Was Zeno Right?

Quantum Clocks and Discreteness in Quantum Gravity:

Theoretical and Experimental Implications

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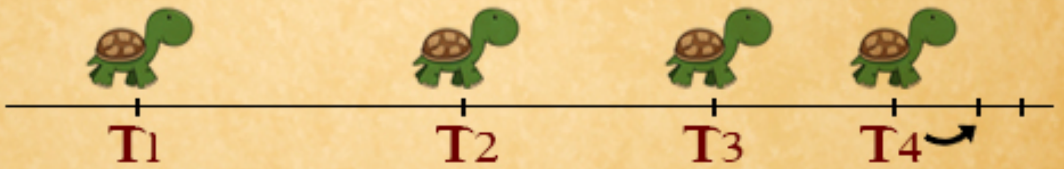
Zeno’s paradox



- 450 BC: Zeno and Parmenides visit Socrates in Athens. Zeno discusses his most famous paradox, known as *Achilles and the tortoise* (Plato, *Parmenides*, 127b-e).
- Zeno states that if one admits the endless divisibility of space, in a race the quickest runner can never overtake the slowest, which is patently absurd, thus demonstrating that the original assumption of infinite divisibility of space is false.
- The error in the reasoning of Zeno was the implicit assumption that an infinite number of tasks (the infinite steps that Achilles have to cover to reach the tortoise) cannot be accomplished in a finite time interval, which is not true if the infinite number of time intervals spent to accomplish all the tasks constitute a sequence whose sum is a convergent mathematical series.
- However the line of reasoning reported above exerts a certain fascination on our brains: **we reluctantly accept the fact that, in a finite segment, an infinite number of separate points may exist.**
- **Zeno’s paradox revisited in terms of Operationalism : is there a lower limit in the possibility of measuring small space (or time) intervals?**

Operationalism
Percy Williams Bridgman (1882-1961)

The concept is defined on the measurements

SR: “time” is the quantity measured by a light-clock (Einstein)

GR: “mass” is defined by

(a) Newton’s Second Law of Motion (inertial)

(b) Newton’s law of universal gravitation (gravitational)

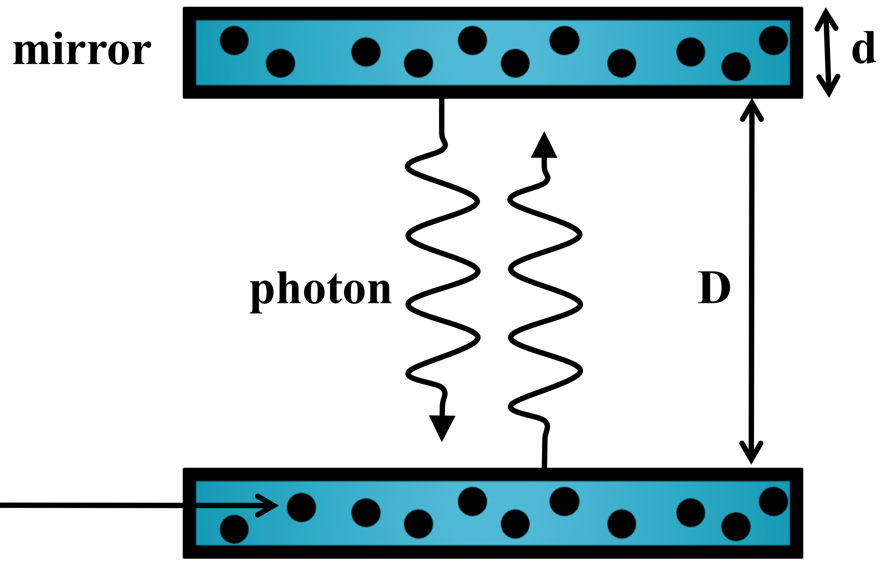
Equivalence Principle (Einstein):

(a) = (b)

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)

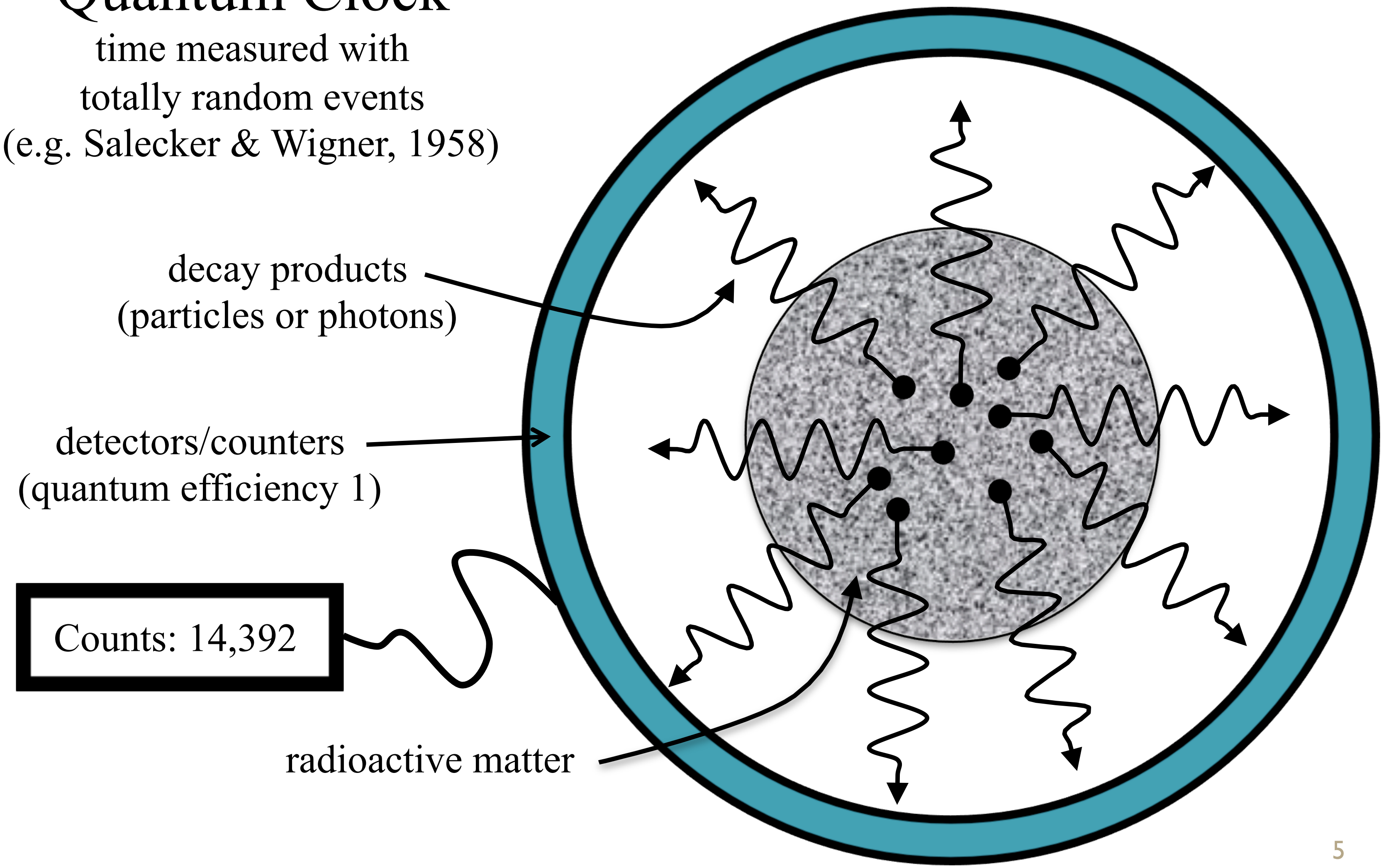
shortest time interval ever measured: 2×10^{-17} s (Schultze et al.2010)

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: $\Delta t \ll \tau_{PART}$

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: $\tau_{PART} \geq \delta t$

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

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

(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:

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

Uncertainty relations proposed in the literature

(see Hossenfel 2012 review)

1) The Salecker Wigner limit (1958) (see e.g. Camelia 1999):

$$\Delta r \geq [\hbar T_{OBS}(1/M_{BODIES} + 1/M_{DEVICE})/2]^{1/2}$$

(uncertainty on the distance of two bodies of total mass M_{BODIES} with a device of mass M_{DEVICE} operating over a time such that $r = c\, T_{OBS}/2$)

2) The Fundamental-Length Hypotheses (Mead 1964, 1966):

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

3) The Generalized Uncertainty Principle (see. e.g. Capozziello et al. 1999):

$$\Delta r \geq \hbar/(2\, \Delta p) + (\alpha/c^3)\, G\, \Delta p$$

4) In String Theory Yoneya (1987, 1989, 1997) proposed:

$$\Delta X_l \times c\Delta T \geq \ell_S^2$$

similar to the uncertainty relation proposed above (see also Doplicher et al. 1995), although:

a) ℓ_S is a free parameter of the theory (sometimes identified with the Planck length).

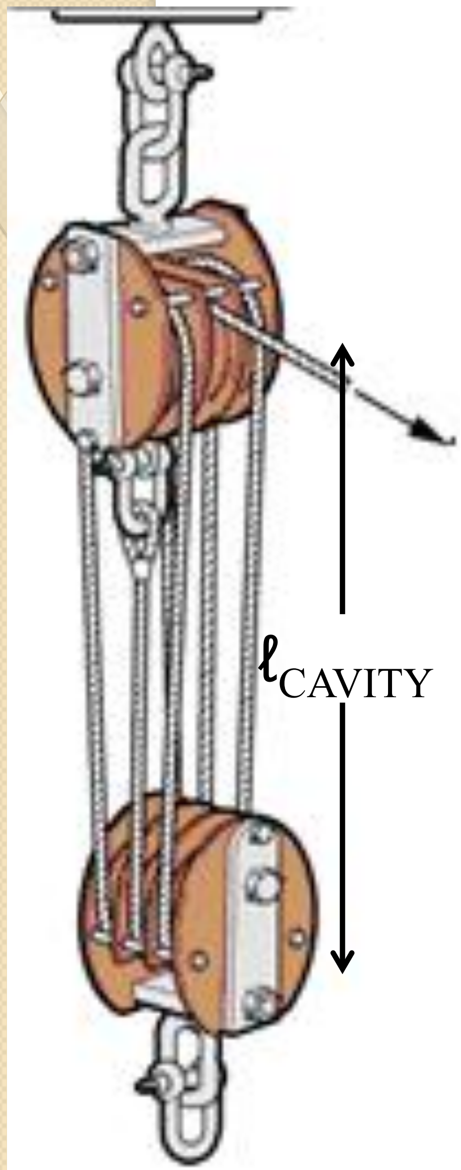
b) the proposed relation is “speculative and hence rather vague yet” (Yoneya).

