

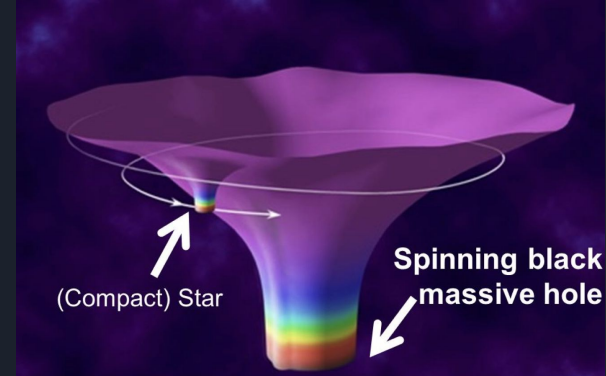
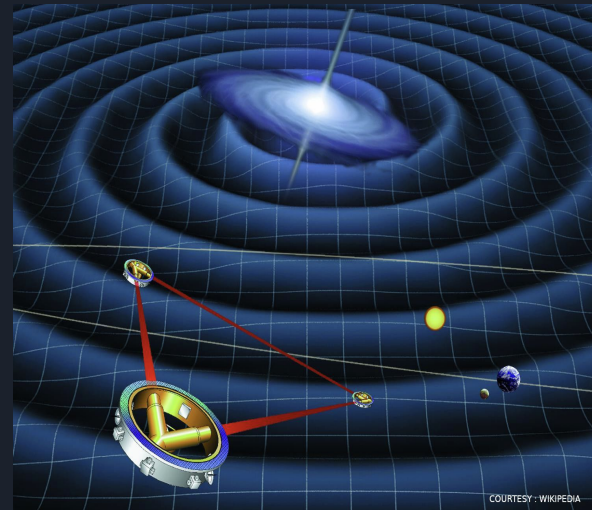
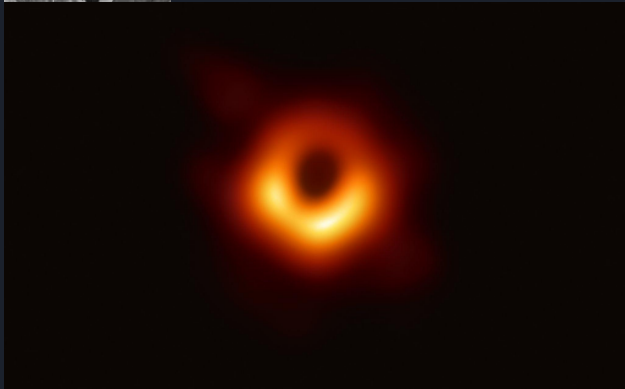
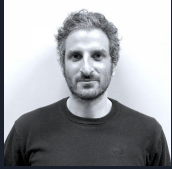
Dark matter, GWs and numerical relativity

Science Fair 2025

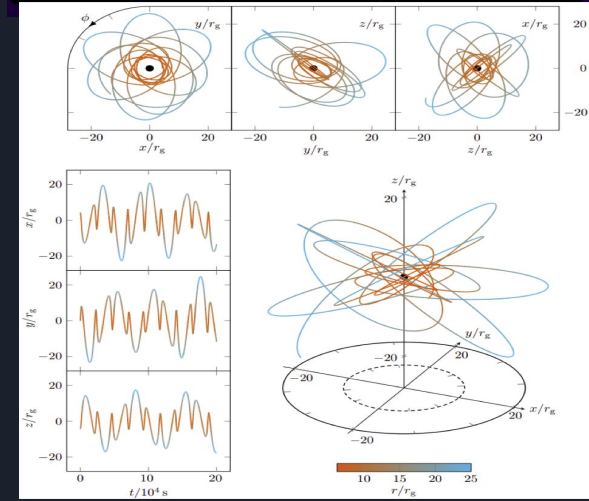
Sayak Datta
Marcelo Rubio

Extreme Mass-Ratio Inspirals (EMRI)

- ❑ Supermassive BH+stellar object
- ❑ BHs are not alone
- ❑ Dark Matter Halo, accretion etc
- ❑ Environment affects EMRI?

