

# **XXV SIGRAV Conference on General Relativity and Gravitation**

Monday, September 4, 2023 - Friday, September 8, 2023

SISSA (Miramare campus)

## **Book of Abstracts**



# Contents

Registration and Welcome . . . . .	1
Jcap Colloquium-Parity Violation in Cosmology . . . . .	1
Binary Neutron Stars: from macroscopic collisions to microphysics . . . . .	1
Amplitudes in AdS from conformal field theory . . . . .	1
### . . . . .	1
Theory: Exploring Conserved Charges in General Relativity Using Covariant Phase Space	2
Theory: On the classification of Generalized Quasitopological Gravities . . . . .	2
Theory: On the nature of Bondi-Metzner-Sachs transformations . . . . .	2
Theory: Can General Relativity Play a Role in Galactic dynamics? . . . . .	3
Theory: Primordial fluctuations from quantum gravity . . . . .	3
Theory: Scale-invariant inflation . . . . .	3
Theory: Bianchi-I cosmologies, magnetic fields and singularities . . . . .	4
Phenomenology: Detection and measurement prospects at the Einstein Telescope: forecasts with GWFAST . . . . .	4
Experiments: Anomalies and open issues of the MICROSCOPE Space Test of the Weak Equivalence Principle . . . . .	5
Phenomenology: Parameter estimation of binary black holes in the endpoint of the up-down instability . . . . .	5
Experiments: ISA accelerometer on-board BepiColombo mission during first Mercury swing-bys –Preliminary observations . . . . .	5
Phenomenology: Multitimescale dynamics of eccentric and precessing binary black holes	6
Parallel 3 . . . . .	6
Phenomenology: Anisotropic Neutron Stars: Exploring Quasinormal Modes in Full General Relativity . . . . .	6
Experiments: Fundamental Physics with GNSS satellites and the Galileo for Science Project . . . . .	7

Phenomenology: Computation of stochastic background from extreme mass ratio inspiral populations for LISA . . . . .	7
Experiments: METRIC: a mission concept for upper atmosphere mapping, gravitational physics and geodesy . . . . .	7
Phenomenology: Glitch systematics on the observation of massive black-hole binaries with LISA . . . . .	8
Experiments: Galactic Dark Matter from General Relativity . . . . .	8
Phenomenology: Characterizing Burst with Linear Memory Events with LIGO-Virgo-KAGRA and Pulsar Timing Array Observatories . . . . .	9
Parallel 7 . . . . .	9
Phenomenology: AGILE search of gamma-ray electromagnetic counterparts of gravitational waves . . . . .	9
Experiments: Status of the GINGER project . . . . .	10
Advance Virgo+ Quantum Noise Reduction system for O4 . . . . .	10
Assemblea dei Soci (in Italian, reserved to SIGRAV members) . . . . .	10
Black hole spectroscopy . . . . .	11
Telescopes on the Moon: the next decades . . . . .	11
Einstein Telescope and the next generation GW observatories: science, technologies and perspectives . . . . .	11
Tests of theories of gravitation in their weak-field and slow-motion limit with laser-tracked satellites . . . . .	11
Plenary talk I . . . . .	12
Gravitation and Cosmology . . . . .	13
The black hole mass function and merger rate across cosmic time . . . . .	13
Plenary talk II . . . . .	13
Gluing, black holes, and all that . . . . .	13
Searching for dark energy off the beaten track . . . . .	13
Shift symmetry in the dark sector . . . . .	14
Gravitational charges on null hypersurfaces . . . . .	14
Plenary talk III . . . . .	14
Social Trip to Aquileia (from Via Beirut-Return to Piazza Oberdan) . . . . .	14
Theory: Bouncing and emergent cosmology from Dark Energy with an unstable de Sitter vacuum . . . . .	14

Phenomenology: Scalar-tensor theories to tackle cosmological tensions . . . . .	15
Experiments: Detecting low-frequency gravitational waves with Pulsar Timing Arrays . . . . .	15
Theory: Beyond the Casimir Wormholes . . . . .	16
Experiments: The Astrometric Gravitational Arena: principles and applications . . . . .	16
Phenomenology: Neural Posterior Estimation with guaranteed exact coverage: the ring-down of GW150914 . . . . .	16
Theory: Fundamental decoherence from quantum spacetime . . . . .	17
Phenomenology: Observational phenomena on black hole with dark matter dress . . . . .	17
Experiments: The European Pulsar Timing Array - the pulsar dataset . . . . .	17
Theory: On the wormhole-warp drive correspondence . . . . .	17
Experiments: Progress on the Astrometric Gravitational Wave Antennas . . . . .	18
Phenomenology: Testing black hole eikonal correspondence . . . . .	18
Theory: Carrollian and Galilean limits of deformed symmetries in 3D gravity . . . . .	18
Phenomenology: Non-ideal GRMHD and compact objects . . . . .	19
Parallel 3 . . . . .	19
Theory: Casimir wormholes with a scalar field . . . . .	19
Parallel 3 . . . . .	20
Phenomenology: Hunting for two rings in black hole images . . . . .	20
Theory: Quantum Euler angles and agency-dependent spacetime . . . . .	20
Phenomenology: Dark Matter in Fractional Gravity I: Astrophysical Tests on Galactic Scales . . . . .	20
Experiments: The second data release from the European Pulsar Timing Array II. Customised Pulsar Noise Models for Spatially Correlated Gravitational Waves . . . . .	21
Theory: Geometry of the black-to-white hole transition . . . . .	21
Experiments: LISA Pathfinder and LISA test-mass charging . . . . .	22
Phenomenology: Testing GR with large catalogs: the cosmic variance of hierarchical stacking . . . . .	22
Theory: Axially symmetric stationary gravitational perturbations of Kerr black hole — Debye vs Weyl, —, Lewis, —, Papapetrou . . . . .	22
Phenomenology: Testing Planck-scale in-vacuo dispersion with GRB neutrinos . . . . .	22
Experiments: Impications of GW searches in the latest data release of the EPTA . . . . .	23
Theory: Vacuum entanglement in near extremal black holes . . . . .	23

Parallel 5 . . . . .	23
Phenomenology: Constraining modifications of black hole perturbation potentials near the light ring with quasinormal modes . . . . .	23
Theory: To Kerr or not to Kerr? . . . . .	24
Phenomenology: A new Paradigm for the Dark Matter Phenomenon . . . . .	24
Experiments: The growing population of the relativistic pulsar binaries . . . . .	24
Theory: Entanglement harvesting from conformal vacuums between two Unruh-DeWitt detectors moving along null paths . . . . .	24
Experiments: Large area space interferometry to measure Solar and galactic gravitomag- netism . . . . .	25
Phenomenology: Spacetime-Symmetry Breaking and the Generation of Gravitational Waves . . . . .	25
Parallel 7 . . . . .	25
Phenomenology: Enlightening Cold Dark Matter’s darkest side via a non-minimal coupling . . . . .	25
Parallel 7 . . . . .	26
Theory: Renormalization and unitarity in an higher derivative scalar theory . . . . .	26
Parallel 7 . . . . .	26
Phenomenology: Test of the Second Postulate of Relativity from Gravitational Wave Ob- servations . . . . .	26
Parallel 8 . . . . .	27
Phenomenology: Spectrogram correlated stacking: A time-frequency domain analysis of the Stochastic Gravitational Wave Background . . . . .	27
Parallel 8 . . . . .	27
Theory: Mapping the landscape of gravity theories . . . . .	27
Parallel 8 . . . . .	28
Phenomenology: Orthogonality and transitions between black-hole quasibound states .	28
Gravitational scattering and radiation: from gedanken to real experiments . . . . .	28
Phenomenology of quantum gravity . . . . .	29
Probing new physics on the horizon of black holes with gravitational waves . . . . .	29
Theory: Self gravity affects quantum states . . . . .	29
Theory: On the canonical equivalence of Jordan and Einstein frames . . . . .	29
Theory: Probing the Big Bang with Quantum Fields . . . . .	30

Theory: A Cosmographic distance functional between Celestial Spheres . . . . .	30
Theory: Quantum field corrections to the equation of state of freely streaming matter in the FLRW space-time . . . . .	31
Parallel 8 . . . . .	31
Theory: Lessons from gravitational physics and beyond: how can we rethink space, time and causal order? . . . . .	31
Theory: A quantum-spacetime model with kinematical IR/UV mixing and its phenomenol- ogy . . . . .	32
Theory: On the dynamics of perturbed Black Holes . . . . .	32
Theory: Regular Black Holes in Lorentz-violating Gravity . . . . .	32
Theory: Black-hole evolution in the presence of scalar fields . . . . .	33
Theory: Unveiling Novel Scalarized Black Hole Solutions in Modified Theories . . . . .	33
Theory: Grand canonical ensemble of a d-dimensional Reissner-Nordström black hole space in a cavity . . . . .	33
Theory: Quantum integrable black holes . . . . .	34
Theory: Constructing accelerating NUT black holes . . . . .	34
Theory: Hawking Radiation without Lorentz Invariance . . . . .	35
Theory: The quantum states of the universe in tomographic form . . . . .	35
Theory: Aspects of kinetic screening - UV completion and the two-body problem . . . . .	35
Phenomenology: Non-gaussian gravitational wave backgrounds across the GW spectrum	36
Phenomenology: From regular black holes to horizonless objects: gravitational perturba- tions and detectability . . . . .	36
Phenomenology: Ultraviolet Sensitivity of Peccei–Quinn Inflation . . . . .	36
Phenomenology: Anharmonic effects on the squeezing of axions perturbations . . . . .	37
Phenomenology: Primordial Black Holes during the QCD phase-transition . . . . .	37
Phenomenology: Measuring deviations from the Kerr geometry with black hole ringdown . . . . .	38
Phenomenology: Nonlinear photon-plasma interaction and the black-hole superradiant instability . . . . .	38
Phenomenology: Information paradox and table-top experiments . . . . .	38
### . . . . .	39
### . . . . .	39
### . . . . .	39

### . . . . .	39
### . . . . .	39
### . . . . .	39
LAG- Liquid Actuated Gravity - Snooping Inverse Square Law at $\approx$ cm distance . . . . .	39
### . . . . .	40
### . . . . .	40
### . . . . .	40
Experiments: Status of the GINGER project . . . . .	40
Theory: Noncommutative Correction to Black Hole Entropy . . . . .	40
Welcome SISSA Director, INFN TS Director & SIGRAV President . . . . .	41
Theory: Probing the Big Bang with Quantum Fields . . . . .	41
Theory: Noncommutative Correction to Black Hole Entropy . . . . .	41
### . . . . .	42
Awards Ceremony (Premio Rampa, SIGRAV Prizes, Amaldi Medals) + Group Photo . . . . .	42

1

## Registration and Welcome

3

## Jcap Colloquium-Parity Violation in Cosmology

Parity symmetry is known to be violated in the weak interaction. Do the physical laws behind the unsolved problems of modern cosmology - cosmic inflation, dark matter, and dark energy - also violate parity symmetry? In this talk, we will discuss theoretical and observational possibilities of parity violation in cosmology, a topic that has received much attention in recent years.

5

## Binary Neutron Stars: from macroscopic collisions to microphysics

I will argue that if black holes represent one the most fascinating implications of Einstein's theory of gravity, neutron stars in binary system are its richest laboratory, where gravity blends with astrophysics and particle physics. I will discuss the rapid recent progress made in modelling these systems and show how the gravitational signal can provide tight constraints on the equation of state and sound speed for matter at nuclear densities, as well as on one of the most important consequences of general relativity for compact stars: the existence of a maximum mass. Finally, I will discuss how the merger may lead to a phase transition from hadronic to quark matter. Such a process would lead to a signature in the post-merger gravitational-wave signal and open an observational window on the production of quark matter in the present Universe.

6

## Amplitudes in AdS from conformal field theory

In this talk I discuss a method to study amplitudes in AdS in the context of the AdS/CFT correspondence. In particular I will discuss how to study loop amplitudes by using the holographic CFT counterpart.

Parallel Sessions / 7

###

## Parallel Sessions / 8

**Theory: Exploring Conserved Charges in General Relativity Using Covariant Phase Space****Corresponding Author:** gloria.odak@gmail.com

In this talk, we delve into the application of the covariant phase space formalism to the study of conservation laws in General Relativity. Our focus is twofold: firstly, we demonstrate the association of the Carter constant with a genuine conserved Noether charge, utilizing the powerful tool provided by the covariant phase space. Secondly, we explore the dependence of the construction of Brown-York charges on the choice of conservative boundary conditions, including Dirichlet, Neumann, and York's mixed boundary conditions defined by holding fixed the conformal induced metric and the trace of the extrinsic curvature. The procedure also suggests a new integrable charge for the Einstein-Hilbert Lagrangian, different from the Komar charge for non-Killing and non-tangential diffeomorphisms. We study how the energy depends on the choice of boundary conditions, showing that both the quasi-local and the asymptotic expressions are affected.

