Ninth International Fermi Symposium
12-17 April 2021

# What Racing Distant Fermi GRB Photons Can Tell Us About our Universe

ROBERT J. NEMIROFF

Michigan Technological University

# Abstract

Do photons of different energies disperse as they race across the universe? Potential reasons for dispersion include violations of Lorentz invariance, violations of the weak equivalence principle, and electromagnetic interactions with the intervening matter. Which parameters make GRBs the most sensitive to these potential differences: their great distance, being seen over such a wide range of energies, or their fast time scale of variation? Also, how can we find a fair race where GRB photons were emitted at nearly the same time? Are higher or lower energy photons expected to win the race? Could racing distant GRB gravitational waves tell us something different from photons? Which Fermi GRBs, so far, have probed the universe the best -- and why? A review of these Fermi GRBs and the limits they impose on fundamental physics is reviewed, along with a comparison of similar limits from other -- and likely future -- GRB detectors.

# A Little About Me

- Not a member the Fermi team
- Has some experience with Fermi data
- Has published in microlensing (PhD), GRBs, sky monitoring (CONCAMs), the ASCL (ascl.net), and APOD (apod.nasa.gov)
- Ask me about Relative Image Doubling in Cherenkov detectors!

# Galileo Ball & GRB Photon Race

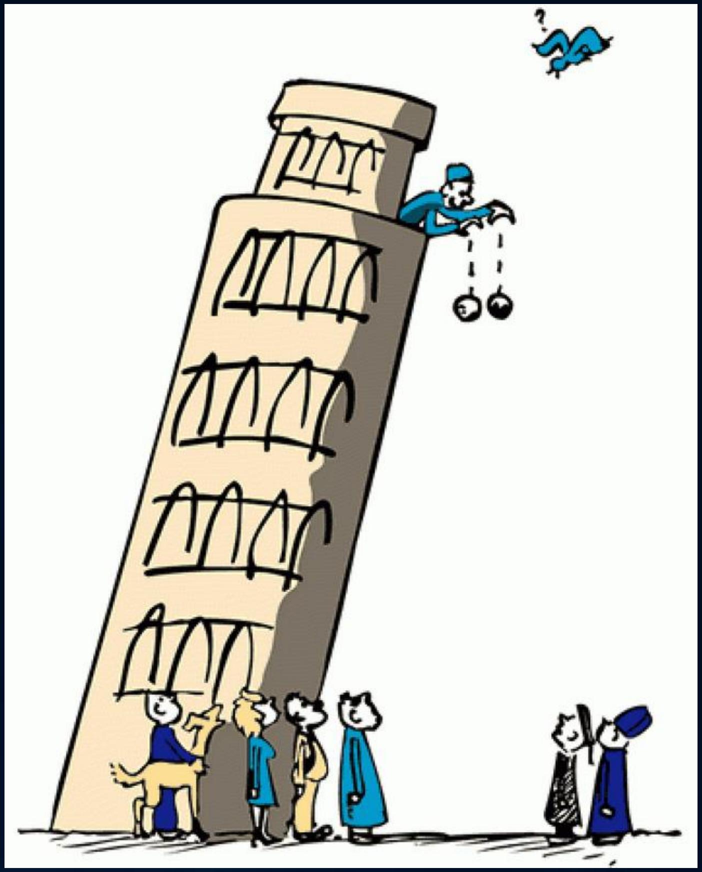


Image Source: https://id.pinterest.com/pin/348606827380020275/

# Rules of the Race

- Photons must all start from the same place
- Photons must all end at the same place

- Photons must all start at the same time
- Photons must all end at the same time

# Reasons the Race Would be a Tie

As a function of photon ENERGY:

- Gravity acts the same
- Lorentz Invariance holds
- Speed of light the same
- Dark energy dispersion the same

