Properties of stars scattered by an SMBH binary in the late evolutionary phase including PN corrections

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ZENTRUM FÜR ASTRONOMIE

Three main phases during an SMBH merger

Pairing phase:

- Black holes sink under dynamical friction;
- Proportional to background density of stars and black hole mass;
- Sinking continues until a Kepler binary is formed;

Hardening phase:

- Binary orbital energy loss due to 3-body encounters with stars;
- Stars are ejected via the gravitational slingshot effect;
- Stars come from a region known as the <u>loss cone</u>;

Gravitational wave inspiral:

- GW emission (*PN 2.5 term*) becomes dominant;
- At separations of order ~ [0.001 - 0.01 pc];
- Ends with coalescence of SMBHs;

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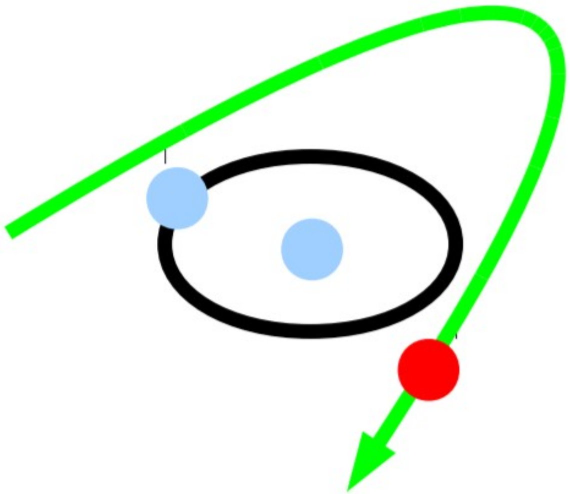
Hardening phase of the merger



- Stars belong to the loss cone if their angular momentum is low enough to reach the center *(centrophilic orbits)*:

$$L \leq L_{crit} = \sqrt{(\eta 2G(M_{BH})a_{BH}},$$

- But the loss cone is emptied within a dynamical timescale

- *Problem:* Not enough stars in the loss cone!

→ Binary stalls at ~ *1 pc* separations

Final Parsec Problem

Loss Cone Refilling and solution to the FPP

Collisional mechanism:

- two-body relaxation effects can scatter stars in the loss cone

→ happens on a relaxation timescale → longer than Hubble Time!

Collisionless mechanism:

$$L \leq L_{crit} = \sqrt{(\eta 2G(M_{BH})a_{BH}},$$

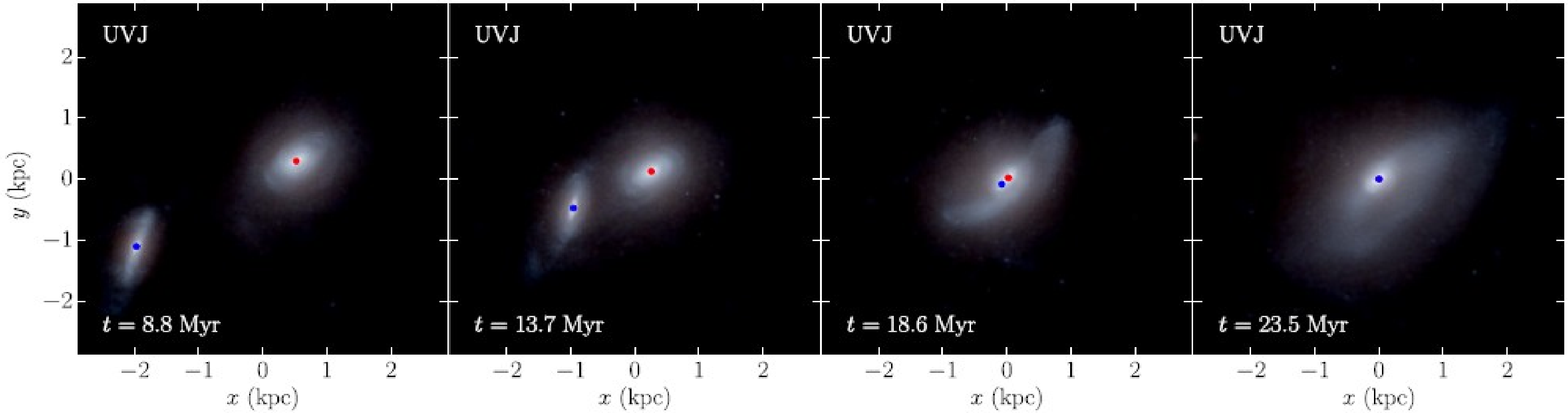
- centrophilic orbits in non-spherical nuclei
- axisymmetric nuclei - only l_z is conserved
- triaxial nuclei - only constraint is $l > 0$

