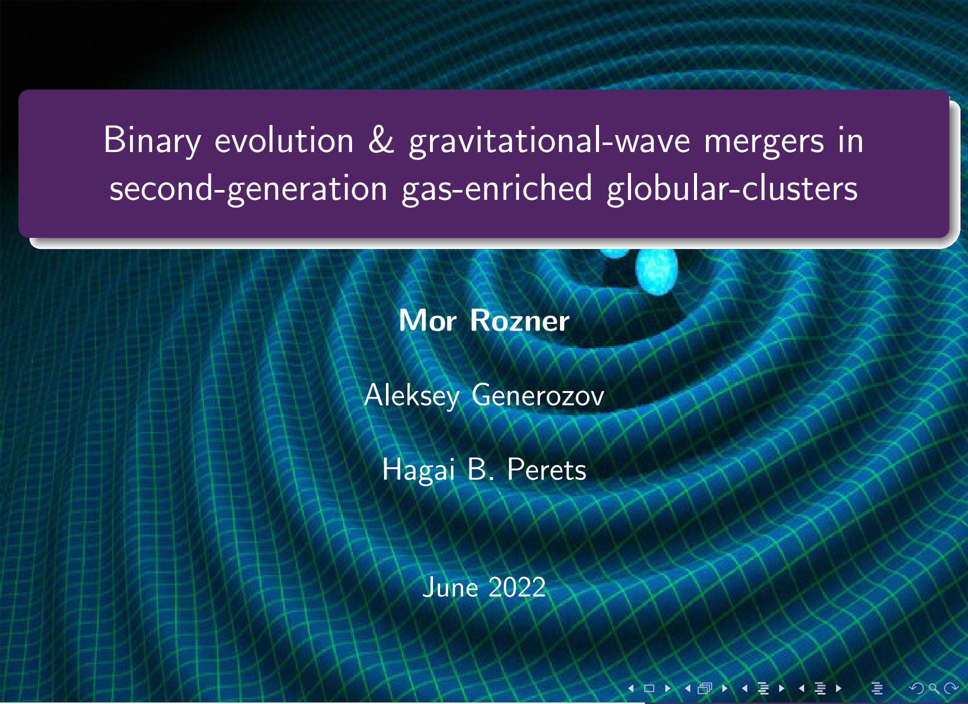

Binary evolution & gravitational-wave mergers in second-generation gas-enriched globular-clusters

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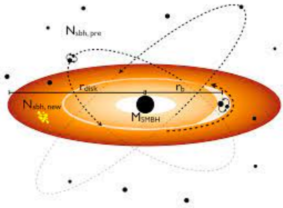
There are many gaseous media



(a) AGN disks (Ford et al 2019)

