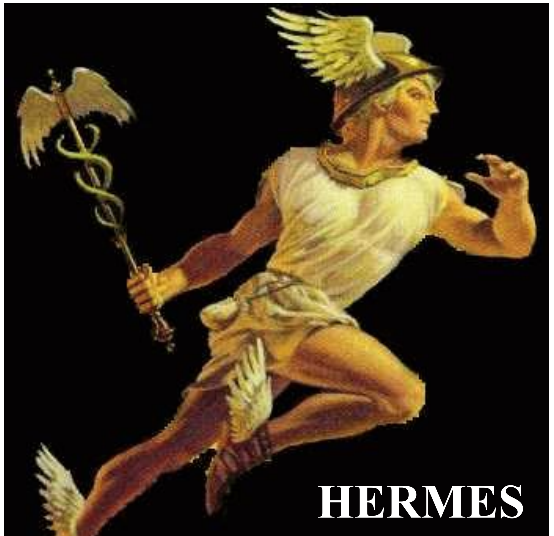


THE 3RD PIETRO BARACCHI CONFERENCE

Nov 3 – 4, 2021 Virtual meeting

GrailQuest

Gamma-ray Astronomy International Laboratory for Quantum Exploration of Space-Time

& HERMES

High Energy Rapid Modular Ensamble of Satellites

Hunting for Gravitational Wave Electromagnetic Counterparts

Probing Space-Time Quantum Foam

On behalf of the HERMES and GrailQuest Collaborations

Please, visit our websites:
http://hermes.dsf.unica.it
www.hermes-sp.eu

Two compelling (astro)-physical problems for the next decades

- Development of Multi-Messenger astronomy (EM counterparts of GW events)

- Is physical space(time) granular or continuous?

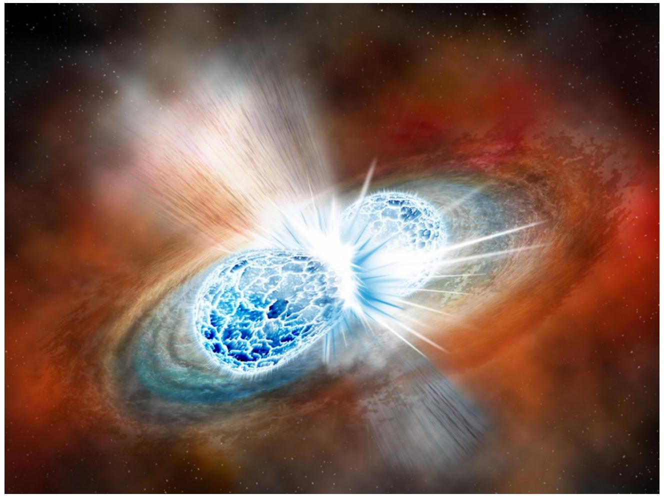
Zeno’s paradoxes and the existence of a “fundamental minimal length” in some string theories: “Atoms of Space”, an effective expression invented by Smolin

dispersion law for light *in vacuo*, that linearly depends on the ratio between photon energy and Planck energy

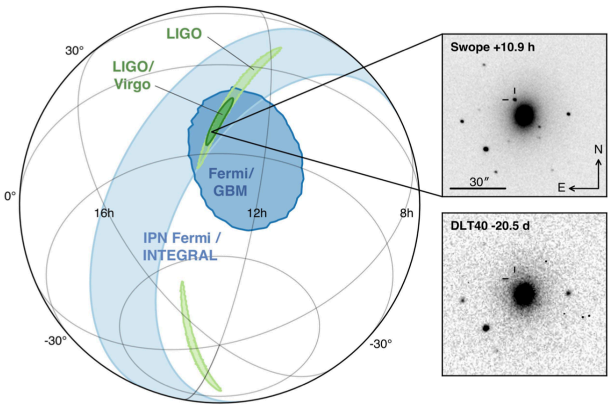
Distributed Astronomy is the key!

