The HERMES project
High Energy Rapid Modular Ensemble of Satellites
Probing Space-Time Quantum Foam
and
Hunting for Gravitational Wave Electromagnetic Counterparts

Luciano Burderi, University of Cagliari
Tiziana Di Salvo – University of Palermo
Andrea Sanna, Alessandro Riggio – University of Cagliari
Fabrizio Fiore, Alessandro Papitto – INAF – Rome Astronomical Observatory
and many others…

Please, visit our website:
http://hermes.dsf.unica.it
The Multi-Messenger Astronomy Paradox

One of the most thrilling research fields in Science: the whole field based on ONE discovery: GRB 170817A - GW170817 connection

S1: within 2025 LIGO – Virgo – KAGRA GW antennas will provide: detectability of NS–NS mergers events like GW170817 within ≈ 200 Mpc localization within:
≈ 100 square deg (LIGO – Virgo)
≈ 10 square deg (LIGO – Virgo – KAGRA)
(quoting Marica Branchesi talk)

GBM would not have been able to detect an event like GRB 170817A but 60% fainter (quoting Peter Veres talk), which means roughly:
S2: Kilonova events seen at angles ≥ 25 degrees (quoting Eleonora Troja talk) undetectable by GBM for D ≥ 1.4 × D(GRB 170817A) ≈ 60 Mpc

S1 + S2 ⇒ No EM counterpart detected, no party!
(quoting George Clooney)

We need a All-sky Monitor at least 10×GBM Area for letting Multi-Messenger Astronomy to develop from infancy to maturity!
HERMES in a nutshell

High Energy Rapid Modular Ensemble of Satellites

Aims:
all Sky Monitor for fast and accurate detection of the position of bright, transient, high-energy events and All Sky Monitor of known bright sources (timing):
• GRBs
• GW events
• high-energy counterparts of Fast Radio Bursts
• flares from Magnetars
• fine GRB temporal structure to perform the first dedicated experiment in Quantum Gravity

How:
temporal triangulation of signals detected by a swarm of LEO nano/micro satellites equipped with:
• keV-Mev scintillators,
• sub μs time resolution
• temporal triangulation

Pros:
• modularity,
• limited cost,
• quick development
Principles of temporal triangulation

Determination of source position through delays in Time of Arrival (ToA) of an impulsive (variable) signal over 3 (or more) spatially separate detectors

position of the source in the sky:
α, δ (2 parameters, \( N_{\text{PAR}} = 2 \))

\[
i = 1, \ldots, N_{\text{SATELLITES}} \\
j = 1, \ldots, N_{\text{SATELLITES}}
\]

\[
\text{DEL}_{ij} = \text{ToA}(i) - \text{ToA}(j)
\]

\[
\text{DEL}_{ij} = - \text{DEL}_{ji} \; ; \; \text{DEL}_{ii} = - \text{DEL}_{jj} = 0
\]

Number of (non trivial) different \( \text{DEL}_{ij} \):
\[
N_{\text{DELAYS}} = N_{\text{SATELLITES}} \times (N_{\text{SATELLITES}} - 1) / 2
\]

Number of independent \( \text{DEL}_{ij} \):
\[
N_{\text{IND}} = N_{\text{SATELLITES}} - 1
\]

Accuracy in determining \( \alpha \) and \( \delta \) with \( N_{\text{SATELLITES}} \):
\[
\sigma_\alpha \approx \sigma_\delta = c \frac{\sigma_{\text{ToA}}}{\text{<baseline>}} \times (N_{\text{IND}} - N_{\text{PAR}} + 1)^{-1/2}
\]
The Gamma-Ray Burst phenomenon

- sudden and unpredictable bursts of hard-X / soft gamma rays with huge flux
- most of the flux detected from 10⁻²⁰ keV up to 1–2 MeV,
- fluences for very bright GRB (about 3/yr) 25 counts/cm²/s (GRB 130427A 160 counts/cm²/s)
- bimodal distribution of duration (0.1–1.0 s & 10.0–100.0 s)
- measured rate (by an all-sky experiment on a LEO satellite): ~0.8/day (estimated true rate ~2/day)
- evidence of submillisecond structures
The Gamma-Ray Burst phenomenon

Millisecond variability (minimum variability time-scale, MacLachlan et al. 2013)
Short: 3 msec (wavelet techniques)
Long: 30 msec (wavelet techniques)
Internal shock model (ultarelativistic, $\gamma \approx 10^2 \div 10^3$, colliding shocks)

BeppoSAX GRBM data

Fermi GBM (8 keV - 40 MeV)

$T_{90}$ vs $\tau_\beta$ (Observer Frame)

$T_{90}$ vs $T_{90}/\tau_\beta$ (Observer Frame)
Number of GRB and Fluxes

Short GRBs:
Duration: 0.2 sec,
Counts (50-300 MeV): 8 c/cm²/s
Averaged photon energy: \((E_{\text{max}} \times E_{\text{min}})^{1/2} = 122\) keV
Fluence: \(0.2 \times 8 \times 122\) keV/cm² = \(3 \times 10^{-7}\) erg/cm²

