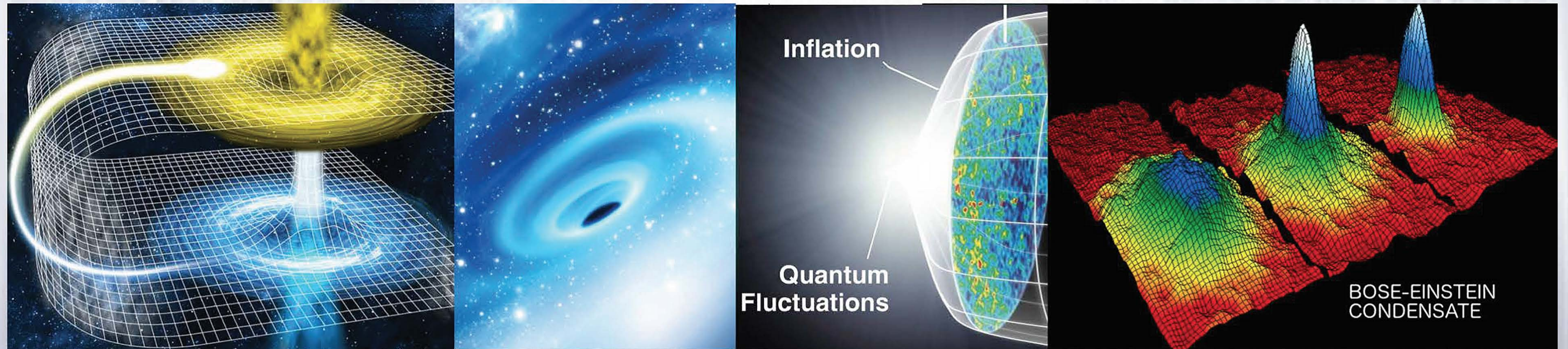
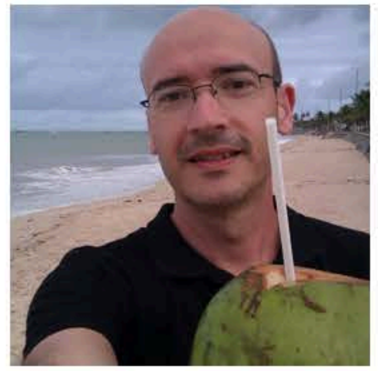
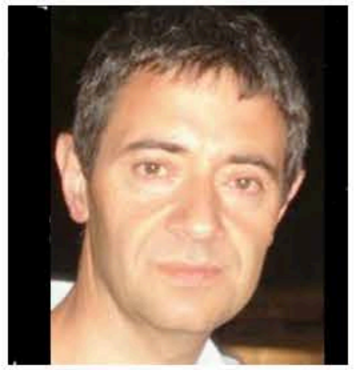
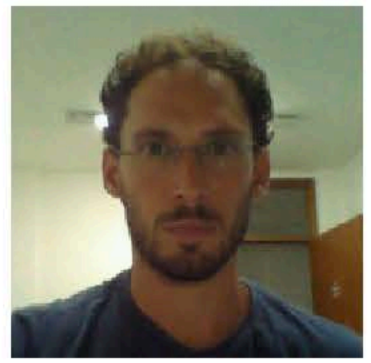
Gravitation and Quantum Fields

QUANTUM BLACK HOLES, COSMOLOGY, AND SUPERGRAVITY



Gravity was once viewed as a kind of innocuous background, certainly irrelevant to Quantum Field Theory. Today gravity plays a central role. (B. de Witt, 2009)

Who we are:

Doctor Members	.	Doctor Members	.
María A. Lledó (T.U.)		Gonzalo J. Olmo (RyC)	
José Navarro Salas (C.U.)		Iván Agulló (LSU, USA)	
Alessandro Fabbri (Doc.Vinculado)		Víctor I. Afonso (Postdoc)	

There are 4 Ph.D. students in our group:

Adrián del Río (FPU)
Adrià Delhom (FPU)
Cintia Menchón (FPI)
Antonio Sánchez Puente

Main research lines:

- Classical and quantum aspects of black holes.
- Hawking radiation. Analogue black holes.
- Modified gravity in astrophysics and cosmology.
- QFT, semiclassical gravity, early universe, and inflation.
- Gravitational anomalies.
- Metric-affine geometry and quantum gravity phenomenology.
- Supergravity and space-time deformations.

QFT in time-dependent backgrounds: early universe, black holes and particle production:

- Combining QFT with gravity leads to gravitational Particle Creation:
  - The generation and amplification of quantum field fluctuations is inevitable during the early universe (inflation) or the gravitational collapse of black holes.
  - It implies that particles, scalar perturbations, and gravitational waves are created out of the vacuum in the very early universe.
  - This constitutes the preferred driving mechanism to explain the generation of cosmic primordial inhomogeneities, observed now in the CMB and the large scale structure of the Universe.
  - It also implies the quantum radiance of black holes (Hawking effect).
  - Particle production by (gravitational) time-dependent backgrounds in fundamental for the Reheating of the Universe after inflation. It is necessary to recover the Hot Big-Bang and to explain the origin of all particles in the Universe.