5) Space-Time Uncertainty Principle (this work Phys. Rev. D, accepted):

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

“demostrated” by means of a *Gedankenexperiment*

Quantum Ruler (LIGO-like Laser Interferometers, LI)



Distance measurements using the "multi-pulley tackle" principle

$\ell_{TOT} = c\ \tau_{STORAGE}$:

$\ell_{TOT} = n_{TRIP}\ \ell_{CAVITY}$

$n_{TRIP} = c\tau_{STORAGE} / \ell_{CAVITY}$

$\Delta\ell \approx \lambda_{LASER}/2 \ \rightarrow \ \Delta\Phi_{INTERF.PATTERN} \approx \pi \ \rightarrow \ \Delta N_{PHOT} \approx \Delta N_{MAX}$

$\Delta N_{MAX} = N \text{ (light)} - 0 \text{ (dark)} = N$

Therefore, to first order:

$\Delta\ell / (\lambda_{LASER}/2) = \Delta N / N$

$\Delta\ell = n_{TRIP}\ \delta\ell_{CAVITY}$

$$\boldsymbol{\delta\ell_{CAVITY} = (\lambda_{LASER}/2)\ \Delta N / (N\ n_{TRIP})}$$

working principle of LI

$\delta\ell_{CAVITY} = (\lambda_{LASER}/2)\ \Delta N\ \ell_{CAVITY} / (c\tau_{STORAGE})$

$\delta\ell_{CAVITY}\ \tau_{STORAGE} = \pi\ \Delta N\ \ell_{CAVITY} / (N\ h\nu_{LASER}/c^2) \times (\hbar/c^2)$

$\delta\ell_{CAVITY}\ \tau_{STORAGE} = \pi\ \Delta N\ \ell_{CAVITY} / (M_{CAVITY}) \times (\hbar/c^2)$

To avoid LI collapse (hoop conjecture):

$\ell_{CAVITY} > 2\ R_{SCH,CAVITY} = 4GM_{CAVITY}/c^2$

$$\boldsymbol{\delta\ell_{CAVITY}\ \tau_{STORAGE} > 4\pi\ (G\hbar/c^4)}$$

The Quantum Clock/Ruler and Special Relativity

In SR "true" temporal and spatial intervals are defined by a combined measure of space and time:

"true" temporal intervals: TIMELIKE intervals measured at the same place ($\Delta r \approx 0$)

"true" spatial intervals: SPACELIKE intervals measured at the same time ($\Delta t \approx 0$)

Generalized "true" temporal interval: any TIMELIKE interval with $|c\Delta t| \geq |\Delta r|$

Generalized "true" spatial interval: any SPACELIKE interval with $|\Delta r| \geq |c\Delta t|$

We represent space and time intervals in a space-time intervals diagram.

We choose the space and time units in order to have c = 1, or $c\Delta t$ as the ordinate.

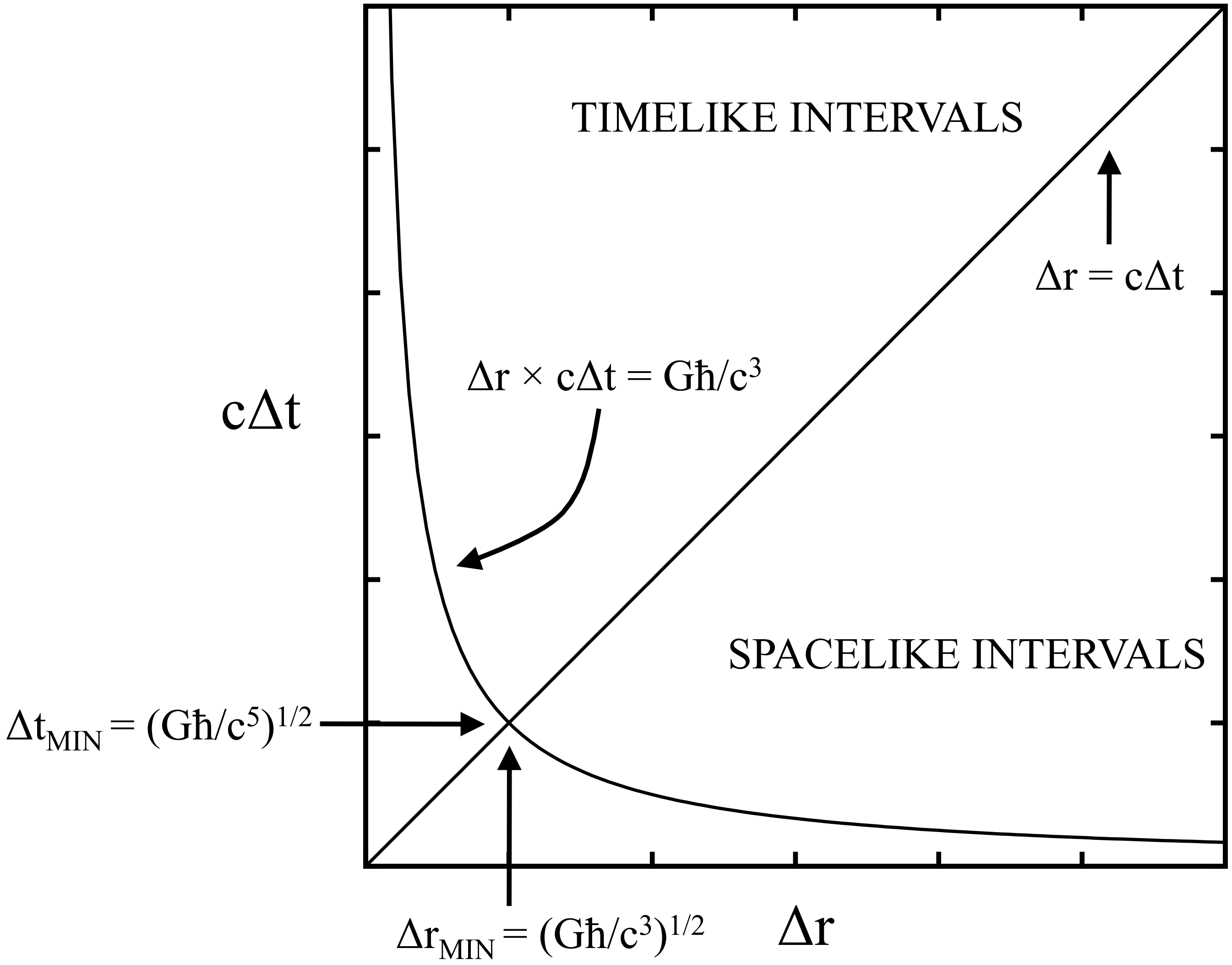
In this representation the bisector defines the null intervals, separating the TIMELIKE intervals, above the bisector, from the SPACELIKE intervals, below.

The extremal relation $\Delta r \times c\Delta t = G\hbar/c^3$ is an hyperbola in the space-time diagram.

Asymptotes: Δr axis and $c\Delta t$ axis.

Vertex at: $\Delta r_{VERTEX} = c\Delta t_{VERTEX} = (G\hbar/c^3)^{1/2} \equiv$ Planck Length $\equiv$ c×Planck Time

The new Uncertainty Relation and the space-time diagram for the intervals



The new Uncertainty Relation and Special (& General ?) Relativity

The following can be deduced:

I) TIMELIKE INTERVALS: $\Delta t_{MIN} = (G\hbar/c^5)^{1/2} = T_{PLANCK} \equiv$ Planck Time

II) SPACELIKE INTERVALS: $\Delta r_{MIN} = (G\hbar/c^3)^{1/2} = R_{PLANCK} \equiv$ Planck Length

III) The Uncertainty Relation is invariant under Lorentz Transformation since:

$\Delta r' = \gamma^{-1}\,\Delta r$ (Lorentz contraction)

$\Delta t' = \gamma\quad\Delta t$ (time dilation)

$\gamma = (1 - (v/c)^2)^{-1/2}$ (Lorentz factor)

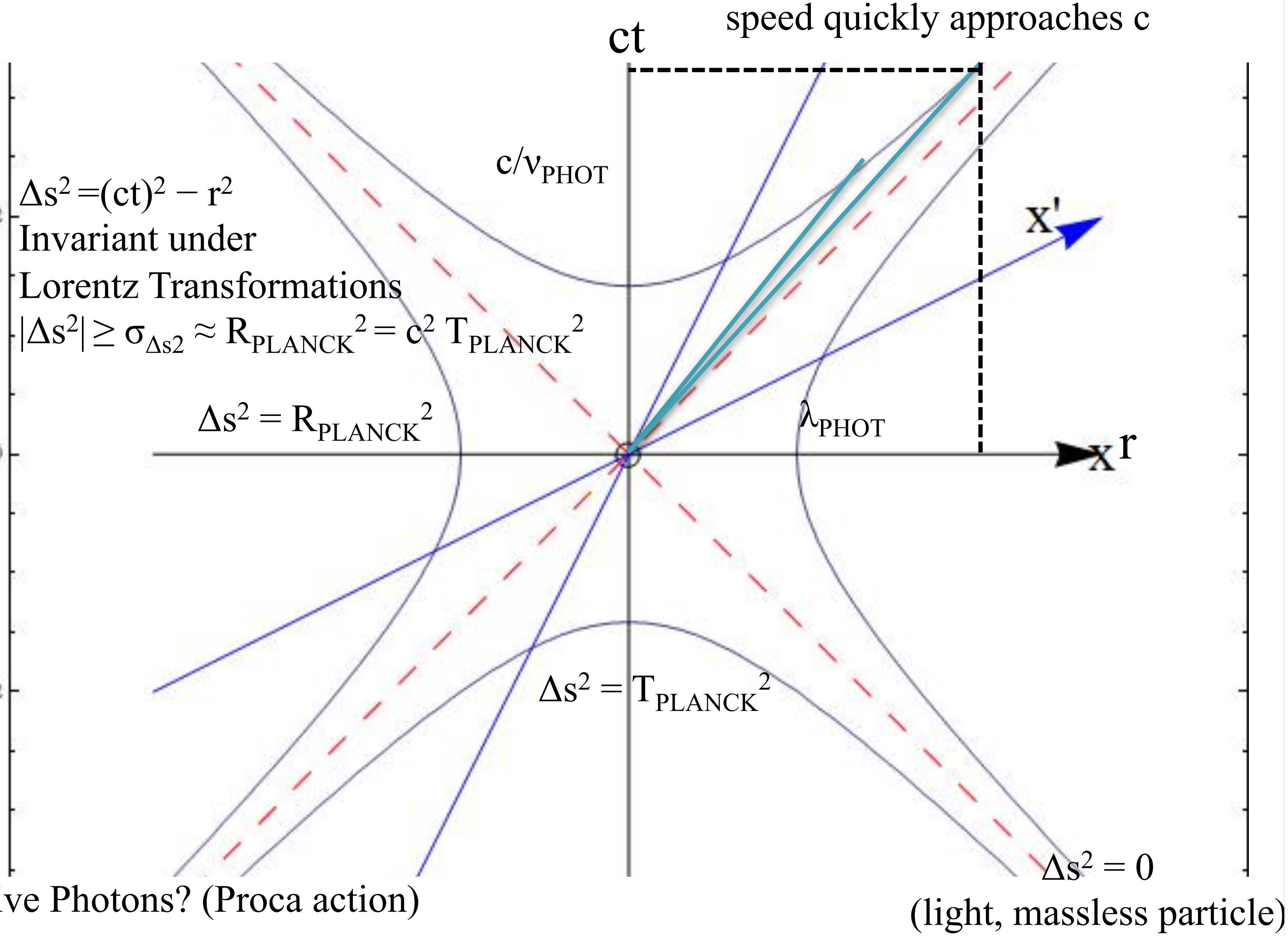
IV) The Uncertainty Relation is invariant in GR metric (?) e.g. Schwarzschild:

$\Delta s^2 = \zeta \times c^2\Delta t^2 - \zeta^{-1} \times \Delta r^2 - r^2 \times (\Delta\theta^2 + \sin^2\theta\,\Delta\varphi^2)$

$\zeta = (1 - R_{SCH}/r)$

$R_{SCH} = 2GM/c^2$ (Schwarzschild radius)

