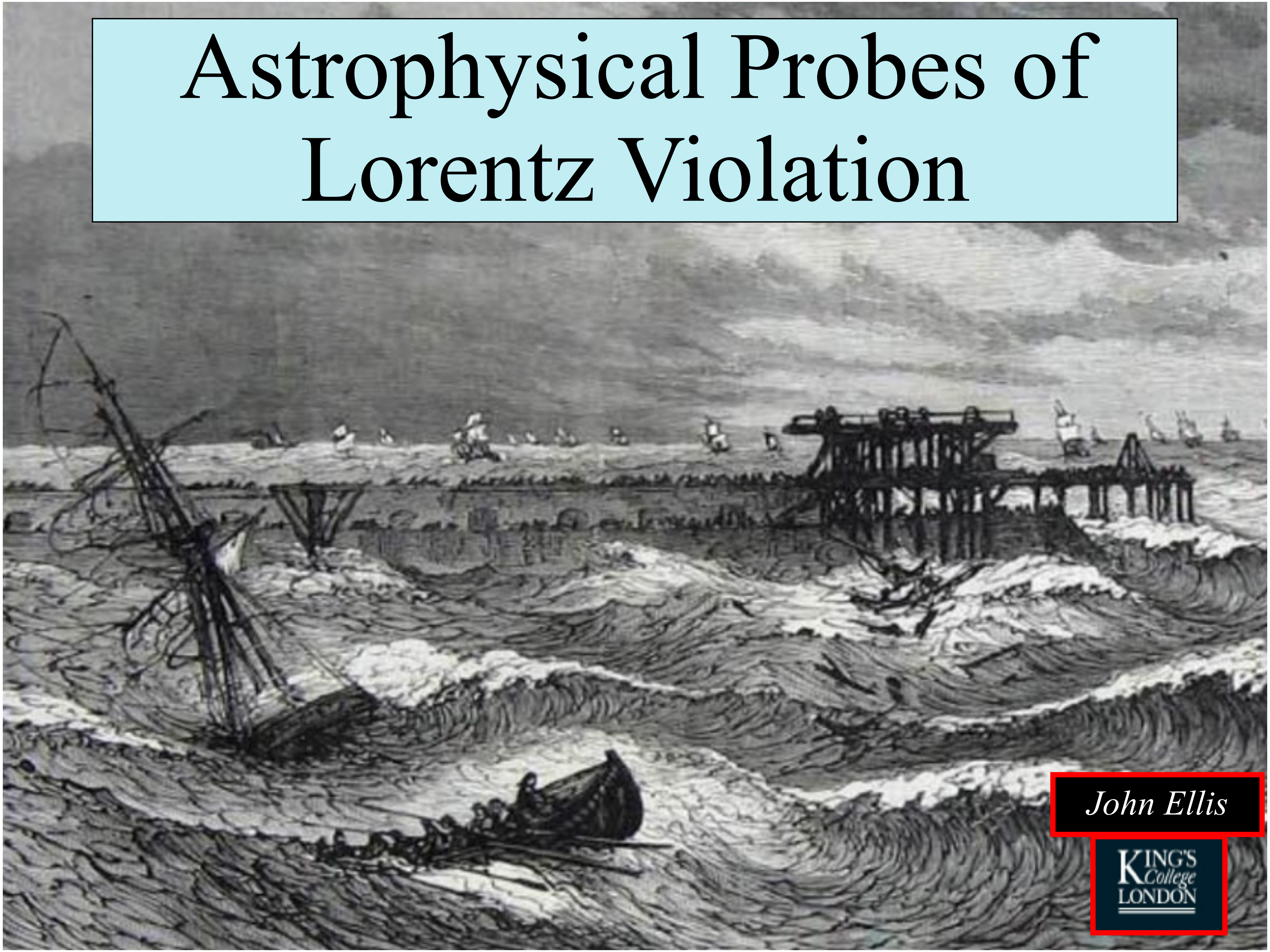
Astrophysical Probes of Lorentz Violation



John Ellis

KING'S College LONDON

Dirac, 1951

Lorentz Invariance is not Sacred

LETTERS TO THE EDITORS

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Is there an Æther ?

In the last century, the idea of a universal and all-pervading æther was popular as a foundation on which to build the theory of electromagnetic phenomena. The situation was profoundly influenced in 1905 by Einstein's discovery of the principle of relativity, leading to the requirement of a four-dimensional formulation of all natural laws. It was soon found that the existence of an æther could not be fitted in with relativity, and since relativity was well established, the æther was abandoned.

Physical knowledge has advanced very much since 1905, notably by the arrival of quantum mechanics, and the situation has again changed. If one re-examines the question in the light of present-day knowledge, one finds that the æther is no longer ruled out by relativity, and good reasons can now be advanced for postulating an æther.

Let us consider in its simplest form the old argument for showing that the existence of an æther is incompatible with relativity. Take a region of space-time which is a *perfect vacuum*, that is, there is no matter in it and also no fields. According to the principle of relativity, this region must be isotropic in the Lorentz sense—all directions within the light-cone must be equivalent to one another. According to the æther hypothesis, at each point in the region there must be an æther, moving with some velocity, presumably less than the velocity of light. This velocity provides a preferred direction within the light-cone in space-time, which direction should show itself up in suitable experiments. Thus we get a contradiction with the relativistic requirement that all directions within the light-cone are equivalent.

This argument is unassailable from the 1905 point of view, but at the present time it needs modification, because we have to apply quantum mechanics to the æther. The velocity of the æther, like other physical variables, is subject to uncertainty relations. For a particular physical state the velocity of the æther at a certain point of space-time will not usually be a well-defined quantity, but will be distributed over various possible values according to a probability law obtained by taking the square of the modulus of a wave function. We may set up a wave function which makes all values for the velocity of the æther equally probable. Such a wave function may well represent the perfect vacuum state in accordance with the principle of relativity.

One gets an analogous problem by considering the hydrogen atom with neglect of the spins of the electron and proton. From the classical picture it would seem to be impossible for this atom to be in a state of spherical symmetry. We know experimentally that the hydrogen atom can be in a state of spherical symmetry—any spectroscopic *S*-state is such a state—and the quantum theory provides an explanation by allowing spherically symmetrical wave functions, each of which makes all directions for the line joining electron to proton equally probable.

We thus see that the passage from the classical theory to the quantum theory makes drastic alterations in our ideas of symmetry. A thing which cannot be symmetrical in the classical model may very well be symmetrical after quantization. This provides a means of reconciling the disturbance of Lorentz symmetry in space-time produced by the existence of an æther with the principle of relativity.

There is one respect in which the analogy of the hydrogen atom is imperfect. A state of spherical symmetry of the hydrogen atom is quite a proper state—the wave function representing it can be normalized. This is not so for the state of Lorentz symmetry of the æther.

Let us assume the four components v_μ of the velocity of the æther at any point of space-time commute with one another. Then we can set up a representation with the wave functions involving the v's. The four v's can be pictured as defining a point on a three-dimensional hyperboloid in a four-dimensional space, with the equation:

$$v_0^2 - v_1^2 - v_2^2 - v_3^2 = 1 \qquad v_0 > 0. \quad (1)$$

A wave-function which represents a state for which all æther velocities are equally probable must be independent of the v's, so it is a constant over the hyperboloid (1). If we form the square of the modulus of this wave function and integrate over the three-dimensional surface (1) in a Lorentz-invariant manner, which means attaching equal weights to elements of the surface which can be transformed into one another by a Lorentz transformation, the result will be infinite. Thus this wave function cannot be normalized.

The states corresponding to wave functions that can be normalized are the only states that can be attained in practice. A state corresponding to a wave function which cannot be normalized should be looked upon as a theoretical idealization, which can never be actually realized, although one can approach indefinitely close to it. Such idealized states are very useful in quantum theory, and we could not do without them. For example, any state for which there is a particle with a specified momentum is of this kind—the wave function cannot be normalized because from the uncertainty principle the particle would have to be distributed over the whole universe—and such states are needed in collision problems.

We can now see that we may very well have an æther, subject to quantum mechanics and conforming to relativity, provided we are willing to consider the perfect vacuum as an idealized state, not attainable in practice. From the experimental point of view, there does not seem to be any objection to this. We must make some profound alterations in our theoretical ideas of the vacuum. It is no longer a trivial state, but needs elaborate mathematics for its description.

I have recently[1] put forward a new theory of electrodynamics in which the potentials A_μ are restricted by:

$$A_\mu A_\mu = k^2,$$

where k is a universal constant. From the continuity of A_0 we see that it must always have the same sign and we may take it positive. We can then put

$$k^{-1} A_\mu = v_\mu \quad (2)$$

and get v's satisfying (1). These v's define a velocity. Its physical significance in the theory is that if there is any electric charge it must flow with this velocity, and in regions where there is no charge it is the velocity with which a small charge would have to flow if it were introduced.

We have now the velocity (2) at all points of space-time, playing a fundamental part in electro-

Quantum-Gravitational Space-Time Foam

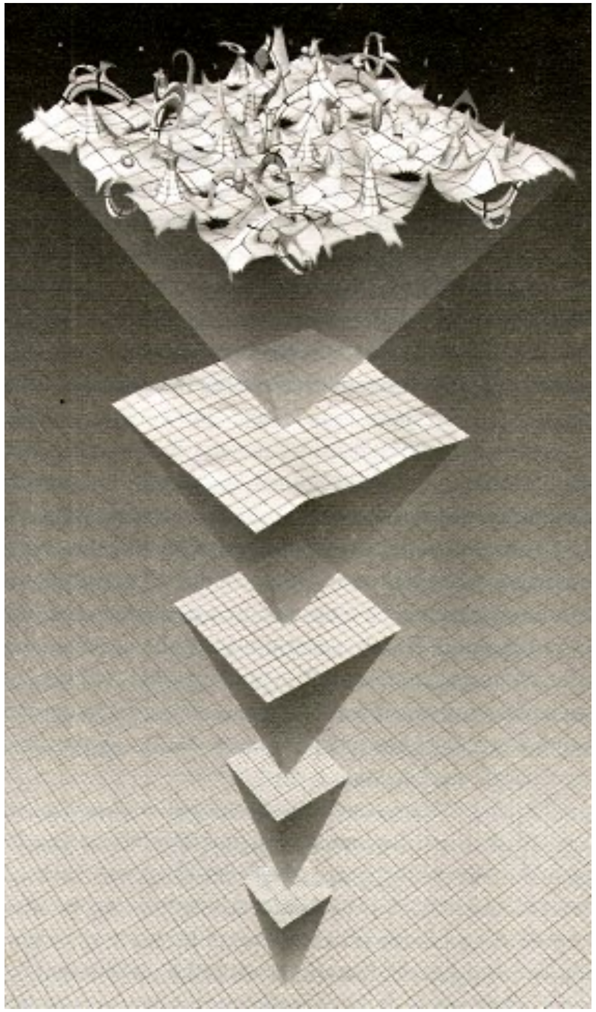
ANNALS OF PHYSICS: **2**, 604–614 (1957)

On the Nature of Quantum Geometrodynamics

JOHN A. WHEELER

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

Classical gravitation, electromagnetism, charge, and mass are described in a preceding article in terms of curved empty space and nothing more. In advance of the detailed quantization of this pure Einstein-Maxwell geometrodynamics, an attempt is made here (1) to bring to light some of the most important properties to be expected for quantized geometrodynamics and (2) to assess whether this theory, without addition of any inventive elements, can contribute anything to the understanding of the elementary particle problem. Gravitational field fluctuations are concluded to have qualitatively new consequences at distances of the order of $(\hbar G/c^3)^{1/2} = 1.6 \times 10^{-33}$ cm. They lead one to expect the virtual creation and annihilation throughout all space of pairs with electric charges of the order $\sim(\hbar c)^{1/2}$ and energies of the order $(\hbar c^5/G)^{1/2} = (2.18 \times 10^{-5}\ \mathrm{g})c^2 = 2.4 \times 10^{22}\ mc^2$.

