MODEST 24

Nicolaus Copernicus Astronomical Center, Warsaw, Poland

SgrA* spin and mass estimates through the detection of an extremely large mass-ratio inspiral

Verónica Vázquez Aceves

veronica@pku.edu.cn

Kavli Institute for Astronomy and Astrophysics, Peking University

In collaboration with Yiren Lin, Alejandro Torres-Orjuela

The Milky Way from the Himalayas, May 2024. Photo by Prashant Kumar [@prashant3052]

What is an XMRI?

XMRIs = Extremely large mass-ratio inspiral = Brown Dwarf (BD) inspiraling around a SMBH

Amaro-Seoane, 2019: arXiv:1903.10871

Mass ratio

$$q = M_{SMBH}/M_{BD} \sim 10^8$$

An inspiraling system evolves **only** due to the emission of gravitational waves

Background photo by Prashant Kumar [@prashant3052]

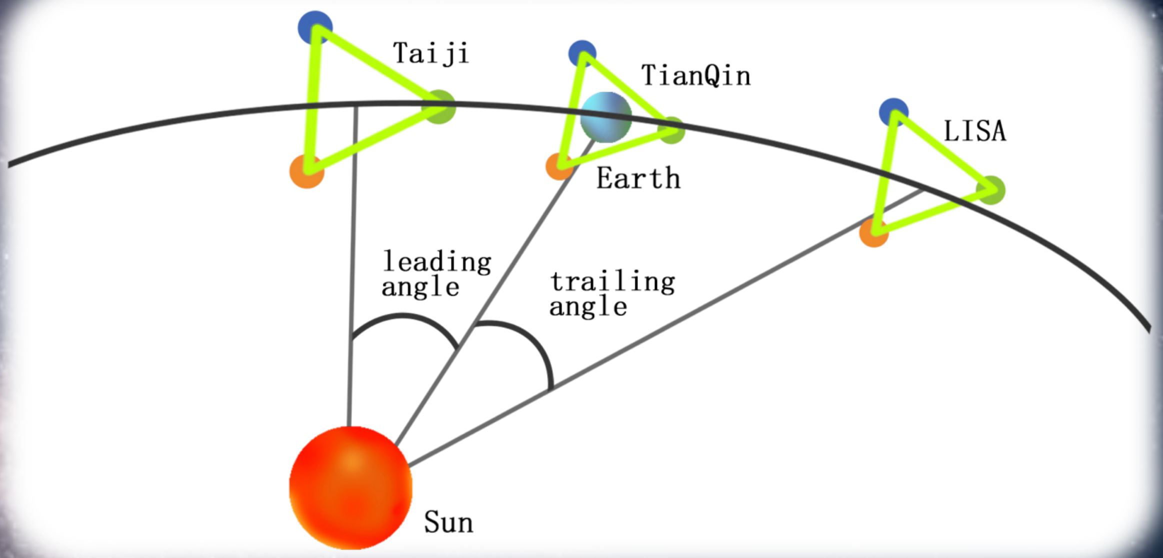
XMRIs in the Galactic Center

- Extremely large mass ratio allows the BD to spend a large amount of time orbiting Sgr A *

- Detecting the GWs emitted by inspiraling systems will give us information about the space time around SMBHs

- If detected in our galaxy: Extract information about SgrA* (like the spin)

- Improve our understanding of galactic dynamics



$q \sim 10^8$

Amaro-Seoane, 2019: arXiv:1903.10871

How are XMRIs formed?

Key process in a dense system:

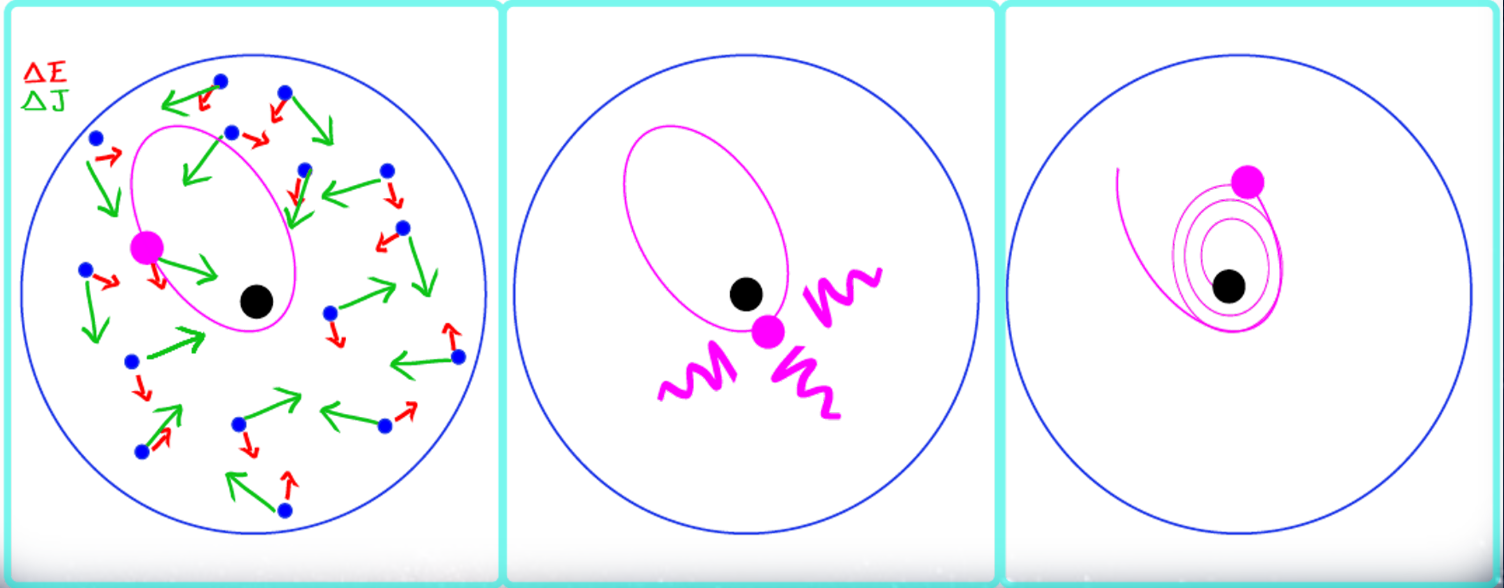
Two-body relaxation

Increases the eccentricity of an orbiting object

At pericenter, the energy loss by GW emission becomes significant.

