Probing Massive and Supermassive Black Holes with Gravitational Waves

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February 19, 2019

Gravitational Wave Spectrum

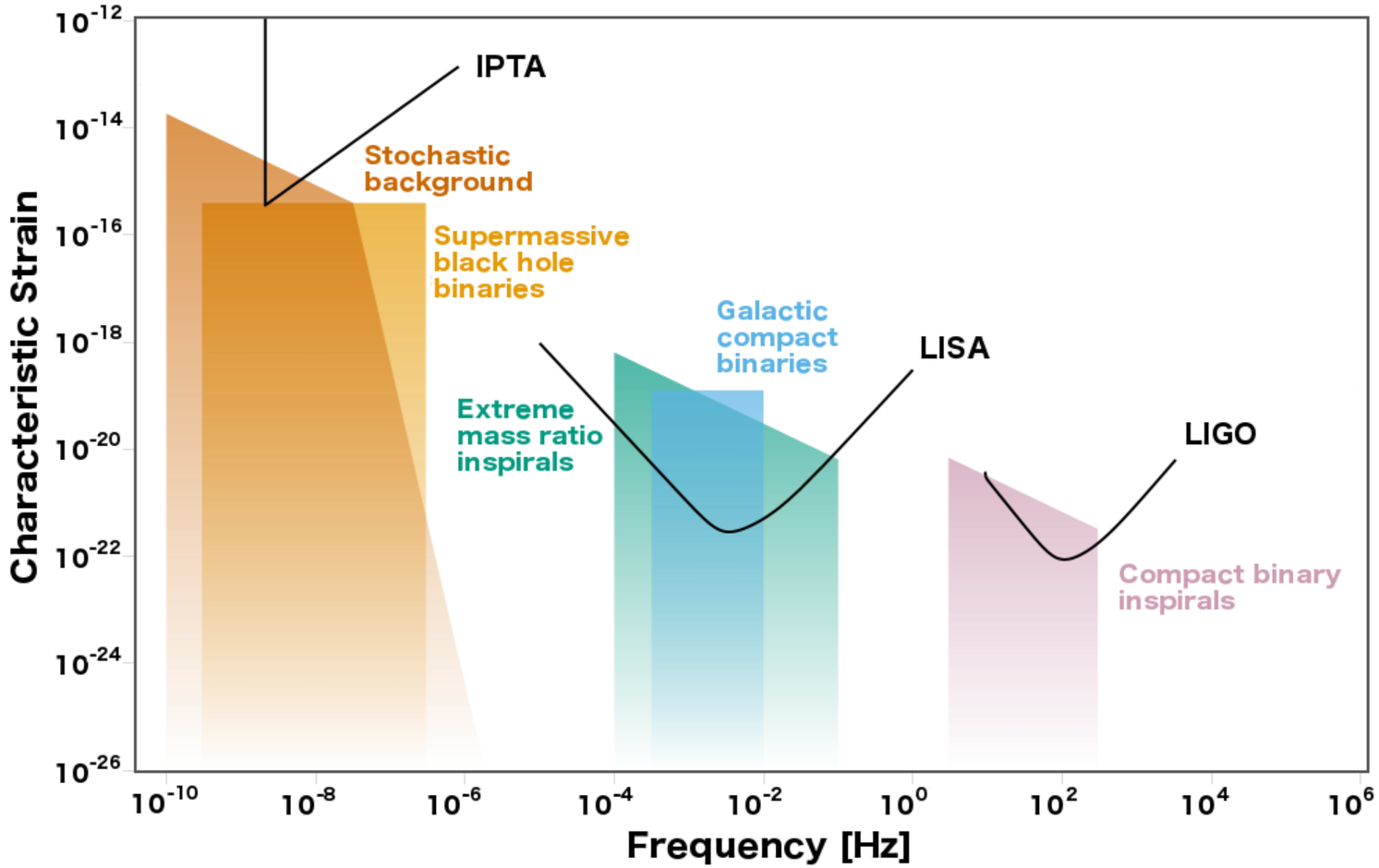


Figure credit: Moore, Cole, Berry 2014 (modified).

Gravitational Wave Spectrum

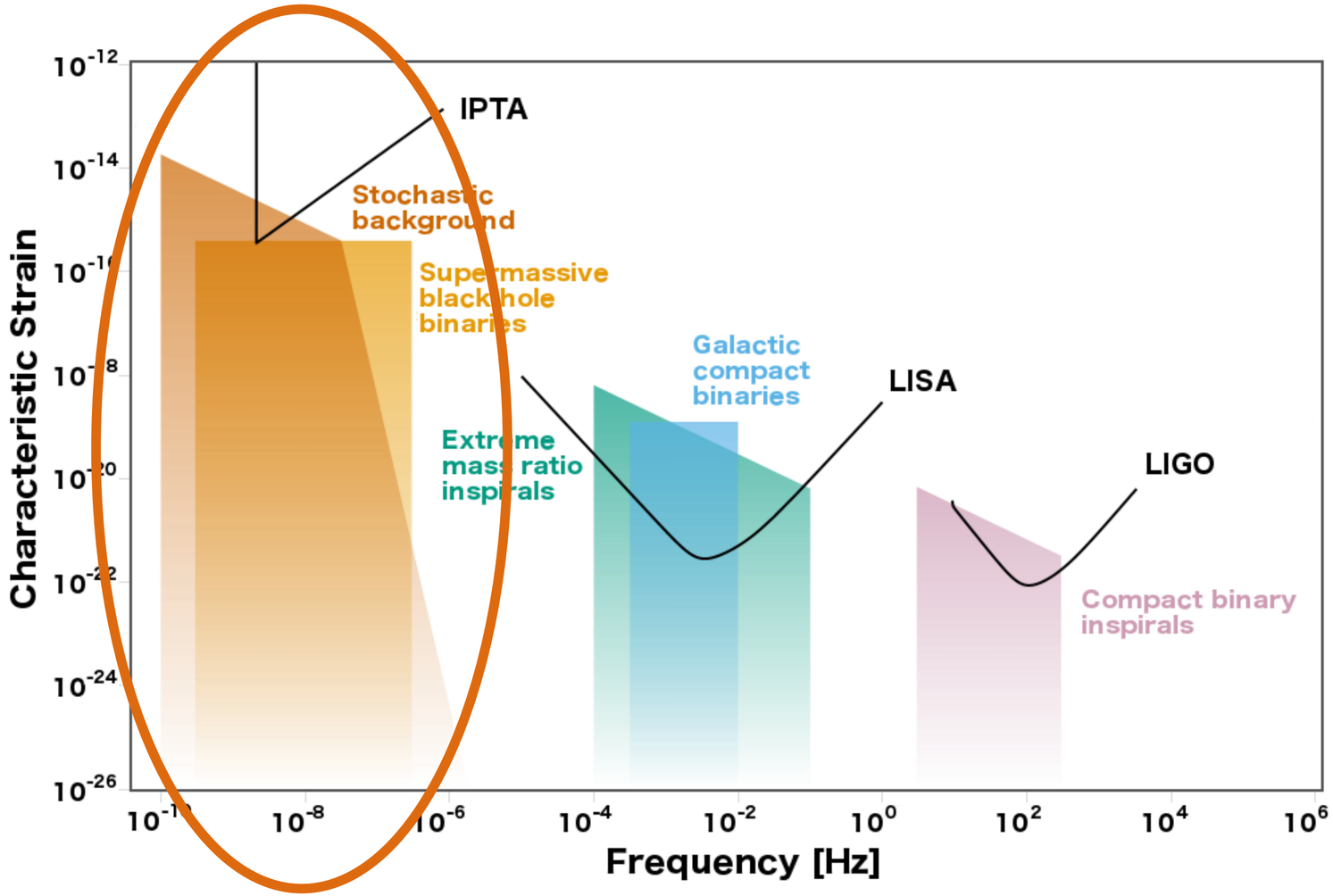


Figure credit: Moore, Cole, Berry 2014 (modified).

Pulsar Timing Arrays

Gravitational waves induce correlated changes in the pulse times of arrival.

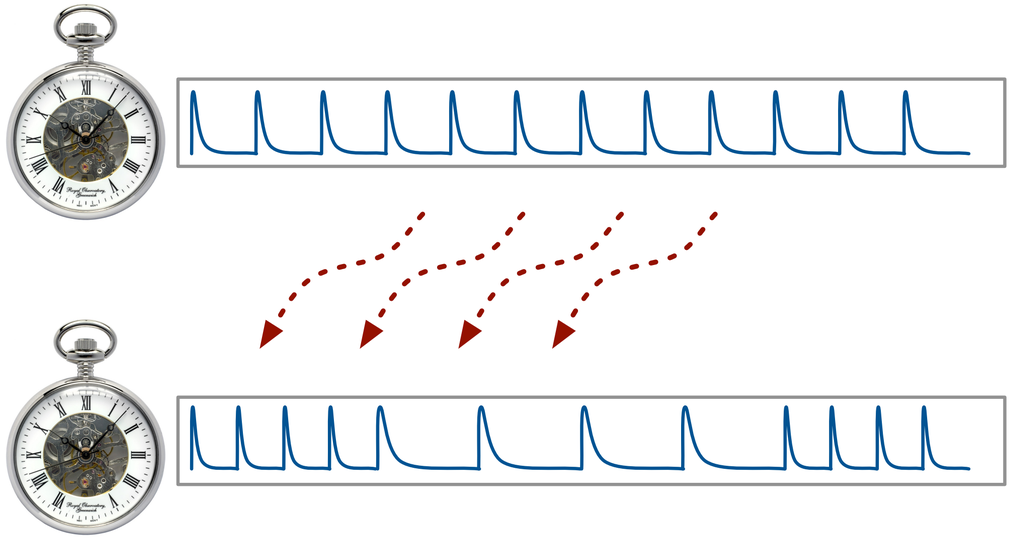


Image credit: S. Chatterjee

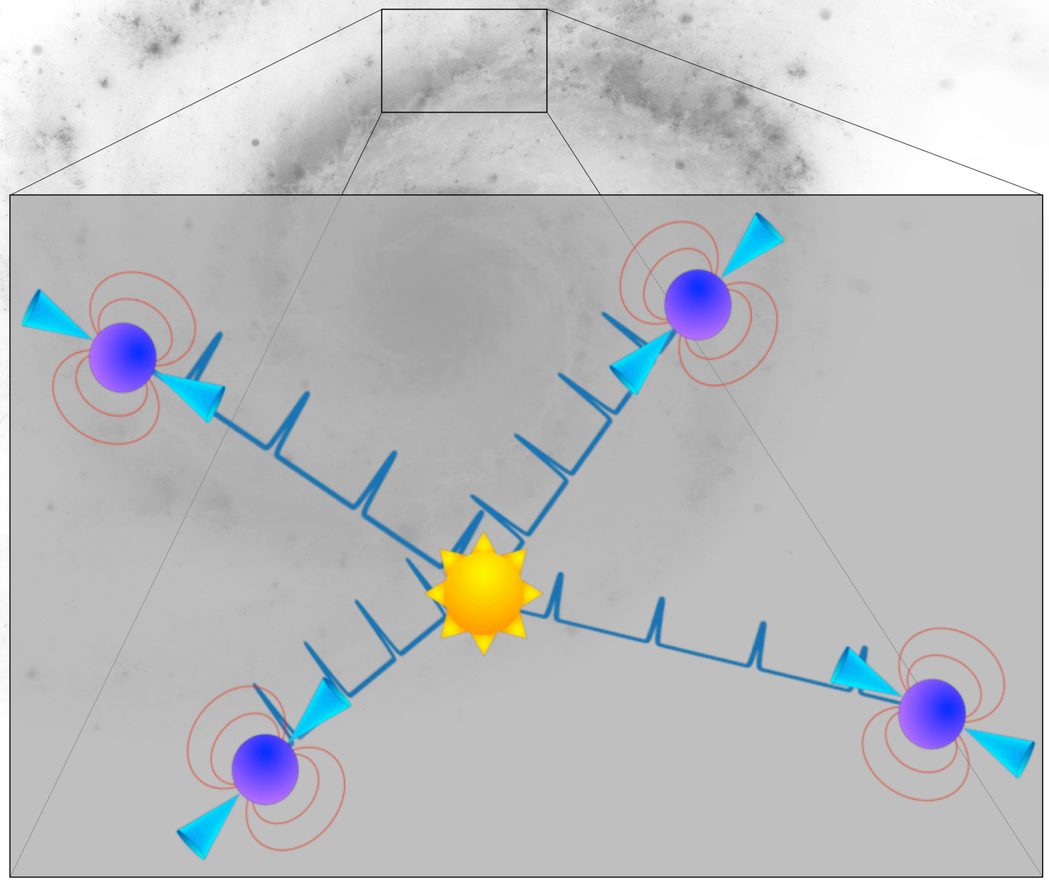


Image credit: J. Hazboun; NASA

Pulsar Timing

Observed times of arrival are fit to a **timing model** to produce residuals.

