in the range hundred–thousand(s) square centimetres). The detector consist in segmented scintillator crystals coupled with Silicon Drift Detectors with broad energy band coverage (keV–MeV range) and excellent temporal resolution ($\leq$ 100 nano–seconds). Very limited (if any) pointing capabilities are required. We forecast that mass production of this simple unit allow a huge reduction of costs. Moreover, the large number of nano/micro/small–satellites involved in the ***GrailQuest*** constellation make this experiment very robust against failure of one or more of its units. Finally we want to observe that ***GrailQuest*** is a modular experiment in which, for each of the detected photons, only three information are essential, namely accurate time–of–arrival of each photon (down to 100 nanosecond, or below), moderate energy resolution (few percent), and detector position (within few tens of meters). This open the compelling possibility to

combine data from different kind of detectors (on board of different kind of satellites belonging, in principle, to different constellations) to achieve the scientific objectives of the ***GrailQuest*** project, making ***GrailQuest*** the first example of modular space–based astronomy.

In past years, modular astronomy (which exploits, by combining them, the observational abilities of different detectors), proved to be very effective in opening up new possibilities for astronomical investigation, just think of the Very Large Baseline Interferometry, an astronomical interferometry in the Radio Band, involving more that thirty radio telescopes all over the world, the Cluster II mission, a space mission of the European Space Agency, with NASA participation, composed of a constellation of four satellites, to study the Earth's magnetosphere, launched in 2000 and recently extended to the end of 2020. In the near future, a constellation of three satellites in formation is planned for the LISA mission, to reveal gravitational waves from space (ref).

Very recently, two extremely successful experiments, of paramount importance for fundamental physics, involve the combined use of several ground–based detectors. One is the LIGO/Virgo Collaboration (involving the two US–based LIGO and the European Virgo facilities) that allowed for the first detection and localisation of gravitational waves. In one case, temporal triangulation techniques, conceptually similar to those proposed for ***GrailQuest*** constellation and described in this work, effectively constrained the position of the event in the sky, allowing for fast subsequent localisation, in the electromagnetic window, of a double Neutron Star merging event. The other is the Event Horizon Telescope (which provides for the combined use of 8 radio/micro–wave observatories spread all over the world) that allowed to obtain the first image of the event horizon around a black hole. We consider these compelling results as the proof that modular astronomy, that benefits from the combined use of distributed detectors (to increase the overall detecting area and allow for unprecedented spatial resolution, in case of the Event Horizon Telescope and the ***GrailQuest*** project), is the new frontier of cutting-edge experimental astronomical science that is performed by exploiting the combination of a large number of detectors distributed all over the Earth surface. The ***GrailQuest*** project is a space-based version of this epochal revolution.
Results: In the following, with accurate Monte-Carlo simulations based on true data obtained from the scintillators of the Gamma Burst Monitor on board of the *Fermi* Satellite, we show that the ***GrailQuest*** constellation is able to achieve the ambitious objectives outlined above, within the budget of a European Space Agency M-class mission.

Keywords constellation of satellites · quantum gravity · γ–ray bursts · γ–ray sources · all–sky monitor

1 Introduction: Was Zeno right? – A brief summary of Quantum Gravity and the in-depth structure of Space and Time

According to Plato, the great Greek philosopher, around 450 BC Zeno and Parmenides, disciple and founder of the Eleatic School, visited Athens [**?**] and encountered Socrates, who was in his twenties. In that occasion Zeno discussed his world famous paradoxes, "four arguments all immeasurably subtle and profound", as claimed by Bertrand Russell in 1903 [**?**].

In essence, Zeno's line of reasoning was probably one of the first time in which a powerful logical method, the so called *reductio ad absurdum*, was applied in the attempt to demonstrate the logical impossibility of the endless division of space and time in the physical world.

Indeed, in his most famous paradox, known as *Achilles and the tortoise*, Zeno states that if one admits as true the endless divisibility of space, in a race the quickest runner can never overtake the slowest, which is patently absurd, thus demonstrating that the original assumption of infinite divisibility of space is false.

The argument is as follows: suppose that the tortoise starts ahead of Achilles, in order to overtake the tortoise, in the first place Achilles have to reach it. In the time that Achilles takes to reach the original position of the tortoise, the tortoise has moved forward by some space, and therefore, after that time, we are left with the tortoise ahead of Achilles (although by a shorter distance). In the second step the situation is the same, and so on, demonstrating that Achilles cannot even reach the tortoise.

Despite of the sophistication of logical reasoning, today we know that the error in the reasoning of Zeno was the implicit assumption that an infinite number of tasks (the infinite steps that Achilles have to cover to reach the tortoise) cannot be accomplished in a finite time interval, which is not true if the infinite number of time intervals spent to accomplish all the tasks constitute a sequence whose sum is a convergent mathematical series.

However the line of reasoning reported above exerts a certain fascination on our brains, which reluctantly accept the fact that, in a finite segment, an infinite number of separate points may exist.

The mighty intellectual edifice of Mechanics developed by Newton has its foundations on the convergence of mathematical series which serves to define the concept of derivative (fluxions, to use the name originally proposed by Newton for them) which are ubiquitous in physics. Classical Physics has this idea rooted in the postulate (often implicitly accepted) that the physical quantities can be conveniently represented and gauged by real numbers.

At the beginning of the last century, the development of Quantum Mechanics has revolutionised this secular perspective. Under the astonished eyes of experimental physicists, Nature acted incomprehensibly when investigated at microscopic scales. It was the genius of Einstein who fully intuited the immense intellectual leap that our minds were obliged to accomplish to understand the physical world. In a seminal paper of 1905 [**?**] the yet unknown clerk of Patent Office in Bern shattered forever the world of Physics by definitely proving, with an elegant explanation of the Brownian motion, that matter is not a continuous substance but it is rather constituted by lumps of mass that were dubbed Atoms by the English physicist Dalton in 1803. The idea that matter is build up by adding together minuscule indivisible particles is very old, sprouted again from a surprising insight of Greek philosophers. The word itself, *Atom*, that literally means indivisible, was coined by the ancient Greek philosophers Leucippus and Democritus, master and disciple, around 450 BC, in the same period in which Zeno was questioning the endless divisibility of space and time!

In the same year Einstein completed the revolution in the physics of the infinitely small by publishing another milestone of human thought [**?**] in which he argued that light is composed of minuscule lumps of energy that were dubbed photons by the American physicist Troland in 1916.

The idea that the fundamental "bricks" of matter were indivisible particles with universal properties characterising them like mass and electrical charge progressively settled in the physics world thanks to the spectacular discoveries of distinguished experimental physicists. In a quick overview in this hall of fame we have to mention (without claiming to perform a comprehensive review) Thomson, who discovered the electron in 1896, Rutherford, who discovered in 1909 that the positive charge of the Atom was concentrated in a small central nucleus, and discovered the proton in 1919, Chadwick, who discovered the neutron in 1932, Reines, who discovered the neutrino in 1956, following Pauli that in 1930 postulated his existence, Gell-Man and Zweig, who proposed the quark existence in 1964, Glashow, Salam and Weinberg, who proposed the existence of the W and Z gauge bosons in 1961, discovered by Rubbia and van der Meer in 1983, Higgs, Brout, Englert, Guralnik, Hagen, and Kibble who postulated the existence of the Higgs boson in 1964, discovered at the CERN laboratories in 2011 by teams leaded by Giannotti and Tonelli.

Summarising, by the beginning of the third millennium physicists have developed and experimentally verified a quite coherent and theoretically robust picture of the world at small scale that they dubbed with the rather unprepossessing expression Standard Model of Particle Physics, where the central role of the indivisible fundamental bricks that build up the world is alluded in the word "Particle". After 2,500 years, the formidable intuition of Greek philosopher has been confirmed: Democritus was right!

But what about Zeno? The mighty and flawless edifice of Calculus, developed by giants of human thought like Archimedes, Newton and Leibniz, and the elegant and audacious construction of Cantor, who demonstrated that even the endless divisibility of fractional numbers was not powerful enough to describe the immense density of real numbers – and the name "real", used by mathematicians to describe this type of numbers allude to the idea that they are essential to adequately gauge the objects of the physical world – seemed to have finally relegated the sophisticated logical arguments of the philosopher from Elea in the endless graveyard of misconceptions.

However, the inverse square law, the universal law discovered by Newton for gravitation, that was successfully extended by Coulomb to the realm of electricity, and effectively generalised by Yukawa in 1930 for a massive scalar field, contained the seed that would resurrected the old proposal of Zeno in the vivacious crowd of modern scientific thought.

The crucial point is that the combination of the indivisible discreteness of some fundamental properties, like mass or charge – that allowed to develop the very concept of *elementary particle*, cornerstone of the Quantum Field Theory, the mathematical formulation behind the Standard Model – is at odds with the generalised Yukawa potential widely used at least in the lowest order formulation of the interaction of a pair of fermions in Quantum Field Theory. The crucial role of the Yukawa potential in the development of Quantum Field Theory is evident when using Feynman Diagrams (firstly presented by Feynman at the Pocono Conference in 1948) to represent the interaction of a pair of fermions. In simple words, the Yukawa potential is divergent with $r \to 0$ and therefore in contrast with the existence of point–like particles.

In our opinion the essence of the conflict between the "granular" world of Quantum Particles (excited states of the fields) and the continuum manifold that is used to represent the Minkowski Space–Time over which the fields are represented has to be ascribed to the difficulty to insert, in the same logical scheme, the indivisible nature of elementary particles and the infinite divisibility of Space–Time over which Quantum Fields are defined.

To fully grasp this important aspect we must quickly summarise the stages through which the Fields, and the Space–Time on which they are defined, have become "actors" of the stage of physics playing an active supporting role, if not dominant, with respect to that of the Particles just discussed.

Together with Quantum Mechanics, General Relativity radically changed our understanding of Space and Time. According to the great philosopher Immanuel Kant, both these quantities are necessary a priori representations that underlies all other intuitions. Indeed, in his Critique of Pure Reason, Kant says: *"Now what are space and time? Are they actual entities? Are they only determinations or also relations of things, but still such as would belong to them even if they were not intuited? Or are they such that they belong only to the form of intuition, and therefore to the subjective constitution of our mind, without which these predicates could not be ascribed to any things at all?"* These fundamental issues, raised by the German philosopher, outline the sense of the immense epistemological revolution bravely fought by the audacious physicists of the nineteenth and twentieth centuries. Indeed, the seminal work of Maxwell and Einstein, just to mention the most prominent actors, has revealed that (electromagnetic) fields, space, and time, are not a priori categories of human thought, but physical objects, susceptible to experimental investigation. Their physical properties would have turned out, in the years to come, to be very different from those that our intuition could suggest to us. The initial albeit crucial point of this investigation can be identified in the Maxwell's proposal of adding the "displacement current" term to one of the electromagnetic laws, already proposed by Coulomb, Faraday, and Ampere. The addition of this term determines a complete feedback of the electric and magnetic fields, in the absence of charges or currents, and, therefore, determines a physical reality for electromagnetic fields, that is independent of the presence of the charges, and currents that generated them. Fields are no longer convenient mathematical tools to compute the forces acting on particles, but constitute physical objects endowed with their own independent existence! From the wave equation implied by these new laws, Maxwell obtained the constant that express the speed of propagation of these fields with respect to the vacuum. The genius of Einstein understood that the combination of the constancy of the speed of light with the principle of relativity, proposed in 1632 by Galilei in his Dialogue on the two greatest systems of the world, was to unhinge our Newtonian conception of absolute Space and Time, independent of each other. This led him to the extraordinary conception of a deformable Space–Time, subject to the Lorentzian invariance constraint. However, the price to pay for this epistemological revolution, was the acknowledge that, operationally – in the Bridgmanian sense of the term [**?**] – it is impossible to synchronise the clocks, and/or to define the distances, in an instantaneous way or, in any case, faster than imposed by the speed of light in vacuum. This led Einstein to the intuition that also Gravity (the only other field known at the time) should propagate through a wave equation, at the same speed determined by Maxwell's equations. Indeed, in their weak field limit, the field equations of General Relativity resemble Maxwell's equations, in the presence of the so–called Gravitomagnetic Field, a field generated by matter currents, in perfect analogy with the Magnetic Field generated by charge currents. Again, through the complete feedback determined by the equations relating temporal and space variations of Gravitational and Gravitomagnetic Fields, a wave equation was capable to describe the propagation of Gravitational Fields through the vacuum, at the very same speed of the Electromagnetic Fields! The overall coherence of this epistemological revolution, imposed by Special Relativity, was guaranteed by acknowledging that Space–Time was a physical entity, subject to oscillations in its texture, and not a couple of philosophical a priori categories, as discussed by Kant.