The orbit reaches a critical semimajor axis a_{crit} such that

$$T_{\mathrm{GW}} \lesssim T_{\mathrm{rlx}}(a_0) \times (1 - e_0^2).$$

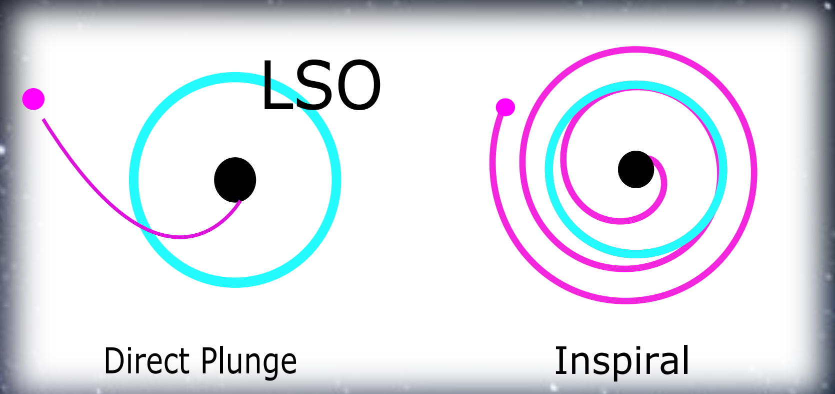


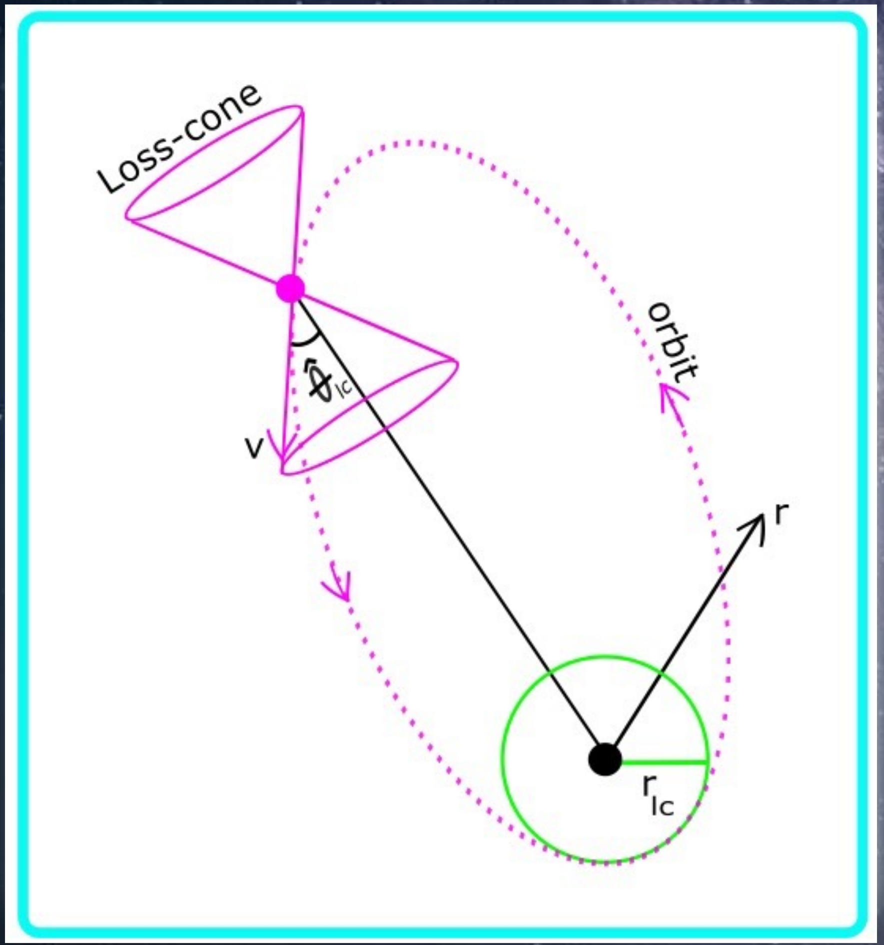
Two-body relaxation

[Hopman & Alexander (2005), Amaro-Seoane et al. (2007)]

But we have to choose our orbit: The pericenter

$$r_p=a(1-e)$$





The loss-cone

We set the pericenter at the Last Stable Orbit

$$r_{lc} = r_p = r_{LSO}$$

Then we find the critical semimajor axis

$$T_{GW} \leq T_{rlx}(a) \times (1-e^2)$$

Tidal disruption radius: $r_t = (\frac{2M}{m_{BD}})^{1/3}\, r_{BD}$

Brown dwarfs: polytrope $P \propto \rho^{1+\frac{1}{n}}$, $n = 1.5$.

$$r_{\rm tidal} = \left(2\frac{(5-n)M}{3m_{\rm BD}}\right)^{1/3} r_{\rm BD} \sim 2.7\, r_{\rm Schw},$$

