Pulsar timing arrays and the evolution of galaxies

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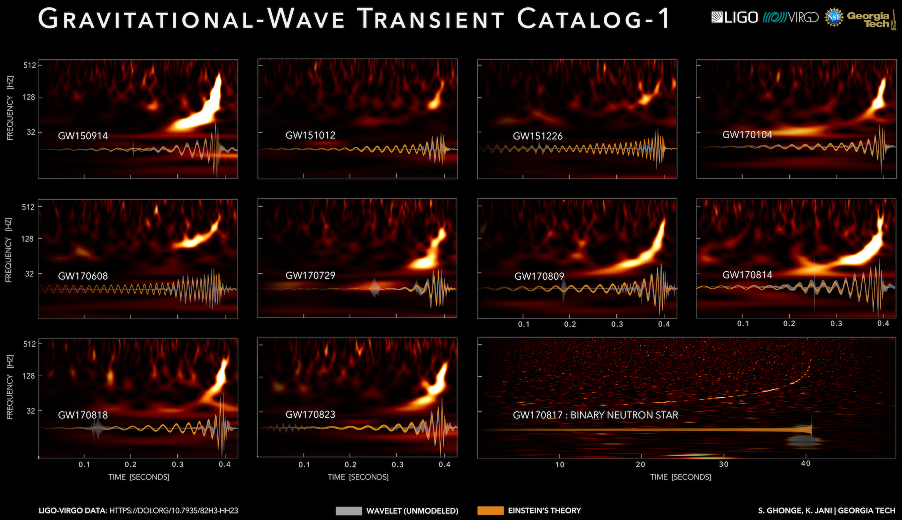
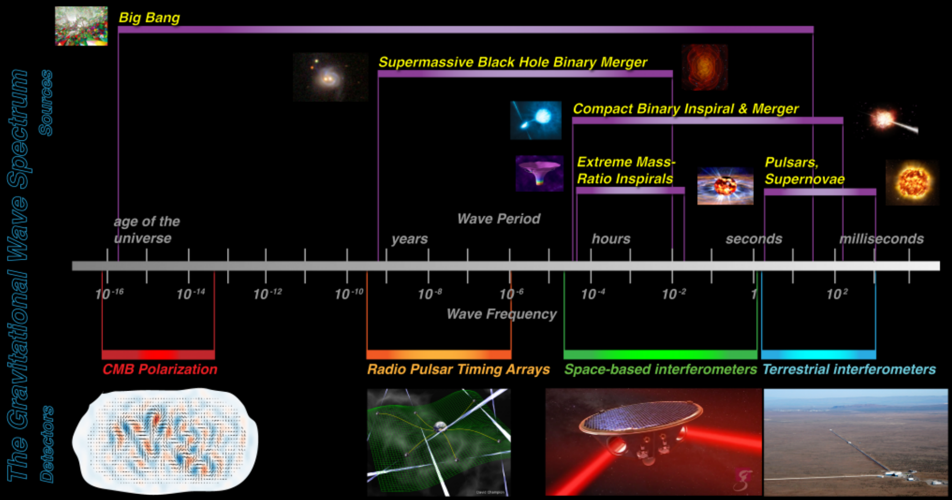
Overview

- What has been seen so far?
- Massive black holes in binaries
- Gravitational waves from massive black hole binaries
- Searching – Pulsar Timing Arrays
- Pulsar timing array results & what can we learn?
- The future

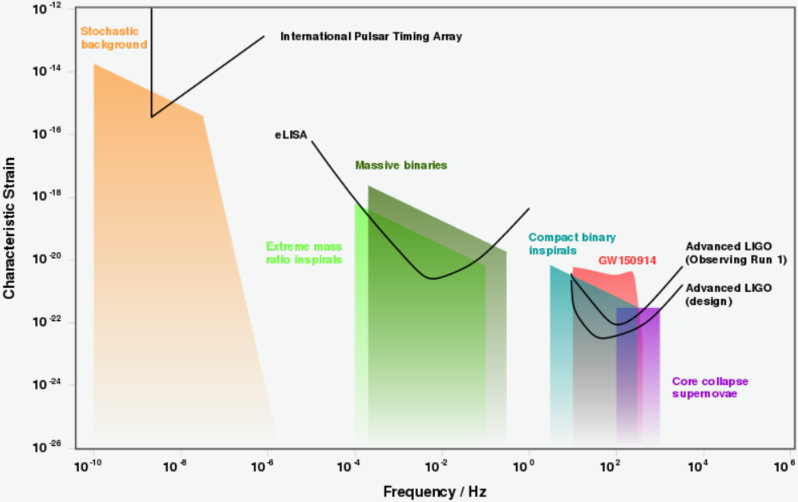
Gravitational waves so far


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH



[NASA/J. I. Thorpe]

Gravitational wave spectrum



[GW Plotter: Moore+2015, `rhcole.com/apps/GWplotter/`]

Super massive black holes

Super massive black hole binaries?