In summary, in modern physics, space and time have progressively changed their role. From mere passive containers of events (in line with the Kantian idea of mental categories) to physical quantities that, combined in the unique hyperbolic geometry implied by the constancy of the speed of electromagnetic waves, are able to deform under the gravitational action of the fields and of the particles. Even with due attention, the Space–Time of General Relativity can be considered, for all intents and purposes, a field with its associated quantum particles (excited states of the fields): the gravitons. In this unifying picture, macroscopic coherent states of a huge number of gravitons are the gravitational waves, recently detected by the LIGO and Virgo observatories.

The tension between the granularity of quantum particles and the continuity of fields (defined by real variables) has been alleviated by renormalisation techniques fully applicable in Gauge Theories of Quantum Field, as shown by Gerard 't Hooft for all fundamental forces except gravity. Renormalisation techniques have proved to be extremely effective in solving the problem of the infinities that arise when, in Quantum Field Theory, we try to combine point–like particles with fields diverging for $r \to 0$. This approach is based on the existence of "charges" of opposite sign capable of producing, in the calculations of the associated physical quantities, terms of opposite sign which, although diverging, cancel each other out, when treated with sufficient care.

Despite their success, renormalisation techniques seem to be inadequate when gravity comes into play. Because of the mass-energy equivalence predicted by Special Relativity, the natural generalisation of the source "charge" of the gravitational field is the entire energy density and not only that associated with the rest mass of the particles. This implies that any type of field attempting to prevent gravitational collapse acts, through the energy density (usually positive) associated with it, as a further source of gravitational field, preventing, in fact, an effective renormalisation.

This last feedback is difficult to eliminate within the framework just described and makes it clear, in our opinion, the conceptual stalemate that prevents, at the present time, to unify the two most revolutionary physical theories of the twentieth century: General Relativity and Quantum Mechanics.

To overcome this formidable impasse, theoretical physics is today exploring more radical approaches that require a new conceptual revolution, a paradigm shift, to use Kuhn's words.

Here we just mention two opposite approaches that tackle the problem of the irresolvable dichotomy of particles and fields from somewhat opposite perspectives. String Theories (see *e.g.* Smolin for reviews and later criticism on this approach) that eliminate the point–like nature of the particles by assigning to each of them a (mono)–dimensional extension: the string. Loop Quantum Gravity (see *e.g.* Rovelli for reviews) that question the smoothness of Space–Time quantising it into discrete energy levels like those observed in classical quantum–mechanical systems to form a complex pregeometric structure (to use the words of Wheeler) dubbed Spin–Network.

In both proposed theories (although with different and somewhat opposite theoretical approaches) emerge a minimal length for physical space (and time). Atoms of Space and Time – to use an efficacious and vivid expression used by Smolin in 2006 – are a necessary consequences of this definitive quantisation of Space–Time.

However the spatial (and temporal) length–scales associated to this quantisation, are minuscule, in terms of standard units, as already suggested in a pioneering and visionary work of Planck in 1899 [**?**]: $\ell_{\rm P} \sim \sqrt{\hbar G/c^3} \sim 10^{-33}$ cm and $t_{\rm P} \sim \sqrt{\hbar G/c^5} \sim 10^{-43}$ s for the Planck length and time, respectively. For comparison, the shortest distance (Compton wavelength) directly measured up to date at Large Hadron Collider at CERN are $\sim 10^{-20}$ cm (for colliding energies of few 10^{12} eV). The shortest time intervals ever measured are just above attoseconds $\sim 10^{-18}$ s (see *e.g.* Hentschel, Nature 2001). Experimentally, at present moment, we are more than ten orders of magnitude above the theoretical limit we would like to probe to effectively constrain our theoretical speculations!

For a quick (and not exhaustive) overview of the variety of theoretical approaches exploring the possibility of the existence of fundamental limits in the ability to measure (and therefore to define, in the Bridgmanian sense) intervals of arbitrarily small space and time, we use, almost textually, what is reported in a recent work by some of us [**?**] and the references therein reported.

Several thought experiments have been proposed to explore fundamental limits in the measurement process of time and space intervals (see *e.g.* [**?**] for an updated and complete review). In particular Mead [**?**] "postulate the existence of a fundamental length" (to use his own words) and discussed the possibility that this length is the Planck length, $\ell_{\rm min} \sim \sqrt{G\hbar/c^3} = \ell_{\rm P}$, which resulted in limitations in the measure of arbitrarily short time intervals originating relations similar to the Space–Time Uncertainty relation proposed in [**?**]. Moreover in a subsequent paper [**?**], Mead discussed an in principle observable spectral broadening, consequence of the postulate the existence of a fundamental length of the order of Planck Length. More recently, in the framework of String Theory a space-time uncertainty relation has been proposed which has the same structure of the uncertainty relation discussed in this paper ([**?**], [**?**], see *e.g.* [**?**] for a discussion of the possible role of a space-time uncertainty relation in String Theory). The relation proposed in String Theory constraints the product of the uncertainties in the time interval $c\Delta T$ and the spatial length ΔX_l to be larger than the square of the string length ℓ_S, which is a parameter of the String Theory. However, to use the same words of Yoneya [**?**], this relation is "speculative and hence rather vague yet". Indeed, in the context of Field Theories, uncertainty relations between space and time coordinates similar to that proposed here have been discussed as an ansatz for the limitation arising in combining Heisenberg's uncertainty principle with Einstein's theory of gravity [**?**]. In 1995 Garay [**?**] postulated and discussed, in the context of Quantum Gravity, the existence of a minimum length of the order of the Planck Length, but followed the idea that this limitation may have a similar meaning to the speed limit defined by the speed of light in Special Relativity, in line with what was already pointed out previously (see *e.g.* [?] and references therein). In the framework of the so called Quantum Loop Gravity (see *e.g.* [?], [?] and [?] for a review) a minimal length appears characteristically in the form of a minimal surface area ([?], [?]): indeed the area operator is quantized in units of $\ell_{\rm P}^2$ [?]. It has been sometimes argued that this minimal length might conflict with Lorentz invariance, because a boosted observer could see the minimal length further Lorentz contracted,

Indeed, some of the proposed theories allow for this Lorentz Invariance Violation (LIV, hereinafter) at some small scale (see e.g. [?], [?], [?] for reviews). This unpleasant feature however is not present in other theories *e.g.* in Loop Quantum Gravity since the minimal area does not appear as a fixed property of geometry, but rather as the minimal (nonzero) eigenvalue of a quantum observable that has the same minimal area $\ell_{\rm P}^2$ for all the boosted observers. What changes continuously in the boost transformation is the probability distribution of seeing one or the other of the discrete eigenvalues of the area (see *e.g.* [?]).

Despite the lack of experimental data against which predictions of different theoretical models of Quantum Gravity can be tested, several rather general consequences can be deduced from the different schemes proposed for the structure of Space–Time. In particular, from some classes of theories, it is evident that the presence of a granular structure of space in which electromagnetic waves (*i.e.* photons, from the quantum point of view) propagate, determines the emergence of a dispersion law for light in vacuum in perfect analogy with what happens for the propagation of photons in a crystal lattice.

The energy scale at which dispersion effects become manifest can be easily computed *e.g.* equating the photon energy, $E = h\nu$, to $\nu \sim 1/t_{\rm P}$ which provides the Planck Energy $E_{\rm P} \sim \sqrt{\hbar c^5/G} \sim 10^{28}$ eV, a huge energy for the particle's world, corresponding to the mass of a paramecium ($M_{\rm P} \sim 0.02$ mg). Again, frustratingly, this energy scale is well beyond any possibility of direct investigation with any kind of colliders in the near and next future. It is worth to note that, in the simplest models, at lowest order, the dispersion law for photons speed $v_{\rm phot}$ is dominated by the linear term: $v_{\rm phot}/c \propto h\nu/\sqrt{\hbar c^5/G}$, with constant of proportionality $\xi \sim 1$.

In our opinion, this unprecedented situation, in which the scale of the expected experimental phenomena is very far from the current possibilities of experimental verification, is hampering any significant progress in our understanding of the ultimate structure of the world. Physics is, after all, an experimental discipline in which continuous comparison with experimental data is essential even to draw unexpected cues from which to develop new theories. This was the case for the development of Relativity and Quantum Mechanics in which bold physicists and epistemologists had to develop new logical models to account for unexpected experimental results that were unimaginable for the classical conception of nature developed by Greek philosophers. Indeed, the fatal blow to the classical conception of physics developed up to Newton and Maxwell, was given by the experimental impossibility to determine the speed of Earth with respect to the *Cosmic Aether* (the medium in which electromagnetic waves propagate) as firmly established by the null result of the Michelson and Morley experiment [?].

Indeed, in the context of Quantum Gravity, we are witnessing a flourishing of countless elegant mathematically daring theories, which testify the lively interest of brilliant minds towards problems of undoubted physical and epistemological relevance that sadly, at the moment, lack the invigorating and vitalising confrontation with constraining experimental data.

For comparison, the recent discoveries of the existence of the Higgs Boson, which confirmed, strengthening it, the Standard Model of Particle Physics, the detection of Gravitational Waves, which confirmed what was predicted a century ago by General Relativity and the recent spectacular image, obtained interferometrically, of the event horizon around a supermassive black hole, which confirmed the formation of trapped surfaces in the Space–Time fabric, have vitalised these very interesting fields of research by opening the doors to new disciplines such as Multi–Messenger Astronomy (ref.).

However, we believe that a *giant leap* is now possible also in the difficult experimental task of investigating the texture of Space on the minuscule scales provided by Quantum Gravity. In the following we will show how the technological progress in Space Sciences and the enormous reduction in the costs necessary to bring detectors into space, can allow us to conceive an ambitious experiment to verify, for the first time, directly, some of the most important consequences of the existence of a discrete structure for the texture of the space. To put it suggestively, twenty-five centuries after the meeting of the Eleatic philosophers with Socrates in Athens, we are able to investigate the problem raised by Zeno in a quantitative way.

In particular, in line with the suggestions outlined in some pioneering work in the field of experimental investigation of Quantum Gravity [**?**], we propose a ambitious albeit robust experiment to directly search for tiny delays in arrival times of photons of different energies determined by the dispersion law for photons discussed above. Given the hugeness of the Planck Energy, we expect, as it will be shown in § **??**, delays $\sim$ few μs for Gamma Ray Burst photons that travelled for more that ten billion years!

These last numbers show, in themselves, the difficulty and ambitiousness of the proposed experiment. We would like to emphasize here, however, that even a null result, that is a solid proof of the non-existence of a linear effect in the law of photonic dispersion for energies normalised to the Planck scale, would constitute a result of capital importance for the progress of fundamental physics. After all, the Michelson and Morley experiment [**?**], decisive for the acceptance, in an understandably conservative scientific community, of the revolutionary ideas on space and time implied by the Theory of Relativity, provided a null result with respect to the possibility of identifying motion with respect to the *Cosmic Aether*!

