Gravitational waves from star-like objects orbiting the Galactic Center black hole

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based on a collaboration with
Alexandre Le Tiec, Frédéric Vincent & Niels Warburton
arXiv:1903.02049

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Observatoire de la Côte d'Azur
Nice, France
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Outline

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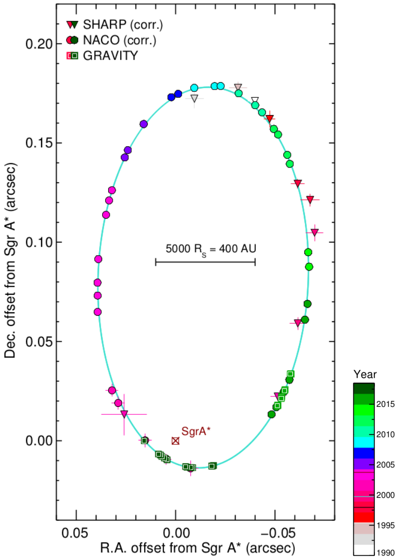
Sgr A*: the massive black hole at the Galactic center



- distance: $d = 8.12\ \mathrm{kpc}$
- mass:

$$\begin{aligned} M &= 4.10\times 10^6\, M_\odot \\ &= 20.2\ \mathrm{s} \qquad (c = G = 1) \\ &= 6.06\times 10^9\ \mathrm{m} \\ &= 4.05\times 10^{-2}\ \mathrm{au} \\ &= 1.96\times 10^{-7}\ \mathrm{pc} \end{aligned}$$

$$\iff 1\ \mathrm{pc} = 5.10\times 10^6 M$$

- spin $J = aM$ unknown yet...

← Orbit of star S2 around Sgr A*

S2: main-sequence B star

orbital period: $P = 16.05\ \mathrm{yr}$

periastron (May 2018):

- $r_{\rm per} = 120\ \mathrm{au} = 3\times 10^3 M$
- $v_{\rm per} = 7650\ \mathrm{km\,s^{-1}} = 0.025\,c$

[GRAVITY team, A&A **615**, L15 (2018)]

Sgr A*: the next image of the Event Horizon Telescope

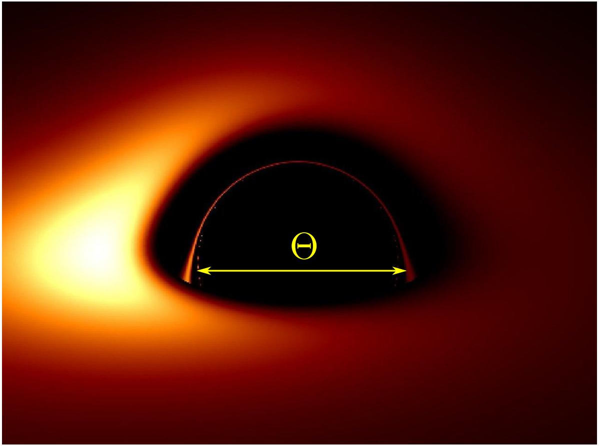


Image of a thin accretion disk around a Schwarzschild BH

[Vincent, Paumard, Gourgoulhon & Perrin, CQG **28**, 225011 (2011)]

Angular diameter of the silhouette of a Schwarzschild BH of mass M seen from a distance d:

$$\Theta = 6\sqrt{3}\,\frac{M}{d} \simeq 2.60\,\frac{2R_{\rm S}}{d}$$

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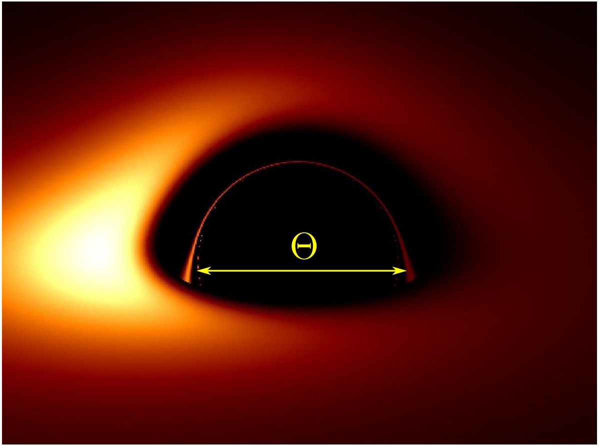

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Largest black holes in the Earth's sky:

Sgr A* : $\Theta = 53\ \mu\text{as}$
M87 : $\Theta = 21\ \mu\text{as}$
M31 : $\Theta = 20\ \mu\text{as}$

Remark: black holes in X-ray binaries are $\sim 10^5$ times smaller, for $\Theta \propto M/d$

No-hair theorem $\Longrightarrow$ central BH = Kerr BH

Dorochkevitch, Novikov & Zeldovitch (1965), Israel (1967), Carter (1971), Hawking (1972)

Within 4-dimensional general relativity, a *stationary* black hole in an otherwise empty universe is necessarily a Kerr-Newmann black hole, which is an electro-vacuum solution of Einstein equation described by only 3 numbers:

- the total mass M
- the total specific angular momentum $a = J/M$
- the total electric charge Q

$\Longrightarrow$ *"a black hole has no hair"* (John A. Wheeler)

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- $Q = 0$: Kerr solution (1963)

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Other special cases:

- $a = 0$: Reissner-Nordström solution (1916, 1918)
- $a = 0$ and $Q = 0$: Schwarzschild solution (1916)
- $a = 0$, $Q = 0$ and $M = 0$: Minkowski metric (1907)

The Kerr metric

Roy Kerr (1963)

Expression in Boyer-Lindquist coordinates:

$$g_{\alpha\beta}\,\mathrm{d}x^\alpha\,\mathrm{d}x^\beta = -\left(1-\frac{2Mr}{\rho^2}\right)\mathrm{d}t^2 - \frac{4Mar\sin^2\theta}{\rho^2}\,\mathrm{d}t\,\mathrm{d}\varphi + \frac{\rho^2}{\Delta}\,\mathrm{d}r^2 + \rho^2\mathrm{d}\theta^2 + \left(r^2+a^2+\frac{2Ma^2r\sin^2\theta}{\rho^2}\right)\sin^2\theta\,\mathrm{d}\varphi^2$$

where $\rho^2 := r^2 + a^2\cos^2\theta$, $\Delta := r^2 - 2Mr + a^2$ and $\boxed{r \in (-\infty, \infty)}$

→ spacetime manifold: $\mathscr{M} = \mathbb{R}^2 \times \mathbb{S}^2 \setminus \{r = 0\ \&\ \theta = \pi/2\}$

→ 2 parameters: M: gravitational mass; $a := J/M$ reduced angular momentum

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→ Schwarzschild solution as the subcase $a = 0$:

$$g_{\alpha\beta}\,\mathrm{d}x^\alpha\,\mathrm{d}x^\beta = -\left(1-\frac{2M}{r}\right)\mathrm{d}t^2 + \left(1-\frac{2M}{r}\right)^{-1}\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2+\sin^2\theta\,\mathrm{d}\varphi^2\right)$$

Basic properties of Kerr metric

- asymptotically flat $(r \to \pm\infty)$
- stationary: metric components independent from t
- axisymmetric: metric components independent from φ
- not static when $a \neq 0$
- contains a black hole $\iff$ $\boxed{0 \leq a \leq M}$

  event horizon: $r = r_+ := M + \sqrt{M^2 - a^2}$
- contains a curvature singularity at $\rho = 0 \iff r = 0$ and $\theta = \pi/2$

Physical meaning of the parameters M and J

- mass M: *not* a measure of the "amount of matter" inside the black hole, but rather a *characteristic of the external gravitational field*
  $\rightarrow$ measurable from the orbital period of a test particle in far circular orbit around the black hole *(Kepler's third law)*

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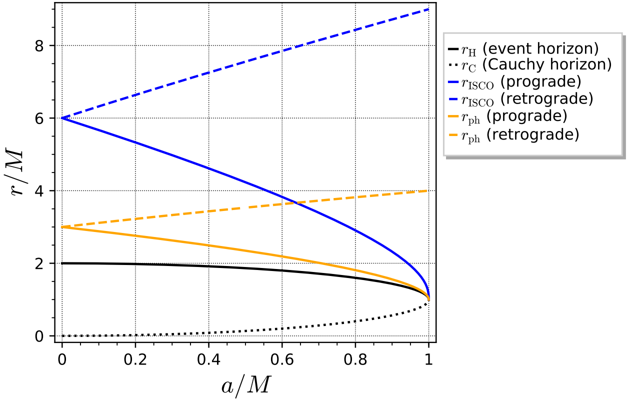
Remark: the radius of a black hole is not a well defined concept: it *does not* correspond to some distance between the black hole "centre" and the event horizon. A well defined quantity is the area of the event horizon, A.
The radius can be then defined from it: for a Schwarzschild black hole:

$$R := \sqrt{\frac{A}{4\pi}} = \frac{2GM}{c^2} \simeq 3 \left(\frac{M}{M_\odot} \right) \ \mathrm{km}$$

Outline

Circular orbits in the equatorial plane of a Kerr black hole

Circular orbits exist and are stable for $r \geq r_{\rm ISCO} = \begin{cases} 6M & \text{for } a = 0 \\ M & \text{for } a = M \end{cases}$

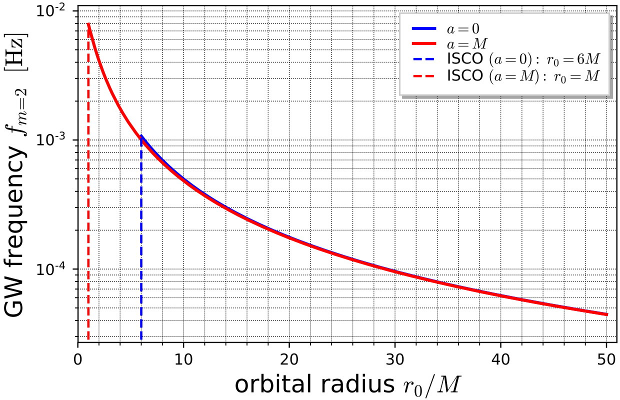


$r_{\rm ISCO}$: radius of the innermost stable circular orbit

$r_{\rm ph}$: radius of circular photon orbit

- $a/M = 0$: Schwarzschild black hole (non-rotating)
- $a/M = 1$: maximally rotating Kerr black hole

