Institute of
Gravitational Wave Astronomy

UNIVERSITY OF BIRMINGHAM

Pulsar timing arrays and constraints on massive black hole binaries

Hannah Middleton

University of Birmingham

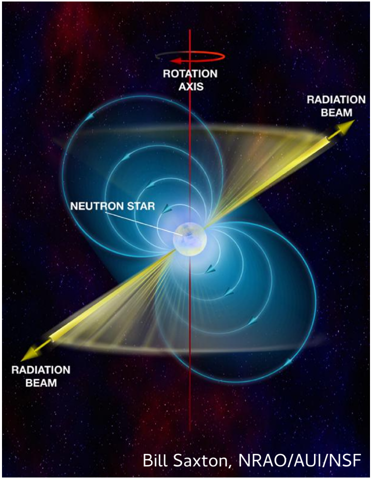
hannahm@star.sr.bham.ac.uk

Bonn, 11 December 2017

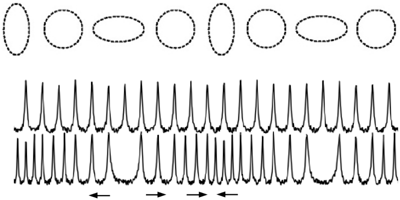
Overview

- Pulsar timing array searches for gravitational wave background
- Results so far
- No detection yet, but upper limits starting to reach astrophysically interesting sensitivities
- Astrophysics – what can we learn about the population of massive black holes?

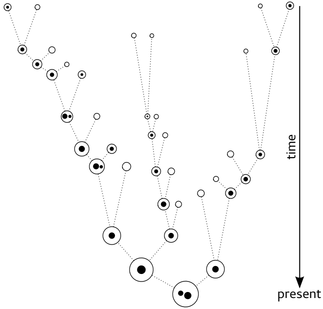
Using millisecond pulsars to search for gravitational waves



- Millisecond pulsars
- Cosmic lighthouses
- Change in distance between Earth and pulsar $\rightarrow$ change in arrival time of pulses



What are we searching for?
Massive black hole binaries



- Massive black holes at the centre of galaxies
- Galaxies merger tree
- Form binaries at the center of merging galaxies
- Stochastic background at nHz frequencies (period $\sim$ years)

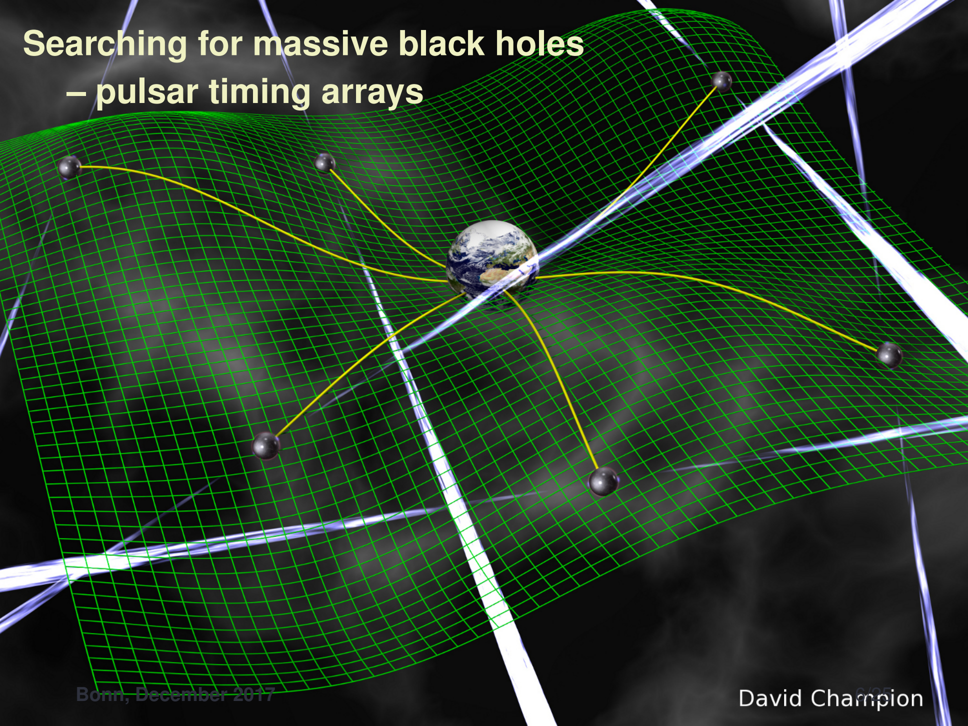
Merger tree image adapted from one by Volonteri


Credit: Hubble Space Telescope

What would we like to know?