Indeed we think that first order dispersion relation has not been investigated with the due accuracy at present. In particular, our major concerns are possible intrinsic delays (characterizing the emission process) overprinted over the tiny quantum delays. This is particularly evident in caveat discussed in Abdo et al. 2009 Nature on GRB090510 and, more recently, in the paper by Wei and Wu, ApJ, 2017 and John Ellis et al. 2019 PhysRevD who set a robust constrain on LIV using Fermi-LAT GRB data of few 10^{17} GeV. Further indications of no LIV violations come from HESS collaboration, in particular from spectral analysis of the blazar Mrk 501 (Lorentz and Burn, 2016), although also in this case a spectral shape and (reasonable) hypothesis on the emission process are assumed. In our opinion, given the importance of the question, a direct robust measure cannot be based on an analysis of a single object and a robust statistical analysis of a rich sample of data is required in which the natural direct timescale of the LIV induced delays in the gamma-ray band (one microsecond) is thoroughly searched. None of the experiments discussed above had the right combination of time resolution and collecting area to effectively scrutinise this regime.

2 *GrailQuest* and its scientific case in a nutshell

The coalescence of compact objects, neutron stars (NS) and black holes (BH), and the sudden collapse to form a BH, hold the keys to investigate both the physics of matter under extreme conditions, and the ultimate structure of space-time. At least three main discoveries in the past 20 years prompted such studies.

First, the arcmin localisation of GRBs (sudden and unpredictable bursts of hard-X/soft-γ rays with huge flux up to 10^{-2} ergs/cm^2/s), enabled for the first time by the instruments on board BeppoSAX, allowed to discover their X-ray and optical afterglows (Costa et al. 1997, van Paradijs et al. 1997), which led to the identification of their host galaxies (Metzger et al. 1997). This definitely confirmed the extragalactic nature of GRBs and assessed their energy budget, thus establishing that they are the most powerful accelerators in the Universe. Even accounting for strong beaming, the energy released can indeed attain 10^{52-53} erg, a large fraction of the Sun rest mass energy, in $\approx 0.1 - 100$ seconds, produced by bulk acceleration of plasmoids to $\Gamma \approx 100 - 1000$ (e.g. Bloom et al. 2009, Abdo et al. 2009).

Second, the large area telescope (LAT) on board the Fermi satellite established GRBs as GeV sources (REF), confirming their capability to accelerate matter up to $\Gamma \approx 100 - 1000$ and allowing us to apply for the first time the program envisioned by Amelino-Camelia and collaborators at the end of the 90' (Amelino-Camelia 1998) to investigate quantum space-time using cosmic sources.

Third, the recent discovery of the gravitational signal from several BH-BH mergers by Advanced Ligo and Virgo (Abbott et al. 2016, 2017a, 2017b), opened a brand new window to investigate the astrophysics of compact object as well as fundamental physics. The gravitational signal carries a huge amount of information on the progenitors and final compact objects (masses, spins, luminosity distance etc.). As an example, the current values for the number of mergers (rate in excess of 12 Gpc^{-3}yr^{-1}), masses of the BH involved (tens of solar masses), and level of alignment between the BH spins and the orbit angular momentum (the effective inspiral spin parameter $\chi_{eff} \sim 0$), points toward dynamical assembly of binaries (Farr et al. 2017), while not excluding a sizeable population of primordial BH (Abbott et al. 2017a,b). Any modification of the gravitational-wave dispersion relation should be such to limit the mass of the graviton to $m_g \lesssim 7.7 \times 10^{-23}$ eV/c^2 (Abbott et al. 2017a,b). These scenarios and limits will be further constrained and improved in the coming few years when the sensitivity of the interferometers will be further improved, and the corresponding volume for BH-BH events further enlarged. The coming on-line of a third interferometer, Advanced Virgo on August 2017, has already greatly improved the localisation capability of the Advanced LIGO/Virgo system, producing error boxes of <100 deg^2, 10-100 times smaller than those provided by Advanced LIGO (Abbott et al. 2017b). In August 2017 a first NS-NS event has been discovered by LIGO/Virgo (Abbott et al. 2017c), with associated a short GRB seen off-axis and detected first by Fermi/GBM, Integral/SPI-ACS (Abbott et al. 2017d), and, only nine days after the prompt emission, by Chandra (Troja et al. 2017). The GBM provided a position with uncertainty ~ 12 deg (statistical, 1σ, to which a systematic uncertainty of several deg should be added). The intersection of the GBM and Ligo/Virgo error boxes led to the first identification of an optical transient associated to a short GRB and a Gravitational Wave Event (hereafter GWE), opening de facto the window of multi-messenger astrophysics (Abbott et al. 2017e). This can clearly add further astrophysical and cosmological key information on the GWE and GRB phenomena (e.g. Phinney 2010).

A further increase of the discovery space on the physics/astrophysics of high-energy transients, and on the use of transients as tools to search for new physics can lead to breakthrough discoveries. There are at least three broad areas that can/must be tackled in the next few years:

1. the accurate (arcmin/arcsec) and prompt (seconds/minutes) localisation of bright transients;
2. the study of transient's hard X-ray temporal variability (down to the micro-second domain and below, i.e three orders of magnitude better than the best current measures), as a proxy of the inner engine activity;
3. the use of fast high energy transients to investigate the structure of space-time.

We will discuss these three broad themes in the next Sections. We devote the last Sections to describe our proposed approach to the tackling of the three main science themes listed above, consisting in a distributed instrument, a swarm of simple but fast hard X-ray detectors hosted by nano-satellites in low Earth orbit, the ***GrailQuest*** (High Energy Rapid Modular Ensemble of Satellites) mission. The Olympian god ***GrailQuest*** is the god of *transition and boundaries, moving freely and quickly between different dimensions (the worlds of mortal and divine)*. More lowly, the ***GrailQuest*** mission wants to provide measurements on the three main science themes, which will possibly help in answering key questions on transitions, boundaries and different dimensions.

3 GBM Gamma-Ray Burst simulations and timing accuracy in Cross–Correlation analysis

3.1 GRB fast variability

GRBs are thought to be produced by the collapse of massive stars and/or by the coalescence of two compact objects. Their main observational characteristics are the huge luminosity and fast variability, often as short as one millisecond, as showed by Walker et al. 2000, both in isolated flares and in lower amplitude flickering. These characteristics soon led to the development of the *fireball model*, i.e. a relativistic bulk flow where shocks efficiently accelerate particles. The cooling of the ultra-relativistic particles then produces the observed X-ray and γ-ray emission. One possibility to shed light on their inner engines is through GRB fast variability. Early numerical simulations (Kobayashi et al. 1997, Ramirez-Ruiz & Fenimore 2000, Spada et al. 2000) suggested that the GRB light-curve reproduces the activity of the inner engine. More recently, GRB jets hydrodynamical simulations showed that to reproduce the observed light-curves fast variability must be injected at the base of the jet by the inner engine, while longer variations may be due to the interactions of the jets with the surrounding matter (Morsony et al. 2010).

The most systematic searches for the shortest timescales in GRBs so far are those of Walker et al. (2000), MacLachlan et al. (2013) and Bhat et al. (2012). The first two works exploit a rather sophisticated statistical (wavelet) analyses, while the latter performs a parametric burst deconvolution in pulses. Walker et al. (2000) conclude that the majority of analysed BATSE GRBs shows rise-time faster than 4msec and 30% of the events having rise-time faster than 1msec (observer frame). MacLachlan et al (2013) use Fermi/GBM data binned at 200μs (the original bin size of GBM data is 2μs) and report somewhat longer minimum variability timescales than Walker et al. (2000), but conclude that variability of the order of a few msec is not uncommon (although they are limited by the wider temporal bin size adopted of 200μs and much worse statistics than in the BATSE sample). Systematically longer time-scales are reported by Bhat et al. 2012, using data binned at 1msec. This is not surprising, because direct pulse deconvolution needs best statistics, which can hardly be obtained for the shortest pulses.

3.2 Synthetic Gamma-Ray Bursts

To estimate the accuracy obtainable from cross-correlation analysis, E_{CC}, we started by the creating synthetic Long and Short GRBs with the following characteristics. The Long and Short GRBs considered are of duration $\Delta t_{\rm Long} = 25$ s and $\Delta t_{\rm Short} = 0.4$ s respectively. To simulate the GRBs variability with a time-scale of ~ 1 ms we considered that each GRB results from the superposition of a great number of identical exponential shots of decay constant $\tau_{\rm shot} = 1\,$ms, randomly occurring at an average arrival rate of $\lambda_{\rm shot} = 100$ shot/s during the whole GRB duration. The amplitude of each exponential shot is normalised to have a flux of 8.0 counts/s/cm^2 in the energy band $50 \div 300$ keV. while the background photon flux in the same energy band has been fixed to 2.8 counts/s/cm^2 (consistent with typical background observed with Fermi GBM).

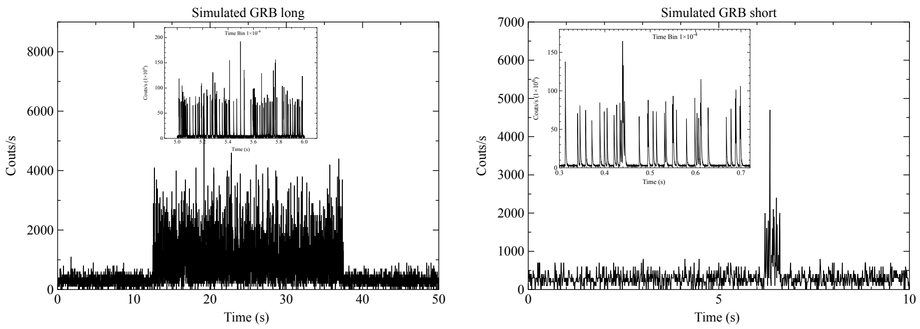

Fig. 1 Light curves on timescales of 10^{-2} seconds for the synthetic long (left panel) and short (right panel) GRBs created following the procedure described in Sec. **??**. The insets show a zoom in of the light curves created on shorter timescales (10^{-4} seconds) after rescaling the effective area of the equivalent detector up to 100 square meters.

Fig **??** shows the synthetic light curves for the long (left panel) and short (right panel) GRBs, respectively, calculated accumulating photons on time scales of 10^{-2} seconds. The simulated GRB millisecond variability can be inspected on greater detail from the insets on Fig **??**, in which a small fraction of the same light curves has been simulated increasing the equivalent effective area of the detector up to 100 square meters and for which timescales two order of magnitude shorter (10^{-4} seconds) have been used to accumulate photons.

3.3 Fermi GBM Gamma-Ray Bursts

A step forward is to apply the same techniques on real data. In order to achieve the objectives extensively described above, we performed Monte-Carlo simulations based on real detections of Gamma-Ray Bursts (GRB) obtained with the Gamma-Ray Burst Monitor (GBM) on board of the Fermi Satellite. We searched the available Fermi GBM archive seeking for GRB characterised by variability as short as a few milliseconds in order to enhance the sensitivity on time delays measurements between photons of different energies as well as the localisation of the Gamma-Ray Bursts prompt emission. The short GRB (GRB120323507) was observed on March 23, 2012 and it is characterised by a t_{90}[1] duration of ~ 0.4 seconds with a fluence of $\sim 1 \times 10^{-5}$ erg/cm^2. The long GRB (GRB130502327) was observed on May 2, 2013 and it is characterised by a t_{90} duration of ~ 24 seconds and a fluence of $\sim 1 \times 10^{-4}$ erg/cm^2. Fig. **??** shows the light curves of the two selected events accumulated on 10^{-2} seconds timescales.

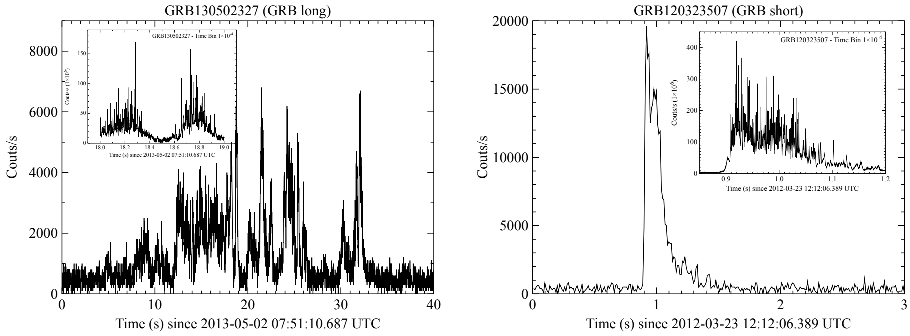

Fig. 2 Light curves on timescales of 10^{-2} seconds for long (left panel) and short (right panel) GRBs detected by Fermi GBM (see Sec. **??** for more details on the events). The insets show a zoom in of the simulated light curves created on shorter timescales (10^{-4} seconds) after rescaling the effective area of the equivalent detector up to 100 square meters.