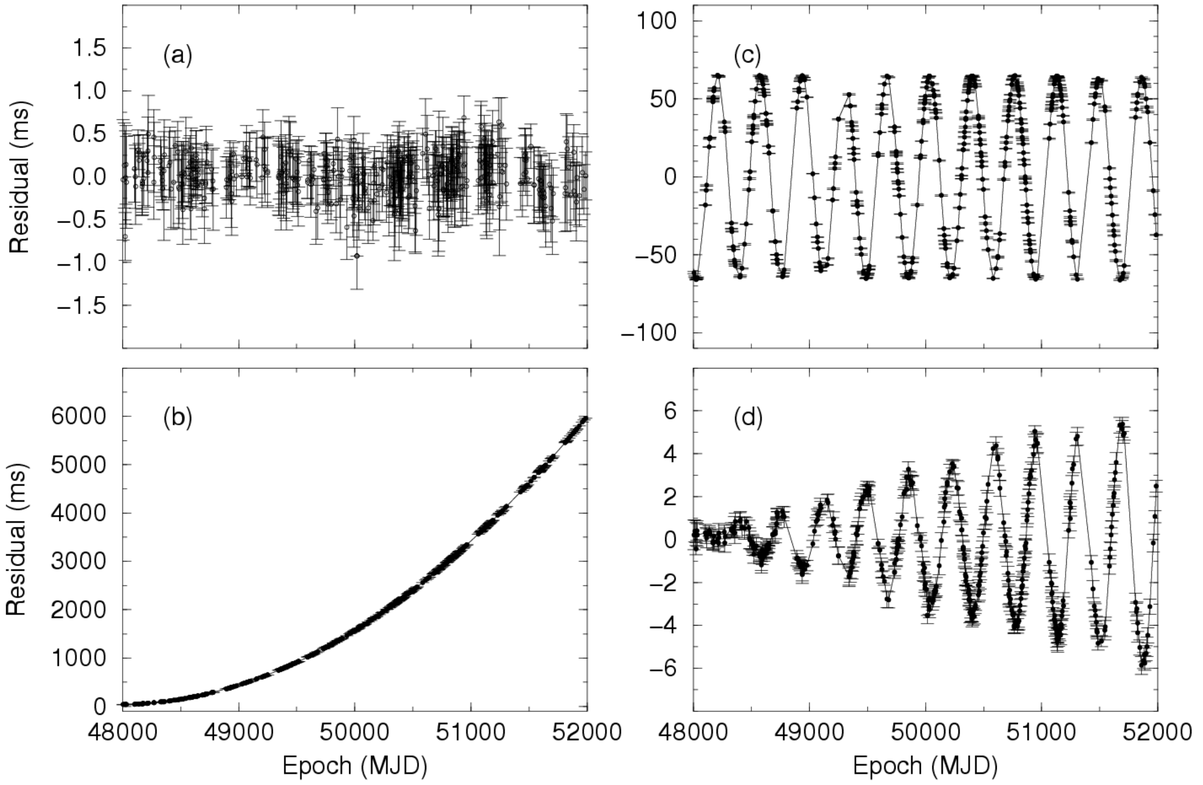


Image credit: Lorimer and Kramer,
The Handbook of Pulsar Astronomy

North American Nanohertz Observatory for Gravitational Waves

Image credits: NRAO/AUI, NAIC, CHIME Collaboration

The International Pulsar Timing Array

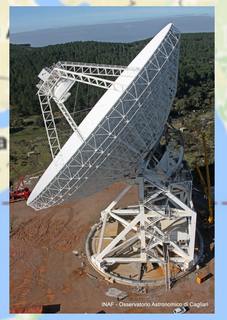
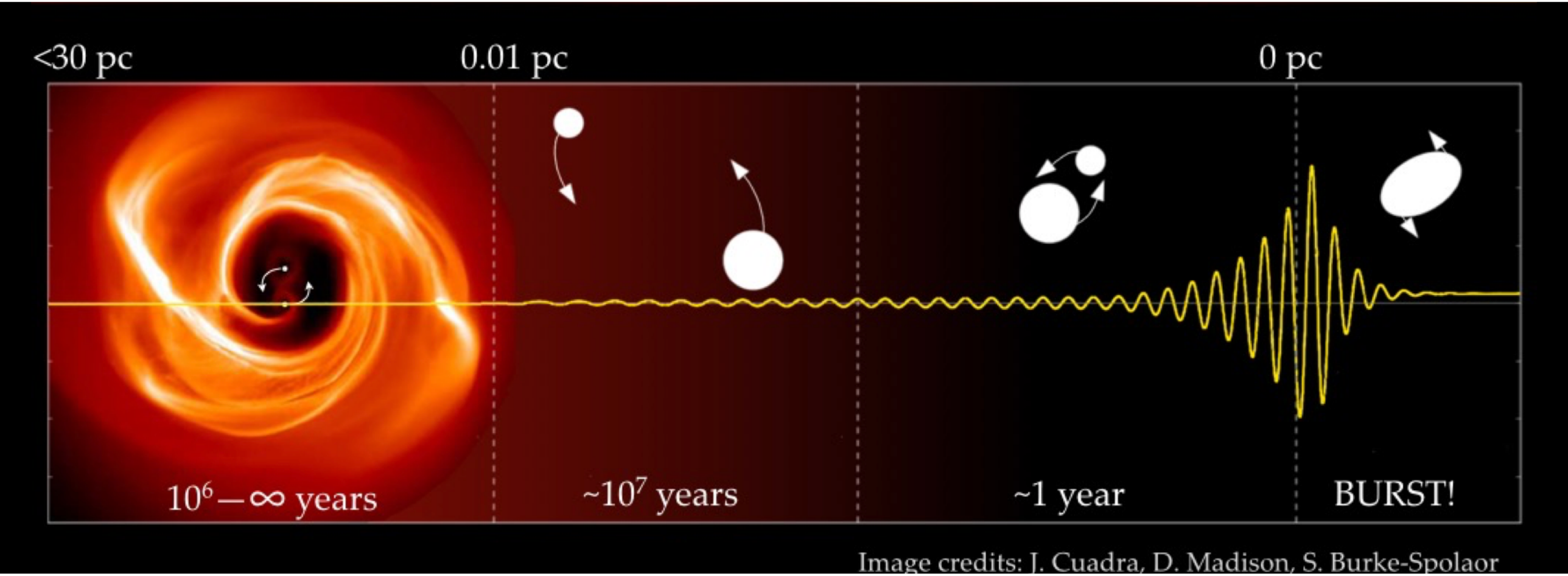


Image credits: NRAO/AUI, NAIC, EPTA, ATNF/CSIRO, Google maps

Supermassive Black Hole Binaries



Supermassive Black Hole Binaries

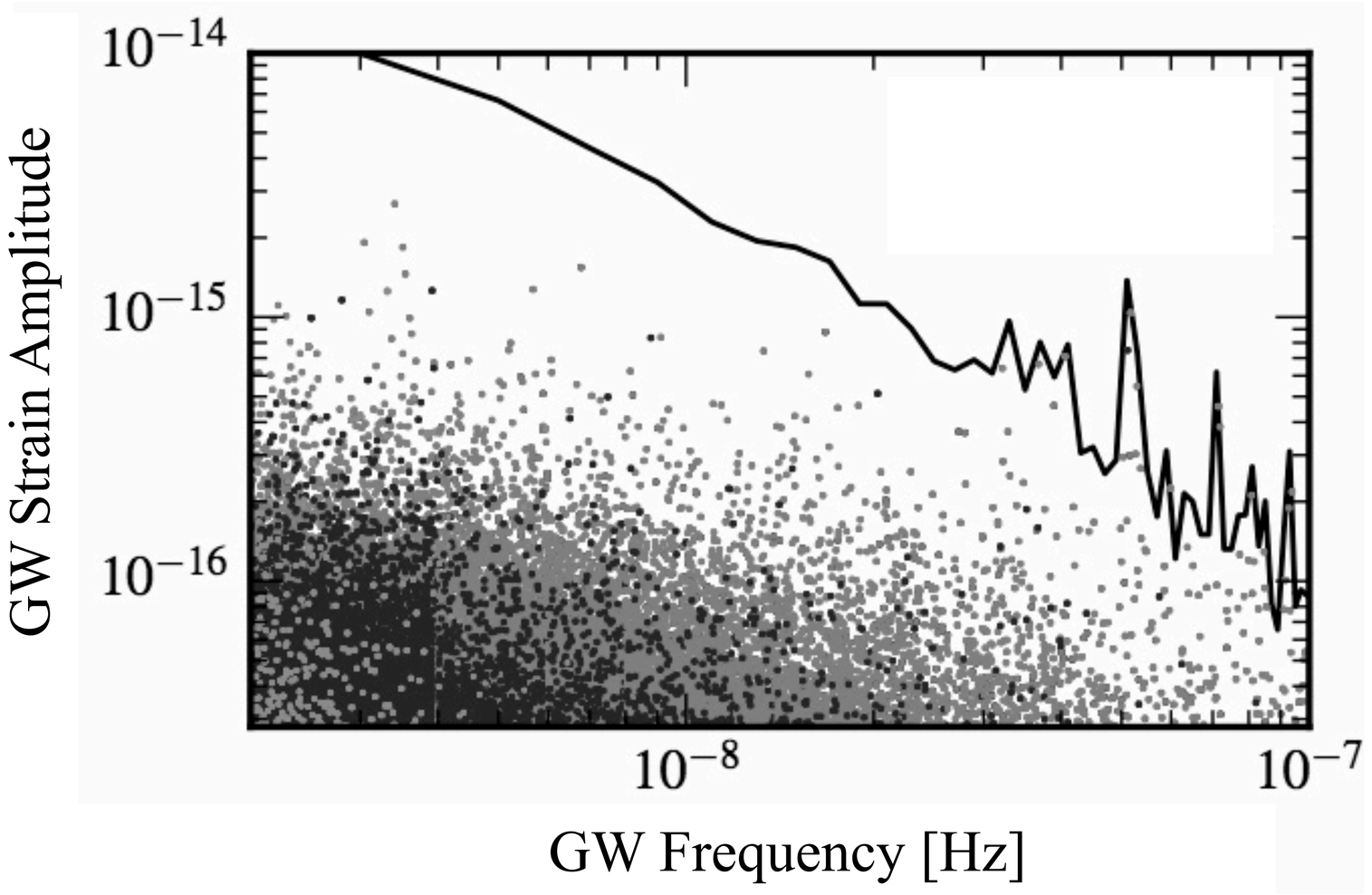


Figure credit: J. Simon

Stochastic GW Background

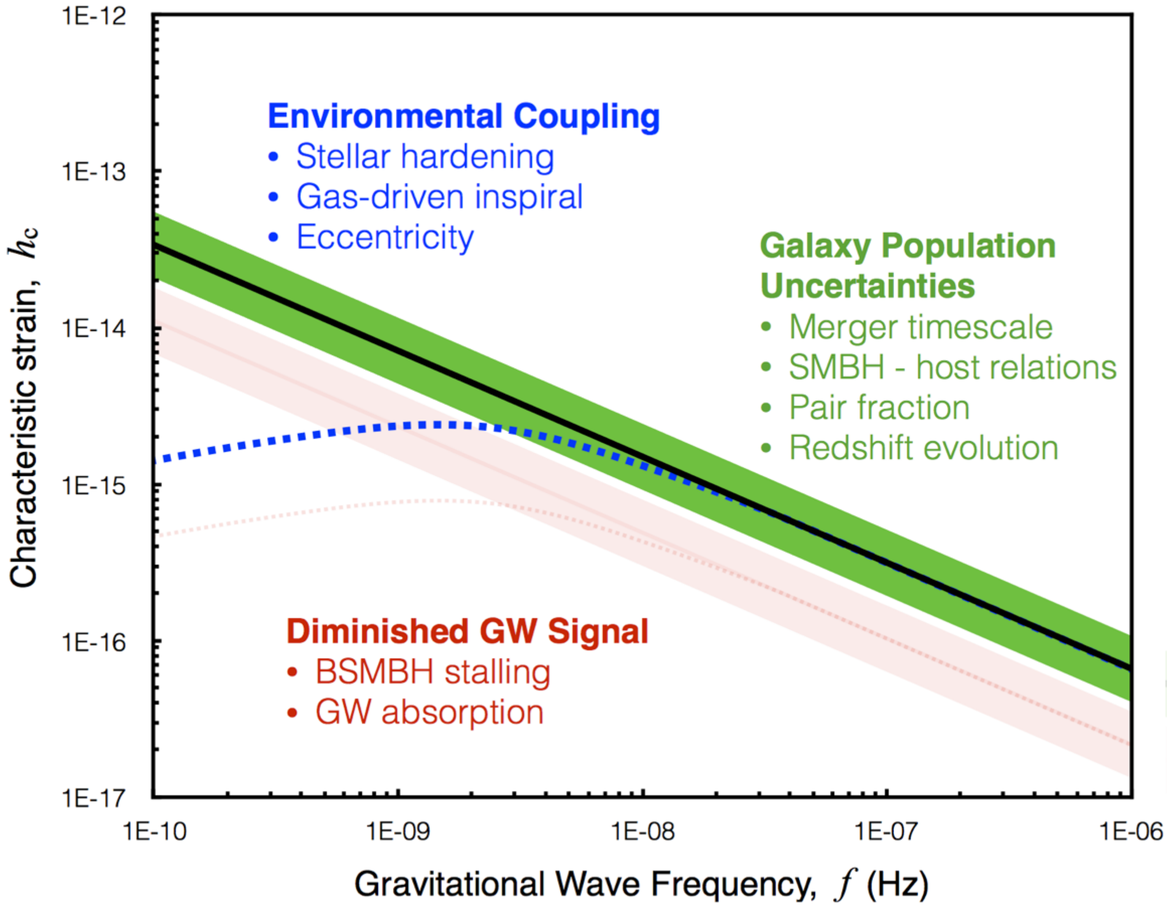


Image credit: S. Burke Spolaor 2015

Assuming circular binaries evolving only due to GW emission,

$$h_c(f) = A_{\rm gw} \left(\frac{f}{f_{1\,\rm yr}} \right)^{-2/3} .$$

If binaries evolve due to GW emission and environmental coupling, there may be a turnover in the spectrum at low frequencies.

