Wave Phenomena Across Scales as Tests of Gravity: The FuSe CA24101 Initiative

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28th International Summer School on Global Analysis and Its Applications

Faculty of Mathematics and Computer Science at Transilvania University of Brașov, Romania

FuSe TESTING FUNDAMENTAL PHYSICS WITH SEISMOLOGY
cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
Funded by the European Union


LET'S EXPLORE THE HIDDEN CONNECTIONS
BETWEEN EARTHQUAKES AND FUNDAMENTAL LAWS OF PHYSICS
Bridging
Physics & Seismology!
Main Challenge
The main aim and objective of the Action is to bridge fundamental physics and Earth scientists, focusing on seismic data's potential to uncover new physics. Through interdisciplinary collaboration, advanced methodologies, and SME engagement, it advances understanding of Earth's structure, astrophysical phenomena, and improves natural catastrophe alert systems.
How we work - FuSe in a nutshell
WG1 – Fundamental Physics: builds the theoretical basis for understanding fundamental interactions, gravity, and matter, and helps connect models with seismic and astrophysical observations.
WG2 – Planetary & Stellar Physics: improves models of the Earth and other celestial bodies, studies interiors, seismicity, and earthquake precursors, and uses deeper seismic, geodetic, and neutrino data.
WG3 – Data Integration & Engineering: turns heterogeneous data into AI-ready, FAIR-compliant streams and develops common data workflows and tools.
WG4 – Experiments, Observations & Instrumentation: links theory to real measurements through experiments, observatories, and advanced instrumentation.
WG5 – Integration of WGs 1–4: unites all groups, harmonizes terminology and methods, constrains models, and helps identify signatures of new physics.
Working groups
Fundamental Physics
WG1
Data Integration & AI
WG3
W5
WG2
Planetary & Stellar Modelling
WG4
Instrumentation & Observations
FuSe
TESTING FUNDAMENTAL PHYSICS WITH SEISMOLOGY
Pan-European network FuSe: a new frontier in exploring seismic phenomena and earthquake precursors
FuSe investigates whether seismic and geomagnetic signals can reveal traces of new physics, while also improving models of Earth's interior. The project focuses on collaboration between physicists, geophysicists, and other specialists, shared data standards, and AI-ready, FAIR-compliant tools. It also emphasizes collaboration with SMEs and the development of sensors, AI algorithms, and alert systems for natural hazards.
cost
Funded by the European Union
FuSe COST Action
CONNECTING THE VERY SMALL WITH THE VERY LARGE
UNDERSTANDING EARTH, UNLOCKING THE UNIVERSE

COST (European Cooperation in Science and Technology) is a funding organisation for research and innovation networks

What is a COST action?

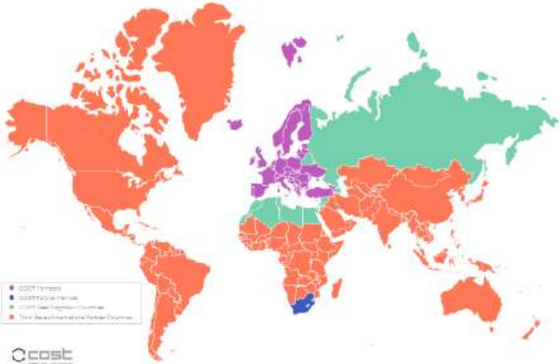
European **networking programme** connecting researchers and innovators across countries and disciplines, supporting collaboration, training, and knowledge.

- **Does not fund research, but networking activities:** meetings, workshops, missions, and training schools
- **Promotes interdisciplinarity, geographical balance, and gender equality:** increase research communities access to funding and infrastructures
- **Bottom-up structure:** topics are proposed by researchers themselves

COST Actions

From proposal to open collaboration

- A COST Action begins with a **proposal** submitted by a group of researchers (“proposers”) from at least seven COST member countries.
- Once the proposal is **approved and funded**, the Action becomes open: **any researcher, institution, or company** from COST member states (and beyond) can freely **join** and contribute to its activities during its four-year duration.



https://www.cost.eu/about/strategy/international-collaboration/

FuSe has a very strong connection with Romania!

