Gravitational wave signals in the pulsar band

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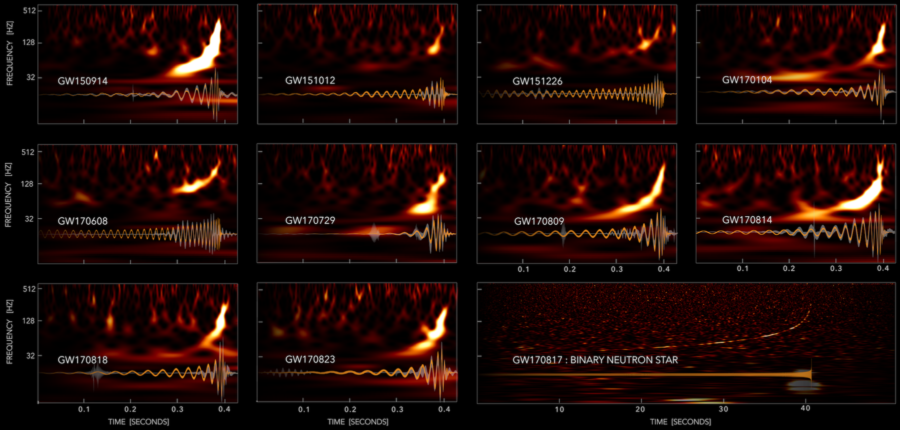
Pulsar Workshop
May 2019, Swinburne

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



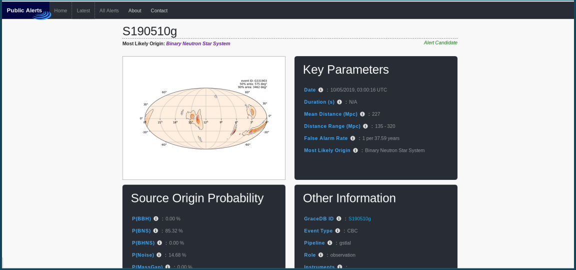
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

WAVELET (UNMODELED)

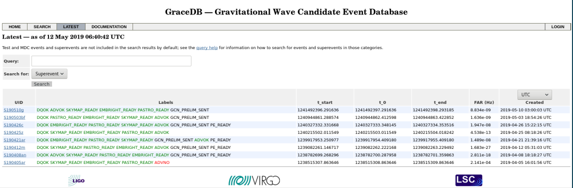
EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH

Public Alerts!



chirp.sr.bham.ac.uk



GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 12 May 2019 06:40:42 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

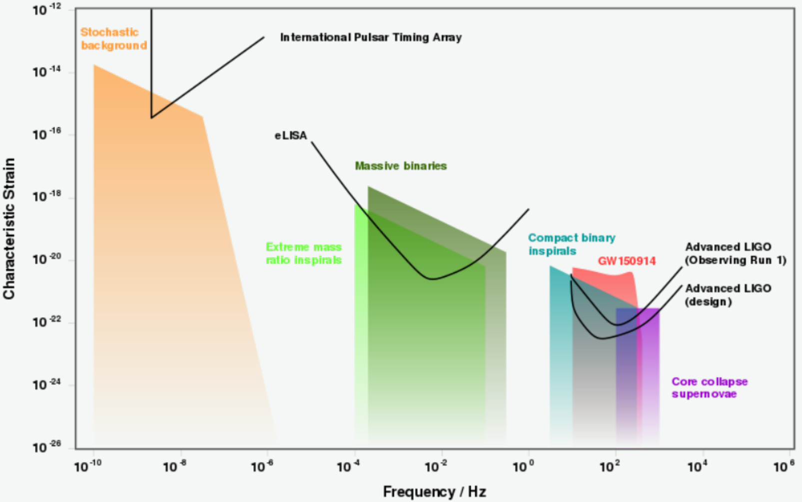
Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190510g	DQOK ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	DQOK PASTRO_READY EMBRIGHT_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY ADVOK GCN_PRELIM_SENT PE_READY	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	DQOK EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT ADVOK PE_READY	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	DQOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY ADVOK GCN_PRELIM_SENT PE_READY	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	DQOK ADVOK SKYMAP_READY PASTRO_READY EMBRIGHT_READY GCN_PRELIM_SENT PE_READY	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	DQOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY ADVNO	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

gracedb.ligo.org

Gravitational wave spectrum



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

Super massive black holes

Super massive black hole binaries?

