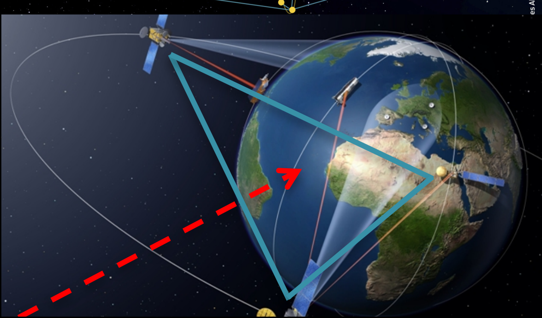


The 4th COSPAR Symposium
Small Satellites for Sustainable Science and Development
Herzliya, Israel, November 7th 2019

The HERMES project

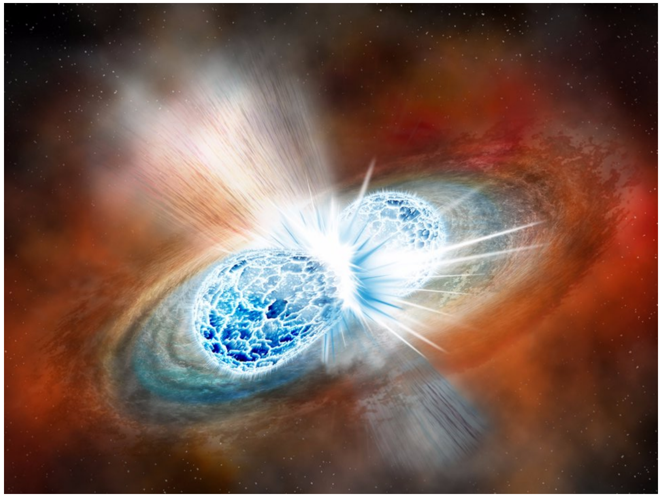
High Energy Rapid Modular Ensemble of Satellites Probing Space-Time Quantum Foam and Hunting for Gravitational Wave Electromagnetic Counterparts

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

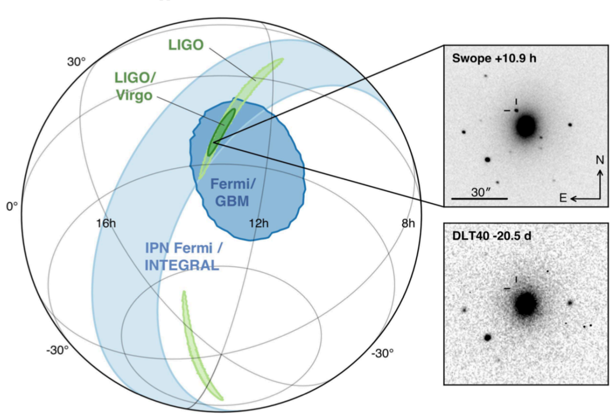
Please, visit our websites:
http://hermes.dsf.unica.it
http://hermes-sp.eu

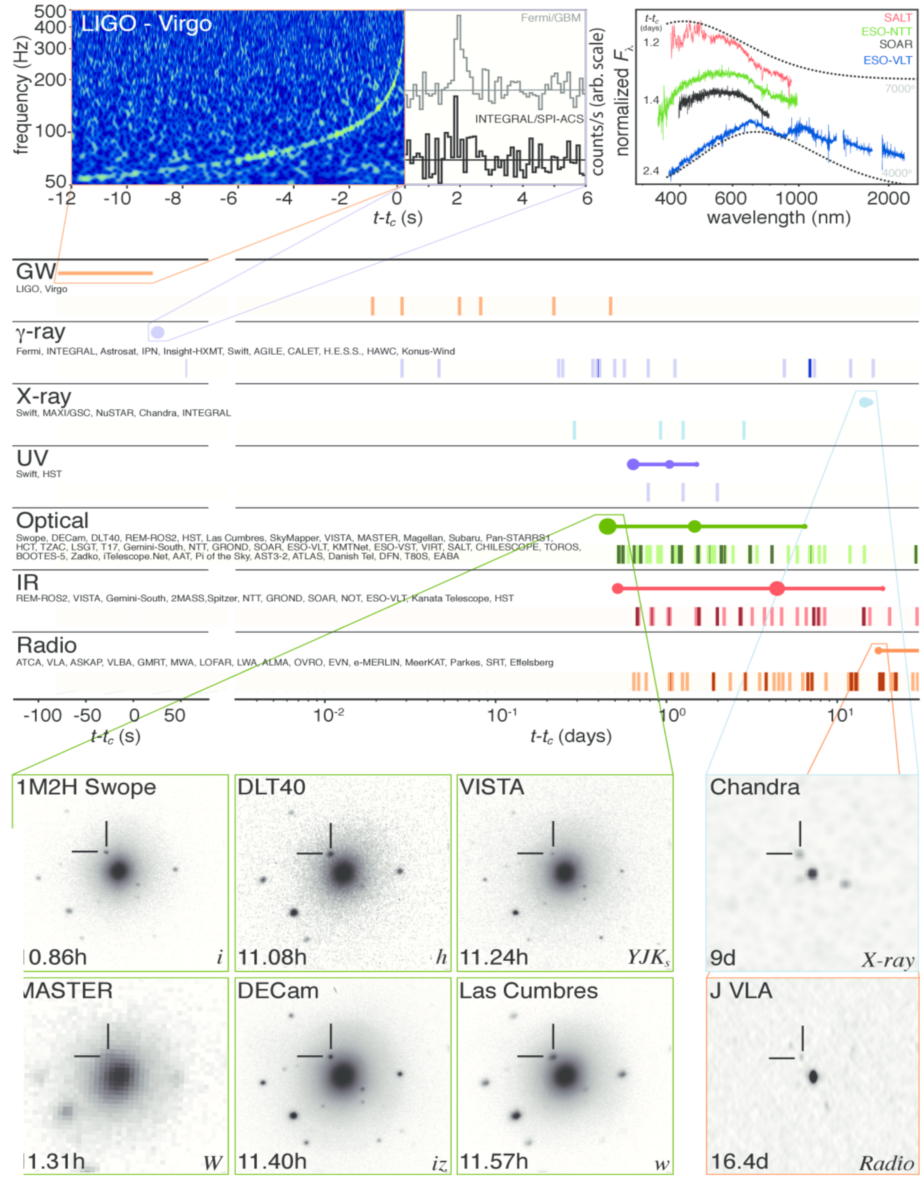
The Multi−Messenger Astronomy

GW170817

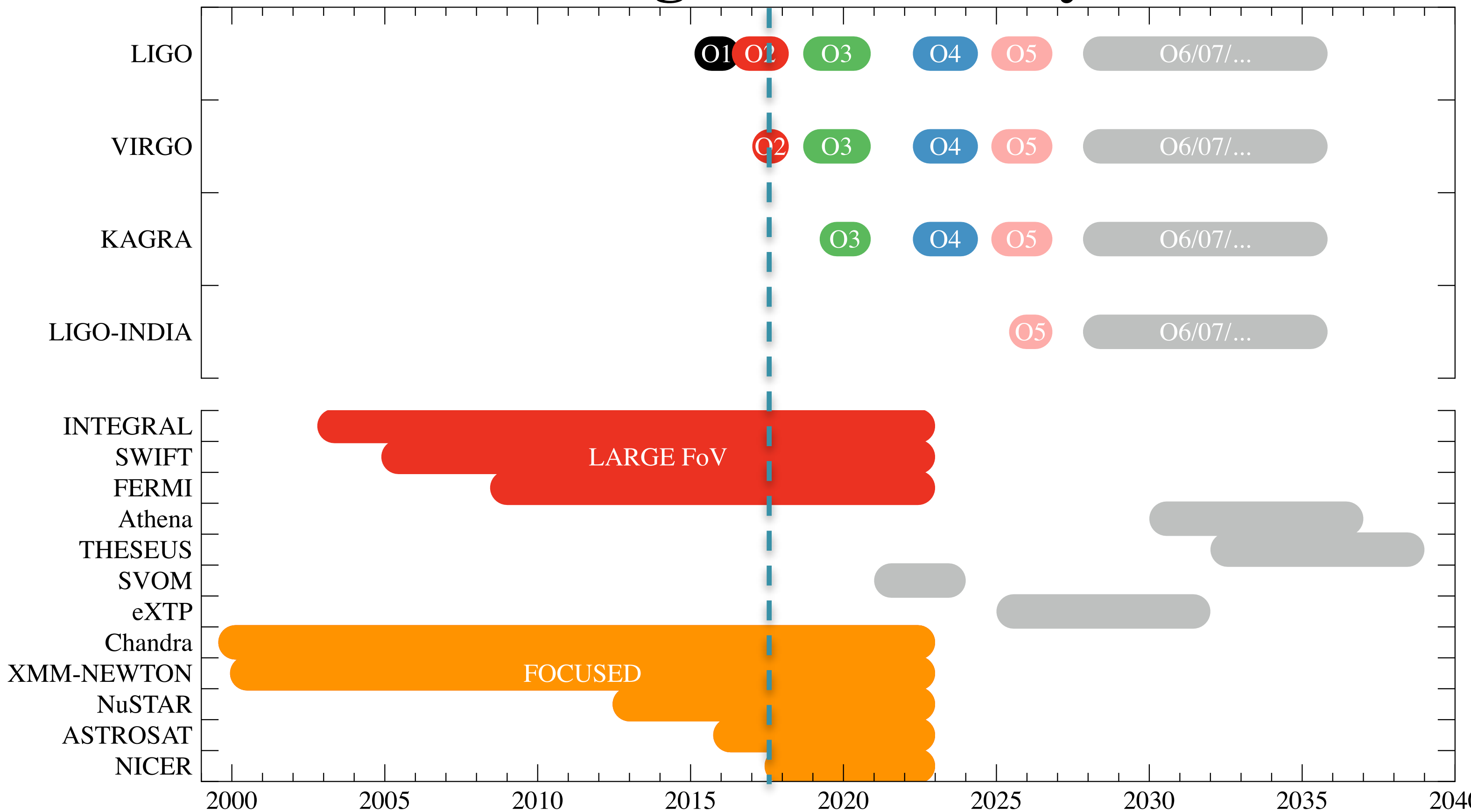


- **NS-NS merging**
- **Host galaxy NGC 4993**
- **~ 40 Mpc**
- **70 observatories**





