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Binaries Wandering Around Supermassive Black Holes Due To Gravito-electromagnetism

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Introduction

A stellar-mass binary black hole (BBH) within the LIGO/ Virgo sources is likely to exist in close proximity to a Kerr supermassive black hole (SMBH), as suggested by recent astrophysical models.

A BBH reaching **several gravitational radii** of a SMBH will induce rich observable signatures in the waveform. **One or two BBH** out of the approximately 100 detected events in LIGO/Virgo may originate from the vicinities of supermassive black holes (SMBHs), accounting for 1-2% of the current detection rate[1-2].

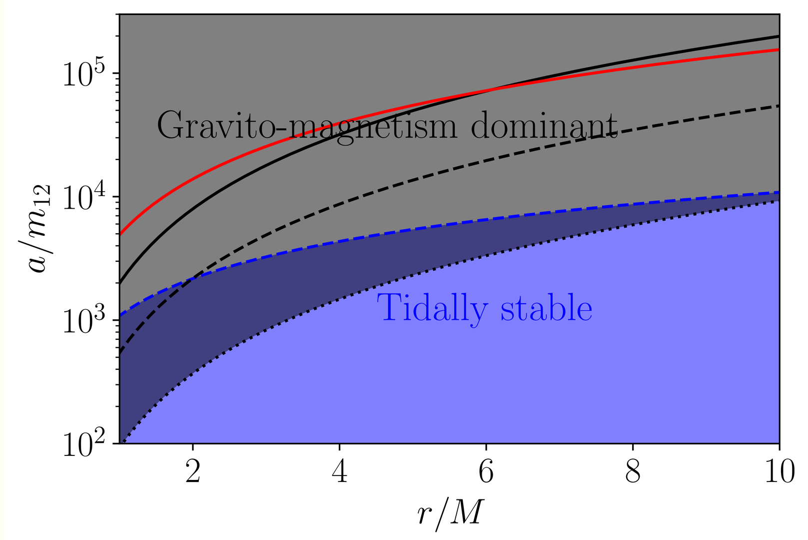

FIG. 1. The parameter space of BBHs around a SMBH

Numerical tools currently available are **inadequate** for simulating such a triple system with accurate representation of the essential relativistic effects.

Since the BBH is normally non-relativistic and much smaller than the curvature radius of the Kerr background, the evolution in the free-fall frame (FFF) reduces to essentially **Newtonian dynamics, except for a perturbative gravito-electromagnetic (GEM)** force. Therefore, the equations of motion in the FFF can be expressed as

$$m_a \frac{d^2\mathbf{x}_a}{d\tau^2} = -m_a m_b \frac{\mathbf{x}_a - \mathbf{x}_b}{|\mathbf{x}_a - \mathbf{x}_b|^3} + \mathbf{F}_a(\tau, \mathbf{x}_a, \mathbf{v}_a).$$

Here we study the BBHs on **near-circular orbits** around a SMBH and track their evolution down to a distance of 2-3 gravitational radii from the SMBH.

Gravito-electromagnetism

The perturbation of GEM forces in the FFF can be formulated with

$\mathbf{F} = -m\mathbf{E} - 2m\mathbf{v} \times \mathbf{B}$,

where the GEM fields are

$\mathbf{E}_\mathbf{i}(\tau, \mathbf{x}) = R_{0i0j}(\tau)x^j$,

$\mathbf{B}_\mathbf{i}(\tau, \mathbf{x}) = -1/2\epsilon_{ijk}R^{jk}{}_{0l}(\tau)x^l$.

The Riemann tensor in the FFF can be transferred from BL through

- tetrad transformations,
- Lorentz transformations,
- and spatial rotations.

