The HERMES project

High Energy Rapid Modular Ensamble of Satellites

Luciano Burderi, University of Cagliari

Collaborators:

Lorenzo Amati, INAF IASF Bologna

Angelo Antonelli, INAF Rome Astronomical Observatory

Angela Bongiorno, INAF Rome Astronomical Observatory

Enrico Costa, INAF IAPS Roma

Tiziana di Salvo, University of Palermo

Marco Feroci, INAF IAPS Roma

Fabrizio Fiore, INAF Rome Astronomical Observatory

Filippo Frontera, University of Ferrara

Rosario Iaria, University of Palermo

Claudio Labanti, INAF IASF Bologna

Alessandro Riggio, University of Cagliari

Andrea Sanna, University of Cagliari

Fabiana Scarano, University of Cagliari

Andrea Vacchi, INFN Trieste

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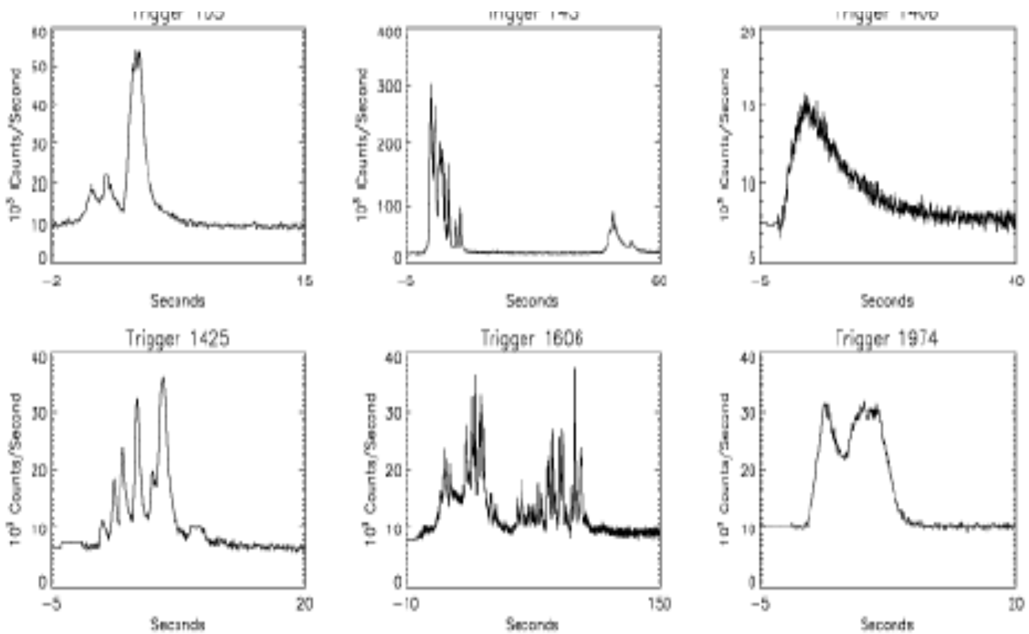
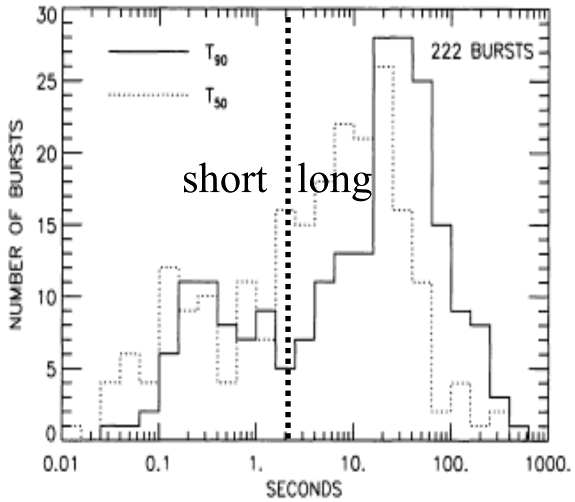
The Gamma-Ray Burst phenomenon

- 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





The Gamma-Ray Burst phenomenon

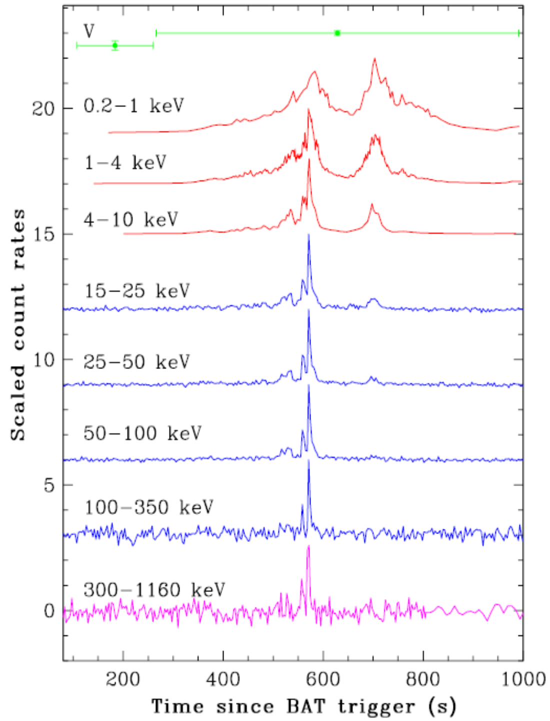
Prompt Emission:

Short: $\tau \approx 0.2$ sec, Fluence $\approx 4 \times 10^{-7}$ erg/cm^2 (25 keV – 1MeV)