The Multi−Messenger Astronomy Paradox



- **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**

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
- inspect fine temporal structure of transients
- **first dedicated experiment in Quantum Gravity**

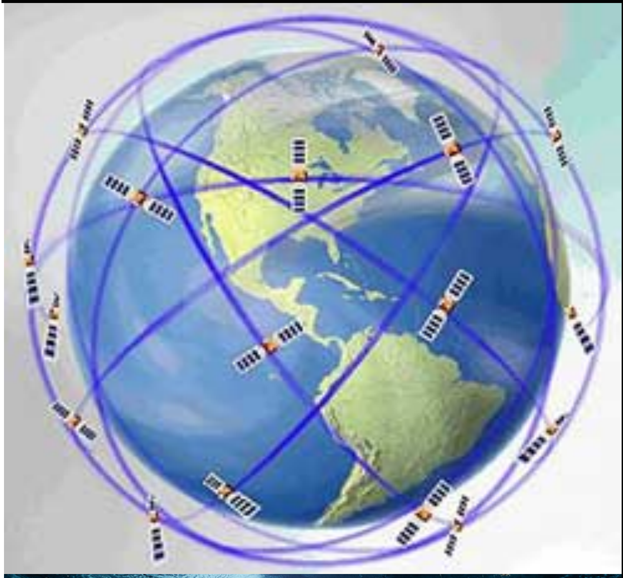
How:

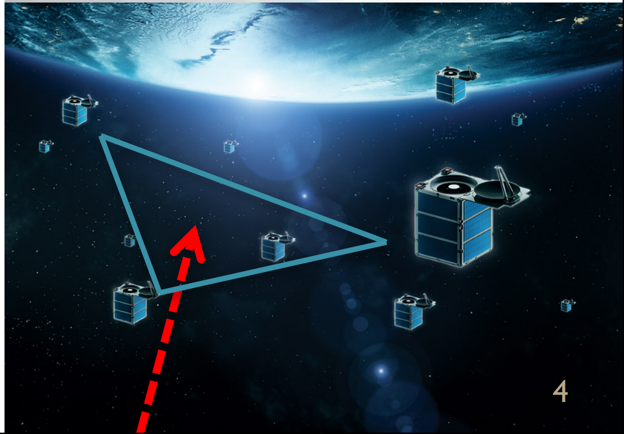
temporal triangulation of signals detected by a **swarm of LEO nano/micro satellites** equipped with:

- keV-Mev scintillators
- sub μs time resolution
- low X-ray background

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, $N_{PAR} = 2$)

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

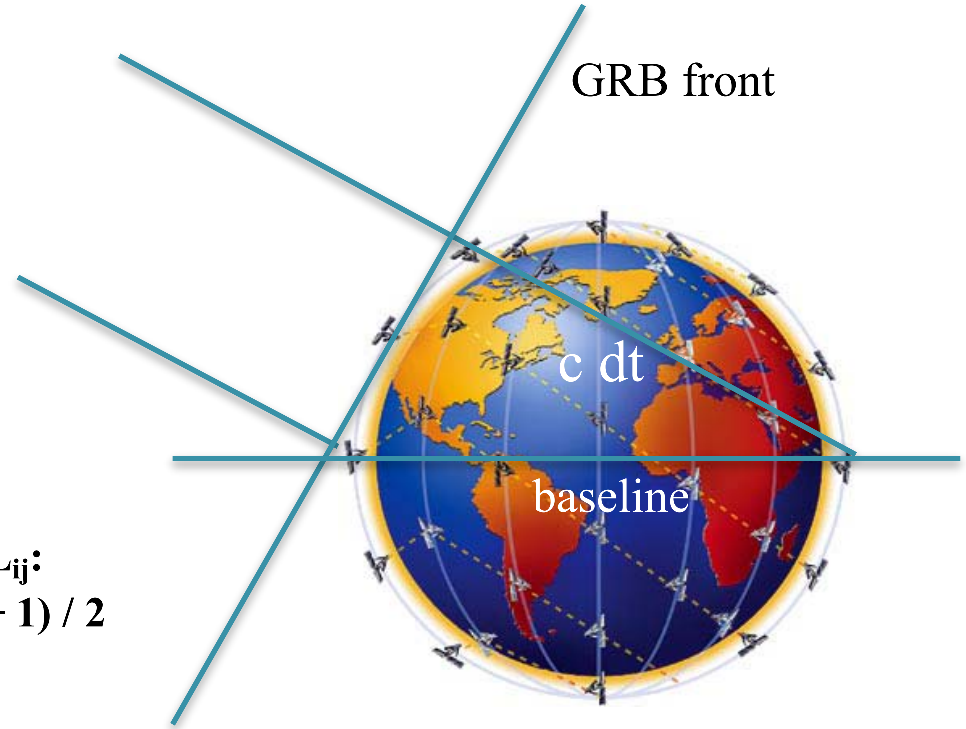
$DEL_{ij} = ToA(i) - ToA(j)$

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

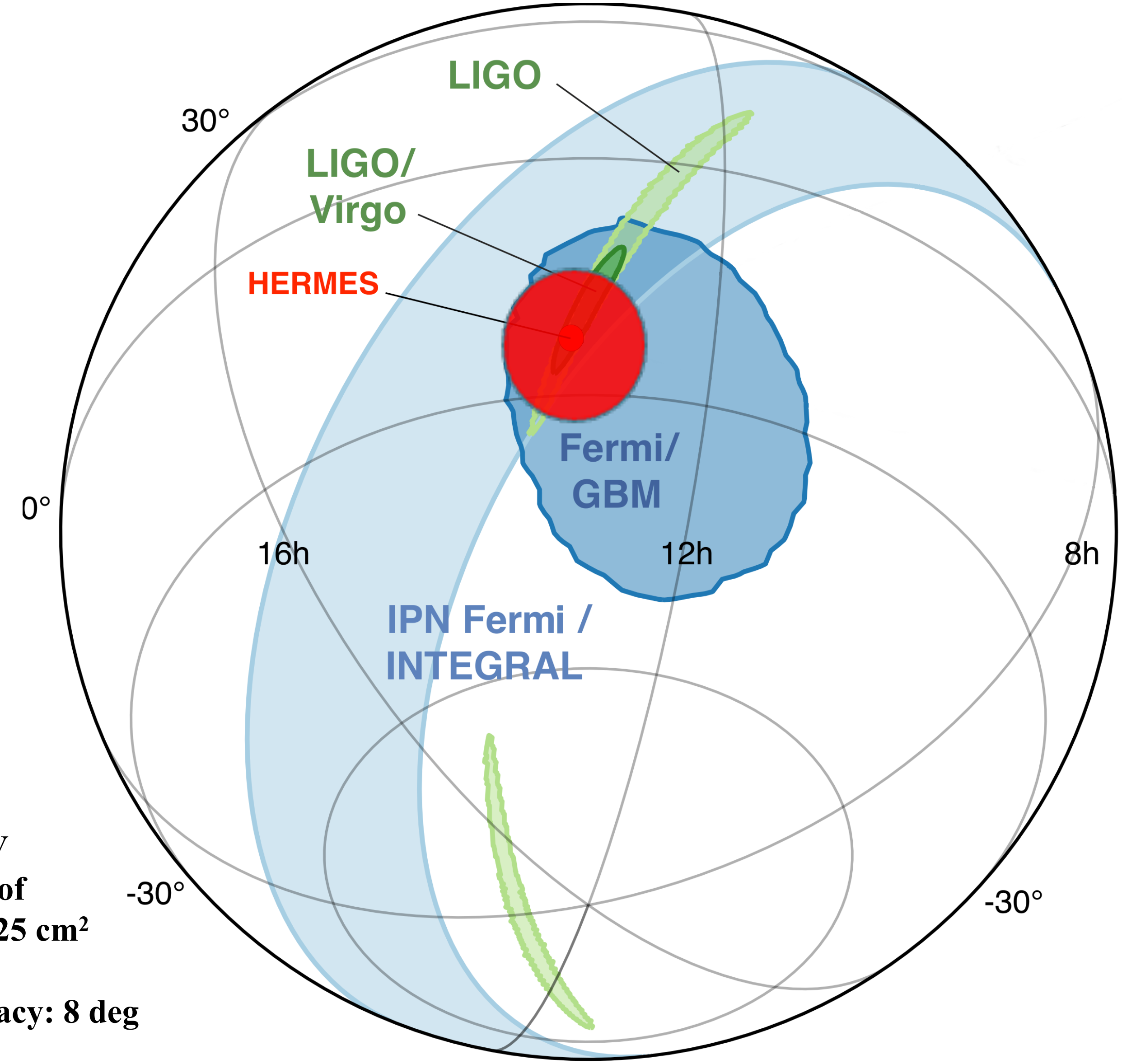
Number of (non trivial) different DEL_{ij}:
$N_{DELAYS} = N_{SATELLITES} \times (N_{SATELLITES} - 1) / 2$