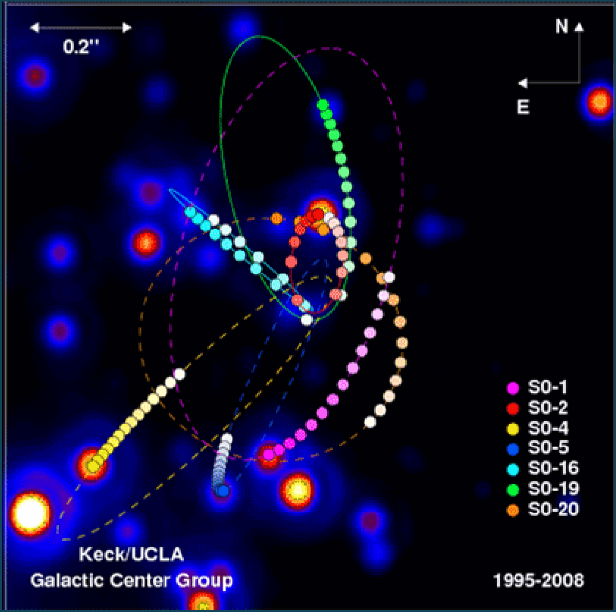
Masses:
$\sim 10^6 M_\odot - 10^9 M_\odot$

[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?

[Event Horizon Telescope]

Other galaxies too?

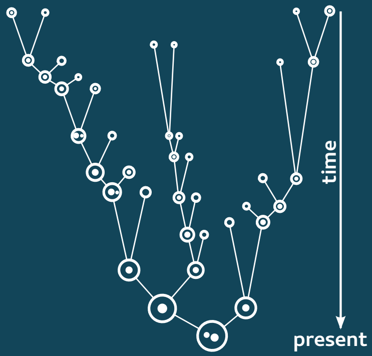
- Massive black holes $10^6 - 10^9\ M_\odot$ in most galaxies [Kormendy & Ho 2013]
- What about massive black hole binaires?

[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

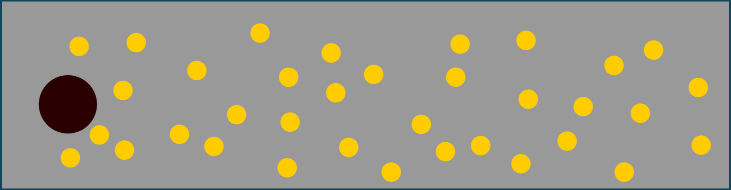


[Volonteri] [NASA]

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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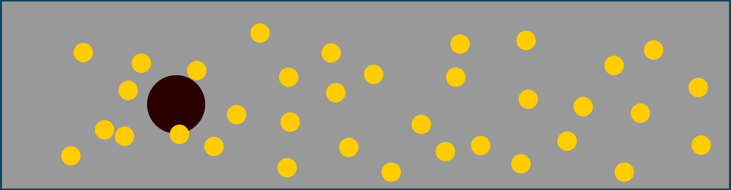

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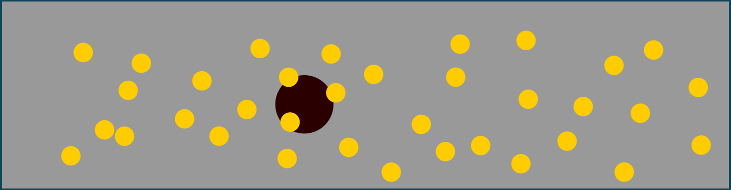