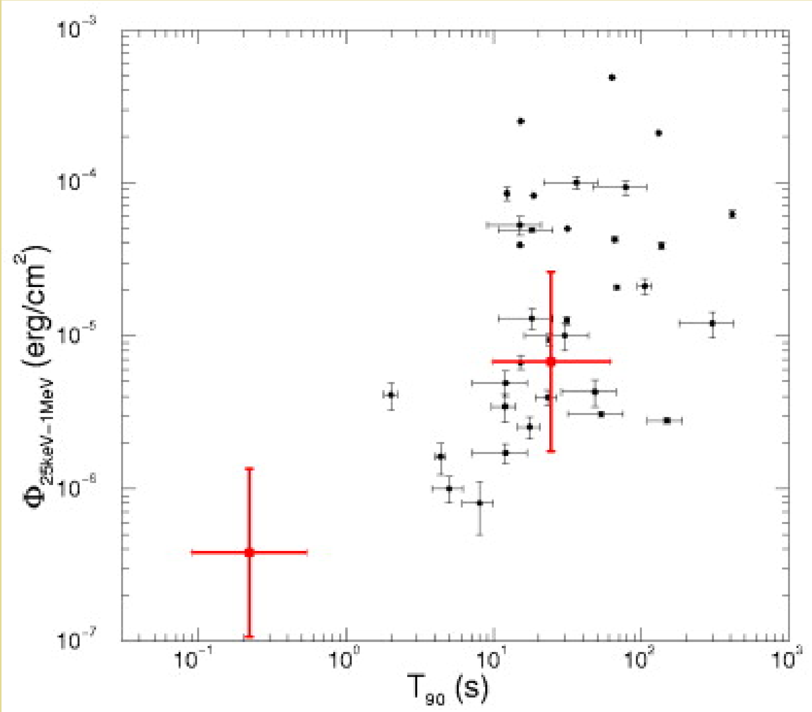
=> Binary NS mergers (**GW sources**)

Long: $\tau \approx 25$ sec, Fluence $\approx 8 \times 10^{-6}$ erg/cm^2 (25 keV – 1MeV)

=> Hypernovae (SNe Massive Stars)



Swift XRT (rare / unique case)
+ Swift/BAT + konus/WIND



(Panaitescu, Kumar, & Narayan 2001)

The Gamma-Ray Burst phenomenon

Millisecond variability (minimum variability time-scale, MacLachlan et al. 2013)

Short: 3 msec (wavelet techniques)

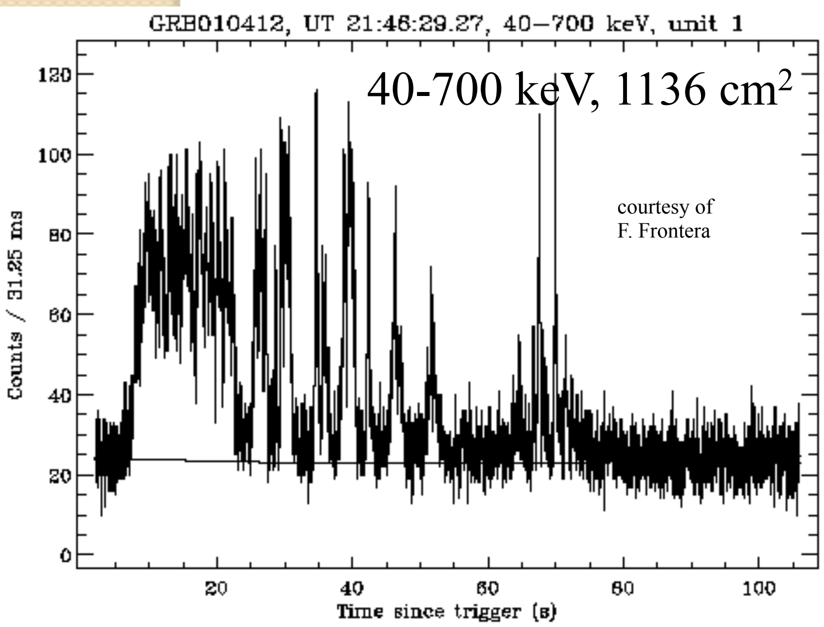
Long: 30 msec (wavelet techniques)

Internal shock model (ultarelativistic, $\gamma \approx 10^2 \div 10^3$, colliding shocks)

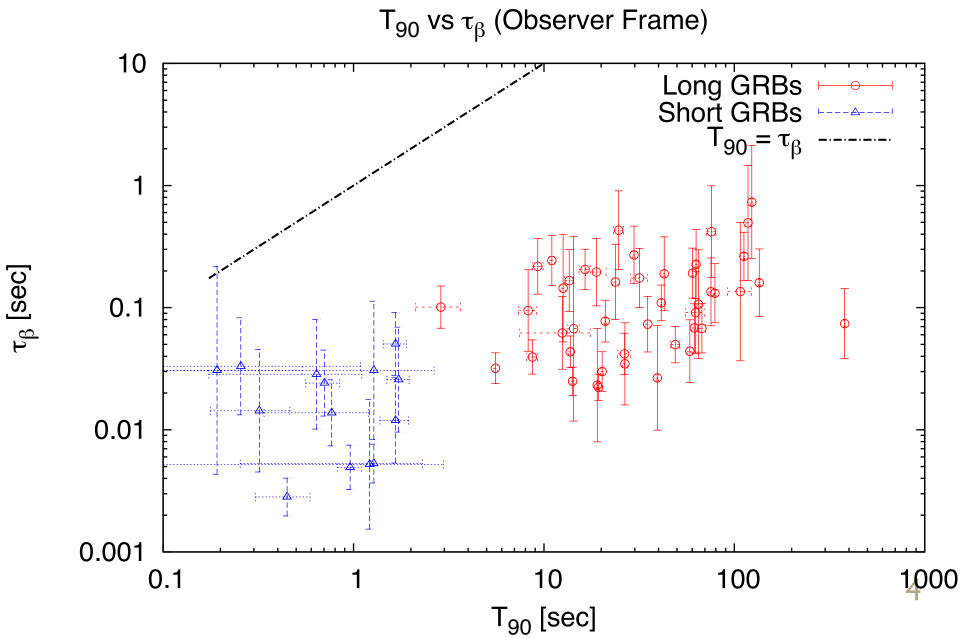
GRB Luminosity Function: < 8 c/s (50-300) keV short

