CUBESATS AND DISTRIBUTED ASTRONOMY: FROM THE HERMES FLEET TO THE FLIGHT OF THE ALBATROS, SURFING THE WAVES OF QUANTUM SPACE-TIME

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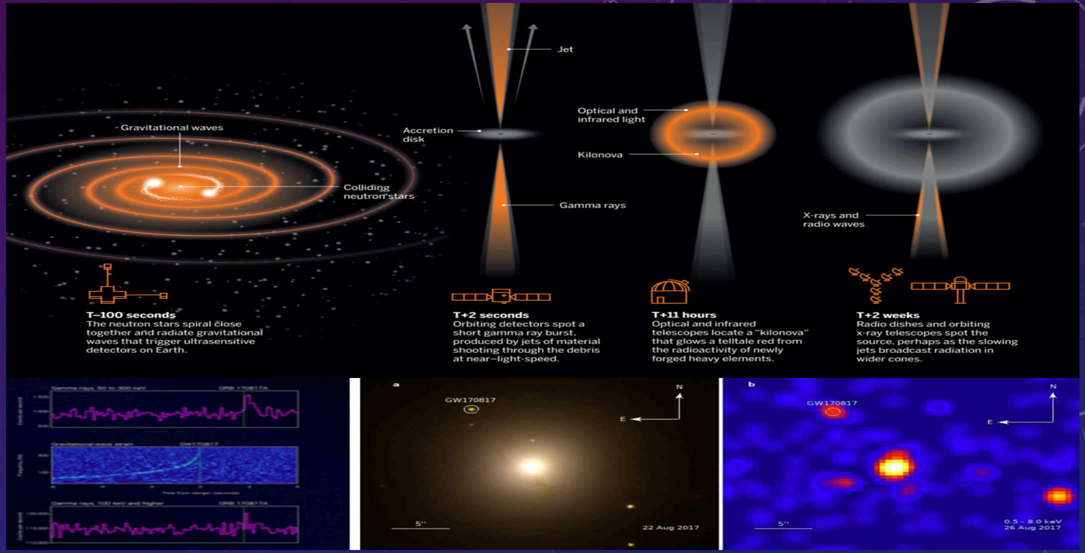
UNIVERSITY OF CAGLIARI

ON BEHALF OF THE ALBATROS AND THE HERMES COLLABORATIONS

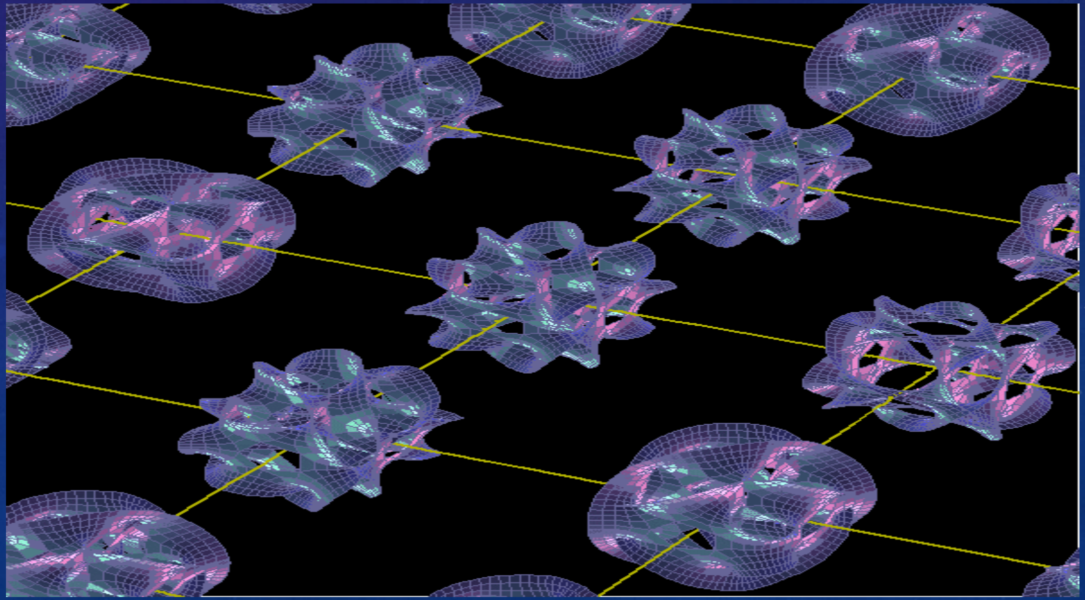
“QUAGRAP meeting” – Napoli – 18-19 April 2024