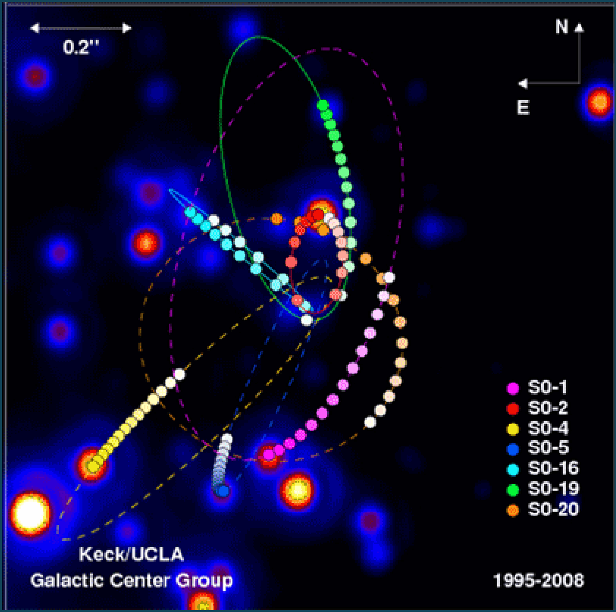
Masses:
$\sim 10^6 M_\odot - 10^9 M_\odot$

[Interstellar]

Questions:

- Are there massive black hole binaries out there?
- How do they form?
- Gravitational waves from them
- What can we learn from these gravitational wave observations?

Our own galaxy



Other galaxies too?

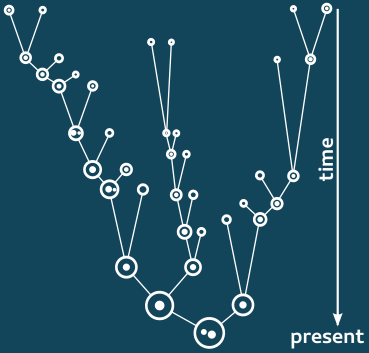
- Massive black holes $10^6 - 10^9\ M_\odot$ in most galaxies [Kormendy & Ho 2013]
- What about massive black hole binaires?

[R. Jay GaBany, Cosmotography]

Merger tree

Galaxy growth by mergers
(White & Rees 1978)

Likely that black hole growth goes hand-in-hand with host galaxy

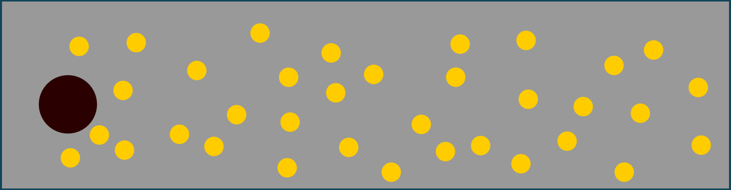


[Volonteri] [NASA]

Galaxy merger

Galaxy merger → **Dynamical Friction** → Final parsec? → Gravitational wave emission

Black holes move through a sea of stars
Stars accellerated in their wake
Black holes lose momentum
$\rightarrow$ sink towards centre of galaxy
Few million years
(Chandrasekhar 1943, Begelman+ 1980)



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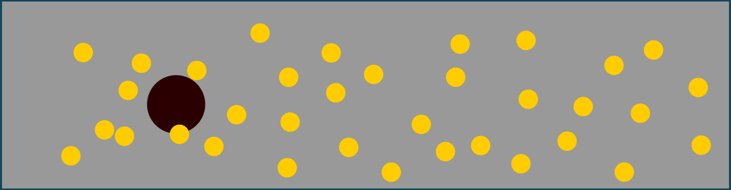

Galaxy merger | **Dynamical Friction** | Final parsec? | Gravitational wave emission

