The physics of black hole binary:
geodesics, relaxation modes and energy extraction

Laura BERNARD (LUTH – Observatoire de Paris)

Journée PhyFOG – 21 mai 2019

Based on arXiv: 1905.05204

In collaboration with: Vitor Cardoso, Taishi Ikeda, Miguel Zilhão

Outline

1. Black hole binary
   i. Null geodesics
   ii. Quasinormal modes
2. Energy extraction
   i. A toy model in 2+1 dimensions
   ii. BH binary in a cavity

Introduction

- Individual black holes
  - Isolated: no-hair theorem
  - Perturbed: quasinormal modes
  - Interaction with its environment: energy extraction

- BH binaries in isolation
  - PN formalism
  - Numerical relativity

Introduction

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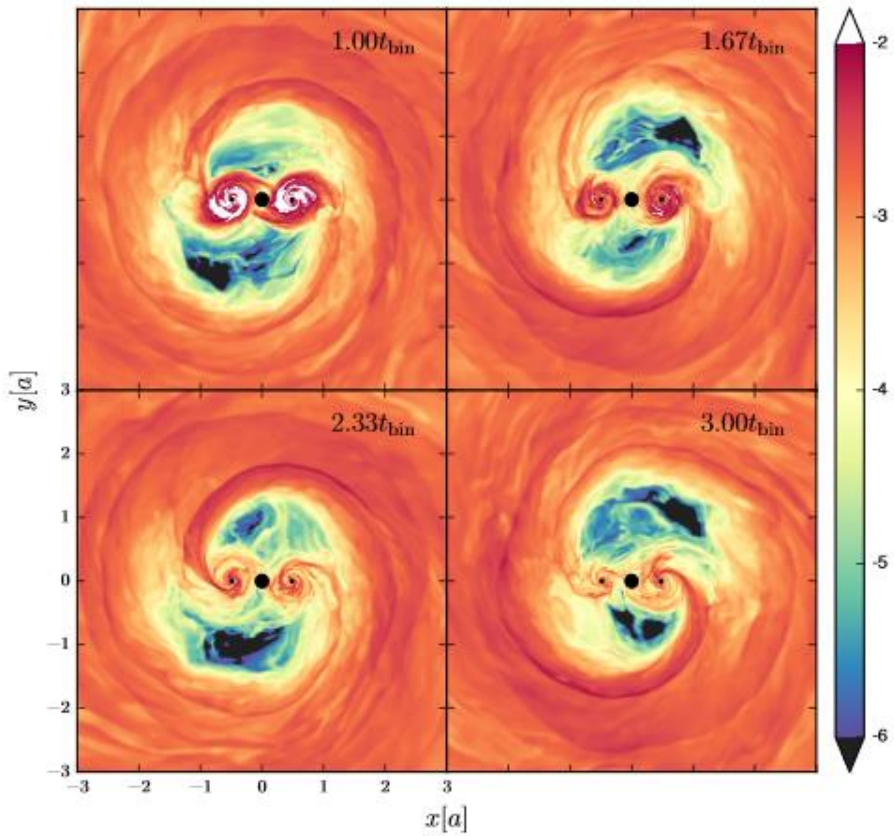
- Perturbed BH binaries ?
  - ➢ Do they have characteristics ringdown modes?
  - ➢ Do they amplify incoming low-frequency radiation?