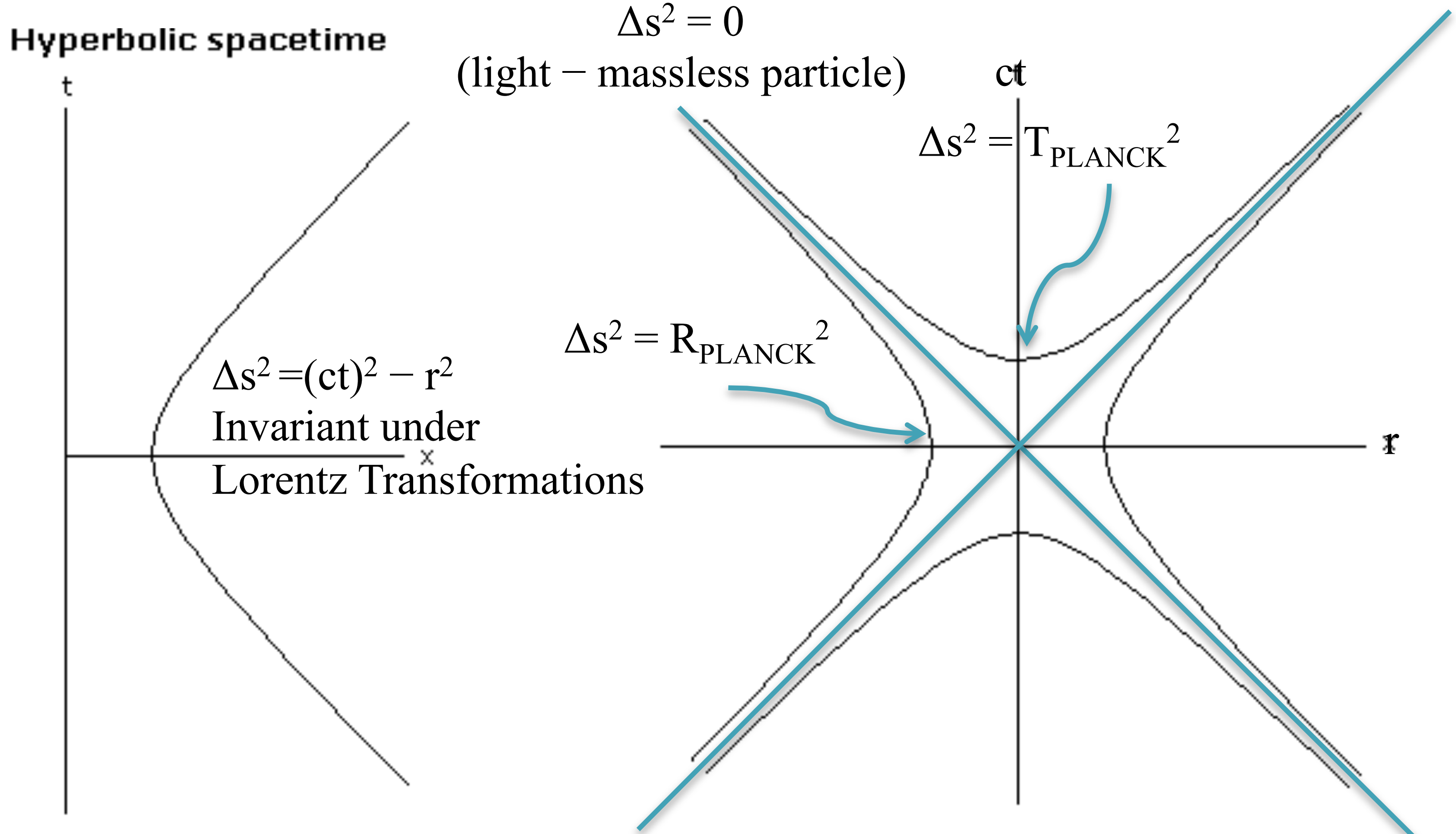
The new Uncertainty Relation and the Minkowski metric: preserving Lorentz Invariance



Massive Photons? (Proca action)

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

The new Uncertainty Relation 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!*

The Quantum Clock with radioactive substance: "in principle" feasibility for an "advanced civilization"

Decaying substance ^7H (1 proton + 6 neutrons, Gurov et al. 2004))

$m_{PART} \approx 7\ m_{PROTON}$

$\tau_{PART} \approx 2.3 \times 10^{-23}$ s

Asssume:

a) $\Delta t = 0.1 \times \tau_{PART}$ ($\Delta t << \tau_{PART}$)

b) $\sigma_{\Delta t} = 0.1 \times t_{PLANCK}$ to test below the Planck scale in a SPACELIKE interval, i.e. with light-crossing time longer than time interval to be measured $(\Delta x/c) > (\Delta t)$

We found:

$\sigma_{\Delta t} / \Delta t = \sigma_{\Delta N} / \Delta N_{\Delta t} = 1/(\Delta N_{\Delta t})^{1/2} = 1/(\lambda N\ \Delta t)^{1/2} = [\tau_{PART} /(N\ \Delta t)]^{1/2}$

Therefore: $(0.1 \times t_{PLANCK})/(0.1 \times \tau_{PART}) = [\tau_{PART} /(N \times 0.1 \times \tau_{PART})]^{1/2}$

$t_{PLANCK} / \tau_{PART} = (10 / N)^{1/2}$

$N = 10 \times (\tau_{PART}/t_{PLANCK})^2 = 10 \times (2.3 \times 10^{-23}\ \text{s}/5.4 \times 10^{-44}\ \text{s})^2 = 1.8 \times 10^{42}$

$M_{CLOCK} = N \times 7\ m_{PROTON} = 2.2 \times 10^{19}\ \text{g} = 3.6 \times 10^{-9}\ M_{EARTH}$

The Quantum Clock with Blackbody Radiation: the Blackbody Clock

Spherical box of radius R where a small (negligible) amount of matter is in equilibrium with an electromagnetic radiation field at a temperature T

$L = 4\pi R^2 \sigma_B T^4$; $\sigma_B = ac/4$; $a = (8\pi^5 k^4)/(15c^3h^3)$; $\langle h\nu \rangle = 3kT$; $E_{BB} = M_{BB}c^2 = (4/3)\pi R^3 a T^4$

$d\langle N_{PH}\rangle/dt = (4\pi R^2 \sigma_B T^4)/(3kT) = [(4/3)\pi R^3 a T^4]\times[c/(4RkT)] = M_{BB}c^2\times[c/(4RkT)]$

$\Delta N_{PHOT\Delta t} \equiv$ number of photons detected in the time Δt

$\Delta t = \Delta N_{PHOT\Delta t} \times (4RkT/c)/(M_{BB}c^2)$

Poisson statistics holds, therefore:

$\varepsilon = \sigma_{\Delta t} / \Delta t = \sigma_{\Delta N} / \Delta N_{PHOT\Delta t} = (\Delta N_{PHOT\Delta t})^{-1/2}$ or $\Delta N_{PHOT\Delta t} = \varepsilon^{-2}$

Therefore:

$\Delta t = (4RkT/c)/(\varepsilon^2 M_{BB}c^2)$

The Blackbody Clock, QM & GR

$\Delta t = (E_{PART} \times \tau_{PART})/(\varepsilon^2 M c^2)$ for Quantum Clock

$\Delta t = (4RkT/c)/(\varepsilon^2 M_{BB} c^2)$ for Blackbody Clock

Heisenberg uncertainty relation implies $E_{PART} \times \tau_{PART} \geq \hbar/2$ for Quantum Clock.

Does Heisenberg uncertainty relation imply $4RkT/c \geq \hbar/2$ for Blackbody Clock?

We have ($p_{PHOT} = \langle h\nu \rangle/c \equiv$ average photon momentum):

$(4RkT/c) = (4/3)\, R\, (3kT/c) = (4/3)\, R\, (\langle h\nu \rangle/c) = (4/3)\, R\, p_{PHOT}$

Since $p_{PHOT} \geq \delta p_{PHOT}$ and $R = \delta r$ we have $R \times p_{PHOT} \geq \delta r \times \delta p_{PHOT}$

Heisenberg uncertainty position-momentum relation: $\delta r \times \delta p \geq \hbar/2$

Therefore: $\Delta t = 1/(\varepsilon^2 M_{BB} c^2) \times (4RkT/c) \geq 1/(\varepsilon^2 M_{BB} c^2) \times (4/3) \times \hbar/2$

$\Delta t \geq (2/3)\, \hbar/(\varepsilon^2 M_{BB} c^2)$ and inserting the GR constraint, $1/M_{BB} > 2G/(c^2 \Delta r)$

$\Delta r\, \Delta t > (4/3)\, G\hbar/(\varepsilon^2 c^4)$

Dropping $\varepsilon^{-2} > 1$, we finally get $\Delta r\, \Delta t > (4/3)\, G\hbar/c^4$ which is the uncertainty relation again.

The "extreme" Quantum Clock: the Hawking Clock

The Quantum Clock and the Blackbody Clock stop working once $\Delta r \longrightarrow 2GM/c^2$
What if we use the Hawking-Bekenstein radiation emitted by a Black Hole to gauge time?

The Hawking Clock is a BlackBody Clock which uses Hawking-Bekenstein radiation emitted from the event Horizon of a Black Hole.

$dN_{PH}/dt = (4\pi R_{SCH}{}^2 \sigma_B T_{BH}{}^4)/(3kT_{BH}) = (4\pi\sigma_B/3k)\, R_{SCH}{}^2 T_{BH}{}^3$
where: $R_{SCH} = 2GM_{BH}/c^2$; $T_{BH} = \hbar c^3/(8\pi k G M_{BH})$

Consider, as before $\Delta t = \Delta N_{PHOT\Delta t} \times 3k/(4\pi\sigma_B R_{SCH}{}^2 T_{BH}{}^3)$
Poisson statistics holds: $\Delta N_{PHOT\Delta t} = \varepsilon^{-2}$, therefore:

$$\Delta t = \varepsilon^{-2} \times 3k/(4\pi\sigma_B R_{SCH}{}^2 T_{BH}{}^3) = [3k/(4\pi\sigma_B)]/(\varepsilon^2 R_{SCH}{}^2 T_{BH}{}^3)$$

The Hawking Clock, QM & GR

QM implies: $T_{BH} = \hbar c^3/(8\pi k G M_{BH})$

GR implies (Hoop Conjecture): $\Delta r > R_{SCH}$

Therefore:

$\Delta r\, \Delta t > [3k/(4\pi\sigma_B)] \times [M_{BH}c^2/(R_{SCH}T_{BH}{}^3)]/(\varepsilon^2 M_{BH}c^2)$

$\Delta r\, \Delta t > 2^8 3^2 5 \times (GM_{BH})^2/(\varepsilon^2 c^5)$

Summarizing:

$\Delta t = \quad (E_{PART} \times \tau_{PART})/\varepsilon^2 \times (Mc^2)^{-1}$ $\quad E_{PART} \times \tau_{PART} \geq \hbar/2$ for Quantum Clock

$\Delta t = (4/3) \times (3RkT/c)/\varepsilon^2 \times (M_{BB}c^2)^{-1}$ $\quad 3RkT/c \geq \hbar/2$ for Blackbody Clock

$\Delta t = (2^8 3^2 5) \times (G/c^9)/\varepsilon^2 \times (M_{BH}c^2)^2$ $\quad$ for Hawking Clock

For Quantum Clock and Blackbody clock the minimum occurs for the greatest clock mass.

For the Hawking Clock the minimum occurs for the smallest Black Hole mass.

The Hawking Clock & the smallest BH mass

Black Holes radiate Hawking-Bekenstein radiation with $\langle E_{PART} \rangle = 3kT_{BH}$

At the end of the evaporation process we must have $\langle E_{PART} \rangle = 3kT_{BH} \approx M_{MIN}c^2$

This gives:

$M_{BH,MIN} = (3k/c^2)\ T_{BH} = (3/8\pi)\ (\hbar c/GM_{BH,MIN})$ or

$M_{BH,MIN} = (3/8\pi)^{1/2}\ (\hbar c/G)^{1/2} = (3/8\pi)^{1/2}\ m_{PLANCK}$

We found:

$\Delta r\ \Delta t > 2^8 3^2 5 \times (GM_{BH})^2/(\varepsilon^2 c^5) > 2^8 3^2 5 \times (GM_{BH,MIN})^2/(\varepsilon^2 c^5)$

$\Delta r\ \Delta t > (2^5 3^3 5/\pi) \times (Gm_{PLANCK})^2/(\varepsilon^2 c^5) = [2^5 3^3 5/(\pi\varepsilon^2)] \times G^2(\hbar c/G)/c^5$

$\Delta r\ \Delta t \geq (2^5 3^3 5/\pi)\ \varepsilon^{-2}\ (G\hbar/c^4)$

$\Delta r\ \Delta t \geq (2^5 3^3 5/\pi)\ G\hbar/c^4$ (dropping $\varepsilon^{-2}>1$)

which confirms the uncertainty relation again.

