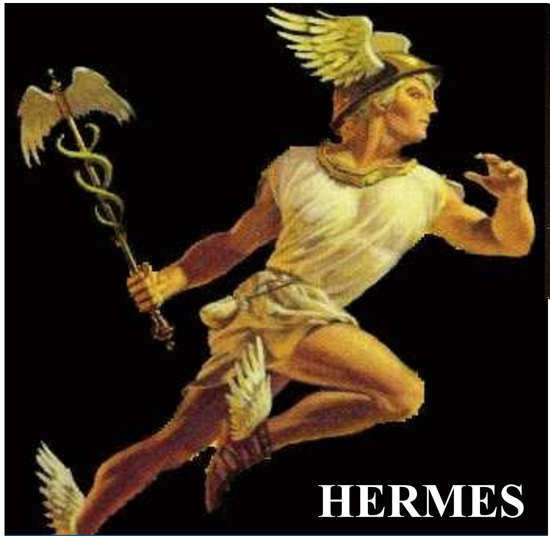


HERMES

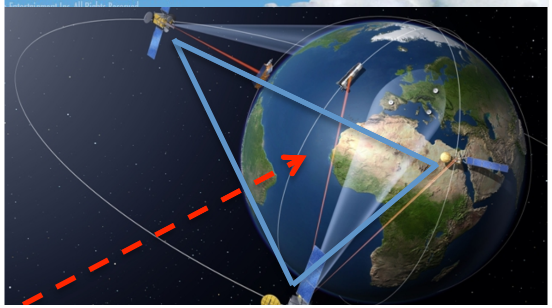
High Energy Rapid Modular Ensamble of Satellites

& *GrailQuest*

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

Hunting for Gravitational Wave Electromagnetic Counterparts
Probing Space-Time Quantum Foam

Luciano Burderi - University of Cagliari
Tiziana Di Salvo, Andrea Sanna, Fabrizio Fiore
On behalf of the HERMES and GrailQuest Collaborations



Please, visit our website:
http://hermes.dsf.unica.it

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

- Multi-messenger astronomy (EM counterparts of GW events)
- Is physical space(time) granular or continuous? (Zeno's paradoxes, existence of a "fundamental (minimal) length" in some string theories, atoms of space, particles vs. fields, …)

The Multi−Messenger Astronomy Paradox

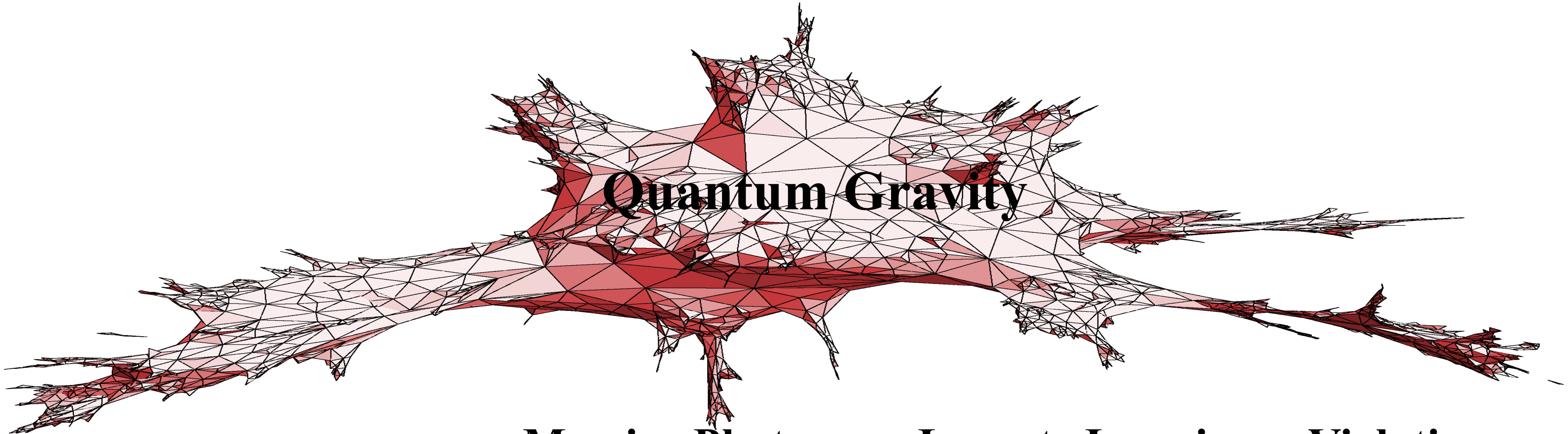
One of he most thrilling research field in Science:
the whole field based on ONE discovery: GRB 170817A - GW170817 connection

S1: within 2025 LIGO − Virgo − KAGRA GW antennas will provide:
detectability of NS−NS mergers events like GW170817 within ≅ 200 Mpc
localization within:
≅ 100 square deg (LIGO − Virgo)
≅ 10 square deg (LIGO − Virgo − KAGRA)

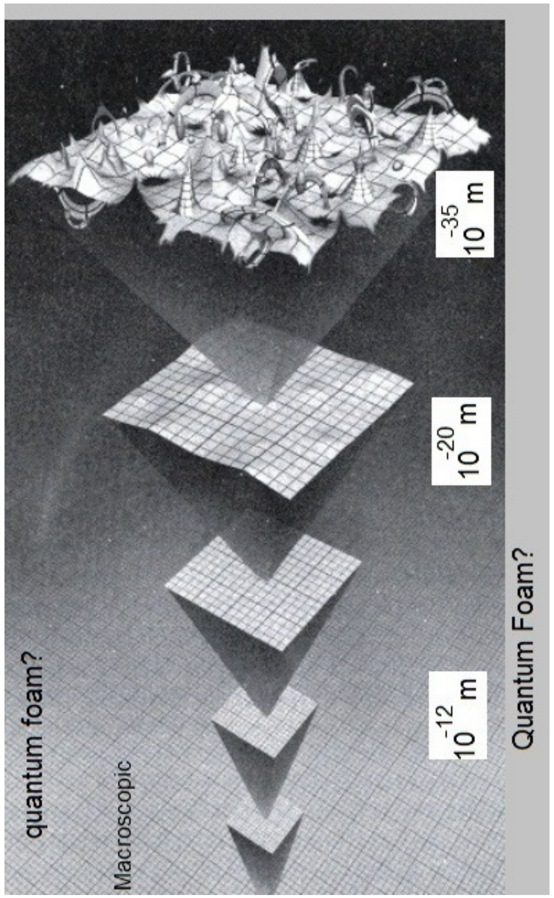
GBM would not have been able to detect an event like GRB 170817A but 60% fainter, which means roughly:
S2: Kilonova events seen at angles ≥ 25 degrees undetectable by GBM
for D ≥ 1.4 × D(GRB 170817A) ≅ 60 Mpc

S1 + S2 ➔ 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!



Quantum Gravity



Massive Photons or Lorentz Invariance Violation

The Fundamental-Length Hypotheses (Mead 1964, 1966)
see also Yoneya (1987, 1989, 1997) in String Theory:

$$\Delta r \geq (G\hbar/c^3)^{1/2}$$

LIV since no Lorentz contraction possible

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)

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

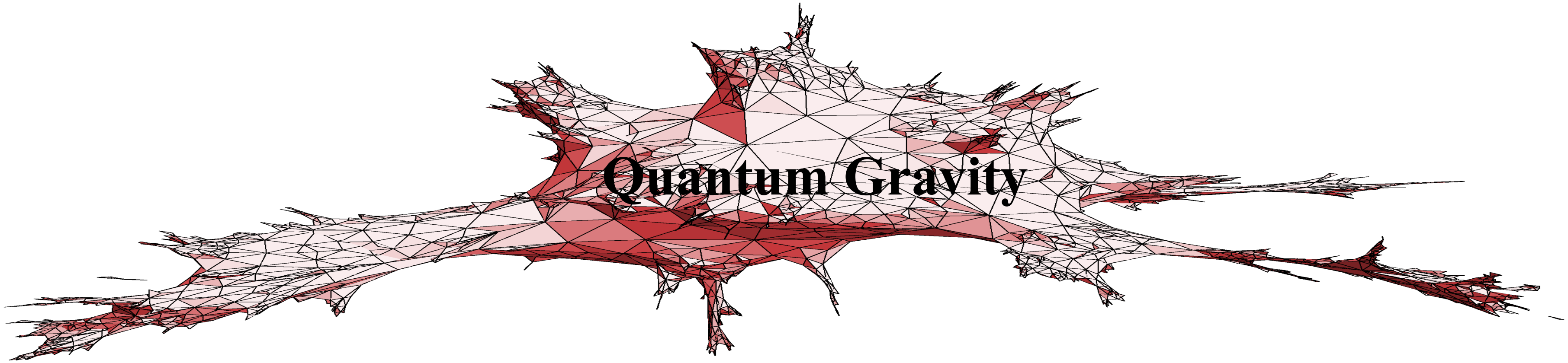
$m_{PLANCK} = (hc/2\pi G)^{½} = 21.8\ 10^{-6}$ g

Implications for travel time of photons:

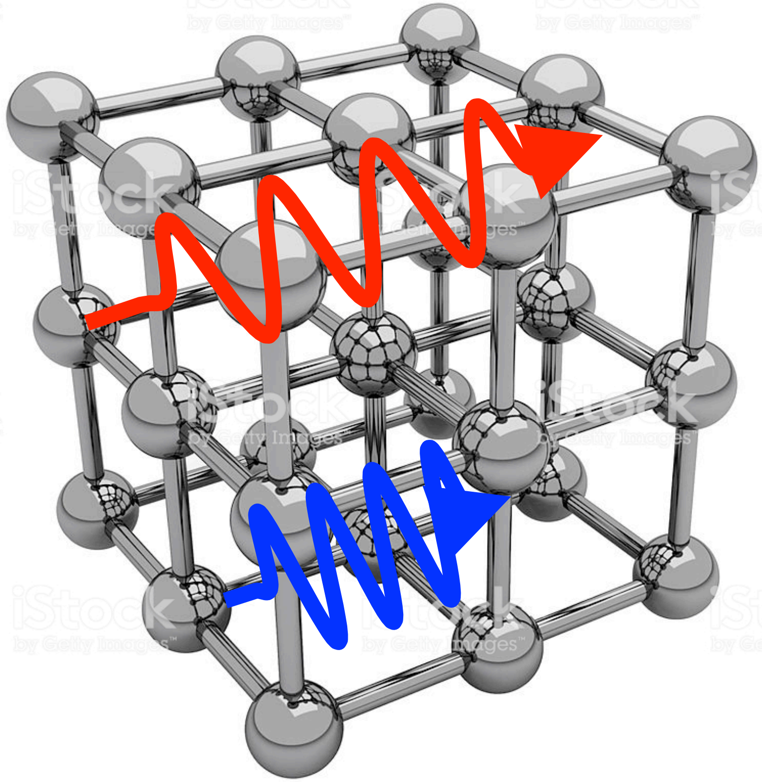
$$\mathbf{\Delta t_{MP/LIV} = \xi\, (D_{TRAV}/c)\, [\Delta E_{phot}/(M_{QG}\, c^2)]^n}$$

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

Quantum Gravity

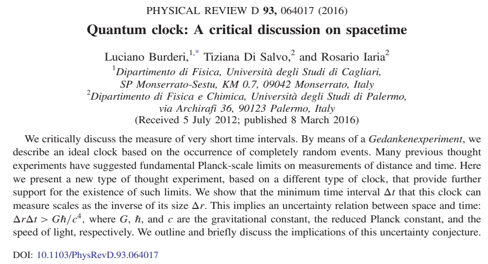


Lorentz Invariance Violation



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

No Lorentz Invariance Violation



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

Quantum clock: A critical discussion on spacetime

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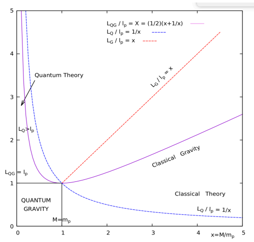
(Received 5 July 2012; published 8 March 2016)

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

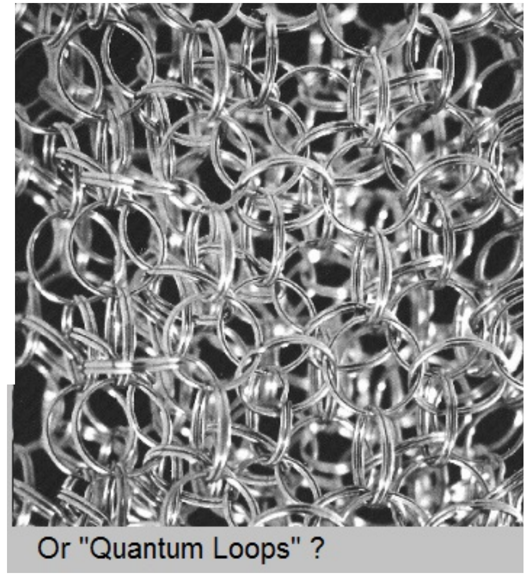
Burderi, Di Salvo, Iaria (2016)



Sanchez, 2018

The Space−Time Uncertainty Relation

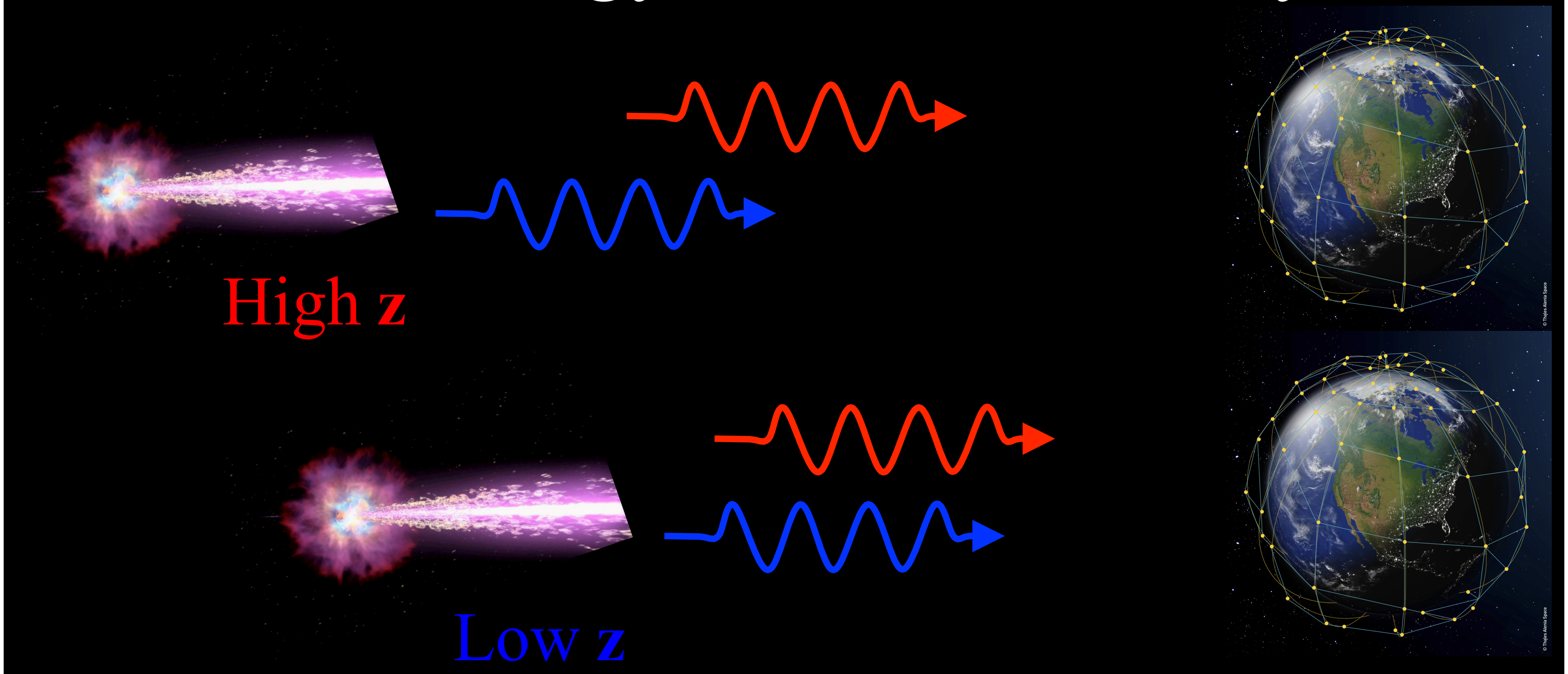
$\Delta r\, \Delta t > G\hbar/c^4$



Loop Quantum Gravity (Rovelli)

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

The energy & redshift delay



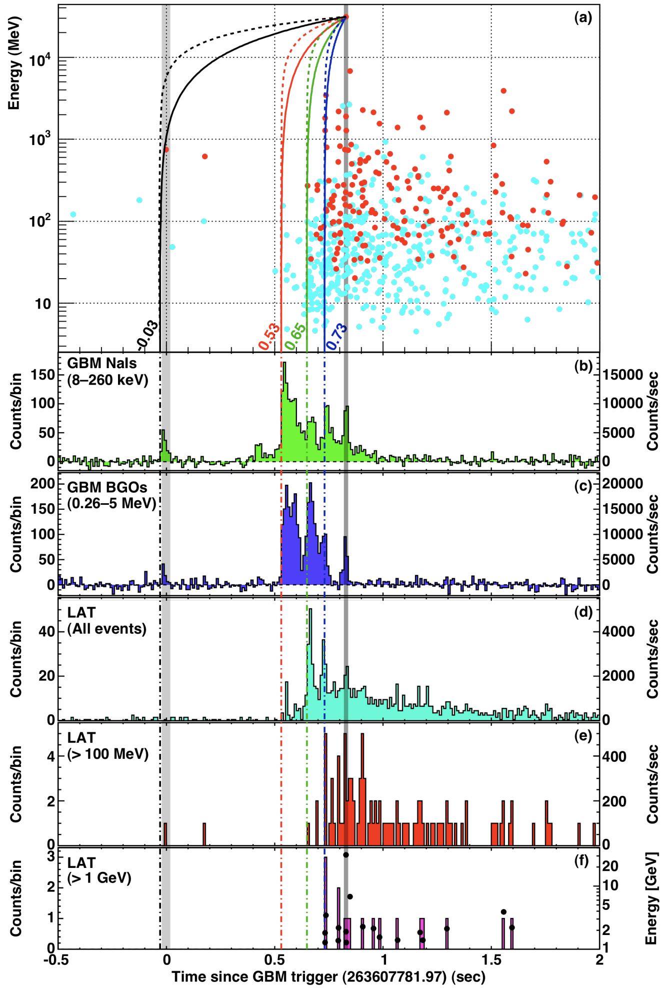
Time lags caused by Quantum Gravity effects:

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

Time lags caused by prompt emission mechanism:

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

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
$\Delta t_{31\mathrm{Gev}} \leq 859$ 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:
$M_{QG} \geq 0.595\ m_{PLANCK}$ ($\Delta t_{31\mathrm{Gev}} \leq 859 + 30$ 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 $t_{\mathrm{START\ GRB}} = -30$ 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

GRB & Lorentz Invariance Violation (LIV) with Fermi

arXiv:1807.00189v1 [astro-ph.HE] 30 Jun 2018

Robust Constraint on Lorentz Violation Using *Fermi*-LAT Gamma-Ray Burst Data

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Abstract

Models of quantum gravity suggest that the vacuum should be regarded as a medium with quantum structure that may have non-trivial effects on photon propagation, including the violation of Lorentz invariance. *Fermi* Large Area Telescope (LAT) observations of gamma-ray bursts (GRBs) are sensitive probes of Lorentz invariance, via studies of energy-dependent timing shifts in their rapidly-varying photon emissions. In this paper we analyze the *Fermi*-LAT measurements of high-energy gamma rays from GRBs with known redshifts, allowing for the possibility of energy-dependent variations in emission times at the sources as well as a possible non-trivial refractive index *in vacuo* for photons. We use statistical estimators based on the irregularity, kurtosis and skewness of bursts that are relatively bright in the 100 MeV to multi-GeV energy band to constrain possible dispersion effects during propagation. We find that the energy scale characterizing a linear energy dependence of the refractive index should exceed a few $\times 10^{17}$ GeV, and we estimate the sensitivity attainable with additional future sources to be detected by *Fermi*-LAT.

$$M_{QG} = m_{PLANCK}/\zeta$$

$$\zeta \geq 22\ (14 \div 50)$$

Conclusions:

index for photons. Depending on the method of consolidation of the results for individual sources, we find that the energy scale M_1 characterizing a linear energy dependence of the refractive index should exceed either 8.4×10^{17} GeV or 2.4×10^{17} GeV. We have also made

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):

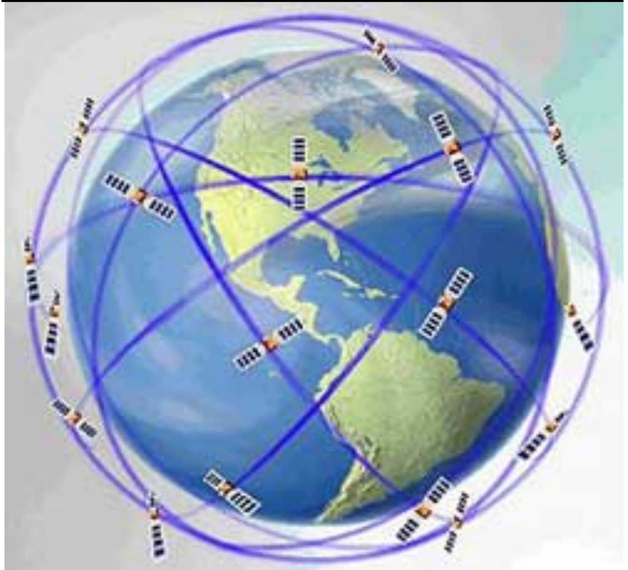
- **GRBs**
- **GW events**
- high-energy counterparts of **Fast Radio Bursts**
- flares from **Magnetars**
- fine GRB temporal structure to perform the
  first dedicated experiment in Quantum Gravity

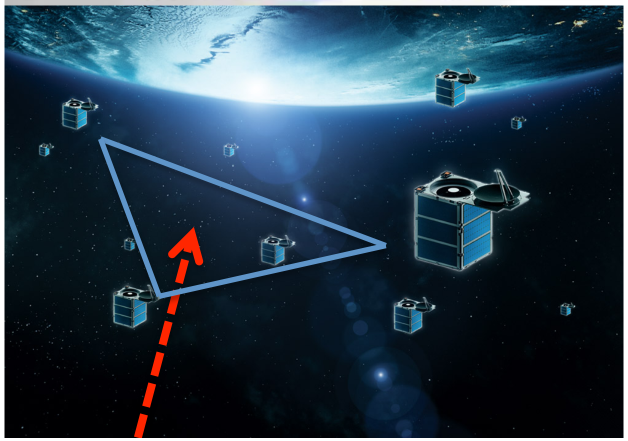
How:
temporal triangulation of signals detected by a **swarm of LEO nano/micro/small satellites** equipped with:

- 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 (variable) signal over 3 (or more) spatially separate detectors

position of the source in the sky:
α, δ (2 parameters, $N_{PAR} = 2$)

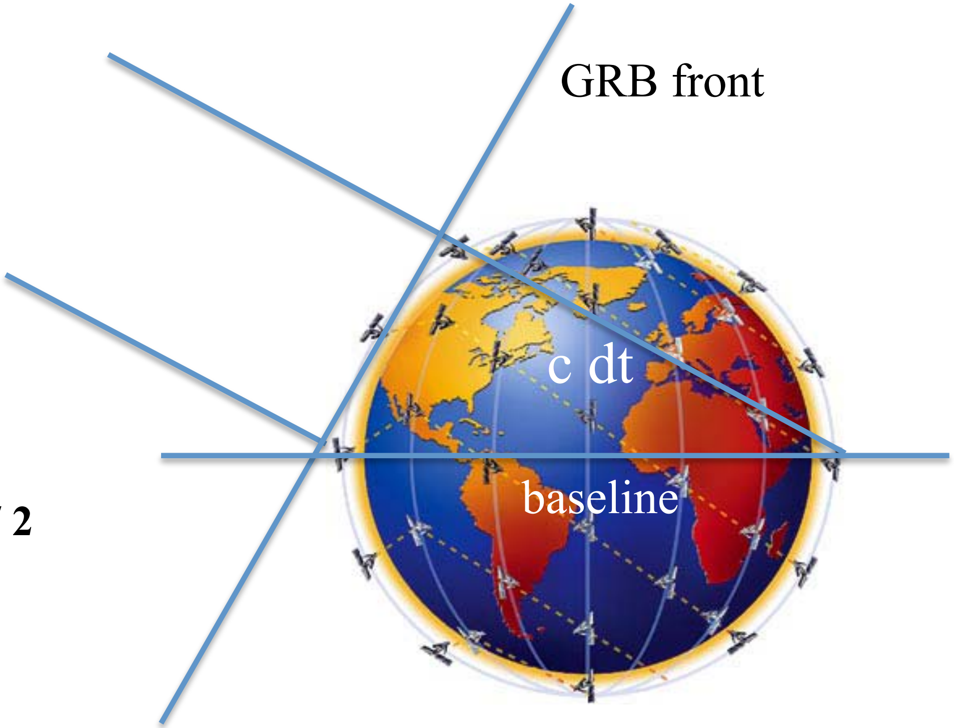
$i = 1, \ldots, N_{SATELLITES}$
$j = 1, \ldots, N_{SATELLITES}$

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

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

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

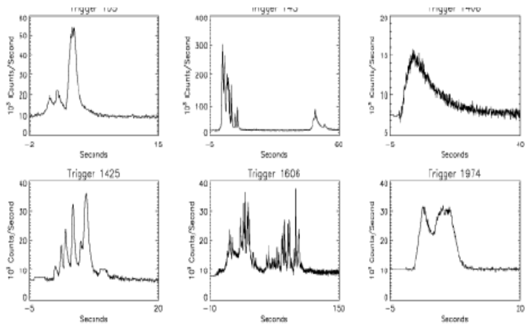
Number of independent DEL_{ij}:
$N_{IND} = N_{SATELLITES} - 1$

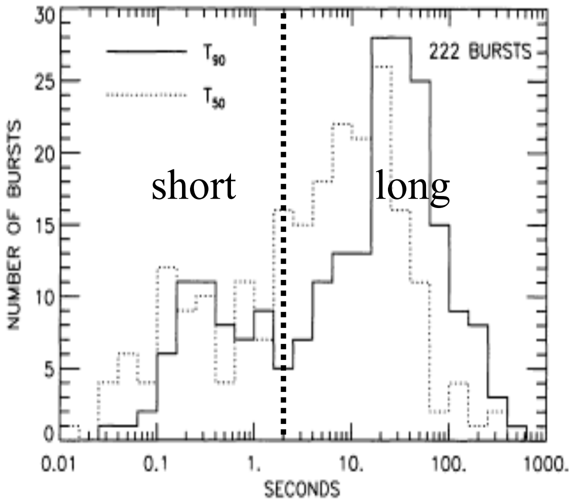


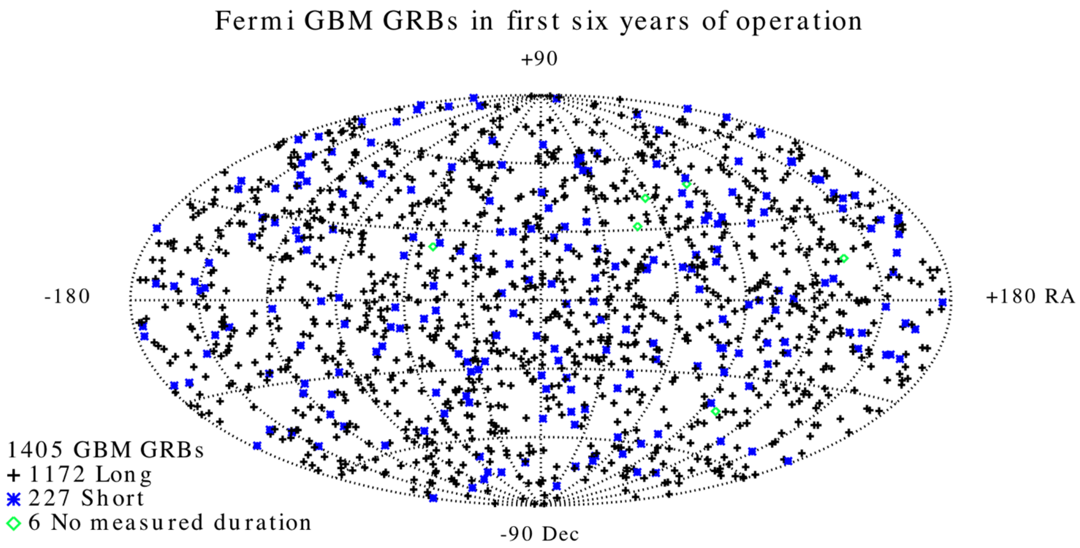
Accuracy in determining α and δ with $N_{SATELLITES}$:
$\sigma_\alpha \approx \sigma_\delta = c\, \sigma_{ToA}/\langle baseline\rangle \times (N_{IND} - N_{PAR} + 1)^{-1/2}$

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







The Gamma-Ray Burst phenomenon

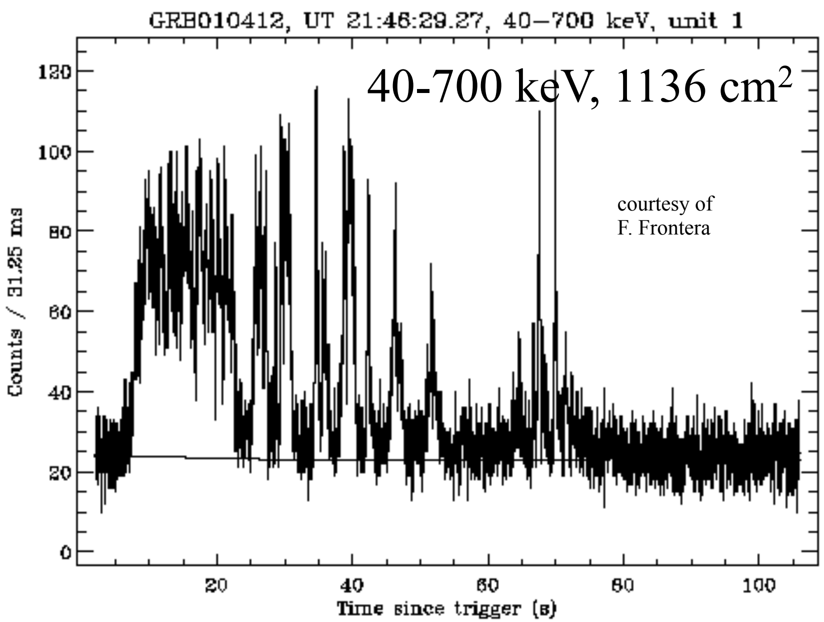
Millisecond variability (minimum variability time-scale, MacLachlan et al. 2013)