## Parallel Sessions / 9

**Theory: On the classification of Generalized Quasitopological Gravities****Corresponding Author:** angelmurcia20@gmail.com

Generalized Quasitopological Gravities (GQTGs) are higher-order extensions of Einstein gravity in  $D$  dimensions satisfying a number of interesting properties, such as possessing second-order linearized equations of motion on top of maximally symmetric backgrounds, admitting non-hairy generalizations of the Schwarzschild-Tangherlini black hole which are characterized by a single metric function or forming a perturbative spanning set of the space of effective theories of gravity. In this work, we classify all inequivalent QTGs at all curvature orders  $n$  and spacetime dimension  $D \geq 4$ . This is achieved after the explicit construction of a dictionary that allows the uplift of expressions evaluated on a single-function static and spherically symmetric ansatz into fully covariant ones. On the one hand, applying such prescription for  $D \geq 5$ , we find the explicit covariant form of the unique inequivalent Quasitopological Gravity that exists at each  $n$  and, for the first time, the covariant expressions of the  $n-2$  inequivalent proper QTGs existing at every curvature order  $n$ . On the other hand, for  $D=4$ , we are able to provide the first rigorous proof of the fact that there is one and only one (proper) inequivalent QTG at each curvature order  $n$ , deriving along the way a simple expression for such four-dimensional representative at every order  $n$ .

## Parallel Sessions / 10

**Theory: On the nature of Bondi-Metzner-Sachs transformations****Corresponding Author:** gesposito@na.infn.it

This work investigates, as a first step, the four branches of BMS

transformations, motivated by the classification into elliptic, parabolic, hyperbolic and loxodromic proposed a few years ago in the literature. We first prove that to each normal elliptic transformation of the complex variable  $z$  used in the metric for cuts of null infinity, there is a corresponding BMS supertranslation. We then study the conformal factor in the BMS transformation of the  $u$  variable as a function of the squared modulus of  $z$ . In the loxodromic and hyperbolic cases, this conformal factor is either monotonically increasing or monotonically decreasing as a function of the real variable given by the modulus of  $z$ . The Killing vector field of the Bondi metric is also studied in correspondence with the four admissible families of BMS transformations. Eventually, all BMS transformations are re-expressed in the homogeneous coordinates suggested by projective geometry. It is then found that BMS transformations are the restriction to a pair of unit circles of a more general set of transformations. Within this broader framework, the geometry of such transformations is studied by means of its Segre manifold.

#### Parallel Sessions / 11

### Theory: Can General Relativity Play a Role in Galactic dynamics?

**Corresponding Author:** [matteoluca.ruggiero@unito.it](mailto:matteoluca.ruggiero@unito.it)

There have been some recent claims about the impact of general relativistic corrections on the dynamics of galaxies, with possible implications for their dark matter content. We examine and analyze the proposed models to discuss their reliability and limitations. Then, we focus on the properties of an exact solution of Einstein's equations describing a self-gravitating system, made of dust, distributed with axial symmetry and in stationary rotation, and discuss its non-Newtonian behavior: we suggest that if this system can be used as simplified model for a galaxy, its dynamics, i.e. the rotation curves, can be determined by peculiar relativistic effects.

#### Parallel Sessions / 12

### Theory: Primordial fluctuations from quantum gravity

**Corresponding Author:** [fvidotto@uwo.ca](mailto:fvidotto@uwo.ca)

In modern cosmology there is an agreement that the seeds of structure formations reside in the quantum fluctuation of the geometry in the early universe, but there is no agreement about how these could be derived from a quantum theory of gravity. In this talk I present a proposal based on the covariant formulation of Loop Quantum Gravity. I describe how to define a wavefunction of the universe in this context, and how we can study fluctuations and correlations between spacial regions. The results obtained so far has been made possible by recent progress in numerical computations. I discuss the current state of this research program and the possible implications for modeling the early universe.

#### Parallel Sessions / 13

## Theory: Scale-invariant inflation

**Corresponding Author:** chiara.cecchini@unitn.it

Fundamental scale invariance has been proposed as a new theoretical principle beyond renormalizability. Besides its highly predictive power, a scale-invariant formulation of gravity could provide a natural explanation for the long-standing hierarchy problem and interesting applications in cosmology.

We present a globally scale-invariant model of quadratic gravity and study its solutions in a spatially flat Robertson-Walker metric. The system admits a dynamical flow from an unstable to a stable fixed point, where scale symmetry gets spontaneously broken, and a mass scale —the Planck mass —is classically generated. This trajectory is compatible with an arbitrarily long stage of inflation which is investigated both at the classical level and at first order in perturbation theory. We further consider the possibility of generating primordial magnetic fields in this context.

Parallel Sessions / 14

## Theory: Bianchi-I cosmologies, magnetic fields and singularities

**Corresponding Author:** kamenshchik@bo.infn.it

We study the effects of a spatially homogenous magnetic field in Bianchi-I cosmological models. In particular, we review the case of a pure magnetic field and two models with dust and a massless scalar field (stiff matter), respectively. For all these cases, we analyse the approach to the singularity in some details and comment about the issue of the singularity crossing.

Parallel Sessions / 15

## Phenomenology: Detection and measurement prospects at the Einstein Telescope: forecasts with GWFAST

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The detection of gravitational waves in 2015, thanks to the LIGO and Virgo interferometers, opened a new window on our Universe. The discoveries during the first three observing runs already had an extraordinary impact on both astrophysics, cosmology, and fundamental physics.

The GW community is now looking at the next long-prepared step: ‘third-generation’ detectors. Thanks to an increase of more than one order of magnitude in sensitivity and a larger bandwidth, Einstein Telescope (ET) and Cosmic Explorer (CE) will have an outstanding potential, capable of triggering fundamental discoveries.

Assessing the capabilities of these extraordinary instruments, which can detect hundreds of thousands of sources per year, is a crucial aspect to make informed decisions. In this talk, after a general overview, I will present recent results of the capabilities of ET alone, and a network made by ET and two CE detectors, obtained using the GWFAST code and focusing in particular on the accuracy in the reconstruction of the parameters of both binary black hole, binary neutron star and neutron star–black hole systems. If time allows, I will further focus on the prospects at ET for more specific science cases, namely high redshift sources and nuclear physics.

## Parallel Sessions / 16

## Experiments: Anomalies and open issues of the MICROSCOPE Space Test of the Weak Equivalence Principle

**Corresponding Author:** [anna.nobili@unipi.it](mailto:anna.nobili@unipi.it)

MICROSCOPE's final results report no violation of the Weak Equivalence Principle (Universality of Free Fall) for Pt and Ti test masses quantified by an Eötvös parameter  $\eta \sim 10^{-15}$ , an improvement by about two orders of magnitude over the best ground tests. The measurement is limited by random noise with  $1/\sqrt{f}$  frequency dependence attributed to thermal noise from internal damping occurring in the grounding wires. From information available and the physics of internal damping we calculate the differential acceleration noise spectral density at the signal frequency, and show it varies widely between experiment sessions. Such large variations are inexplicable if translated into physical quantities such as the quality factor. While calibrations interspersed with measurement sessions may cause some such changes, they cannot explain jumps between consecutive sessions without recalibration. A potential explanation is conjectured related to a fluctuating zero depending on measurement initialization errors. The experiment was severely affected by "glitches"—anomalous acceleration spikes related to radiation from the Earth—injecting significant power at the signal frequency and its harmonics. The procedure used to deal with the glitches depends on introducing artificial data and leaves spurious effects potentially mimicking a violation signal or canceling a real one. An alternative procedure, relying only on real measured data, is proposed, already used in ground tests of the Weak Equivalence Principle by the Eöt-Wash group. Future experiments aiming to exploit the full potential of space must resolve these issues, rely solely on measured data, and, more generally, readdress the experiment design.

## Parallel Sessions / 17

## Phenomenology: Parameter estimation of binary black holes in the endpoint of the up-down instability

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Black-hole binary spin precession admits equilibrium solutions corresponding to systems with (anti-) aligned spins. Among these, binaries in the up-down configuration, where the spin of the heavier (lighter) black hole is co- (counter-) aligned with the orbital angular momentum, might be unstable to small perturbations of the spin directions. The occurrence of the up-down instability leads to gravitational-wave sources that formed with aligned spins but are detected with precessing spins. We present a Bayesian procedure based on the Savage-Dickey density ratio to test the up-down origin of gravitational-wave events. This is applied to both simulated signals, which indicate that achieving strong evidence is within the reach of current experiments, and the LIGO/Virgo events released to date, which indicate that current data are not informative enough.

## Parallel Sessions / 18

## Experiments: ISA accelerometer on-board BepiColombo mission during first Mercury swing-bys – Preliminary observations

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## Parallel Sessions / 19

**Phenomenology: Multiscale dynamics of eccentric and precessing binary black holes****Corresponding Author:** g.fumagalli47@campus.unimib.it

Understanding the dynamics of binary black holes is crucial to extract information from gravitational-wave data. By now, a consistent amount of effort has been put into exploring the phenomenology of black-hole binaries in the Post-Newtonian regime that evolve on quasi-circular orbits and undergo spin precession. We present substantial advances in this area using a multi-timescale approach to the binary dynamics. In particular, this includes a reparametrization of spin precession that is regular across the entire parameter space, an innovative numerical implementation that is orders of magnitude faster, and an initial exploration of the interplay between spin precession and eccentricity.

## Parallel Sessions / 20

**Parallel 3**

## Parallel Sessions / 21

**Phenomenology: Anisotropic Neutron Stars: Exploring Quasinormal Modes in Full General Relativity****Corresponding Author:** smondal@imsc.res.in

The discovery of the Hulse Taylor pulsar gave indirect evidence of gravitational waves, but recent groundbreaking direct detection of gravitational waves by LIGO-VIRGO collaboration opened a new window to look at the celestial entities and cosmos. In this work we focus on exploring the impact of local anisotropic pressure on the quasinormal modes of neutron stars in the framework of general relativity. Prior research has been conducted in this particular area; however, all previous studies have either relied on a Newtonian framework or utilized the Cowling approximation, in which metric perturbations are assumed to be negligible. These considerations, however, do not provide a complete picture of the oscillation characteristics of anisotropic compact stars, as the general relativistic framework also allows us to obtain the damping time of the oscillation, which is crucial for understanding the gravitational waves that the anisotropic compact stars emit. According to theoretical research, anisotropy can develop in neutron stars as a result of a number of circumstances, including high density, the presence of a magnetic field, superfluidity, pion condensation, and a number of others. The discovery of both high-mass and low-mass stars in recent findings further strengthens the supporting evidence regarding the existence of anisotropy in neutron stars. This study focuses on deriving the governing equations for metric perturbations and fluid perturbations from the linearized Einstein equations and conservation of energy-momentum tensor. Specifically, we have employed the Regge-Wheeler gauge to derive the equations for the polar mode of oscillations, while also considering the anisotropy present in neutron stars. In conducting this study, we have incorporated realistic equation of states and utilized an ansatz that accounts for anisotropy with astrophysical significance. We have demonstrated how the mode frequencies and damping times vary with changes in the strength of anisotropy within the system, taking into account observables such as the total mass of the star and the gravitational redshift. This analysis provides a distinctive approach to detect and characterize anisotropy in compact stars, offering valuable insights into the nature of these celestial objects. We have also explored the influence of the equation of state's stiffness on the quasinormal modes of neutron stars in the presence of anisotropy.

## Parallel Sessions / 22

## Experiments: Fundamental Physics with GNSS satellites and the Galileo for Science Project

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Agency (ASI) that aims to provide Fundamental Physics measurements with the Galileo-FOC constellation of the Global Navigation Satellites System (GNSS). The measurements concern both the analysis of satellite orbits and of their atomic-clocks data. A new accurate analysis of the satellites onboard atomic-clocks can lead to the following significant results: i) measuring the gravitational redshift and, consequently, making a local position invariance (LPI) test, and ii) searching for possible Dark Matter candidates in the form of Domain-Wall of Galactic origin. Conversely, precise orbit determination (POD) of satellites allows the relativistic precessions of satellite orbits to be measured at a much higher altitude than previous measurements with passive geodetic satellites such as LAGEOS, LAGEOS II and LARES.

The two satellites GSAT-0201 (Doresa) and GSAT-0202 (Milena) in elliptical orbits will be exploited for the measurement of the gravitational redshift, as the on-board atomic clocks frequency is periodic-modulated with respect to on-ground clocks. Whereas for the Dark Matter constraints, the entire Galileo constellation will be considered: the goal is searching for interactions with possible Dark Matter candidates, such as Domain Walls, that would cross the whole constellation. If this happens, on-board clocks would impulsively change their frequency relative to a reference clock on Earth. Finally, measuring the relativistic precessions will allow us to study possible deviations from General Relativity by comparing its predictions with those of other theories of gravitation.

To pursue the goals of G4S\_2.0 project, a fundamental key point in our analysis is obtaining the satellite's position as a product of the POD. As a consequence, modeling, as better as possible, the complex effects of the Non-Gravitational Perturbations (NGPs), such as the direct solar radiation pressure, is essential. Many of our efforts go in this direction. The state of the art will be presented, both as regards the Fundamental Physics measurements and the development of new models for the NGPs.