Number of independent DEL_{ij}:
$N_{IND} = N_{SATELLITES} - 1$

Accuracy in determining α and δ with $N_{SATELLITES}$:
$\sigma_\alpha \approx \sigma_\delta = c\, \sigma_{ToA}/\langle baseline \rangle \times (N_{IND} - N_{PAR} + 1)^{-1/2}$



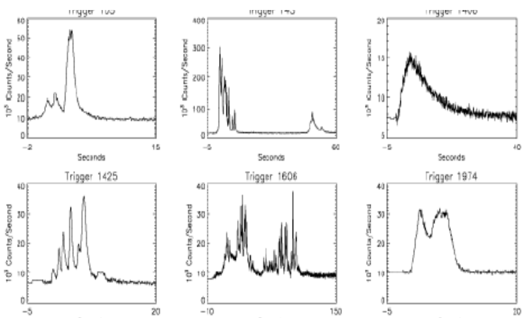
GW Triangulation & EM counterparts (Fermi GBM, INTEGRAL, HERMES Pathfinder)

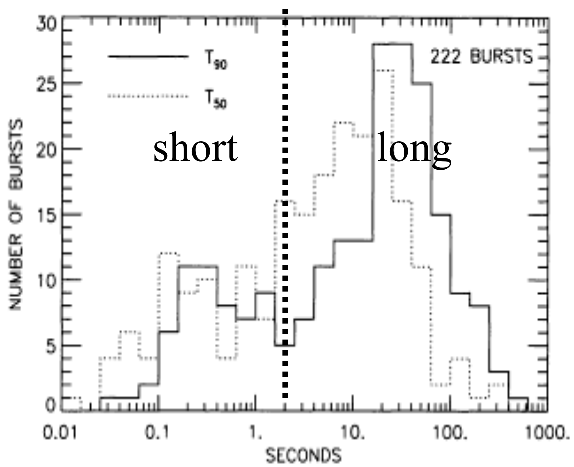


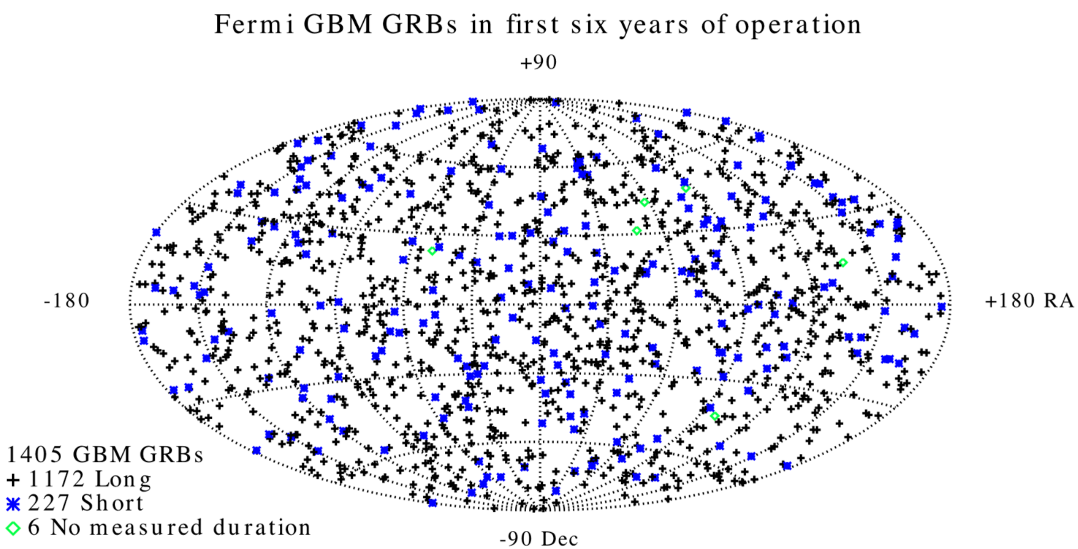
band 50-300 keV
3 satellites each of effective area: 125 cm²
$\sigma_{ToA} \approx 1$ ms
positional accuracy: 8 deg