SCIENTIFIC CHALLENGES FOR THE NEXT DECADES

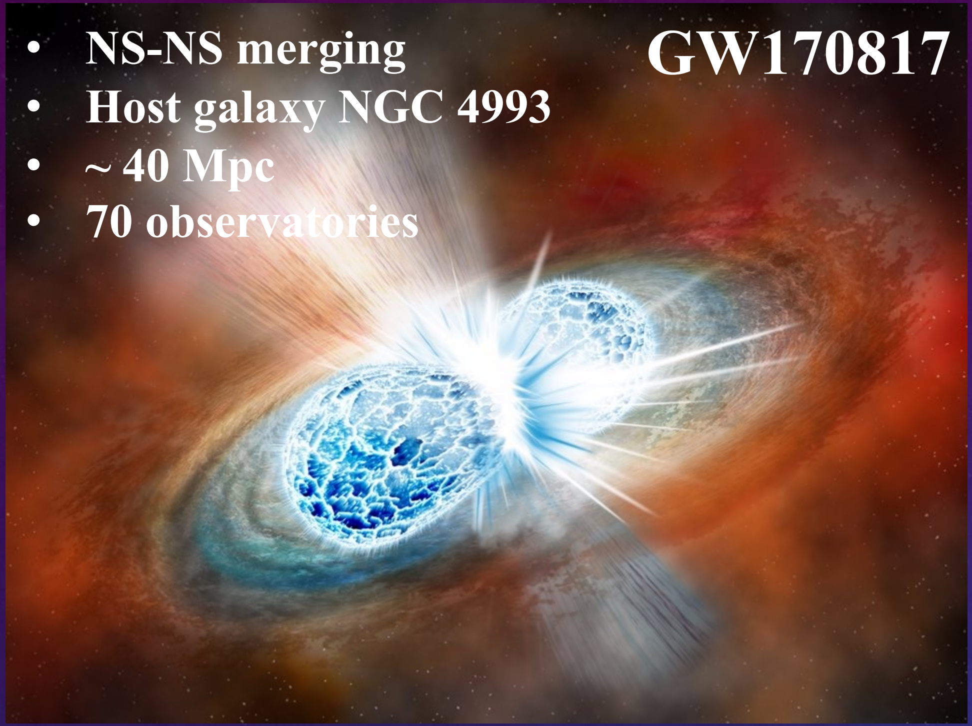
Multi-Messenger Astronomy

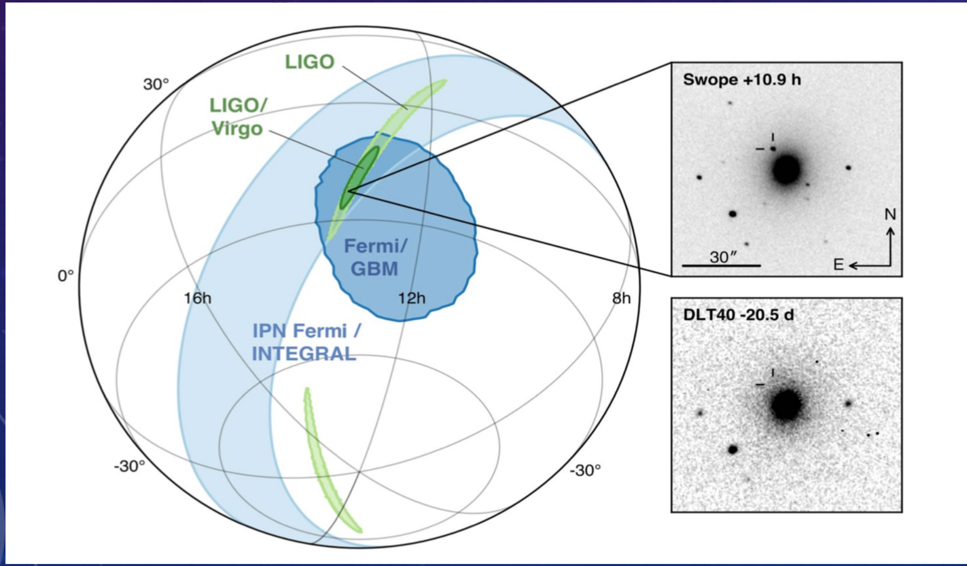


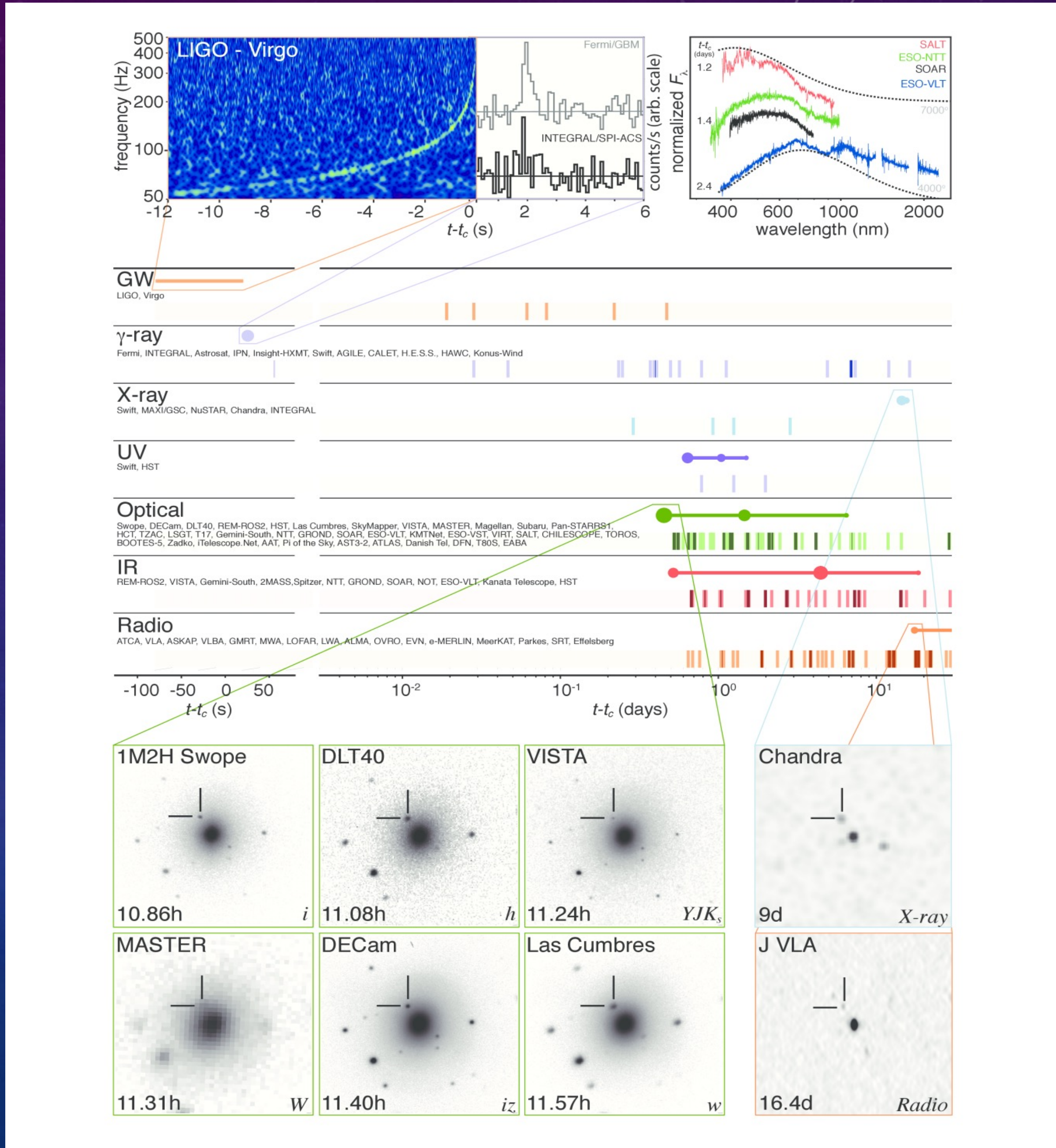
Testing Quantum Gravity theories



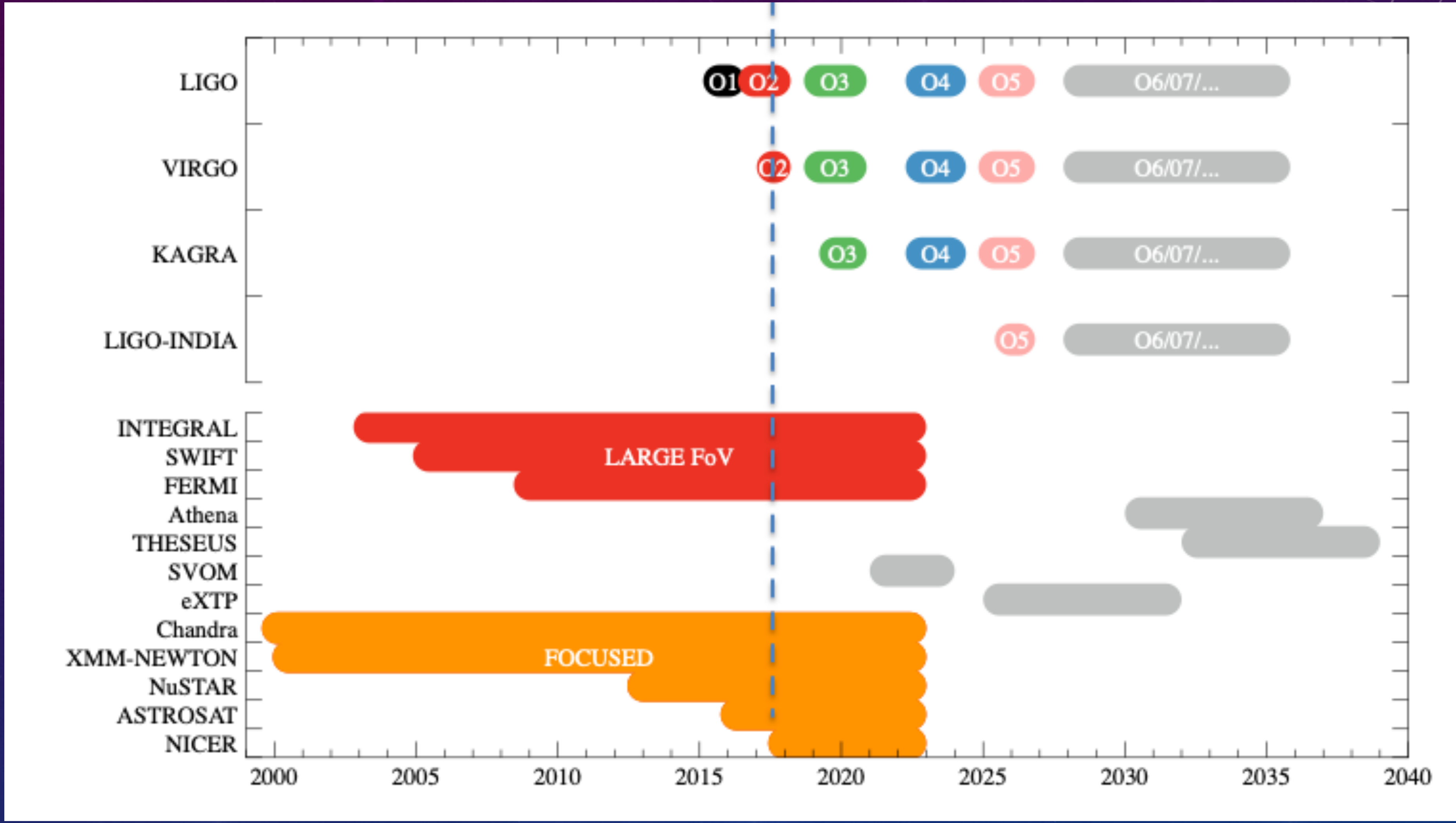
DEVELOPMENT OF MULTI-MESSENGER ASTRONOMY







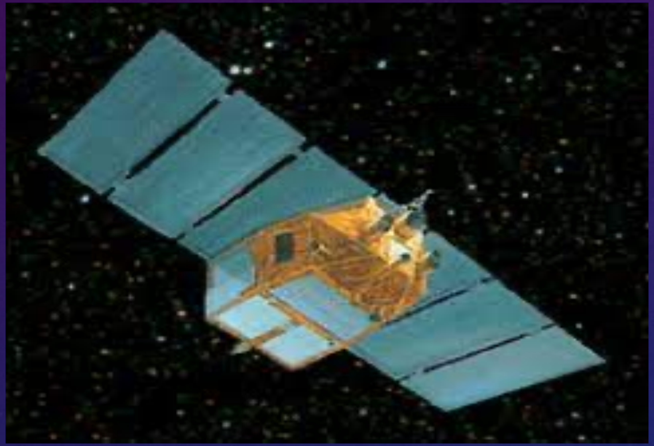
MULTI-MESSENGER PARADOX



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

MONOLITHIC VS DISTRIBUTED HIGH ENERGY OBSERVATORIES

FERMI

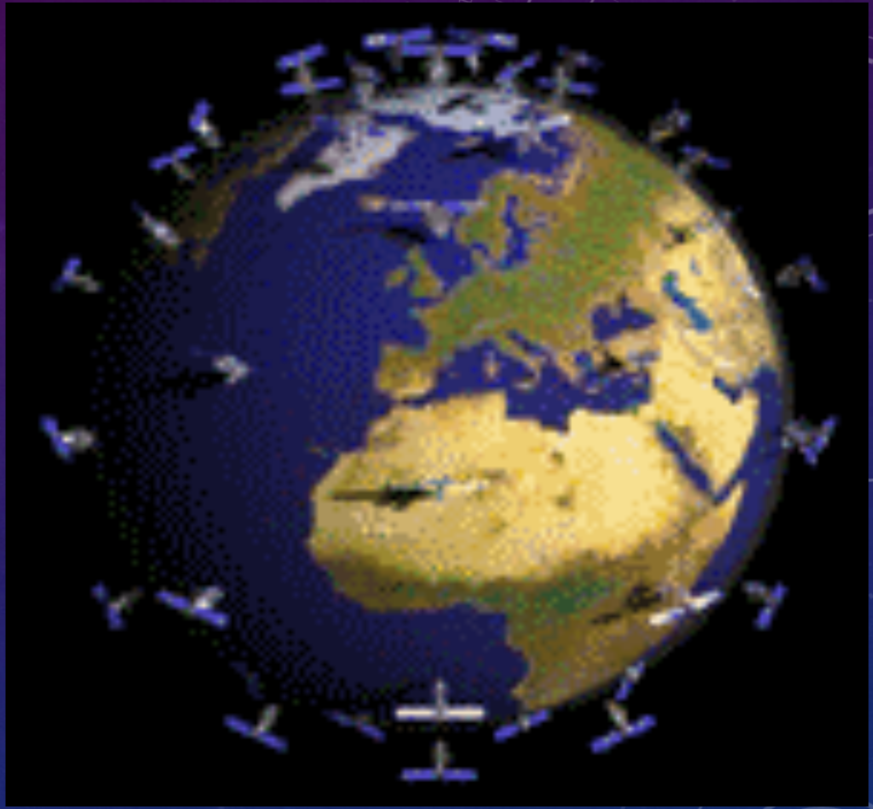


BeppoSAX

AGILE

Pros:

- Reliability
- long heritage



Pros:

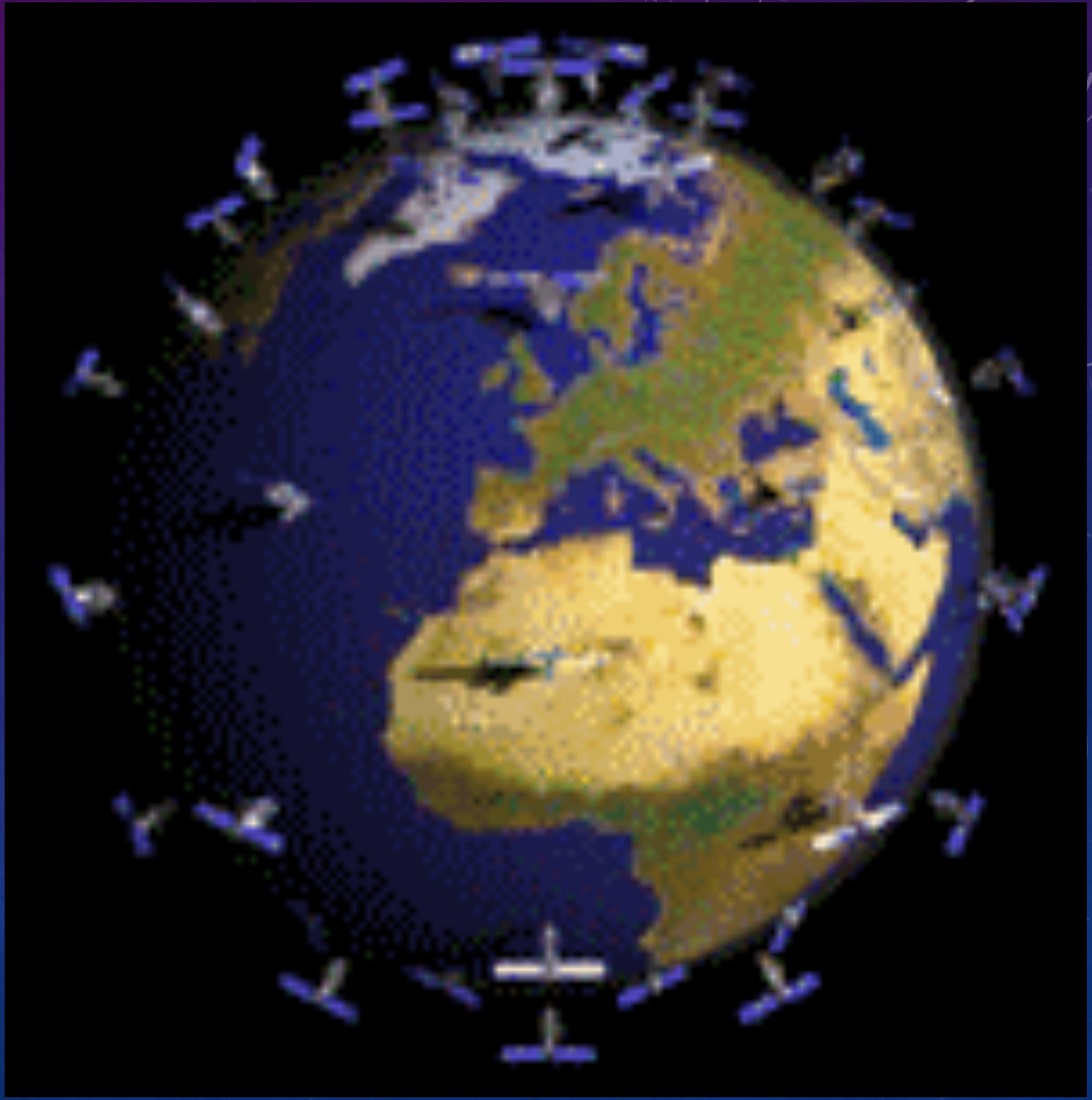
- modularity
- limited cost
- quicker development
- Low risk

HIGH ENERGY RAPID MODULAR ENSEMBLE OF SATELLITES - HERMES

Modular X/gamma-ray ALL-SKY MONITOR

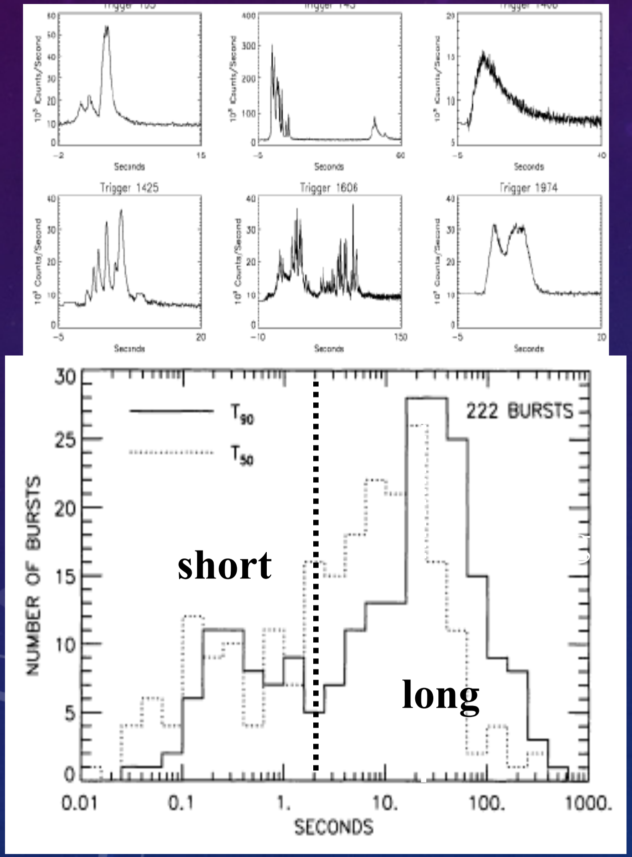
A **swarm tens/hundreds of LEO nano/micro satellites** equipped with:

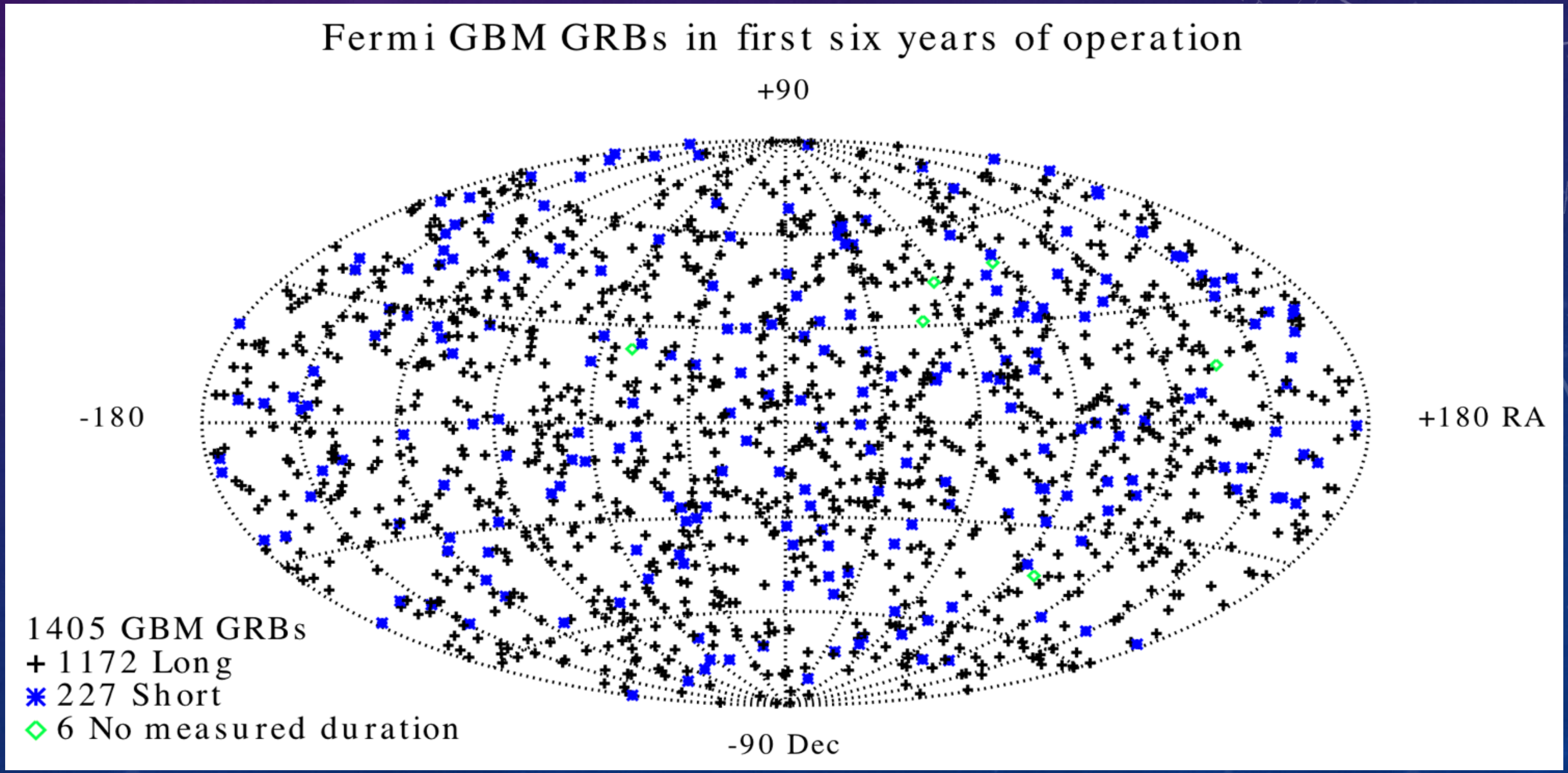
- keV-Mev scintillators,
- sub μs time resolution
- large FoV



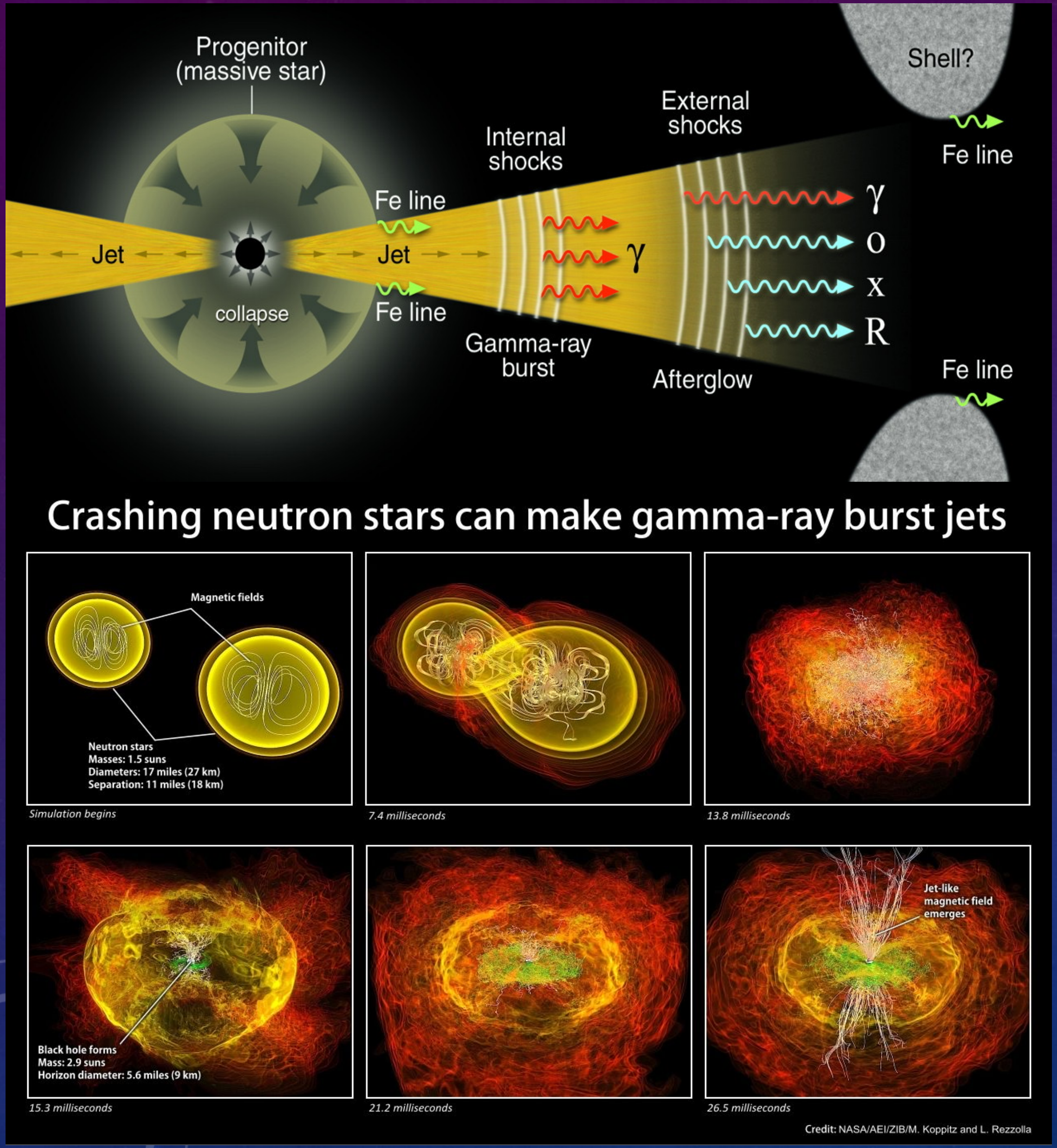
IDEAL TARGETS: GAMMA-RAY BURSTS

- 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,
- bimodal distribution of duration (0.1–1.0 s & 10.0–100.0 s)





IDEAL TARGETS: GAMMA-RAY BURSTS



Long GRBs

BH collaps of a massive star

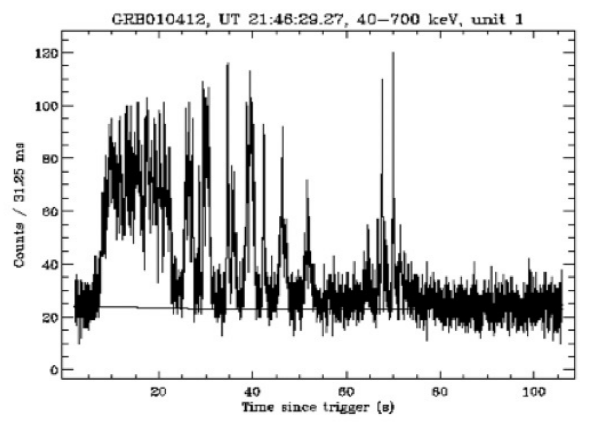
Short GRBs

NS-NS binary system coalescence

GRB – THE FIREBALL MODEL

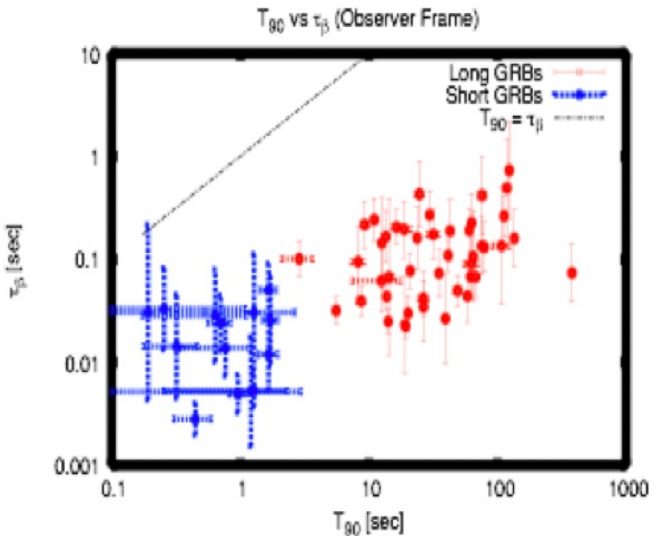
- multiple collision of relativistic shells ($\Gamma = [1 - (v_{jet}/c)^2]^{-1/2} \geq 100$)
- explains rapid variability
- synchrotron radiation and inverse Compton scattering

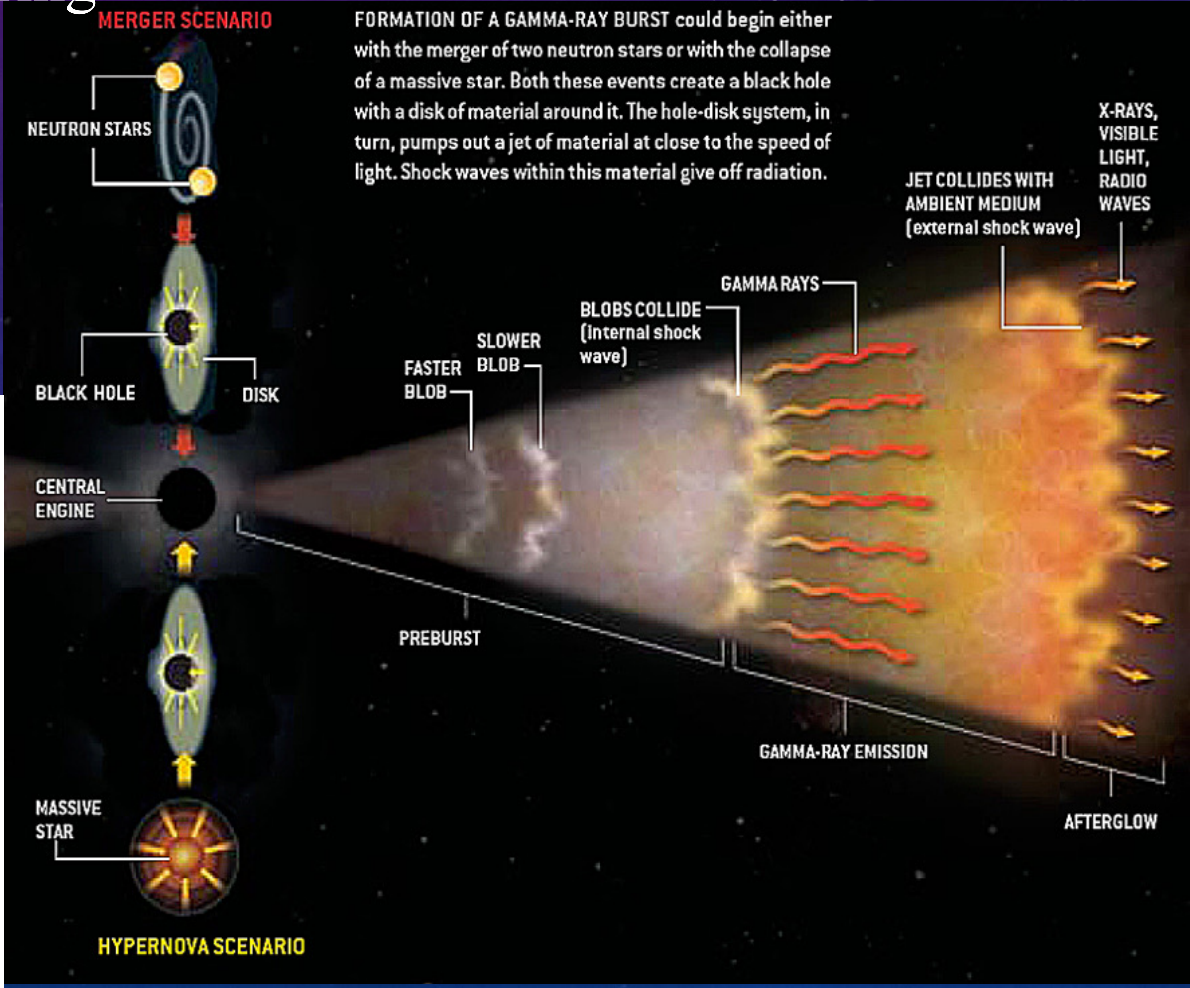
BeppoSAX GRBM data



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

Fermi GBM (8 keV - 40 MeV)





GRB LOCALISATION – TEMPORAL TRIANGULATION (IPN LEGACY)

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:

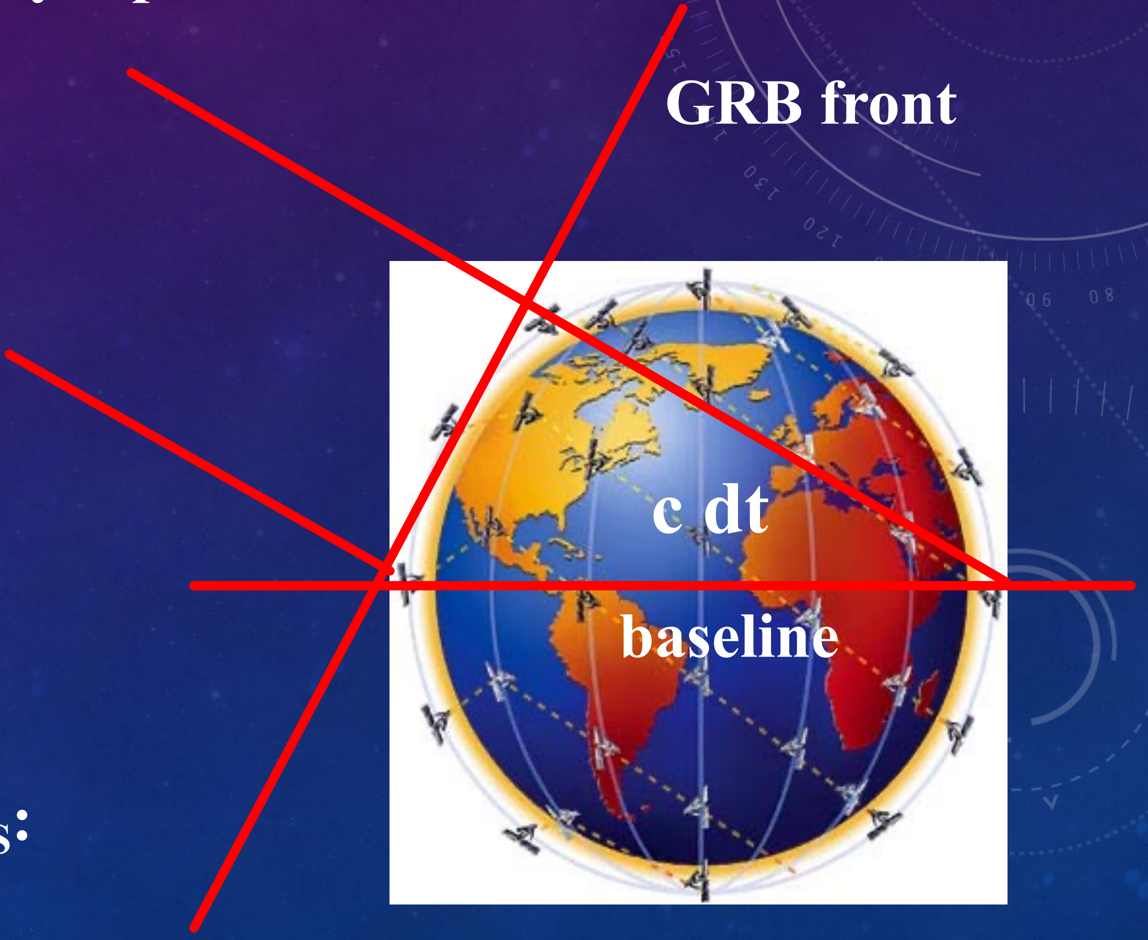
α, δ (2 parameters, $N_{PAR} = 2$)

Number of independent delays:

$N_{DEL} = N_{SATELLITES} \times (N_{SATELLITES} - 1) / 2$

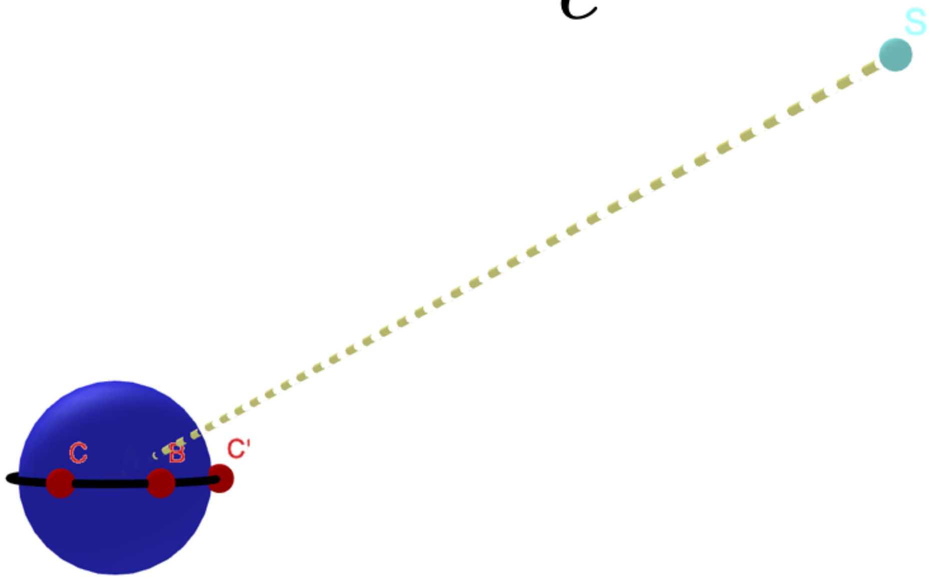
Accuracy in determining α and δ with $N_{SATELLITES}$:

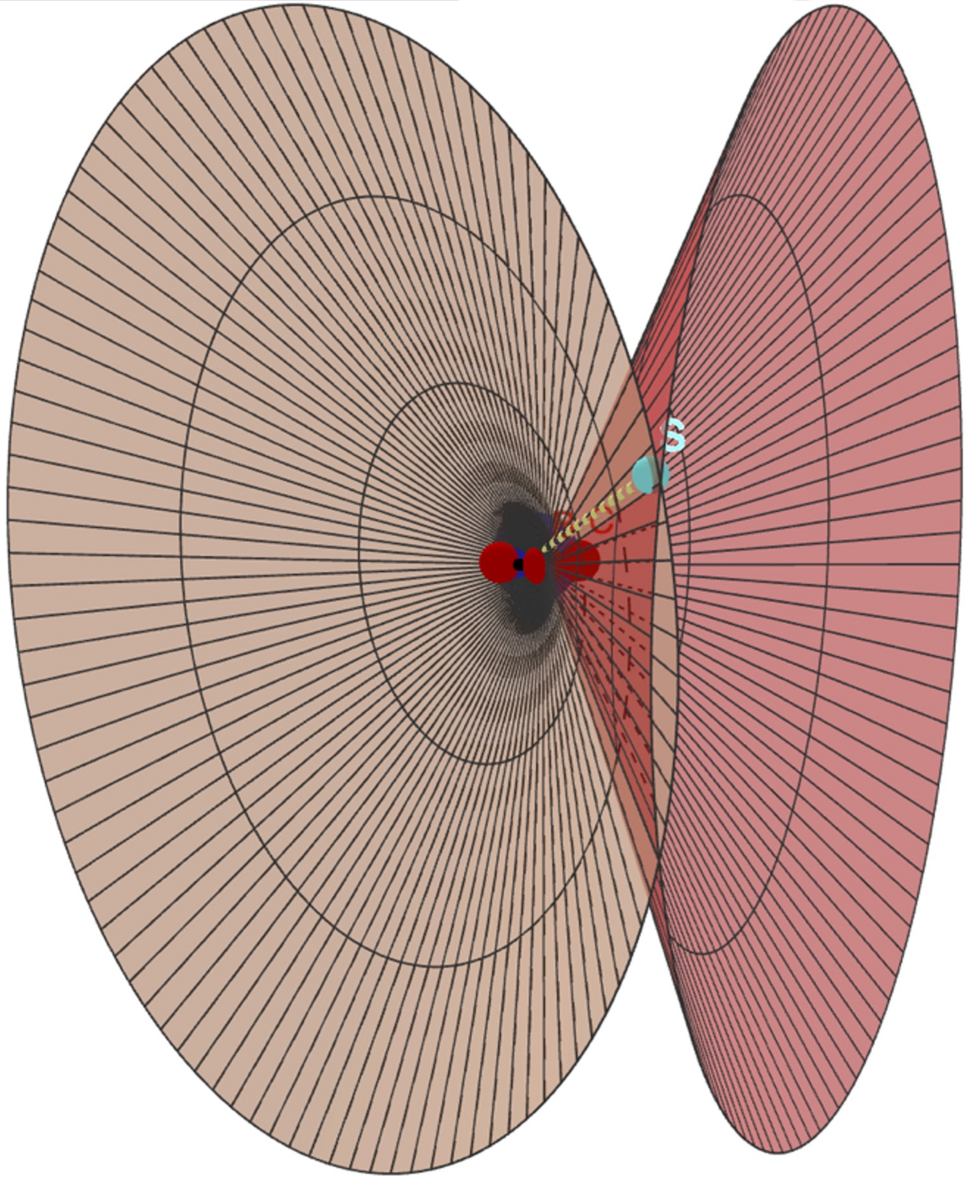
$\sigma_\alpha \approx \sigma_\delta = c\, \sigma_{ToA} / \langle \text{baseline} \rangle \times (N_{DEL} - N_{PAR} - 1)^{-1/2}$



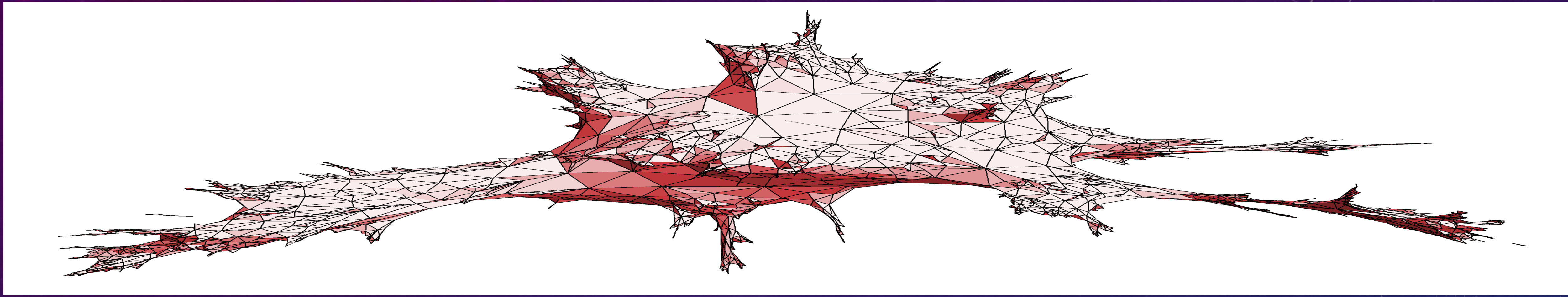
GRB LOCALISATION – TEMPORAL TRIANGULATION (IPN LEGACY)

$$\Delta t_{ij} = \frac{\vec{\rho_{\mathbf{ij}}} \cdot \hat{\mathbf{d}}}{c}$$



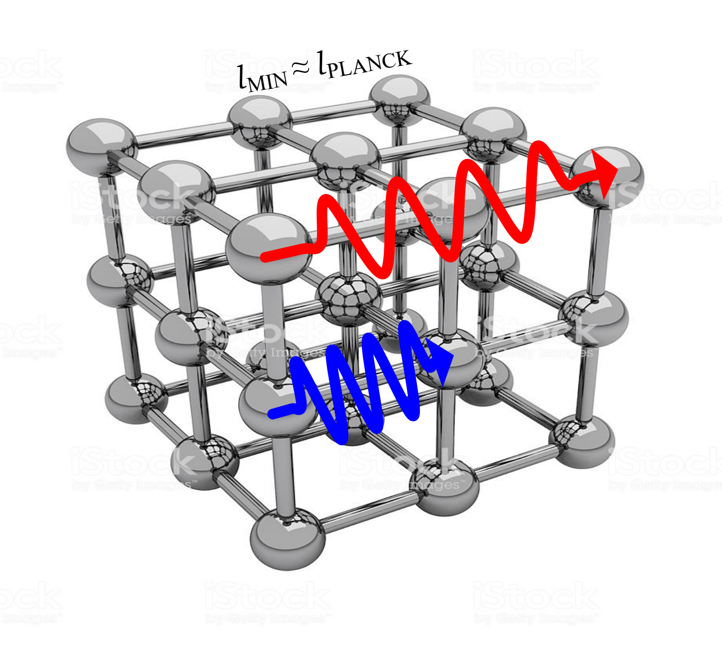


QUANTUM GRAVITY EXPERIMENT



QUANTUM GRAVITY

MINIMAL LENGTH HYPOTHESIS, LIV AND DISPERSION RELATION FOR PHOTONS *IN VACUO*



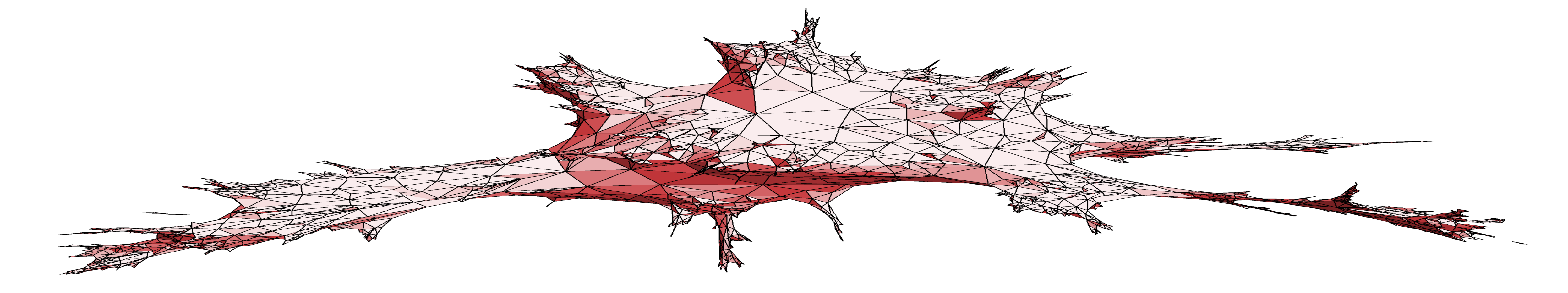
Existence of a Minimal Length (String theories, etc.)

