LIV studies with MAGIC

MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

Giacomo D’Amico

The 20 MAGIC years symposium

Hotel Taburiente Playa, La Palma
October 4, 2023

UNIVERSITAS BERGENSIS

Searching for **violations** of Lorentz symmetries is not just a mere curiosity

Such violations lie at the heart of the most important **problem** of fundamental physics

Theoretical background

Quantum mechanics

Microscopic physics

$$10^{-20}\,m \longleftrightarrow 10^{-8}\,m$$

LHC

Nature 464, 697-703 (2010)

Compton wavelength

$$r \sim \frac{\hbar}{mc}$$

General relativity

Macroscopic physics

$$10^{-6}\,m \longleftrightarrow 10^{20}\,m$$

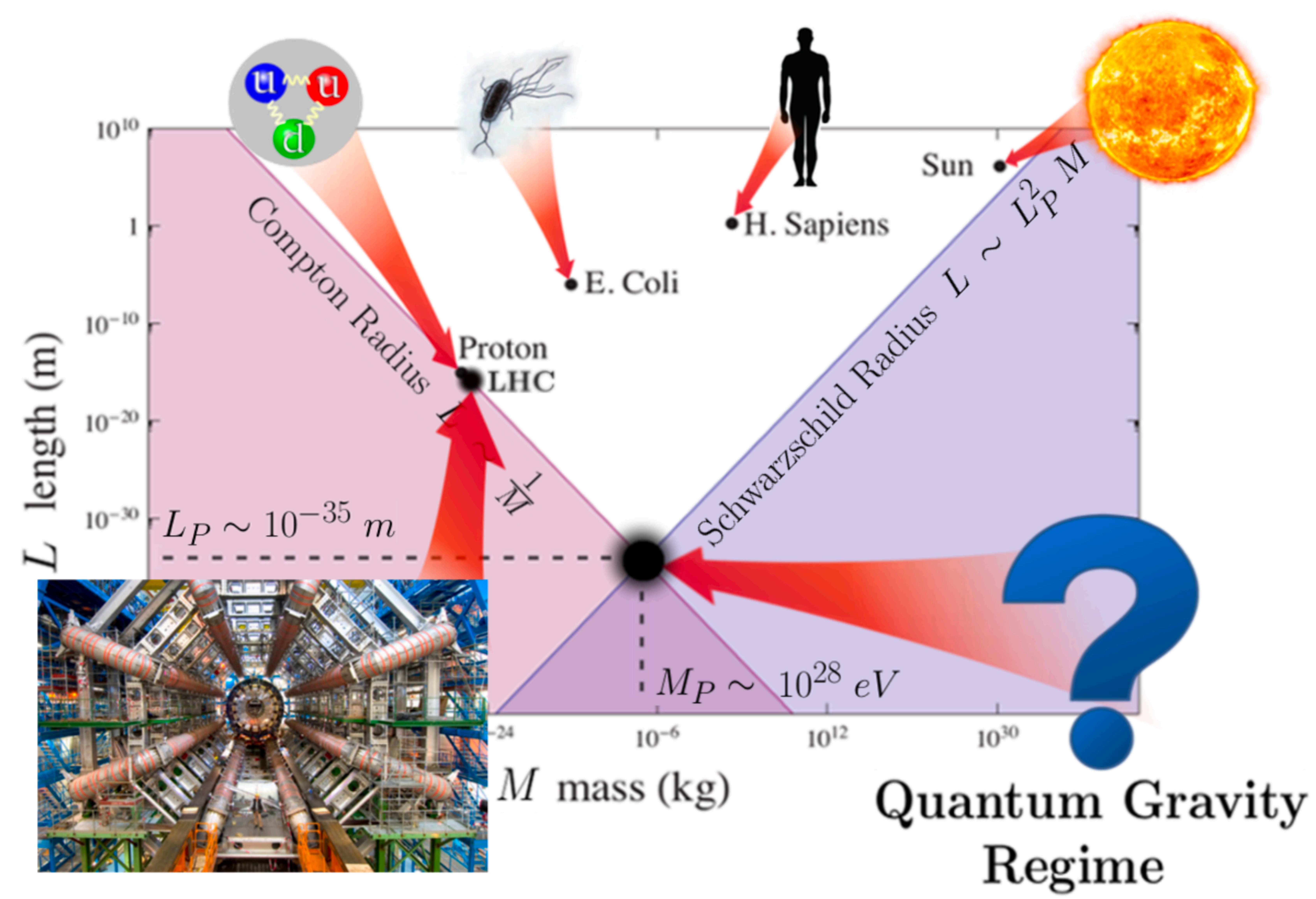
Nature 591, 225–228 (2021)

Assuming Dark Matter

Schwarzschild radius

$$r \sim \frac{G\,m}{c^2}$$

Theoretical background



Theoretical background

Credits: PBS Space Time

Theoretical background

Credits: PBS Space Time

↓ **TOP-DOWN**

✓ solving at once **all aspects** of the quantum-gravity problem

✗ formalisms of very high complexity and **lack** of physical intuition about **observable** and potentially **testable features**

↑ **BOTTOM-UP**

✗ describing only a **small subset** of the departures from standard physics that the quantum-gravity realm is expected to host

✓ producing better opportunities for **experimental testing**

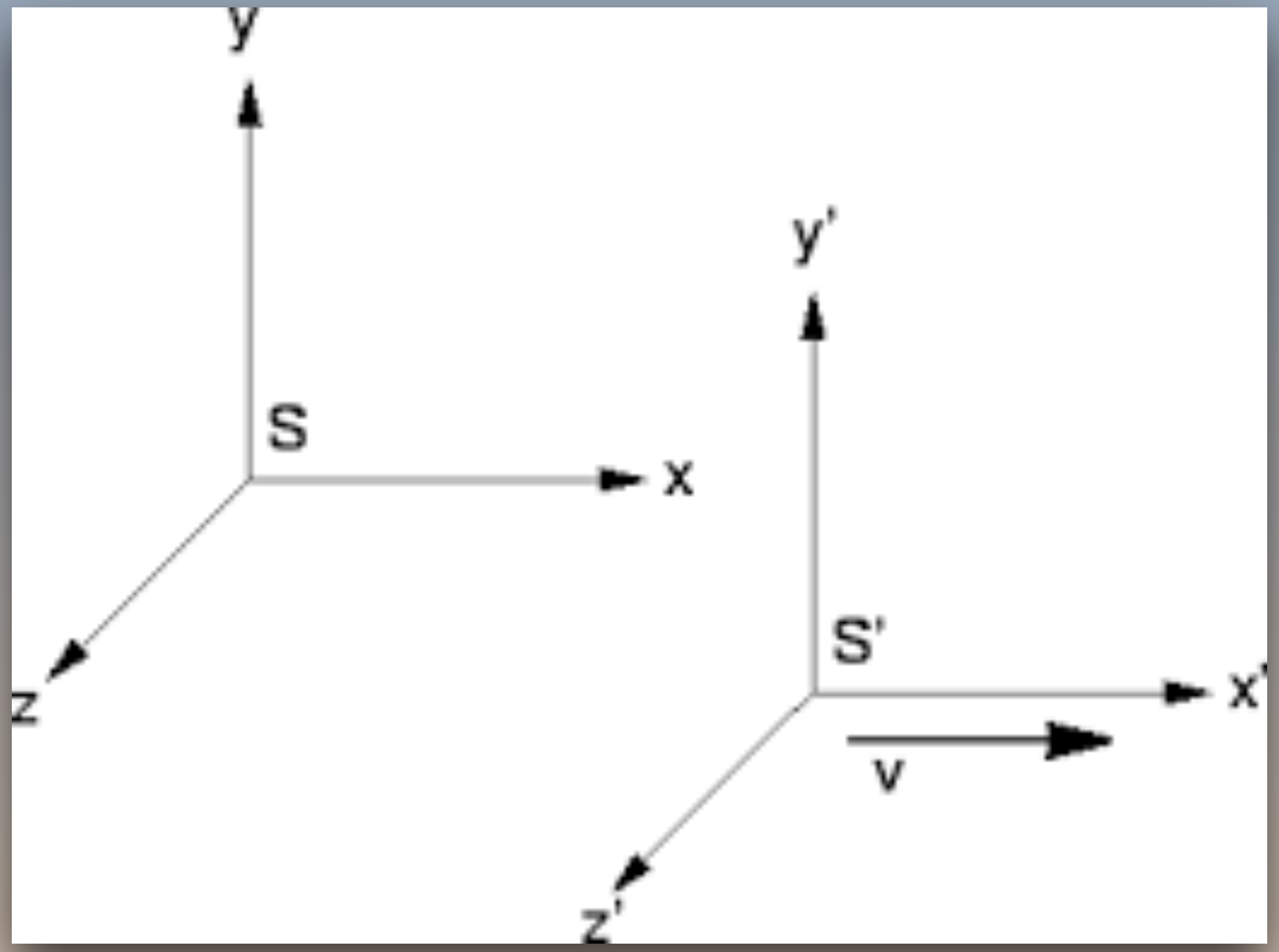
Theoretical background

Galilean invariance

↓

$$E = \frac{1}{2}\frac{p^2}{m}$$

$$v = \frac{\partial E}{\partial p} = \frac{\partial (p^2/2m)}{\partial p} = \frac{p}{m}$$



Theoretical background

Galilean invariance

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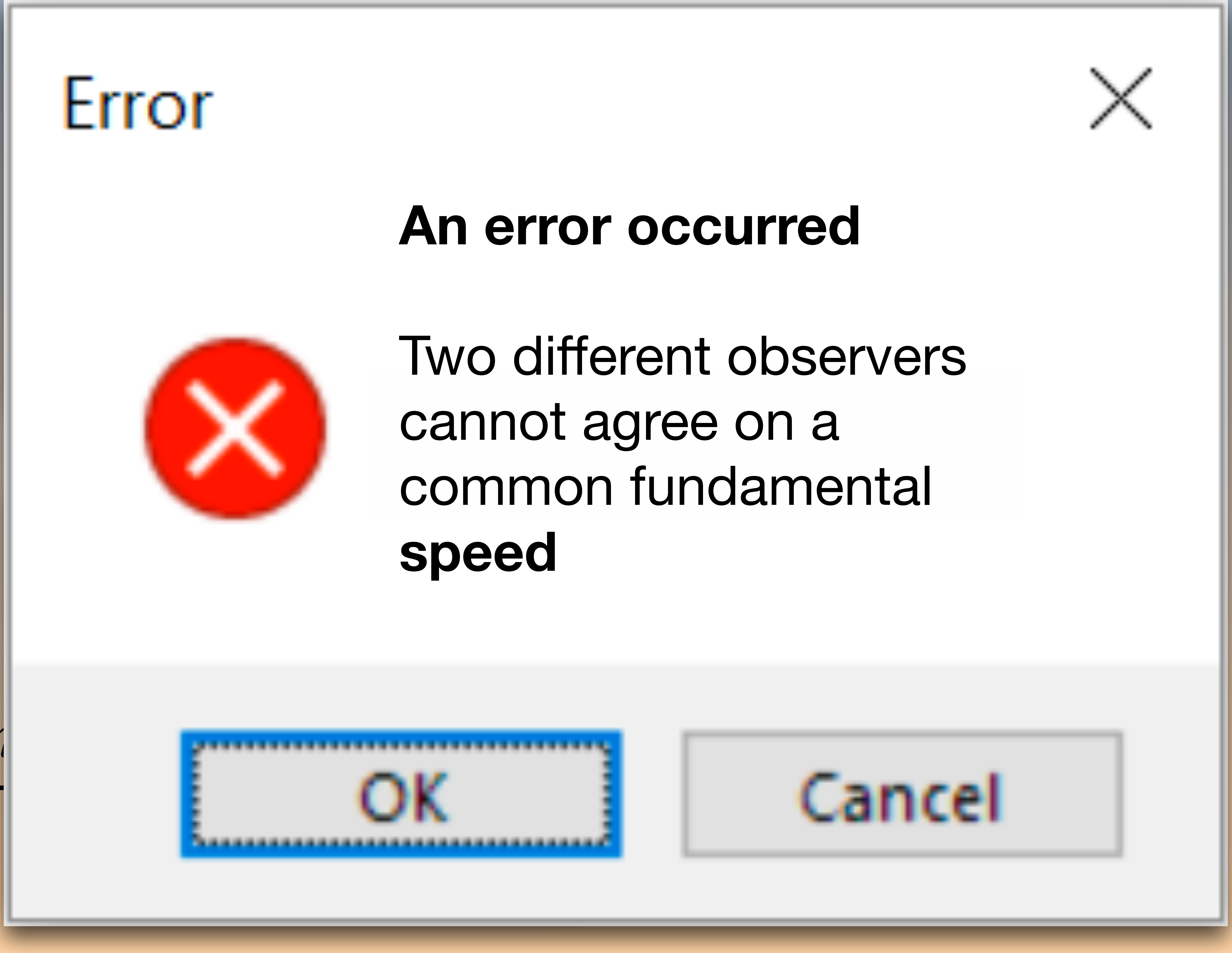