## Parallel Sessions / 23

## Phenomenology: Computation of stochastic background from extreme mass ratio inspiral populations for LISA

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Extreme mass ratio inspirals (EMRIs) are among the primary targets for the Laser Interferometer Space Antenna (LISA). The extreme mass ratios of these systems result in relatively weak GW signals, that can be individually resolved only for cosmologically nearby sources (up to  $\sim 2$ ). The incoherent piling up of the signal emitted by unresolved EMRIs generate a confusion noise, that can be formally treated as a stochastic GW background (GWB). In this paper, we estimate the level of this background considering a collection of astrophysically motivated EMRI models, spanning the range of uncertainties affecting EMRI formation. To this end, we employed the innovative \textit{Augmented Analytic Kludge} waveforms and used the full LISA response function. For each model, we compute the GWB SNR and the number of resolvable sources. Compared to simplified computations of the EMRI signals from the literature, we find that for a given model the GWB SNR is lower by a factor of  $\approx 2$  whereas the number of resolvable sources drops by a factor 3-to-5. Nonetheless, the vast majority of the models result in potentially detectable GWB which can also significantly contribute to the overall LISA noise budget in the 1-10 mHz frequency range.

## Parallel Sessions / 24

## Experiments: METRIC: a mission concept for upper atmosphere mapping, gravitational physics and geodesy

**Corresponding Author:** roberto.peron@inaf.it

We describe here a mission concept - called METRIC (Measurement of EnvironmenTal and Relativistic In-orbit preCessions) - for a spacecraft to be placed in a low Earth orbit, with dedicated instrumentation to provide data useful for atmospheric science, fundamental physics and geodesy. The main scientific objectives are: map the atmospheric density by in-situ acceleration measurement and by spacecraft tracking at altitudes of great interest for satellites deorbiting; perform fundamental physics tests through a precise orbit determination and verification of the equation of motion for a well-characterized test mass; provide an additional, space-based, node to improve the tie among different space geodesy techniques. These three areas being distinct but strongly interrelated in the case of Earth System science, it appears that they can benefit from the availability of a well-calibrated space-based platform such as the one being proposed. Following a discussion of the scientific objectives, the mission idea will be described with a baseline for spacecraft configuration, scientific instruments and data analysis strategies.

Parallel Sessions / 25

## Phenomenology: Glitch systematics on the observation of massive black-hole binaries with LISA

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Detecting and coherently characterizing thousands of gravitational-wave signals is a core data-analysis challenge for the Laser Interferometer Space Antenna (LISA). Transient artifacts, or “glitches”, with disparate morphologies are expected to be present in the data, potentially affecting the scientific return of the mission. We present the first joint reconstruction of short-lived astrophysical signals and noise artifacts. Our analysis is inspired by glitches observed by the LISA Pathfinder mission, including both acceleration and fast displacement transients. We perform full Bayesian inference using LISA time-delay interferometric data and gravitational waveforms describing mergers of massive black holes. We focus on a representative binary with a detector-frame total mass of  $6 \times 10^7 M_\odot$  at redshift 5, yielding a signal lasting  $\sim 30$  h in the LISA sensitivity band. We explore two glitch models of different flexibility, namely a fixed parametric family and a shapelet decomposition. In the most challenging scenario, we report a complete loss of the gravitational-wave signal if the glitch is ignored; more modest glitches induce biases on the black-hole parameters. On the other hand, a joint inference approach fully sanitizes the reconstruction of both the astrophysical and the glitch signal. We also inject a variety of glitch morphologies in isolation, without a superimposed gravitational signal, and show we can identify the correct transient model. Our analysis is an important stepping stone toward a realistic treatment of LISA data in the context of the highly sought-after “global fit”.

Parallel Sessions / 26

## Experiments: Galactic Dark Matter from General Relativity

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General relativistic models of disc galaxies can provide non negligible corrections with respect the Newtonian description, for the rotation speeds and their relationship to the required gravitational mass. This result can be counterintuitive, for an object with sub-relativistic speeds such as a galaxy;

but General Relativity (GR) does not only provide higher order, post-Newtonian corrections to gravitational dynamics. Indeed, GR is a richer theory, which also includes totally non-Newtonian phenomena.

In particular, in the stationary and axisymmetric case, solitonic solutions are admitted for the dragging speed, i.e. the off diagonal term of the metric. The dragging may therefore be a quantity of order  $v/c$ , unlike the dragging effect generated by the well-known gravitomagnetism, which is much weaker. Such a “strong dragging” would sustain a flat rotation curve in the halo of a galaxy, in front of a smaller galaxy mass.

We propose different techniques to empirically observe the possible presence of the strong dragging, in our Galaxy or in some distant ones. The strong dragging is mathematically allowed and, if present in real galaxies, may provide a partial explanation for some fraction of the galactic dark matter (DM). Such a discovery would lead to re-evaluation of the quantity and characteristics of the DM, improving the future experiments to find it.

Parallel Sessions / 27

## Phenomenology: Characterizing Burst with Linear Memory Events with LIGO-Virgo-KAGRA and Pulsar Timing Array Observatories

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Close hyperbolic encounters of black holes (BHs) generate certain Burst With Memory (BWM) events in the frequency windows of the operational, planned, and proposed gravitational wave (GW) observatories. We provide details of our HyperbolicTD & GW\_hyp packages that should allow both LIGO-Virgo-KAGRA (LVK) and Pulsar Timing Array (PTA) consortia to search for such BWM events in their respective datasets.

Further, we present detailed explorations of the detectable parameter space of such events, relevant to these collaborations.

Preliminary investigations reveal that optimally placed BWM events should be visible to megaparsec distances for the existing ground-based observatories. In contrast, maturing PTA datasets should be able to provide constraints on the occurrences of hyperbolic encounters between supermassive BHs to gigaparsec distances. Some preliminary findings from our ongoing injection studies using simulated LVK and PTA datasets will be provided.

Parallel Sessions / 28

## Parallel 7

Parallel Sessions / 29

## Phenomenology: AGILE search of gamma-ray electromagnetic counterparts of gravitational waves

AGILE is an Italian Space Agency (ASI) space mission devoted to gamma-ray observations in the 30 MeV - 50 GeV energy range, with simultaneous X-ray imaging in the 18-60 keV band. Launched in April 2007, the AGILE satellite, with more than 16 years of observation in orbit, is substantially contributing to improve our knowledge of the gamma-ray sky. Thanks to its very fast ground segment alert system, AGILE observations have provided the

fastest response and the most significant upper limits in the energy range above 100 MeV to the first detected gravitational wave event GW150914 by the LIGO-Virgo Collaboration, and to all other GW events detected up to now, including the famous BNS event GW170817. AGILE is actively involved in the hunt for high-energy electromagnetic counterparts of GW during the current LIGO-Virgo-Kagra (LVK) O4 observing run, started in May, 2023.

## Parallel Sessions / 30

### Experiments: Status of the GINGER project

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The measurements of the Earth rotation rate variations, certainly important for Earth science, are relevant also for fundamental physics investigation, as they contain general relativity terms, such as de Sitter and Lense Thirring, and they provide unique data to investigate Lorentz violations. Long term continuous operation and very high sensitivity are required, the limit to be reached to study fundamental physics is 1 part in  $10^9$  of the Earth rotation rate. Present high sensitivity ring laser gyroscopes have record sensitivity for absolute angular rotation, and have already proved the required sensitivity.

The GINGER project is based on an array of ring lasers, the plan is to install it inside the Gran Sasso laboratory at the end of 2024 and start taking data in 2025.

32

### Advance Virgo+ Quantum Noise Reduction system for O4

One of the fundamental noise in gravitational waves detectors is the so called Quantum Noise, that is related to the intrinsic quantum nature of the laser used to interrogate the GW interferometers, i.e. to the uncertainty on amplitude and phase of the coherent state of light that couples with the vacuum fluctuations. Due to the frequency dependent opto-mechanical response of the GW detectors, the amplitude and phase fluctuations is weighted in different way in the detectors frequency band, leading to the so called Radiation Pressure Noise (RPN) at low frequency and to the so called Shot Noise (SN) at high frequency, respectively. By injecting frequency independent squeezed (FIS) vacuum light into the dark port of the GW interferometer a significant reduction of the SN can be and has been observed during the last observations runs, both for Advance Virgo and the two LIGO detectors. Nevertheless the big effort done to reduce in parallel one of the most sensitivity limiting noise in the low frequency region, the technical noise, has revealed the main drawback of the FIS injection: the increasing of the RPN at low frequency.

Moreover, even without FIS injection, the improvement of the low frequency sensitivity for the new upgraded detectors, in any case leads to the need of the quantum noise mitigation in the whole detectors band. For this reason FIS injection has been replaced with frequency dependent squeezed vacuum (FDS). For the current observation run, both Virgo and LIGO collaboration prepared FDS injection. The technique to produce it is based on the phase sensitive response of a filter cavity that allows the squeezing ellipse rotation in the detectors frequency band.

Here, after a general introduction to the QN and the FDS technique, we will present the status of the Quantum Noise Reduction system for the FDS injection into Adv+.

33

### Assemblea dei Soci (in Italian, reserved to SIGRAV members)

34

## **Black hole spectroscopy**

One of the most remarkable possibilities of General Relativity concerns gravitational collapse to black holes. Is the strong field dynamical regime of gravity well described by General Relativity? I will summarize the status of black hole spectroscopy and attempts at probing near horizon physics.

35

## **Telescopes on the Moon: the next decades**

I will review the prospects for future progress in cosmology. The lunar surface allows a unique way forward, to go well beyond current limits. The far side provides a unique radio-quiet environment for probing the dark ages via 21 cm interferometry to seek elusive clues on the nature of inflation via the infinitesimal fluctuations that seeded galaxy formation. Far-infrared telescopes in cold and dark lunar polar craters will probe the cosmic microwave background radiation back to the first months of the Big Bang.

36

## **Einstein Telescope and the next generation GW observatories: science, technologies and perspectives**

A new generation of gravitational wave (GW) observatories will pick up in the next decade; it will be the legacy of the current generation of GW detectors, Advanced LIGO and Advanced Virgo, allowing the exploration of almost the entire Universe through GW signals. Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in US are the pioneer projects aiming to the realisation of a 3rd generation Gravitational Wave Observatory. Benefiting of the momentum given by the scientific successes of the LIGO and Virgo detectors, ET had, in the last few years, important boosts toward its realisation entering in several national and international roadmaps and receiving the support of many European agencies. ET and CE, working together and/or standalone, will be simultaneously new discovery and precision measurement observatories; they have a rich variety of scientific and multidisciplinary targets in astrophysics, nuclear physics, fundamental physics and cosmology. In fact, for example, ET aims to investigate almost the whole Universe, up to the dark ages, through the coalescence of stellar and intermediate mass black holes; it will detect and measure in great detail the gravitational wave signal generated by hundreds of thousands coalescences of neutron stars per year, revealing the nuclear physics governing this kind of stars. ET will be also a technological challenge: in order to achieve the expected sensitivity a new underground research infrastructure will be realised, a multi-interferometer per detector design will be implemented hosting new or updated technologies studied to reduce the noises limiting the current detectors. An overview of the ET observatory science targets, of the observatory design, of the needed technologies and project organisation, will be presented.

37

## **Tests of theories of gravitation in their weak-field and slow-motion**

## limit with laser-tracked satellites

**Corresponding Author:** david.lucchesi@inaf.it

The geodynamic satellites LAGEOS (NASA, 1976), LAGEOS II (ASI/NASA, 1992) and LARES (ASI, 2012) were taken as test masses and their motions were carefully studied and compared with that of a time-like geodesic of General Relativity (GR). This allowed to obtain a series of significant results in the study of the gravitational interaction in the so-called weak-field and slow-motion (WFSM) limit of GR. In this limit, Einstein's equations reduce to a form quite similar to those of electromagnetism, with a gravitoelectric field produced by masses, analogous to the electric field produced by charges, and a gravitomagnetic field produced by mass-currents, analogous to the magnetic field produced by electric currents. These fields are at the origin of two non-classical precessions of the orbit of an artificial satellite. The first precession is due to the mass of the Earth, it is known as Schwarzschild's or Einstein's precession of the orbit. This is a spin-independent secular precession. The second precession is due to the angular momentum (or spin) of the Earth, it is known as the Einstein-Thirring-Lense secular precession of the orbit. The latter is a spin-orbit effect, also known as frame-dragging, and it is related with intrinsic gravitomagnetism.