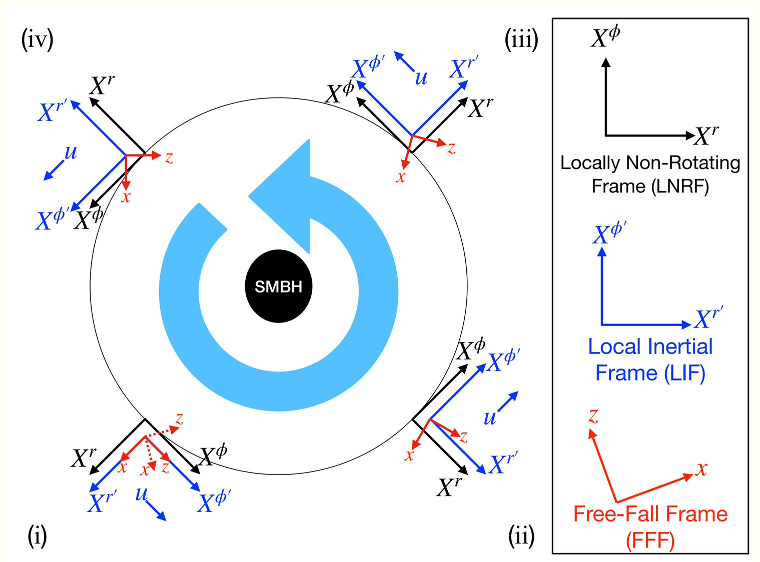

FIG. 3. Different reference frames and their relative orientation as they rotate around the SMBH.

Effects of GEM forces

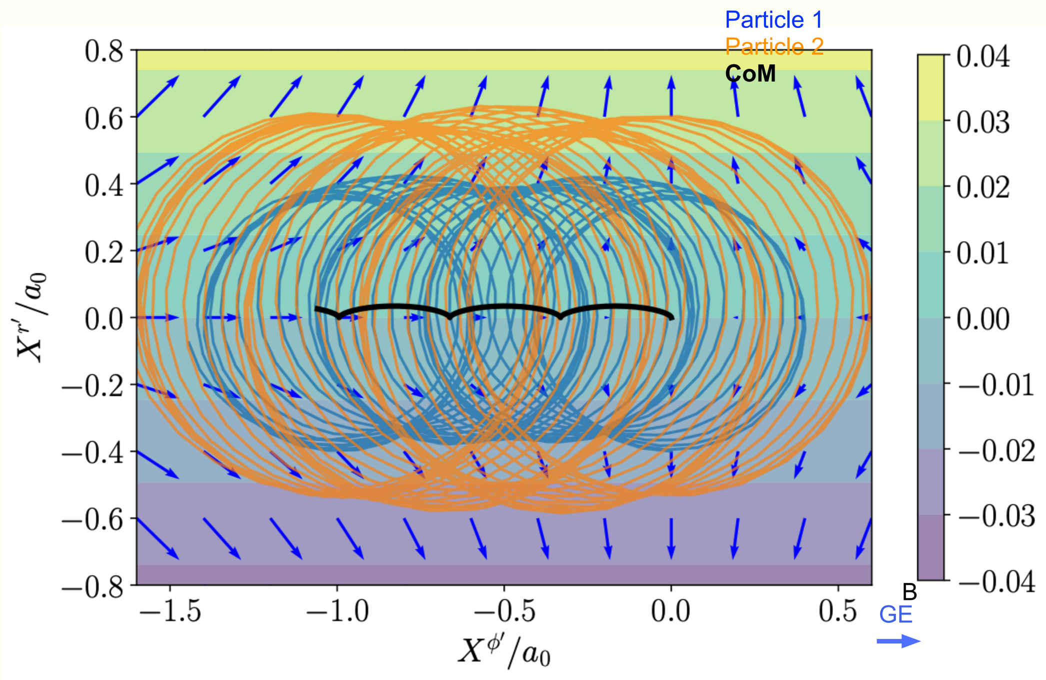

FIG.4. Evolution of the prograde BBH in the FFF. The length is proportional to the strength of the force. The background color indicates the gravitomagnetic field, which is perpendicular to the plane

The center of mass (CoM) of the BBH does **not follow a geodesic line**. We identified the cause of the geodetic deviation to be a nonvanishing GEM force on the CoM.