# Our Goal: Three numbers

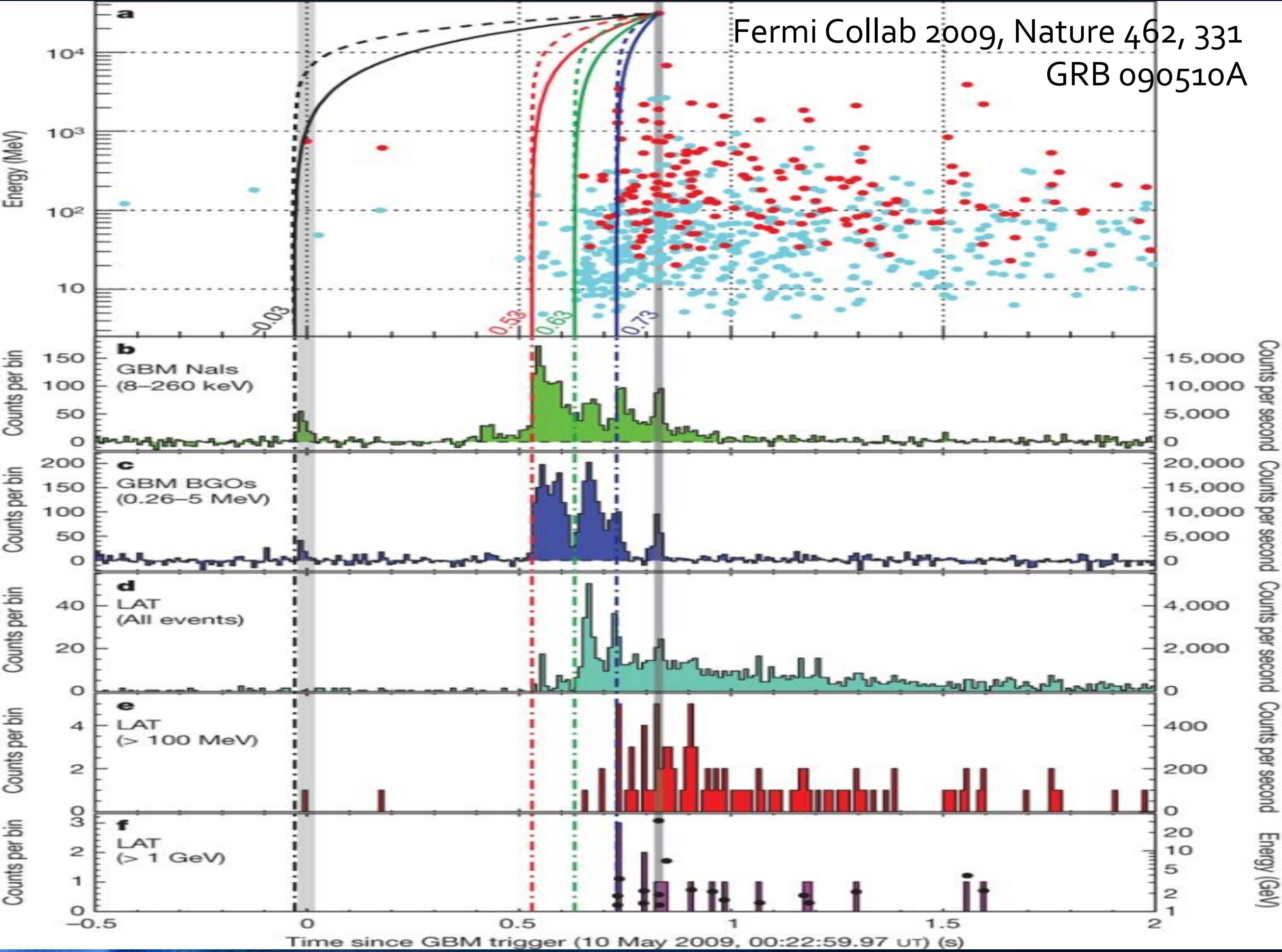
- $\Delta t$: minimize
- $\Delta E$: maximize
- $z$: maximize