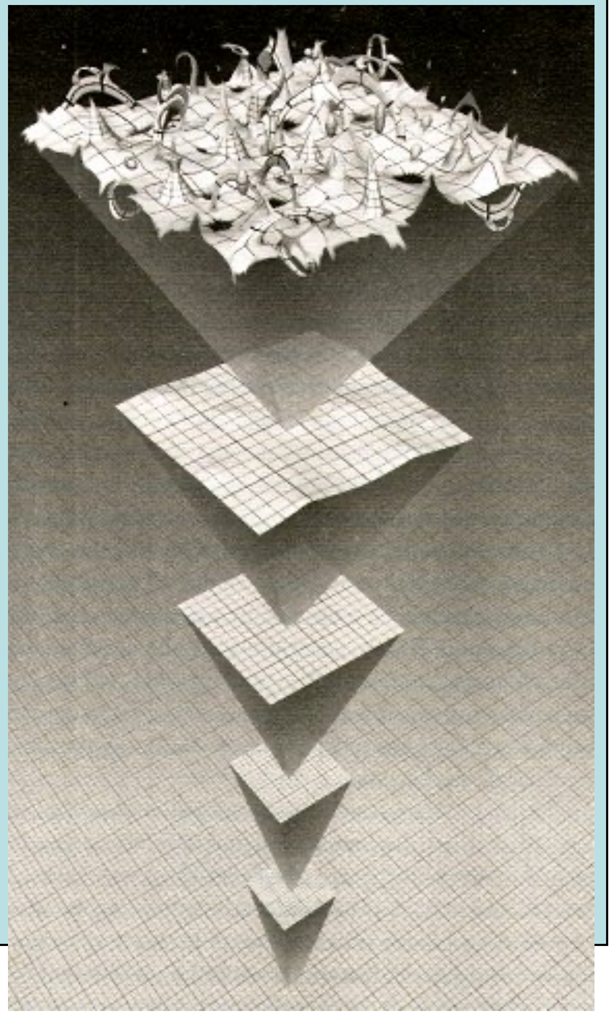


Nature of Quantum-Gravitational Vacuum

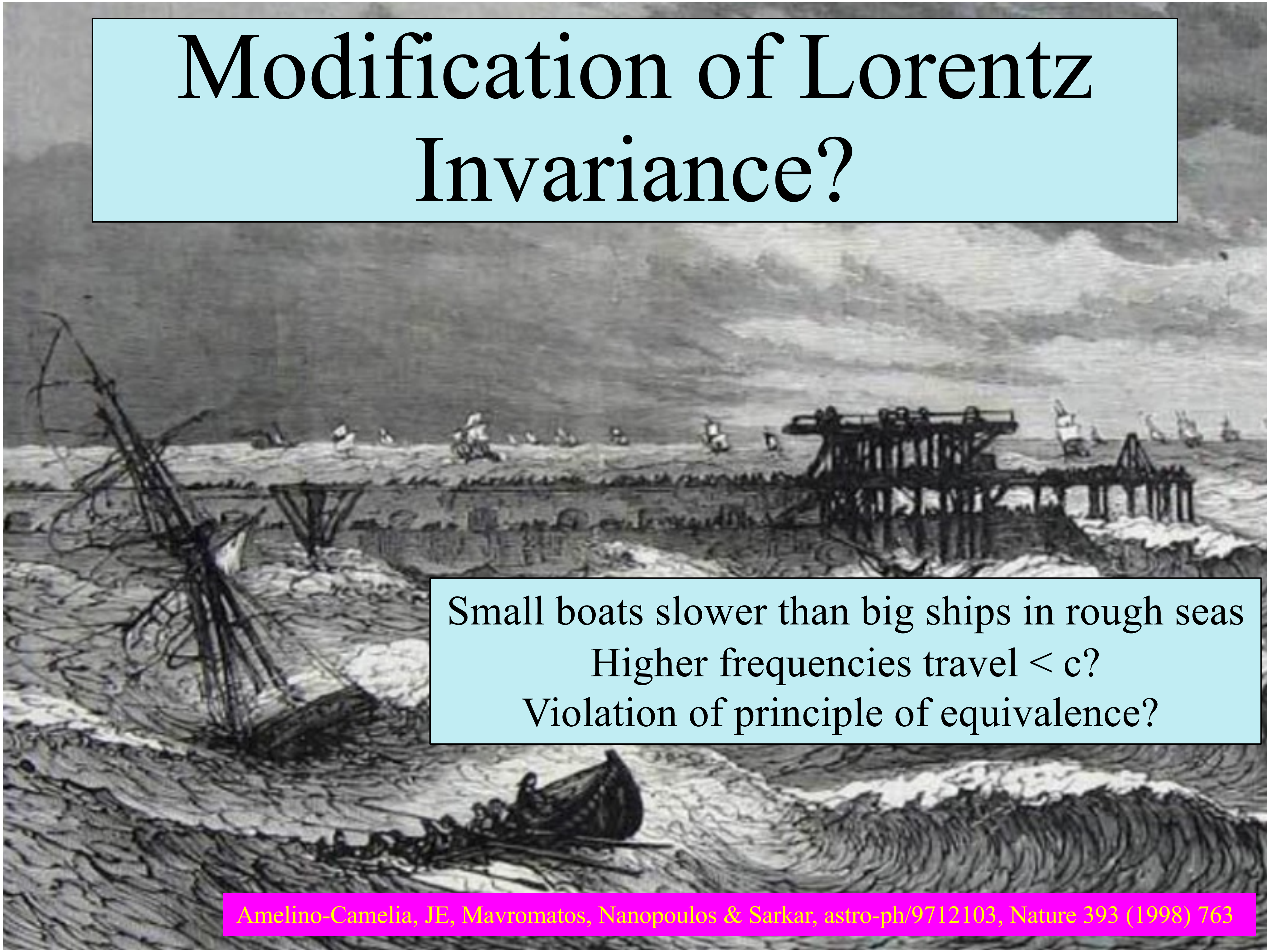
- Expect quantum fluctuations in fabric of space-time
- In natural Planckian units:

  $\Delta E, \Delta x, \Delta t, \Delta \chi \sim 1$
- Fluctuations in energy, space, time, topology of order unity
- **Space-time foam**
- **Manifestations?**
- Lorentz violation?
- Equivalence violation?

(Modification of Quantum Mechanics?)



Modification of Lorentz Invariance?



Small boats slower than big ships in rough seas
Higher frequencies travel < c?
Violation of principle of equivalence?

Amelino-Camelia, JE, Mavromatos, Nanopoulos & Sarkar, astro-ph/9712103, Nature 393 (1998) 763

Space-Time Foam as a Dynamical Medium

- Expect large intrinsic fluctuations at small scales
- Expect back-reaction due to energetic particles
- Non-trivial refractive index
- Effect on propagation that increases with energy:

$$c^2 \mathrm{p}^2 = E^2 \left[1 + \xi E / E_{\mathrm{QG}} + \mathcal{O}(E^2 / E_{\mathrm{QG}}^2)\right] \qquad v = \frac{\partial E}{\partial p} \sim c \left(1 - \xi \frac{E}{E_{\mathrm{QG}}}\right)$$

- Non-critical string model: ξ = -1

(ξ = -1 needed to avoid Čerenkov radiation *in vacuo*)

- Expect: $E_{QG} = O(M_P)$?
- Related to string scale in non-critical string model

Amelino-Camelia, JE, Mavromatos, Nanopoulos & Sarkar, astro-ph/9712103, Nature 393 (1998) 763

Tests of quantum gravity from observations of γ-ray bursts

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The recent confirmation that at least some γ-ray bursts originate at cosmological distances[1–4] suggests that the radiation from them could be used to probe some of the fundamental laws of physics. Here we show that γ-ray bursts will be sensitive to an energy dispersion predicted by some approaches to quantum gravity. Many of the bursts have structure on relatively rapid timescales[5], which means that in principle it is possible to look for energy-dependent dispersion of the radiation, manifested in the arrival times of the photons, if several different energy bands are observed simultaneously. A simple estimate indicates that, because of their high energies and distant origin, observations of these bursts should be sensitive to a dispersion scale that is comparable to the Planck energy scale (~10^{19} GeV), which is sufficient to test theories of quantum gravity. Such observations are already possible using existing γ-ray burst detectors.

photon energies, any analogous quantum-gravity effect could be distinguished by its different energy dependence: the quantum-gravity effect would increase with energy, whereas conventional medium effects decrease with energy in the range of interest[6].

Equation (1) encodes a minute modification for most practical purposes, as E_{QG} is believed to be a very high scale, presumably of the order of the Planck scale $E_P \approx 10^{19}$ GeV. Even so, such a deformation could be rather significant for even moderate-energy signals, if they travel over very long distances. According to equation (1), a signal of energy E that travels a distance L acquires a 'time delay', measured with respect to the ordinary case of an energy-independent speed c for massless particles:

$$\Delta t \approx \xi \frac{E}{E_{QG}} \frac{L}{c} \qquad (2)$$

This is most likely to be observable when E and L are large while the interval δt, over which the signal exhibits time structure, is small. This is the case for GRBs, which is why they offer particularly good prospects for such measurements, as we discuss later.

We first review briefly how modified laws for the propagation of particles have emerged independently in different quantum-gravity approaches. The suggestion that quantum-gravitational fluctuations might modify particle propagation in an observable way can already be found in refs 7 and 9. A phenomenological parametrization of the way this could affect the neutral kaon system[9–11] has been already tested in laboratory experiments, which have set lower limits on parameters analogous to the E_{QG} introduced above at levels comparable to E_P (ref. 12). In the case of massless particles such as the photon, which interests us here, the first example of a quantum-gravitational medium effect with which we are familiar occurred in a string formulation of an expanding Robertson–Walker–Friedman

Astrophysical Probes of Lorentz Violation

- Time delay from distant object:

$$\Delta t \sim \xi \frac{E}{E_{\rm QG}} \frac{L}{c}$$

Amelino-Camelia, JE, Mavromatos, Nanopoulos + Sarkar

- Compare arrivals of photons of different energies from astrophysical source with small intrinsic δt
- Gamma-Ray Bursters, pulsars, active galaxies, …
- Typical sensitivities:

Source	Distance	E	Δt	Sensitivity to M
GRB 920229 [a]	3000 Mpc (?)	200 keV	10^{-2} s	0.6×10^{16} GeV (?)
GRB 980425 [a]	40 Mpc	1.8 MeV	10^{-3} s (?)	0.7×10^{16} GeV (?)
GRB 920925c [a]	40 Mpc (?)	200 TeV (?)	200 s	0.4×10^{19} GeV (?)
Mrk 421 [b]	100 Mpc	2 TeV	280 s	$> 7 \times 10^{16}$ GeV
Crab pulsar [c]	2.2 kpc	2 GeV	0.35 ms	$> 1.3 \times 10^{15}$ GeV
GRB 990123	5000 Mpc	4 MeV	1 s (?)	2×10^{15} GeV (?)

Violation of the Equivalence Principle?

- Non-Universality of Lorentz Violation?
- Do all relativistic particles have same velocity?
- Not necessarily, if particle interactions with space-time foam are non-universal
- (Relativistic) departure from Principle of Equivalence
- Consistent with astrophysics: limits on Lorentz violation for electrons >> m_P
- Expected in non-critical string model of foam

JE, Mavromatos + Nanopoulos

Synchrotron Radiation Constraint from Crab Nebula

Jacobson, Liberati + Mattingly

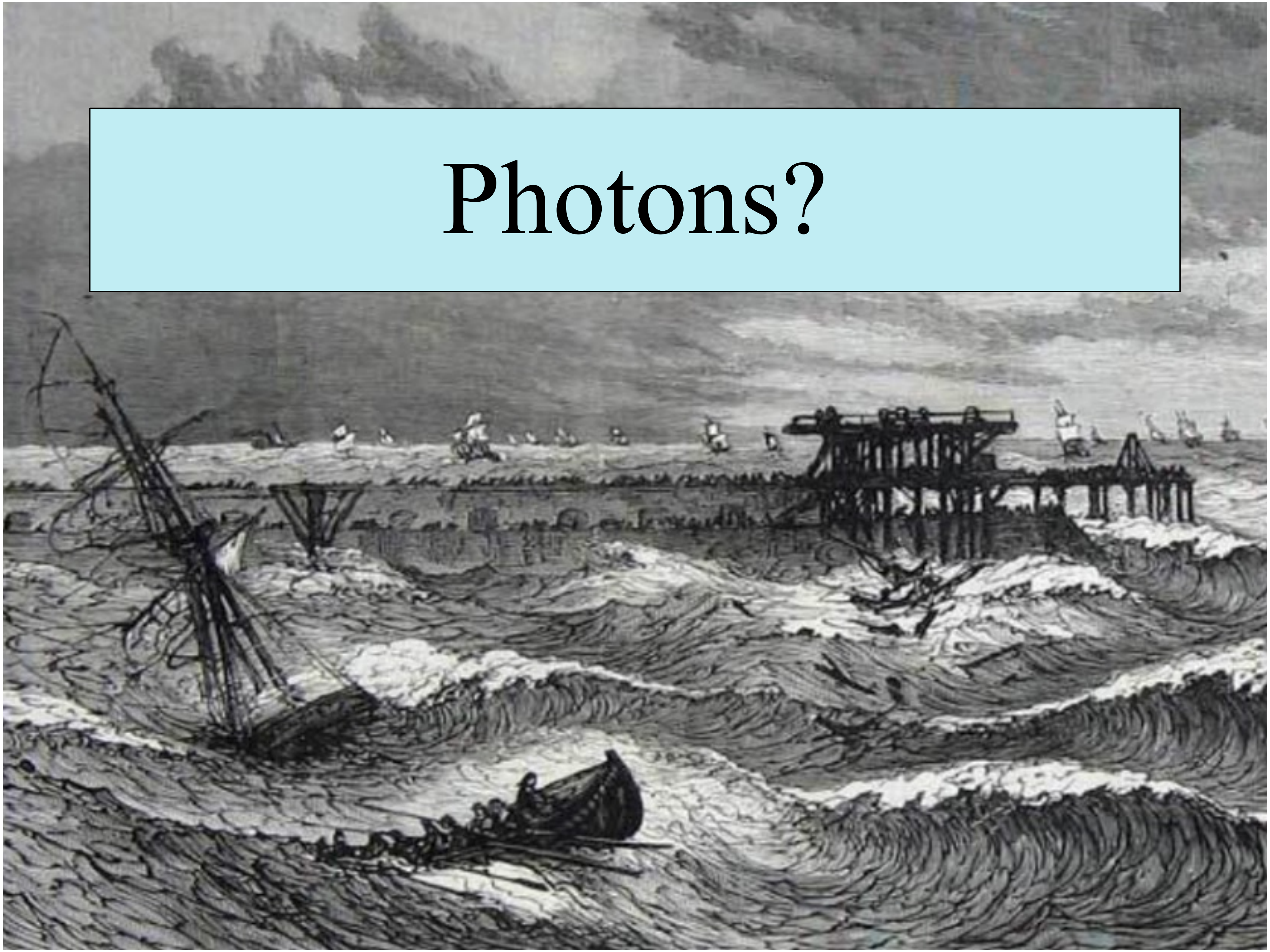
- See 0.5 GeV γ: inverse Compton by > 50 TeV *e*
- Consider modified dispersion relations for both electrons *e* and photons γ: $\omega^2(k) = k^2 + \xi_\gamma \frac{k^3}{M_P} \quad E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^3}{M_P}$
- Lorentz-invariant: $\omega_c^{LI} = \frac{3}{2}\frac{eH}{m_0}\frac{1}{1-\beta^2}$
- QG modification: $\omega_c^{QG} = \frac{3}{\sqrt{2}}\frac{eH}{m_0}\frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^\alpha\right)}$
- For $\xi = (E/m_P)^\alpha$

  data ⟶ $|\xi_e| < \left(\frac{3eH}{m_0}\right)^{\frac{\alpha+2}{2\alpha}}\left(\frac{M_P}{m_0}\right)\left(\frac{2}{\alpha(\alpha+1)}\right)^{1/\alpha}\left(\frac{\alpha}{\alpha+2}\right)^{(\alpha+2)/2\alpha}$
- Lower bound on modification: $\alpha > 1.72$
- If $\alpha = 1$: $m_{QG} > 10^{26}$ GeV

No constraint on LV for photon, none expected for electron

JE, Mavromatos + Nanopoulos

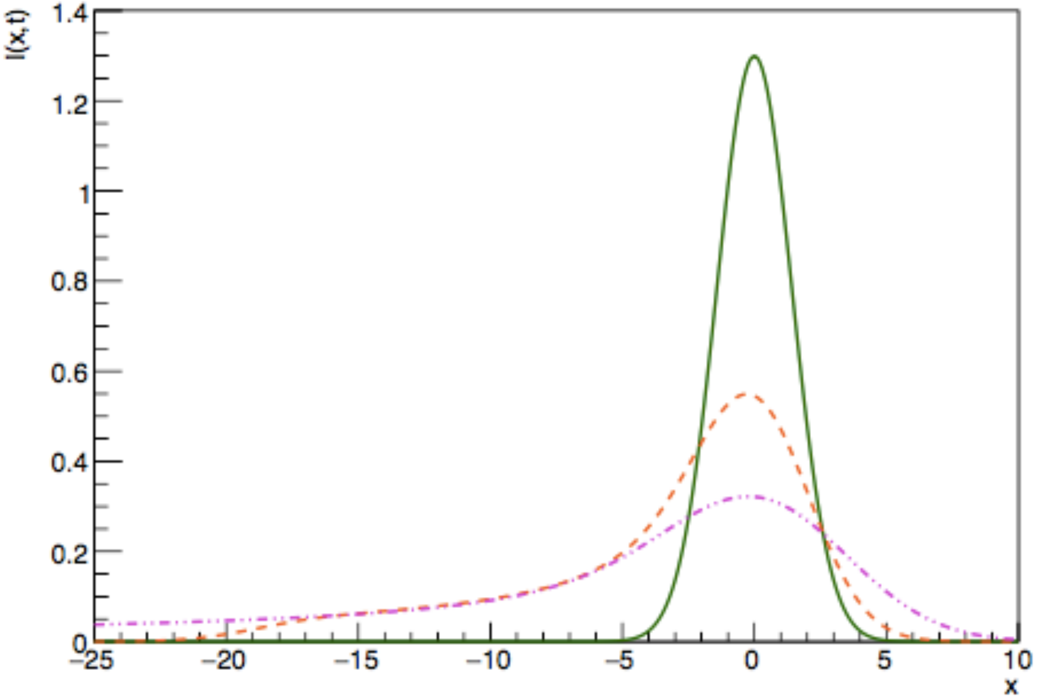
Photons?