- Do massive black holes form binaries and merge?
- Properties of the population of massive black holes
- Galaxy evolution
- Massive black hole – host galaxy relations

Searching for massive black holes – pulsar timing arrays



Not just the gravitational wave background

- Pulsars need to be good timers
  $\rightarrow$ millisecond pulsars

  - Astrometric properties
  - Pulsars in binaries
  - Spin-down
  - Pulse-profile variability
  - Interstellar medium
  - Glitches
  - Timing standards
  - Solar System ephemeris
  - ...

Gravitational wave spectrum

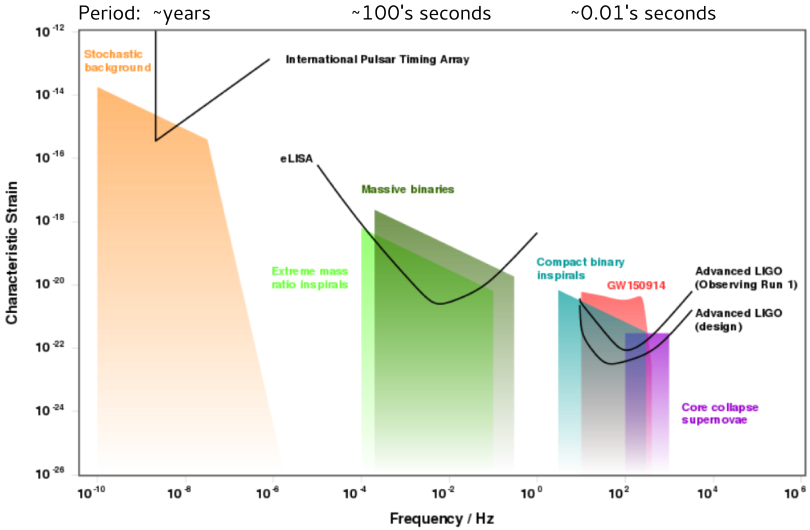


Image from GWPlotter: `rhcole.com/apps/GWplotter/`

Pulsar timing arrays around the world

EPTA

NANOGrav

PPTA

INTERNATIONAL PULSAR TIMING ARRAY

IPTA

Plus, *e.g.*

SKA
FAST
MeerKat
ASKAP

Results so far – upper limits

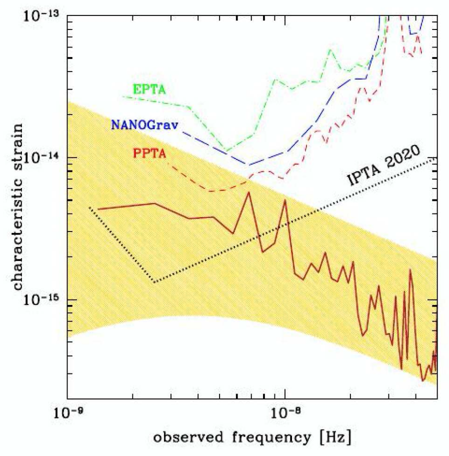


Image: A. Sesana (Hobbs & Dai 2017)

- Most stringent upper limit from Parkes Pulsar Timing array (Shannon+ 2015)
- $h_{ul} < 1 \times 10^{-15}$ at 95% confidence ($f = 1/1\mathrm{yr}$)
- Are predictions in trouble?
  - Eccentricity?
  - Stalling?

Upper limits:

PPTA:Shannon+2015, EPTA:Lentati+2015, NANOGrav:Arzoumanian+2016

How do we know we are getting there?

See Sesana 2013

- Galaxy merger rate:
  - galaxy mass / redshift function
  - pairing fraction
  - merger timescale

- Assign massive black holes to merging pairs
  using black hole – host galaxy relations

- Construct population $\rightarrow$ gravitational wave prediction

- Predictions lie around $h \sim 10^{-15} - 10^{-16}$ at $f = 1\mathrm{yr}^{-1}$

Learning about the population of massive black holes

- What can we learn about the massive black hole binary population given an upper limit?