General relativistic MHD simulations

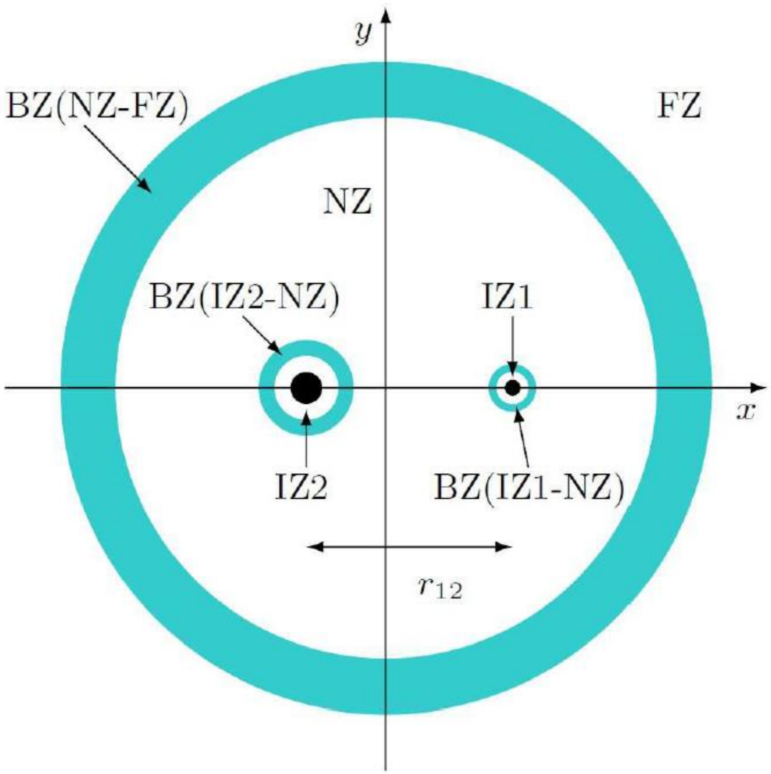
- BH binary metric : asymptotically matched PN theory and BH perturbation theory
- GR-MHD: interaction of the individual mini-disks with the circumbinary disk



[Bowen et al., 2018]

The binary spacetime

- Approximate BH binary [Mundim et al., 2014]



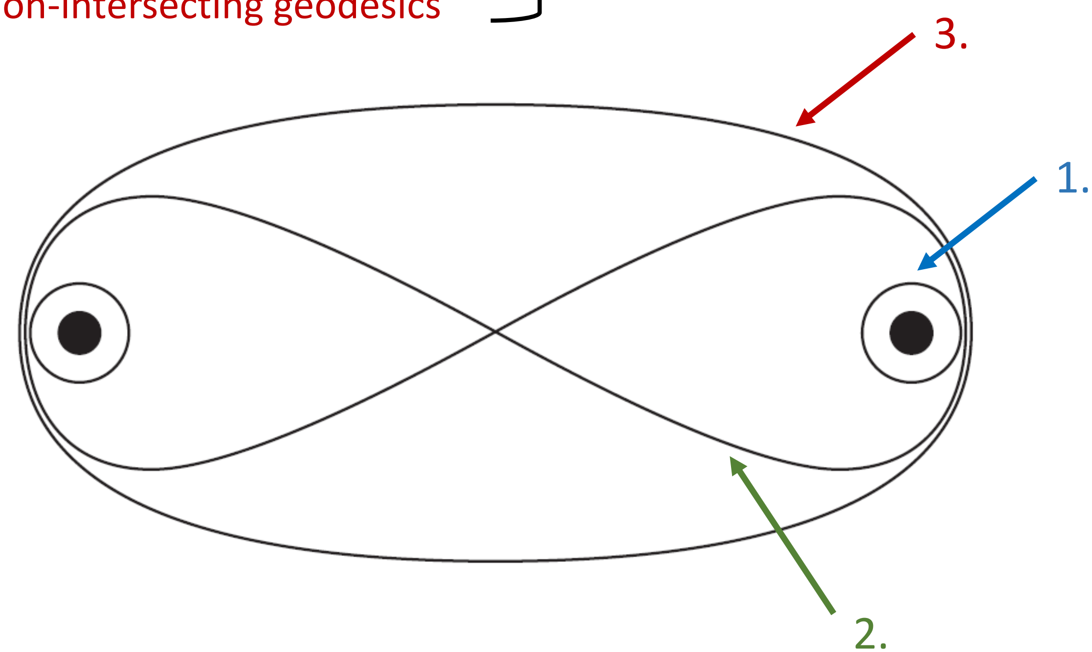
- The metrics
  - IZ1 & 2 : perturbed Schwarzschild BHs
  - NZ : 2PN metric
  - FZ : multipolar-PM expansion
- Asymptotic matching
  - **NZ/FZ** : by construction
  - **IZs/NZ** : parameter and coordinate transformation
- No GW emission, circular orbits