Working Groups

Number	Title	Leader
1	Fundamental physics	Dr Gergely Gábor BARNAFÖLDI
2	Planetary and stellar physics	Dr Severine ROSAT
3	Data integration and engineering	Dr Elena Simona APOSTOL
4	Experiments, observations and instrumentation	Prof Juan Angel SANS TRESSERRAS
5	Integration of WGs 1-4	Dr Virginia STRATI

MC member for Romania: **Nicoleta Voicu**, Transilvania U. of Brașov, **mathematician**, member of WG1

WG3 Leader: **Elena Apostol**, National U. of Science and Technology Politehnica Bucharest, **computer scientist**.

Bucharest 2026, MC1 meeting in Brussels 2025 & the first FuSe conference

Bucharest, University Fountain, 2026 (Revolution)

Brussels, 2025

Brussels, 2025, MC members

1st FuSe conference, Corfu 2026

Upcoming event: 1st FuSe Training School 2026, Tihany, Hungary

We have quite a bit of **funding**, and we're actively looking for good reasons to spend it - supporting (young) participants is our favourite one

Topics:
Gravitational waves
Neutrino tomography
Cosmic rays
Machine learning and artificial intelligence
Planetary seismology
Geoneutrino physics
Hands-on Detectors and Field Exploration

Upcoming event: 2nd FuSe conference, Wrocław 2027

FuSe@Wroclaw 2027
Dates: June 21-25

Expected per diem:
-170 EUR
Travel expenses:
-350Euro

Wrocław is one of Poland's most charming and vibrant cities, offering a unique blend of history, culture, and modern urban life. Famous for its picturesque Market Square, Gothic Cathedral Island, and UNESCO-listed Centennial Hall, the city captivates visitors with its architectural diversity and lively atmosphere. Built around the Odra River, Wrocław features numerous bridges, islands, and riverside boulevards that invite walking and relaxation. The city is also known for its dynamic cultural scene, festivals, cafés, and green spaces. The city is also home to the University of Wrocław, one of the oldest and most prestigious universities in Central Europe, renowned for its academic excellence and international outlook.

LOC: (University of Wroclaw)
Magdalena Matusiak-Małek
Krzysztof Moskwa
Tomasz Trześniewski
Artur Barasiński
(Aneta Wojnar)

⇦ **Main lecture hall**

Let's finally talk about the science behind FuSe

In FuSe, we are kind of obsessed with waves.
If it oscillates, we are interested.

- *Seismic waves*:
  - provide information about the interiors of astrophysical bodies (planets and stars) — a **theory-dependent** procedure;
  - enable tests of theories of gravity, dark matter and dark energy models, as well as particle physics.
- Possible additional *oscillation modes* in astrophysical bodies:
  - searching for signatures of a fifth force and other new physics.
- *Gravitational waves*:
  - probe the "cosmological fluid";
  - probe the interiors of the Earth and the Moon;
  - (earth)quakes? 😮
  - probe extra dimensions.

Basic equations of stellar (sub-)structure[1]

(nonsphericity, magnetic fiels, time-dependency,... ignored here

The structural and thermal differential relations

$$\frac{dp}{dr} = -\frac{Gm}{r^2}\rho, \quad \frac{dm}{dr} = 4\pi r^2\rho, \quad \frac{dL}{dr} = 4\pi r^2\epsilon\rho$$

Criteria for the heat transfer model (e.g. Schwarzschild criterion)

$$\begin{aligned} \nabla_{\mathrm{rad}} &\leq \nabla_{\mathrm{ad}} \quad \text{pure diffusive radiative transport or conduction} \\ \nabla_{\mathrm{rad}} &> \nabla_{\mathrm{ad}} \quad \text{adiabatic convection is present locally} \end{aligned}$$

$$\text{where} \quad \nabla_{\mathrm{rad}} := \left(\frac{d\ln T}{d\ln p}\right)_{\mathrm{rad}} = \frac{3\kappa_{rc}Lp}{16\pi acGmT^4}$$

