



Dark matter, GWs and compact objects

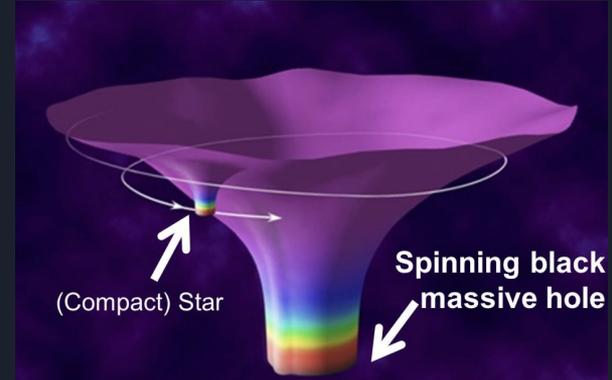
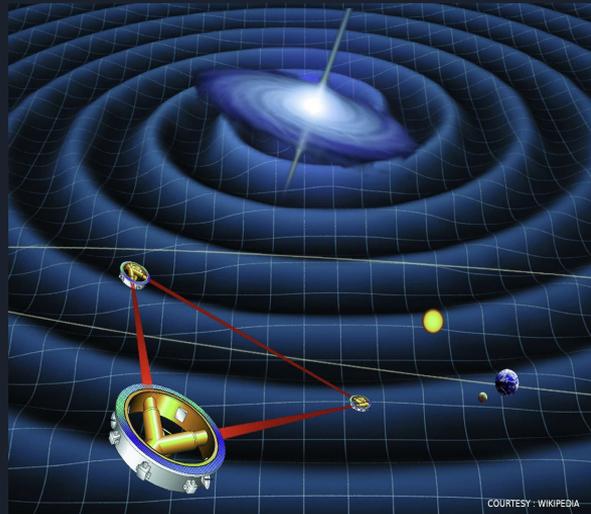
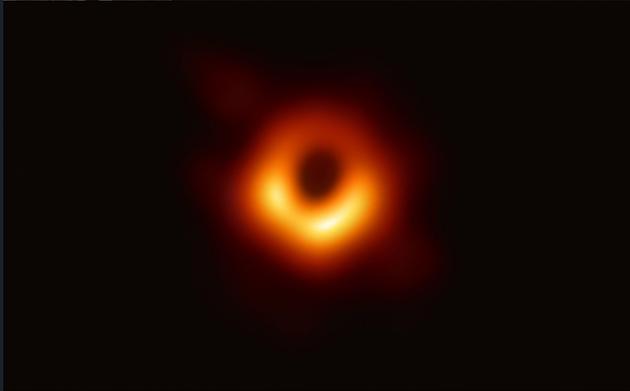
Science Fair 2026

Sayak Datta

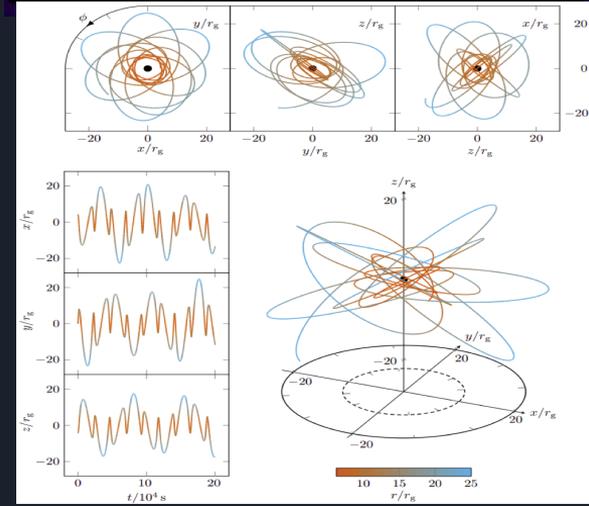


Extreme Mass-Ratio Inspirals (EMRI)