Geodesics

- Closed null geodesics

  1. Circular geodesics around each BH
  2. Eight-shaped trajectory
  3. Global non-intersecting geodesics

All unstable



- Similar result for closed timelike geodesics
  - more stable

Scattering and relaxation modes – the setup

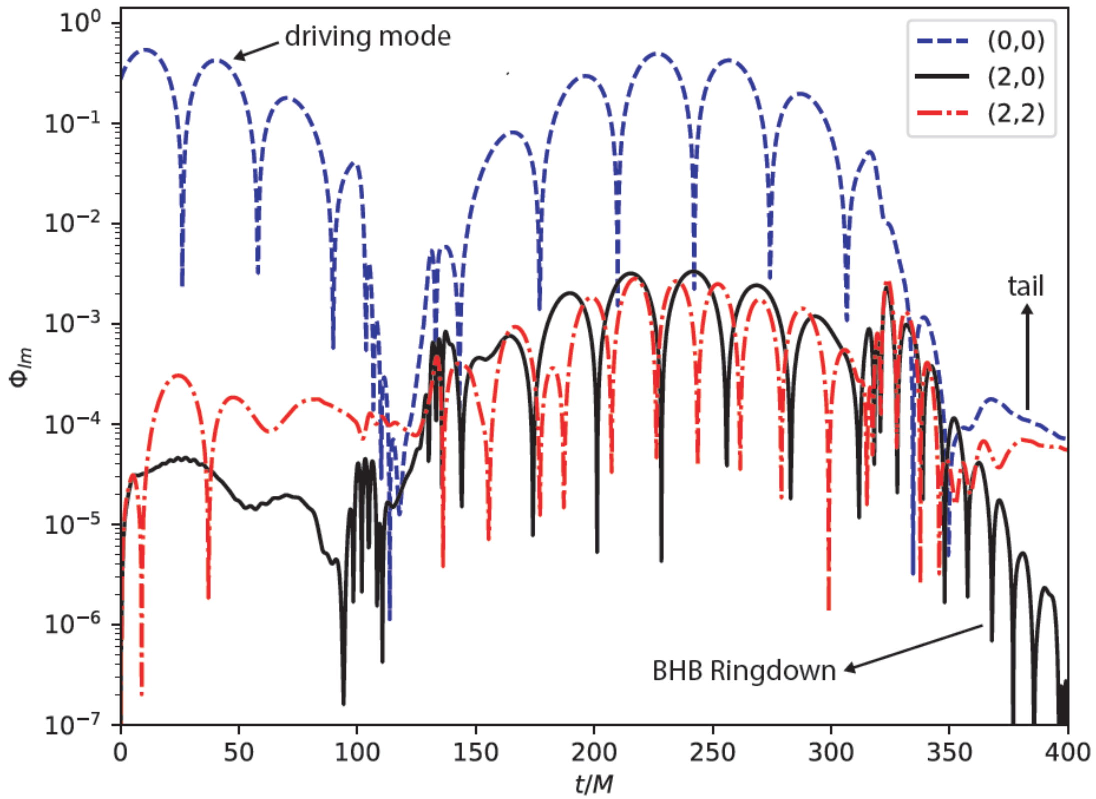
- Fixed background: asymptotically matched spacetime
- Massless scalar field
  - Klein-Gordon equation $\Box\Phi(t,\vec{x}) = 0$
  - Initial spherically symmetric ingoing pulse