(b) protoplanetary disks

(c) **Star forming epochs in GCs**

Dynamics in gaseous media is rich

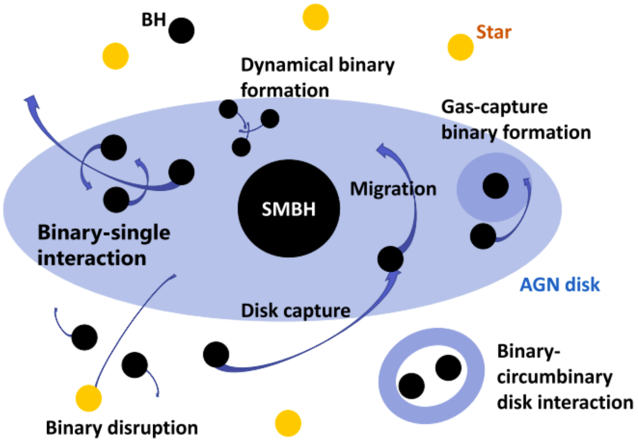


Figure: Borrowed from Tagawa et al 2020

Globular clusters host multiple generations

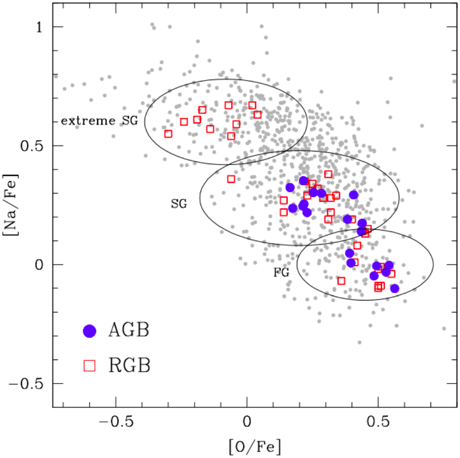
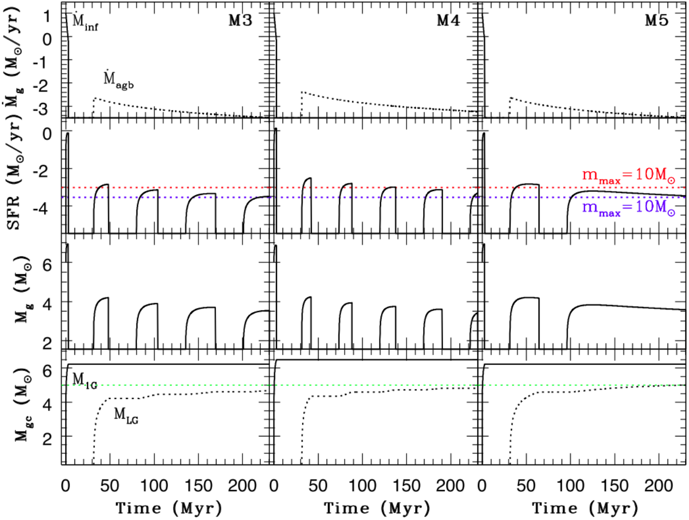


Figure: Behavior of [Na/Fe] as a function of [O/Fe] for the AGB (filled blue circles, this work) and RGB stars of NGC 6752. From Lapenna et al. 2016.

An example of gas from AGB stars – Bekki 2017



Second generation stars could form in disks

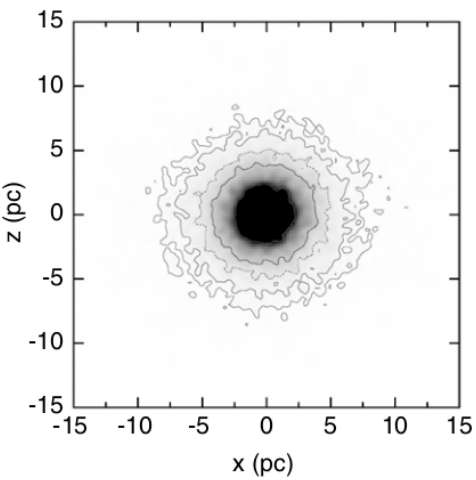


Figure: Projected isodensity contour, borrowed from Mastrobuono-Battisti& Perets 2013

Gaseous media affect on the dynamics

- AGN disks (e.g. McKernan et al 2012, Stone et al 2017, Tagawa et al 2020)

- Protoplanetary disks (e.g. Murray Clay & Perets 2011, Grishin & Perets 2016)

- Mergers between galaxies (e.g. Lin 2008)

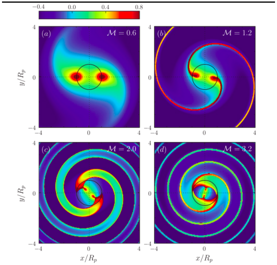


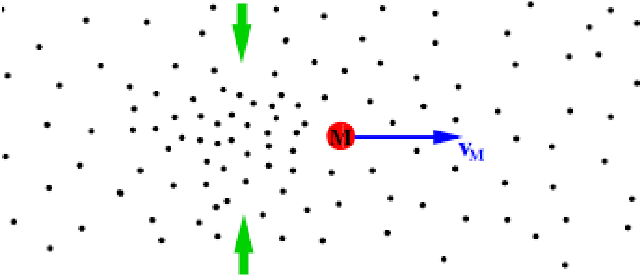
Figure: From Kim et al 2008

Introducing the main characters

- Gas dynamical friction
- Three-body hardening
- Gravitational waves emission

$$\frac{da_{\rm bin}}{dt} = \left.\frac{da_{\rm bin}}{dt}\right|_{\rm hard,\star} + \left.\frac{da_{\rm bin}}{dt}\right|_{\rm GDF} + \left.\frac{da_{\rm bin}}{dt}\right|_{\rm GW}$$

For large separations – gas dynamical friction



You can think about a duck

and then about a binary-duck!