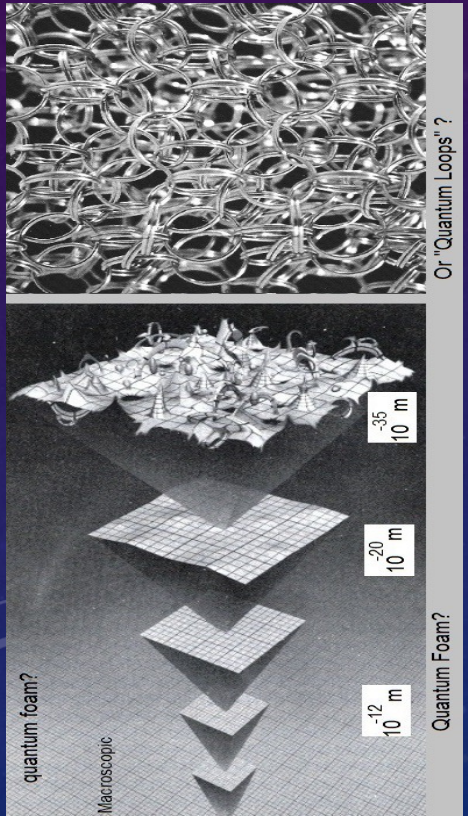
$$l_{MIN} \approx l_{PLANCK} = [Gh/(2\pi c^3)]^{1/2} = 1.6 \times 10^{-33} \text{ cm}$$

implies:

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

QUANTUM GRAVITY EXPERIMENT





DISPERSION RELATION FOR PHOTONS *IN VACUO* AND TRAVEL TIME DELAYS

Accumulation of delays in light propagation:

$$\Delta t_{QG} = \xi \, (D_{TRAV}/c) \, [\Delta E_{obs} / (\zeta E_{Pl})]^n$$

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

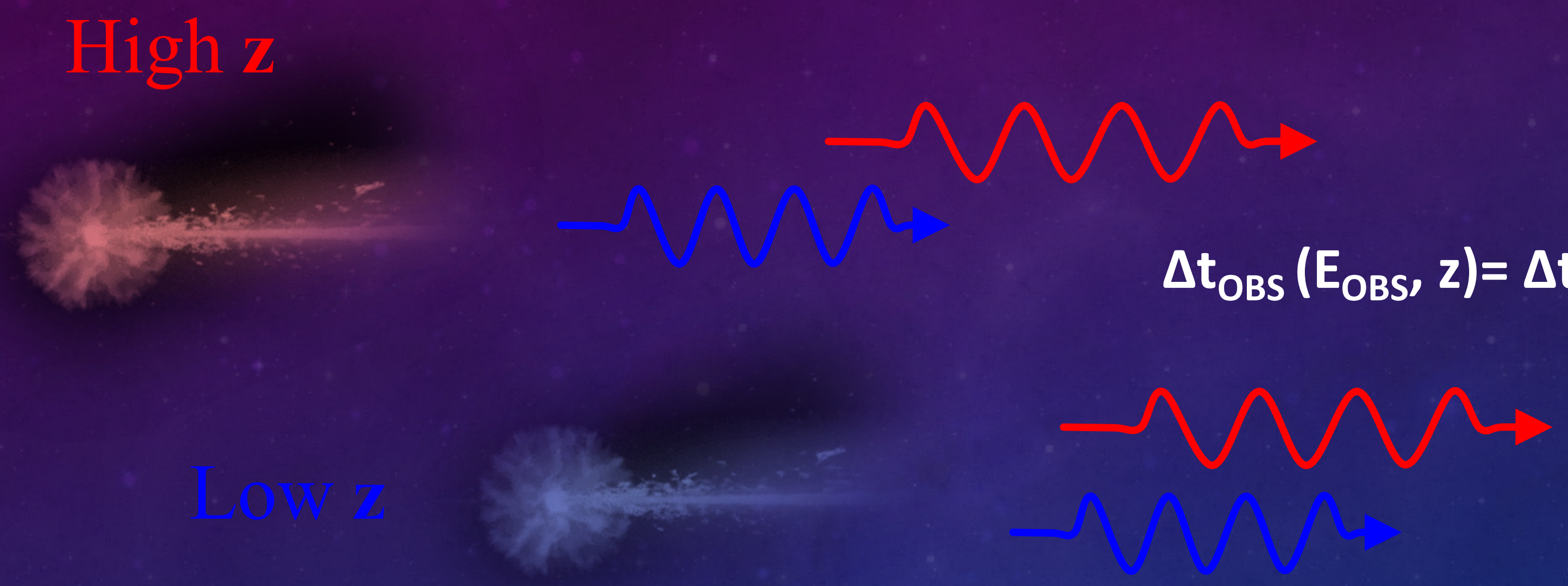
$$D_{TRAV}(z) = (c/H_0) \int_0^z d\beta \, (1+\beta) / [\Omega_\Lambda + (1+\beta)^3 \, \Omega_M]^{1/2}$$

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

QUANTUM GRAVITY EXPERIMENT

THE ENERGY AND REDSHIFT DELAY DEPENDENCE



$$\Delta t_{OBS}\,(E_{OBS}, z) = \Delta t_{INT}\,(E_{OBS}, z) + \Delta t_{QG}\,(E_{OBS}, z)$$

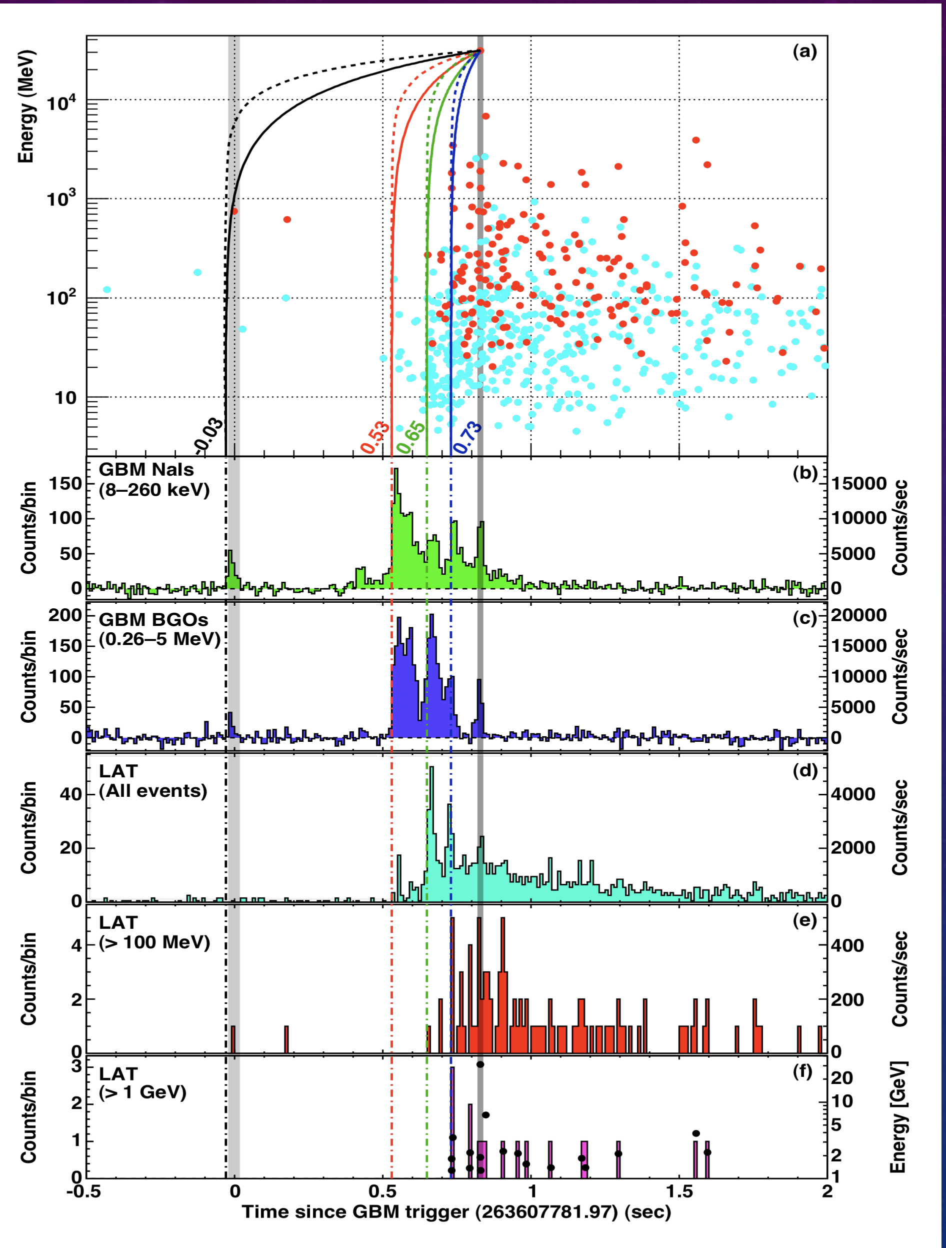
Time lags caused by Quantum Gravity effects:

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

Time lags caused by prompt emission mechanism:

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

QUANTUM GRAVITY: OBSERVATIONAL RESULTS



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): $\xi = ½$; $n=1$

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

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

QUANTUM GRAVITY EXPERIMENT

VERY LARGE EFFECTIVE AREA

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

QUANTUM GRAVITY EXPERIMENT

VERY LARGE EFFECTIVE AREA

$\sigma_{CCF} \approx$ 100 μs/ $(N_{PHOT}/12000)^{-1/2}$ (GRB with ms variability)
10000 nano–satellites of A = 100 cm^2

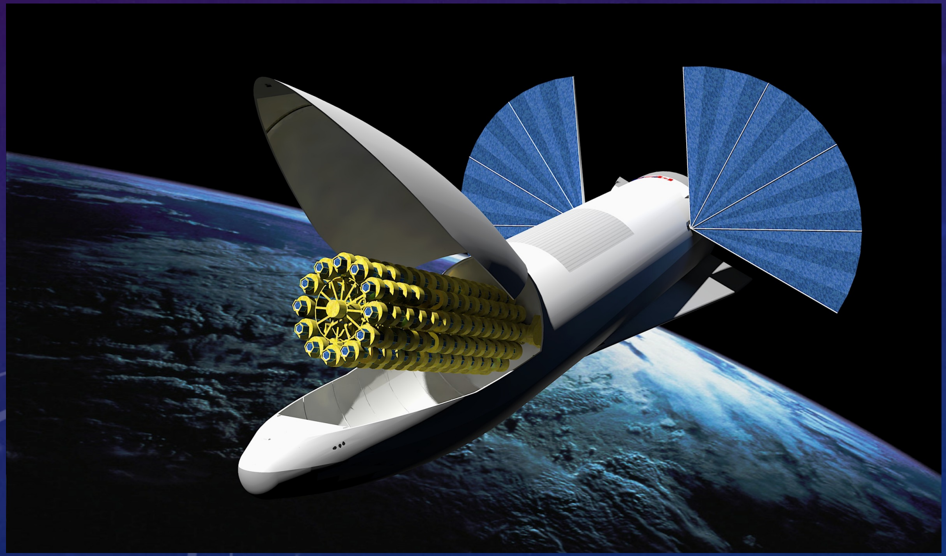
ΛCDM cosmology with $\Omega_\Lambda = 0.6911$ and $\Omega_{\mathrm{Matter}} = 0.3089$

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

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

QUANTUM GRAVITY EXPERIMENT

LARGE CONSTELLATIONS



Starlink Constellation 12,000 sats
SpaceX (Elon Musk)

- 6000 @ 1200 km (by March 2024)
- 60 satellites launched on 16/05/2019
- LEO @ ~550 km
- optical inter–satellite links
- 100 ÷ 500 kg satellites (mass production)

WHISHFUL THINKING:

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!

QUANTUM GRAVITY EXPERIMENT

THE ENERGY AND REDSHIFT DELAY DEPENDENCE

GRB intrinsic spectral lag

Observer frame vs Rest frame

Lags come from GRB central engine emission mechanism at the rest frame:

$$E_{rf} = E_{obs}\,(1+z)$$

Moreover, cosmological dilation implies:

$$\Delta t_{INT}\,(E_{OBS}, z) = \Delta t_{INT}\,(E_{rf})\,(1+z)$$

There is no direct evidence of a correlation between $\Delta t_{INT}(E_{rf})$ and redshift z.