$$\Phi(0,\vec{x}) \equiv \Phi_0 = \frac{\sin\omega r\, W(r)}{r}\, e^{-(r-r_0)^2/\sigma^2}$$

$$\partial_t\Phi(0,\vec{x}) = \partial_r\Phi_0 + \frac{\Phi_0}{r}$$

- Initial parameters
  - Equal-mass BHs
  - BHB separation: $L = 10, 20, 40\ M$
  - $r_0 = 100M,\ \sigma = 40, 80\ M,\ M\omega = 0.01, 0.02, 0.05, 0.1, 0.2, 0.5$

Scattering and relaxation modes – results



$$L = 10M$$

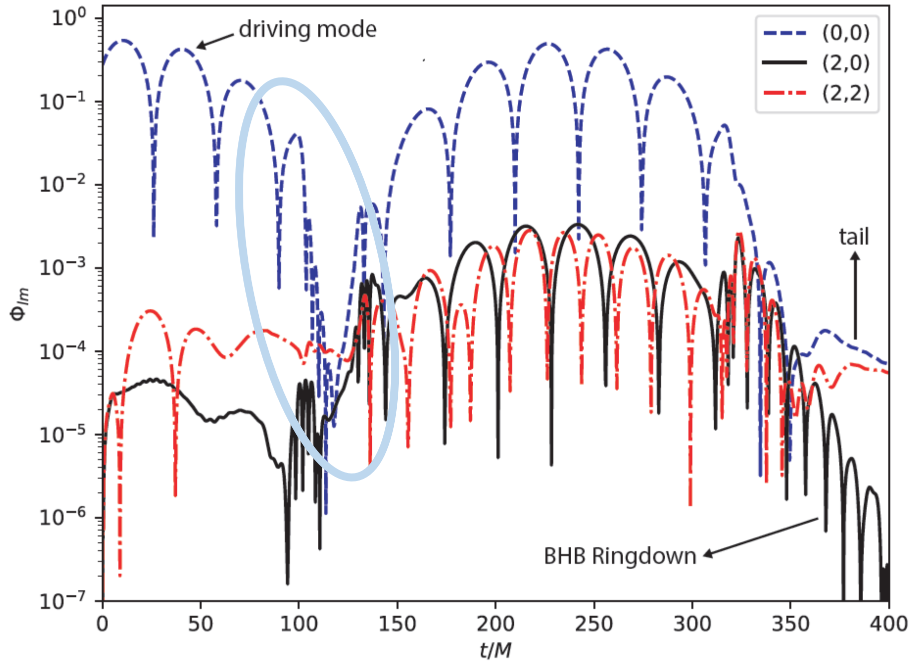
$$r_0 = 100M$$

$$\sigma = 40M$$

$$M\omega = 0.1$$

- Dominant monopolar mode: drives the dynamics
- Excitation of multipolar modes after $t = 100M$
- Tail: power-law in time $\propto t^{-7}$