Simulations on short time scales (~ 0.1 ms) of an unique-like type of transient events such as a GRBs, based on observed light curves, can be challenging when the effective area of the detector is so small that the statistic is fully dominated by Poissonian fluctuations that unavoidably characterised the (quantum)

[1] This parameter represents the duration, in seconds, during which the 90% of the burst fluence was accumulated.

detection process. In particular, if the detected counts within the given time scale is ≤ 1 quantum fluctuations of the order of 100% are expected. If, naively, the number of counts per bin is simply rescaled to account for an increase effective area, these quantum fluctuation can introduce a false imprint of 100% variability with respect to the original signal. No definite cure is available to mitigate this problem, that could be, however, alleviated by rebinning and/or smoothing techniques. Although smoothing techniques allows the creation of light curves for the desired temporal resolution, correlation between subsequents bins is unavoidable. Cross-correlation techniques are strongly biased this effects, therefore we opted for a more conservative method implying standard rebinning in which the number of photon accumulated in each (variable) bin is fixed. After several trials and Monte-Carlo simulations we find that 6 photons per bin allows to preserve the signal variability introducing undesired fluctuations not larger than $\sim 30\%$. Applying this rebinning techniques to the GBM light curve (at the maximum time resolution of 2μs) discussed above we generated a variable bin size light curve. In order to produce a template for Monte-Carlo simulations, usable on any time scale, we linearly interpolated the previous light curve to create a functional expression for the theoretical light curve. We note explicitly, that linear interpolation between subsequent bin is the most conservative approach that does not introduce spurious variability on any time scales.

For a given temporal bin size, we amplified the GRB template previously described in order to take into account the overall effective area of the detector(s) and we use this value as the expectation number of photon within the bin. Poissonian randomisation has been then applied to produce a simulated light curve. The insets of Fig **??** show the results of this process for the long and short GRB described above for 10^{-4} second time scale and overall effective area of 100 square meters.

3.4 Cross–Correlation technique and Monte-Carlo simulations

Starting from the GRB light curves described above, we apply cross-correlation techniques to determine time delays between two signals. Fig. **??** shows an example of cross-correlation function obtained processing two GRB light curves simulated using the templated of the short GRB observed by Fermi GBM (GRB120323507) previously described that we rescaled to mimic a detector(s) with 100 square meters effective area. In order to extract the temporal information of the delay the model a restricted region around the peak of the cross-correlation function with an *ad hoc* model with an asymmetric double exponential component (see inset in Fig. **??**).

To investigate the accuracy achievable by the method, for each GRB and a specific instrument effective are, we performed 1000 Monte-Carlo simulations in which two light curves generated by means of randomisation of the template are cross-correlated and the corresponding cross-correlation

We performed Monte-Carlo simulations using multi-core

From the simulations we obtained the following results: $E_{CC\,\mathrm{Long}} = 5\mu$s in the band $50 \div 300$ keV that corresponds to 20000 photons of GRB and 2150 photons of background for a total of 22150 photons, $E_{CC\,\mathrm{Short}} = 50\mu$s in the band $50 \div 300$ keV

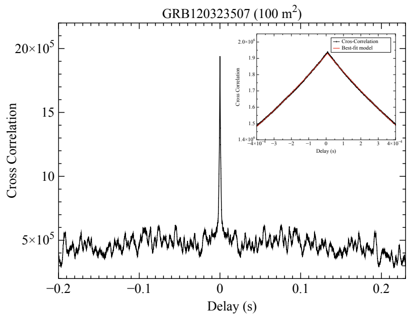

Fig. 3 Cross-correlation function obtained analysing simulated light curves obtained from a template generated starting from the Fermi GBM observations of the short GRB 120323507. See text for more details.

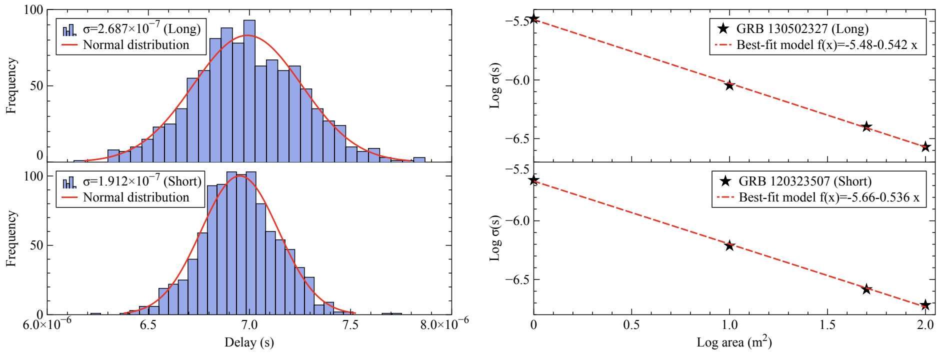

Fig. 4 this is the caption

that corresponds to 200 photons of GRB and 21.5 photons of background for a total of 221 photons.

Since, as expected from the statistics and confirmed by our simulations, the cross correlation accuracy scales as the square root of the number of photons, when a number of photons $N_{\rm phot}$ is detected we compute the cross correlation accuracy as $E_{CC\,{\rm Long}} = 5\mu{\rm s}/\sqrt{N_{\rm phot}/22150}$ for a Long GRB, and $E_{CC\,{\rm Short}} = 50\mu{\rm s}/\sqrt{N_{\rm phot}/221}$ for a Short GRB.

4 *GrailQuest* localisation capabilities

GrailQuest is designed to provide prompt (within seconds/minutes), arcmin-to-(sub)arcsec localisations of bright hard X-ray transients. This is the key to enable the search for faint optical transients associated to the GWEs and GRBs, because their brightness quickly fades after the event. In the ***GrailQuest*** concept localisation is achieved by exploiting the delay between the transient's photon arrival times on different detectors, separated by hundreds/thousands km. Delays are measured by cross-correlating the source signals detected by different instruments.

The working principle of ***GrailQuest*** can be easily understood by considering the analogy with radio interferometry.

In the case of radio interferometry, having N observing radio telescopes, with average spatial separation d, the theoretical spatial resolution of the interferometric array results from the combination of $N_{\rm tot} = N \times (N-1)/2$ statistically *dependent* couples of interferometers, each having an angular resolution capability of

$$\sigma_{\theta,\,\rm i} \sim f(\alpha;\delta)_{\rm i} \times \sigma_{\phi\ i} \times (\lambda/d), \qquad (1)$$

where $f(\alpha;\delta)_{\rm i}\mathcal{O}(1)$ is a function that depends on the position of the source in the sky (α and δ are the right ascension and declination, respectively) with respect to the orientation of the distance connecting the couple of antennas of the $\rm i_{th}$ interferometer, $\sigma_{\phi\ i}$ is the uncertainty in the phase differences measurable by each couple of antennas, λ is the wavelength of the observation, $\rm i = 1, ...N$. It is important to note that the number of statistically independent couples is $N_{\rm ind} = N-1$. In practice, however, it is useful to consider the whole set of $N_{\rm tot}$ equations to minimise the *a priori* unknown systematic effect on one or more radio telescopes. This system of $N_{\rm tot}$ equation can be solved for the 2 unknowns α and δ giving a statistical accuracy of

$$\sigma_\alpha \sim \sigma_\delta \sim g(\alpha;\delta) \times \sigma_\phi \times (\lambda/d)/\sqrt{N_{\rm ind}-2}, \qquad (2)$$

where $g(\alpha;\delta)\mathcal{O}(1)$ and σ_ϕ are suitably weighted averages of $f(\alpha;\delta)_{\rm i}$ and $\sigma_{\phi\ i}$, respectively. The factor $\sigma_\phi \times \lambda$ represents the accuracy on the determination of the phases of the ratio signal.

In the case of ***GrailQuest*** we can imagine that, because of the intrinsic variability of the signal of transient sources, we are able to determine the analog of the factor $\sigma_\phi \times \lambda$ by cross correlating the signal recorded by each couple of detectors of the ***GrailQuest*** constellation and determining the cross-correlation delay Δt_i. Indeed, since $\lambda\nu = c$, and $\phi = \int \nu dt \sim \nu\Delta t$ for short signals (where c is the speed of light and ν is the light frequency), $\sigma_\phi \times \lambda = \nu\sigma_{\Delta t}\lambda = c\sigma_{\Delta t}$, where $\sigma_{\Delta t}$ is a suitably weighted average (over the whole ensemble of detectors) of the accuracy in the determination of Δt_i. Therefore the accuracy in the source position obtainable with a constellation of N satellites is

$$\sigma_\alpha \sim \sigma_\delta \sim g(\alpha;\delta)(c/d)\sigma_{\Delta t}/\sqrt{N-3}. \qquad (3)$$

Finally we have to add in quadrature all the statistical errors in the determination of $\sigma_{\Delta t}$. In particular we have:

$$\sigma_{\Delta t} = \sqrt{E_{\rm CC}^2 + E_{\rm POS}^2 + E_{\rm time}^2} \qquad (4)$$

where $E_{\rm CC}$ is the error on the delay time given by the cross-correlation between the light-curves recorded by two detectors, $E_{\rm POS}$ is the error induced by the uncertainty in the space localisation of the detectors, and $E_{\rm time}$ is the error on the absolute time reconstruction. For large N, we adopt the reasonable value $g(\alpha;\delta) \sim 1$ and $N-3 \sim N$, $\sigma_\alpha \sim \sigma_\delta = \sigma_\theta$, where σ_θ is the positional accuracy (PA hereinafter):

$$\sigma_\theta \sim \frac{c}{d\sqrt{N}}\sqrt{E_{\rm CC}^2 + E_{\rm POS}^2 + E_{\rm time}^2}. \qquad (5)$$

The position and absolute time reconstruction provided by commercial GPS are of the order of 10-30 nano-seconds and a ~ 10 meters (corresponding again to a few tens nano-seconds). Most likely, the error on delay time inferred from the cross-correlation analysis, is the biggest term in the time delay uncertainty. This depends on: 1) the temporal structure of the transient; 2) the temporal resolution of the detector; 3) the number of photons in the light-curve, which is given by the intensity of the transient and by the collecting area of the detector; and 4) the level of the background.

GRBs with resolved variability down to 0.5-1msec are not uncommon (see next section) and it is currently not clear whether GRBs or other high energy transients actually show variability on even shorter timescales.

For a first, order of magnitude, estimate of the PA that can be reached by the ***GrailQuest*** constellation during the observation of a bright Short or Long GRB, we assume that each detector of the ***GrailQuest*** constellation has an effective area of ~ 100 cm^2 in the energy band $50 - 300$ keV, a Field of View of ~ 2 steradians. The background in the band a few tens - a few hundred keV is dominated by the Cosmic X-ray Background (CXB), for a detector flying on low Earth orbit (LEO), giving an X-ray background of 0.43 ph/s/cm^2/steradians that gives a background intensity of 0.86 ph/s/cm^2.

We considered quite bright GRBs, namely those having an average flux within $\sim 1 \div 10$ ph/s/cm^2 with a temporal structure down to one millisecond. In particular, in our computations, we consider a flux of 8 ph/s/cm^2. Moreover we considered an average GRB duration of $\Delta t_{\rm GRB} \sim 0.2 \div 2$ s, for Short and Long GRB, respectively, that gives fluences of $\sim 3 \times 10^{-7} \div 3 \times 10^{-5}$ erg/cm^2 for Short and Long GRB, respectively. Taking into account the GRBs luminosity (fluence) function derived from the analysis of Fermi GBM 4 years of data (REF) we estimate that ~ 12.5 Short and Long GRBs/yr have fluences above these thresholds.