GW frequencies from circular orbits around Sgr A*



Angular velocity of circular equatorial orbits around a Kerr BH

$$\omega_0 = \frac{M^{1/2}}{r_0^{3/2} + aM^{1/2}}$$

Dominant GW frequency

$$f_{m=2} = 2f_0 = \frac{\omega_0}{\pi}$$

Sgr A* mass

$$M = 4.10 \times 10^6\ M_\odot = 20.2\ \mathrm{s}$$

[Gravity team, A&A **615**, L15 (2018)]

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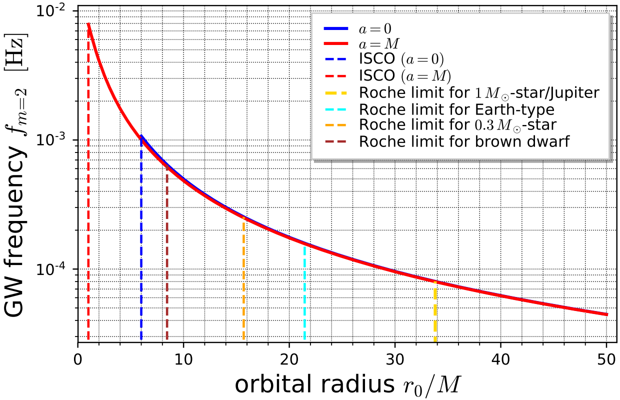

Roche radius: $r_{\rm R} \simeq 1.14 \left(\frac{M}{\rho}\right)^{1/3}$

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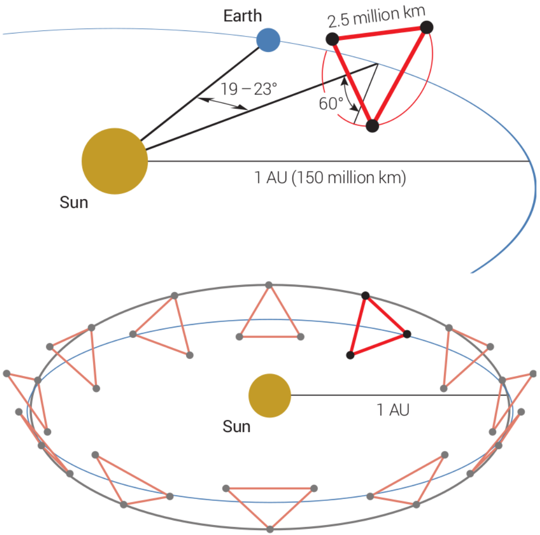
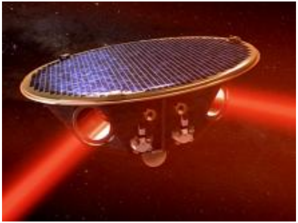
The LISA gravitational wave detector

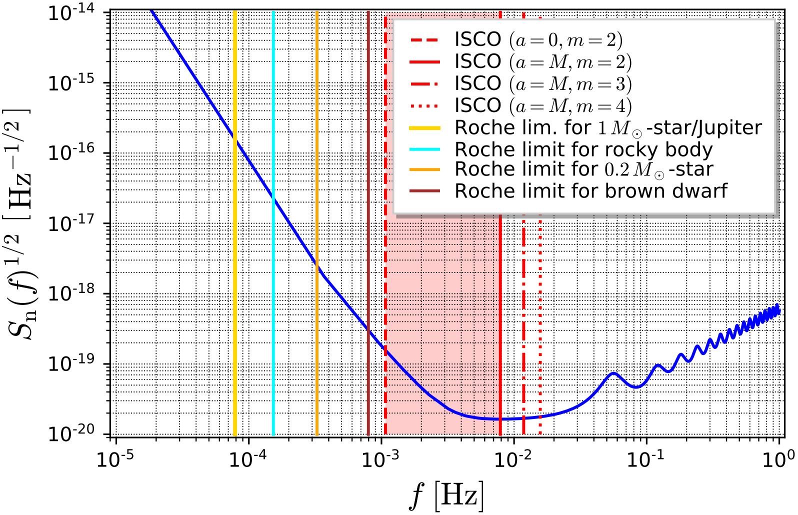


[LISA proposal for L3 (2017)]

Laser Interferometer Space Antenna (LISA)
selected as ESA L3 mission
Launch ∼ 2034



Frequencies of Sgr A* close orbits are in LISA band



ISCO for $a = M$: $f_{m=2} = 7.9\ \mathrm{mHz}$

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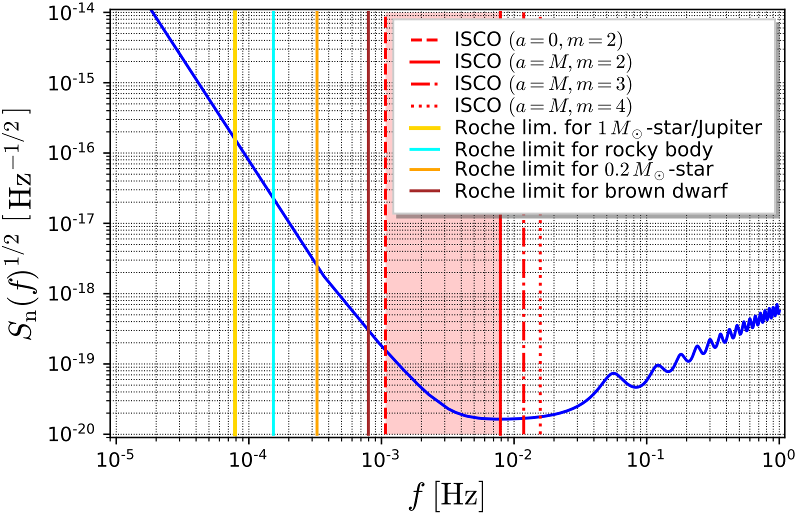

ISCO for $a = M$: $f_{m=2} = 7.9\ \mathrm{mHz}$ ← coincides with LISA max. sensitivity!