14 Short GRB burst per year with count rate > 8 c/s
Simulations of a bright Short GRB (50 – 300 keV)

Background: 0.43 c/s/cm²/steradians

Background for 2 steradians FOV: 0.86 c/cm²/s

Proton fluxes in LEO (580 km): 0.165 c/cm³/s

Activation in equatorial LEO (580 km): \( \leq 0.3 \) c/cm³/s (not included)

Burst duration: 0.2 sec

Source count rate: 7.875 ph/cm²/s

Total number of photons: 178

Exponential shot rate: 100 shot/s

Exponential shot decay time: 1 msec

Band 50-300 keV

Effective area: 100 cm²
Delays from cross-correlation analysis

Temporal resolution: 200 µs
Standard CCF (red)

2 Lightcurves of a short GRB
Δt = 0.25 s
A = 100 cm²
φ_{GRB} = 8 phot/s/cm²
φ_{BCK} = 0.8 phot/s/cm²
N_{PHOT} = 220
λ_{SHOT} = 100 shot/s
τ_{SHOT} = 1 ms
τ_{KERN} = 0.1 ms

Temporal resolution: 1 µs
Standard CCF (black)
Kernel-modified CCF (red)

2 Lightcurves of a short GRB
Δt = 0.25 s
A = 100 cm²
φ_{GRB} = 8 phot/s/cm²
φ_{BCK} = 0.8 phot/s/cm²
N_{PHOT} = 220
λ_{SHOT} = 100 shot/s
τ_{SHOT} = 1 ms
τ_{KERN} = 0.1 ms

Cross-correlation

Delay (s)
Delays from cross-correlation analysis

Histogram of maxima of Kernel-modified CCF (1200 simulations of 2 short GRB)
\[ \Delta t = 0.25 \text{ s}; \varphi_{GRB} = 8 \text{ phot/s/cm}^2; \varphi_{BCK} = 0.8 \text{ phot/s/cm}^2; \lambda_{SHOT} = 100 \text{ shot/s}; \]
\[ \tau_{SHOT} = 1 \text{ ms}; A = 100 \text{ cm}^2; \tau_{KERN} = 0.1 \text{ ms}; N_{PHOT} = 220; \sigma_{CCF} = 74 \mu s \]

Cross-correlation accuracy:
- 3.0 ÷ 60 µsec (Long and Short GRB with millisecond time variability, 40% of bright)

\[ \sigma_{ToA} = 74 \mu s / \sqrt{N_{phot} / 220} \]
HERMES mission concept: a swarm of nano/micro satellites

Tens/hundreds nano/micro satellites each equipped with $\sim 300 \text{ cm}^2$ scintillators (keV – MeV energy band)

HERMES experiment concept: temporal triangulation & increase the effective area

Perform temporal triangulation to derive positions of bright, transient, high-energy events

When a cross-correlation successful $\rightarrow$ add signal from different units
Total Area $\sim 100 \times (100-300 \text{ cm}^2) \sim 1-3 \text{ m}^2$

$\rightarrow$ First possibility to study GRB time structure on very short time scale (sub-$\mu$s $\div$ ms) with excellent statistics
Determination of source position through delays

Accuracy in determining $\alpha$ and $\delta$ with $N_{\text{SATellites}}$:

$$\sigma_\alpha \approx \sigma_\delta = c \frac{\sigma_{\text{ToA}}}{\langle \text{baseline} \rangle} \times (N_{\text{SATellites}} - 3)^{-1/2}$$

$$\sigma_{\text{ToA}} = 236 \, \mu s/ (N_{\text{PHOT}}/220)^{1/2}$$

maximum baseline = $2 \times (R_{\text{EARTH}} + H_{\text{SATellite}}) = 2 \times (6371 + 580) \, \text{km}$

$\langle \text{baseline} \rangle$ = maximum baseline / 2

$N_{\text{PHOT}}(\text{Bright Long GRB}) \approx 100 \times N_{\text{PHOT}}(\text{Bright Short GRB})$

$A = 100 \, \text{cm}^2 \implies N_{\text{PHOT}}(\text{bright short GRB}) \approx 220$

Bright Short GRB

$\sigma_\alpha \approx \sigma_\delta = 35 \, \text{arcmin} \, (3 \, \text{satellites})$

$\sigma_\alpha \approx \sigma_\delta = 5.1 \, \text{arcmin} \, (50 \, \text{satellites})$

$\sigma_\alpha \approx \sigma_\delta = 3.5 \, \text{arcmin} \, (100 \, \text{satellites})$

Bright Long GRB

$\sigma_\alpha \approx \sigma_\delta = 3.2 \, \text{arcminute} \, (3 \, \text{satellites})$

$\sigma_\alpha \approx \sigma_\delta = 32 \, \text{arcsec} \, (50 \, \text{satellites})$

$\sigma_\alpha \approx \sigma_\delta = 22 \, \text{arcsec} \, (100 \, \text{satellites})$
Gravitational Waves detected by LIGO on September the 14th 2015

CHIRP shape and evolution
GW 170817 NS-NS coalescence: EM counterpart GRB170817
GW Triangulation & EM counterparts (Fermi GBM, INTEGRAL)

Large volumes to survey → too many candidates

Successful strategy:

a) all sky continuous observations of HE transients
→ the probability of observing an uncorrelated HE simultaneous event is negligible

b) improve the accuracy of source position
→ reduce the number of candidates

Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg², light green), the initial LIGO-Virgo localization (31 deg², dark green), IPN triangulation from the time delay between Fermi and INTEGRAL (light blue), and Fermi GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hours after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

Chile about 10 hours after the merger with an altitude above the horizon of about 45 degrees.