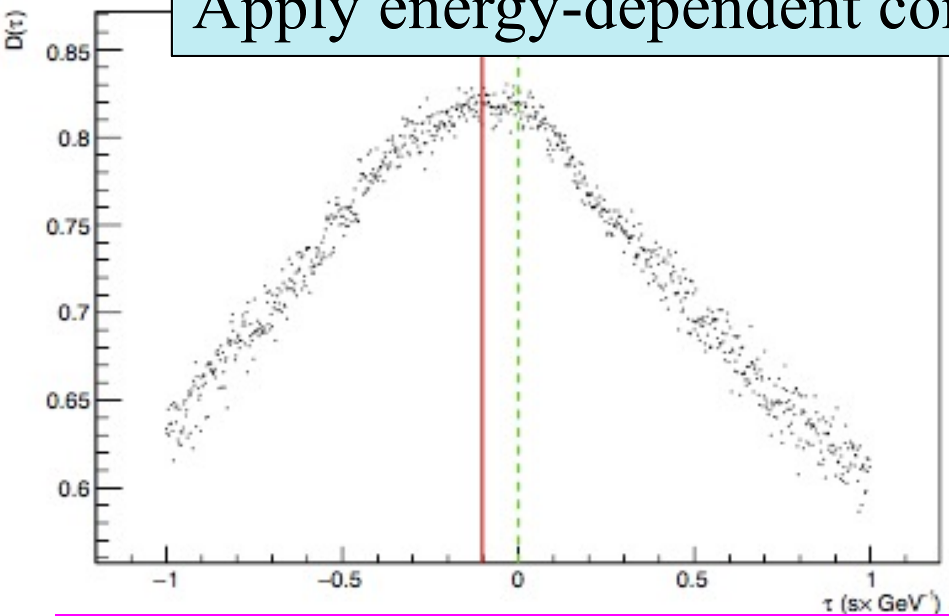
Robust Analysis of Fermi-LAT GRBs

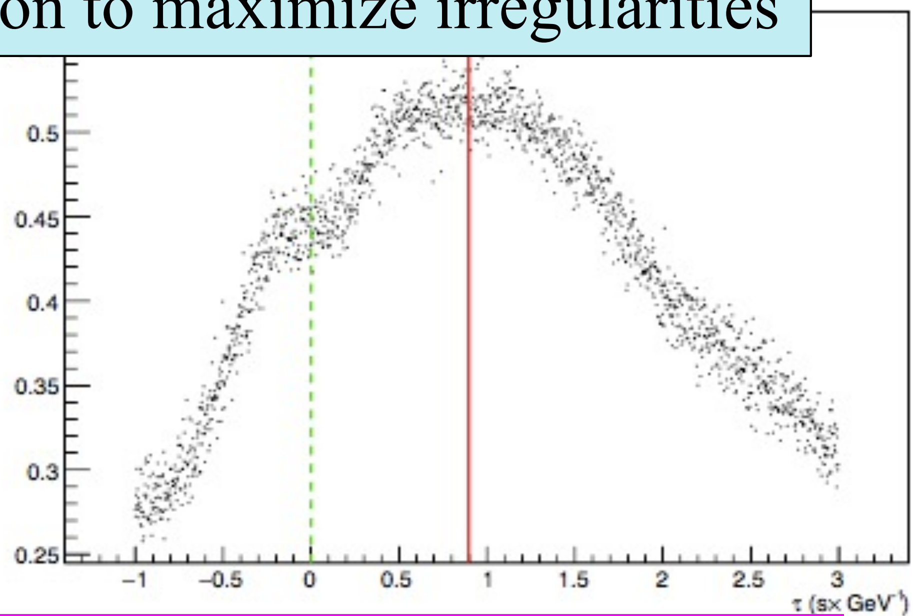
Lorentz violation tends to:

- Smooth out irregularities
- Increase kurtosis
- Increase skewness



Apply energy-dependent correction to maximize irregularities





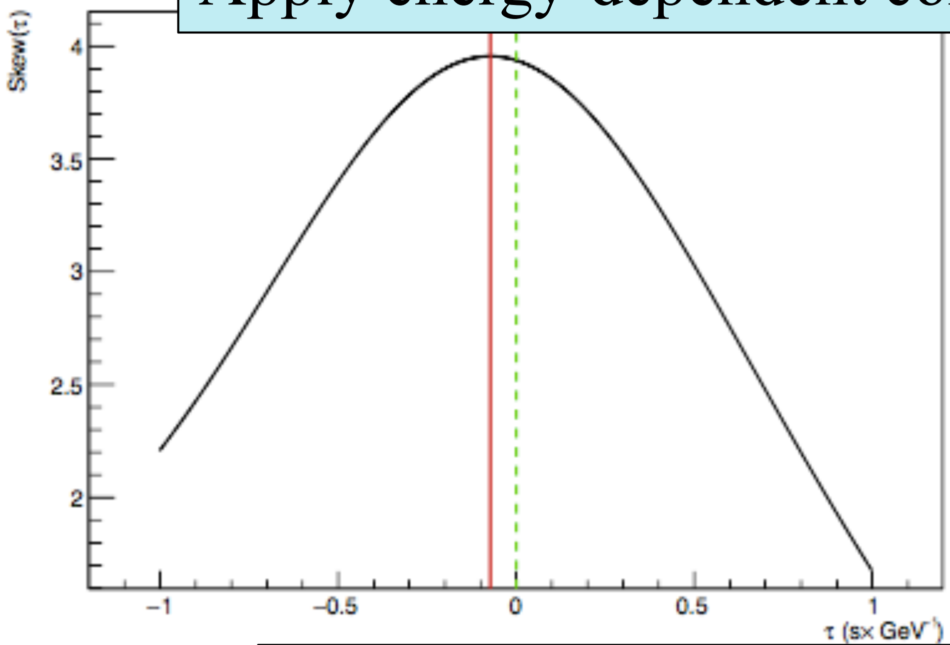
JE, Konoplich, Mavromatos, Nguyen, Sakharov, Sarkisyan-Grinbaum, arXiv:1807.00189

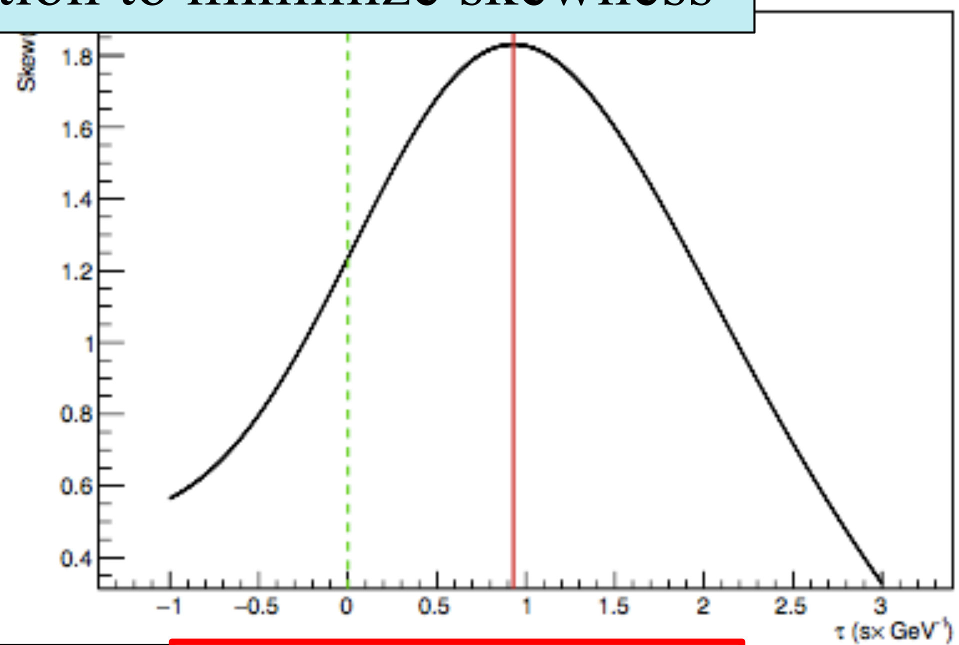
Robust Analysis of Fermi-LAT GRBs

Skewness

$$\mathcal{S}(\tau) = \sqrt{N_W}\,\frac{\sum_{i=0}^{N-1}\left((b_{\rm df}(E_i,\tau) - \overline{b_{\rm df}(\tau)})W_i\right)^3}{\left(\sum_{i=0}^{N-1}\left((b_{\rm df}(E_i,\tau) - \overline{b_{\rm df}(\tau)})W_i\right)^2\right)^{3/2}}$$

Apply energy-dependent correction to minimize skewness

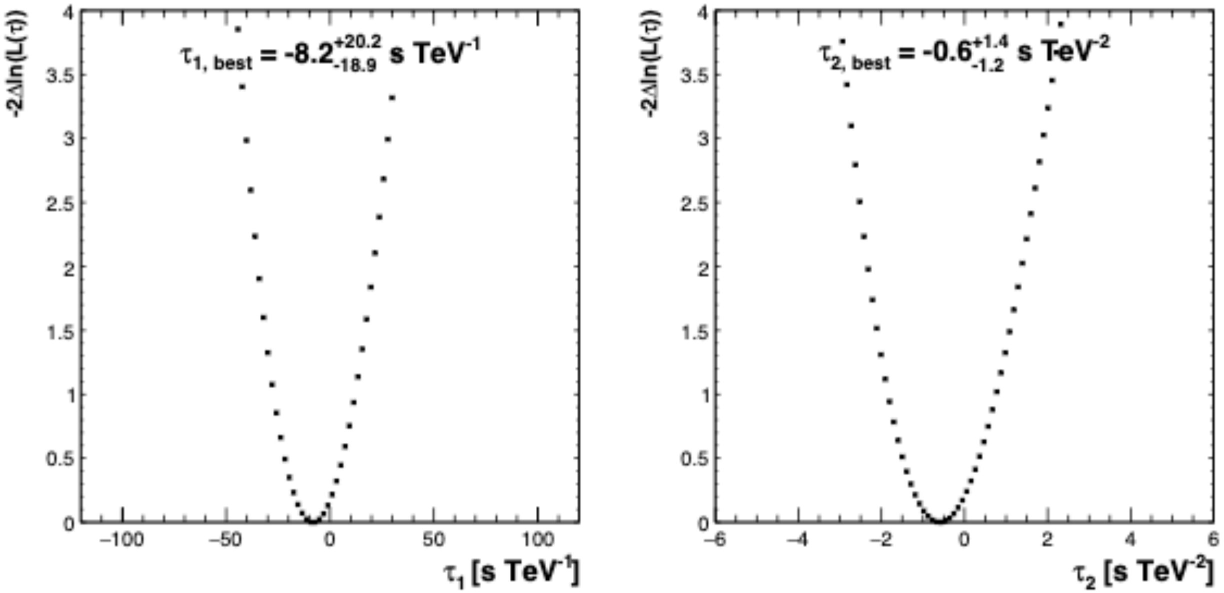




Combined analysis using 8 GRBs: $M_1 \geq 2.4 \times 10^{17}$ GeV

JE, Konoplich, Mavromatos, Nguyen, Sakharov, Sarkisyan-Grinbaum, arXiv:1807.00189

HESS Analysis of Markarian 501



$$\tau_{1,\mathrm{best}} = -8.2 \pm 21.5_{(stat)} \pm 14.2_{(syst)}\ \mathrm{s}\cdot\mathrm{TeV}^{-1}$$

$$\tau_{2,\mathrm{best}} = -0.6 \pm 1.8_{(stat)} \pm 0.7_{(syst)}\ \mathrm{s}\cdot\mathrm{TeV}^{-2}$$

Sensitivities to LV parameters

$$E_{QG,1} > \begin{cases} 3.6\times 10^{17}\ \mathrm{GeV} & \text{(subluminal)}, \\ 2.6\times 10^{17}\ \mathrm{GeV} & \text{(superluminal)}, \end{cases}$$

$$E_{QG,2} > \begin{cases} 8.5\times 10^{10}\ \mathrm{GeV} & \text{(subluminal)}, \\ 7.3\times 10^{10}\ \mathrm{GeV} & \text{(superluminal)}. \end{cases}$$

HESS Collaboration, arXiv:1901.05209

Another Possible Effect of Lorentz Violation

- For effect ~ $(E/E_{QG})^n$
- Time lag:

$$\tau_n = \frac{\Delta t_n}{\Delta E_n} \simeq \pm \frac{n+1}{2} \frac{1}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{H(z')} \mathrm{d}z'$$

- Also: absorption of energetic photons by e^+e^- pair production modified by threshold:

Kifune, astro-ph/9904164
Protheroe & Meyer, astro-ph/0005349

$$\epsilon_{\mathrm{thr}} = \frac{m_e^2 c^4}{E'_\gamma} + \frac{1}{4} \frac{E'^{n+1}_\gamma}{E^n_{\mathrm{QG}}}$$