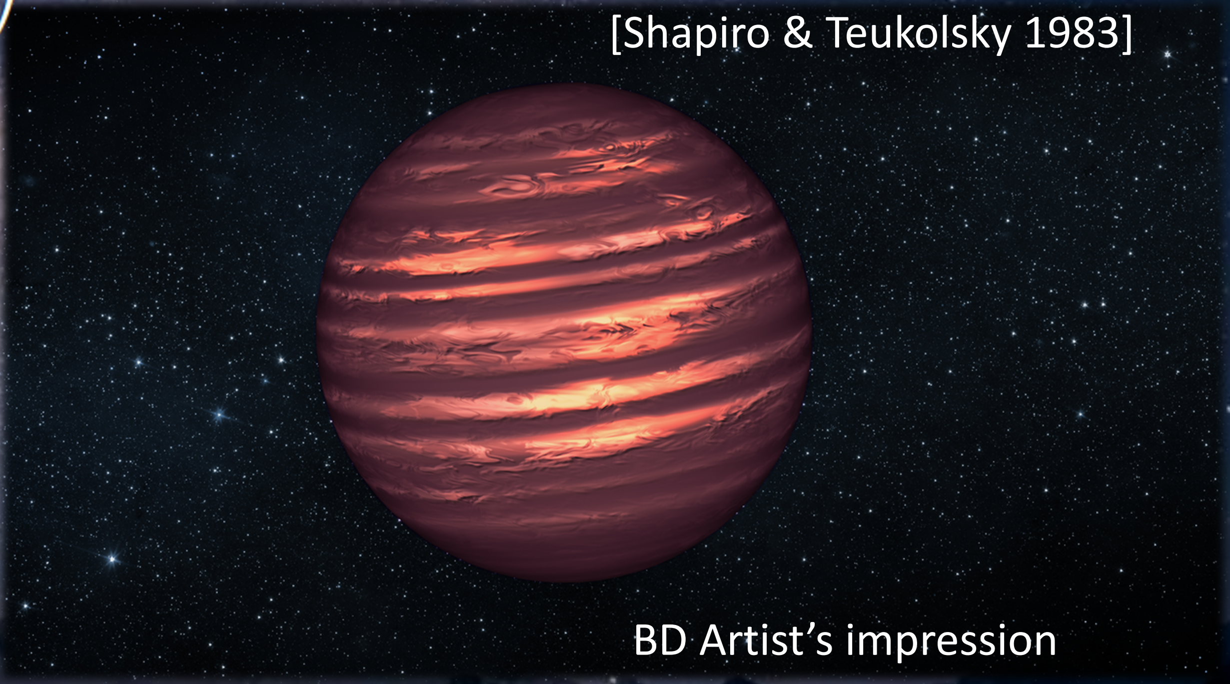
[Shapiro & Teukolsky 1983]

With $M = 4\text{x}10^6 M_\odot$

$m_{BD} = 0.05 M_\odot$

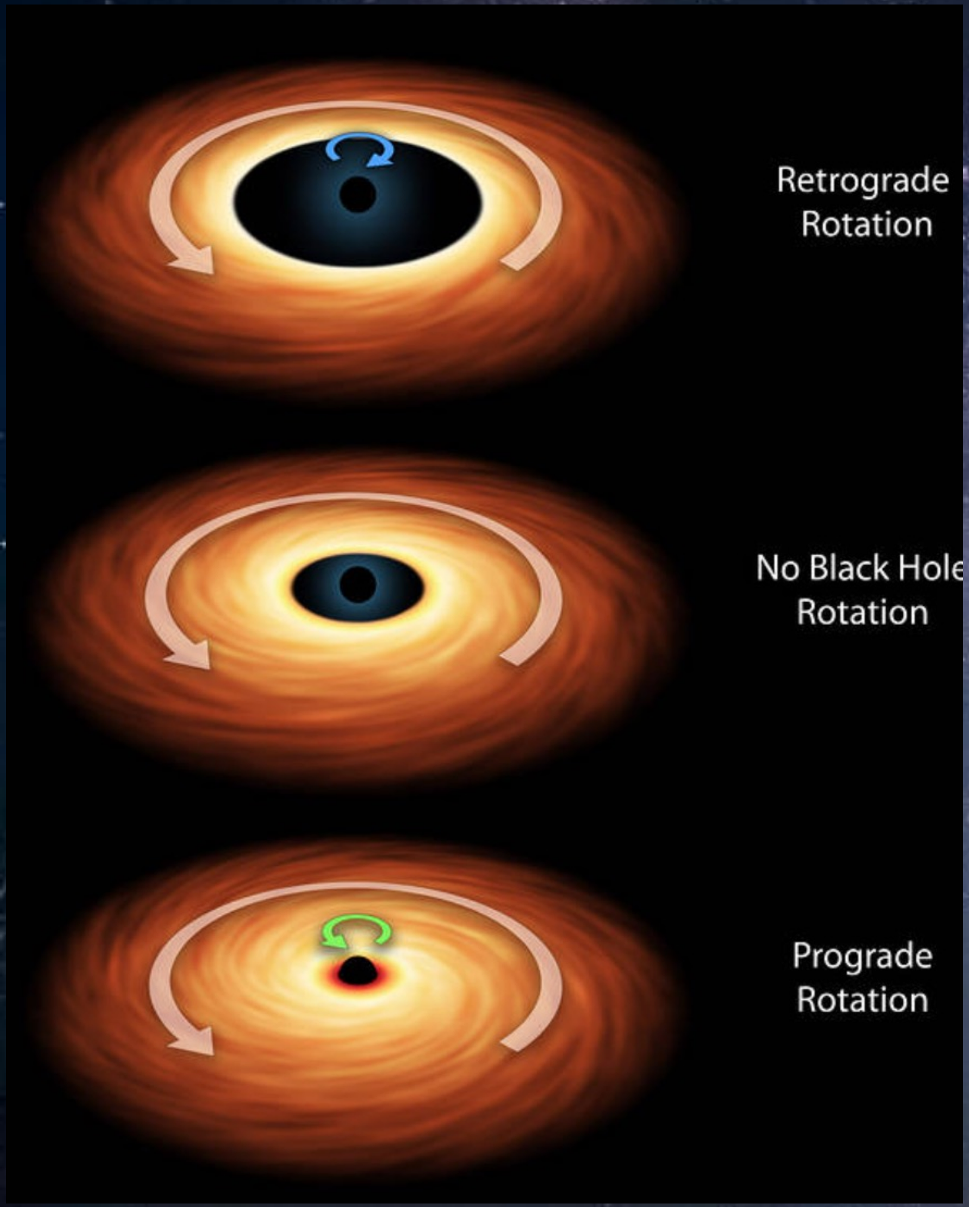
$r_{BD} = 0.083\ R_\odot$

[Sorahana et al. 2013]



BD Artist's impression

What if we have a Kerr BH?