Conclusions on Quantum Clock/Ruler

- by means of a *Gedankenexperiment* with a Quantum Clock/Ruler, based on random rather than periodic events, we propose a new Uncertainty Relation:

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

- the relation is quite general being a necessary consequence of the very first principles of QM (Heisenberg Uncertainty Relations) and of GR (the formation of an Event Horizon for sufficiently high densities)
- when combined with the constrain imposed by SR, the new Uncertainty Relation gives:

$$\Delta t_{MIN} = (G\hbar/c^5)^{1/2} \equiv \text{Planck Time}$$
$$\Delta r_{MIN} = (G\hbar/c^3)^{1/2} \equiv \text{Planck Length}$$

- the relation is invariant in SR (GR, Schwarzschild?)
- the relation makes Space and Time non-commuting quantities (starting point for Quantum Gravity?)
- if, below the Plank scale, space-time has no meaning, Gravity, which is a curvature of space-time, could vanish at those scales (no singularity?)
- we discussed two similar albeit different clocks for which the new Uncertainty Relation holds
- combined with Lorentz Invariance, this relation suggests massive photons (and gravitons?)

Marginally Stable Blackbody (MSBB) & BHs

Energy, Entropy and Mass of a Blackbody:

$\varepsilon_{BB} = aT^4$; $\sigma_{BB} = 4aT^3/3$; $a = (8\pi^5 k^4)/(15c^3h^3)$; $\rho_{BB} = \varepsilon_{BB}/c^2$; $R_{SCH} = 2GM_{BB}/c^2$

$M_{BB} = \varepsilon_{BB}/c^2 \times V_{BB} = (aT^4/c^2) \times (4/3)\pi R^3$; $S_{BB} = \sigma_{BB} \times V_{BB} = (4aT^3/3) \times (4/3)\pi R^3$

$S_{BB} = M_{BB} \times [\sigma_{BB}/(\varepsilon_{BB}/c^2)] = M_{BB} \times [(4aT^3/3)/(aT^4/c^2)]$

$\mathbf{S_{BB} = M_{BB} \times [(4c^2)/(3T)]}$

MSBB ≡ a Blackbody whose radius is just above its Schwarzschild radius

$M_{MSBB} = (aT_{MSBB}{}^4/c^2) \times (4/3)\pi R_{SCH}{}^3 = (aT_{MSBB}{}^4/c^2) \times (4/3)\,\pi\,(2GM_{MSBB}/c^2)^3$

$\mathbf{T_{MSBB} = [(3c^8)/(32\pi G^3 a)] \times M_{MSBB}{}^{-1/2}}$

Entropy of a Marginally Stable Blackbody:

$$\mathbf{S_{MSBB} = (4/3)\times(4\pi G^3 a)^{1/4} \times M^{3/2}}$$

Entropy of a BH (Bekenstein−Hawking):

$S_{BH} = (k/4) \times (4\pi R_{SCH}{}^2/R_{PLANCK}{}^2)$

$R_{PLANCK} = (G\hbar/c^3)^{1/2}$; $m_{PLANCK} = (\hbar c/G)^{1/2}$; $4\pi R_{SCH}{}^2/R_{PLANCK}{}^2 = 16\pi\,(M/m_{PLANCK})^2$

$$\mathbf{S_{BH} = (k/4) \times (16\pi/m_{PLANCK}{}^2) \times M^2}$$

Was Zeno right? No singularities in BHs

Entropy of a Marginally Stable Blackbody:

$S_{MSBB} = (4/3)\times(4\pi G^3 a)^{1/4} \times M^{3/2}$; $a = (8\pi^5 k^4)/(15c^3h^3)$; $m_{PLANCK} = (\hbar c/G)^{1/2}$

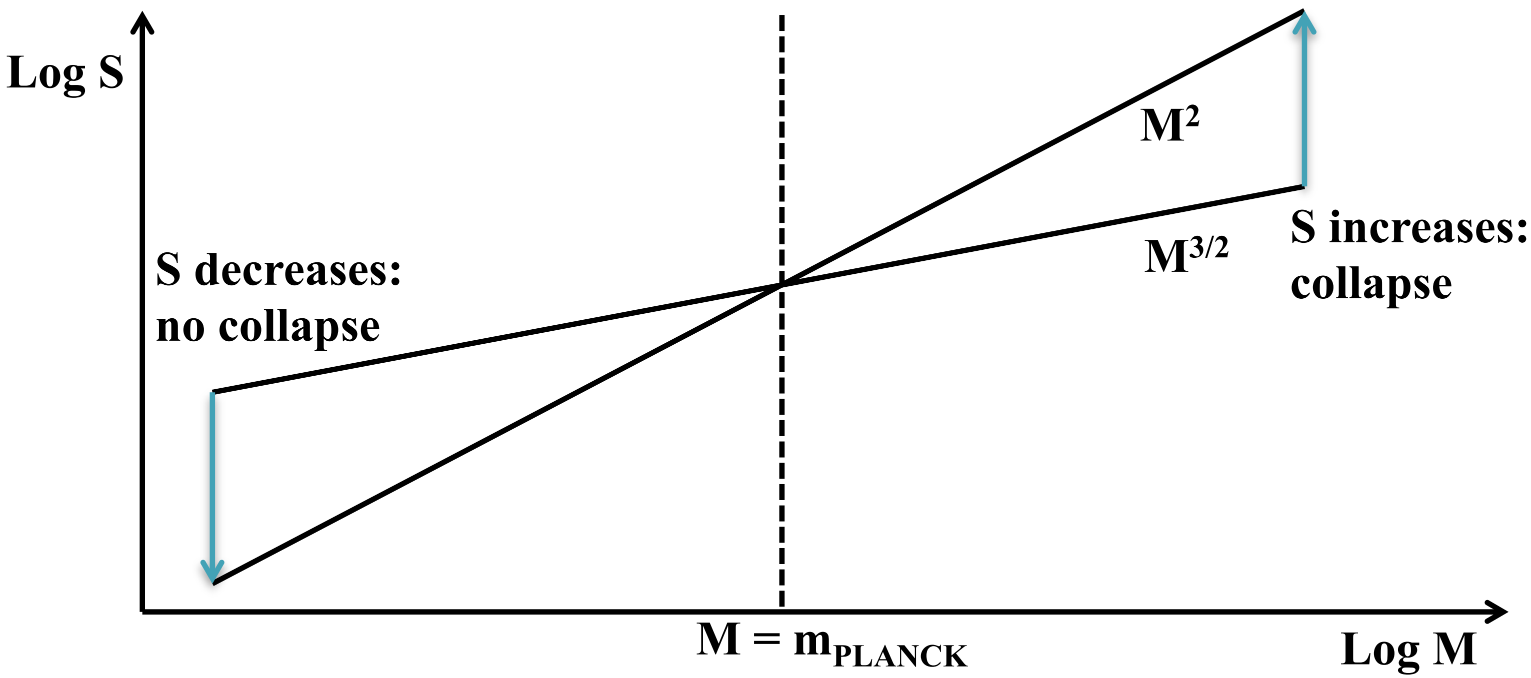
$S_{MSBB} = (8/3) \times 1/(15\times16\pi)^{1/4} \times (k/4) \times (16\pi) \times (M/m_{PLANCK})^{3/2}$

$$\mathbf{S_{MSBB} = 0.509 \times (k/4) \times (16\pi) \times (M/m_{PLANCK})^{3/2}}$$

Entropy of a BH (Bekenstein−Hawking):

$$\mathbf{S_{BH} = (k/4) \times (16\pi) \times (M/m_{PLANCK})2}$$

for $M/m_{PLANCK} = 0.26\ (\approx 1)$ ➔ $S_{MSBB} = S_{BH}$



Was Zeno right? Planckballs (PB)

Stable Planckballs:

for $M_{PB}/m_{PLANCK} = 0.26 \Rightarrow S_{MSBB} = S_{BH}$

for $R_{PB}/R_{PLANCK} = 0.52 \Rightarrow S_{MSBB} = S_{BH}$

$\rho_{PLANCK} = m_{PLANCK}/R_{PLANCK}^3 = c^5/(G^2\hbar) = 5.18 \times 10^{93}$ g/cm^3

$\rho_{PB} = 0.26 \times m_{PLANCK} /[(4/3)\pi(0.52 \times R_{PLANCK})^3] = 0.44 \times \rho_{PLANCK}$

The "size" of a PB "spherical" aggregate is:

$M = (4/3)\, \pi\, R^3\, \rho_{PB}$

A $10^9\, M_{\odot}$ BH has a PB "spherical" aggregate of "radius"

R= 6×10^{-5} fm ($R_{ELECTRON} = e^2/(m_e c^2) = 2.8$ fm

Entropy of a Planckball Aggregate

Different configurations of a Planckball Aggregate

define Space-time microstates

In strict analogy with:

Regge Calculus (triangulation in topology)

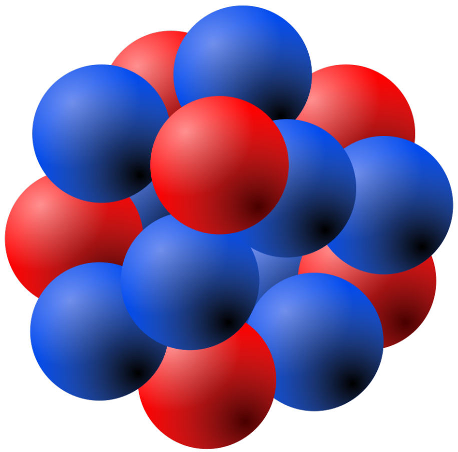
Loop Quantum Gravity (Smolin, Rovelli, et al.)

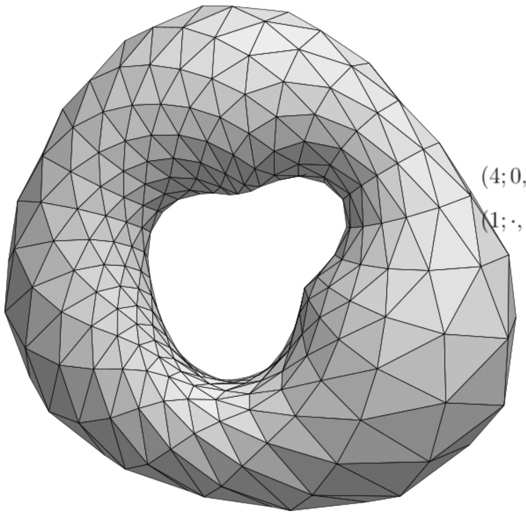
Spin Network

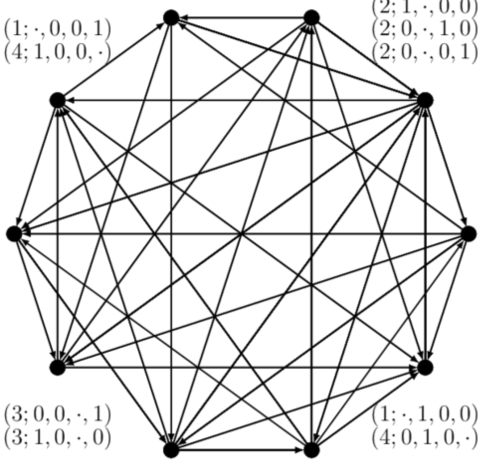
Bose−condensates for BH structure (Dvali, Gomez, et al.)

