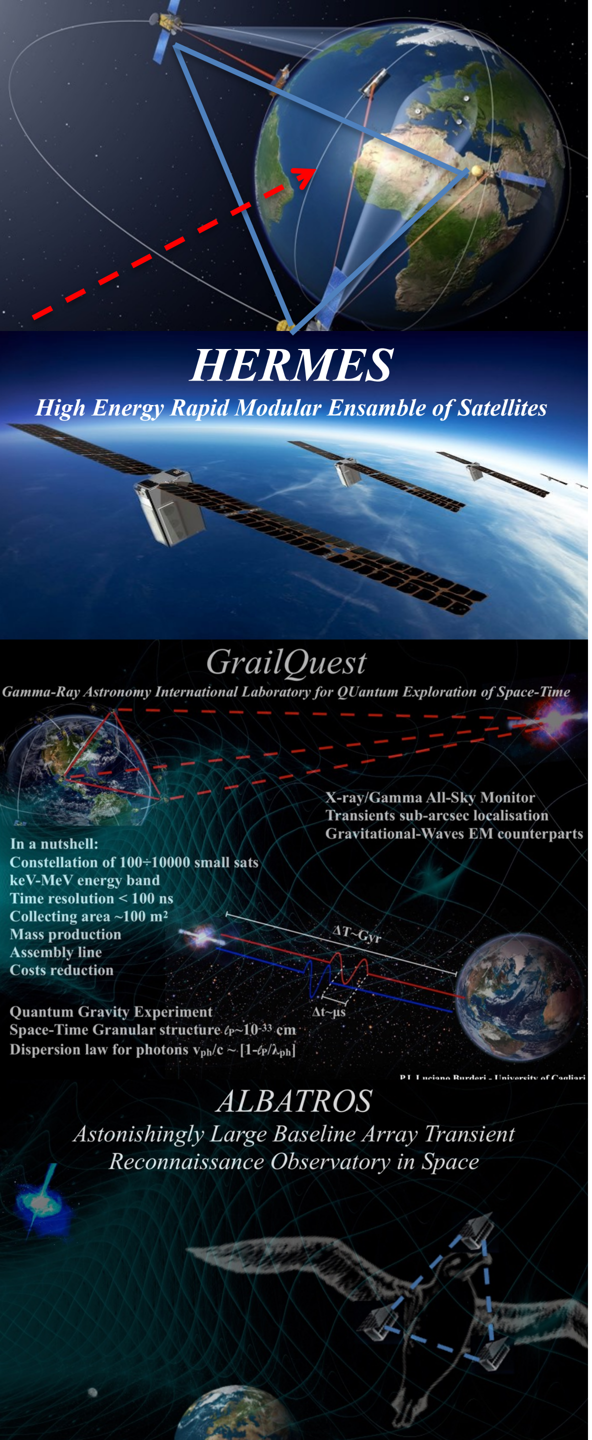



12-15/09/2022, IFPU - Trieste

GRBV

# From the HERMES fleet to the flight of the ALBATROS: surfing the waves of quantum space-time

**Luciano Burderi - University of Cagliari**

Tiziana Di Salvo, Andrea Sanna, Fabrizio Fiore, Alessandro Riggio

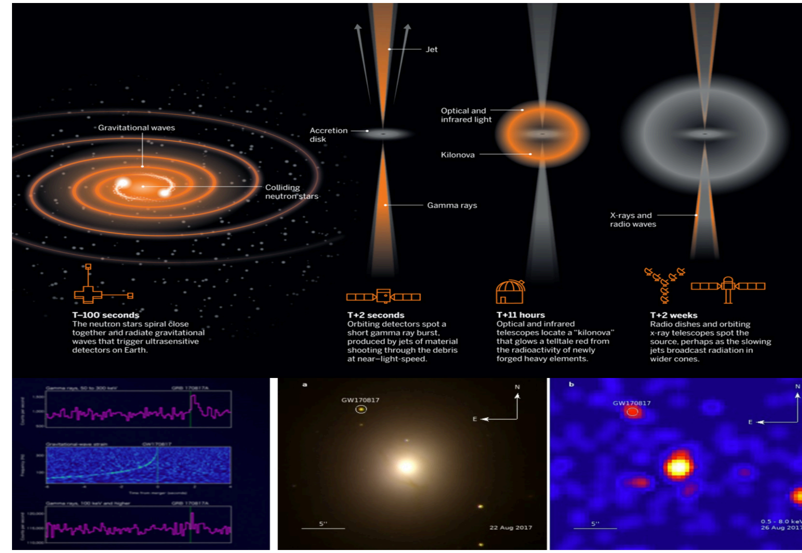
On behalf of the HERMES, GrailQuest and ALBATROS Collaborations