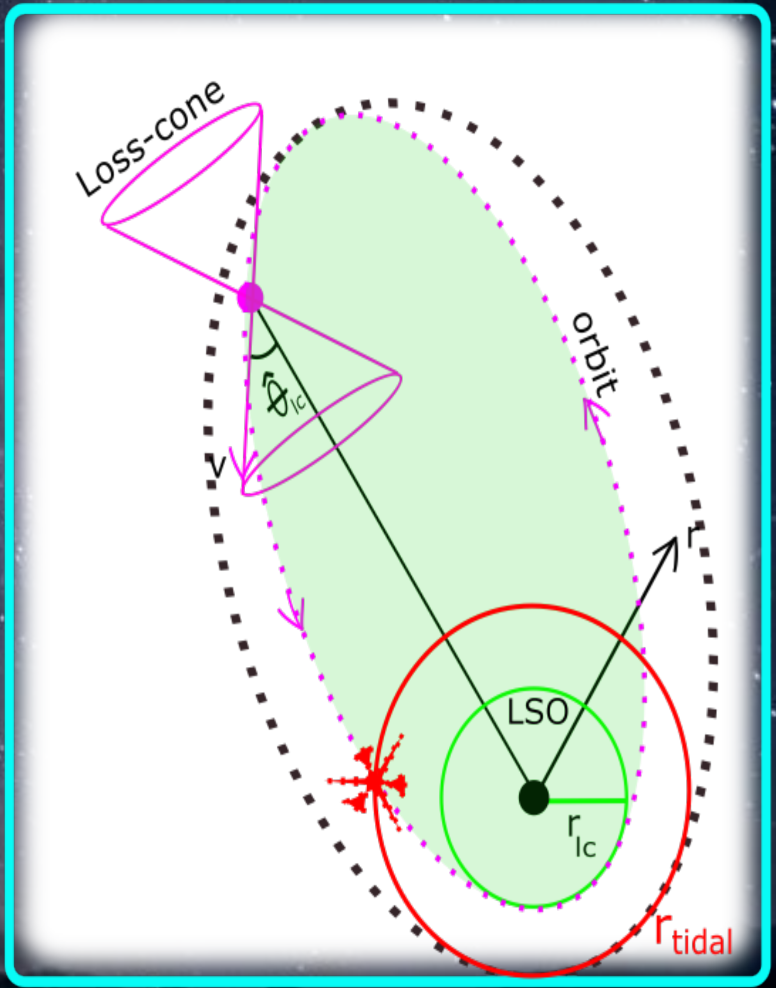


The position of the LSO depends on the spin magnitude (s) and the orbital inclination. The pericenter is:

$$r_p = 4 r_S \quad \mathcal{W}(\theta, s)$$

Where the function $\mathcal{W}(\theta, s)$ gives the shift in the position of the last stable orbit for arbitrary orbital inclinations and spin magnitude, up to s=0.999

[Sopuerta & Yunes, 2011; Amaro-Seoane et al. 2012]



The event rates

$$\dot{\Gamma}_{\rm i} \simeq \int_{a_{\rm min}}^{a_{\rm crit}} \frac{{\rm d}n(a)}{T_{\rm rlx}(a)\,\ln(\widehat{\theta}_{\rm lc}^{-2})},$$

[Hopman & Alexander, 2005; Amaro-Seoane, 2019]

The event rates depend on:

- Initial mass function
- Fraction number of the considered objects
- The relaxation time
- The orbital parameters of the XMRIs