- Lots of work in this area, *e.g.*
  - Shannon+ 2013, 2015
  - Lentati+ 2015
  - Arzoumanian+ 2016
  - Simon & Burke-Spolaor 2016

Learning about the population of massive black holes

- Hierarchical bayesian analysis with astrophysical prior
  - Can we place any constraints on astrophysical predictions?
  - Initial study with circular binaries: Middleton+2016
  - Chen+ 2017, Middleton+ 2017
  - Continuing to build on this work
  - Siyuan Chen, Walter Del Pozzo, Alberto Sesana, Alberto Vecchio, Will Farr

Model

$$h^2(f) = \frac{4G}{\pi c^2 f} \int_0^\infty \mathrm{d}z \int_0^\infty \mathrm{d}\mathcal{M} \frac{\mathrm{d}^2 n}{\mathrm{d}z\mathrm{d}\mathcal{M}} \frac{\mathrm{d}E}{\mathrm{d}f_r}$$

sum sources over redshift & chirp mass

energy spectrum for eccentric binaries

e_t

observed GW frequency

number of sources per redshift and chirp mass interval

emitted GW frequency (source frame)

No stalling of the binaries

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

Phinney 2001 (arXiv:0108028)

Chen, Sesana & Del Pozzo 2017 (arXiv:1612.00455)

Model

chirp mass distribution

$$\frac{d^2 n}{dz\,d\mathcal{M}} = \dot{n}_0 \left[\left(\frac{\mathcal{M}}{10^7 M_\odot} \right)^{-\alpha} \exp\left(-\frac{\mathcal{M}}{\mathcal{M}_*} \right) \right] \left[(1+z)^{\beta} \exp\left(-\frac{z}{z_*} \right) \right] \frac{dt_r}{dz}$$

no. mergers ($\mathrm{Mpc}^{-3}\mathrm{Gyr}^{-1}$)

source frame time

AND e_t

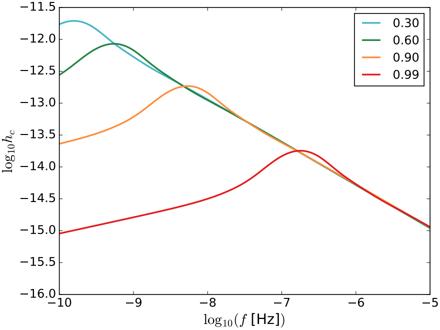
redshift distribution

6 parameters model:

- $\dot{n}_0$ (merger rate density)
- α, $\mathcal{M}_*$ (chirp mass distribution)
- β, z_* (redshift distribution)
- e_t (decoupling eccentricity)

Phinney 2001
Middleton+2016

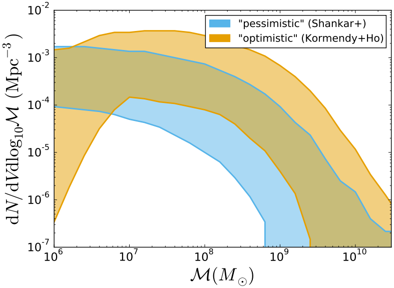
Why is eccentricity important?

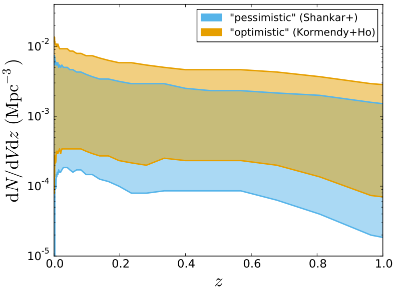


- Some eccentricity at decoupling
- Population of eccentric gravitational wave driven binaries
- Depletes spectrum at low frequency
- This is the **same** for all binaries

Taylor+ 2016 (arXiv:1505.06208)
Chen, Sesana & Del Pozzo 2017 (arXiv:1612.00455)

Astrophysical prior

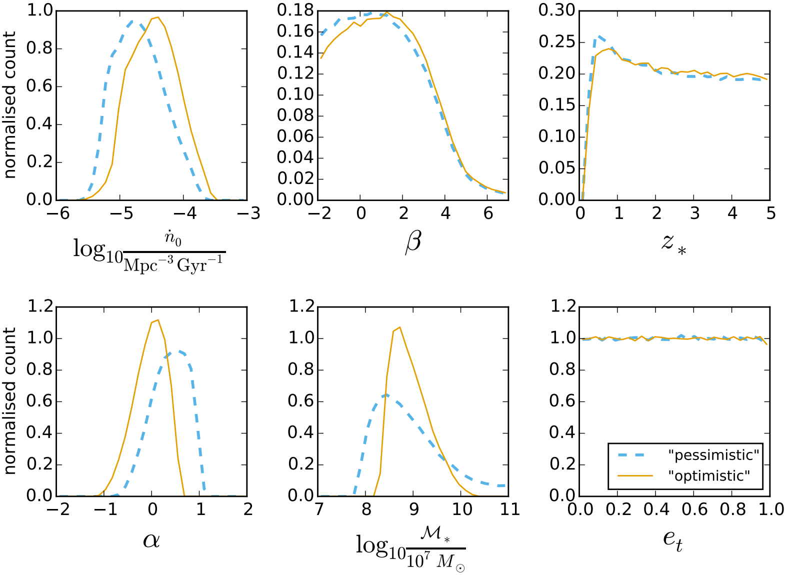




Model	median strain at $f = 1/1\mathrm{yr}$
Pessimistic $\approx$	4×10^{-16}
Optimistic $\approx$	1.5×10^{-15}