The precise and accurate measurement of these two precessions has not only allowed to verify the predictions of the GR but also to place significant constraints on the predictions of some alternative theories of gravitation. These theories may be both metric and non-metric in their consequences. A very interesting aspect in the verification of the gravitational interaction is represented by the possible existence of new long-range interactions. This kind of effect in gravitation has some importance since it cannot be interpreted within the standard Parametrized Post-Newtonian (PPN) formalism currently used in the WFSM limit of GR. Indeed, deviations of the gravitational potential from the Newtonian law would lead to new weak interactions between macroscopic objects that are predicted by several theories of gravity. For these theories, a Yukawa-like parameterization seems general at the lowest order of the interaction and in the non-relativistic limit, independently of the nature of the new field that contributes to mediate the gravitational interaction, that is, of a possible scalar, vector or tensor field.

As already underlined, the main goal is to verify the motion of each test mass along a geodesic of spacetime by means of a very precise determination of their orbits. In this regard, the challenge is represented by a reliable modeling of the main gravitational and non-gravitational perturbations (NGPs) acting on the considered satellites. Indeed, both types of perturbations can have a negative impact in the measurements. Mismodeling of gravitational perturbations, especially of the even zonal harmonic coefficients, can completely mask the tiny relativistic precessions due to GR because of their much larger classical precession of the orbit. Conversely, NGPs are very complicated to model and have a periodic impact in the orbital elements, with very long period perturbations superimposed on the relativistic precessions making their measurement extremely complicated.

Some of these activities were carried out in a previous experiment called LARASE (LAsER RAnged Satellite Experiment, 2013-2019), while others are currently performed in a new experiment called SaToR-G (Satellite Test of Relativistic Gravity), both funded by the National Scientific Committee 2 (CSN2) of the National Institute for Nuclear Physics (INFN).

The results achieved by the two experiments will be presented in the measurement of the main relativistic precessions in the orbits of the satellites together with the consequent limits obtained in several theories of gravitation alternative to GR. These constraints may concern metric theories of gravitation  $\boxtimes$  such as scalar-tensor theories  $\boxtimes$  and non-metric theories of gravitation  $\boxtimes$  such as torsional theories. Finally, the prospects for ongoing and future measurements of the gravitational interaction in the field of the Earth with laser-ranged satellites will be presented.

39

## Gravitation and Cosmology

I will review the main steps, both theoretical and experimental, which led the so-called  $\Lambda$ CDM model to be both useful and successful. I will briefly mention the tensions among different cosmological observations. Finally I will discuss the perspectives of space-born missions and ground-based experiments to test the inflationary scenario via the possible detection of the B-modes of the Cosmic Microwave polarized Background.

40

## The black hole mass function and merger rate across cosmic time

With nearly one hundred gravitational-wave events observed by LIGO and Virgo, the mass function of binary black holes starts revealing a number of features. While the most common primary black hole mass is about 8-10  $M_{\text{sun}}$ , the data show an excess at  $\sim 35 M_{\text{sun}}$  and a long tail extending out to 90  $M_{\text{sun}}$ . Such features must encode the formation history of binary black holes, but their analysis has brought us more questions than answers. In my talk, I discuss several possible scenarios for the emergence of these features, based on novel semi-analytic models of binary evolution and star cluster dynamics. Furthermore, I will show that the merger rate density of binary black holes contains crucial information to explain the formation of such extreme systems as a function of redshift. In particular, metal-poor and metal-free stars are the key progenitors of binary black hole mergers in the early Universe, which will be the target of next-generation ground-based detectors.

41

## Plenary talk II

42

## Gluing, black holes, and all that

I will review recent progress on gluing methods for constructing solutions of the Einstein equations, and other progress in mathematical general relativity

43

## Searching for dark energy off the beaten track

Most of our attempts towards understanding dark energy (DE) have focused on using standard cosmological observations to probe its gravitational signatures, and in particular its equation of state. However, there is potentially a lot to be learned about DE by getting off the beaten track. This talk will discuss the results of my work in this direction over the past 5 years, which include developing

new terrestrial searches for non-gravitational signatures of DE and new ultra-light particles, as well as cosmological and astrophysical tests of DE based on new non-standard probes.

44

## **Shift symmetry in the dark sector**

The standard model of cosmology is a very successful effective tool to describe our Universe. However, there are theoretical and observational motivations to explore different fundamental paradigms for the dark sector. Assuming shift symmetry and minimally coupling to gravity as guiding principles, I will argue that one should go beyond the simplest scalar field case to find interesting phenomenology. Following this spirit, I will present some results obtained in two different scenarios: dark energy modelled with Kinetic Gravity Braiding and a dark sector invariant under transverse diffeomorphisms.

45

## **Gravitational charges on null hypersurfaces**

We review the Wald-Zoupas prescription for gravitational charges at future null infinity, and its recent application to null hypersurfaces at finite distance and to non-expanding horizons. We highlight the importance of anomalous transformations in the phase space introduced by background structures, and how they help explaining a tricky step in the original Wald-Zoupas paper, clarify the relation between those charges and Noether charges, and enter the flux-balance laws of gravitational waves. We then present a modified set of charges at finite distance with better conservation properties, and comment on proposed extensions of the phase space at future null infinity and at finite distances.

46

## **Plenary talk III**

47

## **Social Trip to Aquileia (from Via Beirut-Return to Piazza Oberdan)**

Parallel Sessions / 48

## **Theory: Bouncing and emergent cosmology from Dark Energy with an unstable de Sitter vacuum**

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Dark energy (DE) typically violates the same energy conditions that imply cosmological singularities, hence a DE that dominates at high energy can produce a singularity-free cosmology. If the DE conservation equation admits a high-energy fixed point, this represents an unstable de Sitter vacuum: for flat and open FLRW models this de Sitter state represents the past attractors for what then is an emergent cosmology; for closed models it give rise to a potential barrier against which they bounce off, expanding after contraction. For a suitable equation of state the DE can have a second low-energy fixed point, representing an asymptotic cosmological constant. The DE dominates at nearly times and produces an accelerated phase, following by a decelerated matter dominated phase, finally accelerating again, producing a qualitatively realistic scenario. If DE and Cold Dark Matter (CDM) are suitably nonlinearly coupled at high energy, the coupling naturally produces a high energy de Sitter phase, with flat and open emergent models and closed models bouncing, with all models possibly ending up in a realistic low energy accelerated phase after standard radiation and matter era. In this talk I illustrate these scenario using qualitative methods for specific DE models, coupled and uncoupled. I end with speculations about the extension of this analysis to Bianchi IX models.

Parallel Sessions / 49

## Phenomenology: Scalar-tensor theories to tackle cosmological tensions

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We investigate different extended scalar-tensor theories of gravity. Particularly, we study the theory in the Jordan frame with different non-minimal coupling, with a standard and non-standard kinetic term, and the impact of a cubic interaction term. The nonminimally coupled scalar field, regulating the gravitational strength, moves around recombination because of its coupling to pressureless matter. This mechanism induces a degeneracy between the non-minimal coupling parameters and the value of the Hubble constant  $H_0$ . Depending on the evolution of the scalar field, regulated by the sign of the kinetic term and by the presence of the Galileon term, these models can lead to a larger or lower value of  $H_0$  compared to the standard  $\Lambda$ CDM model and to different value of  $\Omega_8$ . We explore the joint constraints with publicly available cosmological data, and we forecast the constraints expected by future cosmological observations.

Parallel Sessions / 50

## Experiments: Detecting low-frequency gravitational waves with Pulsar Timing Arrays

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Pulsars are highly-magnetized, rapidly-rotating neutron stars that emit beams of radio waves from their magnetic poles. Due to the misalignment of the magnetic and rotation axes of the pulsar, our radio telescopes on Earth can detect a pulse for each rotation of the pulsar as in the ‘lighthouse effect’. Monitoring those pulses and their arrival times at radio telescopes is called “pulsar timing”. The extreme precision with which millisecond pulsars —the type of pulsars with rotation periods of a few tens of milliseconds— rotate make them the most precise “cosmic clocks” in the universe. Pulsar timing data collected over several months or years allows us to collect information about pulsars such as its period, motion, or interstellar medium characteristics. Pulsar timing also offers the exciting possibility of detecting gravitational waves passing through. Indeed, gravitational waves from astrophysical systems located far away, such as supermassive black hole binaries in distant

galaxy mergers, can distort the spacetime fabric as it passes the pulsar-Earth system. This in turn will change the arrival times of the radio signals emitted by pulsars. Monitoring the arrival times for an array of pulsars over several years could enable us to detect low-frequency gravitational waves, which would be seen as a red noise signal in the pulsar timing residuals. In this talk, we review the principles of Pulsar Timing Arrays, the collaborations and radio telescopes working on GW detection, which include the European Pulsar Timing Array collaboration, the Large European Array for Pulsars project, the Sardinia Radio Telescope and synergy with the Gaia collaboration. Finally, we present recent results, which include the presence of a red noise signal that is common to all pulsars of the array and which is seen by all collaborations, and which could be the signature of a stochastic background of low-frequency gravitational waves. We discuss the steps needed to establish the true nature of this signal.

#### Parallel Sessions / 51

### Theory: Beyond the Casimir Wormholes

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After a brief description of what is a traversable wormhole we describe the connection between traversability and the Casimir effect. With the help of an equation of state we also discuss different form of solutions generated by the Casimir source. Yukawa deformations and the addition of an electromagnetic field to the original energy density are also discussed.

#### Parallel Sessions / 52

### Experiments: The Astrometric Gravitational Arena: principles and applications

This talk aims to present the potential of gravitational astrometry as a tool for peering into the fabric of spacetime exclusively using stellar astrometry. Once prescribed a suitable set of geometries and observers, a multiscale investigation consistent with general relativistic-compliant astrometry allows testing general relativistic scenarios for our Galaxy as well as tiny angular variations induced by passing gravitational waves. Results from the application of the recent Gaia data releases and dedicated simulations confirm the effectiveness of such an astrometric gravitational arena, in particular the role of gravitational dragging in determining the flatness of the galactic rotational curve and the implementation of the observation principle of the astrometric gravitational wave antenna in space, on ground and in connection with PTA. The presentation also intends to be an update of the plenary talk held at the last SIGRAV congress.

#### Parallel Sessions / 53

### Phenomenology: Neural Posterior Estimation with guaranteed exact coverage: the ringdown of GW150914

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I will present the analysis of the ringdown phase of the first detected black-hole merger, GW150914, using a simulation-based inference pipeline based on masked autoregressive flows. We obtain approximate marginal posterior distributions for the ringdown parameters, namely the mass, spin,

and the amplitude and phases of the dominant mode and its first overtone. Thanks to the locally amortized nature of our method, we are able to calibrate our posteriors with injected simulations, producing posterior regions with guaranteed (i.e. exact) frequentist coverage of the true values. For GW150914, our calibrated posteriors provide only mild evidence ( $\sim 2$  sigma) for the presence of an overtone, even if the ringdown is assumed to start at the peak of the amplitude.

#### Parallel Sessions / 54

### Theory: Fundamental decoherence from quantum spacetime

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Quantum properties of spacetime can affect the evolution of quantum systems. We discuss this in a noncommutative spacetime setting, showing that the standard Liouville-von Neumann equation is replaced by a Lindblad equation. This leads to a decoherence mechanism by which pure states can evolve into mixed states. The decoherence time for the evolution of a free particle is used to show that the Planck mass is the maximum allowed mass for elementary quantum systems.

#### Parallel Sessions / 55

### Phenomenology: Observational phenomena on black hole with dark matter dress

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The accretion of dark matter around the black hole could lead to the formation of surrounding halo. Such a dark matter dressed black hole can leave characteristic imprints in the observations including gamma-ray, gravitational lensing and gravitational waves. In this talk, I will talk several observational phenomena on the black hole with dark matter dress.

#### Parallel Sessions / 56

### Experiments: The European Pulsar Timing Array - the pulsar dataset

**Corresponding Author:** golam.shaifullah@unimib.it

I will present the second data release of the European Pulsar Timing Array (EPTA), containing high-precision pulsar timing data for 25 millisecond pulsars collected with five of the largest radio telescopes in Europe as well as the Large European Array for Pulsars. This dataset forms the basis for the gravitational wave searches carried out by the EPTA. I will also present results from the timing analysis and inferences on the individual pulsar properties.

#### Parallel Sessions / 57

### Theory: On the wormhole-warp drive correspondence

**Corresponding Author:** kirill.zatrimaylov@sns.it

As was shown by Ellis in gr-qc/0411096, one can establish a correspondence between the Schwarzschild metric and a particular Natario warp drive metric, making it possible for a warp drive spaceship to cross the black hole horizon. We generalize this result to Morris-Thorne wormholes and demonstrate that wormholes without horizons can be mapped to a different “quasi-Natario” class of metrics with a nonzero intrinsic curvature. We prove that these metrics are nonsingular and admit timelike geodesics, making them a viable alternative to Natario–Alcubierre warp drives. We study whether nonzero intrinsic curvature could help to avoid or alleviate the violation of the null energy condition found in all Natario-type metrics (Santiago, Schuster, Visser). For metrics with horizons, we also discuss the possibility to avoid the destruction of the spacecraft by Hawking radiation if the spacecraft’s design allows it to absorb the radiation and use it as an energy source.