- Best source(s): GRBs
- Best detector (so far): Fermi LAT

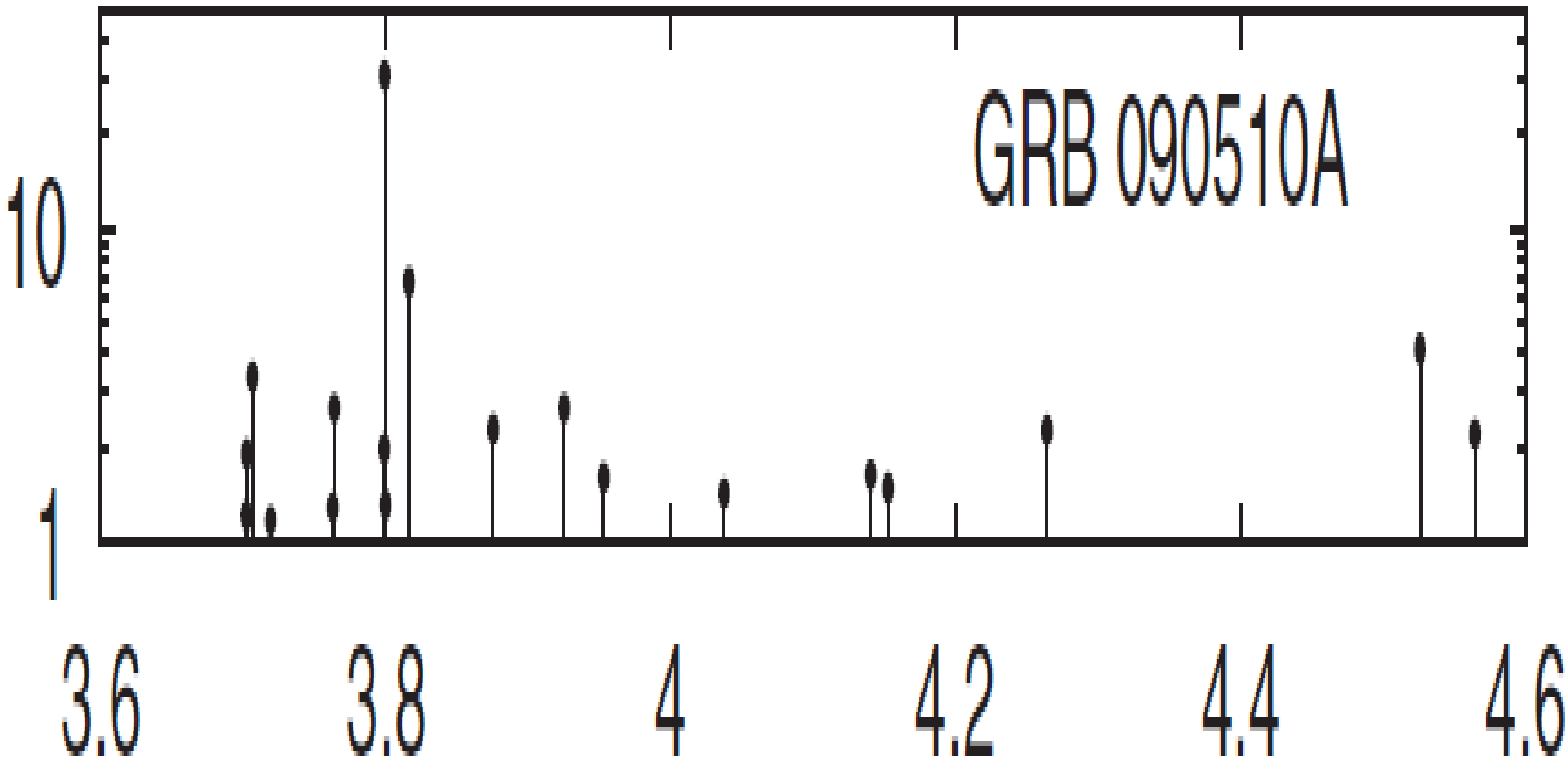
# Are there any precedents for such short duration GRB pulses?

| Name | Δt (sec) | ΔE (MeV) | z | Ref. |
|---|---|---|---|---|
| GRB 790305 | 0.0002 (rise) | 1? | ? | Bhat et al., Nature 1992 |
| GRB 820405 | 0.012 | ~0.1 | ? | Mazets et al., AIP Conf., 1983 |
| GRB 841215 | 0.005 | ~ 1.0 | ? | Laros et al, Nature, 1985 |
| GRB 910711 | 0.008 | ~1.0 | ? | Bhat et al., Nature, 1992 |
| GRB 930229 | 0.0002 (rise) | 0.170 | ? | Schaefer, PRL, 1999 |
| GRB 021206 | < 0.0048 | 14 | 0.3 (pseudo) | Boggs et al., ApJ, 2006 |
| GRB 051221 | < 0.004 | 0.300 | 0.547 | Martinez et al., JCAP, 2006 |
| Informal | reports | of | many | others. |