Short: 3 msec (wavelet techniques)

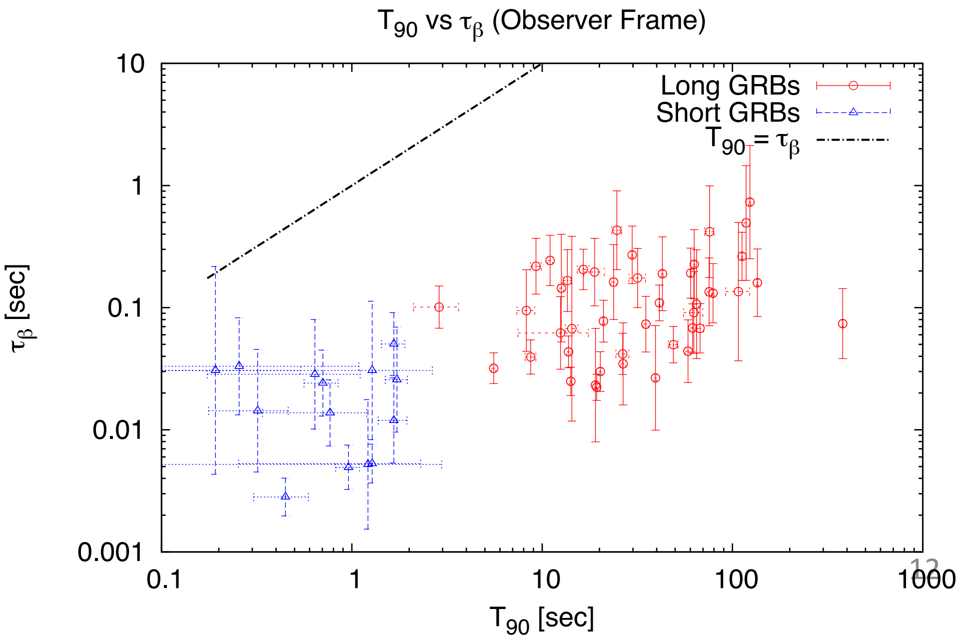
Long: 10 msec (wavelet techniques)

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

BeppoSAX GRBM data



Fermi GBM (8 keV - 40 MeV)



Number of GRB and Fluxes

Long & Short GRBs:

Duration: 20 ÷ 0.2 sec,

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

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

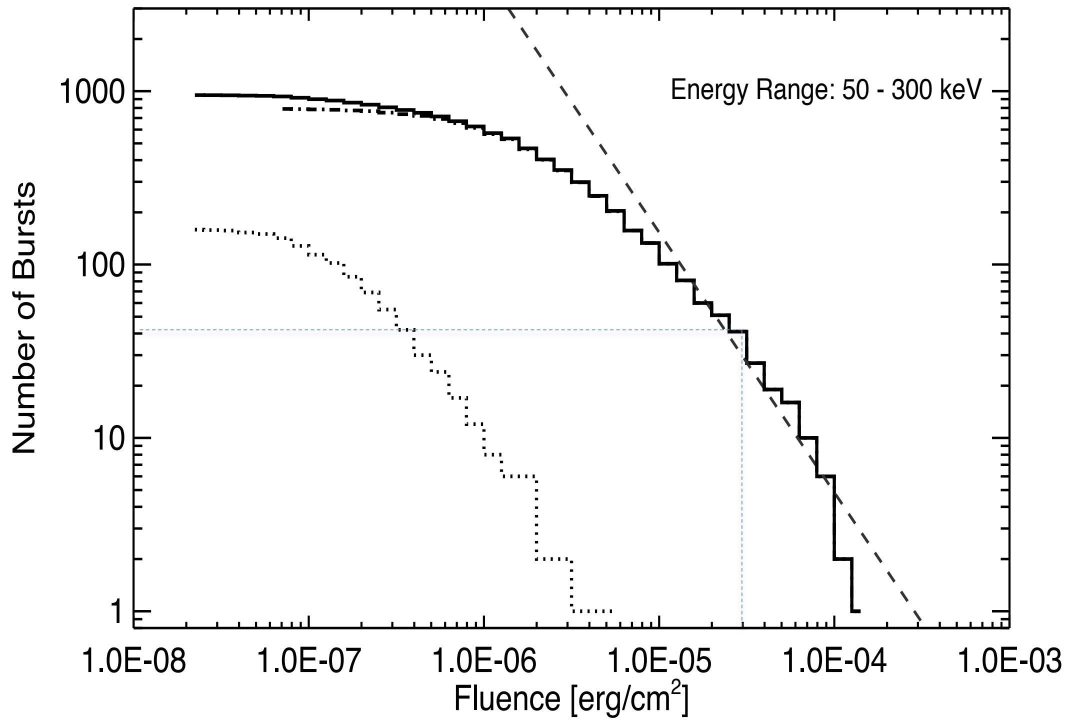
Fluence: 20 x 8 x 122 keV/cm^2 = 3 x 10^{-5} ÷ 3 x 10^{-7} erg/cm^2

Fermi GBM - 4-years data

≈ 30÷40 long & short GRB

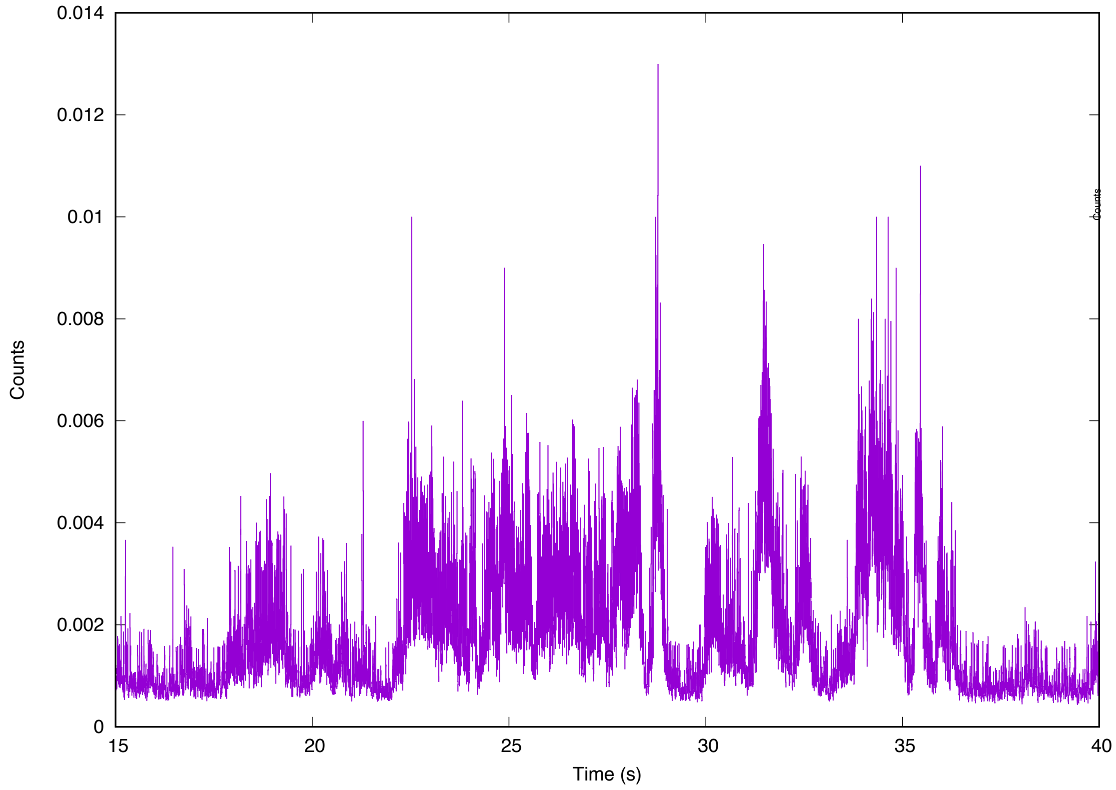
per year with

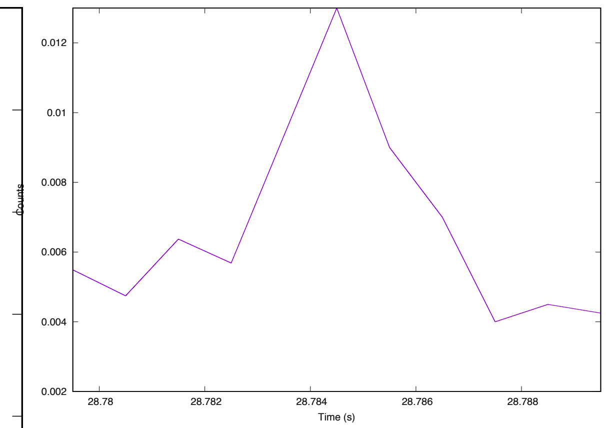
count rate > 8 c/s



Delays from cross-correlation analysis (monte-carlo simulations of a true long GRB)

Template (1μs resolution) of a long GRB (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)

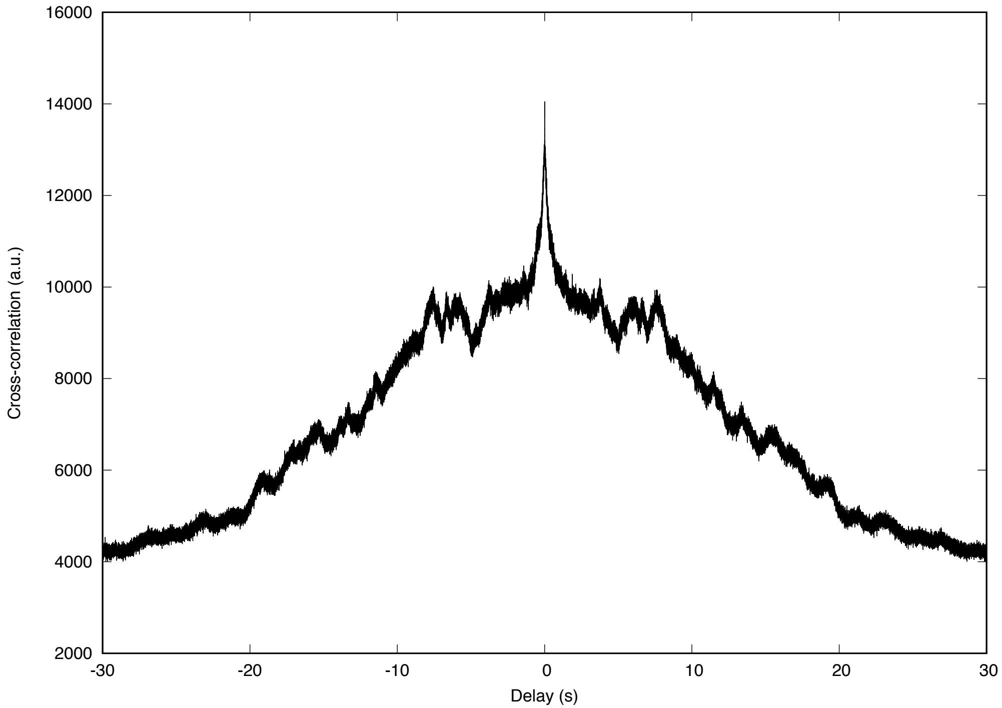


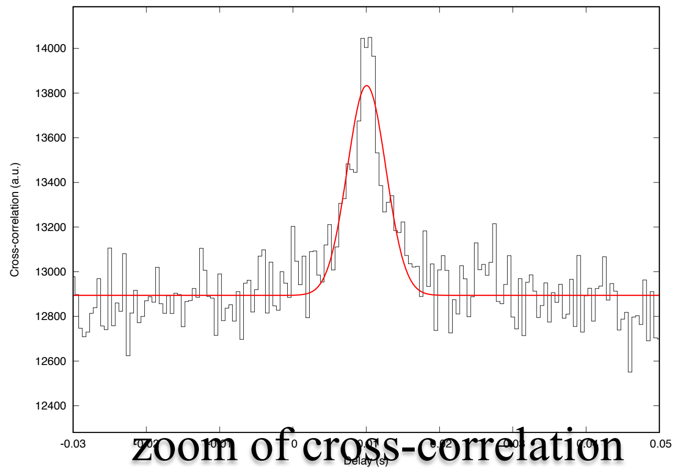


zoom of 10 ms of template centered at the main peak (≈ 5 ms width)

Delays from cross-correlation analysis (monte-carlo simulations of a true long GRB)

Cross-correlation (1μs resolution) of a long GRB (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;
with 56 cm^2 area GAGG detector 50−300 keV band
(Long and Short GRB with millisecond time variability, 40% of bright)



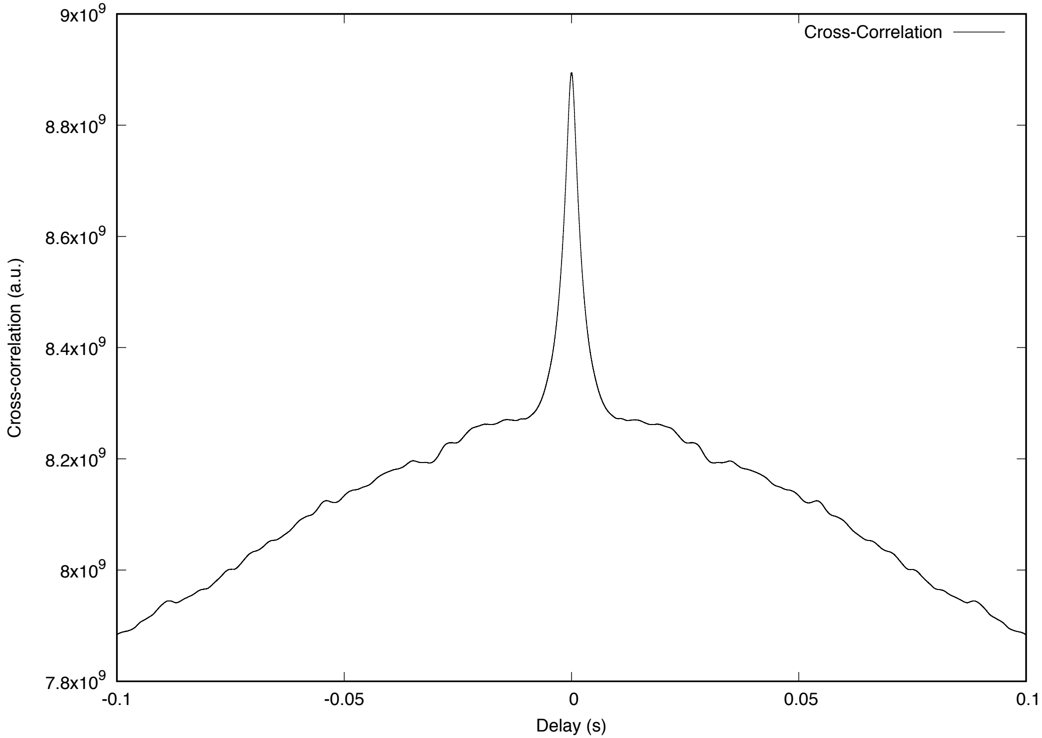


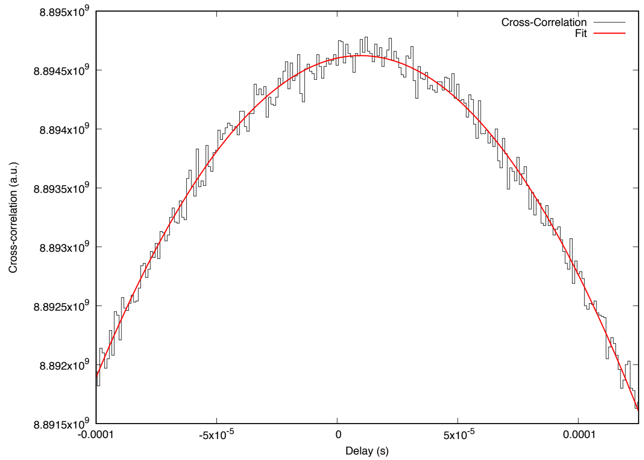
zoom of cross-correlation centered at the main peak (≈ 5 ms width)

True cross−correlation accuracy:
$\boldsymbol{\sigma_{CC} \approx 0.2}$ **msec** $\boldsymbol{\times (N/1.5\ 10^4)^{-0.5}}$

Delays from cross-correlation analysis (monte-carlo simulations of a true long GRB)

Cross-correlation (1μs resolution) of a long GRB (GRB130502327 observed by Fermi GBM) with 100 m^2 area GAGG detector 50−300 keV band
$\Delta t = 40$ 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)



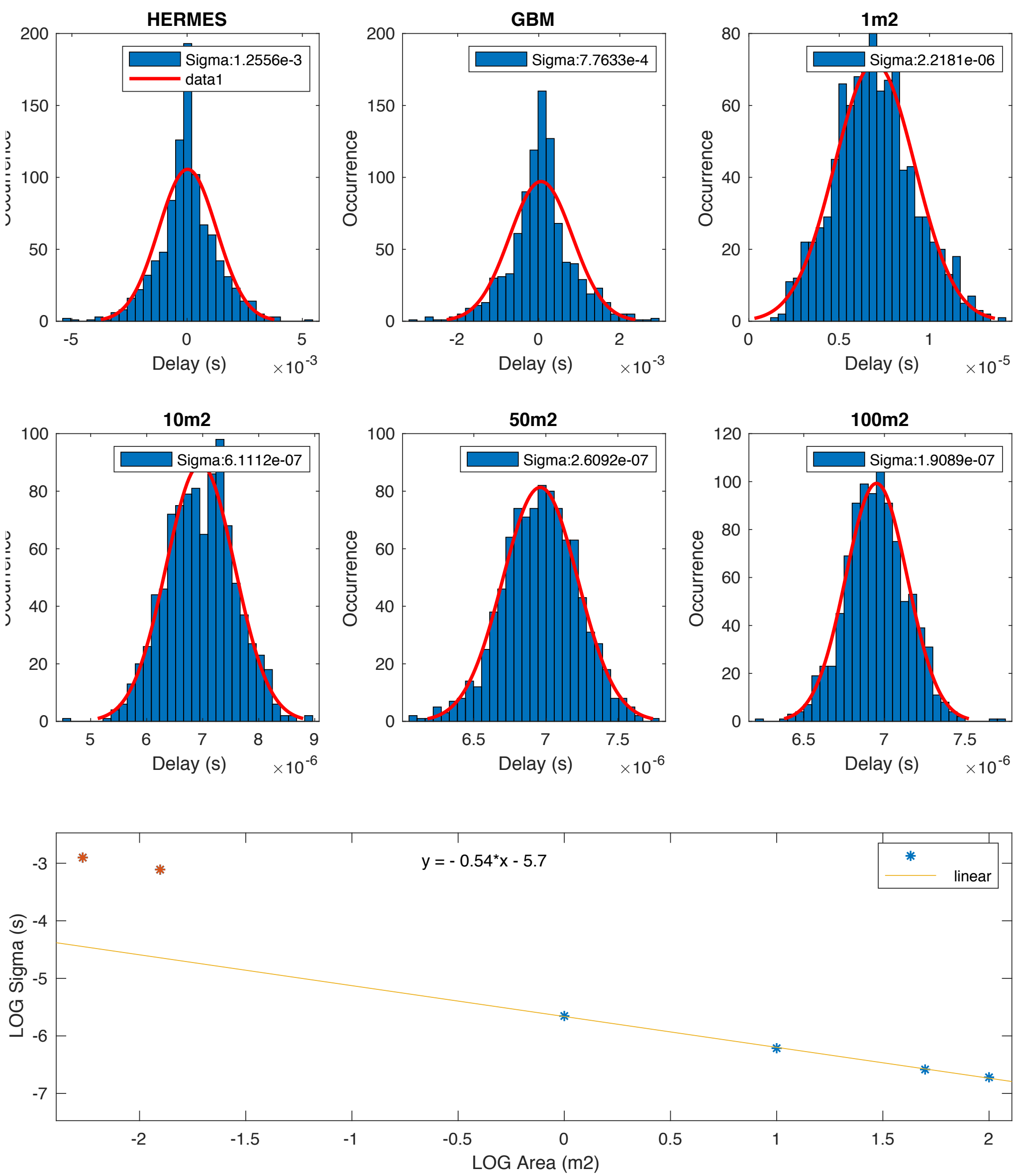


zoom of 10 ms of cross-correlation centered at the main peak (≈ 5 ms width)

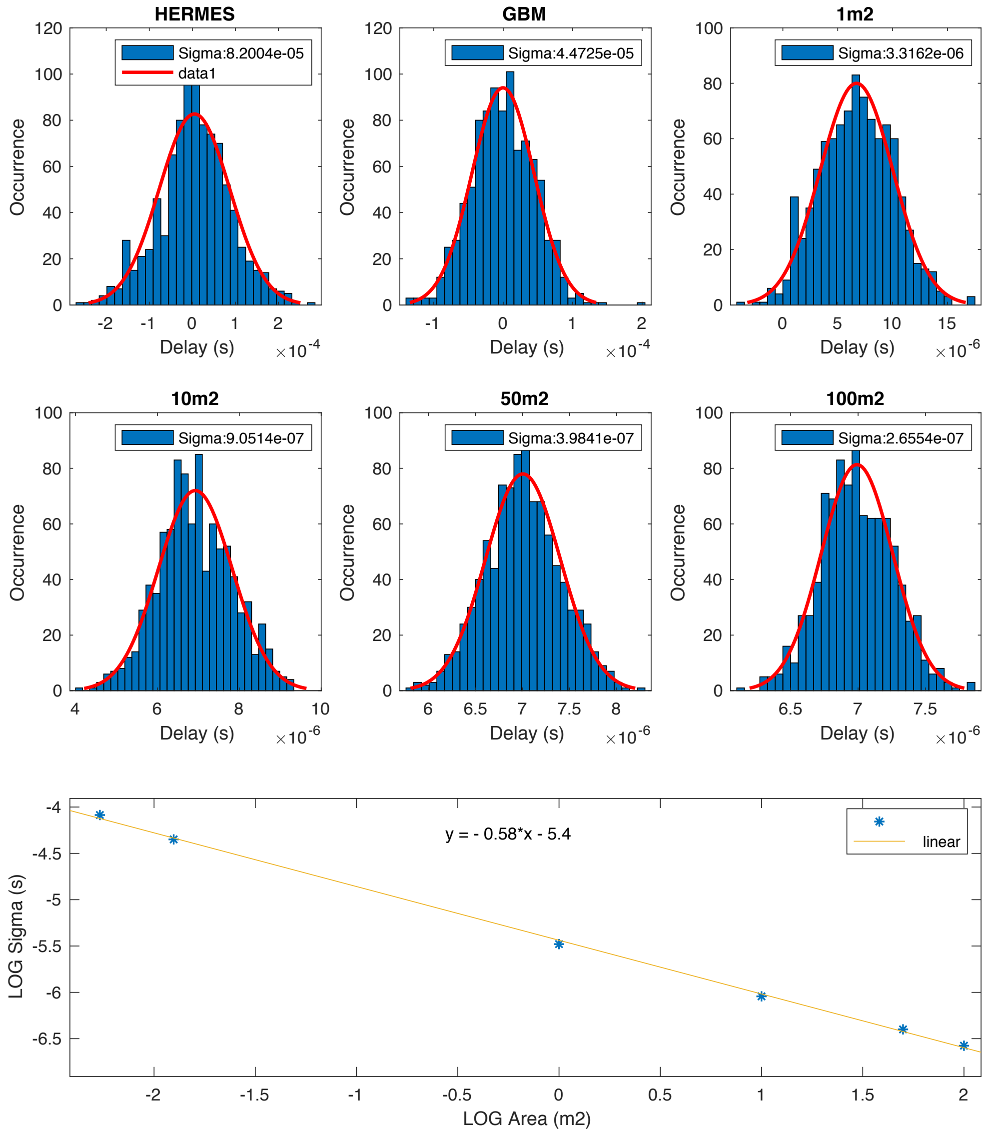
True cross−correlation accuracy:

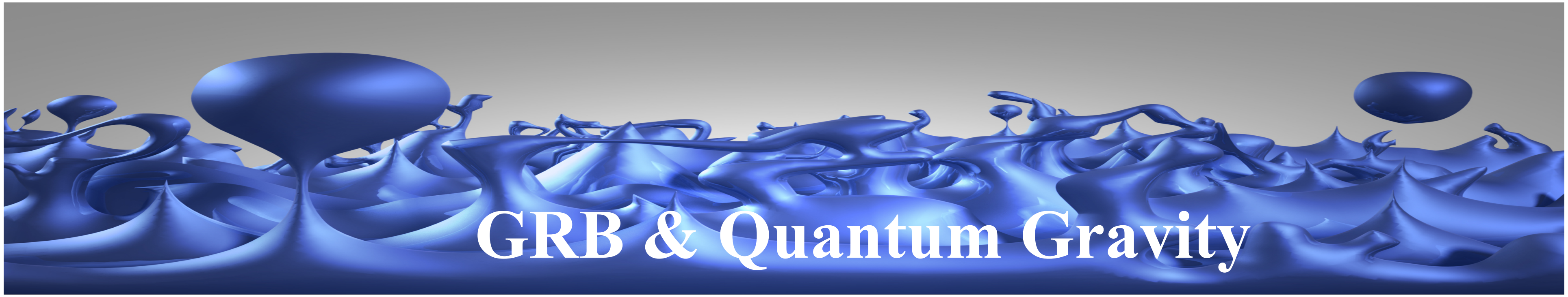
$$\boldsymbol{\sigma_{CC} \approx 0.46\ \mu\text{sec} \times (N/2.6\ 10^8)^{-0.5}}$$

Delays from cross-correlation analysis (monte-carlo simulations of a true short GRB)



Delays from cross-correlation analysis (monte-carlo simulations of a true long GRB)



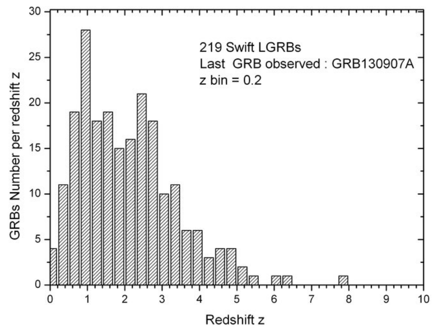


GRB & Quantum Gravity

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

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

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



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

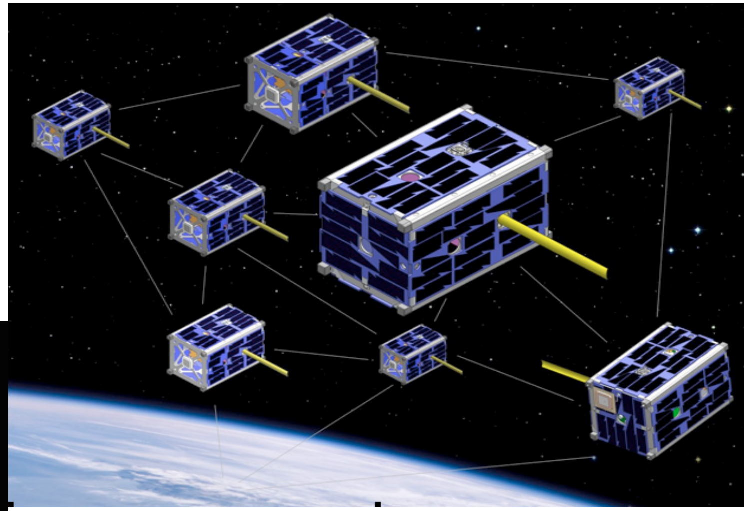
Long GRB – 8.00 (0.86 BCK) c/s (50 $\div$ 300 keV) – $\Delta t = 25$ s – A = 100 m^2

accuracy in cross–correlation from the relation: $E_{CC}(N) = 0.46\,\mu\mathrm{s}\sqrt{N/2.6\ 10^8}$

Energy band MeV	E_{AVE} MeV	N ($\beta=-2.5$) photons	$E_{CC}(N)$ μs	N ($\beta=-2.0$) photons	$E_{CC}(N)$ μs	ΔT_{LIV} ($\xi=1.0,\ \zeta=1.0$) 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

HERMES & *GrailQuest* mission concept: a swarm of nano/micro/small satellites

Tens/hundreds nano/micro satellites $_{2}$
each equipped with ~300÷10,000 cm^2 scintillators
(keV – MeV energy band)



HermeS

HERMES & *GrailQuest* experiment concept: temporal triangulation & increase the effective area

Perform temporal triangulation to derive positions of bright, transient, high-energy events

When a cross-correlation successful → add signal from different units
Total Area ~ 100 x (100-10,000 cm^2) ~ 1-100 m^2

→ First possibility to study GRB time structure on very short time scale (sub-μs ÷ ms) with excellent statistics

Determination of source position through delays

Accuracy in determining α and δ with $N_{SATELLITES}$:
$\sigma_\alpha \approx \sigma_\delta \approx c\ \sigma_{CC}/\langle baseline\rangle \times (N_{SATELLITES} - 3)^{-1/2}$

Accuracy in cross−correlation determination of delays:
$\sigma_{CC} \approx 0.5\ ms/\ (N_{PHOT}/1.5\ 10^4)^{-1/2}$
(valid for long and short GRB with millisecond time variability, 40% of bright)

maximum baseline = $2 \times (R_{EARTH} + H_{SATELLITE}) = 2 \times (6371 + 580)$ km

