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Eccentric mergers in black hole discs around a supermassive black hole

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The Niels Bohr International Academy

MARIE CURIE ACTIONS

OIST

main question:

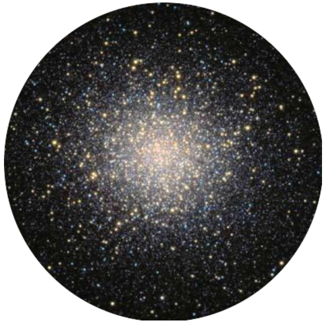
DO BLACK HOLE MERGERS IN GALACTIC NUCLEI HAVE ANY SIGNATURE FEATURE?

i.e. how does the environment galactic nuclei affect the properties of merging compact objects?

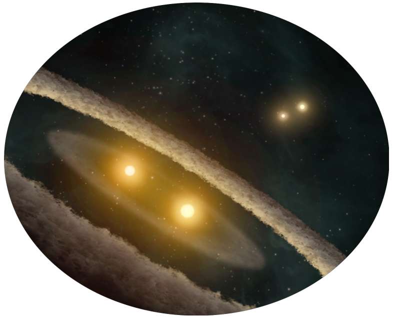
- can the SMBH trigger an excess of eccentric mergers?

- answer: no

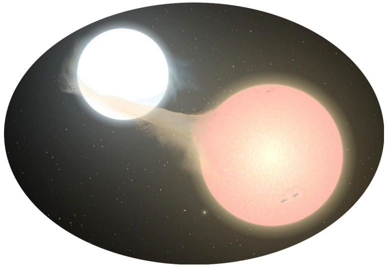
Gravitational waves, from where?



Globular clusters



Isolated triples and multiples



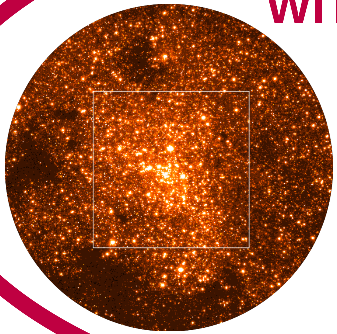
Isolated binaries

$$\frac{Z^2 e^2 c^2}{2GM} \sim \frac{hc^3}{2GM}$$

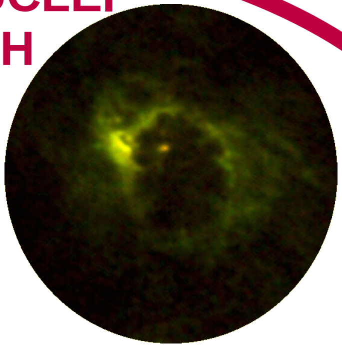
Primordial universe

Young massive clusters

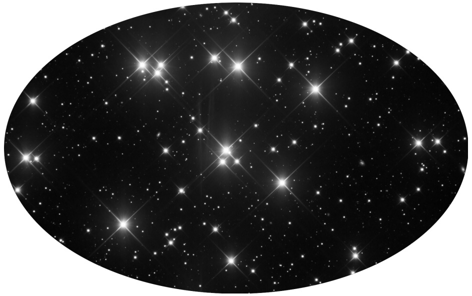
GALACTIC NUCLEI WITH SMBH



Nuclear star clusters



AGN disks



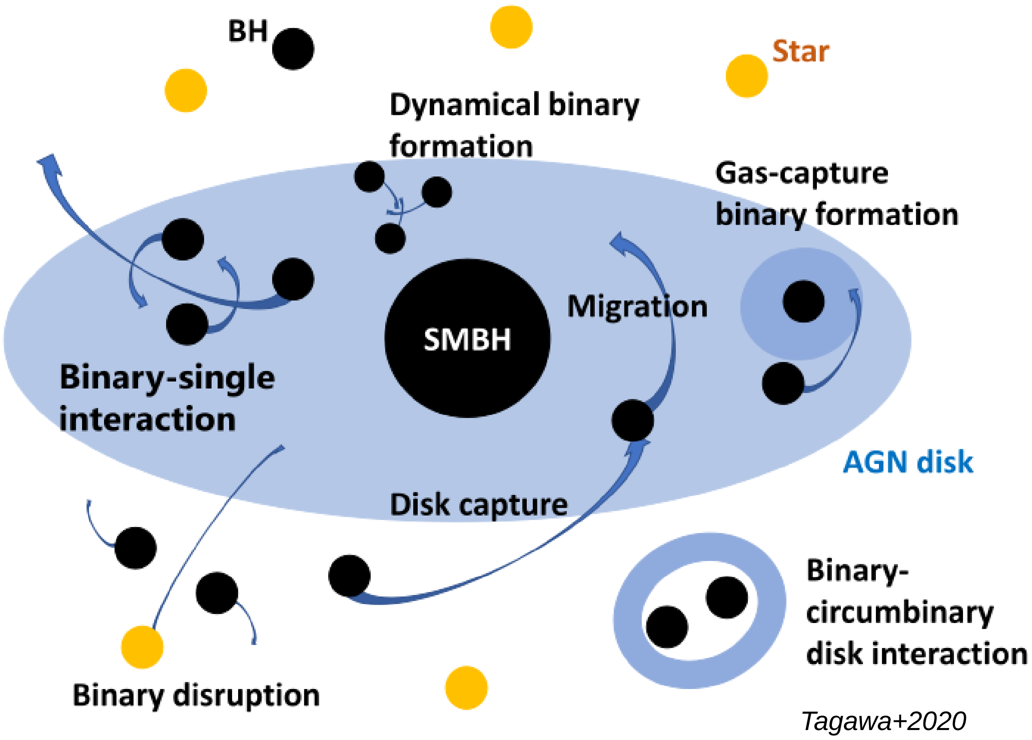
Open clusters

Many pathways to merger in galactic nuclei with SMBH (+ AGN disk)

- **Interactions with the SBMH**
  - von Zeipel-Kozai-Lidov mechanism
  - extreme mass ration inspirals