> 8 c/s (50–300) keV long

BeppoSAX GRBM data



Fermi GBM (8 keV - 40 MeV)



Number of GRB and Fluxes

Short GRBs:

Duration: 0.2 sec,

Counts (50-300 MeV): 8 c/cm^2/s

Averaged photon energy: (Emax x Emin)$^{1/2}$ = 122 keV

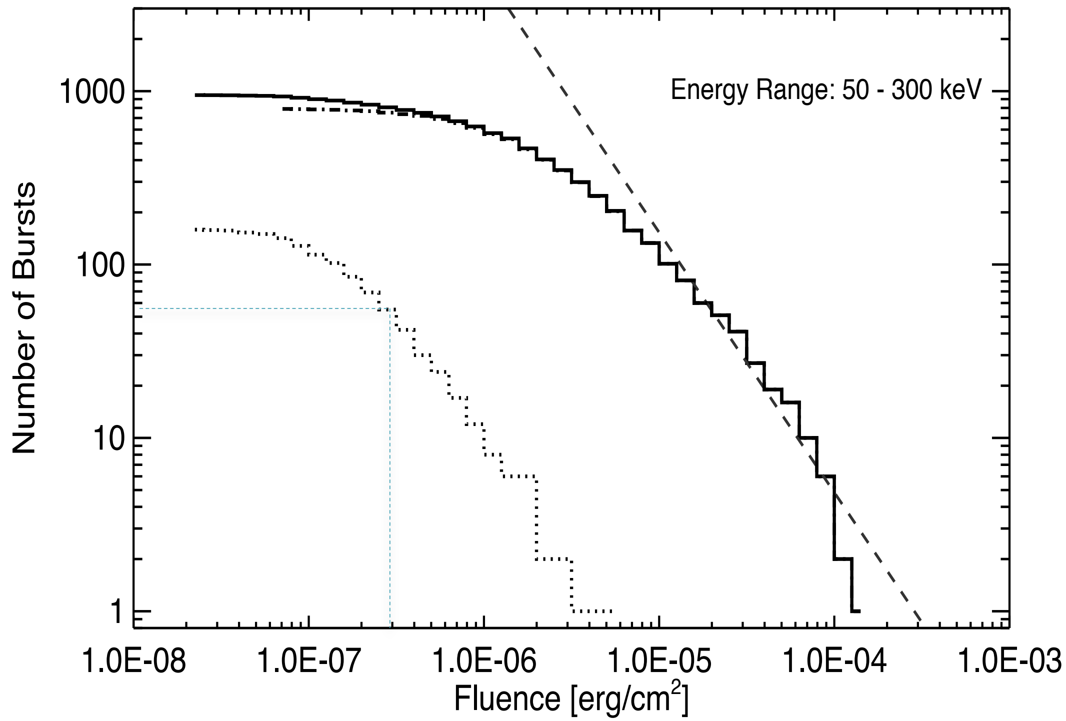
Fluence: 0.2 x 8 x 122 keV/cm^2 = 3 x 10^{-7} erg/cm^2

Fermi GBM - 4-years data

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/cm^2/steradians

Background for 2 steradians FOV: 0.86 c/cm^2/s

Proton fluxes in LEO (580 km): 0.165 c/cm^3/s

Activation in equatorial LEO (580 km): ≤ 0.3 c/cm^3/s (not included)