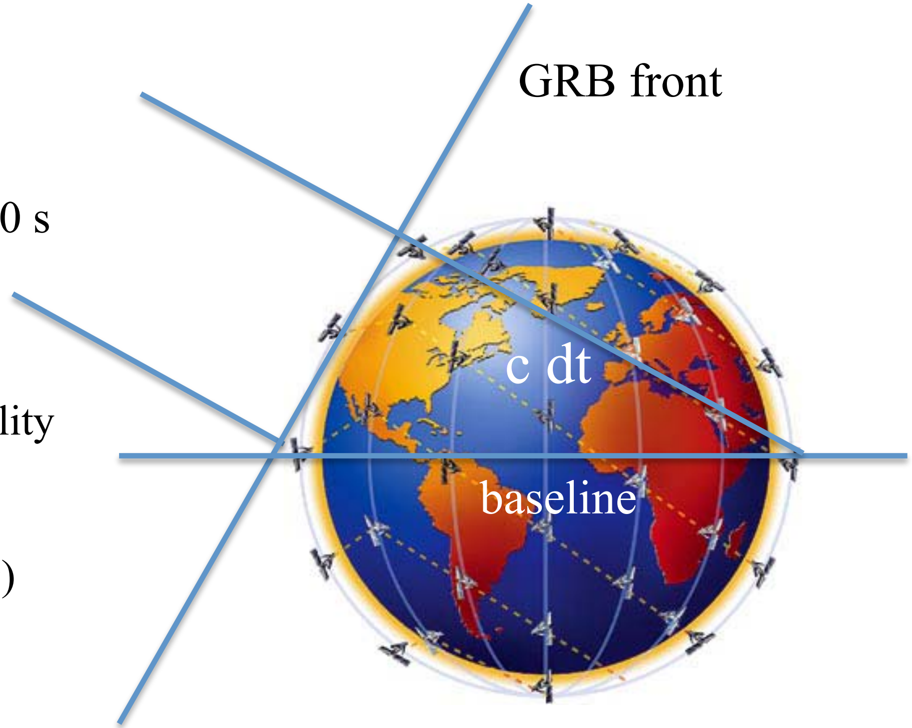
<baseline> = maximum baseline / 2

For:

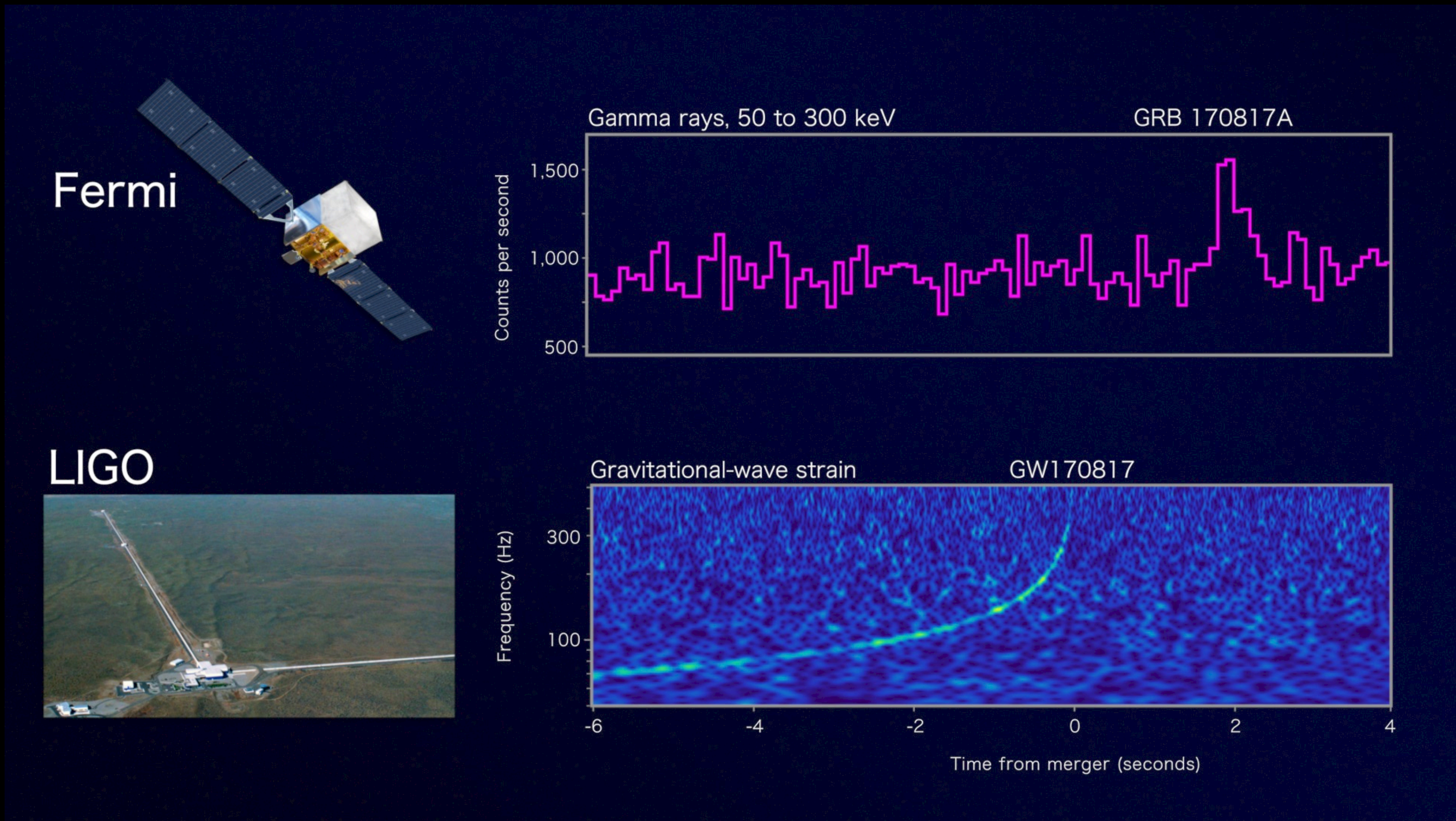
$A = 56\ cm^2$, $\varphi_{GRB} = 6.5\ phot/s/cm^2$, $\Delta t = 40$ s

N_{PHOT}(bright long GRB) ≈ 14500

Bright Long GRB with millisecond variability
$\sigma_\alpha \approx \sigma_\delta \approx$ few degree (3 satellites)
$\sigma_\alpha \approx \sigma_\delta \approx$ few arcmin (100 satellites, 1 m^2)
$\sigma_\alpha \approx \sigma_\delta \approx$ few arcsec (100 satellites, 100 m^2)



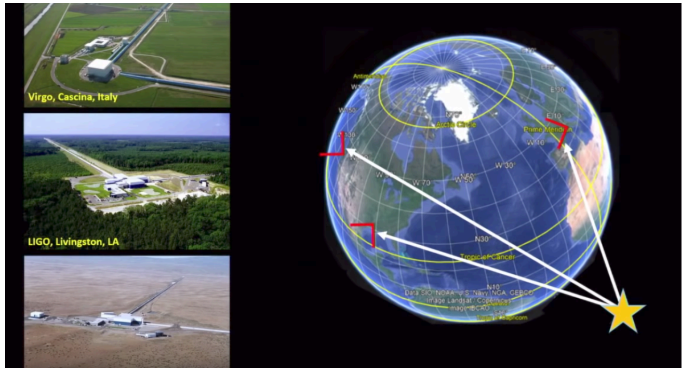
GW 170817 NS-NS coalescence: EM counterpart GRB170817



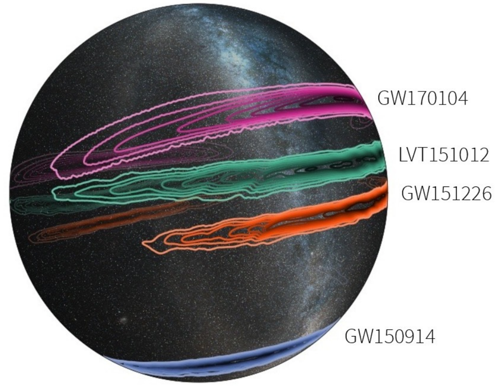
GW Triangulation & EM conterparts (Fermi GBM,INTEGRAL)

Large volumes to survey → too many candidates

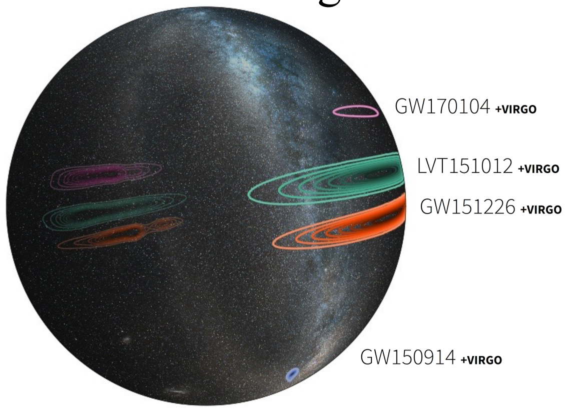
Successful strategy:
a) all sky continuous observations of HE transients
→ the probability of obsering an uncorrelated HE simultaneous event is negligible
b) improve the accuracy of source position
→ reduce the number of candidates

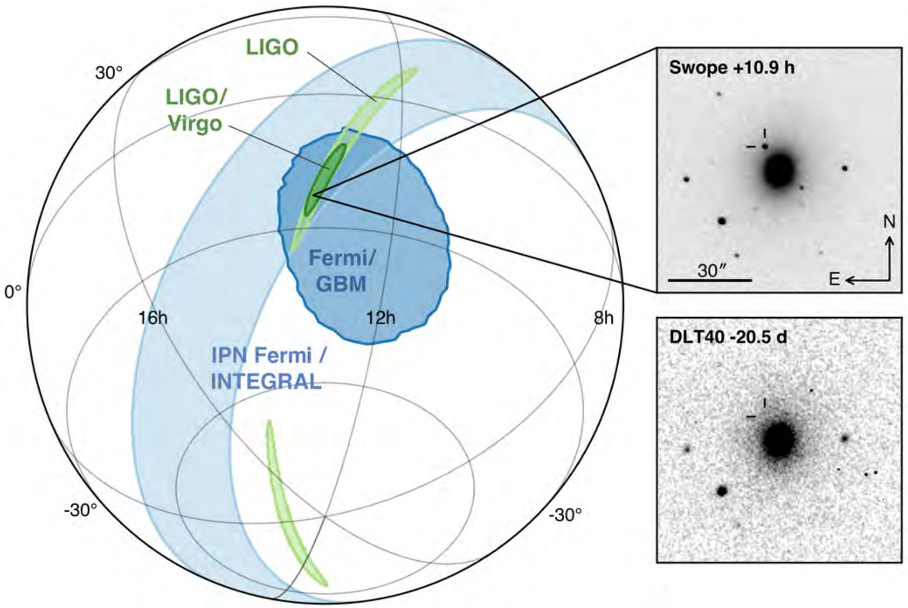


LIGO

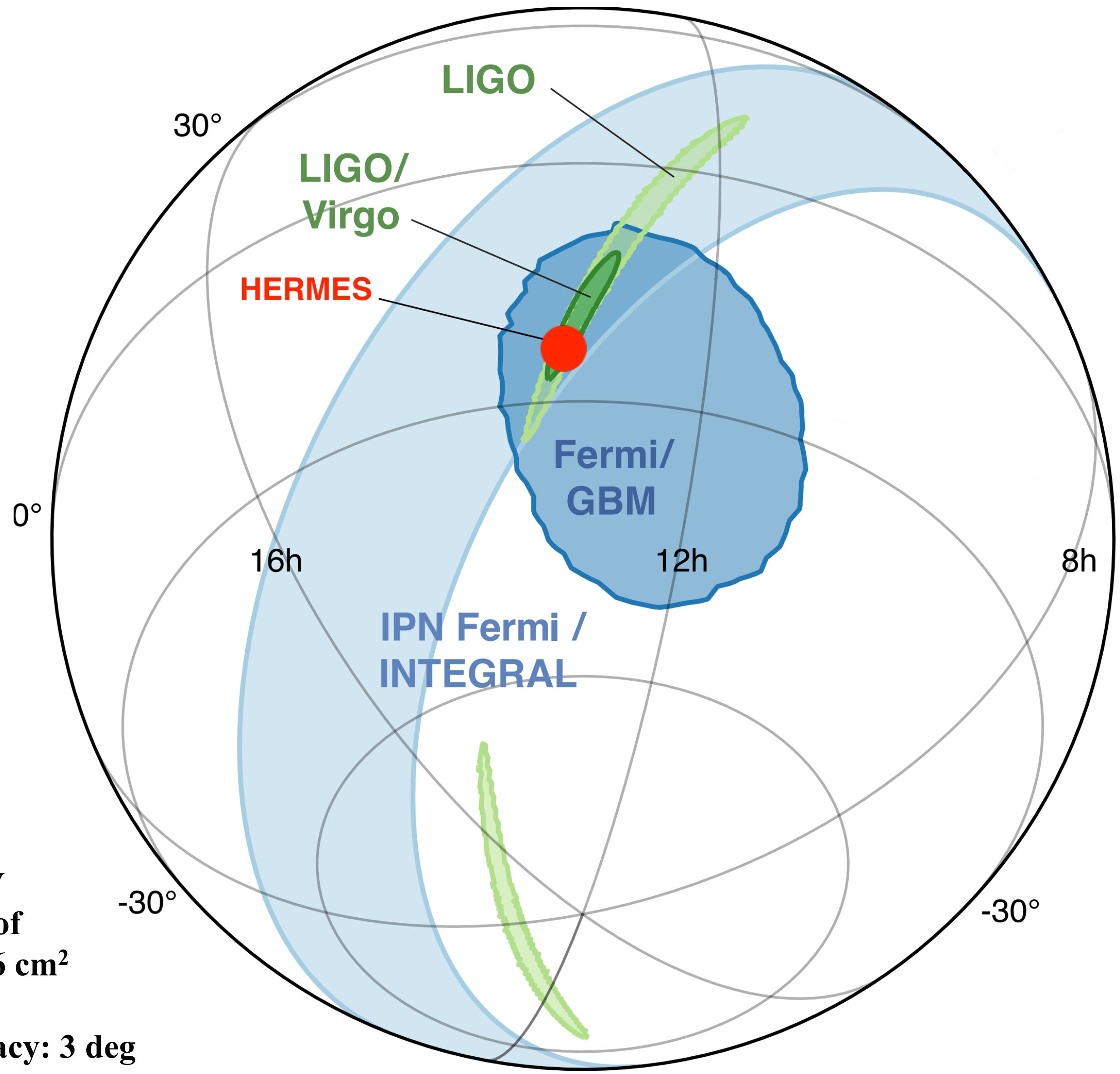


LIGO + Virgo





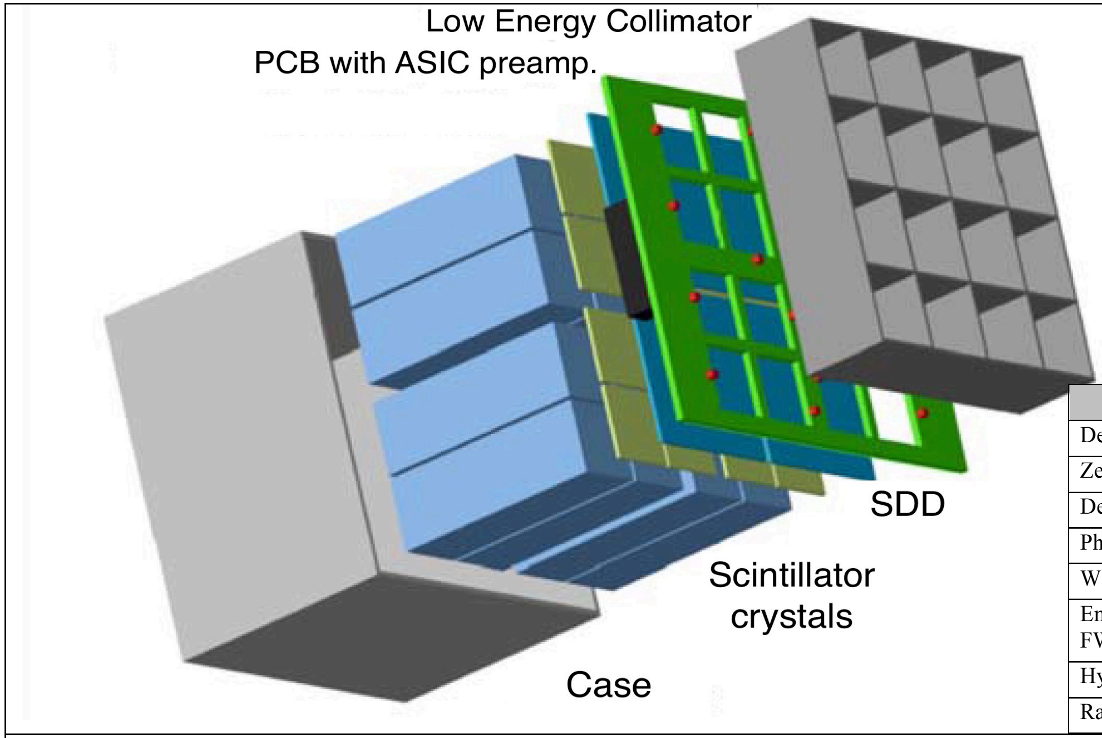
GW Triangulation & EM conterparts (Fermi GBM, INTEGRAL, HERMES Pathfinder)



band 50-300 keV
3 satellites each of
effective area: 56 cm^2
$\sigma_{CC} \approx 1$ ms
positional accuracy: 3 deg

HERMES Pathfinder Photon Detector Unit (PDU) and Modular Detector Unit (MDU = 4 PDU)

- Scintillator Crystal size: 2x1x1 cm
- Number of crystals in one PDU: 4
- Number of crystals in one MDU: 16
- Crystal type: GAGG (Gadolinium Aluminium Gallium Garnet)
- Photo detector: SDD (segmented: 4 SSD 1x1 cm)
- Energy range: 4 keV – few Mev with GAGG
- Energy resolution: ~ 15% at 30 keV
- Effective area: ~ 4 cm^2
- FOV: 2 steradians at low energies
- Temporal resolution: 0.3 μs (goal 0.1 μs)



GAGG characteristics	
Density (g/cm3)	6.63
Zeff	52
Decay time (nsec)	92f – 174s
Photons/keV	56
Wavelength peak (nm)	520
Energy resolution (662 keV FWHM) (%)	5–6
Hygroscopic	No
Radioactive	No

Figure 1 Schematic view of one HERMES modular detector unit (MDU), made by four PDUs.

HERMES 3U CubeSat

- 10×10×30 cm
- Gyroscope Stability on 3 axes
- Collimators ≈ 2 steradians

On board Systems:

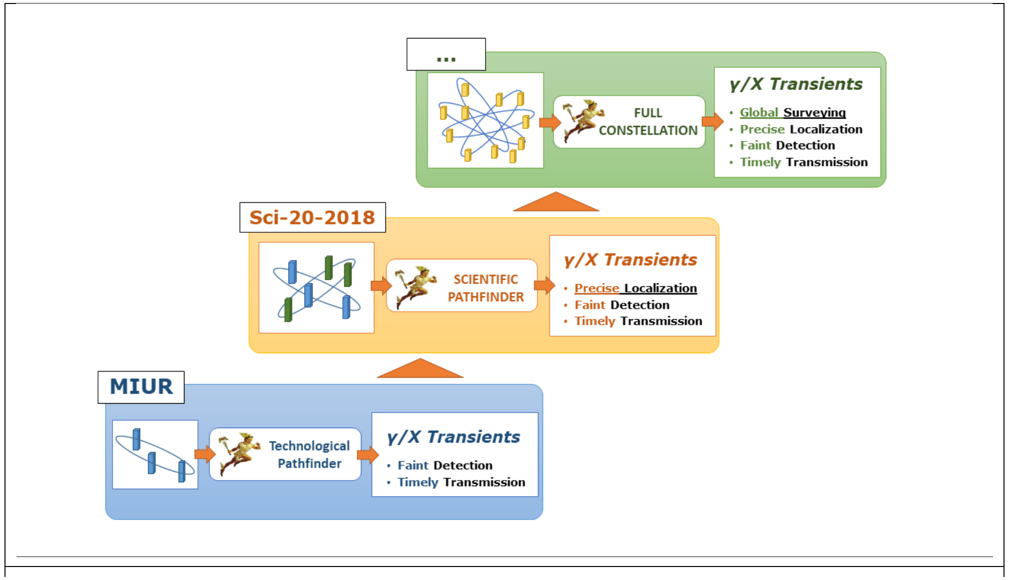
Data recording:

- 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

HERMES project development – incremental strategy



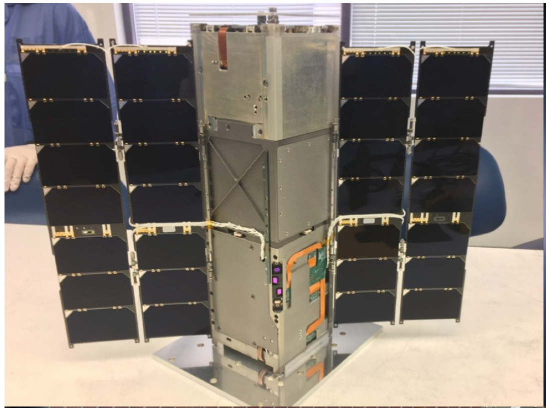
Funding status at 2018, July the 17th

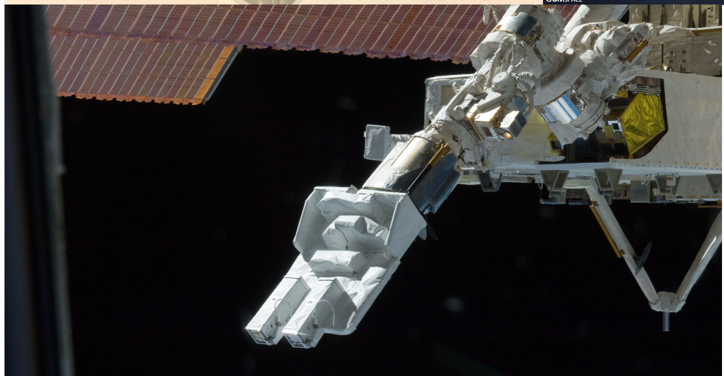
ASI (Italian Space Agency) – 23/12/2016:	€ 500,000
MIUR (Italian Ministry of University and Research) and ASI – 29/11/2017:	€ 1,650,915 (MIUR)
	€ 815,085 (ASI)
EU Horizon 2020 – Call: H2020-SPACE-2018-2020 – 17/07/2018:	€ 3,318,450
ASI (Italian Space Agency) – internal funding 05/02/2019	€ 1,900,000
Total Funding (at 14/02/2019):	**€ 8,184,450**

GrailQuest project development

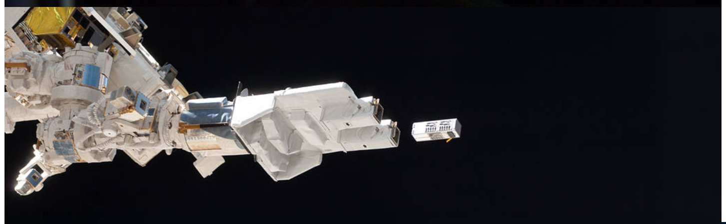
White paper submitted in response to the ESA Voyage 2050 Call (05/08/2019)
Network of nano/micro/small satellites in LEO with an overall effective area of 100 m^2

The HERMES & *GrailQuest* projects: performances of subsequent missions





JEM Small Satellites Orbital Deployer (JSSOD) of JAXA on ISS



Launch of Cubesat from JSODD

Startup OneWeb
640 nanosat in LEO
production:
15 nanosat/week

Starlink (Space X)
12,000 satellites by mid-2020

Pathfinder + Scientific:

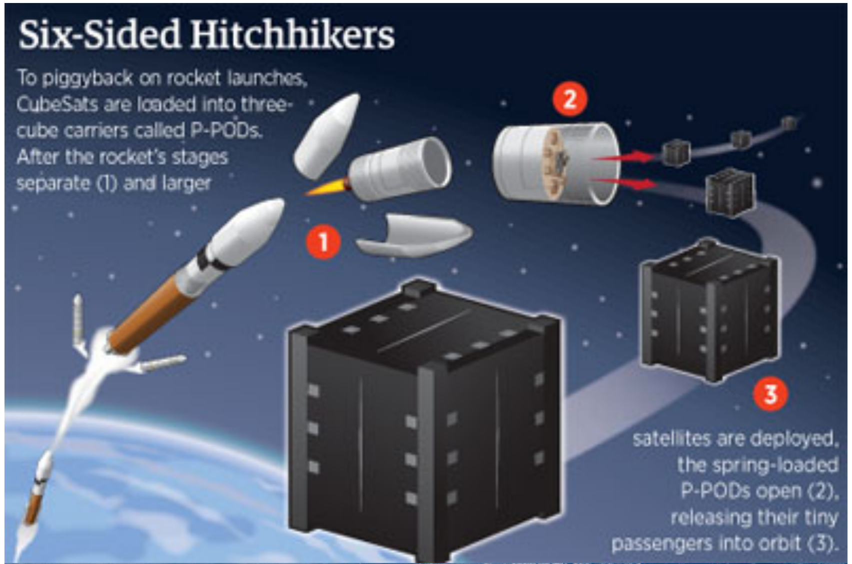
- 8/10 3U Cubesats
  piggyback of bigger satellites
  launched from ISS
- 1/2 detectors located on ISS
- ~ 10 arcminutes position
  of ~ 35 Short 250 Long GRB/year

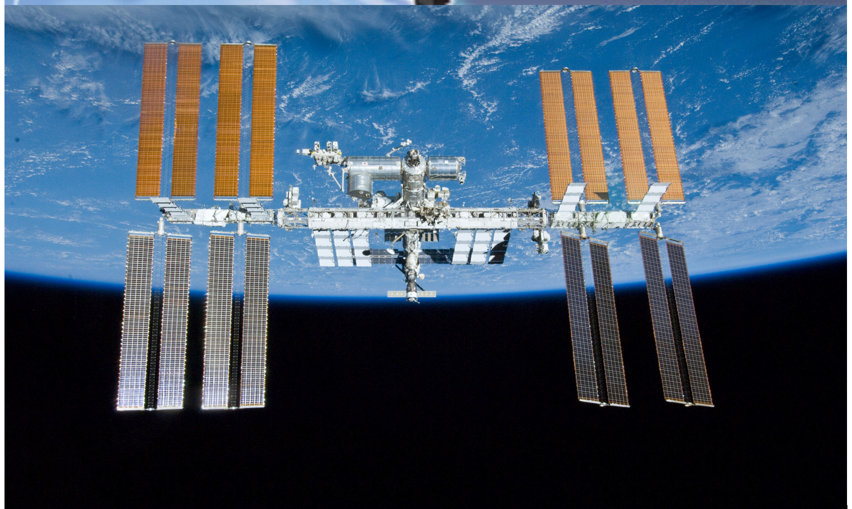
Full configuration:

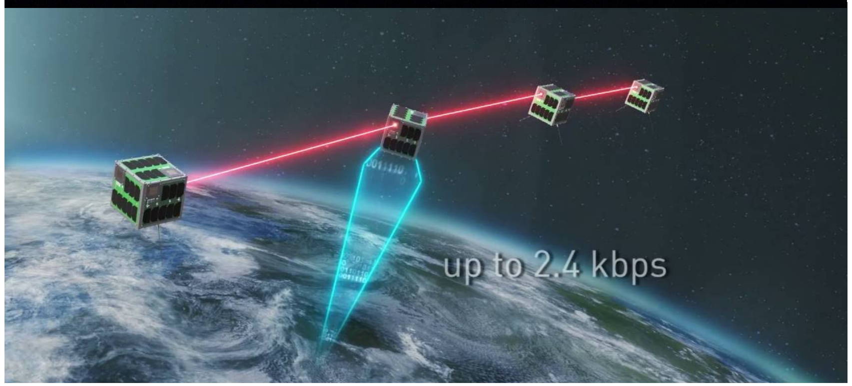
- ~50-100 3/12U Cubesats
- ~10 arcsec position
  of ~ 75 Short 500 Long GRB/year
- 1-3 m^2 collecting area

Future ***GrailQuest***:

- ~ humdreds÷thousands of detector
- From LEO to HEO, Moon and beyond
- arcsec position,
  best quantum space time tests







Why HERMES & *GrailQuest* now

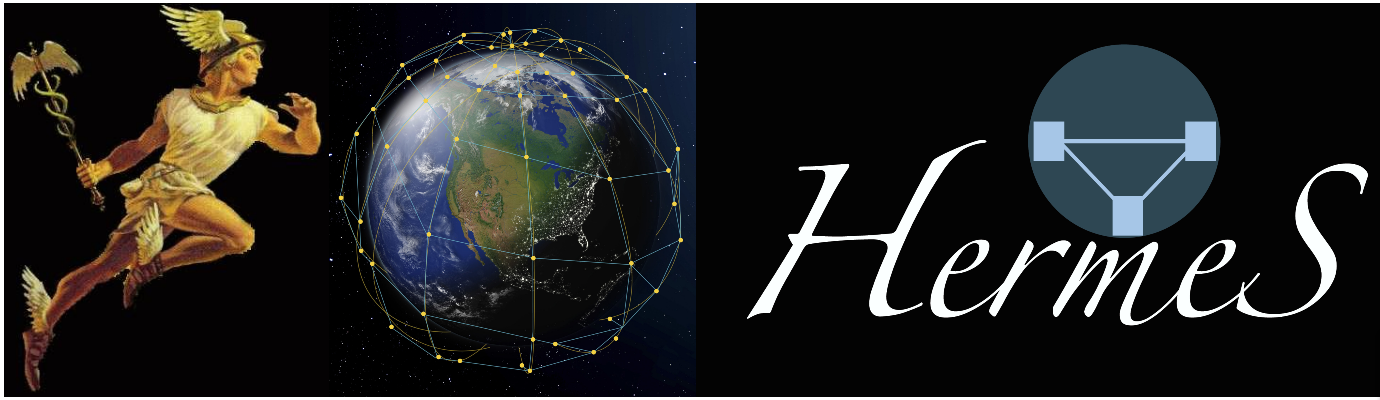
PROS:

- modularity (avoid single point failures, state-of-the-art hardware)
- limited cost (piggyback of bigger satellites, boarded on ISS with cargo refurnishment, off the shelf cheap hardware + in house components)
- quick development (< 5 years to fly first satellites)

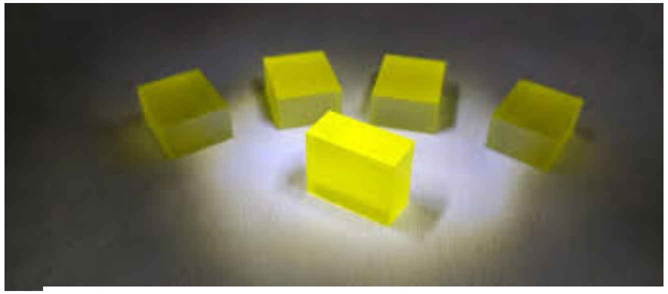
Breakthrough scientific case:

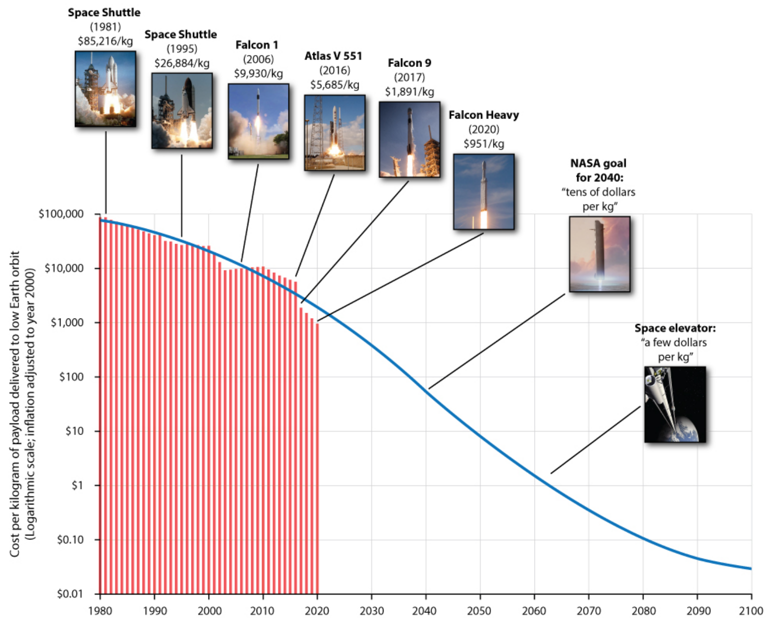
- All-Sky Monitor in HE (keV-MeV)
- EM counterparts of GW events
- Study of GRB variability on unprecedented short temporal scale (sub-μs): physics of the inner engine
- First dedicated experiment of Quantum Gravity

HermeS



Costs of 100 m^2 observatory





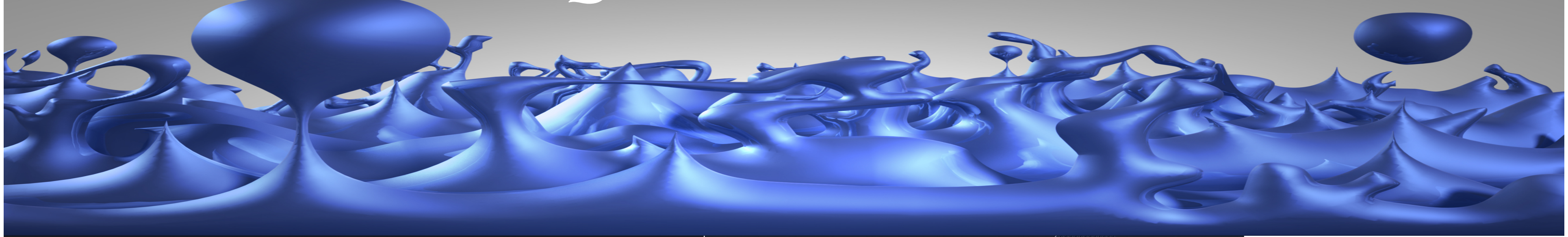
Costs for 100 m^2 detector
GAGG density: 6.6 g/cm^3
cost of 1x1x2 GAGG crystal: 50 $
weight of electronics and control equipment for 64 GAGG crystals detector: 0.5/1.0 kg
weight of spacecraft for 64 GAGG crystals detector (including gyroscope, etc): 3.0/5.0 kg
cost per kg of payload delivered in LEO (Falcon Heavy, 2020): 1000 $

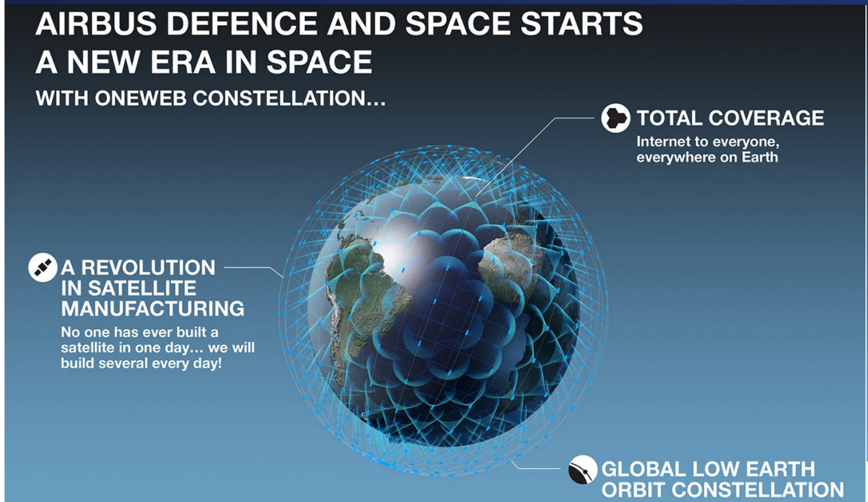
cost of 10^6 1x1x2 GAGG crystals: 50 M$

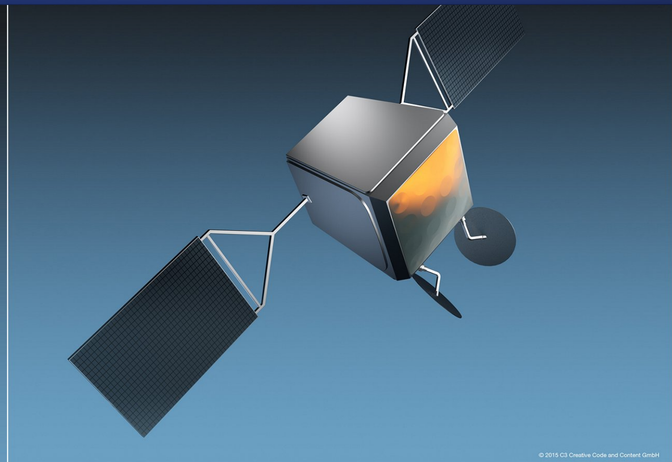
cost of delivering 10^6 1x1x2 GAGG detectors in LEO (Falcon Heavy, 2020): 6.6 M$ + 5/10 M$ (payload) + 30/50 M$ (spacecraft) = 42/67 M$

Total gross cost: (few) 100 M$ (medium mission)

GrailQuest Next Generation – OneWeb



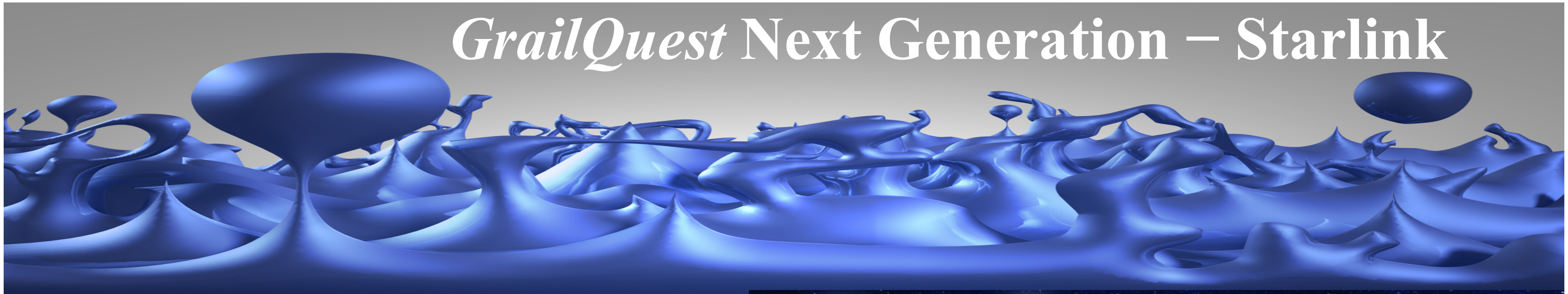




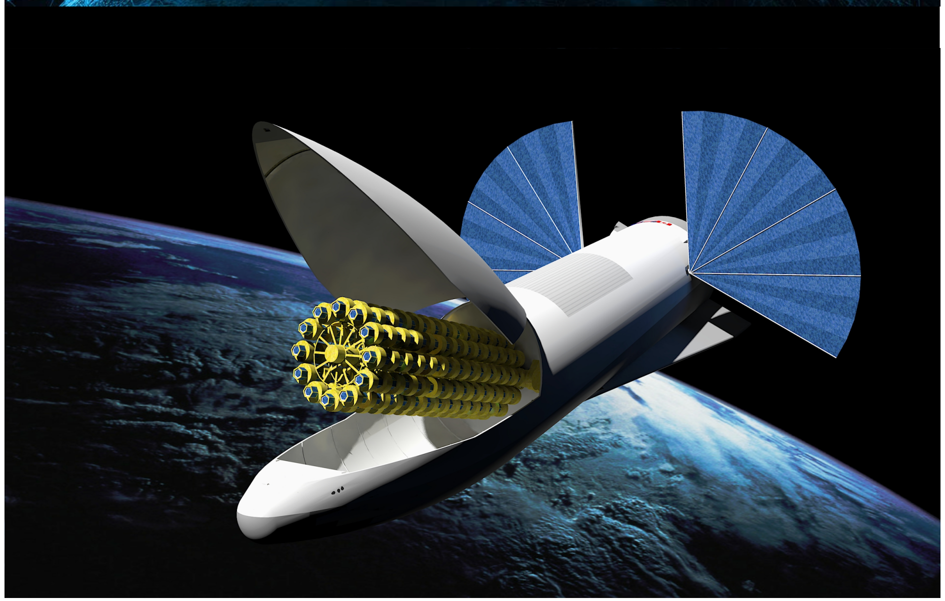
OneWeb Constellation 640 sats
Virgin Galactic (Richard Branson) – Arianespace – Airbus Defence and Space

- 640 @ 1200 km
- 150 kg satellites (mass production)
- **board a 100 cm^2 effective area GAGG crystal – SDD photodetector (position sensitive + coded mask?) module on each satellite**
- **6.4 m^2 effective area All Sky Monitor**

GrailQuest Next Generation – Starlink

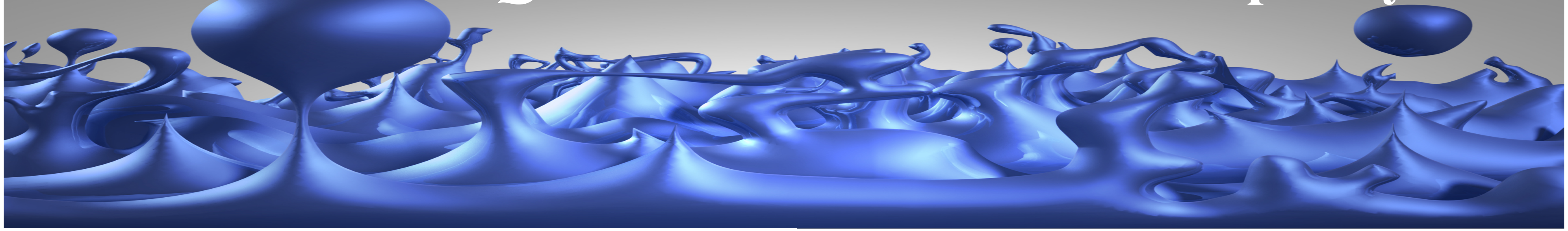


Starlink Constellation 12,000 sats
SpaceX (Elon Musk)



- 4425 @ 1200 km (completed by 2024)ù
- 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!**

GrailQuest Next Generation – Kuiper System



TRENDING   Apollo 11 in Real Time!   On This Day in Space   Amazon Prime Day Deals   Read 'All About Space'   Full Moon

Amazon Lays Out Satellite Constellation Service Goals, Deployment and Deorbit Plans to FCC

By Caleb Henry 4 days ago Tech

Amazon says all the proposed satellite megaconstellations combined can't meet the total consumer demand for broadband. (Image: © Blue Origin webcast of Jeff Bezos' May 9, 2019 Blue Moon Presentation)

WASHINGTON — Amazon released more details on its plan to deploy 3,236 broadband satellites, telling U.S. telecom regulators the constellation can start service in limited areas with less than a fifth of the total co

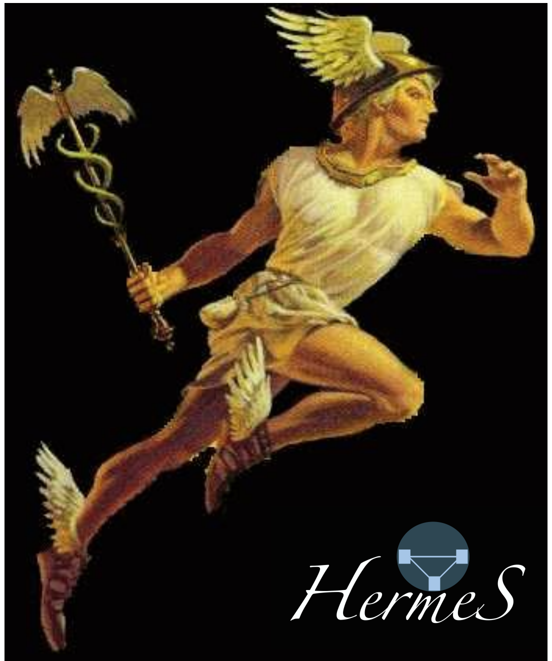
Amazon's Kuiper System satellites will have a design life seven years — less than half communications satellite — and will be launched in five waves, according to a July 4 fi Commission.

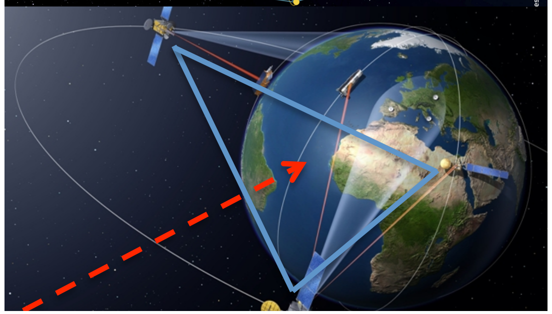
The first wave consists of 578 satellites that would provide internet service in two hor degrees north and 56 degrees north (roughly from Philadelphia north to Moscow) an degrees south (roughly from Hastings, New Zealand, to the top of Great Britain's Sou The subsequent four waves would fill in coverage to the equator.

Amazon's Kuiper System Satellites 3,236 sats
Amazon & Blue Origin(?) (Jeff Bezos)
April 2019

Hale reflector (5.1 m diameter) in Palomar Observatory funded by Rockfeller Foundation in 1928 proposed by George Ellery Hale

Mass production (cut of costs, great intuition of Henry Ford, inventor of the Assembly Line)





Conclusions: the HERMES & *GrailQuest* projects

All sky monitor of High Energy Sources (keV – MeV): GRB, Magnetar, high energy counterparts of GW & FRB, detection & monitoring of transient sources, timing of X-ray pulsators, etc.

- Accuracy in positioning of brigth GRB/GW: ~ 7÷60 arcsec
- 1 – 3 m^2 effective area
- Energy resolution: 15% at 30 keV
- Temporal resolution: ≥ 10 nanoseconds

Quantum Gravity: probing the structure of space-time

Time lags caused by prompt emission mechanism:

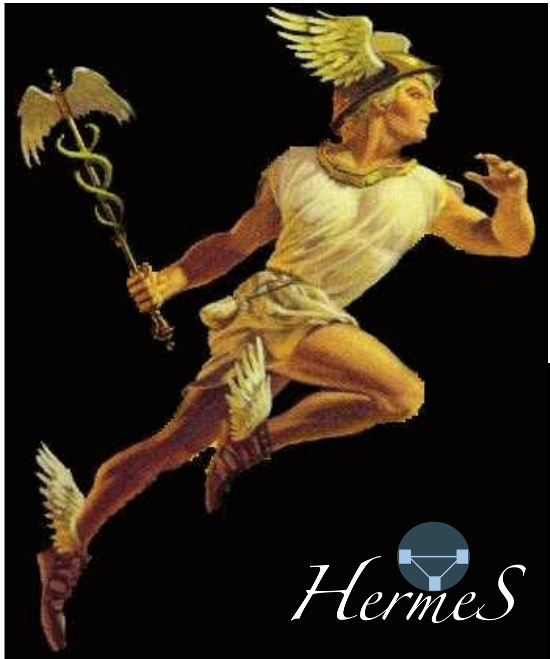
- complex dependence from E_{phot}(Band II) and E_{phot}(Band I)
- independent of $D_{GRB}(z_{GRB})$

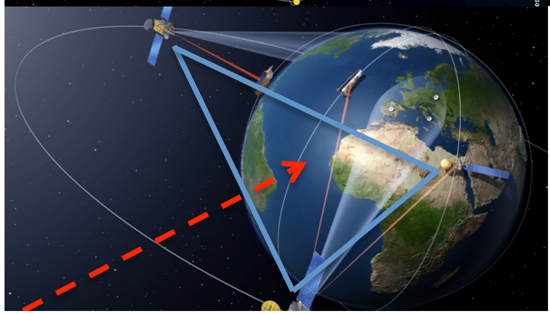
Time lags caused by Quantum Gravity effects:

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

The two effects can be disentangled with:

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





The HERMES project: the movie

Please, visit our website:
http://hermes.dsf.unica.it

That's all Folks!

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

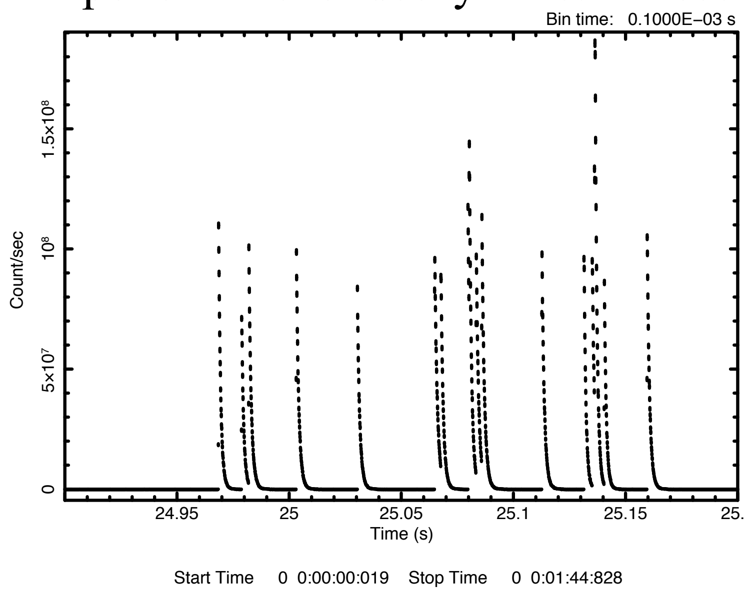
Source count rate: 7.875 ph/cm^2/s

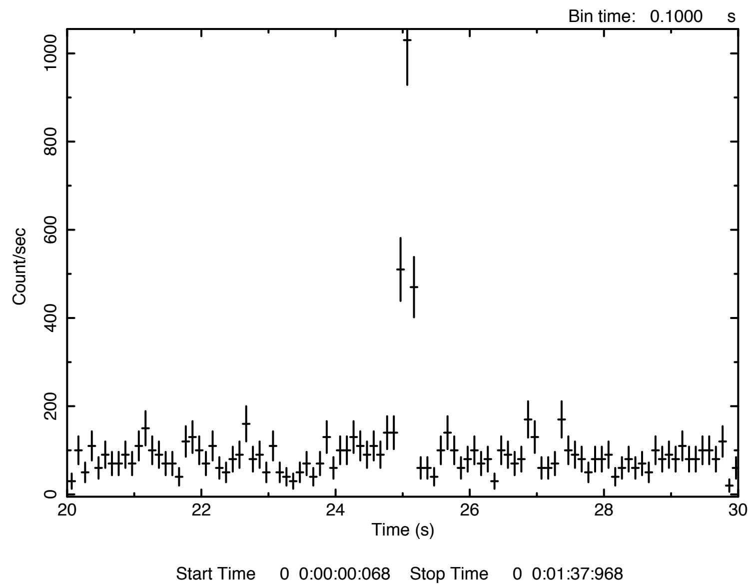
Total number of photons: 178

Exponential shot rate: 100 shot/s

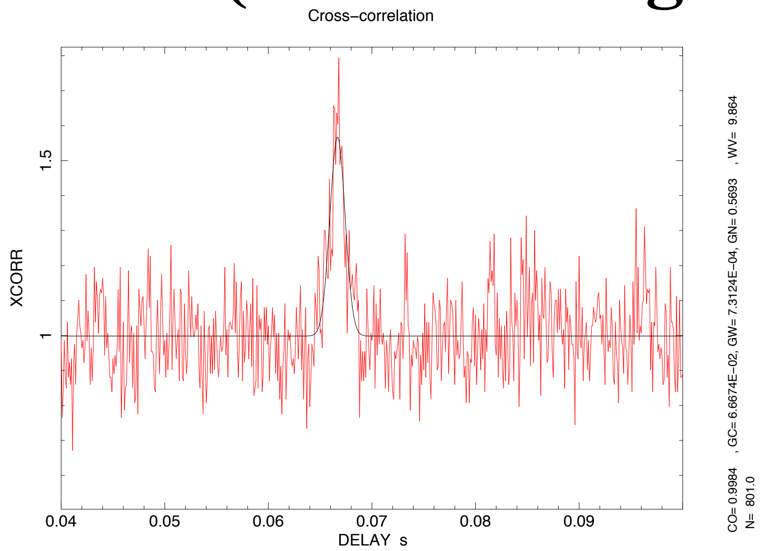
Exponential shot decay time: 1 msec

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





Delays from cross-correlation analysis (simulated light curve of a GRB)

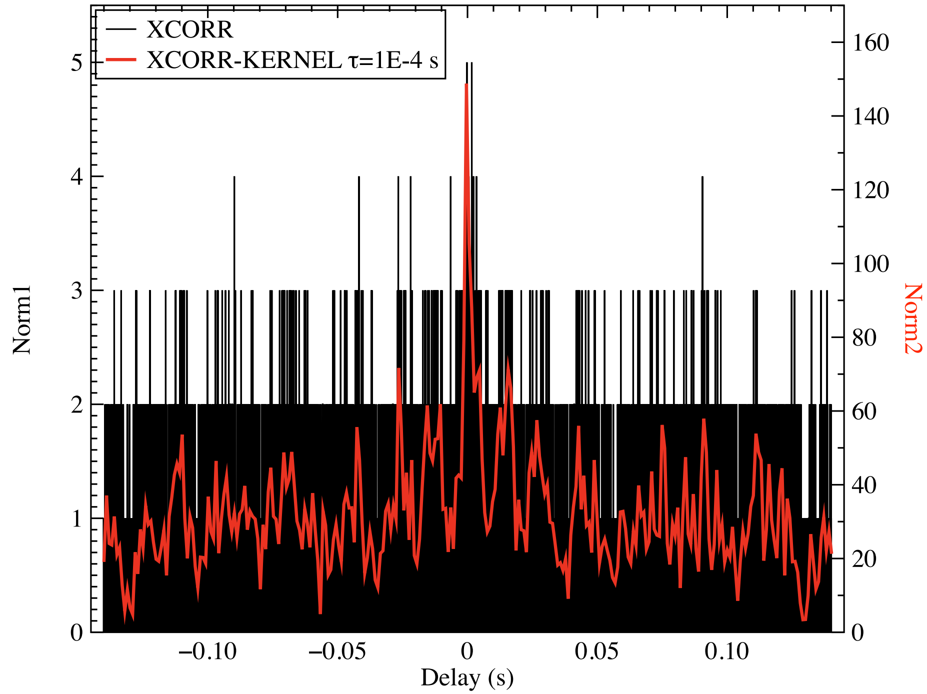


Temporal resolution: 200 µs
Standard CCF (red)

2 Lightcurves of a short GRB
Δt = 0.25 s
A = 100 cm^2
φ_{GRB}= 8 phot/s/cm^2
φ_{BCK}= 0.8 phot/s/cm^2
N_{PHOT} = 220
λ_{SHOT}= 100 shot/s
τ_{SHOT}= 1 ms
τ_{KERN}= 0.1 ms

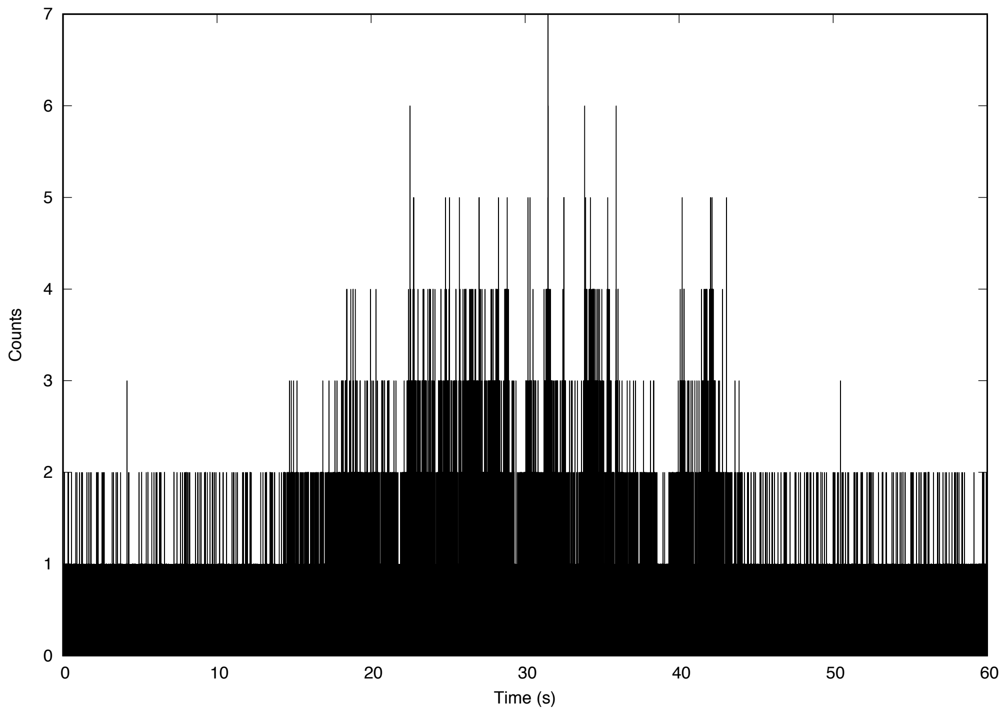
Temporal resolution: 1 µs
Standard CCF (black)
Kernel-modified CCF (red)

2 Lightcurves of a short GRB
Δt = 0.25 s
A = 100 cm^2
φ_{GRB}= 8 phot/s/cm^2
φ_{BCK}= 0.8 phot/s/cm^2
N_{PHOT} = 220
λ_{SHOT}= 100 shot/s
τ_{SHOT}= 1 ms
τ_{KERN}= 0.1 ms



Delays from cross-correlation analysis (lightcurve of a of a true long GRB observed by Fermi GBM)

Lightcurve (1μs resolution) of a long GRB (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;
with 56 cm^2 area GAGG detector 50−300 keV band
(Long and Short GRB with millisecond time variability, 40% of bright)



HERMES Pathfinder Detectors

Detectors on board of each nano satellite (3U)

- 16 PDU on each nanosatellite
- 2×2 array of 4 MDU (modular detector unit made by 4 PDUs) 64 cm^2 (true 56 cm^2) effective area per array

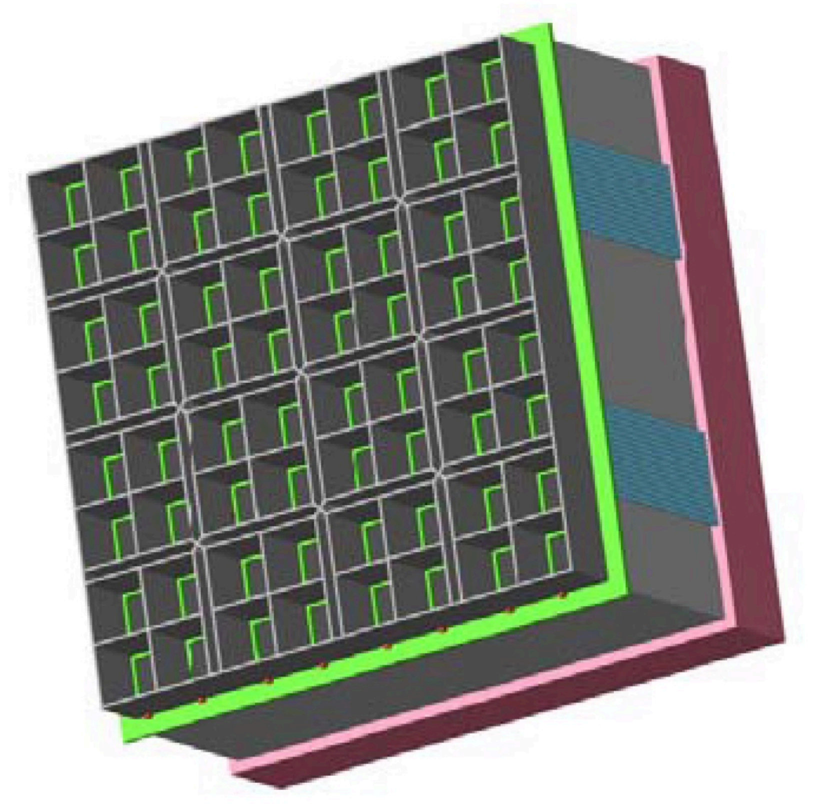


Figure 2: Schematic view of the payload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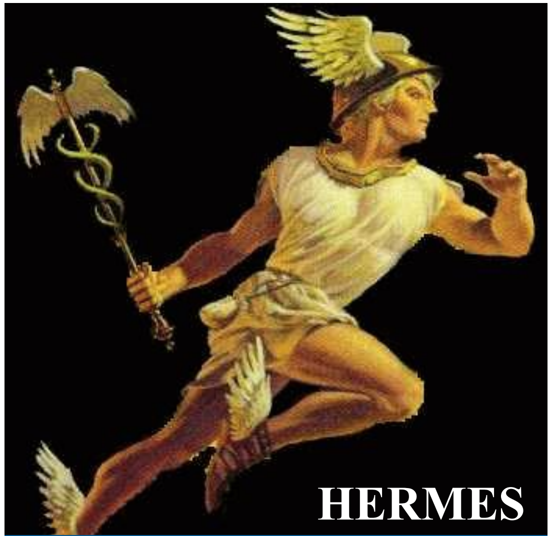
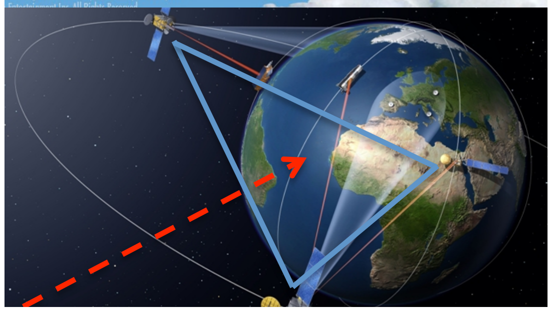




