Stochastic gravitational wave background from stalling binary black holes

Irina Dvorkin (Institut d'Astrophysique de Paris)

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

The era of gravitational wave astronomy, IAP, 26 June 2017

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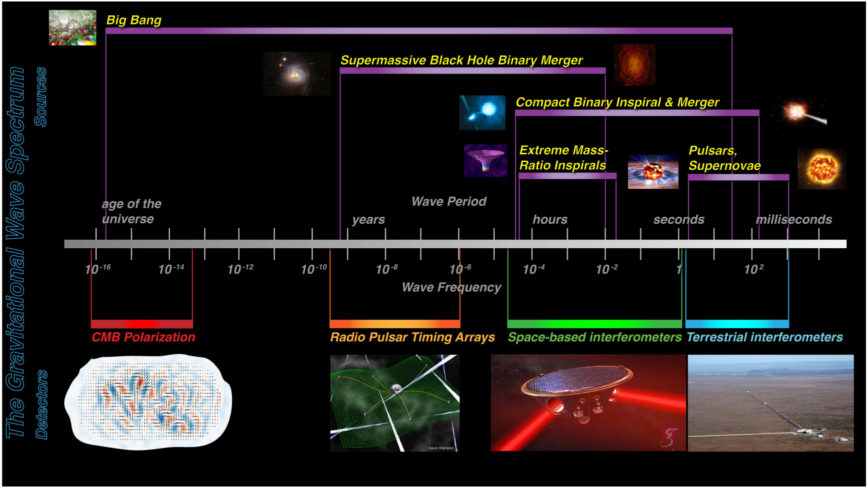
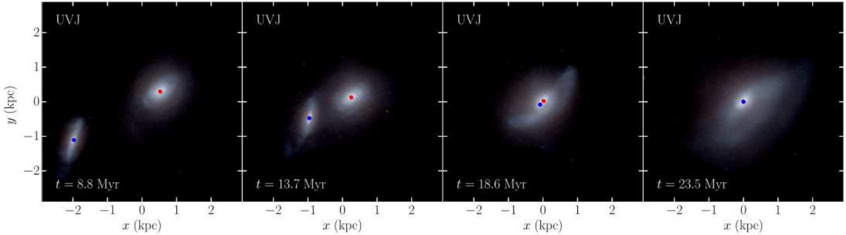
Spectrum of gravitational waves



Massive black hole binaries ($M \sim 10^5 - 10^9 M_\odot$)

- Galaxy merger → satellite falls into the host galaxy



[Khan et al. 2016]

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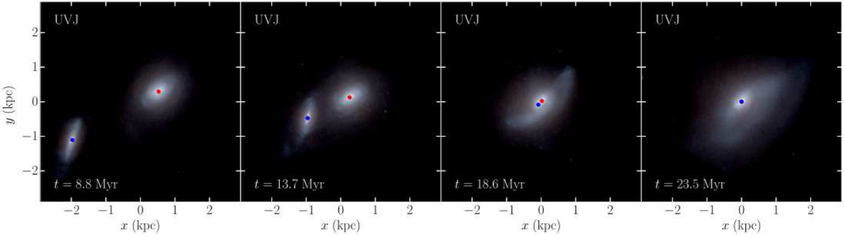

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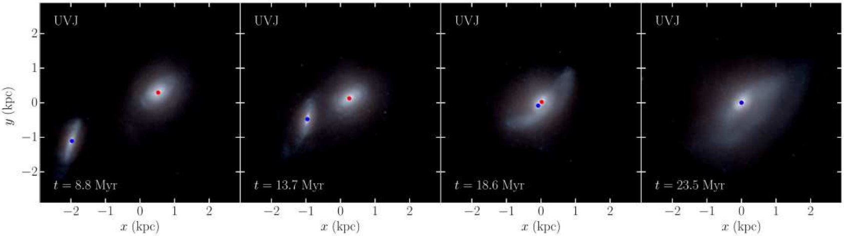