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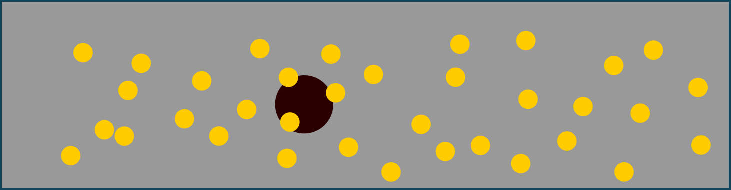

Galaxy merger — **Dynamical Friction** — Final parsec? — Gravitational wave emission

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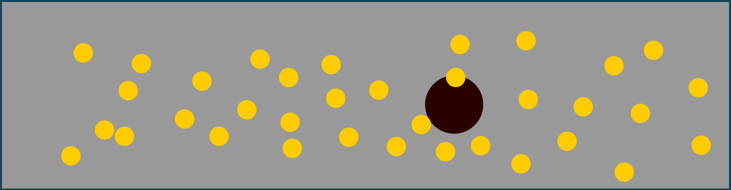

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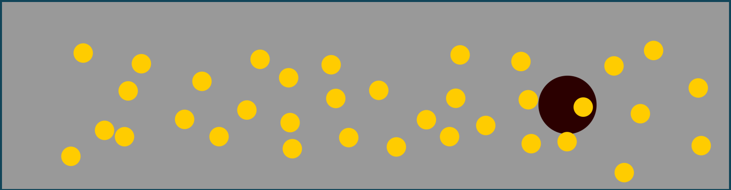


Galaxy merger — Dynamical Friction — **Final parsec?** — Gravitational wave emission

Galaxy merger gets the black holes within a few parsec

Need to get closer for GW emission:

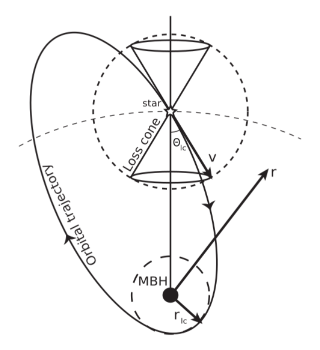
$$a_{\rm gw} = \left[\frac{64}{5}\frac{G^3 M_1 M_2 (M_1 + M_2) F(e)}{c^3}\right]^{1/4}$$

For $M_1 = M_2 = 2 \times 10^7 M_\odot$ $\qquad a_{\rm gw} \sim 0.01{\rm pc}$

Closing the gap

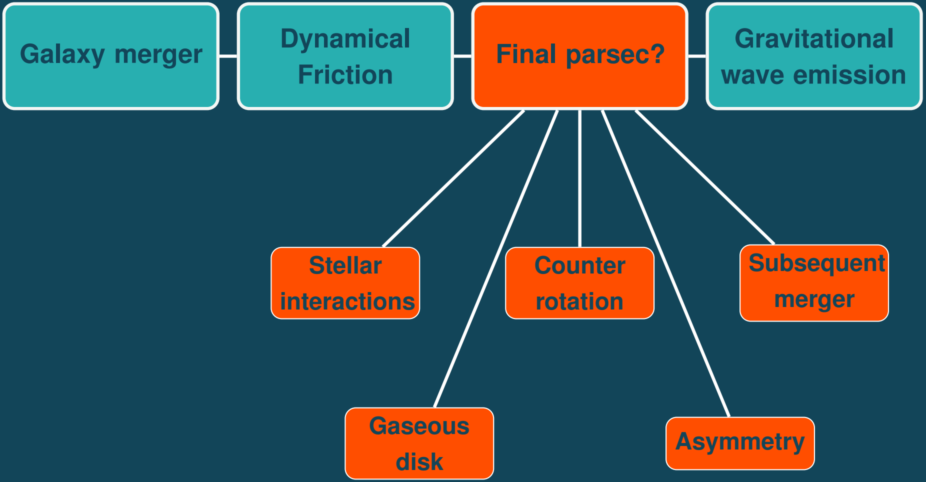
Three body interaction with stars continues to shrink binary.

Eventually stars are depleted



[Merritt 2013]

Quinlan 1996,
Mikkola & Valtonen 1992


Galaxy merger
Dynamical Friction
Final parsec?
Gravitational wave emission
Stellar interactions
Counter rotation
Subsequent merger
Gaseous disk
Asymmetry

Gravitational wave emission!!