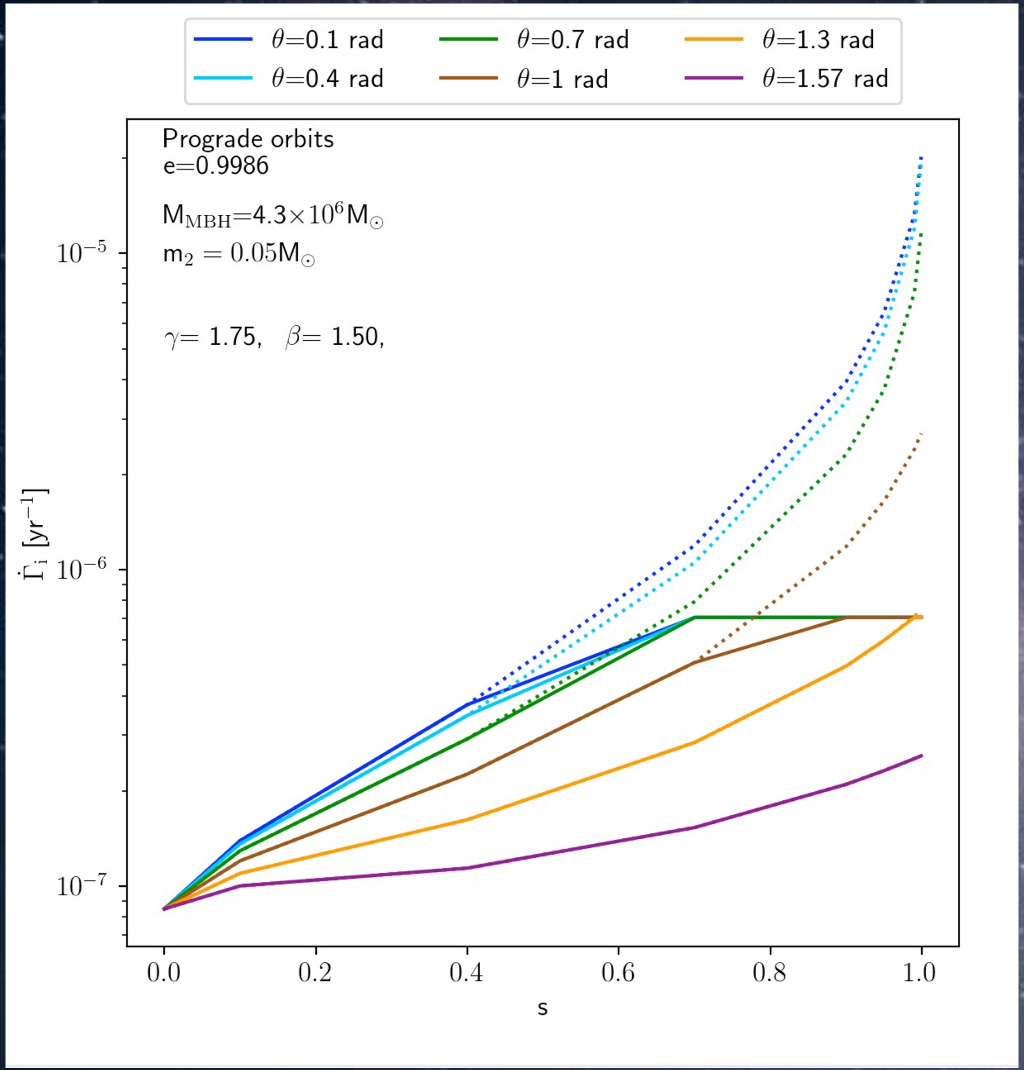
$$\rho(r) \sim r^{-\gamma}$$

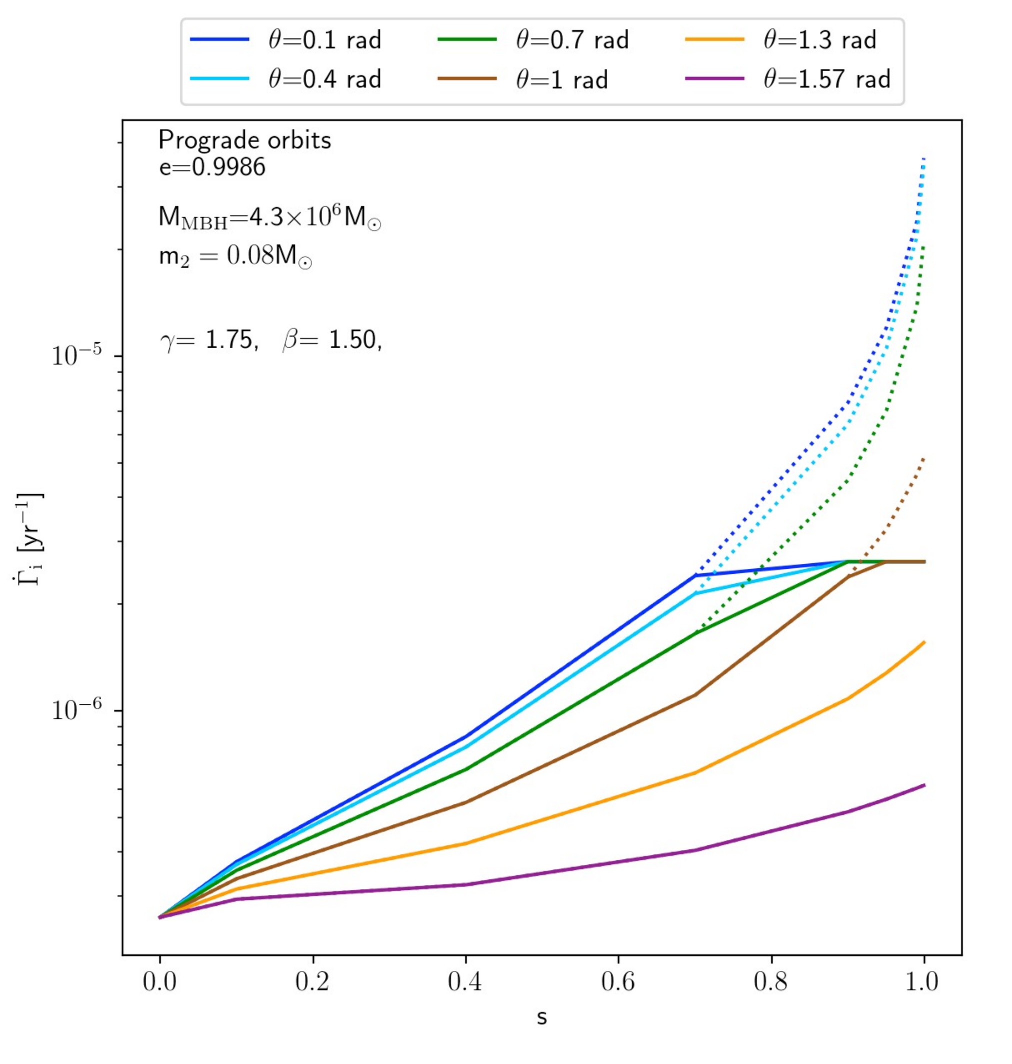
- Density distribution for black holes

$$\rho\,(r) \sim r^{-\beta}$$

- Density distribution for lighter objects

Rates for different BD mass around SgrA*





Dotted lines are the event rates for tidal disruption events

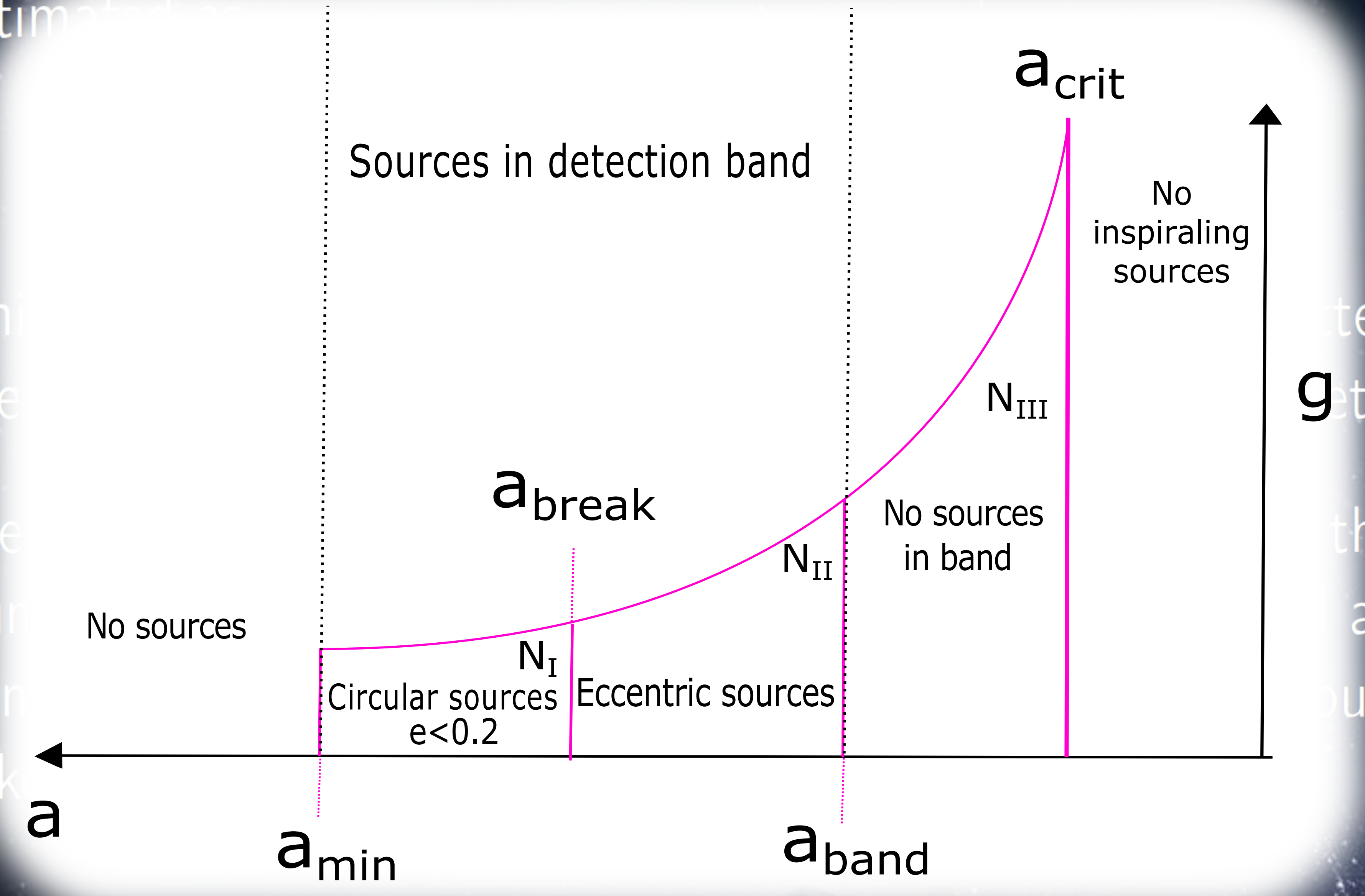
The total number of XMRIs $N_{\rm tot}$ orbiting around SgrA* can be estimated as

$$N_{\rm tot} = \dot{\Gamma}_{\rm XMRI}(a_{\rm crit}) \times T_{\rm GW}.$$

