Title: Wet Extreme Mass Ratio Inspirals May Be More Common For Spaceborne Gravitational Wave Detection

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Abstract: Extreme Mass Ratio Inspirals (EMRIs) can be classified as dry EMRIs and wet EMRIs based on their formation mechanisms. Dry (or the" loss-cone") EMRIs, previsouly considered as the main EMRI sources for the Laser Interferometer Space Antenna, are primarily produced by multi-body scattering in the nuclear star cluster and gravitational capture. In this Letter, we highlight an alternative EMRI formation channel:(wet) EMRI formation assisted by the accretion flow around accreting galactic-center massive black holes (MBHs). In this channel, the accretion disk captures stellar-mass black holes that are intially moving on inclined orbits, and subsequently drives them to migrate towards the MBH-this process boosts the formation rate of EMRIs in such galaxies by orders of magnitude. Taking into account the fraction of active galactic nuclei where the MBHs are expected to be rapidly accreting, we forecast that wet EMRIs will contribute an important fraction of all EMRIs observed by spaceborne gravitational wave detectors and likely dominate for MBH hosts heavier than a few $10^5 M_\odot$.

Wet Extreme Mass Ratio Inspirals May Be More Common for Spaceborne Gravitational Wave Detection

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Channel I: loss cone $\longrightarrow$ dry EMRIs

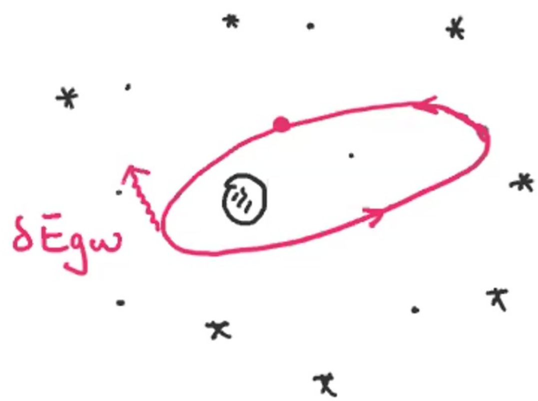


Figure: Loss cone cartoon

2 timescales:

$t_{\rm gw}$: GW emission timescale

$t_{\rm rlx}$: 2-body scatterings

- $t_{\rm gw} > t_{\rm rlx}$: scatterings dominated
  scattered into/away from the MBH
- $t_{\rm gw} < t_{\rm rlx}$: GW emission dominated
  an EMRI formation
  Formate rate is sensitive to the radius where $t_{\rm gw} = t_{\rm rlx}$ (Zwick et al. 2021)

Channel II: AGN disks $\longrightarrow$ wet EMRIs

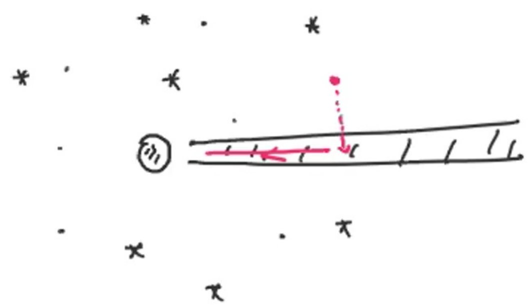


Figure: Disk cartoon

4 timescales:

$t_{\rm rlx}$: 2-body scatterings

$t_{\rm wav}$: inclination/eccentricity damping

$t_{\rm mig}$: migration inward (density waves + head wind)

$T_{\rm disk}$: AGN disk lifetime

$t_{\rm mig} < T_{\rm disk} \Rightarrow$ EMRI formation

No migration trap for realistic and correct disk models!