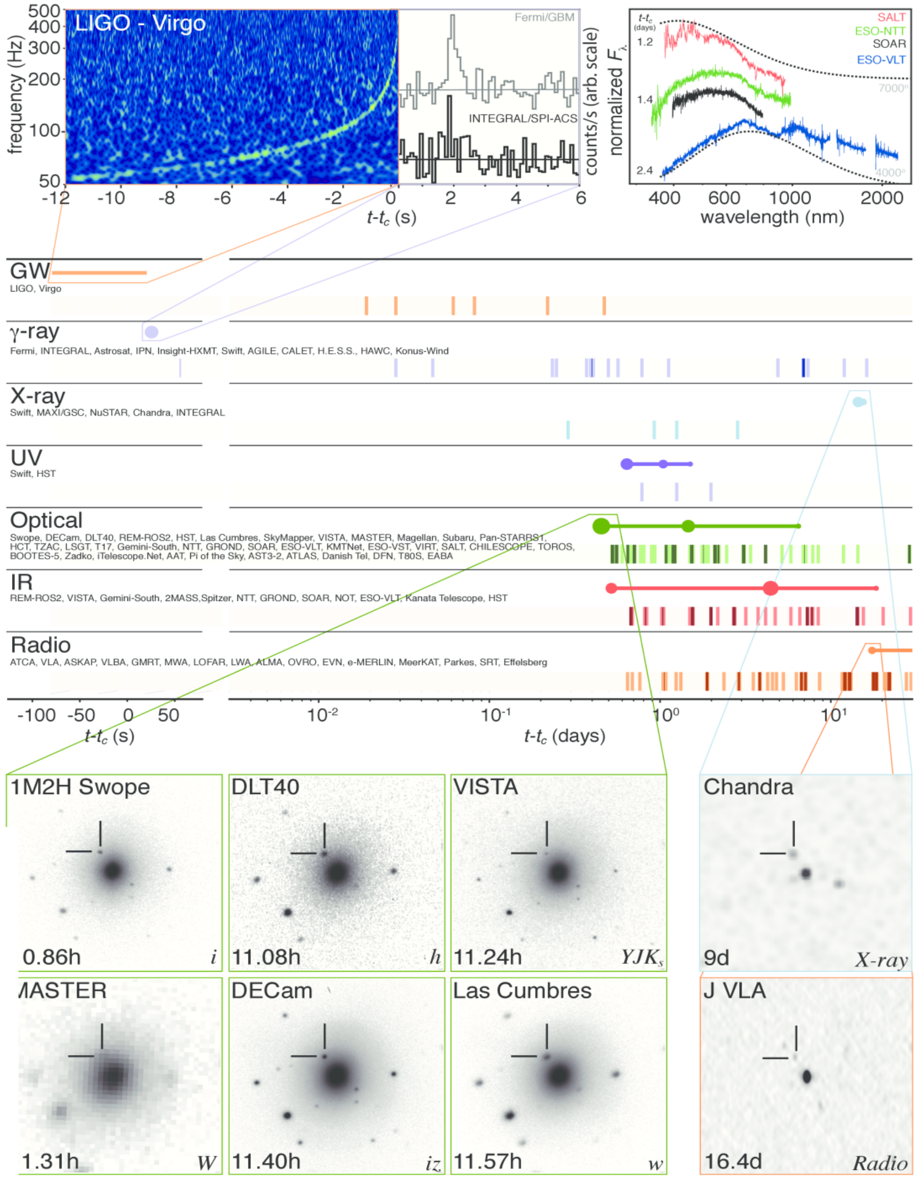
The birth of Multi−Messenger Astronomy

GW170817

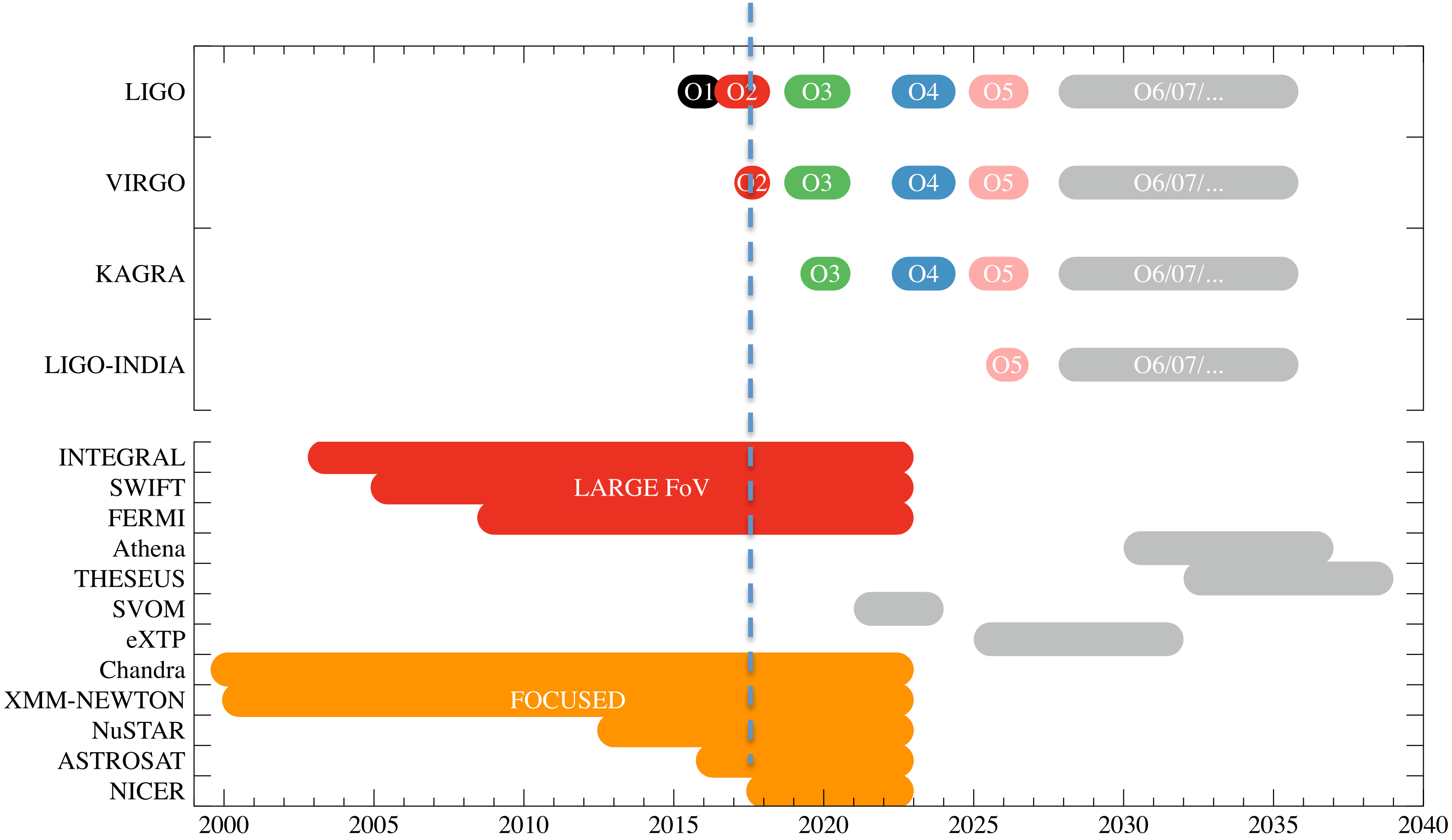


- **NS-NS merging**
- **Host galaxy NGC 4993**
- **~ 40 Mpc**
- **70 observatories**





The Multi−Messenger Astronomy Paradox I



- **2025+** LIGO/VIRGO/KAGRA/LIGO-INDIA will detect GW170817 **within ~ 300 Mpc** with localisation accuracy ~10 deg^2
- FERMI GBM would not have been able to detect GRB 170817A at **D > 60 Mpc**

The Multi−Messenger Astronomy Paradox II

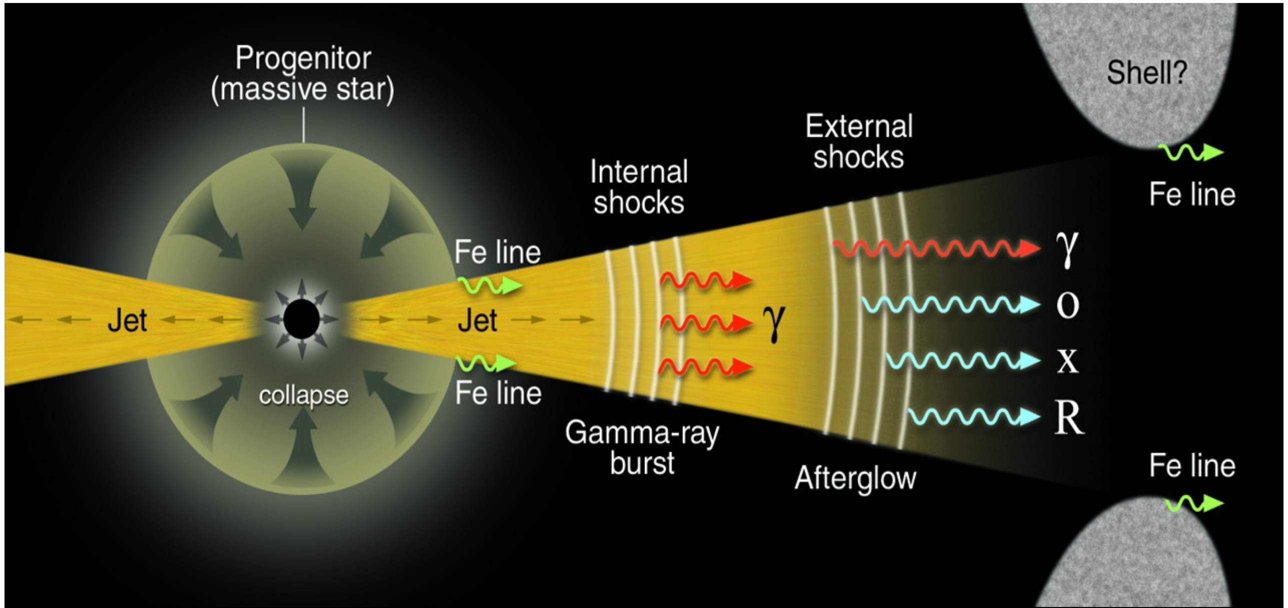
One of he most thrilling research field in Science:
the whole field based on ONE discovery: GRB 170817A - GW170817 connection

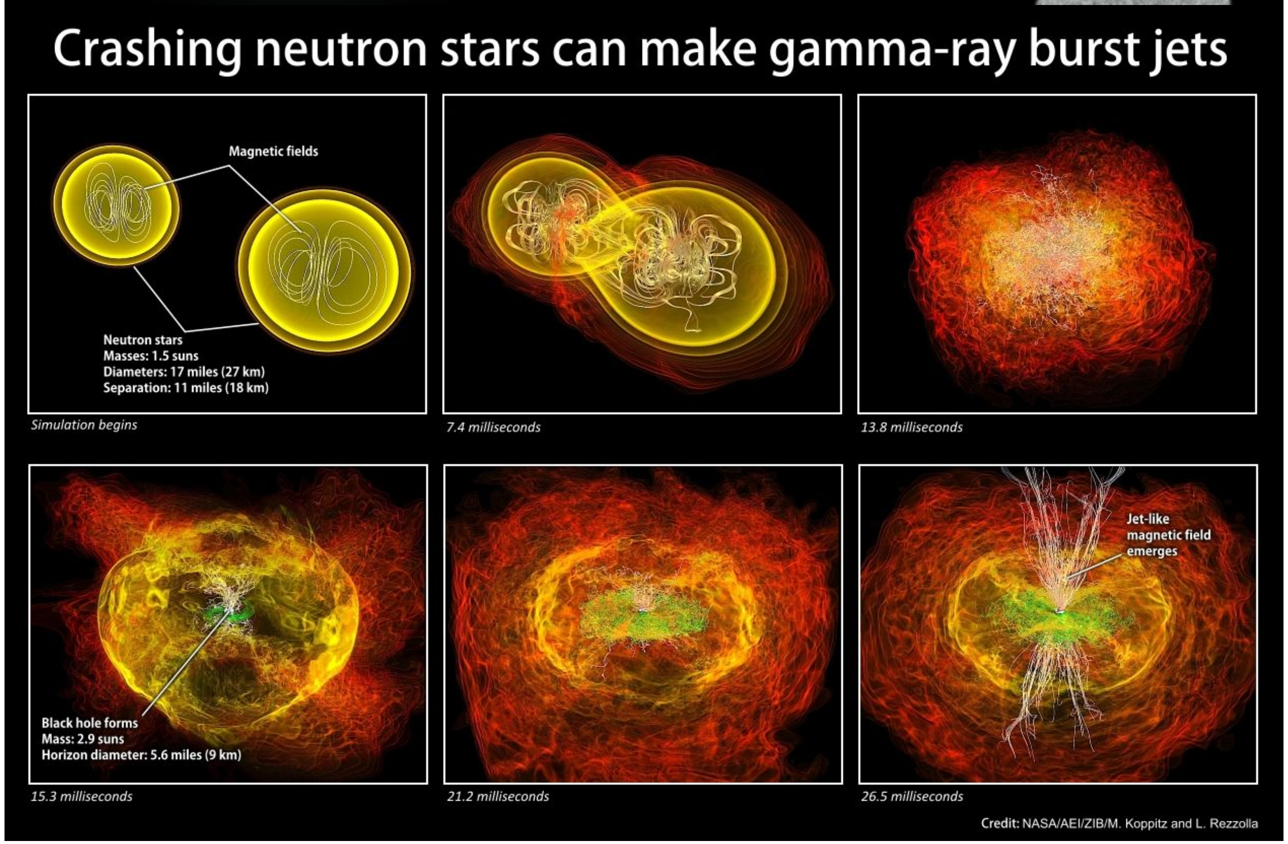
Fact ♯ 1:
within 2025 LIGO − Virgo − KAGRA − Einstein Telescope GW antennas will provide detectability of NS−NS mergers events like GW170817 within ≅ 300 Mpc
Localization accuracies:
100 square deg (LIGO − Virgo)
10 square deg (LIGO − Virgo − KAGRA)

Fact ♯ 2:
GBM would not have been able to detect an event 60% fainter than GRB 170817A.
Kilonova events seen at angles ≥ 25 degrees are undetectable by GBM for distances ≥ 60 Mpc.

Fact ♯ 1 + Fact ♯ 2 ➔ No EM counterpart detected, no party!
(quoting George Clooney)

We need a All-sky Monitor at least 10÷100×GBM Area for letting Multi−Messenger Astronomy to develop from infancy to maturity!