An error occurred

Two different observers cannot agree on a common fundamental **speed**

Theoretical background

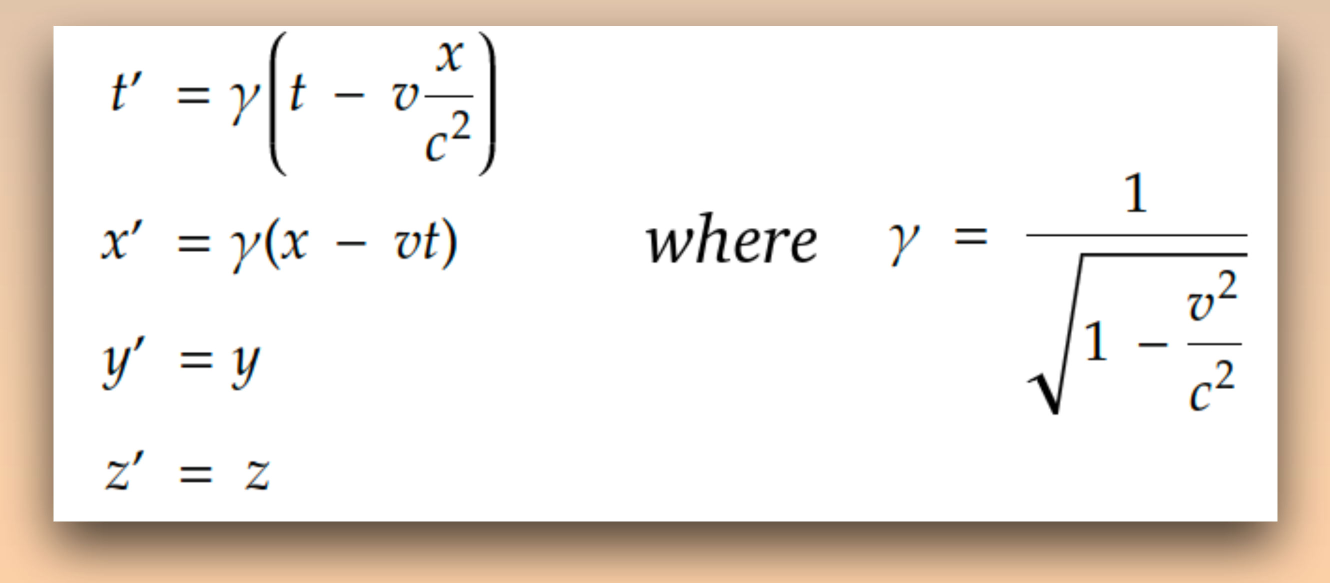
$$\text{Galilean invariance} \xrightarrow{\text{Introducing } \mathbf{c} \text{ as a constant}} \text{Lorentz invariance}$$

$$E = \frac{1}{2}\frac{p^2}{m}$$

$$E^2 = m^2c^4 + p^2c^2$$

$$v = \frac{\partial E}{\partial p} = \frac{\partial\sqrt{p^2c^2 + m^2c^4}}{\partial p} = \frac{pc}{\sqrt{p^2 + m^2c^2}} \longrightarrow c$$

For a massless particle

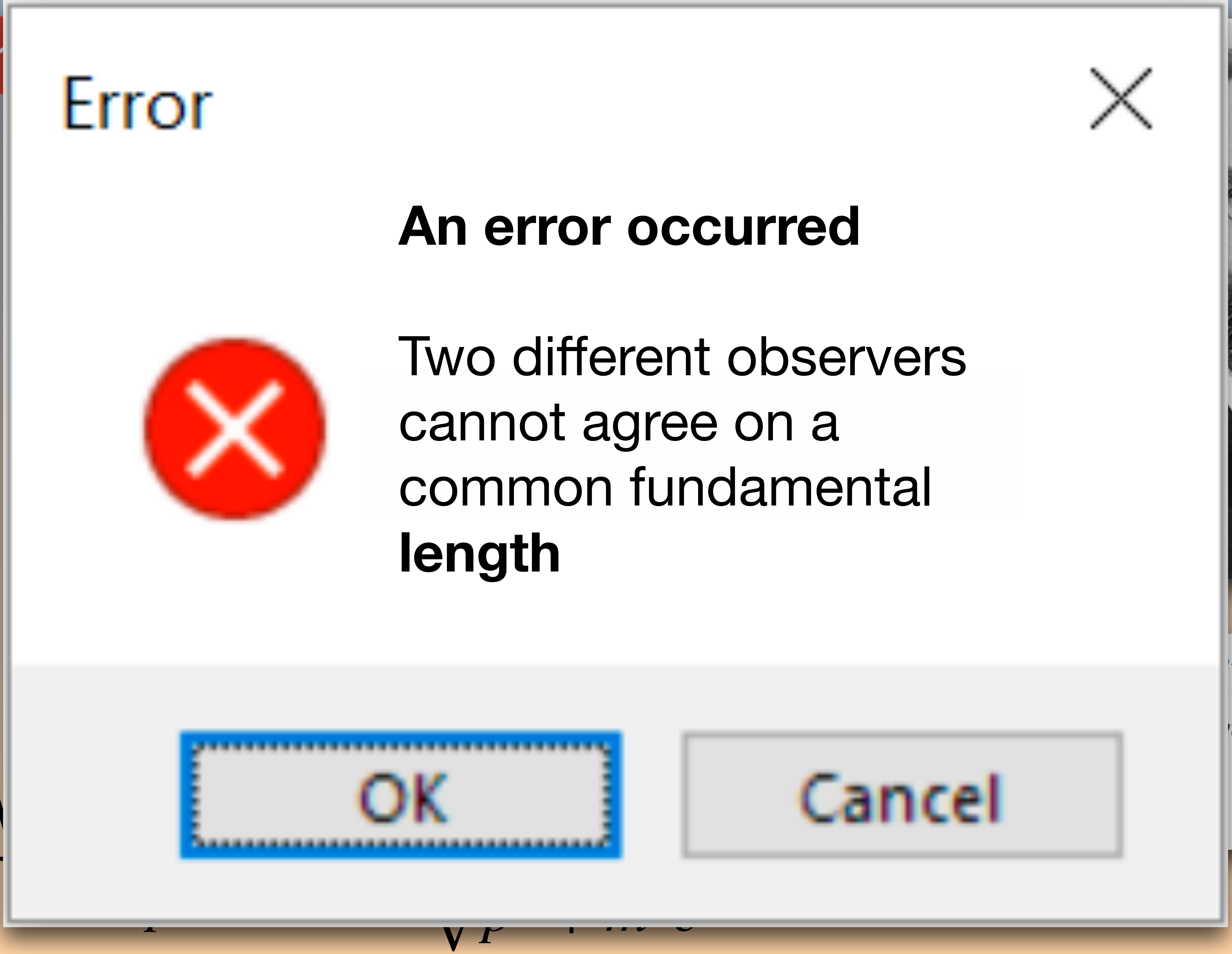


$$\begin{aligned} t' &= \gamma\left(t - v\frac{x}{c^2}\right) \\ x' &= \gamma(x - vt) \qquad \text{where} \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \\ y' &= y \\ z' &= z \end{aligned}$$

Theoretical background

Galilean invarian

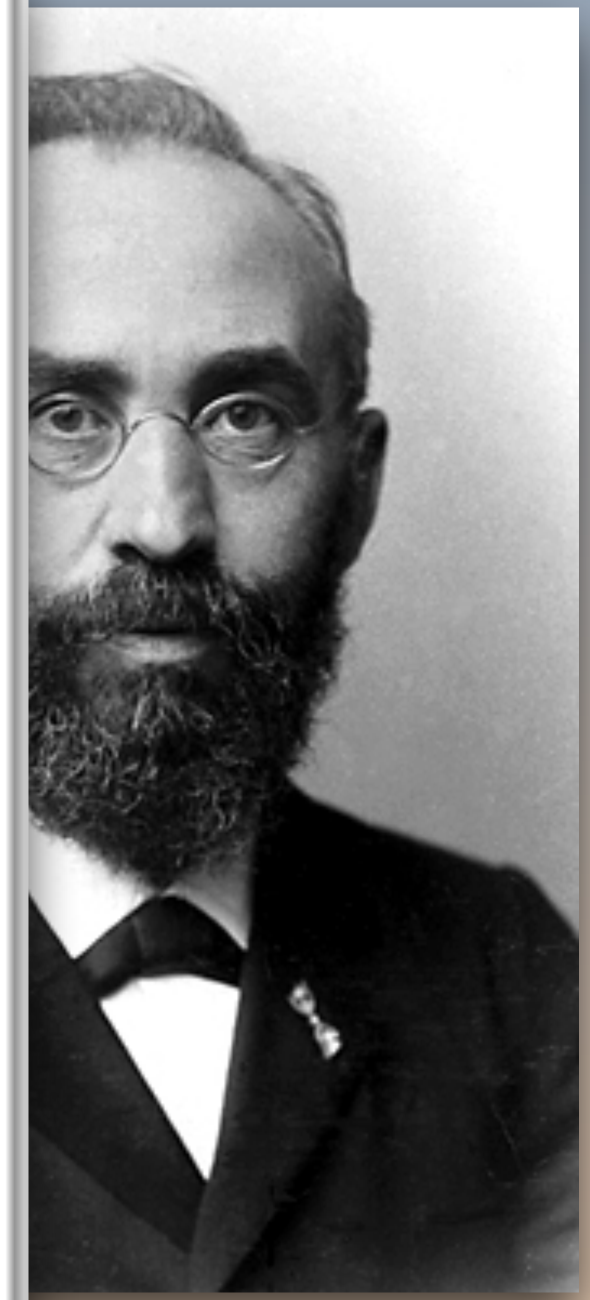
$$E = \frac{1}{2}\frac{p^2}{m}$$



Error

An error occurred

Two different observers cannot agree on a common fundamental **length**



$\frac{x}{c^2})$

$t)$

where $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$

$$v = \frac{\partial E}{\partial p} =$$

Theoretical background

Galilean invariance → **Lorentz invariance** → **LIV**

Introducing **c** as a constant

Introducing **the Planck length** as a constant

$$E = \frac{1}{2}\frac{p^2}{m}$$

$$E^2 = m^2c^4 + p^2c^2$$

$$E^2 = (m^2 + p^2) \times f(E, E_P)$$

Theoretical background

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$$E^2 = m^2c^4 + p^2c^2$$

$$\boxed{E^2 = (m^2 + p^2) \times f(E, E_P)}$$

$$f(E, E_P) \sim 1 \quad \text{for} \quad \mathrm{E/E_P} << 1 \longrightarrow f(E, E_P) = 1 + \sum_{n=1}^{\infty} \overset{\pm 1}{s_n} \left(\frac{E}{E_{QG,n}}\right)^n$$

