CA18108 network: new challenges and opportunities for research in quantum gravity phenomenology

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CA18108 network

Main aim: To investigate possible signatures predicted by *quantum gravity models* in the observation of different *cosmic messengers*, by creating the conditions for a *close collaboration* between theorists and the various experimental communities involved in the detection of such cosmic messengers

Size of the network: 325 researchers from 44 countries (28 COST Members and 2 Near Neighbour countries)

Structure: 6 Working Groups + outreach & diversity group

- *WG1* Theoretical frameworks for QG effects below Planck scale
- *WG2* Phenomenology of quantum gravity
- *WG3* Gamma rays
- *WG4* Neutrinos
- *WG5* Cosmic rays
- *WG6* Gravitational waves

CA18108 activities

- **Sep 02-04, 2019:** Kick-off meeting, Barcelona (Spain)
- **Mar 10-13, 2020:** *First Annual Conference*, Granada (Spain)
- **Dec 14-16, 2020:** DSR20 online meeting
- **Jun 17, 2021:** LHAASO discussion session
- **Sep 27 - Oct 05, 2021:** *First Training School*, Corfu (Greece)
- **Oct 06-08, 2021:** *Second Annual Conference*, Corfu (Greece)
- **March 31, 2022:** Online meeting on combining multi-instrument gamma-ray data in a single LIV study
- **Jul 11-12, 2022:** Workshop on future challenges and opportunities in QGMM, Naples (Italy)
- **Jul 13-15, 2022:** *Third Annual Conference*, Naples (Italy)
- **Sep 01-03, 2022:** Workshop on theoretical and experimental advances in quantum gravity, Belgrade (Serbia)
- **Sep 03-10, 2022:** *Second Training School*, Belgrade (Serbia)
- **Feb 12-21, 2023:** *Third Training School*, Pałac Wojanów (Poland)
- **Jul 11-14, 2023:** *Fourth Annual Conference*, Rijeka (Croatia)

CA18108 activities

- 35 Short-Term Scientific Missions (STSM)
- 4 Virtual Mobility grants
- 2 ITC Conference grants and 1 Dissemination Conference grant
- **Collaborative projects:**
  - Review paper on QG phenomenology
    Progress in Particle and Nuclear Physics **125**, *103948 (2022)*
  - Database with experimental bounds on quantum gravity searches
  - White paper
  - CQG Focus Issue
- PoS publication of the lecture notes of the three TS
- Outreach activities, diversity initiatives, presence in social media

First challenges: LIV, DSR, time delays

Barcelona kick-off meeting (2019):

What would you like other participants to know about your research?

First challenges: LIV, DSR, time delays

- **GRB 190114C:** First observed TeV emission from a GRB by IACTs (Cherenkov Imaging Telescopes) *[MAGIC Collaboration]*
- **DSR modelling** of time delays included in the strategy of the *first combined LIV study* with IACTs (γLIV WG)
- **Critical aspect** of these studies: intrinsic time delays —the *three levels of LIV/DSR phenomenology* (production, propagation and detection) involves astrophysics, theoretical modelling and experimental analysis techniques
- **Divergent findings:** theoretical analyses reporting evidences of photon time delays meet skepticism from experimental collaborations —further work and combined analyses with different sources are in order to clarify the situation

First challenges: LIV, DSR, time delays

- QG phenomenology has been usually connected to sensitivity to the **Planck scale,** but *is this necessarily so?*
- The **LIV scenario** can in fact explore a scale $\Lambda \sim M_P$ at energies $E \ll \Lambda$:
  - The propagation of cosmic free massless particles may present observable time delays thanks to a *distance amplification*
  - *Kinematic thresholds* are modified when $(m^2/\Lambda^2) \sim (E/\Lambda)^n$, which happens for $E \ll \Lambda$
- In a **DSR scenario**, the existence of relativistic invariance changes the situation
  - The *kinematics looses sensitivity to M_P*, since significant modifications only happen at $E \sim \Lambda$
  - The propagation of massless particles *may or may not present time delays* depending on the DSR model