Global geodesics and quasinormal modes



Damped sinusoids

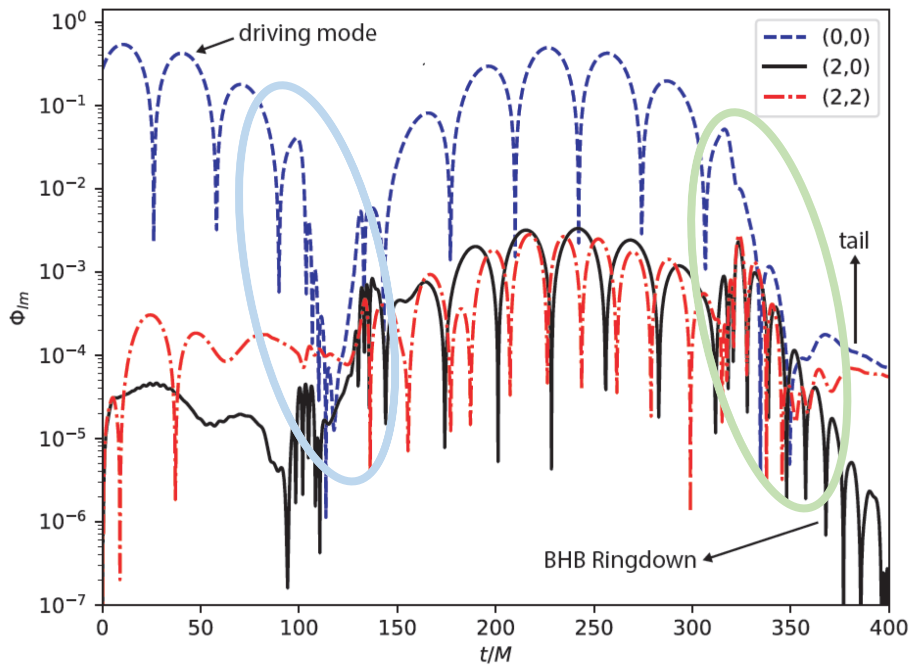
i. QNMs of individual BHs

↔

Geodesics

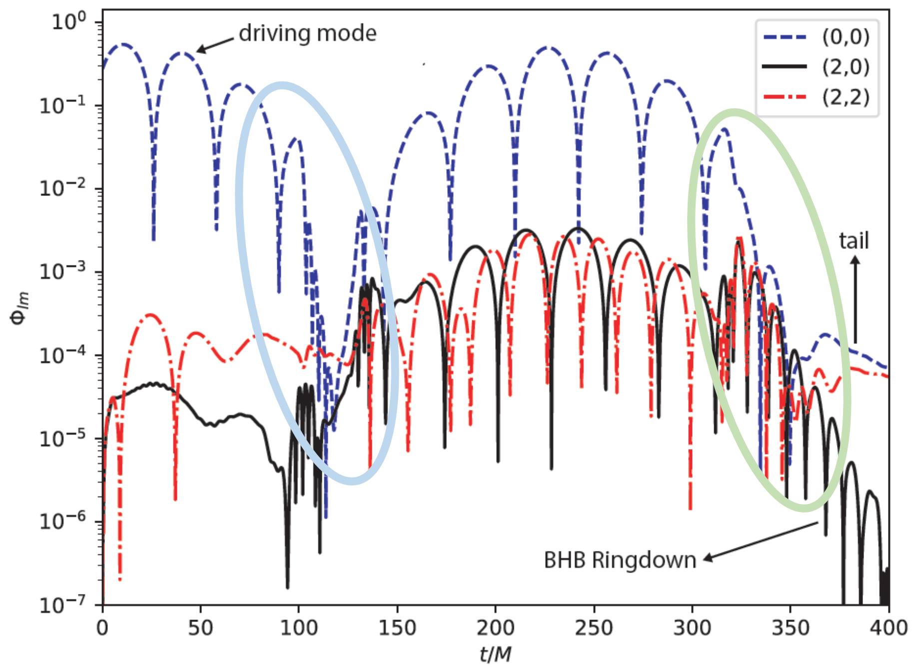
i. Around each BH

Global geodesics and quasinormal modes



Damped sinusoids		**Geodesics**
i. QNMs of individual BHs	⟷	i. Around each BH
ii. Global QNMs: period $T = L + 8M$ ($\pm 20\%$)	⟷	ii. Global geodesics $T = 1/2(2L + T_{LR})$