Fermi Collab 2009, Nature 462, 331
GRB 090510A



# Consider only high energy photons



# Were these 3 photons really isolated?

---- GRB 090510A ----Pass 7----

| Time (s) | Energy (GeV) |
|---|---|
| -507.37014 | 1.93 |
| -380.59269 | 1.15 |
| 3.7022335 | 1.22 |
| 3.7027825 | 1.91 |
| 3.7069414 | 3.37 |
| 3.7194310 | 1.17 |
| 3.7631084 | 1.29 |
| 3.7641773 | 2.68 |
| 3.7991902 | 1.98 |
| 3.7993189 | 30.86 |
| 3.8000964 | 1.31 |
| 3.8167293 | 6.75 |
| 3.8757667 | 2.29 |
| 3.9253115 | 2.67 |
| 3.9530931 | 1.60 |
| 4.0376598 | 1.44 |
| 4.1406114 | 1.64 |
| 4.1527832 | 1.49 |
| 4.2644487 | 2.28 |
| 4.5259632 | 4.12 |
| 4.5643419 | 2.22 |
| 5.1267243 | 1.06 |
| 5.2103540 | 1.68 |
| 5.9021644 | 2.08 |
| 6.1776803 | 1.53 |
| 6.4026321 | 2.78 |
| 6.6466461 | 3.69 |
| 7.8898184 | 1.25 |
| 12.265765 | 1.04 |
| 12.618712 | 1.73 |
| 26.082871 | 1.40 |
| 41.571826 | 1.22 |
| 50.966219 | 1.52 |
| 101.89744 | 1.41 |

# How was significance estimated?

- $\chi^2$ to find flat arrival epochs
- Photon-photon correlation function to find chance that 5 photon pairs with $\Delta t < 1.069$ ms would be found among 11 photons spread uniformly over ~ 0.1745 seconds
- Statistical comparisons to $10^9$ Monte Carlo runs
- Then assume 1.069 ms pairs drawn randomly from a classic Norris GRB pulse shape
  - $\Delta t$ increased to 1.550 ms => "real pulse width"
  - Norris et al, ApJ, 2005, Nemiroff et al, MNRAS, 2012

# Have you told anybody?

PRL **108,** 231103 (2012) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2012

## Bounds on Spectral Dispersion from Fermi-Detected Gamma Ray Bursts

Robert J. Nemiroff, Ryan Connolly, Justin Holmes, and Alexander B. Kostinski

*Department of Physics, Michigan Technological University, 1400 Townsend Drive, Houghton, Michigan 49931, USA*

(Received 23 September 2011; revised manuscript received 27 March 2012; published 8 June 2012)

Data from four Fermi-detected gamma-ray bursts (GRBs) are used to set limits on spectral dispersion of electromagnetic radiation across the Universe. The analysis focuses on photons recorded above 1 GeV for Fermi-detected GRB 080916C, GRB 090510A, GRB 090902B, and GRB 090926A because these high-energy photons yield the tightest bounds on light dispersion. It is shown that significant photon bunches in GRB 090510A, possibly classic GRB pulses, are remarkably brief, an order of magnitude shorter in duration than any previously claimed temporal feature in this energy range. Although conceivably $a > 3\sigma$ fluctuation, when taken at face value, these pulses lead to an order of magnitude tightening of prior limits on photon dispersion. Bound of $\Delta c/c < 6.94 \times 10^{-21}$ is thus obtained. Given generic dispersion relations where the time delay is proportional to the photon energy to the first or second power, the most stringent limits on the dispersion strengths were $k_1 < 1.61 \times 10^{-5}$ sec $\mathrm{Gpc}^{-1}\,\mathrm{GeV}^{-1}$ and $k_2 < 3.57 \times 10^{-7}$ sec $\mathrm{Gpc}^{-1}\,\mathrm{GeV}^{-2}$, respectively. Such limits constrain dispersive effects created, for example, by the spacetime foam of quantum gravity. In the context of quantum gravity, our bounds set $M_1c^2$ greater than 525 times the Planck mass, suggesting that spacetime is smooth at energies near and slightly above the Planck mass.