Microscopic physics (X is shorthand for composition)

$$p = p(\rho, T, X), \quad E = E(\rho, T, X), \quad \kappa = \kappa(\rho, T, X), \quad \epsilon = \epsilon(\rho, T, X)$$

Boundary conditions at the center ($m = 0$, $r = L = 0$) and at the surface ($m = M$, $\rho = T = 0$).

[1] see e.g. *Stellar Interiors, Physical Principles, Structure and Evolution*, C.J. Hansen, S.D. Kawaler, V. Trimble

Non-relativistic equations of modified gravity

Modified Poisson equation[2]

$$\nabla^2\Phi \approx \frac{\kappa}{2}(\rho + \text{modification})$$

For spherical-symmetric spacetime the gravitational potential

$$\Phi(r) = -\frac{GM}{r} - 4\pi G \int_r^R \Big(\rho(r)r + \text{modification}\Big)dr.$$

The hydrostatic equilibrium equation

$$\frac{d\Phi}{dr} = -\rho^{-1}\frac{dP}{dr},$$

+ matter description (EoS and/or "seismic waves", temperature dependence,...)
+ eventual equations for additional fields

(It can be "easily" extended to rotating models[3])

[2] A.W., EPJC 79, 1, 51 (2019) - **H2**, G. Olmo, D. Rubiera-Garcia, A.W. PRD 104, 024045 (2021) - **H9**, and others, not included in the list of scientific achievements presented here.

[3] Chowdhury et al. (A.W.), PRD 109 (2024) 10, 104049; A. Kozak, A.W., in progress.

How to use seismic waves to understand gravity?[5]

geometry (based on a model of gravity)

$$+$$

mass & moment of inertia (observational constraints):

$$=$$

gravity $\sim$ terms including *seismic data*

Result:

Constraints on (quantum) gravitational theories **40 order of magnitude better** than from cosmological data[4] and about **50 order of magnitude better** than data from black holes (shadows, quasi normal modes).

[4] D. Aguiar Gomes et al. (A.W.), JCAP 01 (2024) 011.

[5] A. Kozak, A.W., PRD 104 (2021) 8 - **H10**; 108 (2023) 4, 044055 - **H15**; A. Kozak, A. Pachol, A.W. Annals Phys. 481 (2025) 170136.

Theories of gravity constrained so far

Modified Poisson equation

$$\nabla^2\phi(\mathbf{x}) = 4\pi G\Big(\rho(\mathbf{x}) + \nabla^2\alpha\big(\mathbf{x}, \rho(\mathbf{x})\big)\Big),$$

- Palatini $f(R)$ and Eddington-inspired Born-Infeld gravity (Ricci-based)[6]: $\alpha(r,\rho) = \epsilon/2\rho(r)$, and $\epsilon = 4\beta$

  $-2\times10^9 \lesssim \beta_P \lesssim 10^9\text{m}^2$ for Palatini , $-8\times10^9 \lesssim \epsilon \lesssim 4\times10^9\text{m}^2$ for EiBI

- DHOST theories $\alpha(r,\rho) = \frac{\Upsilon}{4} r^2\rho(r)$

$$-10^{-3} \lesssim \Upsilon \lesssim 10^{-3}$$

- Quantum gravity: Snyder and qGUP ($\beta := \tilde{\beta} M_P^2 c^2$): $\beta < 4.67\times10^{44}$
- Quantum gravity: linear GUP[7]: $-6\times10^{22} \lesssim \sigma \lesssim 3\times10^{22}$ s/kg m

[6] New cosmological data provides bounds $|\beta_P| < 10^{49}$ m^2, Aguiar Gomes+, JCAP 01 (2024) 011