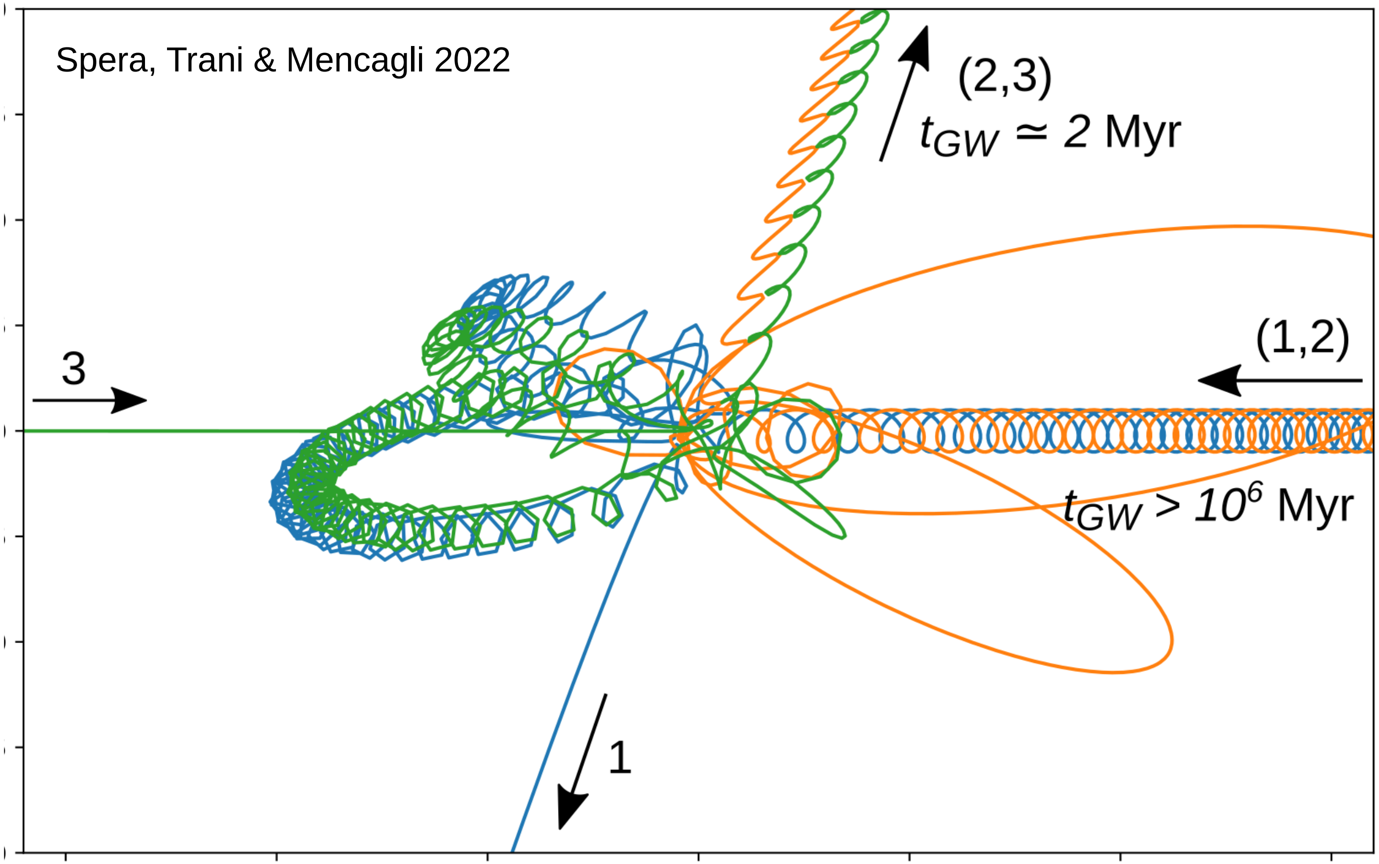
- **Interactions with the AGN**
  - disk captures
  - gas-capture binary formation
  - disk migration
  - binary-circumbinary gas interactions

- **Interactions among BHs**
  - single-single (2-body) encounters
  - binary-single (3-body) encounters



Just like in stellar clusters… or not?

Three-body encounters in *isolation*

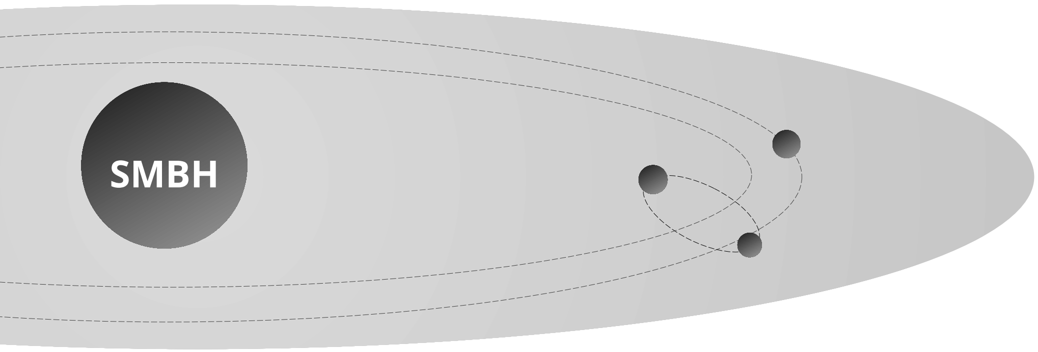


Main effects on GW progenitors:

- Decrease GW merger time by shrinking binary separation / increasing *eccentricity*
- Exchanges tend to equalize the mass ratio of binary members
- No expected correlation between BH spin axis and orbital plane (but see Trani et al. 2021)

Three-body encounters around a SMBH

Happen in a disk of compact objects



Several channels to form a stellar disk around a SMBH:

In AGNs:

- AGN disk gas captures
- Star formation in AGN disk

In "dry" galactic nuclei:

- Disk star formation (as in the galactic center, e.g. von Fenllenberg+2022)
- Anisotropic mass segregation / vector resonant relaxation (e.g. Szolgyen+2022)

Main differences:

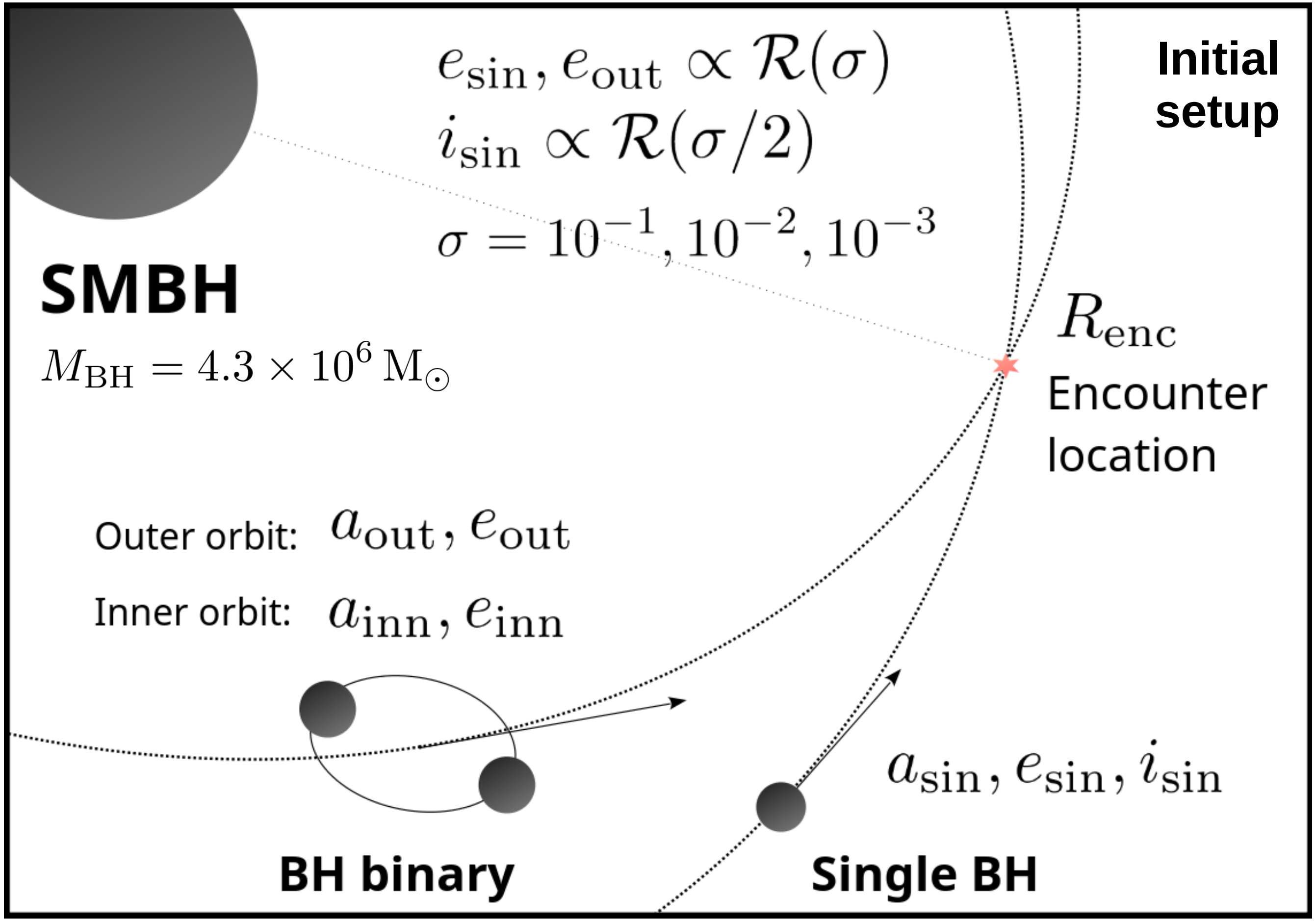
1. Initial orbits are Keplerian around the SMBH
2. The SMBH tidal field limits the binary

How does this affect the properties of merging binaries?

Samsing+2022 suggests an excess of eccentric mergers - but no numerical study exists so far

Methods: N-body simulations including post-Newtonian terms (TSUNAMI, Spera & Trani 2022)

3-body encounters + the SMBH



+ simulations without the SMBH for comparison

3 sets:

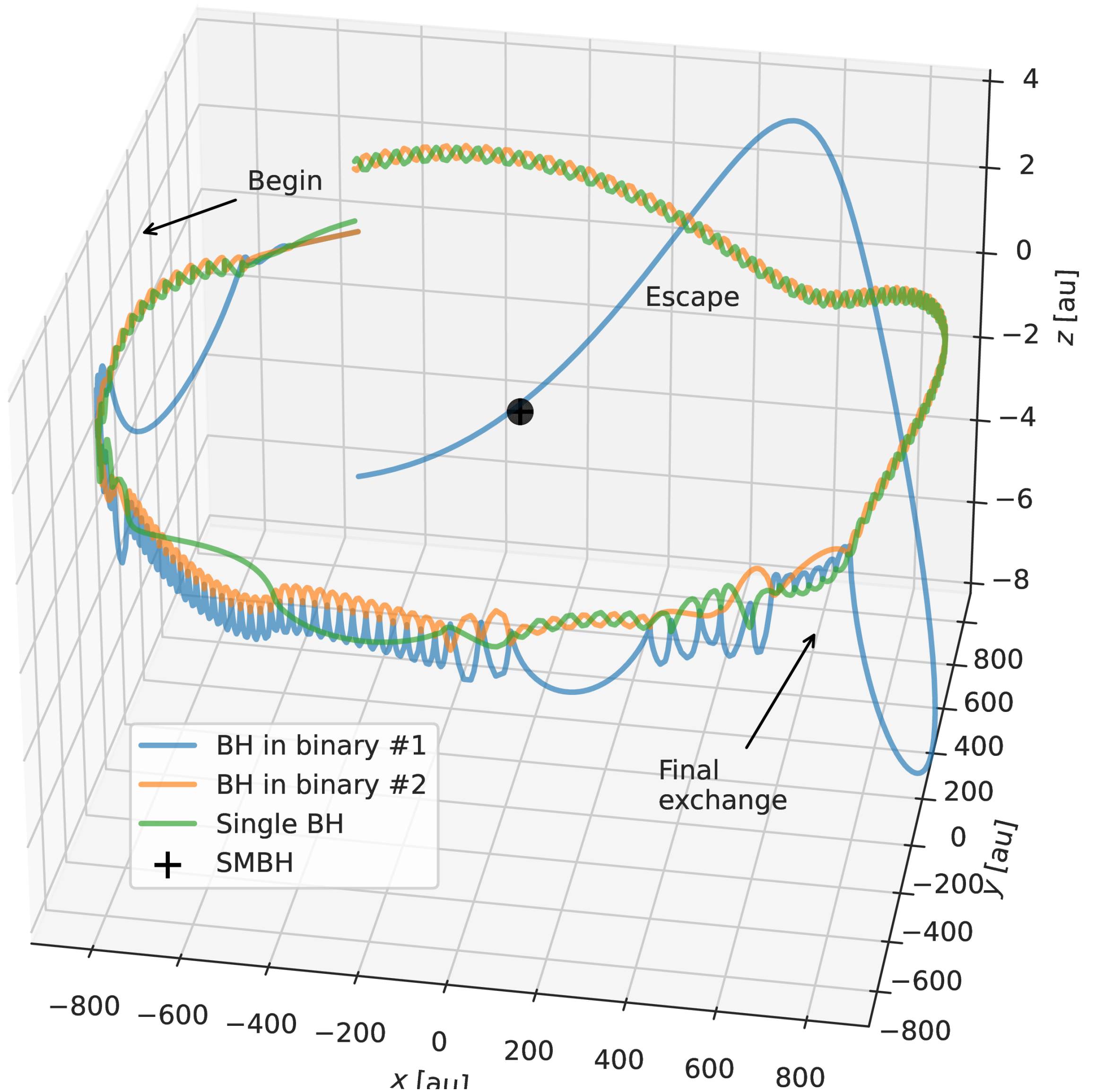
σ-2 fiducial model, disk around a SMBH

σ-2-isol same as fiducial, but **no SMBH**

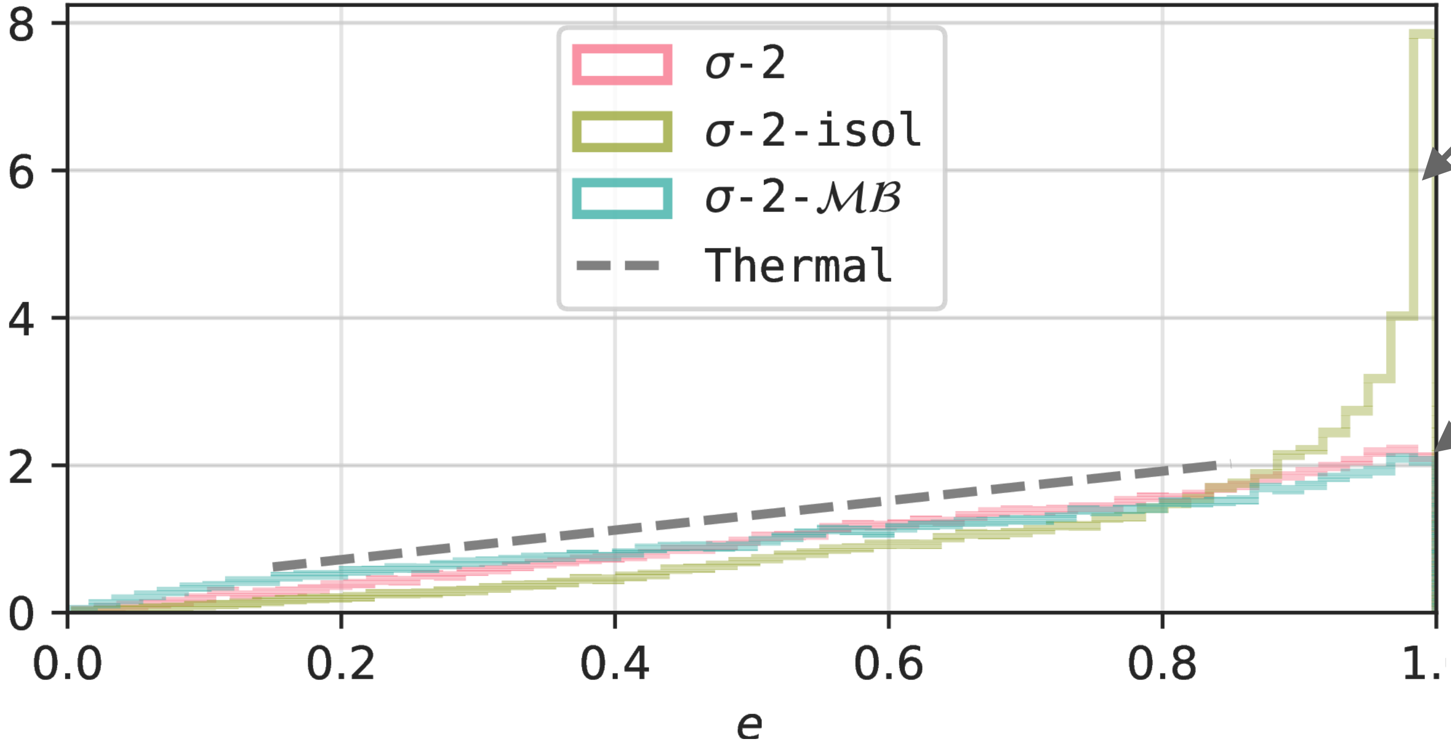
σ-2-isol-$\mathcal{MB}$ **no SMBH**, nuclear star cluster-like model

- Maxwell-Boltzmann velocity dispersion $\sigma_{\mathcal{MB}} = 50\,{\rm km/s}$
- random binary orientations