**Parallel Sessions / 58**

## **Experiments: Progress on the Astrometric Gravitational Wave Antennas**

The operational tenets of an antenna for measuring strength and pin-point direction of Gravitational Waves, based on (sub)micro-arcsecond astrometric monitoring of resolved optical pairs, are reviewed before addressing the technologies (including computational) being considered and developed under different initiatives for its realization.

Along with the space option, by far the most promising in terms of flexibility, discovery potential, and complementarity with current or future facilities, an idea for a ground-based facility/precursor is also presented.

Finally, we discuss the implementation of a digital version of the astrometric antenna under development as a post-operation/legacy program to exploit the astrometric time series taken by the Gaia satellite over its 10+ years of operational life to characterize the GW cosmic background and possibly more.

**Parallel Sessions / 59**

## **Phenomenology: Testing black hole eikonal correspondence**

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Adopting geometric-optics approximations in black hole spacetimes enables the construction of a mapping between black hole images and eikonal black hole quasinormal modes (QNMs). More explicitly, the real part and imaginary part of the QNM frequencies correspond to the ring size and the detailed ring structure of the image, respectively. This correspondence may be violated when going beyond general relativity. In this talk, I’ll discuss the possibility of testing this mapping using real black hole observations. We propose a novel method to test the eikonal correspondence via the comparison of two sets of observables from a nonrotating black hole, one extracted from QNM spectra and the other from the lensed photon rings on the image plane. In particular, I’ll demonstrate that the photon ring observables robustly capture the information of the black hole spacetime itself regardless of the surrounding emission models. Therefore, the proposed test of eikonal correspondence can be validated in quite broad scenarios.

**Parallel Sessions / 60**

## Theory: Carrollian and Galilean limits of deformed symmetries in 3D gravity

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Non-Lorentzian kinematical symmetries, especially the ones corresponding to the Galilei or Carroll relativistic limits (i.e., the speed of light taken to infinity or to zero), are nowadays the subject of vigorous investigations. This also concerns (quantum) deformations of such symmetries, described in the formalism of Lie bialgebras and Hopf algebras. The case of 2+1-dimensional spacetime is of particular interest due to the emergence of deformed symmetries already in the classical theory of gravity. Based on the complete classification of deformations of  $(2+1)d$  spacetime isometry algebras, one may derive their Carrollian and Galilean counterparts. In fact, all quantum deformations of (anti-)de Sitter-Carroll algebra are easily obtained via its well-known isomorphism with either Poincaré or Euclidean algebra, while quantum contractions from the (anti-)de Sitter to (anti-)de Sitter-Carroll case lead to (almost) the same results. The analogous contractions from the (anti-)de Sitter to (anti-)de Sitter-Galilei case provide a variety of (or possibly all) coboundary deformations of (anti-)de Sitter-Galilei algebra. Finally, Carrollian and Galilean contractions of deformations of Poincaré algebra lead to coboundary deformations of Carroll and Galilei algebras, which can also be recovered via contractions in the limit of vanishing cosmological constant.

Parallel Sessions / 61

## Phenomenology: Non-ideal GRMHD and compact objects

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I will present the general formalism for including resistive dissipation and mean-field dynamo amplification of magnetic fields in the set of GRMHD equations, needed to simulate numerically the relativistic plasmas in the environment of compact objects. A selection of applications will be discussed, from the exponential growth and saturation of magnetic fields in thick tori around black holes and in post-merger meta-stable supramassive neutron stars, to the first systematic study of the propagation of magnetized relativistic jets in the presence of finite conductivity.

Parallel Sessions / 62

## Parallel 3

Parallel Sessions / 63

## Theory: Casimir wormholes with a scalar field

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We investigate possible manifolds characterizing traversable wormholes under the existence of a scalar field that is minimally coupled to gravity and has a kinetic and a potential energy. The feature of traversability requires the violation of the null energy condition followed by the existence of an exotic matter providing a negative energy density to the system. For this reason, we use a hypothetical Casimir apparatus with walls that are considered either parametrically fixed or radially variable.

## Parallel Sessions / 64

**Parallel 3**

## Parallel Sessions / 65

**Phenomenology: Hunting for two rings in black hole images****Corresponding Author:** raul@sdu.dk

New physics beyond general relativity can modify image features of black holes and increase the separation between photon rings. For horizonless objects, new physics can generate a set of inner photon rings. Both cases motivate the exploration of synthetic images consisting of two rings. The talk will be focused on assessing the detectability of these features using closure quantities, with the (next-generation) Event Horizon Telescope in mind.

## Parallel Sessions / 66

**Theory: Quantum Euler angles and agency-dependent spacetime****Corresponding Author:** peppefabiano@hotmail.com

Quantum gravity is expected to introduce quantum aspects into the description of reference frames. Here we set the stage for exploring how quantum gravity induced deformations of classical symmetries could modify the transformation laws among reference frames in an effective regime. We invoke the quantum group  $U_q(2)$  as a description of deformed spatial rotations and interpret states of a representation of its algebra as describing the relative orientation between two reference frames. This leads to a quantization of one of the Euler angles and to an aspect of agency dependence: space is reconstructed as a collection of fuzzy points, exclusive to each agent, which depends on their choice of reference frame. Each agent can choose only one direction in which points can be sharp, while points in all other directions become fuzzy in a way that depends on this choice. Two agents making different choices will thus observe the same points with different degrees of fuzziness.

## Parallel Sessions / 67

**Phenomenology: Dark Matter in Fractional Gravity I: Astrophysical Tests on Galactic Scales****Corresponding Author:** fbenetti@sissa.it

We explore the possibility that the dark matter (DM) component in galaxies may originate fractional gravity. In such a framework, the standard law of inertia continues to hold, but the gravitational potential associated to a given DM density distribution is determined by a modified Poisson equation including fractional derivatives (i.e., derivatives of non-integer type), that are meant to describe non-local effects. We derive analytically the expression of the potential that in fractional gravity corresponds to various spherically symmetric density profiles, including the Navarro-Frenk-White (NFW) distribution that is usually exploited to describe virialized halos of collisionless DM as extracted from N-body cosmological simulations. We show that in fractional gravity the dynamics of a test particle moving in a cuspy NFW density distribution is substantially altered with respect to

the Newtonian case (i.e., basing on the standard Poisson equation), mirroring what in Newtonian gravity would instead be sourced by a density profile with an inner core. We test the fractional gravity framework on galactic scales, showing that: (i) it can provide accurate fits to the stacked rotation curves of galaxies with different properties; (ii) it can reproduce to reasonable accuracy the observed shape and scatter of the radial acceleration relation (RAR); (iii) it can properly account for the universal surface density and the core radius vs. disk scale-length scaling relations. Finally, we discuss the possible origin of the fractional gravity behavior as a fundamental or emerging property of the elusive DM component.

## Parallel Sessions / 68

### Experiments: The second data release from the European Pulsar Timing Array II. Customised Pulsar Noise Models for Spatially Correlated Gravitational Waves

The subtle imprints that the gravitational wave background (GWB) induces on pulsar timing data are obscured by many sources of noise that occur on various timescales. These must be carefully modelled and mitigated to increase the sensitivity to the background signal. In this talk, I will present novel techniques and methodologies developed for robustly estimating the noise budget in 25 millisecond pulsars (MSPs) used by the EPTA to search for the GWB. The robustness of any GWB detection depends strongly on the reliability of the pulsar noise models and the assumptions that underly them - typically that the noise is a stationary process modeled by a power-law in the Fourier domain. Here I will discuss some initial explorations of possible deviations from these assumptions. We compare the EPTA datasets across several epochs to explore the stationarity of the noise model hyperparameters, and we also investigate the effect of incorporating low radio frequency data from the Indian Pulsar Timing Array collaboration for a common sample of 10 MSPs. We also demonstrate via simulations the ability of the Bayesian codes to recover the correct hyperparameter posteriors, and show that the choice of low-frequency cut-off in the power-law model can lead to a bias in the exponent of the power-law model.

## Parallel Sessions / 69

### Theory: Geometry of the black-to-white hole transition

**Corresponding Author:** fsoltan2@uwo.ca

The Oppenheimer-Snyder model is the prototypical example of black hole formation by gravitational collapse. It predicts that a black hole horizon is formed once a star collapses to within its own Schwarzschild radius. After that, the collapsing matter reaches Planckian densities in a short proper time. What happens next is outside the reach of general relativity, as it involves the quantum behavior of the gravitational field in the strong field regime.

By considering quantum corrections coming from loop quantum gravity I will show how the quantum-corrected Oppenheimer-Snyder model predicts a non-singular black hole interior and a bounce of the collapsing star. However, this model does not take into account the quantum corrections to the physics of the outer horizon. For this reason, starting from the spacetime of the quantum-corrected Oppenheimer-Snyder model, in which the interior trapped region undergoes a transition to an anti-trapped region (passing through an intermediate non-trapped region), I will then construct a spacetime where the outer horizon undergoes a quantum transition from trapping to anti-trapping as well. In this scenario the black hole evolves into a white hole “remnant” living in the future of the parent black hole, in its same asymptotic region and location.

I will derive the metric describing the spacetime in a single coordinate patch and discuss the resulting geometry of the black-to-white hole transition.

## Parallel Sessions / 70

**Experiments: LISA Pathfinder and LISA test-mass charging**

## Parallel Sessions / 71

**Phenomenology: Testing GR with large catalogs: the cosmic variance of hierarchical stacking****Corresponding Author:** [costantino.pacilio@unimib.it](mailto:costantino.pacilio@unimib.it)

Testing the strong gravity regime of general relativity is a primary goal of gravitational wave detectors. While it is expected that corrections to GR are small and unlikely to be identified with individual events, third generation GW detectors will allow to detect tens-of-thousands of events per year. Therefore, they will pave the way to precision tests by carefully stacking all the detected events. In this talk, I address a challenge to hierarchical tests of GR, arising from the fact that we only detect a single, finite-size realization of the population of events. This can induce biases in the outcome of the test, even when a large catalog has been stacked. I will discuss how to statistically account for this effect and avoid false claims of deviations from GR. Finally, I will comment on the prospects of shifting from a Bayesian paradigm to a frequentist approach when testing GR with gravitational waves.

## Parallel Sessions / 72

**Theory: Axially symmetric stationary gravitational perturbations of Kerr black hole — Debye vs Weyl, Lewis, Papapetrou****Corresponding Author:** [d.kofron@gmail.com](mailto:d.kofron@gmail.com)

The axially symmetric stationary gravitational perturbations of Kerr black hole are analyzed (a) within the framework of the Debye potentials as well as (b) a perturbations of Kerr black hole within the Weyl, Lewis, Papapetrou class of metrics. We find the exact explicit calibration transformation which is needed to connect the metric perturbations in this approach. We also provide the Debye superpotential for a circular mass current/distribution on the Kerr background.

## Parallel Sessions / 73

**Phenomenology: Testing Planck-scale in-vacuo dispersion with GRB neutrinos****Corresponding Author:** [jackderosis@gmail.com](mailto:jackderosis@gmail.com)

GRB (gamma-ray-burst) neutrinos are excellent probes for testing quantum-gravity-induced in-vacuo dispersion. In this scenario, inspired by quantum gravity research and associated with Lorentz Invariance Violation (LIV), empty quantum spacetime behaves like a dispersive medium affecting the propagation of ultrarelativistic particles, whose speed is affected by energy-dependent Planck-scale corrections.

In a recent study (Nature Astronomy (2023)) we investigated the hypothesis that some astrophysical neutrinos detected by the IceCube observatory might be GRB neutrinos, with their travel times

affected by energy-dependent speed. Our findings provide intriguing indications that these neutrinos might indeed experience a delay relative to the detection time of the GRB, proportional to the neutrino's energy.

**Parallel Sessions / 74**

## **Experiments: Implications of GW searches in the latest data release of the EPTA**

**Corresponding Author:** alberto.sesana@unimib.it

EPTA has been taking data for 25 years and has now uncovered the first hint of a common signal in the data. I will discuss what are the consequences on this results for the astrophysics of supermassive black hole binary, processes in the early universe and specific models of dark matter.

**Parallel Sessions / 75**

## **Theory: Vacuum entanglement in near extremal black holes**

**Corresponding Author:** salvatore.ribisi@gmail.com

The notion of particles is ambiguous in curved spacetimes. This often makes it difficult to explicitly picture the process of Hawking radiation in terms of pair creation of particles (one going to infinity as Hawking radiation and the other falling into the singularity).

I will show how such a difficulty can be circumvented in the case of near extremal black holes in 4d for scale invariant quantum fields. The results presented are expected to be relevant in discussions about information in black hole evaporation.