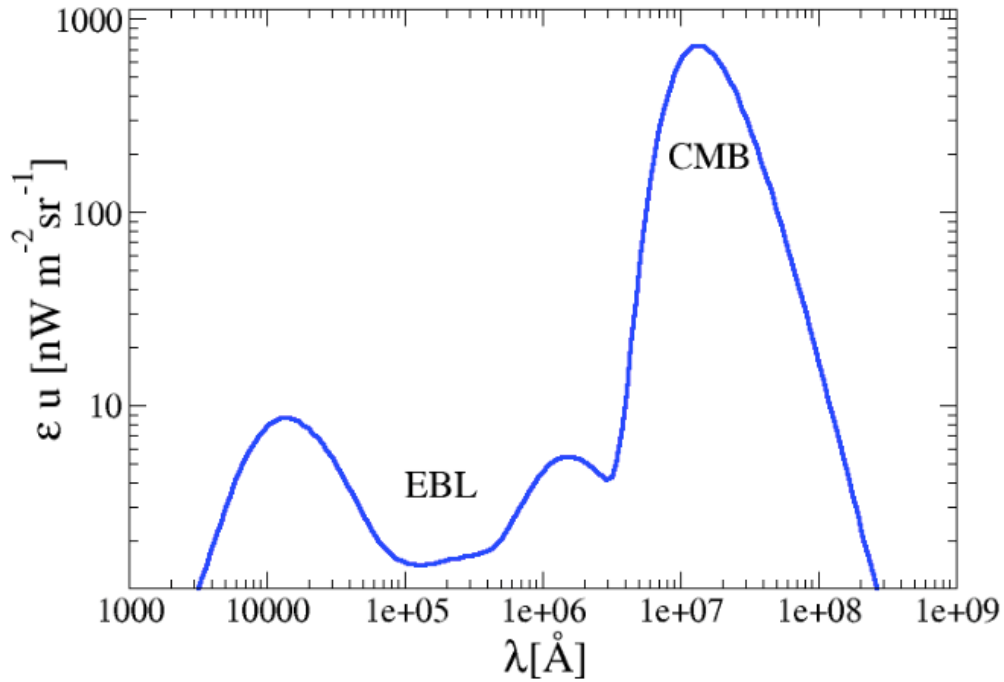
- Competitive sensitivities

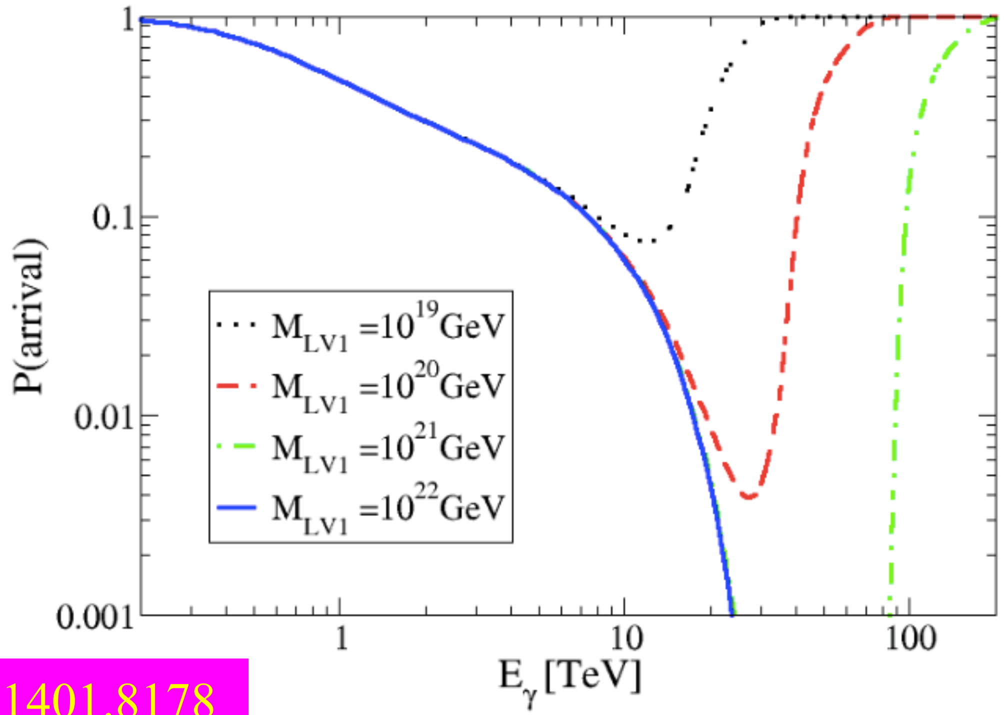
Possible Effect on γ Spectrum

- Expect absorption due to e^+e^- production in collisions with γ background
- Reduced absorption if Lorentz violation via modified (E, p) dispersion relation for γ

Kifune, astro-ph/9904164
Protheroe & Meyer, astro-ph/0005349

- Interesting for CTA

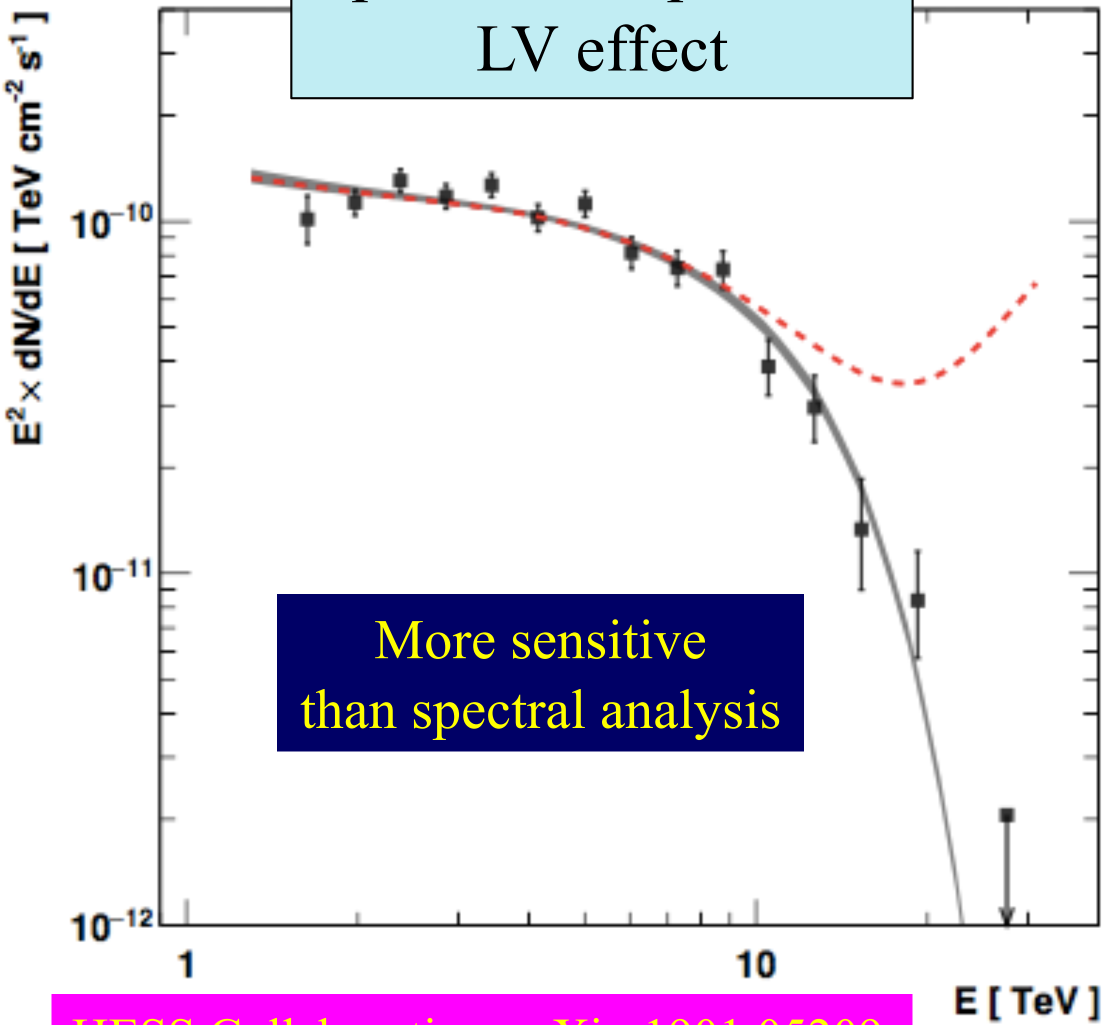




Fairbairn, Nilsson, JE, Hinton & White, arXiv:1401.8178

HESS Analysis of Markarian 501

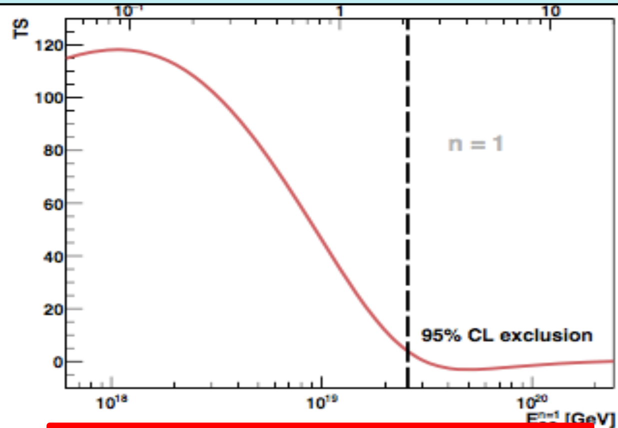
Spectrum vs possible LV effect



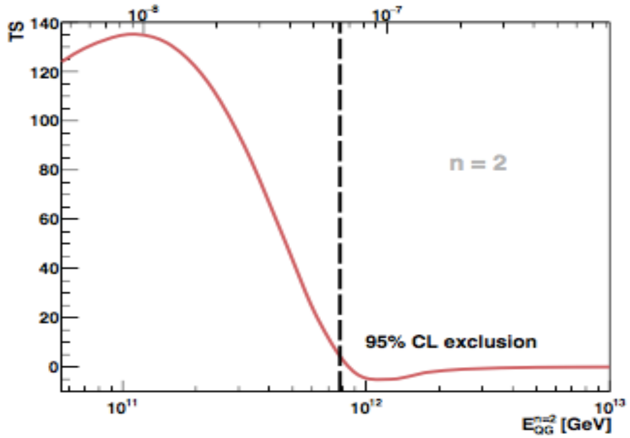
More sensitive than spectral analysis

HESS Collaboration, arXiv:1901.05209

Lower limits on LV scale

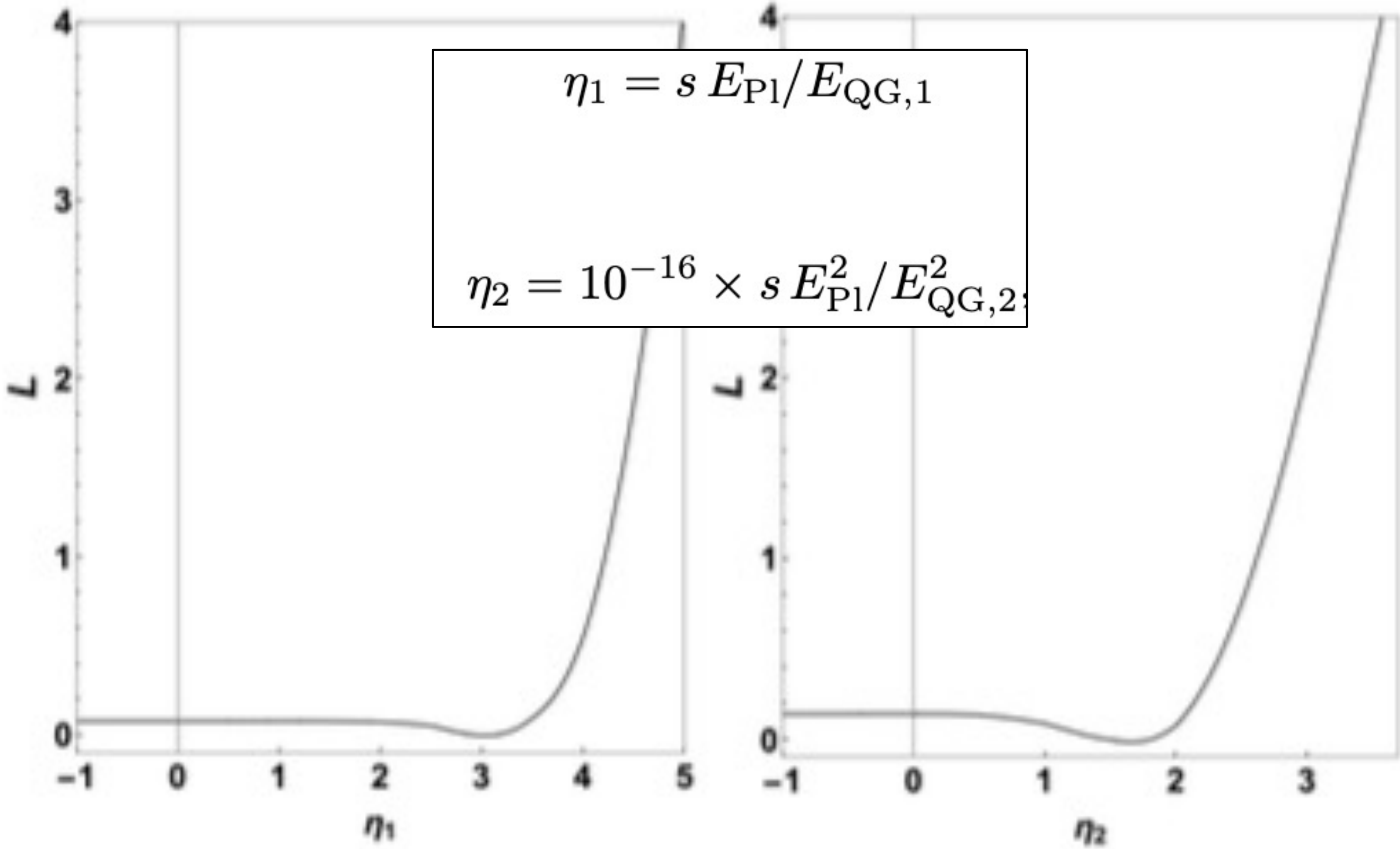


$E_{QG,1} > 2.6 \times 10^{19}$ GeV



$E_{QG,2} > 7.8 \times 10^{11}$ GeV

MAGIC Analysis of GRB 190114C



$$\eta_1 = s\,E_{\mathrm{Pl}}/E_{\mathrm{QG},1}$$

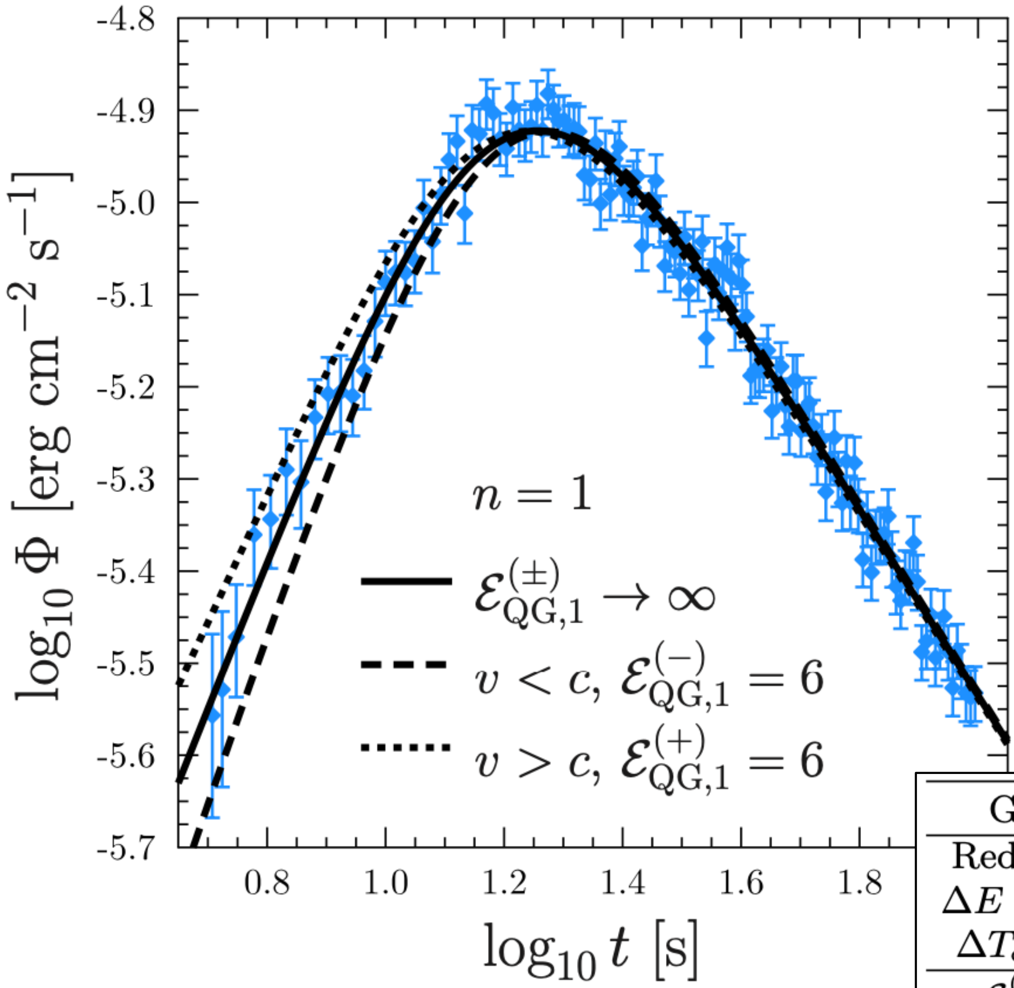
$$\eta_2 = 10^{-16} \times s\,E_{\mathrm{Pl}}^2/E_{\mathrm{QG},2}^2$$

