Probing the vicinity of the Galactic Center black hole with LISA

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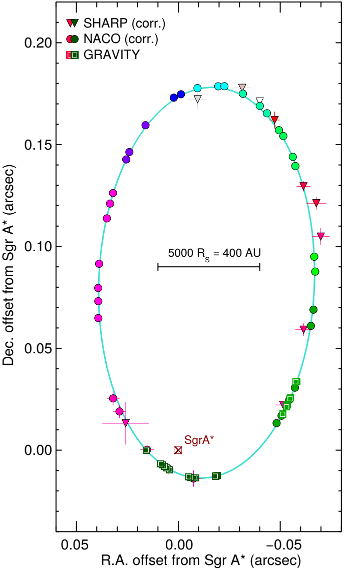
Sgr A* : the Galactic Center black hole

[GRAVITY, A&A 2018]



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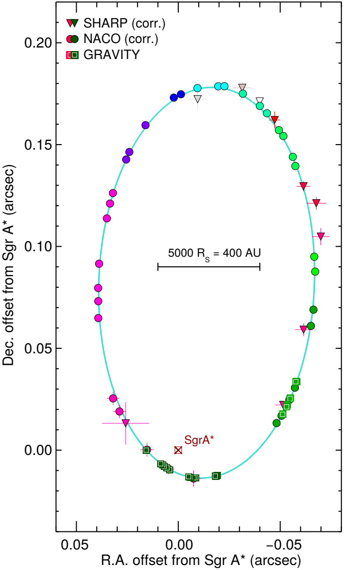

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$$D = 8178 \pm 13 \text{ pc}$$

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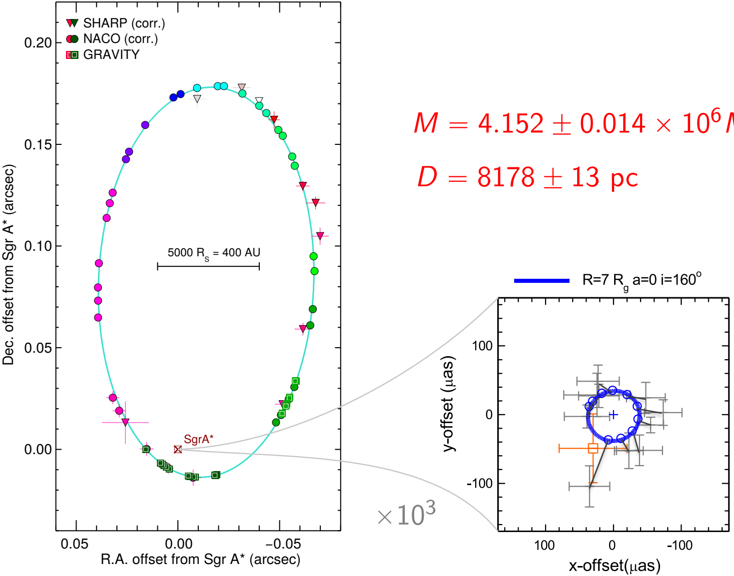