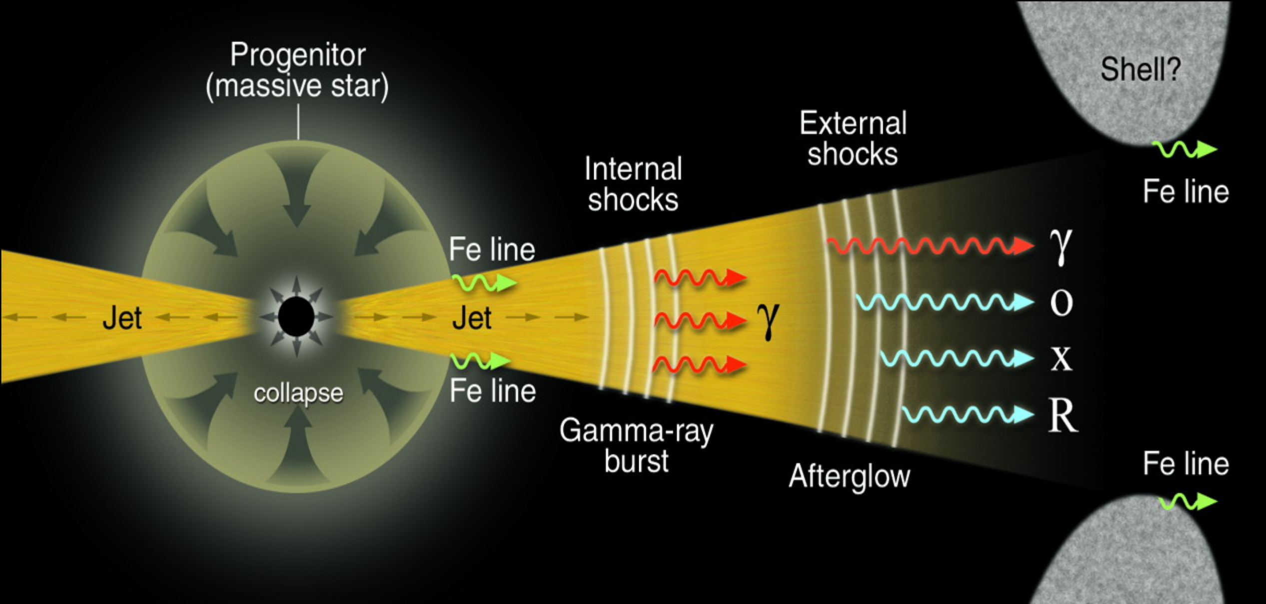
The Gamma-Ray Burst phenomenon

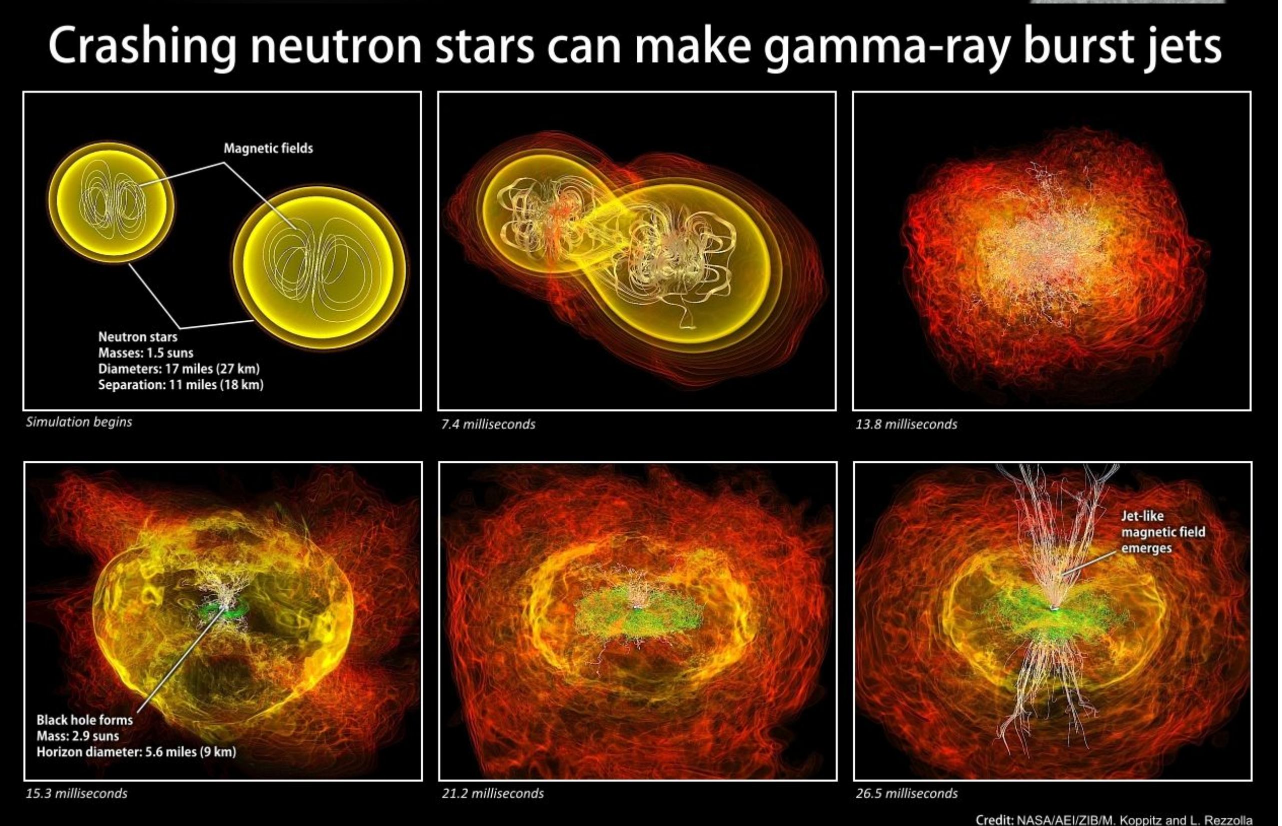
- sudden and unpredictable bursts of hard-X / soft gamma rays with huge flux
- most of the flux detected from 10−20 keV up to 1−2 MeV,
- fluences for very bright GRB (about 3/yr) 25 counts/cm^2/s (GRB 130427A 160 counts/cm^2/s)
- bimodal distribution of duration (0.1−1.0 s & 10.0−100.0 s)
- measured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











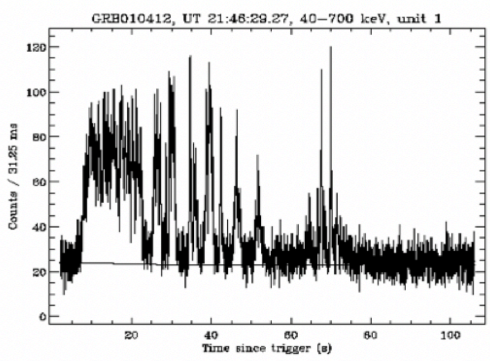
Long GRB:
BH collapse of a massive star

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

GRB - Fireball model

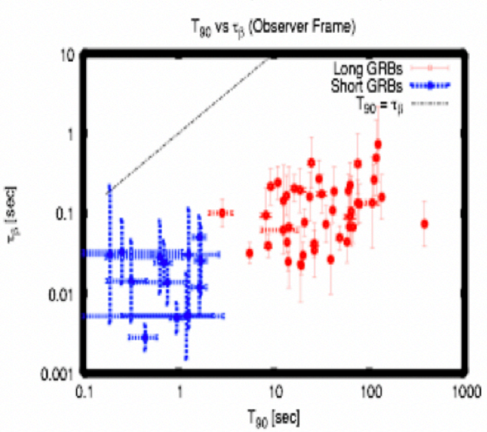
- multiple collision of relativistic shells ($\Gamma = [1 - (v_{jet}/c)^2]^{-1/2} \geq 100$)
- explains rapid variability
- synchrotron radiation and inverse Compton scattering

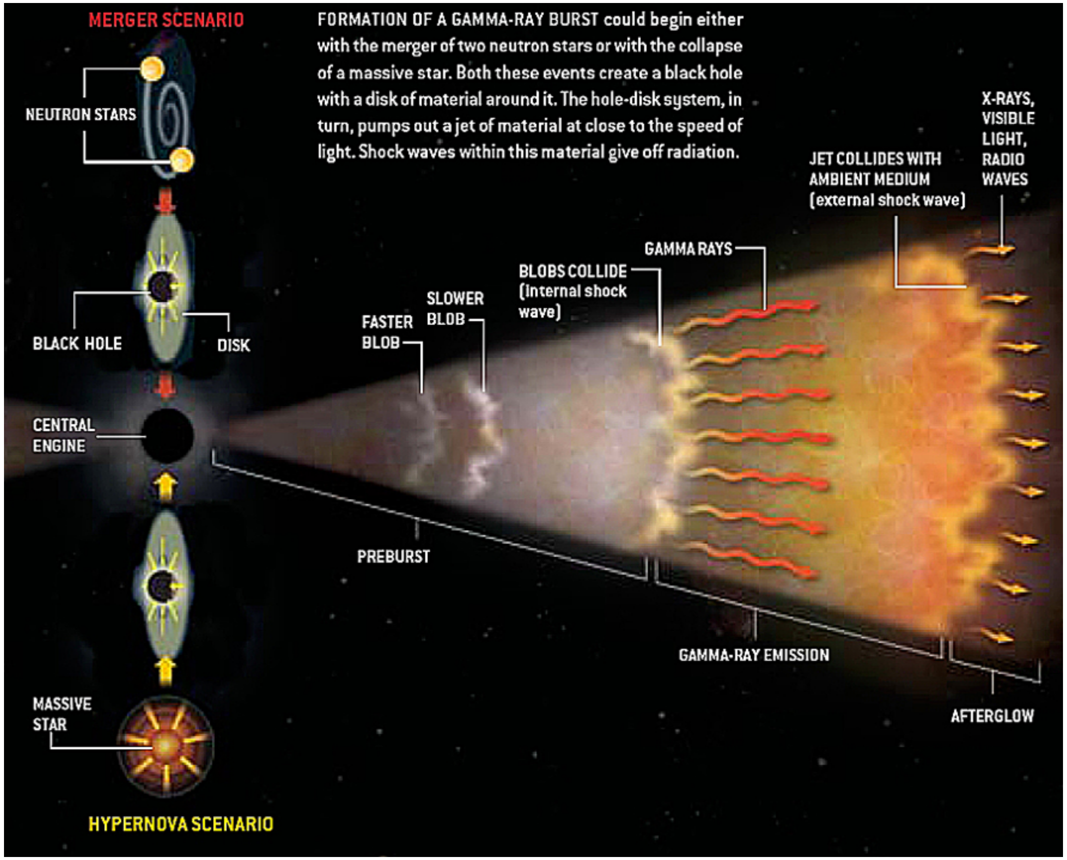
BeppoSAX GRBM data

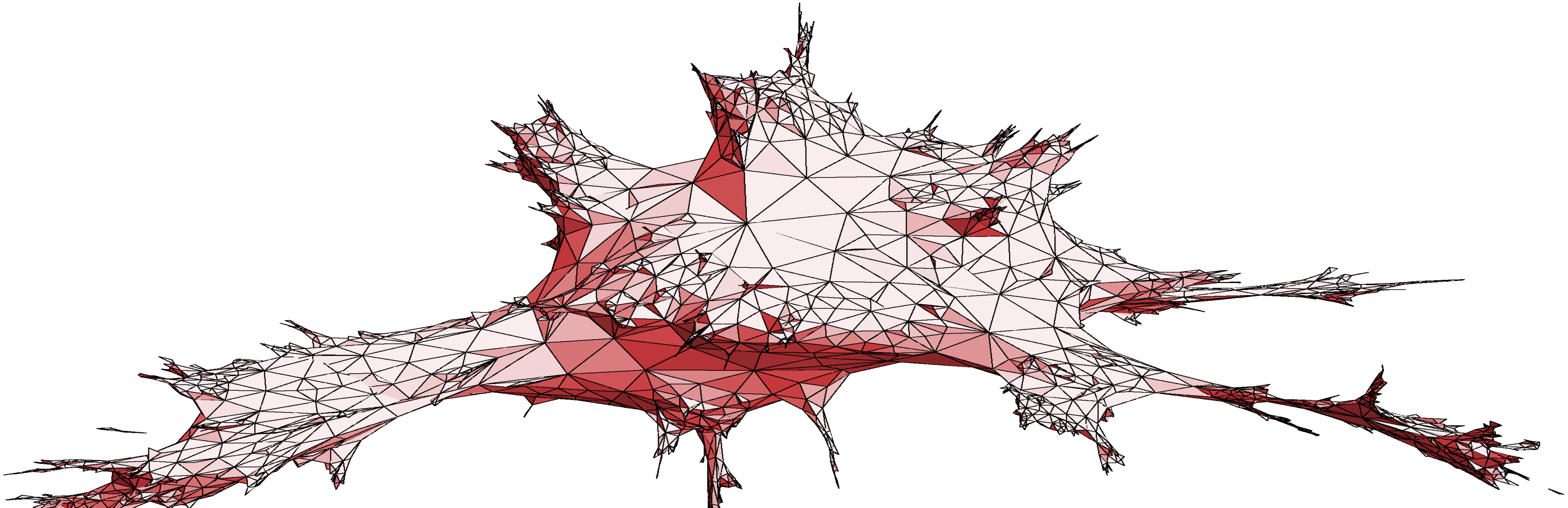


Data 40-700 keV (A=1136 cm2, courtesy of F. Frontera)

