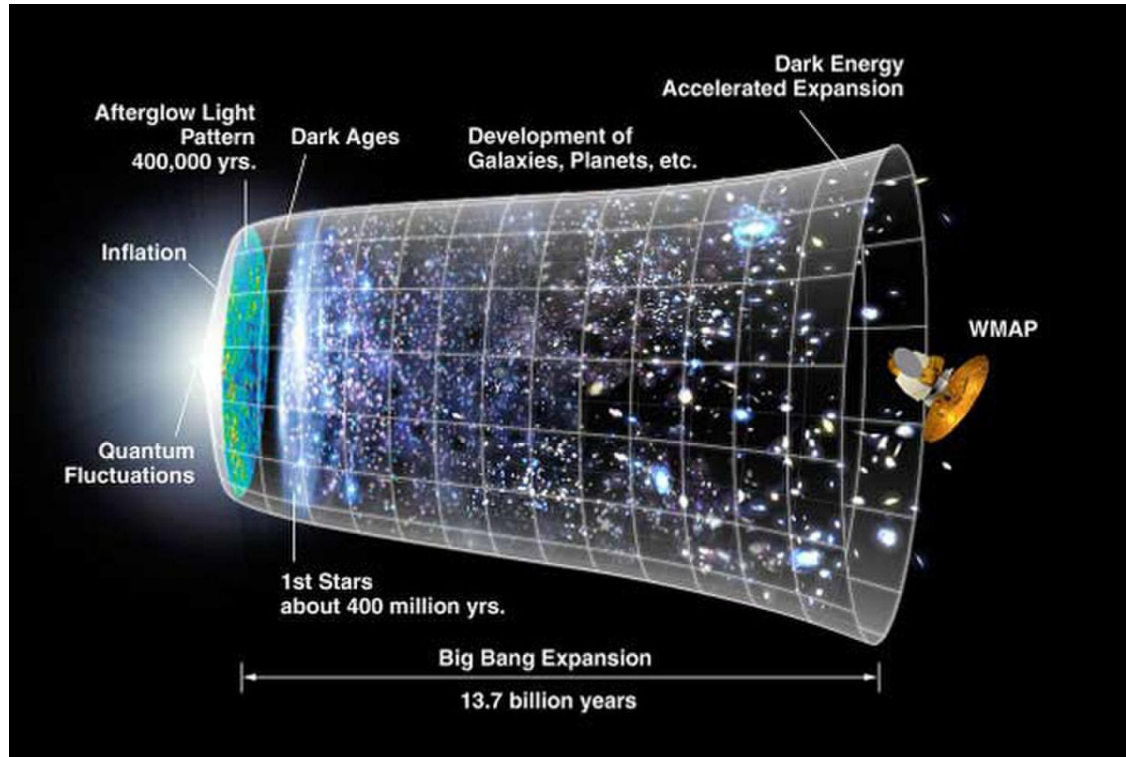


General Relativity & Cosmology

M Bastero-Gil, B Janssen & J Olmedo



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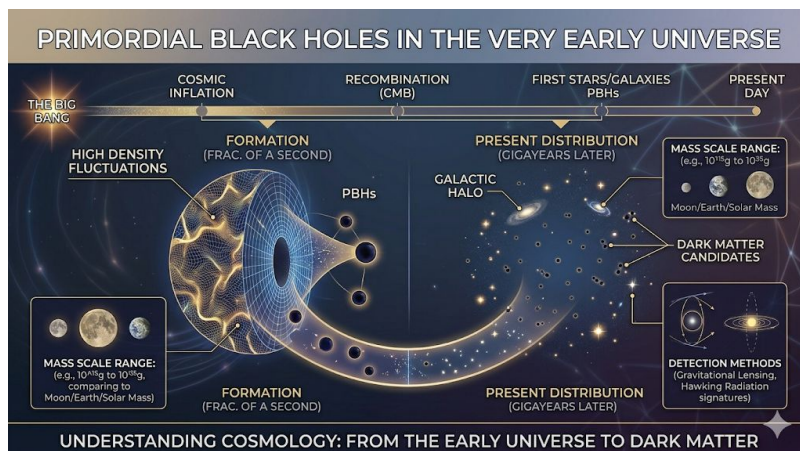
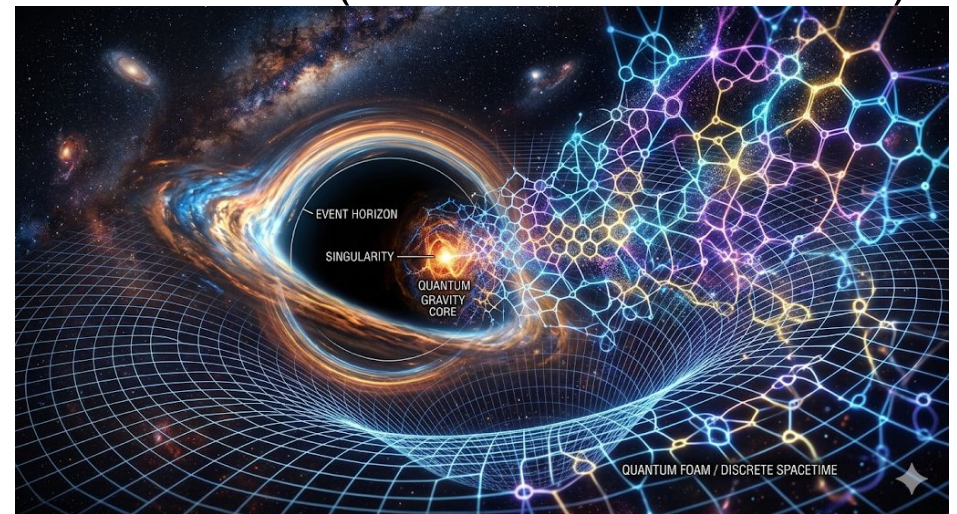
NEQSSUS

Non-equilibrium black holes across aeons: from early universe cosmology to quantum evaporation

«Proyectos de Generación de Conocimiento» 2025 from AEI (currently under review).

Continuation of previous projs PID2020-118159GB-C43 (PIs: Barcelo & Olmedo) & PID2020-119632GB-I00 (PI: Bastero).

The Big Picture: Our research aims to bridge the gap between **General Relativity** and **Quantum Theory** by using black holes as natural laboratories.



Main Goal: To investigate the formation of black holes in the early universe, the fundamental structure of their horizons, and their ultimate fate through quantum evaporation, so we can provide better understanding of their population nowadays.

Meet the Team

Our project is driven by the High Energy Physics Group (FTAE) at the **University of Granada**, with three key figures leading our department's efforts on gravitational physics:

- **Javier Olmedo (IP1):** As one of the project's Principal Investigators, specialized in **black hole physics and cosmology**, with a deep focus on their **quantum aspects** and those of **quantum fields** on these settings.
- **Mar Bastero-Gil:** A leading expert in **inflationary model building**. Mar's work is critical for understanding the seeds of cosmic structure, dark matter, primordial gravitational waves, and the specific predictions of **warm inflation**.
- **Bert Janssen:** Bringing expertise in **String Theory (ST)** and compactification; he investigates **alternatives and extensions to General Relativity**.
- **Two PhD students:** **José Miguel Martín Pérez** and **José Manuel Montes Armenteros**.