11-year Upper Limit on the Stochastic Background

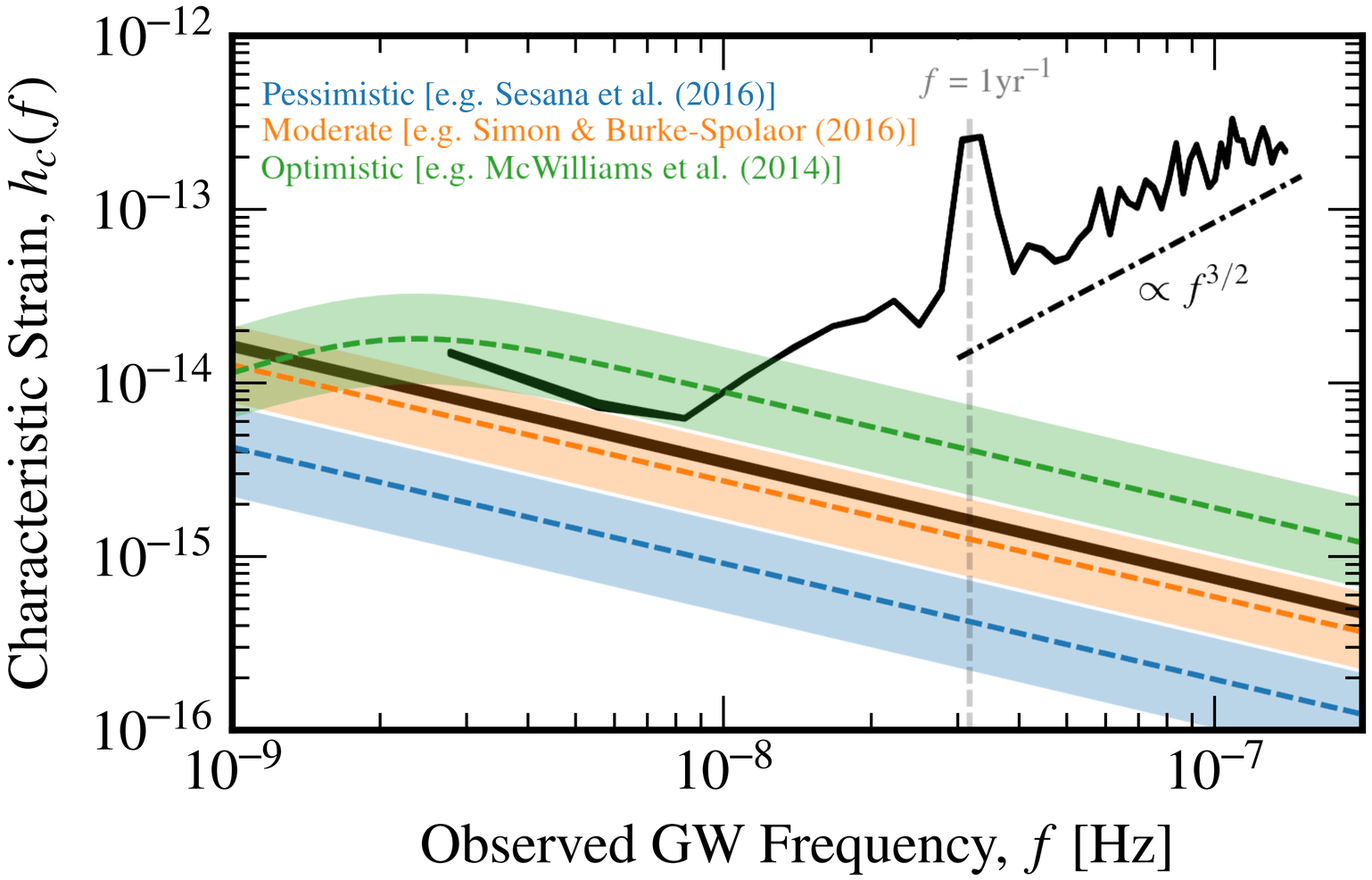


Figure credit: Z. Arzoumanian et al. (2018)

Time to Detection

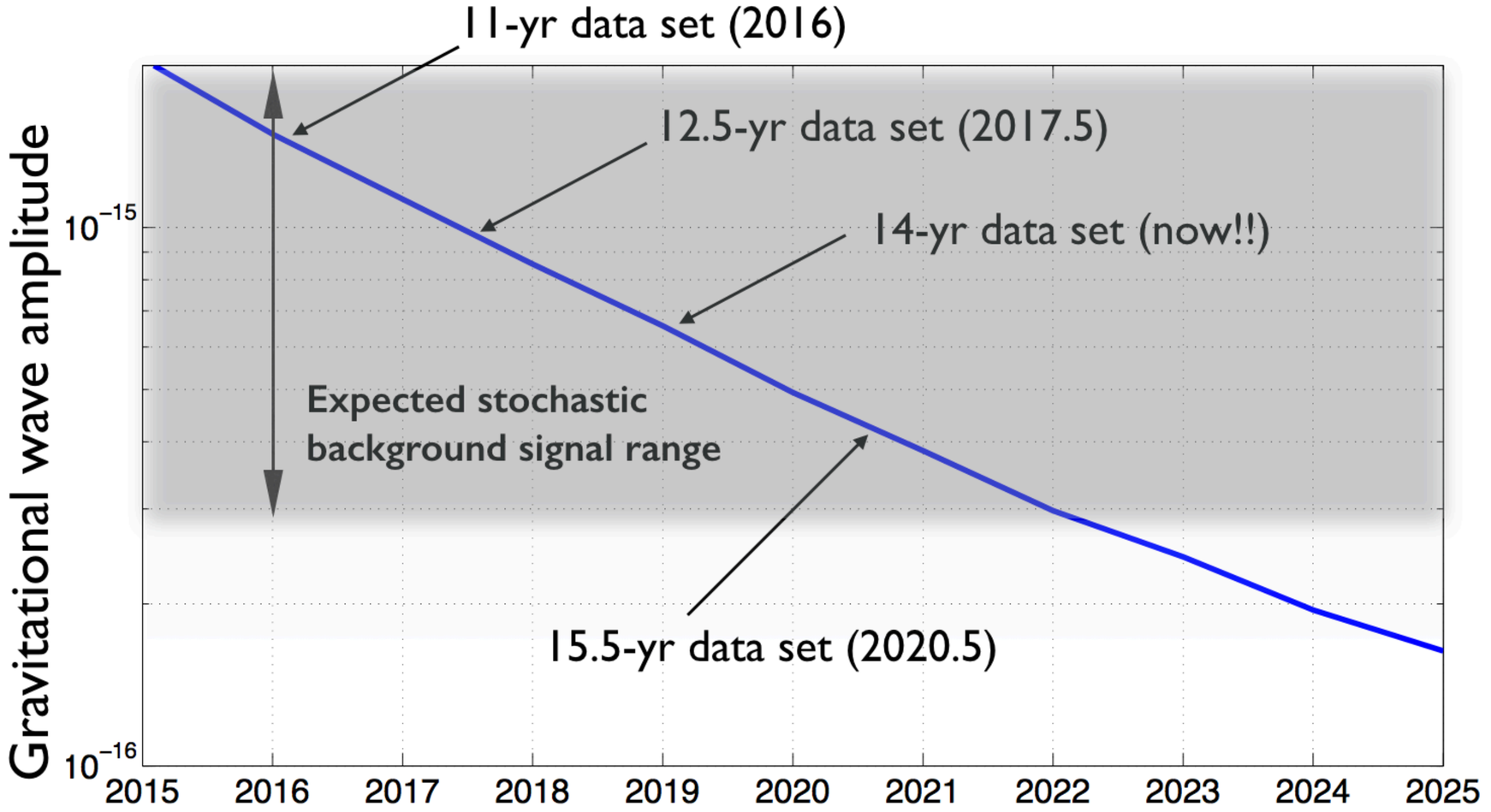
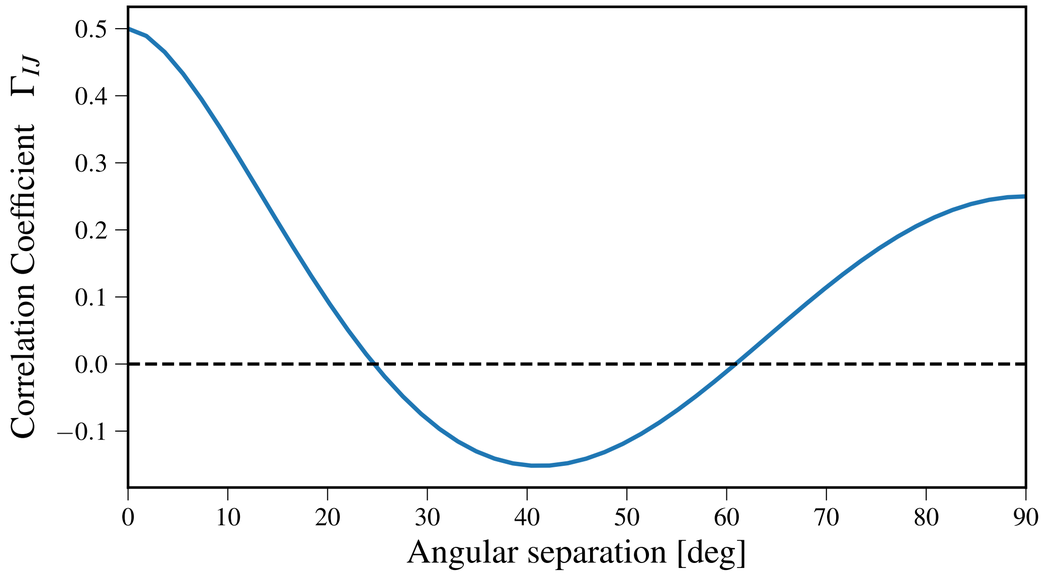


Figure credit: X. Siemens

11-year Data Set Cross-Correlations

The optimal statistic $\hat{A}^2_{gw}$ can be found by fitting the correlated power to the cross-correlation coefficients (Anholm et al. 2009; Demorest et al. 2013; Chamberlin et al. 2015):



Hellings & Downs (1983)