Shankar+ 2016
Kormendy & Ho 2013

Astrophysical prior



Method overview

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

Method overview

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

Method overview

PRIOR
for 6 parameters
with astrophysical
prediction

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

Method overview

PRIOR
for 6 parameters with astrophysical prediction

LIKELIHOOD:
upper limit from PTA results

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

Method overview

PRIOR
for 6 parameters
with astrophysical
prediction

LIKELIHOOD:
upper limit from
PTA results

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

MODEL
with minimal
assumptions

Method overview

PRIOR
for 6 parameters
with astrophysical
prediction

LIKELIHOOD:
upper limit from
PTA results

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

MODEL
with minimal
assumptions

$$\frac{\mathrm{d}^2 n}{\mathrm{d}z\mathrm{d}\mathcal{M}} = \dot{n}_0 \left[\left(\frac{\mathcal{M}}{10^7 M_\odot} \right)^{-\alpha} \exp\left(-\frac{\mathcal{M}}{\mathcal{M}_*} \right) \right] \left[(1+z)^\beta \exp\left(-\frac{z}{z_*} \right) \right] \frac{\mathrm{d}t_r}{\mathrm{d}z}$$

Method overview

PRIOR
for 6 parameters
with astrophysical
prediction

LIKELIHOOD:
upper limit from
PTA results

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

MODEL
with minimal
assumptions

$$\frac{\mathrm{d}^2 n}{\mathrm{d}z\mathrm{d}\mathcal{M}} = \dot{n}_0 \left[\left(\frac{\mathcal{M}}{10^7 M_\odot}\right)^{-\alpha} \exp\left(-\frac{\mathcal{M}}{\mathcal{M}_*}\right)\right] \left[(1+z)^\beta \exp\left(-\frac{z}{z_*}\right)\right] \frac{\mathrm{d}t_r}{\mathrm{d}z}$$

NESTED SAMPLING
cpnest – Veitch & Del Pozzo
github.com/johnveitch/cpnest

Method overview

PRIOR
for 6 parameters
with astrophysical
prediction

LIKELIHOOD:
upper limit from
PTA results

$$\frac{\mathrm{d}^2 n}{\mathrm{d}z\mathrm{d}\mathcal{M}} = \dot{n}_0 \left[\left(\frac{\mathcal{M}}{10^7 M_\odot} \right)^{-\alpha} \exp\left(-\frac{\mathcal{M}}{\mathcal{M}_*} \right) \right] \left[(1+z)^{\beta} \exp\left(-\frac{z}{z_*} \right) \right] \frac{\mathrm{d}t_r}{\mathrm{d}z}$$

