Binaries in the Galactic Centre

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Idea and motivation

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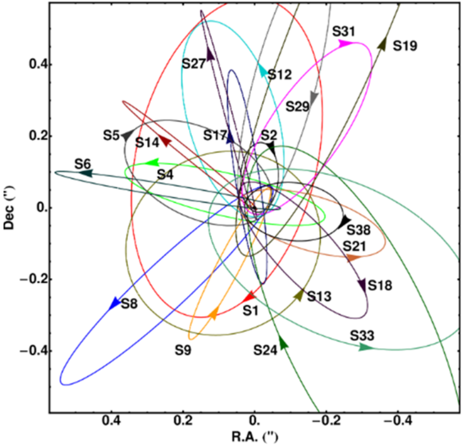

Figure: Stellar orbits of the stars in the central arcsecond [Gillessen et al., 2009].

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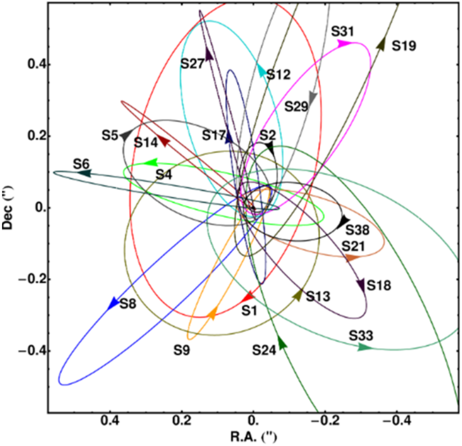

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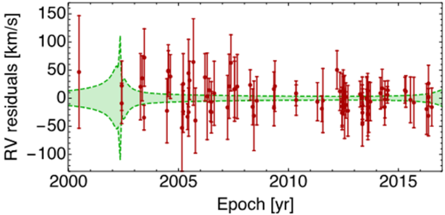

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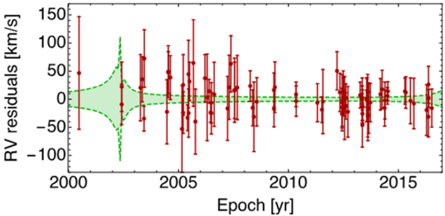
As a first approach, we will focus on S2 star.



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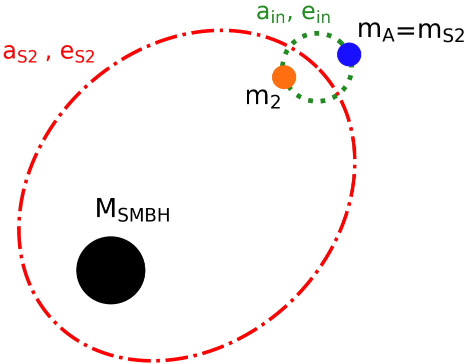

Figure: Adapted from
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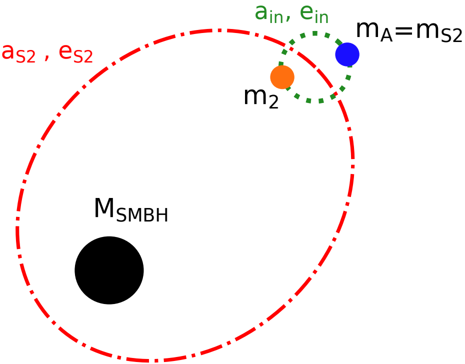

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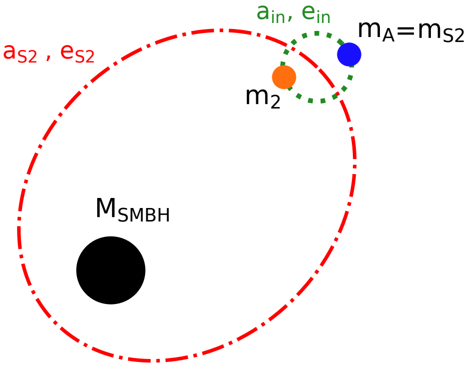