SMBH only provides gravitational potential wherein 3-body encounter takes place



Outcomes Eccentricity distribution of post-encounter binaries

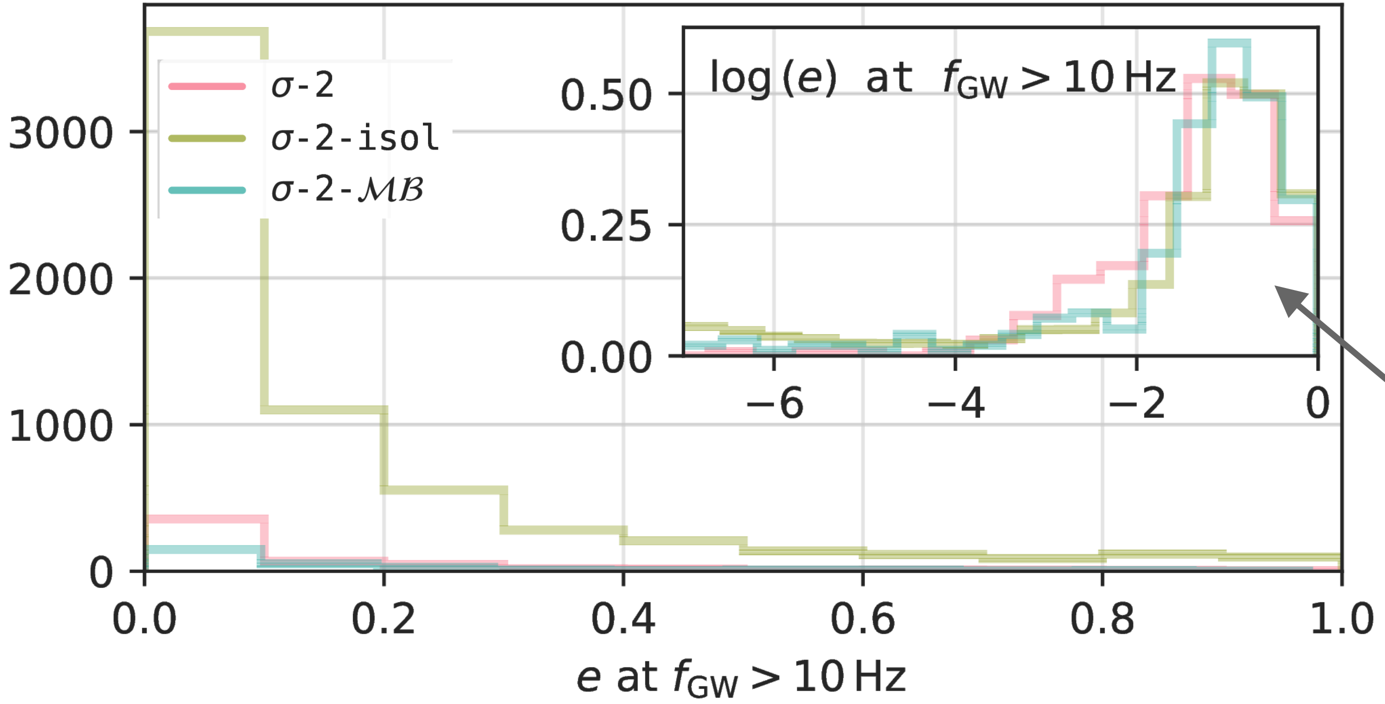


no SMBH eccentricity is super thermal!

with SMBH eccentricity similar to the nuclear star cluster with no SMBH

Outcomes \ Set	σ-2	σ-2-isol	σ-2-$\mathcal{MB}$
Merger	0.54%	6.39%	0.26%

12x more mergers if we neglect the SMBH



Eccentric mergers in LVK band

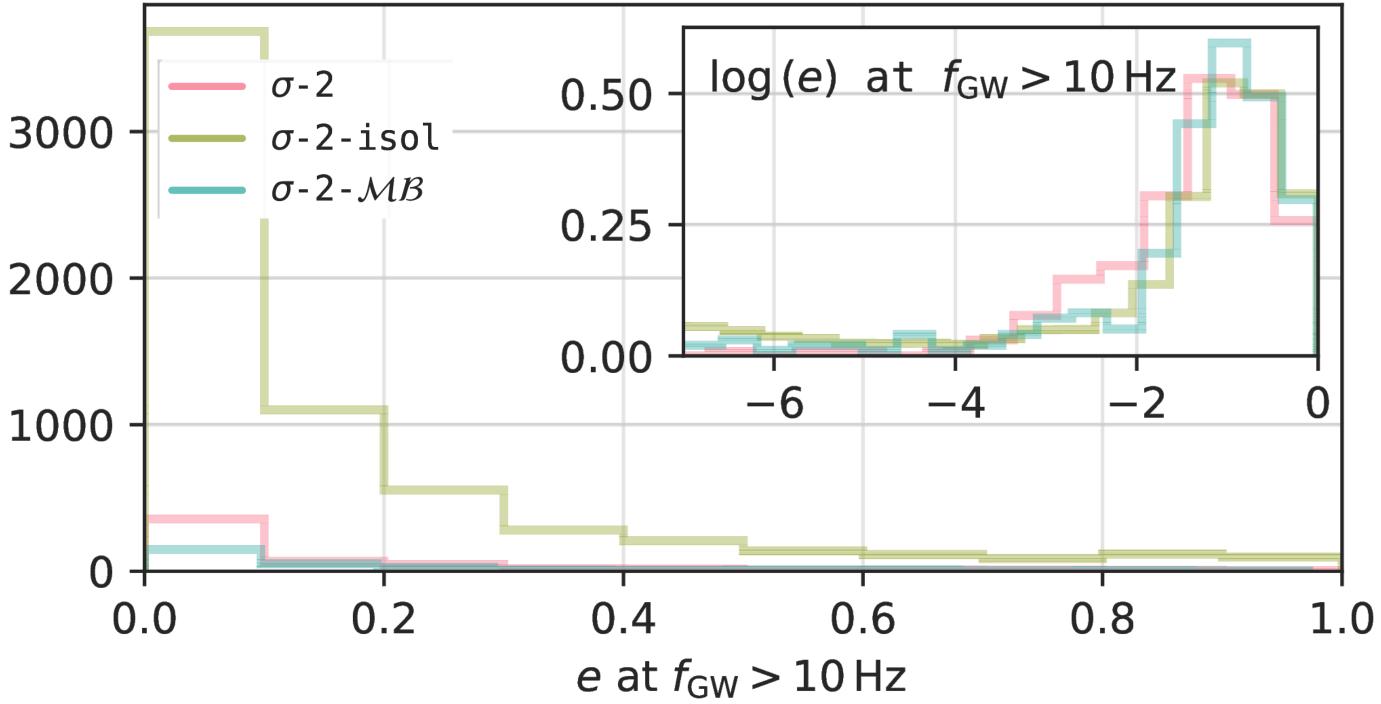
~33% of mergers have $e > 0.1$ at $f_{\rm gw} = 10\,{\rm Hz}$

however

very similar eccentricity profiles

Set / Outcomes	σ-2	σ-2-isol	σ-2-$\mathcal{MB}$
$e > 0.1$ at $f_{\rm GW} > 10\,{\rm Hz}$	0.18%	2.70%	0.11%
"" over total mergers	33.76%	42.25%	42.80%