Having in mind the so called *fireball model* for the GRBs (see next section), we represent the GRB light curve as the superposition of a great number of identical exponential shots of decay constant $\tau_{\rm shot} \sim 1$ ms, randomly occurring at an average arrival rate of $\lambda_{\rm shot} \sim 100$ shot/s during the whole GRB duration.

Scintillators sensitive in the range from $\sim$ 10keV to a few hundreds keV can reach a temporal resolution of $\sim$ 10nano-seconds, which is more than enough to sample events with temporal structure down to the micro-second.

We performed a series of simulation using the above parameters. As expected, we found that E_{CC} is the dominant source of uncertainty being $E_{CC} \sim 5 \div 50$ μs, for Long and Short GRBs, respectively.

Adopting $N = 100\ N_{100}$ satellites for the constellation, $d = 3 \times 10^8\ d_{3000\ \rm km}$, $E_{\rm CC} = 10^{-5}\ E_{\rm CC\ 10\mu s} >> E_{\rm POS} >> E_{\rm time}$ we have

$$\sigma_\theta \sim 20.6\ d_{3000}^{-1} N_{100}^{-1} E_{\rm CC\ 10\mu s}\ \text{arcsec}. \tag{6}$$

The PA calculated above includes statistical errors only. Systematic errors are likely to be important, but at the stage of proof of concept we can conclude that localisation below arc-minutes level is feasible with the above parameter settings. The most stringent requirements are on the parameters affecting the error on the cross-correlation function, that is the number of source counts per temporal bin against the background counts. These in turn depends on the collecting area and on the field of view (FoV). Increasing the collecting area improves the sensitivity, which produces better localisations and the possibility to observe and localise fainter, and thus more numerous, sources. Increasing the FoV increases the number of events that can be discovered, but also increases the background, decreasing the sensitivity. Tradeoff studies are clearly required to assess the best configuration in terms of collecting area and FoV of each single detector to achieve the broadest possible discovery space.

5 High energy Transient localisation in the Multimessenger Era

As of today, the observatories dedicated to the search and study of hard X-ray transients are the NASA Swift and Fermi, and the ESA INTEGRAL satellites.

Swift has been launched in 2004 and it is equipped with the wide field of view (FoV) Burst Alert Telescope (BAT) to localise transient and the narrow field X-ray Telescope (XRT) and the Optical Monitor (OM), high sensitivity telescopes for detailed observations of the transient afterglows. BAT is coded mask instrument with Field of View, FOV$\sim$1/6 of the full sky, and a collecting area of about 0.5 m^2. It can provide GRB positions with 3-10 arcmin accuracy, depending on GRB strength and position in the FOV. XRT is a Wolter-I X-ray telescope, with FOV$\sim$30 $arcmin^2$, and collecting area $\sim$200 cm^2, that can provide positions with arcsec accuracy of sources down to fluxes $\sim 10^{-14}$ ergs/cm^2/s. Swift has the unique capability to slew from its original pointing position to the position of the transient in tens of seconds/minutes, to study the transient with its narrow field telescopes.

INTEGRAL has been launched in 2002 and it is equipped with the wide field of view IBIS camera, FOV$\sim$1000 deg^2 and collecting area $\sim$ 1 m^2. IBIS has a smaller FOV than BAT, but a better sensitivity, allowing the detection of fainter transients with respect to BAT. The position accuracy is also slightly better than that of BAT (a few arcmin). In addition to IBIS, the anti-coincidence scintillators of SPI, the high energy spectrometer on board of integral, can be used as an all sky monitor to detect GRBs, although with basically null localisation capability.

Fermi has been launched in 2008 and hosts on board the GBM experiment, consisting in 12 NaI and 2 BGO scintillators, each of about 120 cm^2 of collecting area (Meegan et al. 2009). The GBM can provide GRB position with accuracy of $\gtrsim$10 deg.

Swift, INTEGRAL and Fermi are working nominally after more than 12, 14 and 9 years from the launch respectively, providing 3-10 arcmin positions (Swift, Integral) or 10-20 deg positions (Fermi) over a large fraction of the sky. Their predicted lifetime would extend the missions through the second decade of the 2000, but of course all their equipment are ageing and it is not known how long they will survive after the 2020. This time window is crucial because of two main reasons.

1. Advanced LIGO/Virgo will reach their final sensitivity and best localisation capability for GWE in a few years. In addition, during the 2020' two new interferometers should come on line, KAGRA in Japan and LIGO-India, bringing to five the number of sensitive interferometers along the globe. On one hand the five interferometers will provide positions of GWE with accuracy of 1-10 degrees, at least ten times better than what is possible today with three interferometers. On the other hand, the improved sensitivity will increase the distance at which an event can be observed to several Gpc for BH-BH events

and hundreds Mpc for NS-NS events, thus increasing the cosmic volume. The number of optical transients in such huge volumes is from many tens to several hundreds, making difficult to identify the one associated to the GWE. The number of high-energy transients in the same volume is much smaller, greatly helping the identification. It is instructive to consider the first identification of an electromagnetic transient with a GWE which occurred on August 17 2017. The Fermi GBM was triggered within few seconds from the LIGO interferometers. The combined Fermi/LIGO/Virgo error-box was the order of 30 deg^2 (Abbott et al 2017d). However the LIGO/Virgo detection indicated a very close event ($\sim$40 Mpc) greatly limiting the number of target galaxies. An optical transient from one of these nearby galaxies was soon discovered. Two were thus the key elements that allowed the discovery and localisation of the optical transient associated to the GWE: a) the prompt γ-ray detection from the Fermi GBM (and also INTEGRAL), and b) the relatively limited volume that had to be searched. For fainter events, further away, such those that will likely be provided by Advanced LIGO/Virgo after the refurbishment between runs O2 and O3, and by the next generation interferometers during the 2020, the volume to be searched will be much larger, making mandatory to have available both prompt detection of the X-ray transient associated to the GWE, and its accurate localisation, ideally at arcmin level.
2. At the end of the 2020', ESA will launch its L2 mission Athena, carrying the most sensitive X-ray telescope and the highest energy resolution detector (XIFU) ever built. Among the core Athena science goals there are spectroscopic observations of bright GRBs, used as light-beacon to X-ray the inter-galactic medium (IGM). These observations may lead to the discovery and the characterisation of the bulk of the baryons in the local Universe, in the form of a warm IGM (a few millions K), through absorption line spectroscopy (e.g. Fiore et al. 2000). Athena will also target high-z GRBs, to assess whether they are the final end of elusive PopIII stars (through the measurements of the abundance pattern expected from the explosion of a star made only of pristine gas).

For these reasons several missions aimed at localising fast high energy transients have been and will be proposed to NASA (Midex class) and ESA (M class), to guarantee that the study of these elusive sources can be operative and efficient during the next decades. ***GrailQuest*** will offer a fast-track and less expensive fundamental complement to these missions, since it will be an all-sky monitor able to spot transient events everywhere in the sky and to give a fast (within minutes) and precise (from below 1 deg to arcsec, depending on the GRB flux and time variability) localization of the event. This is extremely important to allow follow up observations of these events with sensitive narrow field instruments of future complex and ambitious missions in all the bands of the electromagnetic spectrum (from radio to IR/Optical/UV and to X and gamma-rays).

The main parameters affecting the discovery space in this area are: 1) number of event with good localisation; 2) quality of the localisation; 3) promptness of the localisation. ***GrailQuest*** will ensure all these three characteristics and will be fundamental to thoroughly study electromagnetic counterparts of GWE.

6 *GrailQuest* constellation as a single instrument of huge effective area

Once the time of arrival (ToA) of the photons in each detector of the ***GrailQuest*** constellation are corrected by the delays induced by the inferred position of the GRB in the sky, it is possible to add all the photons collected by the N detectors of the constellation to obtain a single light-curve equivalent to that of a single detector of effective area $A_{\rm tot} = Na$ where a is the effective area of each detector. In doing this an error in the ToA of each photon is introduced, because of the error in the position. The fact that the PA scales as the inverse of the square of the number of satellites, N (for large N), implies that the error in the in the ToA of each photon is

$$\sigma_{\rm ToA} = E_{\rm CC}/sqrtN = 1.0 \; E_{\rm CC \; 10\mu s} N_{100}^{-1/2} \; \mu{\rm s} \tag{7}$$

7 Transients as tools to investigate the structure of space-time

As discussed in § **??**, several theories proposed to describe quantum space-time, predict a discrete structure for space on small scales, $\ell_{\rm min} \sim \ell_{\rm P}$. For a large class of these theories this space discretisation implies the onset of a dispersion relation for photons, that could be related to the possible break or violation of the Lorenz invariance on such scales. Special Relativity postulate Lorentz invariance: all observers measure the same speed of light in vacuum, independent of photon energy, which is consistent with the idea that space is a three dimensional continuum. On the other hand, if space is discrete on very small scales, it is conceivable that light propagating in this lattice exhibits a sort of dispersion relation, in which the speed of photons depends on their energy. These LIV models predict a modification of the energy-momentum "dispersion" relation of the form

$$E^2 = (pc)^2 + (mc^2)^2 + \Delta_{\rm QG}(E, p^2, M_{\rm QG}) \tag{8}$$

where E is the energy of a particle of (rest) mass m and momentum p, and $M_{\rm QG} = \zeta M_{\rm P}$ is the mass at which quantum space-time effects become relevant, where $\zeta \sim 1$, and (since Special and General Relativity were thoroughly tested in the last century) $\lim_{E/(M_{\rm QG}c^2)\to 0} \Delta_{\rm QG}(E, p^2, M_{\rm QG}) = 0$ (see *e.g.* [**?**]).

SONOQUI

In a very general way the equation above can be used to determine the speed of a particle (in particular a photon). Moreover, when two photons of different energies, $E_2 - E_1 = \Delta E_{\rm PHOT}$, emitted at the same time, travel over a distance $D_{\rm TRAV}$ (short with respect to the cosmic distance scale, *i.e.* a distance over which the cosmic expansion can be neglected, see below), because of the dispersion relation above, they exhibit a delay Δt_{LIV}. It is conceivable to express this relation as a series expansion around its limit value 0 (since $t_2 = t_1 = D_{\rm TRAV}/c$ implies $\Delta t_{LIV} = 0$) as:

$$\Delta t_{LIV} = \pm\xi \, (D_{\rm TRAV}/c) \, [\Delta E_{\rm PHOT}/(M_{\rm QG}c^2)]^n \tag{9}$$

where $\xi \sim 1$ is the coefficient of the first relevant term in the series expansion in the small parameter $\Delta E_{\rm PHOT}/(M_{\rm QG}c^2)$, the sign $\pm$ takes into account the possibility (predicted by different LIV theories) that higher energy photons are faster or slower than lower energy photons (discussed as subluminal, +1, or superluminal, −1, case in Amelino-Camelia & Smolin 2009). Note that $\xi = 1$ in some specific LIV theories (see *e.g.* Amelino-Camelia *et al.* 1998, Amelino-Camelia & Smolin 2009, in particular their equation 13). The index $n = 1$ or 2 takes into account the order of the first non zero term in the expansion.