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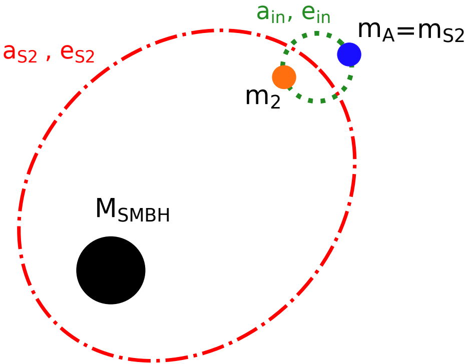

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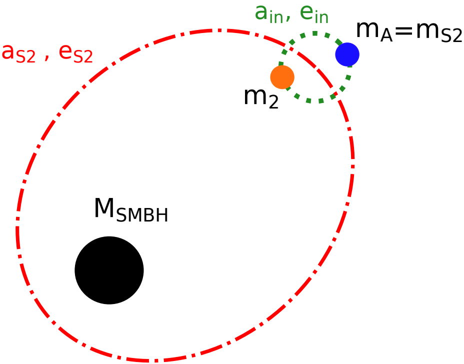

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- Place the binary at apocentre of S2's orbit [GRAVITY Collaboration et al., 2023].
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- Evolve system using N-body code `TidyMESS` with first Post-Newtonian correction [Boekholt and Correia, 2023].

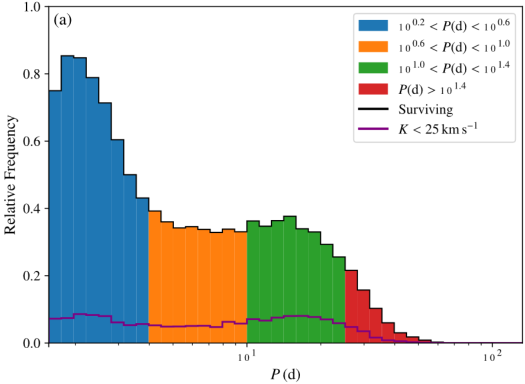
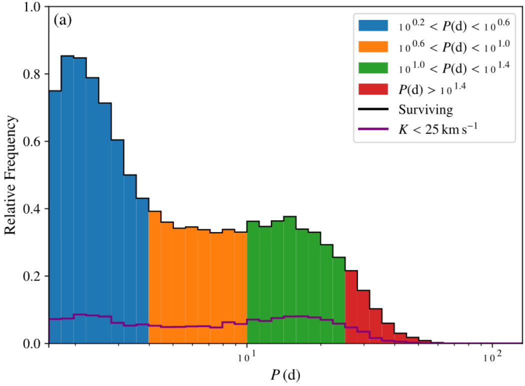


Figure: Distribution of surviving binary orbital periods.



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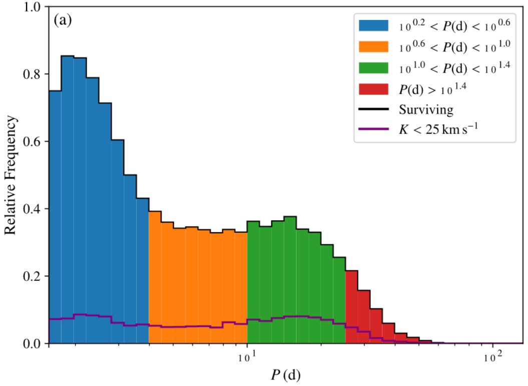

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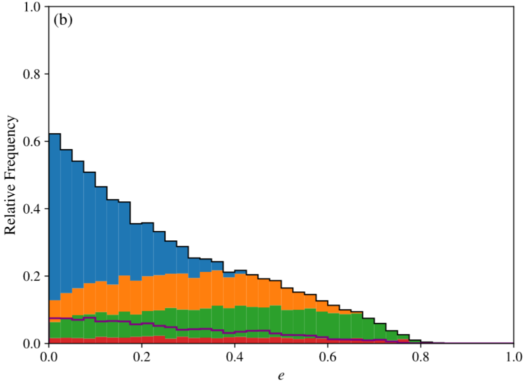
- Binaries with $P >$ 100 days are disrupted.
- Shorter period binaries survive preferentially.