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

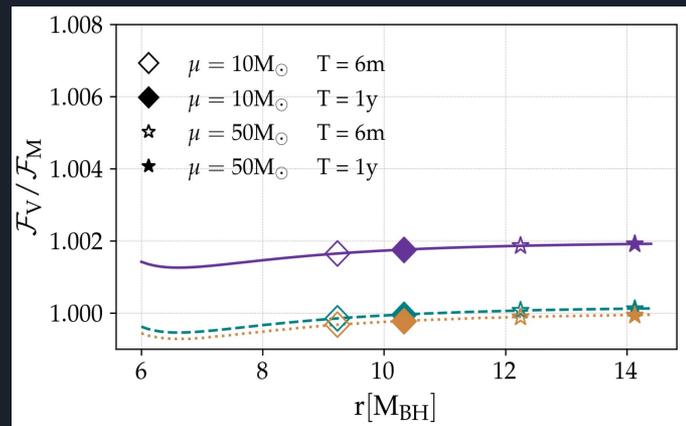


Extreme Mass Ratio Inspirals *EMRI*



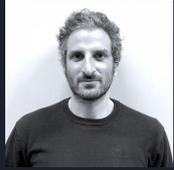
Formalism for environment in EMRIs

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



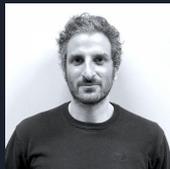
Formalism for environment in EMRIs

- Is that all?

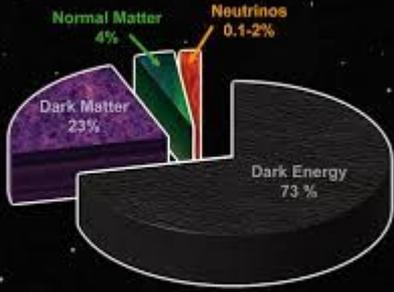


Formalism for environment in EMRIs

- ☐ Halo rotation
- ☐ Halo structure
- ☐ Dark matter
- ☐ Accretion
 - ☐ *Is that all?*
- ☐ Baryonic matter accretion
- ☐ Hot environment
- ☐ Viscosity
- ☐ Dynamical friction
- ☐ Migration
- ☐ Compact object properties
- ☐ Anisotropy?
- ☐ All important?
- ☐ Who knows!

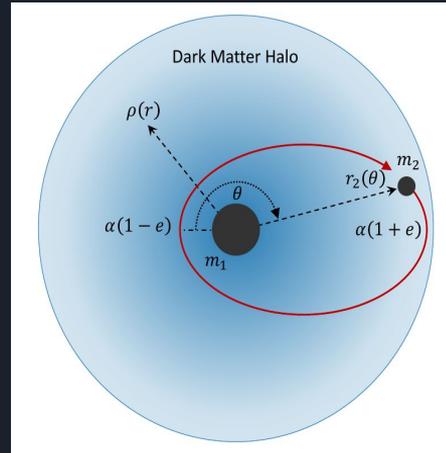
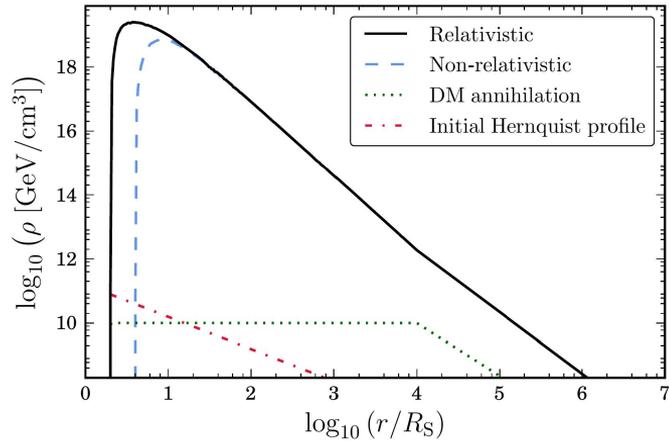


Dark matter spikes



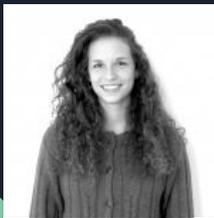
Content of the Universe

- ❑ DM forms “spikes” near BH
- ❑ Affects GW?
- ❑ QNM?