**Parallel Sessions / 76**

## **Parallel 5**

**Parallel Sessions / 77**

## **Phenomenology: Constraining modifications of black hole perturbation potentials near the light ring with quasinormal modes**

**Corresponding Author:** svoelkel@aei.mpg.de

In modified theories of gravity, the potentials appearing in the Schrödinger-like equations that describe perturbations of non-rotating black holes are also modified. In this talk, we ask how such modifications can be constrained with future, high-precision measurements of quasi-normal modes. We use a perturbative framework that allows one to map modifications of the effective potential, in powers of  $M/R$ , to deviations in the quasi-normal mode spectrum. Using MCMC methods, we recover the coefficients in the  $M/r$  expansion in an “optimistic” scenario where we vary them one at

a time, and in a “pessimistic” scenario where we vary them all simultaneously. In both cases, we find that the bounds on the individual parameters are not robust. However, inspired by WKB theory, we demonstrate that the value of the potential and its second derivative at the light ring can be robustly constrained. These constraints allow a more direct comparison between tests based on black hole spectroscopy and observations of black hole “shadows”.

#### Parallel Sessions / 78

### Theory: To Kerr or not to Kerr?

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This talk is devoted to an examination of the Newman-Janis algorithm’s application to an exact regular static black hole’ solution. We observe that the rotating extension obtained with the NJA cannot be described in terms of the same scalar field energy-momentum tensor, with deviations that are somehow ‘confined’ to a small region. It raises an interesting question about what to trust about candidates rotating regular black hole models.

#### Parallel Sessions / 79

### Phenomenology: A new Paradigm for the Dark Matter Phenomenon

**Corresponding Author:** paolo.salucci@sissa.it

The phenomenon of the Dark matter baffles the researchers: the underlying dark particle has escaped so far the detection and its astrophysical role appears complex and entangled with that of the standard luminous particles. We propose that, in order to act efficiently, alongside with abandoning the current scenario, we need also to shift the Paradigm from which it emerged.

#### Parallel Sessions / 80

### Experiments: The growing population of the relativistic pulsar binaries

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The presentation introduces the growing family of the relativistic binary pulsars, highlighting some of the most recent intriguing outcomes resulting from the observations of these systems. In particular the focus will be on the last news from the investigation of the double-pulsar binary PSR J0737-3039. Finally, the perspectives from continuing the monitoring of these systems with present and future instruments will be also presented.

#### Parallel Sessions / 81

### Theory: Entanglement harvesting from conformal vacuums be-

## **tween two Unruh-DeWitt detectors moving along null paths**

**Corresponding Author:** subhajitbarman.phy@gmail.com

It is well-known that the  $(1+1)$  dimensional Schwarzschild and spatially flat FLRW spacetimes are conformally flat. This work examines entanglement harvesting from the conformal field vacuums in these spacetimes between two Unruh-DeWitt detectors, moving along outgoing null trajectories. In  $(1+1)$  dimensional Schwarzschild spacetime, we considered the Boulware and Unruh vacua for our investigations. In this analysis, one observes that while entanglement harvesting is possible in  $(1+1)$  dimensional Schwarzschild and  $(1+3)$  dimensional de Sitter spacetimes, it is not possible in the  $(1+1)$  dimensional de Sitter background for the same set of parameters when the detectors move along the same outgoing null trajectory. The qualitative results from the Boulware and the Unruh vacuums are alike. Furthermore, we observed that the concurrence depends on the distance  $d$  between the two null paths of the detectors periodically, and depending on the parameter values, there could be entanglement harvesting shadow points or regions.

**Parallel Sessions / 82**

## **Experiments: Large area space interferometry to measure Solar and galactic gravitomagnetism**

**Co-author:** Angelo Tartaglia

**Parallel Sessions / 83**

## **Phenomenology: Spacetime-Symmetry Breaking and the Generation of Gravitational Waves**

**Corresponding Author:** nils.nilsson@obspm.fr

Recently, the search for departures from the symmetries of General Relativity has received significant attention in the literature. In this talk, I outline the techniques for probing the nature of spacetime symmetries using the generation stage of gravitational waves. By using a generic effective-field theory, I show our solution scheme of the modified Einstein equations and I write down the the first Post-Newtonian corrections, which includes contributions from the spacetime-symmetry breaking terms. Focusing on the gravitational two-body problem, I write down a simple toy solution, and it becomes clear that in contrast to General Relativity, the monopolar and dipolar contributions are non-vanishing. We comment on the detectability of such signals by the LISA space mission, which has high signal-to-noise galactic binaries well inside its predicted sensitivity band.

**Parallel Sessions / 84**

## **Parallel 7**

**Parallel Sessions / 85**

## **Phenomenology: Enlightening Cold Dark Matter's darkest side**

## via a non-minimal coupling

**Corresponding Author:** ggandolf@sissa.it

The cold dark matter (CDM) paradigm has proven to be relatively successful on cosmological scales, but struggles in fully describing the observed phenomenology on (sub)galactic scales. In this picture, two long-standing issues are the well-known cusp-core controversy and the existence of several tight scaling laws between dark and baryonic quantities, whose explanation is not trivial in the CDM framework. In this talk, I will entail the possibility that CDM could be dynamically non-minimally coupled to gravity, and how such effect has the potential to solve these issues in a single shot. After outlining the theoretical foundations of the model, I will proceed in discussing quantitative astrophysical results achieved in Gandolfi et al. 2021 and Gandolfi et al. 2022 exploiting this non-minimally coupled DM model. The key findings of our analysis are that a) this model can develop cored dark matter profiles with a shape closely following out to several core scale radii the phenomenological Burkert profile, b) it can accurately fit the rotation curves of different kinds of local spiral galaxies and c) it can consistently reproduce the Radial Acceleration Relation, one of the most general relations characterizing the dark-baryonic interplay.

Parallel Sessions / 86

## Parallel 7

Parallel Sessions / 87

## Theory: Renormalization and unitarity in an higher derivative scalar theory

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Higher derivative theories could give a resolution to the problem of renormalizability of quantum gravity as a quantum field theory. I will describe a simple shift symmetric scalar field model with a higher derivative kinetic term and discuss its main properties concerning unitarity and RG flow. The running of the parameters is found both by calculating the two-point and 4-point amplitudes in perturbation theory with dimensional regularization and by applying the Functional Renormalization Group. The analysis of the scattering amplitude also illustrates the Effective Field Theory phase of the theory, and displays a novel feature of the effective operators disappearing in the ultraviolet. Moreover, I will comment on the strong interactions which happen at high energy in such theory. The lessons learned have implications for Asymptotic Safety and for Quadratic Gravity

Parallel Sessions / 88

## Parallel 7

Parallel Sessions / 89

## Phenomenology: Test of the Second Postulate of Relativity from

## Gravitational Wave Observations

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The second postulate of special relativity states that the speed of light in vacuum is independent of the emitter's motion. The test of this postulate so far remains unexplored for gravitational radiation. We analyzed data from the LIGO-Virgo detectors to test this postulate within the ambit of emission models, where the speed of gravitational waves emitted by a source moving with a velocity  $\beta$  relative to a stationary observer is given by  $\beta' = \beta + \alpha\beta$ , where  $\alpha$  is a constant. We have estimated the upper bound on the 90% credible interval over  $\alpha$  to be  $\alpha \leq 8.3 \times 10^{-18}$ , which is several orders of magnitude more stringent compared to previous bounds obtained from electromagnetic observations. The Bayes' factor supports the second postulate, with very strong evidence upholding the principle of relativity for gravitational interactions.

Parallel Sessions / 90

### Parallel 8

Parallel Sessions / 91

## Phenomenology: Spectrogram correlated stacking: A time-frequency domain analysis of the Stochastic Gravitational Wave Background

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The stochastic gravitational wave background (SGWB) originates from numerous faint gravitational wave (GW) signals arising from coalescing compact binary objects. Based on the currently estimated merger rate, where the binary merger events are Poisson-distributed at any instance, the SGWB signal is expected to originate from non-overlapping GW signals. Current efforts to detect this signal involve cross-correlating the strain from multiple detectors in a generic way. In this talk, we present a novel technique, Spectrogram Correlated Stacking (or SpeCs), which goes beyond the usual cross-correlation (and to higher frequencies) by exploiting the higher-order statistics in the time-frequency domain. This method would account for the chirping nature of the individual events that comprise SGWB and enable us to extract more information from the signal due to its intrinsic non-gaussianity. We show that SpeCs improve the signal-to-noise for the detection of SGWB by a factor close to 8, compared to standard optimal cross-correlation methods which are tuned to measure only the power spectrum of the signal. SpeCs can probe beyond the power spectrum and its application to the GW data available from the current and next-generation detectors would speed up the SGWB discovery.

Parallel Sessions / 92

### Parallel 8

Parallel Sessions / 93

## Theory: Mapping the landscape of gravity theories

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Both Einstein's equations and the field equations of a modified theory of gravity can be derived as equations of state from purely thermodynamical considerations, leading to the identification of GR with an equilibrium state of gravity and modified gravity with a non-equilibrium one. This breakthrough made the relationship between gravity and thermodynamics even more intriguing. I will present a new approach to the thermodynamics of modified gravity which is inspired by these results, but follows a starkly different path. A precise description of the approach to equilibrium naturally emerges from using Eckart's first-order irreversible thermodynamics on the effective imperfect fluid describing scalar-tensor gravity. Applications of this framework to cosmology, extensions to different classes of modified theories, and the formulation of two complementary descriptions based on the notions of temperature and chemical potential all contribute to a new and unifying picture of the landscape of gravity theories GR is embedded in.

Parallel Sessions / 94

### Parallel 8

Parallel Sessions / 95

## Phenomenology: Orthogonality and transitions between black-hole quasibound states

**Corresponding Author:** enrico.cannizzaro@uniroma1.it

It is well known that the response of a black hole (BH) to an external perturbation consists in a series of damped sinusoids, dictated by complex frequencies called quasi-normal modes (QNMs). Massive fields also admit a different family of solutions called quasi-bound states (QBSs). Both families of modes dissipate energy at the BH horizon, and QNMs also radiate at infinity. This dissipation causes the non-Hermiticity of the system, and hence a normal-mode spectral analysis is not possible as the spectral theorem does not guarantee the orthogonality of these modes. In a recent work, we introduced a bilinear form under which scalar, massive QBSs (and massive QNMs) are orthogonal in a Kerr background. This product is obtained in a fully relativistic framework, and reduces to the hydrogenic inner product in the non-relativistic limit. Finally, as a practical application, we showed how this bilinear form allows to compute the excitation of modes due to a perturbation to the BH potential, due e.g. to an extreme-mass-ratio companion.

195

## Gravitational scattering and radiation: from gedanken to real experiments

I will attempt to summarize some 35 years of work on semiclassical gravitational scattering, from the early days of (gedanken) transplanckian-energy collisions of particles and strings, to the recent era of (real) black hole encounters. I will emphasize some interesting lessons that the former problem can provide for the latter, while stressing the danger of claiming too naive a connection between the two regimes.

196

## Phenomenology of quantum gravity

In this talk, I will present an overview of the latest progress in the field of quantum gravity phenomenology, focussing on some of the most relevant features of models where the Planck scale governs deformations of relativistic symmetries and illustrating opportunities for experimental tests. These include astrophysical observations, sensitive to residual signatures at low energies, cosmological observations about primordial perturbations, which are directly influenced by Planck-scale physics, and tests using quantum systems which might be sensitive to Planck-scale decoherence.

197

## Probing new physics on the horizon of black holes with gravitational waves

Black holes are the most compact objects in the Universe. According to general relativity, black holes have a horizon that hides a singularity where Einstein's theory breaks down. Recently, gravitational waves opened the possibility to probe the existence of horizons and investigate the nature of compact objects. This is of particular interest given some quantum-gravity models which predict the presence of horizonless and singularity-free compact objects. Such exotic compact objects can emit a different gravitational-wave signal relative to the black hole case. In this talk, I will give an overview of tests of the nature of compact objects with present and future gravitational-wave observations, including ringdown tests and searches for near-horizon structures with gravitational-wave echoes.

Parallel Sessions / 198

## Theory: Self gravity affects quantum states

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We study how self gravitation of quantum systems affects the quantum coherence present in their state. Spatial superpositions of static, large, heavy systems tend to rapidly lose coherence, whereas light or massless particles are unaffected. Furthermore, large and heavy objects also rapidly localize into a single classical position. The ratio of the characteristic size of the system and its Compton length determines the onset of the effects, which become significant at a timescale that is inversely proportional to the system's gravitational self energy. Our results can explain two important aspects of physical systems: the possibility of coherently placing individual particles or photons in distant positions, and the difficulty of maintaining quantum coherence between massive objects.