Results: Eccentricity



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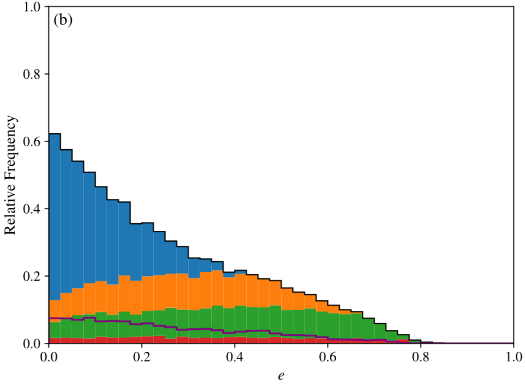

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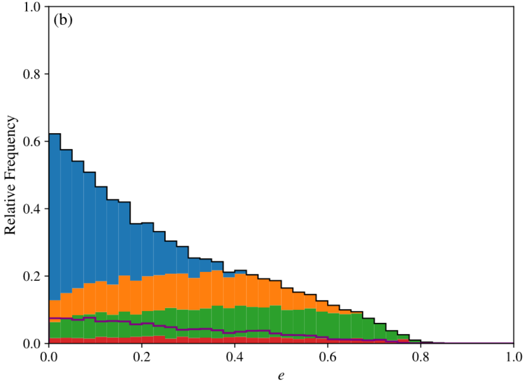

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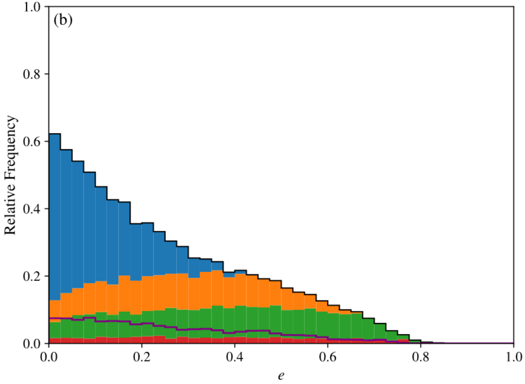

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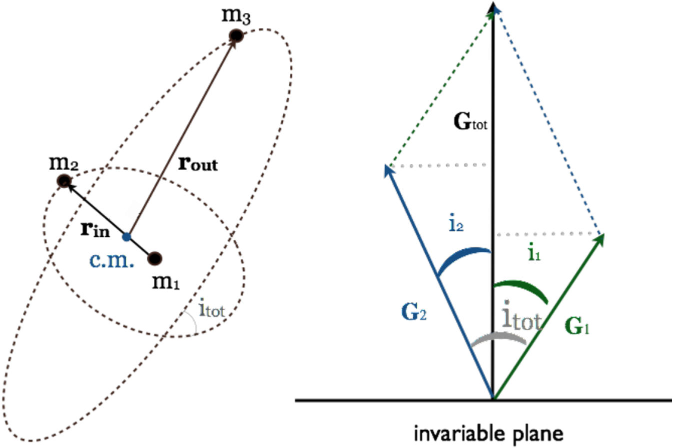
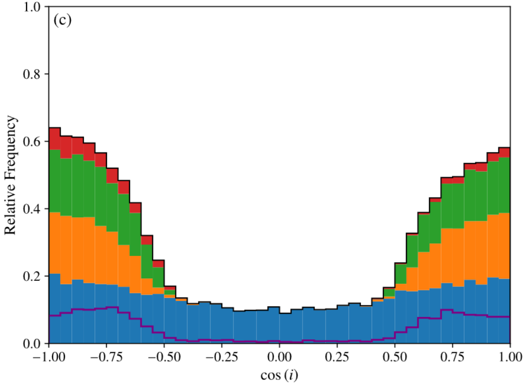


Figure: Schematic representation of the system and its associated angles, adapted from [Naoz, 2016].

