CWs

* SMBH intro

* Supermassive black holes are key components in the assembly and evolution of cosmic structure
* Structure formation is thought to have occurred via a hierarchical clustering process
  → Small galaxies merge together to form larger ones ad infinitum.

* Most galaxies are thought to harbour a massive black hole at their centre.
  → The evolution of black-hole + host is symbiotic.
  → There are well-publicised relationships between the mass of the black-hole and galaxy properties
  e.g. $M_{BH}-\sigma$, $M_{BH}-M_{BULGE}$
  → M_{BH} (of interest to us) $\sim 10^{7} - 10^{10}\, M_{\odot}$
* So, when galaxies merge together, so do the resident black holes.
* The individual black-holes sink together by dynamical friction (from stellar distribution) within the common galactic merger remnant.
* Dynamical friction not efficient enough to bring black-holes close enough together to emit nHz GWs and merge within a Hubble time → "final parsec problem" [Chiara will discuss]
* Other mechanisms in the galactic nuclear environment can couple to the binary, evolve it quickly.

* The binary is hardened i.e. the orbital velocity of the binary is ~ the same (or greater) than the velocity dispersion of ambient stellar distribution.

* At this point the evolution of the binary is driven by the emission of GWs.
    - → We have a distribution of masses with a non-zero quadrupole moment.
    - → The masses orbiting each gives an accelerating quadrupole moment.
    - → Assuming circular binaries, $f_{GW} = 2 f_{orb}$
    - → With mpc orbital separations, $f_{GW} \sim$ nHz.

* Astrophysical distribution

* The distribution of sources in mass + redshift which are resolvable is different from the population dist. of the underlying population → selection effects
* Masses of resolvable sources are weighted to higher mass $\sim 10^9 M_\odot$
* Redshift peaked @ $z \sim 1$ ... favours close binaries but if $\frac{dN}{dV_c} \sim$ const then the distribution favours higher redshift.
* The orbital frequency distribution favour $f_{orb} \gtrsim 10^{-8}$ Hz, where the time spent by each binary in each frequency bin is smaller, so stochasticity of BG breaks down.

Gravitational waveform

* For our target population, systems are pretty far from merger, $\rightarrow$ $f_{LSO} \sim 4.4\times10^{-6} (M/10^9 M_\odot)^{-1}$ Hz
* We are in the early adiabatic inspiral phase of the binary merging process.
  - $\rightarrow$ System emits GWs, loses energy from the orbit,
  - $\rightarrow$ evolves smoothly through geodesics.

* Newtonian leading order is a sufficient description of the waveform.

$$\rightarrow \quad v/c \sim 1.73\times10^{-2} \left(\frac{M}{10^9 M_\odot}\right)^{2/3} \left(\frac{f}{50\,\mathrm{nHz}}\right)^{2/3}$$

* Also, frequency evolution during observation time ($\sim$ 10–20 years) is v. small.

$$\rightarrow \quad \Delta f \sim \dot{f} T \sim 0.05 M_{8.5}^{5/3} f_{50}^{11/3} T_{10}\ \mathrm{nHz}$$

[Mingarelli et al. 2012] * Spin enters phase evolution at 1.5 pN (v^3) + orbital plane precession small.

* $\Rightarrow$ So for circular binaries, our waveform is a simple sinusoid described by leading order in (v/c).

$$\underline{h}(t,\hat{\Omega}) = h_+(t,\hat{\Omega})\,\underline{e}^+(\hat{\Omega}) + h_\times(t,\hat{\Omega})\,\underline{e}^\times$$

$$z(t,\hat{\Omega}) = \frac{\delta\nu}{\nu} = \underline{d} : \underline{h}$$

$$\therefore \; z(t,\hat{\Omega}) = h_+ \underbrace{(\underline{d} : \underline{e}^+)}_{F^+(\hat{\Omega})} + h_\times \underbrace{(\underline{d} : \underline{e}^\times)}_{F^\times(\hat{\Omega})}.$$

⇒ The residuals (or delay-signal, or whatever) are the cumulative redshift of the pulse arrival rate over observation time.

⇒ So, $$s(t) = \int_{t_0}^{t} z(t')\, dt'$$

$$s(t) = F^+ s_+(t) + F^\times s_\times(t)$$

* $$s_+(t) \propto \frac{M^{5/3}}{D_L \omega^{1/3}} \Big[(1+\cos^2 i)\cos 2\psi \sin 2\omega t + 2\cos i \sin 2\psi \cos 2\omega t \Big].$$

$$s_\times(t) \propto \frac{M^{5/3}}{D_L \omega^{1/3}} \Big[(1+\cos^2 i)\sin 2\psi \sin 2\omega t - 2\cos i \cos 2\psi \cos 2\omega t \Big].$$

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* Pulsar term

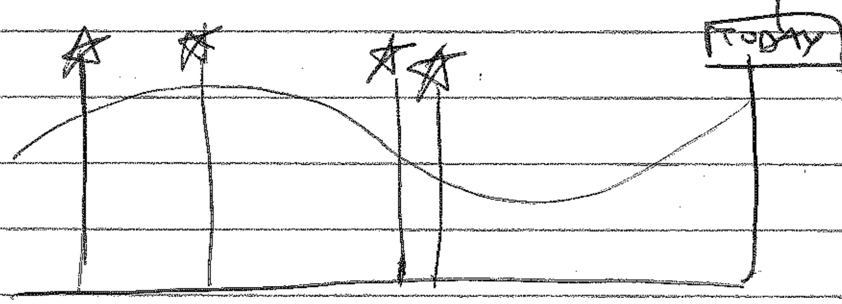
⇒ I said that the redshift was just the projection of the metric tensor along the detector's sensitivity.

⇒ But really $z(t) = \underline{d} : \Delta \underline{h}$

* The signal is really the integrated influence of the GW over the entire photon path.
* The result is an influence from GW at the Earth and at each pulsar.

so $s(t) = F^{+} \Delta S_{+} + F^{\times} \Delta S_{\times}$

$$\rightarrow \quad \Delta S_{+,\times} = S^{e}_{+,\times} - \underbrace{S^{p}_{+,\times}}_{\text{signature of the binary in the past.}}$$



→ ~~[illegible]~~ separate (M, D_L) + improve source localization.

→ Justin will talk about how the pulsar term is a blessing and a curse!

* Extension to eccentricity

→ The environmental mechanisms to drive the binary components close together (and thus mitigate the "final parsec problem") can also leave the binary with significant eccentricity
→ Eccentricity leads to the GW ~~being chromatic~~ having a distribution of frequencies which are integer multiples of f_{orb}.
→ Taylor et al. [2015] gives closed form signal model assuming (i) no evolution over observation time (ii) no evolution of the direction of periapsis passage.
→ At high eccentricity, instead of the dominant GW frequency being "$2 \times f_{orb}$", it is "f_{orb}" itself.
→ Eccentricity is a double-edged sword in terms of detection prospects
→ pushes systems below band into band,
→ but pushes systems already in sensitive region out of band.

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* EM counterparts

* Burke-Spolaor (2013)

→ show plot.
→ Radio AGN
→ periodic jet flux.
→ X-shaped sources.
→ circumbinary disk activity.