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



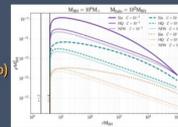
THE MODEL

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)

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

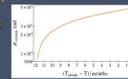


Dark matter properties encoded in:
 $T_{\mu\nu}^{(0)em} = \text{diag}(-\rho(r), 0, P_r(r), P_t(r))$
 $\rho(r) = \bar{\rho}(r)(1 - 4 M_{BH}/r)$ (Hernquist, NFW, Einasto)
 Solution for small compactness $C = M_{BH}/a_c \approx 10^{-4}$
 halo mass and length scale

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

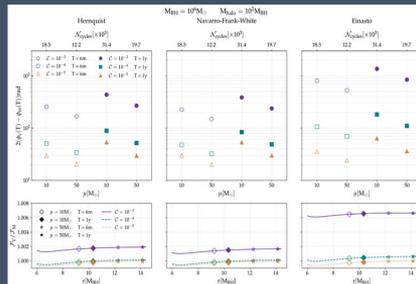
Binary systems: $M_{BH} = 10^2 M_\odot, M_2 = 10^1 M_{BH}$
 $M = 10 M_\odot, 50 M_\odot, C = 10^{-3}, 10^{-4}, 10^{-5}$
 Dark matter halos: $M_{DM} = 10^2 M_\odot$
 in vacuum in dark matter



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
 $F(h_1, h_2) = \max_{\nu, \alpha} \frac{\langle h_1 | h_2 \rangle}{\sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}}$
 $\langle h_1 | h_2 \rangle = 4 \Re \left[\int_{f_{min}}^f \tilde{h}_1(f) \tilde{h}_2^*(f) S_n^{-1}(f) df \right]$

Model	Parameter	Vacuum	Hernquist	NFW	Einasto
Max = 10 ² M _⊙ , M ₂ = 10 ¹ M _⊙ , C = 10 ⁻³	Phase	1.00	0.81	0.81	0.81
	Amplitude	1.00	0.98	0.98	0.98
	Frequency	1.00	1.00	1.00	1.00
Max = 10 ² M _⊙ , M ₂ = 10 ¹ M _⊙ , C = 10 ⁻⁴	Phase	1.00	0.84	0.82	0.82
	Amplitude	1.00	0.97	0.97	0.97
	Frequency	1.00	1.00	1.00	1.00
Max = 10 ² M _⊙ , M ₂ = 10 ¹ M _⊙ , C = 10 ⁻⁵	Phase	1.00	0.95	0.96	0.96
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FISHER MATRIX : third-order assessment

It is included in the plan for future work

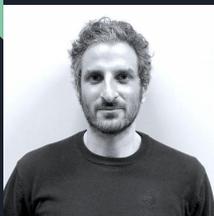
See Sara's poster!

ASYMMETRIC BINARIES AND SCALAR FIELDS

an inspiral journey from fluxes to waveforms to data analysis



See Sara's poster!



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
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EXTREME MASS-RATIO INSPIRALS

Binary systems with a stellar-mass body inspiralling into a massive Black Hole (BH)
 * Primary with $M \sim (10^1 - 10^7)$ solar masses
 * Secondary such that the mass ratio:
 $q = m_2 / M \sim (10^0 - 10^{-3})$
 * Very complicated trajectories → eccentric and off-equatorial orbits

SCIENCE CASE: TEST OF GR

"Are there new fundamental fields in the Universe that affect the gravitational interaction?"
 → Proposed beyond GR-theories feature extra fields or can be reformulated in terms of them → Compact binaries can probe the existence of such new fields

EMRIs AND SCALAR FIELDS

ARE EMRIs SENSITIVE TO NEW FIELDS?

→ In most scalar-tensor theories BHs features no-hair theorem (stationary BHs are just described by the Kerr metric)
 → Hairy BHs: the scalar field couples with high-order curvature terms
 → BH solutions with scalar hair: have scalar "charges" that are not independent but are controlled by the mass of the BH
 → GR deviations scale as $\sim M^n$ ($n > 0$)
 - Charge of the primary is negligible
 - The secondary is endowed with a scalar charge d