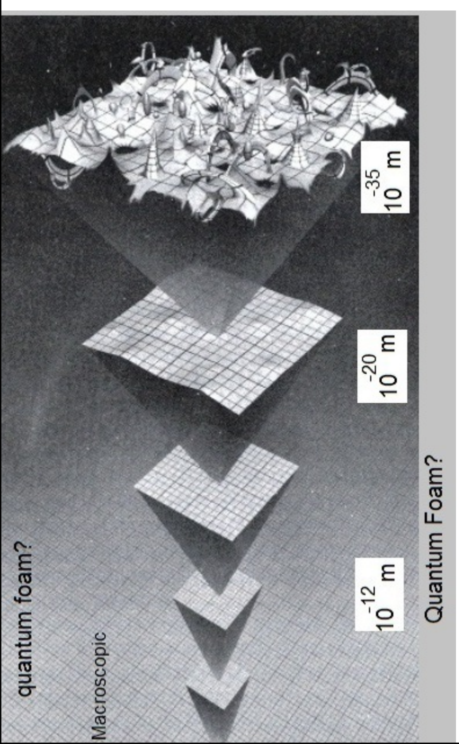
Fermi GBM (8 keV - 40 MeV)







Quantum Gravity
(Massive Photons or Lorentz Invariance Violation)



MP or LIV predictions:

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

$\xi \approx 1$

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

$M_{QG} = \zeta m_{PLANCK} \quad (\zeta \approx 1)$

$m_{PLANCK} = (hc/2\pi G)^{1/2} = 21.8 \; 10^{-6}$ g

Implications for travel time of photons:

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

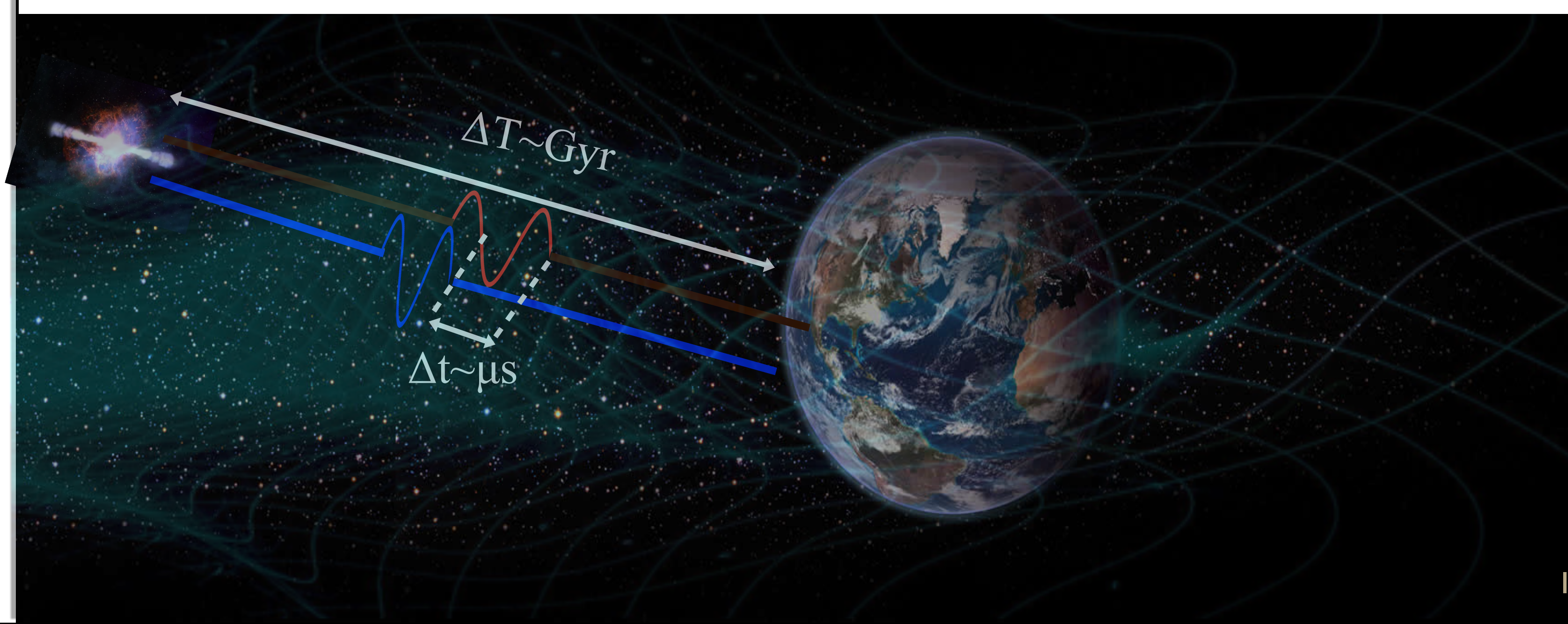
$$D_{TRAV}(z) = (c/H_0)\int_0^z d\beta \, (1+\beta)/[\Omega_\Lambda + (1+\beta)^3 \Omega_M]^{1/2}$$

Voyage 2050 - long term plan in the ESA science programme

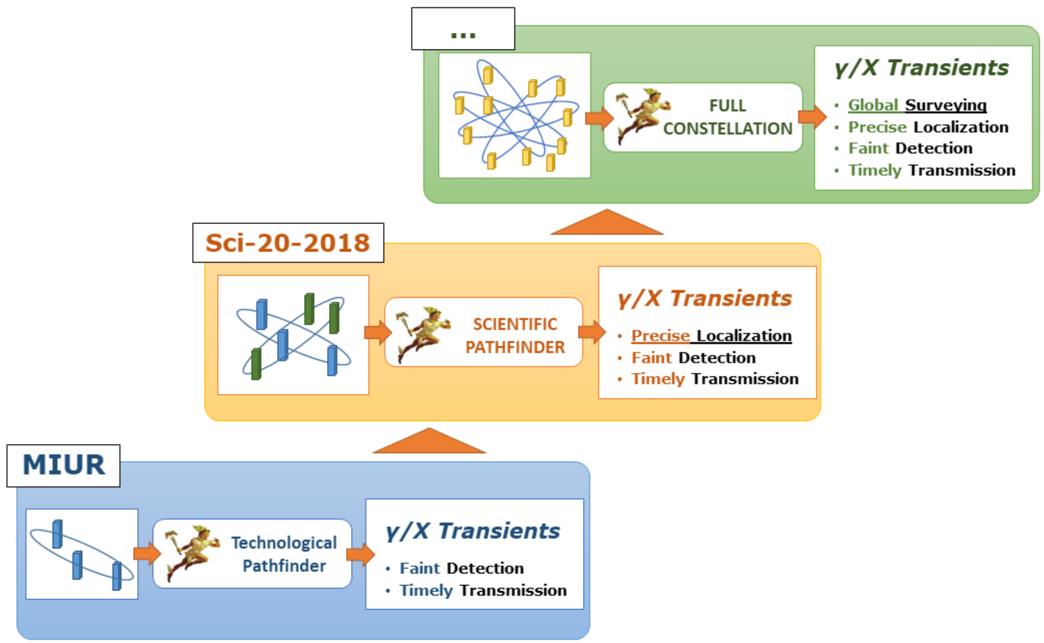
GrailQuest: hunting for Atoms of Space and Time hidden in the wrinkle of Space–Time