Results: Mutual Inclination



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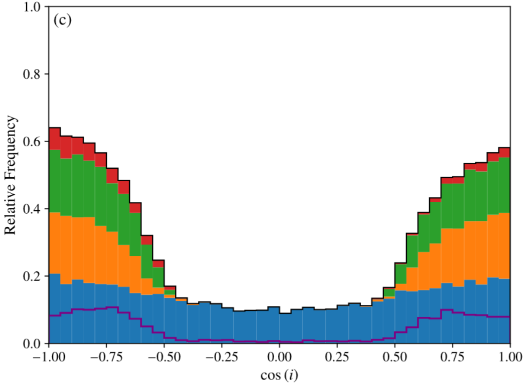

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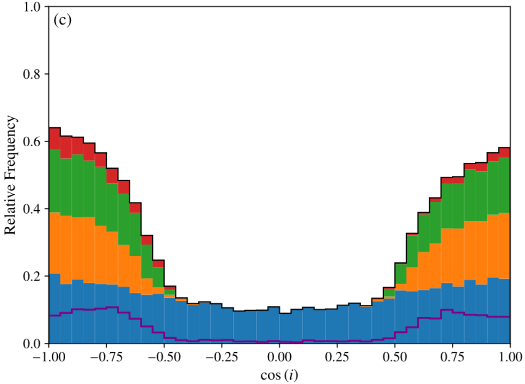

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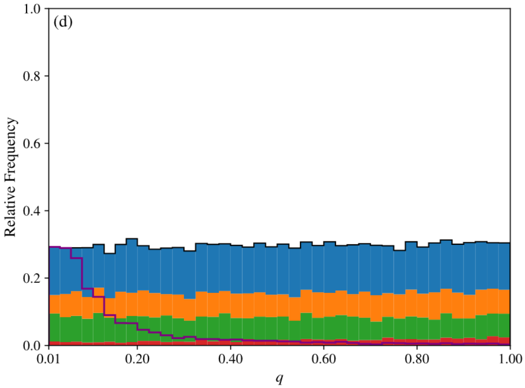
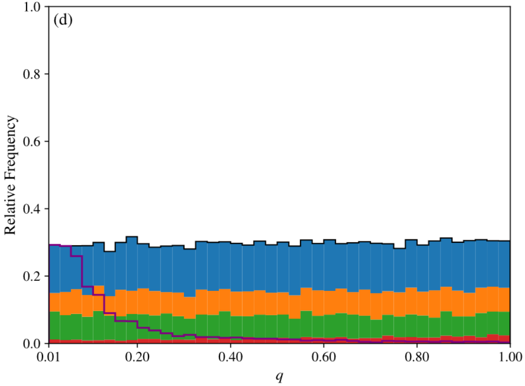


Figure: Distribution of surviving binaries' mass ratios.



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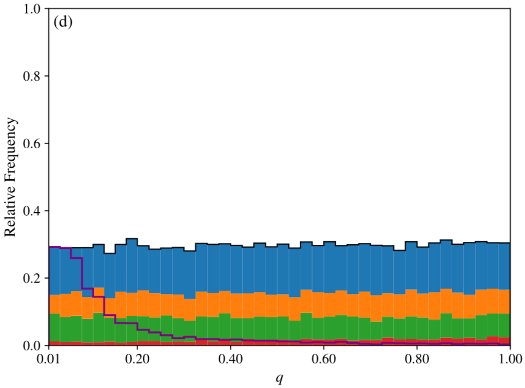

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- Binaries are disrupted uniformly.
- Undetected binaries favour low mass ratios, consistent with observational limits [Chu et al., 2018].

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Thank you for your attention!

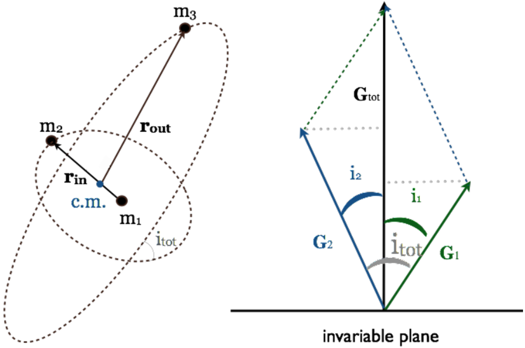
Boekholt, T. C. N. and Correia, A. C. M. (2023).
A direct N-body integrator for modelling the chaotic, tidal dynamics of multibody extrasolar systems: TIDYMESS.
, 522(2):2885–2900.