Stars on triaxial (boxes, pyramids, chaotic) and axisymmetric (saucers) orbits can repopulate the loss cone and enable efficient SMBH coalescence!

- The question(s):
  - How relevant are PN corrections in the hardening phase of the merger?
  - Do other effects play a role in SMBH hardening other than stellar interactions?
  - What are the orbital and phase-space properties of the loss cone stars?
- How:
  - Using high-performance N-body and three-body simulations for final stages of SMBH binary coalescence in gal. nuclei
  - AR-CHAIN code, *Mikkola & Merritt (2006,2008)*
  - φ-GRAPE-hybrid code: φ-GRAPE+ETICS, *Harfst et al. (2007) ; Meiron et al. (2014)*

Initial conditions: System from Khan et al. (2016)

Khan et al. (2016)



- Galaxy merger at $z = 3.5$ followed from *Argo* cosmological simulation
- Two SMBHs are introduced in the galactic cores and resolution is increased
- SMBH masses: $M_1 = 3 \times 10^8 M_\odot$ and $M_2 = 8 \times 10^7 M_\odot$
- Estimated merger time: **$t \approx 17$ Myr** since binary formation *(Avramov et al. 2021)*

Part 1:
Impact of PN corrections at ~1000 R_{sch} separations

- *Avramov et al. (in prep.)*

Numerical setup

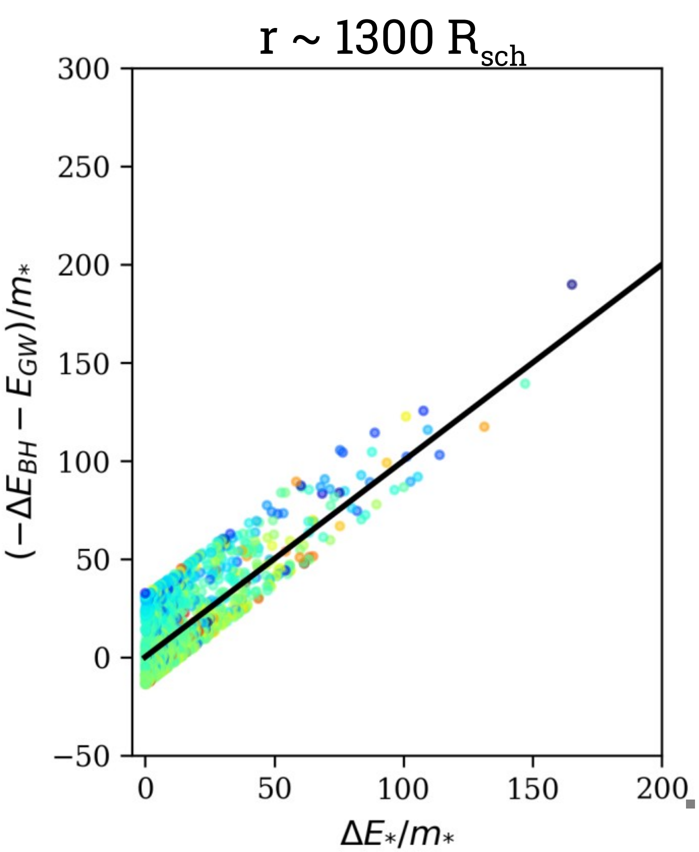
- A series of 3-body scattering experiments using the AR-CHAIN code
- 1000 runs at ~1300 R_{sch} (hardening phase) and 2000 at ~ 900 R_{sch} (GW phase)
- SMBH binary equations of motion corrected up to order 2.5PN
- Star positions initialized uniformly on a spherical shell with D= 100 pc
- Star velocities generated such to guarantee close approaches:

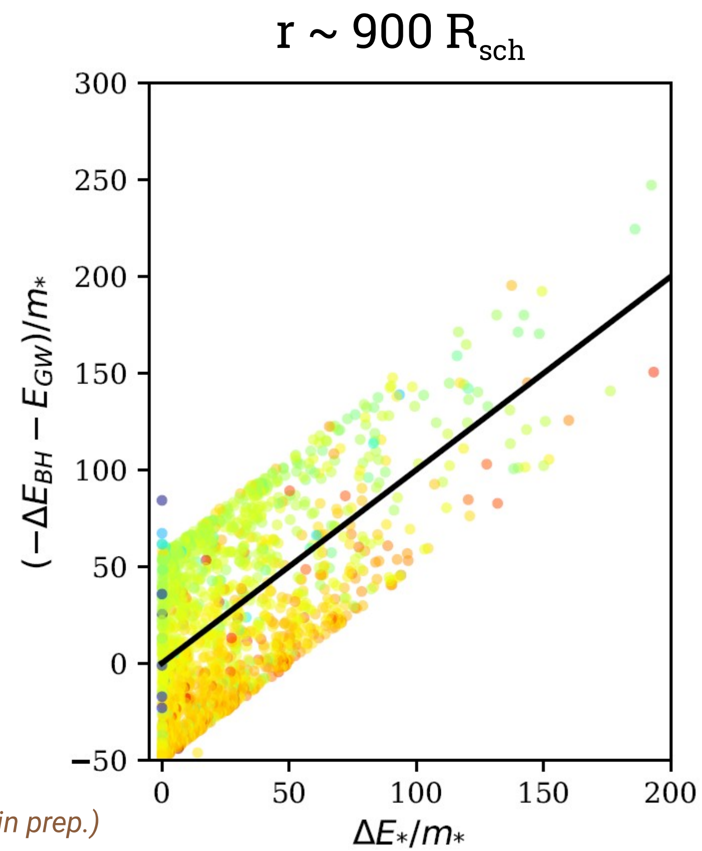
$$r_{\rm p} < 2a_0,$$

Newtonian energy balance of the system

- Using the Newtonian black hole orbital energy formula:

$$-\Delta E_{BH} = \Delta E_* + E_{GW},$$





Avramov et al. (in prep.)

Post-Newtonian energy balance of the system

- In reality: $E_{BH} = E_{Newt} + E_{PN}, \quad E_{PN} = E_{PN1} + E_{PN2} + \ldots$

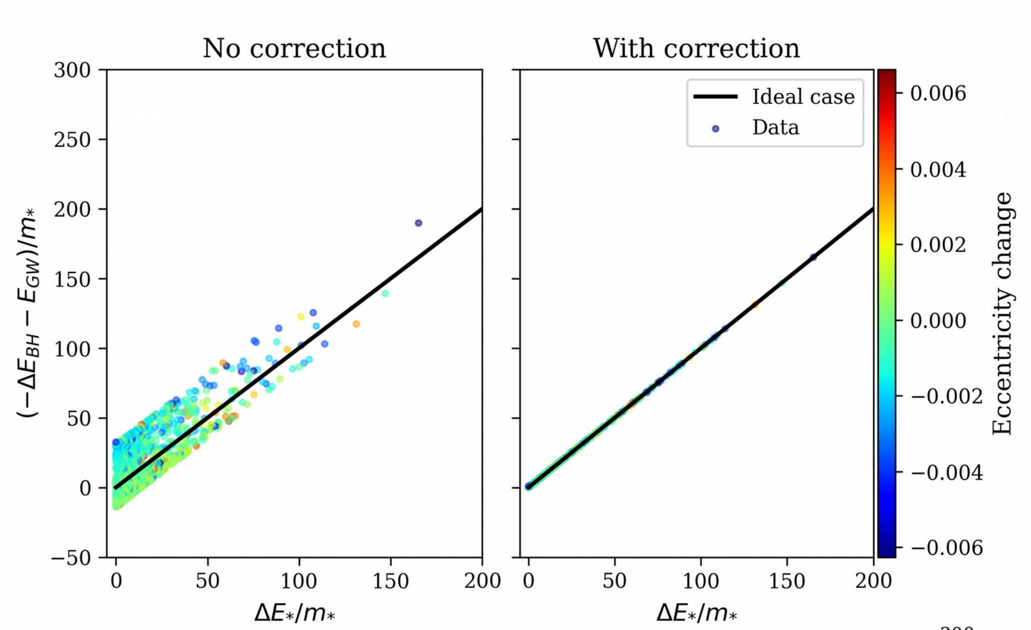
- Even PN terms (1PN, 2PN...) do not carry away net energy from the system and are often omitted from energy considerations