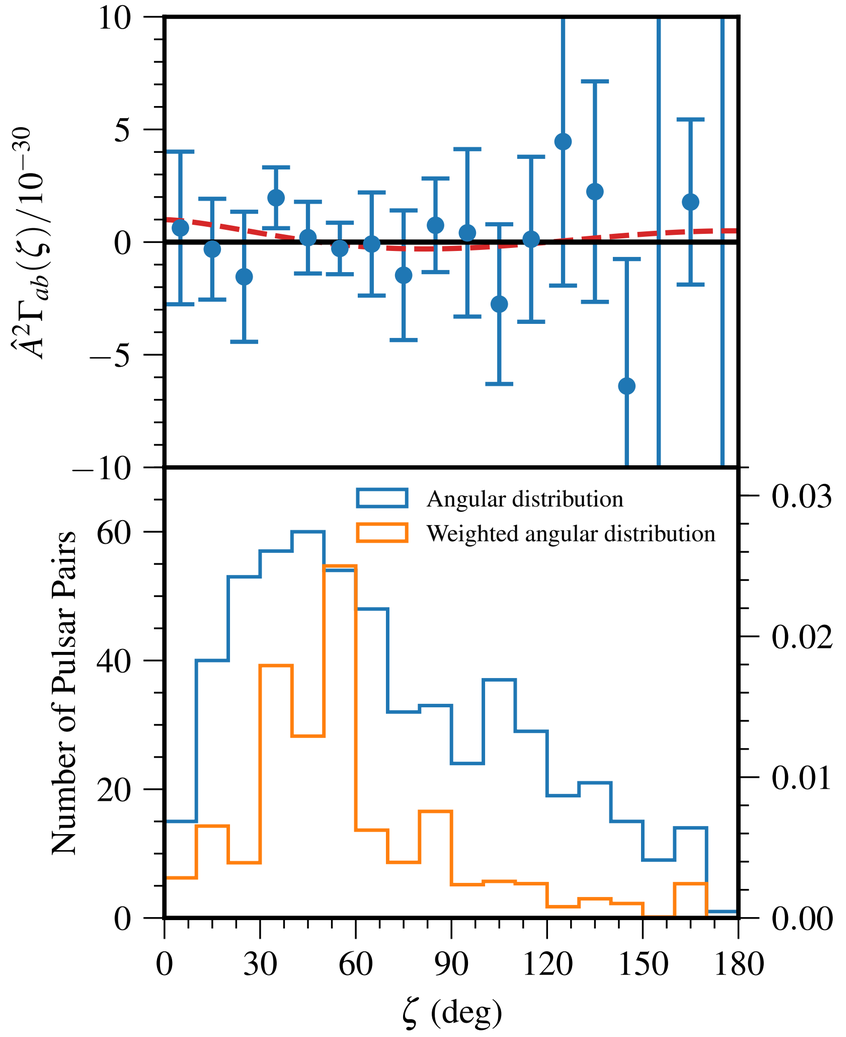
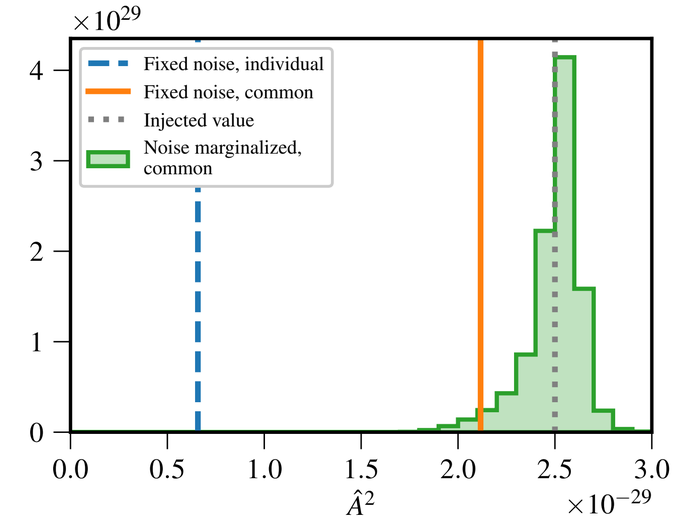
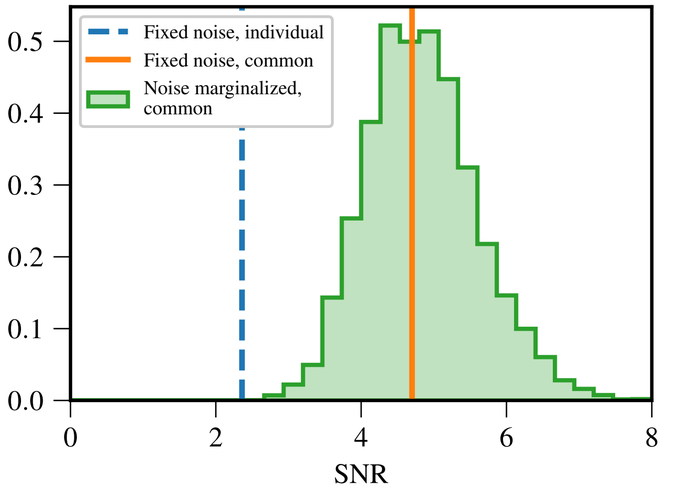


Figure credit: Z. Arzoumanian et al. (2018)

Noise Modeling and the Optimal Statistic





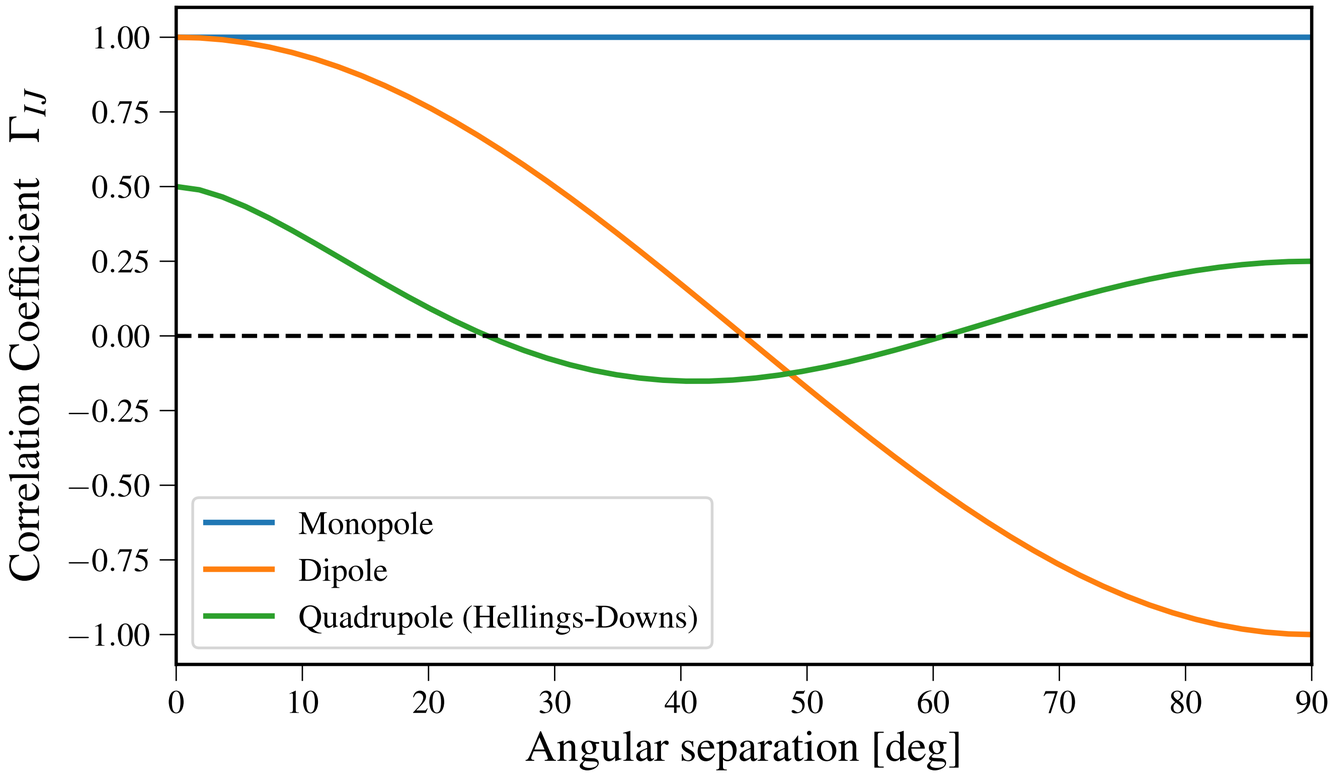
Vigeland, Islo, Taylor, Ellis (2018)

When the red noise parameters are held fixed, the optimal statistic underestimates the strength of the injected GWB.

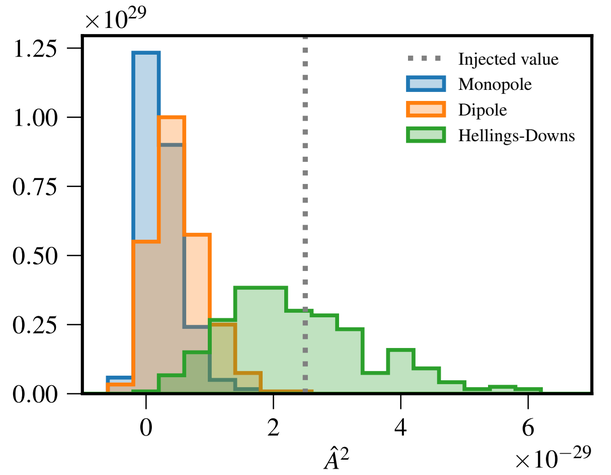
The noise-marginalized optimal statistic recovers injected values of the GWB more accurately.

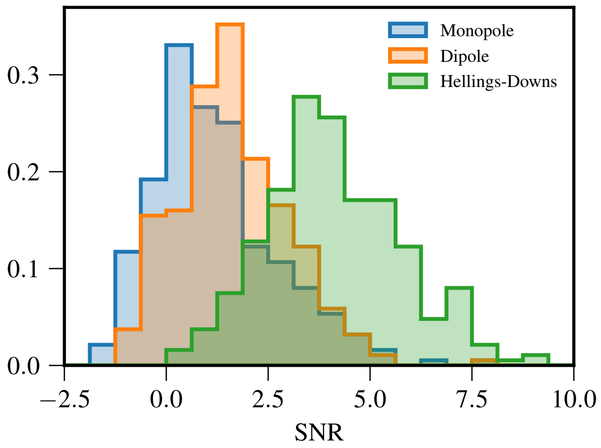
Assessing Spatial Correlations

We can test different spatial correlations by changing the correlation coefficients.



Injected GWB





Vigeland, Islo, Taylor, Ellis (2018)

Alternate Polarizations

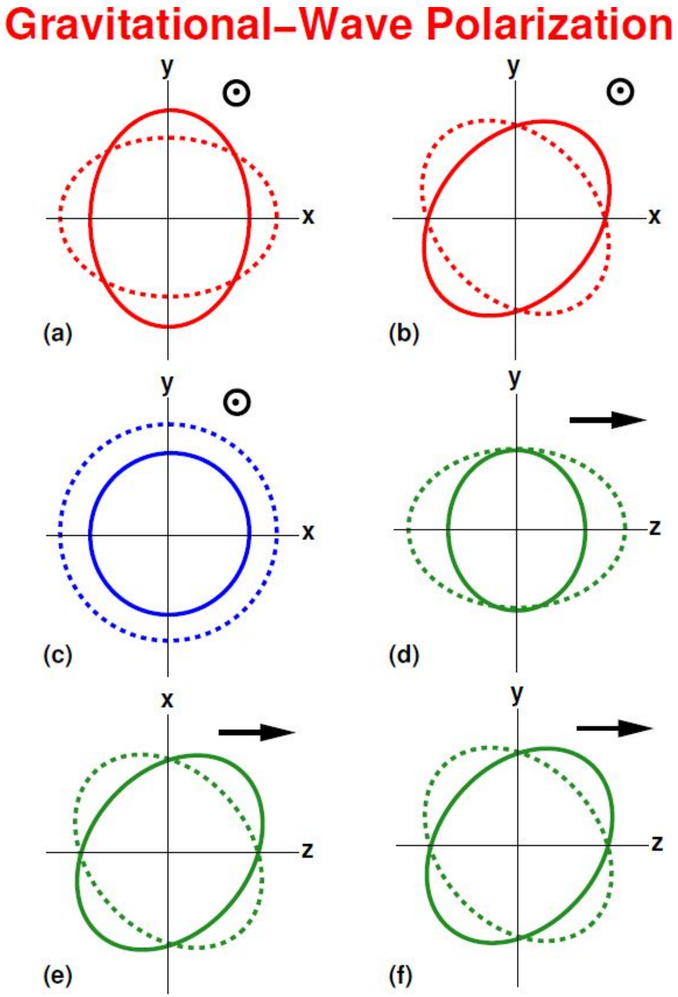
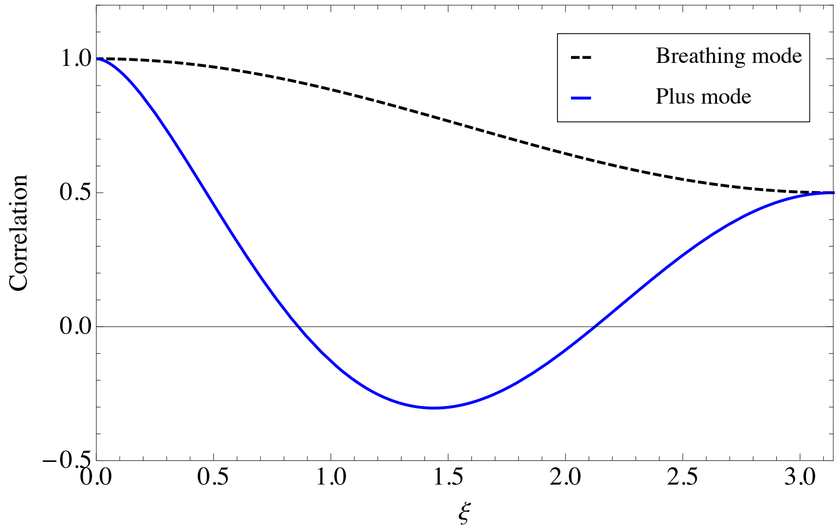


Figure credit: C. Will (2014)

In GR, there are only two GW polarizations. Alternate theories of gravity may allow other polarizations to exist.