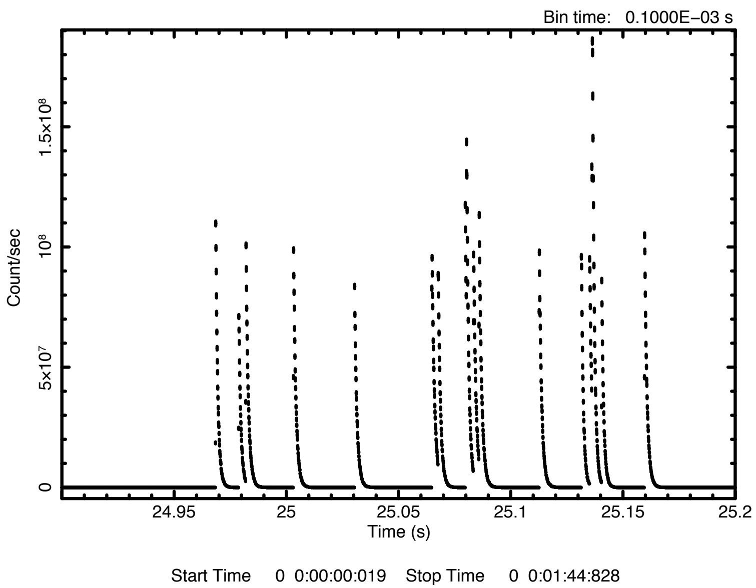
Burst duration: 0.2 sec

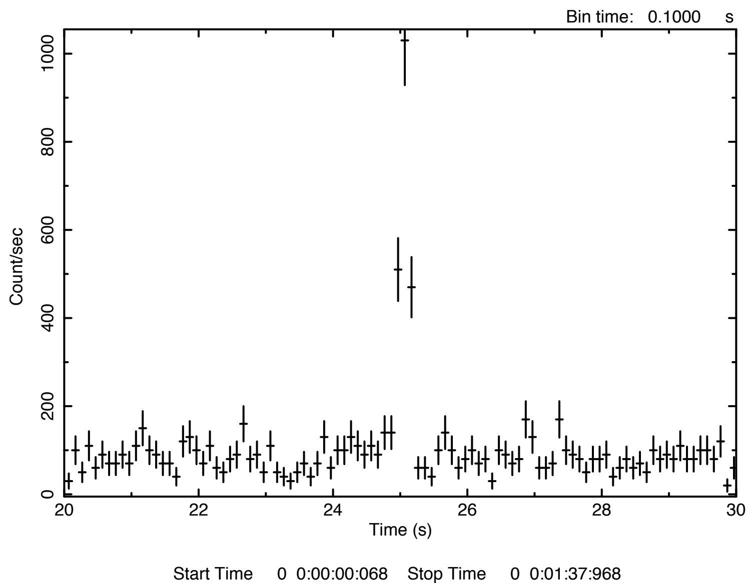
Source count rate: 7.875 ph/cm^2/s

Exponential shot rate: 100 shot/s

Exponential shot decay time: 1 msec

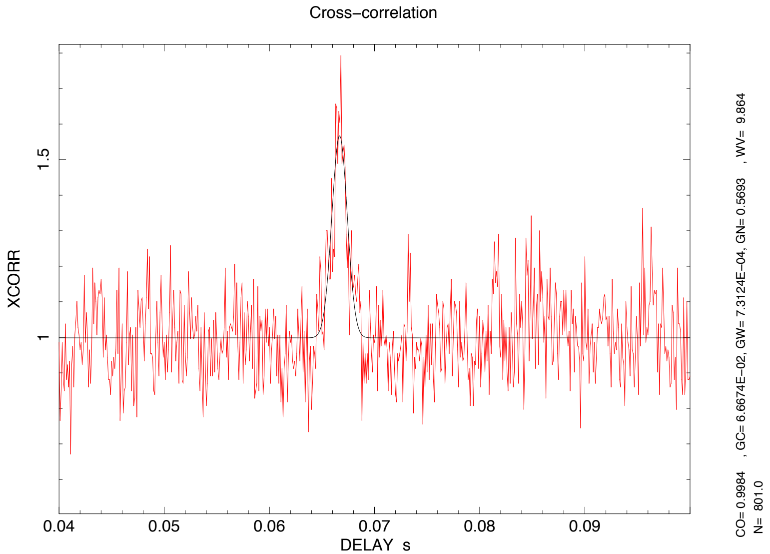
Band 50-300 keV
Effective area: 100 cm^2





Delays from cross-correlation analysis

Cross-correlation of GRB lightcurves from two satellites of 100 cm2 effective area in the 50-300 keV band:



Simulation	Radius [cm]	Expected delay [s]	Measured delay [s]	Error [s]	Error in unit of σ
sim_1.fits	$1\cdot10^9$	$6.67128190\cdot10^{-2}$	$6.66744709\cdot10^{-2}$	$0.0561\cdot10^{-3}$	0.6830805064
sim_2.fits	$9.9\cdot10^8$	$6.60456908\cdot10^{-2}$	$6.59104213\cdot10^{-2}$	$0.1233\cdot10^{-3}$	1.0970766361
sim_3.fits	$9\cdot10^8$	$6.00415371\cdot10^{-2}$	$5.98946773\cdot10^{-2}$	$0.1759\cdot10^{-3}$	0.8349052625
sim_4.fits	$8.1\cdot10^8$	$5.40373834\cdot10^{-2}$	$5.40064611\cdot10^{-2}$	$0.0791\cdot10^{-3}$	0.3911742201
sim_5.fits	$7.2\cdot10^8$	$4.80332297\cdot10^{-2}$	$4.80094887\cdot10^{-2}$	$0.0735\cdot10^{-3}$	0.3228751331
sim_6.fits	$6.3\cdot10^8$	$4.20290760\cdot10^{-2}$	$4.19750251\cdot10^{-2}$	$0.0662\cdot10^{-3}$	0.8163554594
sim_7.fits	$5.4\cdot10^8$	$3.60249223\cdot10^{-2}$	$3.59473675\cdot10^{-2}$	$0.0646\cdot10^{-3}$	1.2007242824
sim_8.fits	$4.5\cdot10^8$	$3.00207686\cdot10^{-2}$	$2.9960330\cdot10^{-2}$	$0.0764\cdot10^{-3}$	0.7907702189
sim_9.fits	$3.6\cdot10^8$	$2.40166149\cdot10^{-2}$	$2.39778887\cdot10^{-2}$	$0.0709\cdot10^{-3}$	0.5464393152
sim_10.fits	$2.7\cdot10^8$	$1.80124611\cdot10^{-2}$	$1.79572739\cdot10^{-2}$	$0.0612\cdot10^{-3}$	0.9024896271
sim_11.fits	$1.8\cdot10^8$	$1.20083074\cdot10^{-2}$	$1.19955540\cdot10^{-2}$	$0.0864\cdot10^{-3}$	0.1475920279
sim_12.fits	$9\cdot10^7$	$0.60101537\cdot10^{-2}$	$5.99619420\cdot10^{-3}$	$0.0766\cdot10^{-3}$	0.1822152926

Error in cross-correlation accuracy: 84 μsec
Number of independent estimate of delays: Nsatellite – 1
Position of the source in the sky, (α, δ): 2 parameters
Statistical improvement in determining the position in the sky with Nsatellite:
$(\text{Nsatellite} - 1 - 2)^{1/2} = 8.5$
Error in delay accuracy: 8.5 μsec (Nsatellite = 100)
12 μsec (Nsatellite = 50)