- The odd term 2.5PN corresponds to GW emission

- Even terms can however induce oscilations that are relevant for studying individual interactions

$$E_{PN1} = \frac{\mu}{c^2}\left\{\frac{3v^4}{8} - \frac{9m_1m_2v^4}{8m^2} + \frac{m}{r}\left(\frac{m_1m_2\left(\vec{n}\cdot\vec{v}\right)^2}{2m^2} + \frac{3v^2}{2} + \frac{m_1m_2v^2}{2m^2}\right) + \frac{m^2}{2r^2}\right\}$$

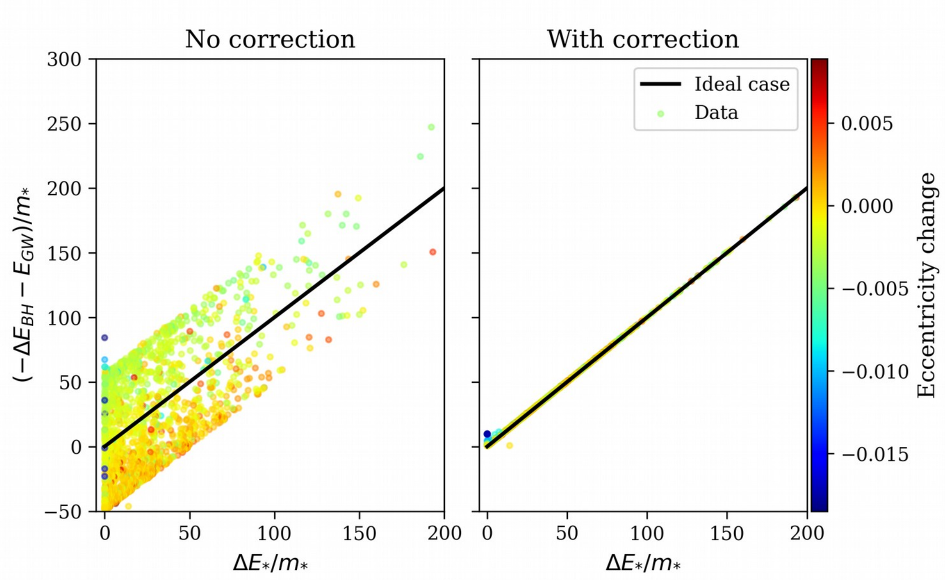
$$\Delta E_* = -\Delta E_{Newt} - \Delta E_{PN} - E_{GW}.$$



Even PN corrections to the orbital energy completely resolve the energy discrepancy!

r ~ 900 R_{sch}

r ~ 1300 R_{sch}



Must be included even in the hardening phase

- *Avramov et al. (in prep.)*

Part 2:
Properties of loss cone stars

- *Avramov et al. (2021)*

Initial conditions and numerical setup

- Khan et al. 2016 data initiated during hardening phase at BH separation ~$1650R_{sch}$
- Run stopped at separation of ~ $650\ R_{sch}$
- Particles: $N= 6x10^6$
- Post-Newtonian included up to PN 2.5 term
- Using the φ-GRAPE-hybrid code

•We monitor and identify stars stars which enter and exit the binary vicinity ($10a_{bh}$)
•Enables accurate investigation of energy and orbital parameter changes