Previous studies of Sgr A* as a source for LISA

- Freitag (2003) [ApJ **583**, L21]: GW from orbiting stars at quadrupole order; low-mass main-sequence (MS) stars are good candidates for LISA
- Barack & Cutler (2004) [PRD **69**, 082005]: $0.06 M_\odot$ MS star observed $10^6 \mathrm{yr}$ before plunge $\Longrightarrow$ SNR = 11 in 2 yr of LISA data $\Longrightarrow$ Sgr A*'s spin within 0.5% accuracy
- Berry & Gair (2013) [MNRAS **429**, 589]: extreme-mass-ratio burst (single periastron passage on a highly eccentric orbit) $\Longrightarrow$ GW burst $\Longrightarrow$ LISA detection of $10 M_\odot$ for periastron $< 65M$; event rate could be $\sim 1\,\mathrm{yr}^{-1}$
- Linial & Sari (2017) [MNRAS **469**, 2441]: GW from orbiting MS stars undergoing Roche lobe overflow $\Longrightarrow$ detectability by LISA; possibility of a *reverse chirp signal (outspiral)*
- Kühnel et al. (2018) [arXiv:1811.06387]: GW from an ensemble of macroscopic dark matter candidates orbiting Sgr A*, such as primordial BHs, with masses in the range $10^{-13} - 10^3 \ M_\odot$
- Amaro-Seoane (2019) [arXiv:1903.10871]: *Extremely Large Mass-Ratio Inspirals (X-MRI)* $\Longrightarrow$ brown dwarfs orbiting Sgr A* should be detected in great numbers by LISA: ~ 20 in band at any time

Our study

All previous studies have been performed in a Newtonian framework (quadrupole formula). Now, for orbits close to the ISCO, relativistic effects are expected to be important.

$\Longrightarrow$ we have adopted a fully relativistic framework:

- Sgr A* is modeled as a Kerr BH and GW are computed via the theory of perturbations of the Kerr metric
- tidal effects are evaluated via the theory of Roche potential in the Kerr metric developed by Dai & Blandford (2013) [MNRAS **434**, 2948]

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Limitation: circular equatorial orbits; valid for

- inspiralling compact objects arising from the tidal disruption of a binary *(zero-eccentricity EMRI)*
- main-sequence stars formed in an accretion disk
- compact objects resulting from the most massive of such stars
- $\sim 1/4$ of the population of brown dwarfs studied by Amaro-Seoane (2019)

Outline

Waveforms from circular orbits

computed as linear perturbations of Kerr metric (Teukolsky 1973)

Detweiler (1978)

$$h_+ - \mathrm{i} h_\times = \frac{2\mu}{r} \sum_{\ell=2}^{\infty} \sum_{\substack{m=-\ell \\ m\neq 0}}^{\ell} \frac{Z^{\infty}_{\ell m}(r_0)}{(m\omega_0)^2} \, {}_{-2}S^{am\omega_0}_{\ell m}(\theta,\varphi) \, \mathrm{e}^{-\mathrm{i}m(\omega_0(t-r_*)+\varphi_0)}$$

μ: mass of orbiting object; (t, r, θ, φ): Boyer-Lindquist coordinates of the observer
${}_{-2}S^{am\omega_0}_{\ell m}(\theta,\varphi)$: spheroidal harmonics of spin weight -2

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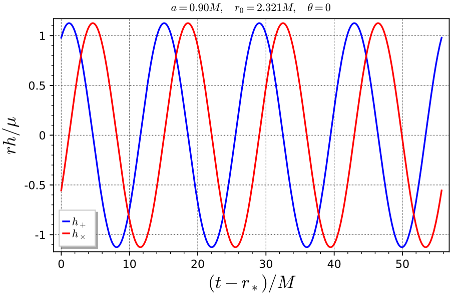
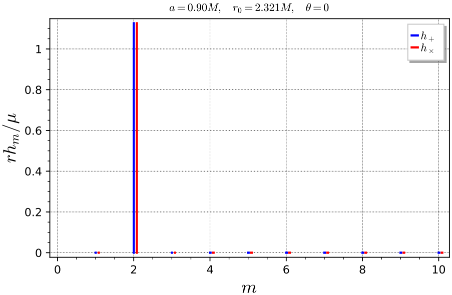
Example for $a = 0.9\,M$, $r_0 = r_{\rm ISCO}(a)$ and viewing angle $\theta = 0$ (face-on)





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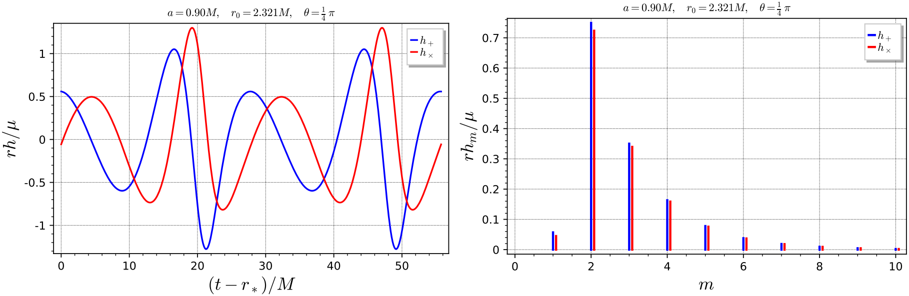
Example for $a = 0.9\,M$, $r_0 = r_{\rm ISCO}(a)$ and viewing angle $\theta = \pi/4$