Determination of source position through delays

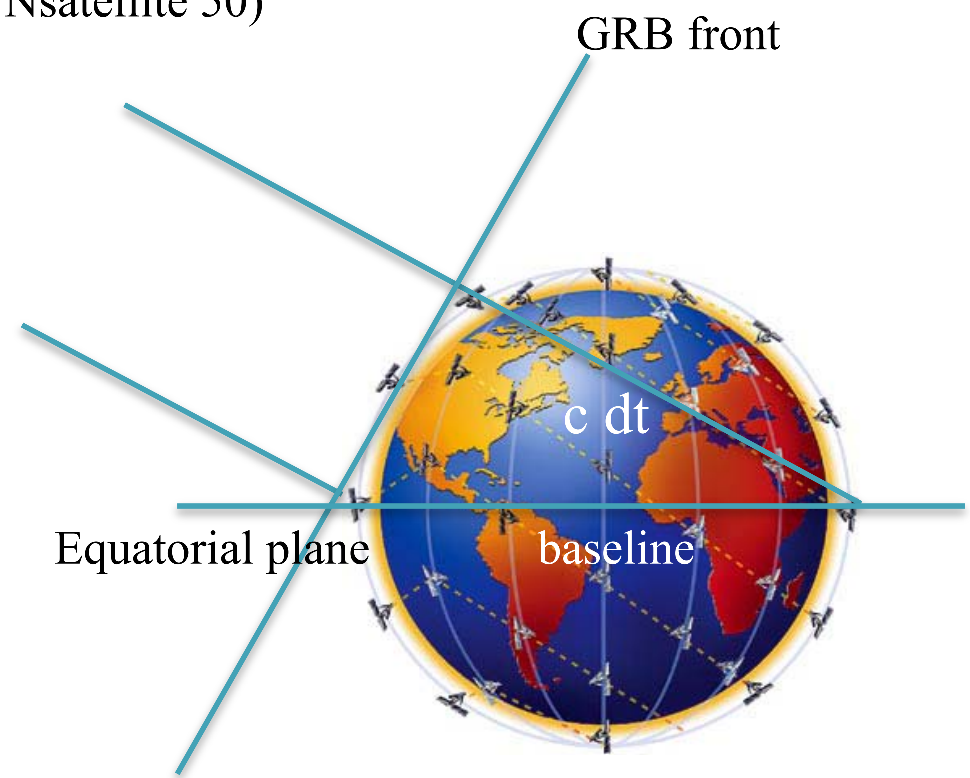
Error in accuracy ≈ c × (error in delay accuracy / average baseline)

Maximum baseline = 2 × (Rearth + Hsatellite) = 2 × (6371 + 580) km

Average baseline = Maximum baseline / 2

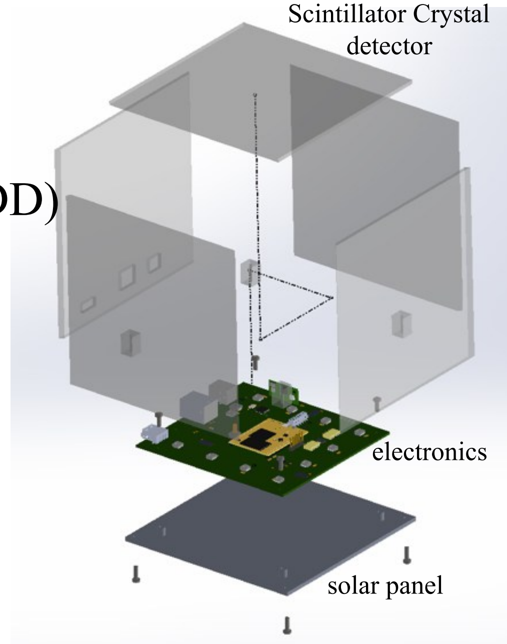
Error in accuracy = 75 arcsec (for Nsatellite 100)

Error in accuracy = 110 arcsec (for Nsatellite 50)

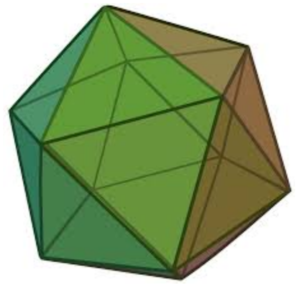


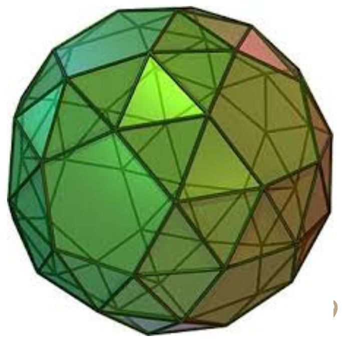
Detector and satellite

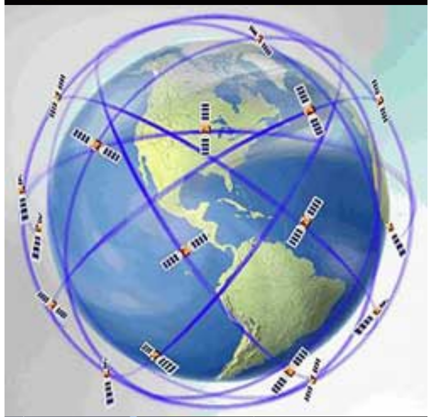
Detector
Scintillator Crystals:
CsI (classic) or $LaBr_3$ or $CeBr_3$ (rise − decay: 0.5 − 20 ns)
Photo-detector:
Silicon Photo Multiplier (SiPM) or Silicon Drift Detector (SDD)
Effective area: 10 × 10 cm
Crystal thickness: 1 cm
Weight: 0.5 – 1 kg
Energy band: 50 − 300 keV
Energy resolution: 15% at 30 keV
Temporal resolution: ≤ 10 nanoseconds



Satellite
5 detectors on a cubic structure + solar panel
Weight: ≤ 10 kg
Shielding
Grating shields to reduce proton flux to 0.165 c/cm^3/s
Collimator
2 stearadians
(0.6 stearadians Icosahedron 20 faces,
0.13 stearadians Snub Dodecahedron 92 faces,
strong reduction of X-ray background)
Data recording
Continuous recording of buffered data