DOI: 10.1103/PhysRevLett.108.231103 PACS numbers: 98.70.Rz, 03.30.+p, 04.60.Pp, 14.70.Bh

# Weak Equivalence Principle (WEP)

- “mass and weight are locally measured to have an identical ratio for all bodies.” (paraphrase) – Isaac Newton [1]
- “the acceleration imparted to a body by a gravitational field is independent of the nature of the body.” – Albert Einstein [2]
- Modern restatement: All objects fall the same.
- Weak EP: bodies that are not themselves gravitationally bound fall the same.

# How presented limits on WEP violations improve on previous limits

- GRBs with more rapid fluctuations are used.
  - Previously: smallest dt used about 0.1 sec
  - Here: smallest dt used 0.00022 sec
- More distant GRBs are used.
  - Previously: A GRB with z=0.895
  - Here: A GRB with z~9.4 (photometric) is used, although a more conservative redshift of 6.5 is used for a conservative limit on dgamma
- Galaxies and Clusters of Galaxies are inferred as masses creating the Shapiro time delays.
  - Previously: Only the gravitational potential of our Milky Way
  - Here: Galaxy clusters along the line of sight

# Shapiro Time Delay: In Principle

$$t_{Shapiro} = -\frac{1+\gamma}{c^3}\int_{D_S}^{D_O} U(\mathbf{r}(t),t)dr,$$

- t_Shapiro is the time delay created by a mass along the line of sight to a source in excess of the crossing time without the mass.
- DS and DO are the light travel times to the source and observer.
- U(r) is the gravitational potential of a mass that is creating the Shapiro time delay.
- γ is the parametrized post Newtonian (PPN) variable that characterizes a violation of the WEP. General Relativity predicts γ = 1, while the WEP predicts Δγ=0.

# Computation: A cylinder with random clusters of galaxies thrown inside

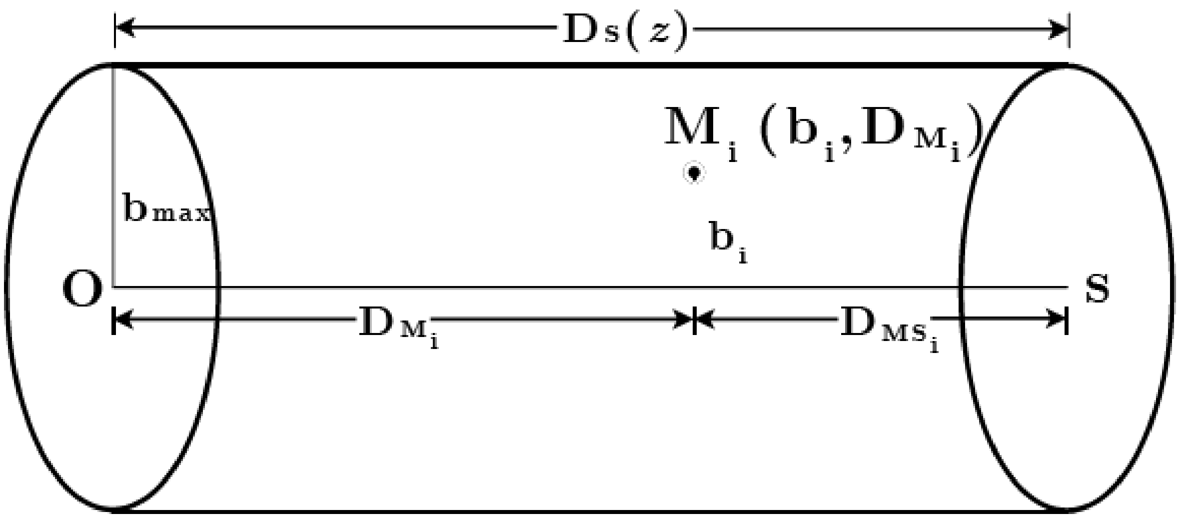



FIG. 1. For a source located at $D_S(z)$, each intermediate mass ($M_i$) near the light path between the observer ($O$) and the source ($S$) is placed randomly at comoving cylindrical coordinate $(r, z) = (b_i, D_{M\,i})$.