Quantum-gravity energy scale

Theoretical background

Galilean invariance → **Lorentz invariance** → **LIV**

Introducing **c** as a constant

Introducing **the Planck length** as a constant

$$E = \frac{1}{2}\frac{p^2}{m}$$

$$E^2 = m^2c^4 + p^2c^2$$

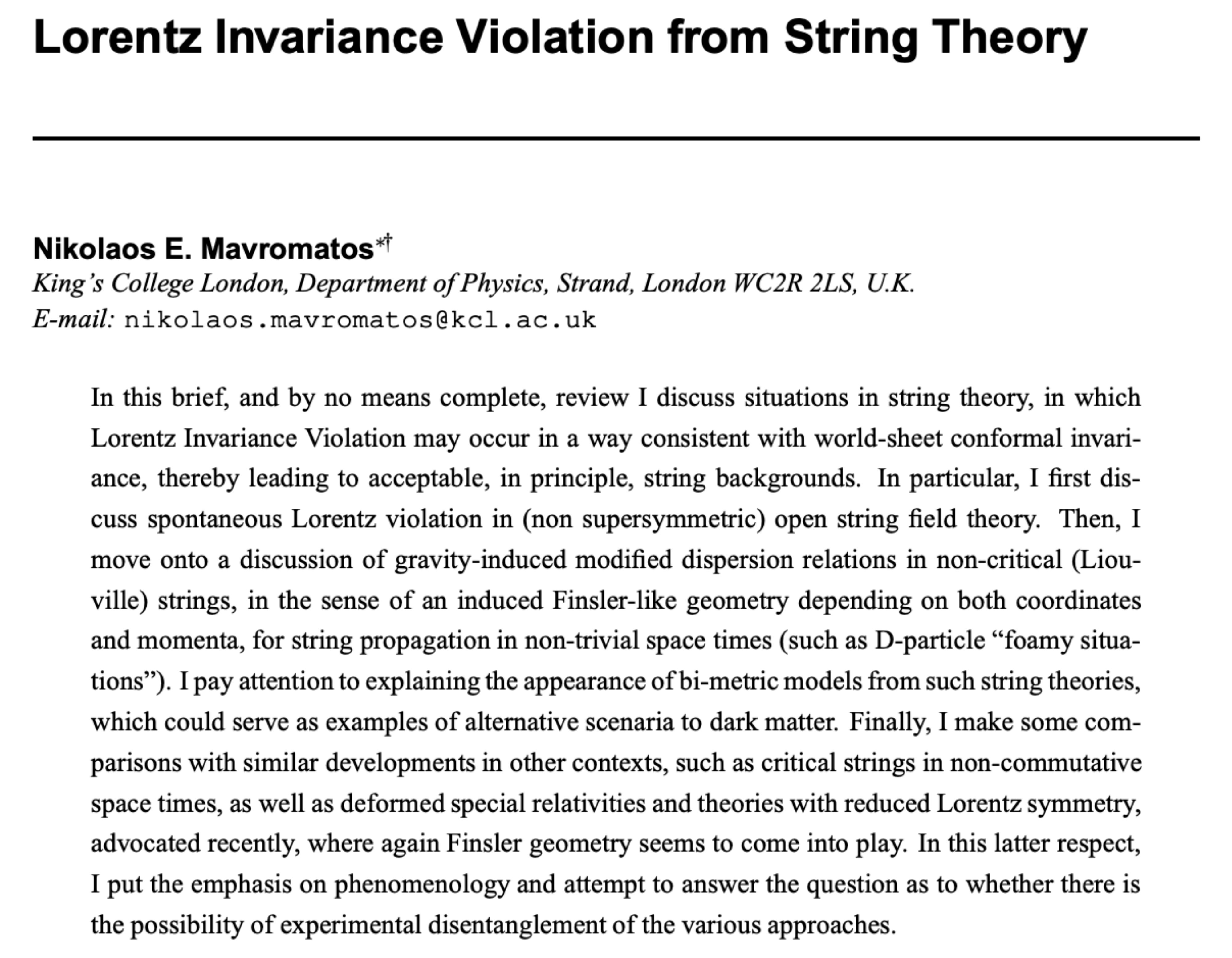
$$E^2 = (m^2 + p^2) \times f(E, E_P)$$

$$S_n = \begin{cases} +1, \text{ superluminal} \\ -1, \text{ subluminal} \end{cases}$$

$$v_\gamma = \frac{\partial E}{\partial p} \simeq c\left[1 + \sum_{n=1}^{\infty} S_n \frac{n+1}{2}\left(\frac{E}{E_{\mathrm{QG},n}}\right)^n\right]$$

Theoretical background

In case I haven’t convinced you so far with heuristic arguments



Lorentz Invariance Violation from String Theory

Nikolaos E. Mavromatos[*†]
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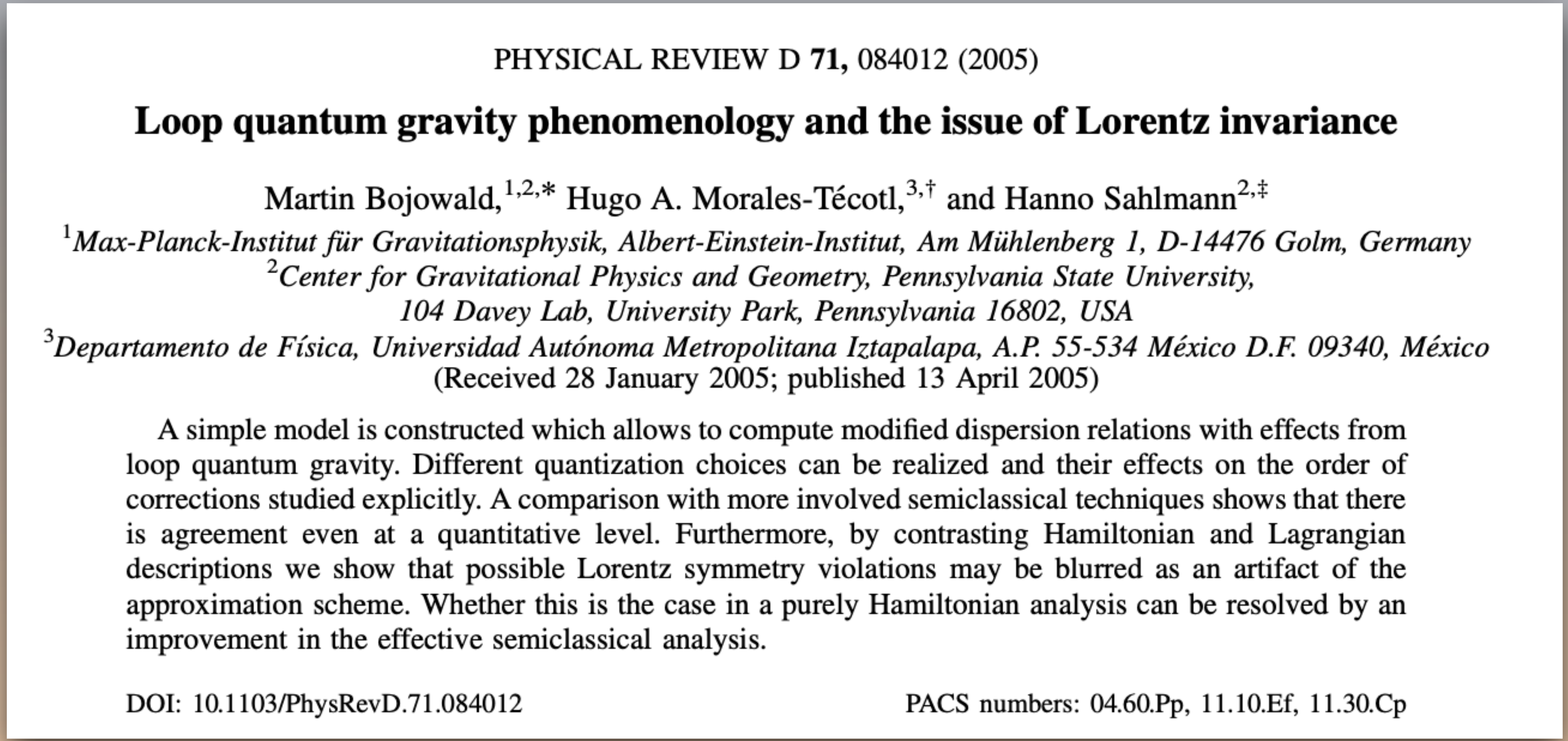
E-mail: `nikolaos.mavromatos@kcl.ac.uk`

In this brief, and by no means complete, review I discuss situations in string theory, in which Lorentz Invariance Violation may occur in a way consistent with world-sheet conformal invariance, thereby leading to acceptable, in principle, string backgrounds. In particular, I first discuss spontaneous Lorentz violation in (non supersymmetric) open string field theory. Then, I move onto a discussion of gravity-induced modified dispersion relations in non-critical (Liouville) strings, in the sense of an induced Finsler-like geometry depending on both coordinates and momenta, for string propagation in non-trivial space times (such as D-particle “foamy situations”). I pay attention to explaining the appearance of bi-metric models from such string theories, which could serve as examples of alternative scenaria to dark matter. Finally, I make some comparisons with similar developments in other contexts, such as critical strings in non-commutative space times, as well as deformed special relativities and theories with reduced Lorentz symmetry, advocated recently, where again Finsler geometry seems to come into play. In this latter respect, I put the emphasis on phenomenology and attempt to answer the question as to whether there is the possibility of experimental disentanglement of the various approaches.



PHYSICAL REVIEW D **71,** 084012 (2005)

Loop quantum gravity phenomenology and the issue of Lorentz invariance

Martin Bojowald,[1,2,*] Hugo A. Morales-Técotl,[3,†] and Hanno Sahlmann[2,‡]
[1]*Max-Planck-Institut für Gravitationsphysik, Albert-Einstein-Institut, Am Mühlenberg 1, D-14476 Golm, Germany*
[2]*Center for Gravitational Physics and Geometry, Pennsylvania State University, 104 Davey Lab, University Park, Pennsylvania 16802, USA*
[3]*Departamento de Física, Universidad Autónoma Metropolitana Iztapalapa, A.P. 55-534 México D.F. 09340, México*
(Received 28 January 2005; published 13 April 2005)

A simple model is constructed which allows to compute modified dispersion relations with effects from loop quantum gravity. Different quantization choices can be realized and their effects on the order of corrections studied explicitly. A comparison with more involved semiclassical techniques shows that there is agreement even at a quantitative level. Furthermore, by contrasting Hamiltonian and Lagrangian descriptions we show that possible Lorentz symmetry violations may be blurred as an artifact of the approximation scheme. Whether this is the case in a purely Hamiltonian analysis can be resolved by an improvement in the effective semiclassical analysis.

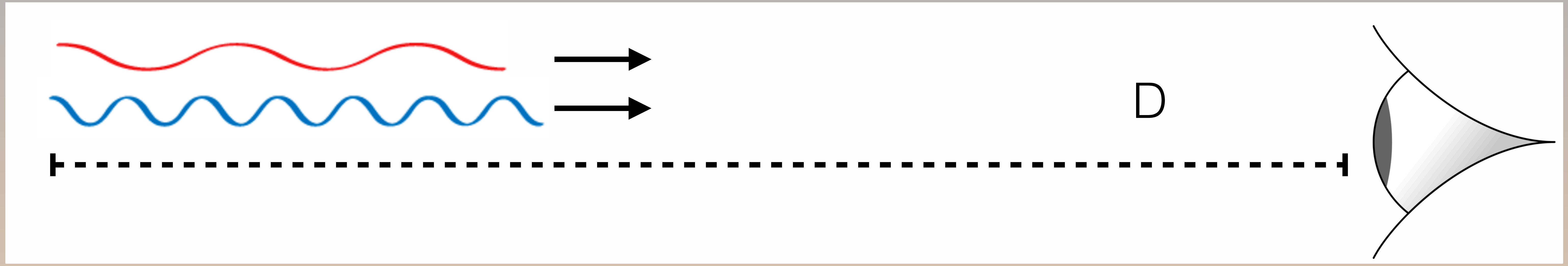
DOI: 10.1103/PhysRevD.71.084012 PACS numbers: 04.60.Pp, 11.10.Ef, 11.30.Cp

… and many more

Energy-dependent group velocity

$$v_\gamma = \frac{\partial E}{\partial p} \simeq c \left[1 + \sum_{n=1}^{\infty} S_n \frac{n+1}{2} \left(\frac{E}{E_{\mathrm{QG},n}} \right)^n \right]$$

$$S_n = \begin{cases} +1, \text{ superluminal} \\ -1, \text{ subluminal} \end{cases}$$



$$\boxed{\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_2^n - E_1^n}{E_{QG}^n} D(z)}$$

$$D(z) = \frac{1}{H_0} \int_0^z dz' \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

Testing it here in a lab?