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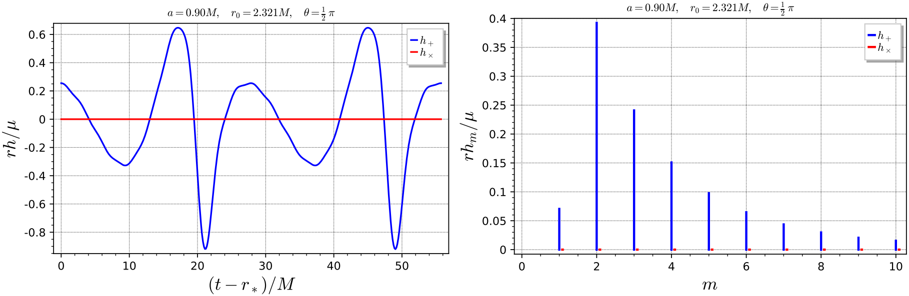
Example for $a = 0.9\,M$, $r_0 = r_{\mathrm{ISCO}}(a)$ and viewing angle $\theta = \pi/2$ (edge-on)



Implementation: the kerrgeodesic_gw package

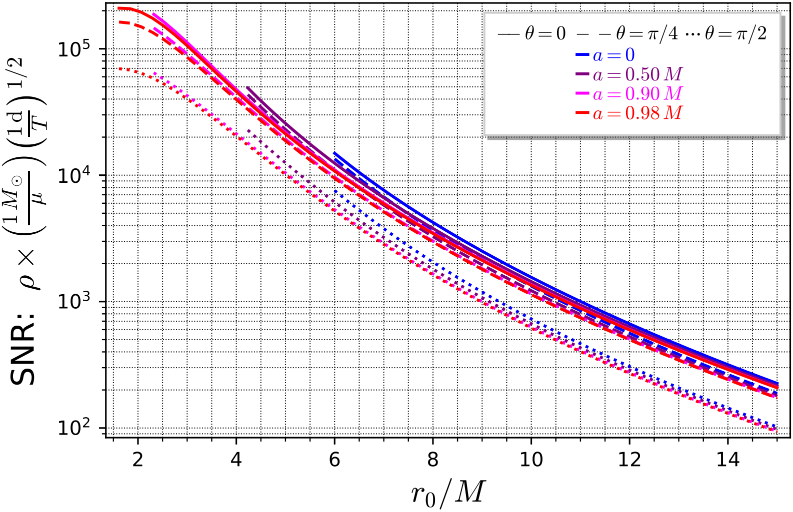
All computations (GW waveforms, SNR in LISA, enegy fluxes, inspiralling time, etc.) have been implemented as a Python package for the open-source mathematics software system SageMath:

kerrgeodesic_gw

kerrgeodesic_gw is

- entirely open-source:
  https://github.com/BlackHolePerturbationToolkit/kerrgeodesic_gw
- is distributed via the PyPi (the Python Package Index):
  https://pypi.org/project/kerrgeodesic-gw/
  so that the installation in SageMath is very easy:
  `sage -pip install kerrgeodesic_gw`
- is part of the *Black Hole Perturbation Toolkit*:
  http://bhptoolkit.org/

Signal-to-noise ratio in the LISA detector



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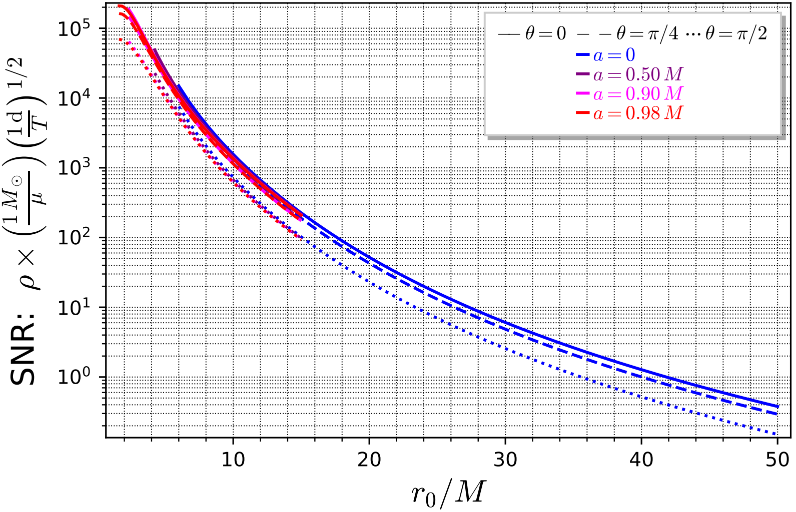