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

Contact Scientist: Luciano Burderi



HERMES project development − incremental strategy

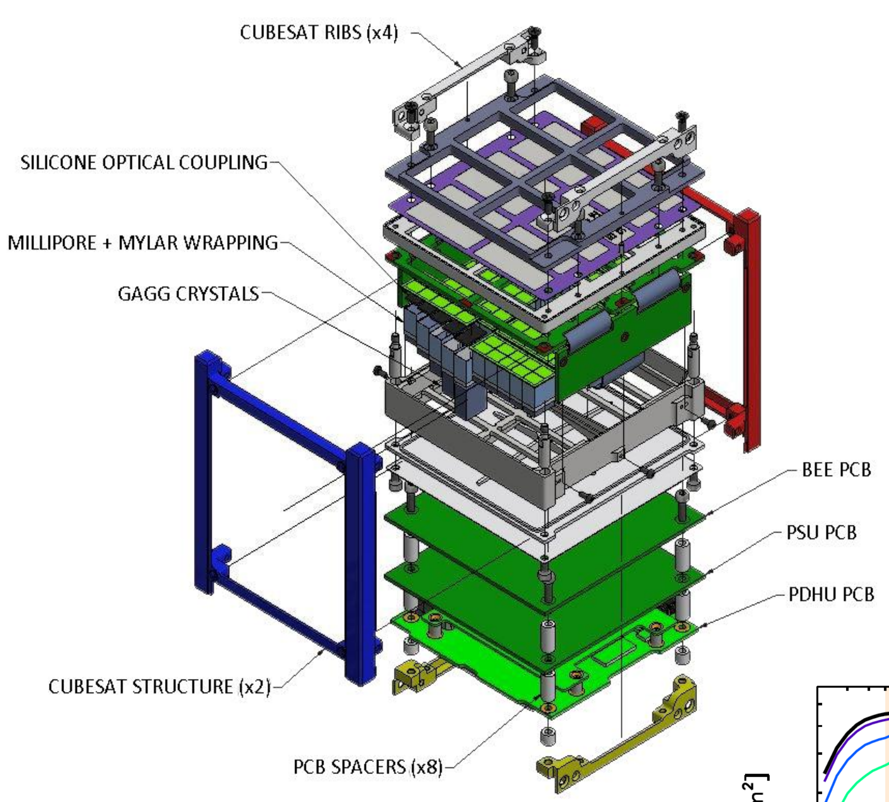


Funding status at 2019, July

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

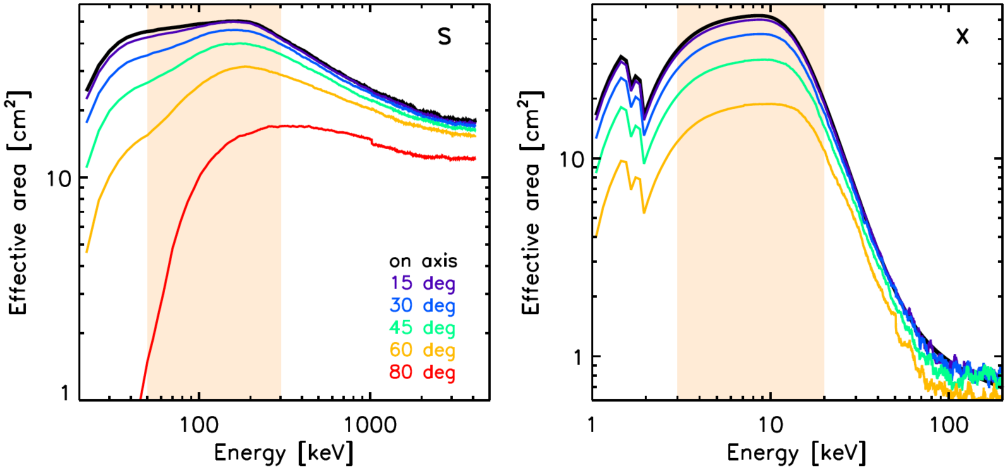
Total Funding (at 06/2019): € 8,184,450

HERMES Pathfinder Payload



Silicon Drift Devises
+
Scintillator Crystals (GAGG)

- Broad energy band (3-1000 keV)
- High time resolution (0.2 μs)
- Effective area ~50 cm^2
- Energy resolution: 15% at 30 keV
- Reduced X-ray background



HERMES Next Generation – OneWeb

Future of astronomy ..
Mon, 11 November 201..

Sales Ended

Details

Description

IMPORTANT: Due to space limitations, to register your interest in attending this event and submit an abstract, please get a ticket and also send an email to NatureAstronomy@nature.com.

The goal of the event is to investigate astronomical research ideas that could be addressed by small satellites or cubesat missions.

The event will be split into two parts. The morning part will be 6 invited presenters, 3 from academia, 2 from the industry and one from the government. These are:

Prof Giovanna Tinetti, UCL – Blue Skies Limited

Prof Stephen Serjeant, Open University

Dr Martin Elvis, Harvard-Smithsonian

Dr Markos Trichas, Airbus (smallsat platforms)

Mr Doug Liddle, InSpace (cubesat platforms)

Mr Andrew Ratcliffe, UKSA (space policy)

We also invite contributed presentations (10 mins + 5 mins for Q&A) from interested participants. We will look for ideas that can address the following question:

"The launch of the first 6 out of 900 OneWeb satellites earlier this year and the establishment by Airbus-OneWeb Satellites of the first-ever assembly line capable of producing 2 small satellites per day marks the beginning of a new era for space. An era which allows the rapid production and deployment of highly capable small satellites at a cost comparable to that of Cubesats yet able to comprehensively address commercial and operational security needs. New Space could offer significant benefits to the scientific community which has until now relied almost exclusively on space agency developments, namely large monolithic systems that offer world-class capabilities for new scientific discoveries but which require

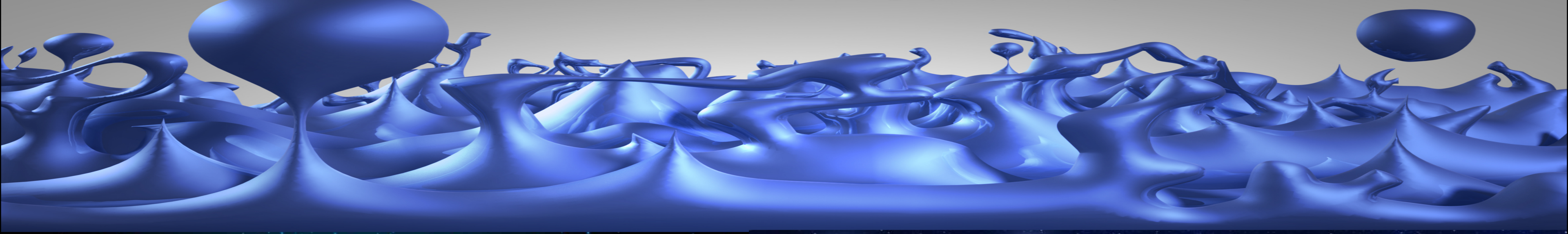
Date And Time

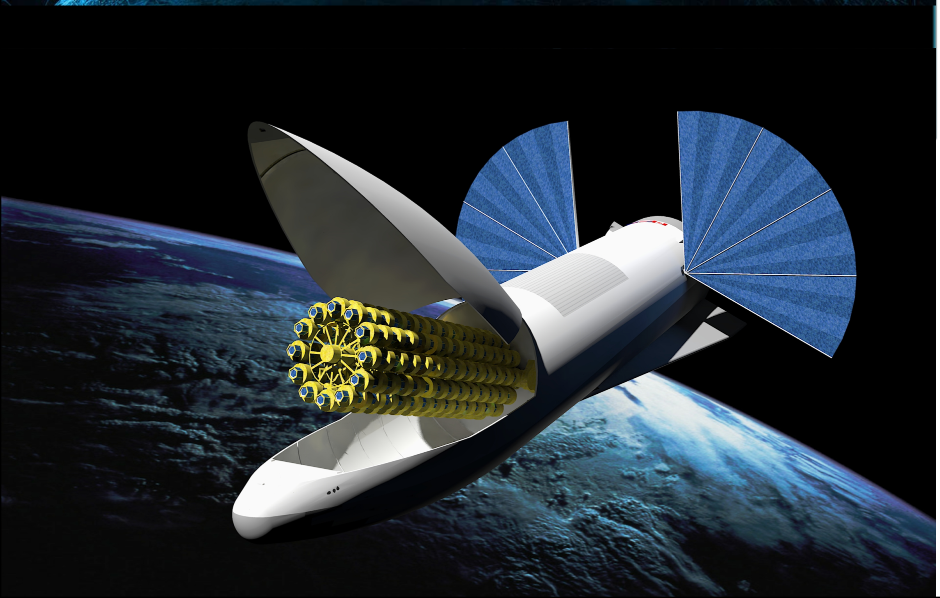
Mon, 11 November 2019
09:00 – 18:00 GMT
Add to Calendar

