Gravitational wave science with pulsar timing arrays and the Square Kilometre Array

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Gravitational waves (GWs)

*Space-time perturbations* travelling at the speed of light in form of waves (like electromagnetic waves)

Predicted by Einstein's General Relativity: fundamental prediction of the theory that *has not been directly tested*.

\[
g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu\nu} \ll 1
\]

massive black hole binaries (MBHBs) forming following galaxy mergers are the loudest sources below micro-Hz frequencies
Structure formation in a nutshell

From De Lucia et al. 2006

Ferrarese & Merritt 2000, Gebhardt et al. 2000

Volonteri Haardt & Madau 2003
Structure formation in a nutshell

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During galaxy mergers, MBHBs will inevitably form!

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QUESTIONS:

* What is the role of MBHBs in structure formation?
* What is the MBHB merger rate?
* How do they pair together?
* How do they interact with their environment?
* How to they get to the GW regime?
* Is there a last parsec problem?
Heuristic scalings

We want compact accelerating systems
Consider a BH binary of mass $M$, and semimajor axis $a$

$$h \sim \frac{R_S}{a} \frac{R_S}{r} \sim \frac{(GM)^{5/3}(\pi f)^{2/3}}{c^4 r}$$

In astrophysical scales

$$h \sim 10^{-20} \frac{M}{M_\odot} \frac{\text{Mpc}}{D}$$

$$f \sim \frac{c}{2\pi R_S} \sim 10^4 \text{Hz} \frac{M_\odot}{M}$$

$10 M_\odot$ binary at $100$ Mpc: $h \sim 10^{-21}$, $f < 10^3$

$10^6 M_\odot$ binary at $10$ Gpc: $h \sim 10^{-18}$, $f < 10^{-2}$

$10^9 M_\odot$ binary at $1$ Gpc: $h \sim 10^{-14}$, $f < 10^{-5}$
Timing residual from MBH binaries

GWs affect the arrival time of radio pulses (Sazhin 1979)

* the delay is proportional to the wave amplitude $h$

* when a timing model for the pulsar is fitted out, a residual of order $hf^2$ is left

$10^9 M_\odot$ binary at 1Gpc: $h \sim 10^{-15}$, $f \sim 10^{-8}$

Implies a residual $\sim 100$ns

100ns is the accuracy at which we can time the most stable millisecond pulsars today!
The GW spectrum

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PTA sensitive to MBHBs!
GW signal from a MBHB population

Characteristic amplitude of a GW signal coming from a certain source population

\[ h_c^2(f) = \int_0^\infty dz \int_0^\infty dM \frac{d^3N}{dzdMd\ln f_r} h^2(f_r) \]

\[ \delta t_{bkg}(f) \approx \frac{h_c(f)}{(2\pi f)} \]

For circular GW driven MBHBs \( dN/d\ln f \propto f^{-8/3} \)

\[ h_c(f) = A \left( \frac{f}{\text{yr}^{-1}} \right)^{-2/3} \]

There are, however, many other sources of red noise in pulsar timing: intrinsic spin noise, DM effects, etc.
This very red signal has a peculiar correlation pattern among different pairs of pulsars, given by the quadrupolar nature of gravitational waves.

Other sources of red noise are uncorrelated!
IT IS ESSENTIAL TO CORRELATE THE SIGNAL OF AS MANY PULSARS AS POSSIBLE
Pulsar Timing Arrays (PTAs)

World-wide detection effort

EPTA: 9 institutes
5 telescopes
40 scientists

NANOGrav: 10 institutes
2 telescopes
40 scientists

PPTA: 4 institutes
1 telescope
20 scientists
Where we stand: theory vs observations

characteristic amplitude vs observed frequency [Hz]
Where we stand: theory vs observations

van Haasteren et al 2011
5 EPTA pulsars

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5 EPTA pulsars

Shannon et al 2013
6 PPTA pulsars
Where we stand: theory vs observations

van Haasteren et al 2011
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EPTA+PPTA+NANOGrav
all pulsars
Where we stand: theory vs observations

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EPTA+PPTA+NANOGrav
all pulsars

characteristic amplitude

all models

observed frequency [Hz]

Where we stand: theory vs observations

- van Haasteren et al. 2011
  - 5 EPTA pulsars

- Shannon et al. 2013
  - 6 PPTA pulsars

- EPTA + PPTA + NANOGrav
  - all pulsars

- SKA

Where we stand: theory vs observations

van Haasteren et al 2011
5 EPTA pulsars

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EPTA+PPTA+NANOGrav
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* SKA

SKA will probe the overall amplitude and *shape* of the signal

\[ h_c (f) \propto N_0^{1/2} f^{-\gamma} M_c^{5/6} \]

Information about “population parameters”
1-Galaxy merger rate \( \leftarrow \) MBHB merger rate
   affects the number of sources at each frequency \( \rightarrow N_0 \)
2-MBH mass – merging galaxy relation
   affects the mass of the sources \( \rightarrow M_c \)

Information about “local dynamics”
1-Accretion (when? how?)
   affects the mass of the sources \( \rightarrow M_c \)
2-MBHB – environment coupling (gas & stars)
   affects the chirping rate of the binaries \( \rightarrow \gamma \)
   affects the eccentricity \( \rightarrow \) chirping rate \( \rightarrow \gamma \) & single source detection
SKA will probe the overall amplitude and *shape* of the signal

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affects the chirping rate of the binaries ---> $\gamma$
affects the eccentricity ---> chirping rate ----> $\gamma$ & single source detection
Particularly bright sources might stand above the 'confusion noise' level generated by other sources.
- We recover the **correct number of sources** (no false positive)
- We can determine the **source parameters** with high accuracy:
  > SNR within few%
  > sky location within few deg offset
  > frequency at sub-bin level

- Extremely promising, needs test on more realistic situations
MBHB+circumbinary disk

- Opt/IR dominated by the outer disk. Steady?
- UV generated by the Inner disks. Periodic variability.
- X ray corona. Periodic variability
- Variable broad emission lines (in response to the UV/X ionizing continuum)
- Double fluorescence 6.4keV Kα iron lines

Credits: C. Roedig
1-Pulsar timing arrays provide an effective method to detect low frequency (nHz) gravitational waves from massive black hole binaries

2-The signal level depends on the *MBH merger rate* and on the *MBH-host relations*. GW limits are becoming interesting in discarding 'optimistic' scenarios.

3-*IPTA might lead to a GW detection* in the near future

....but....

4-*Only with SKA* we will have a complete description of the *stochastic background* (amplitude, shape)

5-SKA will likely resolve several individual MBHBs opening the era of *low frequency multimessenger astronomy*