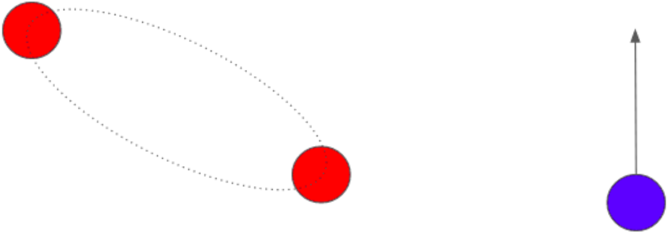
For large separations – gas dynamical friction

$$\left.\frac{da_{\rm bin}}{dt}\right|_{\rm GDF} = -\frac{8\pi G^{3/2} a_{\rm bin}^{3/2}}{\sqrt{m_1+m_2}} \rho_g(t) \frac{m}{v_{\rm rel}^2} f\left(\frac{v_{\rm rel}}{c_s}\right)$$

$a_{\rm bin}$ – binary separation
$m = m_1 = m_2$ – masses of the binary companions
$\rho_g = \rho_{g,0} e^{-t/\tau_g}$, ρ_g – gas density, τ_g – gas density
$v_{\rm rel}$ – relative velocity

Intermediate separations – three-body hardening

$$\left.\frac{da_{\rm bin}}{dt}\right|_{3-body} = -\frac{2\pi G n_\star m_{\rm pert}(2m + m_{\rm pert})a_{\rm bin}^2}{m v_\infty}$$



Finally – gravitational waves!

$$\left.\frac{da}{dt}\right|_{\mathrm{GW}} = -\frac{64G^3 m_1 m_2 (m_1 + m_2)}{5c^5 a^3}$$

All together now

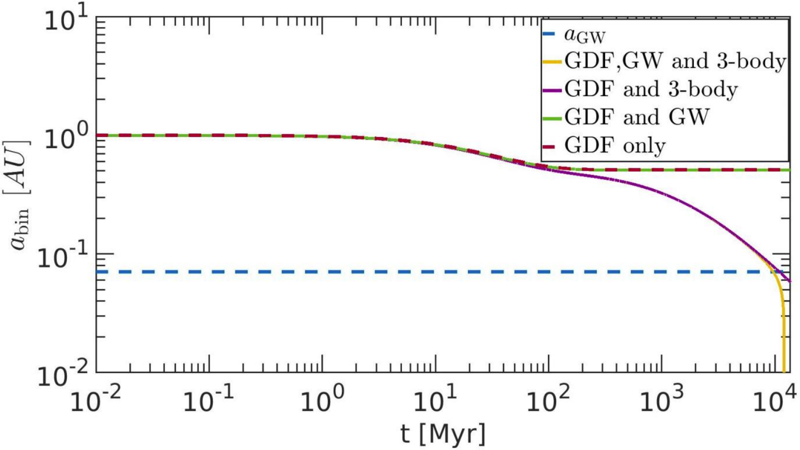


Figure: $m_1 = m_2 = 10\ M_\odot$ (**Rozner** & Perets 2022)

Gas hardening is very efficient

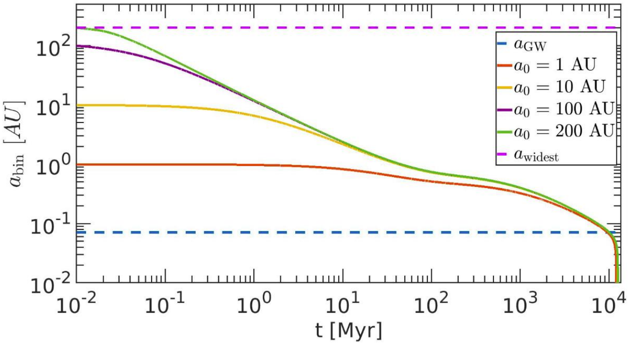
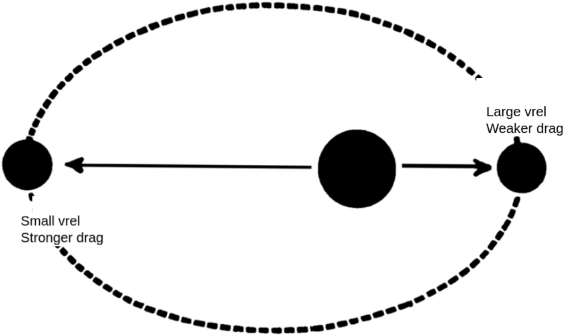


Figure: $m_1 = m_2 = 10\ M_\odot$ (**Rozner** & Perets 2022)

What happens in eccentric evolution?



