Searching for Quantum Gravity using Gamma Ray Bursts

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The Large Area Telescope Collaboration

- The mission is a NASA/DOE and international effort
- United States
  - California State University at Sonoma
  - UC Santa Cruz - Santa Cruz Institute of Particle Physics
  - Goddard Space Flight Center - Laboratory for High Energy Astrophysics
  - Naval Research Laboratory
  - The Ohio State University
  - Stanford University (SLAC and HEPL/Physics)
  - University of Washington
  - Washington University in St. Louis
- France
  - IN2P3, CEA/Saclay
- Italy
  - INFN, ASI
- Japan
  - Hiroshima University
  - ISAS, RIKEN
- Sweden
  - Royal Institute of Technology (KTH)
  - Stockholm University

PI: Peter Michelson (Stanford & SLAC)
~ 250 members
Managed at the Stanford Linear Accelerator Center

Some members of the LAT collaboration
About GLAST

- Set to launch in late December
- GLAST will observe a broad energy range with superior acceptance and resolution than previous instruments
- LAT: 20 MeV - >300 GeV
- GBM: 8 keV - 25 MeV
- Looking in new energy regimes leads to unexpected discoveries

Credit: NASA and General Dynamics
Lorentz violation and the speed of light

• Why test the constancy of the speed of light?
  • One of the fundamental constants of physics
  • Its constant speed is a requirement in relativity
  • Also a requirement in quantum field theories
  • Quantum Gravity: the long sought after unification of gravity with quantum mechanics is poorly understood and may include Lorentz invariance violation

• No shortage theoretical ideas that produce deviations from c = constant
  • ‘Foamy’ nature of space time acts as a refractive index - gr-qg/0312044
  • ‘Doubly Special’ Relativity keeps L.I. but changes c - gr-qg/0207085
  • Lorentz violating SUSY - hep-ph/0505029
  • Loop Quantum Gravity - gr-qg/9403008
  • Spontaneous symmetry breaking in string theory - hep-th/0012060
  • Canonically quantized gravity involves Lorentz violation - gr-qc/9901023
  • ... see the review by Mattingly for more - gr-qc/0502097
Some mathematical details

- Usual assumption is that the L.I. dispersion is modified
  \[ E^2 = m^2 + p^2 \rightarrow E^2 = F(p,m) \]

- Since the world is apparently nearly L.I. we Taylor expand the dispersion relation in the CMB rest frame (where \( p = 0 \) for a massive particle, or in the frame where the CMB energies is equal to its momentum)
  \[ E^2 = m^2 + p^2 + F^{(1)}_i p^i + F^{(2)}_{ij} p^i p^j + F^{(3)}_{ijk} p^i p^j p^k + \ldots \]
  \[ E^2 = m^2 + p^2 + E_P f^{(1)}_i p^i + f^{(2)}_{ij} p^i p^j + f^{(3)}_{ijk} p^i p^j p^k / E_P + \ldots \]

- Usual assumptions about the expansion parameters
  - \( E_P \sim 10^{19} \text{ GeV} \) (the scale at which we expect to see new physics)
  - We preserve rotational invariance, but break boost invariance:
    \[ E^2 = m^2 + p^2 + E_P f^{(1)}_i |p| + f^{(2)} |p|^2 + f^{(3)} |p|^3 / E_P + \ldots \]
  - The \( f^{(3)} |p|^3 / E_P \) term is relevant for astrophysical tests
  - The first two terms modify low energy behaviour, whereas the fourth and higher order terms do not provide measurable speed differences
Current bounds for one analysis

- Modified dispersion relation leads to an energy dependent speed of light
- In one case, the velocity is lower at high energies
  - \( v \approx c [1 - \xi (E/E_{PL})] \)
  - \( \Delta t \approx \xi (\Delta E/E_{PL}) \times (L/c) \sim \xi (\Delta E/E_{PL}) \times H_0^{-1} \int dz/h(z) \)
    - \( \xi = f^{(3)} \) in previous notation
- Gamma Ray Bursts produce short intense flares over 7+ orders of magnitude of energy
- By performing a time of flight measurement we can place limits on the speed of light at various energies
  - We look for a systematic differences in arrival times of photons at different energies proportional to distance
- Current GRB observations limited to lower energy regimes (BATSE, BeppoSAX, HETE, SWIFT energies), hence the time delays will be small leading to limits of \( E_{PL} \geq a \text{ few} \times 10^{16} \text{ GeV} \) (e.g. astro-ph/0310307)
  - TeV observations by Milagro lead to similar bounds (astro-ph/9810044)
The impact of GLAST data

- Here the arrival time for photons from a GRB with five pulses is shown.
- The GRB was placed at $z \sim 1$.
  - Mean redshift $\sim 2$.
- In **black**, we see the arrival times if there is no QG effect.
- In **green**, the arrival times if $E_{PL} \sim 10^{18}$ GeV.
- In **red**, the arrival times if $E_{PL} \sim 10^{19}$ GeV.
- The LAT will be able to make this measurement assuming no fine tuning of expansion parameters.

If we see no delay,
$$E_{PL} > (L \cdot \Delta E)/(c \cdot \Delta t)$$

If we see a delay,
$$E_{PL} = (L \cdot \Delta E)/(c \cdot \Delta t)$$

Naive energy scale that GLAST can probe
$$\frac{(L \cdot \Delta E)}{(c \cdot \Delta t)} = \frac{(10^{28} \text{cm})(10^2 \text{GeV})}{(10^{10} \text{cm})(10^{-4} \text{s})} = 10^{24} \text{GeV}$$
Conveniences and inconveniences

✓ GRB pulses become narrower at ‘high’ energies
✓ If the trend hold at LAT energies this will be very helpful for the determination of bounds on $E_{PL}$
๏ GRBs are distant, poorly understood objects
๏ It is possible that for one burst the high energy emission is systematically delayed which would cause a fake signal for that burst
๏ Most analyses use single (very bright) bursts, to make the measurements (e.g. astro-ph/0610571)
❖ Looking for consistency between bursts with redshift measurements presents a way around this problem (e.g. astro-ph/0510172)
  • The effect should be correlated linearly with distance
  • All astrophysical objects (e.g.) AGN flares should show the same effects
❖ At OSU we are developing our own systematic analysis of multiple bursts to determine whether or not the effect is present in LAT data with statistical accuracy
Higher order effects

• What if the time delay is proportional to energy to some power?
  \[ \Delta t = (L/c)(a \cdot E/E_{PL})^b \]

• Here we get a feeling for the sensitivity of time delay measurements to the QG scale as a function of the power law index

• We are basically insensitive to higher order corrections

Milagro collaboration
Conclusions

• Physics at the Plank scale is inherently interesting, yet difficult to test and model
• By measuring the speed of light at high and low(er) energies, GLAST will be able to set stringent limits on, or discover the effects of Quantum Gravity and Lorentz Invariance violation
• Even with a clear signal from GRBs, a discovery of this magnitude would require extensive cross checks from other astrophysical phenomena