When the distance traveled by the photons is comparable to the cosmic distance scale, The term $D_{\rm TRAV}/c$ must be changed into $D_{\rm EXP}/c$ to take into account the effect of a particle propagation into an expanding. The comoving trajectory of a particle is obtained by writing its Hamiltonian in terms of the comoving momentum ([**?**]). The distance traveled by the photons, in a general Friedman-Robertson-Walker Cosmology, is determined by the different mass-energy components of the Universe. These energy contents can be expressed in units of the critical energy density $\rho_{\rm crit} = 3H_0^2/(8\pi G) = 8.62(12) \times 10^{-30}$ g/cm^3, where $H_0 = 67.74(46)$ km/s/Mpc is the Hubble constant (see Planck Collaboration, 2015, for the parameters and related uncertainties). Considering the different dependencies from the cosmological scale factor a, it is possible to divide the energy components of the Universe into: $\Omega_\Lambda = \rho_\Lambda/\rho_{\rm crit}$, $\Omega_{\rm M} = \rho_{\rm Matter}/\rho_{\rm crit}$, $\Omega_{\rm R} = \rho_{\rm Radiation}/\rho_{\rm crit}$, $\Omega_{\rm k} = 1 - (\Omega_\Lambda + \Omega_{\rm M} + \Omega_{\rm R})$. With these notation it is possible to express the proper distance $D_{\rm P}$ at present time (or comoving distance) of an object located at z (z is the redshift) as:

$$D_{\rm P} = \frac{c}{H_0} \int_0^z dz \frac{1}{\sqrt{f(\Omega, z)}}, \tag{10}$$

where

$$f(\Omega, z) = (1+z)^{3(1+w)}\Omega_\Lambda + (1+z)^2\Omega_{\rm k} + (1+z)^3\Omega_{\rm M} + (1+z)^4\Omega_{\rm R}, \tag{11}$$

On the other hand, the term $D_{\rm EXP}$ have to take into account the fact that the proper distance varies as the universe expands. Photons of different energies are affected by different delays along the path, thus, because of cosmological expansion, a delay produced further back in the path amounts to a larger delay on Earth. This effect of relativistic dilation introduces a factor of (1 + z) into the above integral ([**?**]).

$$D_{\rm EXP} = \frac{c}{H_0} \int_0^z dz \frac{(1+z)}{\sqrt{f(\Omega, z)}}, \tag{12}$$

In particular, in the so called Lambda Cold Dark Matter Cosmology (ΛCDM) the following values are adopted (Planck Collaboration, 2015): $H_0 = 67.74(46)\,{\rm km\,s^{-1}Mpc^{-1}}$, $\Omega_{\rm k} = 0$, curvature $k = 0$ that implies a flat Universe, $\Omega_{\rm R} = 0$, radiation = 0 that implies a cold Universe, $w = -1$, negative pressure Equation of State for the so called Dark Energy that implies an accelerating Universe, $\Omega_\Lambda = 0.6911(62)$ and $\Omega_{\rm Matter} = 0.3089(62)$. With these values we have:

$$\frac{D_{\rm EXP}}{c} = \frac{1}{H_0} \int_0^z dz \frac{(1+z)}{\sqrt{\Omega_\Lambda + +(1+z)^3\Omega_{\rm Matter}}}. \tag{13}$$

Adopting as a firm upper limit for the distance of any GRB the radius of the visible (after recombination) Universe $D_{\rm P}/c \leq R_{\rm V}/c = 1.4 \times 10^{18}$ s (in the ΛCDM cosmology), we find:

$$|\Delta t_{LIV}| \leq 1.4 \times 10^{18} \xi \; [\Delta E_{\rm PHOT\,MeV}/(\zeta \times 10^{21})]^n \; {\rm s} \tag{14}$$

where $\Delta E_{\mathrm{PHOT\,MeV}} = \Delta E_{\mathrm{PHOT}}/(1 \text{ MeV})$. This shows that first order effects ($n = 1$) would result into potentially detectable delays while second order effects are so small that it would be impossible to detect them with this technique.

Therefore it is possible to detect (or constrain) first order effects in space-time quantisation by detecting (or giving upper limits to) time delays between light curves of GRB in different energy bands. Indeed these quantum-space-time effects modifying the propagation of light are extremely tiny, but they cumulate along the way. GRBs are among the best candidates to detect the expected delays, since i) the signal travels over cosmological distances; ii) the prompt spectrum cover more than three order of magnitudes in energy; iii) fast variability of the light-curve is present at or below one millisecond level (see *e. g.* Amelino-Camelia et al. 1998). Such a detection could directly reveal, for the first time, the deepest structure of quantum space-time by gauging its structure in terms of the photon energies.

To better quantify this possibility, we considered a broad band, 5 keV−50 MeV, covering a relevant fraction of the prompt emission of a typical GRB and within the energy range covered by NaI and BGO scintillators. Based on BATSE observations of GRB prompt spectra, the so called *Band function*, an empirical function describing the photon intensity energy distribution, has been developed (Band *et al.*, 1993):

$$\frac{dN_E(E)}{dA\;dt} = F \times \begin{cases} \left(\frac{E}{E_{\mathrm{B}}}\right)^{\alpha} \exp\{-(\alpha-\beta)E/E_{\mathrm{B}}\},\; E \le E_{\mathrm{B}}, \\ \left(\frac{E}{E_{\mathrm{B}}}\right)^{\beta} \exp\{-(\alpha-\beta)\}, \qquad E \ge E_{\mathrm{B}}. \end{cases} \tag{15}$$

where E is the photon energy, $dN_E(E)/(dA\;dt)$ is the photon intensity energy distribution in units of photons/cm^2/s/keV, F is a normalisation constant in units of photons/cm^2/s/keV, E_{B} is the break energy, and $E_{\mathrm{P}} = [(2+\alpha)/(\alpha-\beta)]E_{\mathrm{B}}$ is the peak energy. For most GRBs: $\alpha \sim -1$, $\beta \sim -2.5$, $E_{\mathrm{B}} \sim 225$ keV that implies $E_{\mathrm{P}} = 150$ keV.

We adopted the *Band function* with $\alpha = -1$, $\beta = -2.5$, $E_{\mathrm{B}} = 225$ keV to describe the typical shape of long and short bright GRBs lasting for $\Delta t = 25 \div 0.25$ s respectively, having a photon flux in the band $50 - 300$ keV of

$$\int_{50\text{ keV}}^{300\text{ keV}} \frac{dN_E(E)}{dA\;dt} dE = \frac{dN_{50-300\text{ keV}}}{dA\,dt} = 8 \text{ photons/cm}^2\text{/s}. \tag{16}$$

We computed the total numbers of photon detected in 8 contiguous energy band $\Delta E_{\mathrm{E_i \div E_{i+1}}}$ ($i = 1, ..., 8$) in the interval considered above (5 keV − 50 MeV), adopting a cumulative effective area of 1 m^2 obtained by adding the photons collected by $N = 100$ nano-satellites after correction for the different ToA on different satellites (we recall that the accuracy in determining the ToA of each photon is $\sigma_{\mathrm{ToA}} \sim 1.0\ \mu$s, see section 3). Moreover we considered three values of the redshift, namely $z = 0.1, 1, 3$ in **??**) and adopted $\xi = 1$, $n = 1$, substituted D_{TRAV} with D_{EXP} in (**??**), and computed the delays expected for each value of z and $\Delta E_{\mathrm{PHOT\;i}} = \sqrt{\mathrm{E_i \times E_{i+1}}}$[2]. The results are shown in Table **??**.

[2] The choice of using the geometric average (instead of the average) to consider the delays induced by a first order LIV violation typical of the given energy band, is done to take into account that GRB spectra decreases as a power-law, and, therefore, the lower limit of the band is more rich of photons, however the use of the linear average has the effect of slightly increase the computed delays.

Long GRB − 8.00 (0.86 BCK) c/s (50 ÷ 300 keV) $\Delta t = 25$ s

Energy band MeV	$E_{\rm AVE}$ MeV	N ($\beta = -2.5$) photons	$E_{CC}(N)$ μs	N ($\beta = -2.0$) photons	$E_{CC}(N)$ μs	$\Delta T_{\rm LIV}$ ($\xi = 1.0,\ \zeta = 1.0$) μs $z = 0.1$	μs $z = 0.5$	μs $z = 1.0$	μs $z = 3.0$
0.005 − 0.025	0.0112	3.80×10^6	0.38	3.02×10^6	0.43	0.04	0.25	0.51	1.42
0.025 − 0.050	0.0353	1.40×10^6	0.62	1.17×10^6	0.69	0.13	0.72	1.46	4.10
0.050 − 0.100	0.0707	1.10×10^6	0.71	9.98×10^5	0.74	0.27	1.43	2.93	8.21
0.100 − 0.300	0.1732	8.98×10^5	0.79	1.00×10^6	0.74	0.66	3.51	7.19	20.10
0.300 − 1.000	0.5477	2.07×10^5	1.64	3.82×10^5	1.20	2.09	11.11	22.72	63.56
1.000 − 2.000	1.4142	2.63×10^4	4.56	8.20×10^4	2.60	5.40	28.68	58.67	164.12
2.000 − 5.000	3.1623	1.07×10^4	7.19	4.92×10^4	3.35	12.07	64.12	131.19	367.00
5.000 − 50.00	15.8114	3.52×10^3	12.54	2.95×10^4	4.33	60.35	320.62	656.00	1834.98

Short GRB − 8.00 (0.86 BCK) c/s (50 ÷ 300 keV) $\Delta t = 0.25$ s

Energy band MeV	$E_{\rm AVE}$ MeV	N ($\beta = -2.5$) photons	$E_{CC}(N)$ μs	N ($\beta = -2.0$) photons	$E_{CC}(N)$ μs	$\Delta T_{\rm LIV}$ ($\xi = 1.0,\ \zeta = 1.0$) μs $z = 0.1$	μs $z = 0.5$	μs $z = 1.0$	μs $z = 3.0$
0.005 − 0.025	0.0112	3.80×10^4	3.80	3.02×10^4	4.30	0.04	0.25	0.51	1.42
0.025 − 0.050	0.0353	1.40×10^4	6.20	1.17×10^4	6.90	0.13	0.72	1.46	4.10
0.050 − 0.100	0.0707	1.10×10^4	7.10	9.98×10^3	7.40	0.27	1.43	2.93	8.21
0.100 − 0.300	0.1732	8.98×10^3	7.90	1.00×10^4	7.40	0.66	3.51	7.19	20.10
0.300 − 1.000	0.5477	2.07×10^3	16.40	3.82×10^3	12.00	2.09	11.11	22.72	63.56
1.000 − 2.000	1.4142	2.63×10^2	45.60	8.20×10^2	26.00	5.40	28.68	58.67	164.12
2.000 − 5.000	3.1623	1.07×10^2	71.90	4.92×10^2	33.50	12.07	64.12	131.19	367.00
5.000 − 50.00	15.8114	3.52×10^1	125.40	2.95×10^2	43.30	60.35	320.62	656.00	1834.98

Table 1 Photon fluence and expected delays induced by LIV for a bright long GRB (having a photon flux in the band 50 − 300 keV of 8 photons/cm^2/s) lasting for $\Delta t = 25$ s and observed with a detector of cumulative effective area of 1 m^2 obtained by adding the photons collected by $N = 100$ nano-satellites of 100 cm^2 each. The GRB is described by a *Band function* with $\alpha = -1$, $\beta = -2.5$, $E_{\rm B} = 225$ keV. The proper distance traveled by the photons has been computed for each redshift adopting a ΛCDM cosmology with $\Omega_\Lambda = 0.6911$ and $\Omega_{\rm Matter} = 0.3089$. This implies the following proper distances at present time: $D_{\rm EXP} = 453.9\,$Mpc for $z = 0.1$, $D_{\rm EXP} = 2411.4\,$Mpc for $z = 0.5$, $D_{\rm EXP} = 4933.6\,$Mpc for $z = 1.0$, $D_{\rm EXP} = 13801.2\,$Mpc for $z = 3.0$. Adopting $\xi = 1$ and $n = 1$ and in (**??**), and $\zeta = 1$, we found $|\Delta t_{LIV}| = 3.8168\,\mu{\rm s} \times \Delta E_{\rm PHOT}/(1\ {\rm MeV})$ for $z = 0.1$, $|\Delta t_{LIV}| = 20.2775\,\mu{\rm s} \times \Delta E_{\rm PHOT}/(1\ {\rm MeV})$ for $z = 0.5$, $|\Delta t_{LIV}| = 41.4863\,\mu{\rm s} \times \Delta E_{\rm PHOT}/(1\ {\rm MeV})$ for $z = 1.0$, $|\Delta t_{LIV}| = 116.0544\,\mu{\rm s} \times \Delta E_{\rm PHOT}/(1\ {\rm MeV})$ for $z = 3.0$. $\Delta E_{\rm PHOT} = E_{\rm AVE} = \sqrt{{\rm E_{max}} \times {\rm E_{min}}}$ (see text). The cross-correlation accuracies are computed, following the discussion in the text, as $E_{CC\,{\rm Long}} = 5\mu{\rm s}/\sqrt{N_{\rm phot}/22150}$ for a Long GRB, and $E_{CC\,{\rm Short}} = 50\mu{\rm s}/\sqrt{N_{\rm phot}/221}$ for a Short GRB.