This equation does not take into account if the GWs emitted by the system are within the detection band of space-borne detectors.

We construct a density function $g = dN/da$ that gives us the number of sources orbiting at a given semimajor axis, and a continuity function that describes the rate at which the source takes a given semimajor axis. [Amaro-Seoane et al. 2019]

The total number of XMRIs $N_{\rm tot}$ orbiting around SgrA* can be estim...



Th... ted by

the ... tectors.

We ... the

nu... a

co... urce

tak...

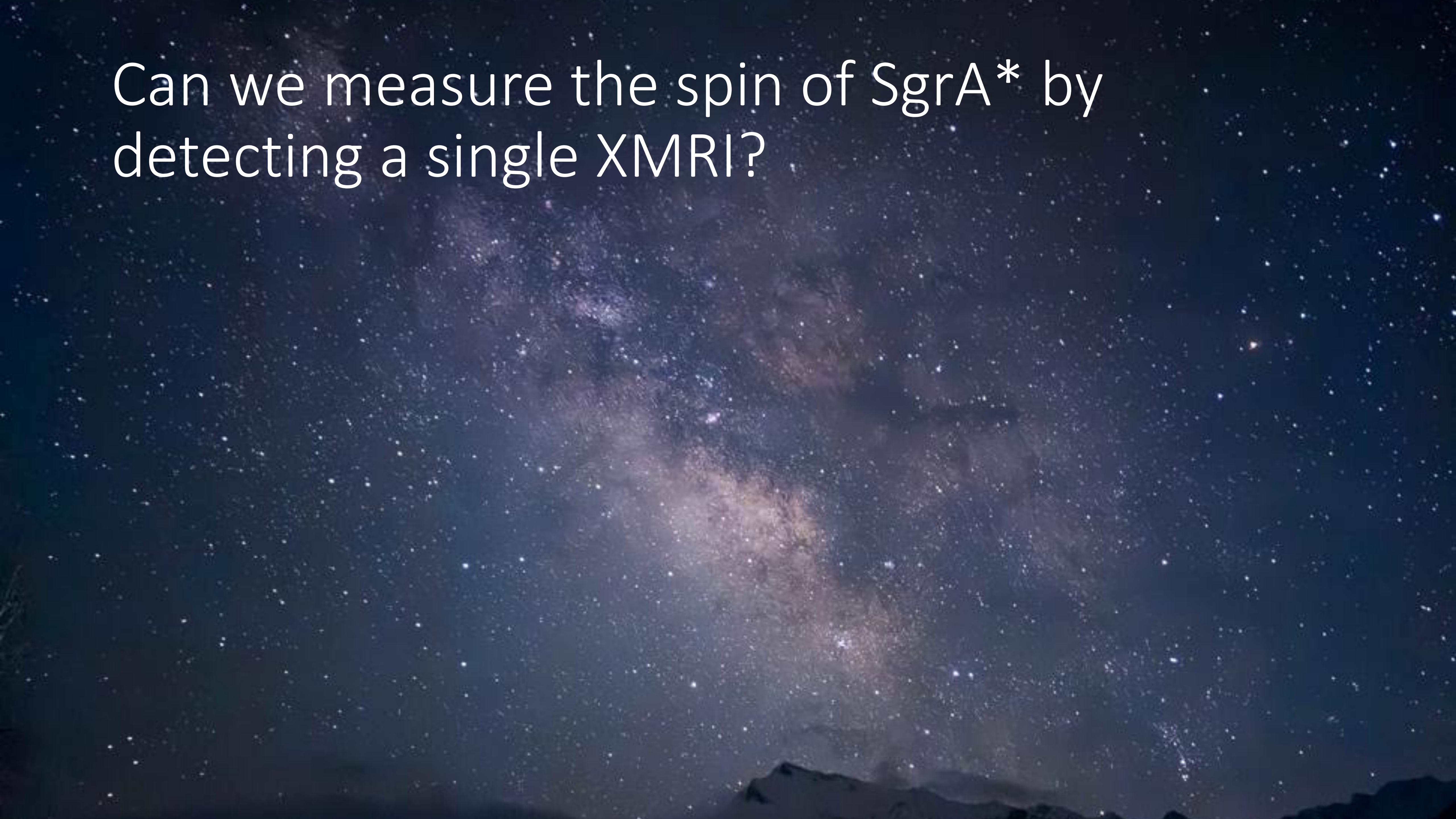
SgrA* spin (a)	Circular XMRIs	Eccentric XMRIs
0.1	0	8^{+9}_{-3}
0.9	1	12^{+6}_{-4}