HERMES SP

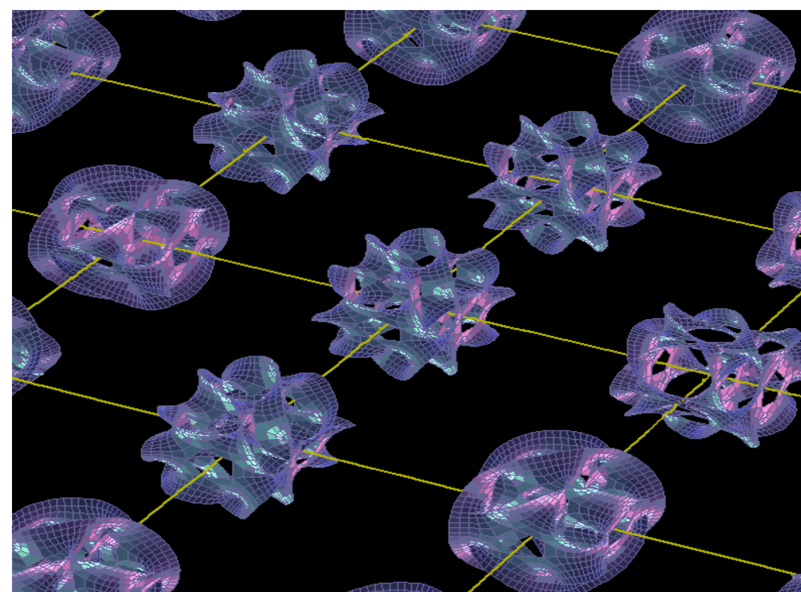
HermeS

# SCIENTIFIC CHALLENGES FOR THE NEXT DECADES

## Multi-Messenger Astronomy

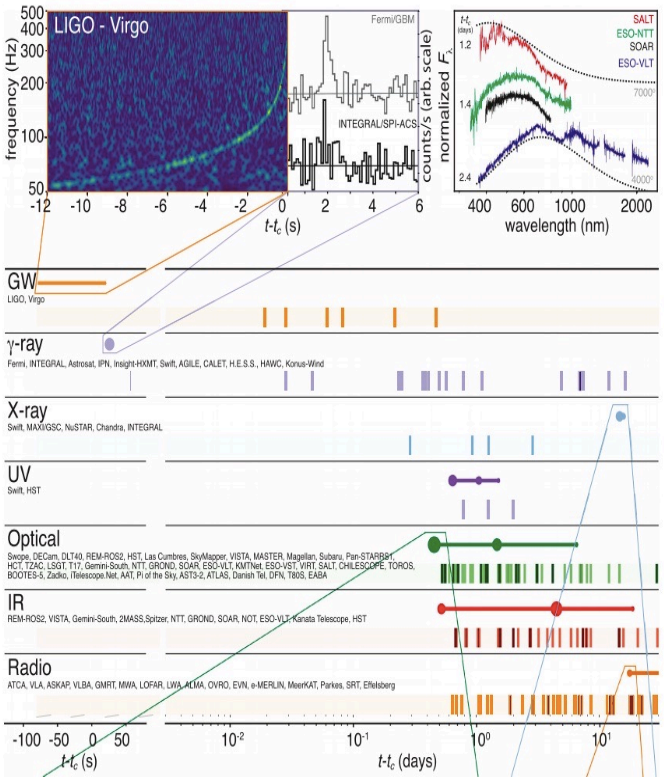



## Testing Quantum Gravity

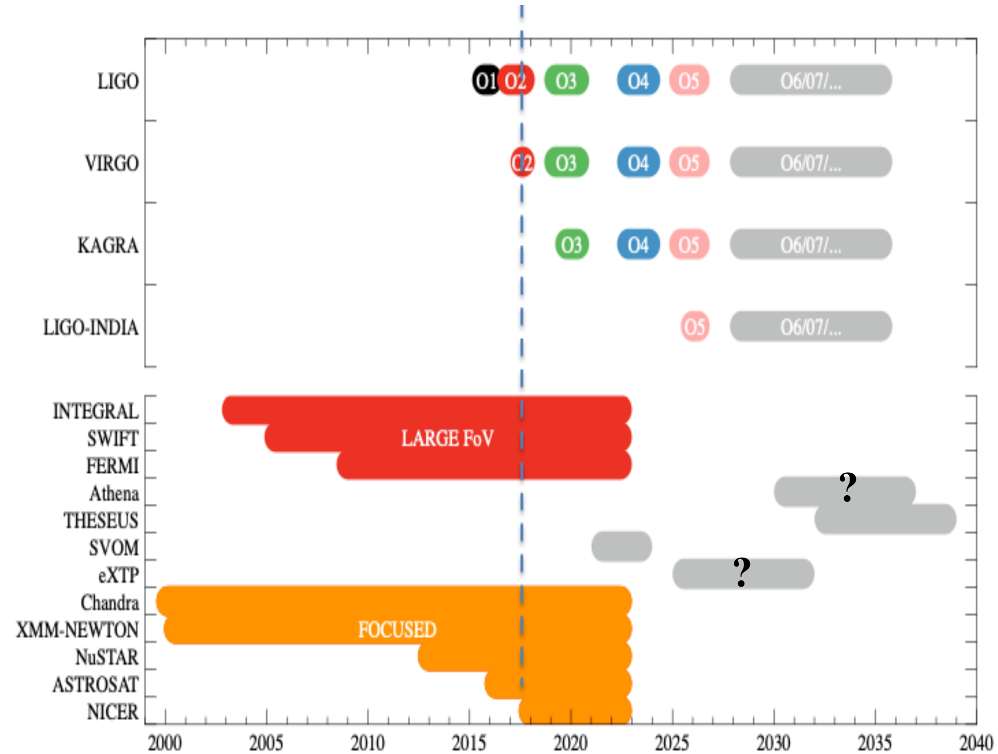


# Development of Multi-messenger astronomy

## GW/GRB 170817



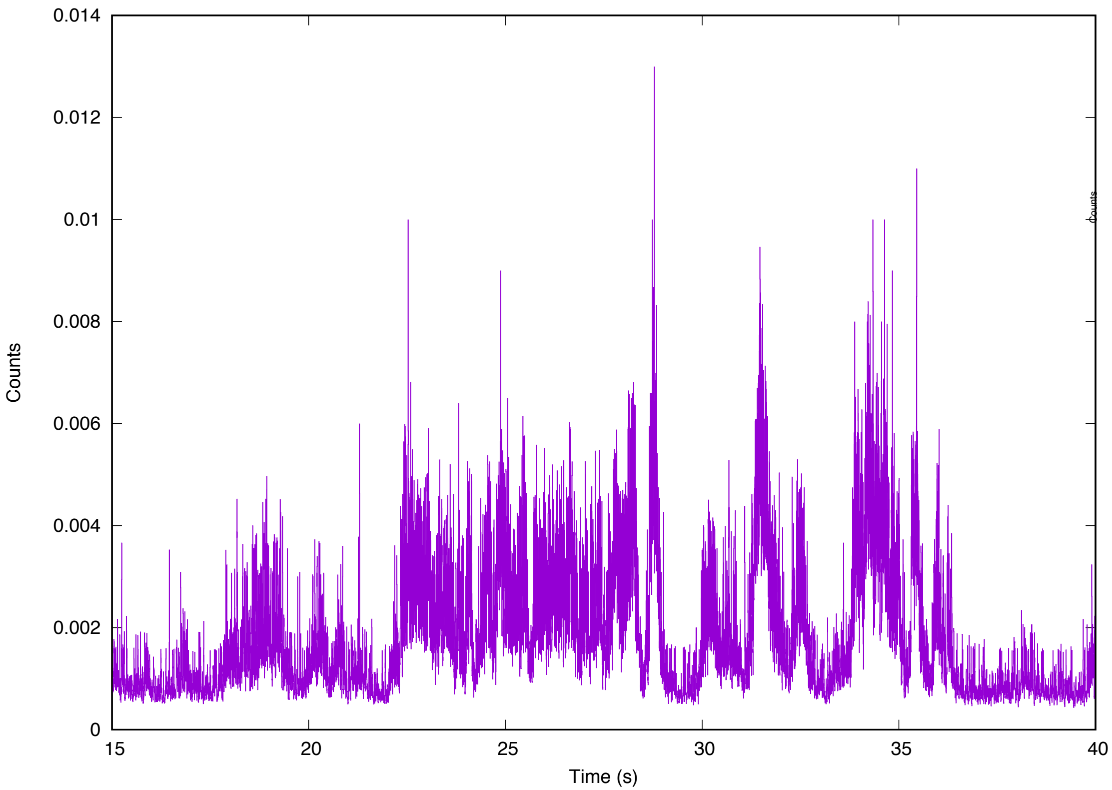

## Multi-Messenger Astronomy Paradox

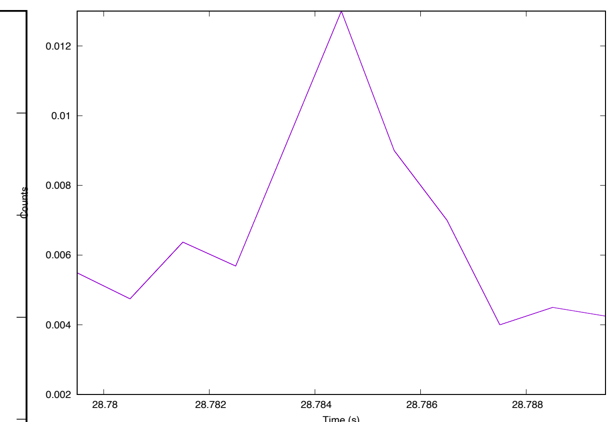



**We need a high-energy All-sky Monitor with large area to allow Multi−Messenger Astronomy to develop from infancy to maturity!**

# Monte-Carlo simulations of a true long GRB

Template (1ms resolution) of a long GRB ( derived from GRB130502327 observed by Fermi GBM)
$\Delta t = 40$ s; $\varphi_{GRB} = 6.5$ phot/s/cm$^2$; $\varphi_{BCK} = 2.8$ phot/s/cm$^2$; variability ≈ 5 ms;
(Long and Short GRB with millisecond time variability, 40% of bright)



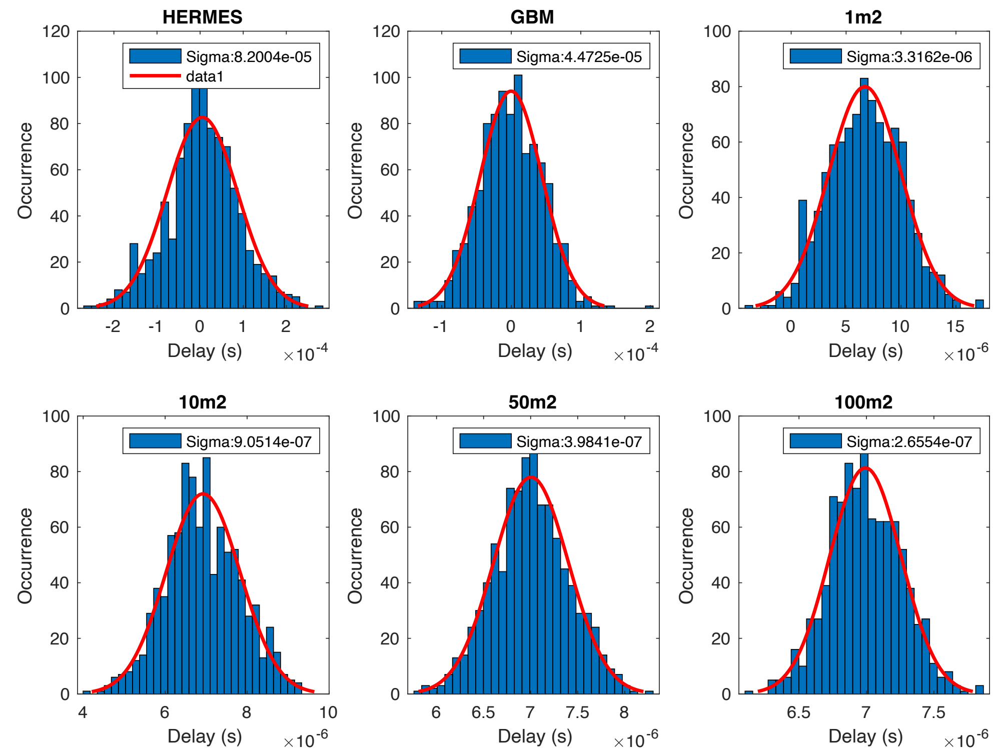




zoom of 10 ms of template centered at the main peak (≈ 5 ms width)

# Accuracy in delays from cross–correlation analysis

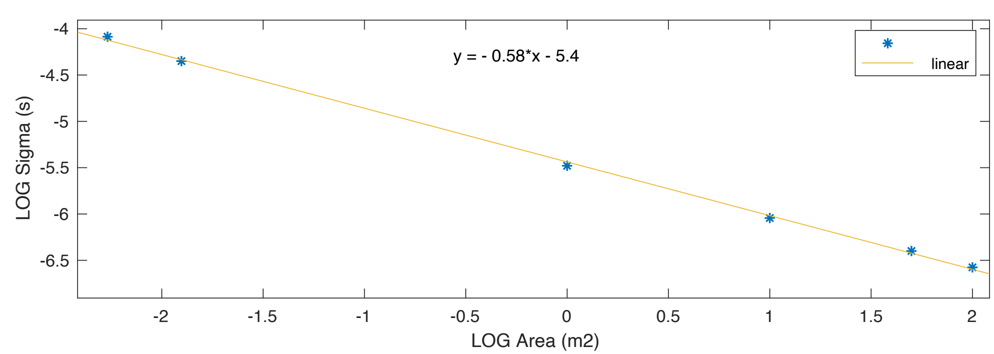
Accuracy in determining delays from a bright long GRB with
$\Delta t = 40$ s;
$\varphi_{GRB} = 6.5$ phot/s/cm$^2$;
$\varphi_{BCK} = 2.8$ phot/s/cm$^2$;
variability timescale $\approx 5$ ms;

1000 pair of Monte-Carlo simulations for detectors of different effective areas A