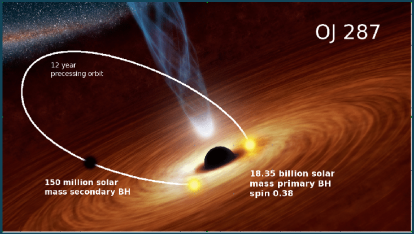
Time to merger from 0.01pc:

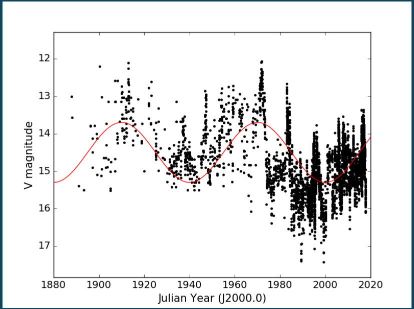
$$t_{\mathrm{merge}}(a) = 5.8 \times 10^6 \left(\frac{a}{0.01pc} \right)^4 \left(\frac{10^8 M_\odot}{M_1} \right)^3 \frac{M_1^2}{M_2(M_1 + M_2)} \text{ years}$$

Observational evidence for MBHBs

OJ287

- massive black hole binary candidate
- quasi-periodic outbursts observered $\sim 12\mathrm{yr}$
- timing consistent with GW emission
- next burst expected July 2019
- [Valtonen+2008, Dey+2018]





[Dey+2018]

Observational evidence for MBHBs

- PG 1302102 – periodicity $\sim 1884 \pm 88\mathrm{days}$ [Graham+2015]
- PSO J334.2028+01.4075 – periodicity $542 \pm 15\mathrm{days}$ [Liu+2015]
- radio galaxy 0402+379 at $a \sim 7.3\mathrm{pc}$ [Rodriguez+2006]
- 111 candidates in the Catelina Real Time Transient Survey [Graham+2015]

Massive black hole binaires are out there!

What kind of gravitational waves do we expect to see?

Gravitational waves from Massive black hole binairies

GW freqs

Transition to GW driven at ~nHz

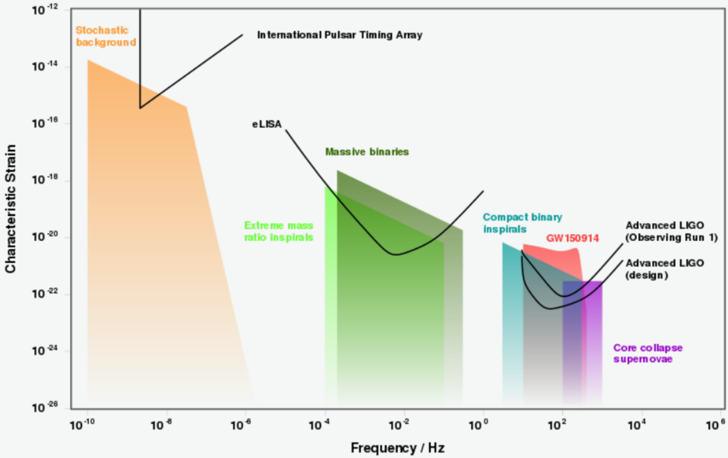
Frequency of merger:

$$f_{\mathrm{gw,isco}} = \frac{1}{\pi 6\sqrt{6}} \frac{c^3}{G M_{\mathrm{T}}}$$

Some typical numbers

total mass M_{T}	merger frequency $f_{\mathrm{gw,isco}}$
$60 M_{\odot}$	~ 100Hz
$200 M_{\odot}$	~ 10Hz
$10^9 M_{\odot}$	$\sim 10^{-6}$Hz

GW freqs

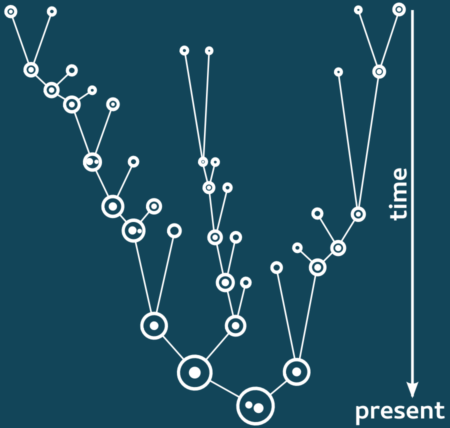


Massive black hole binaries merge way before LIGO/Virgo band.