Limits on QG parameters from time-lag analysis

$E_{\mathrm{QG},1}$ [10^{19} GeV]	0.28
$E_{\mathrm{QG},2}$ [10^{10} GeV]	7.3

MAGIC Collaboration, arXiv:2001.09728

Analysis of GRB 221009A



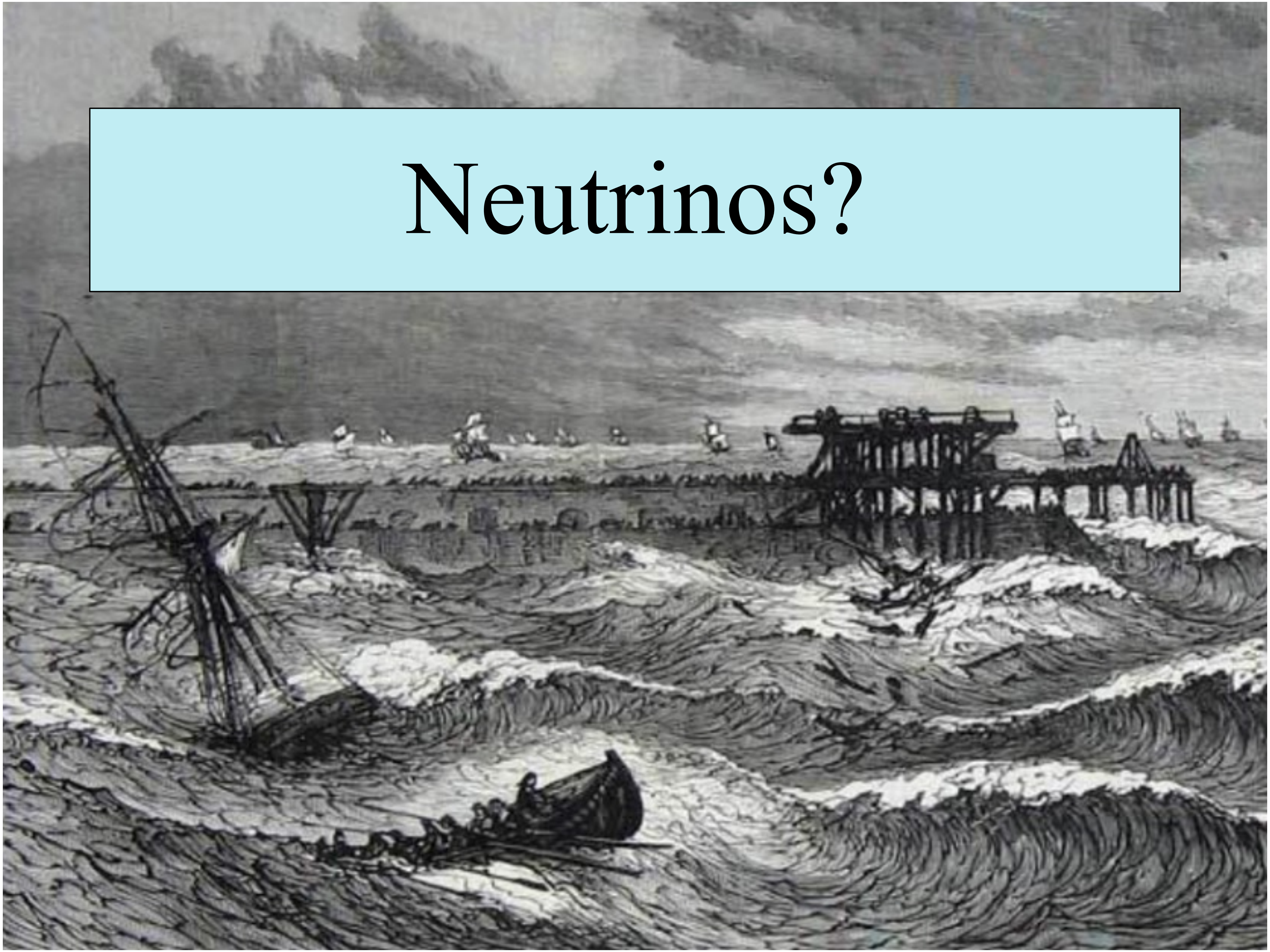
Piran & Ofengeim, arXiv:2308.03031

Brightest GRB Ever:
z = 0.151, E < 7 TeV$^{(*)}$
Comparison of LV limits with other GRBs (in Planck units)

(*) Would be strengthened by ~ 3 if higher-energy events included

GRB	090510[a]	190114C	221009A
Red Shift	0.903	0.425	0.151
ΔE [TeV]	10^{-4} — 0.03	0.3 — 1	0.2 — 7
$\Delta T_{\rm obs}$ [s]	0.15 — 0.217	30 — 60	9 — 14
$\mathcal{E}^{(\sigma)}_{\rm QG,1}$	11^- 5.2^+	0.23^- 0.45^+	5.9^- 6.2^+
$\mathcal{E}^{(\sigma)}_{\rm QG,2}/10^{-8}$	0.7^- 0.77^+	0.46^- 0.52^+	5.8^- 4.6^+

Neutrinos?



Early Constraints on Neutrino Lorentz Violation

- First MINOS measurement of neutrino velocity:

$$(v - c)/c > - 2.4 \times 10^{-5}$$

MINOS Collaboration, arXiv:0706.0437 [hep-ex]

corresponded to

$$M_1 > 10^5 \text{ GeV}$$

- Improved MINOS measurement

$$(v - c)/c > - 1 \times 10^{-6}$$

MINOS Collaboration, arXiv:1507.04328

corresponds to

$$M_1 > 3 \text{ x } 10^6 \text{ GeV}$$

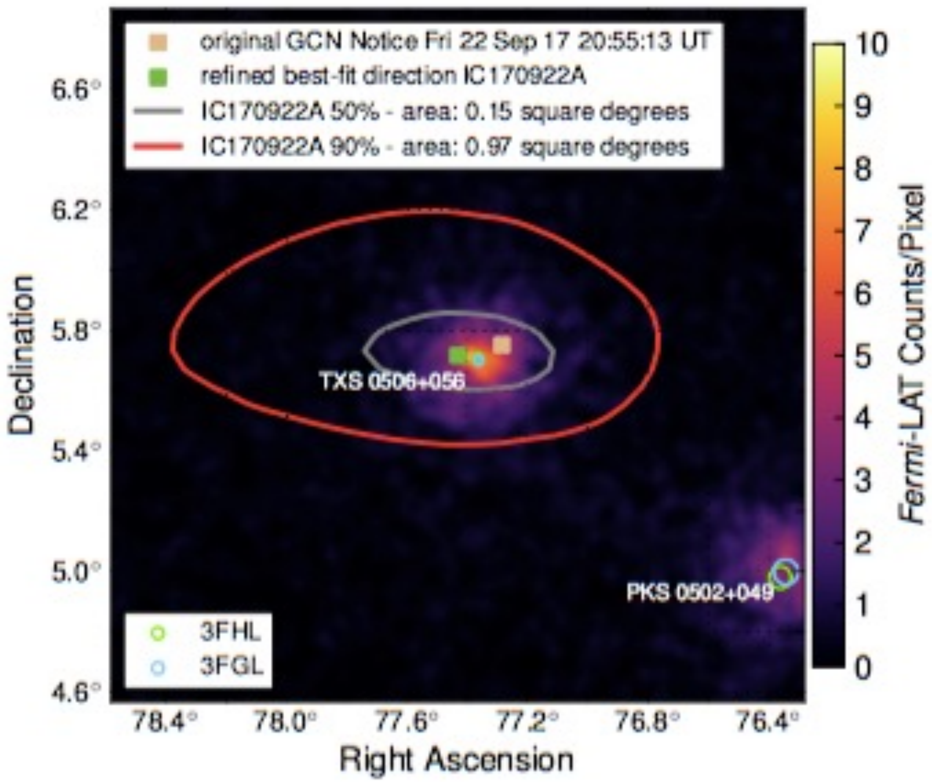
- Coincidence between neutrinos from supernova 1987a in Kamioka II, IMB and Baksan experiments:

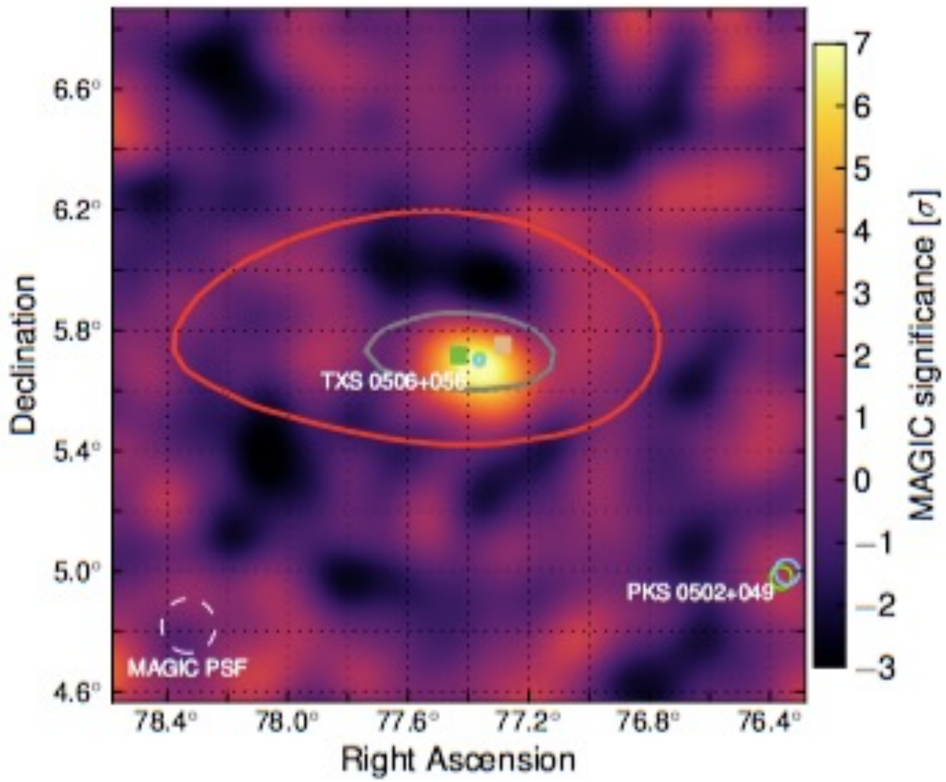
$$M_1 > 2.7 \times 10^{10} \text{ GeV}$$

Ellis, Harries, Meregaglia, Sakharov, & A.Rubbia, arXiv:0805.0253 [hep-ph]

Multimessenger Observations of Blazar TXS 0506+056

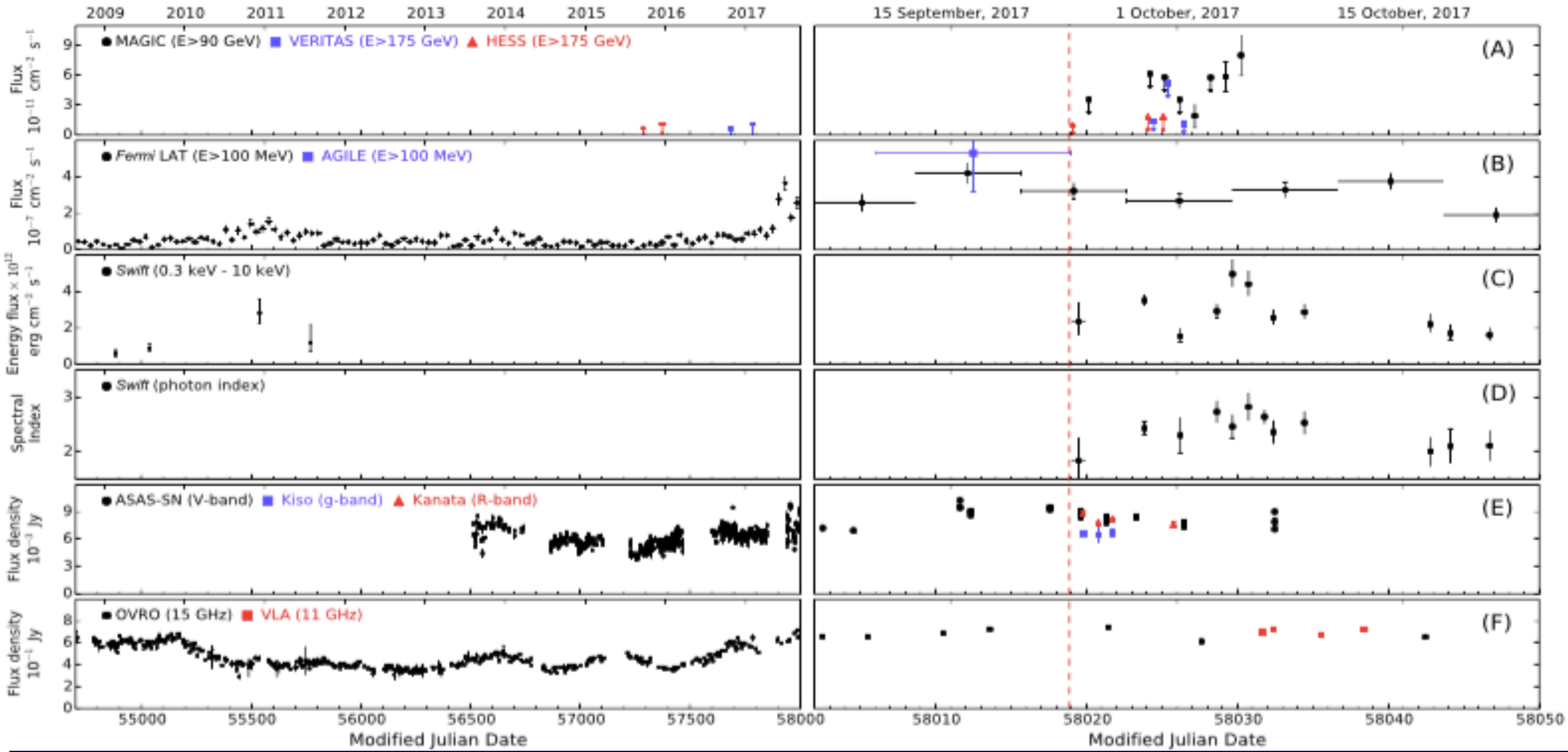
IceCube-170922A vs *Fermi*-LAT (left), MAGIC (right)