[7] A.W., PRD 109, 024011 (2024) - **H18**

Challenging the concept of continuous space-time[8]

→ In Quantum Gravity the geometry of space-time (space-time continuum) has no operational meaning

→ common in many approaches: "quantum spacetime - unlikely to admit a fundamental description in terms of a differentiable manifold"

- Loop Quantum Gravity (minimal area/volume)
- String Theory (minimal length uncertainty relations from high-energy scattering)
- Spin Foam Models (effective noncommutative QFTs)
- Group Field Theory, Causal Dynamical Triangulation

The space-time - non-local:

$$\Delta x^\mu \Delta x^\nu \gtrsim (L_p)^2$$

→ the coordinates are non-commutative

$$[x^\mu, x^\nu] \neq 0$$

[8] Doplicher, Fredenhagen and Roberts, "Quantum structure of space-time at the Planck scale and quantum fields" Commun.Math.Phys. 172 (1995) 187-220 [arxiv:hep-th/0303037]; Seiberg - Witten, String theory and noncommutative geometry, JHEP 09 (1999)

Quantum gravity[9]

Observation:

Modifies Heisenberg uncertainty principle (GUP, EUP)

$$\Delta x_i \Delta p_i \geq \frac{\hbar}{2}\Big(1 + \text{modification}\Big)$$

or/and dispersion relation

$$E^2 + p^2\Big(1 + \text{modification}\Big) = m^2$$

[9] LQG, Doubly Special Relativity, String Theory, Noncommunative geometry,...

The weighted phase space volume is modified (D - dim of the phase space)[10].

$$\frac{d^D\mathbf{x}d^D\mathbf{p}}{1+\text{modification}}$$

Consequence: modified partition function ($z = e^{\mu/k_B T}$)

$$\ln \mathcal{Z} = \frac{V}{(2\pi\hbar)^3}\frac{g}{\pm 1}\int \ln\left(1 \pm z e^{-E/k_B T}\right)\frac{d^3p}{1+\text{modification}}$$

Conclusion: Quantum Gravity modifies thermodynamics

$$P = k_B T\frac{\partial}{\partial V}\ln\mathcal{Z},$$

$$n = k_B T\frac{\partial}{\partial \mu}\ln\mathcal{Z}\mid_{T,V},$$

$$U = k_B T^2\frac{\partial}{\partial T}\ln\mathcal{Z}\mid_{z,V}$$

MG as an effective theory derived from QG

[10] A. Pachoł, Nucl.Phys.B 1010 (2025) 116771

Crystals in Noncommutative Backgrounds[12]

Main idea

We study Einstein crystals as low-energy systems sensitive to modified quantum phase space effects.

- Snyder background leads to GUP-type corrections:

$$[\hat{x}, \hat{p}] = i\hbar \left(1 + \theta \hat{p}^2\right)$$

- Snyder–de Sitter background leads to GEUP-type corrections:

$$[\hat{x}, \hat{p}] = i\hbar \left(1 + \alpha \hat{x}^2 + \zeta \hat{p}^2 + \sqrt{\alpha\zeta}(\hat{x}\hat{p} + \hat{p}\hat{x})\right)$$

- These deformations modify the harmonic oscillator spectrum and therefore the thermodynamics of crystals[11].

[11] Diamond is used as a realistic example of an Einstein crystal at low temperatures.

[12] A. Pachoł, AW, Phys.Rev.D 113 (2026) 11, 116028; in preparation

Key Results

- The partition function receives noncommutative corrections:

$$Z = Z_{\rm undef} + \Delta Z_{\rm NC}$$

  and its positivity imposes bounds on the deformation parameters.
- Internal energy and heat capacity are modified:

$$U = U_{\rm undef} + \Delta U_{\rm NC}, \qquad C_V = C_{V,\rm undef} + \Delta C_{V,\rm NC}.$$

- For generic values of the noncommutative parameters, the heat capacity may become unphysical:

$$C_V < 0 \quad \text{or} \quad \frac{C_V}{3Nk_B} > 1.$$

- The theory parameter "sensitive" to the energy scale - at higher temperatures, the increased vibrational activity of particles enhances the role of momentum-dependent corrections in the uncertainty relation.