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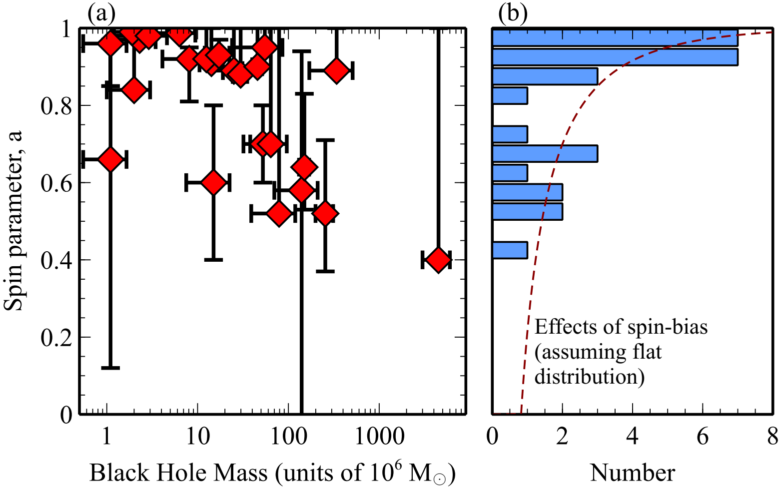
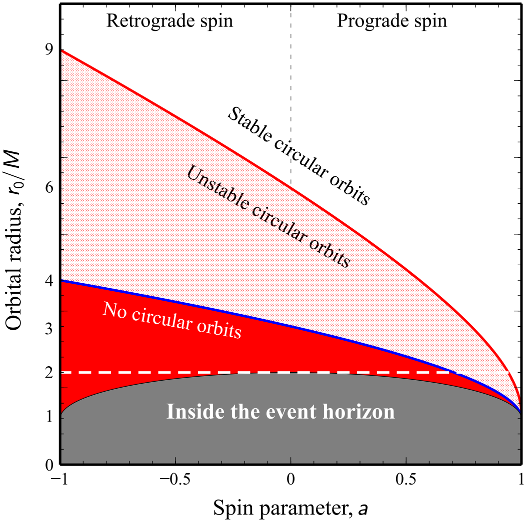
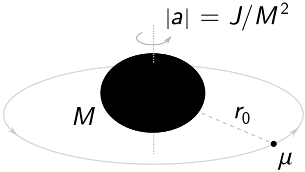
Spin distribution of supermassive BHs

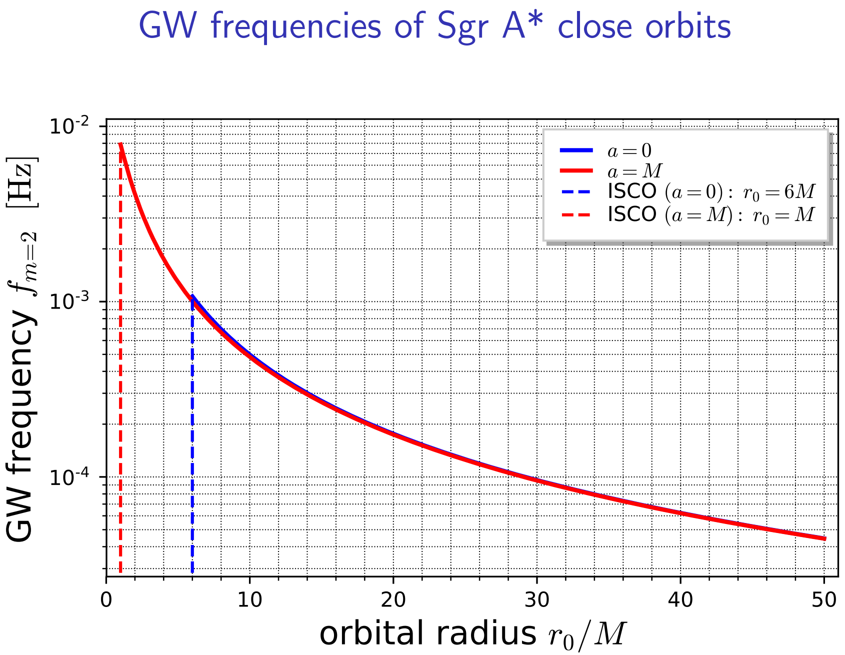
[Reynolds, Nat. Astron. 2019]