Our Research Network

While our department forms the core, NEQSSUS is a collaborative effort involving experts in out-of-equilibrium systems and mathematical physics:

- **Antonio Lasanta (IP2):** Expert in non-equilibrium physics.
- **Laiachi El Kaoutit:** Provides the mathematical framework for noncommutative algebra and geometry.
- **Fernando Barbero & Eduardo Villaseñor:** experts in **Loop Quantum Gravity (LQG)** and the mathematical foundations of dynamical and isolated horizons.
- The group has **national and international collaborations:**
 - **MBG** has international collaborators (**J. Rosa** and **R. Ramos**) and continuous collaborations at **LPSC-Grenoble**.
 - **JO** has active collaborations with **A. Ashtekar (PSU)**, members of the **Theory Gravity Group at LSU** and **M. Martín-Benito (UCM)**.
 - **BJ** presently collaborates with **A. Jiménez-Cano (UPM)** and **M. Sánchez (UGR)**.

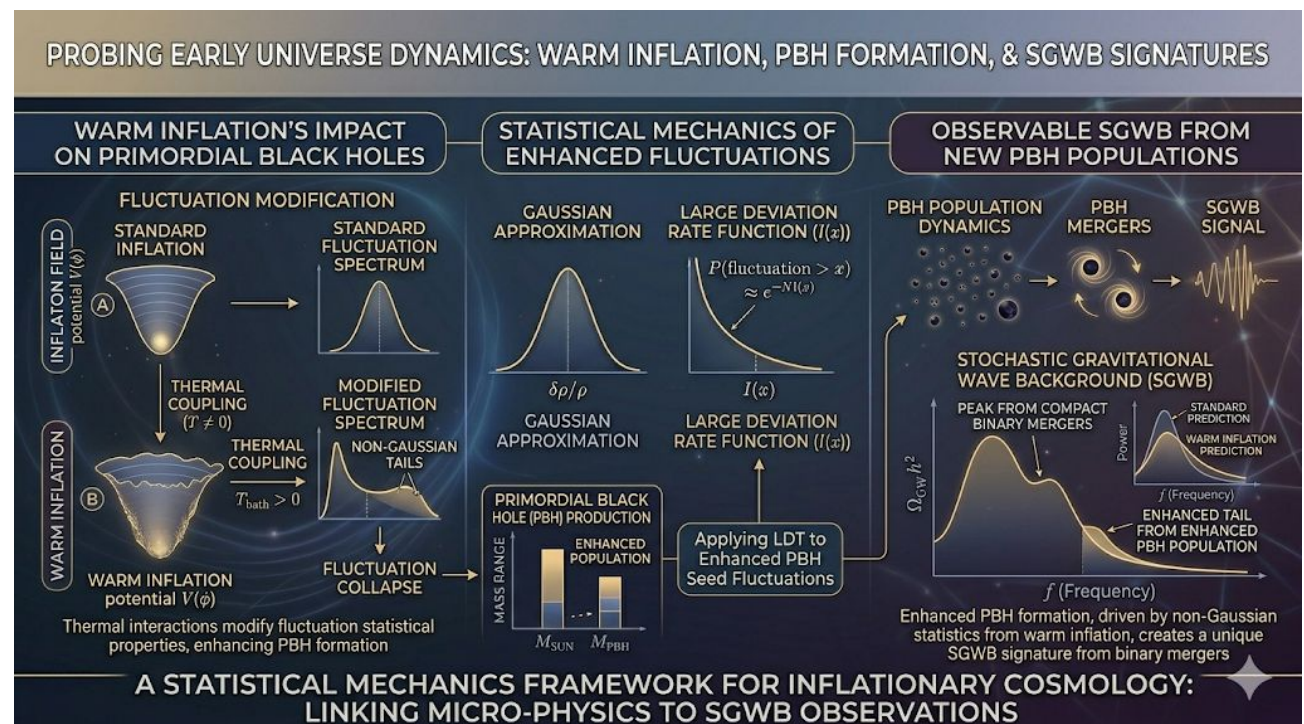
Physics Objective 1 – Primordial Black Holes (PBHs)

We are researching black holes that formed from large fluctuations in the **very early universe**.

- **Warm Inflation (WI):** Unlike standard models, we study inflation where a thermal radiation bath is maintained. This might naturally enhance primordial fluctuations, making it a "fertile ground" for PBHs.