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- Galaxy merger → satellite falls into the host galaxy
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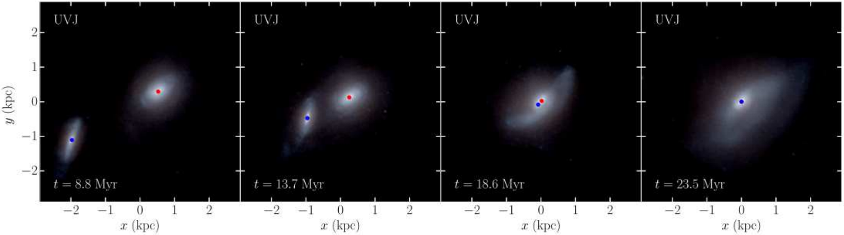
- Scattering of stars that intersect the orbit (loss cone) → orbit decays
- Emission of GW → merger



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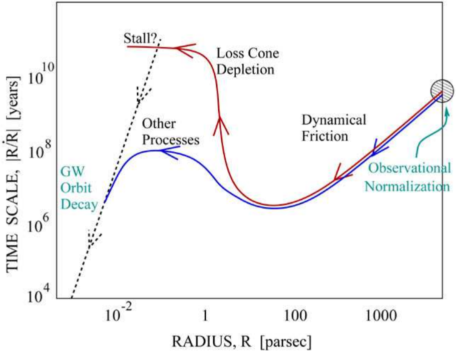
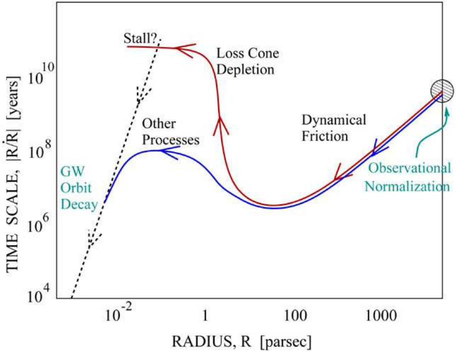
Final-parsec problem



Begelman, Blandford & Rees (1980)

Final-parsec problem

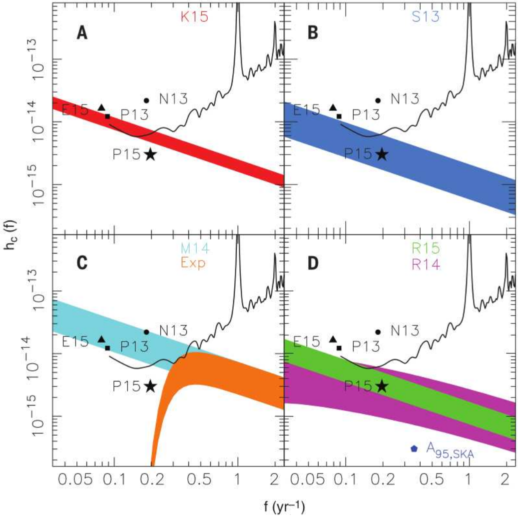


Solutions:

- 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]

Current upper limits from PTAs

[Parkes PTA: Shannon et al. 2015]



What are we missing?

- $M - \sigma$ relation is biased → lower amplitude
- Efficient coupling binary-environment → less time in band
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What if all the binaries stall?

Stochastic background from BH binaries

- Seeds: PopIII remnants ($\sim 200 M_\odot$); direct collapse ($\sim 10^5 M_\odot$)
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- BH binaries form when galaxies merge

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Stochastic GW background:

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

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

Stalling radius

- Hardening radius: orbital decay through interactions with the bulge

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

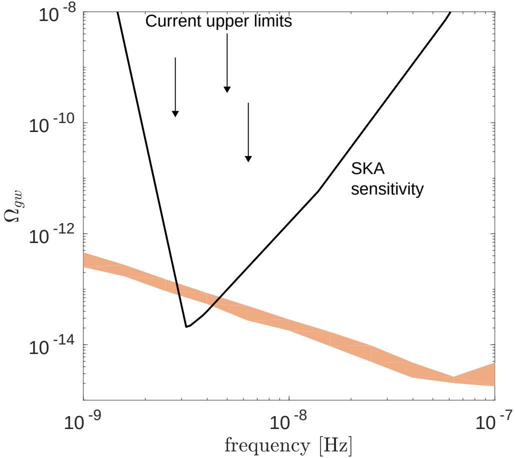
- 'GW radius': GW emission drives coalescence in a Hubble time

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

[Mass ratio: $q = \frac{m_2}{m_1} \leq 1$, stellar velocity dispersion σ]