Conclusion: crystal thermodynamics can provide a low-energy window into GUP/GEUP-type quantum gravity effects.

A New Laboratory Probe of Gravity[13]

Idea: combine seismic waves and cosmic-ray muons

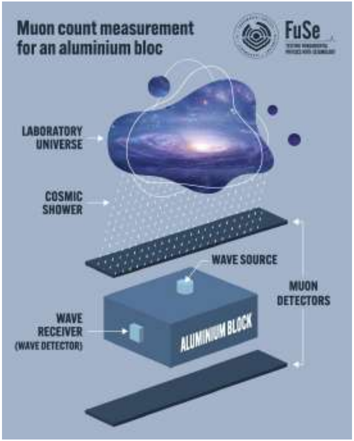
- Quantum-gravity effects modify the phase-space measure and therefore the thermodynamics of solids.
- Using the anharmonic Debye model, gravity corrections induce modifications of the bulk modulus:
$$K = K_0 + \Delta K_{\mathrm{grav}}.$$
- Seismic measurements provide: v_P, v_S, while muon tomography independently determines the density ρ.
- Combining both observables removes the dominant density-related uncertainty:
$$K = \rho\left(v_P^2 - \frac{4}{3}v_S^2\right).$$
- This enables a gravity-independent determination of elastic and thermodynamic properties of materials.

[13] AW, arXiv:2604.07333

Seismic waves and cosmic rays[14]

- Stronger constraints are obtained at higher temperatures, indicating a temperature-dependent sensitivity to quantum-gravity corrections.
- The achievable bounds are comparable to existing laboratory constraints from GUP-inspired experiments.

Muon tomography and seismology provide a promising low-energy window on quantum gravity.



[14] AW, arXiv:2604.07333

Gravitational Waves as Probes of the Cosmic Medium[15]

Key idea: gravitational waves do not only test gravity - they can also probe what the Universe is made of.

LIGO event **GW150914** whose signal propagated over a distance of about

$$L \simeq 410 \text{ Mpc}.$$

If the cosmic medium has nonzero shear viscosity η, the GW amplitude is attenuated:

$$h_{ij} \propto \frac{L_0}{L} \exp\left[-\frac{\beta L}{2}\right], \qquad \beta = 16\pi G\eta.$$

- Ideal fluids do not dissipate gravitational waves.
- Shear viscosity of dark matter or dark energy would damp the signal.
- Comparing the observed and predicted waveform constrains the viscous properties of the cosmic fluid.

Gravitational waves can act as "standard probes" of the invisible medium: they may help distinguish collisionless dark matter from dissipative or self-interacting dark sectors.

[15] Goswami et al., Phys. Rev. D 95, 103509 (2017).

Gravitational Waves as a Probe of the Earth's Interior[16]

The Earth can be viewed as a giant gravitational-wave detector.

A passing gravitational wave produces an effective **Dyson force**

$$\boxed{\mathbf{f}_{\mathrm{GW}} = \nabla\mu \cdot (\hat{\mathbf{e}}_r \cdot \mathbf{h})}$$

where μ is the shear modulus and h_{ij} is the metric perturbation. **Key consequence**

$$\boxed{\text{GWs interact only with spatial variations of } \mu}$$

The interaction is concentrated at major elastic discontinuities such as

- Earth's surface (solid Earth $\to$ atmosphere),
- core–mantle boundary.

The Earth's response therefore depends directly on its **internal elastic structure**.

Normal-mode excitation
Passing GWs excite only **quadrupolar spheroidal modes** which carry information about the Earth's interior.
The induced displacement is obtained through the Green-function formalism

$$\mathbf{u}(\mathbf{r}, t) = \int G(\mathbf{r}, \mathbf{r}', t)\, \mathbf{f}_{\mathrm{GW}}\, dV'.$$

Applications

- probe Earth's interior,
- test gravity in the mHz band,
- future synergy with LISA.