Chu, D. S. et al. (2018).
Investigating the Binarity of S0-2: Implications for Its Origins and Robustness as a Probe of the Laws of Gravity around a Supermassive Black Hole.
, 854(1):12.

Chu, D. S. et al. (2023).
Evidence of a Decreased Binary Fraction for Massive Stars within 20 milliparsecs of the Supermassive Black Hole at the Galactic Center.
, 948(2):94.

Do, T., Hees, A., Ghez, A., Martinez, G. D., Chu, D. S., Jia, S., Sakai, S., Lu, J. R., Gautam, A. K., O'Neil, K. K., Becklin, E. E., Morris, M. R., Matthews, K., Nishiyama, S., Campbell, R., Chappell, S., Chen, Z., Ciurlo, A., Dehghanfar, A., Gallego-Cano, E., Kerzendorf, W. E., Lyke, J. E., Naoz, S., Saida, H., Schödel, R., Takahashi, M., Takamori, Y., Witzel, G., and Wizinowich, P. (2019).
Relativistic redshift of the star S0-2 orbiting the Galactic Center supermassive black hole.
Science, 365(6454):664–668.

Farago, F. and Laskar, J. (2010).
High-inclination orbits in the secular quadrupolar three-body problem.



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The Kozai-Lidov Hamiltonian may be written as
[Lee and Peale, 2003, Farago and Laskar, 2010, Morais and Correia, 2012]:

$$H_{KL} = -Gm_A m_\bullet \left(\frac{1}{r_{A\bullet}} - \frac{1}{r_\bullet} \right) - Gm_B m_\bullet \left(\frac{1}{r_{B\bullet}} - \frac{1}{r_\bullet} \right) .$$

Performing the average over both orbits, we may write:

$$\bar{H}_{KL} \equiv \langle H_{KL} \rangle_{M_\bullet, M} \propto \left[\left(2 + 3e^2\right) \left(3\cos^2 i - 1\right) + 15e^2 \sin^2 i \cos\left(2\omega\right) \right],$$

Momentum	Conjugate Momentum
M	$L = \beta\sqrt{\mu a}$
$M_\bullet$	$L_\bullet = \beta_\bullet \sqrt{\mu_\bullet a_\bullet}$
ω	$L\sqrt{1 - e^2}$
$\omega_\bullet$	$L_\bullet \sqrt{1 - e_\bullet^2}$
Ω	$G\cos\left(i\right)$
$\Omega_\bullet$	$G_\bullet \cos\left(i_\bullet\right)$

Table: Delaunay variables (action-angle variables) for the triple system

Then, using action-angle variables one obtains:

$$\dot{L} = \frac{d\bar{H}_{KL}}{dM} = 0 \iff L = \text{const.} \iff a = \text{const.}\,,$$

$$\dot{L}_\bullet = \frac{d\bar{H}_{KL}}{dM_\bullet} = 0 \iff L_\bullet = \text{const.} \iff a_\bullet = \text{const.}\,.$$

Additionally, $\bar{H}_{KL}$ does not depend on $\omega_\bullet$, hence:

$$\dot{G}_\bullet = \frac{d\bar{H}_{KL}}{dG_\bullet} = 0 \iff G_\bullet = \text{const.} \iff e_\bullet = \text{const.}\,.$$

Finally, given that $G_{\mathrm{TOT}}^2 = G^2 + G_\bullet^2 + 2GG_\bullet \cos(i) = \text{const.}$, $G_\bullet = \text{const.}$ and $G_\bullet \gg G$ we have that:

$$\left(1 - e^2\right) \cos\left(i\right) \approx \text{const.}$$

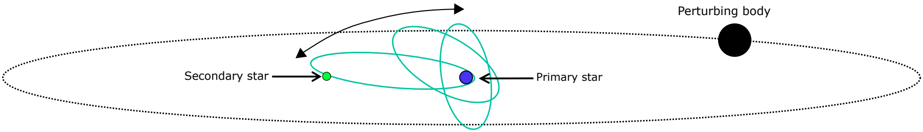

Figure: Diagram with a binary being perturbed by a massive distant body with Kozai-Lidov oscillations depicted adapted from Konstantin Batygin.