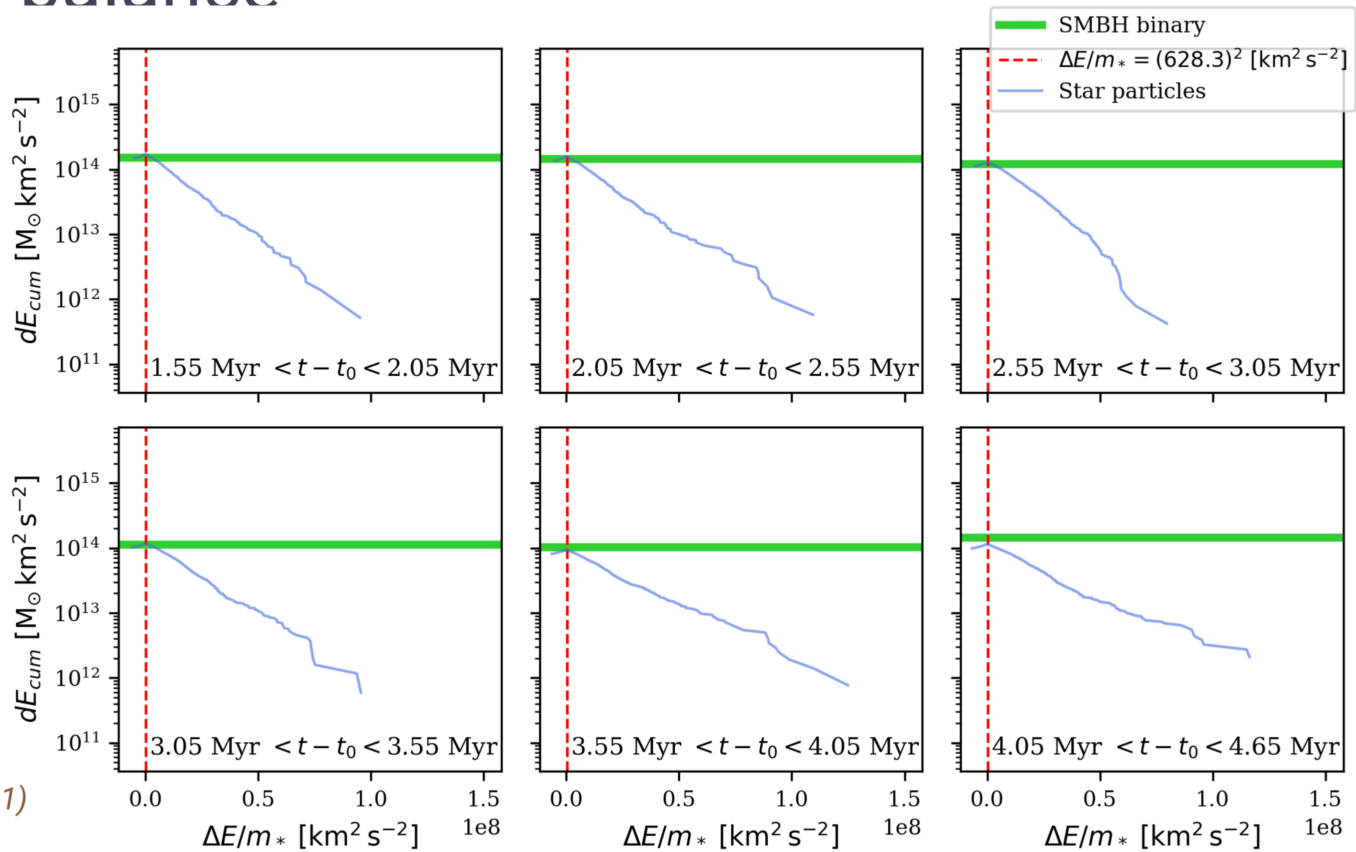
- system slightly triaxial at all times in the simulation