SETUP OF THE THEORY

Massless scalar field ϕ non-minimally coupled to the gravity sector
 $S[g, \phi, \psi] = S_g[g, \psi] + \alpha S_\phi[g, \psi] + S_m[g, \phi, \psi]$ non-minimally coupling
 dimensionalful coupling $[\alpha] = (\text{mass})^2$
 Scalar field equations:
 $G_{\mu\nu} = 8\pi\mu \int \frac{\delta^2[x^a - z^a(\tau)]}{\sqrt{-g}} u_\mu u_\nu d\tau$ background spacetime → Kerr metric (gravitational wave radiation)
 $\square\phi = -4\pi d \mu \int \frac{\delta^2[x^a - z^a(\tau)]}{\sqrt{-g}} d\tau$ extra energy loss due to ϕ (scalar radiation) $E = E_{\text{grav}} + E_{\text{scalar}}$

MEW: MODIFIED EMRI WAVEFORMS



SCALAR FLUXES ON GENERIC ORBITS

To include beyond-GR corrections we need to modify the phase, i.e. the inspiral trajectory

$$h(t) = \sum_{\ell, m} \tilde{H}_{\ell m}(t, \theta, \phi) e^{i\ell\omega t + i m \phi}$$

depends on fluxes (gravitational + scalar)

Waveform generation with few:

- Offline step: grid for amplitudes and fluxes
 - Online step: interpolation and integration to build waveforms
- python package for the rapid generation of adiabatic EMRI waveforms

Flux grid in the 4-dimensional parameter space :

$$a/M = [-0.999, 0.999] \quad e = [0, 1]$$

$$p/M = [p_{\text{min}}, 200] \quad \Theta = [0, \pi]$$

→ order (10^6) points, i.e. fluxes:

$$\tilde{E}^{\text{(grav, scalar)}}(a, p, e, \theta) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \sum_{\ell_1=0}^{\ell} \sum_{m_1=-\ell_1}^{m_1} \tilde{E}_{\ell, m, \ell_1, m_1}^{\text{(grav, scalar)}}$$

We developed a C++ code to construct scalar energy fluxes

CONSTRAINTS ON THE SCALAR CHARGE

GOALS:
 → Understand the constraints on the scalar charge with LISA observations
 → Perform a systematic study by varying the parameters of binaries
 → Focus on the dependence of the constraints on the mass ratio (from EMRI to IMRI regime)

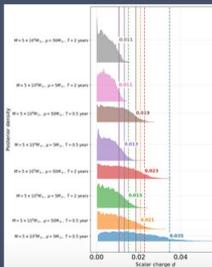


INGREDIENTS:
 → GR waveforms (few)
 → Beyond GR waveforms (few + mew)
 → Bayesian inference pipeline (er.yr: MCMC sampler)

$$\text{posterior } p(d|y) = \frac{\text{likelihood } p(y|\theta) \text{ priors } p(\theta)}{p(y)}$$

$$\theta = M, \mu, a/M, T_{\text{obs}}, D_L, \theta_s, \phi_s, \theta_{\ell}, \phi_{\ell}, \Phi_{\ell}, d$$

STRATEGY:
 True model: GR waveform ($d = 0$)
 Recovered with: beyond GR waveform ($d \neq 0$)
 → upper bound on d tells us how strong the constraint is



What's going on inside neutron stars?

Stellar Oscillations as Probes of Neutron Star Interiors

Akshita Mittal
(akshita.mittal@gssi.it)

Supervisors: Andrea Maselli, Kostas Kokkotas, Leonardo Gualtieri

Why?

- BNS GW signals probe dense matter
- Post-merger remnants emit **kHz oscillations**
- Current models fail for rapid, non-equilibrium stars
- Next-gen detectors boost high-frequency sensitivity
- Need **models linking oscillations** → **stellar properties**

Neutron Star Asteroseismology

Mode oscillations

Mass and radius relations

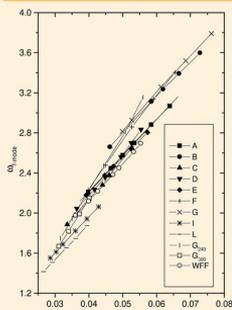
Neutron Star Background

$$\frac{dm(r)}{dr} = 4\pi r^2 \epsilon$$

$$\frac{dp}{dr} = -\frac{(\epsilon + p) [m(r) + 4\pi r^3 p]}{r [r - 2m(r)]}$$

For a metric and an EoS, you can connect the interior of a NS to the observables.