Parallel Sessions / 199

## Theory: On the canonical equivalence of Jordan and Einstein frames

**Corresponding Author:** ggionti@specola.va

A longstanding issue is the equivalence between the Jordan and the Einstein frames. It is believed, but not completely proved, that the cosmological physical observables are the same in the two frames. Our aim is to tackle this problem from the perspective of the Hamiltonian formalism. For this reason, we will perform the Hamiltonian analysis of the Brans-Dicke theory with Gibbons-Hawking-York boundary term both in the Jordan and the Einstein frames. Contrary to several claims made in the literature in the past, it will be shown that the transformations from the Jordan to the Einstein frames are not Hamiltonian canonical transformations. We will show that if we perform a gauge fixing on the lapse and shifts functions and implement them as secondary Dirac's constraints in the ADM formalism, the primary first-class constraints will become second class. In this way, we can eliminate these degrees of freedom replacing the Poisson brackets with the Dirac's brackets and solve the second-class constraints. On this reduces phase space, the Hamiltonian transformations from the Jordan to the Einstein frames are Hamiltonian canonical transformations. In our opinion, this does not mean that Jordan and Einstein frames, from Hamiltonian point of view, are physically equivalent. In fact, we have only shown that solutions of the equations of motion in the Jordan frame can generate solutions of the equations of motion in the Einstein frame. Furthermore, we will see that the Jordan Frame is canonically equivalent, under some transformations called anti-Newtonian transformations, to a frame whose solutions, in the limit, behave as Carrollian Gravity.

#### Parallel Sessions / 200

### Theory: Probing the Big Bang with Quantum Fields

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The singularity theorems of Penrose and Hawking are based on geodesic incompleteness and predict the occurrence of classical singularities under rather general circumstances. In general relativity, these singularities represent absolute boundaries where space-time ends.

Physically, however, this criterion refers to the fate of point like classical test particles. We raise the question: What if one uses quantum fields instead? Intuitively, quantum probes are much more fundamental and bear a richer structure. We will begin with the proof that one can unambiguously evolve quantum fields across them in a rigorous sense. Thus when probed with quantum fields, the big bang is not an absolute boundary where physics breaks down. Additionally we will discuss the behavior of composite operators such as the expectation values of renormalized products of fields and the renormalized stress-energy tensor and show that they too remain well-defined as distributions.

The overall conclusion is twofold: first quantum mechanical considerations provide more refined tools to probe classically singular structures, and second, the big bang singularity of classical general relativity is tamer when seen from a quantum perspective.

#### Parallel Sessions / 201

### Theory: A Cosmographic distance functional between Celestial Spheres

**Corresponding Author:** francesca.familiari01@universitadipavia.it

The standard model of cosmology, known as the  $\Lambda$ CDM model, is based on the Friedmann-Lemaître-Robertson-Walker (FLRW) class of models. It successfully describes the energy composition of the universe, with 68.3% attributed to Dark Energy, 26.8% to Dark Matter, and 4.9% to Ordinary Matter. However, it leaves us with the challenge of understanding the nature of the Dark Universe. The model assumes the universe is homogeneous and isotropic, which provides a reasonably accurate description for the present era and scales ranging from about  $\approx 100h-1\text{Mpc}$  to the visual horizon of our past light-cone.

However, as we explore spatial regions within the range of around  $\leq 100h-1\text{Mpc}$ , we observe that the distribution of matter (both dark and visible) becomes highly anisotropic with significant density variations. In standard cosmology, we treat these inhomogeneities as perturbations of a homogeneous background. Yet, if we wish to move beyond perturbation theory and enter a fully relativistic regime, we currently lack precise mathematical tools to understand the actual evolution of space-time.

To address these challenges, an alternative approach to cosmology called the direct observational approach (Cosmographic approach), becomes valuable. This focuses on determining the dynamics of spacetime based on observational data accessible on the past light-cone of the observer, rather than starting with a predefined family of models. By adopting this cosmographic point of view, we can make progress in understanding the quantitative impact of late-epoch inhomogeneities on the global dynamics of the universe.

In this framework, we consider the perspectives of two observers: an ideal Friedmannian observer and a Phenomenological observer. We compare their respective Celestial Spheres by using a shape functional. We show that this procedure provides a rigorous scale-dependent distance between the Friedmannian and the phenomenological light-cones. We can express this functional in terms of observable physical quantities characterizing measurements along our past light-cone, making it, in principle, computable. Finally, the functional may also be interpreted as a scale-dependent effective field which may be of relevance in selecting the FLRW model that best fit the observational data.

#### Parallel Sessions / 202

### **Theory: Quantum field corrections to the equation of state of freely streaming matter in the FLRW space-time**

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We calculate the energy density and pressure of a scalar field after its decoupling from a thermal bath in the spatially flat Friedman-Lemaître-Robertson-Walker space-time, within the framework of quantum statistical mechanics. By using the density operator determined by the condition of local thermodynamic equilibrium, we calculate the mean value of the stress-energy tensor of a real scalar field by subtracting the vacuum expectation value at the time of the decoupling. The obtained expressions of energy density and pressure involve corrections with respect to the classical free-streaming solution of the relativistic Boltzmann equation, which may become relevant even at long times.

We present preliminary numerical and analytical results for the quantum corrections of energy density and pressure for specific expansion rates  $a(t)$ .

#### Parallel Sessions / 203

### **Parallel 8**

#### Parallel Sessions / 204

### **Theory: Lessons from gravitational physics and beyond: how can we rethink space, time and causal order?**

**Corresponding Author:** silvia.debianchi@unimi.it

The first part of this contribution highlights the main results of the ERC project PROTEUS with regard to the conceptual difficulties encountered in current quantum gravity approaches. The second part of the talk is devoted to the discussion of more recent work on the foundations of quantum gravity with emphasis on their impact on the philosophical understanding of space, time and causal order. Perspective research at the intersection of philosophy and cosmology is discussed and current projects and networks are presented, emphasizing the relevance of the study of gravitational waves and its implications.

#### Parallel Sessions / 205

### Theory: A quantum-spacetime model with kinematical IR/UV mixing and its phenomenology

**Corresponding Author:** domenico.frattulillo@unina.it

I present a doubly special relativistic model inspired from the  $k$ -lightlike non-commutative spacetime framework. A kinematical IR/UV mixing mechanism emerges naturally from the deformed energy-momentum dispersion relation, when considering particles with very small speeds. Thus, this model is suited for studying Planck-scale corrections to atom interferometry experiments.

#### Parallel Sessions / 206

### Theory: On the dynamics of perturbed Black Holes

**Corresponding Author:** lenzi@ice.csic.es

Perturbation theory of vacuum spherically symmetric spacetimes is a crucial tool for understanding the dynamics of black hole (BH) perturbations as well as BH scattering phenomena. Since the pioneering work of Regge and Wheeler it is known that the equations for the perturbations can be decoupled in terms of (gauge-invariant) master functions that satisfy  $1 + 1$  wave equations. However, while in the literature only few master equations are known, the full landscape of master equations was recently found, clarifying that Einstein equations actually allows for an infinite set of them. Moreover, it turned out that this is a consequence of the presence of an infinite number of symmetries for the dynamics of perturbed non-rotating BHs. Besides, such symmetries can be associated with the infinite hierarchy of Korteweg-de Vries (KdV) equations. As a consequence, there is also an infinite number of conserved quantities, the KdV integrals. After reviewing the landscape of master equations for BH perturbations and how the KdV integrals naturally arise in this context, we show that these integrals fully determine the BH greybody factors. We exploit the fact that the problem of finding the greybody factors in BH scattering using these conserved quantities can be cast as a moment problem, which has been largely studied during the last century in a wide range of mathematical and physical contexts. There are a number of numerical approaches to tackle the moment problem but a natural semi-analytical solution is given in terms of Padé approximants. The results are compared with previous calculations with the WKB approximation. This whole picture is not restricted to applications to scattering by non-rotating BHs. In fact, it can be used to describe a quite wide variety of physical systems, provided they are described by a Schrodinger equation with a bound state-less potential barrier.

#### Parallel Sessions / 207

### Theory: Regular Black Holes in Lorentz-violating Gravity

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There is growing evidence that Hořava gravity may be a viable quantum theory of gravity. It is thus legitimate to expect that gravitational collapse in the full, non-projectable version of the theory should result in geometries that are free of spacetime singularities. Previous analyses have shown that such geometries must belong to one of the following classes: simply connected regular black holes with inner horizons; non-connected black holes “hiding” a wormhole mouth (black bounces); simply connected or non-connected horizonless compact objects. In this talk, I will describe examples of possible “regularisations” of a (singular) black hole solution in the low-energy limit of non-projectable Hořava gravity, i.e. khronometric theory. Though these examples do not constitute vacuum solutions, their study contributes to shed light on the interplay between singularity removal and broken Lorentz invariance.

**Parallel Sessions / 208**

## **Theory: Black-hole evolution in the presence of scalar fields**

**Corresponding Author:** marco.decesare@na.infn.it

I will present recent analytical results on the evolution of the trapping horizon of a spherically symmetric black hole, as due to the backreaction of scalar radiation on the geometry in the low-frequency approximation. A simple closed-form expression can be derived for the expansion rate of the horizon in terms of initial data for the scalar field on past null infinity. This is obtained by solving the field equations to second order in perturbation theory in the vicinity of the horizon, and using matched asymptotic expansions to compute the evolution of wave packets through the potential barrier.

**Parallel Sessions / 209**

## **Theory: Unveiling Novel Scalarized Black Hole Solutions in Modified Theories**

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This presentation delves into the study of ‘hairy’ black holes within the framework of Einstein scalar Maxwell gravity and Einstein scalar Gauss-Bonnet theories, with a focus on revealing new scalarized black hole solutions. We revisit established scalarization phenomena and venture into new solution territories, particularly highlighting the blend of linear and non-linear scalarization in Einstein Scalar Maxwell gravity. Our goal also includes the identification of new scalarized black hole solutions in Gauss-Bonnet theory with a Maxwell field, while outlining their observational significance. Our approach leverages numerical techniques to scrutinize asymptotically flat, spontaneous, and non-linear scalarized black holes in the Einstein-Maxwell-Scalar model, with a keen emphasis on the horizon radii and scalar field intensities. We culminate with an analysis of how scalarization sources shape the horizon area. Our research enhances the comprehension of black hole scalarization and paves the way for continued investigation in this exciting field.

**Parallel Sessions / 210**

## **Theory: Grand canonical ensemble of a d-dimensional Reissner-Nordström black hole space in a cavity**

**Corresponding Author:** tiago.vasques.fernandes@tecnico.ulisboa.pt

The grand canonical ensemble of a  $d$ -dimensional Reissner-Nordström black hole space in a cavity is analyzed through the Euclidean path integral approach. The partition function of the ensemble is given in terms of the fixed temperature and fixed electric potential at the boundary of the cavity. One performs the zero loop approximation, i.e., only the contribution of the solutions which are stationary points of the action are considered. One finds two solutions for the charged black hole,  $\mathfrak{N}+1$  and  $\mathfrak{N}+2$ , where  $\mathfrak{N}+2$  is the largest. The stability is analyzed through perturbations of the reduced action, yielding instability of  $\mathfrak{N}+1$  and stability of  $\mathfrak{N}+2$ . Through the correspondence between the partition function and the thermodynamic grand potential, one obtains the mean energy, mean charge, the entropy and the thermodynamic pressure of the system. Now, a spontaneous process in the grand canonical ensemble can never increase the grand canonical potential  $\mathfrak{N}$ , otherwise the second law of thermodynamics would be violated. Thus, it is of interest to compare, for a cavity with fixed size, temperature, and electric potential, the value of  $\mathfrak{N}$  for the black hole  $\mathfrak{N}+2$  solution with the value of  $\mathfrak{N}$  of a nongravitating charged shell, which serves as a model for charged hot flat space. In this way, one can investigate possible phase transitions between black holes and hot flat space.

**Parallel Sessions / 211**

## Theory: Quantum integrable black holes

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We consider black holes generically sourced by quantum matter described by regular wavefunctions. This allows for integrable effective energy densities and the removal of Cauchy horizons in spherically symmetric configurations. Moreover, we identify the ultrarigid rotation of the Kerr spacetime as causing the existence of an inner horizon in rotating systems, and describe general properties for quantum matter cores at the centre of rotating black holes with integrable singularities and no Cauchy horizon.

**Parallel Sessions / 212**

## Theory: Constructing accelerating NUT black holes

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We employ Ehlers transformations, Lie point symmetries of the Einstein field equations, to efficiently endorse accelerating metrics with a nontrivial NUT charge. Under this context, we begin by re-deriving the known C-metric NUT spacetime described by Chng, Mann, and Stelea in a straightforward manner, and in the new form of the solution introduced by Podolský and Vrátný. Next, we construct for the first time an accelerating NUT black hole dressed with a conformally coupled scalar field. These solutions belong to the general class of type I spacetimes, therefore cannot be obtained from any limit of the Plebański-Demiański family whatsoever and their integration needs to be carried out independently. Including Maxwell fields is certainly permitted, however, the use of Ehlers transformations is subtle and requires further modifications. Ehlers transformations do not only

partially rotate the mass parameter such that its magnetic component appears, but also rotate the corresponding gauge fields. We present a Reissner-Nordström-C-metric NUT-like black hole that correctly reproduces the Reissner-Nordström-C-metric and Reissner-Nordström-NUT line elements in the corresponding limiting cases but with a misaligned electromagnetic potential.