**Best fit formula:**

$$\sigma_{DELAYS} \approx \sigma_{ToA} = 3.3\ \mu s \times (A/1\ m^2)^{-0.58}$$



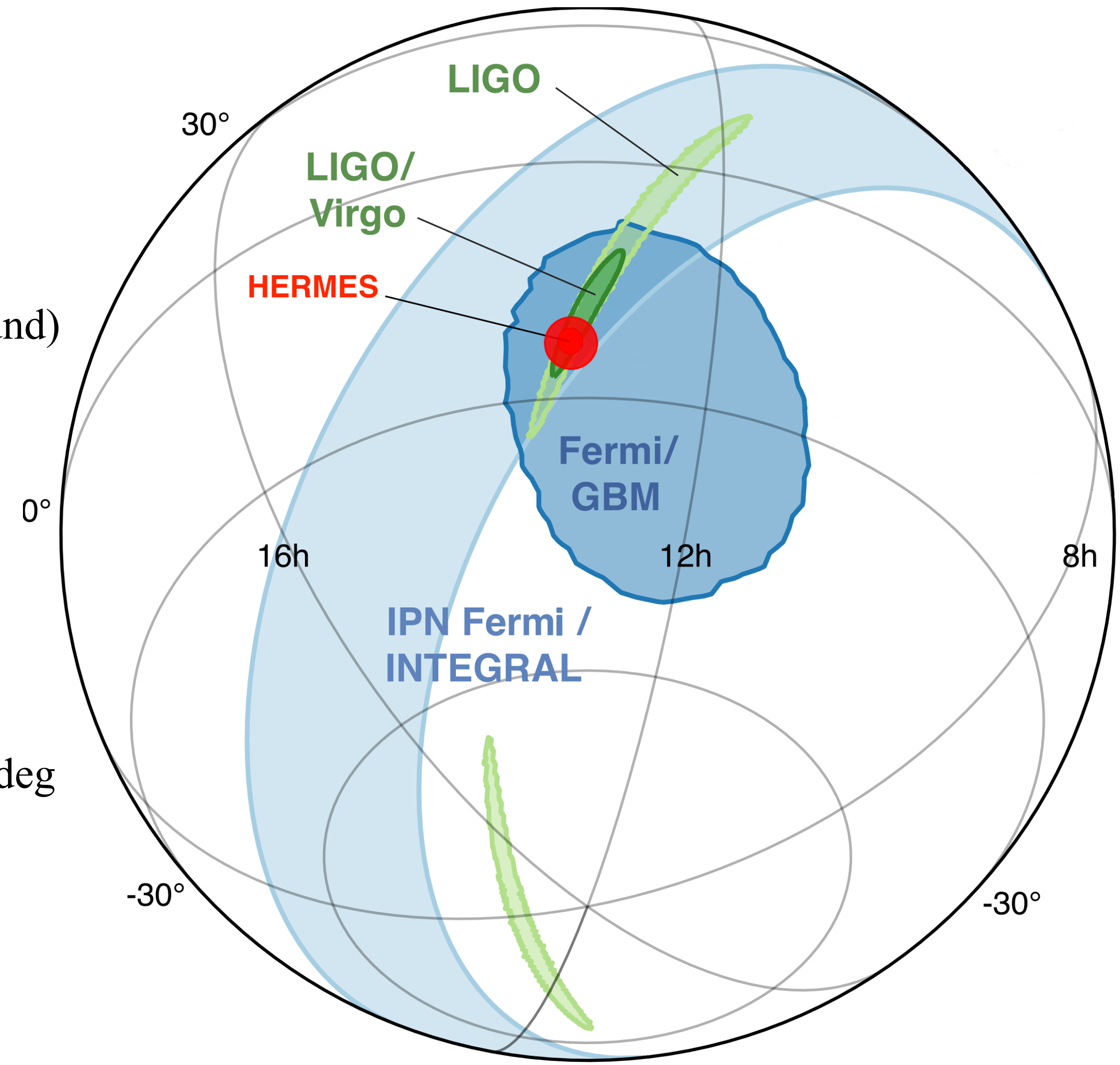
# GW Triangulation & EM counterparts (Fermi GBM, INTEGRAL, HERMES Pathfinder)

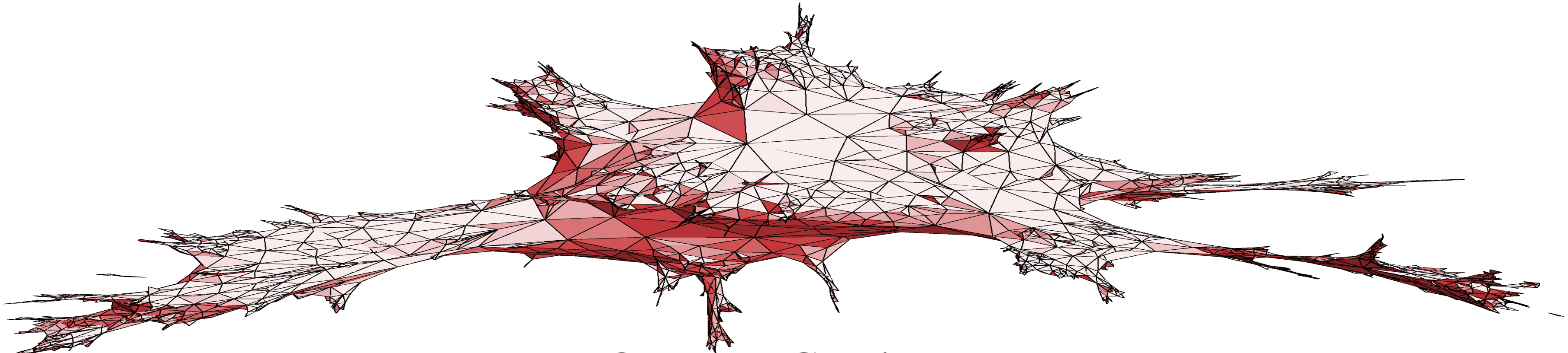
Example:

long bright GRB
6.5 phot/s/cm² (source)
3 phot/s/cm² (background)
30 s duration
50-300 keV band

3 satellites each of effective area: 50 cm²

$\sigma_{ToA} \approx 1$ ms
<baseline> ≈ 6000 km
positional accuracy: 3 deg



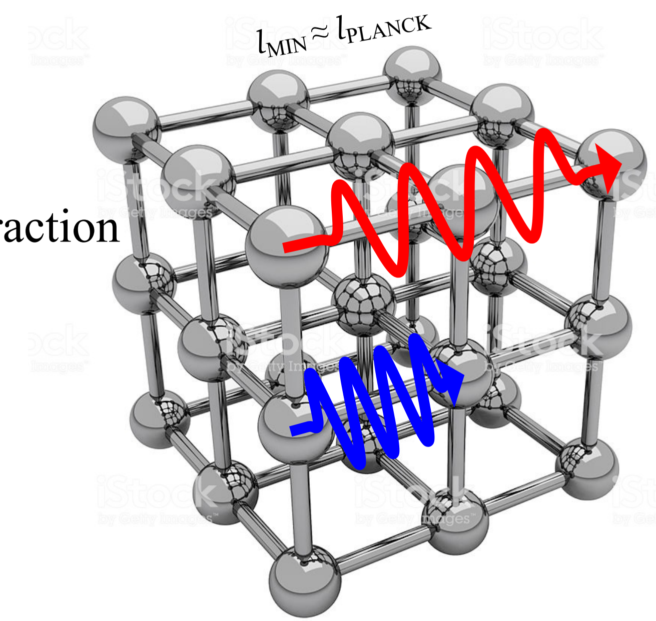


**Quantum Gravity**

**Minimal Length Hypotesis,  LIV and Dispersion Relation for photons *in vacuo***

Existence of a Minimal Length (String theories, etc.)

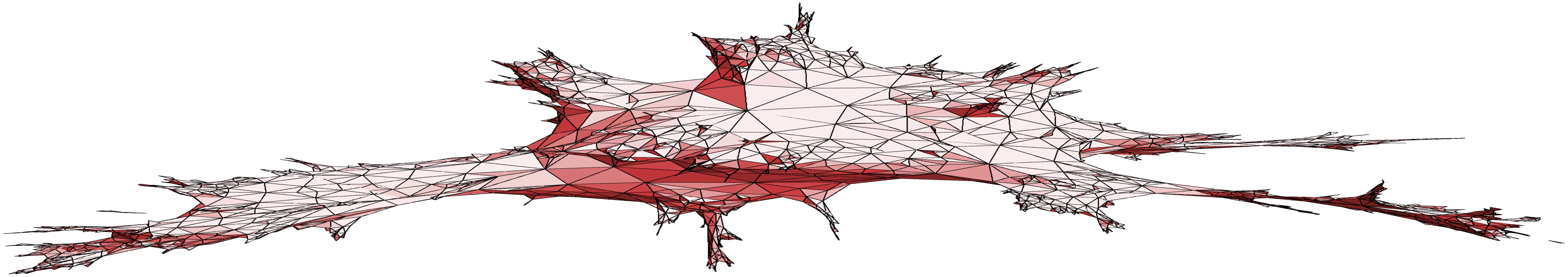
$$l_{MIN} \approx l_{PLANCK} = [Gh/(2\pi c^3)]^{1/2} = 1.6 \times 10^{-33} \text{ cm}$$




implies:

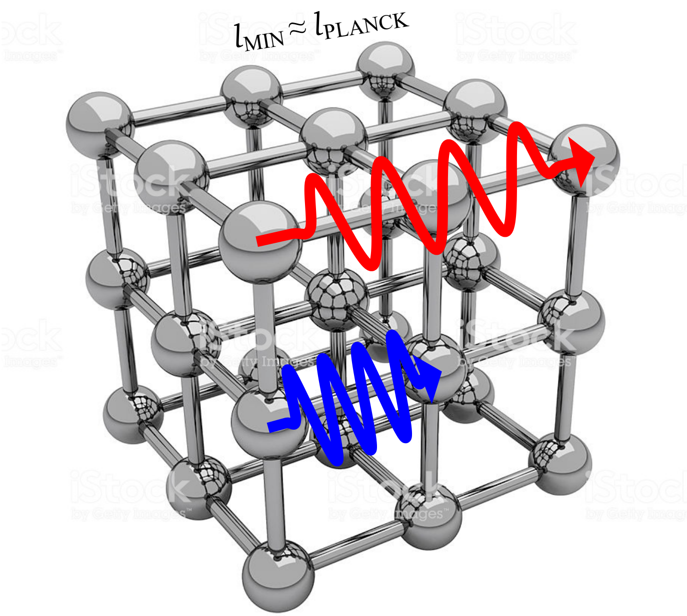
i) Lorentz Invariance Violation (LIV): no further Lorentz contraction
ii) Space has the structure of a crystal lattice and therefore
iii) Existence of a dispersion law for photons *in vacuo*

$|v_{phot}/c - 1| \approx \xi E_{phot}/(M_{QG}\, c^2)^n$
$\xi \approx 1$
n = 1,2 (first or second order corrections)
$M_{QG} = \zeta\, m_{PLANCK} \quad (\zeta \approx 1)$
$m_{PLANCK} = (hc/2\pi G)^{½} = 21.8\ 10^{-6}$ g

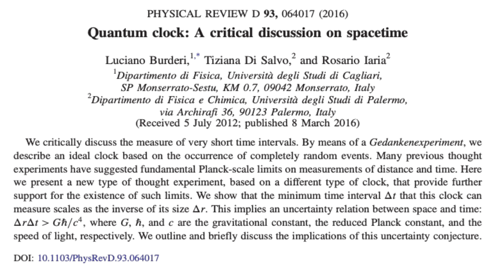


# First and second order Dispersion Relation for photons *in vacuo*

## LIV theories




## No LIV theories


PHYSICAL REVIEW D **93,** 064017 (2016)

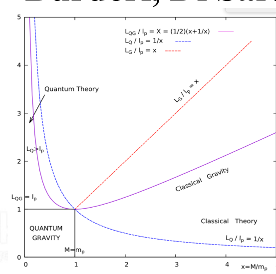
**Quantum clock: A critical discussion on spacetime**

Luciano Burderi,[1,*] Tiziana Di Salvo,[2] and Rosario Iaria[2]
[1]*Dipartimento di Fisica, Università degli Studi di Cagliari, SP Monserrato-Sestu, KM 0.7, 09042 Monserrato, Italy*
[2]*Dipartimento 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 thought 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.

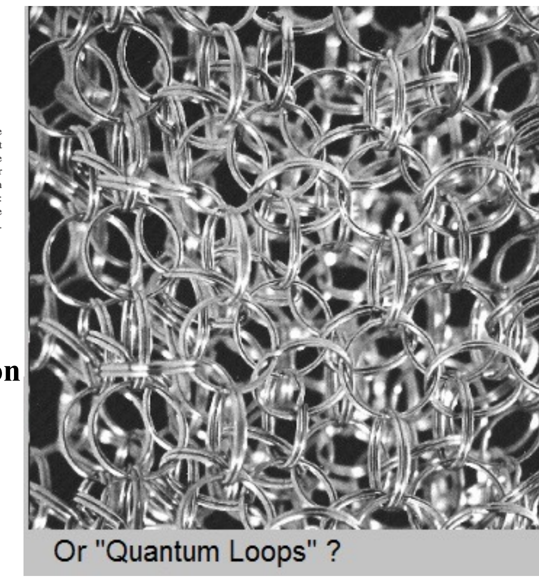
DOI: 10.1103/PhysRevD.93.064017

**Burderi, Di Salvo, Iaria (2016)**




**Space−Time Uncertainty Relation**
$\Delta r \, \Delta t > G\hbar/c^4$

**& Sanchez, 2018**




**Loop Quantum Gravity (Rovelli)**

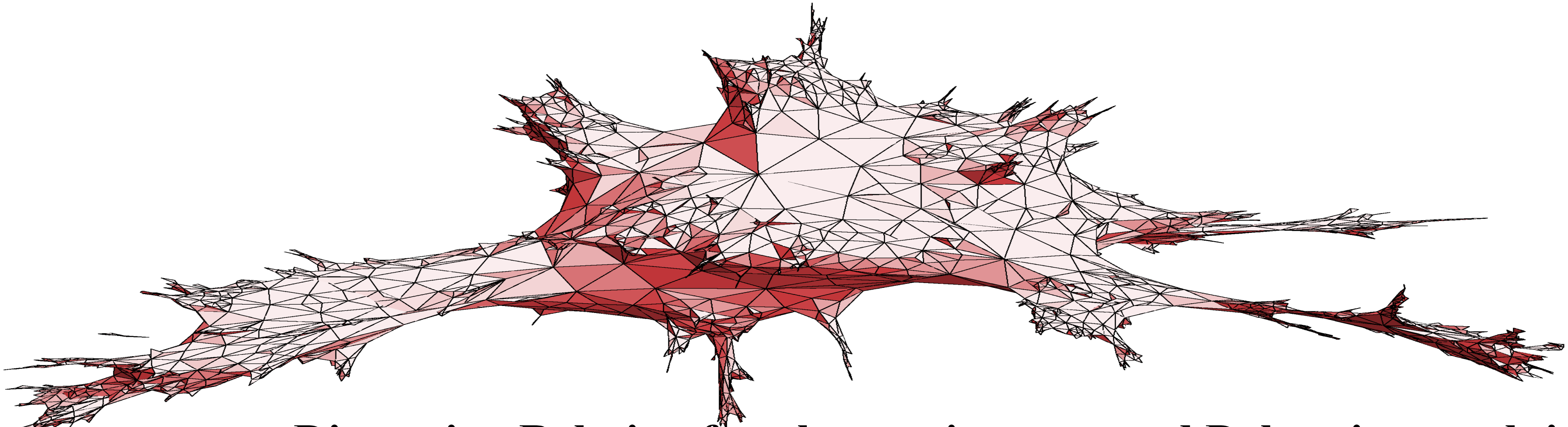
First Order Dispersion Relation

$v_{phot}/c \approx 1 - \xi \, E_{phot}/(M_{Planck} \, c^2)$

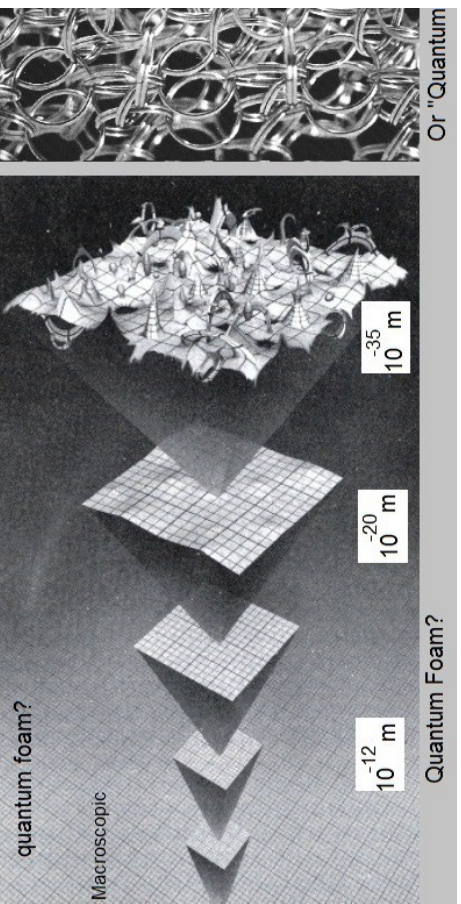
Second Order Dispersion Relation

$v_{phot}/c \approx 1 - \xi \, [E_{phot}/(M_{Planck} \, c^2)]^2$

$\xi = 1/2$ (Burderi et. al., in preparation)



# Dispersion Relation for photons *in vacuo* and Delays in travel time




Accumulation of delays in light propagation:

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

The distance traveled by photons takes into account the cosmological expansion:

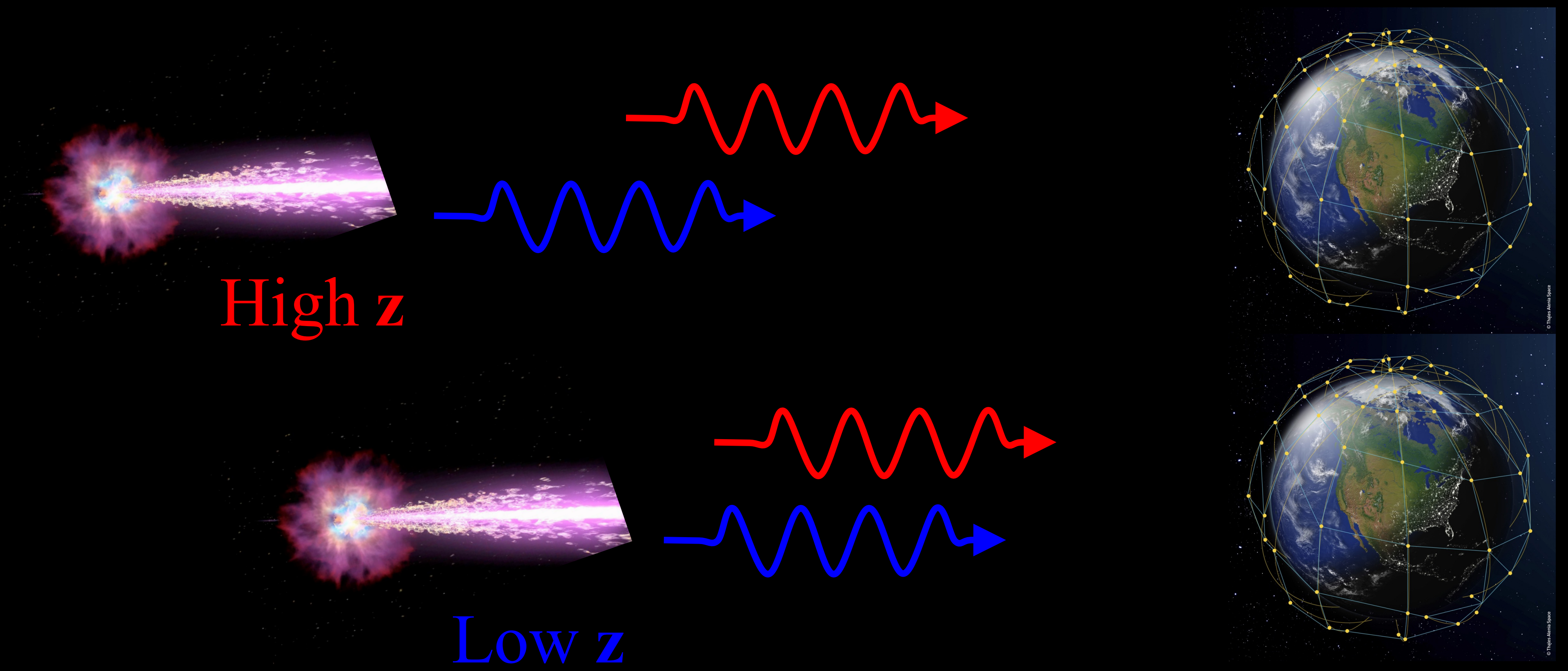
$$D_{TRAV}(z)=(c/H_0)\int_0^z d\beta \, (1+\beta)/[\Omega_\Lambda+(1+\beta)^3 \, \Omega_M]^{1/2}$$

z: cosmological redshift

$\Omega_\Lambda$: ratio between the energy density due to the cosmological constant and the critical (closure) density of the Universe

$\Omega_M$: ratio between the energy density due to the matter and the critical (closure) density of the Universe

# The *Energy* & *Redshift* delay




Time lags caused by Quantum Gravity effects:

- $\propto |E_{phot}(\text{Band II}) - E_{phot}(\text{Band I})|$
- $\propto D_{GRB}(z_{GRB})$

Time lags caused by prompt emission mechanism:

- complex dependence from $E_{phot}$(Band II) and $E_{phot}$(Band I)
- independent of $D_{GRB}(z_{GRB})$

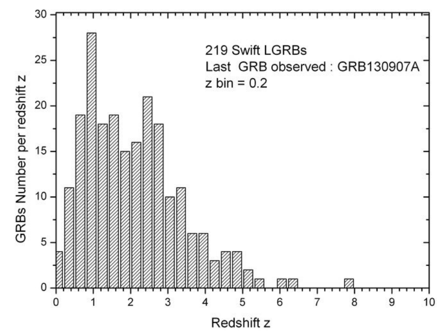
# GRBs & Quantum Gravity

$$\frac{\mathbf{dN_E(E)}}{\mathbf{dA\ dt}} = \mathbf{F} \times \begin{cases} \left(\frac{\mathbf{E}}{\mathbf{E_B}}\right)^{\alpha} \exp\{-(\alpha-\beta)\mathbf{E}/\mathbf{E_B}\}, & \mathbf{E} \le \mathbf{E_B}, \\ \left(\frac{\mathbf{E}}{\mathbf{E_B}}\right)^{\beta} \exp\{-(\alpha-\beta)\}, & \mathbf{E} \ge \mathbf{E_B}. \end{cases}$$

$$\sigma_{CC} \approx 0.46\ \mu\text{sec} \times (2.6\ 10^8/N)^{0.5}$$

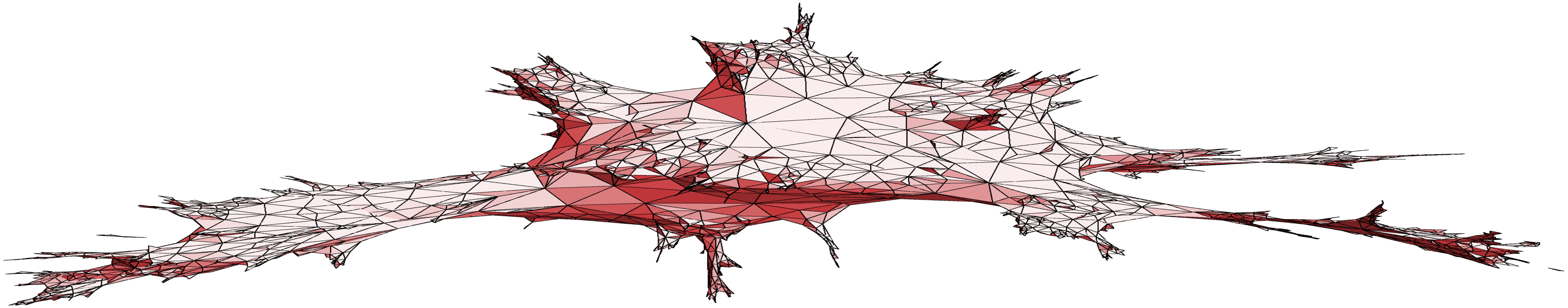
$$\Delta t_{MP/LIV} = \xi\, (D_{TRAV}/c)\, [\Delta E_{phot}/(M_{QG}\, c^2)]^n$$

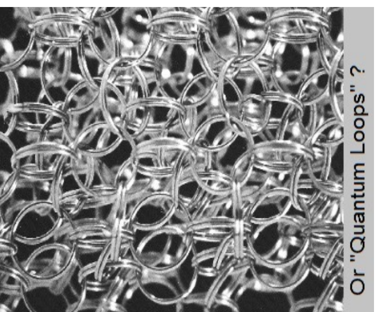
$$D_{TRAV}(z) = (c/H_0)\int_0^z d\beta\, (1+\beta)/[\Omega_\Lambda + (1+\beta)^3\, \Omega_M]^{1/2}$$

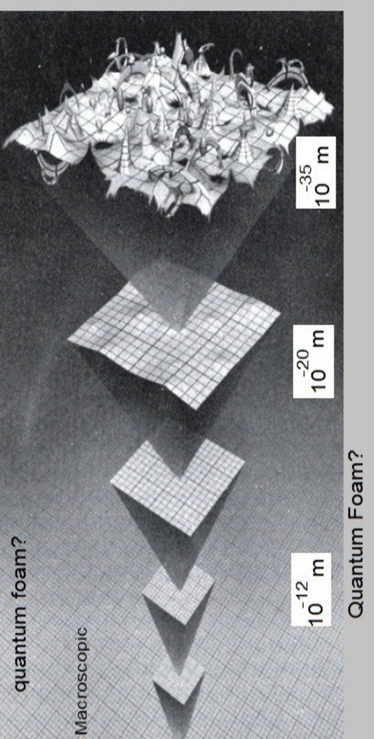



Bright Long GRB: 8.00 (0.86 BCK) c/s ($50 \div 300$ keV) $-$ $\Delta t = 25$ s
Spectral shape: *Band* function with $\alpha = -1$, $\beta = -2.5 \div -2.0$, $E_B = 225$ keV
Detector effective area: $A = 100\ m^2$
Accuracy in cross–correlation in function of the number of photons: $E_{CC}(N) = 0.46\,\mu s\sqrt{2.6\ 10^8/N}$
$\Lambda$CDM cosmology: $\Omega_\Lambda = 0.6911$ and $\Omega_{Matter} = 0.3089$

| Energy band MeV | $E_{AVE}$ MeV | $N$ ($\beta = -2.5$) photons | $E_{CC}(N)$ $\mu s$ | $N$ ($\beta = -2.0$) photons | $E_{CC}(N)$ $\mu s$ | $\Delta T_{LIV}$ ($\xi = 1.0$, $\zeta = 1.0$) $\mu s$ $z = 0.1$ | $\mu s$ $z = 0.5$ | $\mu s$ $z = 1.0$ | $\mu s$ $z = 3.0$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.005 – 0.025 | 0.0112 | $3.80 \times 10^8$ | 0.38 | $3.02 \times 10^8$ | 0.43 | 0.04 | 0.25 | 0.51 | 1.42 |
| 0.025 – 0.050 | 0.0353 | $1.40 \times 10^8$ | 0.62 | $1.17 \times 10^8$ | 0.69 | 0.13 | 0.72 | 1.46 | 4.10 |
| 0.050 – 0.100 | 0.0707 | $1.10 \times 10^8$ | 0.71 | $9.98 \times 10^7$ | 0.74 | 0.27 | 1.43 | 2.93 | 8.21 |
| 0.100 – 0.300 | 0.1732 | $8.98 \times 10^7$ | 0.79 | $1.00 \times 10^8$ | 0.74 | 0.66 | 3.51 | 7.19 | 20.10 |
| 0.300 – 1.000 | 0.5477 | $2.07 \times 10^7$ | 1.64 | $3.82 \times 10^7$ | 1.20 | 2.09 | 11.11 | 22.72 | 63.56 |
| 1.000 – 2.000 | 1.4142 | $2.63 \times 10^6$ | 4.56 | $8.20 \times 10^6$ | 2.60 | 5.40 | 28.68 | 58.67 | 164.12 |
| 2.000 – 5.000 | 3.1623 | $1.07 \times 10^6$ | 7.19 | $4.92 \times 10^6$ | 3.35 | 12.07 | 64.12 | 131.19 | 367.00 |
| 5.000 – 50.00 | 15.8114 | $3.52 \times 10^5$ | 12.54 | $2.95 \times 10^6$ | 4.33 | 60.35 | 320.62 | 656.00 | 1834.98 |