Taking the world's most sensitive experiment: **LIGO/VIRGO**

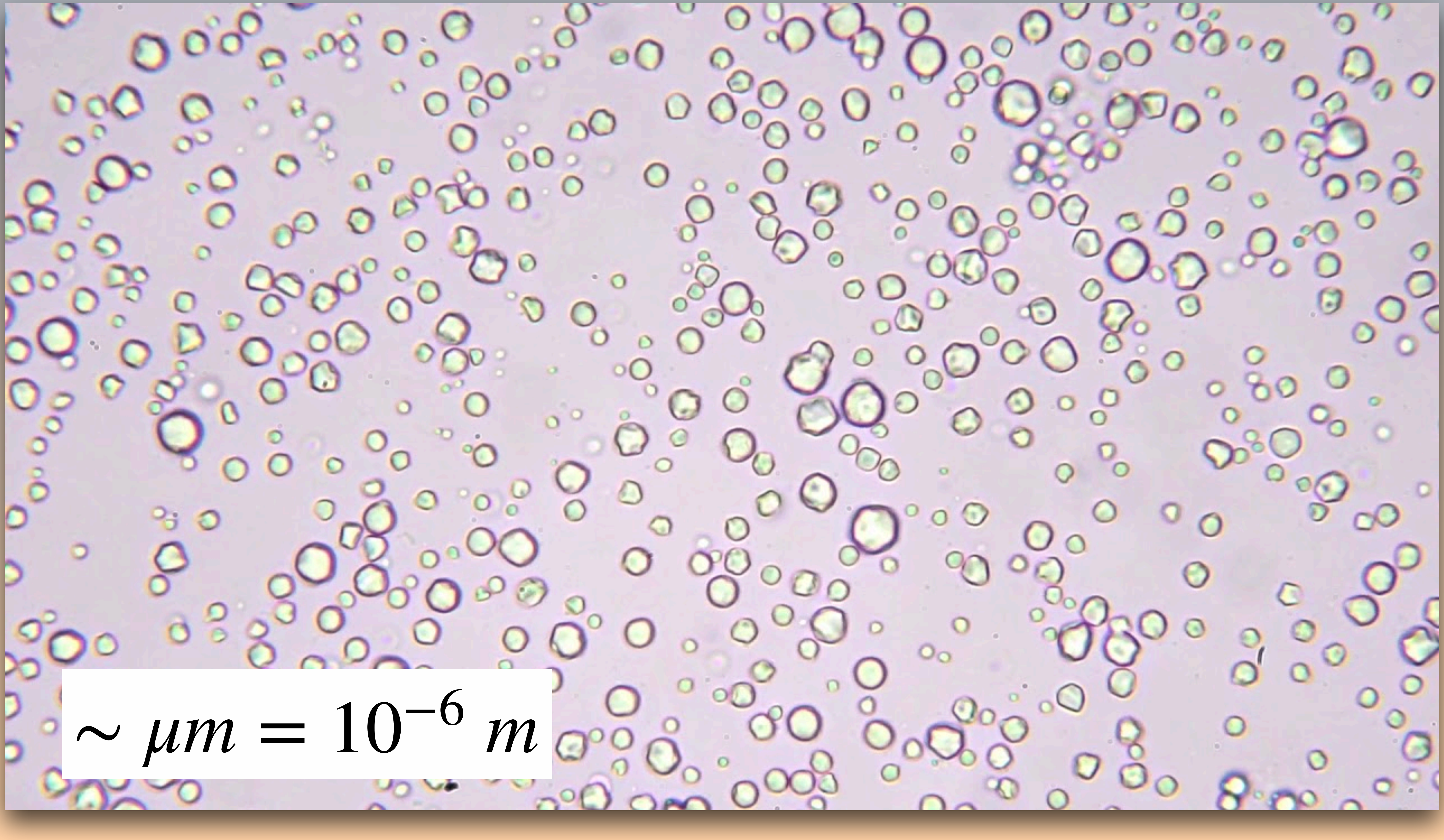
Sensitivity $\longrightarrow$ $\frac{10^{-18}\,m}{c} \simeq 10^{-27}\,s$

Planck correction $\longrightarrow$ $\frac{\Delta E}{M_P}\frac{D}{c} \simeq \frac{1\,eV}{M_P}\frac{280 \cdot 4\,km}{c} \simeq 10^{-31}\,s$

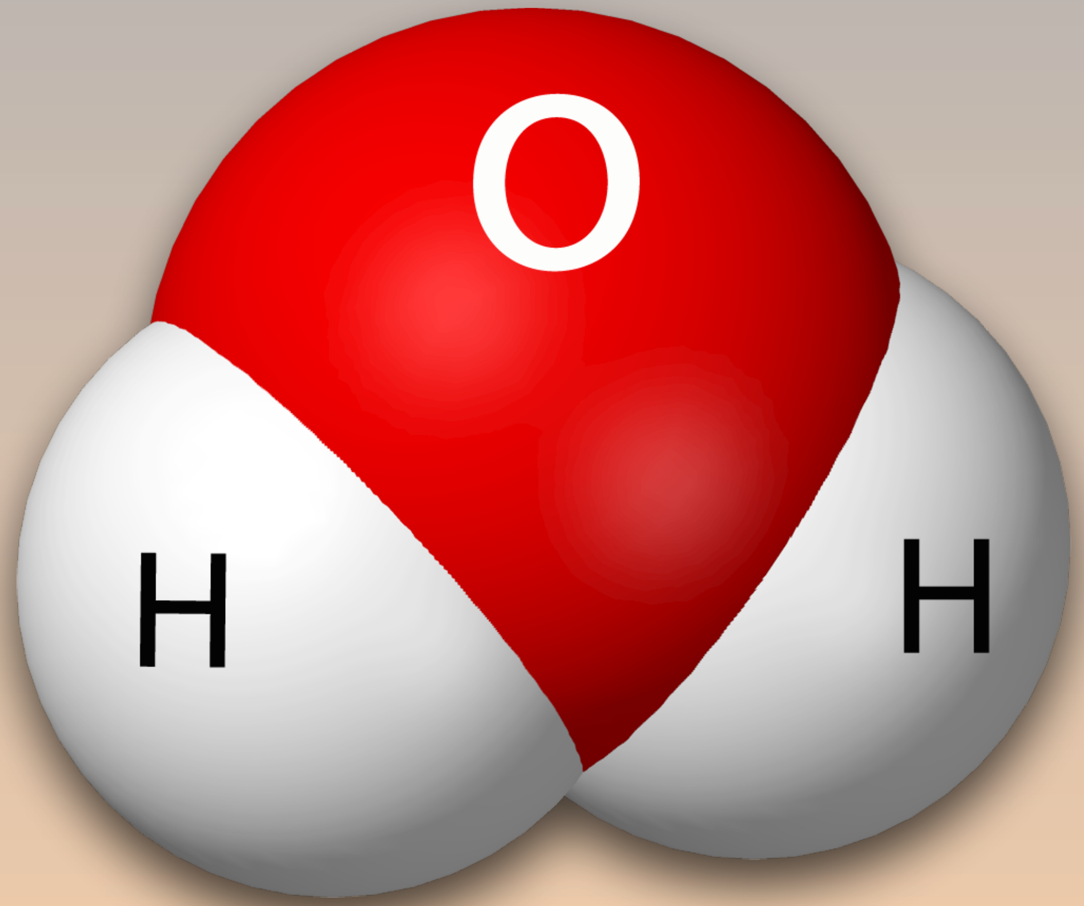
✗ Quantum-gravity correction is **4 orders of magnitude smaller** than the experimental sensitivity!

We need an amplifier!

Analogy from the Brownian motion



$\sim \mu m = 10^{-6}\ m$



$\sim 0.1\ nm = 10^{-10}\ m$

We need an amplifier!

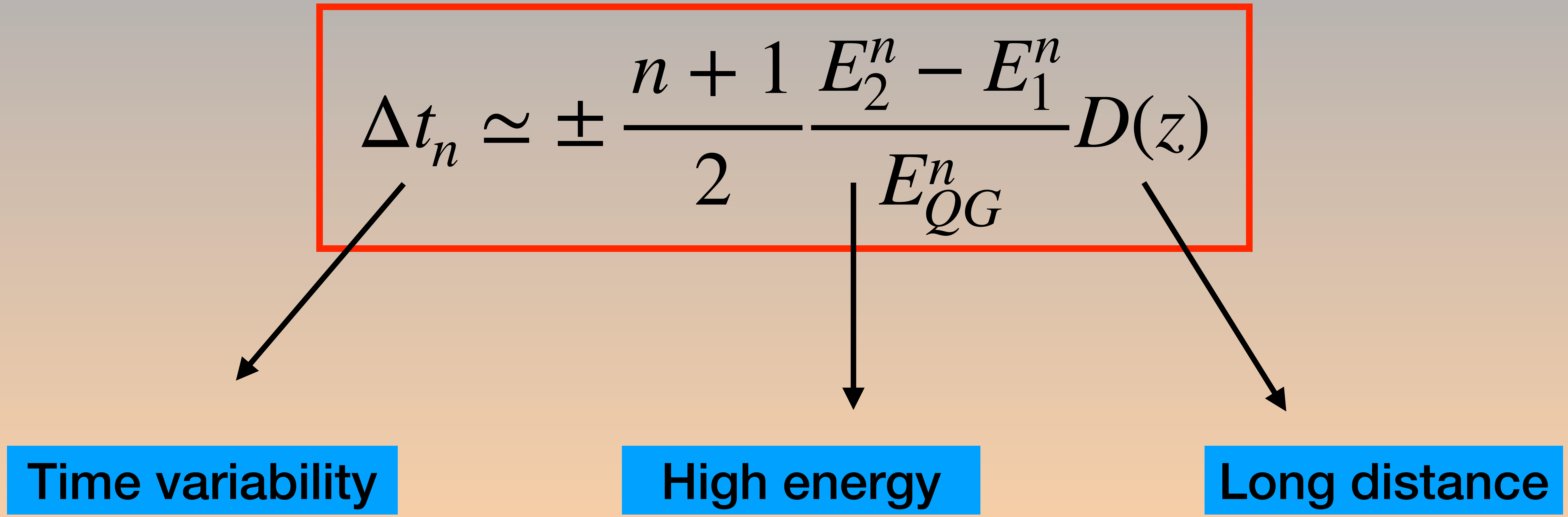
$$\Delta t \sim \frac{\overset{\displaystyle 1\ \text{TeV}}{\overset{\searrow}{E}}}{\underset{\displaystyle \sim 10^{16}\ \text{TeV}}{\underset{\nearrow}{E_P}}} \times D$$

We need an amplifier!

$$\Delta t \sim \frac{\overset{1\ \text{TeV}}{\overset{\searrow}{E}}}{\underset{\sim 10^{16}\ \text{TeV}}{\underset{\nearrow}{E_P}}} \times \overset{\propto \frac{1}{H_0} \sim 10^{17}\ \text{s}}{\overset{\swarrow}{D}} \sim 1 - 10\ \text{s}$$