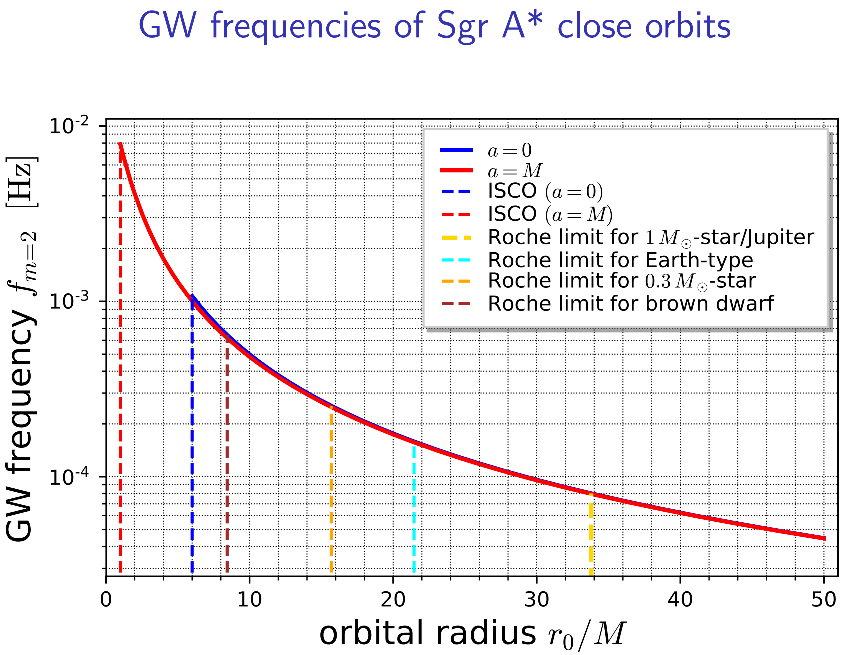


Circular orbits around a Kerr black hole






GW frequencies of Sgr A* close orbits
GW frequency $f_{m=2}$ [Hz]
orbital radius r_0/M
$a=0$
$a=M$
ISCO $(a=0): r_0=6M$
ISCO $(a=M): r_0=M$
10^-2
10^-3
10^-4
0
10
20
30
40
50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Roche limit for $1\,M_\odot$-star/Jupiter
Roche limit for Earth-type
Roche limit for $0.3\,M_\odot$-star
Roche limit for brown dwarf

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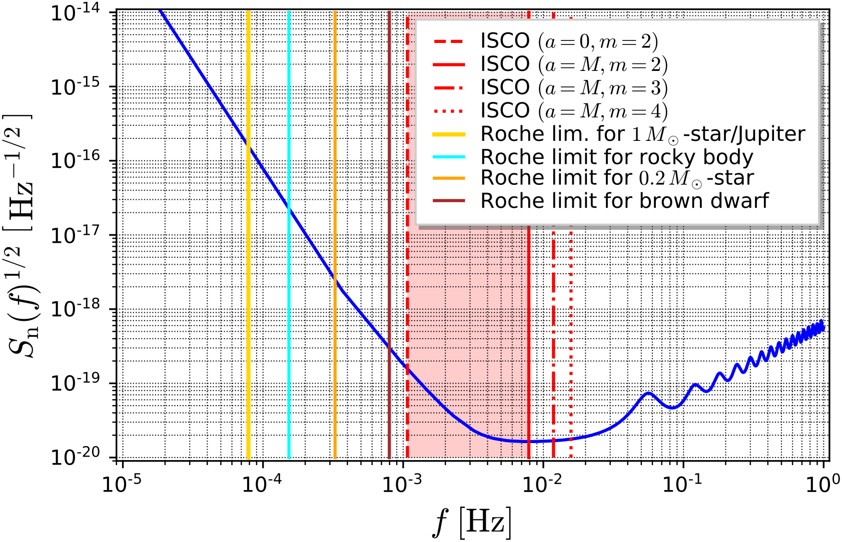

Previous work on Sgr A* as a LISA source

- Low-mass main-sequence stars are good candidates for LISA
  [Freitag, ApJ **583** (2003) L21] [Barack & Cutler, PRD **69** (2004) 082005]
- Zero-eccentricity EMRIs from binaries tidally split by Sgr A*
  [Miller *et al.*, ApJ **631** (2005) L117]
- Extreme mass ratio bursts of GW from highly eccentric orbits
  [Berry & Gair, MNRAS **429** (2013) 589]
- GW from orbiting MS stars undergoing Roche lobe overflow
  [Linial & Sari, MNRAS **469** (2017) 2441]
- Ensemble of macroscopic dark matter candidates, e.g. PBHs
  [Kühnel *et al.* (2018), gr-qc/1811.06387]
- LISA could detect tens of brown dwarfs orbiting Sgr A*
  [Amaro-Seoane (2019), gr-qc/1903.10871]