Number of links of n nodes: $\mathbf{N_{LINKS} = n \times (n-1) / 2}$

Number of d.o.f. of each link: $\mathbf{Z = Integer \geq 2}$







Entropy of a Planckball Aggregate

Aggregate of n Planckballs:

$n = M_{BH}/M_{PB} = = M_{BH}/(0.26 \times m_{PLANCK})$

$S = k \ln(W)$

$W \equiv$ number of microstates

$W = W_{PB1} \times W_{PB2} \times \ldots \times W_{PBn} \times W_{NETWORK}$

$W_{PB1} = W_{PB2} = \ldots = W_{PBn} = W_{PB}$

$W_{NETWORK} = Z^{n\times(n-1)/2}$

$W = W_{PB}^{\,n} \times Z^{n\times(n-1)/2}$

$\ln(W_{PB}) = 0.843$

$S = k \ln(W_{PB}^{\,n} \times Z^{n\times(n-1)/2}) = n\, k \ln(W_{PB}) + n\times(n-1)/2\; k \ln(Z)$

$\mathbf{S = (k/4) \times (16\pi) \times \{ A(Z) \times (M_{BH}/m_{PLANCK})^2 + B(Z) \times (M_{BH}/m_{PLANCK}) \}}$

$A(Z) = [\ln(Z)/1.686]$ $\quad A(2) = 0.411 \approx 1$

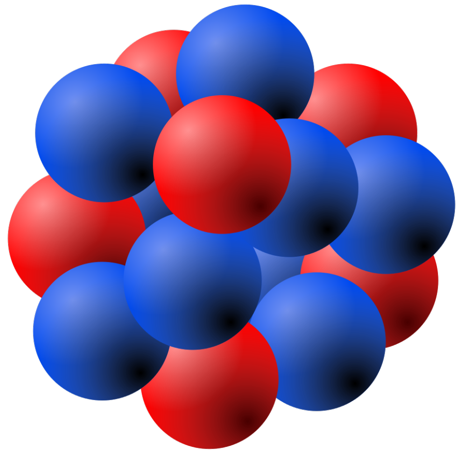
$B(Z) = [0.843 - \ln(Z)/2]/3.255$ $\quad B(2) = 0.152 \approx 1$

for $M_{BH} >> m_{PLANCK}$:

$\mathbf{S \approx (k/4) \times (16\pi) \times A(Z) \times (M_{BH}/m_{PLANCK})^2}$

to be compared with:

$\mathbf{S_{BH} = (k/4) \times (16\pi) \times (M_{BH}/m_{PLANCK})^2}$



The HERMES project

High Energy Rapid Modular Ensamble of Satellites

1) **H.E.R.M.E.S. High Energy Rapid Modular Experiment Scintillator**
   ASI Bando di ricerca per Nuove idee di strumentazione scientifica per missioni future di Osservazione ed Esplorazione dell'Universo: finanziato il 23 dicembre 2016 **€ 400,000 + € 100,000** (cofinanziamento)
2) **H.E.R.M.E.S. Pathfinder - High Energy Rapid Modular Ensemble of Satellites: uno sciame di satelliti per sondare la struttura dello Spazio-Tempo e le controparti elettromagnetiche delle Onde Gravitazionali**
   Progetto PREMIALE capofila ASI: presentato il 4 novembre 2016 **€ 3,761,000 + € 2,140,000** (cofinanziamento)

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

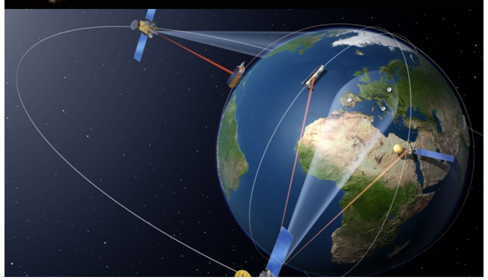
Alessandro Riggio, University of Cagliari

Andrea Sanna, University of Cagliari

Fabiana Scarano, University of Cagliari

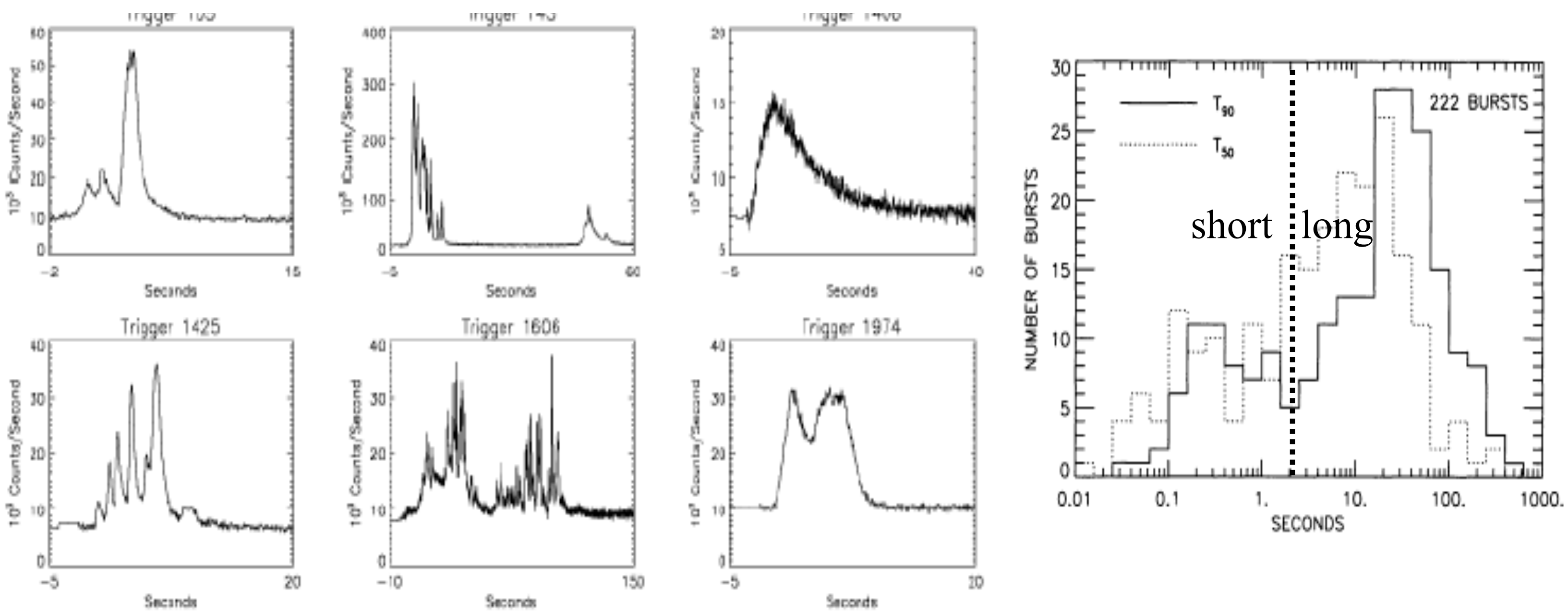
Andrea Vacchi, INFN Trieste

and many others…



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

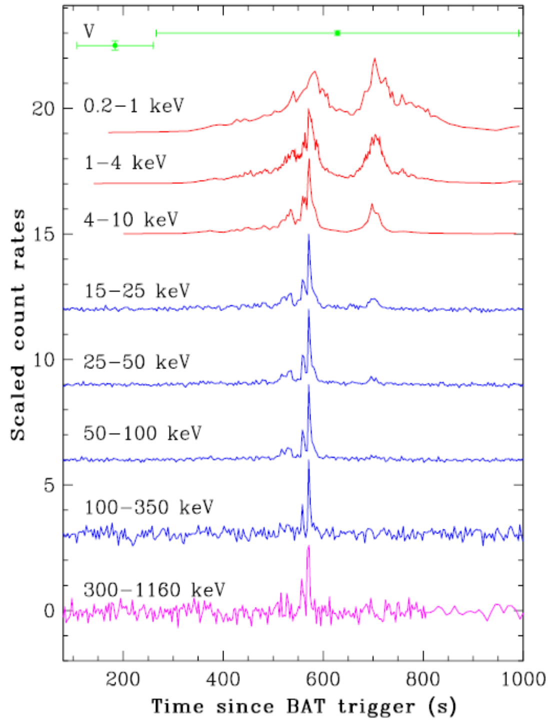
Prompt Emission:

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

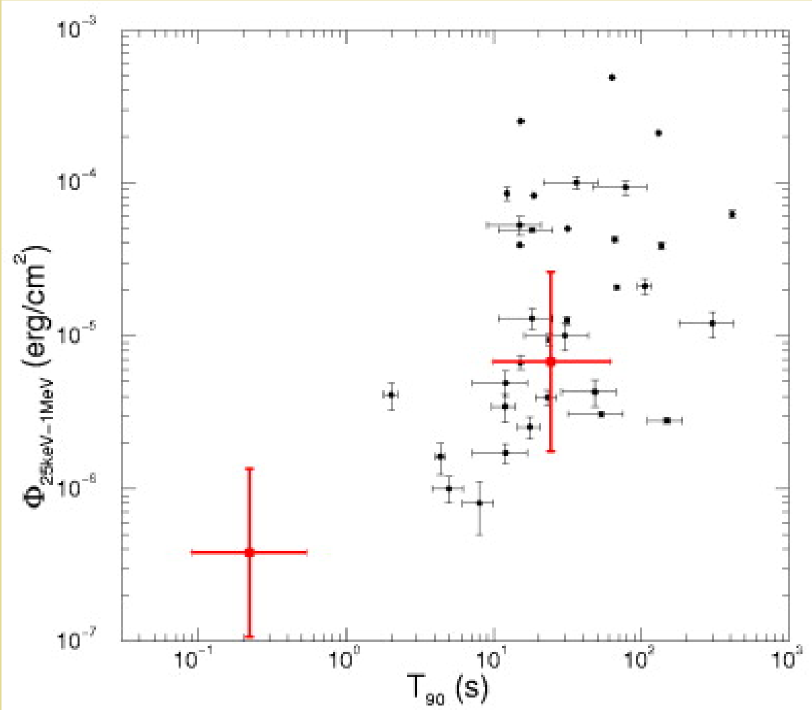
=> Binary NS mergers (**GW sources**)

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

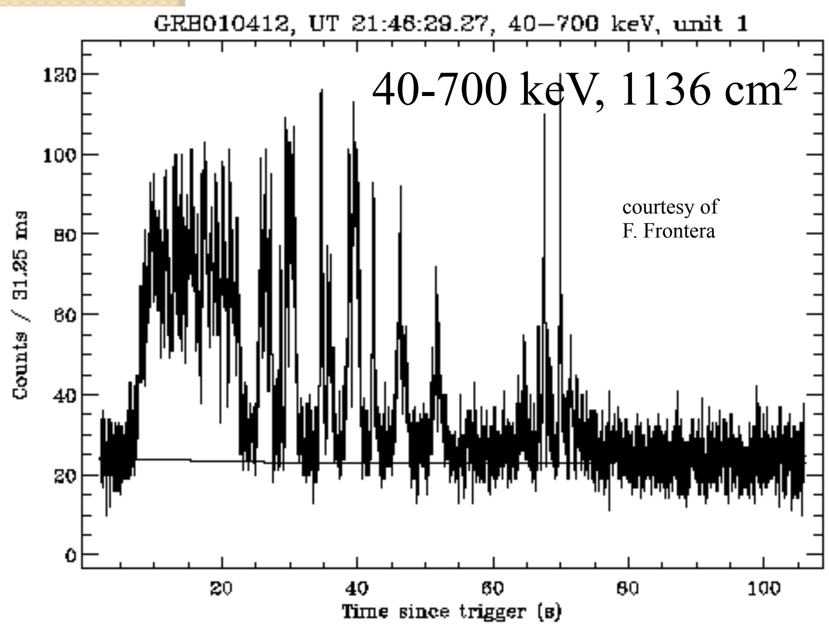
Millisecond variability (minimum variability time-scale, MacLachlan et al. 2013)