May 2021: LHAASO opens the PeV window to γ rays

- Our Action organized an **online session** with members of the LHAASO collaboration to discuss their results and the possible implications for QG phenomenology
- Our galaxy is apparently **full of PeVatrons**; the precise determination of the sources is highly relevant for QG tests
- **Challenges** and **opportunities** in the analysis of the QG effects in the γ-transparency of the universe:
  - *Uncertainties* in the photon background (EBL)
  - *LIV studies* rely on kinematic modifications of the $\gamma_h \gamma_l \to e^+ e^-$ threshold, making assumptions on the corrections to σ
  - The *superluminal* scenario is strongly constrained; the *subluminal* scenario, however, could explain a larger transparency
  - *DSR models without time delays* may allow for corrections in the transparency of the Universe with a high-energy scale significantly below the Planck mass

May 2021: LHAASO opens the PeV window to γ rays

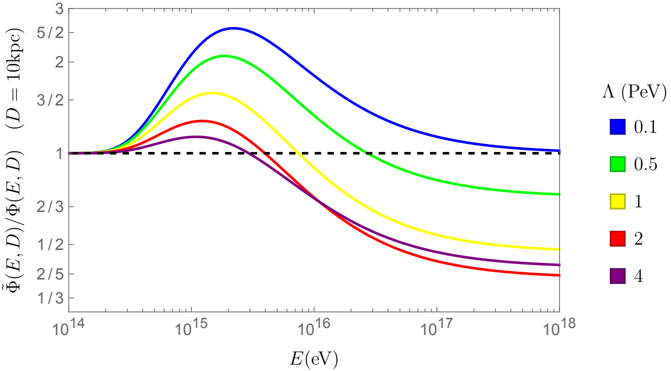
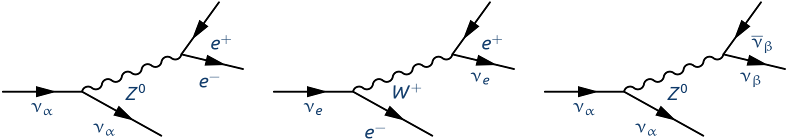


Figure 1: Ratio between the observed fluxes of high-energy gamma rays in the DSR and SR cases for values of Λ near the end of the observed LHAASO spectrum (PeV scale), corresponding to sources at a distance $D = 10$ kpc *[from Eur. Phys. J. Plus* **137***, 768 (2022)]*

March 2021: Evidence for the Glashow resonance

IceCube observed a particle shower consistent with the resonant formation of a W^- boson in the interaction of a ~ 6.3 PeV antineutrino with an electron *(Glashow resonance)*

This is relevant for LIV studies, which were considered as a possible explanation for an **apparent cutoff** in the high-energy neutrino spectrum at the PeV scale: superluminal neutrinos can loose energy very effectively through *pair-production* and *neutrino splitting* processes



Neutrinos and gamma rays

- **IceCube** and **ANTARES** have unsuccesfully tried to find *correlations* between neutrino events and GRBs
- There are however some indications of a correlation with large enough **time windows:** is this compatible with the previous *neutrino decay* processes?
- Recent **analytical calculations** for the neutrino *decay widths* and *probability distributions* may be relevant to explore the LIV scenario, which could also modify the standard *flavor composition* at Earth
- Latest results from IceCube **(June 2023)** seem to establish a correlation between gamma rays and neutrinos at much lower *(TeV)* energies (no time analysis, though; the identification of the sources is the next challenge)

Ultra high-energy cosmic rays (UHECRs)

- The **GZK cutoff** (suppression of the UHECR spectrum at the highest energies because of their interaction with the photon background) was originally understood to provide a *test of LIV*
- However, several **open questions** raise doubts on the *sensitivity* of the highest part of the CR spectrum to LIV:
  - Which is the *origin of the observed flux suppression* (propagation vs source effects)?
  - Which is the *composition of the UHECRs* (LIV effects depend on their proton fraction)?
  - Are there modifications in the *hadronic interactions* producing air showers in the atmosphere?
- The interactions of the UHECRs with the EBL/CMB is also a source of **cosmogenic photons and neutrinos;** LIV effects can modify the standard flux expectations