12 September 2019 – Bologna

X-RAY ASTRONOMY 2019

HERMES

High Energy Rapid Modular Ensamble of Satellites

& *GrailQuest*

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

Probing Space-Time Quantum Foam
Hunting for Gravitational Wave Electromagnetic Counterparts

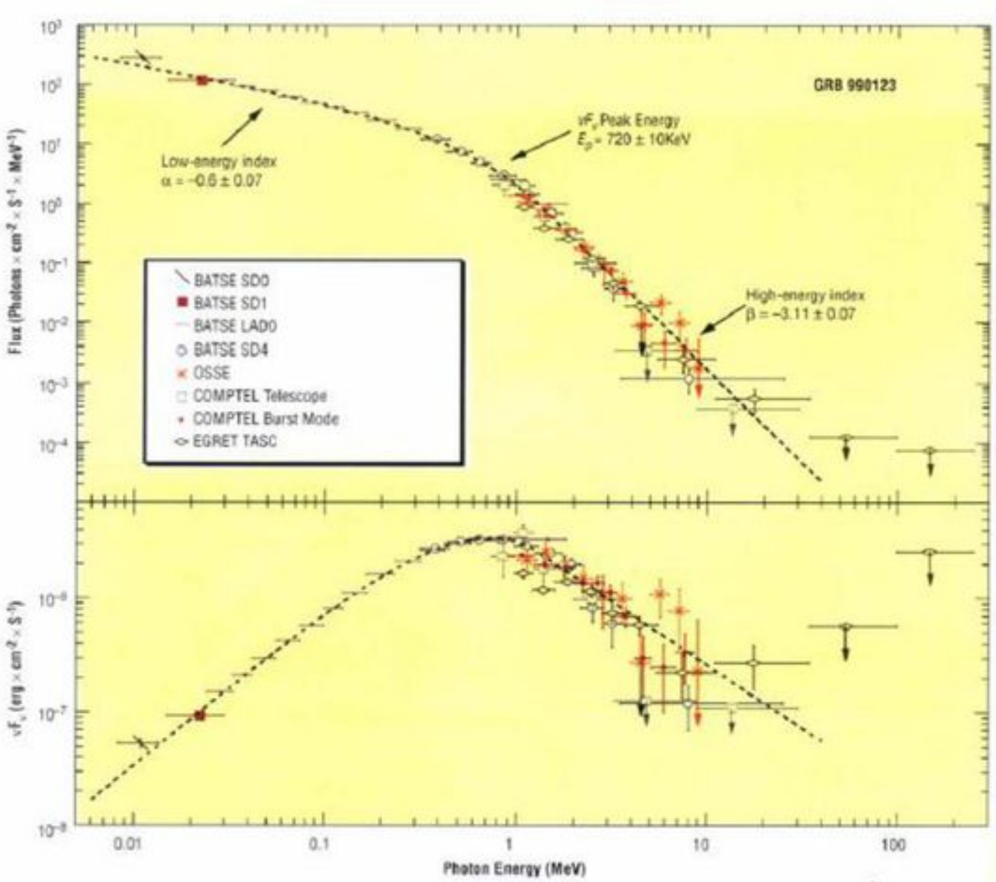
Luciano Burderi - University of Cagliari
Tiziana Di Salvo, Andrea Sanna, Fabrizio Fiore
On behalf of the HERMES and GrailQuest Collaborations

Please, visit our website:
http://hermes.dsf.unica.it

HermeS

The Ep,i – Eiso correlation

- GRB spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy
- $E_p = E_0 \times (2 + a)$ = observed peak energy of the $\nu F \nu$ spectrum

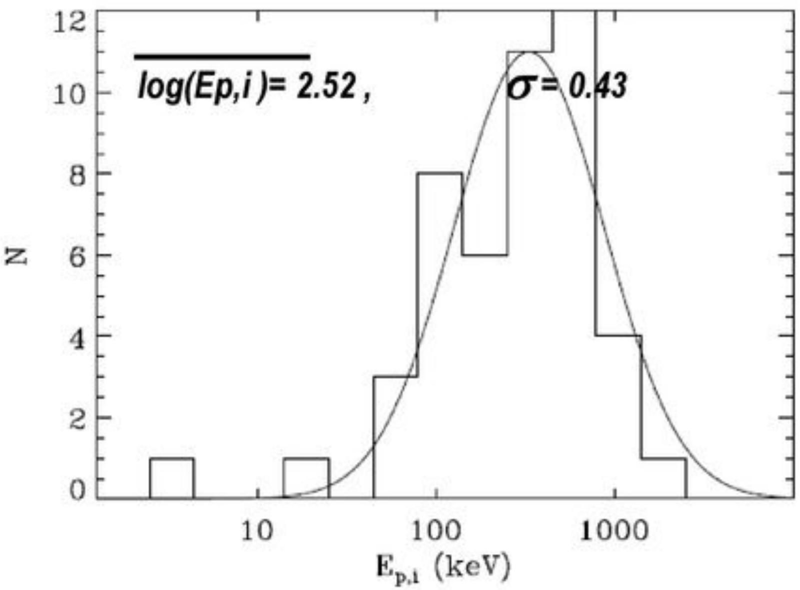


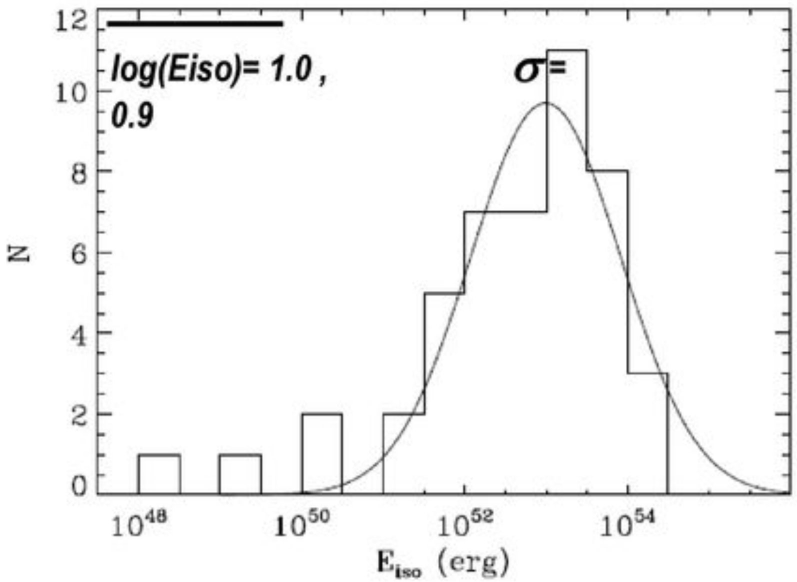
- from redshift, fluence and spectrum, it is possible to estimate the cosmologica-rest frame peak energy, Ep,i, and the radiated energy assuming isotropic emission, Eiso

- isotropic luminosities and radiated energy are huge; both Ep,i and Eiso and span several orders of magnitude

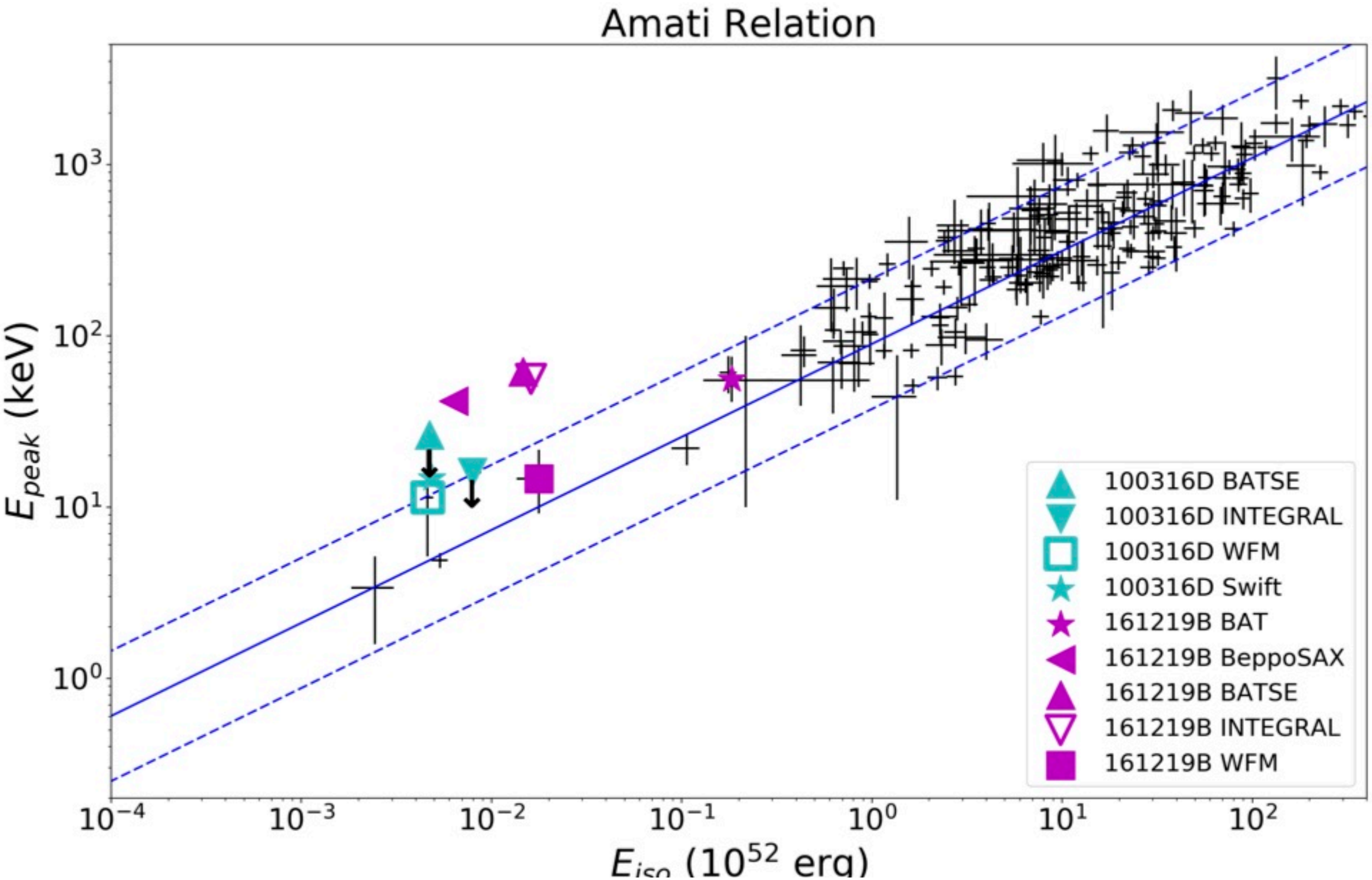
$$E_{p,i} = E_p \times (1 + z)$$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\, N(E)\, dE \ \ \mathrm{erg}$$

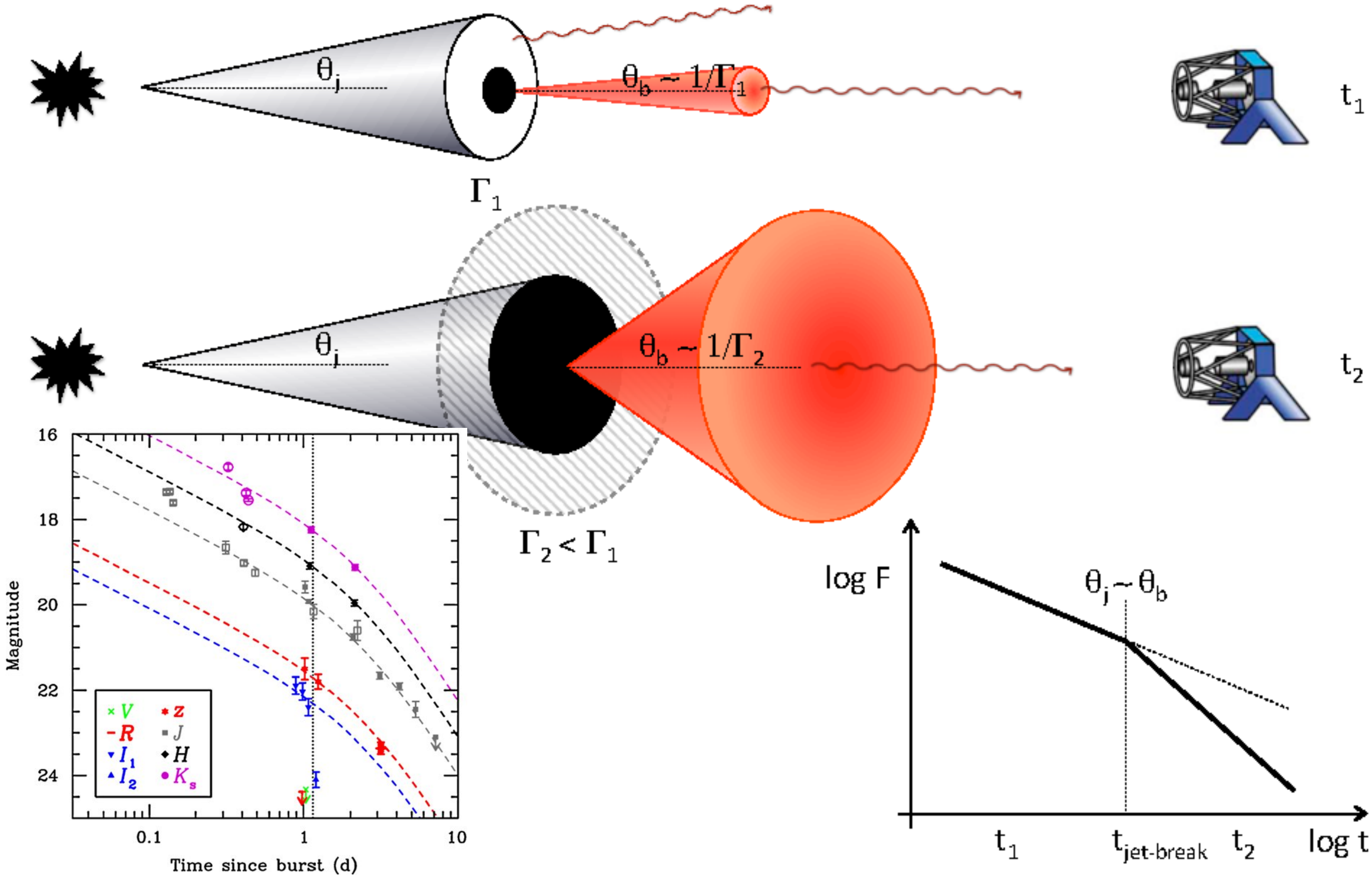




(Amati, MNRAS, 2006)



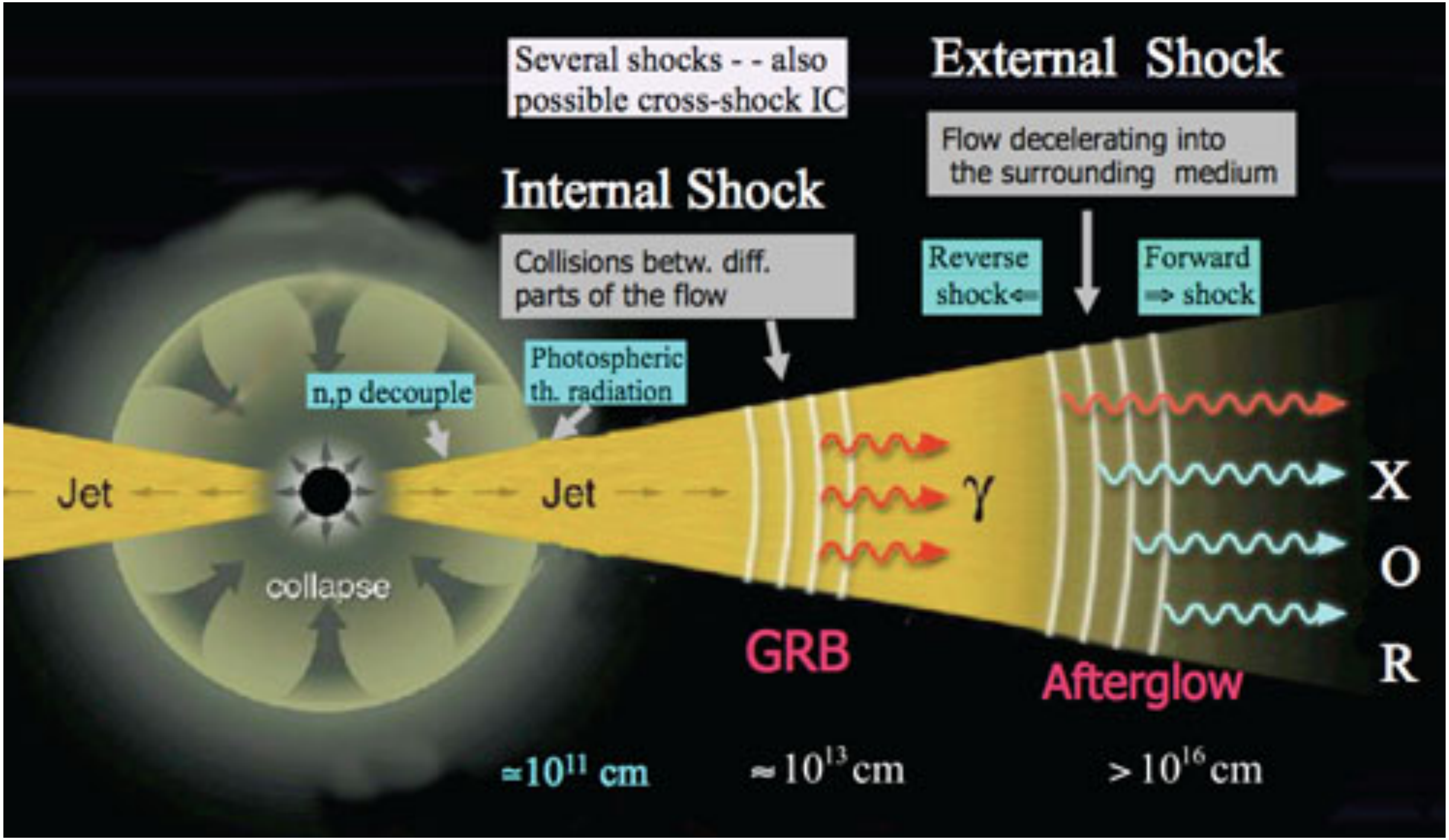
Possibility of finding the redshift(distance) from Epeak (spectra):
Powerful standard candels for Cosmology!

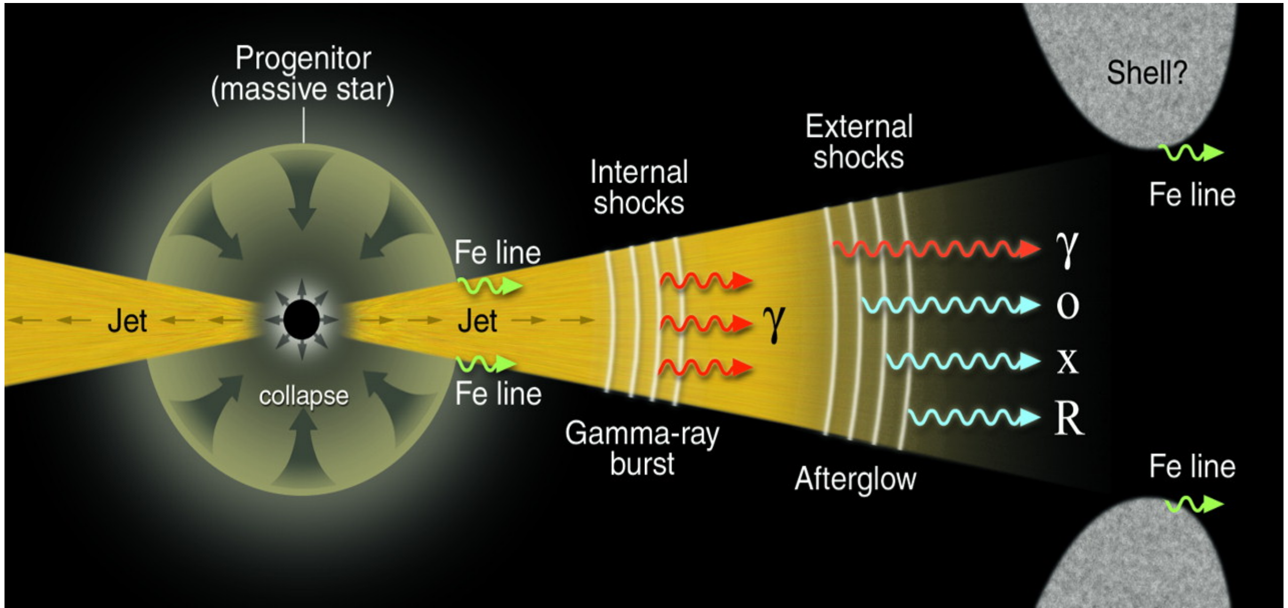


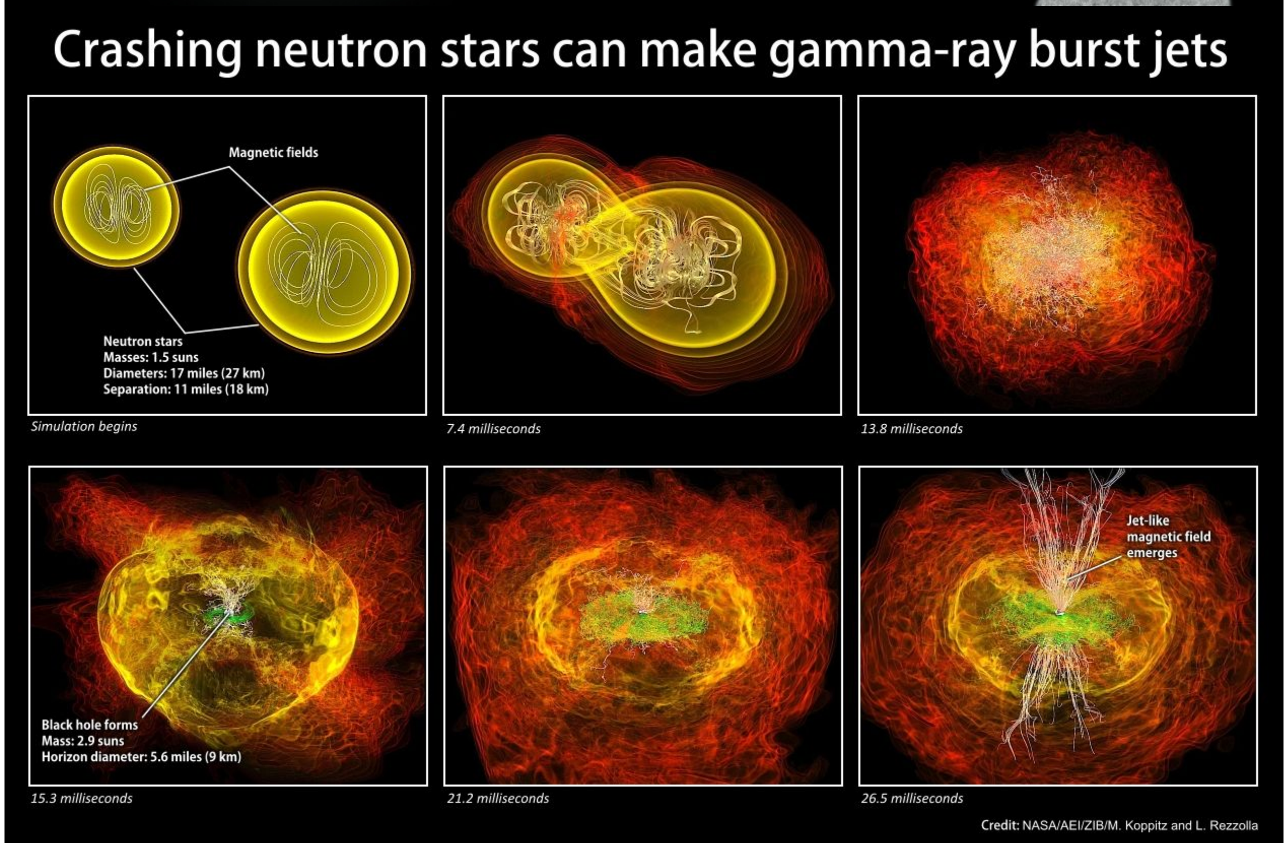
θ_j
$\theta_b \sim 1/\Gamma_1$
t_1
Γ_1
θ_j
$\theta_b \sim 1/\Gamma_2$
t_2
$\Gamma_2 < \Gamma_1$
Magnitude
Time since burst (d)
V
R
I_1
I_2
z
J
H
K_s
log F
$\theta_j \sim \theta_b$
t_1
$t_{jet\text{-}break}$
t_2
log t

GRB emission 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





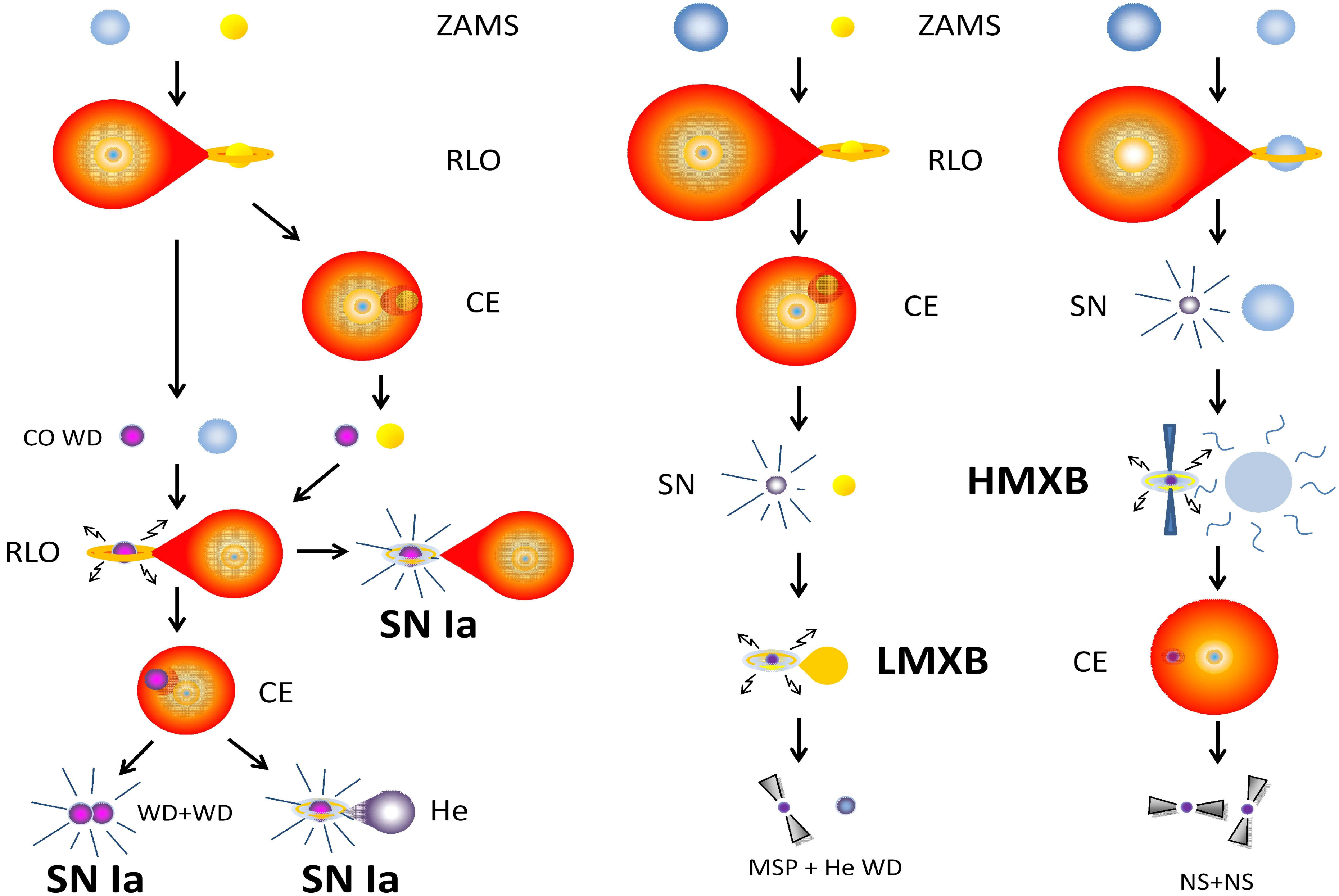


Long GRB:
BH collapse of a
massive star

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

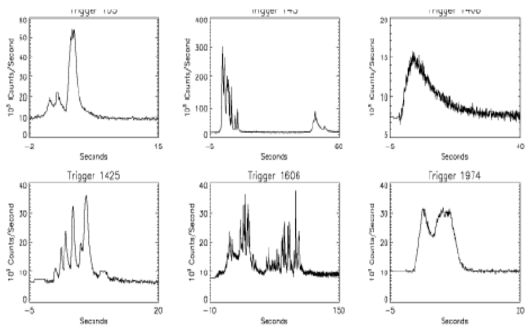

Progenitor
(massive star)
External
shocks
Shell?