Our study

Fully relativistic framework

- Gravitational waveform from solution of Teukolsky equation
- Tidal effects from theory of Roche potential in Kerr metric

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All computations have been implemented in a Python package for *SageMath* that is part of the *Black Hole Perturbation Toolkit*:

http://bhptoolkit.org/

Roche radius in the Kerr metric

[Dai & Blanford, MNRAS 2013]

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

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	Jupiter	**Sun**	**Earth**	**red dwarf**	**brown dwarf**	**white dwarf**
$\mu/M_\odot$	9.55×10^{-4}	1	3.0×10^{-6}	0.20	0.062	0.80
$R/R_\odot$	0.10	1	9.17×10^{-3}	0.22	0.078	5.58×10^{-3}
$\rho/\rho_\odot$	0.94	1	3.91	18.8	131.	1.10×10^{6}
$r_{\rm R}/M$	34.9	34.2	21.9	13.3	7.31	0.28

(nonspinning black hole, irrotational body)

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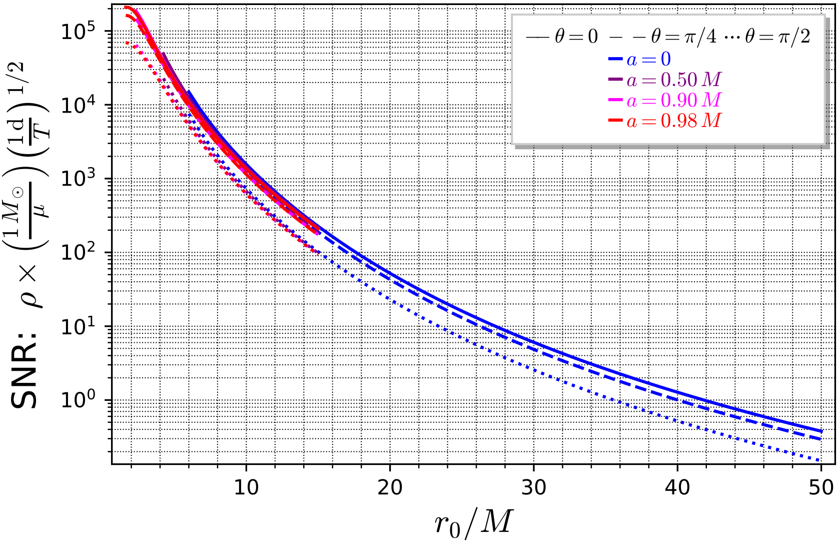
$$\frac{R_\odot}{r_0} \leqslant \frac{R_\odot}{r_{\mathrm{R}}} \simeq \frac{0.1M}{34M} \simeq 3\times 10^{-3} \quad \longrightarrow \quad \text{point-particle approximation}$$