- **Observables:** We are looking for **Stochastic Gravitational Wave Backgrounds** that serve as "smoking guns" for these early universe events.

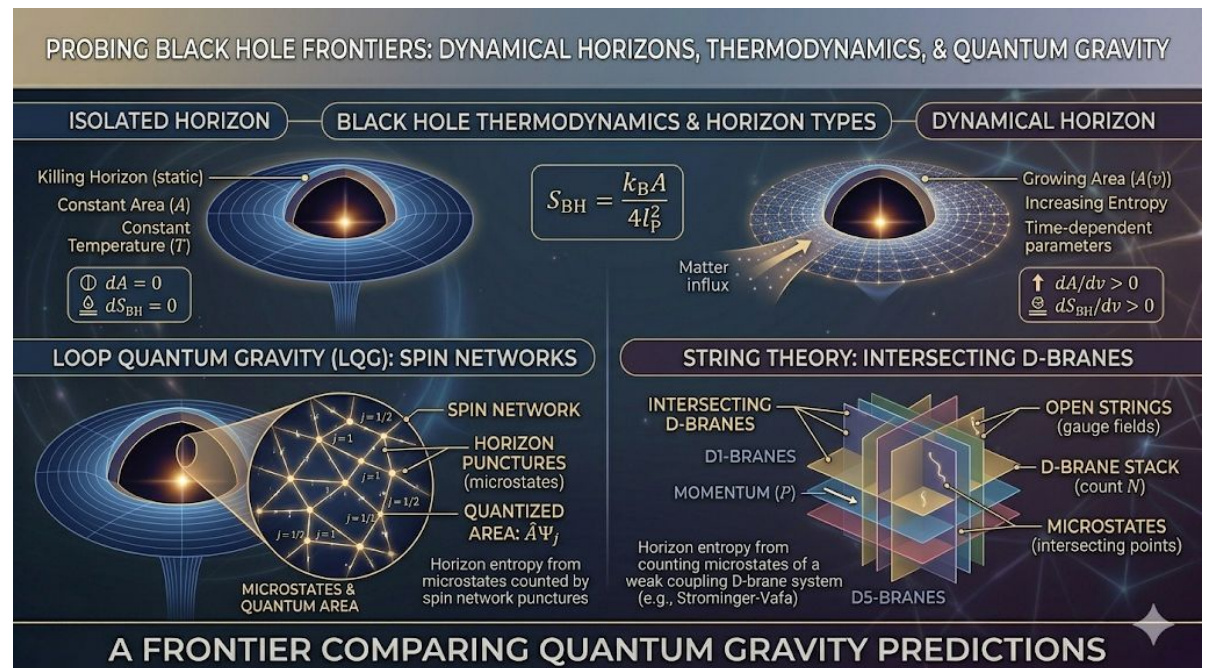
- **Statistical Mechanics:** We apply **Large Deviation Theory** to describe the rare, extreme fluctuations that lead to gravitational collapse.



Physics Objective 2 – Horizon Structure & Entropy

To understand black holes, we must look at the "surface" that defines them.