$$p(\theta|dM) = \frac{p(\theta|M)p(d|M,\theta)}{p(d|M)}$$

POSTERIOR

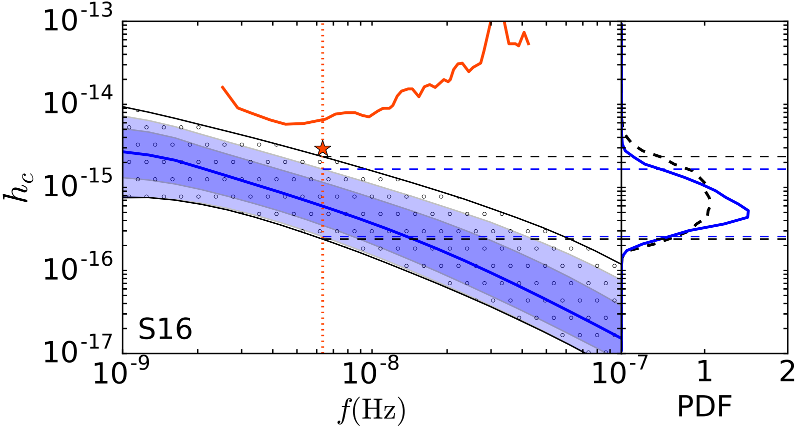
MODEL
with minimal
assumptions

NESTED SAMPLING
cpnest – Veitch & Del Pozzo
github.com/johnveitch/cpnest

POSTERIOR DISTRIBUTIONS
FOR 6 PARAMETERS &
EVIDENCES

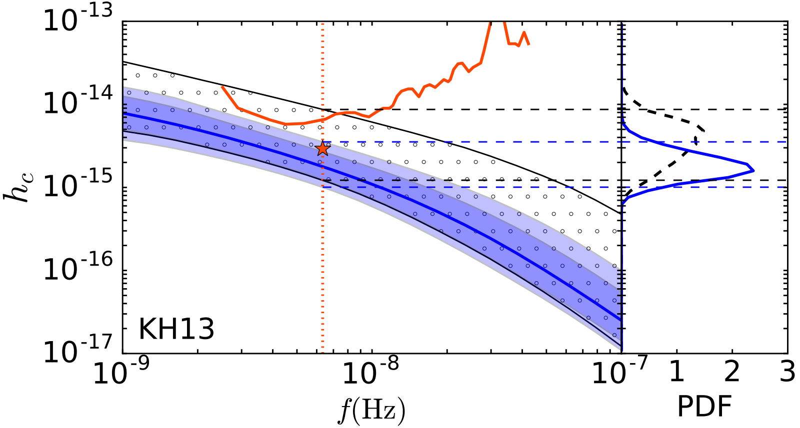
Results

'PESSIMISTIC'



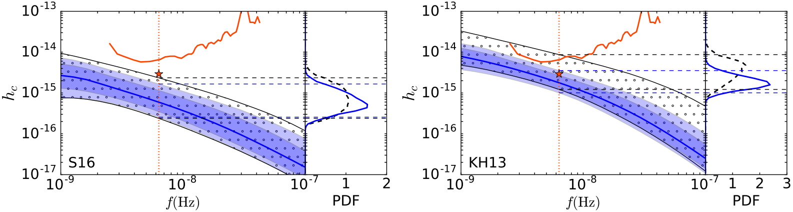
Results

'OPTIMISTIC'



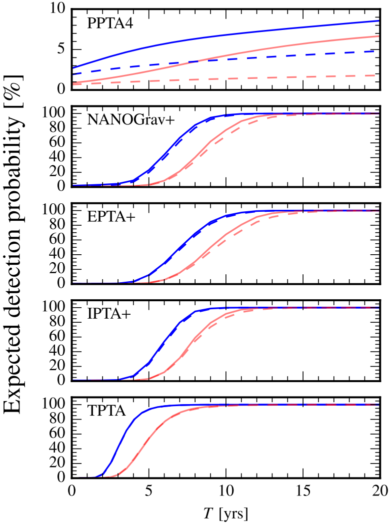
Results

- Realistic astrophysical models are consistent with observations so far
- Don't need stalling
- Don't need eccentricity



How long will it take?

Taylor+2016



4 pulsars (as in Shannon+2015)

37 pulsars (as in Arzoumanian+2015)
+4 new pulsars each year (250ns)

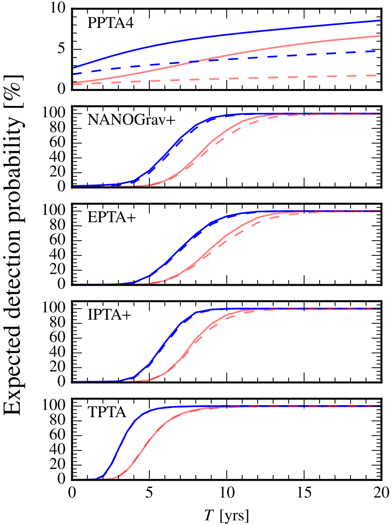
42 pulsars (as in Caballero+2015)
+4 new pulsars each year (250ns)

49 pulsars (as in Verbiest+2016)
+6 new pulsars each year (250ns)

50 pulsars (100ns)

How long will it take?

Taylor+2016



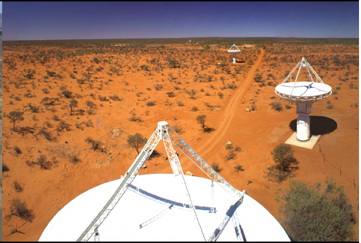
- larger arrays
  → ∼ 80% probability of detection within 10 years
- smaller arrays
  → doesn't look good for next 20 years!

The future

FAST (Credit: Chinese Academy of Sciences)

SKA (Credit: SKA Organisation)

MeerKAT (Credit: www.ska.ac.za/gallery/meerkat/)



ASKAP (Credit Brian Boyle)

Summary

- Pulsar timing arrays will answer questions like:
  - do massive black holes merge?
  - some information on astrophysical predictions
  - galaxy evolution, $M - \sigma$ relation
- Current observations
  - still consistent with astrophysical predictions
  - starting to reach astrophysically interesting sensitivity
  - Keep looking!