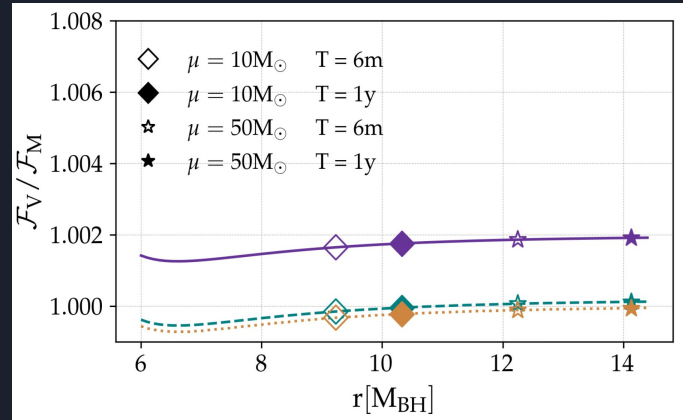
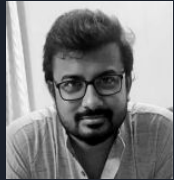
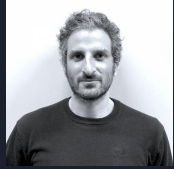


Extreme Mass Ratio Inspirals *EMRI*



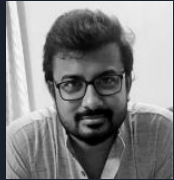
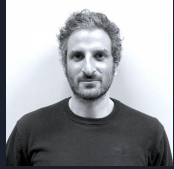
Formalism for environment in EMRIs

- Identify it's strength
- Add it perturbatively on BH
- Compute EMRI
- Non-rotating DONE!!!
- Is it spinning?



Formalism for environment in EMRIs

- Is that all?



- ☐ Halo rotation
- ☐ Halo structure
- ☐ Dark matter

Accretion

- ☐☐ Baryonic matter accretion

- ☐ Hot environment

- ☐ Viscosity

- ☐ Dynamical friction

- ☐ Migration

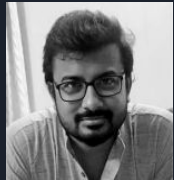
- ☐ Compact object properties

- ☐ Anisotropy?

- ☐ All important?

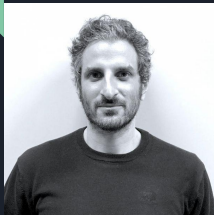
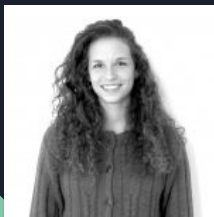
- ☐ Who knows!

Formalism for environment in EMRIs



Exploring the DETECTABILITY of ASYMMETRIC BINARIES

surrounded by DARK MATTER HALOS



MOTIVATION

GENERAL FRAMEWORK

Laser Interferometer Space Antenna sensitivity band: mHz frequency band
 → new families of sources dim to ground based detectors
 → coalescing binaries with large mass asymmetries evolving in band for tens thousand of cycles
 → precise measurement of source parameters
 → golden sources for tests of fundamental astrophysics

EXTREME MASS-RATIO INSPIRALS

Binary systems with a stellar-mass body inspiralling into a massive black hole
 • Primary with $M \sim (10^1 - 10^2)$ solar masses
 • Secondary such that the mass ratio: $q \equiv m_2 / M \sim (10^{-4} - 10^{-3})$

SCIENCE CASE

Study of the environment in which the binary evolves
 → asymmetric binaries become particle physics laboratories
 → infer dark matter properties



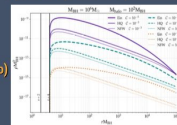
THE MODEL

THEORETICAL FRAMEWORK: PERTURBATION THEORY APPROACH



Schwarzschild black hole in a dark matter density profile
 Background Spacetime (static-spherically symmetric metric) + Small Perturbation (caused by the secondary body)

$$G_{\mu\nu}^{(0)} = 8\pi T_{\mu\nu}^{(0)em} \quad G_{\mu\nu}^{(1)} = 8\pi T_{\mu\nu}^{(1)em} + 8\pi T_{\mu\nu}^P$$

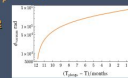


Dark matter properties encoded in:
 $T_{\mu\nu}^{(0)em} = \text{diag}(-\rho(r), 0, P_r(r), P_t(r))$
 $\rho(r) = \bar{\rho}(r)(1 - 4 M_{BH}/r)$ (Hernquist, NFW, Einasto)
 Solution for small compactness $C = M_{BH}/a_c \approx 10^{-4}$
 halo mass and length scale

ADIABATIC EVOLUTION OF ORBITAL PARAMETERS

Equations of motion: $\frac{dr}{dt} = -\dot{E} \frac{dr}{dE_p} \quad \frac{d\Phi}{dt} = \omega_p$