PTAs can put constraints on the power in alternate polarizations (Chamberlin & Siemens 2012; Cornish, O'Beirne, Taylor, and Yunes 2018)



Chamberlin & Siemens (2012)

Individual Sources

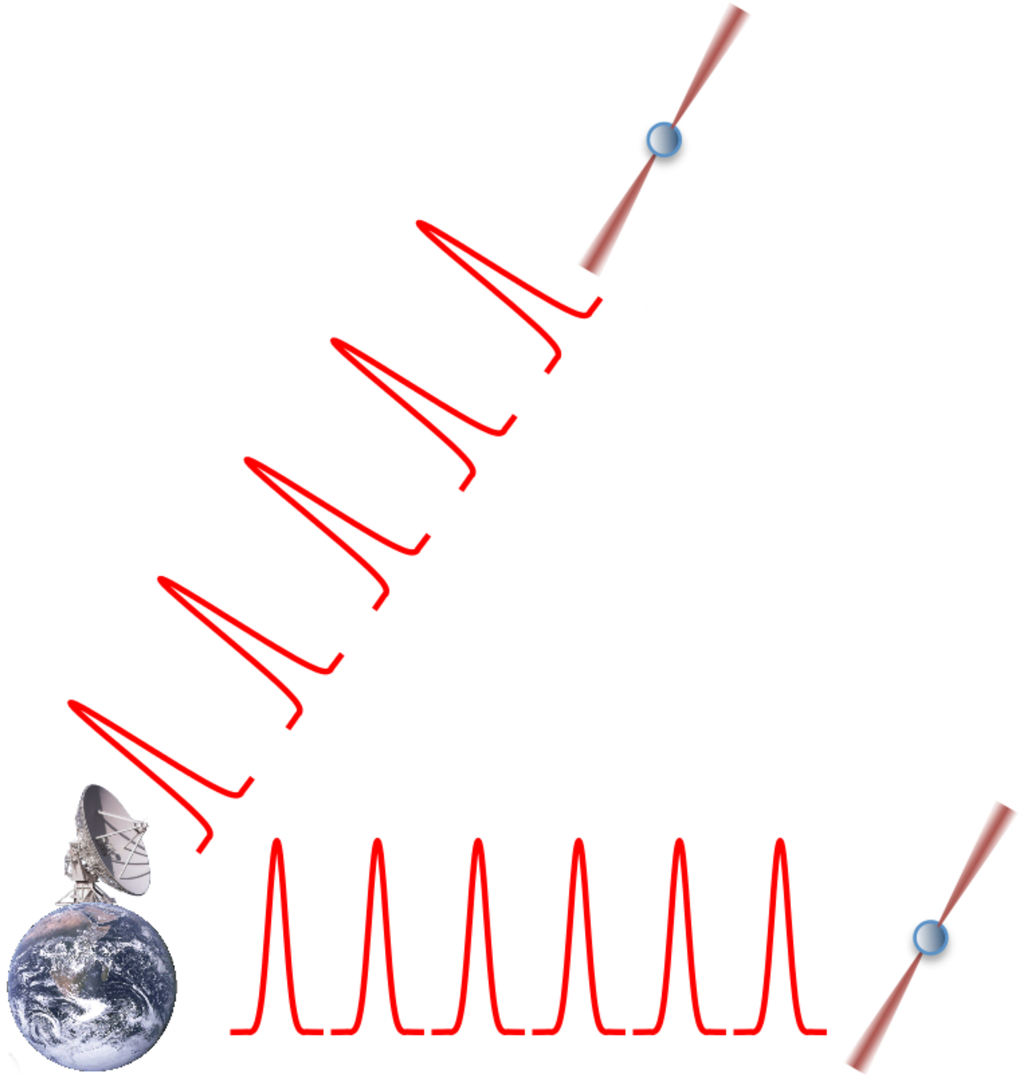
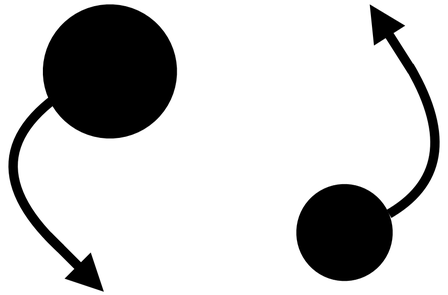


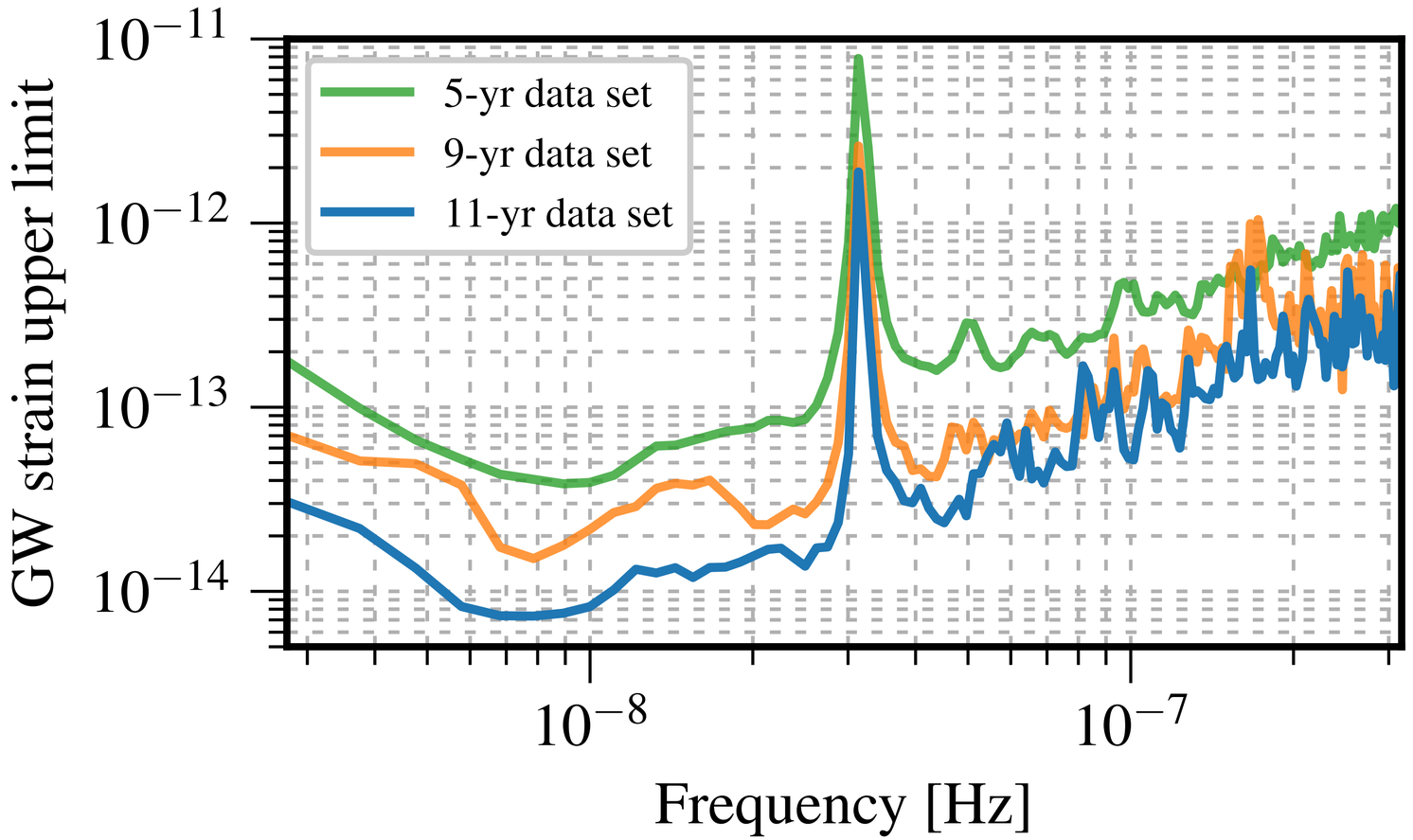
Figure credit: NANOGrav (modified)



$$s(t,\hat{\Omega}) = \sum_{+,\times} F^{A}(\hat{\Omega})\,[s_A(t_p) - s_A(t_e)]$$

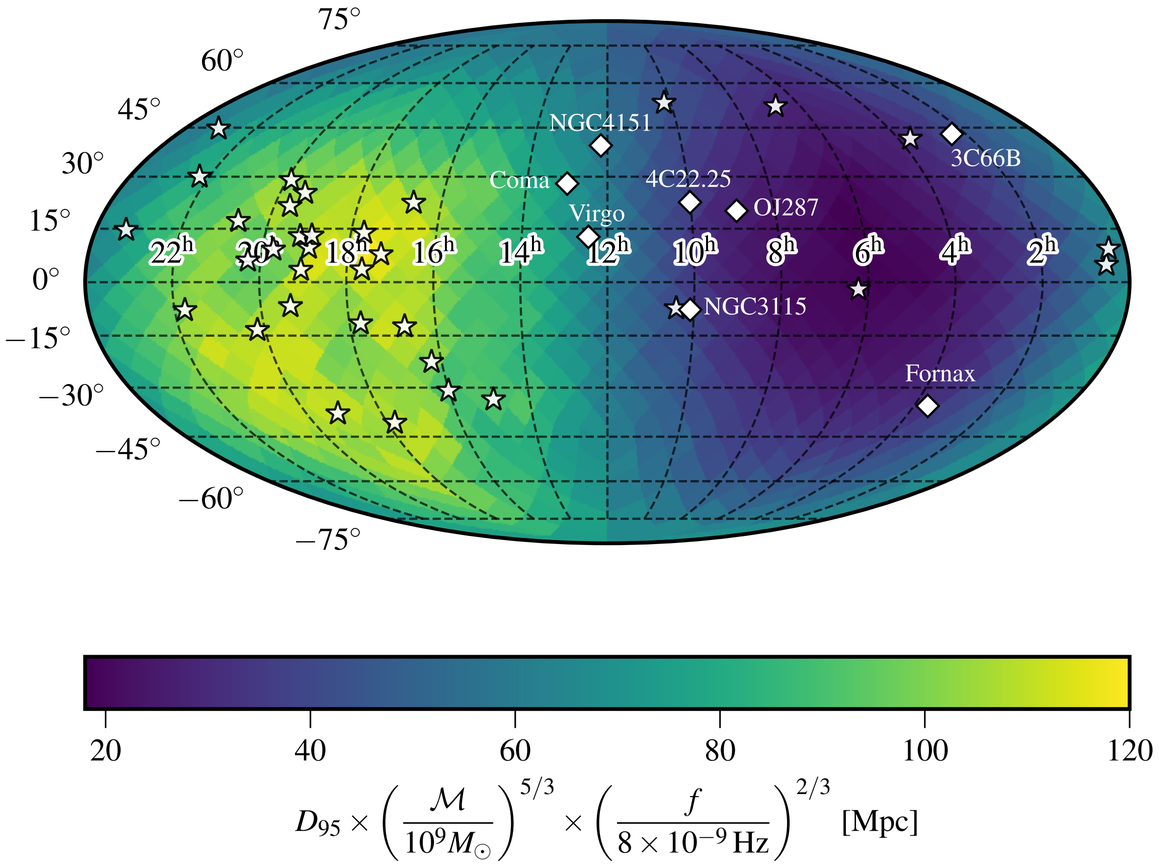
$$\omega(t) = \omega_0 \left[1 - \frac{256}{5}\mathcal{M}^{5/3}\omega_0^{8/3}(t - t_0)\right]^{-3/8}$$

Limits on Individual SMBHBs

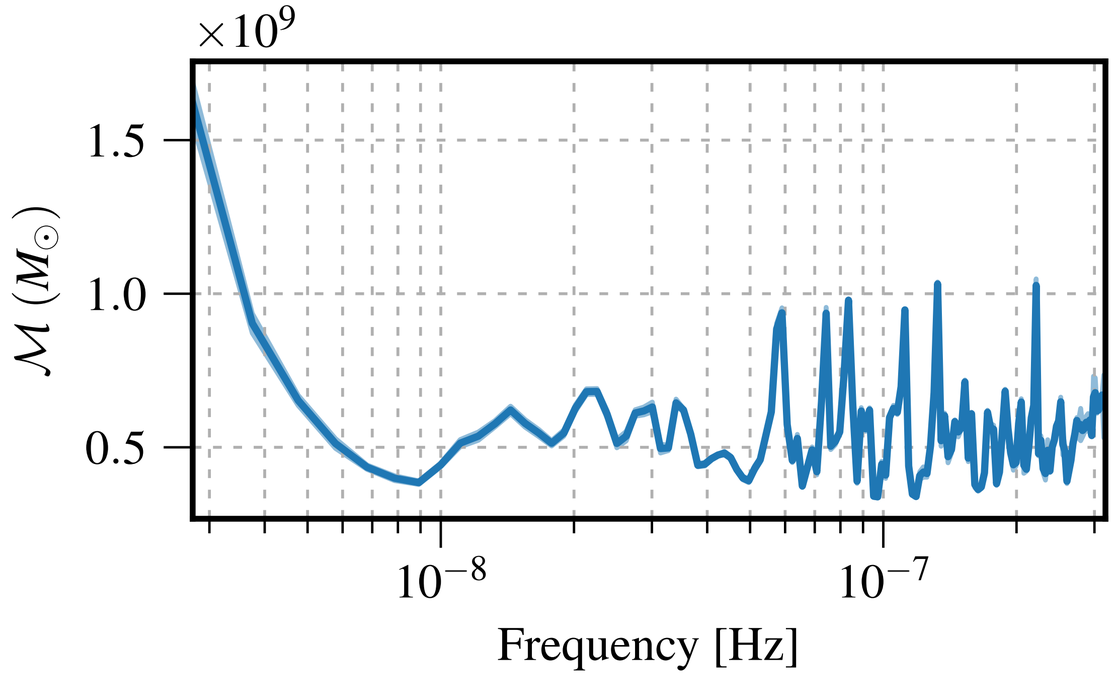


K. Aggarwal et al., submitted to ApJ, arXiv: 1812.11585.

Limits on Individual SMBHBs



There are no SMBHBs in the Virgo Cluster with $\mathcal{M} > 1.6 \times 10^9\ \mathrm{M}_\odot$.