# Shapiro Time Delay: In Practice

$$t_{Shapiro} = (1+\gamma)\sum_{i=1}^{n}(1+z_{M\,i})\frac{GM_i}{c^3}\ln\frac{4D_{M\,i}D_{MS\,i}}{b_i{}^2}.$$

- t_Shapiro is the total time delay created by all cluster masses along the line of sight to a GRB.
- a single cluster along the line of sight has mass Mi, light travel distance Dmi, and redshift zi
- Light from the GRB passes each mass at impact parameter bi.
- The maximum allowed impact parameter is bmax = 10 Mpc, taken from the largest observed radius of weak gravitational lensing distortions on background galaxies [12, 13].
- γ is the parametrized post Newtonian (PPN) variable that characterizes a violation of the WEP. General Relativity predicts γ = 1, while the WEP predicts Δγ=0.

# Computed distribution of Shapiro time delays for galaxy clusters in the cylinder out to redshift 1

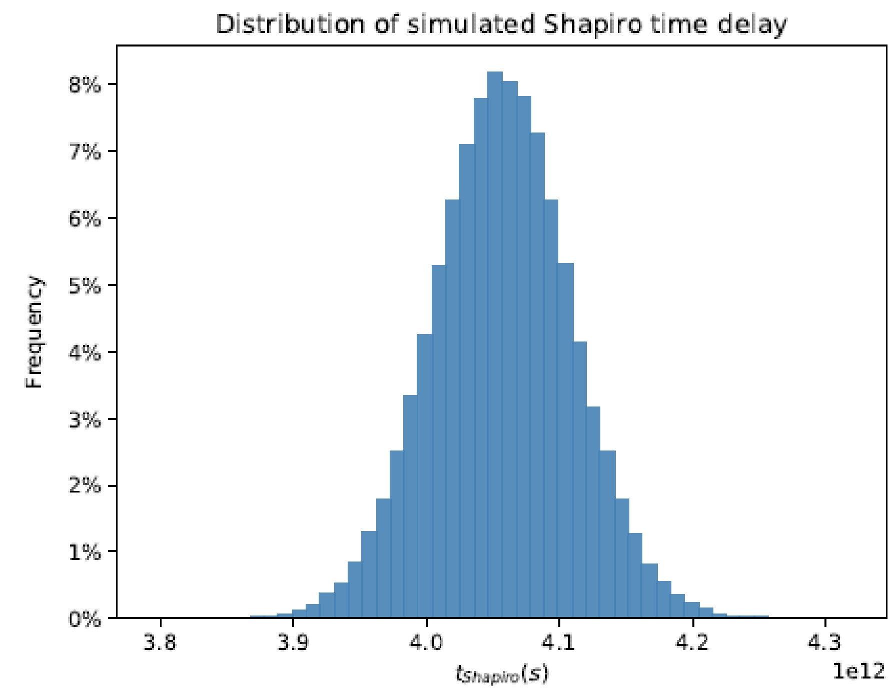



FIG. 2. Distribution of Shapiro time delay for a source located at $z_S = 1$ and all clusters within comoving radius of $b_{max} = 10$ Mpc are considered.

# Results
## Table 1: Data and WEP Violation Limits

| Name | Instrument | $\Delta t_{Obs}$ ms | $E_{min}$ MeV | $E_{max}$ MeV | $z$ | $\Delta\gamma(E_{max}, E_{min})$ |
|---|---|---|---|---|---|---|
| GRB 910711 | BATSE | 16 | 0.1 | 0.3 | $> 0.1$ (assumed) | $1.6 \times 10^{-13}$ |
| GRB 920229 | BATSE | 0.22 | 0.03 | 0.2 | $> 0.1$ (assumed) | $2.1 \times 10^{-15}$ |
| GRB 021206 | RHESSI | 4.8 | 3 | 10 | $> 0.15$ (pseudo) | $2.8 \times 10^{-14}$ |
| GRB 051221A | Konus-Wind | 4 | 0.07 | 0.3 | 0.547 (spectral) | $4.7 \times 10^{-15}$ |
| GRB 090429 | Swift | 1200 | 0.25 | 0.5 | 6.5 (pseudo) | $1.2 \times 10^{-13}$ |
| GRB 090510 | Fermi | 1.0 | 1580 | 24,700 | 0.897 (spectral) | $6.6 \times 10^{-16}$ |