#### Parallel Sessions / 213

### Theory: Hawking Radiation without Lorentz Invariance

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It's a well-known fact that Lorentz Violating (LV) theories of gravity, such as Horava-Lifshitz gravity, highlight possibility of a renormalizable, non-Lorentz-invariant UV completion of General Relativity (GR).

On the phenomenological side, the breaking of Local Lorentz Invariance gives a different notion of causality, for which the LV-Black Hole solutions assume a different internal structure with respect to GR.

Surprisingly, if one studies the behaviour of quantum fields on top of this geometries, one discovers that LV-BHs still radiate by Hawking effect.

In this talk, I will present how the different notion of causality in these theories affects Hawking radiation and how this could possibly lead to observable LV signatures.

#### Parallel Sessions / 214

### Theory: The quantum states of the universe in tomographic form

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In this talk I present some new results in the program of formulating Quantum Cosmology in a tomographic representation. In particular I show new solutions of the Wheeler-De Witt equation recently obtained together with the correspondent tomograms.

#### Parallel Sessions / 215

### Theory: Aspects of kinetic screening - UV completion and the two-body problem

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New light scalar degrees of freedom may alleviate the dark matter and dark energy problems, but if coupled to matter, they generally mediate a fifth force. In order for this fifth force to be consistent with existing constraints, it must be suppressed close to matter sources, e.g. through a non-linear screening mechanism. The focus of this talk will be shift-symmetric scalar-tensor theories that exhibit kinetic screening (k-essence). First, I will discuss the theoretical consistency of such theories. In particular, whether screening is compatible with the standard UV completion and what kind of breaking of the shift symmetry preserves screening. Second part of the talk will focus on the two-body problem in k-essence. I will show how the Helmholtz decomposition of the Noether current associated to the shift symmetry allows for the analytic understanding of the two-body problem in a good agreement with the numerical results. In particular, the fifth force is screened slightly more

efficiently in equal-mass systems than in the extreme mass-ratio ones. However, systems with comparable masses also exhibit regions where the screening is ineffective. These descreened spheroidal regions (bubbles) could in principle be probed in the solar system with sufficiently precise space accelerometers.

#### Parallel Sessions / 216

### Phenomenology: Non-gaussian gravitational wave backgrounds across the GW spectrum

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Stochastic gravitational wave backgrounds (SGWBs) are, to date, yet to be unequivocally observed. At the  $\sim 10^{-4}$ – $10^{-3}$  frequencies, tentative evidence for the observation of such signals has been recently reported.

In this talk, I will focus on prospects for the detection of SGWBs of astrophysical origin in the  $10^{-4}$ – $10^{-3}$  frequency range.

I will show how recent progress in statistics and data-analysis tools for ground-based detectors might offer the opportunity for an imminent detection of popcorn-like SGWBs.

Moreover, I will describe the most recent findings on expected SGWBs of astrophysical origin, observable with future space-based observatories (e.g. LISA). They will pollute the observed data-streams, with far-reaching implications on the parameter reconstruction of individual resolvable sources.

#### Parallel Sessions / 217

### Phenomenology: From regular black holes to horizonless objects: gravitational perturbations and detectability

**Corresponding Author:** [vvellucc@sissa.it](mailto:vvellucc@sissa.it)

Black holes represents a break down of General Relativity because of the presence of the central singularity where the space-time is no more defined and the theory is no more predictive. There are two possible alternatives to black holes to describe the compact objects that we see in our Universe: regular black holes whose horizon hides a regular core and ultracompact horizonless objects. I will present an effective metric that interpolates between these two possibilities depending on the value of a regularization parameter. I will discuss gravitational perturbations of this solution, possible instabilities and deviations of the QNMs spectrum from that of singular black holes. Finally I will discuss the possible detectability of these deviations with the next generation of gravitational wave detectors.

#### Parallel Sessions / 218

### Phenomenology: Ultraviolet Sensitivity of Peccei–Quinn Inflation

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The radial direction of the Peccei–Quinn field can drive cosmic inflation, given a non-minimal coupling to gravity. This scenario has been considered to simultaneously explain inflation, the strong CP problem, and dark matter. We argue that Peccei–Quinn inflation is extremely sensitive to higher-dimensional operators. Further combining with the discussion on the axion quality required for solving the strong CP problem, we examine the validity of this scenario. We also show that after Peccei–Quinn inflation, resonant amplifications of the field fluctuation is inevitably triggered.

Parallel Sessions / 219

## Phenomenology: Anharmonic effects on the squeezing of axions perturbations

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It is well known in cosmology that the history of the Universe undergoes a period of quasi exponential expansion. The fluctuations of the inflaton field are believed to have a quantum origin, however the CMB sky we observe today is classical. Therefore the questions whether the initial perturbations have a quantum or classical origin and how to discriminate them arise. Actually inflation itself provides an explanation for the “classicalization” of the originally quantum perturbations. They are squeezed due to the fast expansion of the universe. A squeezed state is a special quantum state for which one variable is allowed to have an arbitrarily small uncertainty, while its conjugate counterpart has a very big uncertainty correspondingly. This is indeed the most quantum state we could think about, however, from an observational point of view, it is indistinguishable from a classical phase-space distribution. In this talk, I will present the evolution in time of the perturbations of axion-like particles, introducing the notion of Bogoliubov coefficients and squeezing parameters. I will also present the link between these mathematical notions and physical observables, in order to address the question about the observability of the quantum nature of these perturbations. Moreover I will study the modification of the squeezing parameters due to anharmonic effects. An exponential increase in the Bogoliubov coefficients, i.e. in the average energy density of the perturbations, is observed.

Parallel Sessions / 220

## Phenomenology: Primordial Black Holes during the QCD phase-transition

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Primordial black holes (PBHs) could have been formed in the very early Universe from large amplitude perturbations of the metric. Their formation is naturally enhanced during the quark-hadron phase transition, because of the softening of the equation of state: at a scale between 1 and 3 solar masses, the threshold is reduced of about 10% with a corresponding abundance of PBHs significantly increased by three order of magnitudes. Performing detailed numerical simulations we have computed the modified mass function for such black holes, showing that the minimum of the QCD transition works as an attractor solution. Making then a confrontation with the LVK phenomenological models describing the GWTC-3 catalog, we have found that a sub-population of such PBHs formed in the solar mass range is compatible with the current observational constraints and could explain some of the interesting sources emitting gravitational waves detected by LIGO/VIRGO in the black hole mass gap, such as GW190814, and other light events.

## Parallel Sessions / 221

**Phenomenology: Measuring deviations from the Kerr geometry with black hole ringdown****Corresponding Author:** kallol17@iisertvm.ac.in

Black holes in General Relativity are famously characterized by two “hairs” only, the mass and the spin of the Kerr spacetime. Theories extending General Relativity, however, allow in principle for additional black hole charges, which will generally modify the multipole structure of the Kerr solution. Here, we show that gravitational wave observations of the post-merger ringdown signal from black hole binaries may permit measuring these additional “hairs”. We do so by considering spacetime geometries differing from the Kerr one at the level of the quadrupole moment, and computing the differences of their quasinormal mode frequencies from the Kerr ones in the eikonal limit. We then perform a Bayesian analysis with current and future gravitational wave data and compute posterior constraints for the quadrupole deviation away from Kerr. We find that the inclusion of higher modes, which are potentially observable by future detectors, will allow for constraining deviations from the Kerr quadrupole at percent level.

## Parallel Sessions / 222

**Phenomenology: Nonlinear photon-plasma interaction and the black-hole superradiant instability****Corresponding Author:** fabrizio.corelli@uniroma1.it

Superradiant scattering provides a interesting way of extracting energy from a rotating black hole by means of amplification of low-frequency electromagnetic (EM) radiation. If plasma in the accretion disk prevents the outgoing radiation from escaping to infinity, this process can happen repeatedly, triggering an instability that can lead to the appearance of bursts.

However, investigating this scenario requires a nonlinear treatment of the interaction between the EM field and plasma, due to the high intensity of radiation generated by the numerous superradiant scatterings. In this context, a particularly interesting possibility that has been suggested in literature is that overdense plasmas become transparent to intense EM fields, leading to an energy leak that quenches the instability.

In a recent work done in collaboration with Enrico Cannizzaro and prof. Paolo Pani, we simulated in a flat spacetime 3+1 setup the fully nonlinear interaction between an EM wave packet and a plasma barrier, with the purpose of exploring the phenomenology of this interesting regime. While we did not observe transparency, we found that the momentum transferred by the EM field to the barrier can set the system in a blow-out state in which energy can escape from the black hole. In this talk I will present the results of our numerical simulations, discussing the possible implications for superradiant instability.

## Parallel Sessions / 223

**Phenomenology: Information paradox and table-top experiments****Corresponding Author:** d.p.f.shahbazi@gmail.com

Black holes can be simulated by water in a tank or in general in analogue gravity models known as dumb holes. If one simulates the Hawking radiation in these models finds that the loss of information is equal to the loss of the momentum of the fluid over the dumb hole horizon. However, due to

the steadiness of the horizon one expects that there is a missing momentum over the horizon. By imposing Newton's second law of motion to the horizon and the contribution of the missing momentum the island prescription appeared. The analysis of the information paradox in the analogue gravity models shows the point that the island prescription which is an ad hoc solution to the paradox in holography arises naturally in the analogue gravity models by imposing Newton's second law. Then it seems that the analysis of high energy physics problems in the analogue gravity opens up a new avenue in high energy physics

**Parallel Sessions / 224****###****Parallel Sessions / 225****###****Parallel Sessions / 226****###****Parallel Sessions / 227****###****Parallel Sessions / 228****###****Parallel Sessions / 229****###****Parallel Sessions / 230****LAG- Liquid Actuated Gravity - Snooping Inverse Square Law at  
∞ cm distance**

**Corresponding Author:** massimo.bassan@roma2.infn.it

**Parallel Sessions / 231**

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**Parallel Sessions / 232**

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**Parallel Sessions / 233**

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**Parallel Sessions / 234**

## **Experiments: Status of the GINGER project**

**Corresponding Author:** angela.divirgilio@pi.infn.it

The measurements of the Earth rotation rate variations, certainly important for Earth science, are relevant also for fundamental physics investigation, as they contain general relativity terms, such as de Sitter and Lense Thirring, and they provide unique data to investigate Lorentz violations. Long term continuous operation and very high sensitivity are required, the limit to be reached to study fundamental physics is 1 part in  $10^9$  of the Earth rotation rate. Present high sensitivity ring laser gyroscopes have record sensitivity for absolute angular rotation, and have already proved the required sensitivity.

The GINGER project is based on an array of ring lasers, the plan is to install it inside the Gran Sasso laboratory at the end of 2024 and start taking data in 2025.

**Parallel Sessions / 235**

## **Theory: Noncommutative Correction to Black Hole Entropy**

Noncommutative geometry is an established potential candidate for including quantum phenomena in gravitation. We outline the formalism of Hopf algebras and its connection to the algebra of infinitesimal diffeomorphisms. Using a Drinfeld twist we deform spacetime symmetries, algebra of vector fields and differential forms leading to a formulation of noncommutative Einstein equations. We study a concrete example of charged BTZ and RN spacetime and deformations stemming from the so called angular twist. The entropy of the noncommutative black hole is obtained using the brick-wall method. We provide the method to calculate corrections to the Bekenstein-Hawking entropy in higher orders in WKB, but we present the final result in the lowest WKB order. The result is that even in the lowest order in WKB, the entropy, in general, contains higher powers in  $\hbar$ , and it

has logarithmic corrections. In contrast, such logarithmic corrections in the commutative setup appear only after the quantum effects are included through higher order WKB corrections or through higher loop effects. Our analysis thus provides further evidence towards the hypothesis that the noncommutative framework is capable of encoding quantum effects in curved spacetime.

236

## Welcome SISSA Director, INFN TS Director & SIGRAV President

Parallel Sessions / 237

### Theory: Probing the Big Bang with Quantum Fields

**Corresponding Author:** mschneid@sissa.it

The singularity theorems of Penrose and Hawking are based on geodesic incompleteness and predict the occurrence of classical singularities under rather general circumstances. In general relativity, these singularities represent absolute boundaries where space-time ends.

Physically, however, this criterion refers to the fate of point like classical test particles. We raise the question: What if one uses quantum fields instead? Intuitively, quantum probes are much more fundamental and bear a richer structure. We will begin with the proof that one can unambiguously evolve quantum fields across them in a rigorous sense. Thus when probed with quantum fields, the big bang is not an absolute boundary where physics breaks down. Additionally we will discuss the behavior of composite operators such as the expectation values of renormalized products of fields and the renormalized stress-energy tensor and show that they too remain well-defined as distributions.

The overall conclusion is twofold: first quantum mechanical considerations provide more refined tools to probe classically singular structures, and second, the big bang singularity of classical general relativity is tamer when seen from a quantum perspective.

Parallel Sessions / 238

### Theory: Noncommutative Correction to Black Hole Entropy

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**Parallel Sessions / 239**

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**240**

**Awards Ceremony (Premio Rampa, SIGRAV Prizes, Amaldi Medals)  
+ Group Photo**