Signal-to-noise ratio in the LISA detector



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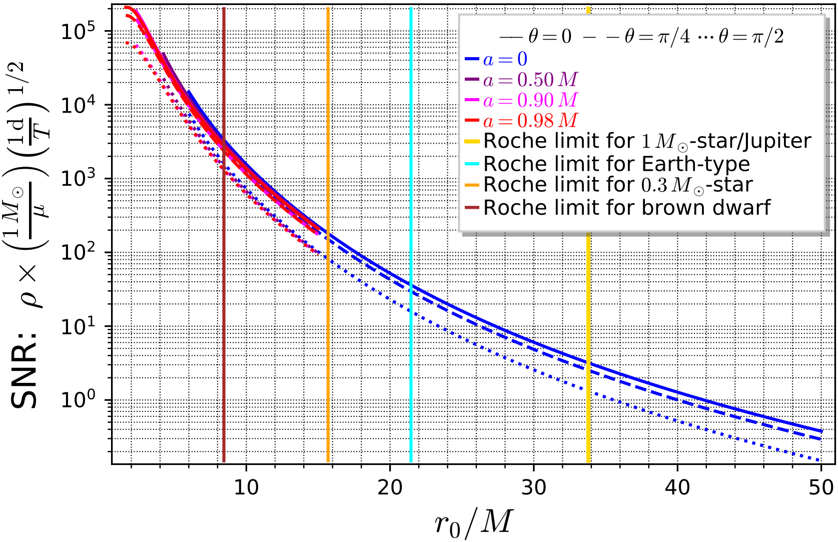
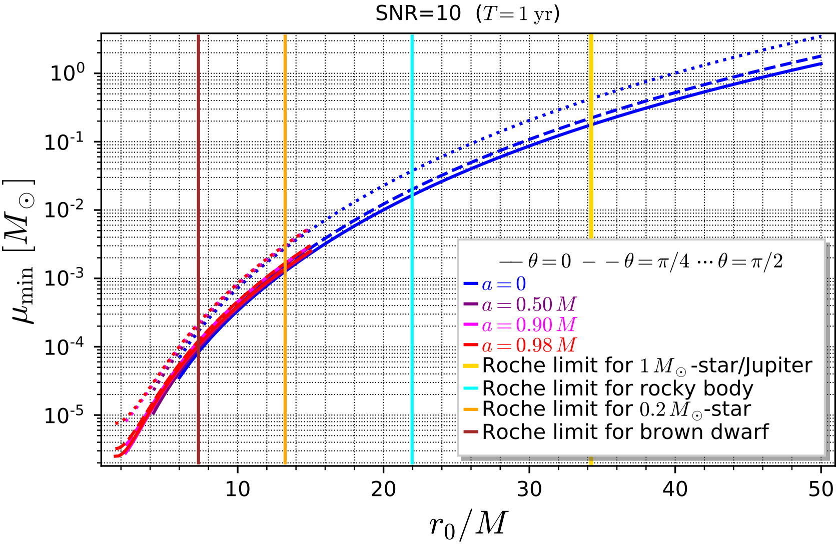


Signal-to-noise ratio in the LISA detector

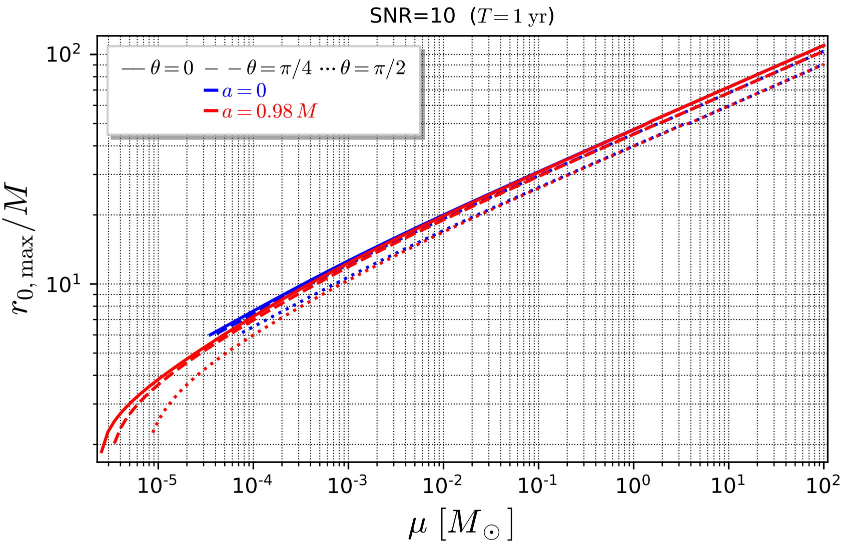
Object	r_0/M	**SNR (1d)**	**SNR (1yr)**
$1M_\odot$ star	34.5	3.2	61
$0.3M_\odot$ red dwarf	15.7	54	1.0×10^3
$0.05M_\odot$ brown dwarf	8.4	165	3.2×10^3
compact object ($a = 0$)	6	1.5×10^4	2.8×10^5
compact object ($a = 0.5$)	4.2	4.9×10^4	9.4×10^5
compact object ($a = 0.98$)	1.6	2.1×10^5	4.0×10^6

(inclination angle $\theta = 0$)