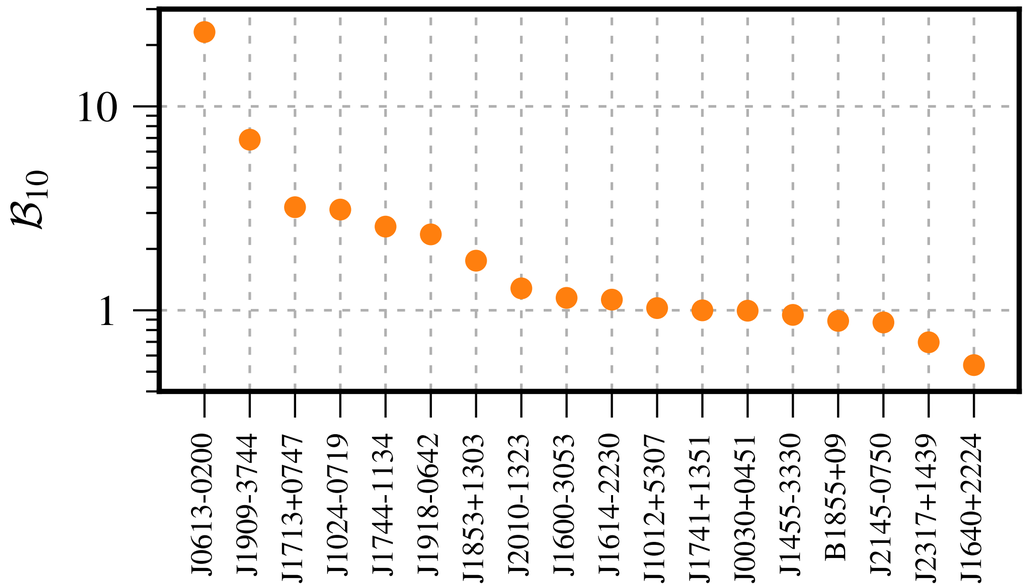


K. Aggarwal et al., submitted to ApJ, arXiv: 1812.11585.

Identifying Problem Pulsars

“Dropout” parameters determine whether the GW signal is included in the model for a particular pulsar’s residuals:

$$\delta \mathbf{t} = \mathrm{TM} + \mathrm{WN} + \mathrm{RN} + \kappa\ \mathrm{GW}$$



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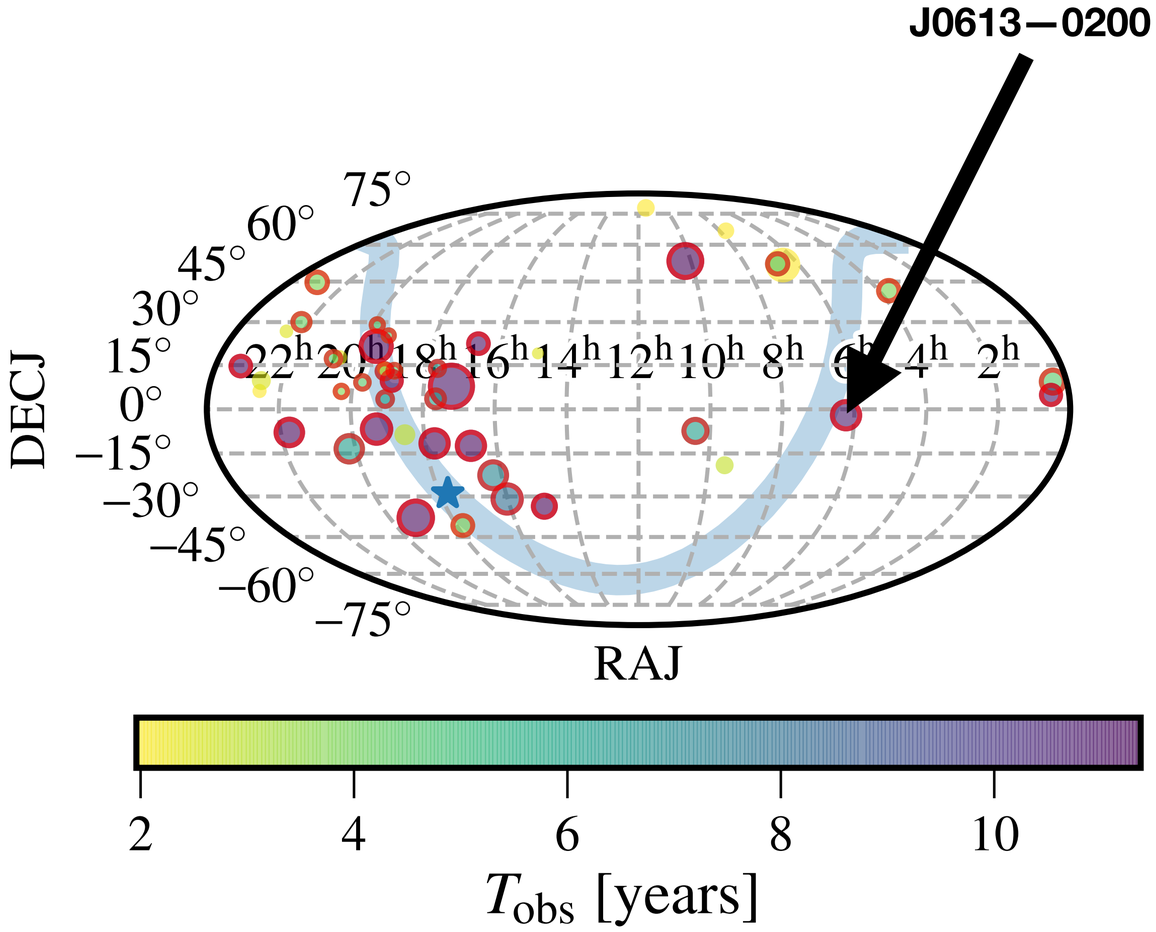
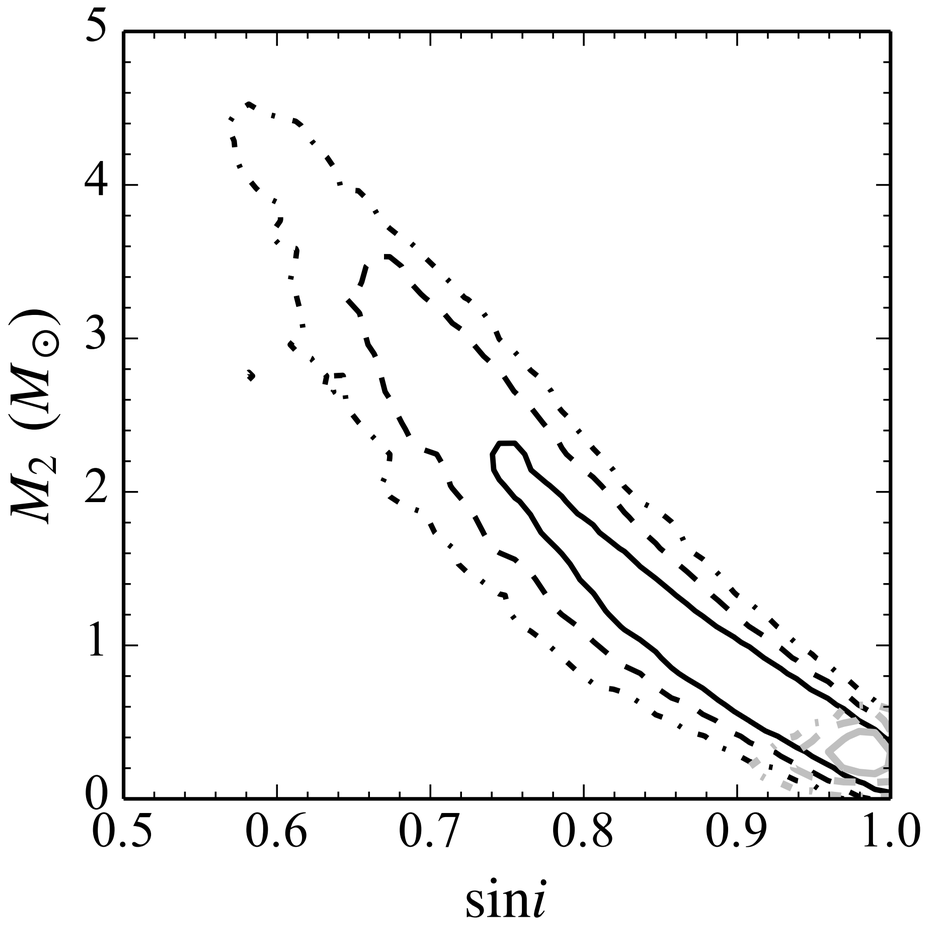


Z. Arzoumanian et al. (2018)

Bayesian Pulsar Timing

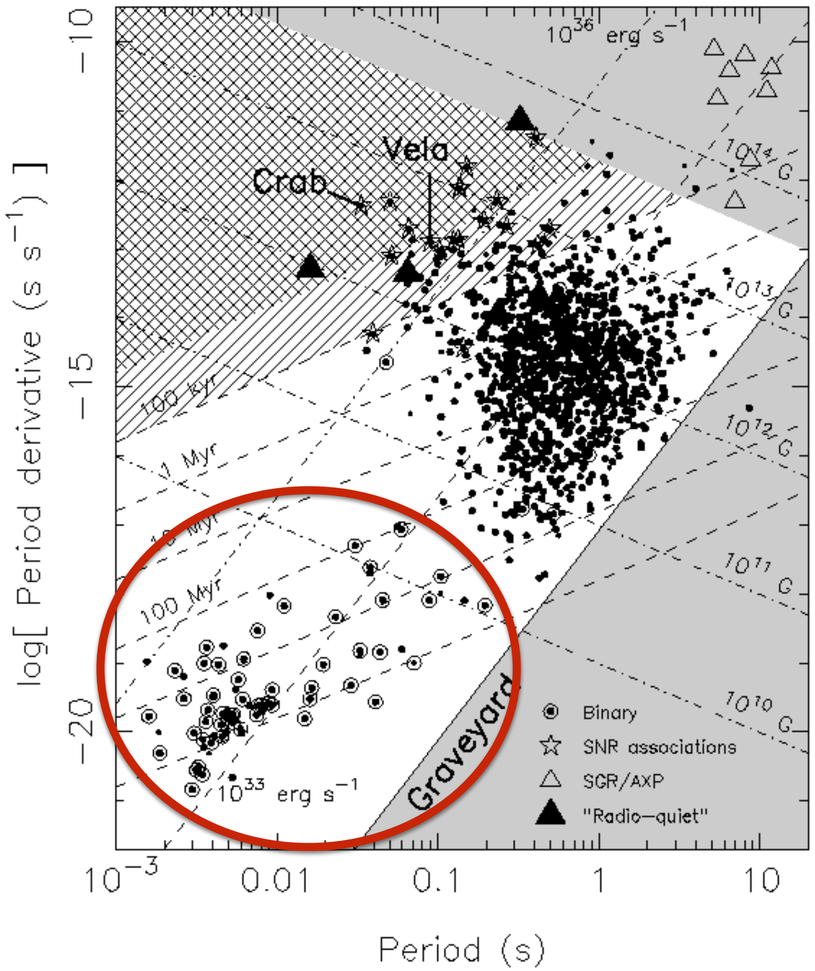


Vigeland and Vallisneri (2014)

Using Bayesian inference to fit observations to the timing model gives better parameter uncertainties, especially when parameters are highly degenerate (Lentati, Alexander, Hobson, et al. 2014; Vigeland & Vallisneri 2014).

Information from other types of observations (radio interferometry, optical photometry, etc.) can be incorporated as priors.

Millisecond Pulsar Formation



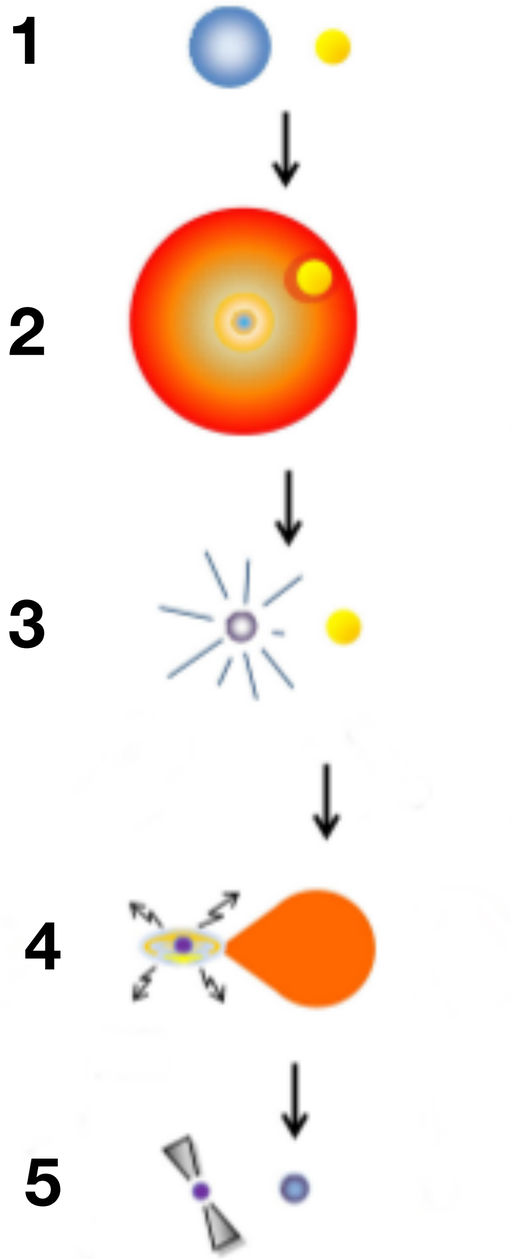
From the *Handbook of Pulsar Astronomy* by Lorimer and Kramer

Millisecond pulsars have small spin periods (1 - 30 ms), weaker magnetic fields.