Table: Number of circular sources and eccentric sources in band for XMRIs with a fixed orbital inclination of $i = 0.1$ rad for two different spin values.

Sources in the circular regime have a Signal to Noise Ratio (SNR) $\gtrsim$1,000, while for the eccentric regime the SNR$\sim$ 50.

[Amaro Seoane et al, 2019, Vazquez-Aceves et al., 2023]

Can we measure the spin of SgrA* by detecting a single XMRI?

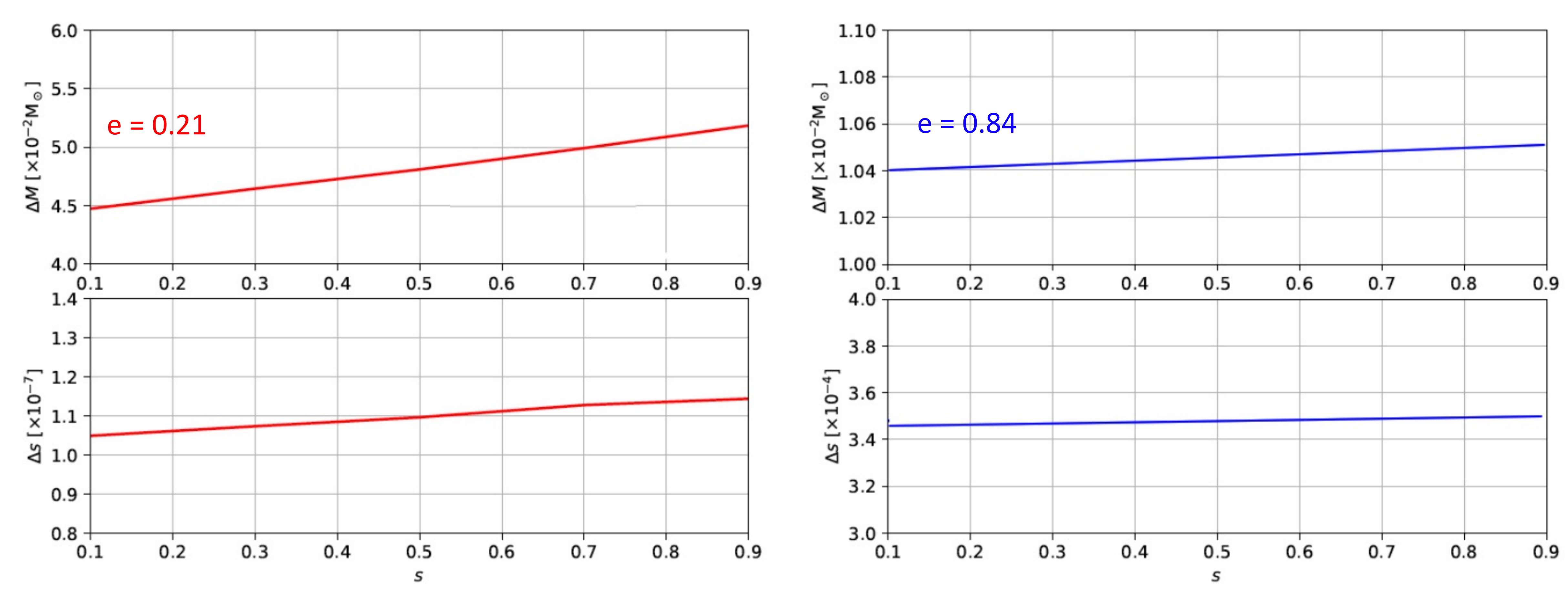


Can we measure the spin of SgrA* by detecting a single XMRI?

YES

How good?

Accuracy for the measurements of the mass and spin of SgrA*.