Short: 3 msec (wavelet techniques)

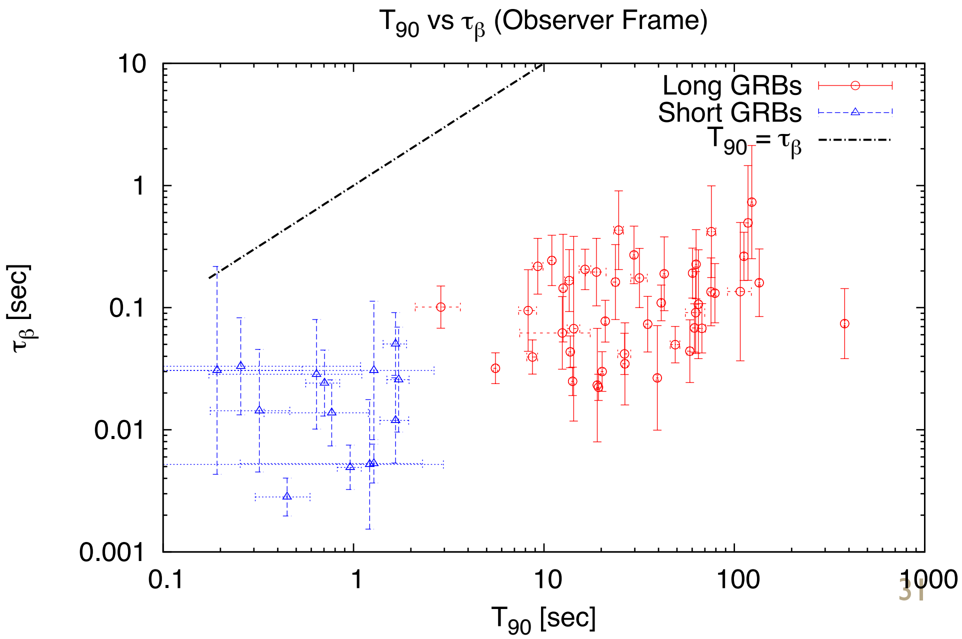
Long: 30 msec (wavelet techniques)

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

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

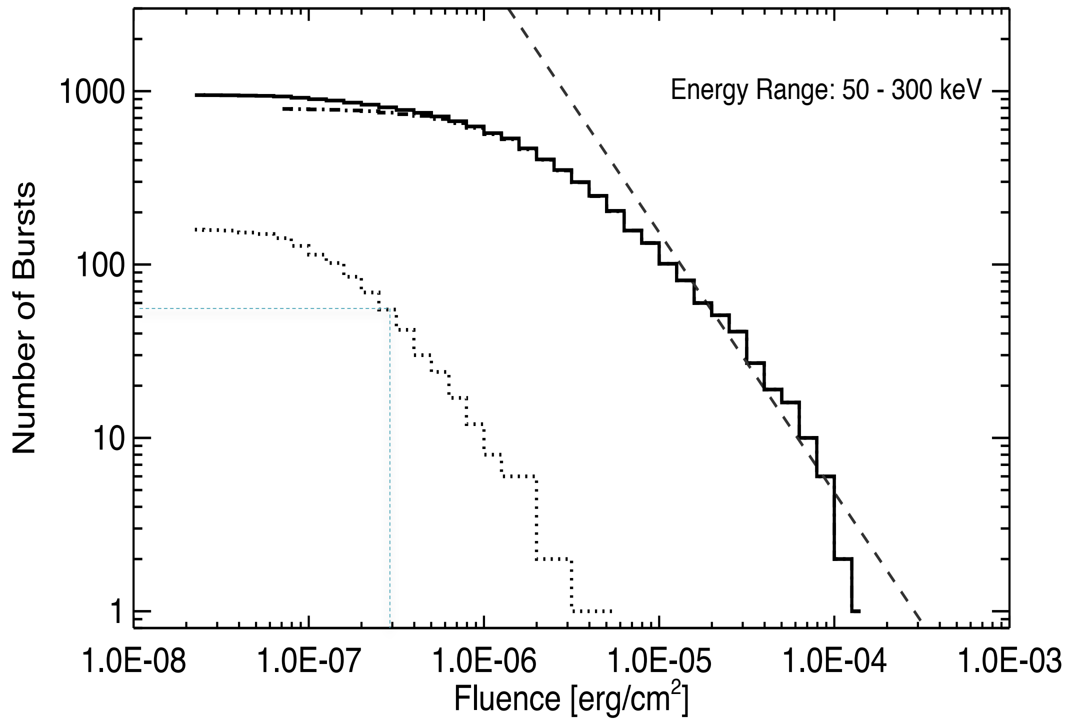
Fluence: 0.2 x 8 x 122 keV/cm^2 = 3 x 10^{-7} erg/cm^2

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): $\leq$ 0.3 c/cm^3/s (not included)

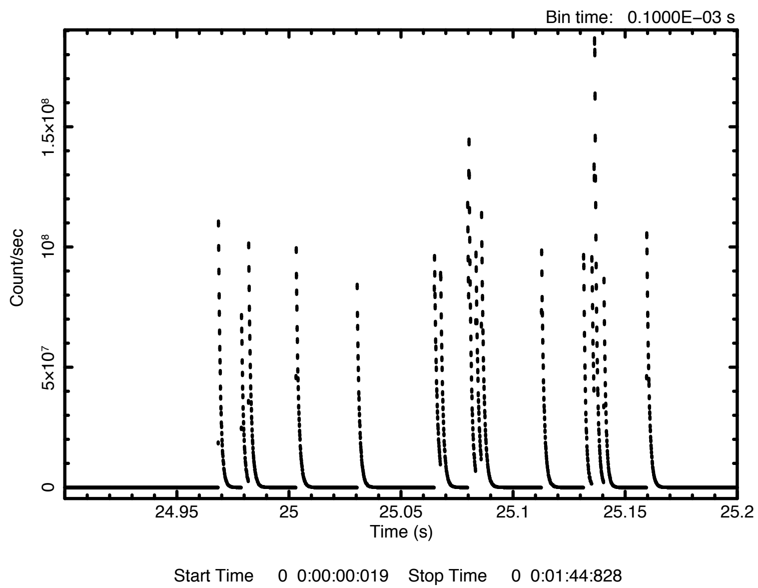
Burst duration: 0.2 sec

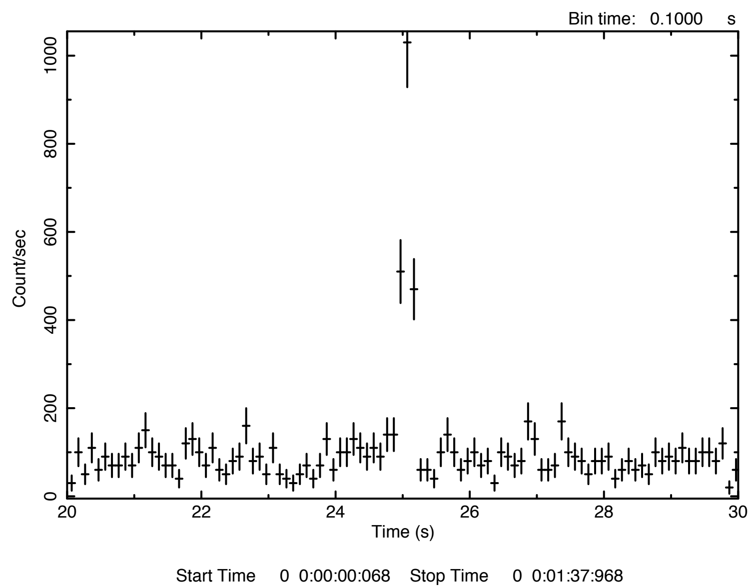
Source count rate: 7.875 ph/cm^2/s

Exponential shot rate: 100 shot/s

Exponential shot decay time: 1 msec

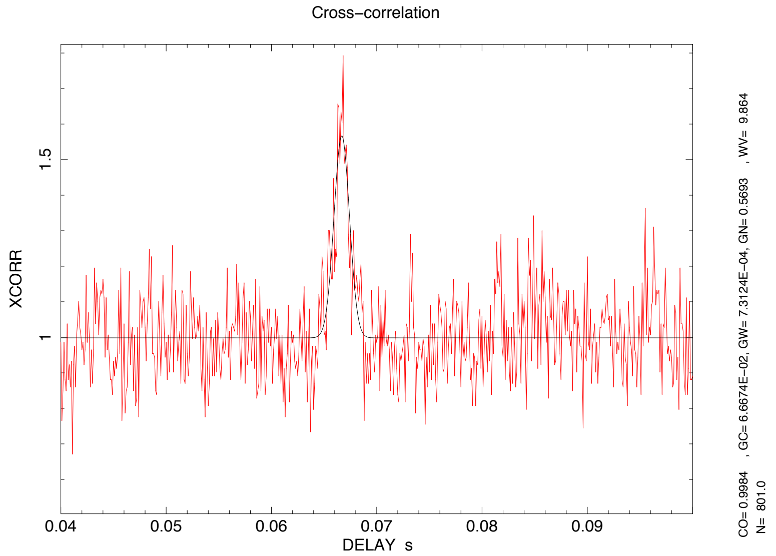
Band 50-300 keV
Effective area: 100 cm^2





Delays from cross-correlation analysis

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



Background signal = 0.86 ph s^{-1} cm^{-2} **Detector's Area** = 100 cm^2
Shot rate = 100 shot/s **Shot time** = 0.2 s $\tau = 10^{-3}$ s

Short GRB

Flux [ph s^{-1} cm^{-2}]	Time resolution [μs]	Expected delay t_e [ms]	Measured delay t_m [ms]	$\Delta t = t_e - t_m$ [μs]	Error [μs]
7.8	100	66.71282	66.66771	45.11	63.01
	10	66.71282	66.73298	-20.16	58.49
7.8 · 10	100	66.71282	66.70084	11.98	19.48
	10	66.71282	66.73610	-23.28	6.00
	1	66.71282	66.71012	2.70	4.77
7.8 · 50	100	66.71282	66.70610	6.72	24.04
	10	66.71282	66.70444	8.38	6.54
	1	66.71282	66.71322	-0.40	1.82
	0.1	66.71282	66.71475	-1.93	0.96
7.8 · 100	100	66.71282	66.71243	0.39	19.21
	10	66.71282	66.71387	-1.05	5.70
	1	66.71282	66.71750	-4.68	2.04
	0.1	66.71282	66.71384	-1.02	0.57

Background signal = 0.86 ph s^{-1} cm^{-2} **Detector's Area** = 100 cm^2
Shot rate = 100 shot/s **Shot time** = 20 s $\tau = 10^{-3}$ s

Long GRB

Flux [ph s^{-1} cm^{-2}]	Time resolution [μs]	Expected delay t_e [ms]	Measured delay t_m [ms]	$\Delta t = t_e - t_m$ [μs]	Error [μs]
7.8	100	66.71282	66.71544	-2.62	17.70
	10	66.71282	66.71482	-2.00	6.59
	1	66.71282	66.71361	-0.79	4.03
7.86 · 10	100	66.71282	66.71465	-1.83	17.92
	10	66.71282	66.71320	-0.38	5.60
	1	66.71282	66.71235	0.47	1.62
7.8 · 50	100	66.71282	66.71276	0.06	18.33
	10	66.71282	66.71320	-0.38	5.54
	1	66.71282	66.71252	0.30	1.65
7.8 · 100	100	66.71282	66.71294	-0.12	17.44
	10	66.71282	66.71318	-0.36	5.49
	1	66.71282	66.71294	-0.12	1.62