Evolution in a fixed observation time
 → from an initial radius up to the ISCO



SYSTEM CONFIGURATIONS

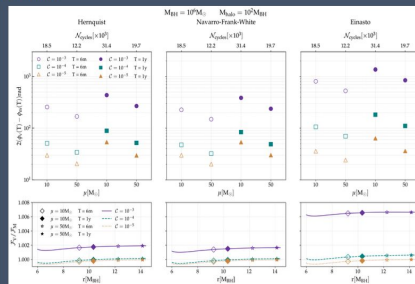
Binary systems: $M_{BH} = 10^2 M_\odot, M_2 = 10^1 M_\odot$
 $M_{BH} = 10 M_\odot, M_2 = 50 M_\odot$
 Dark matter halos: $C = 10^{-3}, 10^{-4}, 10^{-5}$
 in vacuum in dark matter



RESULTS : ASSESSING THE DETECTABILITY OF DARK MATTER HALOS

DEPHASING : first-order assessment

Difference in the GW phase evolution between the EMRI in vacuum and one in dark matter



FAITHFULNESS : second-order assessment

Estimate of how much two signals differ, weighted by the noise spectral density of LISA
 $F(h_1, h_2) = \max_{\nu, \alpha} \sqrt{\langle h_1 | h_2 \rangle} / \sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}$
 $\langle h_1 | h_2 \rangle = 4 \Re \left[\int_{f_{min}}^{f_{max}} \tilde{h}_1(f) \tilde{h}_2^*(f) S_n^{-1}(f) df \right]$

Model	Mass	Compactness	Vacuum	Hernquist	NFW	Einasto
M _{BH} = 10 ² M _⊙ , M ₂ = 10 ¹ M _⊙ , C = 10 ⁻³	100	0.01	0.81	0.81	0.81	0.81
	100	0.02	0.81	0.81	0.81	0.81
	100	0.03	0.81	0.81	0.81	0.81
M _{BH} = 10 ² M _⊙ , M ₂ = 10 ¹ M _⊙ , C = 10 ⁻⁴	100	0.01	0.81	0.84	0.82	0.82
	100	0.02	0.81	0.87	0.83	0.83
	100	0.03	0.81	0.87	0.83	0.83
M _{BH} = 10 ² M _⊙ , M ₂ = 10 ¹ M _⊙ , C = 10 ⁻⁵	100	0.01	0.81	0.97	0.86	0.84
	100	0.02	0.81	0.97	0.86	0.84
	100	0.03	0.81	0.97	0.86	0.84
M _{BH} = 10 M _⊙ , M ₂ = 50 M _⊙ , C = 10 ⁻³	100	0.01	0.81	0.81	0.81	0.81
	100	0.02	0.81	0.81	0.81	0.81
	100	0.03	0.81	0.81	0.81	0.81
M _{BH} = 10 M _⊙ , M ₂ = 50 M _⊙ , C = 10 ⁻⁴	100	0.01	0.81	0.82	0.82	0.82
	100	0.02	0.81	0.82	0.82	0.82
	100	0.03	0.81	0.82	0.82	0.82
M _{BH} = 10 M _⊙ , M ₂ = 50 M _⊙ , C = 10 ⁻⁵	100	0.01	0.81	0.83	0.82	0.82
	100	0.02	0.81	0.83	0.82	0.82
	100	0.03	0.81	0.83	0.82	0.82