Most are found in binaries with a stellar remnant companion.

Thought to have been spun up via accretion in an X-ray binary.

How to Make a MSP



1. Start with a **binary system** with two main-sequence stars. One must be fairly massive (>10 solar masses).
2. The more massive star runs out of fuel and becomes a **red giant**.
3. The more massive star explodes in a **supernova**, leaving behind a **pulsar**.
4. The less massive star runs out of fuel and becomes a **red giant**. It expands, and matter from the red giant is pulled onto the pulsar. This is an **X-ray binary**.
5. The less massive star runs out of matter to give to the pulsar and becomes a **white dwarf** or **neutron star**. The pulsar has been spun up to a **millisecond pulsar**.

Figure modified from Tauris (2011).

MSP Formation Scenarios: LMXB

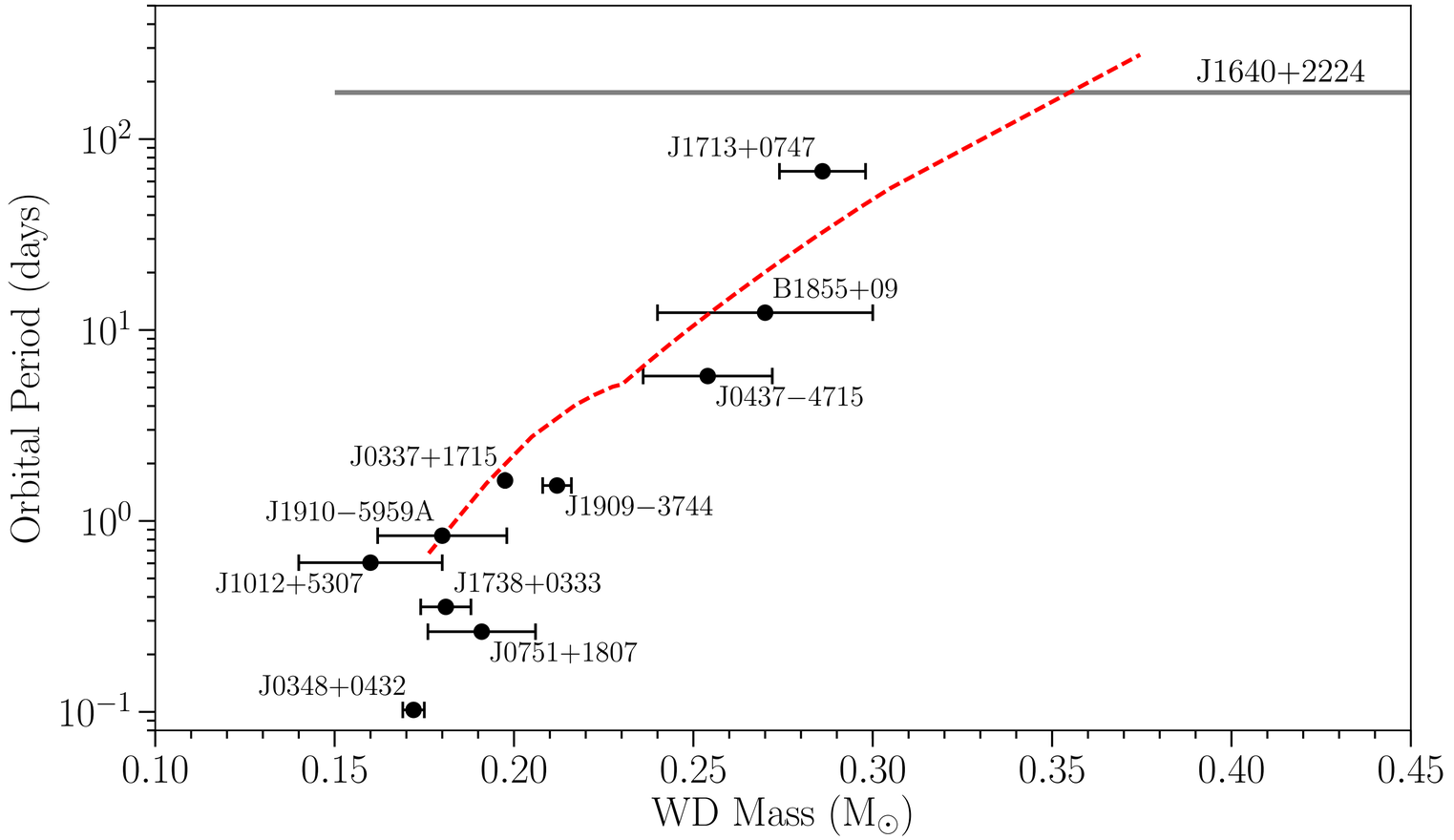
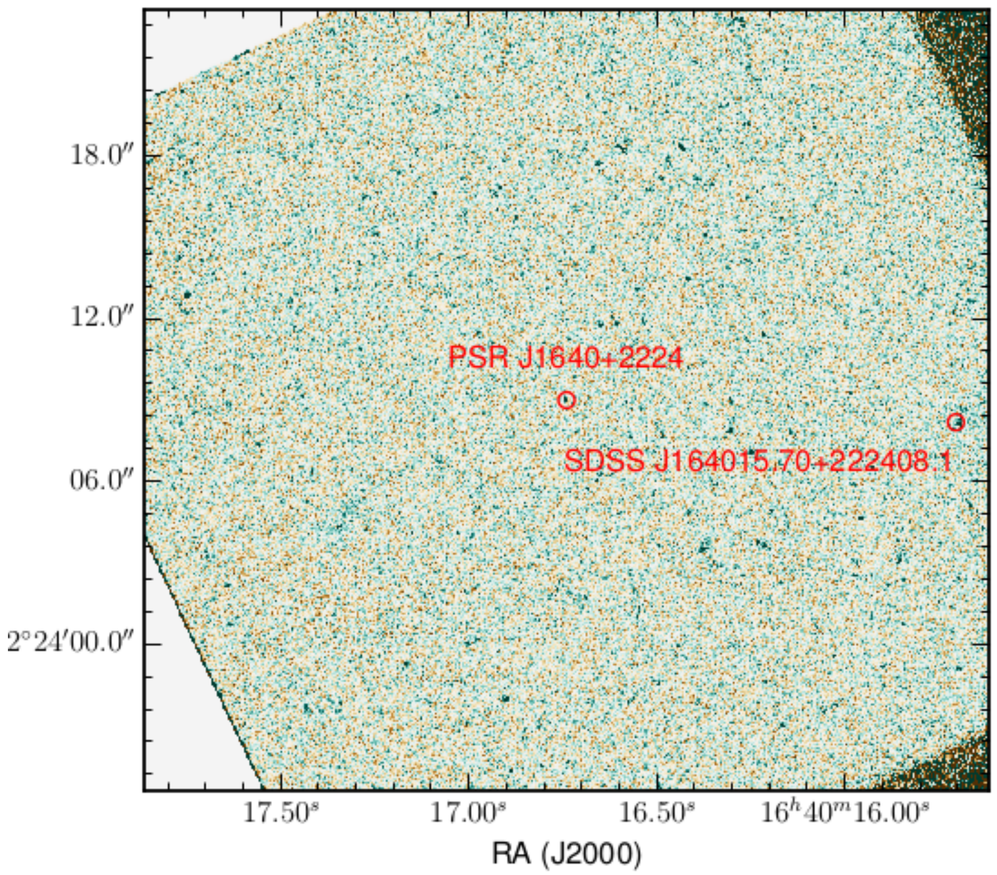
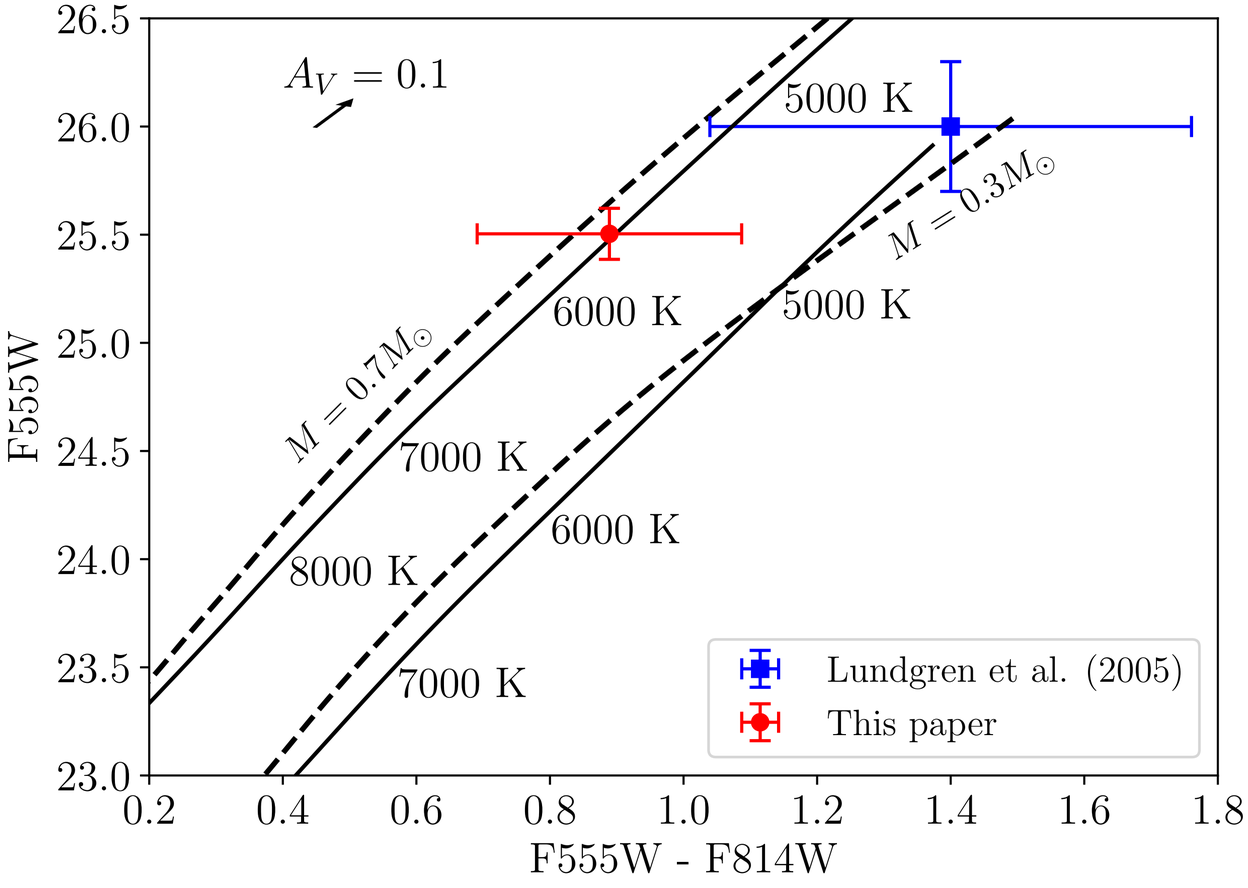


Figure modified from Swiggum et al. 2017. Porb-Mwd relation from Istrate et al. 2016.