# **Search for a first order Dispersion Relation in a sample of GRBs of known redshift** (Burderi *et al.* Exp. Astr., 2021)

Accumulation of delays in light propagation:

$$\mathbf{\Delta t_{LIV} = \xi\,(D_{TRAV}/c)\,[\Delta E_{phot}/(M_{QG}\,c^2)]^n}$$

For a sample of **i = 1…N** GRB of known redshift $\mathbf{z_i}$ at a given energy **E**, adopt:

$\mathbf{n = 1;\ \ D_{TRAV}/c = \tau_0 f(z);\ \ M_{QG} = \zeta\, m_{PLANCK};\ \ \Delta E_{phot} = E - E_0}$

$\mathbf{\tau(E)}$ **= intrinsic spectral delay at E;** $\mathbf{\xi/\zeta = \alpha(E) \approx 1}$ **= delay constant at E**

$\mathbf{\tau_0 = 1/H_0}$

$\mathbf{f(z_i) = \int_0^z d\beta\, (1+\beta)/[\Omega_\Lambda + (1+\beta)^3\, \Omega_M]^{1/2}}$

Thus we have:

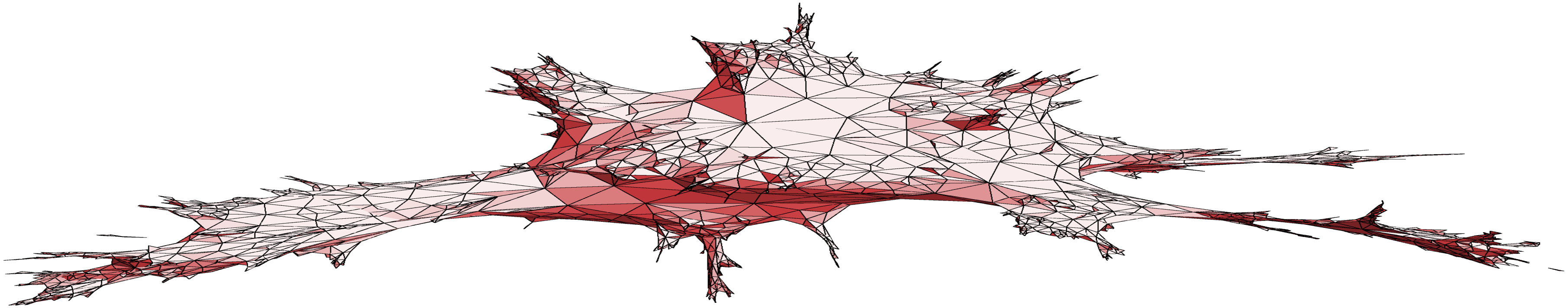
$$\mathbf{\Delta t_i = \tau(E) + \tau_0 f(z_i) \times \alpha(E)(E - E_0)/(m_{PLANCK}c^2)}$$

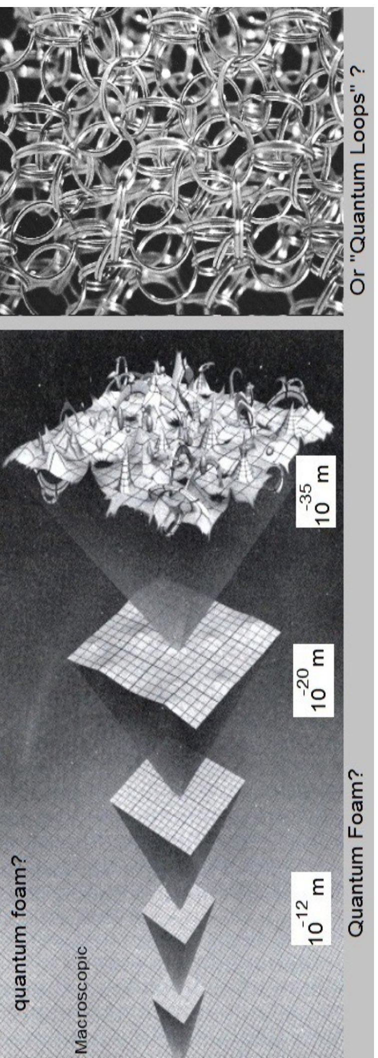
Plot $\mathbf{\Delta t_i}$ vs. $\mathbf{t_i = \tau_0 f(z_i)(E - E_0)/(m_{PLANCK}c^2)}$ and fit with

$\mathbf{\Delta t_i = \tau(E) + \alpha(E) \times t_i}$ to obtain $\mathbf{\tau(E)}$ and $\mathbf{\alpha(E)}$

If a first order dispersion relation is present, $\mathbf{\alpha(E) = \alpha}$ for any energy **E**

Compute the average value of $\mathbf{\alpha(E)}$ and its standard deviation: $\mathbf{\alpha = \langle \alpha(E) \rangle}$ and $\mathbf{\sigma_\alpha}$, for all the energy considered,






# Search for a first order Dispersion Relation in a sample of GRBs of known redshift

Since all the errors are of statistical origin, the accuracy of the method depend on the number of photons detected.

If the the delays are detectable (or constrained) for **α(E) ≈ 1** with **one GRB** and a detector of effective area **A = 100 m²**, the same number of photons and, therefore, accuracy is possible with a sample of **N = 1000** GRBs and a detector of effective area

$$\mathbf{A^* = 100\ m^2/N = 100\ m^2/1000 = 10^6\ cm^2/1000 = 10^3\ cm^2}$$

# Location of GRBs with fleets of satellites and redshifts

Accuracy in determining delays from Monte-Carlo simulations of 100 pairs of GRBs of fluence 260 (112 BCK) photons/cm$^2$ with detectors of different effective areas:

$\boldsymbol{\sigma_{DELAYS} \approx \sigma_{ToA} = 3.3\ \mu s \times (A/1\ m^2)^{-0.58}}$

Accuracy in determining $\alpha$ and $\delta$ with $N_{SATELLITES}$ ($N_{IND} = N_{SATELLITES} - 1$; $N_{PAR} = 2$):

$\boldsymbol{\sigma_\alpha \approx \sigma_\delta = c\ \sigma_{ToA}/\langle baseline\rangle \times (N_{IND} - N_{PAR})^{-1/2}}$

Large fleet of small satellites in Low Earth Orbits:

$A = 30 \times 30$ cm $\approx 0.1$ m$^2$

$\sigma_{ToA} \approx 12.5\ \mu s$

$N_{SATELLITES} \approx 1000$

<baseline> ≈ 6,000 km

**$\sigma_\alpha \approx \sigma_\delta \approx 4$ arcsec**

Three satellites with detectors of 1 m$^2$ effective area in Earth−Moon Lagrangian points:

$A \approx 1.0$ m$^2$

$\sigma_{ToA} \approx 3.3\ \mu s$

$N_{SATELLITES} = 3$

<baseline> ≈ 400,000 km

**$\sigma_\alpha \approx \sigma_\delta \approx 0.5$ arcsec**

Three satellites with detectors of 400 cm$^2$ effective area in *Cart-wheel* orbits:

$A \approx 1.0$ m$^2$

$\sigma_{ToA} \approx 21.3\ \mu s$

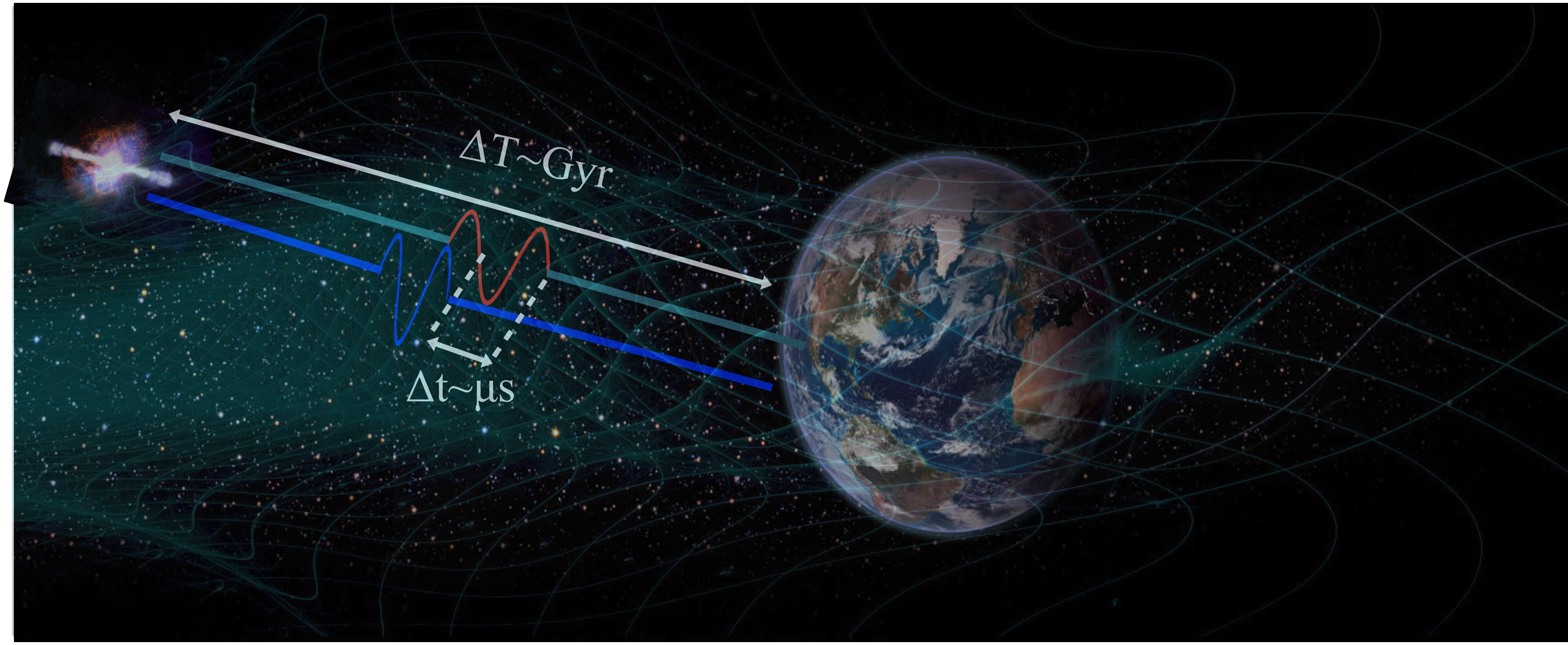
$N_{SATELLITES} = 3$

<baseline> ≈ 2,500,000 km

**$\sigma_\alpha \approx \sigma_\delta \approx 0.5$ arcsec**

Once the position is known, the redshift of the GRB host galaxy is obtained through pointed observations of large optical telescopes.

# *GrailQuest*: First Quantum-Gravity dedicated experiment




Robust Quantum Gravity Experiment to:

i) Search for a Dispersion law for photons $v_{ph}/c \sim [1-l_P/\lambda_{ph}]$

ii) Explore Space−Time Granular structure down to $l_P \sim 10^{-33}$ cm

Performed by means of a Constellation of 100÷10000 small sats with:

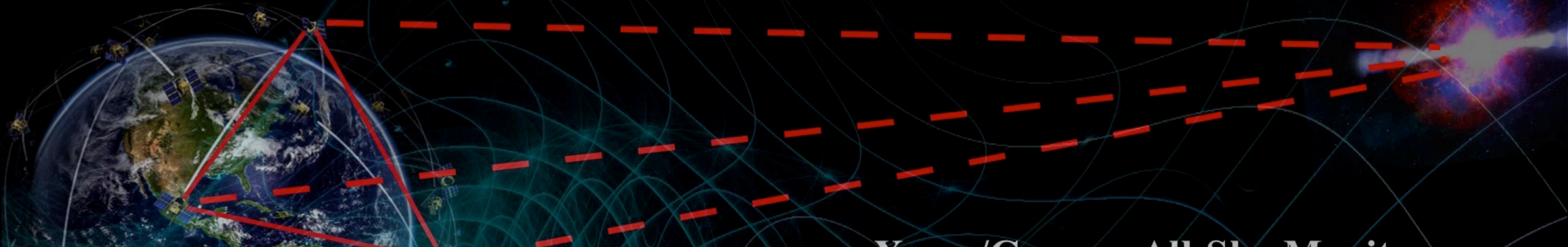
i) Total collecting area: ~100 $m^2$

ii) Energy band: 50 keV − 50 MeV

iii) Time resolution: < 0.1 μs

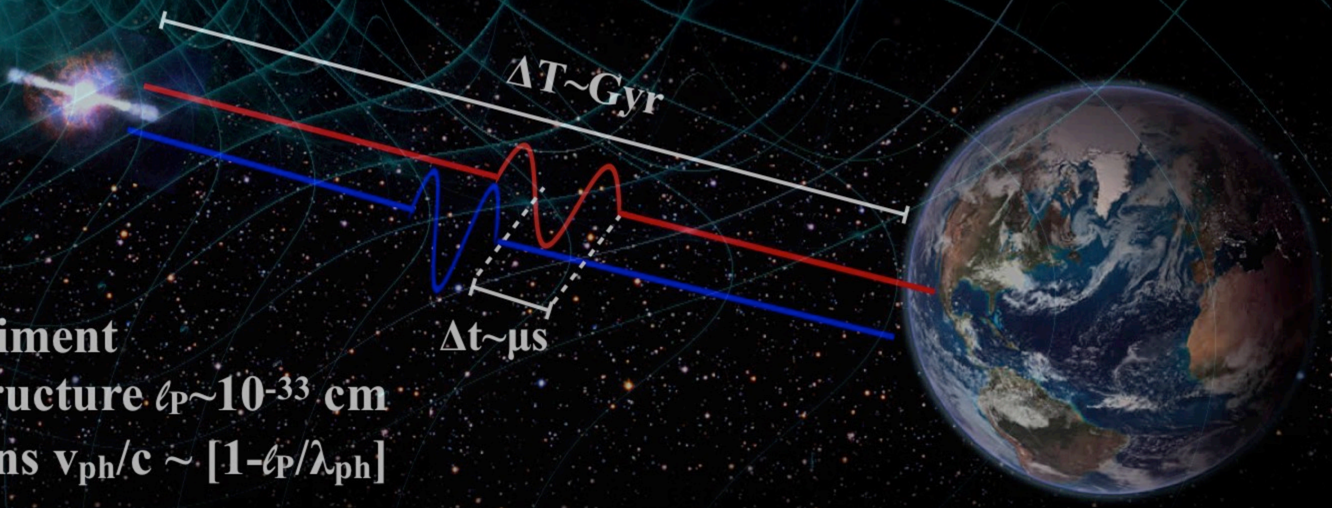
# *GrailQuest*

***Gamma-Ray Astronomy International Laboratory for QUantum Exploration of Space-Time***



**X-ray/Gamma All-Sky Monitor**
**Transients sub-arcsec localisation**
**Gravitational-Waves EM counterparts**

**In a nutshell:**
**Constellation of 100÷10000 small sats**
**keV-MeV energy band**
**Time resolution < 100 ns**
**Collecting area ~100 m²**
**Mass production**
**Assembly line**
**Costs reduction**




**Quantum Gravity Experiment**
**Space-Time Granular structure $\ell_P \sim 10^{-33}$ cm**
**Dispersion law for photons $v_{ph}/c \sim [1-\ell_P/\lambda_{ph}]$**


**P.I. Luciano Burderi - University of Cagliari**

# *GrailQuest* selected for the 2019 Call for White Papers for the Voyage 2050 long term plan in the ESA Science Programme


Voyage 2050 - long term plan in the ESA science programme

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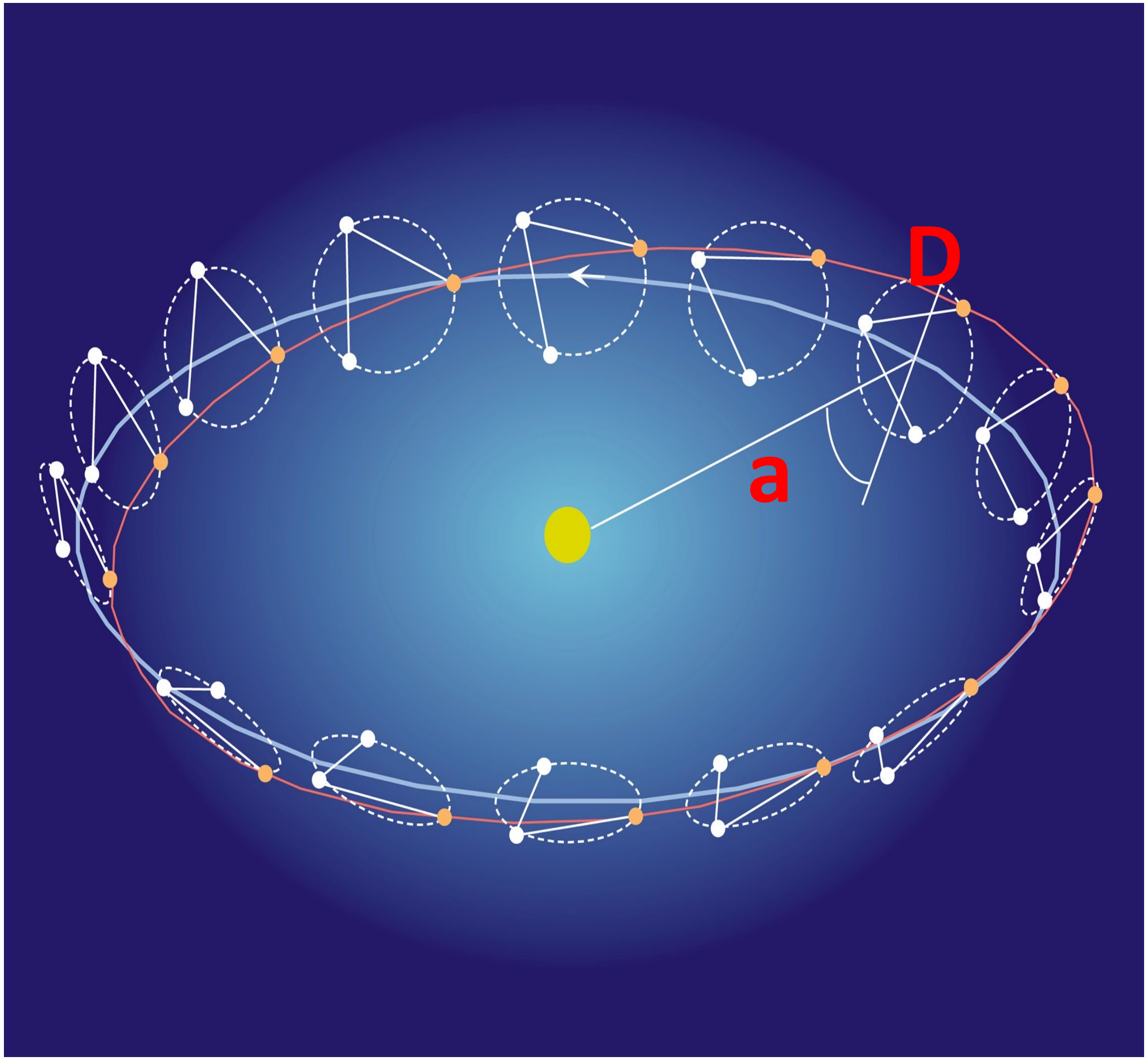
## *GrailQuest*: hunting for Atoms of Space and Time hidden in the wrinkle of Space–Time