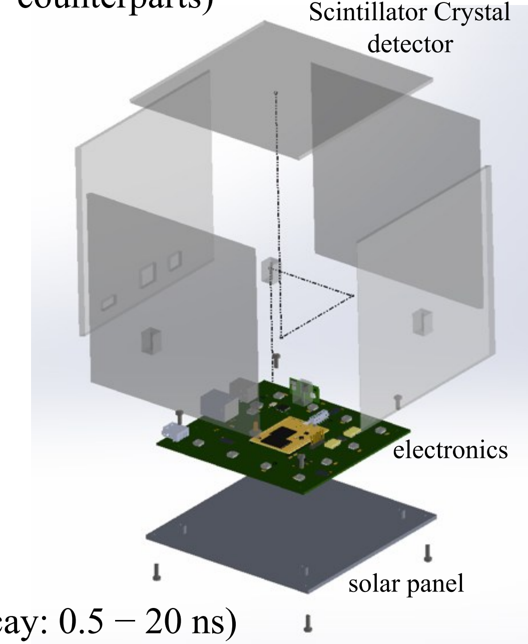






The HERMES mission

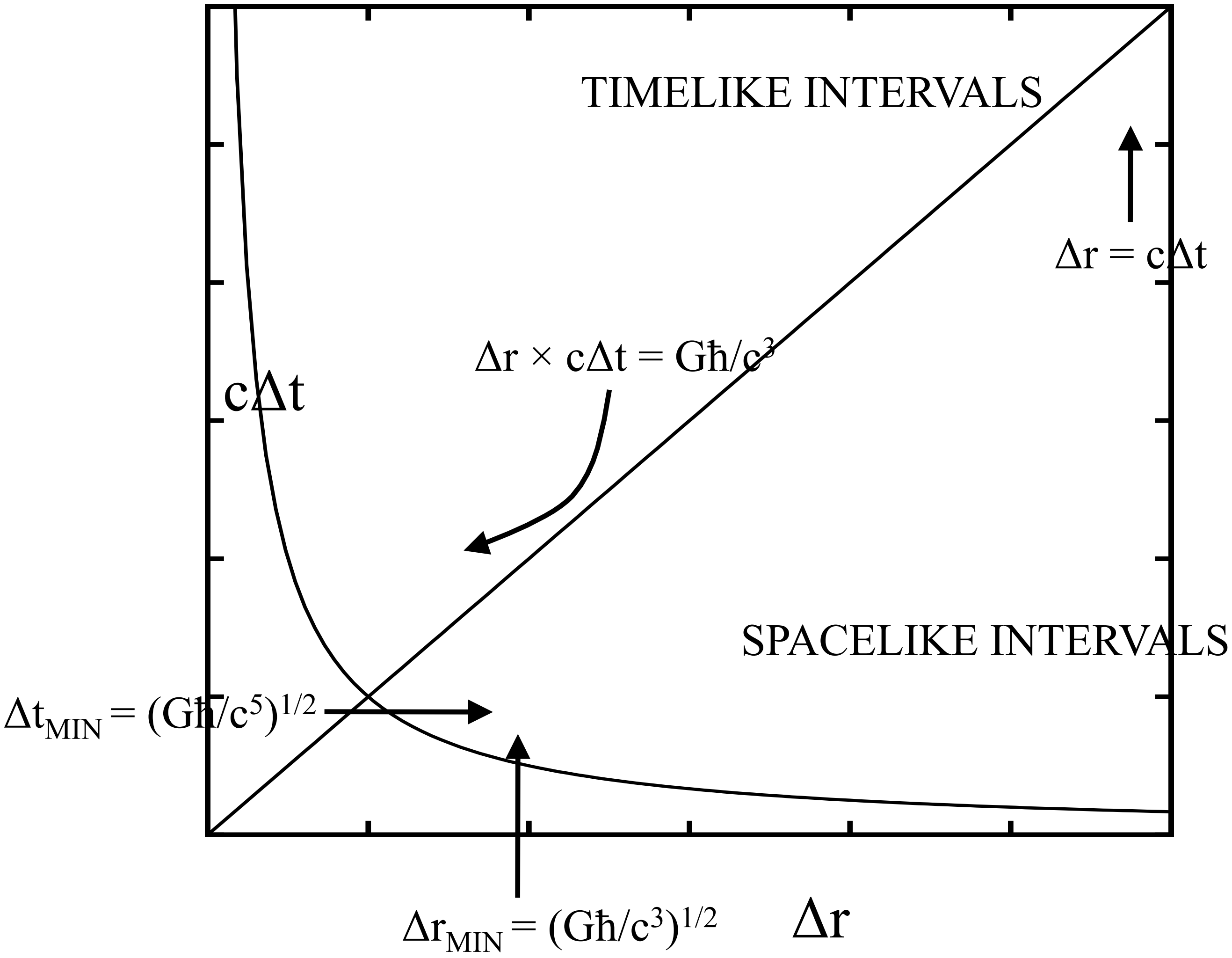
High Energy Rapid Modular Experiment Satellites
(a nanosatellite swarm monitor for GRB & High Energy GW counterparts)