[GW Plotter: Moore+2015, `rhcole.com/apps/GWplotter/`]

Stochastic background

- Expect many binaries – population
- Stochastic background



[Volonteri]

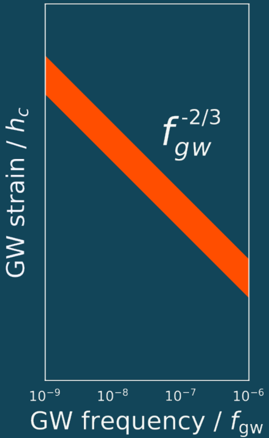
Stochastic background

For circular binairies:

$$h_c^2(f_{gw}) = \frac{4G^{5/3}}{3\pi^{1/3}c^2} f_{gw}^{-4/3} \int_o^\infty \int_o^\infty N(z, \log_{10}\mathcal{M}) \frac{\mathcal{M}^{5/3}}{(1+z)^{1/3}} \mathrm{d}z \mathrm{d}\log_{10}\mathcal{M}$$

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$$

$$h_c \sim f_{gw}^{-2/3}$$



How can we predict $h_c(f_{gw})$?

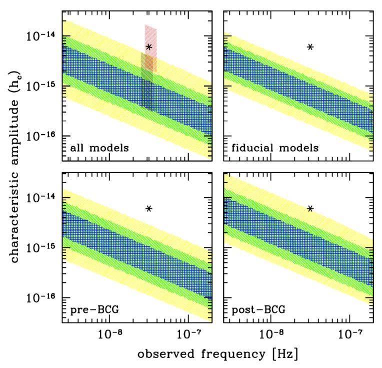
Galaxy stellar mass fraction

Galaxy pair fraction

Merger timescale for MBHB

MBH – host scaling relation

Prediction



Range of predictions

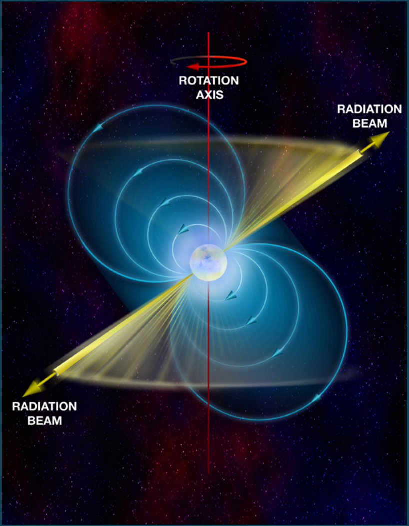
Sesana 2013

How can we detect these gravitational waves?

- GW source ✓
- Idea of what the signal might look like ✓
- Detector???