Renormalization and backreaction equations:

- Gravity introduces new UV divergences in QFT. It is very important to develop efficient methods to deal with them, renormalize, and produce finite observables.
  - We have worked out a consistent extension of the Adiabatic Regularization method for spin 1/2 fields. Explicit expressions for the renormalized stress-energy tensor for Dirac fields in expanding universes allow for numerical calculations.
  - Due to renormalization, matter fields interacting with a background scalar field (via Yukawa coupling) requires interactions of the form: $\chi_1 \phi^2 R$ and also $\chi_2 \phi R$. This result might be relevant for Higgs inflation.
  - We have produced Einstein backreaction equations, including particle creation and vacuum polarization effects, to rigorously account for the (non-perturbative) preheating phase after inflation.

Future perspectives:

- We will analyze numerically the backreaction equations for reheating. We will particularly look at observable signatures:
  Source of Gravitational Waves, Non-Gaussianities in the Cosmic Microwave Background, residual vacuum (dark) energy.

- We have shown that the electric-magnetic duality symmetry of the free electromagnetic field is broken at the quantum level in presence of a background gravitational field, in parallel to the chiral anomaly for massless Dirac fermions. We have found that
  $$< \nabla_\mu J^\mu_D >= \frac{\hbar}{24\,\pi^2} R_{\alpha\beta\mu\nu} * R^{\alpha\beta\mu\nu}$$

- This seems to imply gravity distinguishes left-handed from right-handed photons. We will investigate phenomenological implications of this result in Kerr black holes.

Now it seems that the empirical notions on which the metric determinations of Space are based, the concept of a solid body and a light ray, lose their validity in the infinitely small; it is therefore quite definitely conceivable that the metric relations of Space in the infinitely small do not conform to the hypotheses of geometry; and in fact, one ought to assume this as soon as it permits a simpler way of explaining phenomena. . . .

Riemann’s dissertation, “On the hypotheses which lie at the foundations of geometry” 1854.

Supergeometry, supersymmetry and supergravity:

- Born as a way of overcoming no go theorems for unifications, supersymmetry has not yet revealed its full power. While many theorists are interested in supersymmetry only for its relation to some dynamical theory (String Theory or some phenomenological extension of the Standard Model), we look at supersymmetry as inevitable from a consistency point of view. According to this idea, supergravity is the natural generalization of GR which Nature must show in some regime. The new developments in the non trivial generalization of algebraic geometry called supergeometry offer a different and powerful insight into the fundamentals of physical theories.

- The most recent work on this subject is 'Superfields, nilpotent superfields and superschemes' by M. A. Lledó, where, besides offering a sound interpretation of the concept of superfield, some non linear representations of supersymmetry (used in supergravity-inspired cosmological models) are linked to superschemes with non regular points.

- In this line of work we intend, in the future, to analyze constraints for superfields in superspace of higher supersymmetry, where the superfield approach has not been very succesful.

Quantum spacetime and superspacetime:

- The nature of spacetime at very short distances is unknown and a theory of quantum gravity would have to give a model for quantum spacetime. We study deformations of conformal or Minkowski (super)spacetime, which may be serve as a local model for general `quantum manifolds'. The mathematical structure of conformal space is very rich and offers many different directions for deformation. In `The Segre embedding of the quantum conformal superspace' R. Fioresi, E. Latini, M. A. Lledó, and F. Nadal (to appear) one of these directions is explored, but there are others, related to the quantization of coadjoint orbits. These are, themselves, related to 'fuzzy spaces' by group representation theory).

- Two more subjects linked to quantization: the quantization of special varieties appearing as target spaces of scalar fields in supergravity and the possibility of generalizing the quantum logic of Von Neumann in terms of many valued logics in order to reproduce the commutation relations of a quantum spacetime (which are not the canonical commutation relations of quantum mechanics).

Modified gravity, black holes, and quantum gravity phenomenology (I):

- Main results so far:
  - Modified gravity alternatives to dark matter at galactic and cluster of galaxies scales. Hybrid metric-Palatini theories introduce new mechanisms to evade local gravity constraints. Gravitational lensing by galaxies in MONDian scenarios is consistent with observations if the Einstein equiv. principle holds at such scales.
  - Found explicit examples of electromagnetic geons: charged point particles seen as self-gravitating free electromagnetic fields with wormhole topology. Some of these solutions are consistent with the notion of black hole remnant. New physics at TeV scale (nonlinear QED) could bring these objects within the reach of LHC.
  - Found that black hole singularities (in arbitrary dimension) are replaced by wormholes when the space-time geometry is of metric-affine type. Topology seems to be a crucial element to progress in the understanding of singularities.
  - Gravitational waves in metric-affine theories of gravity in cosmology and brane-worlds depend very weakly on the particular gravity Lagrangian considered. This leads to a strong degeneracy in the predictions of different models.
  - Found that bouncing cosmologies in Born-Infeld type gravity theories are robust. The fact that they also remove singularities in black hole scenarios makes these models particularly interesting to build an improved classical completion of GR at high energies.