Testing it from astrophysical observations

3 ingredients are needed for a LIV study



$$\boxed{\Delta t_n \simeq \pm \frac{n+1}{2} \frac{E_2^n - E_1^n}{E_{QG}^n} D(z)}$$

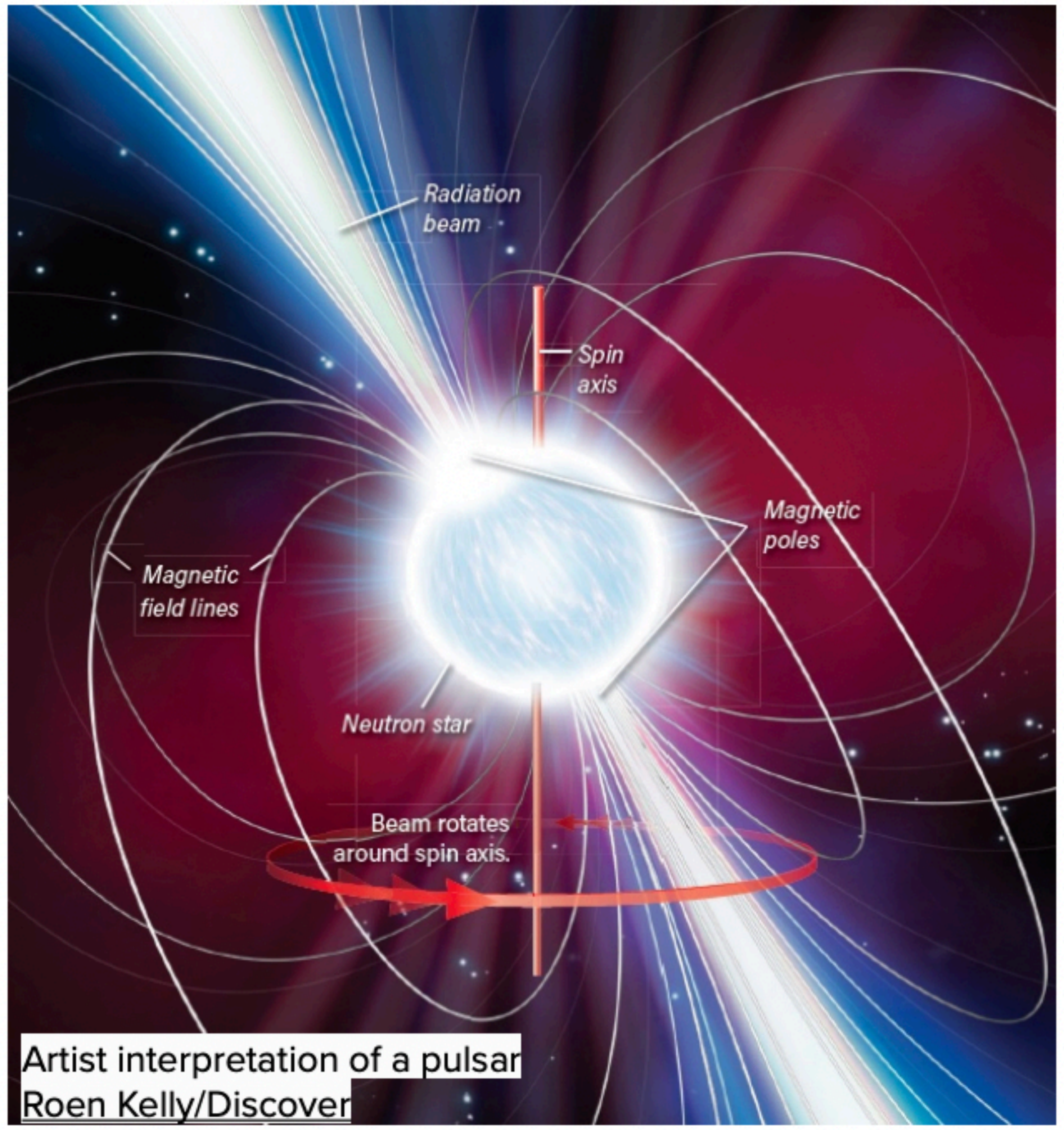
Time variability

High energy

Long distance

Type of sources for LIV studies

Pulsars

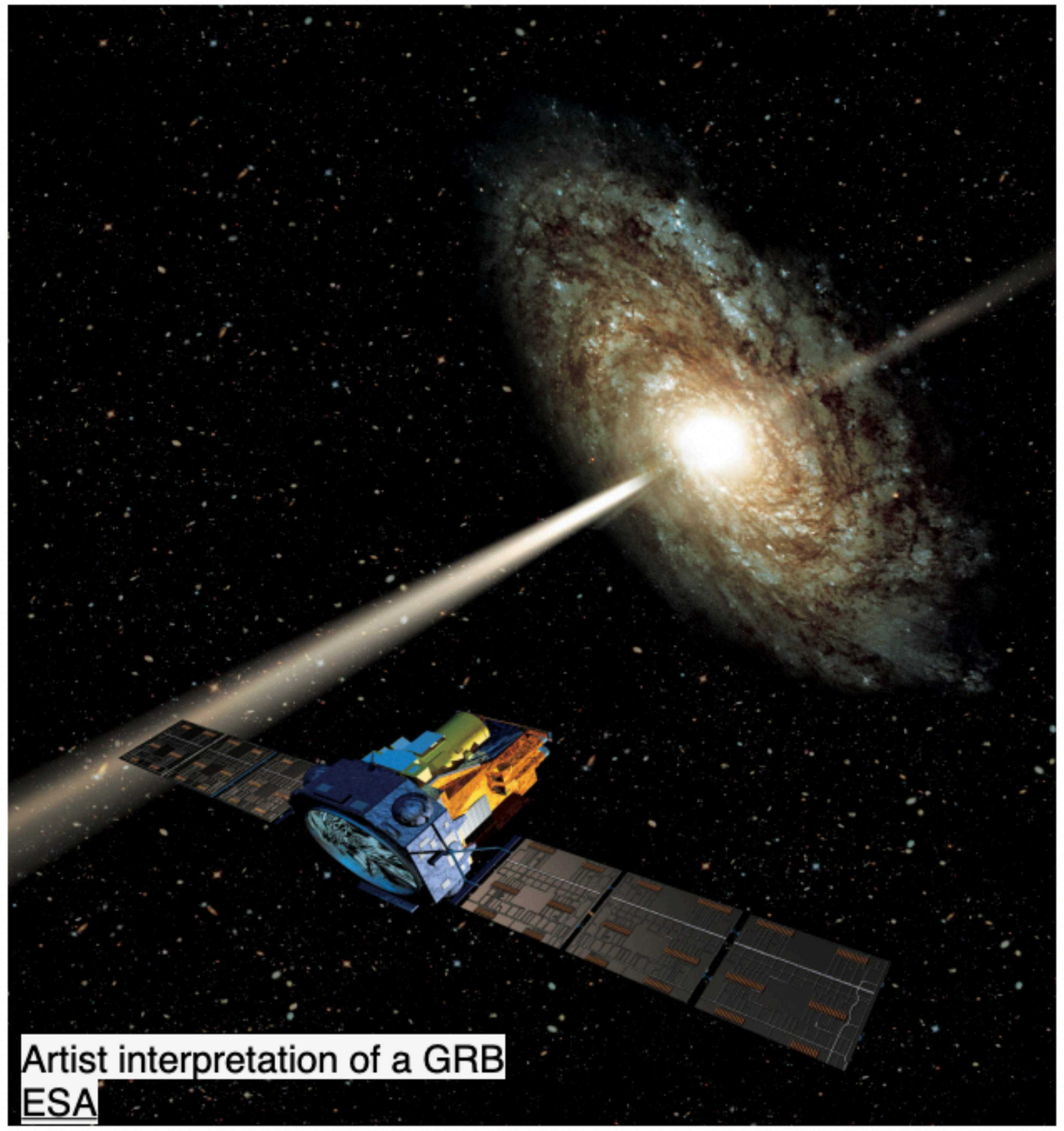


Artist interpretation of a pulsar
Roen Kelly/Discover

Time variability	High energy	Long distance
A lot!	Yes!	No

Type of sources for LIV studies

Gamma-ray bursts

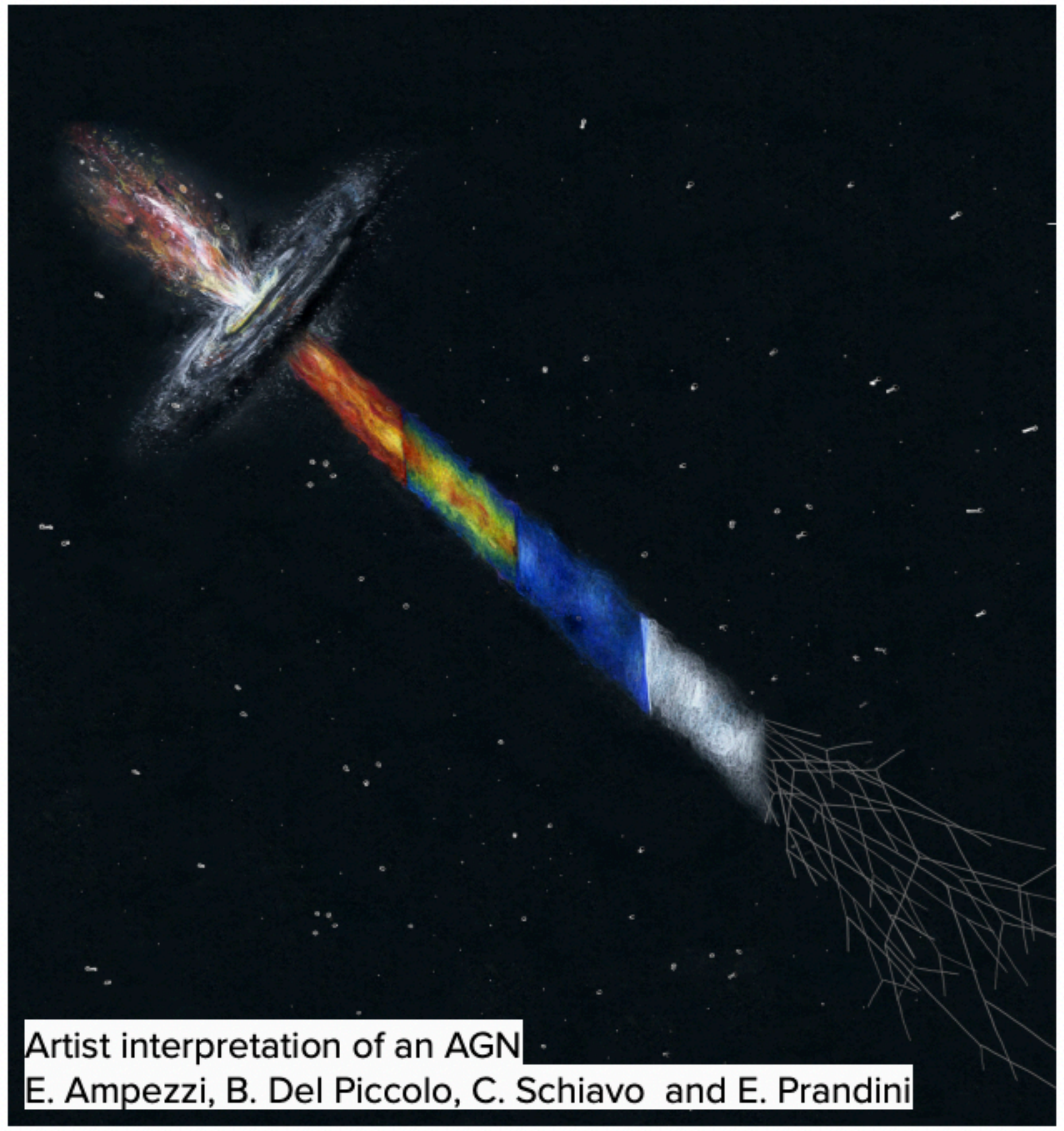


Artist interpretation of a GRB
ESA

Time variability	High energy	Long distance
Yes, if you catch the prompt emission	**Not very good** because of EBL	**Yes!**