The One-Meter, Two-Hemisphere (1M2H) team was the first to discover and announce (Aug 18 01:05 UTC; Coulter et al. 2017a) a bright optical transient in an i-band image acquired on Aug 17 at 23:33 UTC (tc+10.87 hr) with the 1 m Swope telescope at Las Campanas Observatory in Chile. The team used an observing strategy (Gehrels et al. 2016) that targeted known galaxies (from White et al. 2011) in the three-dimensional LIGO-Virgo localization taking into account the galaxy stellar mass and star-formation rate (Coulter et al. 2017). The transient, designated Swope Supernova Survey 2017a (SSS17a), was i = 17.057 ± 0.018 mag (Aug 17 23:33 UTC, tc+10.87 hr) and did not match any known asteroids or supernovae. SSS17a (now with the IAU designation AT2017gfo) was located at (J2000.0) = 13 h 09 m 48 s 0.085 ± 0.018, All apparent magnitudes are AB and corrected for the Galactic extinction in the direction of SSS17a (E(B-V)=0.109 mag; Schlafly & Finkbeiner 2011).

Five other teams took images of the transient within an hour of the 1M2H image (and before the SSS17a announcement) using different observational strategies to search the LIGO-Virgo sky localization region. They reported their discovery of the same optical transient in a sequence of GCNs: the Dark Energy Camera (01:15 UTC; Allam et al. 2017), the Distance Less Than 40 Mpc survey (01:41 UTC; Yang et al. 2017a), Las Cumbres Observatory (04:07 UTC; Arcavi et al. 2017a), the Visible and Infrared Survey Telescope for Astronomy (05:04 UTC; Tanvir et al. 2017a), and MASTER (05:38 UTC; Lipunov et al. 2017a). Independent searches were also carried out by the Rapid Eye Mount (REM-GRAWITA, optical, 02:00 UTC; Melandri et al. 2017a), Swift UVOT/XRT (ultraviolet, 07:24 UTC; LIGO + Virgo).
GW Triangulation & EM counterparts (Fermi GBM, INTEGRAL, HERMES Pathfinder)

band 50-300 keV
3 satellites each of effective area: 100 cm²
$\sigma_{\text{ToA}} \approx 1$ ms (estimated for S/N $\approx 1$)
positional accuracy: 2.5 deg
HERMES Pathfinder Photon Detector Unit (PDU) and Modular Detector Unit (MDU = 4 PDU)

- Scintillator Crystal size: 2x2x1 cm
- Crystal type: GAGG (Gadolinium Aluminium Gallium Garnet)
- Photo detector: SDD (segmented: 4 SSD 1x1 cm)
- Energy range: 4 keV – few MeV with GAGG
- Energy resolution: ~ 15% at 30 keV
- Effective area: ~ 4 cm²
- FOV: 2 steradians at low energies
- Temporal resolution: 0.01 – 0.1 µs

Figure 1 Schematic view of one HERMES modular detector unit (MDU), made by four PDUs.

<table>
<thead>
<tr>
<th>GAGG characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>6.63</td>
</tr>
<tr>
<td>Zeff</td>
<td>52</td>
</tr>
<tr>
<td>Decay time (nsec)</td>
<td>92f – 174s</td>
</tr>
<tr>
<td>Photons/keV</td>
<td>56</td>
</tr>
<tr>
<td>Wavelength peak (nm)</td>
<td>520</td>
</tr>
<tr>
<td>Energy resolution (662 keV FWHM) (%)</td>
<td>5–6</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>No</td>
</tr>
<tr>
<td>Radioactive</td>
<td>No</td>
</tr>
</tbody>
</table>
HERMES Pathfinder Detectors (3U nanosatellites)

Detectors on board of each nanosatellite (3U)
• 16 PDU on each nanosatellite
• 2×2 array of 4 MDU (modular detector unit made by 4 PDUs) 64 cm² effective area per array

• Gyroscope Stability on 3 axes
• Collimators ≈ 2 steradians

On board Systems:

Data recording:
• continuous on temporary buffer
• trigger capability for data recording
• continuous download of data (VHF) for monitoring of known bright sources

Data download:
• VHF data transmission
• IRIDIUM constellation for data transmission
this project and represent a significant enhancement of the detector system with respect to its baseline design.

2. The interface of the GPS receiver with a local oscillator. Our baseline solution is to use a commercial GPS providing the absolute time and a local oscillator on the second stage FEE, see Figure 3. This may achieve precisions of the order of hundreds nanoseconds. While this is enough to fulfil the HERMES timing requirements (1 µsec or slightly less), this does not fully exploit the extremely good timing performances of the GAGG crystals (decay time of ~100 nanoseconds). Reaching a timing precision of tens of nanoseconds would allow a perfect sampling of the GAGG decay time. We will perform a trade-off study to understand which are the advantages of developing an ad hoc board including both a GPS and a local oscillator, and if this architecture would allow pushing the accuracy toward the goal of tens of nanoseconds.