Location

Springer Nature Campus
2 Crinan Street
London
N1 9SQ
United Kingdom
View Map

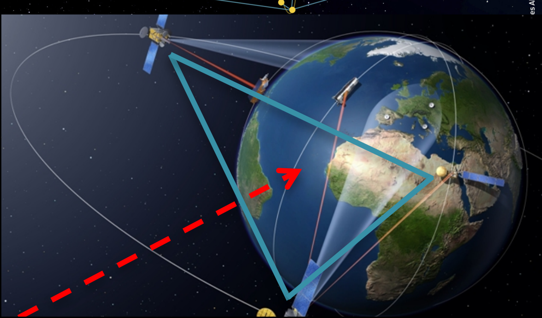
HERMES Next Generation – Starlink



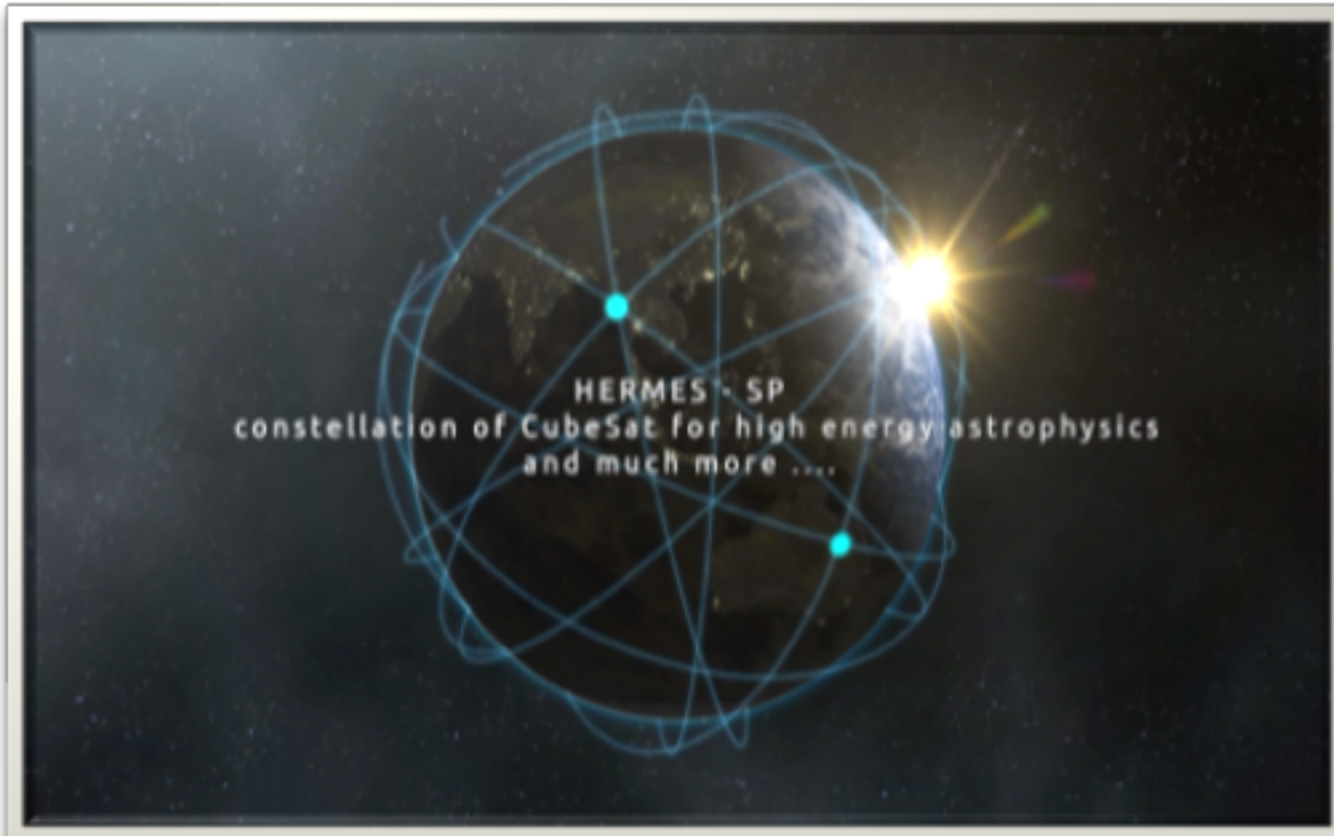


Starlink Constellation 12,000 sats
SpaceX (Elon Musk)

- 4425 @ 1200 km (completed by 2024)
- 60 satellites launched on 16/05/2019
- 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 cm^2 effective area GAGG crystal – SDD photodetector (position sensitive + coded mask?) module on each satellite**
- **120 m^2 effective area All Sky Monitor!**



The HERMES project: the movie



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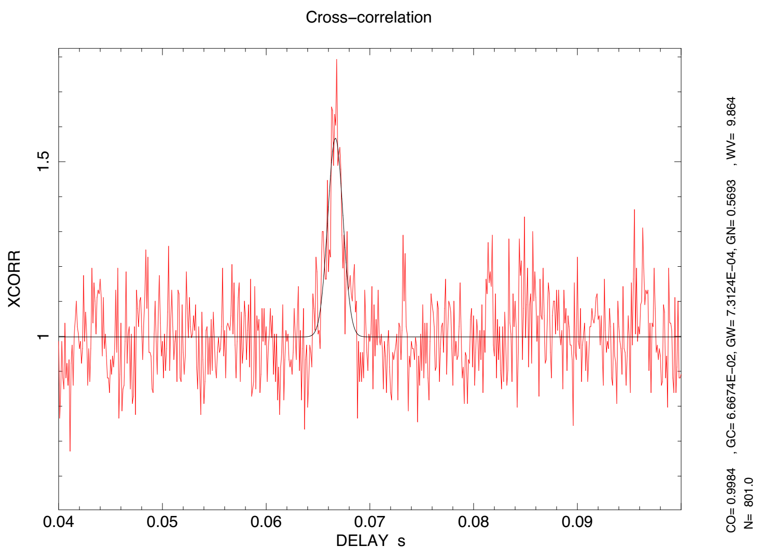
http://hermes-sp.eu

Thank you

Delays from cross-correlation analysis

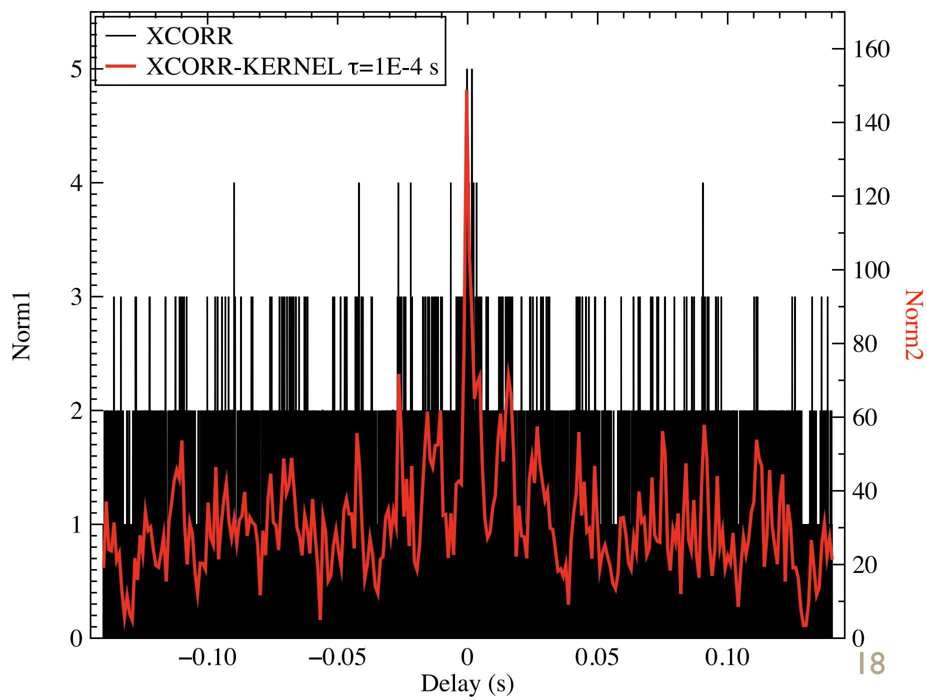


Temporal resolution: 200 μs
Standard CCF (red)

2 Lightcurves of a short GRB
$\Delta t = 0.25$ s
$A = 100$ cm^2
$\varphi_{GRB} = 8$ phot/s/cm^2
$\varphi_{BCK} = 0.8$ phot/s/cm^2
$N_{PHOT} = 220$
$\lambda_{SHOT} = 100$ shot/s
$\tau_{SHOT} = 1$ ms
$\tau_{KERN} = 0.1$ ms

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

2 Lightcurves of a short GRB
$\Delta t = 0.25$ s
$A = 100$ cm^2
$\varphi_{GRB} = 8$ phot/s/cm^2
$\varphi_{BCK} = 0.8$ phot/s/cm^2
$N_{PHOT} = 220$
$\lambda_{SHOT} = 100$ shot/s
$\tau_{SHOT} = 1$ ms
$\tau_{KERN} = 0.1$ ms