Cosmogenic neutrinos

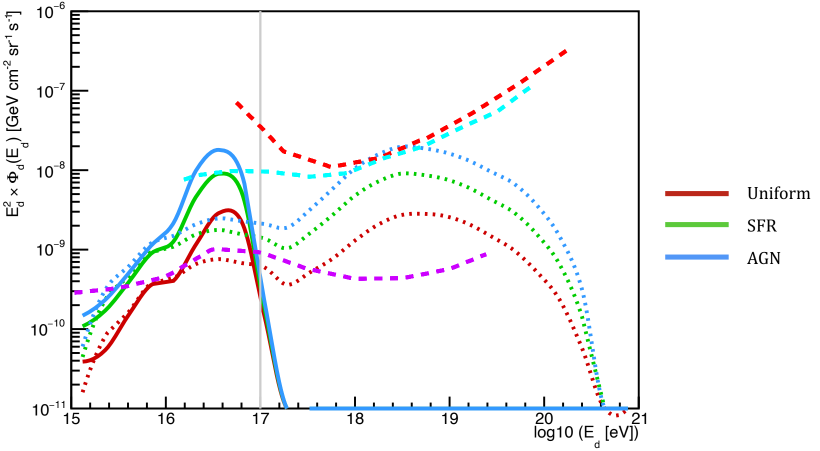


Figure 2: Cosmogenic neutrino flux at Earth for $n = 2$, $\Lambda/M_P = 2.19$ and for different models for the production of the UHECR, and the 90% CL upper limits of IceCube (dashed cyan), Auger (dashed red), and IceCube-Gen2 (dashed purple) *(see M. Reyes' talk)*

Gravitational waves

- The observation of **GW170817** and **GRB 170817A** provided insights on fundamental physics, the origin of short GRBs, and constrained *LIV and modified gravity theories*
- We are witnessing the **dawn of a multimessenger era**, where the different messengers will provide *complementary information*, constraining QG models and modifications to GR
- The first indications for a *nano-Hz gravitational wave signal* in pulsar timing arrays **(June 2023)** opens again a new window in GW astrophysics that will surely have implications in QG phenomenology

Future prospects

- A number of **new results and upgrades** of instruments in the near future (CTA, LHAASO, KM3NeT, IceCubeGen-2, Askaryan detectors, LIGO and other GW detector upgrades) will deepen in the *new astrophysical windows* recently opened; in particular, they will improve the *sensitivity to the fluxes* of the cosmic messengers in their highest energy ranges, allowing to better *explore departures* of special relativity present in phenomenological models of QG
- These experimental advancements will have to be accompanied by **theoretical developments** in the formulation of the phenomenological consequences of LIV and DSR models

Future prospects

- In particular, it may be necessary to analyze the phenomenological sensitivity to a *high-energy scale* $\Lambda \ll M_P$ in a scenario of **deformed relativistic invariance**
- This may be relevant for models in which the **effective energy scale of QG** Λ is characterized by a combination of the Planck scale and further parameters of the theory
- Depending on the magnitude of Λ, **particle physics experiments** could be sensitive to QG effects
- Note than **a deformation of relativistic invariance is conceptually very different from LIV:** it lies beyond the framework of effective field theory, and the issue of *locality* can be behind some conceptual issues in DSR theories *(soccer-ball problem, spectator problem)*

Future prospects

- The **LIV** (sensitivity to $\Lambda \sim M_P$) and **DSR** (sensitivity to $\Lambda \ll M_P$) scenarios give **different phenomenology** for the *different cosmic messengers* (e.g., time delays, the presence of decays forbidden in SR). A *multimessenger analysis* will be necessary to distinguish between them as explanations of *anomalies* (such as the absence of expected correlations)
- The cooperation between the different communities in the **CA18108 network** (and beyond) has the potential of finding new paths of discovery for quantum gravity effects in the physics of the cosmic messengers and will be essential to tackle with the new challenges that will emerge in them

Thank you for your attention.

Extra slides

New perspective of DSR

Composition law in DSR

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Interpretation of DSR as a modification of locality in interactions

→

Modifications to locality at smaller distances than those presently explored

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Effects only on interactions between elementary particles

←

Relativistic compatibility between elementary and non-elementary particles: no effects in propagation

←

Possibility of deformations at sub-Planckian scales and solution to *spectator* and *soccer ball* problems

(see Universe ***9****, 150 (2023))*