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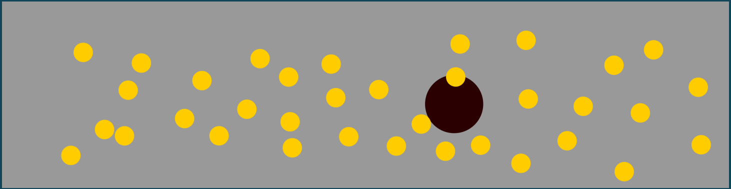

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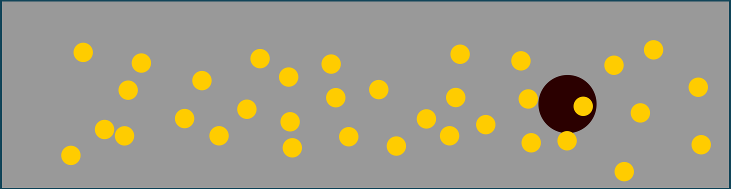


Galaxy merger — Dynamical Friction — **Final parsec?** — Gravitational wave emission

Galaxy merger gets the black holes within a few parsec

Need to get closer for GW emission:

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

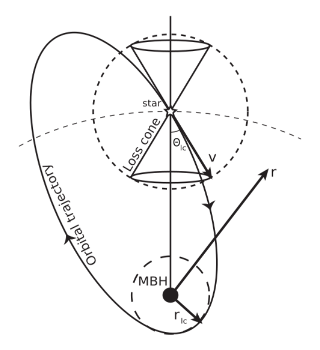
For $M_1 = M_2 = 2 \times 10^7 M_\odot$ $\qquad a_{\rm gw} \sim 0.01 \mathrm{pc}$

Closing the gap

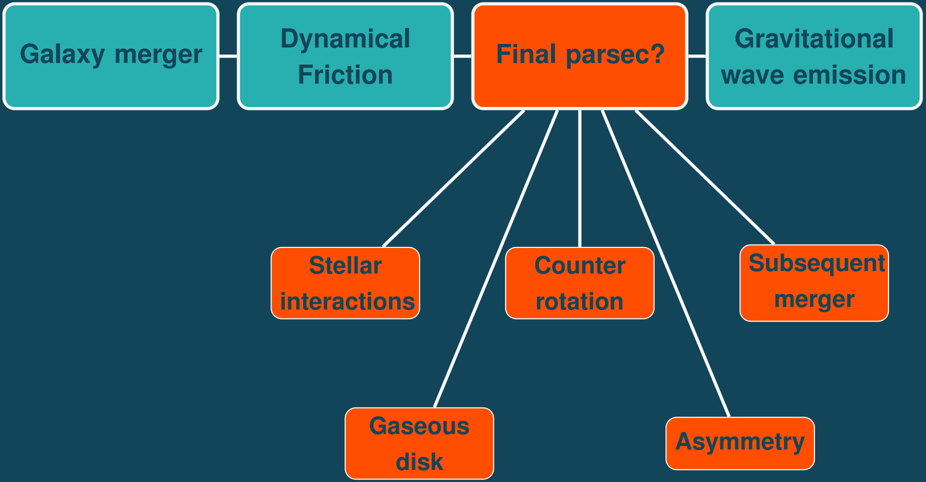
Three body interaction with stars continues to shrink binary.

Eventually stars are depleted

Quinlan 1996,
Mikkola & Valtonen 1992



[Merritt 2013]


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

Gravitational wave emission!!

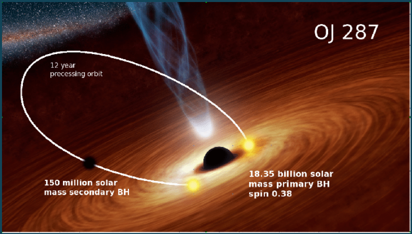
Time to merger from 0.01pc:

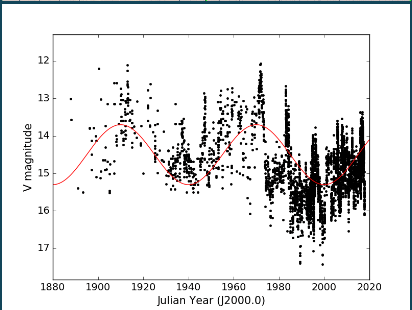
$$t_{\rm merge}(a) = 5.8\times10^{6}\left(\frac{a}{0.01pc}\right)^{4}\left(\frac{10^{8}M_{\odot}}{M_1}\right)^{3}\frac{M_1^2}{M_2(M_1+M_2)}\ \text{years}$$

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 $\sim$nHz

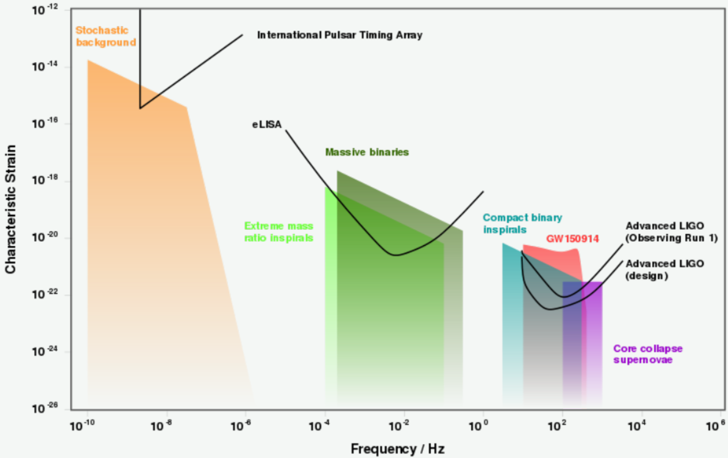
Frequency of merger:

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

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

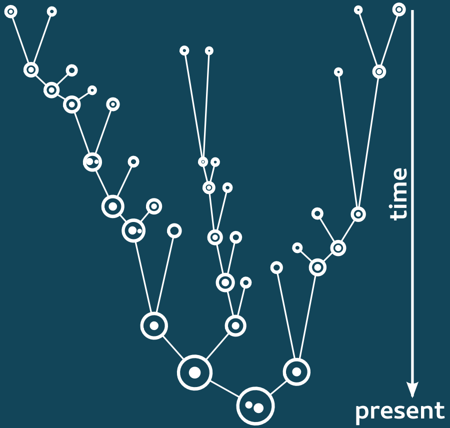


Massive black hole binaries merge way before LIGO/Virgo band.

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

Stochastic background

- Expect many binaries – population
- Stochastic background



[Volonteri]

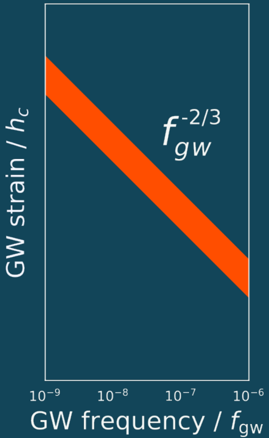
Stochastic background

For circular binairies:

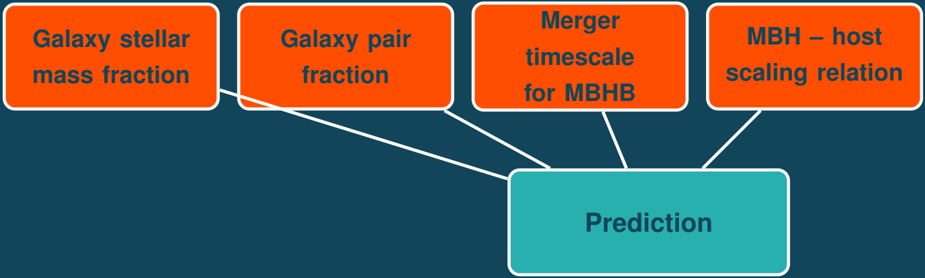
$$h_c^2(f_{\rm gw}) = \frac{4G^{5/3}}{3\pi^{1/3}c^2} f_{\rm gw}^{-4/3} \int_o^\infty \int_o^\infty N(z, \log_{10}\mathcal{M}) \frac{\mathcal{M}^{5/3}}{(1+z)^{1/3}} {\rm d}z{\rm d}\log_{10}\mathcal{M}$$

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

$$h_{\rm c} \sim f_{\rm gw}^{-2/3}$$



How can we predict $h_{\rm c}(f_{gw})$?