Dry EMRI rate (no disk): Fokker-Planck equation

$E := \phi(r) - v^2/2, R := J^2/J_c^2(E),$ $f_i(t, E, R)$ with i= star, sBH

$$\mathcal{C}(E,R)\frac{\partial f_i}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial}{\partial E}f_i + D_{ER}\frac{\partial}{\partial R}f_i + D_E f_i\right) + \frac{\partial}{\partial R}\left(D_{RR}\frac{\partial}{\partial R}f_i + D_{ER}\frac{\partial}{\partial E}f_i + D_R f_i\right)$$

Integro-differential equation with $D_{xy}[f_i] = \int\int f_i dEdR$ and $D_x[f_i] = \int\int f_i dEdR$

Initial condition:

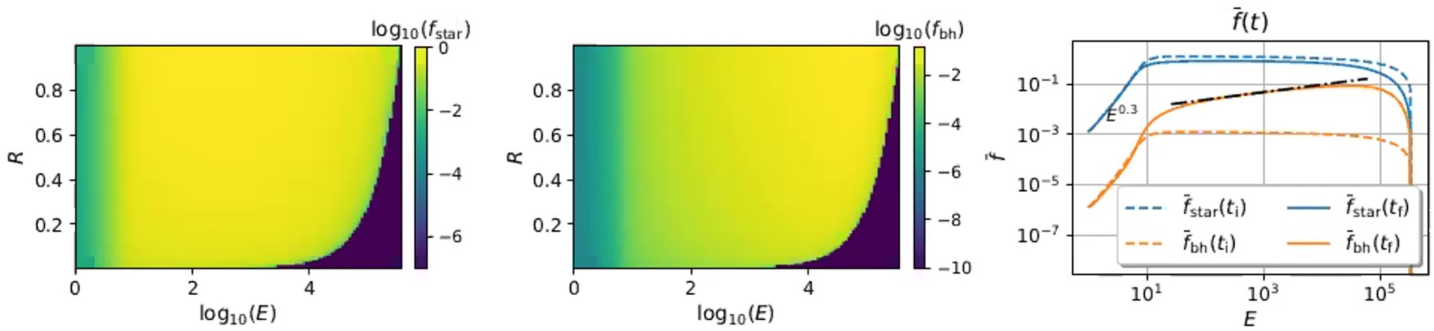
Tremaine's cluster model with $m_{star} = 1M_\odot, m_{sbh} = 10M_\odot$

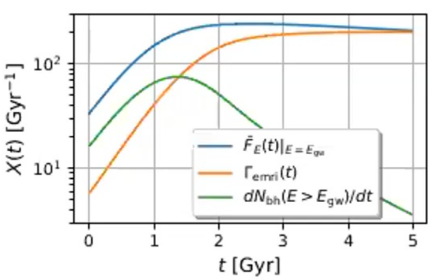
$$f_{\rm star}(t=0,E,R) = f_{\rm star}(E), \quad N_{\rm star}(r < r_h = GM_\bullet/\sigma^2) \sim M_\bullet/M_\odot$$

$$f_{\rm sbh}(t=0,E,R) = 10^{-3} f_{\rm star}(E)$$

Fiducial model: Galactic MBH $M_\bullet = 4 \times 10^6 M_\odot$

Left/Middle: $f(t_f = 5\,Gyr, E, R)$. Right: $\bar{f}_i(t, E) = \int_0^1 f_i(t, E, R)dR$





$$\hat{\Gamma}(M_\bullet) \approx 210 \left(\frac{M_\bullet}{4 \times 10^6 M_\odot}\right)^{-0.28} \text{Gyr}^{-1}$$

$$\hat{\Gamma}(M_\bullet) \propto \frac{N_{sbh}|_{E>E_{\rm gw}}}{t_{\rm rlx}} \propto \frac{\sigma^3}{M_\bullet}$$