Type of sources for LIV studies

Active Galactic Nuclei



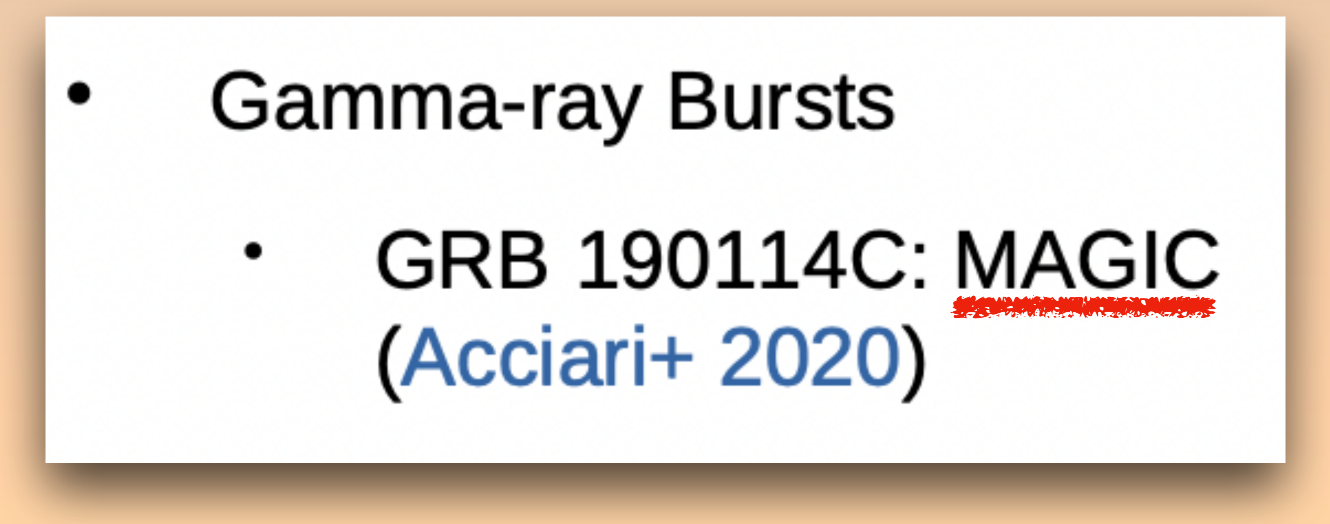
Artist interpretation of an AGN
E. Ampezzi, B. Del Piccolo, C. Schiavo and E. Prandini

Time variability	High energy	Long distance
Yes, when they are flaring	Not very good because of EBL	Yes!

Sources analyzed so far by IACTs in search for LIV effects

- Flaring AGN
  - Markarian 501 2005 flare: MAGIC (Albert+ 2008; Martinez & Errando, 2009)
  - PKS 2155-304 2006 flare: H.E.S.S. (Aharonian+ 2008; Abramowski+ 2011)
  - PG 1553+113 2012 flare: H.E.S.S. (Abramowski+ 2015)

- Pulsars
  - Crab: MAGIC & VERITAS (Otte 2011; Zitzer 2013; Ahnen+ 2017)
  - Vela: H.E.S.S. (Chrétien+ 2015)



- Gamma-ray Bursts
  - GRB 190114C: MAGIC (Acciari+ 2020)

NO LIV EFFECTS OBSERVED SO FAR

MAGIC studies in search for LIV effects

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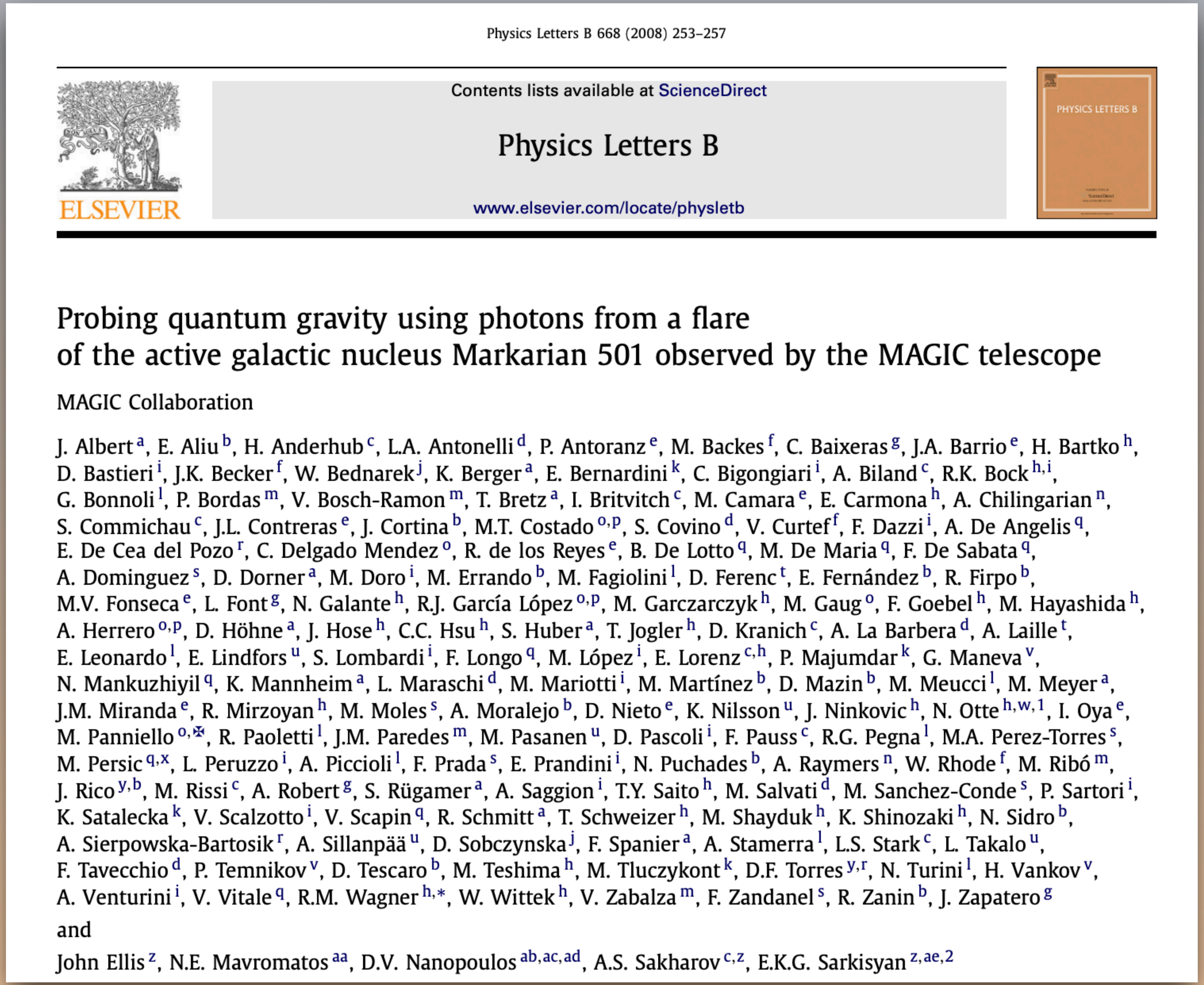
Physics Letters B 668.4 (2008): 253-257

290 citations



Physics Letters B 668 (2008) 253–257

Contents lists available at ScienceDirect

Physics Letters B

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ELSEVIER

Probing quantum gravity using photons from a flare
of the active galactic nucleus Markarian 501 observed by the MAGIC telescope

MAGIC Collaboration

J. Albert [a], E. Aliu [b], H. Anderhub [c], L.A. Antonelli [d], P. Antoranz [e], M. Backes [f], C. Baixeras [g], J.A. Barrio [e], H. Bartko [h], D. Bastieri [i], J.K. Becker [f], W. Bednarek [j], K. Berger [a], E. Bernardini [k], C. Bigongiari [i], A. Biland [c], R.K. Bock [h,i], G. Bonnoli [l], P. Bordas [m], V. Bosch-Ramon [m], T. Bretz [a], I. Britvitch [c], M. Camara [e], E. Carmona [h], A. Chilingarian [n], S. Commichau [c], J.L. Contreras [e], J. Cortina [b], M.T. Costado [o,p], S. Covino [d], V. Curtef [f], F. Dazzi [i], A. De Angelis [q], E. De Cea del Pozo [r], C. Delgado Mendez [o], R. de los Reyes [e], B. De Lotto [q], M. De Maria [q], F. De Sabata [q], A. Dominguez [s], D. Dorner [a], M. Doro [i], M. Errando [b], M. Fagiolini [l], D. Ferenc [t], E. Fernández [b], R. Firpo [b], M.V. Fonseca [e], L. Font [g], N. Galante [h], R.J. García López [o,p], M. Garczarczyk [h], M. Gaug [o], F. Goebel [h], M. Hayashida [h], A. Herrero [o,p], D. Höhne [a], J. Hose [h], C.C. Hsu [h], S. Huber [a], T. Jogler [h], D. Kranich [c], A. La Barbera [d], A. Laille [t], E. Leonardo [l], E. Lindfors [u], S. Lombardi [i], F. Longo [q], M. López [i], E. Lorenz [c,h], P. Majumdar [k], G. Maneva [v], N. Mankuzhiyil [q], K. Mannheim [a], L. Maraschi [d], M. Mariotti [i], M. Martínez [b], D. Mazin [b], M. Meucci [l], M. Meyer [a], J.M. Miranda [e], R. Mirzoyan [h], M. Moles [s], A. Moralejo [b], D. Nieto [e], K. Nilsson [u], J. Ninkovic [h], N. Otte [h,w,1], I. Oya [e], M. Panniello [o,✠], R. Paoletti [l], J.M. Paredes [m], M. Pasanen [u], D. Pascoli [i], F. Pauss [c], R.G. Pegna [l], M.A. Perez-Torres [s], M. Persic [q,x], L. Peruzzo [i], A. Piccioli [l], F. Prada [s], E. Prandini [i], N. Puchades [b], A. Raymers [n], W. Rhode [f], M. Ribó [m], J. Rico [y,b], M. Rissi [c], A. Robert [g], S. Rügamer [a], A. Saggion [i], T.Y. Saito [h], M. Salvati [d], M. Sanchez-Conde [s], P. Sartori [i], K. Satalecka [k], V. Scalzotto [i], V. Scapin [q], R. Schmitt [a], T. Schweizer [h], M. Shayduk [h], K. Shinozaki [h], N. Sidro [b], A. Sierpowska-Bartosik [r], A. Sillanpää [u], D. Sobczynska [j], F. Spanier [a], A. Stamerra [l], L.S. Stark [c], L. Takalo [u], F. Tavecchio [d], P. Temnikov [v], D. Tescaro [b], M. Teshima [h], M. Tluczykont [k], D.F. Torres [y,r], N. Turini [l], H. Vankov [v], A. Venturini [i], V. Vitale [q], R.M. Wagner [h,*], W. Wittek [h], V. Zabalza [m], F. Zandanel [s], R. Zanin [b], J. Zapatero [g]

and

John Ellis [z], N.E. Mavromatos [aa], D.V. Nanopoulos [ab,ac,ad], A.S. Sakharov [c,z], E.K.G. Sarkisyan [z,ae,2]