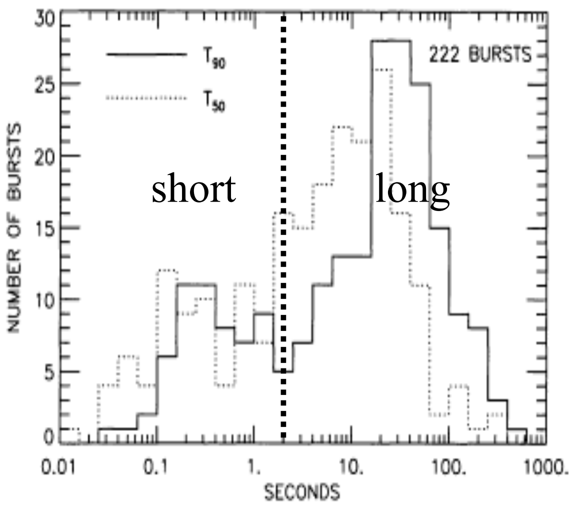
NS–NS

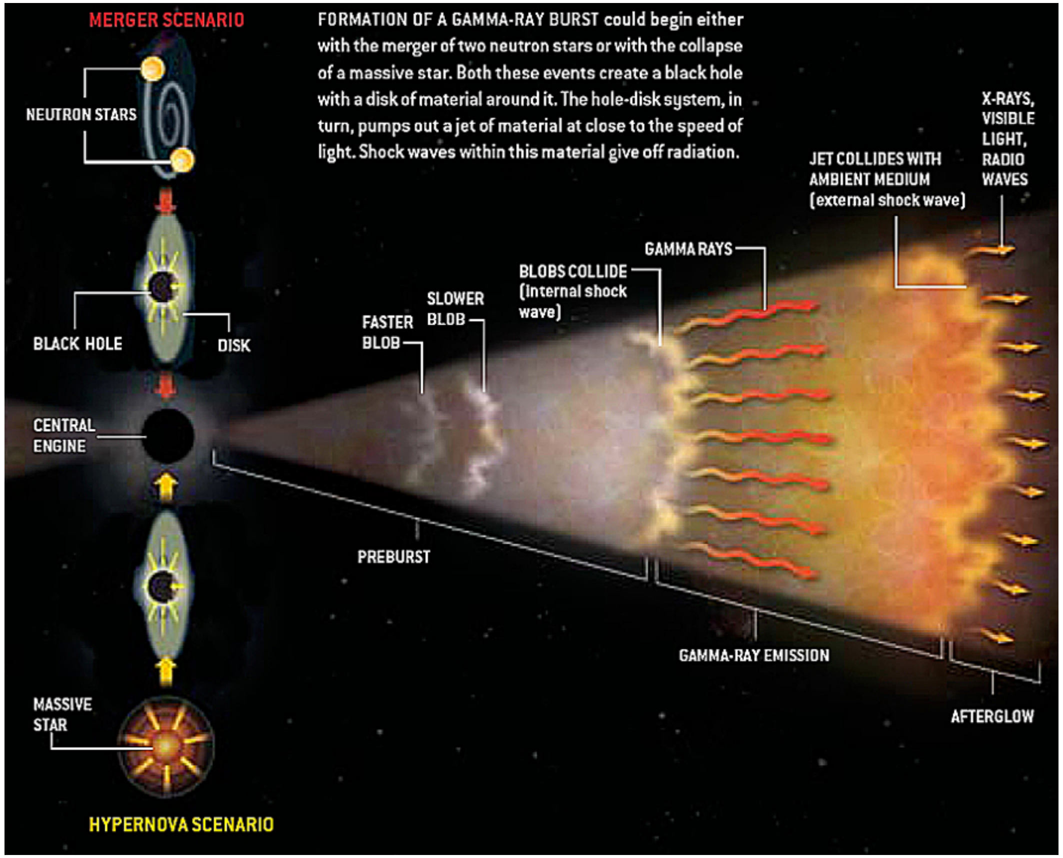

ZAMS
RLO
CE
CO WD
RLO
SN Ia
CE
WD+WD
He
SN Ia
SN Ia
ZAMS
RLO
CE
SN
LMXB
MSP + He WD
SN
HMXB
CE
NS+NS

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



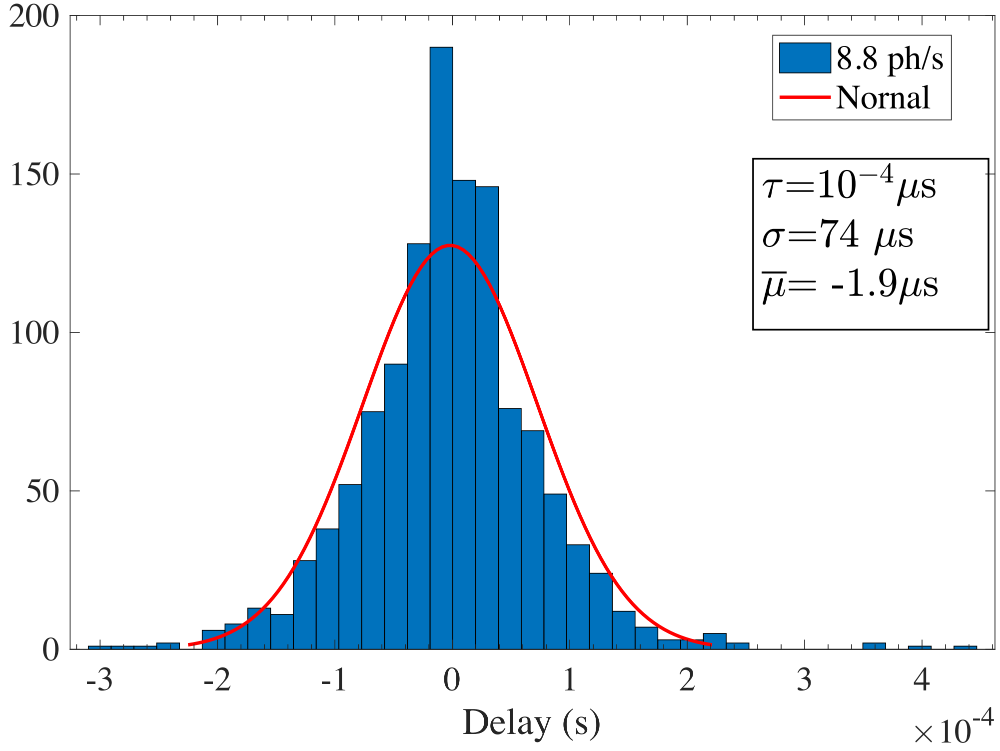




Delays from cross-correlation analysis (simulated light curve of a GRB)

Histogram of maxima of Kernel-modified CCF (1200 simulations of 2 short GRB)

$\Delta t = 0.25$ s; $\varphi_{GRB} = 8$ phot/s/cm^2; $\varphi_{BCK} = 0.8$ phot/s/cm^2; $\lambda_{SHOT} = 100$ shot/s; $\tau_{SHOT} = 1$ ms; $A = 100$ cm^2; $\tau_{KERN} = 0.1$ ms; $N_{PHOT} = 220$; $\sigma_{CCF} = 74$ µs

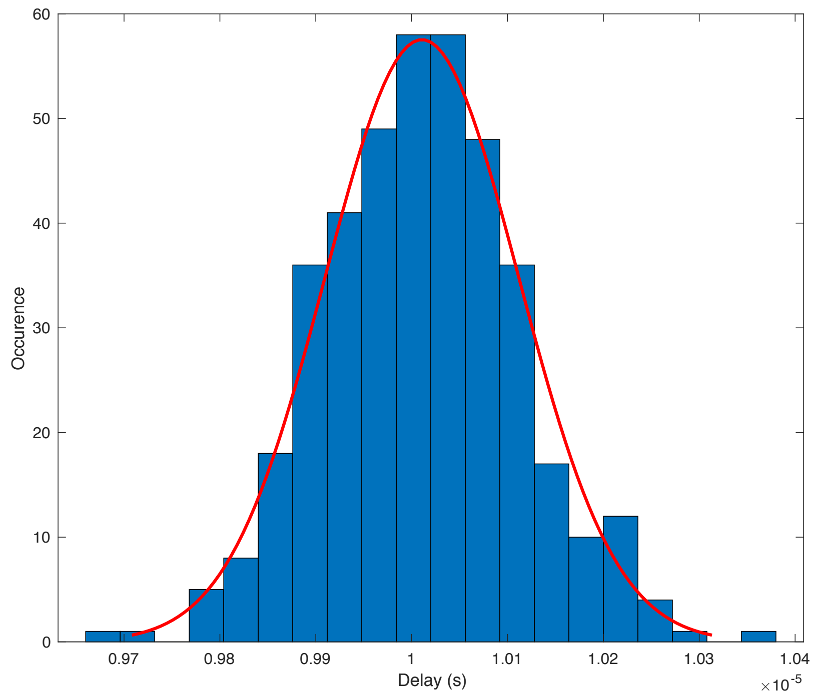


cross–correlation accuracy ($\tau_{SHOT} = 1$ ms):

$\boldsymbol{\sigma_{CC} \approx 74\ \mu\text{sec} \times (N/220)^{-0.5}}$

Delays from cross-correlation analysis (monte-carlo simulations of a true long GRB)

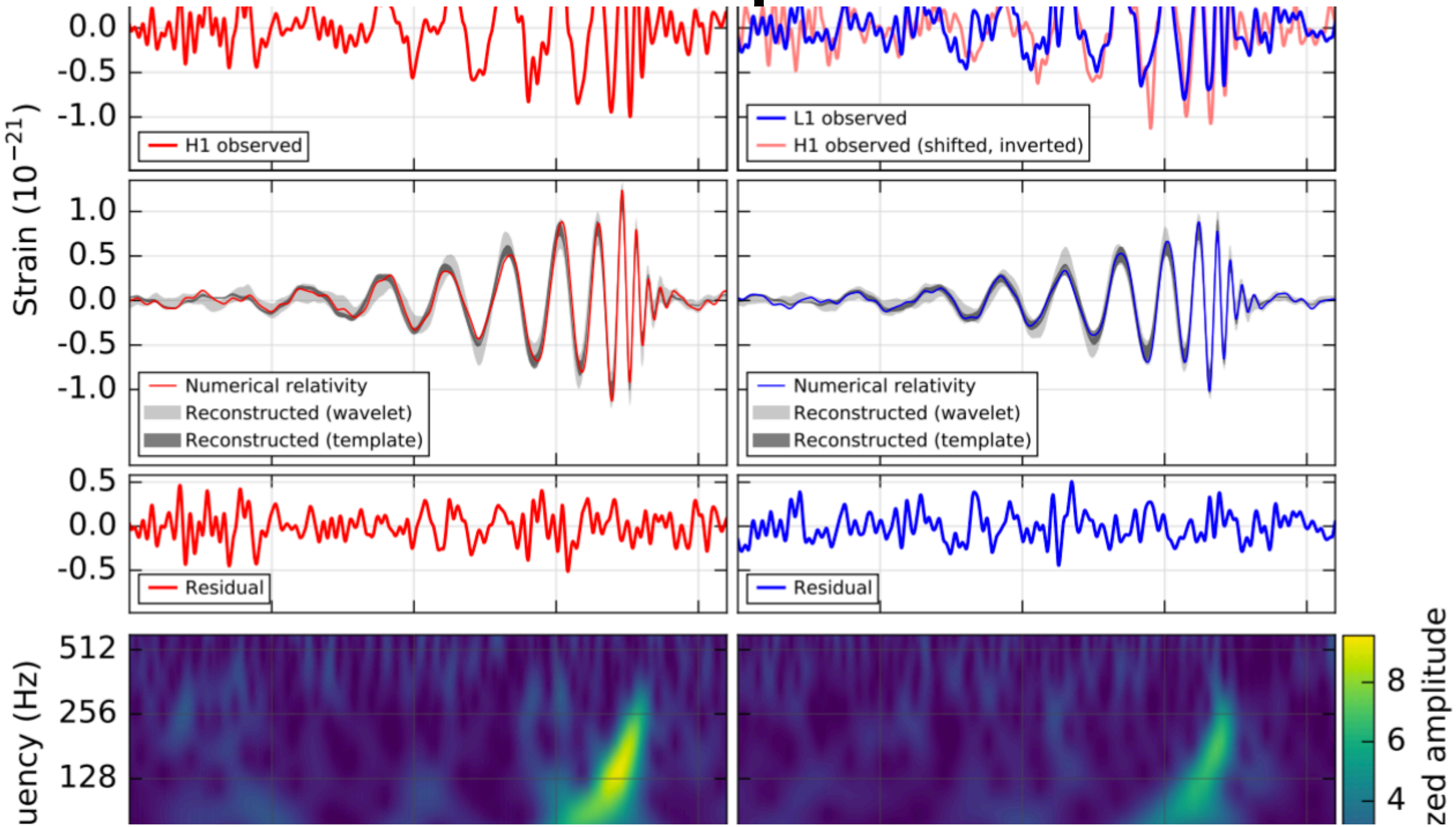
Histogram of CCF (500 simulations of 2 long GRB with 10 μs delay)
$\Delta t = 40$ s; $\varphi_{GRB} = 6.5$ phot/s/cm^2; $\varphi_{BCK} = 0.8$ phot/s/cm^2; variability = 1 ms;
$A = 100$ m^2; $N_{PHOT} = 2.6\ 10^8$; $\sigma_{CCF} = 0.1\mu s$

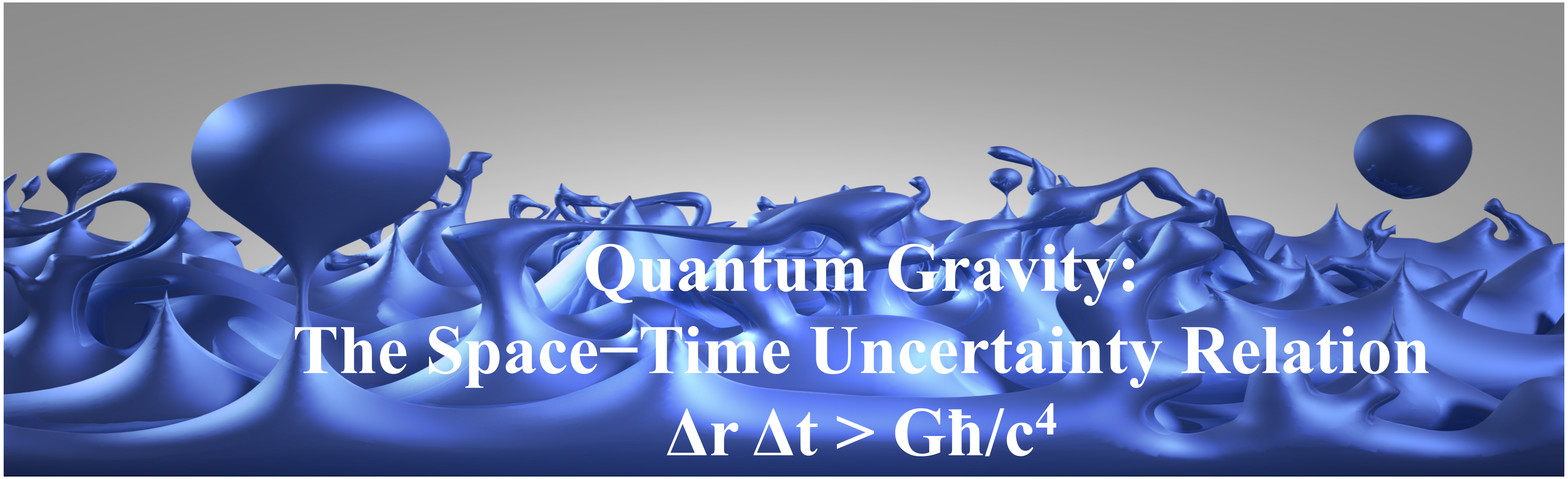


Cross-correlation accuracy:

- 0.1 μsec (Long and Short GRB with millisecond time variability, 40% of bright)

Gravitational Waves detected by LIGO on September the 14th 2015 CHIRP shape and evolution





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

Quantum clock: A critical discussion on spacetime

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(Received 5 July 2012; published 8 March 2016)

We critically discuss the measure of very short time intervals. By means of a *Gedankenexperiment*, w describe an ideal clock based on the occurrence of completely random events. Many previous though experiments have suggested fundamental Planck-scale limits on measurements of distance and time. Her we present a new type of thought experiment, based on a different type of clock, that provide furthe support for the existence of such limits. We show that the minimum time interval Δt that this clock ca 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 th speed of light, respectively. We outline and briefly discuss the implications of this uncertainty conjecture

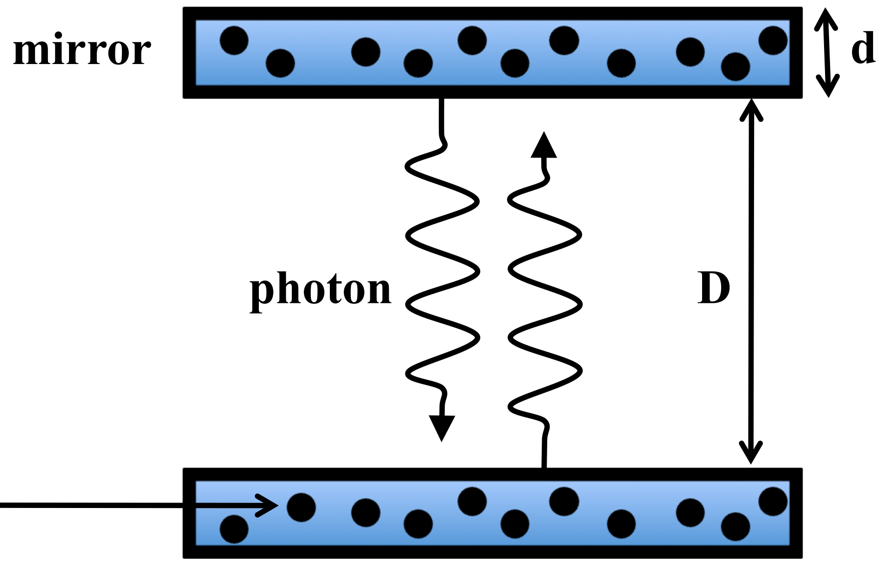
DOI: 10.1103/PhysRevD.93.064017

Operational definition of "time"

time ≡ a physical quantity that is measured by an appropriate clock

Light Clock

time measured with strictly periodic events



electrons in the metal

$\delta x \geq \lambda_C = \hbar/(m_e c)$

(see e.g. Garay 1995)

$\Delta t = D/c \geq \Delta t_{MIN} = \hbar/(m_e c^2) \cong 1.3 \times 10^{-21}$ s

(since $D \geq d \geq \delta x \geq \lambda_C = 3.9 \times 10^{-11}$ cm)

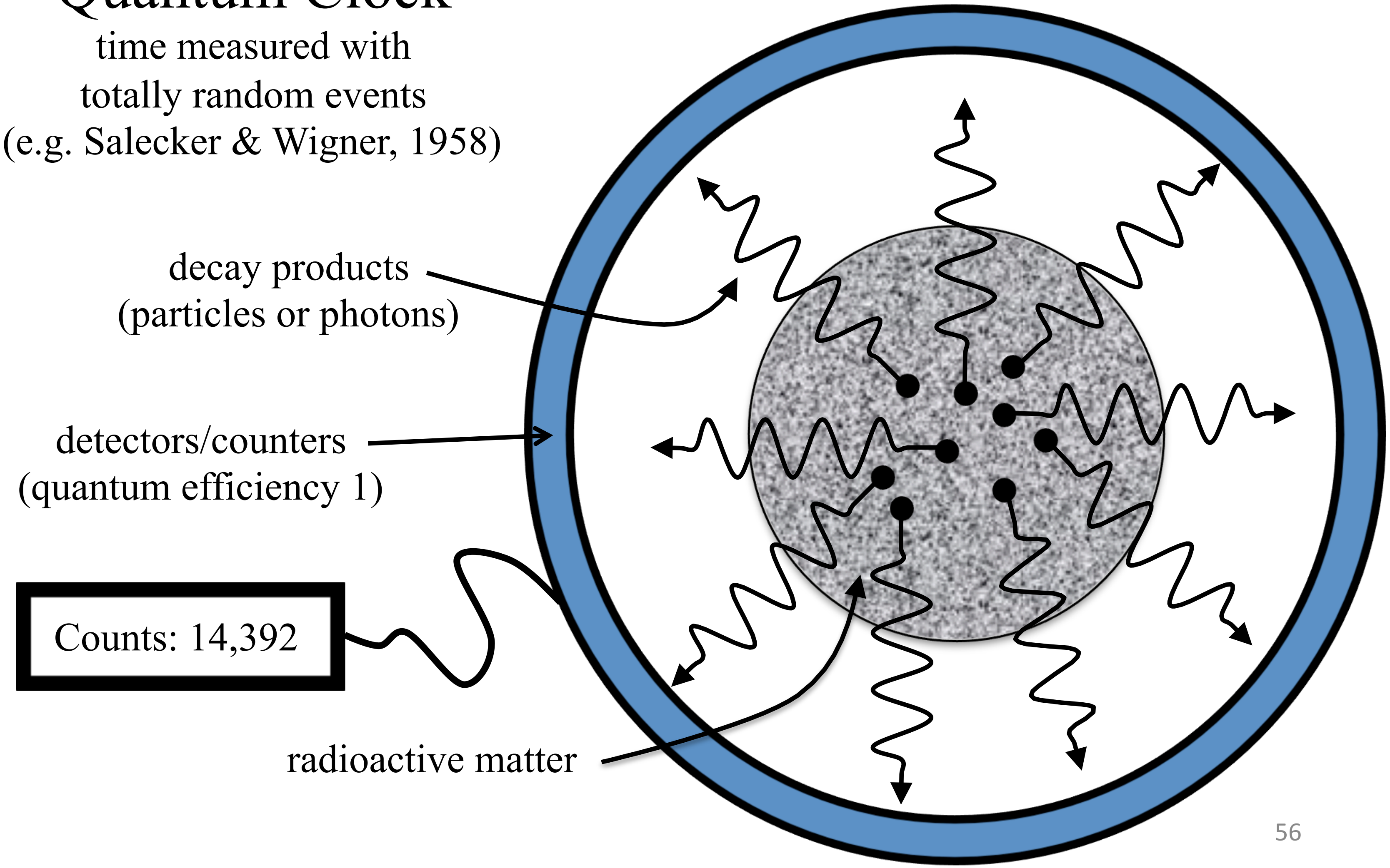
shortest time interval ever measured: 2×10^{-17} s (Schultze et al.2010)

Operational definition of “time”

time ≡ a physical quantity that is measured by an appropriate clock

Quantum Clock

time measured with
totally random events
(e.g. Salecker & Wigner, 1958)



The Quantum Clock with radioactive substance

Completely random process: a statistical process whose probability of occurrence is constant (independent of time):

$$dP = \lambda\, dt \qquad (\lambda = \text{constant})$$

Radioactive decay: $dN = -\lambda N\, dt$ (where $\lambda^{-1} = \tau_{PART}$)

Assume: $\Delta t << \tau_{PART}$

Number of expected decays in the interval Δt: $\Delta N_{\Delta t} = \lambda N\, \Delta t$

Fluctuations with Poissonian statistics: $\sigma_{\Delta N} = (\lambda N\, \Delta t)^{1/2}$

Quantum Clock working principle: compute time by counting the decays

$$\Delta t = \Delta N_{\Delta t} / (\lambda N)$$

relative error in time = relative error in number of decays

$\sigma_{\Delta t} / \Delta t = \varepsilon = \sigma_{\Delta N} / \Delta N_{\Delta t} = 1 / (\Delta N_{\Delta t})^{1/2} \leq 1$ $\longrightarrow$ $\Delta N_{\Delta t} = 1/\varepsilon^2$

Mass of the Quantum Clock: $M = N \times m_{PART}$ $\longrightarrow$ $N = M/m_{PART}$

Energy of the decaying particle: $E_{PART} = m_{PART}\, c^2$

$$\Delta t = (1/\varepsilon^2)/(\lambda M/m_{PART}) = (m_{PART}\, c^2)/(\varepsilon^2 \lambda M c^2) = (E_{PART} \times \tau_{PART})/(\varepsilon^2 M c^2)$$

The Quantum Clock and Quantum Mechanics

Heisenberg uncertainty relation between the energy and the decay time of a particle confined inside a potential well (decay by tunneling through the potential barrier):

$$\delta E \times \delta t \geq \hbar/2$$

Asssume (for simplicity) that the radioactive substance is destroyed in the decay (e.g. $\pi_0 \longrightarrow 2\gamma$).

The whole energy of the particle is involved and therefore: $E_{PART} \geq \delta E$

The decay time must be measurable and therefore: $\tau_{PART} \geq \delta t$

$$E_{PART} \times \tau_{PART} \geq \hbar/2$$

$$\Delta t = (E_{PART} \times \tau_{PART}) / (\varepsilon^2 Mc^2) \geq \hbar / (2\varepsilon^2 Mc^2)$$

(compare to Salecker & Wigner 1958, and Ng & van Dam 2003)

The Quantum Clock and General Relativity

To let the decaying particle escape and be detected, the size ($\Delta r \approx \Delta r_{CIRC} = C/2\pi$) of the Quantum Clock must be larger than its Schwarzschild Radius (Hoop Conjecture, Thorne, 1972):

$$\Delta r > R_{SCH} = 2GM/c^2$$

Therefore:

$$1/M > 2G/(c^2 \Delta r)$$

(see Amelino-Camelia (1995) for a lower bound in the uncertainty for the measurement of a distance, in which this condition is included)

Therefore, the Quantum Clock equation is:

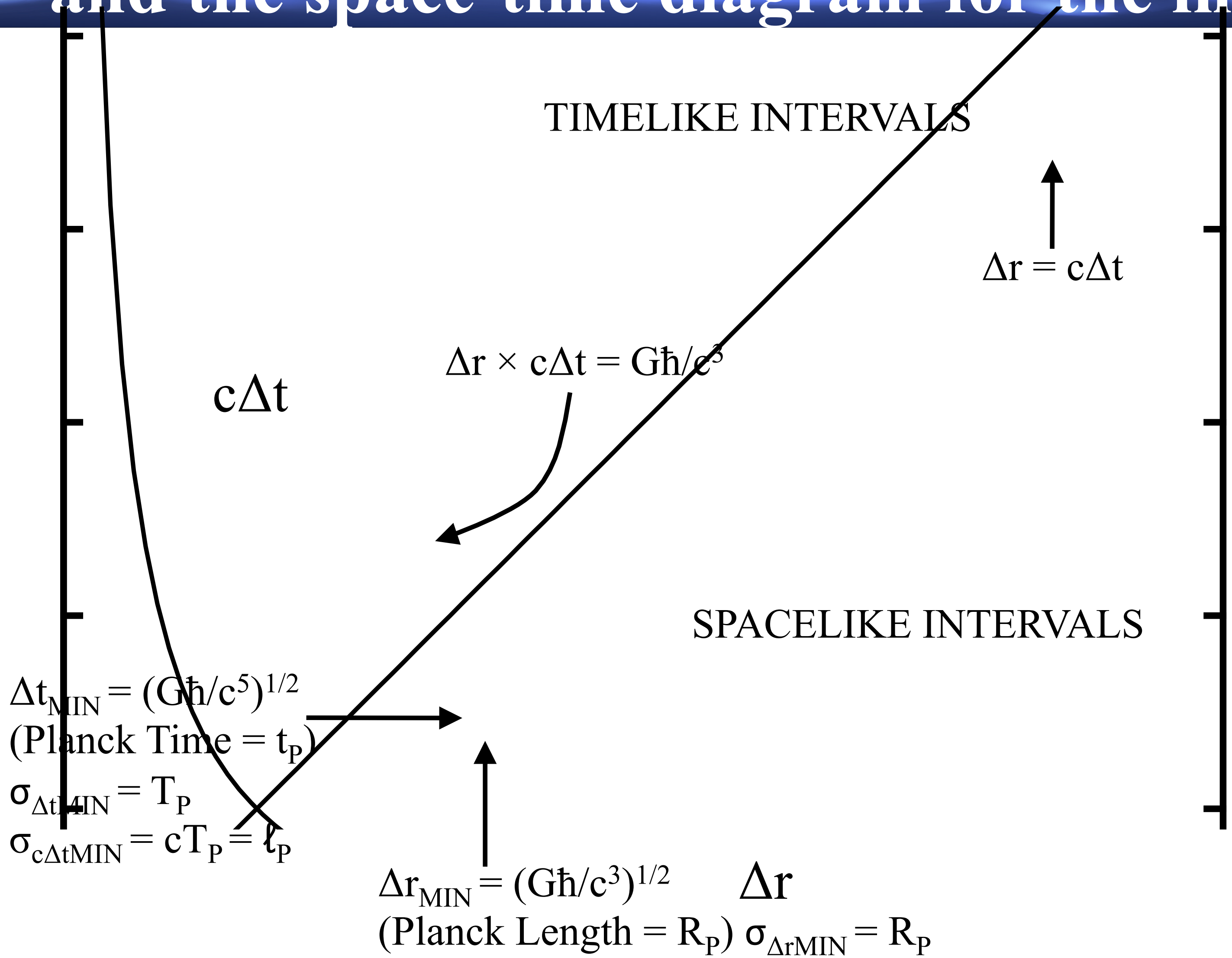
$$\Delta t \geq \hbar/(2\varepsilon^2 M c^2) > G\hbar/(\varepsilon^2 c^4 \Delta r)$$

Finally, since at least one decay occurred, $\varepsilon = 1 / (\Delta N_{\Delta t})^{1/2} \leq 1$.