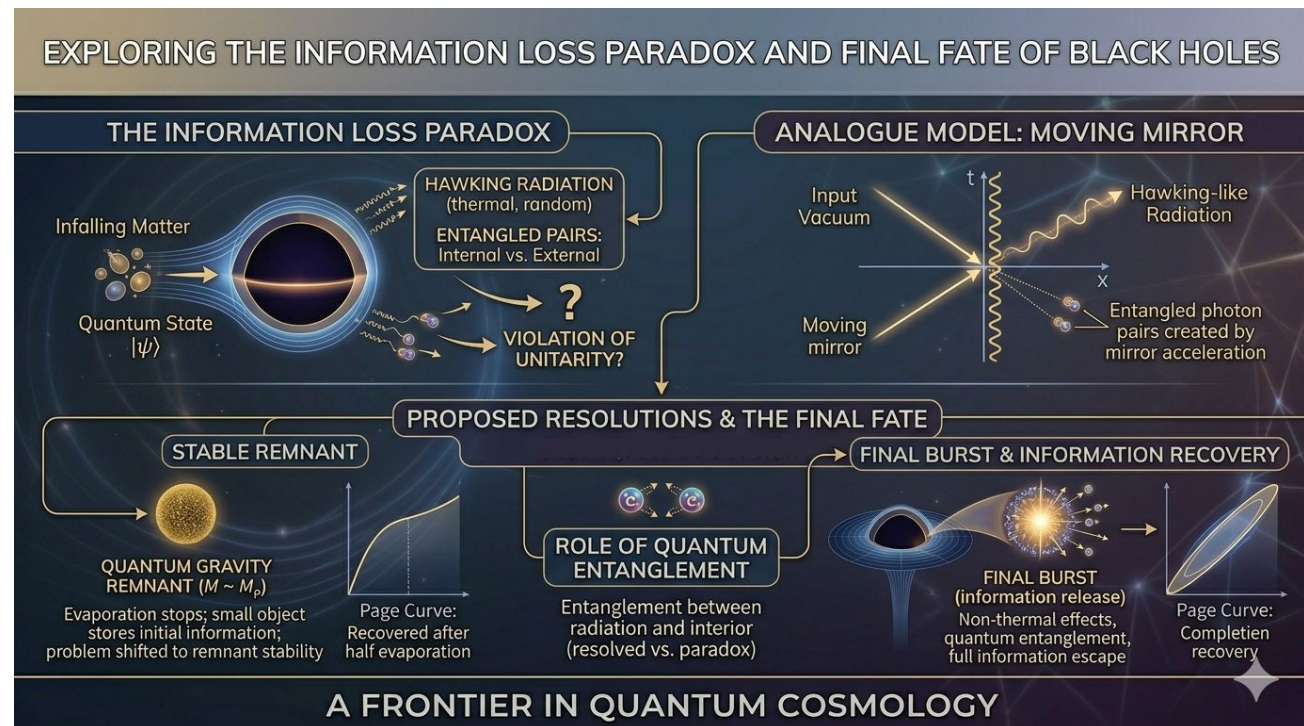
- **Beyond Event Horizons:** We focus on **Dynamical and Isolated Horizons**, which allow us to describe black holes that are gaining or losing mass in real-time.
- **The Microscopic Picture:**
 - **In LQG:** We use **Spin Networks** and combinatorial techniques to count the quantum "punctures" on a horizon to calculate its entropy.
 - **In String Theory:** We study **intersecting D-branes** (specifically D(-1)-D7 configurations) to identify the microstates that reproduce black hole thermodynamics.



Physics Objective 3 – The Final Fate of Black Holes

What happens when a black hole evaporates completely? This remains one of the greatest puzzles in physics (the **Information Loss Paradox**).

- **Quantum Remnants:** We are developing **effective spacetime geometries** to describe black holes as they reach the Planck scale, to see if they leave stable relics or a final explosion.
- **Quantum Entanglement:** Using **moving mirror cavities** in laboratory settings, we simulate Hawking radiation to see how quantum information is distributed between the black hole and its environment.



Methodology & Impact

- **Numerical & Analytical Power:** Our work combines advanced differential geometry with high-performance computing on the **ALHAMBRA** and **Proteus clusters**.
- **Expected Impact:** We expect to deliver new constraints on dark matter, deeper insights into the Big Bang, and testable predictions for the next generation of gravitational wave detectors. Results will be published in peer reviewed journals and disseminated in international conferences.

Summary

- **Summary:** NEQSSUS connects the smallest quantum scales to the largest cosmic structures via primordial black hole physics.
- **Departmental Strength:** With the combined expertise of Mar, Bert, and Javier, our group is uniquely positioned to lead this interdisciplinary frontier of gravitation and cosmology.