Three units will then be realised and tested in the framework of this project. The injection in orbit of these additional units will again be provided by ASI, as piggy-bags of VEGA flights at the end of this project (second half of 2021, first half 2022).

Design of the Mission Operation Centre and of the Scientific Operation Centre is part of this project, as well as the development of all complex data analysis software for the transient position determination, including accurate determination of satellite position through the GPS system. MOC and SOC operations will be provided by ASI, as well as data archive and data processing in the framework of the ASI SSDC.

3. The HERMES Full Constellation will be studied in detail in the framework of this project. We will use the experience accumulated from the development of the HERMES-SP experiment to design a robust mission concept. A feasibility study (Phase A) will be carried out, including both payload and SM. Politecnico di Milano will adopt the Concurrent Design approach to cope with the HERMES FC architectural complexity. The HERMES-SP project will put the Consortium in the best position to prepare a proposal to the ESA and/or to National funding Agencies for the realisation of the full constellation. Figure 7 shows the overall incremental philosophy adopted to get to the final full constellation, splitting the final goal in intermediate smaller objectives to verify, validate and strengthen the attainable science quality.

Funding status at 2018, July the 17th

ASI (Italian Space Agency) – 23/12/2016: € 500,000
MIUR (Italian Ministry of University and Research) and ASI – 29/11/2017: € 1,650,915 (MIUR) € 815,085 (ASI)
ASI (Italian Space Agency) – internal funding 05/02/2019 € 1,900,000

Total Funding (at 14/02/2019): € 8,184,450
The HERMES Project: performances of subsequent missions

Pathfinder + Scientific:
- 8/10 3U Cubesats piggyback of bigger satellites launched from ISS
- 1/2 detectors located on ISS
- ~10 arcminutes position of ~35 Short 250 Long GRB/year

Full configuration:
- ~50-100 3/12U Cubesats
- ~10 arcsec position of ~75 Short 500 Long GRB/year
- 1-3 m² collecting area

Future:
- ~(ten)thousands of detector
- From LEO to HEO, Moon and beyond
- (sub?)arcsec position, best quantum space time tests (see below)

Startup OneWeb
- 640 nanosat in LEO production:
- 15 nanosat/week

Starlink (Space X)
- 12,000 satellites by mid-2020
Why HERMES now

**PROS:**

- modularity (avoid single point failures, state-of-the-art hardware)
- limited cost (piggyback of bigger satellites, boarded on ISS with cargo refurbishment, off the shelf cheap hardware + in house components)
- quick development (< 5 years to fly first satellites)

**Breakthrough scientific case:**

- All-Sky Monitor in HE (keV-MeV)
- EM counterparts of GW events
- Study of GRB variability on unprecedented short temporal scale (sub-μs): physics of the inner engine
- First dedicated experiment of Quantum Gravity (see below)

VHF data download from a HERMES satellite
Quantum Gravity: The Space–Time Uncertainty Relation
$\Delta r \Delta t > G\hbar/c^4$

PHYSICAL REVIEW D 93, 064017 (2016)

Quantum clock: A critical discussion on spacetime

Luciano Burderi,¹,* Tiziana Di Salvo,² and Rosario Iaria²

¹Dipartimento di Fisica, Università degli Studi di Cagliari,
SP Monserrato-Sestu, KM 0.7, 09042 Monserrato, Italy
²Dipartimento di Fisica e Chimica, Università degli Studi di Palermo,
via Archirafi 36, 90123 Palermo, Italy
(Received 5 July 2012; published 8 March 2016)

We critically discuss the measure of very short time intervals. By means of a Gedankenexperiment, we describe an ideal clock based on the occurrence of completely random events. Many previous though experiments have suggested fundamental Planck-scale limits on measurements of distance and time. Here we present a new type of thought experiment, based on a different type of clock, that provide further support for the existence of such limits. We show that the minimum time interval $\Delta t$ that this clock can measure scales as the inverse of its size $\Delta r$. This implies an uncertainty relation between space and time $\Delta r \Delta t > G\hbar/c^4$, where $G$, $\hbar$, and $c$ are the gravitational constant, the reduced Planck constant, and the speed of light, respectively. We outline and briefly discuss the implications of this uncertainty conjecture.