Mildly pessimistic model

All binaries stall at a_{gw} [SKA: observe 50 pulsars for 10 yrs, 30 ns accuracy]



[Dvorkin & Barausse (2017)]

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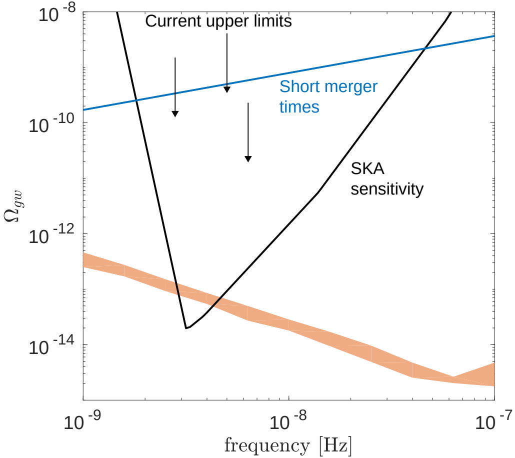
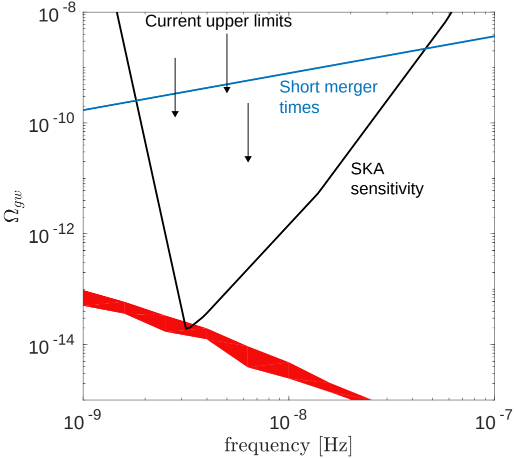


[Dvorkin & Barausse (2017)]

Very pessimistic model

All binaries stall at $MAX(a_{gw}, a_h)$ [SKA: observe 50 pulsars for 10 yrs, 30 ns accuracy]



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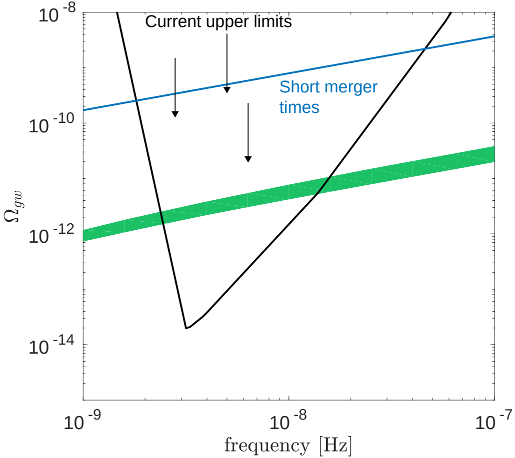
Unexpectedly optimistic model

All binaries arrive to a_h and evolve from there



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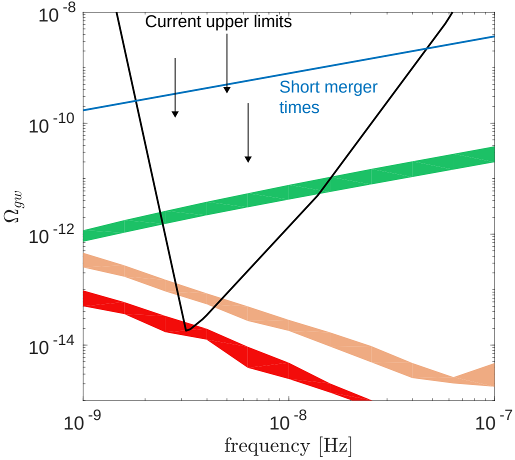

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How many systems with $a_h < a_{gw}$?