see also Amaro-Seoane2011,Preto2010

Wet EMRI rate: modified Fokker-Planck equation

In presence of the disk: stars/sBHs $f_i(t, \iota, E, R)$

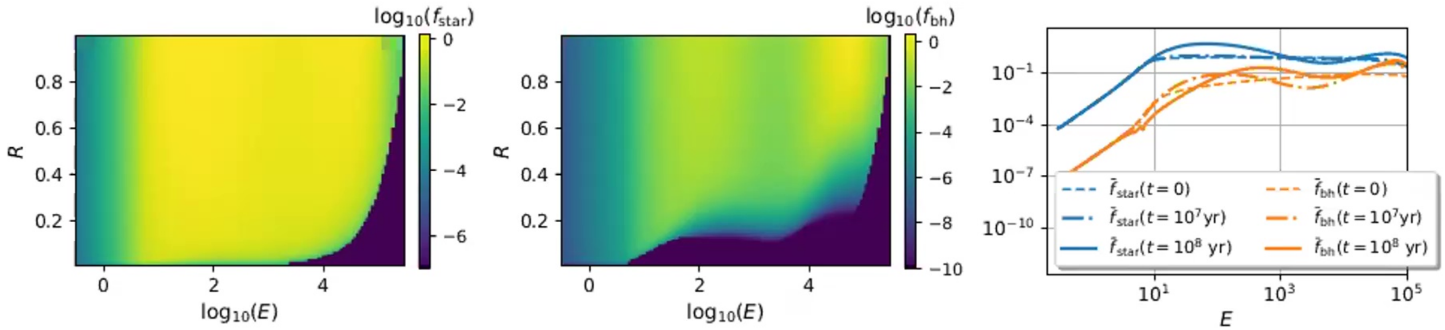
$$f_i(t, \iota, E, R) \Rightarrow f_i(t, E, R) = \int_{\text{disk surface}}^{\text{polar direction}} f_i(t, \iota, E, R) d\iota$$

$$\mathcal{C}(E, R)\frac{\partial f}{\partial t} = \frac{\partial}{\partial E}\left(D_{EE}\frac{\partial}{\partial E}f + D_{ER}\frac{\partial}{\partial R}f + \tilde{D}_E f\right) + \frac{\partial}{\partial R}\left(D_{RR}\frac{\partial}{\partial R}f + D_{ER}\frac{\partial}{\partial E}f + \tilde{D}_R f\right) + S$$

3 disk effects: inclination damping/disk capture S, inward migration $\tilde{D}_E$, eccentricity damping $\tilde{D}_R$

Fiducial model: $M_\bullet = 4 \times 10^6 M_\odot$

Initial condition: final state of the no-disk MBH-star/sBH cluster.

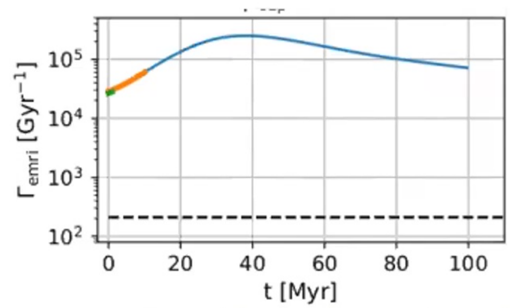


Left/middle: $f_i(t = 10^7 yr, E, R)$. Right: $\bar{f}_i(t, E)$

Disk assisted EMRI rate:

$$\Gamma_{\rm emri}(t; T_{\rm disk}) = \int_{t_{mig} < T_{disk}} -S \; dEdR$$

$$T_{\rm disk}[Myr] = 1/10/100$$



Branch ratios of the two channels

$M_\bullet = 4 \times 10^6 M_\odot$, $\frac{\langle \Gamma_{\rm wet} \rangle}{\langle \Gamma_{\rm dry} \rangle} = \mathcal{O}(10^2 - 10^3)$

$M_\bullet = 1 \times 10^5 M_\odot$, $\frac{\langle \Gamma_{\rm wet} \rangle}{\langle \Gamma_{\rm dry} \rangle} = \mathcal{O}(10^1 - 10^2)$

AGN fraction: $f_{\rm AGN}(z \lesssim 1) \sim 1\%$, $f_{\rm AGN}(z \gtrsim 1) \sim 1\% - 10\%$

Additional astrophysics we can learn from wet EMRIs

Dry vs Wet EMRIs: distinguishable by different eccentricities (high vs low) and different inclinations (isotropic vs aligned ?).

Wet EMRIs only:

- LISA: EMRI source properties ($M_\bullet, \vec{a}_\bullet$) and environmental effects (structure of AGN accretion disks)
- ngEHT: AGN jet emission (direction/luminosity),disk emission (EM emission), MBH shadow size ($M_\bullet/D$)
- Synergy:
  $M_\bullet, \vec{a}_\bullet \leftrightarrow$ jet launch/strength,
  $M_\bullet + M_\bullet/D_A \Rightarrow$ distance ladder calibration $D_A(z)$,
  disk structure + EM emission $\Rightarrow$ accretion physics