IceCube, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S, *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, *Swift*/*NuSTAR*, VERITAS, and VLA/17B-403 teams
arXiv:1807.08816

Electromagnetic Follow-up to IC170922



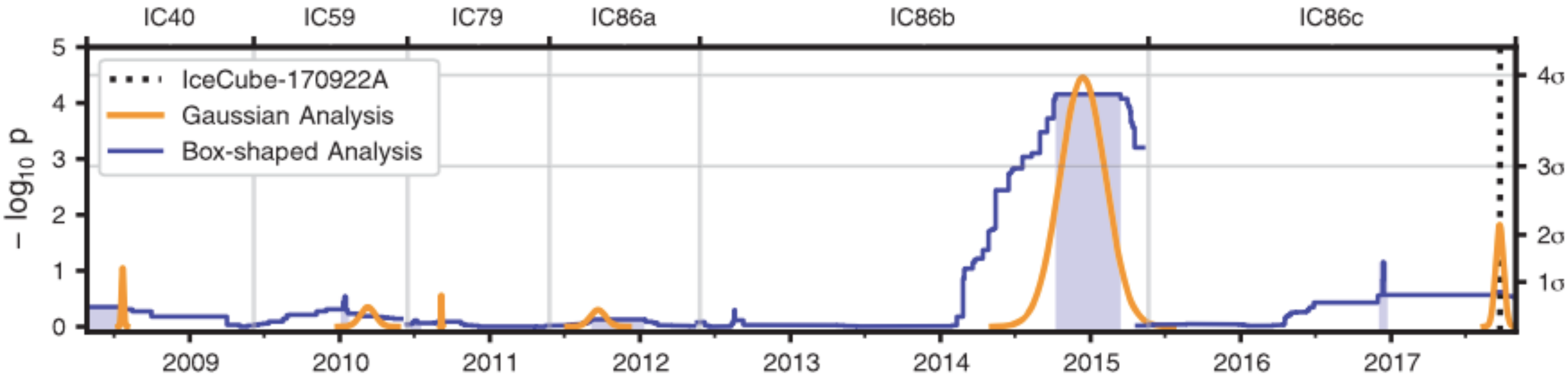
γ-ν coincidence: most sensitive limits on Lorentz violation in neutrino propagation

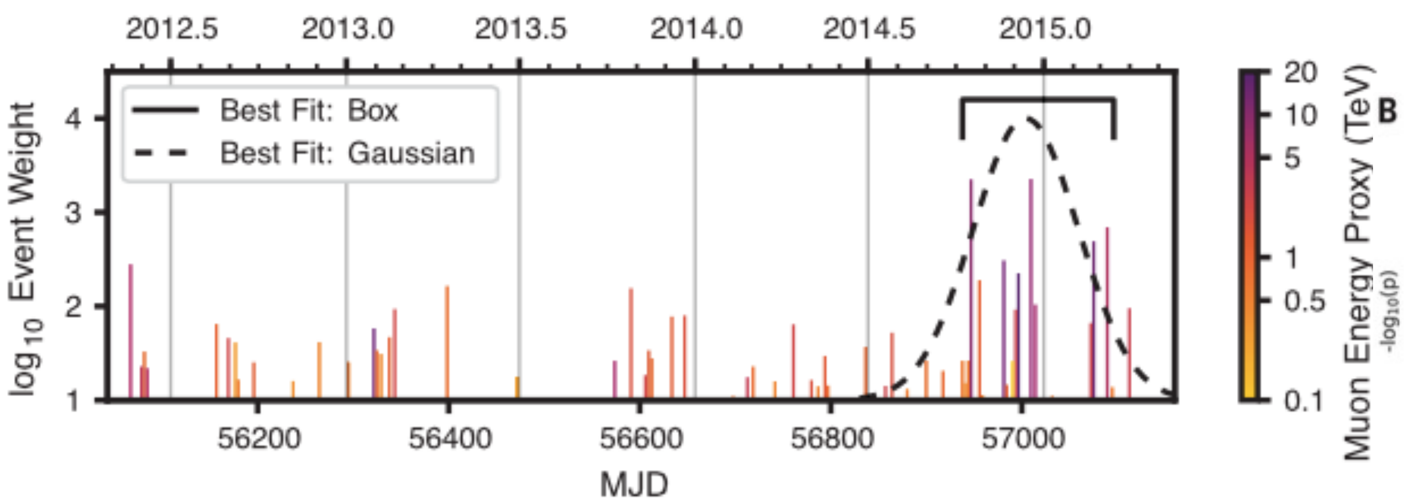
$$M_1 \gtrsim \frac{H_0^{-1}}{\Delta t} E \int_0^{z_{\rm src}} \frac{(1+z)}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \approx 3 \times 10^{16}\ {\rm GeV}$$

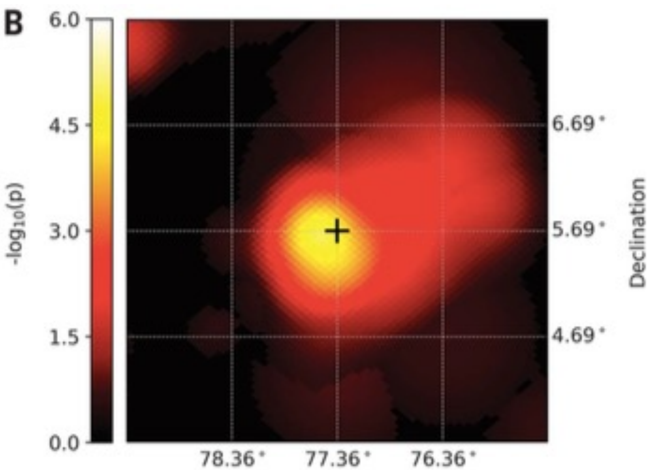
$$M_2 \gtrsim \left[\frac{3}{2} \frac{H_0^{-1}}{\Delta t} E^2 \int_0^{z_{\rm src}} \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \right]^{1/2} \approx 10^{11}\ {\rm GeV}$$

JE, Mavromatos, Sakharov & Sarkisyan-Grinbaum, arXiv:1807.05155

Earlier Neutrino Flare from TXS 0506+056







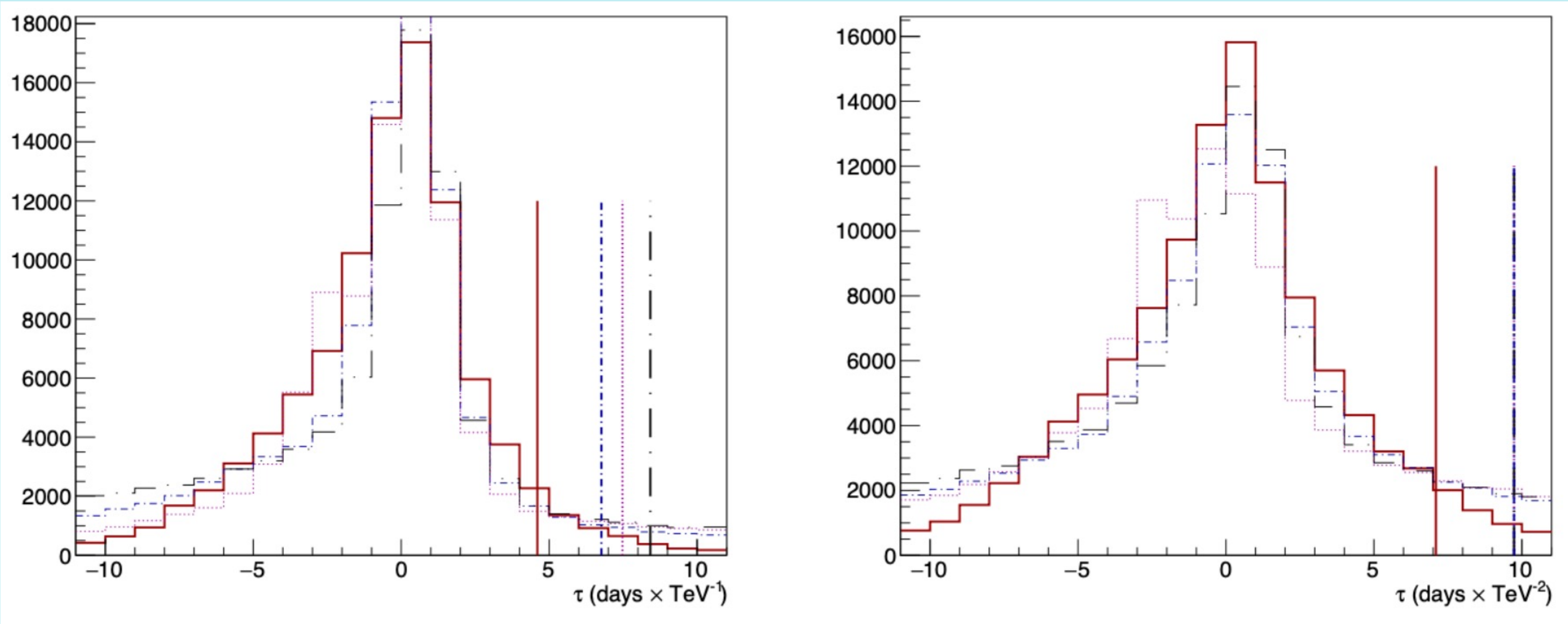
Supports interpretation of IC170922

IceCube Collaboration

Bustamante, JE, Konoplich & Sakharov, *in preparation*

Analysis of Neutrino Burst from TXS 0506+056

- Compensation of possible Lorentz violation:
  - Kolmogorov-Smirnov, skewness, kurtosis, combination



- 95% CL limits for linear, quadratic:

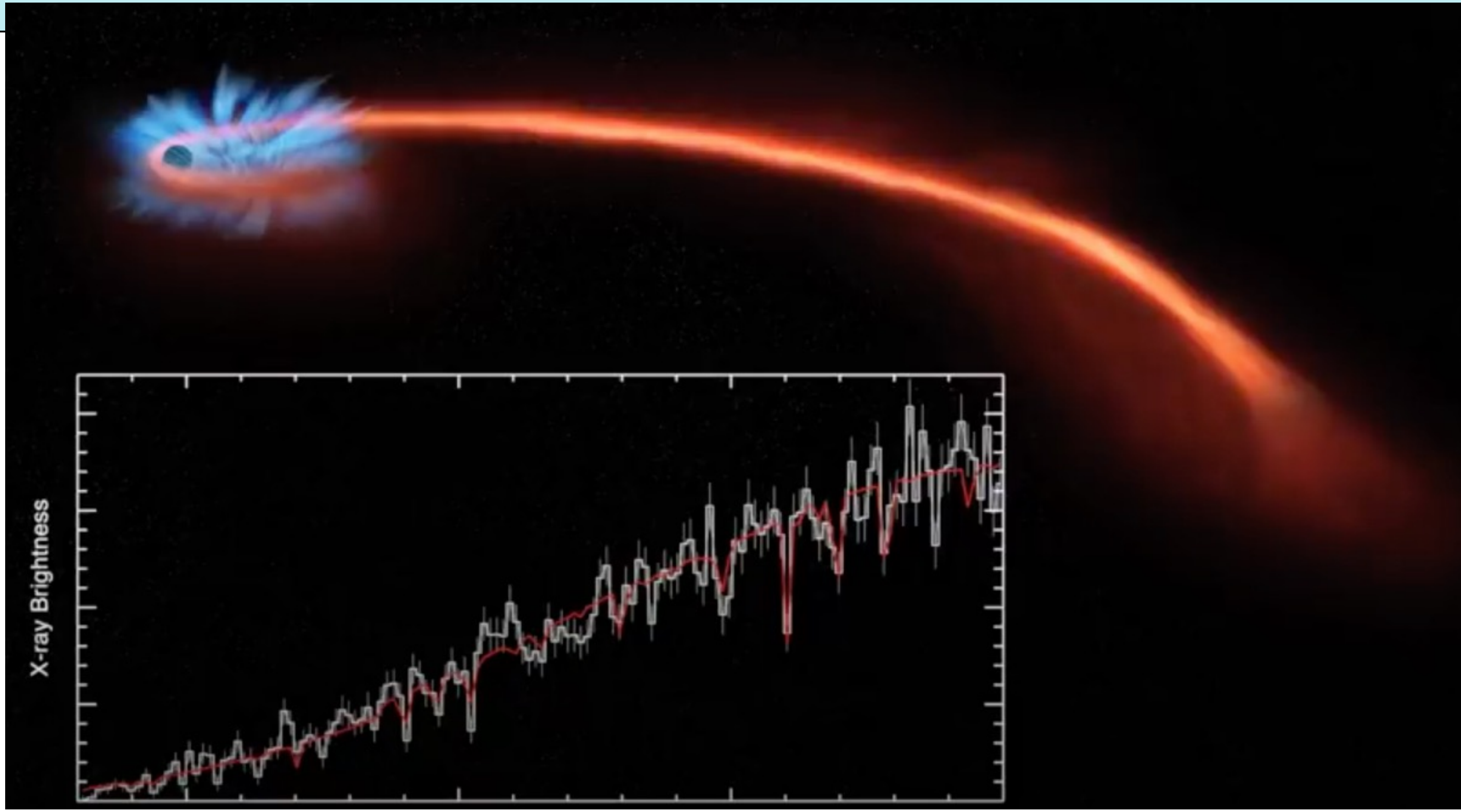
$$M_1 > 4.0 \times 10^{14}\ \text{GeV}, \qquad M_2 > 6.7 \times 10^{8}\ \text{GeV}$$

Stop press: 3 neutrinos in 1 day from PKS 0625-35: $M_1 > 10^{16}$ GeV, $M_2 > 10^{10}$ GeV (?)