Quantum Gravity delay

Observer frame vs Rest frame

$$\Delta t_{QG}\,(E_{OBS}, z) = \Delta t_{QG}\,(E_{rf}, z) = \frac{\xi}{H_0}\left(\frac{E_{rf}}{\zeta E_{pl}}\right)^n \times$$

$$\times \left(\frac{1+n}{2}\right)\left(\frac{1}{1+z}\right)^n \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

QUANTUM GRAVITY EXPERIMENT

THE ENERGY AND REDSHIFT DELAY DEPENDENCE

Total observed spectral lag:

$$\Delta t_{total}(E_{rf}; z) = \Delta t_{INT}(E_{rf})(1+z) + \frac{\xi}{H_0}\left(\frac{E_{rf}}{\zeta E_{pl}}\right)^n \left(\frac{1+n}{2}\right)\left(\frac{1}{1+z}\right)^n \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

Let’s define the quantity:

$$\tau_{total}(E_{rf}; z) = \frac{\Delta t_{total}(E_{rf}; z)}{(1+z)} =$$

$$= \Delta t_{INT}(E_{rf}) + \frac{\xi}{H_0}\left(\frac{E_{rf}}{\zeta E_{pl}}\right)^n \left(\frac{1+n}{2}\right)\left(\frac{1}{1+z}\right)^{n+1} \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

QUANTUM GRAVITY EXPERIMENT

THE ENERGY AND REDSHIFT DELAY DEPENDENCE

We now define the function $u(z)$:

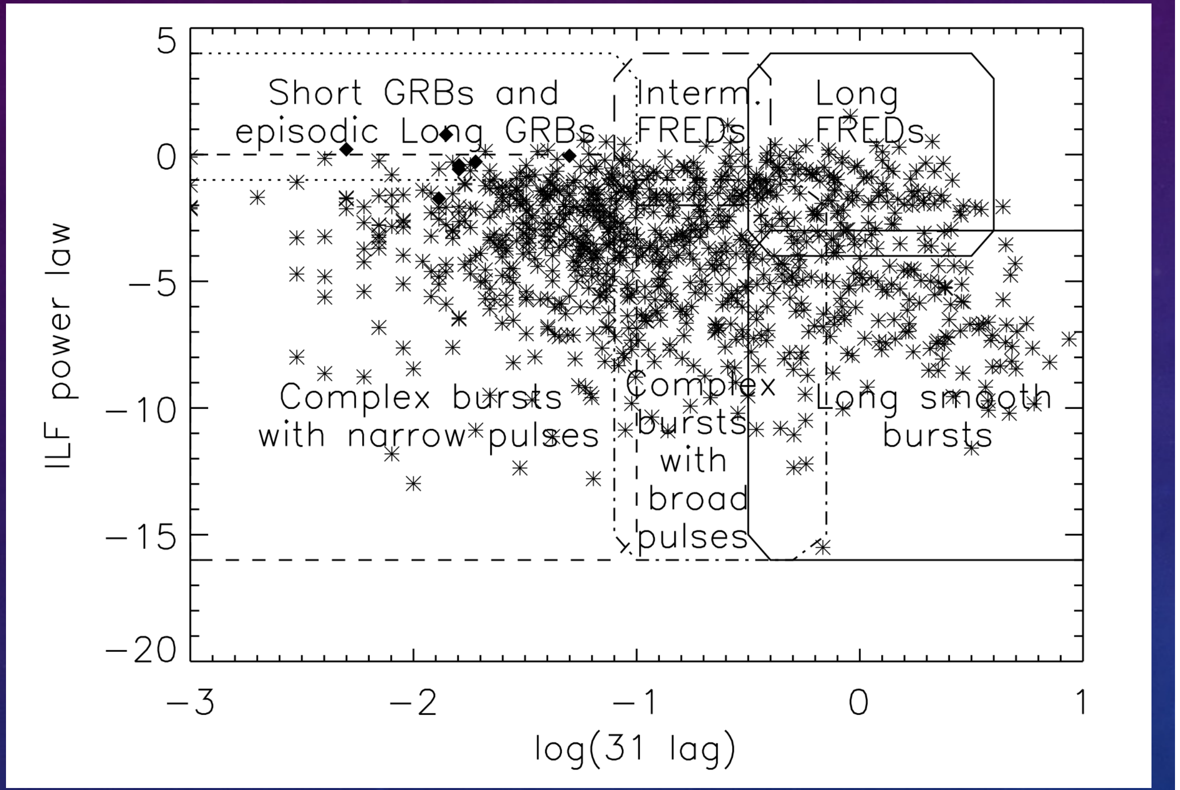
$$u(z) = \left(\frac{1+n}{2}\right)\left(\frac{1}{1+z}\right)^{n+1} \int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$$

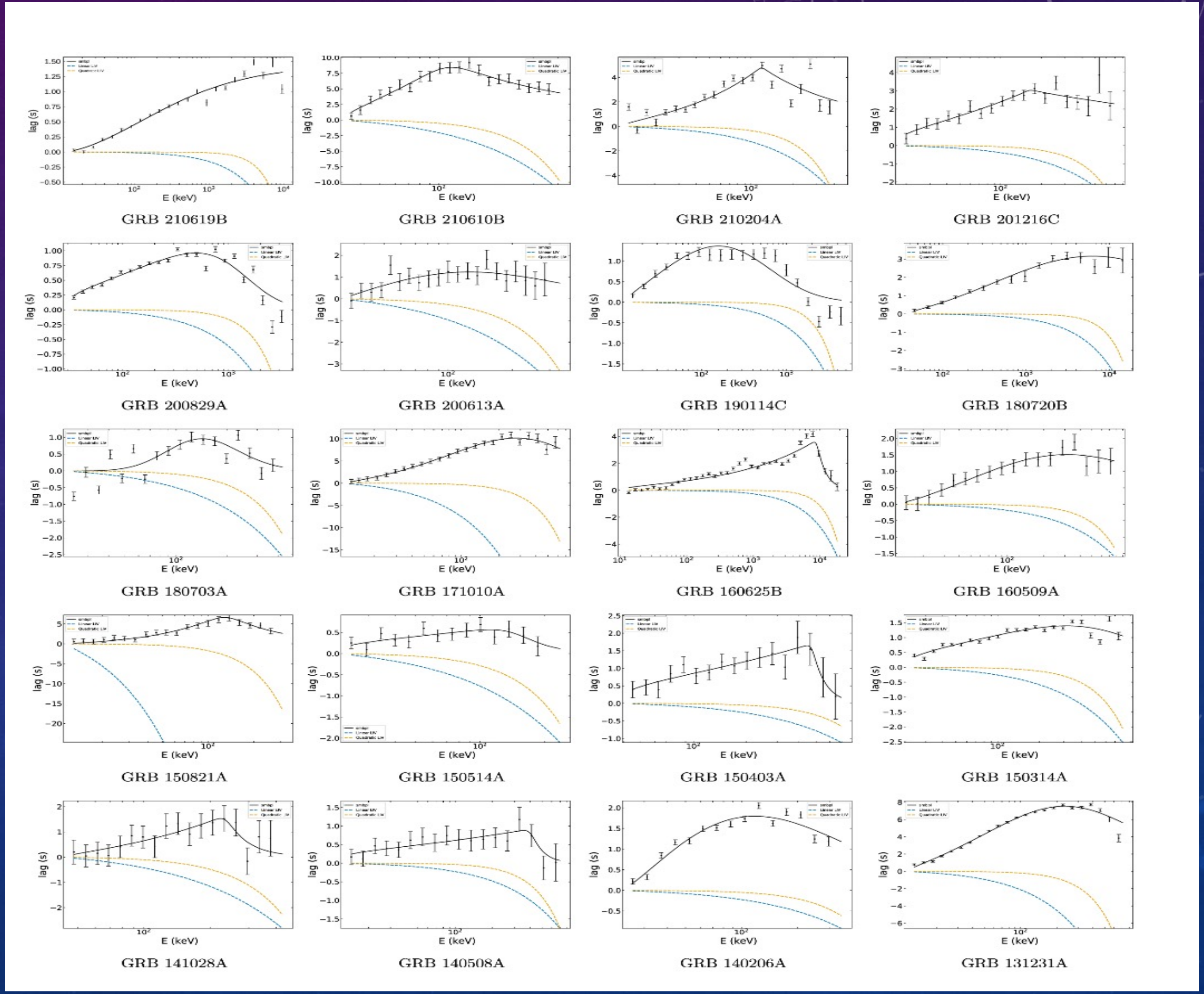
This formalism allows us to express the lags as follows:

$$\boldsymbol{\tau_{total}(E_{rf};\mathrm{z}) = \Delta t_{INT}(E_{rf}) + \frac{\xi}{H_0}\left(\frac{E_{rf}}{\zeta E_{pl}}\right)^n u(z)}$$

QUANTUM GRAVITY EXPERIMENT

OBSERVATIONAL HINTS ON GRB'S INTRINSIC DELAYS





QUANTUM GRAVITY EXPERIMENT

THE POWER OF THE SAMPLE

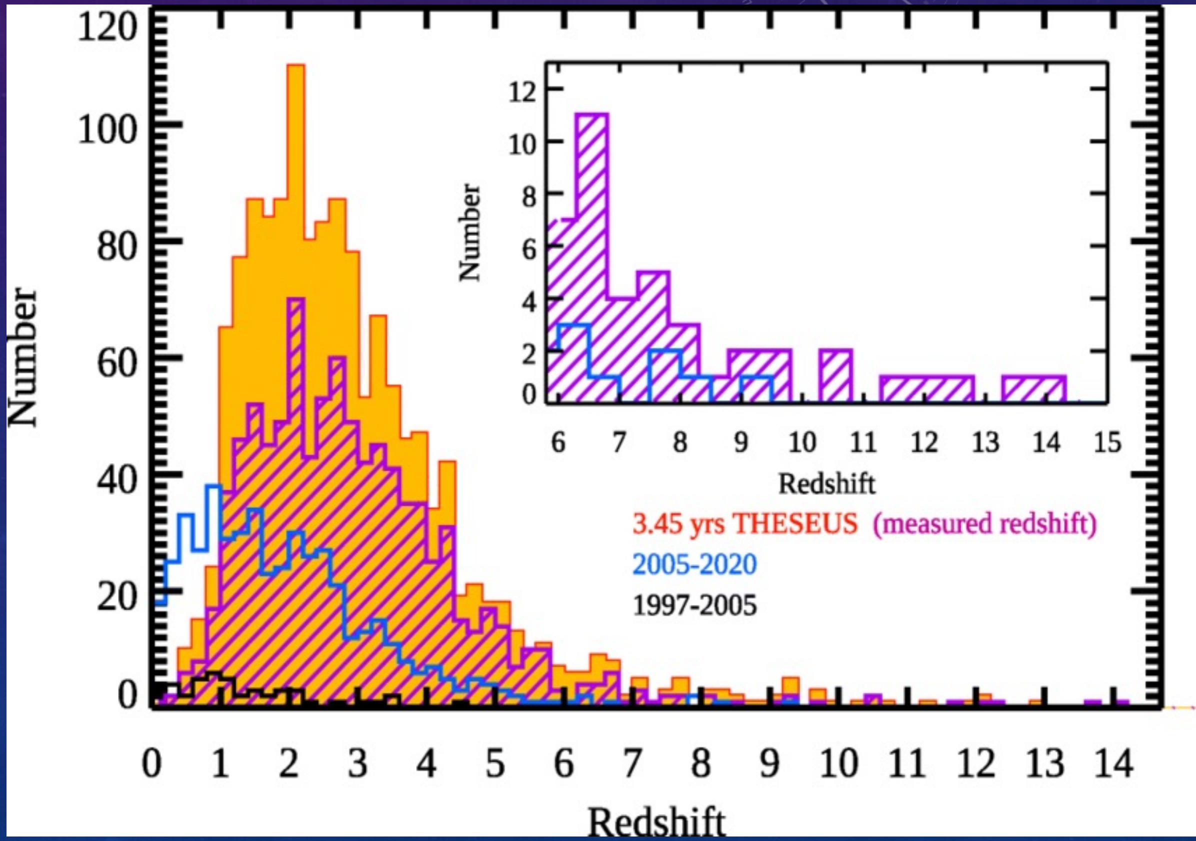
Let's consider a sample of N GRBs with known z and let's define a number M of common energy bands in the rest frame of the GRBs.

For each energy band $\boldsymbol{E_{rf,i}}$ we can fit the function

$$\tau_{total}(E_{rf,i};z) = \Delta t_{INT}(E_{rf,i}) + \frac{\xi}{H_0}\left(\frac{E_{rf,i}}{\zeta E_{pl}}\right)^n u(z)$$

Obtaining M values of the quantity

$$\eta(E_{rf,i}) = \frac{\xi}{H_0}\left(\frac{E_{rf,i}}{\zeta E_{pl}}\right)^n$$



QUANTUM GRAVITY EXPERIMENT

THE POWER OF THE SAMPLE

Finally, we define the new variable

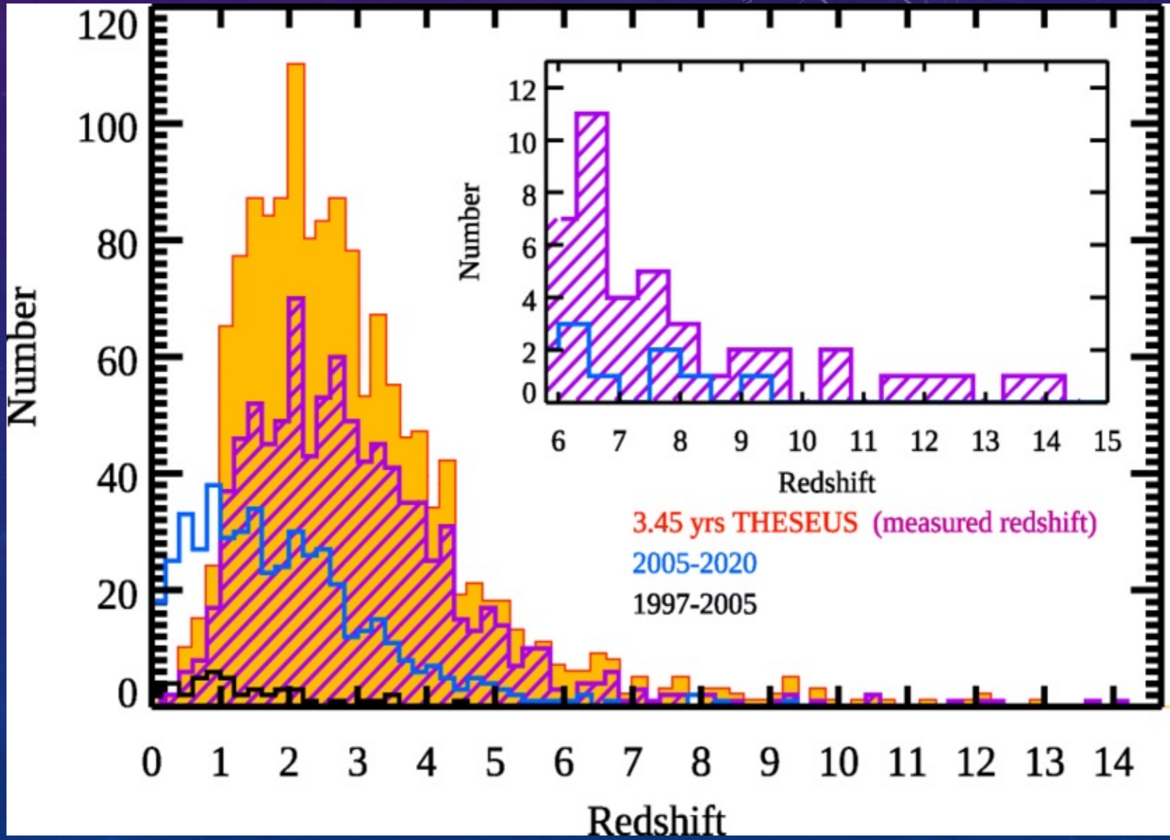
$$s(E_{rf}) = \frac{1}{H_0}\left(\frac{E_{rf}}{E_{pl}}\right)^n$$