GRB progenitors

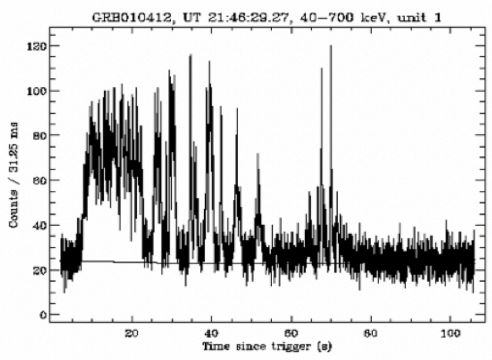
Long GRB:
BH collapse of a massive star

Short GRB:
NS–NS binary system coalescence (emission of GW)

GRB - Fireball model

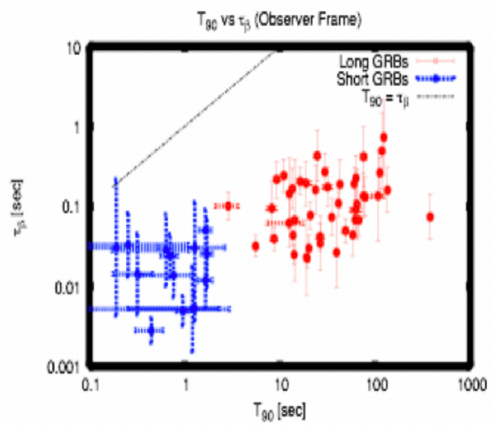
- jet emission (about 10° opening angle)
- multiple collision of relativistic shells ($\Gamma = [1 - (v_{jet}/c)^2]^{-1/2} \geq 100$)
- explains rapid variability
- synchrotron radiation and inverse Compton scattering
- energetics: 10^{51} ergs released in 50 s

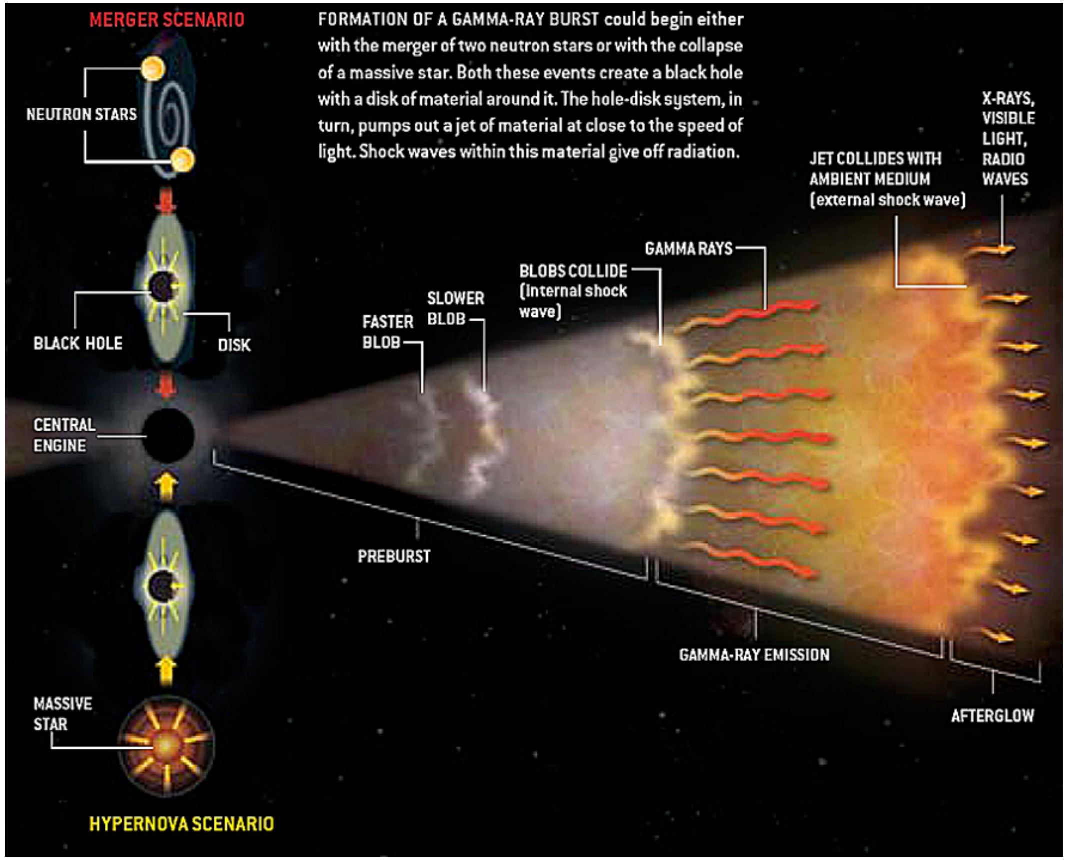
BeppoSAX GRBM data



Data 40-700 keV (A=1136 cm2, courtesy of F. Frontera)

Fermi GBM (8 keV - 40 MeV)





HERMES & *GrailQuest* in a nutshell

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):

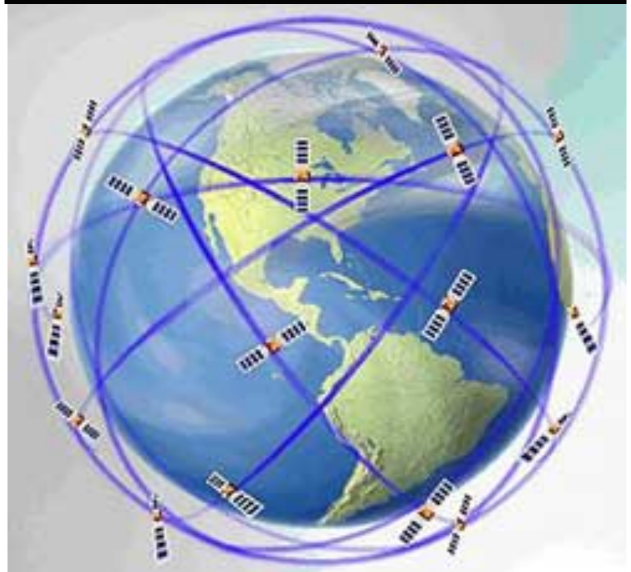
- **GRBs**
- **GW events**
- high-energy counterparts of **Fast Radio Bursts**
- flares from **Magnetars**
- ***GrailQuest*** (only)
  first dedicated experiment in Quantum Gravity

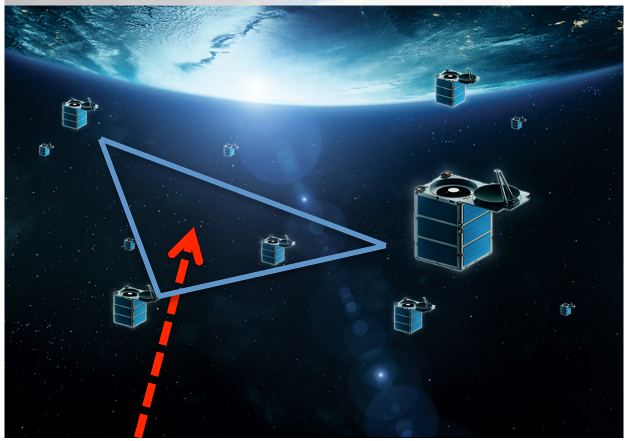
How:
temporal triangulation of signals detected by a **swarm of LEO nano/micro/small satellites** equipped with:

- keV-Mev scintillators,
- sub μs time resolution
- temporal triangulation

Pros:

- modularity,
- limited cost,
- quick developement

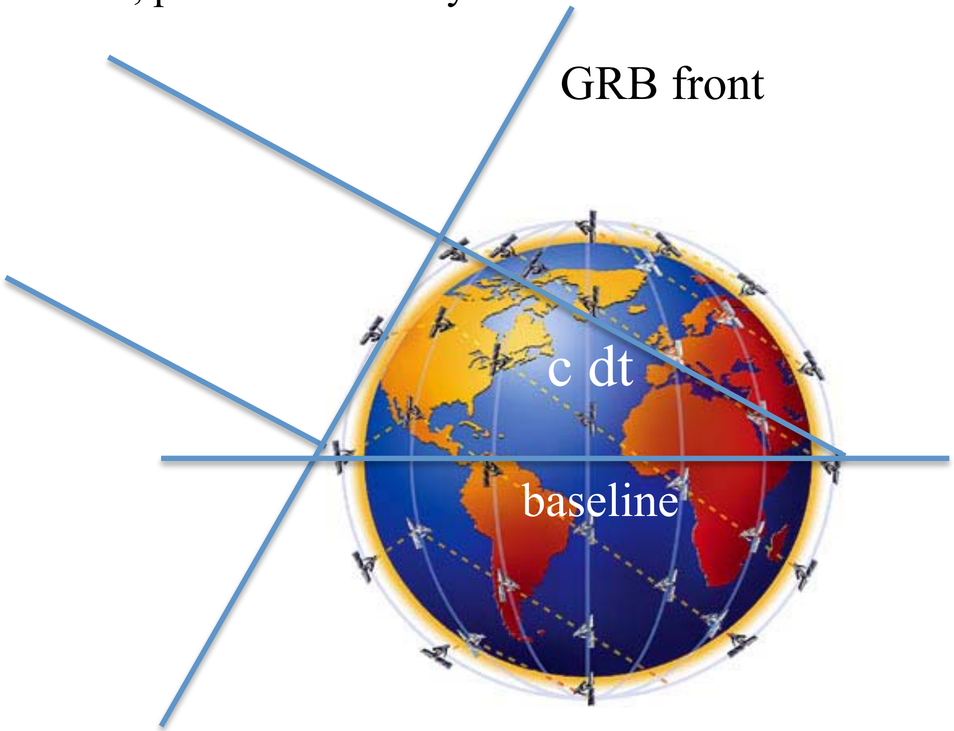




Principles of temporal triangulation

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

Transient source in the sky defined by time of the event, position in the sky:
T_0, α, δ (3 parameters, $N_{PAR} = 3$)



$i = 1, \ldots, N_{SATELLITES}$
$j = 1, \ldots, N_{SATELLITES}$

$DEL_{ij} = ToA(i) - ToA(j)$

$DEL_{ij} = -DEL_{ji}$; $DEL_{ii} = -DEL_{jj} = 0$

Number of (non trivial) different DEL_{ij}:
$N_{DELAYS} = N_{SATELLITES} \times (N_{SATELLITES} - 1) / 2$