Bradascio et al, arXiv:2308.16699

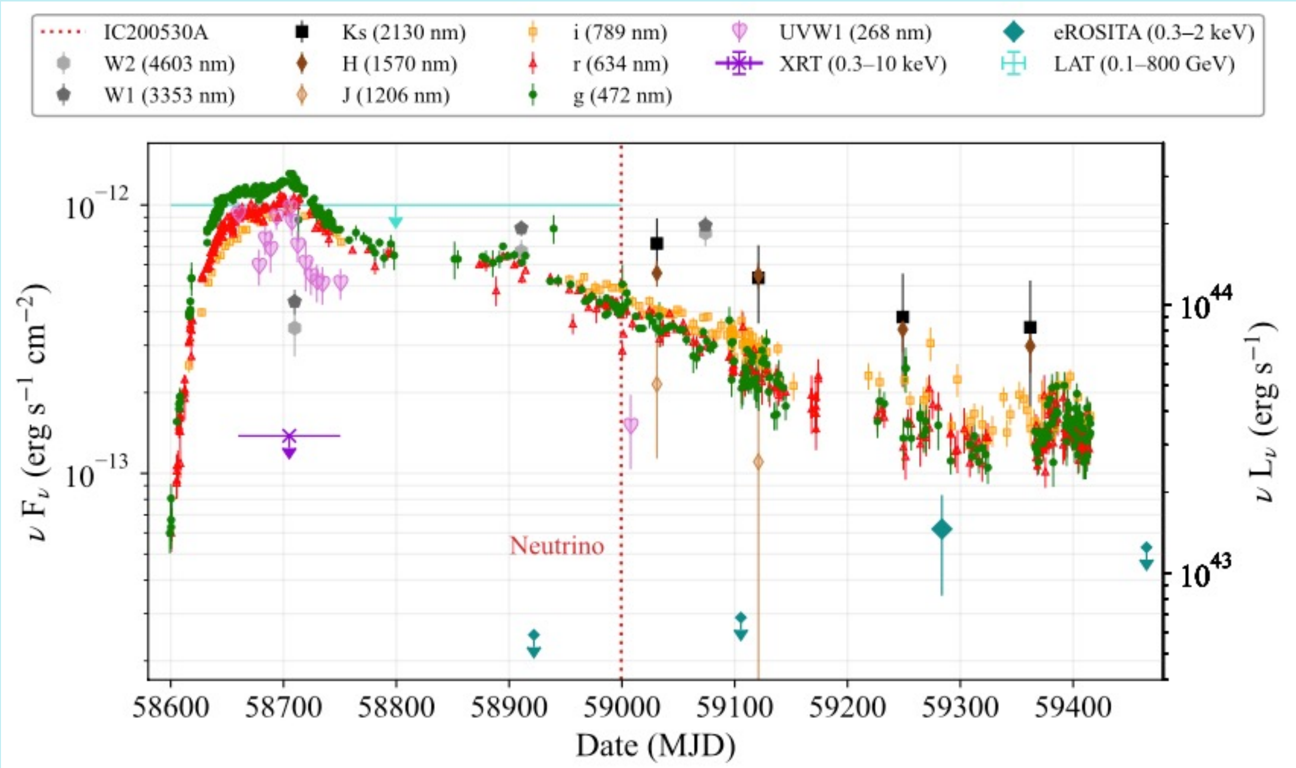
Neutrinos from Tidal Disruption Events

- Stars captured by massive black holes disrupted, subject to "spaghettification"
- Squeezing, heating, X-ray emission: neutrinos?



Neutrinos from Tidal Disruption Events

- Tidal disruption events accompanied by neutrinos:



- AT2019dsg: 200 TeV neutrino, time-lag ½ yr, z = 0.051
- AT2019fdr: 80 TeV neutrino, time-lag 1 yr, z = 0.267
- AT2019aacl: 170 TeV neutrino, time-lag 0.4 yr, z = 0.036
- Sensitivities to $M_1 \sim 3 \times 10^{14}$ GeV

Bustamante, JE, Konoplich & Sakharov, *in preparation*

Bustamante, JE, Konoplich & Sakharov, *in preparation*

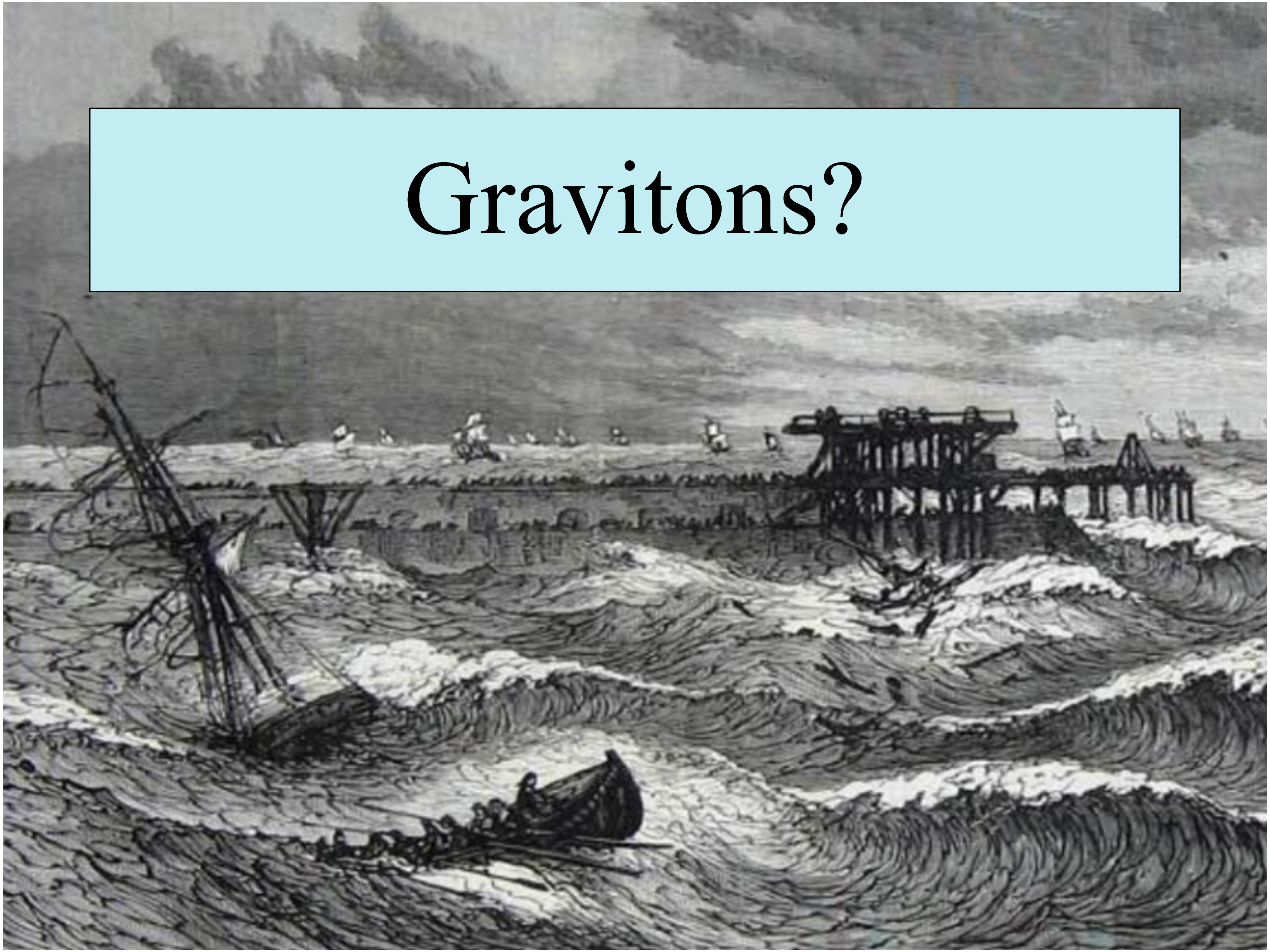
IceCube Constraints on Lorentz Violation

- From energetic extragalactic neutrinos:

Source	Redshift	Remark	Telescope ν	E_ν [TeV]	Δt [days]	Significance	Lower limit on LV scale [GeV]	
							Linear, M_1	Quadratic, M_2
PKS B1424-418	1.522	Single ν/γ	HESE-35	2000	160	5%	1.1×10^{17}	7.6×10^{11}
TXS 0506+056	0.3365	Single ν/γ	IC170922A	200	10	0.3%	3.7×10^{16}	1.1×10^{11}
TXS 0506+056	0.3365	Multiple ν	Several IC	~ 100	~ 100	0.8%	4.0×10^{14}	6.7×10^{8}
GB6 J1040+0617	≥ 0.7351	Single ν/γ	IC141209A	100	100	30%	(4.2×10^{15})	(2.9×10^{10})
PKS 0735+178	≥ 0.424	$4\nu/\gamma$	IC211208A	170	10	See text	(3.0×10^{16})	(1.1×10^{10})
PKS 1123+264	2.341	Single ν/γ	IC120523A	> 200	10	See text	(2.6×10^{17})	(4.1×10^{11})
TXS 0506+056	0.3365	Single ν/radio	GVD210418CA	220	200	See text	$(\sim 2.0 \times 10^{15})$	$(\sim 2.6 \times 10^{10})$
PKS 0625-35	0.055	Three ν	IceCube	63 - 302	1	3.56σ	$(\sim 10^{16})$?	$(\sim 10^{10})$?
AT2019dsg	0.051	Single ν/γ	IC191001A	200	150	*TDE events*	3.5×10^{14}	1.0×10^{10}
AT2019fdr	0.267	Single ν/γ	IC200530A	80	393	*combined*	3.0×10^{14}	6.3×10^{9}
AT2019aacl	0.036	Single ν/γ	IC191119A	170	148	*6×10^{-4}*	2.1×10^{14}	7.4×10^{9}

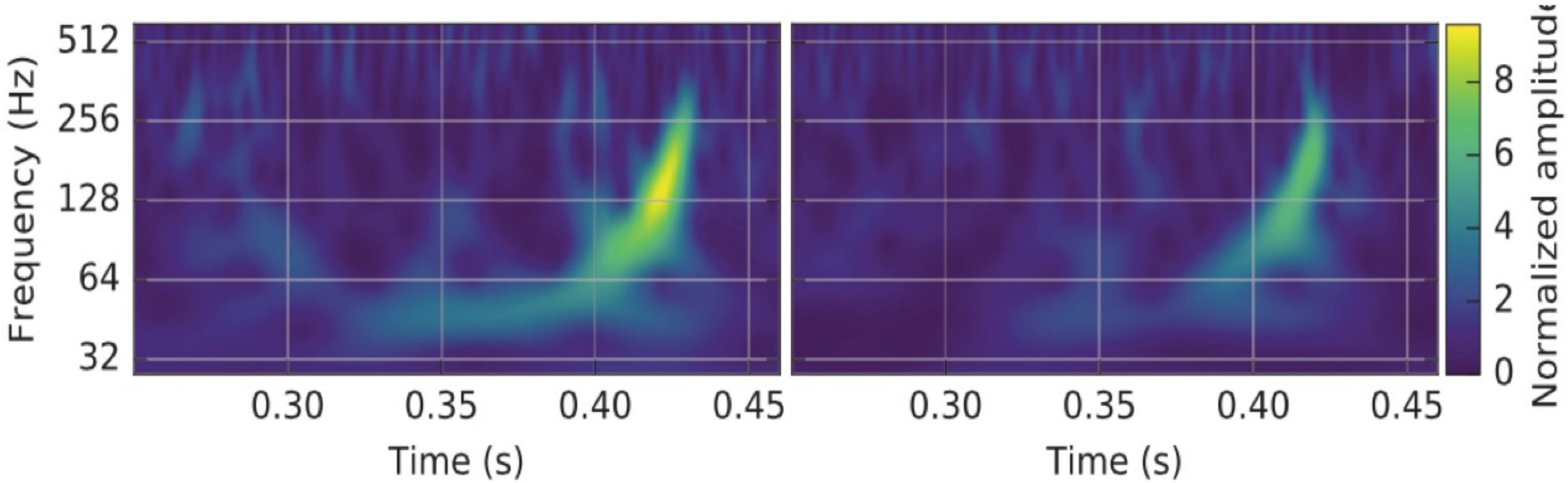
- For comparison:
  - Accelerator neutrinos: $M_1 > 1 \times 10^5$ GeV, $M_2 > 600$ GeV
  - SN1987A: $M_1 > 2.7 \times 10^{10}$ GeV, $M_2 > 4.6 \times 10^4$ GeV

Gravitons?



The Gravitational Chirp …

- … heard around the world

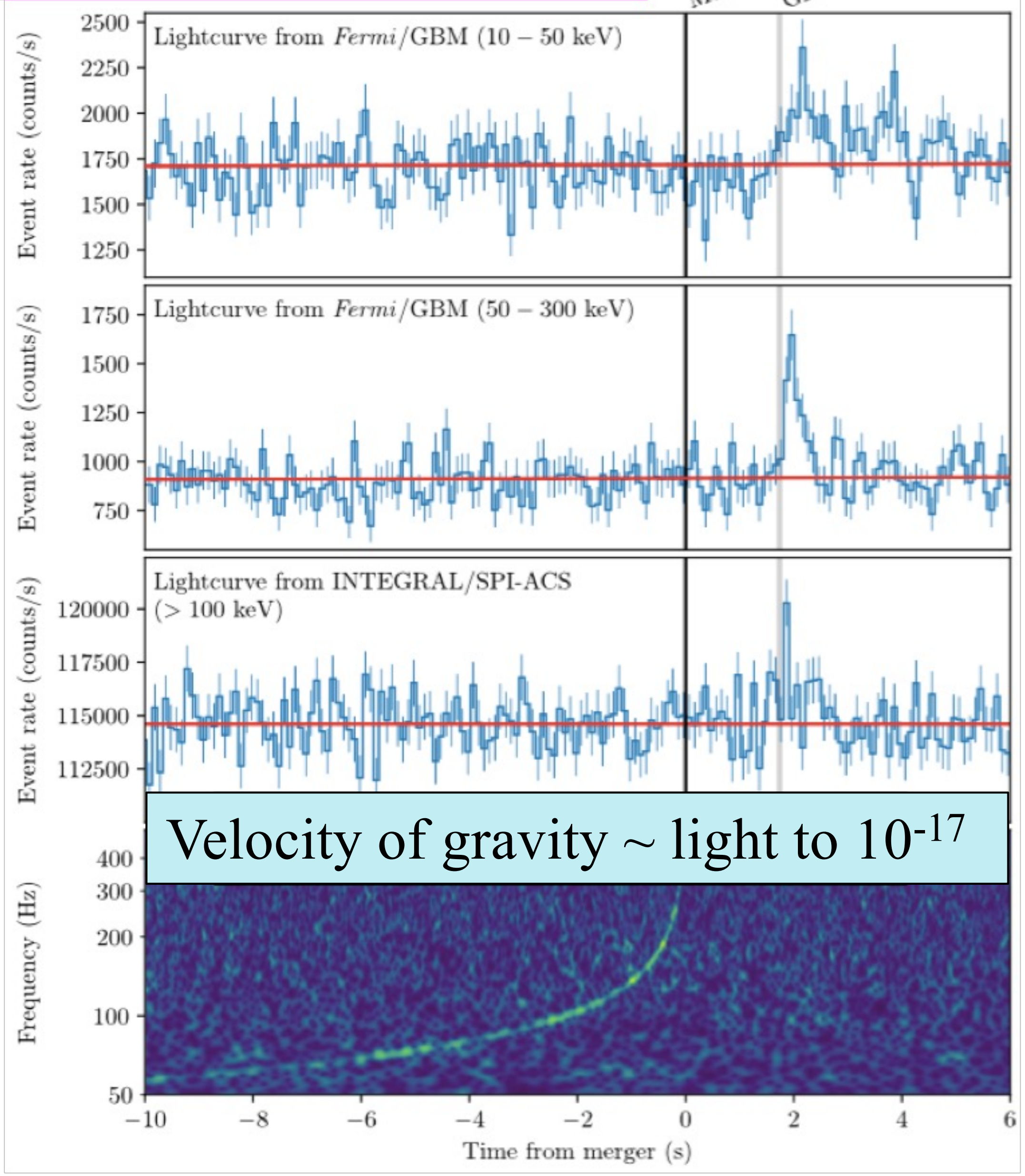


- Frequency increases with time during inspiral
- Followed by ringdown of combined black hole
- Graviton mass < 10^{-27} × mass of electron LIGO
- Waves of different frequencies have similar speeds