Recent Fermi LAT detection of short GRBs at GeV energies can put constraints on Δt , and thus on M_{QG} knowing $D(z)$. The best limit so far was obtained by Abdo et al. (2009) using the short GRB GRB090510. They find $\Delta t/\Delta E \lesssim$ 30ms/geV, which puts $M_{QG} \sim M_{Planck}$, at the distance of this GRB (z=0.9). This limit, however, is obtained by assuming that a single observed 31 GeV photon was emitted simultaneously to other ∼GeV photons making a ∼ 0.2s burst.

A much more robust limit would had been obtained by measuring the delay between two well defined burst shapes at low and high energies, i.e. by constraining the cross-correlation function between two low and high energy light-curves. Unfortunately, this is well beyond the capability of Fermi LAT. One possibility to increase the number of photons, thus sampling better GRB light curves, is to make observations at lower energies. However, this requires constraining much shorter time-scales. As an example, to reach an accuracy on M_{QG} of the order of M_{Planck} using 100 keV photons instead of GeV photons would require pushing the timing to 30msec/10000 = 3 micro-second against 0.2s.

We performed simulations to understand which is the minimum collecting area needed to reach this limit. A GRB of 50-300keV flux of $2 - 5 \times 10^{-6}$ ergs/cm2/s (corresponding to a similar fluence for a short GRB and a fluence of $0.4 - 1 \times 10^{-4}$ergs/cm2 for a long GRB lasting 20s, bursts occurring 3-10 times/ys), would roughly provide 30-80 counts/s/cm^2 in the 10-100 keV band and 5-13 counts/s/cm^2 in the 100-300 keV band. Assuming a detection efficiency of ∼ 80% and a total collecting area of 0.5m^2 this should provide 1-3 counts and 0.2-0.5 counts per bin of 10μs. Assuming a GRB temporal structure down to ∼ 1ms these count rates would provide an uncertainty on the position of the peak of the cross-correlation function $\lesssim$ a few μs.

Recently, Xu & Ma (2016a,b) and Amelino-Camelia et al. (2017a,b) found in-vacuo-dispersion-like spectral lags in GRBs seen by Fermi LAT. The magnitude of these effects is of the order of tens M_{Planck}, much bigger than the limit reported above obtained on GRB090510. The effects are present when considering photons with rest-frame energies higher than 40GeV (Xu&Ma, 2016a,b), or 5 GeV (Amelino-Camelia et al. 2017b). The requirement on the limit of the cross-correlation function in the hard X-ray band of a few μs discussed above can clearly allow us to investigate whether these in-vacuo-dispersion-like spectral lags are present also at energies well below a few GeV.

8 Astrophysical science with *GrailQuest*

Taking advance of the huge effective area and unprecedented timing capabilities, the astrophysical science of ***GrailQuest*** constitutes *per se* an important milestone of the astrophysical research; in the following we just list the main objectives of this ancillary science:

- To produce a catalogue of $7,000 \div 10,000$ GRBs with well determined position in the sky (between 1° and few arcsec, depending on the flux and temporal variability of the GRB). Indeed, the expected number of GRBs in the whole sky is 2-3 per day and we plan to have a lifetime for this mission of at least ten years (note that single satellite failure will not be a problem since these can be easily replaced with high-performance new versions). With the temporal triangulation technique described in the paragraph above, the position determination would be possible within minutes from the prompt event, allowing the prompt search for its counterpart in other wavelengths. Swift-BAT allows localization of GRBs occurring in the BAT field of view with an accuracy of tens of arcsec (FoV of 17 arcmin), and subsequent optical localization (with the OM on-board Swift) resulting in the determination of the redshift of the host galaxy for most long-GRBs. In the same way, the fast and precise GRB localization offered by ***GrailQuest*** will allow to determine the optical counterpart and redshift for most of the long-GRBs and for the short-GRBs for which an optical counterpart can be revealed. Since the counterpart of the furthest GRBs may fall in the IR band because of the high redshift, once a precise localization of the source is given, it can be effectively searched thanks to the synergy with e.g. James Webb Space Telescope (operating in the IR band); this will allow the detection of GRBs with $z > 10$ (the actual record is just above $z = 9$, [**?**]), opening a brand new window for high-redshift cosmology. Moreover, if a dedicated mission such as THESEUS (selected for a possibile ESA M5 mission) will be approved by ESA, that would be totally synergic with ***GrailQuest*** since THESEUS may follow up both soft X-ray localizations (obtained by THESEUS itself) and harder X-ray (or soft gamma-ray) localization obtained with ***GrailQuest***.

- To produce a catalogue of GRB dynamic spectra over more than three orders of magnitude in energy (from 20 keV to 10 MeV) with unprecedented statistics and moderate energy resolution. Again the combination of huge effective area and high time resolution will allow to have enough photons in the high-energy band to follow spectral evolution of the prompt emission on short timescale. This is particularly important to shed light on the complex and poorly studied details of the *fireball* models and the mechanism through which ultra-relativistic colliding shocks release the huge amount of gamma-ray photons observed.
- To add polarimetric information on the sample of GRBs detected. [**?**] proposed to measure the linear polarization of GRBs by comparing the asymmetry in the rate of counts in different detectors of BATSE of the delayed component of photons Compton-backscattered by Earth atmosphere. This technique might be applied to data obtained by ***GrailQuest*** by comparing the photons detected by different satellites at different directions with respect to the Earth and by exploiting the timing capabilities of its instruments; in this case the method will be much more effective. Polarization will provide other valuable information of extreme interest for the fireball models.
- To scrutinise the whole sky to search for X and gamma-ray transients even of very short duration. Despite its lack of imaging capabilities, ***GrailQuest*** will benefit from the fact that background is relatively low at energies above few tens of keV. The huge area will guarantee an unprecedented sensitivity allowing to detect (signal-to-noise ratio > 1) transient phenomena even at the shortest temporal scale, mitigating the effects of the quantum-detection process that are blinding our sensitivity when the number of photons detected is small. It might exist a large class of fast transients that remained undiscovered up to date because of the small fluence associated with their short time duration. In the radio band this has been the case of the recently discovered Fast Radio Bursts (FRBs, see [**?**] as a review). Indeed, some theories predict

a high energy counterpart of these compelling phenomena and ***GrailQuest*** is the right instrument for searching these counterparts. ADD HERE THEORY OF ROVELLI-VIDOTTO?

- To monitor all kind of high-energy transients, both galactic and extra-galactic events, such as the flaring activity of magnetars, outbursts of Black-Hole or Neutron Star transients, the occurrence of tidal disruption events (CHECK whether are visible in the high-energy band) and so on. The monitoring of the high-energy sky has been very important in the last years to discover new events and/or peculiar behaviors or for a detailed characterization of already known sources. ***GrailQuest*** will be a large area all-sky monitor , with good-temporal and moderate-energy resolution, able to add important information for the full understanding and the thoroughly study of high-energy transients, whose behavior may give important advances in fundamental physics regarding strong gravity and extremely high-density matter.
- To perform high-quality timing studies of known high-energy pulsators. The most interesting window in this field is certainly the population of millisecond pulsars (accreting and/or transitional and/or rotationally powered, see e.g.[**?**]) and the enigmatic gamma-ray pulsars. Millisecond pulsars often show (transient) X-ray and gamma-ray emission whose properties are not completely understood yet. This emission may be caused by intra-binary shocks of the pulsar emission (consisting of both radiation and high-energy particles) with a wind of matter from the companion star. In this case, a modulation of the X and gamma-ray emission with the orbital period is expected and may be searched for with ***GrailQuest***. Also, the orbital period evolution of these systems is very important to address in order to investigate their formation history and their connection with Low Mass X-ray Binaries, as envisaged by the recycling scenario. Orbital evolution may also be studied in high inclination X-ray binary systems (containing Black Holes or Neutron Stars) where periodic signatures (such as dips and/or eclipses) are observed. Despite the lack of imaging capabilities and no possibility of background rejection, ***GrailQuest*** is capable to detect any (quasi-)periodic signal for which the period is known thanks to folding techniques coupled with a huge collecting area. This makes this instrument an ideal tool to perform timing studies of any kind of high-energy (quasi-)periodic signal.

9 Detector description

The key requirement of a for the a detector in the ***GrailQuest*** contest are an active area of the order of 100 cm2, precision timing of the event down to 10–100 nsec precision, a continuous extension of the energy band for X and soft gamma-rays from few keV to some MeV and a moderate energy resolution in a robust assembly suitable for space environment. A technique for X/gamma detectors widely used in countless space experiments but that is continuously renewed thanks to the evolving of the technology is based on the use of scintillators materials coupled to suitable photodetector and electronics. Nowadays inorganic scintillator materials like Lanthanum Bromide (LaBr3:Ce), GAGG (Gadolinium Aluminium Gallium Garnet) or similar, combine high scintillation light emission with fast response and high efficiency. The choice of the scintillator can already today span in a certain number of materials whose characteristics allow when combined with a fast and efficient photodetector to fullfill ***GrailQuest*** project requirements. The criteria for the choice of scintillator can then take into account parameters like intrinsic low background of the material, non hygroscopic, cost, radiation damage. A fast photodetector for the readout of the scintillation light can be Photomultiplier (PMT) or solid state Silicon-PMT (Si-PM) both devices having a response to a light pulse than can be contained in few nano-sec. The QE of both kind of devices when optically coupled to the above mentioned kind of scintillators, to detect X-rays below 10 keV. The criteria for the choice of the photodetector can take into account the dimension and roughness of the device and its ageing in the radiation environment of the space. The architecture of an ***GrailQuest*** detector con be organized so that the detector itself can be divided in modules of some ten of square cm each so that the whole detector can be assembled to the necessary size adding modules, this will also ease the processing of intense impulsive events reducing the pile-up of signals in the same module.

10 Conclusion: ***GrailQuest*** mission concept

10.1 Summary of requirements from science cases

The scientific requirements from the three main science cases discussed in the previous sections are listed below.

- Achieving arcmin to arcsec uncertainty on GRB localisation of a sizeable number ($\gtrsim 10$) of GRB/yr.
- Achieving a delay time between detection and localisation as short as a few minutes.
- Achieving a sampling of the temporal structure of GRB and other transients down to a fraction of μs.
- Constraining $\Delta t/\Delta E$ at the level of a few micro-seconds at 100 keV for a sizeable sample of GRB (($\gtrsim 10$/yr), a constrain similar to what Fermi provided for 1 GRB since 2008.

This scientific requirements define the following high level technologic requirements:

- Large ($\gtrsim 50$) number of detectors separated by an average distance of several thousands km.
- Collecting area for each detectors of $\gtrsim 100\text{cm}^2$
- Total collecting area of the order of 1m^2
- Energy range of detectors at least 50-300 keV
- Temporal resolution of detectors $\lesssim 10 - 100$ nano-seconds.
- Field of View of each detector $\gtrsim 2$ steradians.
- Capability of the swarm to observe the same point in the sky (within tens of deg) for the longest possible time during each orbit.
- Absolute position reconstruction of each satellite carrying a detector $\lesssim$ a few m.
- Absolute time reconstruction $\lesssim 10 - 30$nano-seconds.
- Capability to download full burst information on short (minutes) timescales (through dedicated ground station and/or Iridium uplink).

