Intermediate mass ratio inspirals

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Dvorkin and Barausse, MNRAS (2017) [arXiv:1702.06964]

LISA days, APC, 12 October 2017

Institut d'astrophysique de Paris

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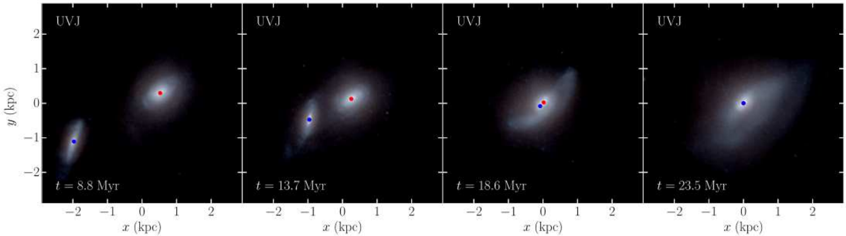
  - Need more accurate waveforms [Mandel & Gair (2009)]
- PTA sources: Contribution to the stochastic GW background [Dvorkin & Barausse (2017)]

Massive black hole binaries

- Galaxy merger → satellite falls into the host galaxy



[Khan et al. 2016]

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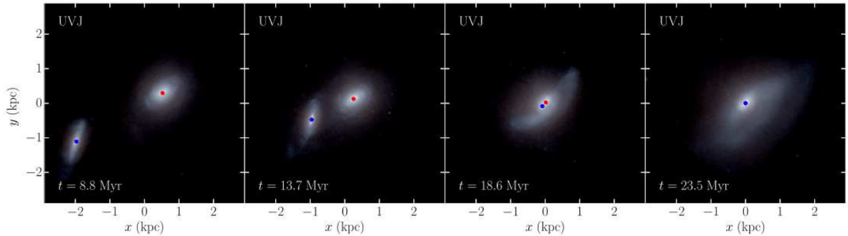

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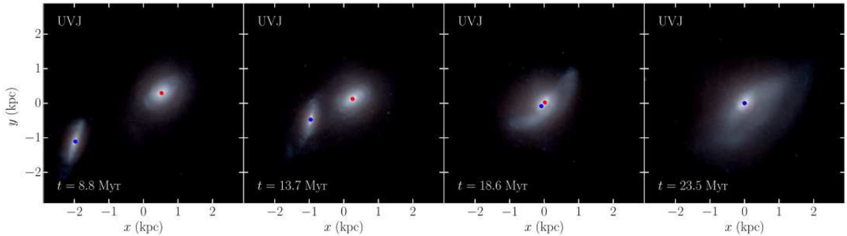

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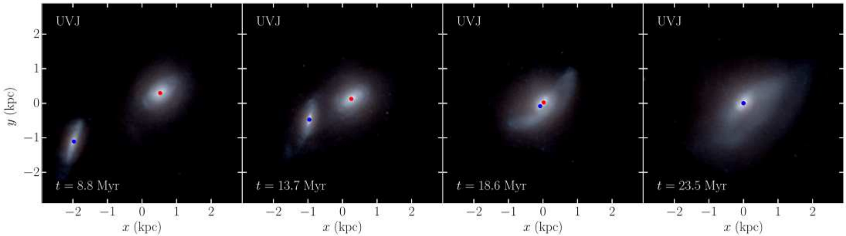
- Emission of GW → merger



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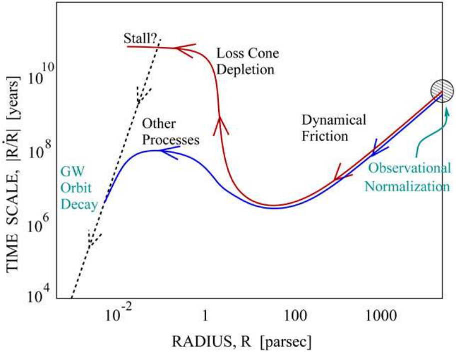
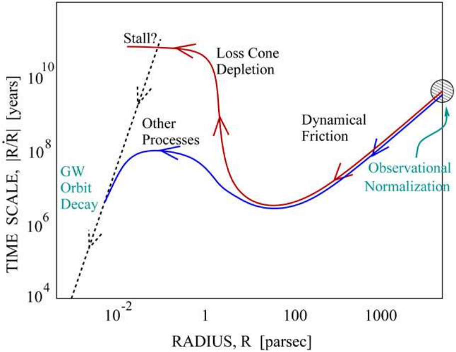
Final-parsec problem



Begelman, Blandford & Rees (1980)

Final-parsec problem



Solutions:

- Galaxy rotation [Holley-Bockelmann & Khan 2015]
- Tri-axial galactic potential [Yu 2002; Vasiliev et al. 2014; Sesana & Khan 2015]
- Disc migration [Haiman et al. 2009]
- Interactions with a third BH [Hoffman & Loeb 2007; Bonetti et al. 2016; Bonetti et al. 2017a,b]

Avoiding the final-parsec problem

- Hardening radius

$$a_h = 11 \left(\frac{m_1+m_2}{10^8 M_\odot}\right) \left[\frac{q}{(1+q)^2}\right] \left(\frac{\sigma}{100\mathrm{km/s}}\right)^{-2} \ \mathrm{pc}$$

- 'GW radius'

$$a_{gw} = 7 \times 10^{-2} \left(\frac{m_1+m_2}{10^8 M_\odot}\right)^{3/4} \left[\frac{q}{(1+q)^2}\right]^{1/4} \times \left(\frac{t_H}{13\ \mathrm{Gyr}}\right)^{1/4} \ \mathrm{pc}$$

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→ For $q \lesssim 10^{-3}$: $a_h < a_{gw}$ → guaranteed merger!

But:

→ Do binaries with $q \lesssim 10^{-3}$ become bound ?

→ Is dynamical friction efficient if $q \lesssim 10^{-3}$?

How to get $q \lesssim 10^{-3}$ binaries

Dynamical friction timescale for a satellite BH in the host galaxy:

$$t_{\rm DF} \approx \frac{19{\rm Gyr}}{\ln(1 + M_{\rm h,\star}/M_{\rm bh,s})} \left(\frac{R}{5{\rm kpc}}\right)^2 \frac{\sigma_{\rm h}}{200{\rm km/s}} \frac{10^8 M_\odot}{M_{\rm bh,s}}$$

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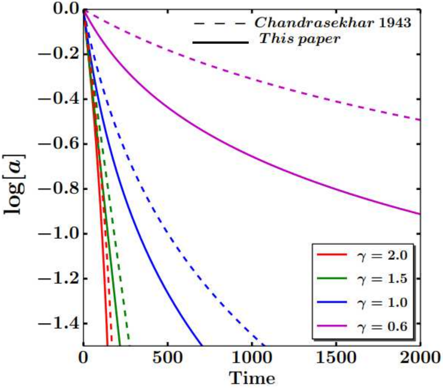
$$t_{\rm DF} \approx 0.38{\rm Gyr} \times \left(\frac{M_{\rm bh,h}}{10^9 M_\odot}\right)^{0.5} \left(\frac{M_{\rm bh,s}}{10^6 M_\odot}\right)^{-0.1} (1+z)^{-2.44} \times \left[1 + 0.07 \ln\left(\frac{M_{\rm bh,h}}{10^9 M_\odot}\right) - 0.08 \ln\left(\frac{M_{\rm bh,s}}{10^6 M_\odot}\right)\right]^{-1}$$

DF timescale depends on stellar density profile

Stellar density $\rho \propto r^{-\gamma}$



[Dosopoulou & Antonini (2016)]

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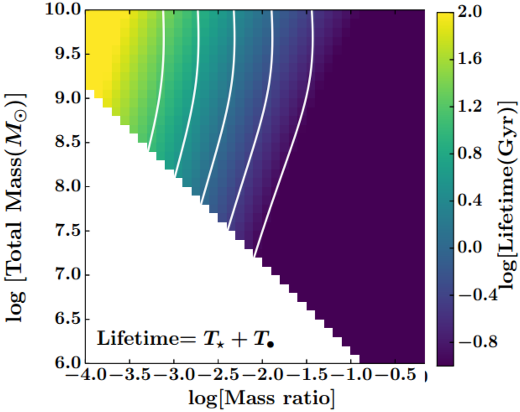
$\gamma = 0.6$



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Stochastic background from BH binaries

- Seeds: PopIII remnants ($\sim 200 M_\odot$); direct collapse ($\sim 10^5 M_\odot$)
- BH-galaxy co-evolution model [Barausse (2012)]
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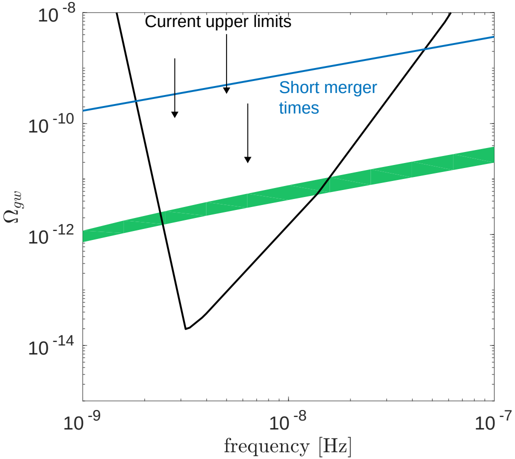
Stochastic GW background:

$$\Omega_{\mathrm{gw}}(f) = \frac{f}{\rho_c c^2} \int dM_c dz \frac{d^2 n}{dM_c dz} \frac{dE}{df}$$