Non-Rotating Neutron Star

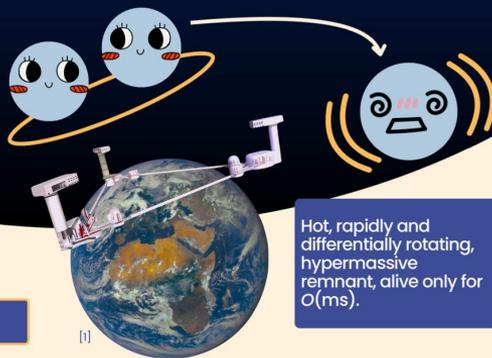


Questions to be addressed:

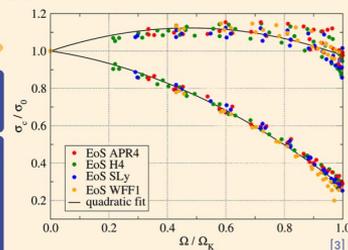
How does this change when you add more realistic effects?

- Differential rotation
- Finite temperature effects
- Viscosity

Post-Merger Neutron Stars



Hot, rapidly and differentially rotating, hypermassive remnant, alive only for $O(\text{ms})$.

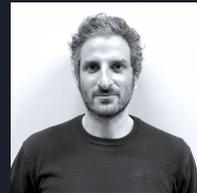


See Akshita's poster!

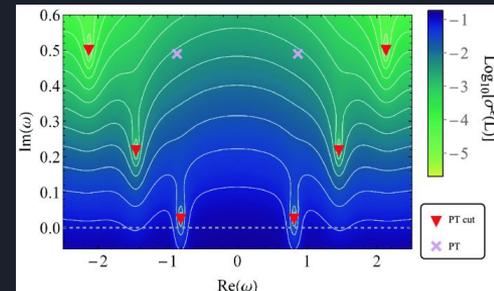
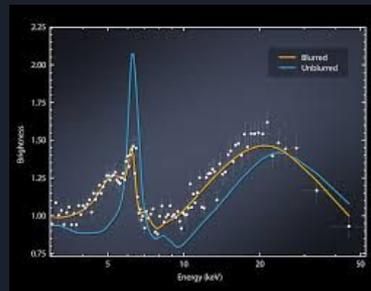
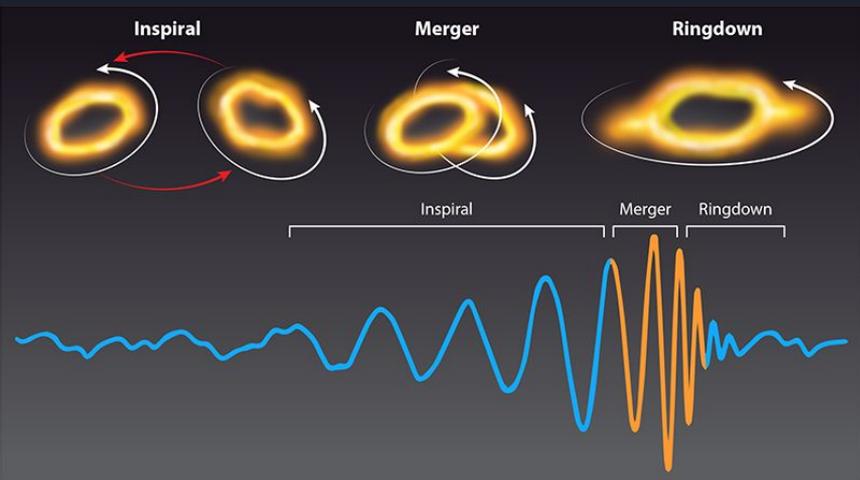


Asymmetric mass binaries and BH spectroscopy

- Ringdown phase for BH systems with mass asymmetry
- GW signals from orbital configurations.

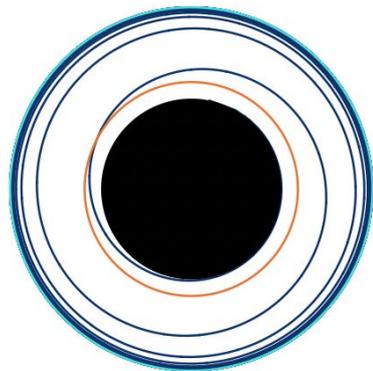


- Spectroscopy to find BH QNMs, in matter halos.