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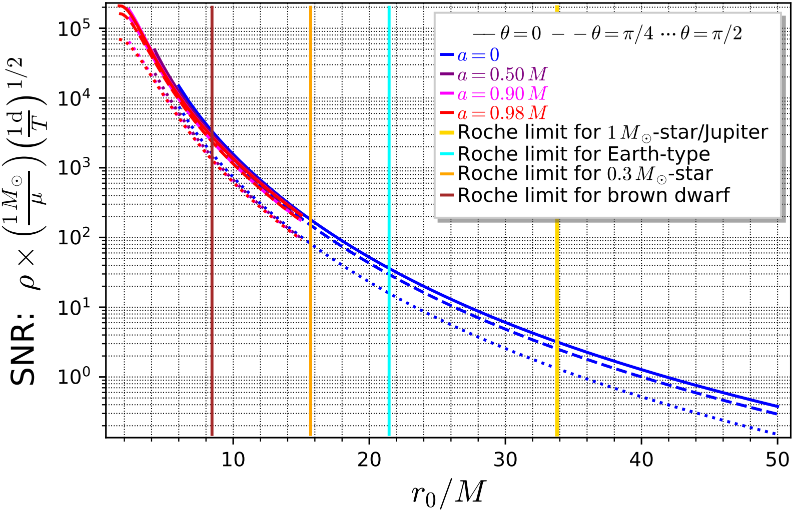

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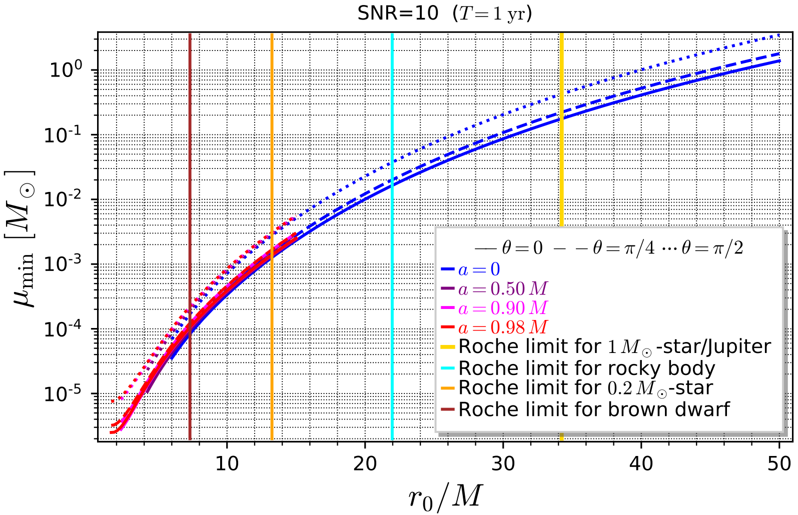
Signal-to-noise ratio in the LISA detector

object	r_0/M	SNR$\times\dfrac{1\,M_\odot}{\mu}$ (1 day)	SNR$\times\dfrac{1\,M_\odot}{\mu}$ (1 year)
Solar-type star / Jupiter	34.5	3.2	61
rocky body	21.5	36	690
$0.3M_\odot$-MS star	15.7	180	3.4×10^3
$0.05M_\odot$-brown dwarf	8.4	3.3×10^3	6.4×10^4
compact object ($a=0$)	6	1.5×10^4	2.8×10^5
compact obj. ($a=0.5M$)	4.23	4.9×10^4	9.4×10^5
compact obj. ($a=0.98M$)	1.61	2.1×10^5	4.0×10^6

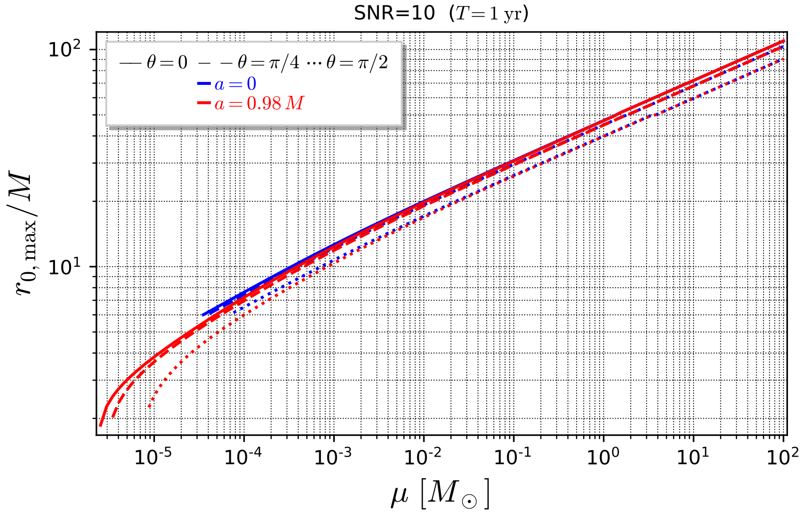
MS: main sequence
compact object: white dwarf, neutron star, stellar-mass black hole

Minimal detectable mass by LISA

Detection criteria: SNR $\geq$ 10
Observation time: 1 yr



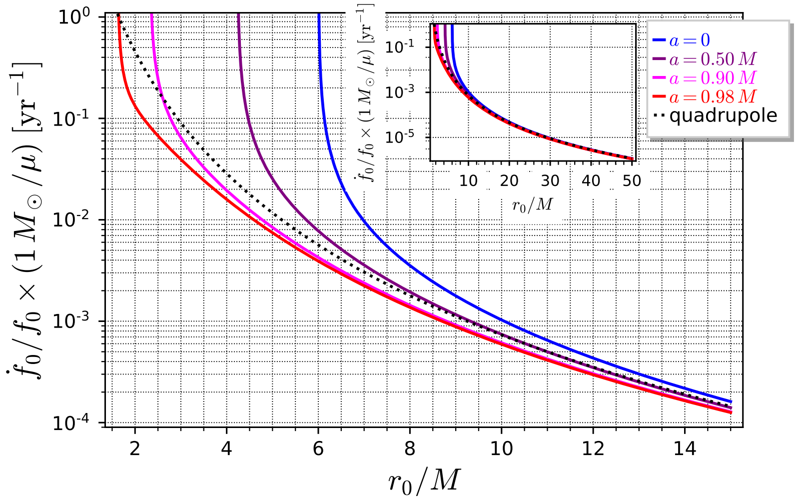
Maximum orbital radius for LISA detection