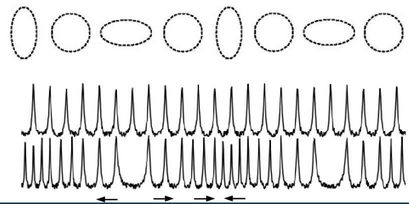
Pulsar Timing Arrays

Using millisecond pulsars to search for gravitational waves

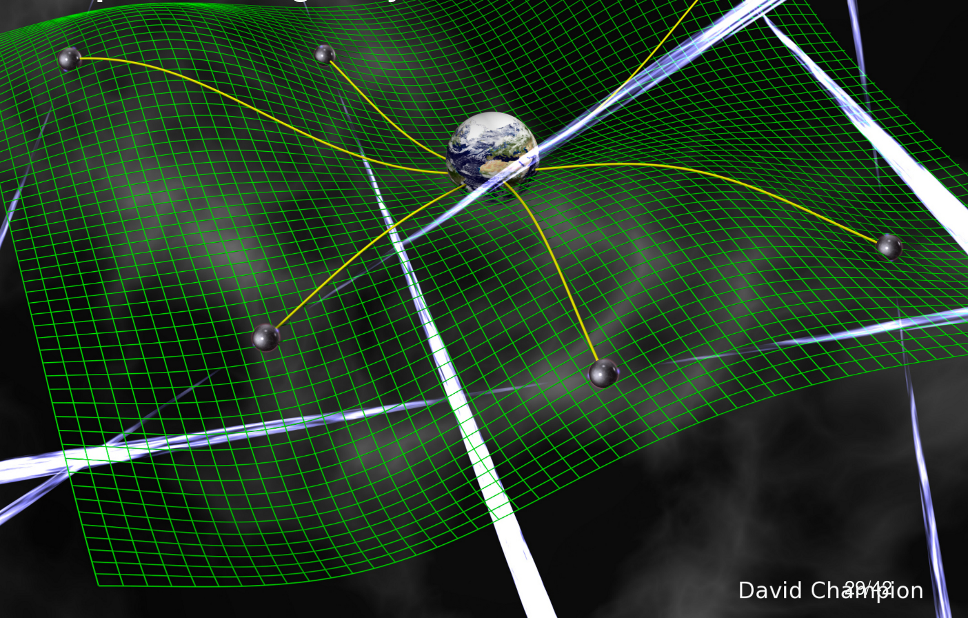


Bill Saxton, NRAO/AUI/NSF

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



Searching for massive black holes – pulsar timing arrays



David Champion

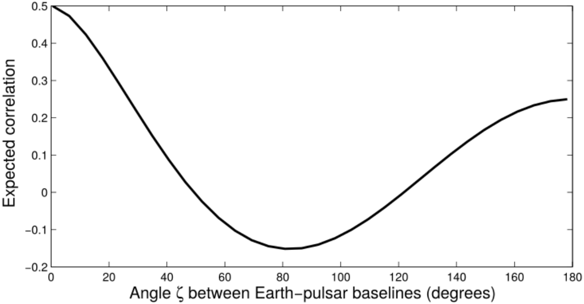
Measure Pulse Time of Arrival

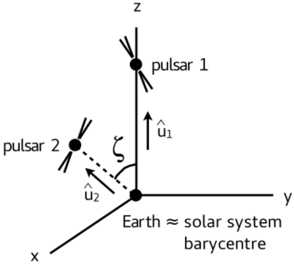
- Observe pulsars for a long time
- Compare expected time of arrival to observed
- Pulsars need to be good timers
  $\rightarrow$ millisecond pulsars
- But, not just gravitational waves...
  - Pulsars in binaries
  - Spin-down
  - Pulse-profile variability
  - Interstellar medium
  - Glitches
  - Timing standards
  - Solar System ephemeris
  - ...

Look for correlations

- Measure time of arrivals
- Hellings & Downs Curve
- Look for correlations between pulsars

Hellings & Downs 1983





[Jenet & Romano 2015]

Looking for Gravitational waves

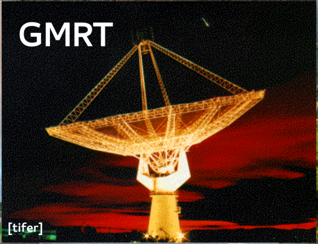
Groups around the world are searching for the background


Parkes
[D.McClenagham/CSIRO]


Nancay
[SATorchinsky]


Westerbork
[A.Renting]


Lovell
[M. Peel]


GMRT
[tifer]

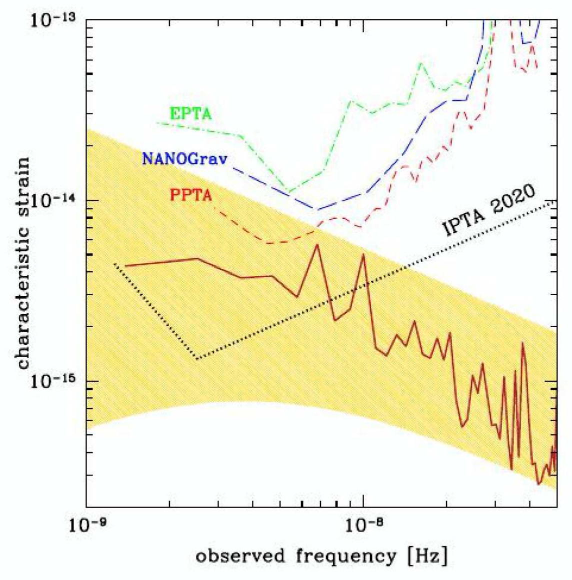

Arecibo
[NAIC]


Sardinia
[INAF]


Effelsberg
[MPIfR]


Green Bank
[NRAO]