Number of independent measurements:
$N_{IND} = N_{SATELLITES}$

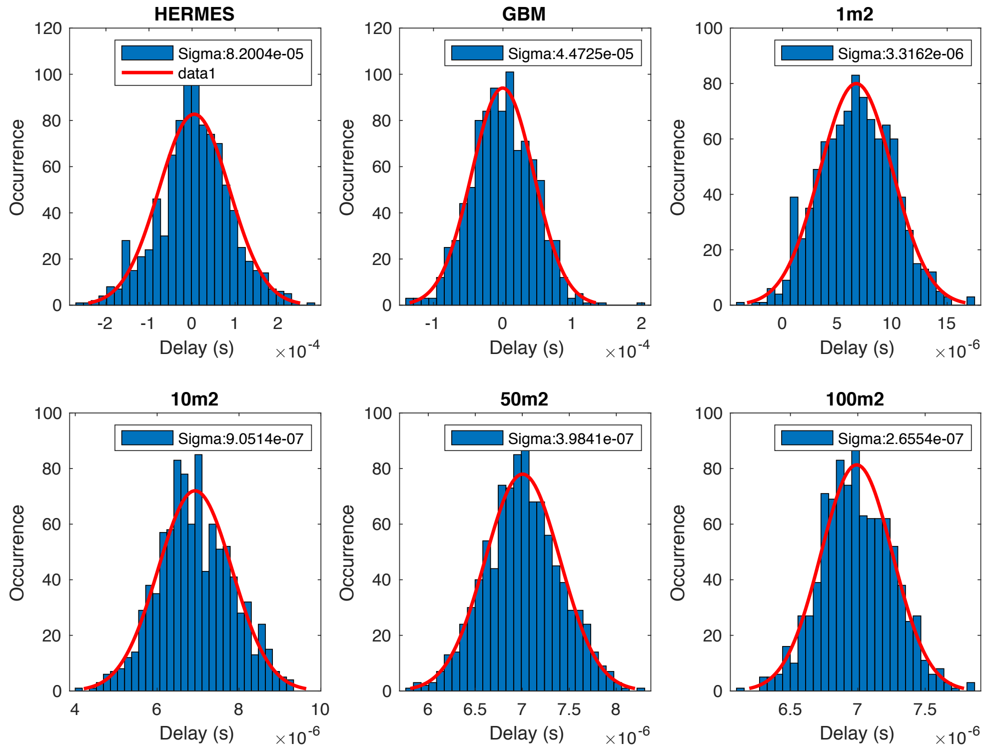
Statistical accuracy in determining α and δ with $N_{SATELLITES}$:

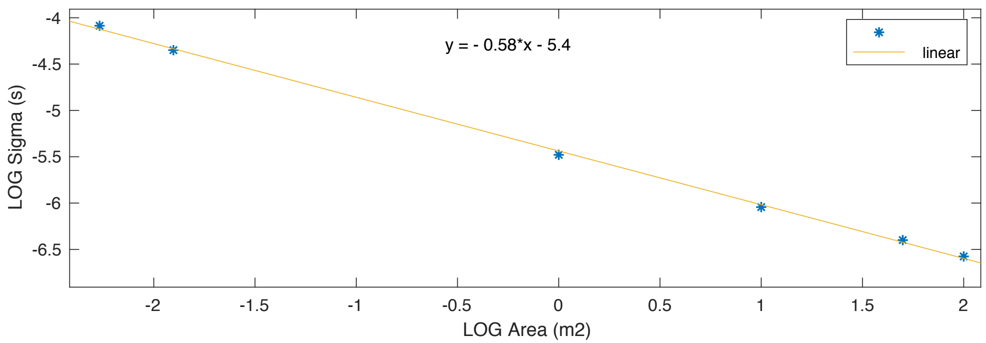
$$\sigma_\alpha \approx \sigma_\delta = c\, \sigma_{ToA} / \langle baseline \rangle \times (N_{IND} - N_{PAR})^{-1/2}$$

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 ≈ 5 ms;

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





Best fit formula:

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

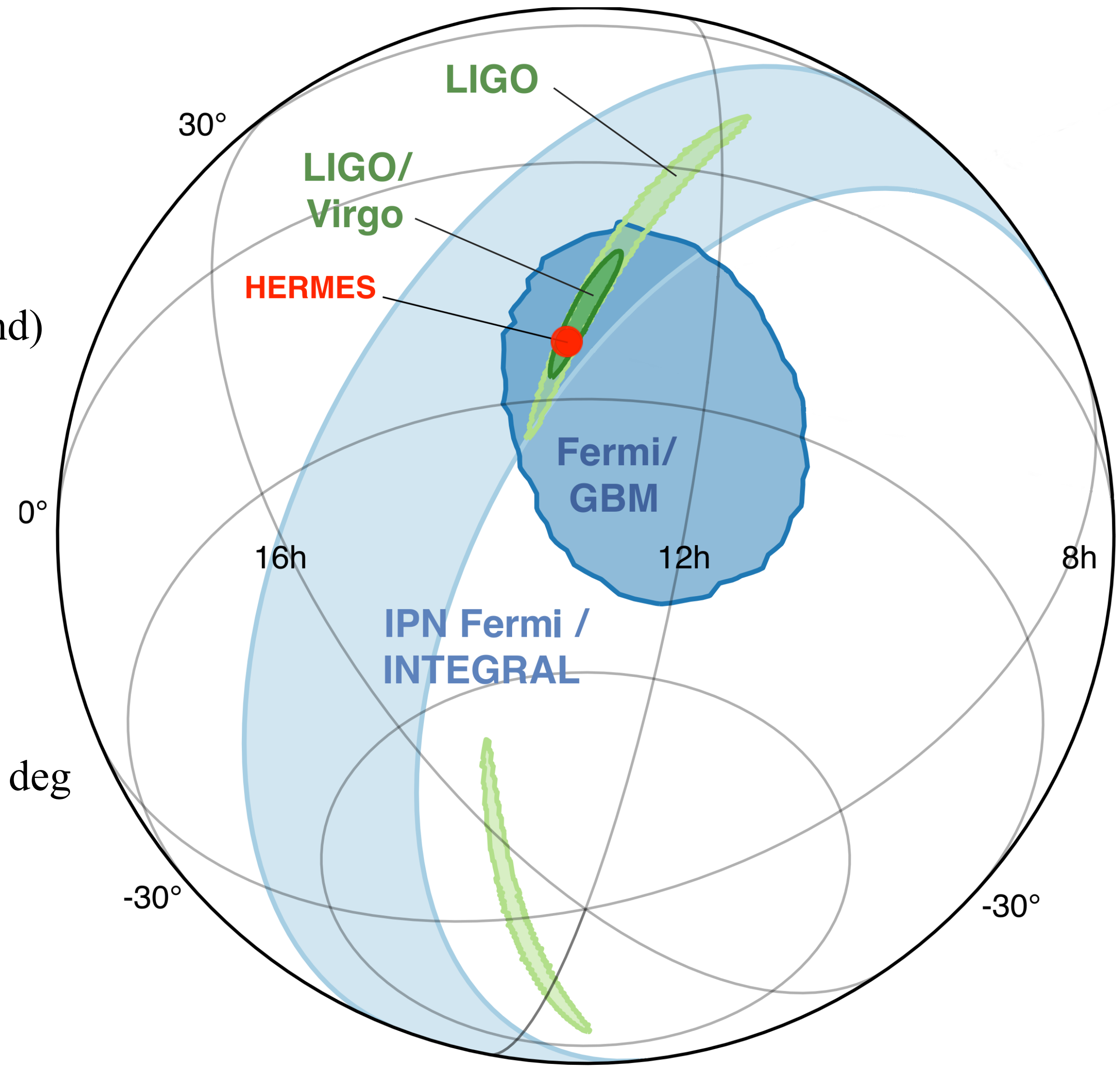
GW Triangulation & EM counterparts (Fermi GBM, INTEGRAL, HERMES Pathfinder)

Example:

long bright GRB
6.5 phot/s/cm^2 (source)
3 phot/s/cm^2 (background)
30 s duration
50-300 keV band

6 satellites each of effective area: 50 cm^2

$\sigma_{ToA} \approx 1$ ms
<baseline> $\approx$ 6000 km
positional accuracy: 1.7 deg



HERMES 3U CubeSat

- 10×10×30 cm
- Gyroscope Stability on 3 axes
- FoV(FWHM) ≈ 3 steradians

On board Systems:

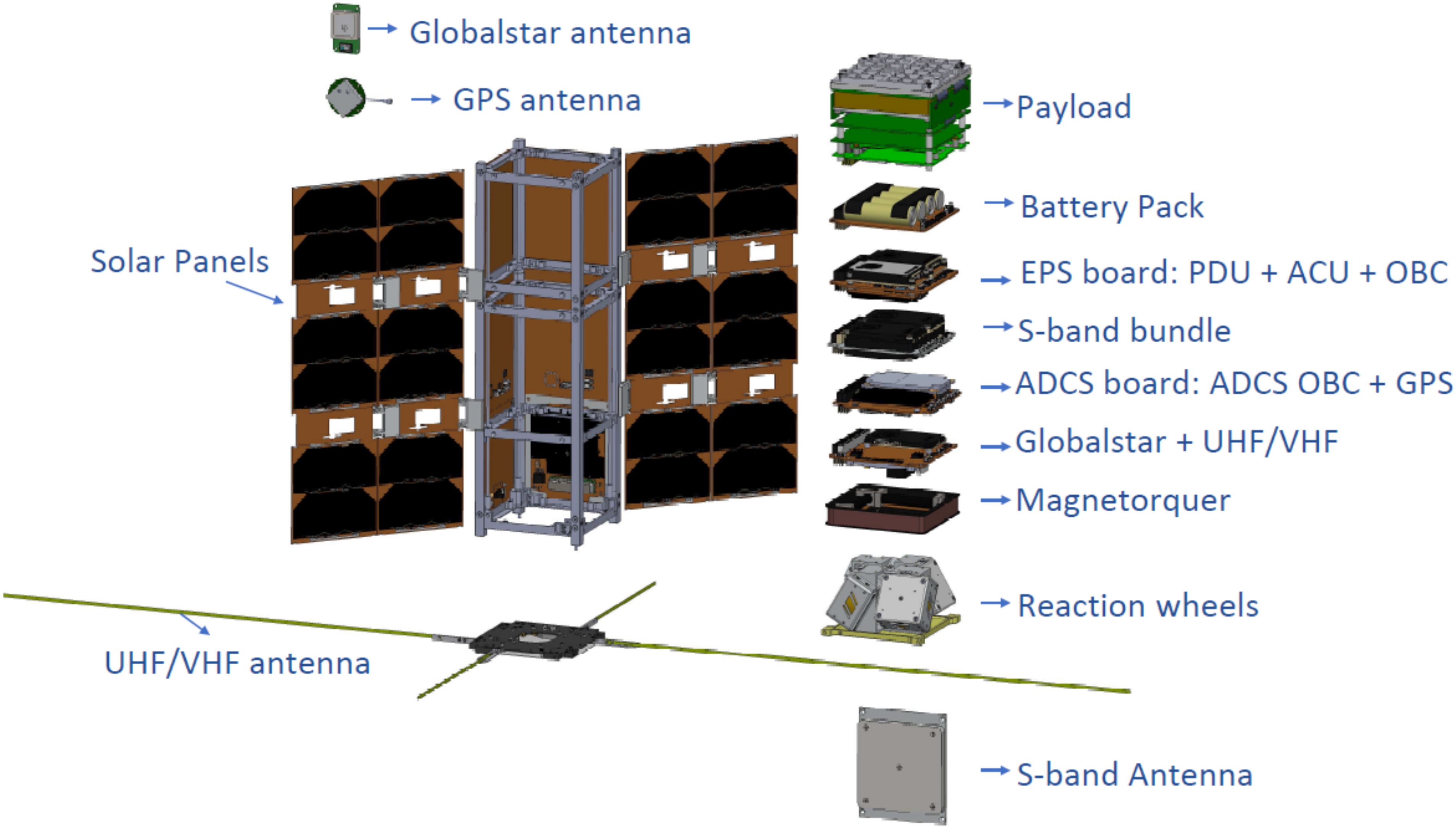
Data recording:

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

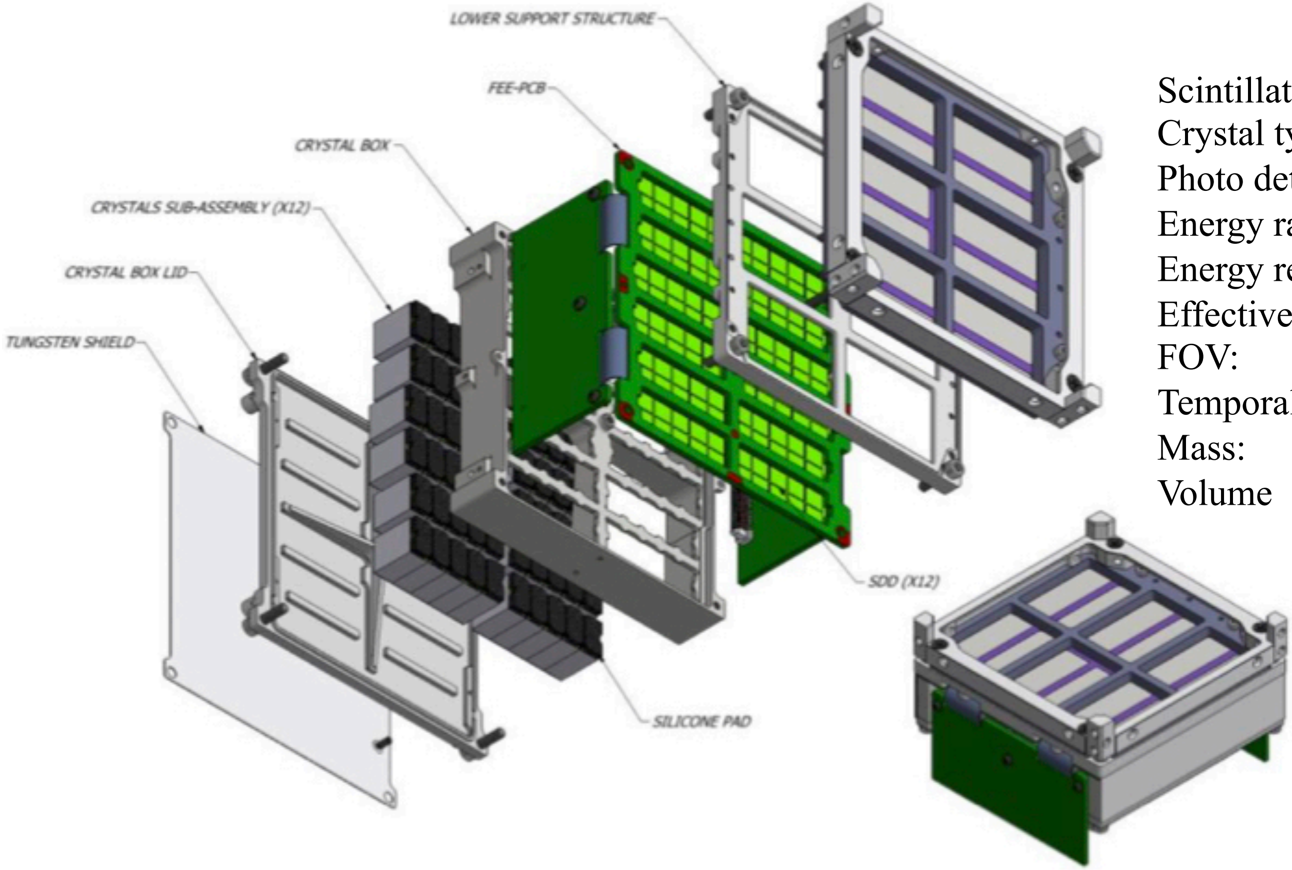
Data download:

- S−band download on ground stations (equatorial orbit)
- VHF data transmission
- IRIDIUM constellation for data transmission

Spacecraft

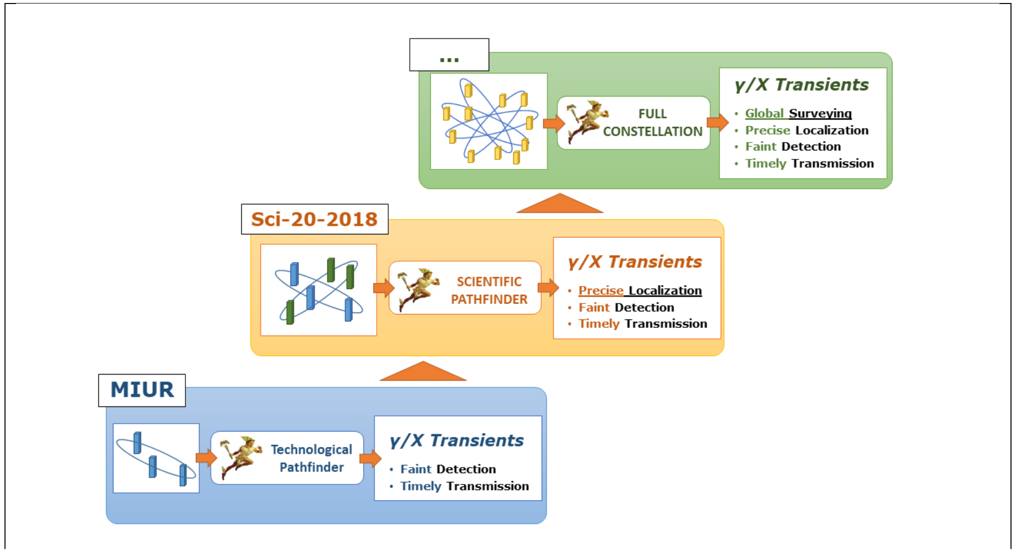

Globalstar antenna
GPS antenna
Solar Panels
UHF/VHF antenna
Payload
Battery Pack
EPS board: PDU + ACU + OBC
S-band bundle
ADCS board: ADCS OBC + GPS
Globalstar + UHF/VHF
Magnetorquer
Reaction wheels
S-band Antenna

Payload Design



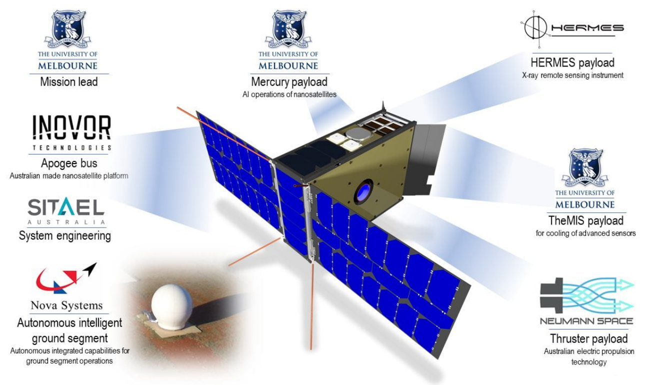
Scintillator Crystal size:	0.7×1.2×1.5 cm
Crystal type:	60 GAGG crystals
Photo detector:	120 SDD (1x0.5 cm)
Energy range:	4 keV ÷ ≥ 0.5 Mev
Energy resolution:	~ 10% at 30 keV
Effective area:	~ 56 cm^2
FOV:	~ 3 steradians (FWHM)
Temporal resolution:	~ 0.5 μs
Mass:	1.8 kg
Volume	< 10×10×12.5 cm