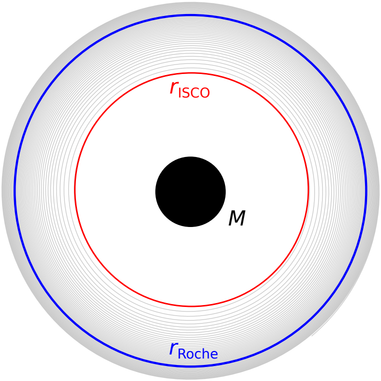
Minimal detectable mass by LISA



Maximal orbital radius for LISA detection



Time spent in LISA band during inspiral



Adiabatic inspiral driven by energy balance:

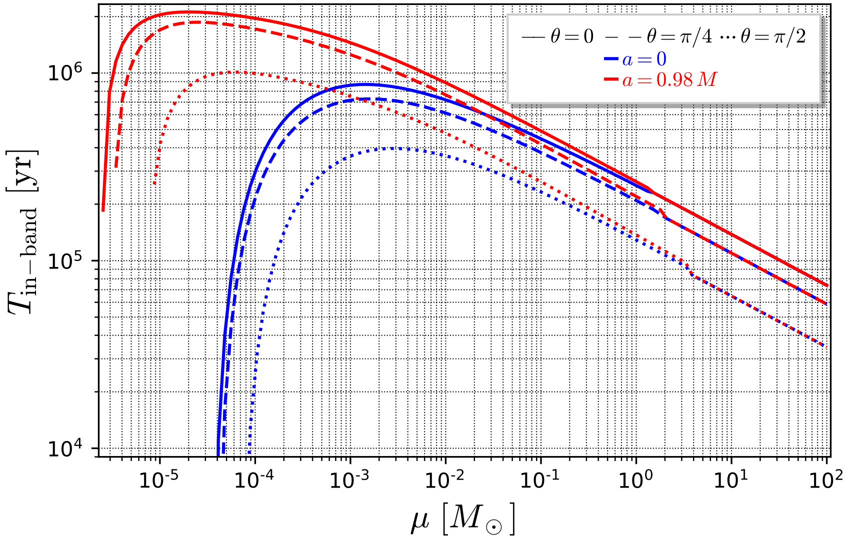
$$\dot{E} = -(\mathcal{F}_\infty + \mathcal{F}_\text{H}) \simeq -\mathcal{F}_\infty$$

$$\downarrow$$

$$T_\text{insp}[r_1, r_2] \simeq \int_{r_2}^{r_1} \frac{E'(r)}{\mathcal{F}_\infty(r)} \, \mathrm{d}r$$

$$T_\text{in-band} = T_\text{insp}[r_{0,\text{max}}, r_\text{min}] \quad \text{where} \quad \begin{cases} r_\text{min} = r_\text{ISCO} & \text{(compact object)} \\ r_\text{min} = r_\text{Roche} & \text{(other body)} \end{cases}$$

Time in-band for an inspiralling compact body



Time in-band for brown dwarfs and MS stars

	brown dwarf	**red dwarf**	**Sun-type**	**$2.4M_\odot$-star**
$\mu/M_\odot$	0.062	0.20	1	2.40
$\rho/\rho_\odot$	131.	18.8	1	0.37
$r_{0,\mathrm{max}}/M$	28.2	35.0	47.1	55.6
r_{Roche}/M	7.31	13.3	34.2	47.6
$T_{\text{in-band}}$ $[10^5\,\mathrm{yr}]$	4.98	3.72	1.83	0.94

(nonspinning black hole, irrotational star, inclination angle $\theta = 0$)

Brown dwarfs are promising candidates

X-MRIs:
Extremely Large Mass-Ratio Inspirals

Pau Amaro-Seoane[1, 2, 3, 4]

[1] *Institute of Space Sciences (ICE, CSIC) & Institut d'Estudis Espacials de Catalunya (IEEC) at Campus UAB, Carrer de Can Magrans s/n 08193 Barcelona, Spain*

[2] *Kavli Institute for Astronomy and Astrophysics at Peking University, 100871 Beijing, China*

[3] *Institute of Applied Mathematics, Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China*

[4] *Zentrum für Astronomie und Astrophysik, TU Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*

(Dated: May 30, 2019)

For my dear friend Tal Alexander. Thanks for having been a human being.