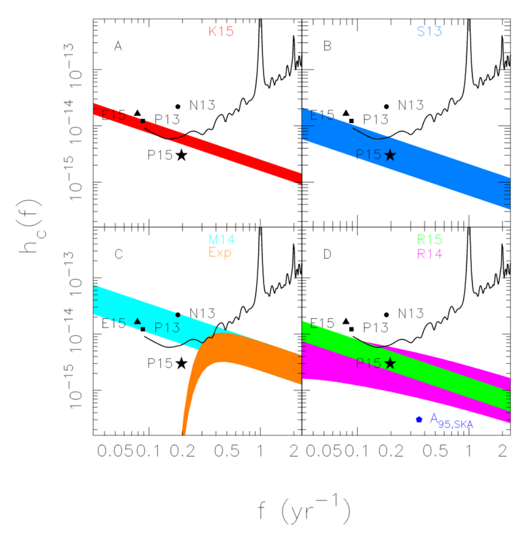
Some PTA results



[Hobbs & Dai 2017]

What does this tell us?

Some PTA results



[Shannon+2015]

Results:

PPTA: Shannon+2015,

EPTA: Lentati+2015,

NANOGrav: Arzoumanian+2018,

Inference with upper limits

A detection will tells us:

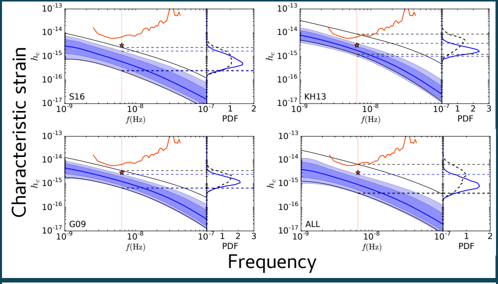
- **Do massive black holes form binaires?**
- galaxy merger rate
- redshift and mass distributions
- are the binaries eccentric?

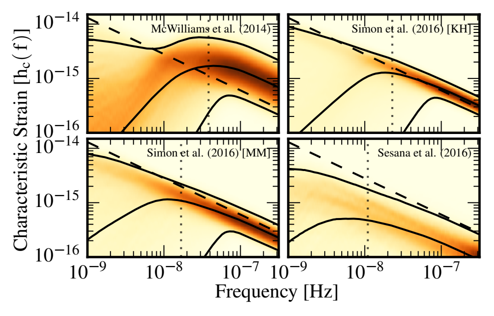
E.g. Chen+2017a,b, Middleton+2018

Inference with upper limits

Non-detections are informative too.

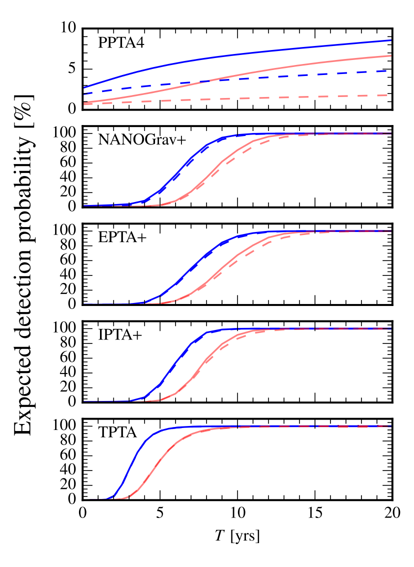
e.g. Arzoumanian+2018, Shannon+2015, Middleton+2018





[Middleton+2018] [Arzoumanian+2018]

Are we nearly there yet?



[Taylor+2016]

- larger arrays
  $\rightarrow \sim 80\%$ probability of detection within 10 years
- smaller arrays
  $\rightarrow$ doesn't look good for next 20 years!
- Taylor+2016

What if still no detection?

What could be going on?

- Is something speeding up the binary evolution?
  - Eccentricity
  - More star / gas interaction than expected
- Or slowing them down?
  - Stalling before they reach gravitational wave emission

Future telescopes

Conclusions

- PTAs probe low frequency gravitational wave spectrum
- Learn about the population of massive black hole binaries
- Relate this to galaxy evolution
- New telescopes will push sensitivity further
- Keep timing!

Find out more:

Parkes Pulsar Timing Array:
`www.atnf.csiro.au/research/pulsar/ppta/`

International Pulsar Timing Array: `http://ipta4gw.org/`

Enterprise PTA analysis software:
`https://enterprise.readthedocs.io`