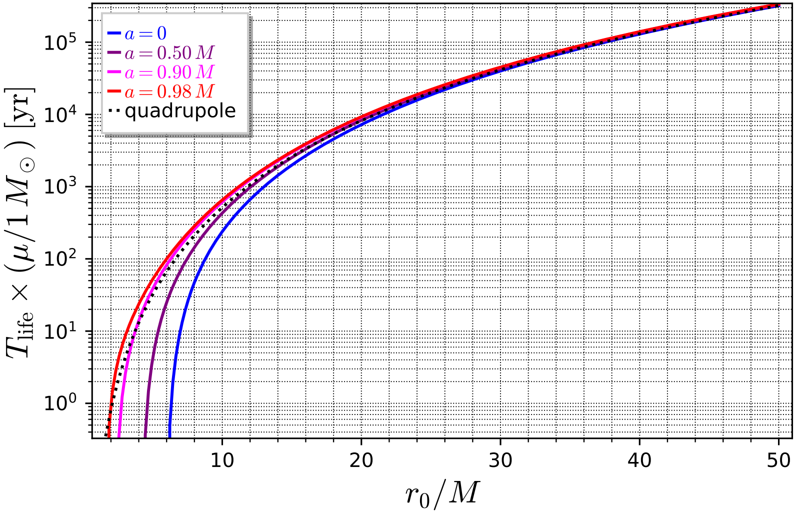
Maximum orbital radius $r_{0,\max}$ for a SNR $= 10$ detection by LISA in one year of data, as a function of the mass μ of the object orbiting around Sgr A*.

Outline

Orbital decay in reaction to gravitational radiation



Life time of circular orbits



$T_{\rm life}$: time for a compact object to reach the ISCO on the slow inspiral induced by gravitational radiation reaction

Time spent in LISA band

Inspiral time from orbit r_0 to orbit r_1 due to reaction to gravitational radiation:

$$T_{\rm ins}(r_0, r_1) = \frac{M^2}{2\mu} \int_{r_1/M}^{r_0/M} \frac{1 - 6/x + 8\bar{a}/x^{3/2} - 3\bar{a}^2/x^2}{\left(1 - 3/x + 2\bar{a}/x^{3/2}\right)^{3/2}} \frac{\mathrm{d}x}{x^2(\tilde{L}_\infty(x) + \tilde{L}_{\rm H}(x))}$$

where $\tilde{L}_{\infty,\rm H}(x) := (M/\mu)^2 L_{\infty,\rm H}(xM)$ and L_∞ (resp. $L_{\rm H}$) is the total GW power emitted at infinity (resp. through the BH event horizon) by a particle of mass μ orbiting at $r = xM$

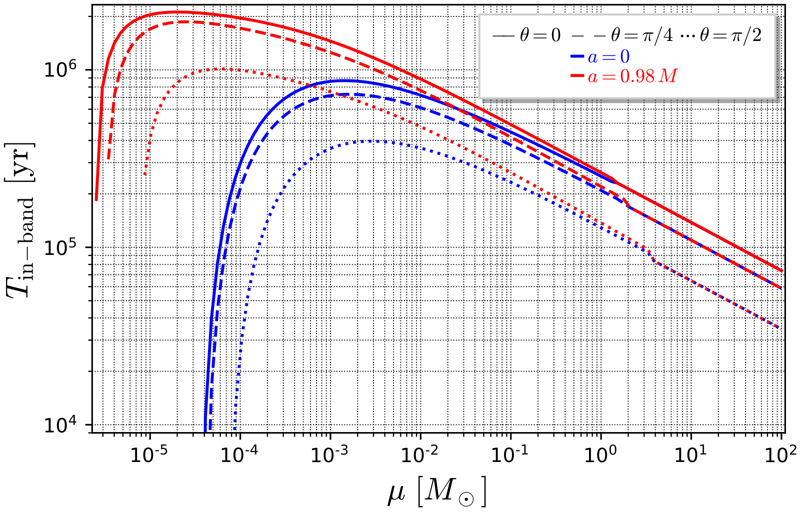
Compact object

$T_{\text{in-band}} = T_{\rm ins}(r_{0,\max}, r_{\rm ISCO}) = T_{\rm life}(r_{0,\max})$

MS stars and brown dwarfs

$T_{\text{in-band}} \geq T_{\text{in-band}}^{\rm ins} = T_{\rm ins}(r_{0,\max}, r_{\rm Roche})$