neglecting the SMBH dramatically overestimates # of (eccentric) mergers



Eccentric mergers in LVK band

~33% of mergers have $e > 0.1$ at $f_{\rm gw} = 10\,{\rm Hz}$

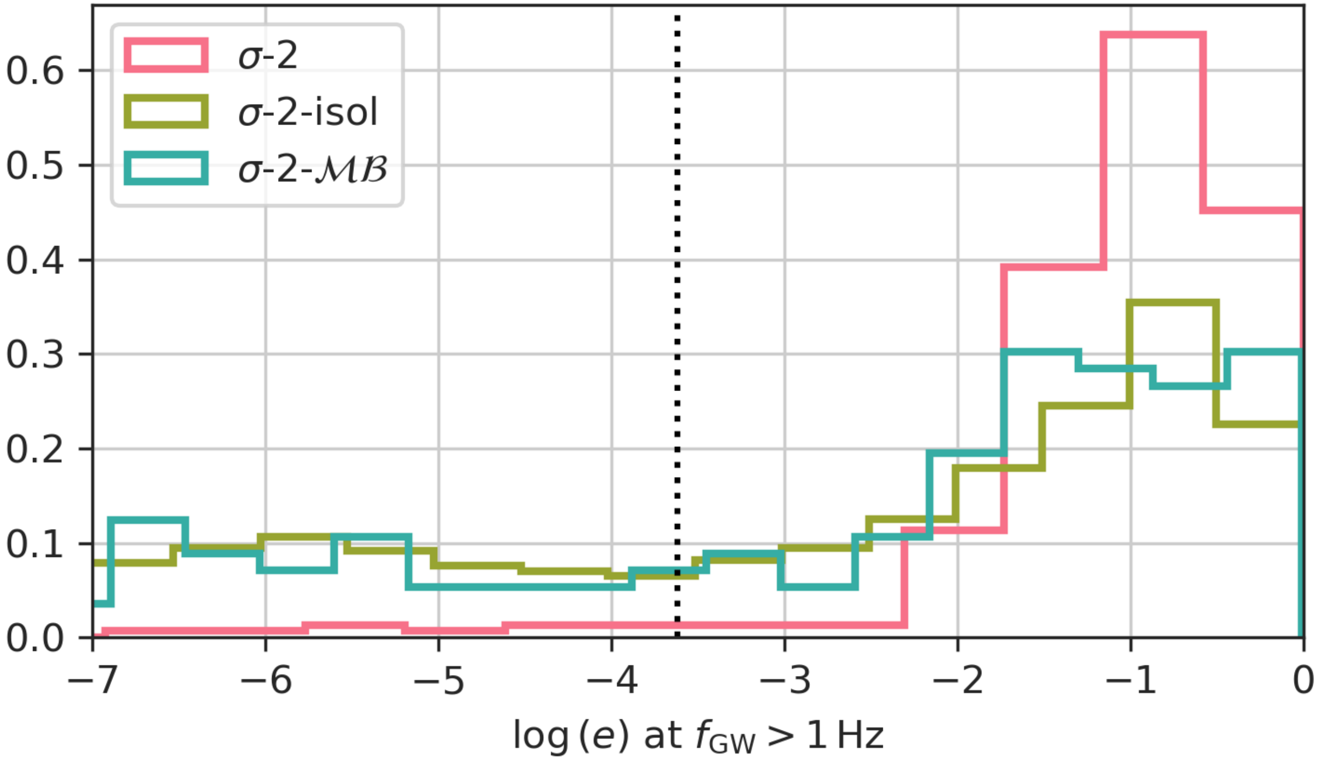
however

very similar outcomes to the nuclear star cluster case

Outcomes \ Set	σ-2	σ-2-isol	σ-2-$\mathcal{MB}$
$e > 0.1$ at $f_{\rm GW} > 10\,{\rm Hz}$	0.18%	2.70%	0.11%
"" over total mergers	33.76%	42.25%	42.80%
Merger	0.54%	6.39%	0.26%

neglecting the SMBH dramatically overestimates # of (eccentric) mergers

Eccentric mergers entering ET band



About 26% of all mergers with

$$e > 0.1 \quad \text{at } f_{\rm gw} = 1\,{\rm Hz}$$

45% of mergers with detectable eccentricities in ET

Conclusions

1. Mergers from 3-body encounters in black hole disks are very similar to their counterpart in nuclear star clusters without a SMBH

2. Previous studies that neglected the role of the SMBH have overestimated the fraction of mergers / eccentric mergers by ~12x / 2x times

3. ~33% of in-cluster mergers have high (>0.1) eccentricities in LVK band, ~45% have detectable eccentricities in the ET band

(4) Not all disks are equal: disk velocity dispersion controls the merger efficiency