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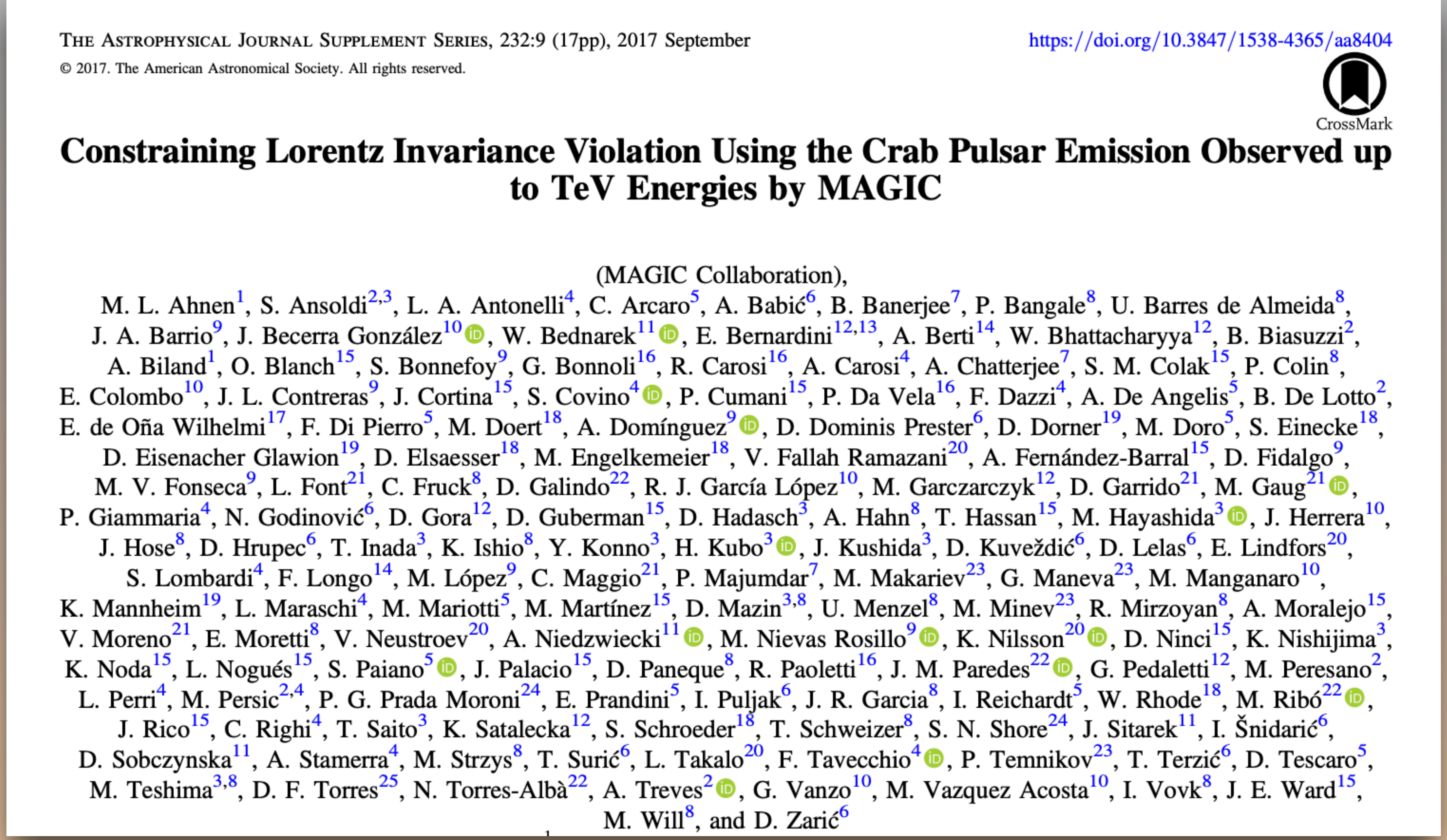
The Astrophysical Journal Supplement Series 232.1 (2017): 9

48 citations



The Astrophysical Journal Supplement Series, 232:9 (17pp), 2017 September https://doi.org/10.3847/1538-4365/aa8404

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CrossMark

Constraining Lorentz Invariance Violation Using the Crab Pulsar Emission Observed up to TeV Energies by MAGIC

(MAGIC Collaboration),
M. L. Ahnen[1], S. Ansoldi[2,3], L. A. Antonelli[4], C. Arcaro[5], A. Babić[6], B. Banerjee[7], P. Bangale[8], U. Barres de Almeida[8],
J. A. Barrio[9], J. Becerra González[10], W. Bednarek[11], E. Bernardini[12,13], A. Berti[14], W. Bhattacharyya[12], B. Biasuzzi[2],
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L. Perri[4], M. Persic[2,4], P. G. Prada Moroni[24], E. Prandini[5], I. Puljak[6], J. R. Garcia[8], I. Reichardt[5], W. Rhode[18], M. Ribó[22],
J. Rico[15], C. Righi[4], T. Saito[3], K. Satalecka[12], S. Schroeder[18], T. Schweizer[8], S. N. Shore[24], J. Sitarek[11], I. Šnidarić[6],
D. Sobczynska[11], A. Stamerra[4], M. Strzys[8], T. Surić[6], L. Takalo[20], F. Tavecchio[4], P. Temnikov[23], T. Terzić[6], D. Tescaro[5],
M. Teshima[3,8], D. F. Torres[25], N. Torres-Albà[22], A. Treves[2], G. Vanzo[10], M. Vazquez Acosta[10], I. Vovk[8], J. E. Ward[15],
M. Will[8], and D. Zarić[6]

MAGIC studies in search for LIV effects

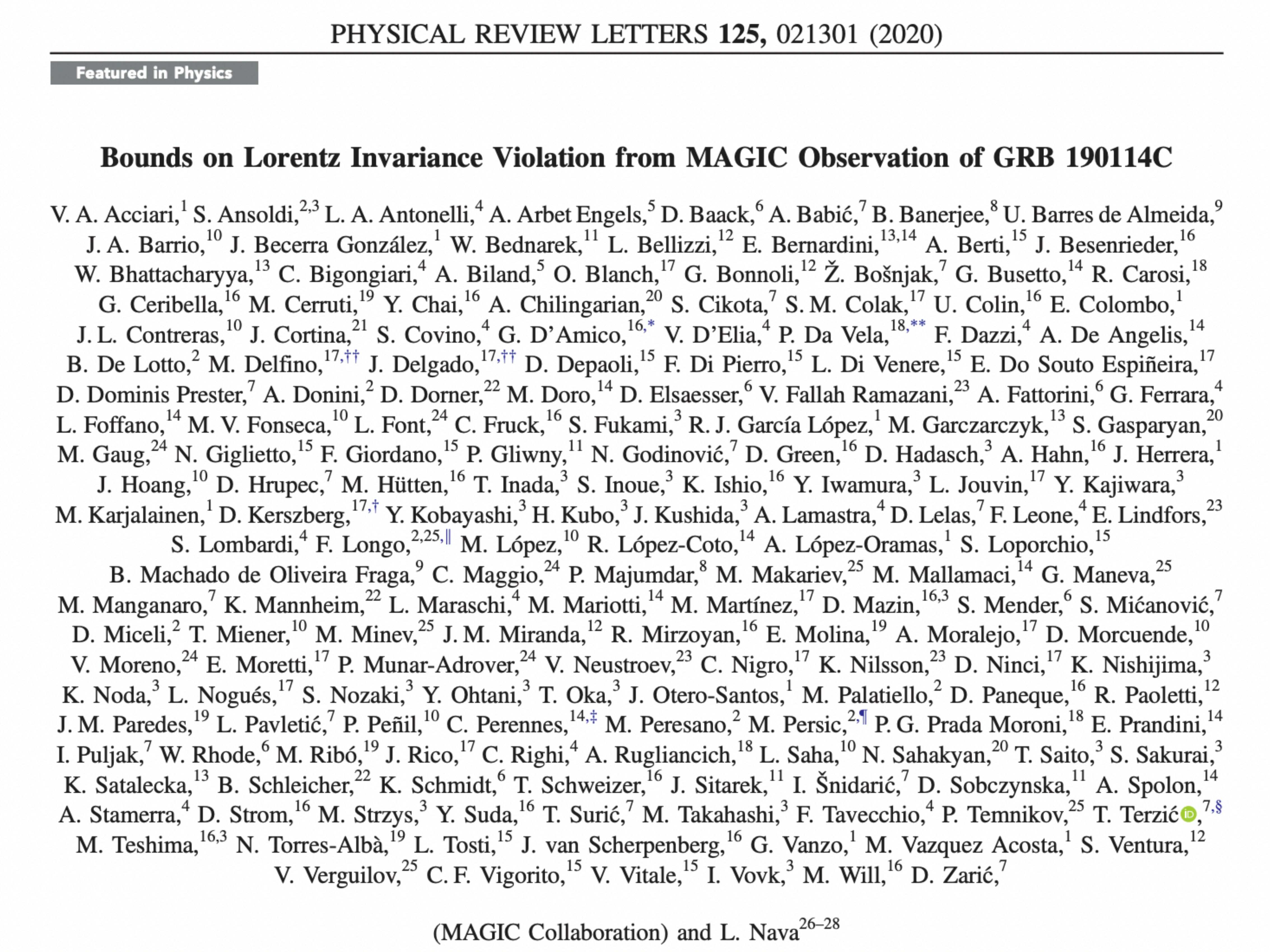
- Flaring AGN
  - Markarian 501 2005 flare: MAGIC (Albert+ 2008; Martinez & Errando, 2009)
  - PKS 2155-304 2006 flare: H.E.S.S. (Aharonian+ 2008; Abramowski+ 2011)
  - PG 1553+113 2012 flare: H.E.S.S. (Abramowski+ 2015)

- Pulsars
  - Crab: MAGIC & VERITAS (Otte 2011; Zitzer 2013; Ahnen+ 2017)
  - Vela: H.E.S.S. (Chrétien+ 2015)

- Gamma-ray Bursts
  - GRB 190114C: MAGIC (Acciari+ 2020)

Physical review letters 125.2 (2020): 021301

72 citations



PHYSICAL REVIEW LETTERS **125,** 021301 (2020)

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Bounds on Lorentz Invariance Violation from MAGIC Observation of GRB 190114C

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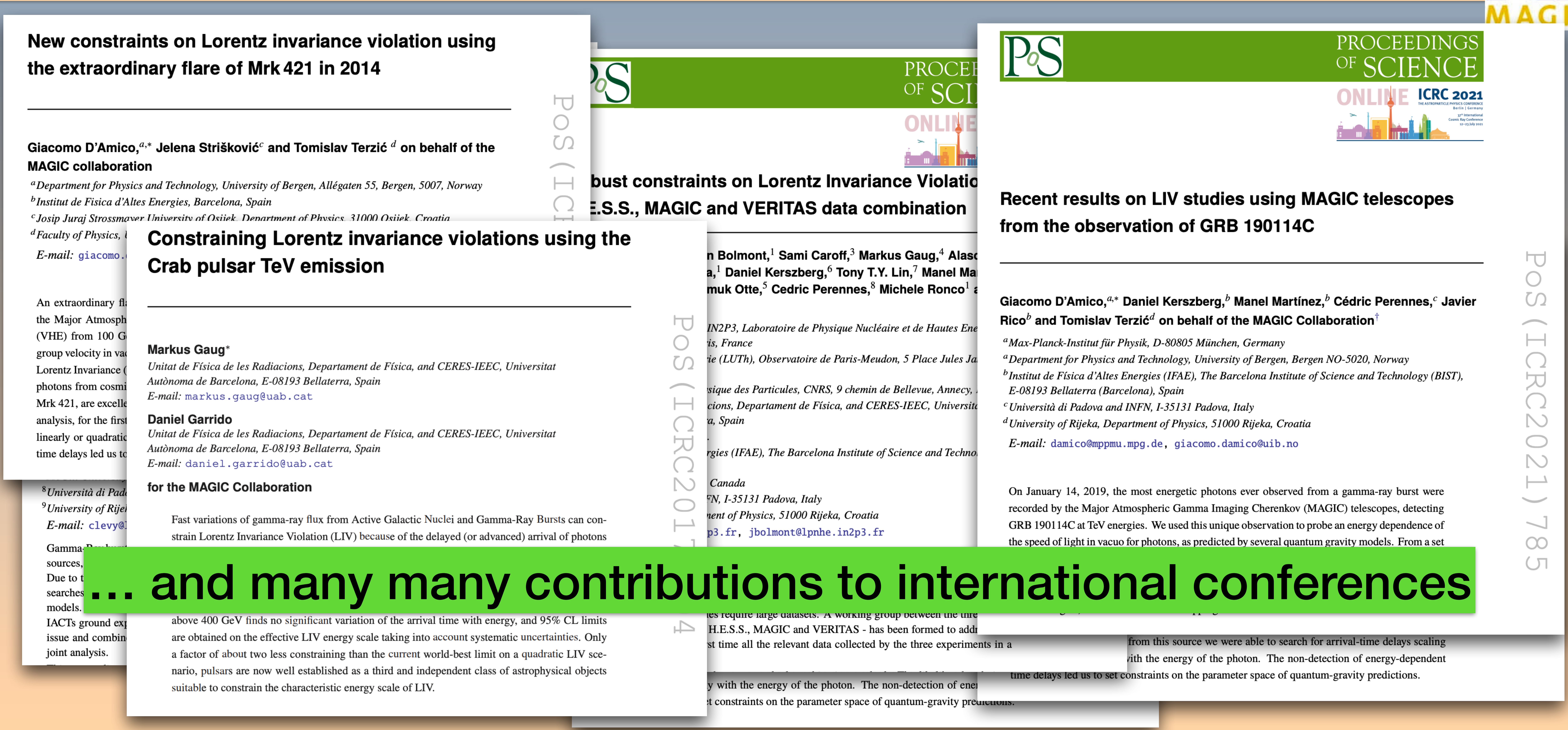
(MAGIC Collaboration) and L. Nava[26–28]