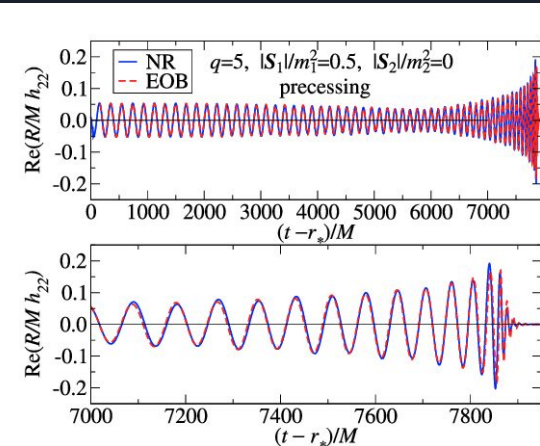
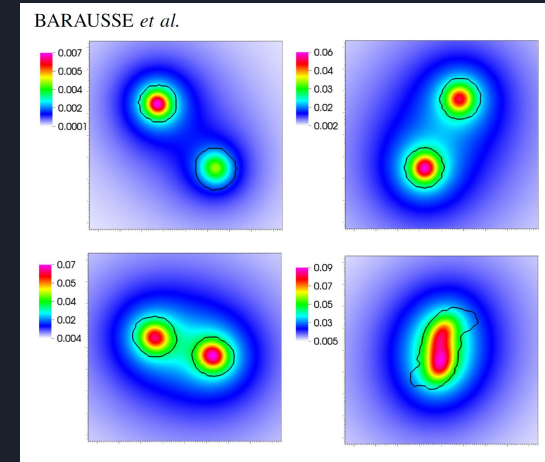
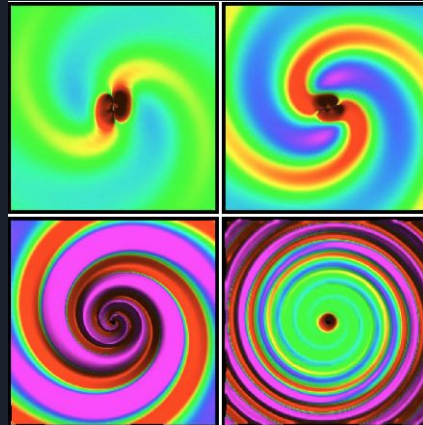
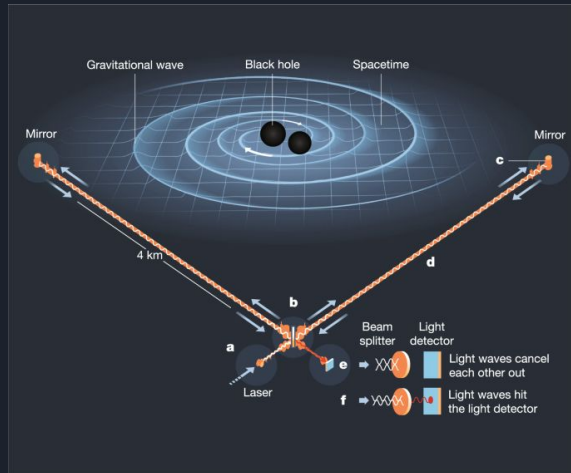
FISHER MATRIX : third-order assessment

It is included in the plan for future work

See Sara's poster!

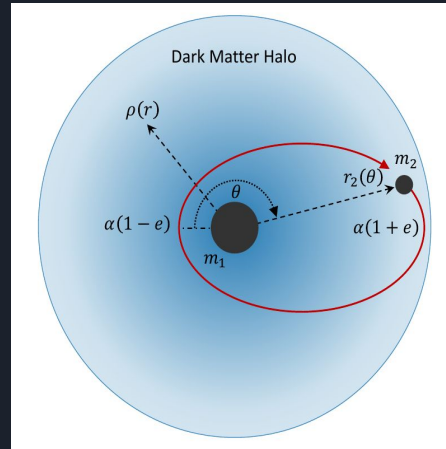
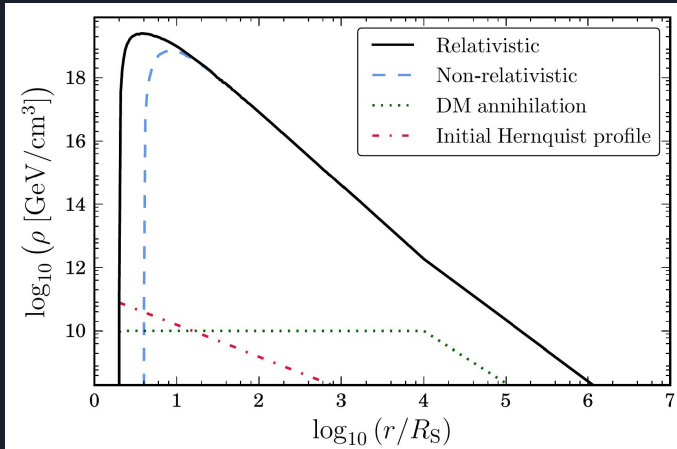
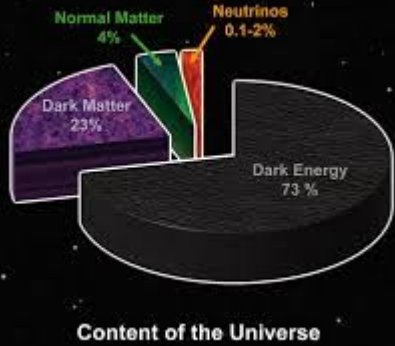
Numerical Relativity

- scenarios that cannot be accurately modelled by perturbative or analytical calculations
- little or no symmetry at all!
- GR and beyond...