# All Photon Races are Ties to within Error

Limits on:

- WEP violations
  - $\Delta\gamma < 6.6 \times 10^{-16}$
- LI violations
  - $\ell_{QG} < 1.53 \times 10^{-3}\, \ell_{Planck}$ (mean)
- Speed of light
  - $\Delta c/c < 6.94 \times 10\text{-}21$ (over $\Delta E \sim 24.7$ GeV)

# Acknowledgements

- Matipon Tangmatitham (former grad student)
- Katyayani Trivedi (current student)
- J. Bonnell (Fermi Team: Data)
- J. Norris (Fermi Team: Data)
- J. Scargle (Fermi Team: Background)
- K. Wood (Fermi Team: “That might be important!” )
- V. Trimble (1993 email)

[1] I. Newton, *Philosophiae Naturalis Principia Mathematica. Auctore Js. Newton, by Newton, Isaac, 1687.* (1687).
[2] A. Einstein, *The Meaning of Relativity by Albert Einstein. Princeton University Press, 2004. ISBN: 978-0-691-12027-0* (2004).
[3] I. I. Shapiro, Fourth Test of General Relativity, Physical Review Letters **13**, 789 (1964).
[4] C. M. Will, The confrontation between general relativity and experiment, Living Reviews in Relativity **9**, 3 (2006).
[5] J.-J. Wei, H. Gao, X.-F. Wu, and P. Mészáros, Testing Einstein's Equivalence Principle With Fast Radio Bursts, Physical Review Letters **115**, 261101 (2015), arXiv:1512.07670 [astro-ph.HE].
[6] X.-F. Wu, H. Gao, J.-J. Wei, P. Mészáros, B. Zhang, Z.-G. Dai, S.-N. Zhang, and Z.-H. Zhu, Testing Einstein's weak equivalence principle with gravitational waves, Phys. Rev. D **94**, 024061 (2016), arXiv:1602.01566 [astro-ph.HE].
[7] S. Boran, S. Desai, E. O. Kahya, and R. P. Woodard, GW170817 falsifies dark matter emulators, Phys. Rev. D **97**, 041501 (2018), arXiv:1710.06168 [astro-ph.HE].
[8] H. Gao, X.-F. Wu, and P. Mészáros, Cosmic Transients Test Einstein's Equivalence Principle out to GeV Energies, Astrophysical Journal **810**, 121 (2015), arXiv:1509.00150 [astro-ph.HE].
[9] A. Nusser, On Testing the Equivalence Principle with Extragalactic Bursts, Astrophysical Journal Letters **821**, L2 (2016), arXiv:1601.03636.
[10] N. A. Bahcall, F. Dong, P. Bode, R. Kim, J. Annis, T. A. McKay, S. Hansen, J. Schroeder, J. Gunn, J. P. Ostriker, M. Postman, R. C. Nichol, C. Miller, T. Goto, J. Brinkmann, G. R. Knapp, D. O. Lamb, D. P. Schneider, M. S. Vogeley, and D. G. York, The Cluster Mass Function from Early Sloan Digital Sky Survey Data: Cosmological Implications, Astrophys. J. **585**, 182 (2003), astro-ph/0205490.
[11] N. A. Bahcalland R. Cen, The mass function of clusters of galaxies, **407**, L49 (1993).
[12] R. Mandelbaum, A. Slosar, T. Baldauf, U. Seljak, C. M. Hirata, R. Nakajima, R. Reyes, and R. E. Smith, Cosmological parameter constraints from galaxy-galaxy lensing and galaxy clustering with the SDSS DR7, **432**, 1544 (2013), arXiv:1207.1120.
[13] A. Leauthaud, S. Saito, S. Hilbert, A. Barreira, S. More, M. White, S. Alam, P. Behroozi, K. Bundy, J. Coupon, T. Erben, C. Heymans, H. Hildebrandt, R. Mandelbaum, L. Miller, B. Moraes, M. E. S. Pereira, S. A. Rodríguez-Torres, F. Schmidt, H.-Y. Shan, M. Viel, and F. Villaescusa-Navarro, Lensing is low: cosmology, galaxy formation or new physics?, **467**, 3024 (2017), arXiv:1611.08606.
[14] G. J. Fishman, C. A. Meegan, R. B. Wilson, T. A. Parnell, W. S. Paciesas, G. N. Pendleton, H. S. Hudson, J. L. Matteson, L. E. Peterson, T. L. Cline, B. J. Teegarden, and B. E. Schaefer, The BATSE Experiment for the GRO - Solar Flare Hard X-Ray and Gamma-Ray Capabilities, in *Bulletin of the American Astronomical Society*, , Vol. 21 (1989) p. 860.
[15] P. N. Bhat, G. J. Fishman, C. A. Meegan, R. B. Wilson, M. N. Brock, and W. S. Paciesas, Evidence of sub-millisecond structure in a gamma-ray burst, Nature (London) **359**, 217 (1992).
[16] E. Berger, Short-Duration Gamma-Ray Bursts, **52**, 43 (2014), arXiv:1311.2603 [astro-ph.HE].
[17] J. Greiner, Localized GRBs web table (2019).
[18] B. E. Schaeferand K. C. Walker, A Gamma-Ray Burst with a 220 Microsecond Rise Time and a Sharp Spectral Cutoff, **511**, L89 (1999), astro-ph/9810270.
[19] B. E. Schaefer, Severe Limits on Variations of the Speed of Light with Frequency, Physical Review Letters **82**, 4964 (1999), astro-ph/9810479.
[20] S. E. Boggs, C. B. Wunderer, K. Hurley, and W. Coburn, Testing Lorentz Invariance with GRB 021206, **611**, L77 (2004), astro-ph/0310307.
[21] M. Rodríguez Martínez, T. Piran, and Y. Oren, GRB 051221A and tests of Lorentz symmetry, **5**, 017 (2006), astro-ph/0601556.
[22] A. M. Soderberg, E. Berger, M. Kasliwal, D. A. Frail, P. A. Price, B. P. Schmidt, S. R. Kulkarni, D. B. Fox, S. B. Cenko, A. Gal-Yam, E. Nakar, and K. C. Roth, The Afterglow, Energetics, and Host Galaxy of the Short-Hard Gamma-Ray Burst 051221a, Astrophys. J. **650**, 261