The detection of the gravitational waves (GWs) emitted in the capture process of a compact object by a massive black hole (MBH) is known as an extreme-mass ratio inspiral (EMRI) and represents a unique probe of gravity in the strong regime and is one of the main targets of the Laser Interferometer Space Antenna (LISA). The possibility of observing a compact-object EMRI at the Galactic Centre (GC) when LISA is taking data is very low. However, the capture of a brown dwarf (BD), an X-MRI, is more frequent because these objects are much more abundant and can plunge without being tidally disrupted. An X-MRI covers some $\sim 10^8$ cycles before merger, and hence stay on band for millions of years. About 2×10^6 yrs before merger they have a signal-to-noise ratio (SNR) at the GC of 10. Later, 10^4 yrs before merger, the SNR is of several thousands, and 10^3 yrs before the merger a few 10^4. Based on these values, this kind of EMRIs are also detectable at neighbour MBHs, albeit with fainter SNRs. We calculate the event rate of X-MRIs at the GC taking into account the asymmetry of pro- and retrograde orbits on the location of the last stable orbit. We estimate that at any given moment, and using a conservative approach, there are of the order of $\gtrsim 20$ sources in band. From these, $\gtrsim 5$ are highly eccentric and are located at higher frequencies, and about $\gtrsim 15$ are circular and are at lower frequencies. Due to their proximity, X-MRIs represent a unique probe of gravity in the strong regime. The mass ratio for a X-MRI at the GC is $q \sim 10^8$, i.e., three orders of magnitude larger than stellar-mass black hole EMRIs. Since backreaction depends on q, the orbit follows closer a standard geodesic, which means that approximations work better in the calculation of the orbit. X-MRIs can be sufficiently loud so as to track the systematic growth of their SNR, which can be high enough to bury that of MBH binaries.

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A low-mass star candidate?

MNRAS **474,** 3380–3390 (2018)
Advance Access publication 2017 November 15

A 149 min periodicity underlies the X-ray flaring of Sgr A*

Elia Leibowitz★
School of Physics & Astronomy and Wise Observatory, Sachler Faculty of Exact Sciences, Tel Aviv University

Accepted 2017 November 13. Received 2017 November 13; in original form 2017 May 9

ABSTRACT

In a paper in 2017, I have shown that 39 large X-ray flares of Sgr A* that were recorded by *Chandra* observatory in the year 2012 are concentrated preferably around tick marks of an equi-distance grid on the time axis. The period of this grid as found in that paper is 0.1033 d. In this work I show that the effect can be found among all the large X-ray flares recorded by *Chandra* and *XMM – Newton* along 15 yr. The mid-points of all the 71 large flares recorded between years 2000 and 2014 are also tightly grouped around tick marks of a grid with this period, or more likely, 0.1032 d. This result is obtained with a confidence level of at least 3.27σ and very likely of 4.62σ. I find also a possible hint that a similar grid is underlying IR flares of the object. I suggest that the pacemaker in the occurrences of the large X-ray flares of Sgr A* is a mass of the order of a low-mass star or a small planet, in a slightly eccentric Keplerian orbit around the SMBH at the centre of the Galaxy. The radius of this orbit is about 6.6 Schwarzschild radii of the BH.

Key words: black hole physics – Galaxy: centre – X-rays: individual: Sgr A*.

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$T = 1$ day

$\Downarrow$

$\boxed{\text{SNR} = 76}$

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Summary

- We have computed the GW emission and SNR in LISA for close circular orbits around Sgr A* in full general relativity
- Compact objects, MS stars of mass $\lesssim 2.5 M_\odot$ and brown dwarfs orbiting Sgr A* are all detectable in 1 yr of data
- LISA can detect orbiting masses close to the ISCO as small as $1 M_\oplus$ if Sgr A* is a fast rotator $\rightarrow$ primordial BHs
- The time spent in LISA band (SNR $\geqslant 10$) during the slow inspiral is $\sim 10^5 - 10^6$ yr, making brown dwarfs promising candidates

Sgr A* is a valuable target for LISA