Error in cross-correlation accuracy: 0.6 ÷ 60 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 $N_{SATELLITES}$:
$(N_{SATELLITES} - 1 - 2)^{1/2}$ = 6.9/9.8 ($N_{SATELLITES}$ = 50/100)
Error in delay accuracy: 0.09÷8.7/0.06÷6.1 µsec ($N_{SATELLITES}$ = 50/100)

Determination of source position through delays

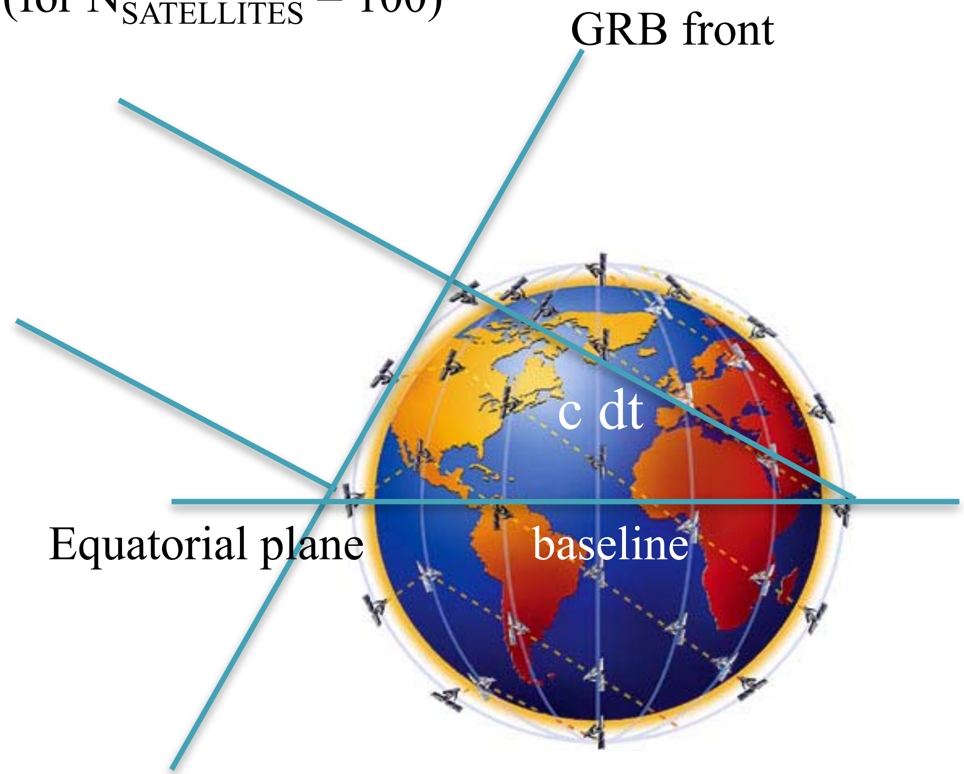
Error in accuracy ≈ c × (error in delay accuracy / average baseline)

Maximum baseline = 2 × (R_{EARTH} + $H_{SATELLITE}$) = 2 × (6371 + 580) km

Average baseline = Maximum baseline / 2

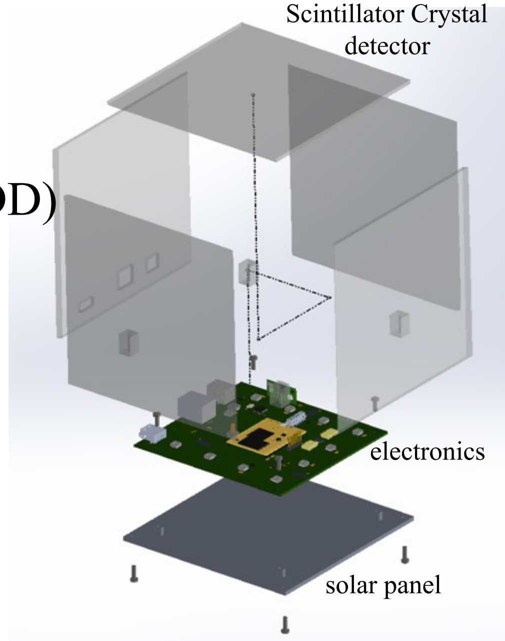
Error in accuracy = 0.80÷78 arcsec (for $N_{SATELLITES}$ = 50)

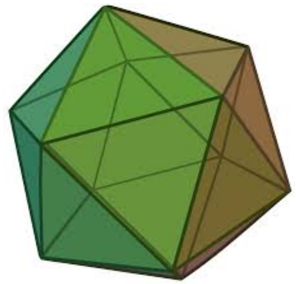
Error in accuracy = 0.53÷54 arcsec (for $N_{SATELLITES}$ = 100)

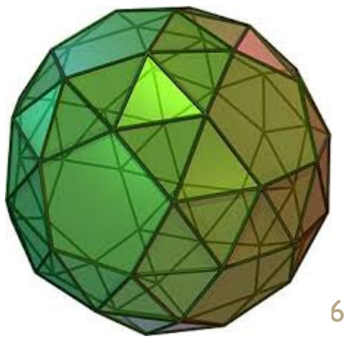


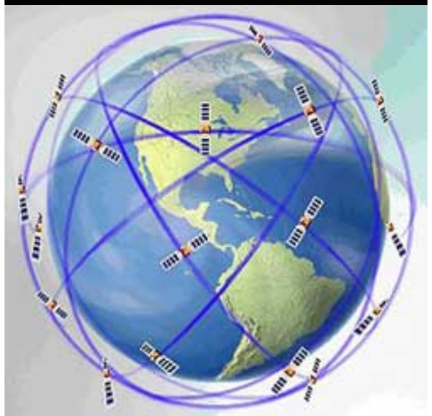
Detector and satellite

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





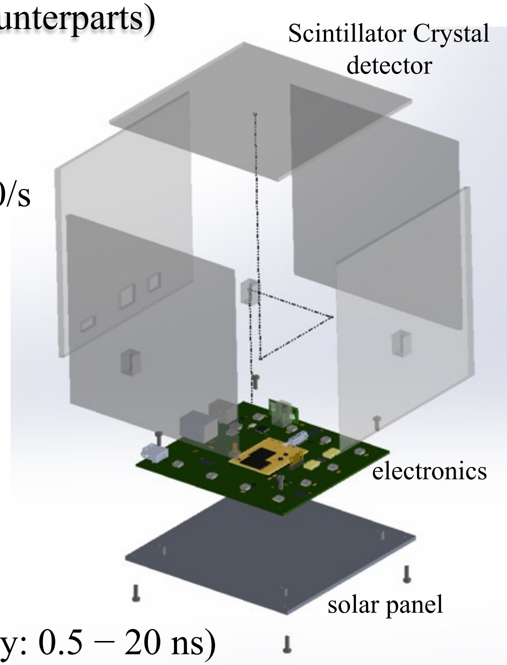




The HERMES mission

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 0.2÷20 s, shot noise $\tau = 1$ ms, rate = 100/s

Instrument

N = 50/100 Nano Satellites (Modules) in Low Earth Orbit

Average separation between Modules: 6000 km

Module (weight $\leq$ 10 kg)

5 Detectors

Field of View of each Detector: 2 steradians

GPS absolute temporal accuracy $\leq$ 100 nanoseconds

GPS based Module positional accuracy: $\leq$ 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: $\leq$ 10 nanoseconds

Mission performance

Accuracy in delays between Average GRB lightcurves of two Modules (cross correlation techniques): 0.09÷8.7/0.06÷6.1 μsec for Average GRBs

Continuous recording of buffered data

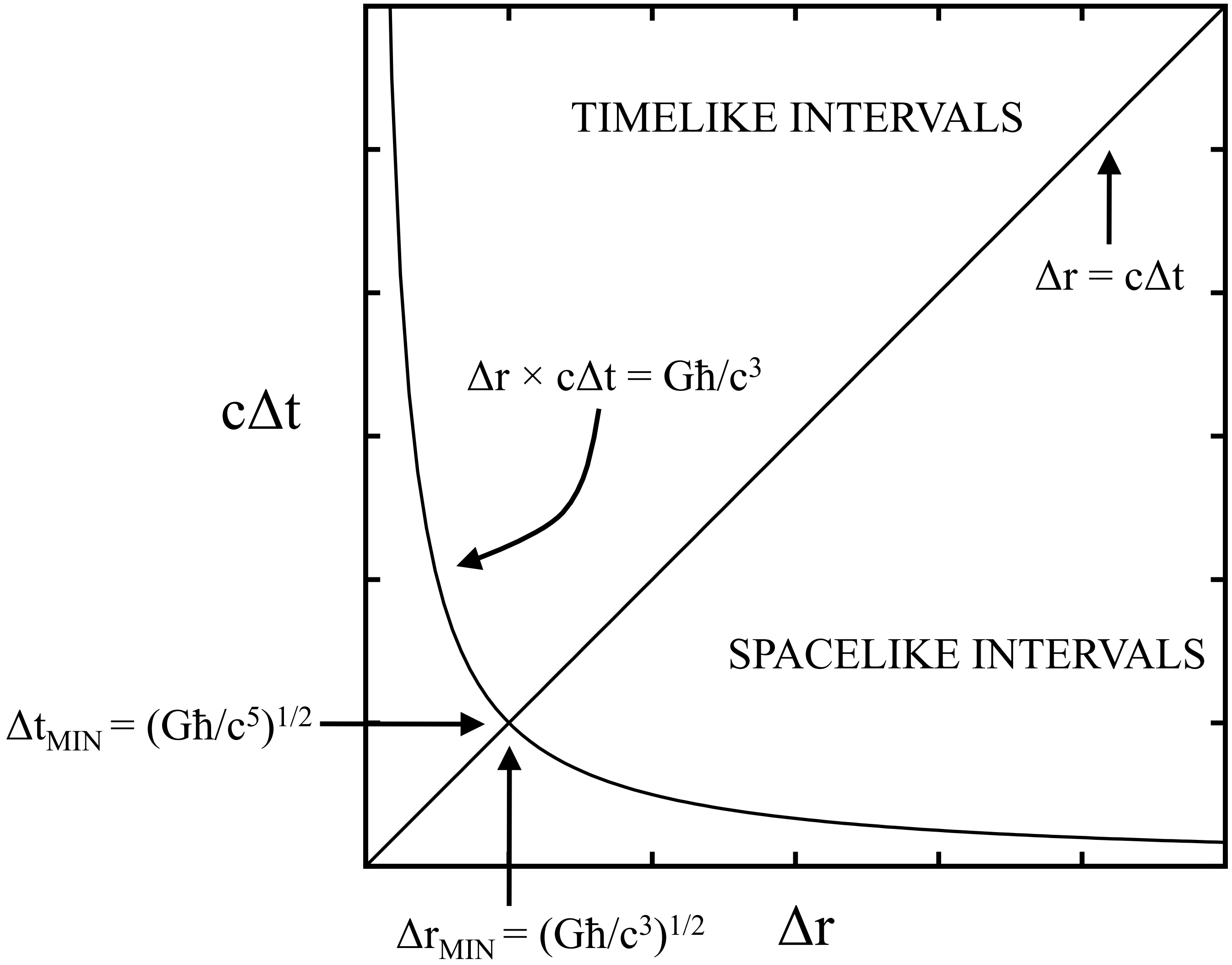
Triggered to ground telemetry transmission