DOI: 10.1103/PhysRevD.93.064017
The Uncertainty Relation $\Delta r \Delta t > \frac{G\hbar}{c^4}$ and the space-time diagram for the intervals

**TIMELIKE INTERVALS**

$c\Delta t$

**SPACELIKE INTERVALS**

$\Delta r \times c\Delta t = \frac{G\hbar}{c^3}$

$\Delta t_{\text{MIN}} = \left(\frac{G\hbar}{c^5}\right)^{1/2}$

Planck Time

$\Delta r_{\text{MIN}} = \left(\frac{G\hbar}{c^3}\right)^{1/2}$

Planck Length
Geometrical Structure of Space–Time

Minkowski metric: preserving Lorentz Invariance

\[ \Delta s^2 = 0 \]

(light – massless particle)

\[ \Delta s^2 = (ct)^2 - r^2 \]

is invariant under Lorentz Transformations

The general form of a hyperbola

A plot of the hyperbola that represents all values of \( t \) and \( x \) that observers might measure for a given spacetime interval.
The new Uncertainty Relation and the Minkowski metric: preserving Lorentz Invariance

\[ \Delta s^2 = (ct)^2 - r^2 \]

Invariant under Lorentz Transformations

\[ |\Delta s^2| \geq \sigma_{\Delta s^2} \approx R_{\text{PLANCK}}^2 = c^2 T_{\text{PLANCK}}^2 \]

Massless Particles \( \xrightarrow{\text{Lorentz Invariance, not vice versa!}} \)

Massive Photons? (Proca action)
Quantum Gravity
(Massive Photons or Lorentz Invariance Violation)

MP or LIV predictions:

\[ |v_{\text{phot}}/c - 1| \approx \xi \frac{E_{\text{phot}}}{(M_{\text{QG}} c^2)^n} \]

\[ \xi \approx 1 \]

\( n = 1, 2 \) (first or second order corrections)

\[ M_{\text{QG}} = \zeta m_{\text{PLANCK}} \quad (\zeta \approx 1) \]

\[ m_{\text{PLANCK}} = \left( \frac{hc}{2\pi G} \right)^{\frac{1}{2}} = 21.8 \times 10^{-6} \text{ g} \]

Implications for travel time of photons:

\[ \Delta t_{\text{MP/LIV}} = \xi \left( D_{\text{TRAV}}/c \right) \left[ \Delta E_{\text{phot}}/(M_{\text{QG}} c^2) \right]^n \]

\[ D_{\text{TRAV}}(z) = \left( c/H_0 \right) \int_0^z d\beta \frac{(1+\beta)}{[\Omega_\Lambda+(1+\beta)^3 \Omega_M]^{1/2}} \]
Fermi GBM & LAT detection of short ($\Delta T<1$ s) GRB 090510
$z = 0.903(3)$, $d = 1.8 \times 10^{28}$ cm
($\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$, $h = 0.71$)
(Abdo et al. 2009)

“Cleanest” constraints based on one photon detected at 31 GeV
$\Delta t_{31\text{GeV}} \leq 859$ ms (+30 ms because GRB started 30 ms before 0)
$\delta t/\delta E \leq 30$ ms/GeV (35 MeV – 31 GeV)

LIV predictions:
Relative Locality Models (Freidel, Smolin 2011): $\xi = \frac{1}{2}$ ; n=1

Data of GRB 090510 imply:
$M_{\text{QG}} \geq 0.595 \ m_{\text{PLANCK}}$  ($\Delta t_{31\text{GeV}} \leq 859 + 30$ ms; $E_{\text{ph}} \geq 28$ GeV)
$M_{\text{QG}} \geq 0.610 \ m_{\text{PLANCK}}$  ($\delta t/\delta E \leq 30$ ms/GeV)

Caveats, assumptions:
i) photon at 31 GeV emitted after $t_{\text{START GRB}} = -30$ ms (not before)
ii) physical delays in emission process (e.g. comptonization) not considered

Solution to effectively probe SpaceTime structure:
cross-correlation of GRB lightcurves at different (close) energies.
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Solution to effectively probe SpaceTime structure:
cross-correlation of GRB lightcurves at different (close) energies
Robust Constraint on Lorentz Violation Using Fermi-LAT Gamma-Ray Burst Data

John Ellis\textsuperscript{a}, Rostislav Konoplich\textsuperscript{c,d}, Nikolaos E. Mavromatos\textsuperscript{a,e}, Linh Nguyen\textsuperscript{d}, Alexander S. Sakharov\textsuperscript{c,d,f}, Edward K. Sarkisyan-Grinbaum\textsuperscript{f,g}

\textsuperscript{a} Theoretical Particle Physics and Cosmology Group, Physics Department, King’s College London, Strand, London WC2R 2LS, United Kingdom
\textsuperscript{b} National Institute of Chemical Physics & Biophysics, R¨ avala 10, 10143 Tallinn, Estonia; Theoretical Physics Department, CERN, CH-1211 Gen`eve 23, Switzerland
\textsuperscript{c} Department of Physics, New York University 726 Broadway, New York, NY 10003, United States of America
\textsuperscript{d} Physics Department, Manhattan College 4513 Manhattan College Parkway, Riverdale, NY 10471, United States of America
\textsuperscript{e} Currently also at: Department of Theoretical Physics and IFIC, University of Valencia - CSIC, Valencia, E-46100, Spain
\textsuperscript{f} Experimental Physics Department, CERN, CH-1211 Gen`eve 23, Switzerland
\textsuperscript{g} Department of Physics, The University of Texas at Arlington 502 Yates Street, Box 19059, Arlington, TX 76019, United States of America