Therefore, we can linearly fit the M sample $\eta(E_{rf})$ with the function:

$$f(E_{rf}) = \left(\frac{1}{\zeta}\right)^n s(E_{rf}) = \Delta_{QG}\, s(E_{rf})$$

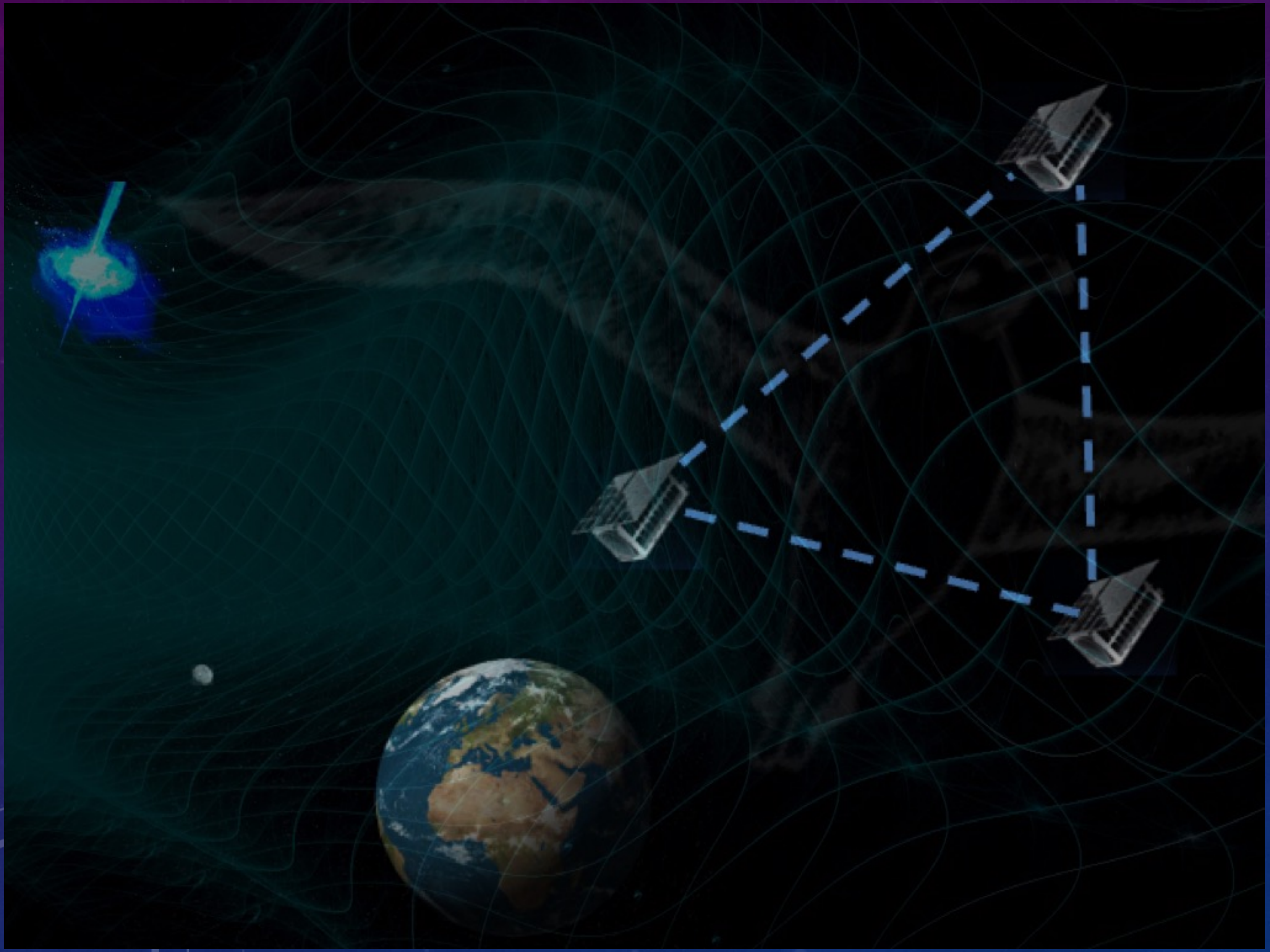
Interestingly, the uncertainty on Δ_{QG} improves as

$$\sigma_{\Delta_{QG}} \propto \frac{1}{\sqrt{NM}}$$



THE ALBATROS MISSION

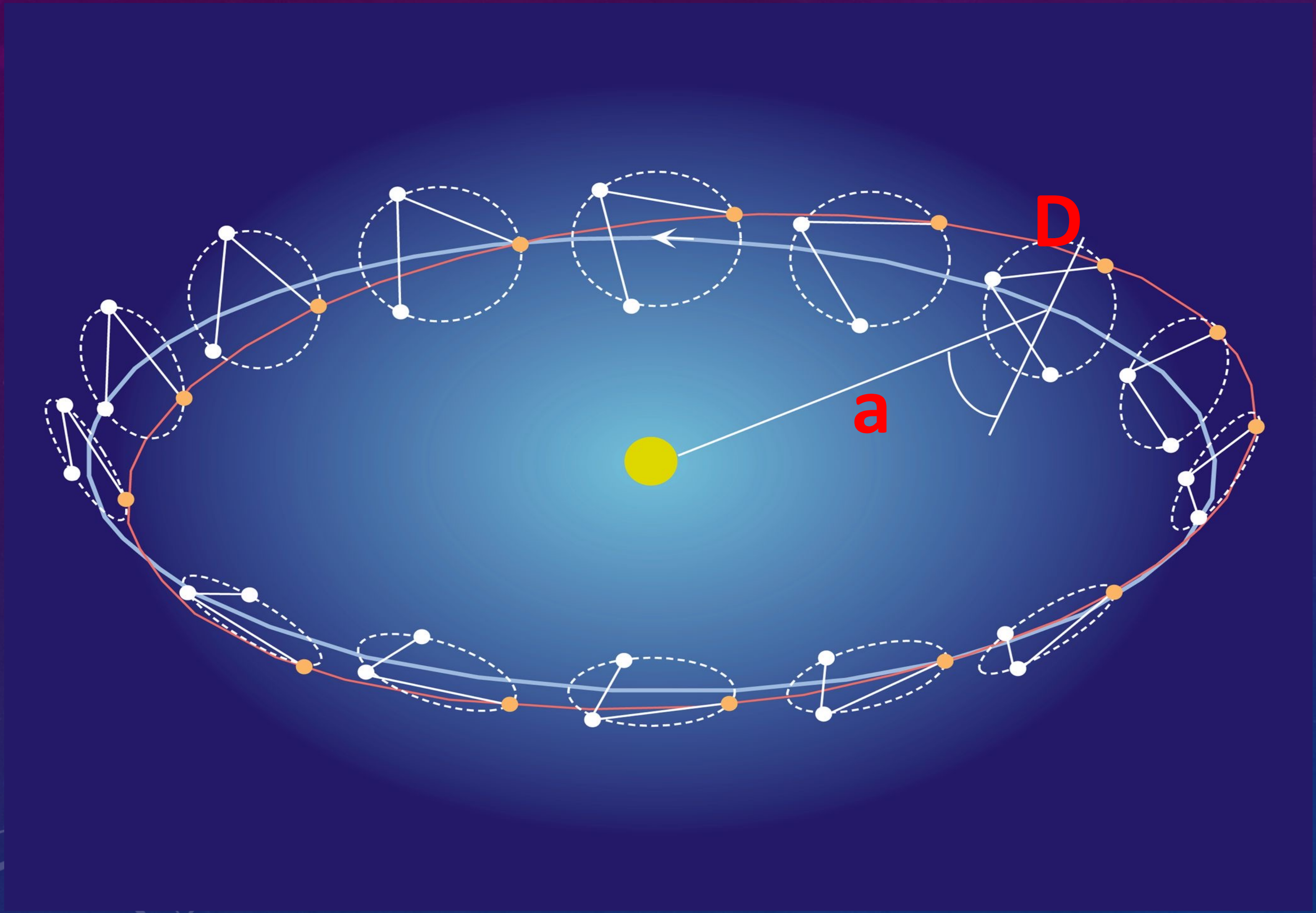
(Astonishingly Large Baseline Array Transient Reconnaissance Observatory from Space)



Properties:

- 3 satellites in heliocentric orbits
- 2x400 cm^2 detectors (~20 kg) per satellite pointing in opposite directions
- keV – MeV energy band
- Sub-microsecond time resolution
- 4π steradians FoV (whole sky)
- 1 GRB/day detection rate
- 75% expected success in GRB redshift determination with ground-based facilities follow-up

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 (i≈degrees) 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: LOCALIZATION CAPABILITIES

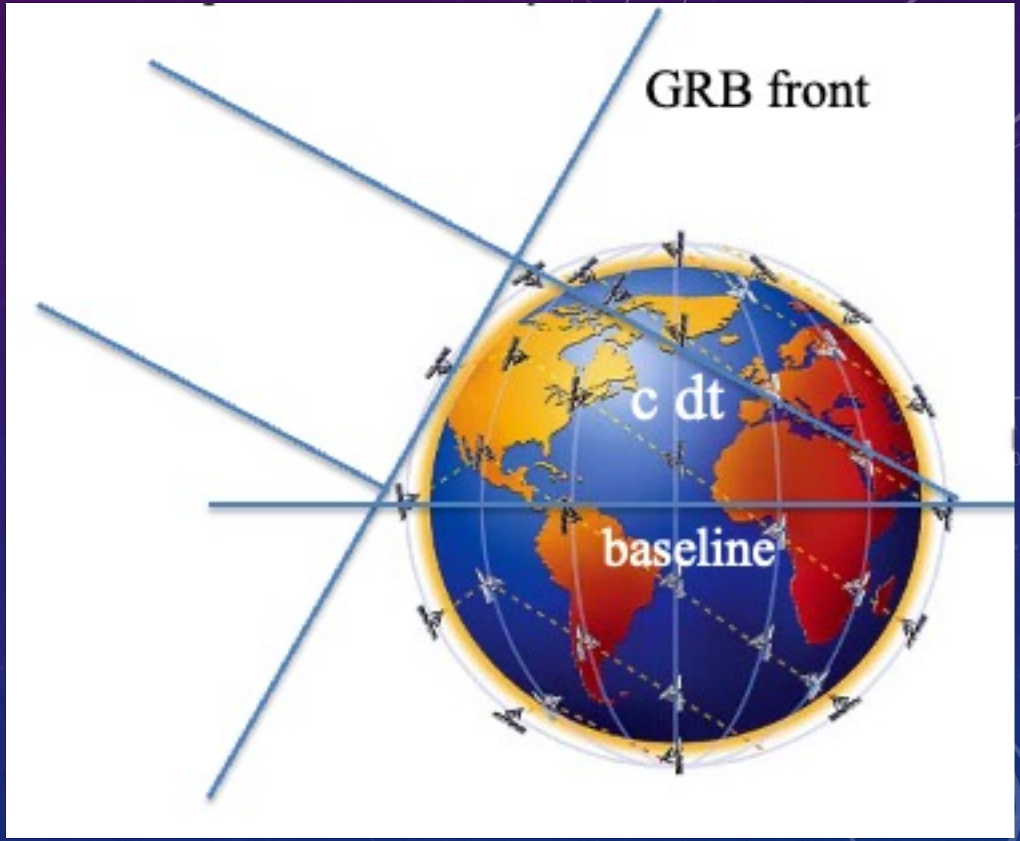
Determination of source position through Delays in Time of Arrival (ToA) of an impulsive event (variable signal) over 3 (or more) spatially separate detectors