# References

(2006), astro-ph/0601455.

[23] A. Cucchiara, A. J. Levan, D. B. Fox, N. R. Tanvir, T. N. Ukwatta, E. Berger, T. Krühler, A. Küpcü Yoldaş, X. F. Wu, K. Toma, J. Greiner, F. E. Olivares, A. Rowlinson, L. Amati, T. Sakamoto, K. Roth, A. Stephens, A. Fritz, J. P. U. Fynbo, J. Hjorth, D. Malesani, P. Jakobsson, K. Wiersema, P. T. O'Brien, A. M. Soderberg, R. J. Foley, A. S. Fruchter, J. Rhoads, R. E. Rutledge, B. P. Schmidt, M. A. Dopita, P. Podsiadlowski, R. Willingale, C. Wolf, S. R. Kulkarni, and P. D'Avanzo, A Photometric Redshift of z ˜ 9.4 for GRB 090429B, Astrophys. J. **736**, 7 (2011), arXiv:1105.4915.

[24] R. J. Nemiroff, R. Connolly, J. Holmes, and A. B. Kostinski, Bounds on Spectral Dispersion from Fermi-Detected Gamma Ray Bursts, Physical Review Letters **108**, 231103 (2012), arXiv:1109.5191.

[25] A. A. Abdo, M. Ackermann, M. Ajello, K. Asano, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet, G. Barbiellini, M. G. Baring, and et al., A limit on the variation of the speed of light arising from quantum gravity effects, Nature (London) **462**, 331 (2009), arXiv:0908.1832 [astro-ph.HE].

Image Sources

Leaning Tower of Pisa: Saffron Blaze via Wikipedia

Fermi Satellite: NASA