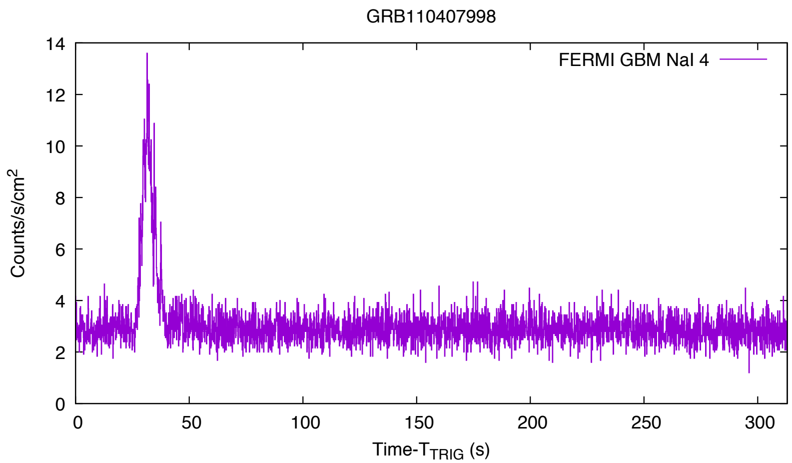


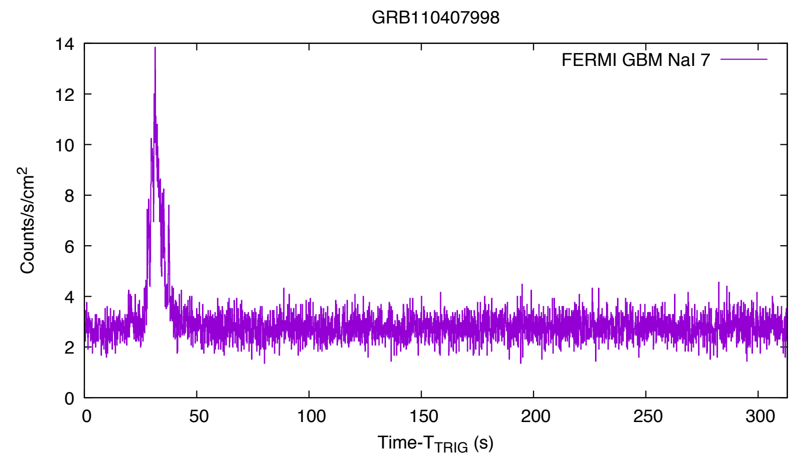
Delays from cross-correlation analysis (GBM data)

GRB data (absence of millisecond variability):

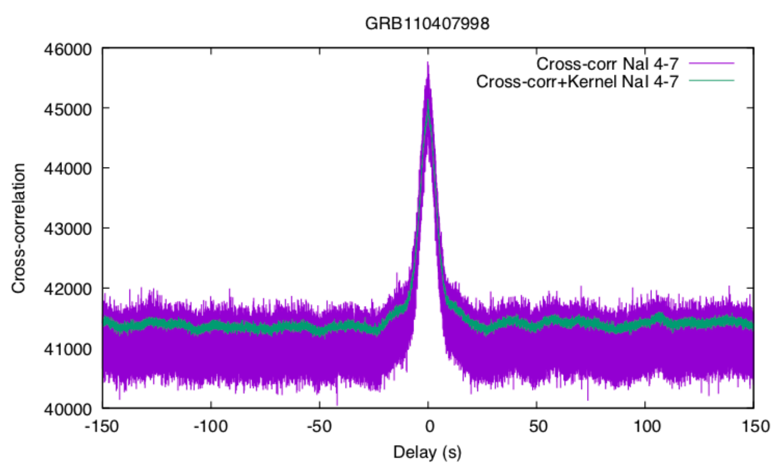
Δt = 10 s; φ_{GRB}= 7 phot/s/cm^2; φ_{BCK}= 3 phot/s/cm^2;

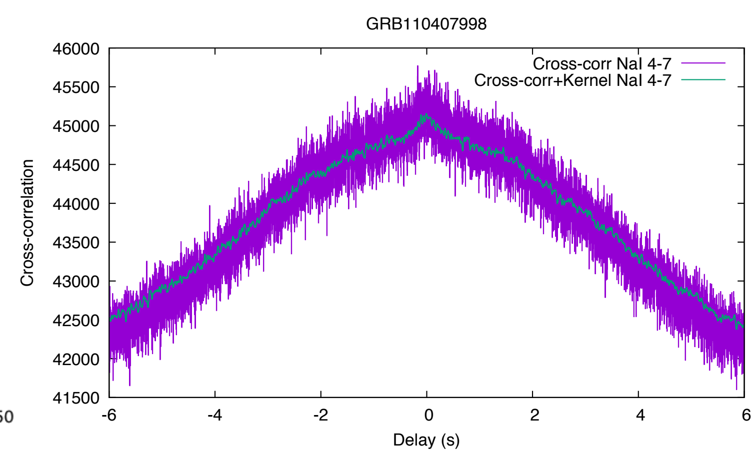
A = 125 cm^2; N_{PHOT} = 8750 (source) + 3750 (bkg) = 12500

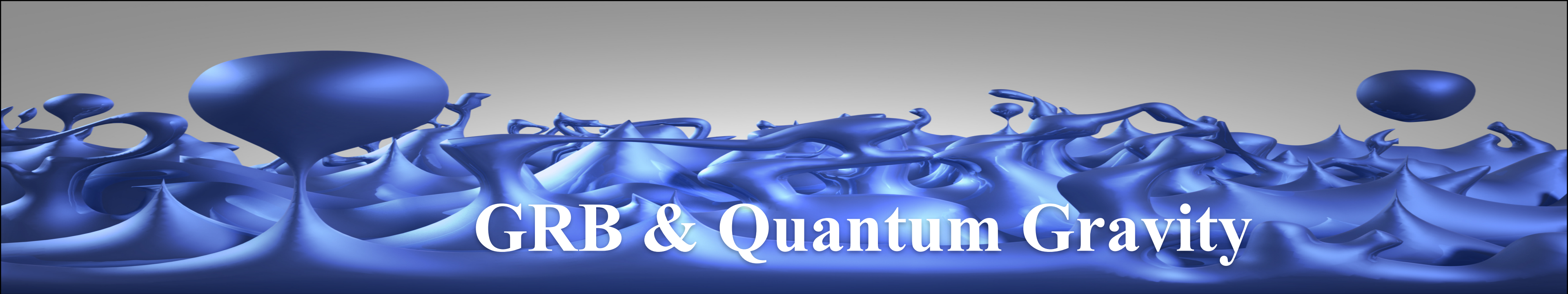




Kernel-modified CCF: bin = 1 ms; kernel = 7 ms $\sigma_{CCF} \approx 3$ ms $\sigma_\alpha \approx \sigma_\delta \approx 15$ deg







GRB & Quantum Gravity

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

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

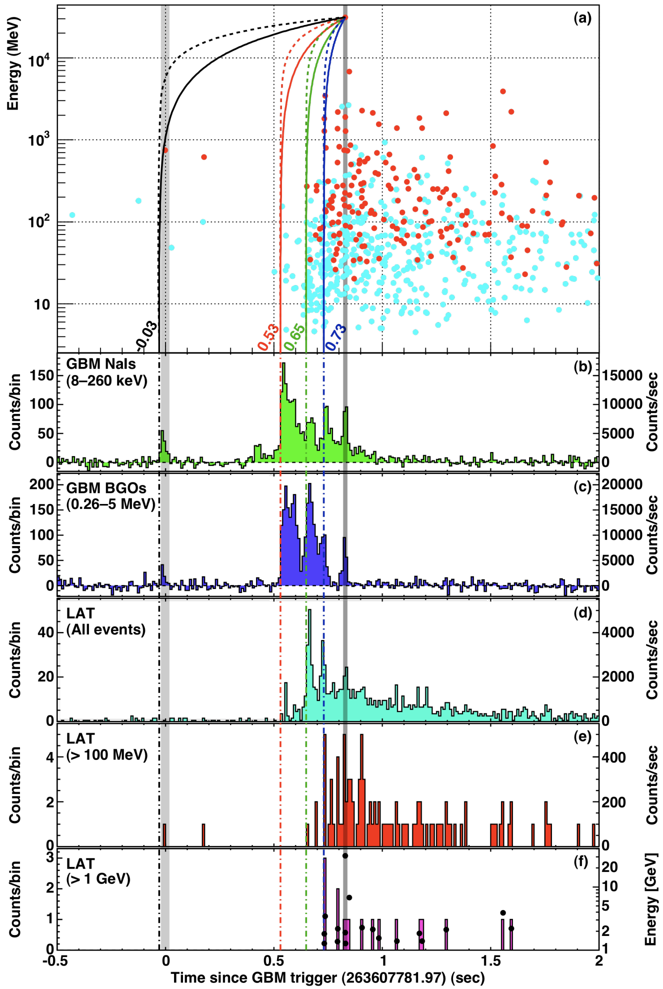
$$\frac{\mathbf{dN_E(E)}}{\mathbf{dA\ dt}} = \mathbf{F} \times \begin{cases} \left(\frac{\mathbf{E}}{\mathbf{E_B}}\right)^{\alpha} \exp\{-(\alpha-\beta)\mathbf{E}/\mathbf{E_B}\}, & \mathbf{E} \le \mathbf{E_B}, \\ \left(\frac{\mathbf{E}}{\mathbf{E_B}}\right)^{\beta} \exp\{-(\alpha-\beta)\}, & \mathbf{E}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

$\sigma_{CCF} \approx$ 100 μs/ $(N_{PHOT}/12000)^{-1/2}$ (GRB with ms variability)

100 nano−satellites of A = 100 cm²

Energy band	E_{AVE}	N ($\beta = -2.5$)	$E_{CC}(N)$	N ($\beta = -2.0$)	$E_{CC}(N)$	ΔT_{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	3.80×10^6	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

GRB & Lorentz Invariance Violation (LIV) with Fermi



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

Caveats, assumptions:
i) photon at 31 GeV emitted after $t_{START\ GRB} = -30$ 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

HERMES 3U CubeSat

- 10×10×30 cm
- Gyroscope Stability on 3 axes

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