Probing ringdown physics in asymmetric black hole mergers

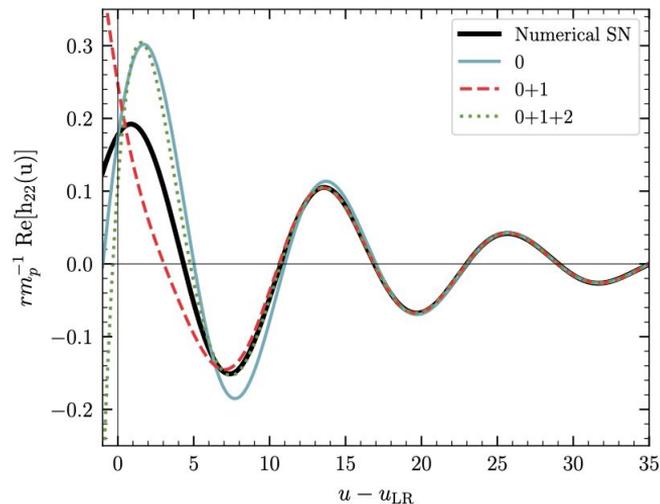
From plunge dynamics...



- ISCO
- Analytical Plunge
- Light Ring

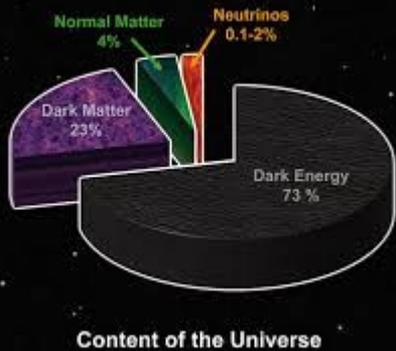
Using the right description for the **plunge** of the secondary in **asymmetric binaries** in **frequency domain**

[M. Della Rocca, LP+ \(2025\)](#)

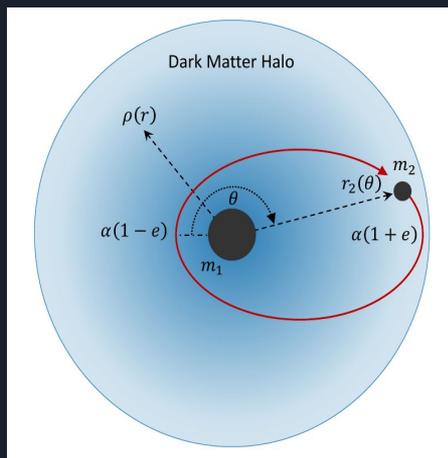
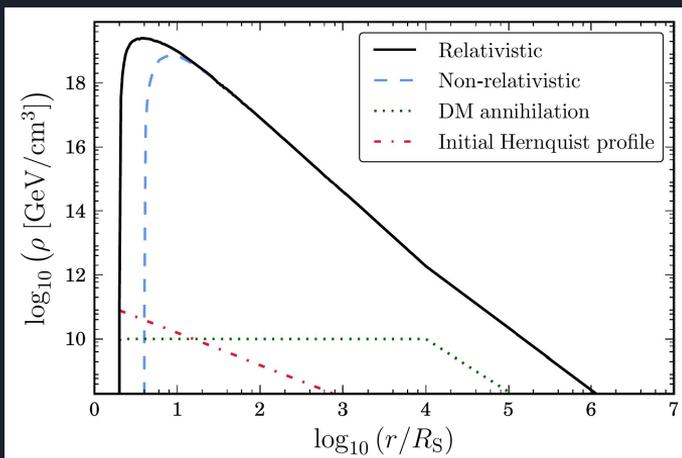


Reconstructing the amplitude of the **ringdown** signal for a circular, equatorial plunge in terms of **excitation coefficients**

Perturbation and QNM



- How EMRI injects energy into medium?
- Affects GW?
- QNM?



Course: GC5 - Sayak Datta



- What are Neutron stars?
- What makes them?
- How do they respond in tide?
- Does LIGO see them?
- What GW tells about them?
- How?
- What is in the future?