Abstract

Models of quantum gravity suggest that the vacuum should be regarded as a medium with quantum structure that may have non-trivial effects on photon propagation, including the violation of Lorentz invariance. Fermi Large Area Telescope (LAT) observations of gamma-ray bursts (GRBs) are sensitive probes of Lorentz invariance, via studies of energy-dependent timing shifts in their rapidly-varying photon emissions. In this paper we analyze the Fermi-LAT measurements of high-energy gamma rays from GRBs with known redshifts, allowing for the possibility of energy-dependent variations in emission times at the sources as well as a possible non-trivial refractive index \textit{in vacuo} for photons. We use statistical estimators based on the irregularity, kurtosis and skewness of bursts that are relatively bright in the 100 MeV to multi-GeV energy band to constrain possible dispersion effects during propagation. We find that the energy scale characterizing a linear energy dependence of the refractive index should exceed either $8.4 \times 10^{17}$ GeV or $2.4 \times 10^{17}$ GeV. We have also made

\begin{align*}
M_{\text{QG}} &= \zeta m_{\text{PLANCK}} \\
\zeta &\geq 27
\end{align*}

Conclusions:

index for photons. Depending on the method of consolidation of the results for individual sources, we find that the energy scale $M_1$ characterizing a linear energy dependence of the refractive index should exceed either $8.4 \times 10^{17}$ GeV or $2.4 \times 10^{17}$ GeV. We have also made
\[
\Delta t_{\text{MP/LIV}} = \zeta \left( \frac{D_{\text{TRAV}}}{c} \right) \left[ \Delta E_{\text{phot}} / (M_{\text{QG}} c^2) \right]^n
\]

\[
\frac{dN_E(E)}{dA \, dt} = F \times \left\{ \begin{array}{l}
\left( \frac{E}{E_B} \right)^\alpha \exp\{- (\alpha - \beta)E/E_B \}, \ E \leq E_B, \\
\left( \frac{E}{E_B} \right)^\beta \exp\{- (\alpha - \beta) \}, \ E \geq E_B.
\end{array} \right.
\]

\[
D_{\text{TRAV}}(z) = (c/H_0) \int_0^z d\beta \frac{(1+\beta)}{[\Omega_\Lambda + (1+\beta)^3 \Omega_M]^{1/2}}
\]

\[
E_{\text{CC Short}} = 50 \mu s / \sqrt{N_{\text{phot}} / 221}
\]

**Short GRB** – 8.00 (0.86 BCK) c/s (50 ÷ 300 keV) \( \Delta t = 25 \) s

A = 10\(^4\) cm\(^2\) → 100 nano – satellites of A = 10\(^2\) cm\(^2\)

<table>
<thead>
<tr>
<th>Energy band (MeV)</th>
<th>( E_{\text{AVE}} ) (( \beta = -2.5 )) MeV</th>
<th>( N ) (( \beta = -2.5 )) photons</th>
<th>( E_{\text{CC}}(N) ) (( \beta = -2.0 )) ( \mu s )</th>
<th>( N ) (( \beta = -2.0 )) photons</th>
<th>( E_{\text{CC}}(N) ) ( \mu s )</th>
<th>( \Delta T_{\text{LIV}} ) (( \xi = 1.0, \ \zeta = 1.0 )) ( \mu s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005 – 0.025</td>
<td>0.0112</td>
<td>3.80 \times 10^4</td>
<td>3.80</td>
<td>3.02 \times 10^4</td>
<td>4.30</td>
<td>0.04</td>
</tr>
<tr>
<td>0.025 – 0.050</td>
<td>0.0353</td>
<td>1.40 \times 10^4</td>
<td>6.20</td>
<td>1.17 \times 10^4</td>
<td>6.90</td>
<td>0.13</td>
</tr>
<tr>
<td>0.050 – 0.100</td>
<td>0.0707</td>
<td>1.10 \times 10^4</td>
<td>7.10</td>
<td>9.98 \times 10^3</td>
<td>7.40</td>
<td>0.27</td>
</tr>
<tr>
<td>0.100 – 0.300</td>
<td>0.1732</td>
<td>8.98 \times 10^3</td>
<td>7.90</td>
<td>1.00 \times 10^4</td>
<td>7.40</td>
<td>0.66</td>
</tr>
<tr>
<td>0.300 – 1.000</td>
<td>0.5477</td>
<td>2.07 \times 10^3</td>
<td>16.40</td>
<td>3.82 \times 10^3</td>
<td>12.00</td>
<td>2.09</td>
</tr>
<tr>
<td>1.000 – 2.000</td>
<td>1.4142</td>
<td>2.63 \times 10^2</td>
<td>45.60</td>
<td>8.20 \times 10^2</td>
<td>26.00</td>
<td>5.40</td>
</tr>
<tr>
<td>2.000 – 5.000</td>
<td>3.1623</td>
<td>1.07 \times 10^2</td>
<td>71.90</td>
<td>4.92 \times 10^2</td>
<td>33.50</td>
<td>12.07</td>
</tr>
<tr>
<td>5.000 – 50.00</td>
<td>15.8114</td>
<td>3.52 \times 10^1</td>
<td>125.40</td>
<td>2.95 \times 10^2</td>
<td>43.30</td>
<td>60.35</td>
</tr>
</tbody>
</table>