MAGIC studies in search for LIV effects



New constraints on Lorentz invariance violation using the extraordinary flare of Mrk 421 in 2014

Giacomo D'Amico,[a,*] **Jelena Strišković**[c] **and Tomislav Terzić** [d] **on behalf of the MAGIC collaboration**

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bust constraints on Lorentz Invariance Violatio E.S.S., MAGIC and VERITAS data combination

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H.E.S.S., MAGIC and VERITAS - has been formed to addr
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Constraining Lorentz invariance violations using the Crab pulsar TeV emission

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for the MAGIC Collaboration

Fast variations of gamma-ray flux from Active Galactic Nuclei and Gamma-Ray Bursts can constrain Lorentz Invariance Violation (LIV) because of the delayed (or advanced) arrival of photons

above 400 GeV finds no significant variation of the arrival time with energy, and 95% CL limits are obtained on the effective LIV energy scale taking into account systematic uncertainties. Only a factor of about two less constraining than the current world-best limit on a quadratic LIV scenario, pulsars are now well established as a third and independent class of astrophysical objects suitable to constrain the characteristic energy scale of LIV.

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Recent results on LIV studies using MAGIC telescopes from the observation of GRB 190114C

Giacomo D'Amico,[a,*] **Daniel Kerszberg,**[b] **Manel Martínez,**[b] **Cédric Perennes,**[c] **Javier Rico**[b] **and Tomislav Terzić**[d] **on behalf of the MAGIC Collaboration**[†]

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On January 14, 2019, the most energetic photons ever observed from a gamma-ray burst were recorded by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes, detecting GRB 190114C at TeV energies. We used this unique observation to probe an energy dependence of the speed of light in vacuo for photons, as predicted by several quantum gravity models. From a set

from this source we were able to search for arrival-time delays scaling with the energy of the photon. The non-detection of energy-dependent time delays led us to set constraints on the parameter space of quantum-gravity predictions.

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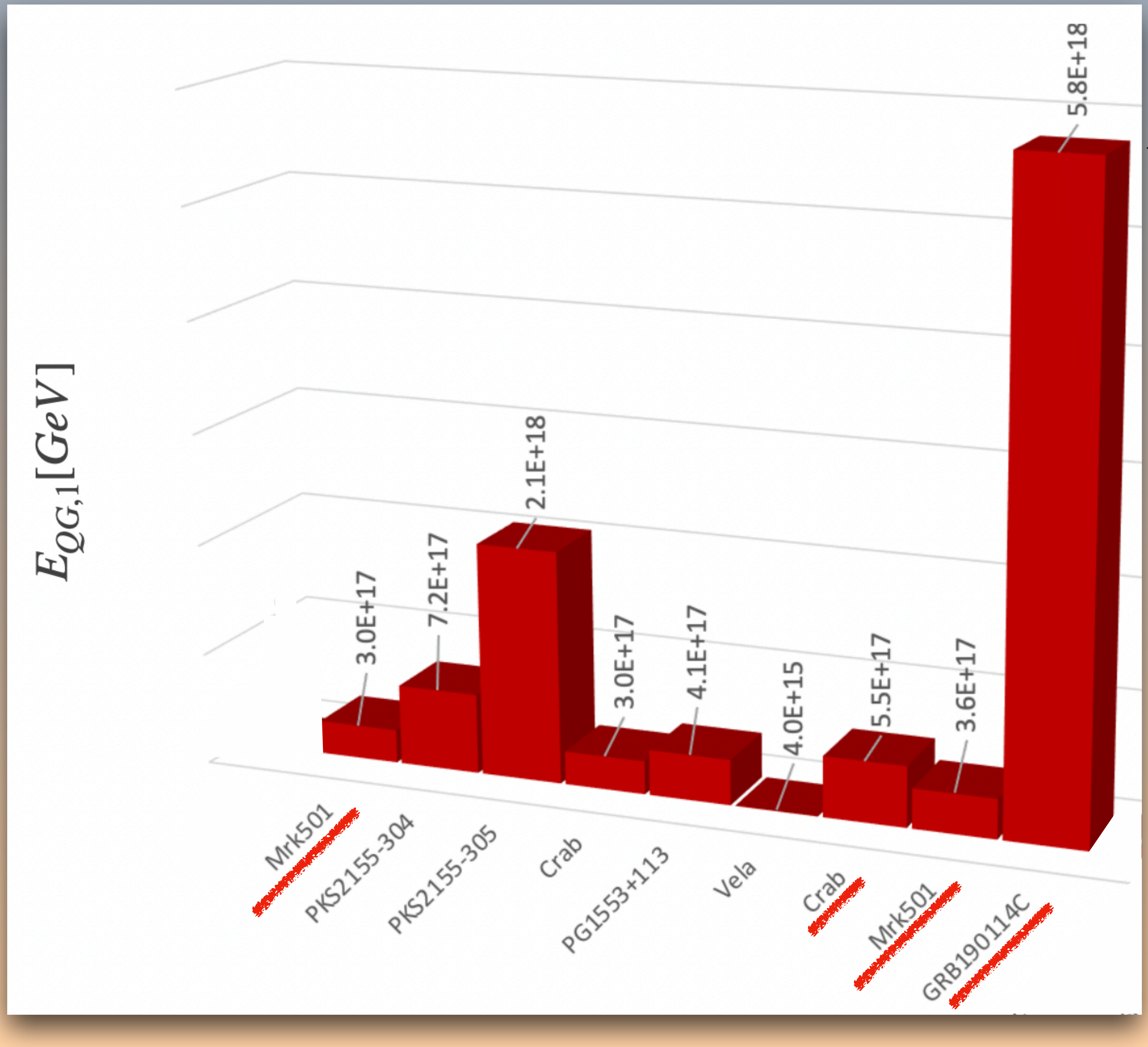
… and many many contributions to international conferences

Sources analyzed so far by IACTs in search for LIV effects

Lower bounds on the quantum-gravity energy scale obtained so far by Cherenkov telescopes



MAGIC analysis on GRB 190114C

Image credits: Jelena Strišković

Sources analyzed so far by IACTs in search for LIV effects

TAKEHOME MESSAGE:

MAGIC has **pioneered** the exploration of LIV using gamma-ray observations

being the **first collaboration** to investigate these effects with a **GRB**

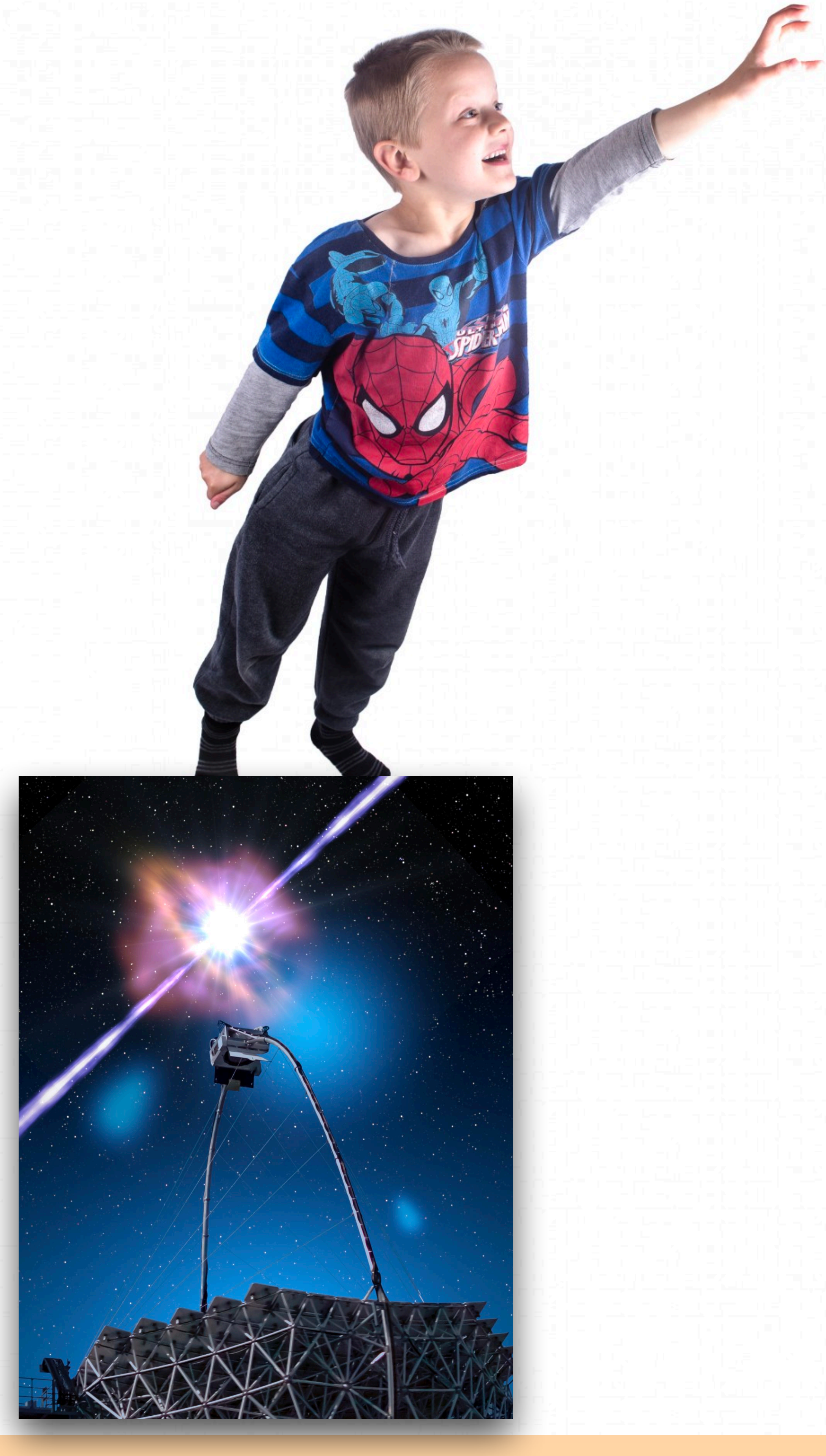
achieving energy scales nearing the **Planck energy!**

Outlook

THE PLANCK ENERGY SCALE

Outlook

THE PLANCK ENERGY SCALE



Outlook

THE PLANCK ENERGY SCALE

THANK YOU FOR YOUR ATTENTION