Therefore we get the new Space-Time Uncertainty Relation:

$$\Delta r \, \Delta t > G\hbar/c^4$$

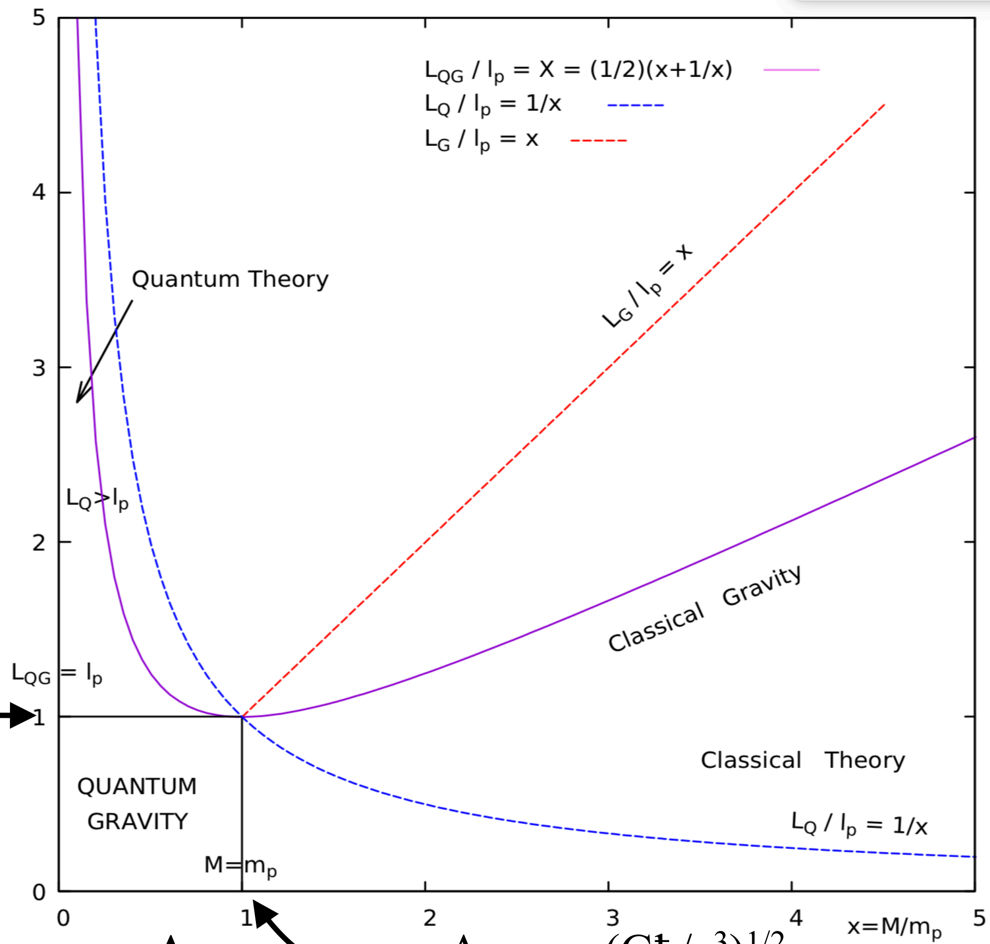
The Uncertainty Relation $\Delta r\, \Delta t > G\hbar/c^4$ and the space-time diagram for the intervals



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

Sanchez, 2018

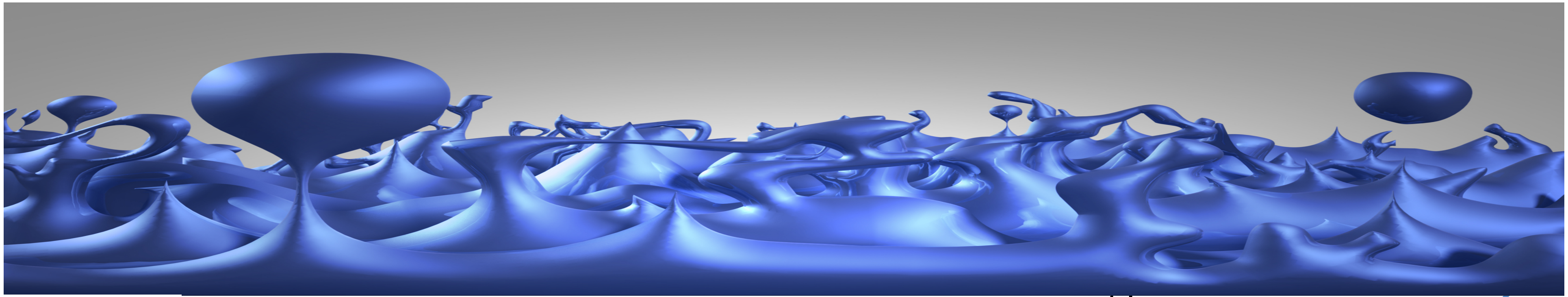
$c\Delta t$



$\Delta t_{MIN} = (G\hbar/c^5)^{1/2}$
(Planck Time = t_P)
$\sigma_{\Delta tMIN} = T_P$
$\sigma_{c\Delta tMIN} = cT_P = \ell_P$

Δr

$\Delta r_{MIN} = (G\hbar/c^3)^{1/2}$
(Planck Length = R_P) $\sigma_{\Delta rMIN} = R_P$

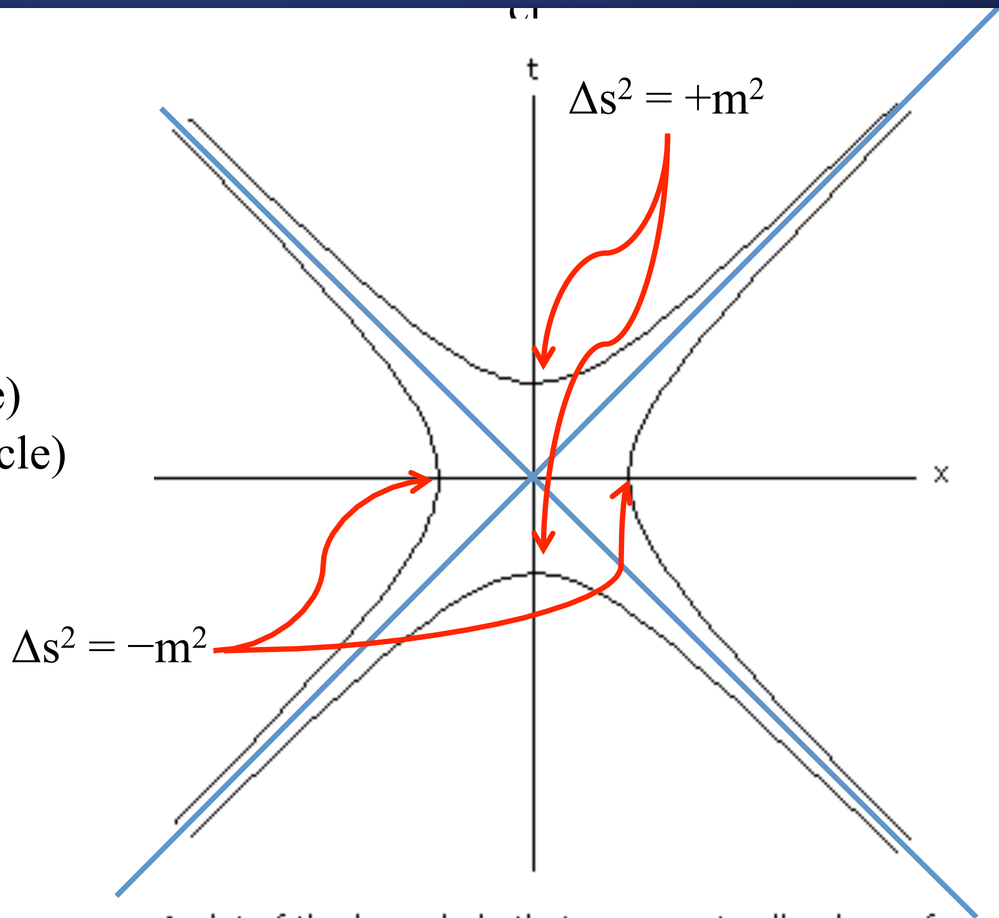


Hyperbolic spacetime

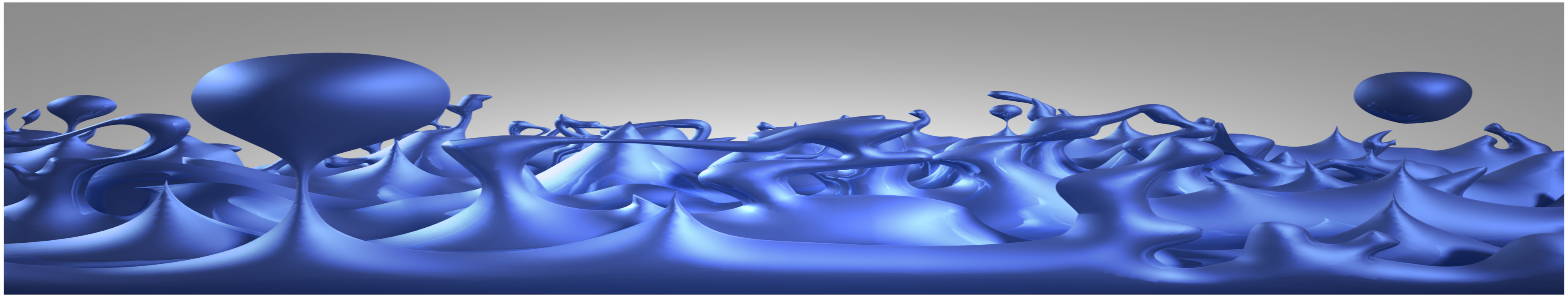
Fundamental Postulate
of Special Relativity:
the interval:

$\Delta s^2 = (ct)^2 - r^2 = +m^2$ (time-like hyperbolae)
$\Delta s^2 = (ct)^2 - r^2 = -m^2$ (space-like hyperbolae)
$m \geq 0$ ($m=0 \Rightarrow \Delta s^2 = 0$ light − massless particle)

is invariant under
Lorentz Transformations



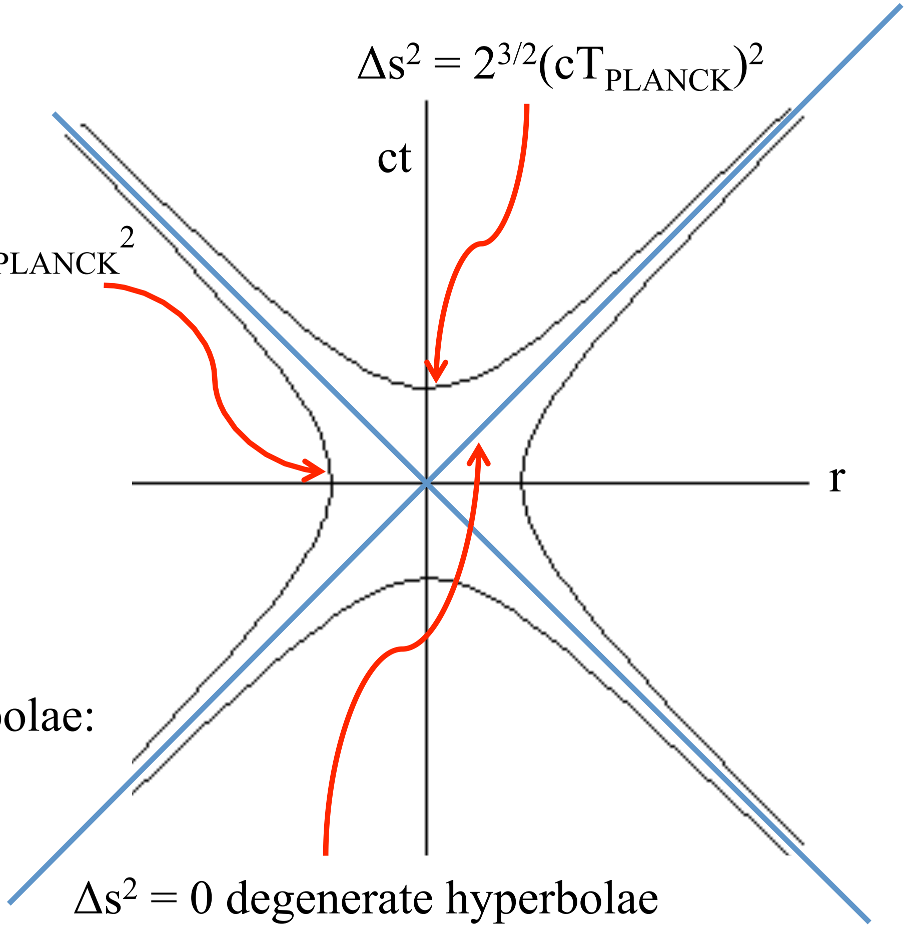
A plot of the hyperbola that represents all values of t and x that observers might measure for a given spacetime interval.



Uncertainty in $c\,T_{PLANCK}$ and R_{PLANCK}:
$\sigma_{cTp} = \sigma_{Rp} = R_P$

reflects on uncertainty on interval Δs^2:
$\sigma(|\Delta s^2|) \geq 2^{3/2}(cT_P)^2 = 2^{3/2}R_P{}^2$
$\sigma(|\Delta s^2|) \approx (cT_P)^2 = R_P{}^2$

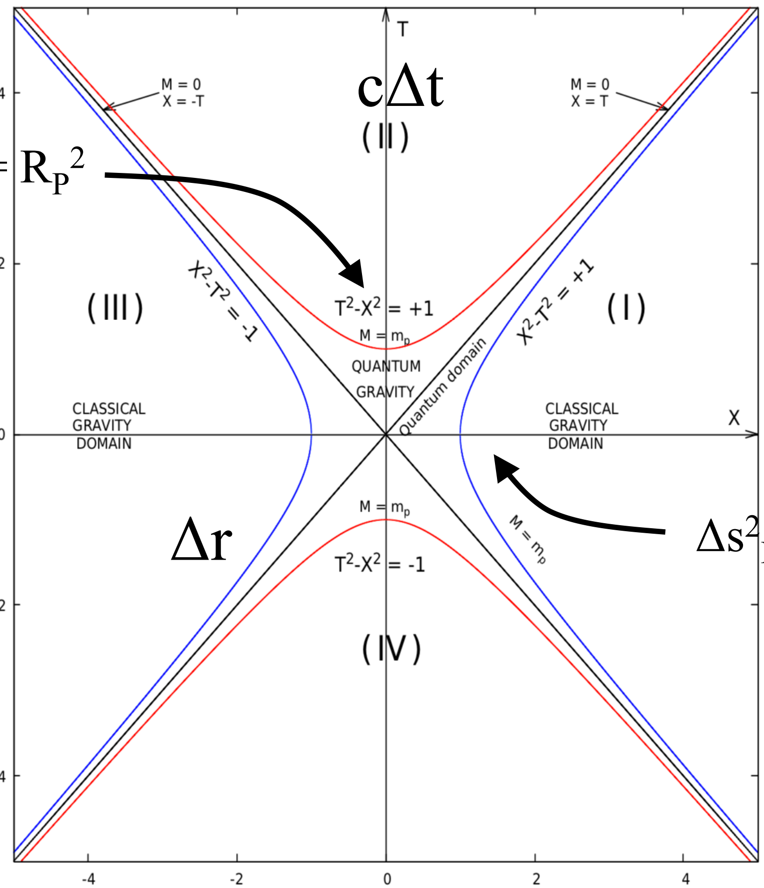
Fuzzy region of spacetime within the two hyperbolae:
$\Delta s^2 = (ct)^2 - r^2 = +2^{3/2}(cT_{PLANCK})^2$ (time-like)
$\Delta s^2 = (ct)^2 - r^2 = -2^{3/2}R_{PLANCK}{}^2$ (space-like)



$\Delta s^2 = 0$ degenerate hyperbolae
(light − massless particle)
lie in the fuzzy region

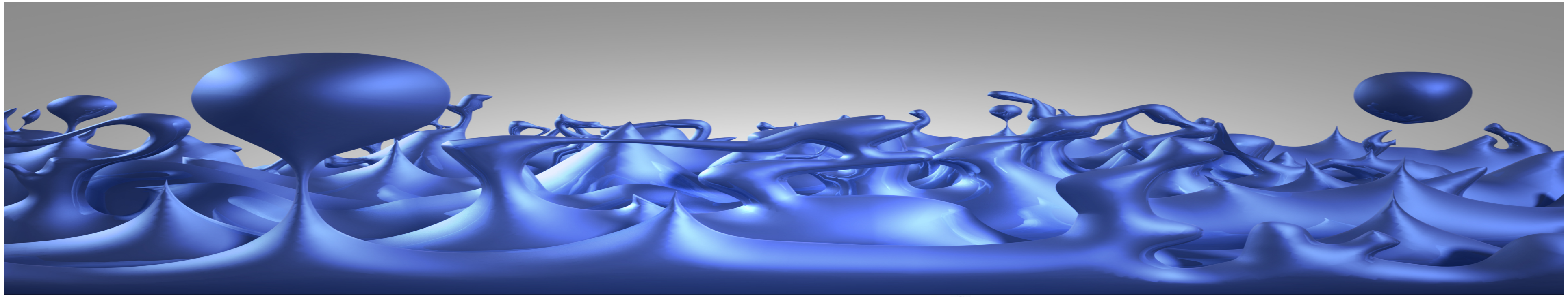
Geometrical Structure of Quantum Space−Time
Fuzzy Minkowski metric: preserving Lorentz Invariance

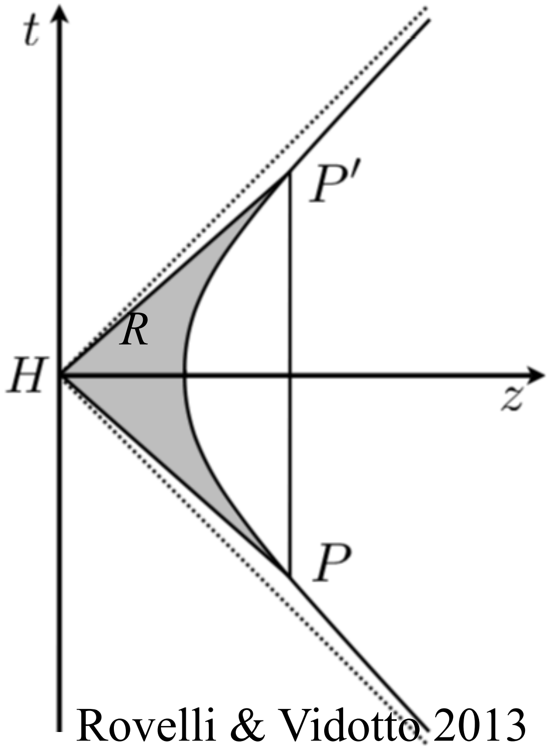
$\Delta s^2_{MIN} = (G\hbar/c^3) = R_P^2$

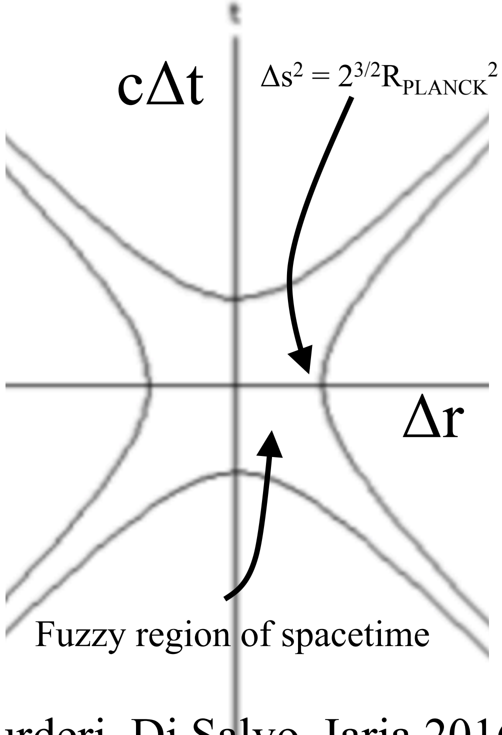


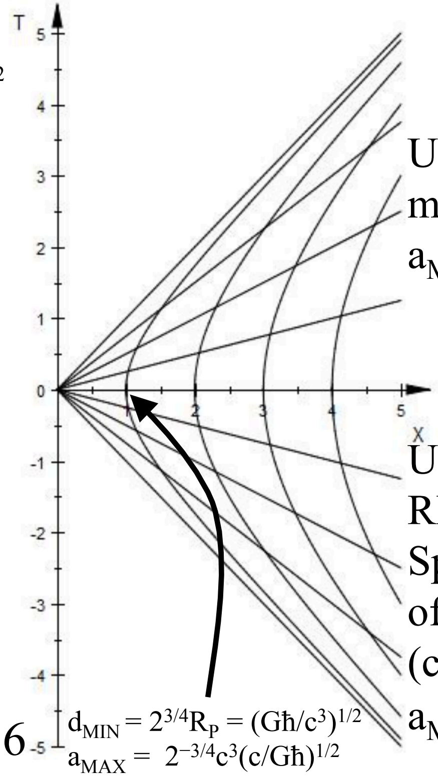
$\Delta s^2_{MIN} = (G\hbar/c^3) = R_P^2$

see Sanchez, N. G. 2018, Int.J.Mod.Phys. D28 no.03, 1950055
for similar results with a different approach









Uniformly accelerated motion in SR:
a_{MCRF} = constant

Uniformly accelerated RF in SR:
Spacetime trajectories of Observers
$(ct)^2 - x^2 = -d^2$
$a_{MCRF} = c^2/d$

Rovelli & Vidotto 2013 Burderi, Di Salvo, Iaria 2016
Lorentzian area of *R*

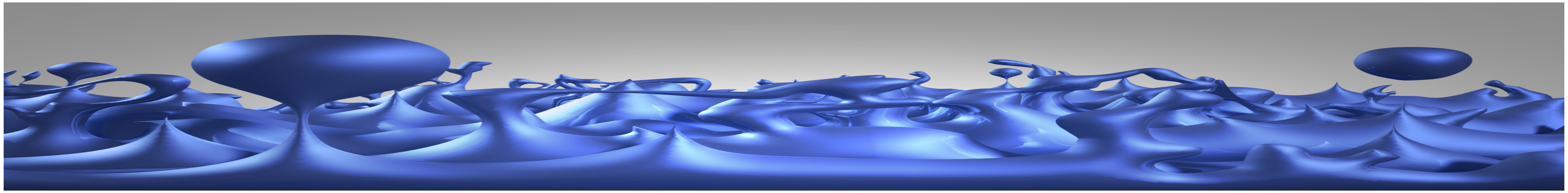
Figure 2.1: Rindler wedge. Straight lines correspond to constant times t, curved lines represent constant values of x.

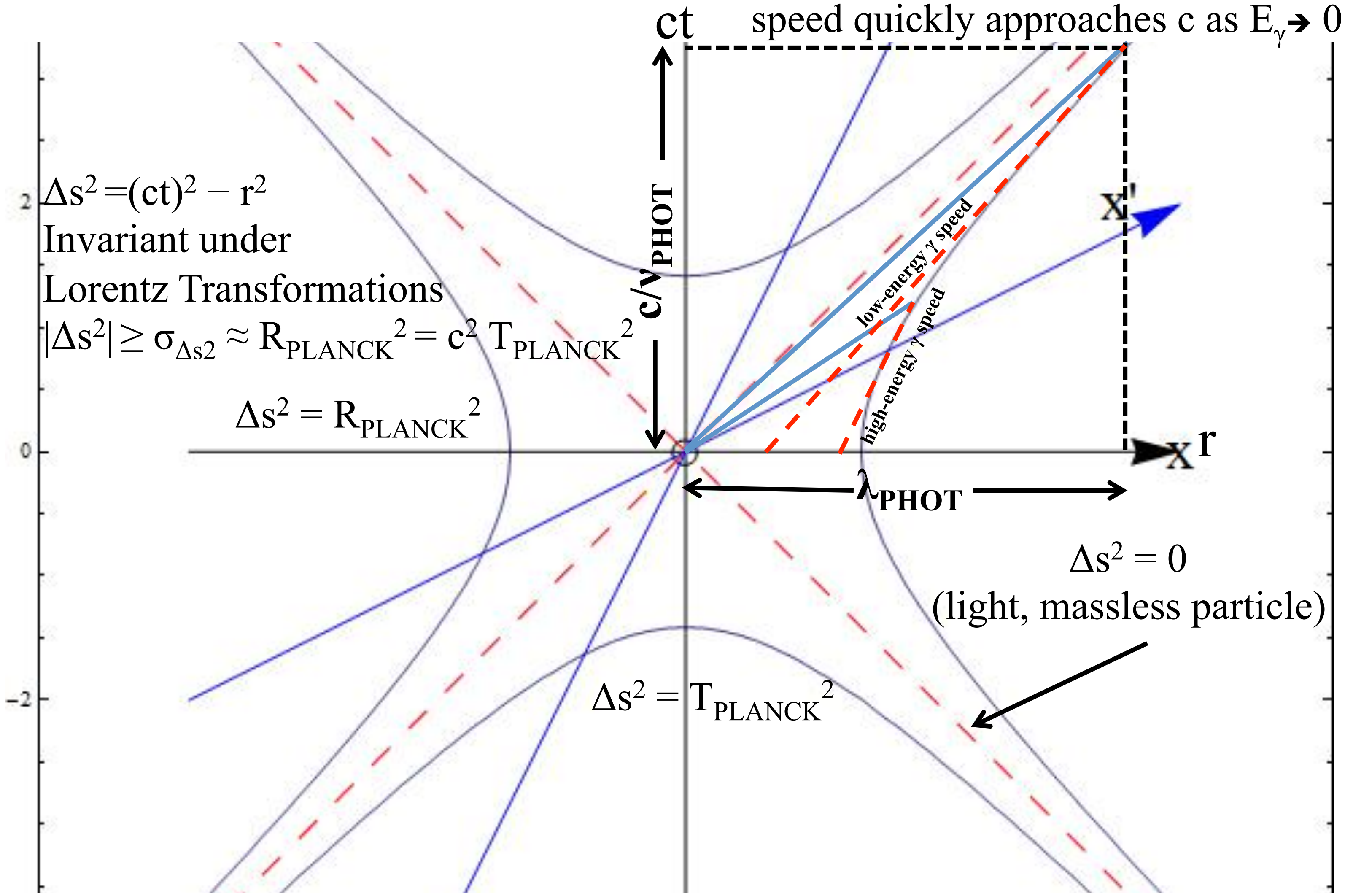
for similar results with a different approach see *e.g.*:

Caianiello, E. R. 1981, Lett. Nuovo Cimento 32, 65: $a_{Caianiello} = 2mc^3/\hbar$

for $m = m_P = (\hbar c/G)^{1/2}$, $a_{Caianiello} = 2c^3(c/G\hbar)^{1/2}$ $[a_{Burderi} = 2^{-3/4}c^3(c/G\hbar)^{1/2}]$

Rovelli, C., Vidotto, F. 2013, Phys. Rev. Lett., 111, 1303

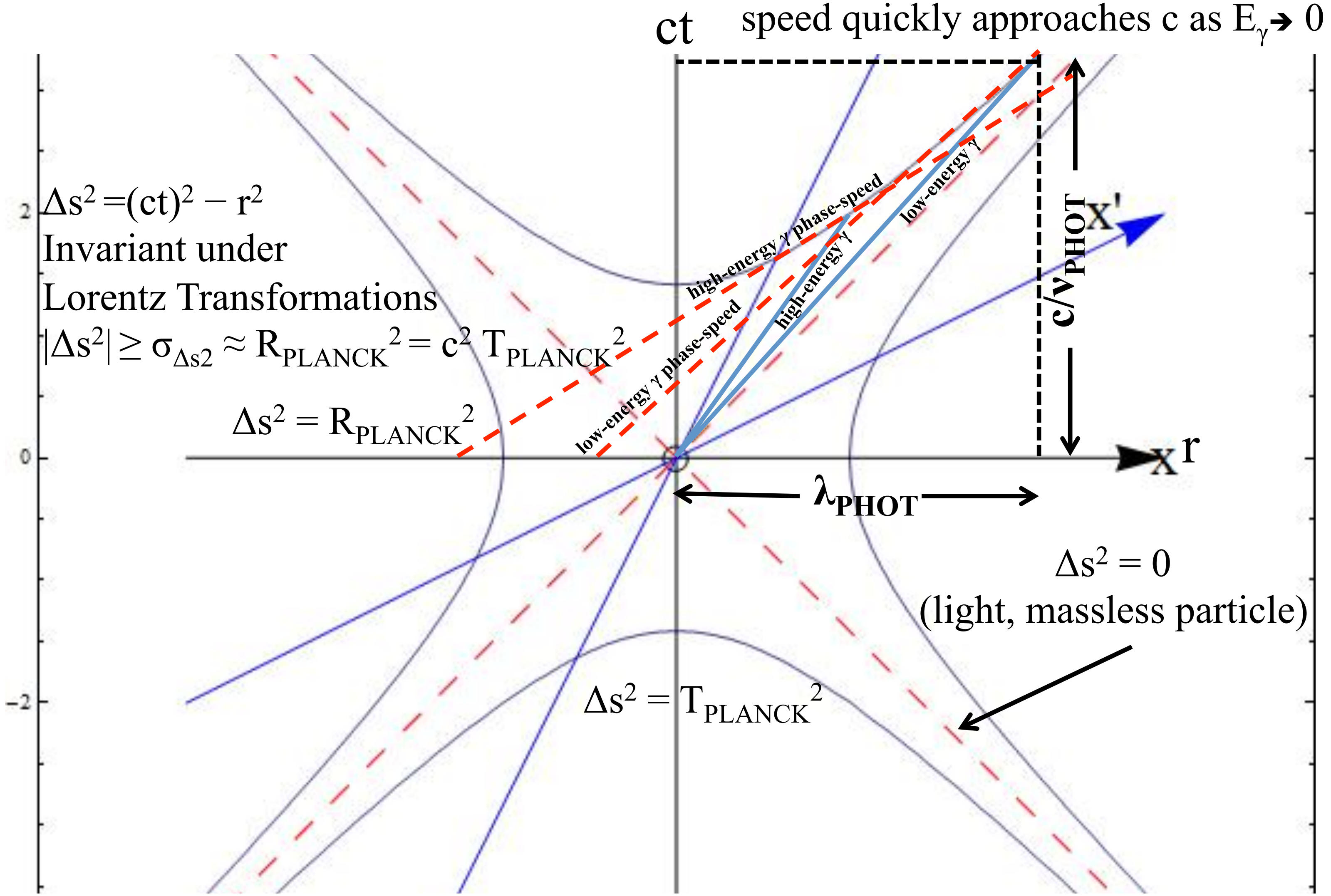




Massive Photons? (Proca action)