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

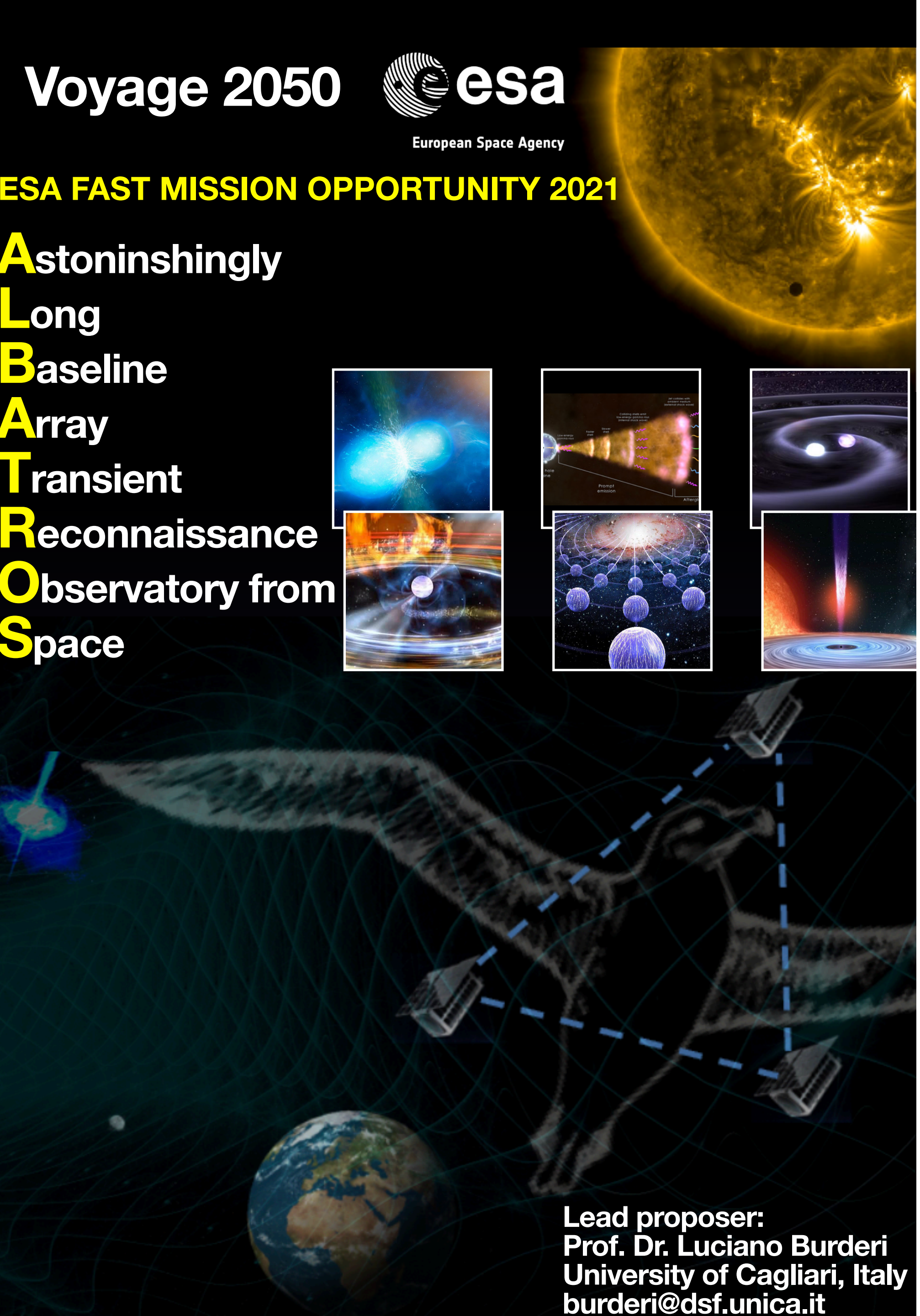
Contact Scientist: Luciano Burderi Download paper at arXiv:1911.02154v2

# The *ALBATROS* mission: cart-wheel orbits




3 satellites in "Cart-wheel" orbits (e.g., LISA orbits):

- 3 heliocentric orbits with a=1AU
- 3 slightly different small inclinations (idegrees) w.r.t. to eclipting plane
- Equatorial triangle of side D 2.5 $10^6$ km
- Contact to ground up to 23 hours per day
- Wet mass ~ 230 kg per satellite
- Dry mass  ~ 165 kg per satellite




# The *ALBATROS* mission

Three satellites in "*Cart-wheel*" orbits:
3 heliocentric orbits with a = 1AU and 3 slightly different small inclinations ($i \approx 0.5°$) w.r.t. the ecliptic plane: equilateral triangle of side $D \approx 2.5\ 10^6$ km.

Two 400 cm$^2$ effective area detectors (HERMES like) per satellite pointing in opposite directions w.r.t. the equilateral triangle plane.
FoV: $4\pi$ steradians (whole sky)

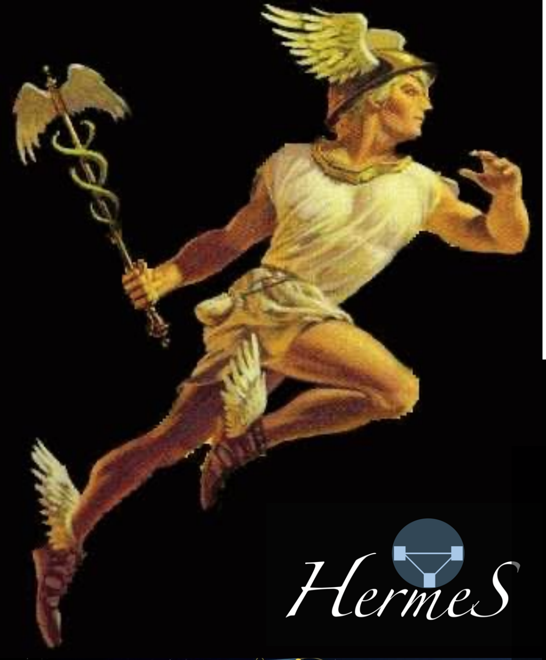
Detection rate: 1÷2 GRB/day

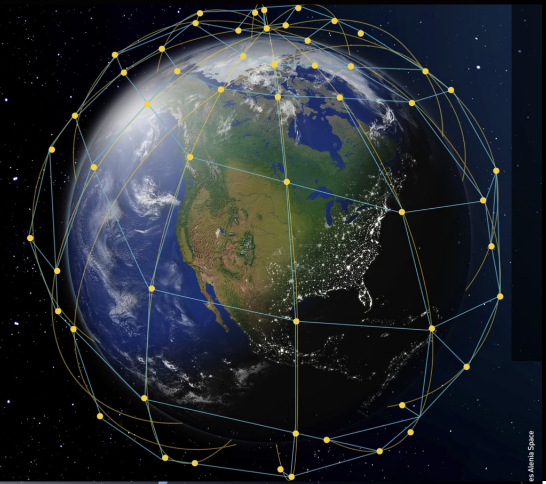
Positional accuracy with Temporal Triangulation Techniques:
$\sigma_\alpha \approx \sigma_\delta \approx c\ \sigma_{\Delta t} / B \approx 24$ arc-sec $\times$ $(B/2.5 \times 10^6\ \mathrm{km})^{-1}$ $\times$ $(\sigma_{\Delta t}/1\mathrm{ms})$ implies: $\sigma_\alpha \approx \sigma_\delta \approx 0.5$ arc-sec for 400 cm$^2$ detectors

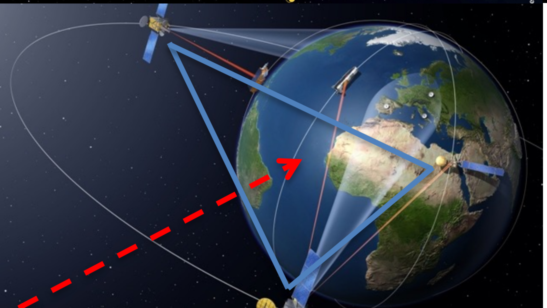
Prompt follow-up with ground-based optical telescopes: 75% success in determination of redshift z

Number of GRB with determined redshift detected in 4 yr nominal mission lifetime $N \approx 1000$

Effective constrain of first order (LIV) Quantum Gravity dispersion law for photons





# The HERMES project: the movie

## That's all Folks!

**Please, visit our websites:**

**http://hermes.dsf.unica.it**

**www.hermes-sp.eu**