Global geodesics and quasinormal modes



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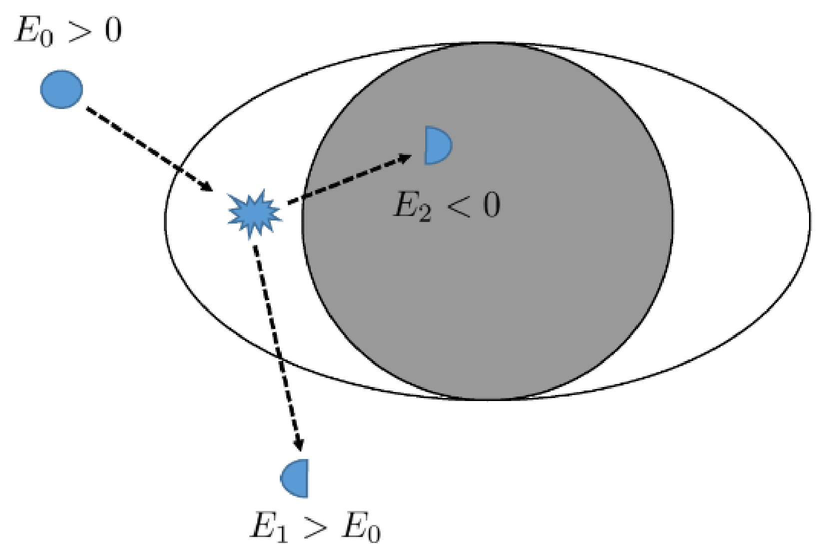
➤ Depends only on mass and separation of the binary, not initial parameters

Energy extraction

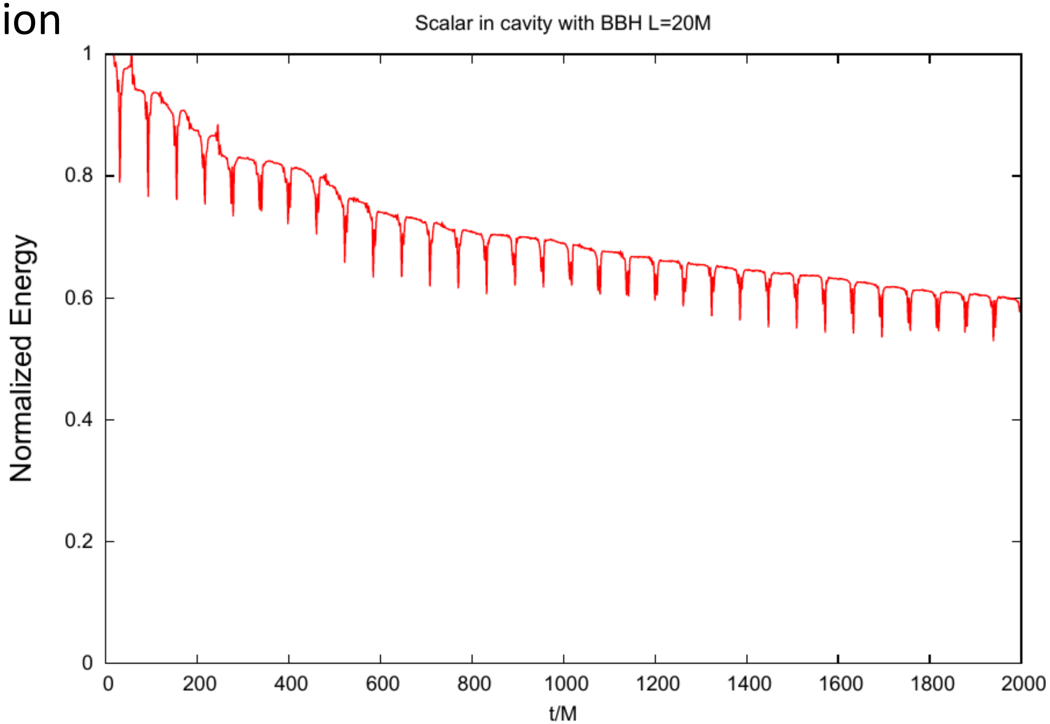
- Spinning BHs
  - Transfer rotational energy to bosonic fields: **superradiance**
  - Inside a cavity with reflecting boundaries: instability