Range of accuracy in positioning of GRB: 0.80÷78/0.53÷54 arcsec

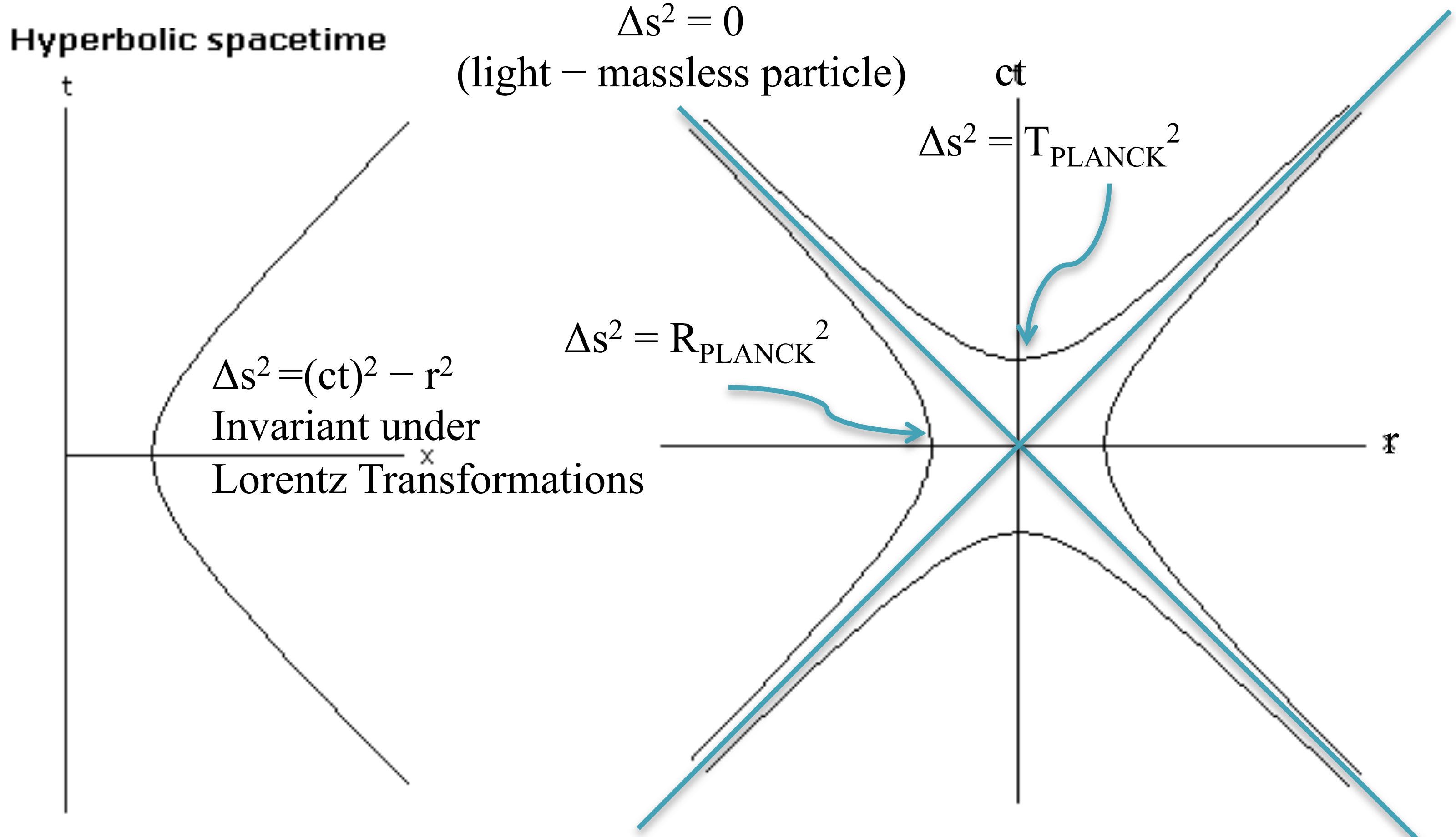
Modular structure: overall effective area 1 m^2 every 100 modules

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	Flux (Bright GRBs)	Fluence ($1\ m^2$, 10 s)	Expected $\Delta t_{QGR} \propto D_{GRB}/c$ for Quantum Gravity effects, z = 0.9	z = 3.0
(keV)	(counts/cm^2/s)	(counts)	(μs)	(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 GW, etc.)

- Accuracy in positioning of GRB/GW: 0.80÷78/0.53÷54 arcsec
- 0.5/1 m^2 effective area (50 – 300 keV)
- Energy resolution: 15% at 30 keV
- Temporal resolution: $\leq$ 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)

Conclusions II

Cheap:

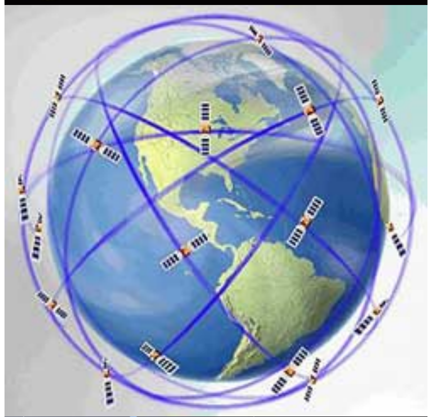
simple detector & nano(small)satellites:
up to 100 million € for 100 satellites
see e.g. Thales Alenia Space:
40 kg – 100 W, 3 axes pointing, LEO,
cost ≈ 1 M€ (“*deep throat*”, private comm.)

Fast:

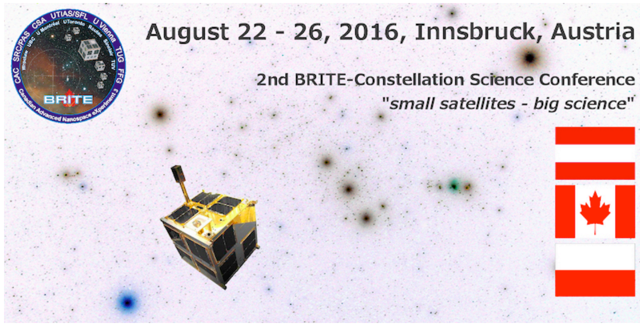
few years (≤ 5 years) to flight the first satellite(s)

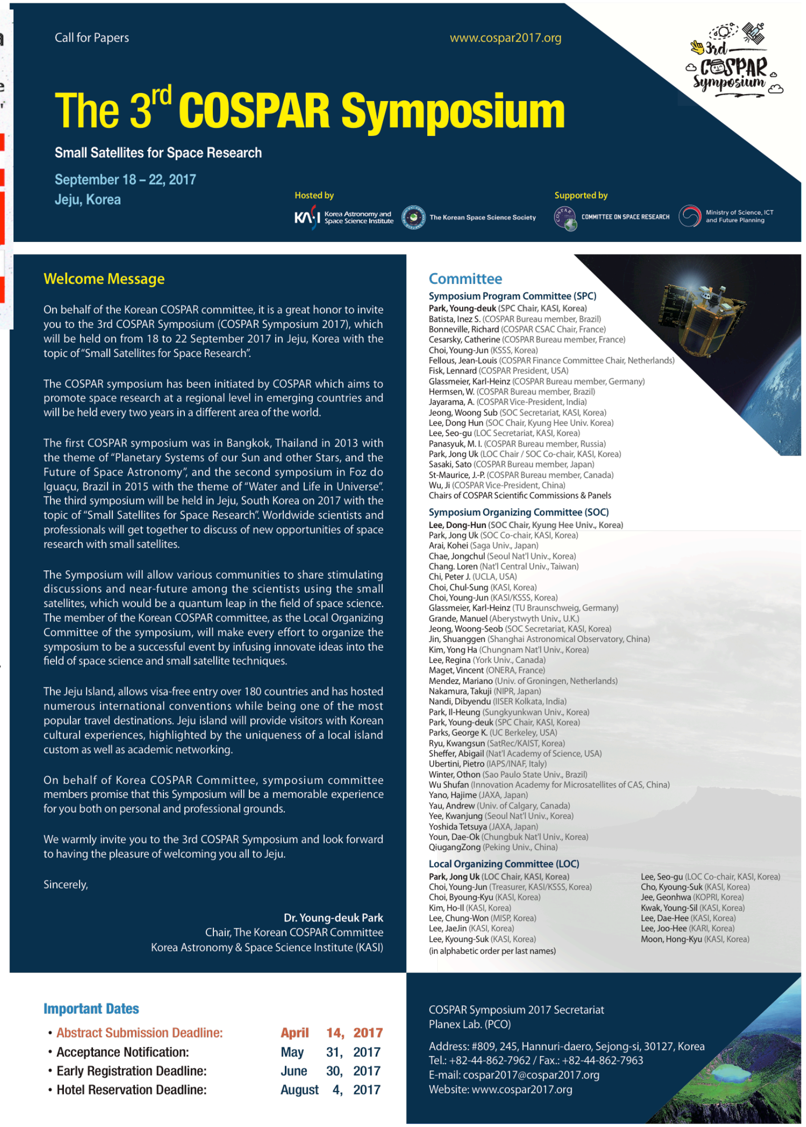
Modular:

robust against one or more satellite(s) failure



Growing interest in constellation of small satellites…





Call for Papers

www.cospar2017.org

The 3rd COSPAR Symposium

Small Satellites for Space Research

September 18 – 22, 2017
Jeju, Korea

Hosted by: Korea Astronomy and Space Science Institute; The Korean Space Science Society

Supported by: COMMITTEE ON SPACE RESEARCH; Ministry of Science, ICT and Future Planning

Welcome Message

On behalf of the Korean COSPAR committee, it is a great honor to invite you to the 3rd COSPAR Symposium (COSPAR Symposium 2017), which will be held on from 18 to 22 September 2017 in Jeju, Korea with the topic of "Small Satellites for Space Research".

The COSPAR symposium has been initiated by COSPAR which aims to promote space research at a regional level in emerging countries and will be held every two years in a different area of the world.

The first COSPAR symposium was in Bangkok, Thailand in 2013 with the theme of "Planetary Systems of our Sun and other Stars, and the Future of Space Astronomy", and the second symposium in Foz do Iguaçu, Brazil in 2015 with the theme of "Water and Life in Universe". The third symposium will be held in Jeju, South Korea on 2017 with the topic of "Small Satellites for Space Research". Worldwide scientists and professionals will get together to discuss of new opportunities of space research with small satellites.

The Symposium will allow various communities to share stimulating discussions and near-future among the scientists using the small satellites, which would be a quantum leap in the field of space science. The member of the Korean COSPAR committee, as the Local Organizing Committee of the symposium, will make every effort to organize the symposium to be a successful event by infusing innovate ideas into the field of space science and small satellite techniques.

The Jeju Island, allows visa-free entry over 180 countries and has hosted numerous international conventions while being one of the most popular travel destinations. Jeju island will provide visitors with Korean cultural experiences, highlighted by the uniqueness of a local island custom as well as academic networking.

On behalf of Korea COSPAR Committee, symposium committee members promise that this Symposium will be a memorable experience for you both on personal and professional grounds.

We warmly invite you to the 3rd COSPAR Symposium and look forward to having the pleasure of welcoming you all to Jeju.

Sincerely,

Dr. Young-deuk Park
Chair, The Korean COSPAR Committee
Korea Astronomy & Space Science Institute (KASI)

Committee

Symposium Program Committee (SPC)

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Important Dates

• Abstract Submission Deadline:	April	14,	2017
• Acceptance Notification:	May	31,	2017
• Early Registration Deadline:	June	30,	2017
• Hotel Reservation Deadline:	August	4,	2017

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The H.E.R.M.E.S. project will be presented in Plenary and dedicated sessions at the
3rd COSPARSymposium,
Small Satellites for Space Research
South Korea, September 18–22, 2017
Invited talks:
Fabrizio Fiore
Luciano Burderi

That's all Folks!