How many **core** and **halo** particles?
core particles must fullfil **one** of these crtieria:

$$r_p < 0.5R_{infl} \quad \text{or} \quad r < R_{infl},$$

- Gives us ~2e+5 **core** particles

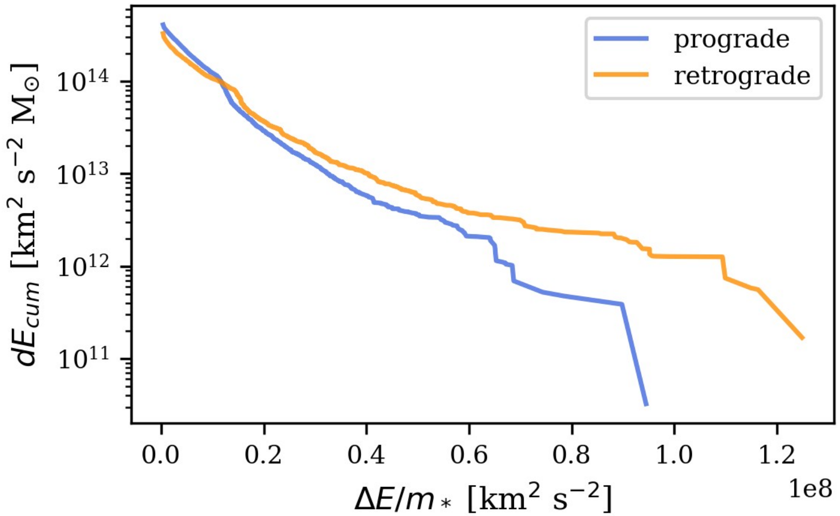
Energy balance



Avramov et al. (2021)

Stellar hardening completely accounts for the SMBH binary energy evolution and all other possible effects can be neglected

Inclination of loss cone stars

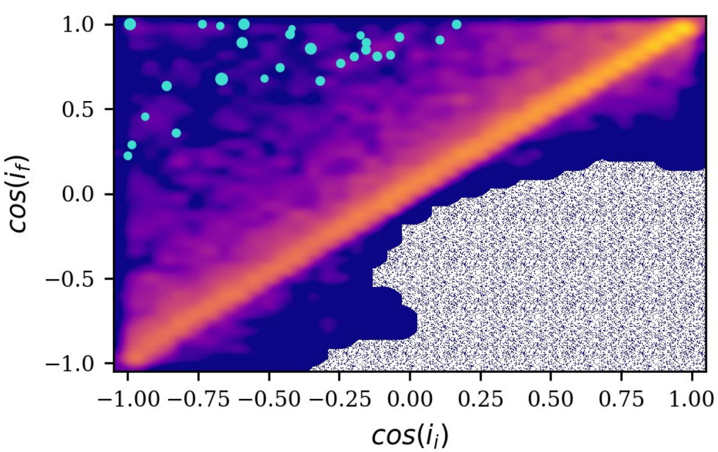


- While smaller in number, retrograde orbits are the most energetic

- Therefore they make up for 45% of the overall energy exchange

- Most energetic encounters show an angular momentum sign-flip change during the energetic interaction

- These correspond to retrograde orbits that cross the SMBH binary orbit and experience a ≈180^0 scattering