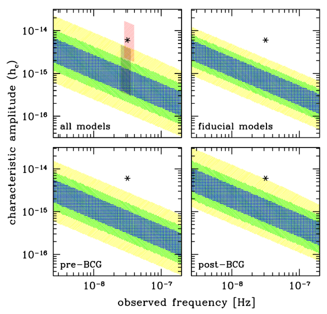

Galaxy stellar mass fraction
Galaxy pair fraction
Merger timescale for MBHB
MBH – host scaling relation
Prediction

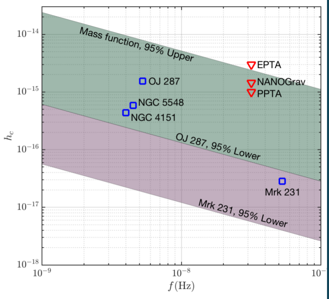
Predicting

Range of predictions e.g.

Sesana 2013

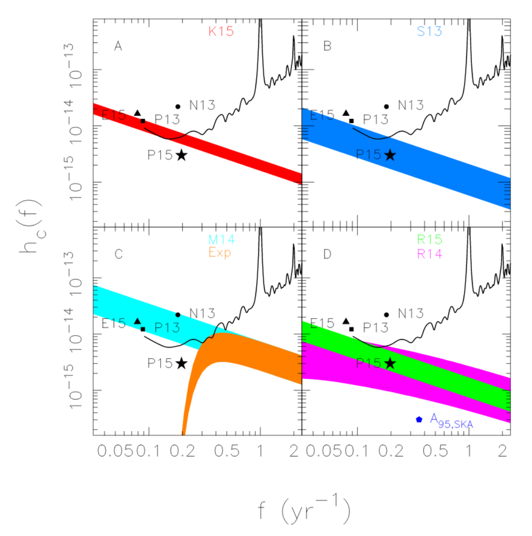
Zhu+ 2018





What can we learn by looking for nHz gravitational waves?

Some PTA results



[Shannon+2015]

Results:

PPTA: Shannon+2015,

EPTA: Lentati+2015,

NANOGrav: Arzoumanian+2018,

Inference with upper limits

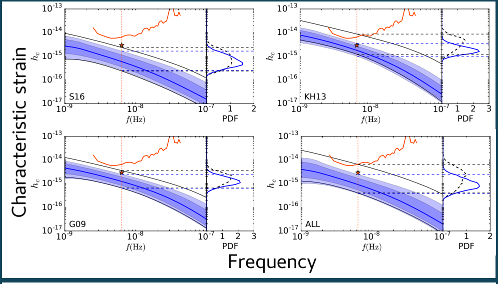
A detection will tells us:

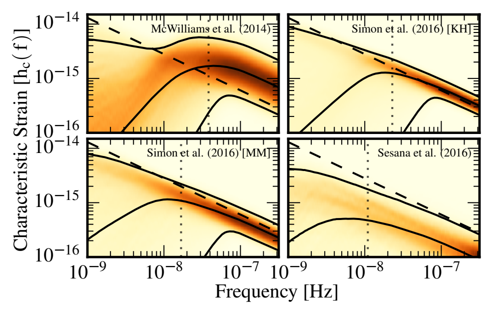
- **Do massive black holes form binaires?**
- galaxy merger rate
- redshift and mass distributions
- are the binaries eccentric?

Inference with upper limits

Non-detections are informative too.

e.g.
Arzoumanian+2018,
Shannon+2015,
Chen+2017a,b
Middleton+2018





[Middleton+2018] [Arzoumanian+2018]

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

Conclusions

- PTAs probe low frequency gravitational wave spectrum
- Learn about the population of massive black hole binaries
- Relate this to galaxy evolution