10.2 ***GrailQuest***: a modular high energy transient experiment

The scientific and technologic requirements presented above naturally drive the design of the ***GrailQuest*** concept. The full ***GrailQuest*** constellation will include the order of 100 detectors hosted on nano-satellites in Low Earth Orbit with an average separation between the modules of thousands km. The detectors will consist of a scintillator with high sensitivity in the band 50-300 keV (nominal) and temporal resolution 10-100 nano-seconds. The size of each detector would be $\sim 10 \times 10$cm. The field of view of each detector will be several steradians. A trade-off between number of units recording the same event and portion of the sky monitored must be performed. A continuous recording of the data is foreseen onboard. Recorded data are deleted and overwritten unless a burst is detected. In this case, data obtained several seconds before and tens of seconds after the burst are transferred to an on-board memory. Data analysis will be then carried out on Earth after the data from the on-board memory have been downloaded through dedicated Ground Stations and/or the Iridium system.

The biggest advantages of ***GrailQuest*** with respect to standard High Energy Astrophysics experiments are three:

1. modularity;
2. timing accuracy;
3. limited cost and quick development

The first allows: a) to first fly a reduced version of ***GrailQuest*** (say 4-12 units, the ***GrailQuest*** pathfinder) to prove the concept; b) avoid single (or even multiple) point failures: if one or several units are lost the constellation and the experiment is not lost; c) first test the hardware with the first launches and then improve it, if needed, with the following launches. The second allows ***GrailQuest*** to open the new window of micro-second variability in bright transients. Finally, ***GrailQuest*** will exploit commercial off-the-shelf hardware and the trend in reducing the cost of both manufacturing and launching nano-satellites over the next years. ***GrailQuest*** would naturally fit a scheme where production of identical units would follow the development and testing of a first *test unit*. The development of a engineering and qualification models, and all tests at the level of critical components, will be performed only for the *test unit*. For the other units only the flight model will be realised, and these units will be tested only at the system level. All this will bring costs down and speed up the realisation of the full mission.

A technological pathfinder of the ***GrailQuest*** concept has been recently funded by Italian MIUR, which the goal of producing and testing a few units. A research and development program for the payload had been funded by ASI.

References

1. Plato, *Parmenides*, 127b-e
2. B. Russell, *The Principles of Mathematics* (Cambridge University Press, Cambridge, 1927).
3. A. Einstein, *Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen*, Ann. Phys. (Berlin) **322**, 549 (1905)
4. A. Einstein, *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*, Ann. Phys. (Berlin) **17**, 132 (1905).

5. A. Einstein, *Zur Elektrodynamik bewegter Körper*, Ann. Phys. (Berlin) **322**, 891 (1905).
6. P. Bridgman, *The Logic of Modern Physics*, publ. MacMillan, New York (1927).
7. M. Planck, *´Uber irreversible Strahlungsvorgaenge* Sitzungsberichte der K´oniglich Preuischen Akademie der Wisseschaften zu Berlin - Erster Halbband Berlin: Verl. d. Kgl. Akad. d. Wiss., (1899).
8. A.A. Michelson and E.W. Morley, *On the Relative Motion of the Earth and the Luminiferous Ether* (1887). American Journal of Science **34**, 333 (1887).
9. L. Burderi, T. Di Salvo and R. Iaria, *Quantum clock: A critical discussion on spacetime*, Phys. Rev. D **93**, 064017 (2016)
10. S. Hossenfelder, arXiv:1203.6191 (2012)
11. P.J. Garay, Int. J. Mod. Phys. **A10**, 145 (1995)
12. C.A. Mead, Phys. Review **135**, 849 (1964)
13. C.A. Mead, Phys. Review **143**, 990 (1966)
14. T. Yoneya, *Wandering in the Fields*, Eds. K. Kawarabayashiand & A. Ukawa, World Scientific (1987)
15. T. Yoneya, Mod. Phys. Lett. **A4**, 1587 (1989)
16. T. Yoneya, arXiv:hep-th/9707002 (1997)
17. S. Doplicher, K. Fredenhagen, J.E. Roberts, Commun. Math. Phys. **172**, 187 (1995)
18. H.H. Borzeszkowski and H.J. Treder, *The Meaning of Quantum Gravity*, publ. Reidel, Dordrecht (1988)
19. C. Rovelli and L. Smolin, Phys. Rev. Lett. **61**, 1155 (1988)
20. C. Rovelli and L. Smolin, Nucl. Phys. B **331**, 80 (1988)
21. C. Rovelli, *Loop Quantum Gravity*, in Living Reviews in Relativity 1, (1998), http:// www.livingreviews.org/ Articles/ Volume1/ 1998-1rovelli
22. C. Rovelli and L. Smolin, Nucl. Phys. B **442**, 593 (1995); Erratum: Nucl. Phys. B **456**, 734 (1995)
23. A. Ashtekar, and J. Lewandowski, Quantum Theory of Geom- etry I: Area Operators. Class Quant Grav **14** A55 (1997)
24. C. Rovelli, Nucl. Phys. B **405**, 793 (1993)
25. C. Rovelli and S. Speziale, Phys. Rev. D **67**, 4019 (2003)
26. D. Mattingly, Living Rev. Relativity, **8**, 5 (2005)
27. G. Amelino-Camelia and L. Smolin, Phys. Rev. D **80**, 084017 (2009)
28. S. Liberati, *Tests of Lorentz invariance: a 2013 update* (2013)
29. G. Amelino-Camelia *et al.*, *Tests of Quantum Gravity from Observations of Gamma-Ray Bursts*, Nature **393**, 763 (1998)
30. Abbott, B.P. et al., Observation of Gravitational Waves from a Binary Black Hole Merger, Physical Review Letters, **116**, 061102 (2016)
31. Abbott, B.P. et al., GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2, Physical Review Letter, **118**, 221101 (2017a)
32. Abbott, B.P. et al., GW170814 : A three-detector observation of gravitational waves from a binary black hole, Physical Review Letter, **119**, 161101 (2017b)
33. Abbott, B.P. et al., GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Physical Review Letter, **119**, 161101 (2017c)
34. Abbott, B.P. et al., Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, Astrophysical Journal Letters, **848**, L13 (2017d)
35. Abbott, B.P. et al., Multi-messenger Observations of a Binary Neutron Star Merger, Astrophysical Journal Letters, **848**, L12 (2017e)
36. Abdo, A.A. et al., Fermi observations of high-energy gamma-ray emission from GRB080916C, Science, **323**, 1688 (2009a)
37. Abdo, A.A. et al., A limit on the variation of the speed of light arising from quantum gravity effects, Nature, **706**, 138 (2009)
38. Amelino-Camelia, G. et al. Tests of quantum gravity from observations of γ-ray bursts, Nature, **395**, 525 (1998)
39. Amelino-Camelia, G., Are we at the dawn of quantum-gravity phenomenology?, Lecture Notes in Physics, **541**, p.1, arXiv:gr-qc/9910089
40. Amelino-Camelia, G. and Smolin, L. Prospects for constraining quantum gravity dispersion with near term observations, arXiv:0906.3731 (2009)
41. Amelino-Camelia, G. In vacuo dispersion features for gamma-ray-burst neutrinos and photons, Nature AStronomy, **1**, 139 (2017a)
42. Amelino-Camelia, G. In-vacuo-dispersion-like spectral lags in gamma-ray bursts, arXiv:1707.02413

43. Bhat, P.N. et al., Temporal Deconvolution Study of Long and Short Gamma-Ray Burst Light Curves, The Astrphysical Journal, **744**, 141 (2012)
44. Bloom, J. et al., Observations of the Naked-Eye GRB080219B: Implications on Nature's brightest explosions, The Astrophysical Journal, **691**, 723 (2009)
45. Costa, E. et al., Discovery of an X-ray afterglow associated with the γ-ray burst of 28 february 1997, Nature, **387**, 783 (1997)
46. Dichiara, S. et al. Average power density spectrum of long GRBs detected with BeppoSAX/GRBM and with Fermi/GBM, Montly Notices of the Royal Astronomy Society, **431**, 3608 (2013)
47. Farr, W. M. et al., Distinguishing spin-aligned and isotropic black hole populations with gravitational waves, Nature, **548**, 426 (2017)
48. Fenimore, E.E. and Ramirez-Ruiz, E. Redshifts For 220 BATSE Gamma-Ray Bursts Determined by Variability and the Cosmological Consequences, arXiv:astro:ph/000417v2 2000
49. Fiore, F. et al. Probing the Warm Intergalactic Medium through Absorption against Gamma-Ray Burst X-Ray Afterglows, The Astrphysical Journal Letters, **544**, L7 (2000)
Kobayashi, S. et al., Can Internal Shocks Produce the Variability in Gamma-Ray Bursts? The Astrophysical Journal, **490**, 92 (1997)
50. MacLachlan, G,A. et al. Minimum variability time-scales of long and short GRBs, Montly Notices of the Royal Astronomy Society, **432**, 857
51. Metzger, M.R. et al., Spectral constraints on the redshift of the optical counterpart of the γ-ray burst og 8 May 1997, Nature, **387**, 878 (1997)
52. Meegan, C. et al., The Fermi Gamma-ray Burst monitor, The Astrophysical Journal, **702**, 791 (2009)
53. Morsony, B.J, et al. The Origin and Propagation of Variability in the Outflows of Long-duration Gamma-ray Bursts, The Astrophysical Journal, **723**, 267 (2010)
54. Nakar, E. and Piran, T. Gamma-Ray-Burst light curves-another clue on the inner engine, The Astrophysical Journal Letters, **572**, L139 (2002)
55. Phinney, E.,S. Finding and Using Electromagnetic Counterparts of Gravitational Wave Sources, A white paper for the Astro2010 Decadal Review, arXiv:0903.0098 (2009)
56. Sari, R. and Piran, T. Cosmological gamma-ray bursts: internal versus external shocks, Montly Notices of the Royal Astronomy Society, **287**, 110 (1997)
57. Spada, M. Analysis of Temporal Features of Gamma-Ray Bursts in the Internal Shock Model, The Astrophysical Journal, **537**, 824 (2000)
58. Ramirez-Ruiz, E. and Fenimore, E.E. Pulse Width Evolution in Gamma-Ray Bursts: Evidence for Internal Shocks, The Astrophysical Journal, **539**, 712 (2000)
59. Troja, E. et al., The X-ray counterpart to the gravitational wave event GW 170817, Nature, in press, arXiv:1710.05433
60. van Paradijs, J. et al., Transient optical emission from the error box of the γ-ray burst of 28 February 1997, Nature, **386**, 686 (1997)
61. Walker, K.C. et al. Gamma-Ray Bursts Have Millisecond Variability, Astrophysical Journal, **537**, 264 (2000)
62. Xu, H and Ma, B. Q. Astroparticle. Physics. **82**, 72 (2016)
63. Xu, H and Ma, B. Q. Physics. Letters. B, **760**, 602 (2016)
64. Jacob, U. and Piran, T. Lorentz-violation-induced arrival delays of cosmological particles, JCAP, 1, 031 (2008)
65. Revnivstev, M. G. Measurements of the Cosmic X-ray Background of the Universe and the MVN Experiment, *Astronomy Letters*, **40**, 667 (2014)
66. Cucchiara, A. Levan, A.J. Fox, D.B. Tanvir, N.R. Ukwatta, T.N. et al., A PHOTOMETRIC REDSHIFT OF $z \sim 9.4$ FOR GRB 090429B, The Astrophysical Journal, **736**, 7 (2011)
67. M. McConnell, D. Forrest, W.T. Vestrand, M. Finger, Using BATSE to measure gamma-ray burst polarization, in Gamma-ray bursts: 3rd Huntsville symposium. AIP Conference Proceedings, **384**, 851 (1996)
68. D. R. Lorimer, A decade of fast radio bursts, Nature Astronomy, **2**, 860 (2018)
69. S. Campana and T. Di Salvo, Accreting Pulsars: Mixing-up Accretion Phases in Transitional Systems, in The Physics and Astrophysics of Neutron Stars, Astrophysics and Space Science Library, **457**, 149 (2018).