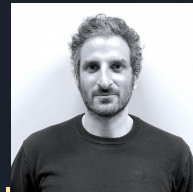
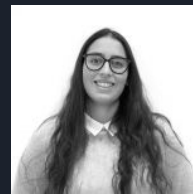
Dark matter spikes

- ❑ Prediction of DM spikes
- ❑ Use NR to evolve initial DM configurations leading to the development of DM “spikes”
- ❑ Compare with analytical predictions

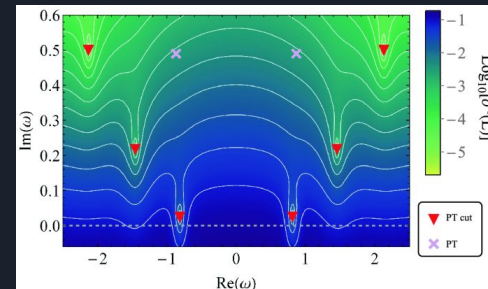
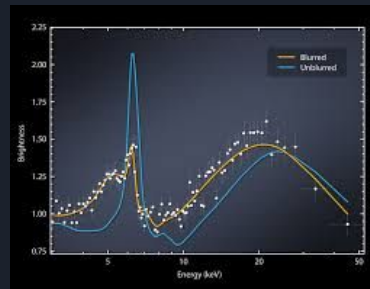
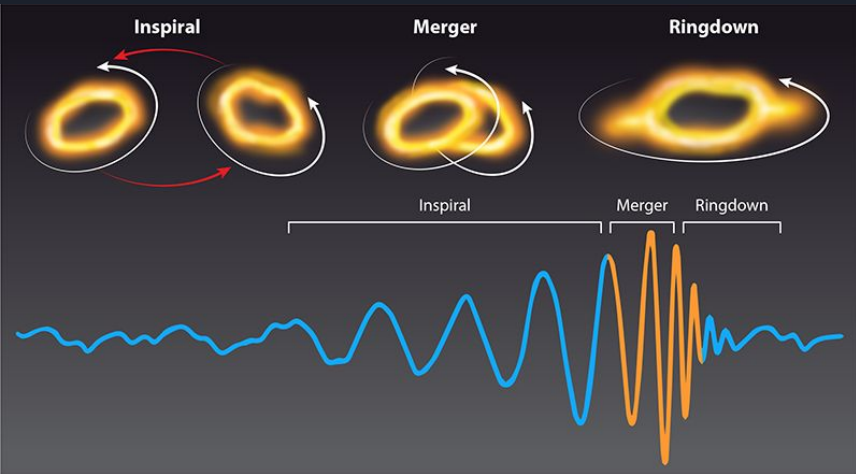


Asymmetric mass binaries and BH spectroscopy

- ringdown phase for BH systems with significant mass asymmetry
- characterize the associated GW signals from orbital configurations (inclination, eccentricity).



- Use BH spectroscopy to find BH QNMs, embedded in matter halos.



See also Laura's poster!

Ringling Black Holes: the soundtrack of spacetime



GRAN SASSO
SCIENCE INSTITUTE

Modeling the ringdown to probe new physics

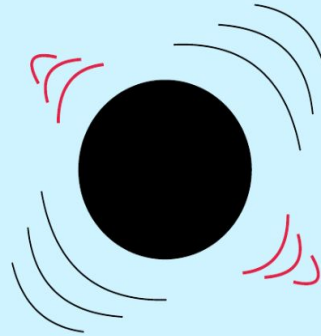
Laura Pezzella

Supervisor: Prof. Andrea Maselli



Ringdown

- ▶ For coalescing events, the signal should comprise three pieces: an **inspiral**, a **merger** and a **ringdown** waveform.
- ▶ The **ringdown** waveform originates from the **distorted final product** of the merger.
- ▶ The **amplitudes** depend on the **specific process** that formed the final BH.



Quasi-normal modes

- ▶ The **gravitational signal** emitted during the ringdown is well modeled by a **superposition** of quasi-normal modes (QNMs)
- ▶ The quasi-normal modes are **complex eigenvalues** $\omega^{(n)} = \omega_R^{(n)} + i\omega_I^{(n)}$
- ▶ QNMs **frequencies** depend only on the **final BH's parameters** (mass M and spin J in GR)