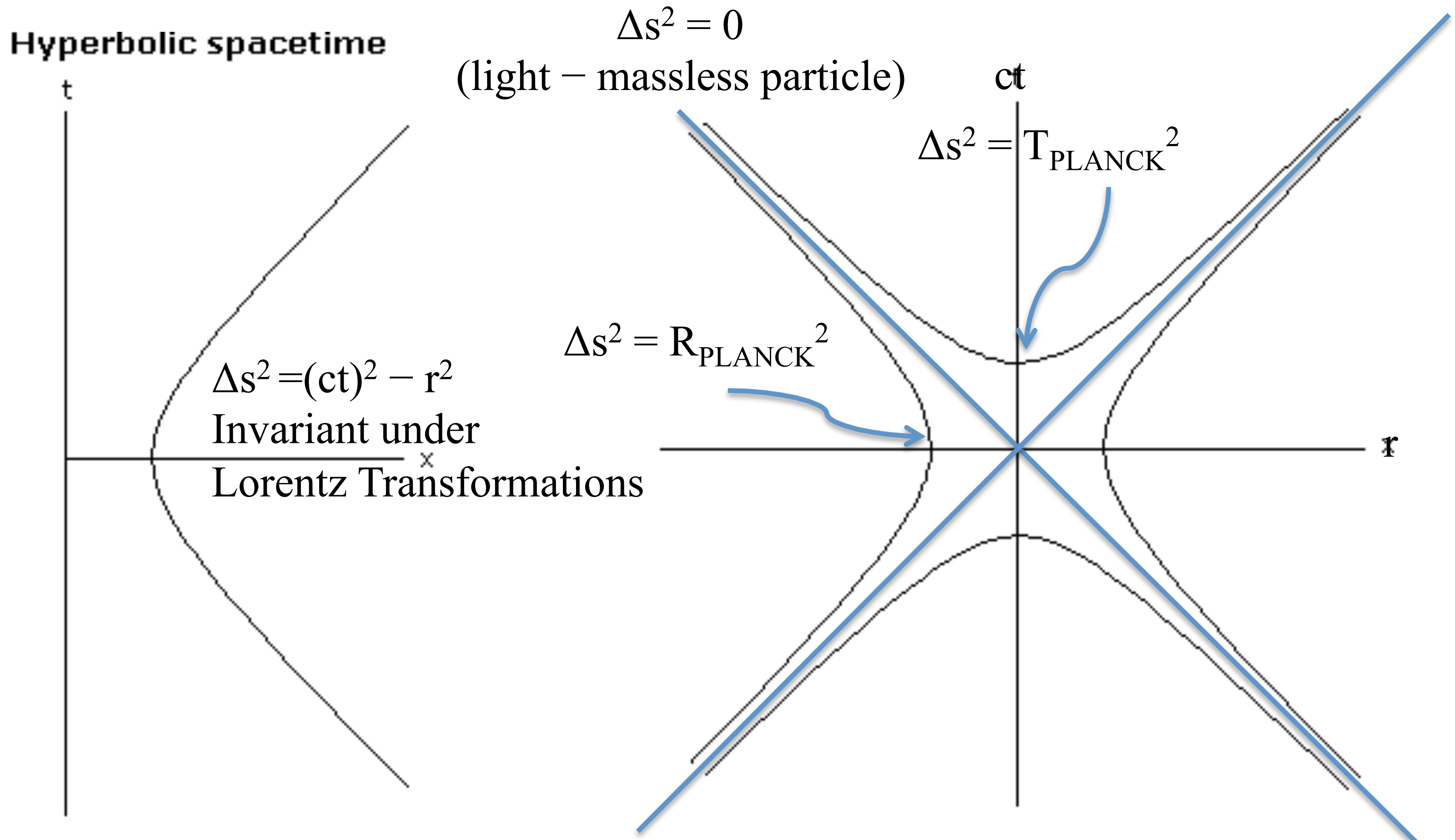
GRB statistics
Average GRBs: 300/yr
Bright GRBs: 30/yr
GRB structure: duration 25 s, shot noise $\tau = 1$ ms, rate = 100/s
Instrument
N ≥ 100 Nano Satellites (Modules) in Low Earth Orbit
Average separation between Modules: 6000 km
Module (weight ≤ 10 kg)
5 Detectors
Field of View of each Detector: 2 steradians
GPS absolute temporal accuracy ≤ 100 nanoseconds
GPS based Module positional accuracy: ≤ 10 m
Detector
Scintillator Crystals: CsI (classic) or $LaBr_3$ or $CeBr_3$ (rise − decay: 0.5 − 20 ns)
Photo-detector: Silicon Photo Multiplier (SiPM) or Silicon Drift Detector (SDD)
Effective area: 10 × 10 cm
Weight: 0.5/1 kg
Energy band: 3 keV − 50 MeV
Energy resolution: 15% at 30 keV
Temporal resolution: ≤ 10 nanoseconds
Mission performance
Accuracy in delays between Average GRB lightcurves of two Modules (cross correlation techniques): 20 microseconds for Average GRBs
Continuous recording of buffered data
Triggered to ground telemetry transmission
Accuracy in positioning of Bright GRBs: 75 – 110 arcsec
Range of accuracy in positioning of GRB: from 25 to 330 arcsec
Modular structure: overall effective area 1 m^2 every 100 modules

The Uncertainty Relation $\Delta r\, \Delta t > G\hbar/c^4$ and the space-time diagram for the intervals

(Burderi, Di Salvo, Iaria, Physical Review D, **93**, 064017, 2016)



The new Uncertainty Principle and the Minkowski metric: preserving Lorentz Invariance



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.

Massive Photons? (Proca action)

Massless Particles $\longrightarrow$ Lorentz Invariance, not *vice versa!*

GRB & Quantum Gravity
(Massive Photons or Lorentz Invariance Violation)

MP or LIV predictions:

$|v_{phot}/c - 1| \approx \xi E_{phot}/(M_{QG} c^2)^n$ $(\xi \approx 1 \quad n = 1,2)$ and $M_{QG} = \zeta m_{PLANCK}$ $(\zeta \approx 1)$

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

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

Band (keV)	Flux (Bright GRBs) (counts/cm^2/s)	Fluence (1 m^2, 10 s) (counts)	Expected $\Delta t_{QGR} \propto D_{GRB}/c$ for Quantum Gravity effects: z = 0.9 (μs)	z = 3.0 (μs)
2 − 25	24.7	2,470,000	0	0
25 − 50	6.2	620,000	1	2
50 − 100	5.5	550,000	2	3
100 − 300	6.1	610,000	3	5
300 − 1000	2.4	240,000	12	19
1000 − 2000	0.4	40,000	28	45
2000 − 5000	0.15	15,000	65	104
5000 − 50000	0.07	7,000	421	671

Conclusions I

All sky monitor of Gamma Bursts (GRB, Magnetar, High Energy counterparts of Gravitational Waves, etc.)