\[ \Delta T_{\text{LIV}} (\xi = 1.0, \ \zeta = 1.0) \]
\[ \Delta t_{\text{MP/LIV}} = \xi \left( \frac{D_{\text{TRAV}}}{c} \right) \left( \frac{\Delta E_{\text{phot}}}{M_{\text{QG} c^2}} \right)^n \]

\[
\frac{dN(E)}{dA \, dt} = F \times \begin{cases} 
\left( \frac{E}{E_B} \right)^\alpha \exp\{- (\alpha - \beta) E/E_B\}, & E \leq E_B, \\
\left( \frac{E}{E_B} \right)^\beta \exp\{- (\alpha - \beta)\}, & E \geq E_B.
\end{cases}
\]

\[ D_{\text{TRAV}}(z) = (c/H_0) \int_0^z d\beta \left( 1 + \beta \right)/[\Omega_\Lambda + (1 + \beta)^3 \Omega_M]^{1/2} \]

**GRB & Quantum Gravity**

**Short GRB** – 8.00 (0.86 BCK) c/s (50 ÷ 300 keV) \( \Delta t = 25 \) s

A = 4 \times 10^4 \text{ cm}^2 \rightarrow 400 \text{ nano-satellites of } A = 10^2 \text{ cm}^2

<table>
<thead>
<tr>
<th>Energy band (MeV)</th>
<th>E_{\text{AVE}} (\beta = -2.5) \text{ MeV}</th>
<th>N (\beta = -2.5) \text{ photons}</th>
<th>E_{\text{CC}}(N) (\beta = -2.5) \mu s</th>
<th>E_{\text{CC}}(N) (\beta = -2.0)</th>
<th>\Delta T_{\text{LIV}} (\xi = 1.0, \zeta = 1.0)</th>
<th>z = 0.1</th>
<th>z = 0.5</th>
<th>z = 1.0</th>
<th>z = 3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005 – 0.025</td>
<td>0.0112</td>
<td>1.52 \times 10^5</td>
<td>1.90</td>
<td>1.21 \times 10^5</td>
<td>2.15</td>
<td>0.04</td>
<td>0.25</td>
<td>0.51</td>
<td>1.42</td>
</tr>
<tr>
<td>0.025 – 0.050</td>
<td>0.0353</td>
<td>5.60 \times 10^4</td>
<td>3.10</td>
<td>4.68 \times 10^4</td>
<td>3.45</td>
<td>0.13</td>
<td>0.72</td>
<td>1.46</td>
<td>4.10</td>
</tr>
<tr>
<td>0.050 – 0.100</td>
<td>0.0707</td>
<td>4.40 \times 10^4</td>
<td>3.55</td>
<td>3.99 \times 10^4</td>
<td>3.70</td>
<td>0.27</td>
<td>1.43</td>
<td>2.93</td>
<td>8.21</td>
</tr>
<tr>
<td>0.100 – 0.300</td>
<td>0.1732</td>
<td>3.59 \times 10^4</td>
<td>3.95</td>
<td>4.00 \times 10^4</td>
<td>3.70</td>
<td>0.66</td>
<td>3.51</td>
<td>7.19</td>
<td>20.10</td>
</tr>
<tr>
<td>0.300 – 1.000</td>
<td>0.5477</td>
<td>8.28 \times 10^3</td>
<td>8.20</td>
<td>1.53 \times 10^4</td>
<td>6.00</td>
<td>2.09</td>
<td>11.11</td>
<td>22.72</td>
<td>63.56</td>
</tr>
<tr>
<td>1.000 – 2.000</td>
<td>1.4142</td>
<td>1.05 \times 10^3</td>
<td>22.80</td>
<td>3.28 \times 10^3</td>
<td>13.00</td>
<td>5.40</td>
<td>28.68</td>
<td>58.67</td>
<td>164.12</td>
</tr>
<tr>
<td>2.000 – 5.000</td>
<td>3.1623</td>
<td>4.28 \times 10^2</td>
<td>35.95</td>
<td>1.97 \times 10^3</td>
<td>16.75</td>
<td>12.07</td>
<td>64.12</td>
<td>131.19</td>
<td>367.00</td>
</tr>
<tr>
<td>5.000 – 50.00</td>
<td>15.8114</td>
<td>1.41 \times 10^2</td>
<td>62.70</td>
<td>1.18 \times 10^3</td>
<td>21.65</td>
<td>60.35</td>
<td>320.62</td>
<td>656.00</td>
<td>1834.98</td>
</tr>
</tbody>
</table>
GRB & Quantum Gravity

\[
\Delta t_{\text{MP/LIV}} = \xi \left( \frac{D_{\text{TRAV}}}{c} \right) \left[ \Delta E_{\text{phot}}/(M_{\text{QG}} c^2) \right]^n
\]

\[
\frac{dN_E(E)}{dA \ dt} = F \times \begin{cases}
\left( \frac{E}{E_B} \right)^\alpha \exp\{-(\alpha - \beta)E/E_B\}, & E \leq E_B, \\
\left( \frac{E}{E_B} \right)^\beta \exp\{-(\alpha - \beta)\}, & E \geq E_B.
\end{cases}
\]

\[
D_{\text{TRAV}}(z) = (c/H_0) \int_0^z d\beta (1+\beta)/[\Omega_\Lambda +(1+\beta)^3 \Omega_M]^{1/2}
\]

\[
E_{\text{CC Long}} = 5 \mu s / \sqrt{N_{\text{phot}}/22150}
\]

\[
E_{\text{CC Short}} = 50 \mu s / \sqrt{N_{\text{phot}}/221}
\]