Time in LISA band for an inspiralling compact object



Time in LISA band for brown dwarfs and MS stars

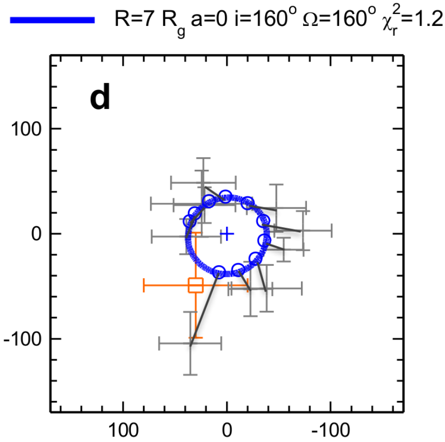
Results for

- inclination angle $\theta = 0$
- BH spin $a = 0$ (outside parentheses) and $a = 0.98M$ (inside parentheses)

	brown dwarf	red dwarf	Sun-type	$2.4\,M_\odot$-star
$\mu/M_\odot$	0.062	0.20	1	2.40
$\rho/\rho_\odot$	$131.$	18.8	1	0.367
$r_{0,\max}/M$	28.2 (28.0)	35.0 (34.9)	47.1 (47.0)	55.6 (55.6)
$f_{m=2}(r_{0,\max})$ [mHz]	0.105 (0.106)	0.076 (0.076)	0.049 (0.049)	0.038 (0.038)
$r_{\rm Roche}/M$	7.31 (6.93)	13.3 (13.0)	34.2 (34.1)	47.6 (47.5)
$T^{\rm ins}_{\text{in-band}}$ $[10^5\ {\rm yr}]$	4.98 (5.55)	3.72 (3.99)	1.83 (1.89)	0.938 (0.945)

Outline

What about the accretion flow?



Orbital motion of a flare at $r_0 \sim 7M$
observed by GRAVITY

[GRAVITY team, A&A **618**, L10 (2018)]

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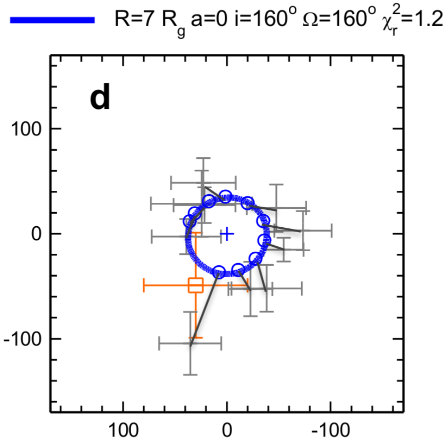

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Total mass of the accretion flow: $\sim 10^{-11} M_\odot$

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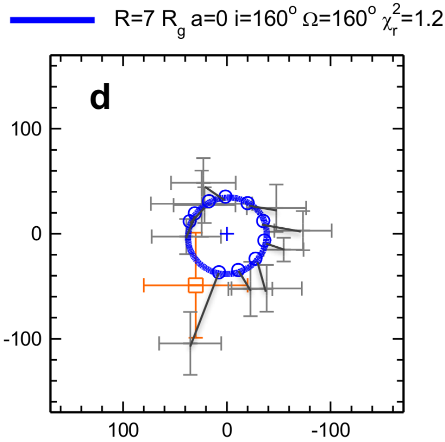

Orbital motion of a flare at $r_0 \sim 7M$ observed by GRAVITY

[GRAVITY team, A&A **618**, L10 (2018)]

Total mass of the accretion flow: $\sim 10^{-11} M_\odot$

$\Longrightarrow$ inhomogeneities (such as flares) not detectable by LISA

Artificial sources?

The massive BH Sgr A* is a unique object in our Galaxy.
If[1] an advanced civilization exists, or has existed, in the Galaxy, it would seem unlikely that it has not shown any interest in Sgr A*...

It would indeed seem natural that an advanced civilization has put some material in close orbit around Sgr A*, for instance to extract energy from Sgr A* via the Penrose process.

Whatever the reason for which the advanced civilization acted so (it could be for purposes that we humans simply cannot imagine), any orbital motion necessarily emit gravitational waves and if the mass is large enough, these waves could be detected by LISA.

This potentiality is discussed further in [Abramowicz, Bejger, Gourgoulhon & Straub, arXiv:1903.10698], in the form of a long lasting Jupiter-mass orbiter, left as a "messenger" by an advanced civilization, which possibly disappeared billions of years ago.

[1] Granted, this is a big *if*...

Outline

Conclusions

- We have computed GW emission and SNR in LISA for close circular orbits around Sgr A* in full general relativity.
- The time spent in LISA band (SNR ≥ 10) during the slow inspiral has been evaluated.
- All computations have been implemented in an open-source SageMath package, `kerrgeodesic_gw`, as part of the Black Hole Perturbation Toolkit.
- LISA has the capability to detect orbiting masses close to the ISCO as small as $\sim 10 M_{\rm Earth}$ or even $\sim 1 M_{\rm Earth}$ if Sgr A* is a fast rotator ($a \geq 0.9M$); this could involve primordial BHs or very dense artificial objects.
- White dwarfs, NSs, stellar BHs, BHs of mass $\geq 10^{-4} M_\odot$, MS stars of mass $\leq 2.5\, M_\odot$ and brown dwarfs orbiting Sgr A* are all detectable in 1 yr of LISA data with SNR ≥ 10.
- The longest times in-band, of the order of 10^6 years, are achieved for primordial BHs of mass $\sim 10^{-3} M_\odot$ down to $10^{-5} M_\odot$, depending on the spin of Sgr A*, as well as for brown dwarfs, just followed by white dwarfs and low mass MS stars.