Emission frequency f is twice the orbital frequency f_o of the binary

Stochastic background in the PTA band

All binaries arrive to a_h and evolve from there [SKA: observe 50 pulsars for 10 yrs, 30 ns accuracy]



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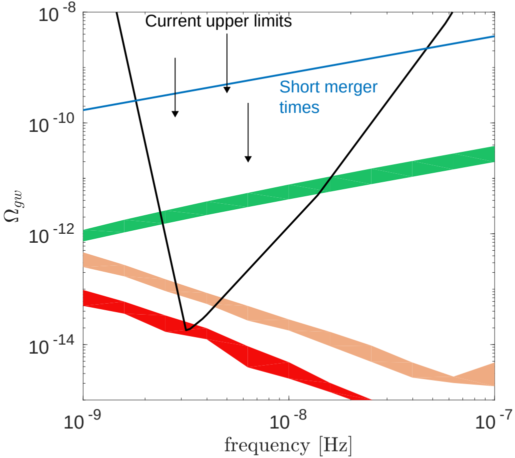

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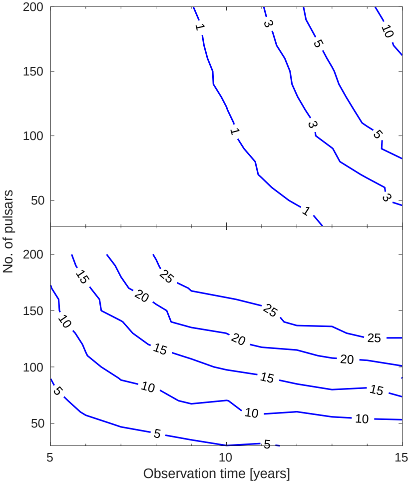
Detection prospects with future PTA

SKA-based PTA, 30 ns timing accuracy



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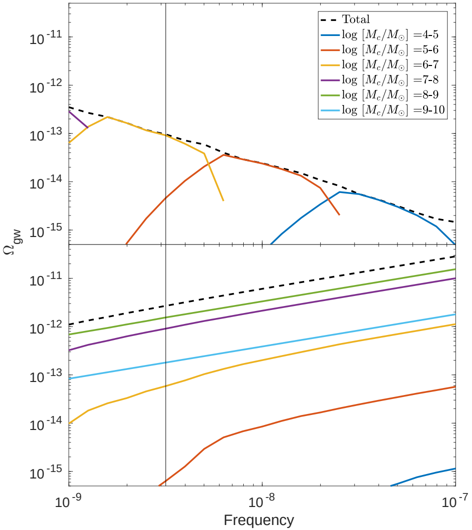
Mass distribution



[Dvorkin & Barausse (2017)]

Intermediate mass ratio inspirals with LISA

[Dvorkin & Barausse (2017)]

Light seeds:

- 0.5 events per year
- Mass ratio $q \sim 10^{-4} - 10^{-3}$
- Typical source: $(10^3 - 10^4 M_\odot \text{ BH}) + (10^6 - 10^7 M_\odot \text{ BH})$
- Typical SNR: $50 - 200$

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Heavy seeds: only ~ 0.07 events per year

Conclusions

- Intermediate mass ratio BH binaries ($q \lesssim 10^{-3}$) are guaranteed to merge within a Hubble time since $a_h < a_{gw}$
- GW background from these sources can be detected with SKA within 5-10 years of observations, if the final-parsec problem is not solved by other mechanisms
- If the BH seeds are light, LISA will see ~ 0.5 IMRIs per year

Additional slides

Merging binaries

Emitted spectrum:

$$\frac{dE_s}{d\ln f_s} = \frac{(G\pi)^{2/3}}{3} M_c^{5/3} f_s^{2/3}$$

Stochastic background:

$$\Omega_{\mathrm{gw}}(f) = \frac{(G\pi)^{2/3}}{3} \frac{f^{2/3}}{\rho_c c^2} \int dM_c dz \frac{d^2 n}{dM_c dz} \frac{M_c^{5/3}}{(1+z)^{1/3}}$$

Stalling binaries

Emitted power:

$$\frac{dE_s}{dt_s}(f_{\rm stall}) = \frac{32c^5}{5G}\left(\frac{GM_c}{c^3}\pi f_{\rm stall}\right)^{10/3}$$

Stochastic background:

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c c^2}\int dM_c dz \frac{d^2 n}{dM_c dz}\frac{dE_s}{dt_s}\left|\frac{dt_s}{dz}\right|$$