Deviation from a geodesic

Our simulations reveal a series of dynamical effects. The most notable one is **a radial oscillation and azimuthal drift of the BBH relative to the SMBH**. These results provide new insight into the evolution and detection of the EMRIs containing BBHs.

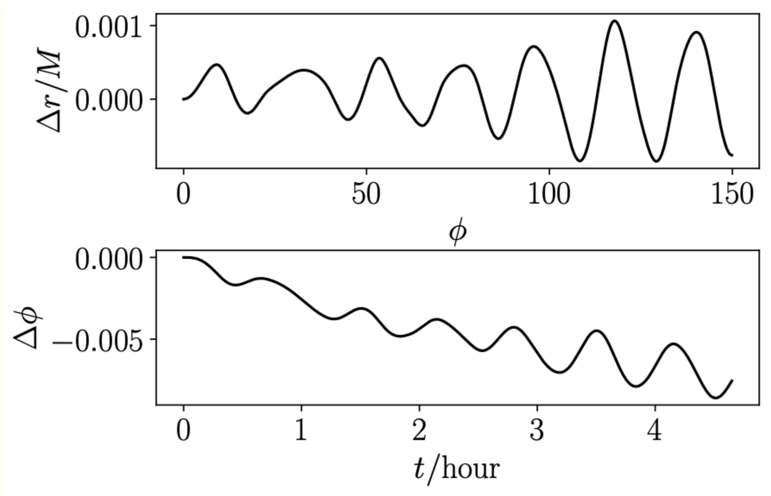

FIG. 5. Variation of the radial (upper panel) and azimuthal (lower panel) Boyer-Lindquist coordinates with respect to a circular geodesic. r =2.8M.

Observable signatures

Orbital frequency of inner orbit（**BBH**）is about 10 milli-Hertz. With the gravitational and Doppler redshifts, it remains **in the sensitive band of LISA.**

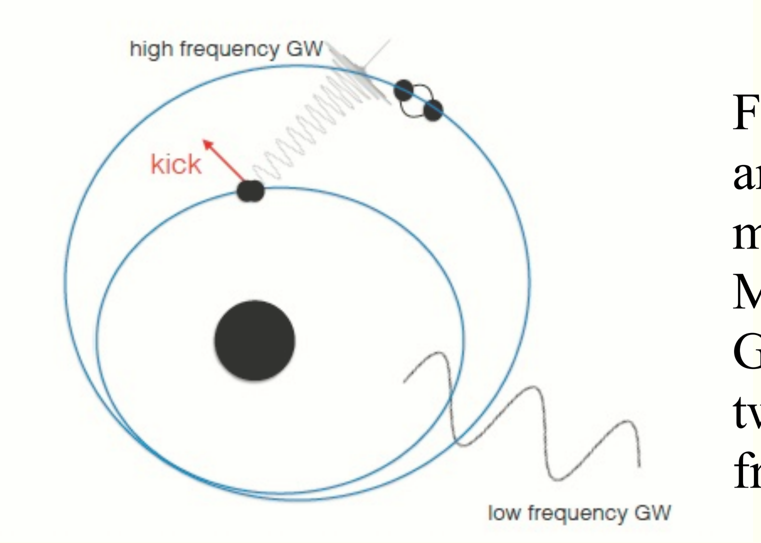

FIG.6. Physical picture of a BBH around the SMBH [4]. The motion of the BBH around the MBH generates low-frequency GWs and the coalescence of the two small BHs produces high-frequency waves.

The outer orbit (**CoM around SMBH**) is about 1mHz. Therefore, the GWs may also be detectable by LISA. The deviation is **detectable** by contrasting the observed signal with a standard EMRI. A mismatch over a period of one to two weeks would be sufficient to reveal.

Referrece

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[2] P. Peng and X. Chen, Mon. Not. R. Astron. Soc. 505, 1324(2021)

[3] X. Chen and W.-B. Han, Commun. Phys. 1, 53 (2018).