HERMES project development – incremental strategy



SpIRIT

Space Industry – Responsive – Intelligent – Thermal Nanosatellite



Funding status at 2020, December

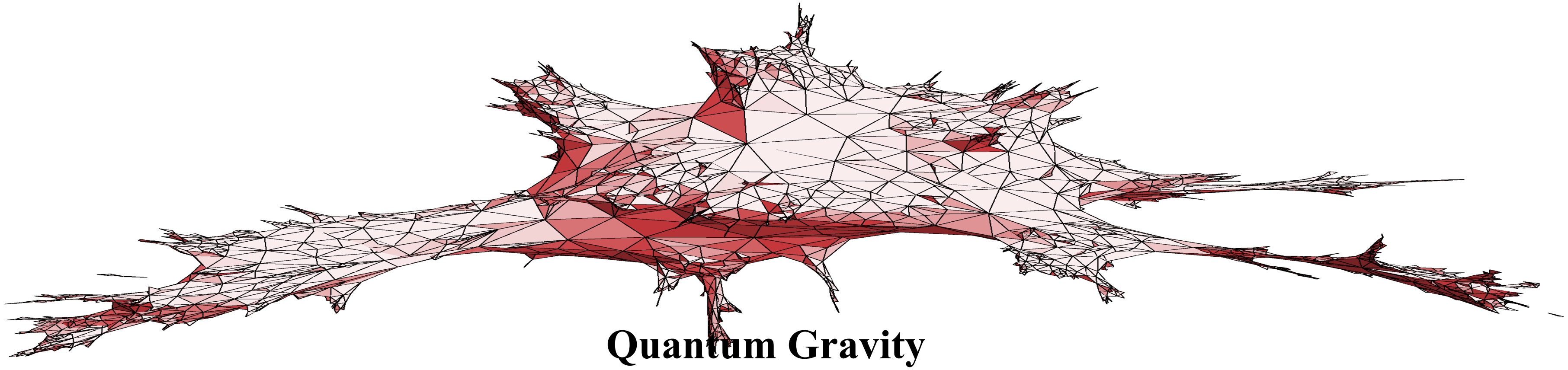
ASI (Italian Space Agency) – 23/12/2016:	€ 500,000
MIUR (Italian Ministry of University and Research) and ASI – 29/11/2017:	€ 1,650,915 (MIUR)
	€ 815,085 (ASI)
EU Horizon 2020 – Call: H2020-SPACE-2018-2020 – 17/07/2018:	€ 3,318,450
ASI (Italian Space Agency) – internal funding 05/02/2019	€ 1,900,000
Total Funding (at 12/2020):	**€ 8,184,450**

Incremental strategy:

Hermes Technological Patfinder (ASI funding): 3 3U satellites equatorial (launch 2023)

Hermes Scientific Patfinder (EU H2020 funding): 3 3U satellites equatorial (launch 2023)

Hermes on Spirit (ASI + Austalian Space Agnecy): 1 6U satellite SSO orbit (launch 2022)

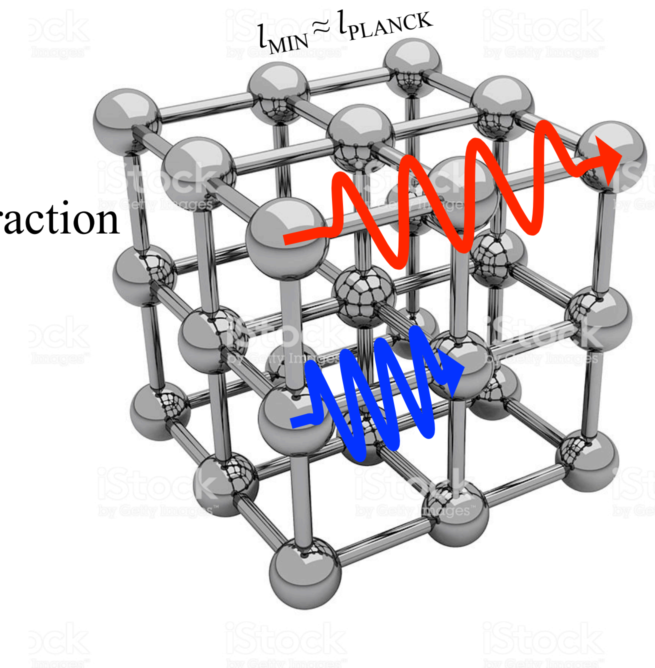


Quantum Gravity

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

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

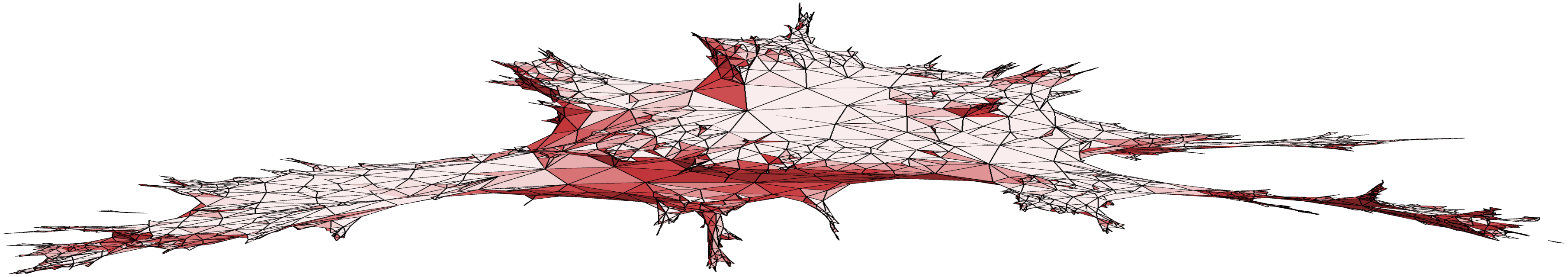
$$l_{MIN} \approx l_{PLANCK} = [Gh/(2\pi c^3)]^{1/2} = 1.6 \times 10^{-33} \text{ cm}$$



implies:

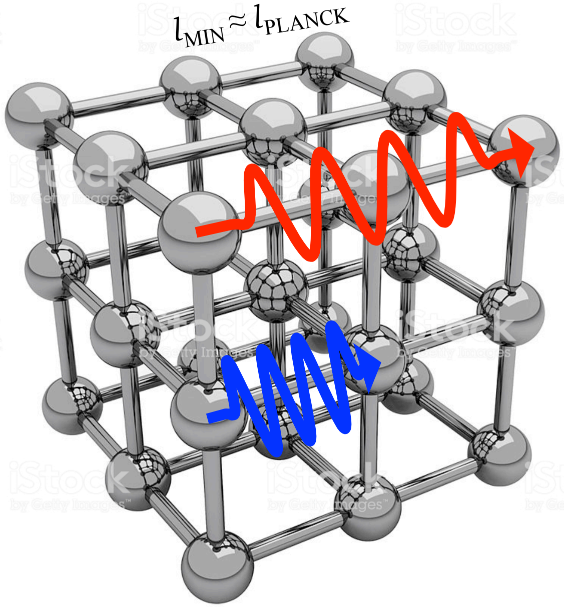
i) Lorentz Invariance Violation (LIV): no further Lorentz contraction
ii) Space has the structure of a crystal lattice and therefore
iii) Existence of a dispersion law for photons *in vacuo*

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

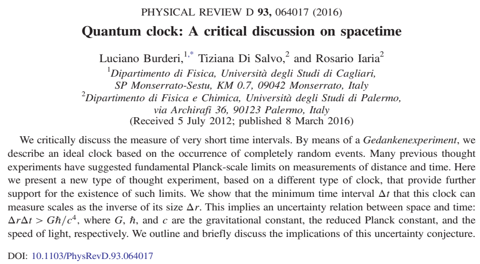


First and second order Dispersion Relation for photons *in vacuo*

LIV theories



No LIV theories



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

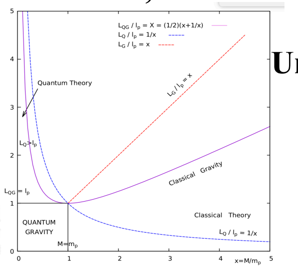
Quantum clock: A critical discussion on spacetime

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 Δt that this clock can measure scales as the inverse of its size Δr. 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.

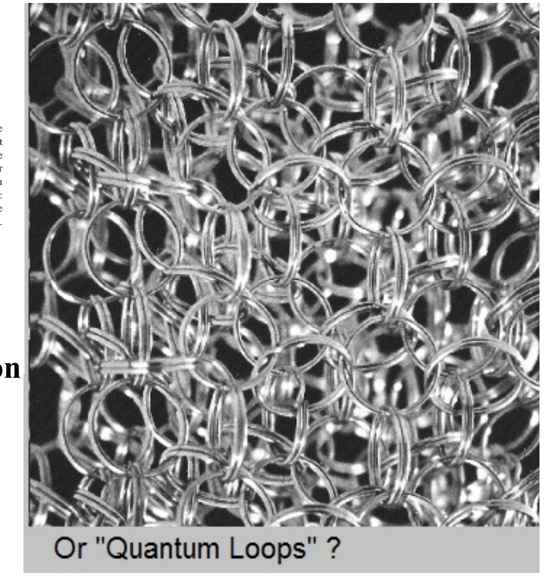
DOI: 10.1103/PhysRevD.93.064017

Burderi, Di Salvo, Iaria (2016)