- Gravitational slingshot
  - Transfer kinetic energy from moving planets to scattered objects

BH binary in a cavity in 3+1 dimensions

- Non-spinning BHB in a cavity
  - absorption is too large
  - timescales for energy extraction is too large
- Preliminary results:
  - Less absorption for larger separation
  - Less absorption for vectors



- A way out:
  - Spinning BHB
  - Compact stars

A toy model in 2+1 dimensions

- The setup
  - A binary of two reflecting objects
  - Inside a cavity
  - In flat 2+1 dimensions
  - Massless scalar with Gaussian initial profile
- Initial parameters
  - Orbital frequency, separation and cavity size

A toy model in 2+1 dimensions

- The setup
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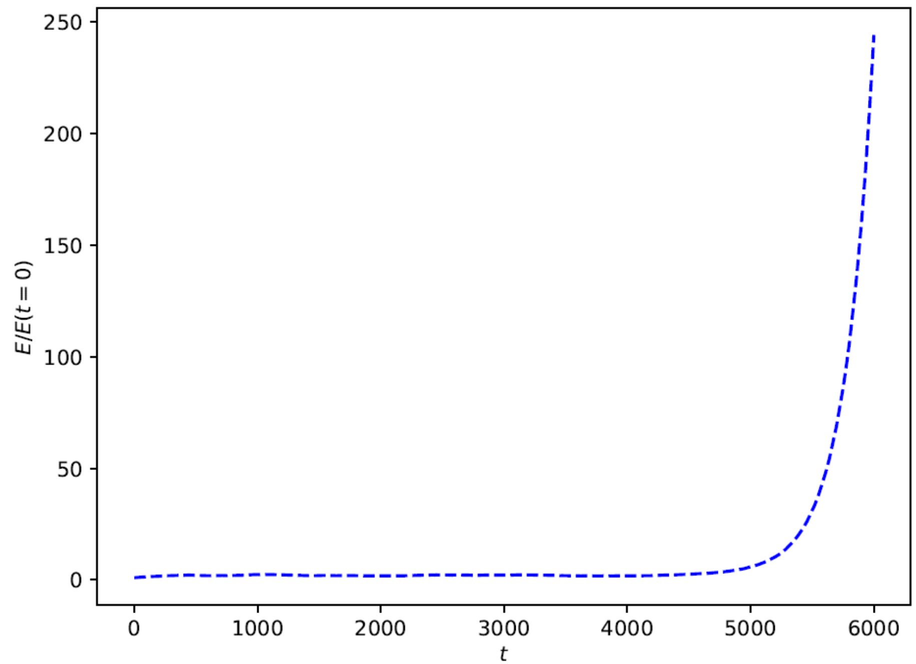
- Initial parameters
  - Orbital frequency, separation and cavity size
- Results
  - Total energy increases with time
  - Only when $\omega \sim t_{LR}$

Total energy



Concluding remarks

- Evidence of correspondence between geodesics and quasinormal modes of BH binaries
  - BHB spectroscopy in the future
- A small particle orbiting one BH could resonantly excite the global QNMs
  - For $L = 38M$ $\longrightarrow$ particle at the ISCO of one BH
- Energy extraction and instability
  - Spinning BHs
  - Compact stars
  - Is the instability relevant for astrophysical systems (i.e. during a binary lifetime) ?

Majumdar-Papapetrou spacetime

- Exact solution in GR describing two maximally charged BHs: $Q = M$

$$ds^2 = -\frac{dt^2}{U^2} + U^2\left(d\rho^2 + \rho^2 d\phi^2 + dz^2\right) \quad \text{with} \quad U(\rho,\, z) = 1 + \frac{M}{\sqrt{\rho^2 + (z-a)^2}} + \frac{M}{\sqrt{\rho^2 + (z+a)^2}}$$

- Closed null geodesics: instable
- Closed timelike geodesics: stable