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

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

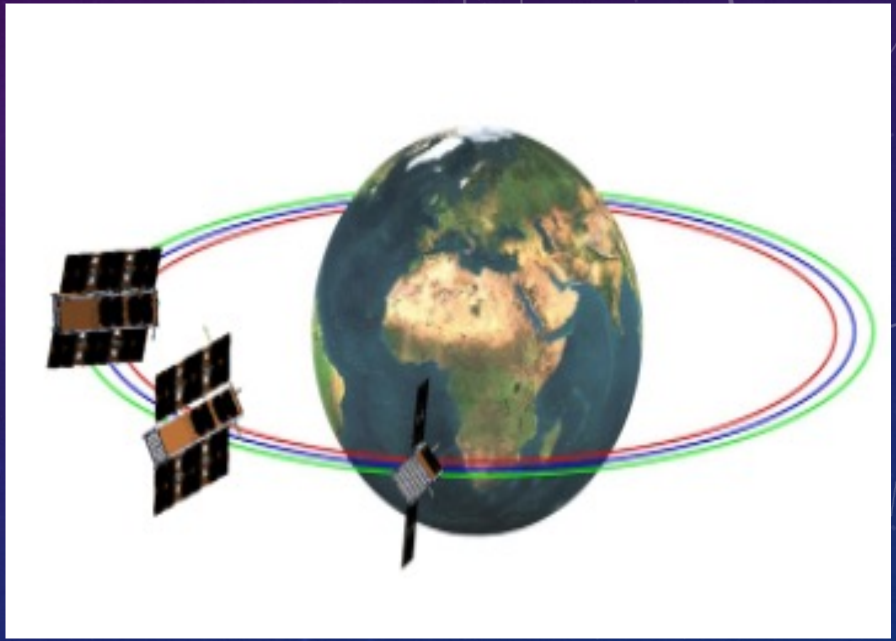
$$\sigma_\alpha \approx \sigma_\delta = c\, \sigma_{ToA} / \langle baseline \rangle \times (N_{SAT} - N_{PAR})^{-1/2}$$

$$\sigma_\alpha \approx \sigma_\delta \approx c\, \sigma_{ToA} / B \approx 24 \text{ arcsec} \times (B / 2.5 \times 10^6 \text{ km})^{-1} \times (\sigma_{ToA} / 1\text{ms})$$

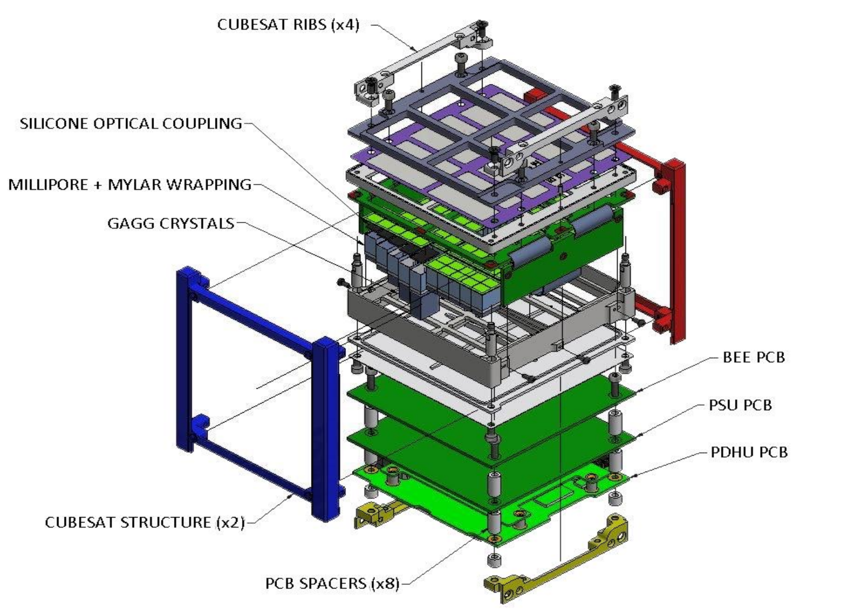


HERMES PATHFINDER + SPIRIT IN A NUTSHELL

- **In orbit demonstrator**
- HERMES Pathfinder: six 3U cubesat equipped with advanced X-ray/gamma/ray wide field detector; funded by ASI & EC H2020
- SpIRIT: 6U cubesat managed by University of Melbourne and funded by ASA. Host 1 HERMES-PF X-ray/gamma-ray payload + S-band system.

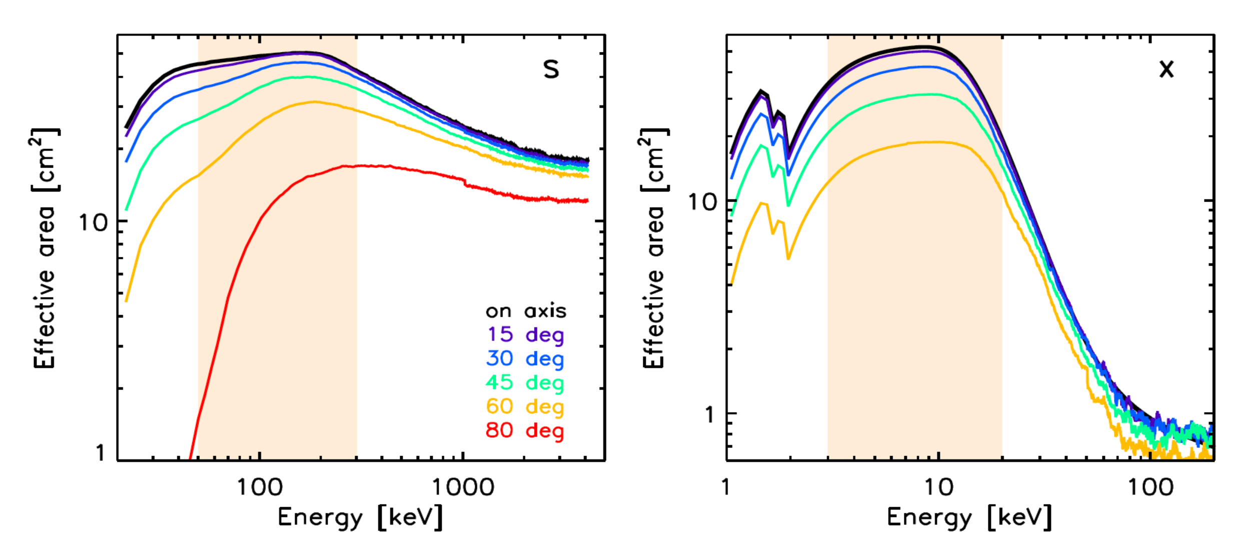


HERMES PATHFINDER: PAYLOAD



Silicon Drift Detector + GAGG Cristals

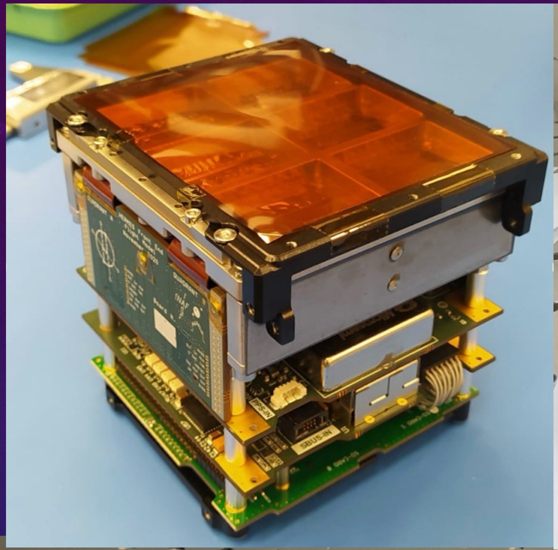
Scintillator Crystal size:	0.7×1.2×1.5 cm
Crystal type:	60 GAGG crystals
Photo detector:	120 SDD (1x0.5 cm)
Energy range:	3 keV ÷ ≥ 0.5 Mev
Energy resolution:	~ 10% at 30 keV
Effective area:	~ 56 cm^2
FOV:	~ 3 steradians (FWHM)
Temporal resolution:	~ 0.5 µs
Mass:	~1.5 kg
Volume	< 10×10×12.5 cm



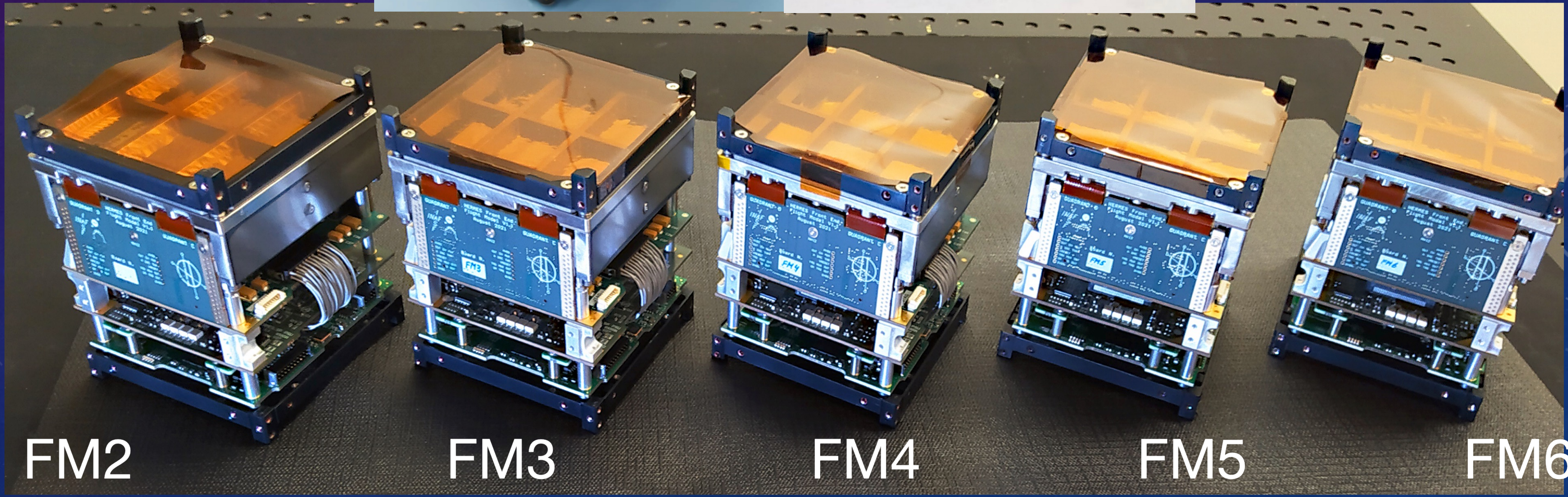
HERMES PATHFINDER & SPIRIT PAYLOAD

FAMILY PICTURE

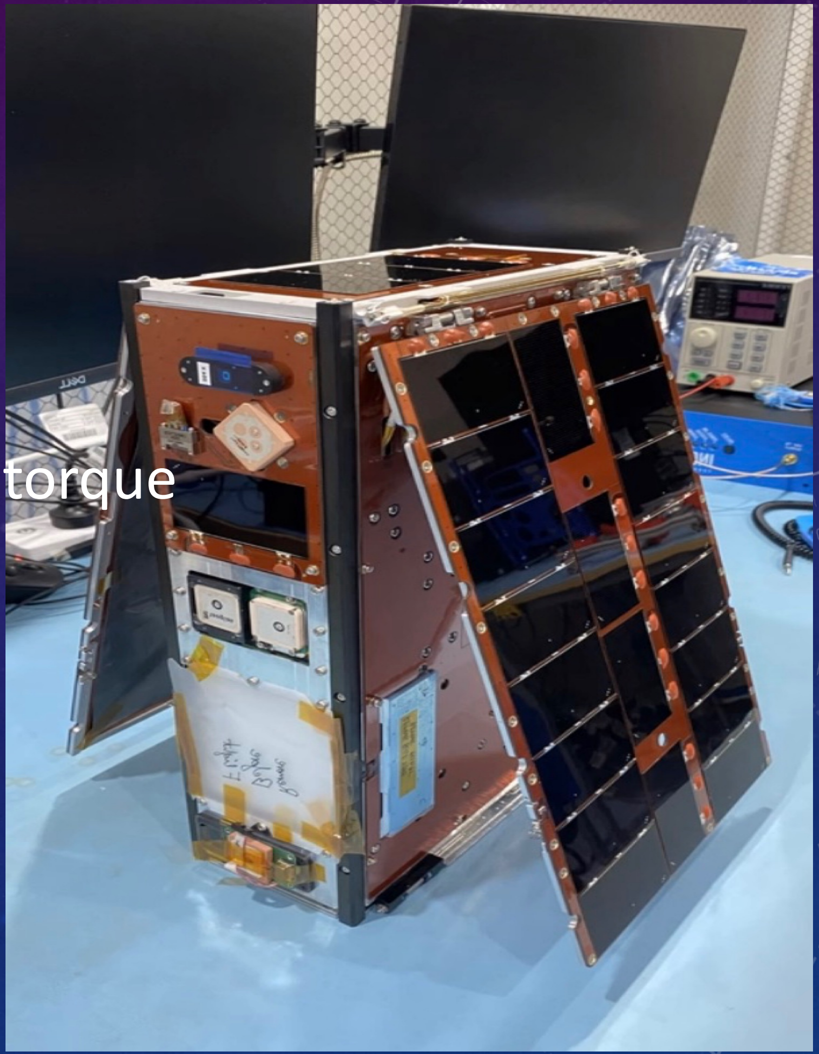
FMI
SpIRIT



PFM



SPIRIT: STATUS UPDATE



- Launch! December 1st, 2023, OK
- Deployment OK, Detumbling OK
- Safe mode just after detumbling because of a failure of a magnetorque
- Communications OK, UHF beacon received by SatNogs
- Communications OK, about 15m per day of link with AU GS
- OBC OK
- New firmware uploaded to operate with 2 magnetorques instead of 3
- Communications between PDHU - PMS and MMS established. PDHU OK

HERMES PATHFINDER: STATUS UPDATE

- PFM fully integrated, environmental test to support qualification review started in Dec. 2023 @POLIMI labs. QR closed in Jan 2024
- FM1, integration started end Nov. 2023, and full integration by Feb 2024.
- Acceptance review for six FMs second half of 2024
- Launch early 2025

THE HERMES PROJECT: THE MOVIE

Thanks for the attention!

Please join the HERMES Science Team:

https://www.hermes-sp.eu/?page_id=3643#ScienceTeam