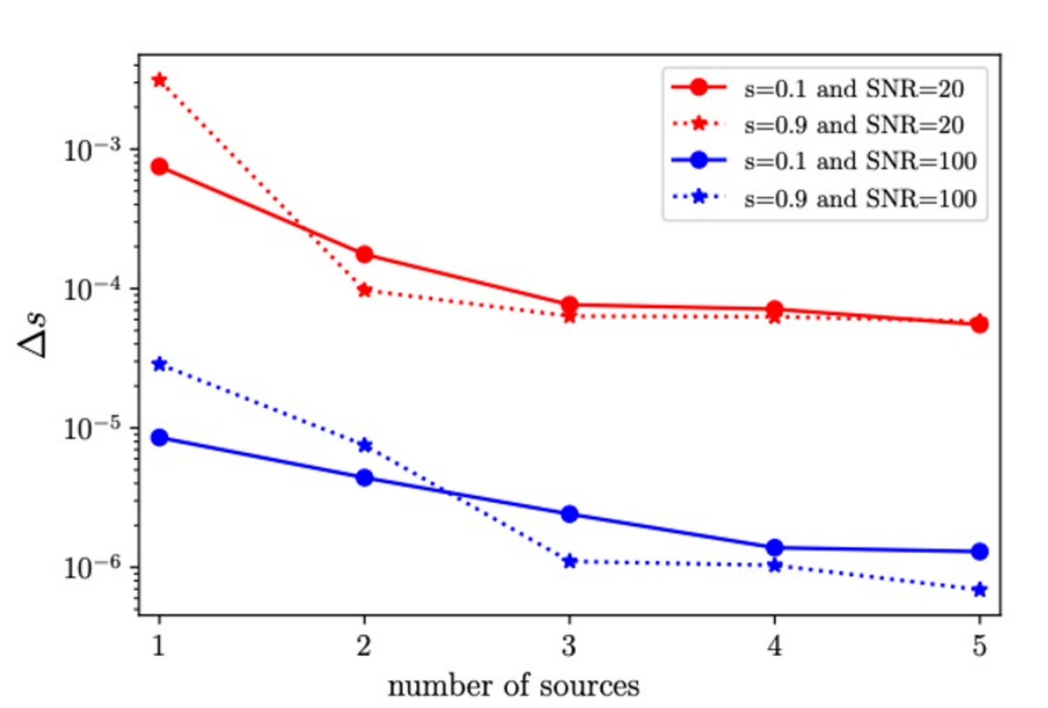
[Vazquez-Aceves et al., 2023]

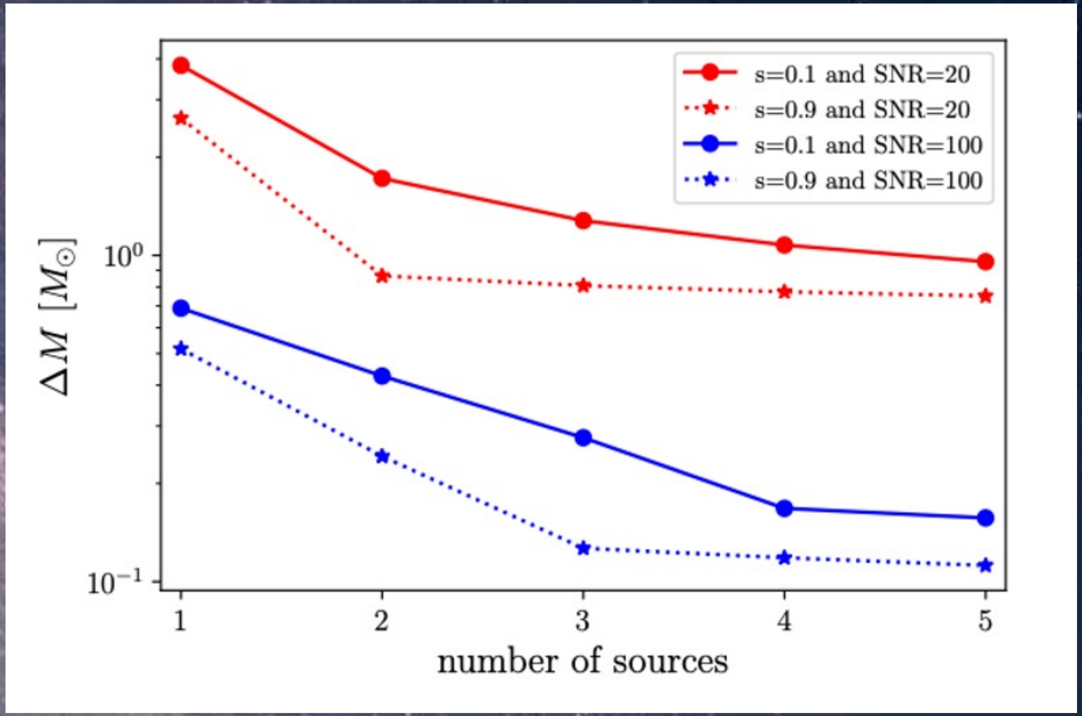
Waveforms: PN2.5 [Barack & Cutler (2004), Fang & Huang (2020)]

Fisher matrix analysis to estimate how accurately the spin and the mass of SgrA* can be measured.
[Finn 1992; Coe 2009; Klein et al. 2016]

What if we have a few sources?

We take detectable sources (SNR $\gtrsim$ 20)





Conclusions

- We expect XMRIs to be abundant and most likely, the loudest sources in our Galaxy.
- Future space-borne detectors will be able to detect at least one circular XMRI if the spin of SgrA* is high (s$\simeq$0.9) and ~ 10 eccentric XMRIs regardless of the spin value.
- Detecting just one XMRI will allow us to measure the mass of SgrA* with an accuracy of the order of $10^{-2}M_{\odot}$.
- The spin can be measured with an accuracy between 10^{-4} and 10^{-7}.
- The spin magnitude of SgrA has an impact on the orbital parameters and the number of XMRIs. Different scenarios are worth exploring as there is currently no restriction on the spin of SgrA *.

veronica@pku.edu.cn

How often these tidal disruptions occur?

We can obtain the event rates of successful XMRIs

$$\dot{\Gamma}_{\mathrm{i}} \simeq \int_{a_{\min}}^{a_{\mathrm{crit}}} \frac{\mathrm{d}n(a)}{T_{\mathrm{rlx}}(a)\,\ln(\widehat{\theta}_{\mathrm{lc}}^{-2})},$$

[Hopman & Alexander, 2005; Amaro-Seoane, 2019]

Ntot is the total number of objects (main-sequence stars, compact objects, and substellar objects) within the influence radius of the MBH

$$\mathrm{d}n(a) = f_{\mathrm{sub}}(3-\beta)\frac{N_{\mathrm{tot}}}{R_{\mathrm{h}}}\left(\frac{a}{R_{\mathrm{h}}}\right)^{2-\beta} da.$$

f_{sub} is the fraction number of the considered species obtained from a Kroupa broken power law, $\varphi(m) \propto \frac{1}{m_*^{\alpha}}$, with m_* the average stellar mass. [Kroupa, 2001]