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

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



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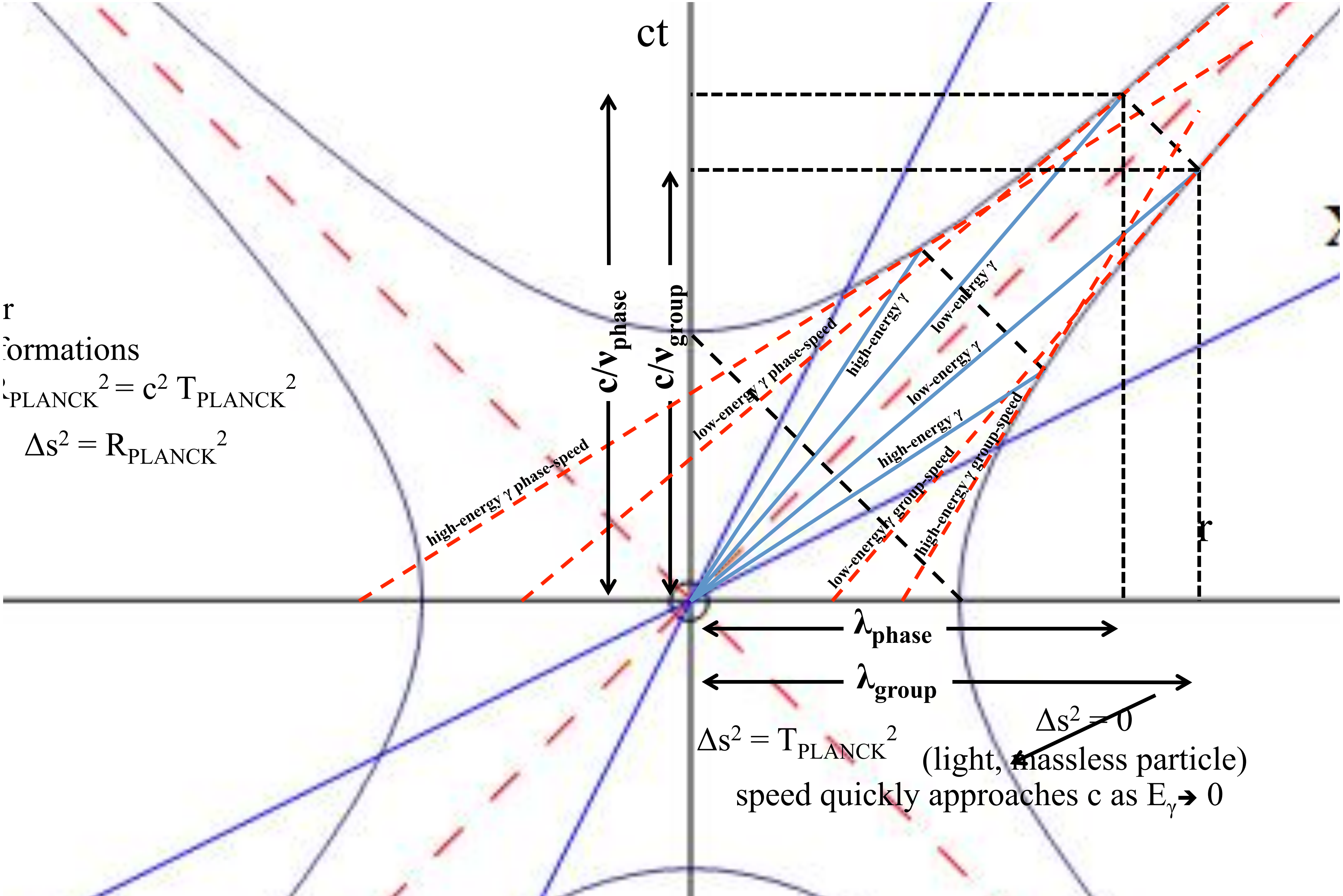
Massless Particles ⟶ Lorentz Invariance, not *vice versa!*



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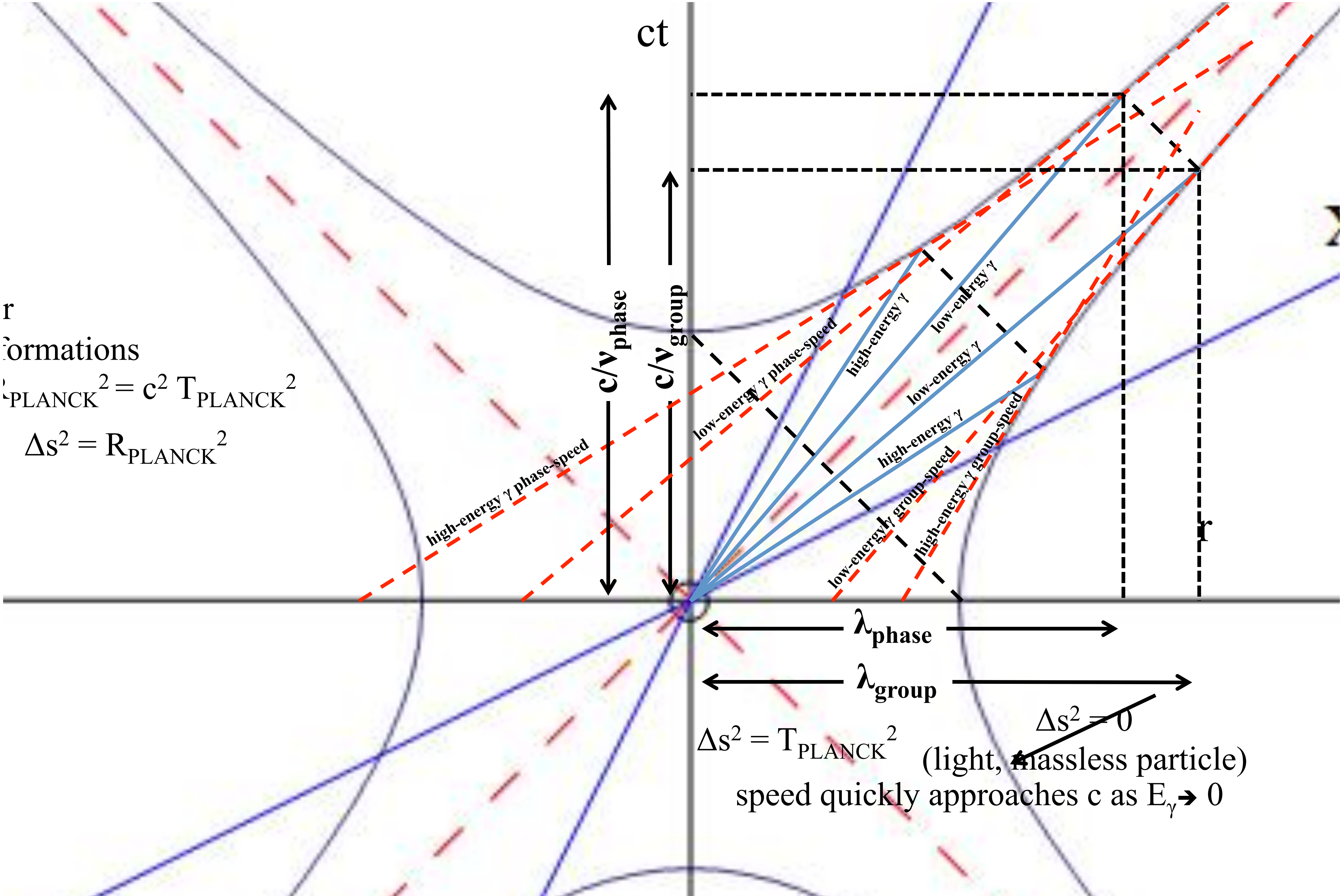

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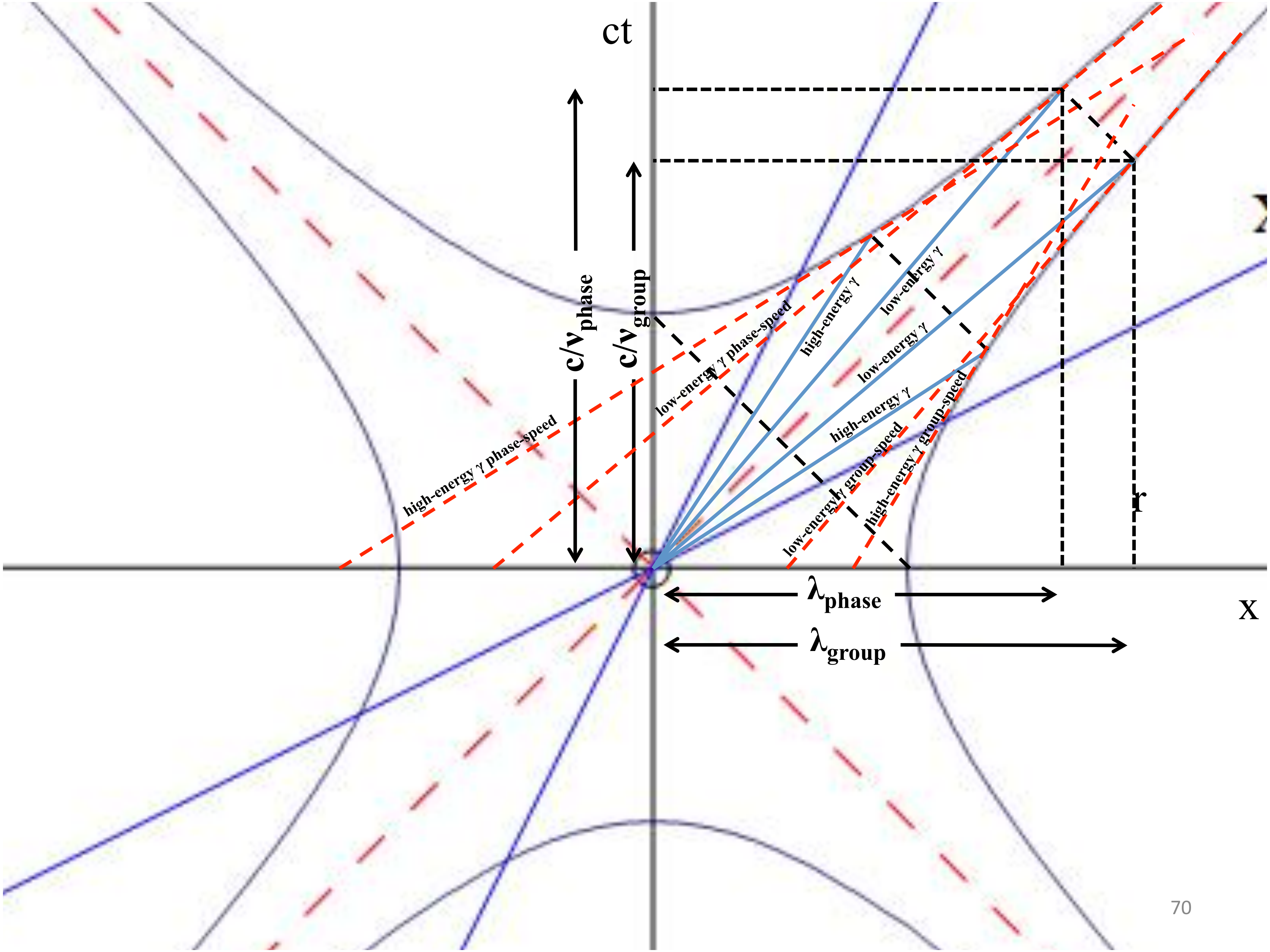
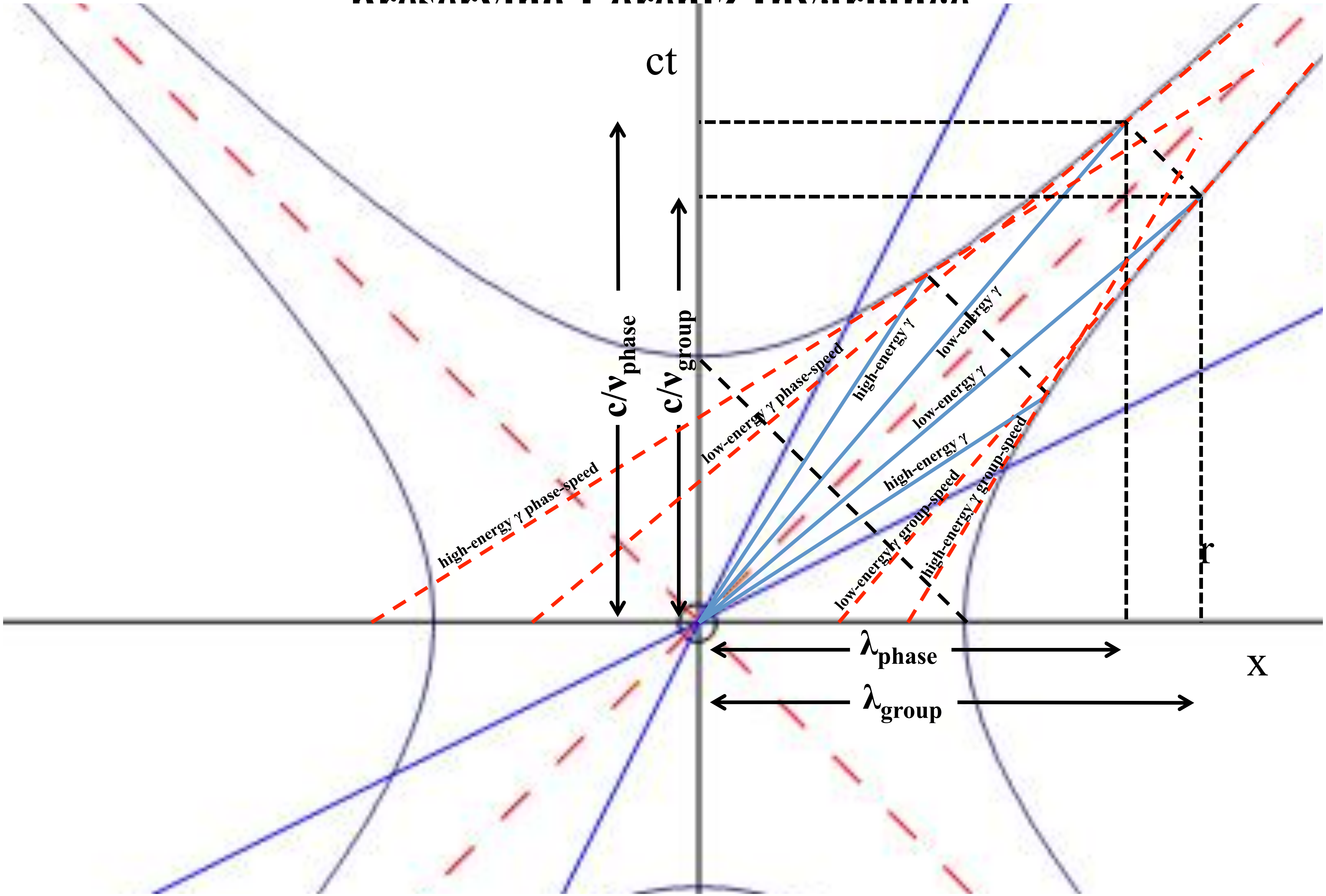
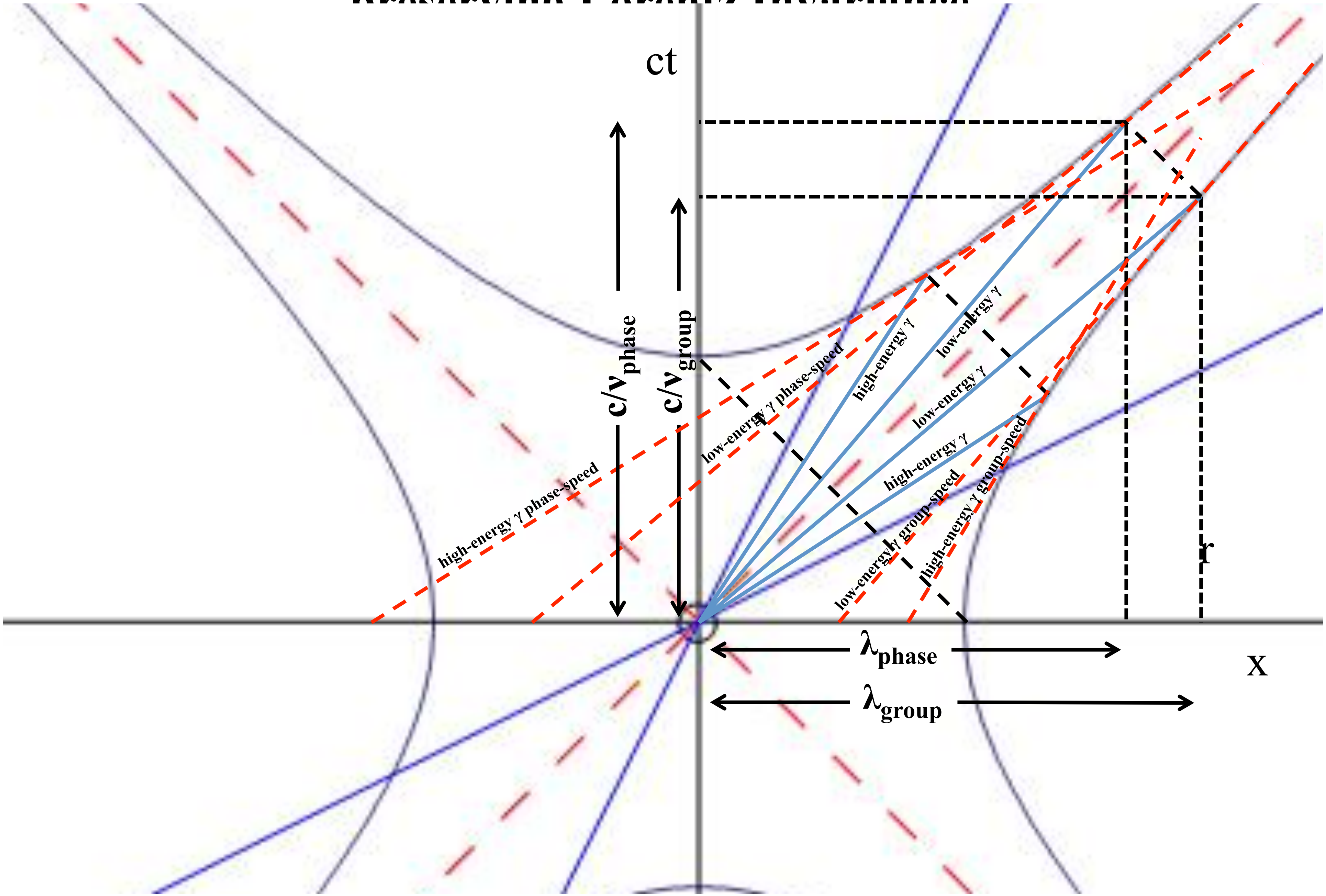

ct
c/v_phase
c/v_group
high-energy γ phase-speed
low-energy γ phase-speed
high-energy γ
low-energy γ
low-energy γ
high-energy γ
low-energy γ group-speed
high-energy γ group-speed
r
λ_phase
λ_group
x

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



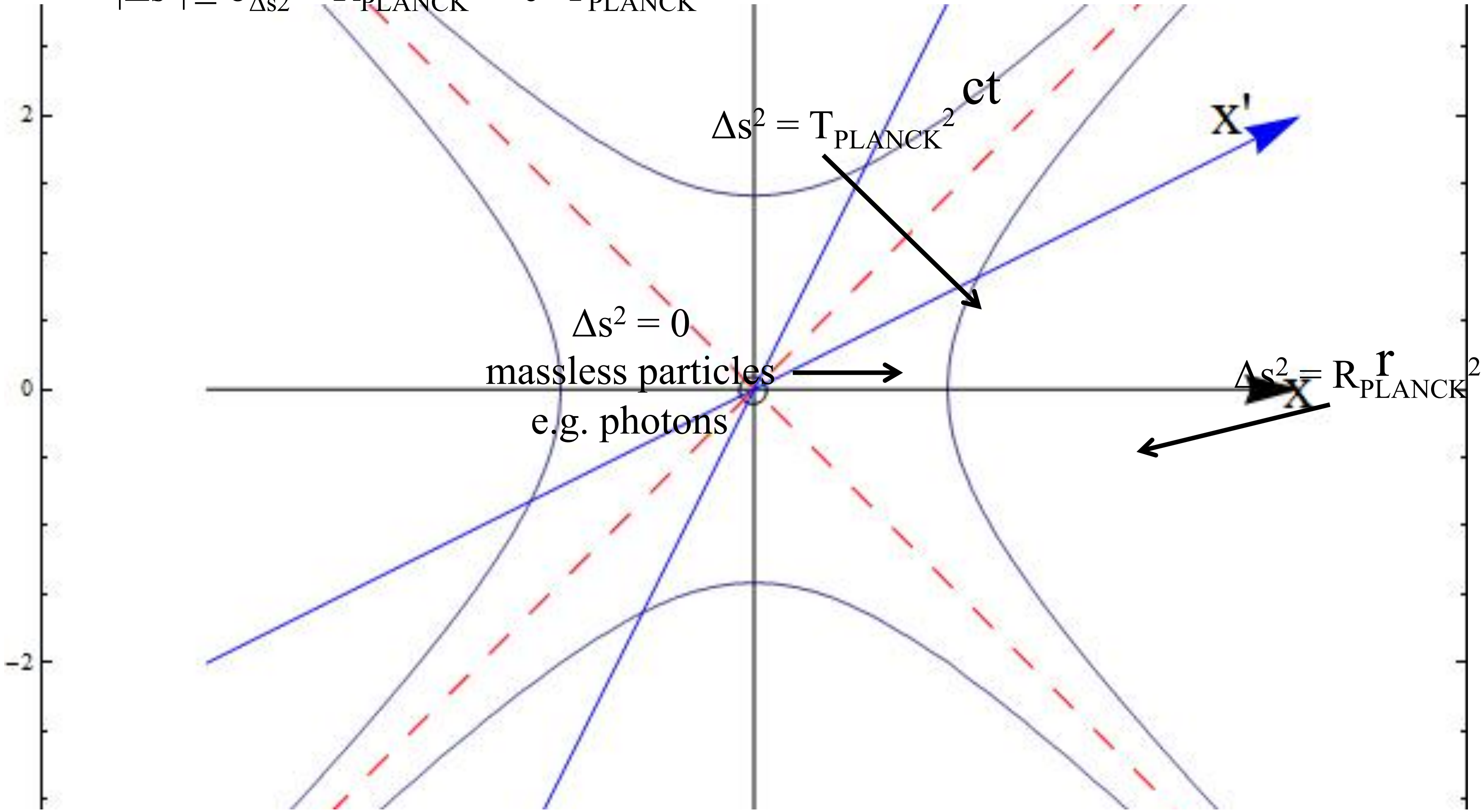
The new Uncertainty Relation and the Minkowski metric: preserving Lorentz Invariance



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

$\Delta s^2 = (ct)^2 - r^2$ invariant under Lorentz Transformations

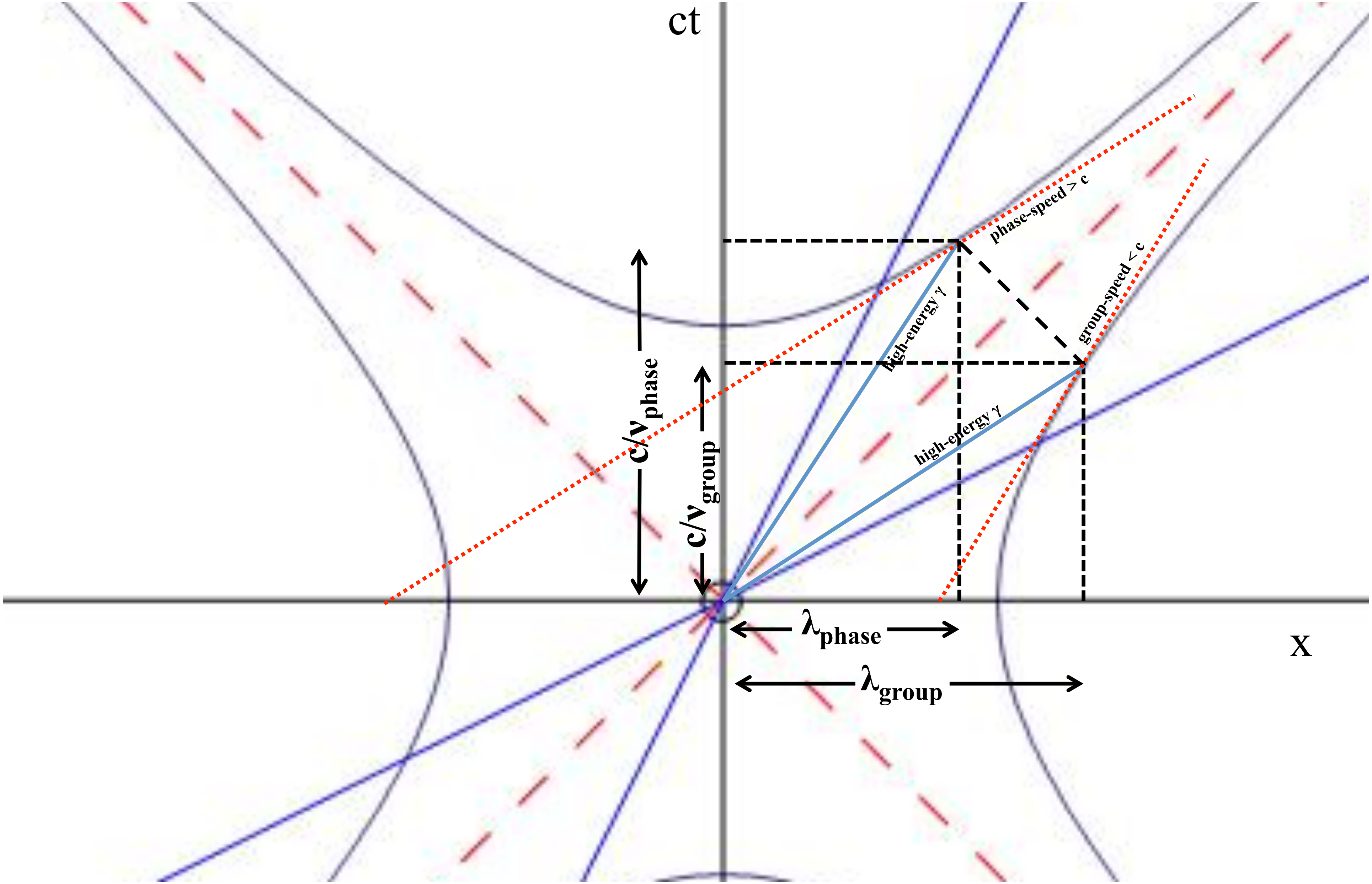
$|\Delta s^2| \geq \sigma_{\Delta s2} \approx R_{PLANCK}{}^2 = c^2\, T_{PLANCK}{}^2$



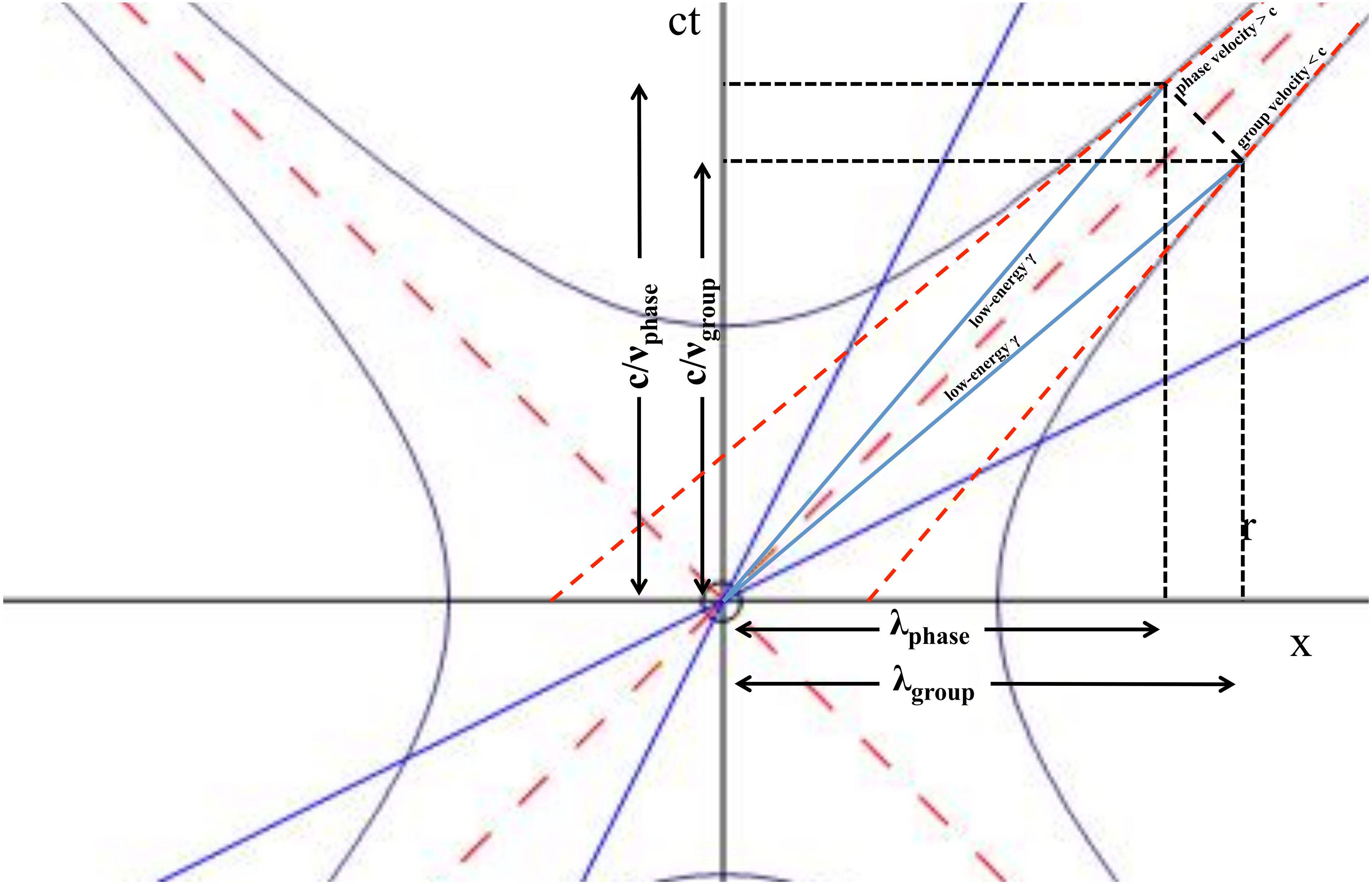
Massive Photons? (Proca action)

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

high energy photons phase and group velocities
group speed approaches 0 as $E_\gamma \rightarrow m_{PLANCK}\, c^2$



low energy photons phase and group velocities
group speed approaches c as $E_\gamma \to 0$



Probing space-time structure with GRAAL (Gamma-Ray Astronomy Anctartica Laboratory

Tethered balloon−borne experiment
$10 \div 100$ m^2 effective area

(GRAAL − Gamma Ray Astronomy Antarctica Laboratory
Alternatives:
GRAAL: Gamma Ray Astronomy Aerostatic Laboratory
GRAIL: Gamma Ray Astronomy International Laboratory
(Burderi, Di Salvo, Amati, Frontera, Rapisarda, Costa, et al.)

Challenges:

- carbonium fiber tether $30 \div 40$ km long safetly pass through the Jet Stream air currents at the base of the startosphere ($\approx$ 20 km) (Antarctica?)
- avoid too high particle background (Antarctica bad, but strong GRB not background dominated)

Advantages:

- huge effective area: $10 \div 100$ m^2
- multi−purpose scientific platform (CMB cosmology, atmospheric studies, etc.)
- low−cost WRT satellites