Accuracy in positioning of Bright GRBs: 75 – 110 arcsec

range of accuracy in positioning of GRB: from 25 to 330 arcsec

1 m^2 effective area (50 – 300 keV)

Energy resolution: 15% at 30 keV

Temporal resolution: $\leq$ 10 nanoseconds

Quantum Gravity: probing the ultimate structure of space-time

Time lags

caused by prompt emission mechanism:

complex dependence from E_{phot}(Band II) and E_{phot}(Band I)

independent of $D_{GRB}(z_{GRB})$

caused by Quantum Gravity effects:

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

$\propto D_{GRB}(z_{GRB})$

the two effects can be disentangled with experimentally measured:

Δt_{QGR} (HERMES)

z_{GRB} (optical, follow-up observations of host galaxy)

Conclusions II

1) Cheap:

simple detector & nano(small)satellites:
up to 100 million € for 100 satellites
see e.g. Thales Alenia Space:
40 kg – 100 W, 3 axes pointing, LEO,
cost ≈ 1 M€ (“*deep throat*”, private comm.)

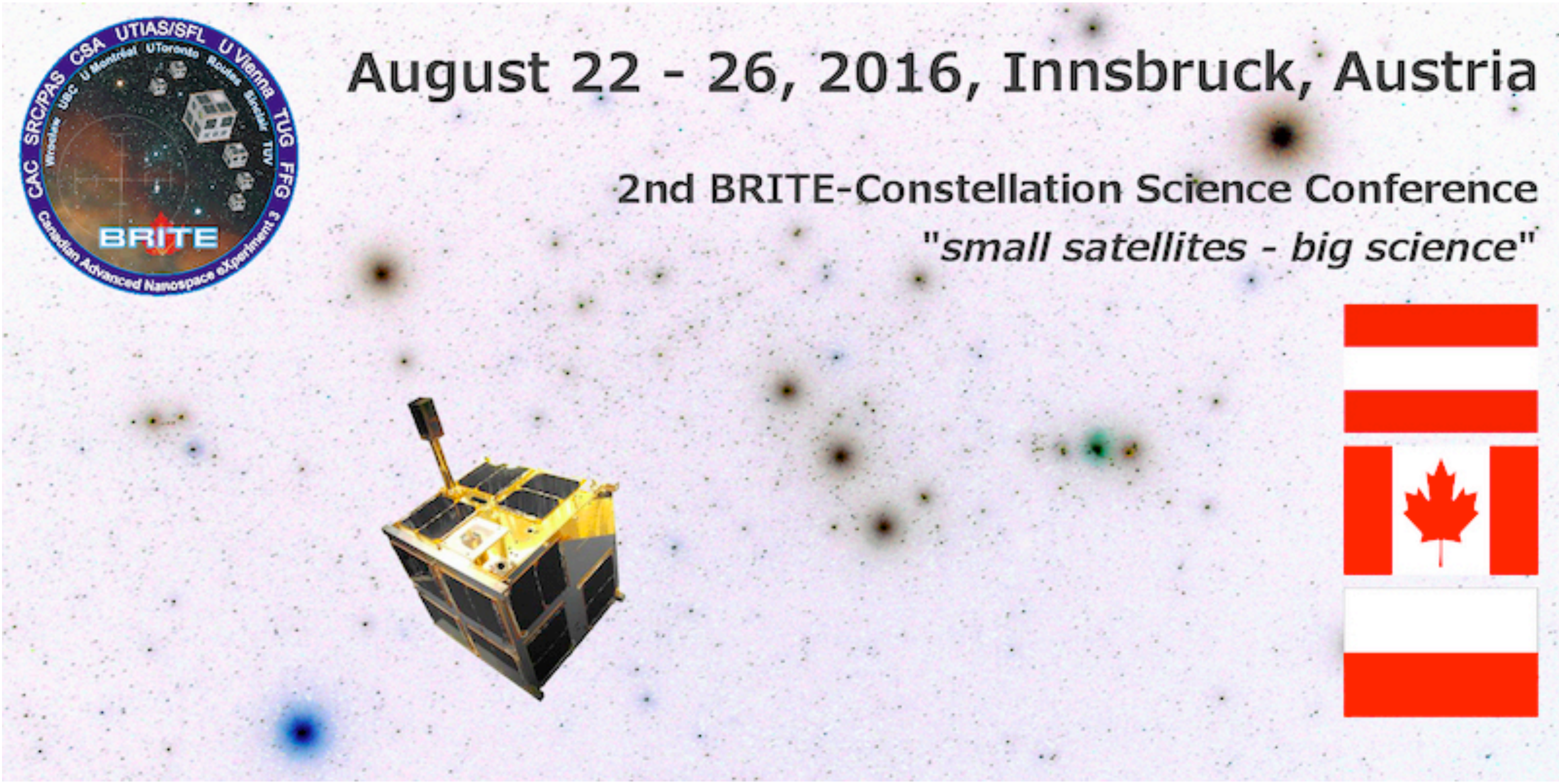
2) Fast:

few years (≤ 5 years) to flight the first satellite(s)

3) Modular:

robust against one or more satellite(s) failure

Growing interest in constellation of small satellites…



That's all Folks!