Constrain Lorentz violation JE, Mavromatos & Nanopoulos, arXiv:1602.04764

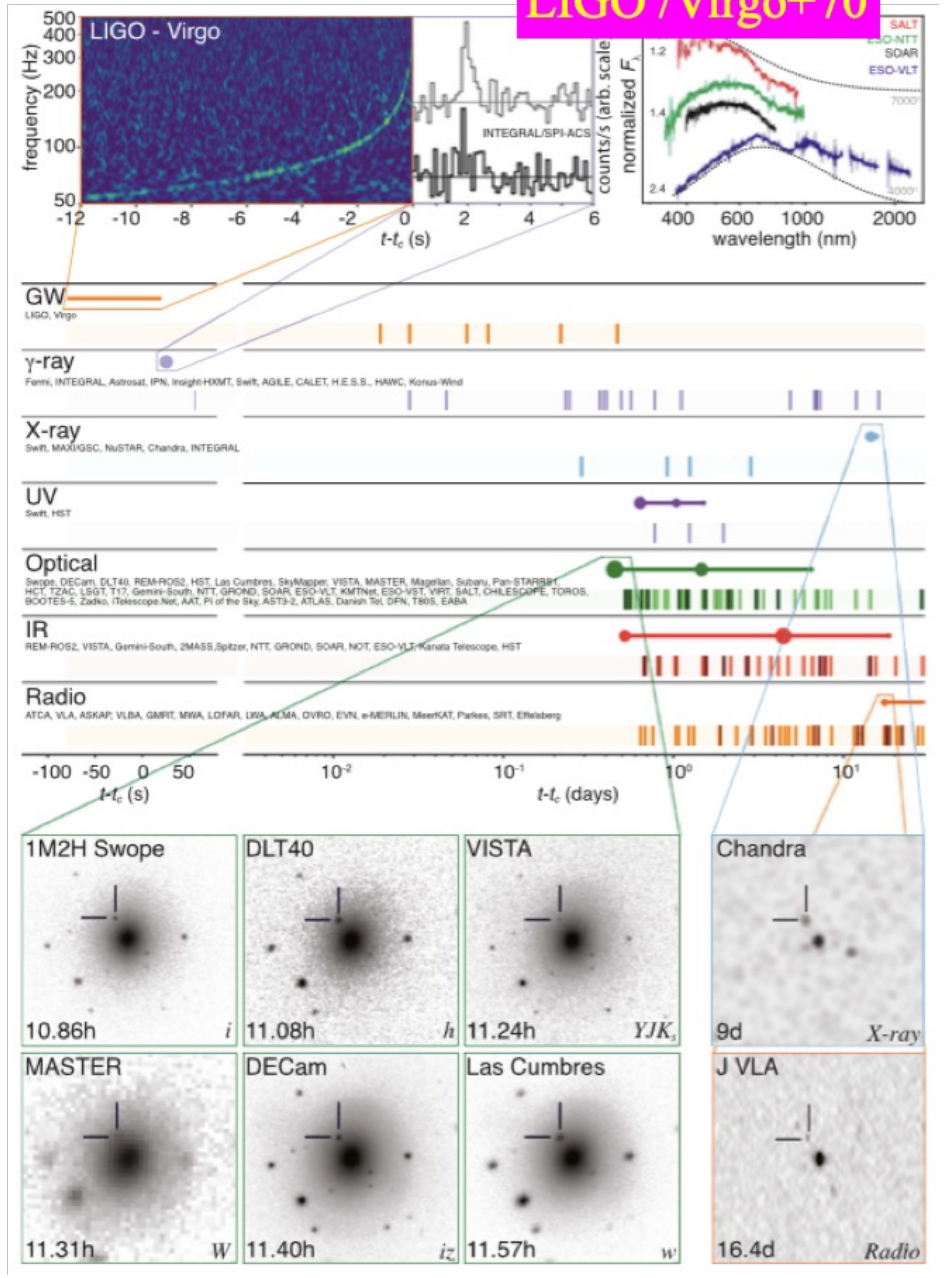
Observations of Neutron Star Merger

LIGO /Virgo/Fermi/INTEGRAL



Velocity of gravity ~ light to 10^{-17}

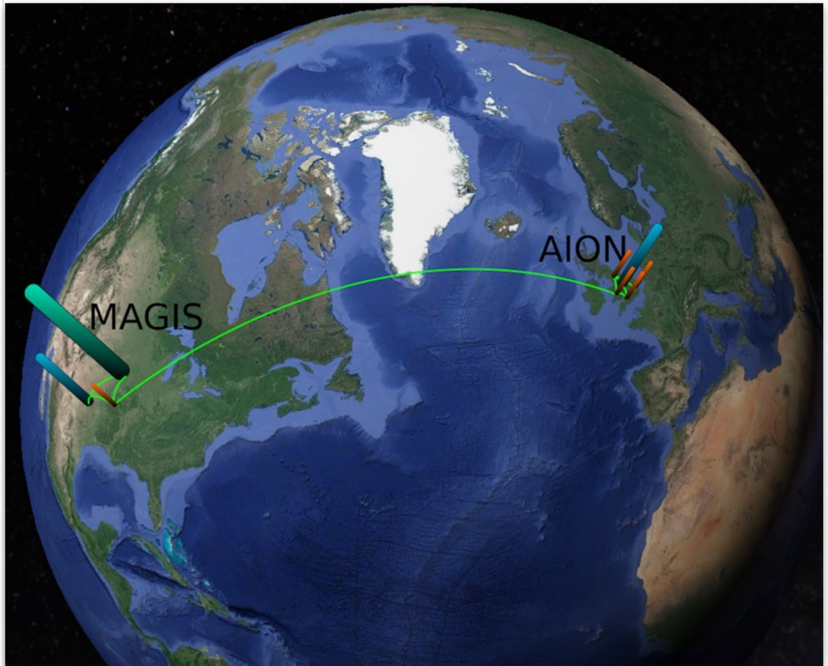
LIGO /Virgo+70



AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], A Beniwal[1], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], J. Carlton, G. Elertas[5], J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell, C. McCabe, D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh, M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge



Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

AION: Proposed Programme

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

Oxford

Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning

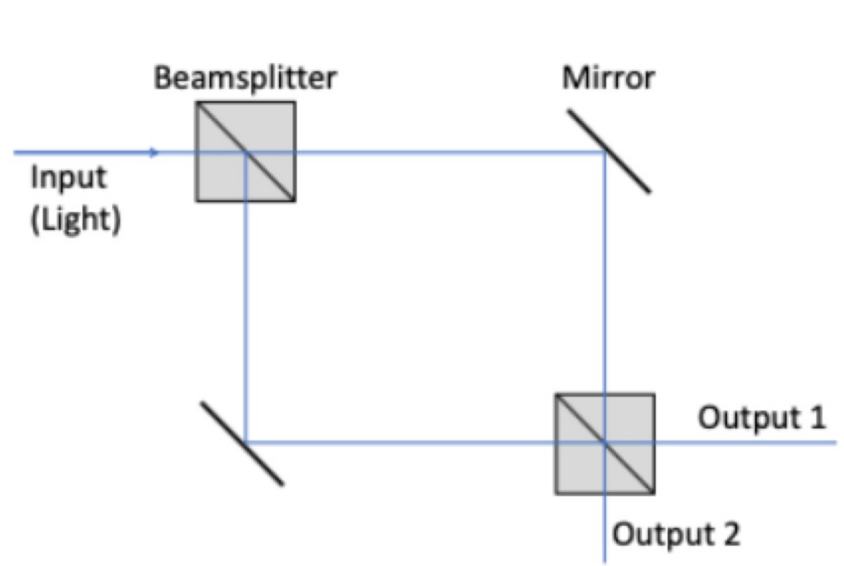
Boulby? CERN?

- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4
  - Space-based version

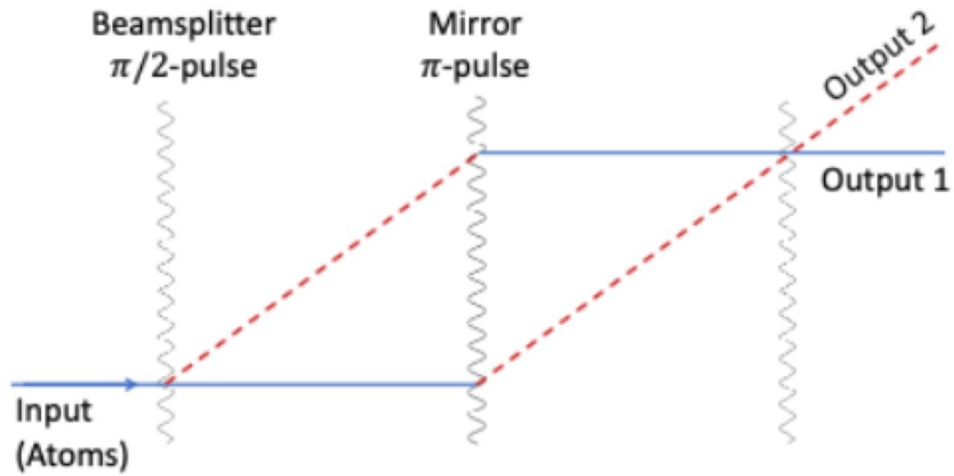
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

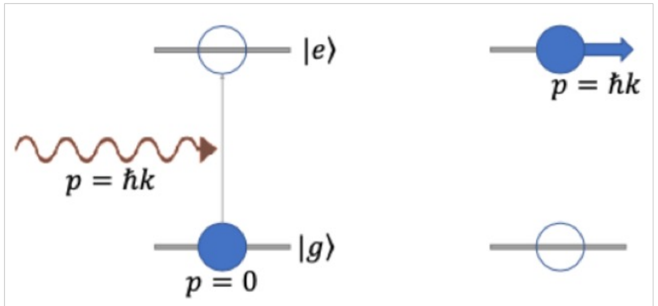


Atom Interferometer



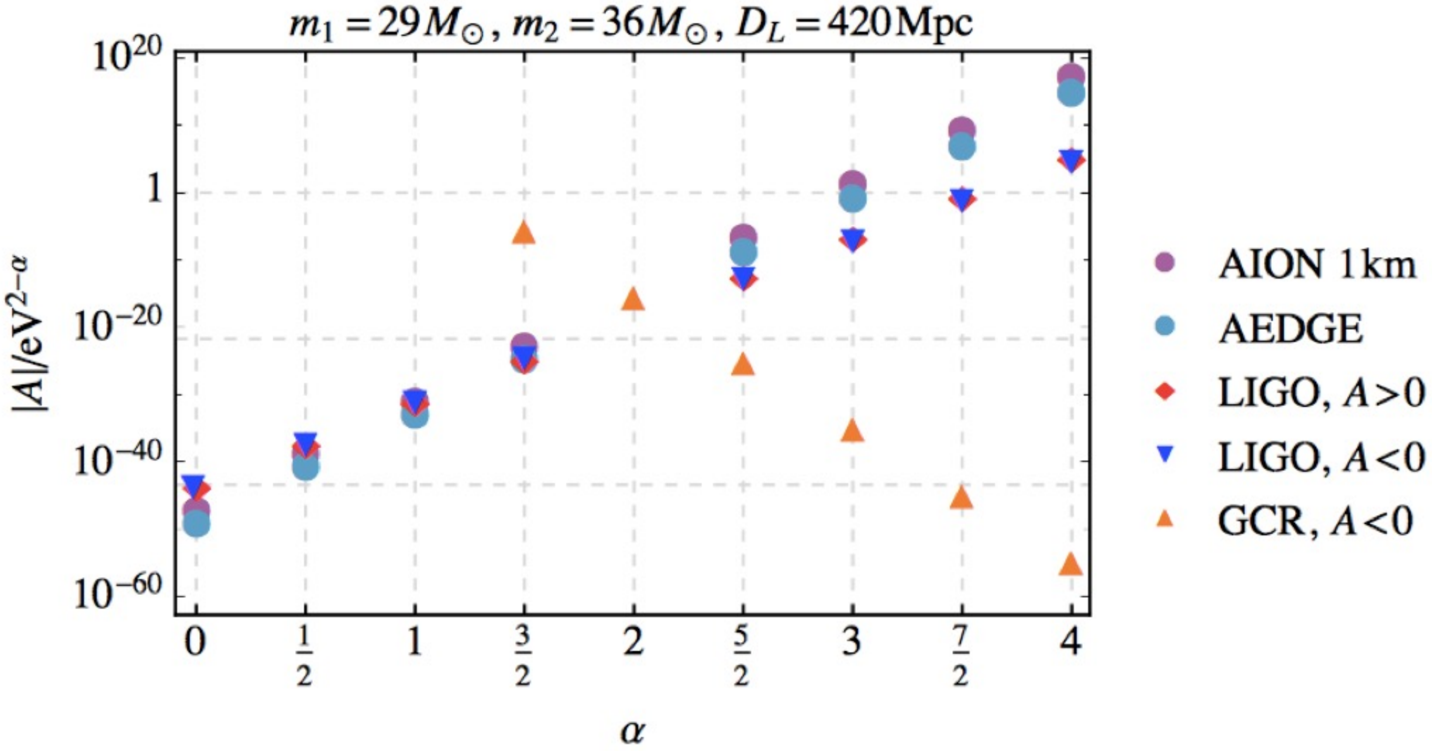
Laser excitation gives momentum kick to excited atom, which follows separated space-time path

Interference between atoms following different paths



Lorentz Violation

- Modified dispersion relation: $E^2 = p^2 + Ap^\alpha$



- AION 1-km: sensitivity 10 × LIGO for α = ½
- AEDGE: sensitivity 1000 × LIGO for α = ½

JE & Vaskonen: arXiv:2003.13480

Subir: The Face that Launched 1309 Lorentz-Violating Papers (so far)