[16] Dyson (1969); Ben-Menahem (1983); Majstorović (2019)

One story is an anecdote. A thousand is evidence

A call for action
against bullying, harassment and misuse of power in academia

by Aneta Wojnar, Betti Hartmann, Anna Pachoł, Julia Contreras-García, Mariam Tórtola, and Elena-Simona Apostol

Banner design by Małgorzata Radowska

One story is an anecdote
A thousand is evidence

We are collecting the experiences of women in academia.
Every story is read. Every story counts.
Share your story anonymously

Scan the QR code to share your story

Many women and members of underrepresented and marginalized groups in academia can recall moments that left a lasting mark on their feeling of belonging in academia: a supervisor who crossed professional

Over the past months, however, a growing number of academics have begun sharing their experiences with one another. What emerged was not a collection of isolated stories, but a striking pattern.

17 Editors: Saskia Demulder and Verónica Errasti Díez.

The campaign

First steps when you are a target:

1. Talk to women (locally, globally) - we already have a big network
2. Hire a lawyer

Take-Home Message

- Join FuSe :)
- Use waves as a tool for understanding nature.

Multumesc!

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Funded by the European Union

Astrophysical bounds on Generalized Uncertainty Principle[18]

Our bound when more realistic physics taken into account

$\beta \leq 1.36 \times 10^{48}$ from low-mass stars (A. Pachol, A.W., Eur.Phys.J.C 83 (2023) 12, 1097) - **H17**

$\beta < 4.67 \times 10^{44}$ from Earthquakes (A. Kozak, A. Pachol, A.W., Annals of Physics, 2025)

Experiment	Reference	Upper bound on β
Perihelion precession (Solar System, 1)	[328, 330]	10^{34}
Time-of-flight measurements	[327]	10^{16}
Equivalence principle (pendula)	[246]	10^{73}
Gravitational bar detectors	[406, 407]	10^{93}
Equivalence principle (atoms)	[408]	10^{45}
Low-mass stars	[409]	10^{48}
LIV in torsion pendulum	[171]	10^{51}
Perihelion precession (Solar System, 2)	[129, 161]	10^{69}
Perihelion precession (pulsars)	[129]	10^{71}
Gravitational redshift	[161]	10^{76}
Black hole quasi normal modes	[257]	10^{77}
Light deflection	[129, 161]	10^{78}
Time delay of light	[161]	10^{81}
Black hole shadow	[253]	10^{90}
Black hole shadow	[257, 265]	10^{90}

[18] See review by Bosso+, CQG 40.19 (2023): 195014

Tabletop experiment bounds on Generalized Uncertainty Principle[19]

Our bound when more realistic physics taken into account

$\beta \leq 1.36 \times 10^{48}$ from low-mass stars (A. Pachol, A.W., Eur.Phys.J.C 83 (2023) 12, 1097) - **H17**

$\beta < 4.67 \times 10^{44}$ from Earthquakes (A. Kozak, A. Pachol, A.W., Annals of Physics, 2025)

Experiment	Reference	Upper bound on β
Phonon cavity	[399]	10^{46}
Harmonic oscillators	[400, 401]	10^{60}
LIV in hydrogen atom	[304]	10^{30}
Scanning tunneling microscope	[65, 373]	10^{33}
μ anomalous magnetic moment	[65, 402]	10^{33}
Hydrogen atom	[54, 57, 95, 395, 396]	10^{34}
Lamb shift	[65, 403]	10^{36}
^{87}Rb interferometry	[404, 405]	10^{39}
Kratzer potential	[90]	10^{46}
Stimulated emission	[110]	10^{46}
Landau levels	[65, 69, 403]	10^{50}
Quantum noise	[112]	10^{57}

19 See review by Bosso+ 2023 Class. Quantum Grav. 40 195014