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

& Sanchez, 2018



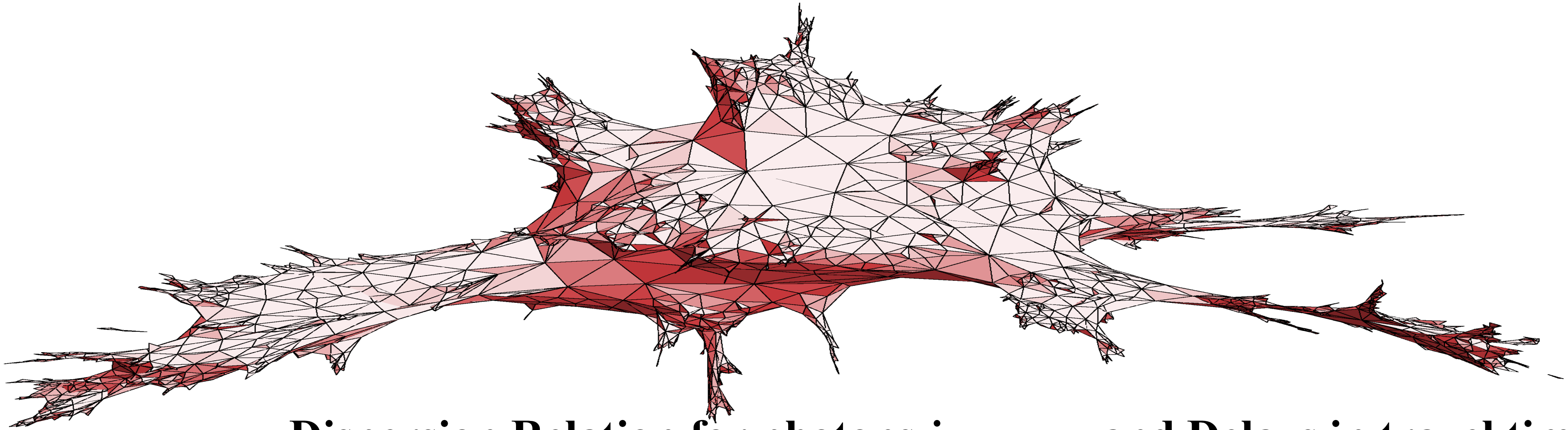
Loop Quantum Gravity (Rovelli)

First Order Dispersion Relation

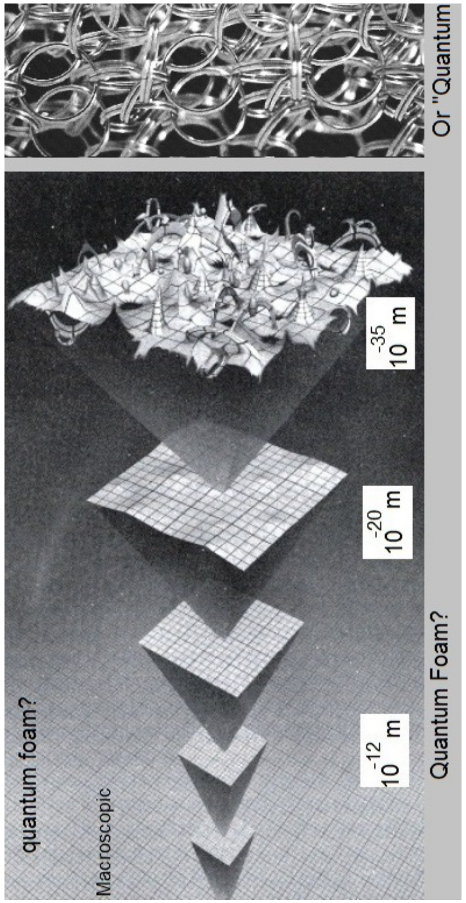
$v_{phot}/c \approx 1 - \xi \, E_{phot}/(M_{Planck} \, c^2)$

Second Order Dispersion Relation

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



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



Accumulation of delays in light propagation:

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

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

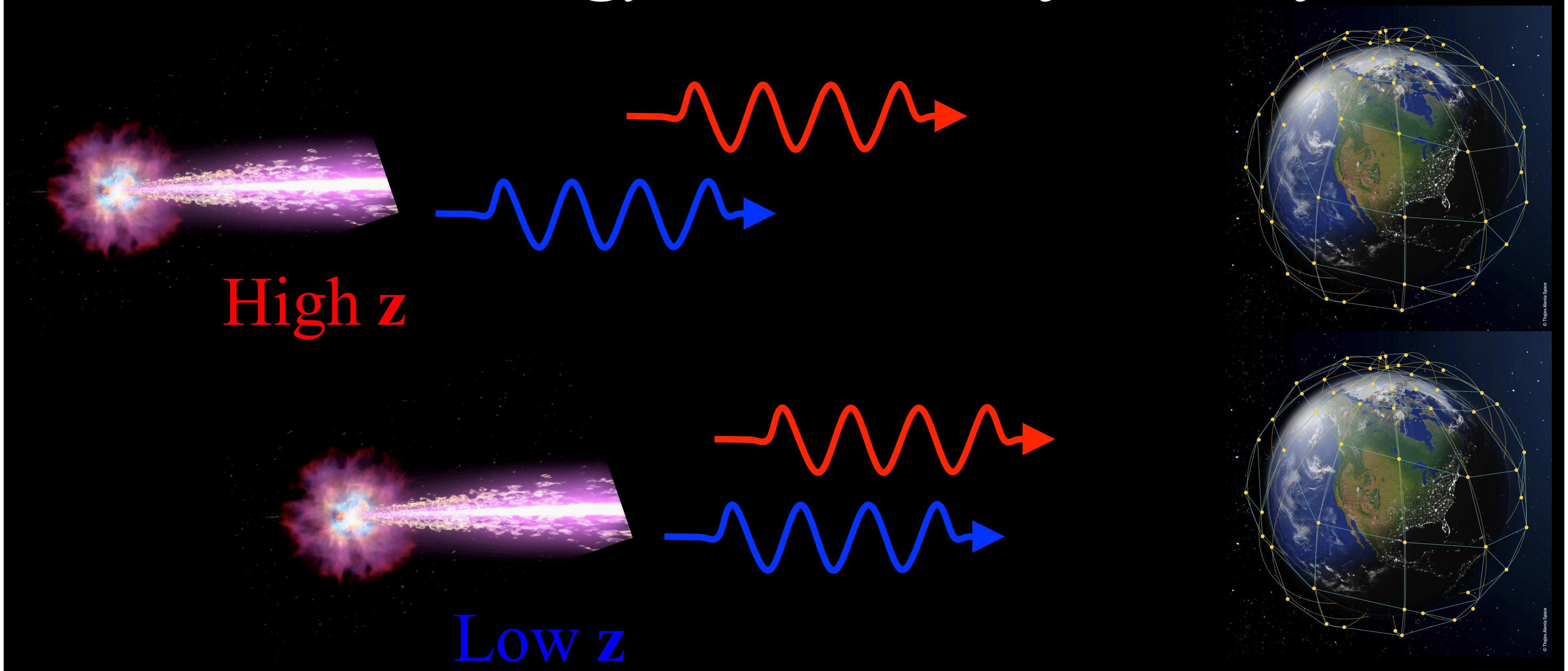
$$D_{TRAV}(z)=(c/H_0)\int_0^z d\beta\,(1+\beta)/[\Omega_\Lambda+(1+\beta)^3\,\Omega_M]^{1/2}$$

z: cosmological redshift

Ω_Λ: ratio between the energy density due to the cosmological constant and the critical (closure) density of the Universe

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

The *Energy & Redshift* delay

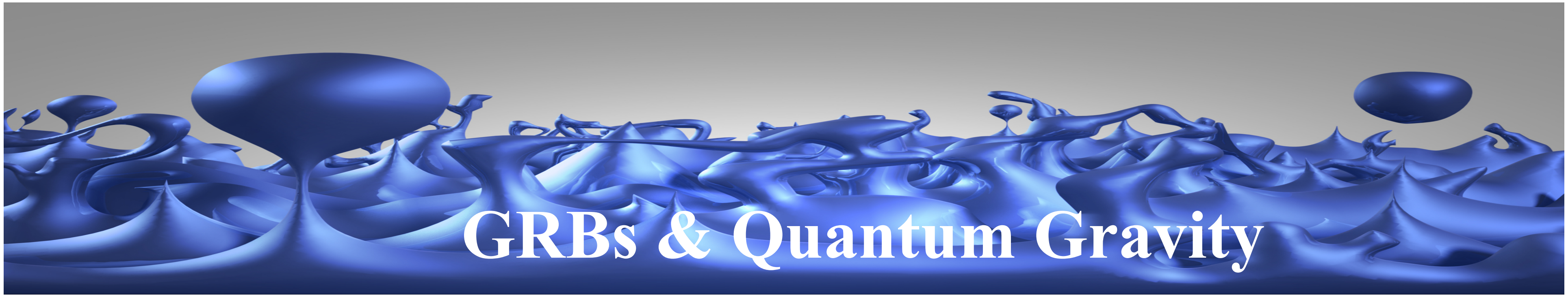


Time lags caused by Quantum Gravity effects:

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

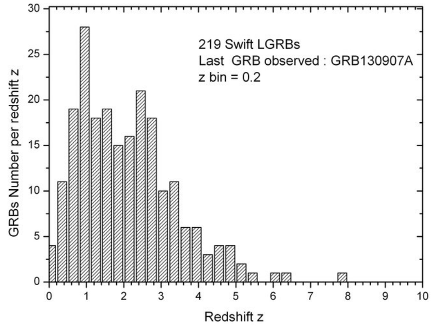
Time lags caused by prompt emission mechanism:

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



GRBs & Quantum Gravity

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



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

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

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

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

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

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:

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

Accuracy in determining α and δ with $N_{SATELLITES}$ ($N_{IND} = N_{SATELLITES}$; $N_{PAR} = 3$, T_0, α, δ):

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

Large fleet of small satellites in Low Earth Orbits:

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

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

$N_{SATELLITES} \approx 1000$

$\langle baseline\rangle \approx 6{,}000\ km$

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

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

$A \approx 1.0\ m^2$

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

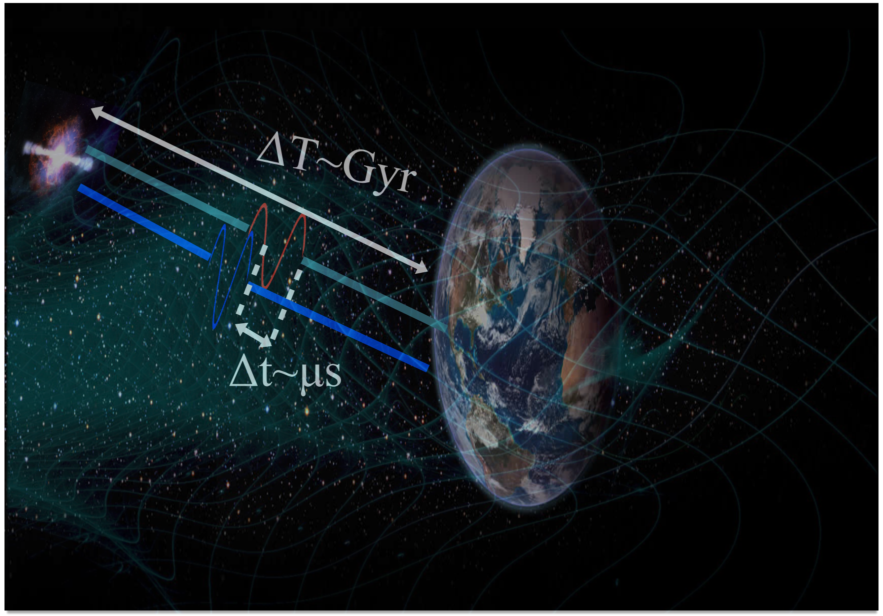
$N_{SATELLITES} = 3$

$\langle baseline\rangle \approx 400{,}000\ km$

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

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

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



Download paper at arXiv:1911.02154v2

Experimental Astronomy
https://doi.org/10.1007/s10686-021-09745-5

ORIGINAL ARTICLE

Check for updates

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

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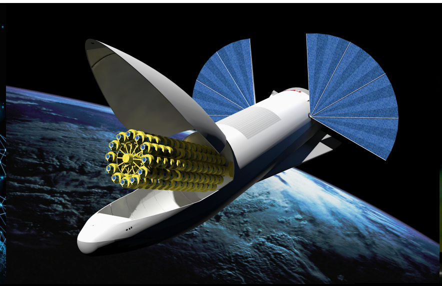
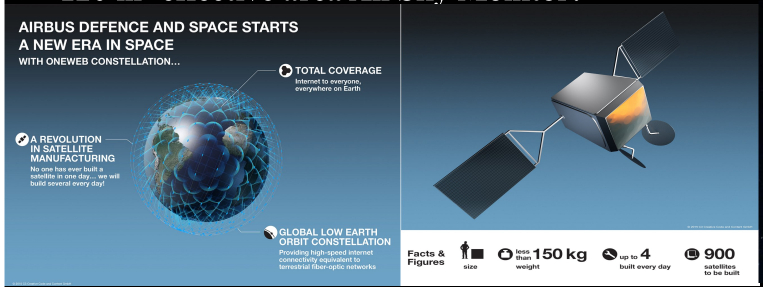
Starlink Constellation
12,000 sats
SpaceX
(Elon Musk)



- 4425 @ 1200 km (completed by 2024)
- 7518 @ 340 km
- up to 1,000,000 fixed satellite earth stations & optical inter–satellite links
- 100 ÷ 500 kg satellites (mass production)
- 1700 satellites launched at 02/11/2021
- **board a 10×10 = 100 cm^2 effective area detector on each satellite**
- **120 m^2 effective area All Sky Monitor!**

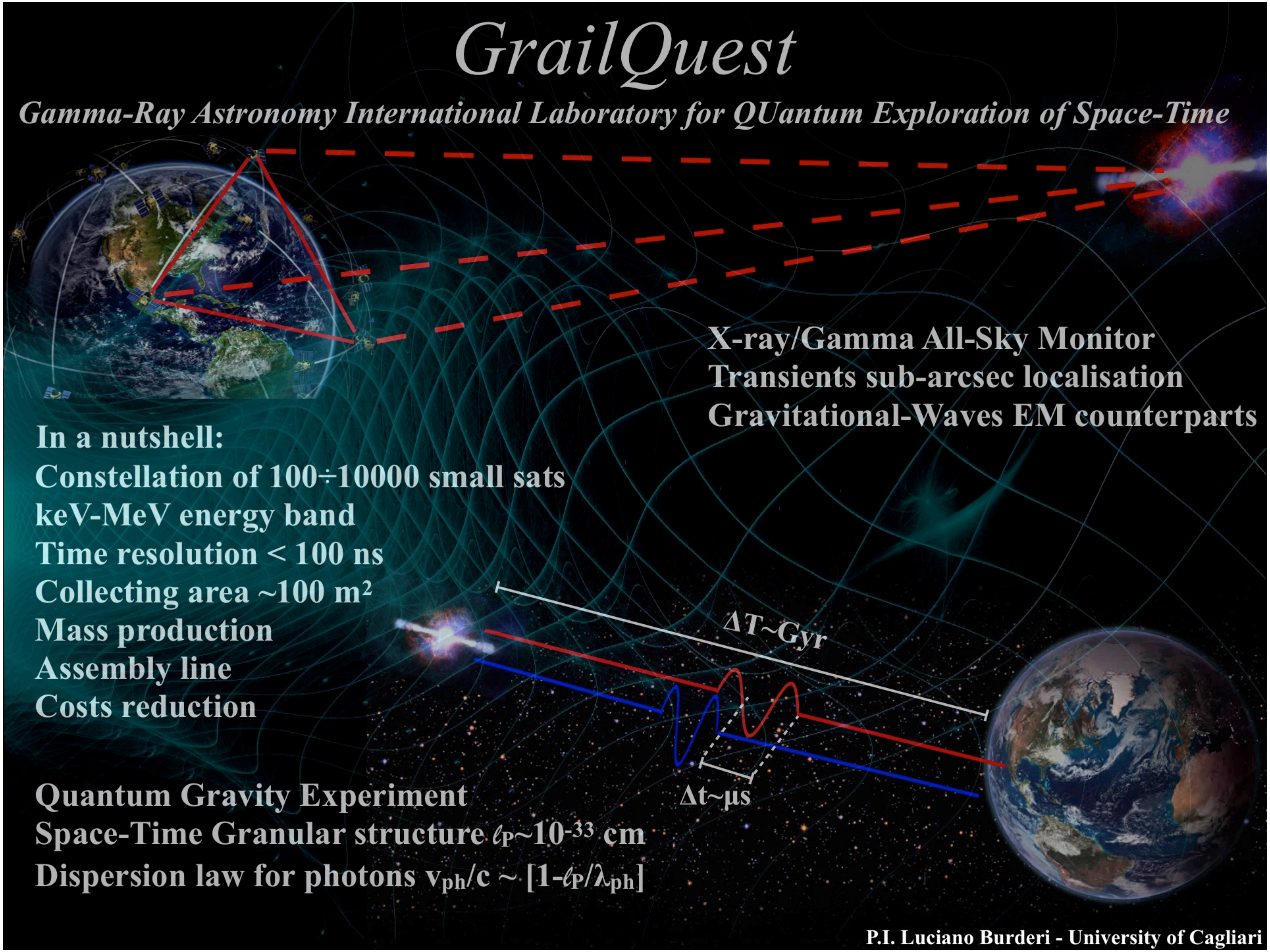
OneWeb Constellation
650 sats,
Virgin Galactic
(Richard Branson)
Arianespace
Airbus Defence and Space

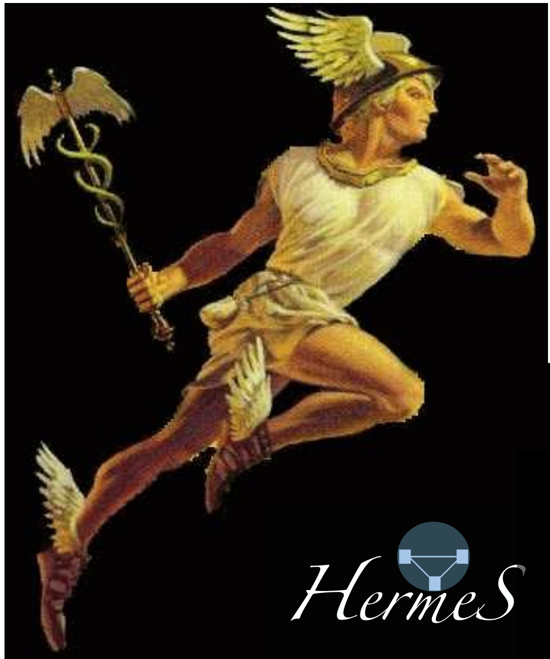


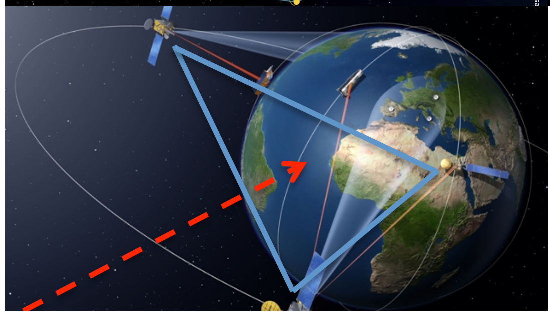
- 900 @ 1200 km (648 initial phase)
- 150 kg satellites (mass production)
- 330 satellites launched at 02/11/2021
- **board a 30×30 = 900 cm^2 effective area detector on each satellite**
- **81 m^2 effective area All Sky Monitor**

Amazon’s Kuiper System
3,236 sats
Amazon & Blue Origin
(Jeff Bezos)

- 3200 @ 1200 km
- First 2 satellites launch in 2022
- **board a 30×30 = 900 cm^2 effective area detector on each satellite**
- **288 m^2 effective area All Sky Monitor**


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
ΔT~Gyr
Δt~μs
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





The HERMES project:
the movie

That's all Folks!

Please, visit our websites:

http://hermes.dsf.unica.it

www.hermes-sp.eu