Future work

+ Add population synthesis-informed binary population

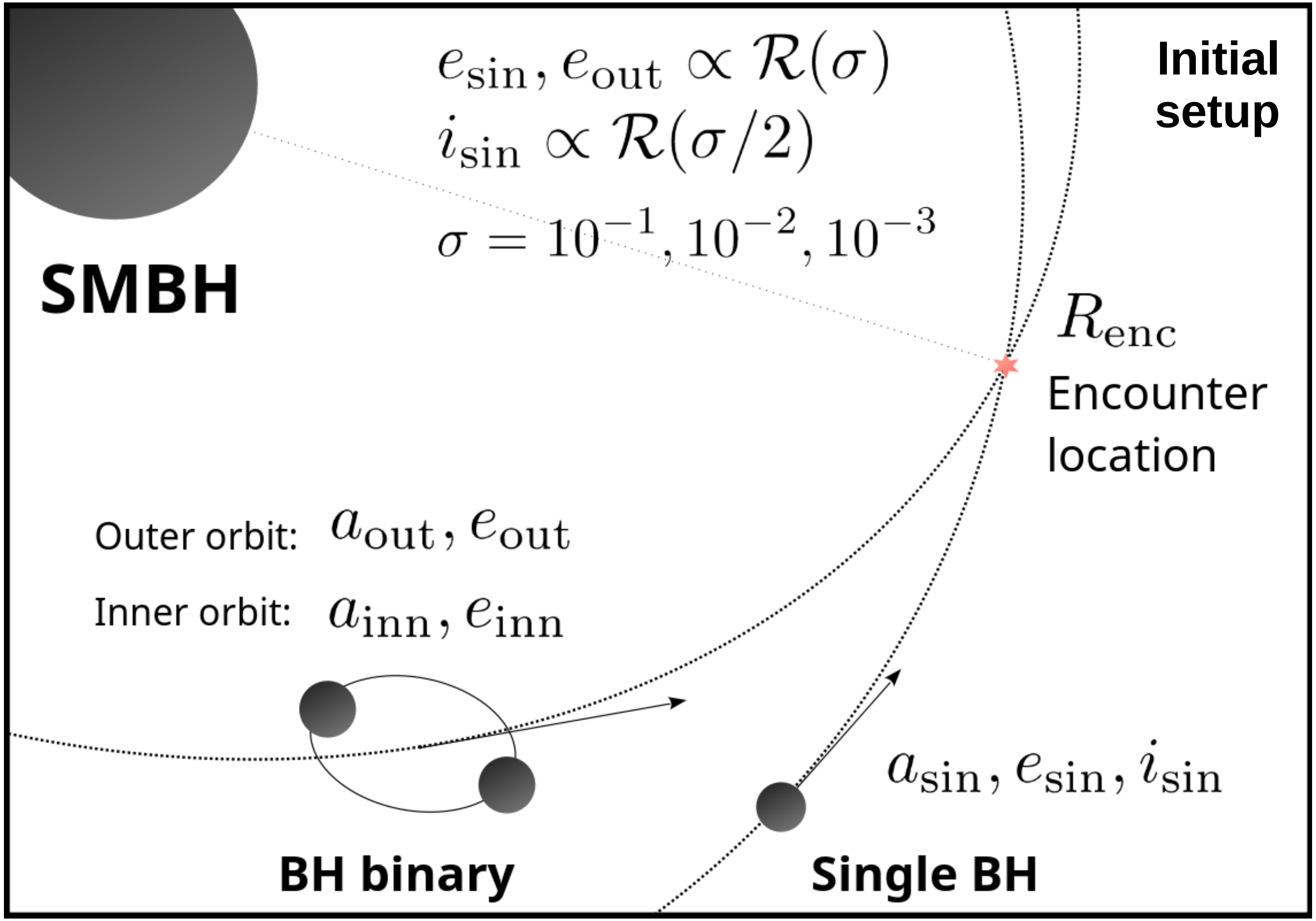
+ Consider encounter rates for different disk types

+ Add drag and migration forces for BHs embedded in AGNs

Property	Values
$a_{\rm inn}$	$\log \mathcal{U}(0.1, R_{\rm Hill}/2)$
$e_{\rm inn}$	0
$i_{\rm inn}$	0
$e_{\rm sin}, e_{\rm out}$	$\mathcal{R}(\sigma)$
$i_{\rm sin}$	$\mathcal{R}(\sigma/2)$
$m_1, m_2, m_{\rm sin}$	$\log \mathcal{U}(10, 50)\,{\rm M}_\odot$
σ	$10^{-1}, 10^{-2}, 10^{-3}$

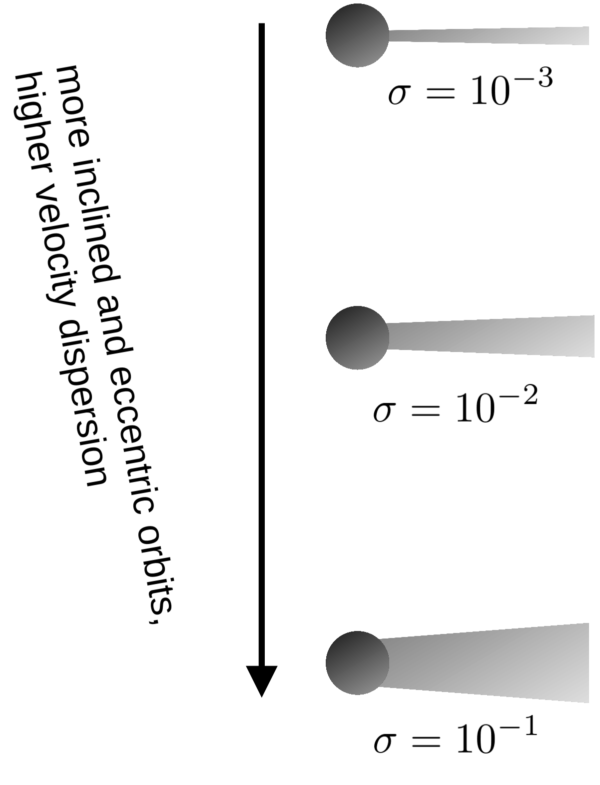
Methods: direct N-body simulations including post-Newtonian terms (TSUNAMI)

3-body encounters + the SMBH



Three types of disks:

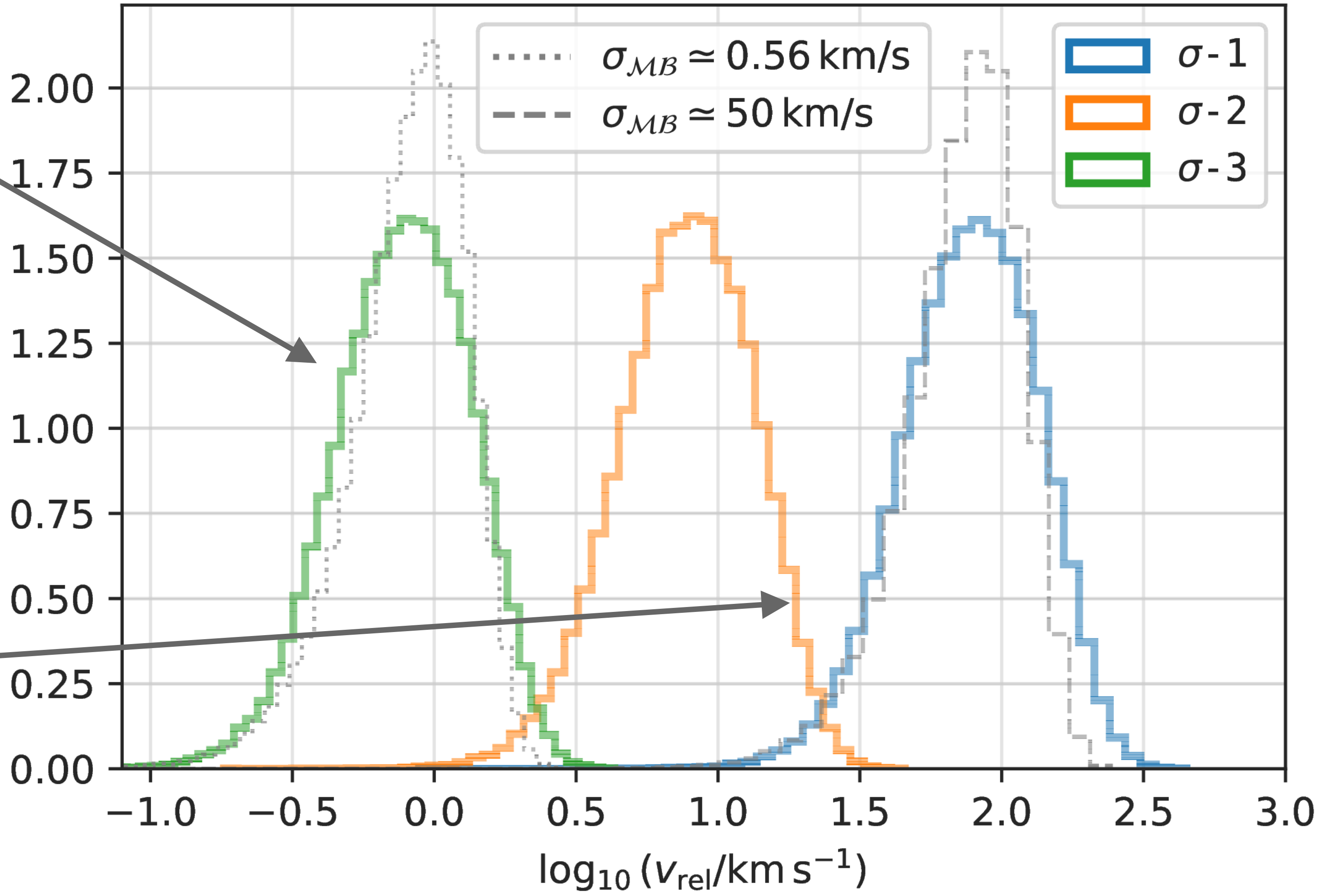
σ : dimensionless velocity dispersion



Distributions relative velocity between the binary and the single

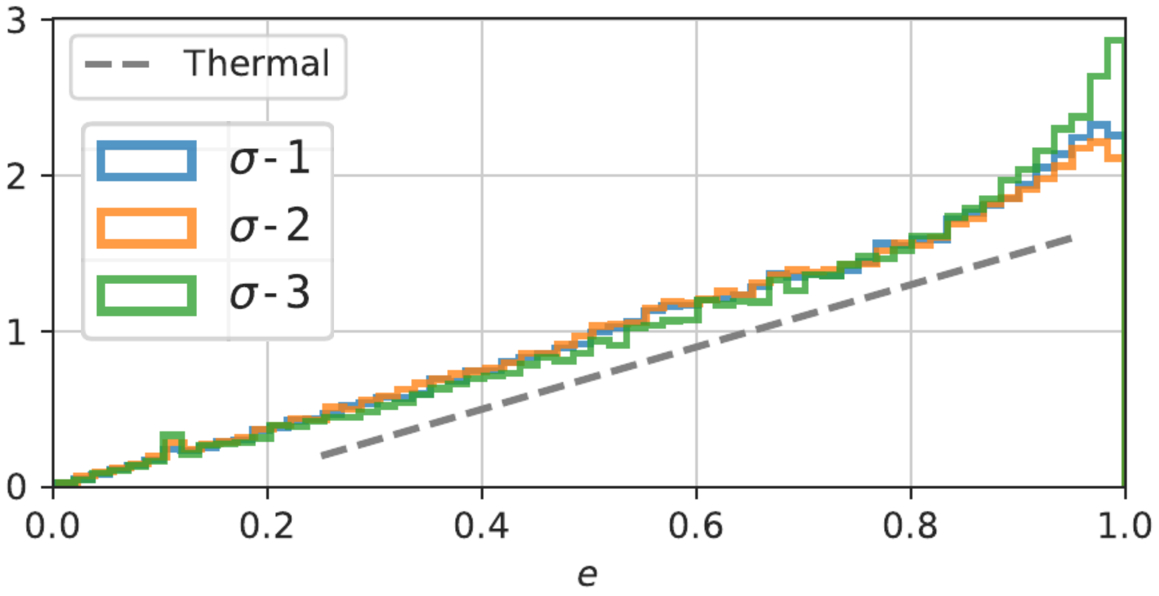
Very thin disk: velocity dispersion comparable to open clusters!

Very thick disk: velocity dispersion comparable to nuclear star clusters without a SMBH



Outcomes

Final binary eccentricities



Number of mergers

Outcomes \ Set	$\sigma-1$	$\sigma-2$	$\sigma-3$
Merger	0.44%	0.54%	0.824%

Outcomes \ Set	σ-1	σ-2	σ-3
Prompt flyby	11.55%	3.53%	4.99%
Prompt exchange	46.02%	35.99%	32.82%
Resonant original	18.48%	26.55%	25.68%
Resonant exchange	18.66%	33.40%	35.70%
Breakup	4.85%	0%	0%
Merger	0.44%	0.54%	0.824%
$t_{\mathrm{GW}} < t_{\mathrm{Hubble}}$	37.31%	38.5%	42.13%

Outcomes \ Set	σ-2	σ-2-isol	σ-2-$\mathcal{MB}$
Prompt flyby	3.20%	1.17%	97.19%
Prompt exchange	32.95%	41.10%	0.27%
Resonant original	27.43%	22.16%	0.07%
Resonant exchange	35.90%	28.21%	0.02%
Breakup	0%	$\sim 10^{-3}$%	2.44%
Merger	0.54%	6.39%	0.26%
$t_{\rm GW} < t_{\rm Hubble}$	38.31%	47.85%	34.31%
$e > 0.1$ at $f_{\rm GW} > 10\,{\rm Hz}$	0.18%	2.70%	0.11%
"" over total mergers	33.76%	42.25%	42.80%