Modified gravity, black holes, and quantum gravity phenomenology (II):

- *Impact of curvature divergences on physical observers in a WH space-time with horizons*, Classical and Quantum Gravity (2016), G.J. Olmo, D. Rubiera-Garcia, A. Sanchez-Puente
  - Invited contribution to the blog CQG+ of the journal Classical and Quantum Gravity. The paper on which that post was based has reached more than 9200 downloads!
  - The CQG paper is within the top 5% of all research outputs scored by Altmetric, with 30 news stories in the international media.
  - Also in El Mundo, El Confidencial, Europa Press, Levante, 20 minutos, ... thanks to a press release by IFIC!!!
  -

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Wormholes can fix black holes

— Diego Rubiera-Garcia (left, Lisbon University) and Gonzalo J. Olmo (right, University of Valencia – CSIC) after crossing a wormhole that connects Europe with the beaches of the Brazilian Northeast.

According to Einstein's theory of general relativity (GR), black holes are ferocious beasts able to swallow and destroy everything within their reach. Their strong gravitational pull deforms the space-time causal structure in such a way that nothing can get out of them once their event horizon is crossed. The fate of those incautious observers curious enough to cross this border is to suffer a painful spaghettification process due to the strong tidal forces before being destroyed at the center of the black hole.

Antonio Sánchez Puente

Modified gravity, black holes, and quantum gravity phenomenology (III):

- Future perspectives:
  - Construction of relativistic gravity models consistent with MOND dynamics (without "external field effect") and cosmological observations. The existence of MOND-like behavior in wide binary stars in our galaxy is a critical test for such theories.
  - Constraining Born-Infeld type gravity models with compact objects (neutron stars and black holes). We will explore quasinormal modes (gravitational waves), instabilities, EoS-independent physics, possibility of wormhole-like interiors, ...
  - Inflationary and pre-inflationary scenarios in Born-Infeld type cosmologies.
  - Exploration of scalar and fermionic geons as a way to interpret matter fields in terms of geometry/topology. Mass, charge, and spin as topological properties of the space-time.
  - Deepen into the notion of singular space-time and its implications for quantum gravity and the construction of effective theories at low energy densities.
  - Extend QFT in curved space-times to scenarios with torsion and non-metricity. This is specially relevant for cosmology and condensed matter physics.
  - Establish correspondences between 2+1 gravity models and condensed matter systems such as graphene with defects in the continuum limit.

Acoustic black holes and Hawking radiation:

- 2016 has been a crucial year for investigations on Acoustic Black Holes:
  - In a series of experiments, J. Steinhauer (Haifa, Israel) found the first observational evidence of the analogue Hawking radiation in Bose-Einstein Condensates (BECs) [Nat. Phys. 2016] through the measurement of the 'density correlator', as proposed years before (2008) by members of the group (a workshop on this topic was organized at IFIC in 2009).
- New collaboration initiated with an experimental group in Paris (C. Westbrook, Institut d'Optique/Laboratoire Charles Fabry):
  - Purpose: to study the features of the Hawking effect in 'momentum correlators', typical observable in BECs experiments where measurements are performed with the TOF ('time of flight') technique.
  - Results of an analytical study, confirming the viability of such an experiment both to identify Hawking radiation and to highlight its quantum properties, have been published in Phys. Rev. Lett. (2015) as Editor's suggestion and appeared as 'Actualité Scientifique' of the INP (National Institute for Physics) of CNRS (Highlight 2015).
  - Such an experiment, for which C. Westbrook has received funding from the French ANR, would complement Steinhauer's 'in situ' measurements and is important to provide an independent check of the existence of the Hawking effect in these systems.

Quantum backreaction:

- To have a precise comparison between theoretical predictions and experimental data, a nontrivial acoustic black hole model in a 1D BEC has been constructed
  - The wave equation of the (linear) fluctuations admits exact solution and the scattering coefficients are analytically available at all frequencies - Phys. Rev. D (2016).
  - These results will allow a more accurate computation of the density correlation functions compared to the (analytical) results present in the literature.
- Important question both in BECs and in gravity: how do quantum effects modify the background solutions? (quantum backreaction). This is an open question for acoustic black holes.
  - Much progress has been done recently on the study of quantum corrections in three dimensional black holes and naked singularities in 2+1 gravity theories.
  - It has been shown that quantum effects act as 'quantum censors' by dressing (static) naked singularities with a horizon (Phys. Lett. B (2016)).
  - The semiclassical Einstein equations have been solved for the first time (and, moreover, analytically) in the case of rotating (BTZ) black holes.
  - The success of this analysis gives us the hope to be able to attack the same problem for Kerr black holes in 3+1 dimensions.

Upcoming conferences organized by our group:

- 12th Iberian Cosmology Meeting (IberiCOS): 10-12 April 2017 (Register, it's free!!!)

- GR22 - 13th Amaldi : 07-12 July 2019