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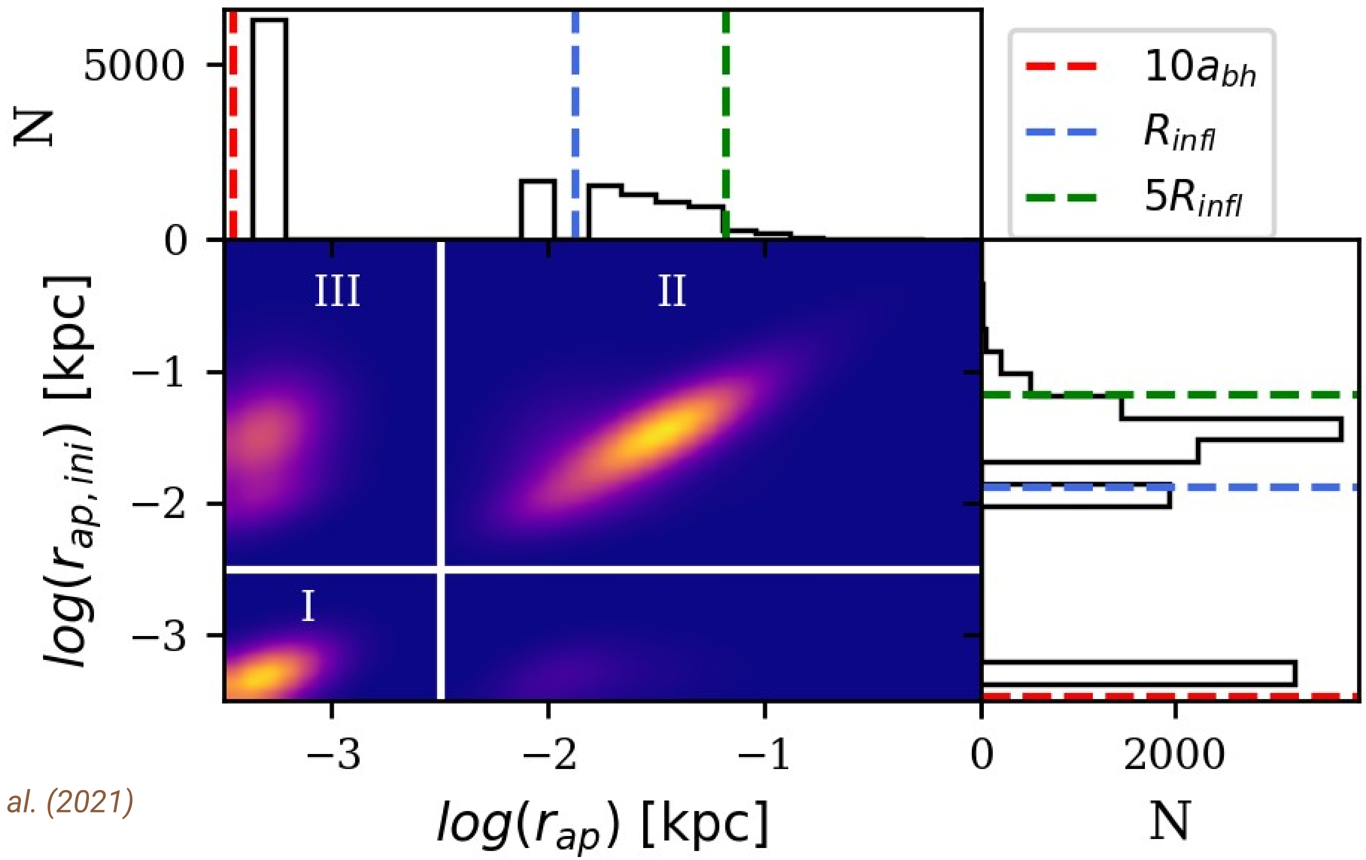

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Population I - result from the random motion of the SMBH around the center

Populations II-III - stars on centrophilic orbits that refill the loss cone
Population III - gets captured and is put on an eccentric orbit

Stellar populations I-III

Population I - result from the random motion of the SMBH around the center

Populations II-III - stars on centrophilic orbits that refill the loss cone
Population III - gets captured and is put on an eccentric orbit

	N	$\langle \Delta E/m \rangle$ [km^2 s^{-2}]	$\langle dt \rangle$ [yr]	dE_{cum} [$M_\odot$ km^2 s^{-2}]
Total	13383	5.11×10^6	153.73	7.36×10^{14}
Population 1	2816	4.51×10^6	177.57	1.77×10^{14}
Population 2	6680	4.79×10^6	138.95	3.33×10^{14}
Population 3	3465	5.93×10^6	166.94	1.95×10^{14}

Potential type	Fraction of encounters (%)
Spherical	0.0
Axisymmetric	23.8
Triaxial	76.2

- 76.2 % of centrophilic orbits can only originate in triaxial nuclei

Take-home with you:

- Conservative PN terms (1PN) must be included in the energy balance already at $\sim 1000\ R_{sch}$ separations
- Stellar hardening alone can resolve the FPP in triaxial, gas-poor systems
- Most energetic interactions result in a sign-flip change in angular momentum
- Three distinct populations found in distribution of loss cone stars
- 76% of centrophilic orbits can only originate in triaxial nuclei