Long GRB – 8.00 (0.86 BCK) c/s (50 ÷ 300 keV) \( \Delta t = 25 \) s
\( A_{\text{TOT}} = 10^4 \) cm\(^2\) → 100 nano – satellites of \( A = 10^2 \) cm\(^2\)

Short GRB – 8.00 (0.86 BCK) c/s (50 ÷ 300 keV) \( \Delta t = 25 \) s
\( A = 10^6 \) cm\(^2\) → 10,000 nano – satellites of \( A = 10^2 \) cm\(^2\)

| Energy band | \( E_{\text{AVE}} \) (meV) | \( N_{\beta = -2.5} \) photons | \( E_{\text{CC}}(N) \) (\( \mu s \)) | \( N_{\beta = -2.0} \) photons | \( E_{\text{CC}}(N) \) (\( \mu s \)) | \( \Delta T_{\text{LIV}} \) (\( \xi = 1.0, \ \zeta = 1.0 \)) (\( \mu s \)) |
|-------------|----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| MeV         | MeV                       |                 |                 |                 |                 |                 |                 |                 |
| 0.005 – 0.025 | 0.0112                     | 3.80 \times 10^6 | 0.38             | 3.02 \times 10^6 | 0.43             | 0.04            | 0.25            | 0.51            | 1.42            |
| 0.025 – 0.050 | 0.0353                     | 1.40 \times 10^6 | 0.62             | 1.17 \times 10^6 | 0.69             | 0.13            | 0.72            | 1.46            | 4.10            |
| 0.050 – 0.100 | 0.0707                     | 1.10 \times 10^6 | 0.71             | 0.98 \times 10^5 | 0.74             | 0.27            | 1.43            | 2.93            | 8.21            |
| 0.100 – 0.300 | 0.1732                     | 8.98 \times 10^5 | 0.79             | 1.00 \times 10^6 | 0.74             | 0.66            | 3.51            | 7.19            | 20.10           |
| 0.300 – 1.000 | 0.5477                     | 2.07 \times 10^5 | 1.64             | 3.82 \times 10^5 | 1.20             | 2.09            | 11.11           | 22.72           | 63.56           |
| 1.000 – 2.000 | 1.4142                     | 2.63 \times 10^4 | 4.56             | 8.20 \times 10^4 | 2.60             | 5.40            | 28.68           | 58.67           | 164.12          |
| 2.000 – 5.000 | 3.1623                     | 1.07 \times 10^4 | 7.19             | 4.92 \times 10^4 | 3.35             | 12.07           | 64.12           | 131.19          | 367.00          |
| 5.000 – 50.00 | 15.8114                    | 3.52 \times 10^3 | 12.54            | 2.95 \times 10^4 | 4.33             | 60.35           | 320.62          | 656.00          | 1834.98         |
Starlink Constellation 12,000 sats
SpaceX (Elon Musk)

- 4425 @ 1200 km (completed by 2024)
- 7518 @ 340 km
- up to 1,000,000 fixed satellite earth stations (February 2019)
- optical inter-satellite links
- 100 ÷ 500 kg satellites (mass production)
- **board a 100 cm² effective area GAGG crystal – SDD photodetector (position sensitive + coded mask?) module on each satellite**
- 120 m² effective area All Sky Monitor!
OneWeb Constellation 640 sats
Virgin Galactic (Richard Branson) – Arianespace – Airbus Defence and Space

- 640 @ 1200 km
- 150 kg satellites (mass production)
- board a 100 cm² effective area GAGG crystal – SDD photodetector (position sensitive + coded mask?) module on each satellite
- 6.4 m² effective area All Sky Monitor
Conclusions: the HERMES project

All sky monitor of High Energy Sources (keV – MeV): GRB, Magnetar, high energy counterparts of GW & FRB, detection & monitoring of transient sources, timing of X-ray pulsators, etc.

- Accuracy in positioning of bright GRB/GW: ~ 7÷60 arcsec
- 1 – 3  m² effective area
- Energy resolution: 15% at 30 keV
- Temporal resolution: ≥ 10 nanoseconds

Quantum Gravity: probing the structure of space-time

Time lags caused by prompt emission mechanism:
- complex dependence from $E_{\text{phot}}(\text{Band II})$ and $E_{\text{phot}}(\text{Band I})$
- independent of $D_{\text{GRB}}(z_{\text{GRB}})$

Time lags caused by Quantum Gravity effects:
- $\propto |E_{\text{phot}}(\text{Band II})–E_{\text{phot}}(\text{Band I})|$
- $\propto D_{\text{GRB}}(z_{\text{GRB}})$

The two effects can be disentangled with:
- $\Delta t_{\text{QGR}}$ (HERMES)
- $z_{\text{GRB}}$ (optical, follow-up observations of host galaxy)
The HERMES project: the movie

Please, visit our website:
http://hermes.dsf.unica.it
That’s all Folks!