- Hardening radius

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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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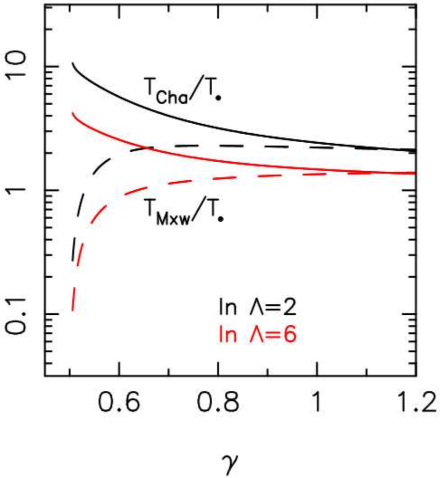
But: if the satellite BH retains its stellar bulge until it is tidally stripped, its effective mass is larger → small $t_{\rm DF}$

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

DF timescale depends on stellar density profile

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



[Dosopoulou & Antonini (2016)]

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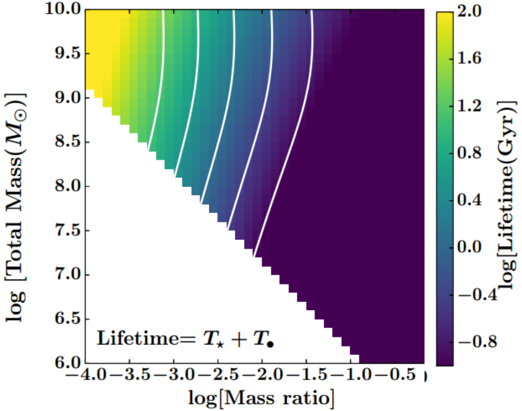
$\gamma = 0.6$



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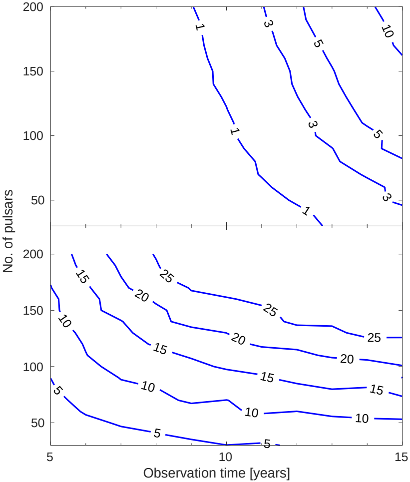
Detection prospects with future PTA

SKA-based PTA, 30 ns timing accuracy



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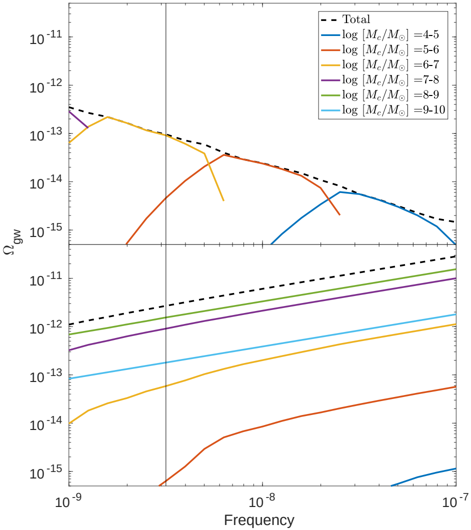
Mass distribution



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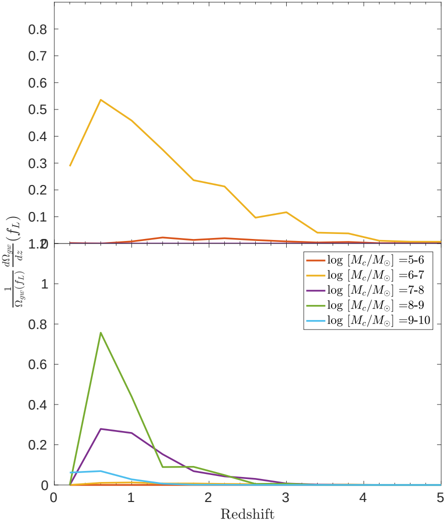
Redshift distribution



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Conclusions

- Even in the most pessimistic scenario, massive BH binaries produce a GW background detectable after $10 - 15$ years of observations with a future generation of PTAs

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- Even in the most pessimistic scenario, massive BH binaries produce a GW background detectable after $10-15$ years of observations with a future generation of PTAs

- There might exist a sub-population of massive BH binaries for which $a_h < a_{gw}$, which are guaranteed to merge within a Hubble time
  - Will be detected with SKA within 5-10 years of observations
  - Will be detected with current PTAs after 15 years of observations
  - LISA will see ~ 0.5 such events per year as intermediate-mass-ratio inspirals ($q \lesssim 10^{-3}$)

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:

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