$$\left.\frac{da_{\text{bin}}}{dt}\right|_{\text{GDF}} = -\frac{8\pi G^{3/2} a_{\text{bin}}^{3/2}}{\sqrt{m_1+m_2}} \rho_g(t) \frac{m}{v_{\text{rel}}^2} f\left(\frac{v_{\text{rel}}}{c_s}\right)$$

We consider orbit-averaged equations

For $v_g = 0$ relative to the center of mass of the binary

$$\mathbf{F}_{\rm drag} = F_0 \mathbf{v}_{\rm rel}/v_{\rm rel}^3,$$

$$\left.\overline{\frac{da}{dt}}\right|_{\rm GDF} = \frac{4F_0(1-e^2)^2}{\pi m_{\rm bin}\Omega^3 a^2}\int_0^{2\pi}\frac{df}{(1+e\cos f)^2\sqrt{1+2e\cos f+e^2}},$$

$$\left.\overline{\frac{de}{dt}}\right|_{\rm GDF} = \frac{F_0(1-e^2)^3}{\pi m_{\rm bin}\Omega^3 a^3}\int_0^{2\pi}\frac{(e+\cos f)df}{(1+e\cos f)^2(1+2e\cos f+e^2)^{3/2}}$$

The merger timescales shorten

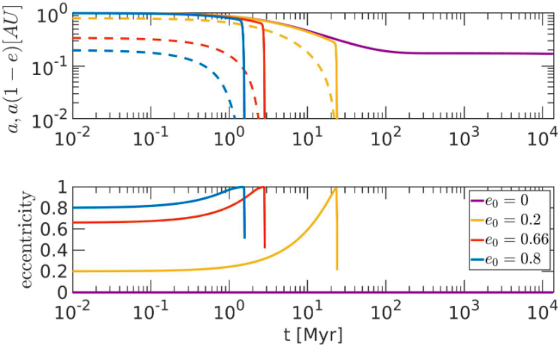


Figure: $m_1 = m_2 = 10\ M_\odot,\ a_0 = 1\ \mathrm{AU}$ orbit-averaged calculation. (**Rozner** & Perets 2022)

Eccentric vs. non-eccentric binaries

	eccentric $e_0 = 0.66$	**circular** $e_0 = 0$
timescales	rapid merger $< 1\ \mathrm{Gyr}$	slower merger $> 1\ \mathrm{Gyr}$
regimes of dominance	gas → GWs	gas → 3-body → GWs
observed eccentricity	might be eccentric in LISA	circular

We can estimate the number of mergers

$$N_{\rm merge} \sim f_{\rm disk} f_{\rm bin,surv} f_{\geq 20 M_{\odot}} f_{\rm ret} f_{\rm merge} N_{\star}$$

$f_{\rm disk}$ – fraction of stars in the disk
$f_{\rm bin,surv}$ – survival fraction of binaries
$f_{\rm 20M_{\odot}}$ – fraction of stars with mass $\geq 20 M_{\odot}$
$f_{\rm ret}$ – retention fraction
$f_{\rm merge}$ – merger fraction (from the binaries specified above)

Now we can calculate the rate

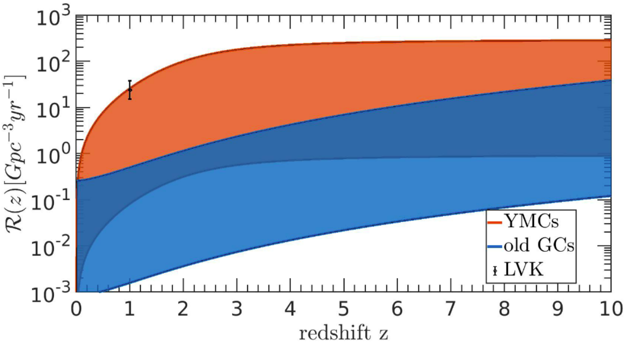


Figure: The cumulative contribution to GWs rate (Rozner & Perets 2022)

Future prospects & implications

- Setting initial conditions for other GWs channels
- Pulsar retention fractions will change (Perets 2022)
- The distribution of binary separations will change
- Setting constraints on the gas amounts in GCs
- We can form short-lived binaries (Rozner, Generozov & Perets in prep.)

Takeaways

- GCs tend to host multiple generations

- Star forming environments are gas-rich

- Gas dissipation assists in hardening – leads to a production of more GWs

- It also affects inderctly on other GWs channels – by setting different initial conditions

Rozner & Perets 2022 https://arxiv.org/pdf/2203.01330.pdf