White Dwarf Cooling Curves





Deller, Vigeland, Kaplan, et al. (2016)
Vigeland, Deller, Kaplan, et al. (2018)

Gravitational Wave Spectrum

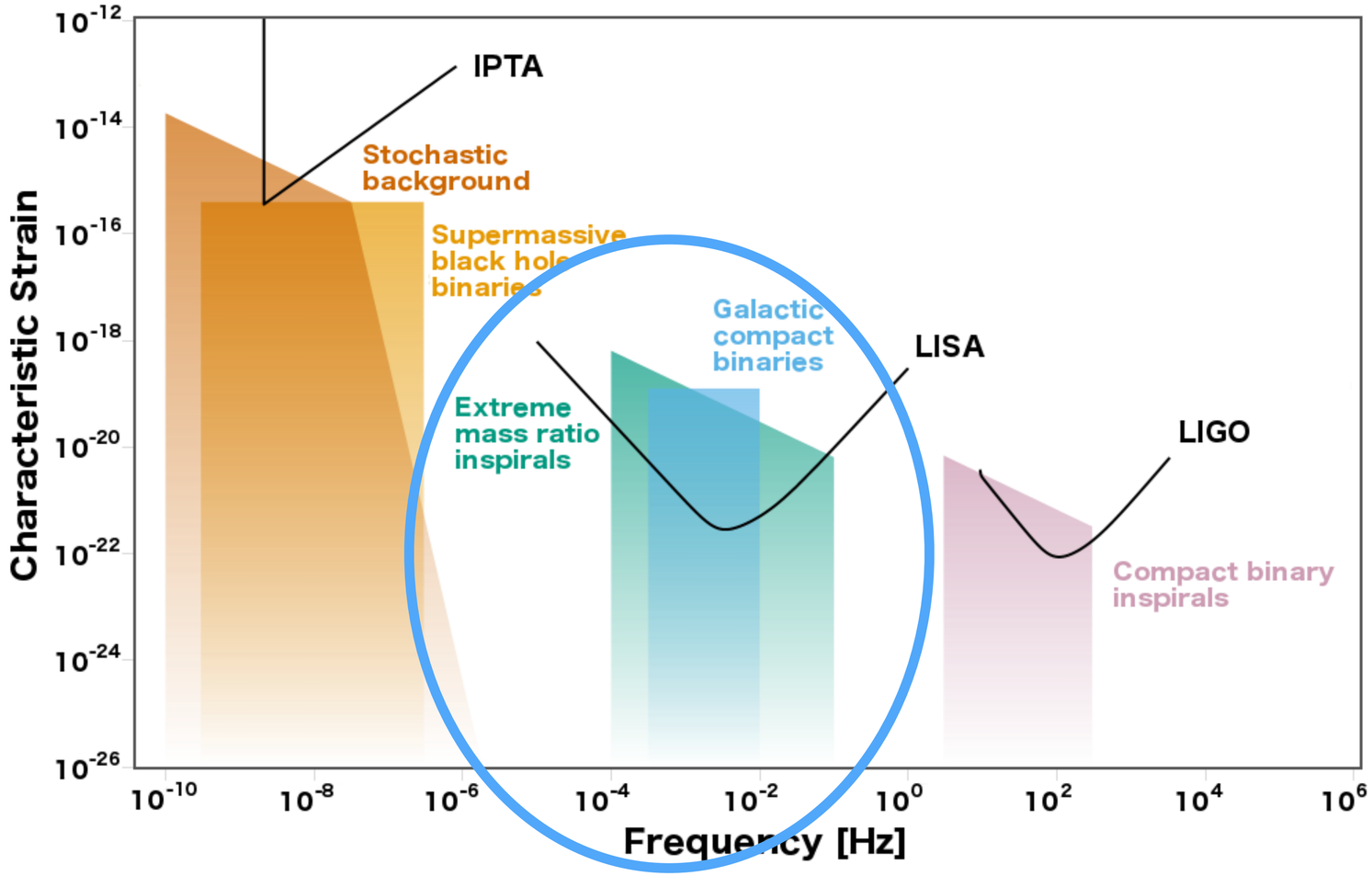


Figure credit: Moore, Cole, Berry 2014 (modified).

LISA

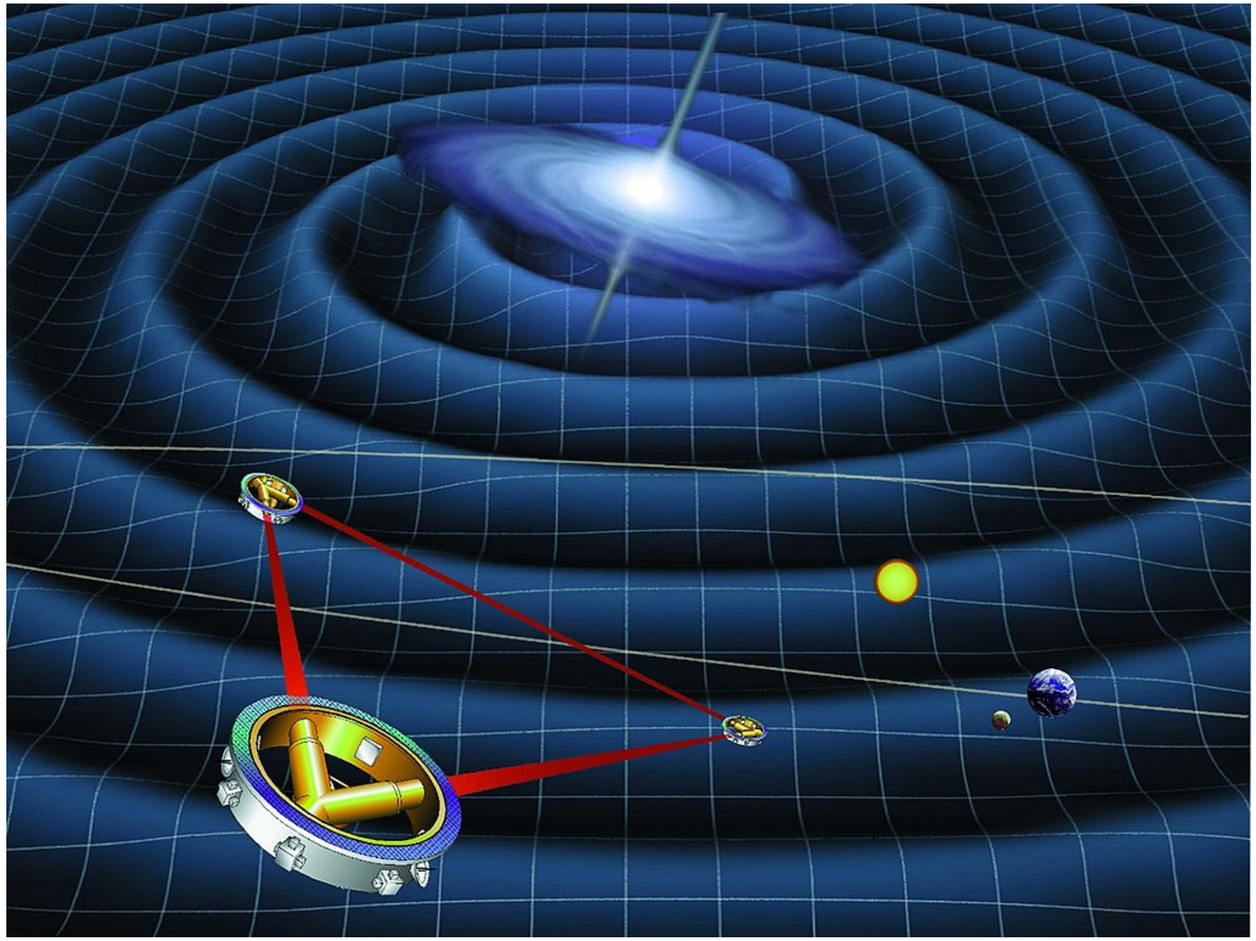
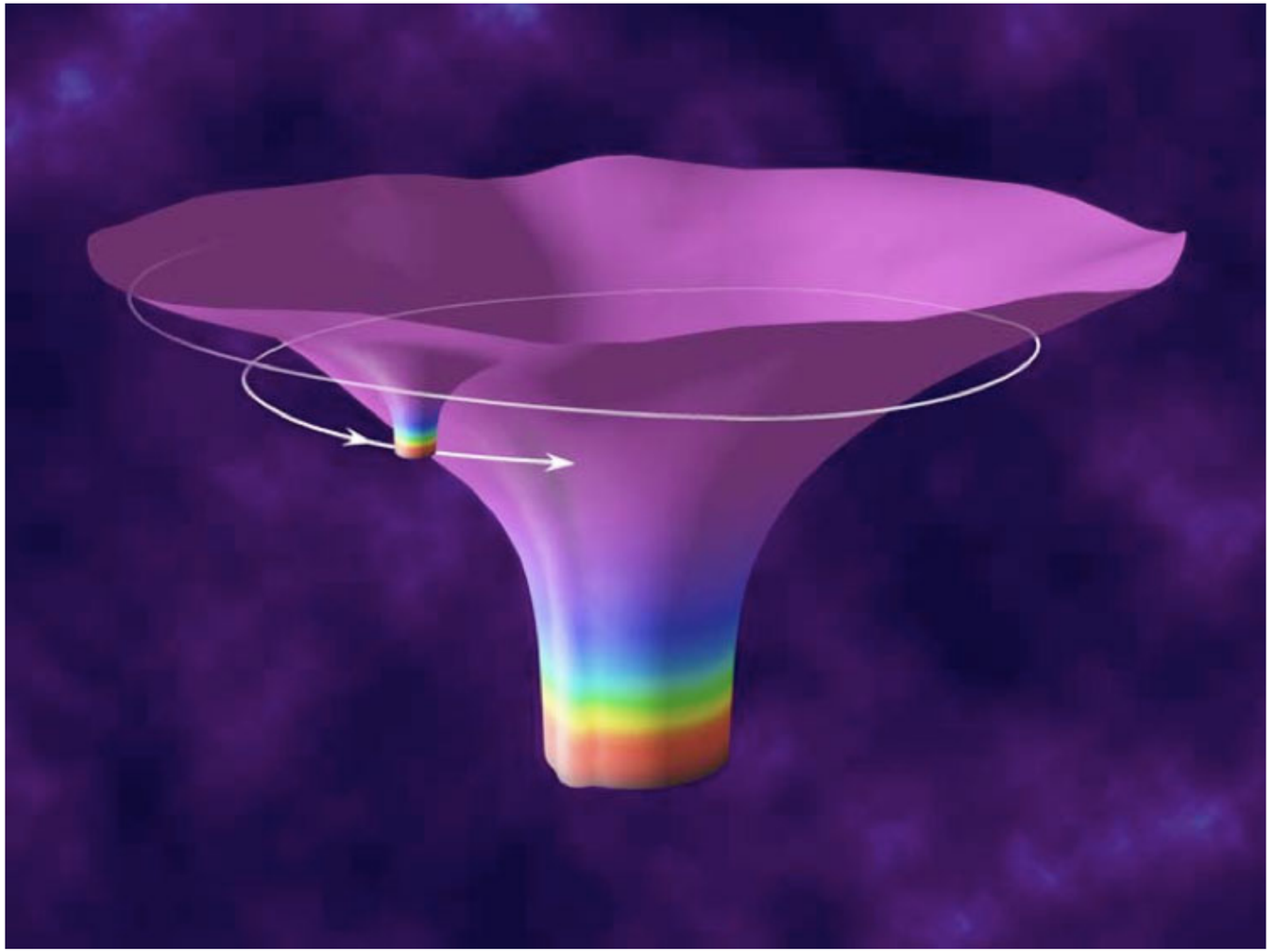


Image credit: NASA

The Laser Interferometer Space Antenna (LISA) consists of three spacecraft in a triangular formation separated by 5 million km.

LISA is scheduled to launch in 2034.

Extreme Mass-Ratio Inspirals



Newtonian analog: geodesy

$$\Phi = -\frac{GM}{r} + \frac{GM}{r}\sum_{lm}\left(\frac{R}{r}\right)^{l+1} B_{lm} Y_{lm}(\theta, \phi)$$

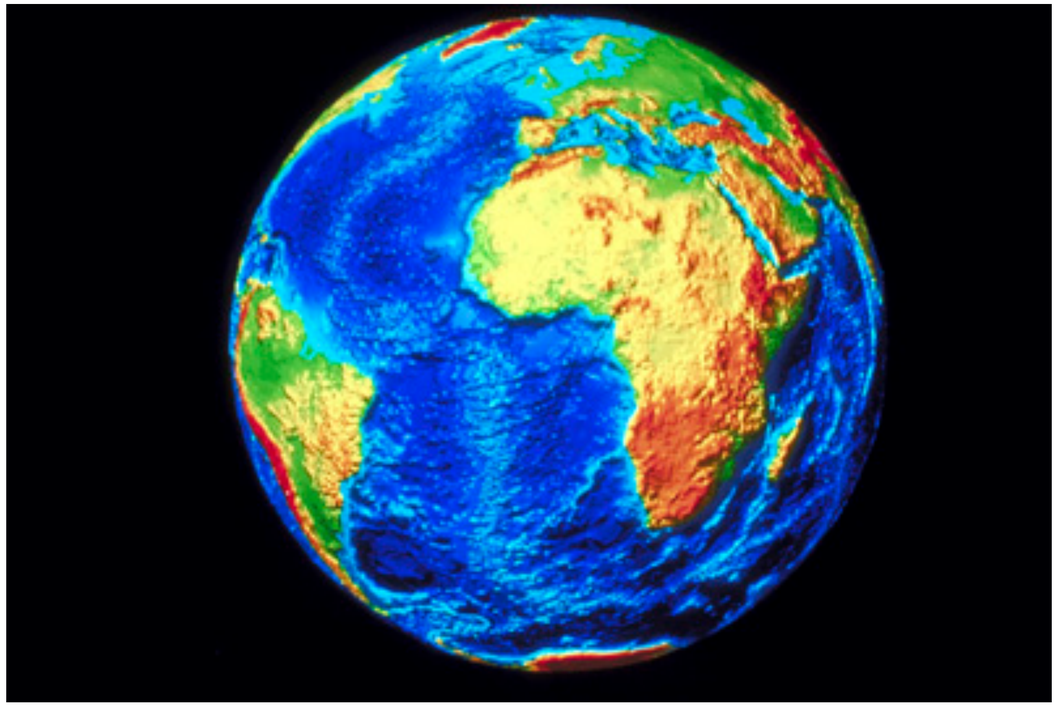


Image credit: National Geospatial-Intelligence Agency

Bumpy Black Holes

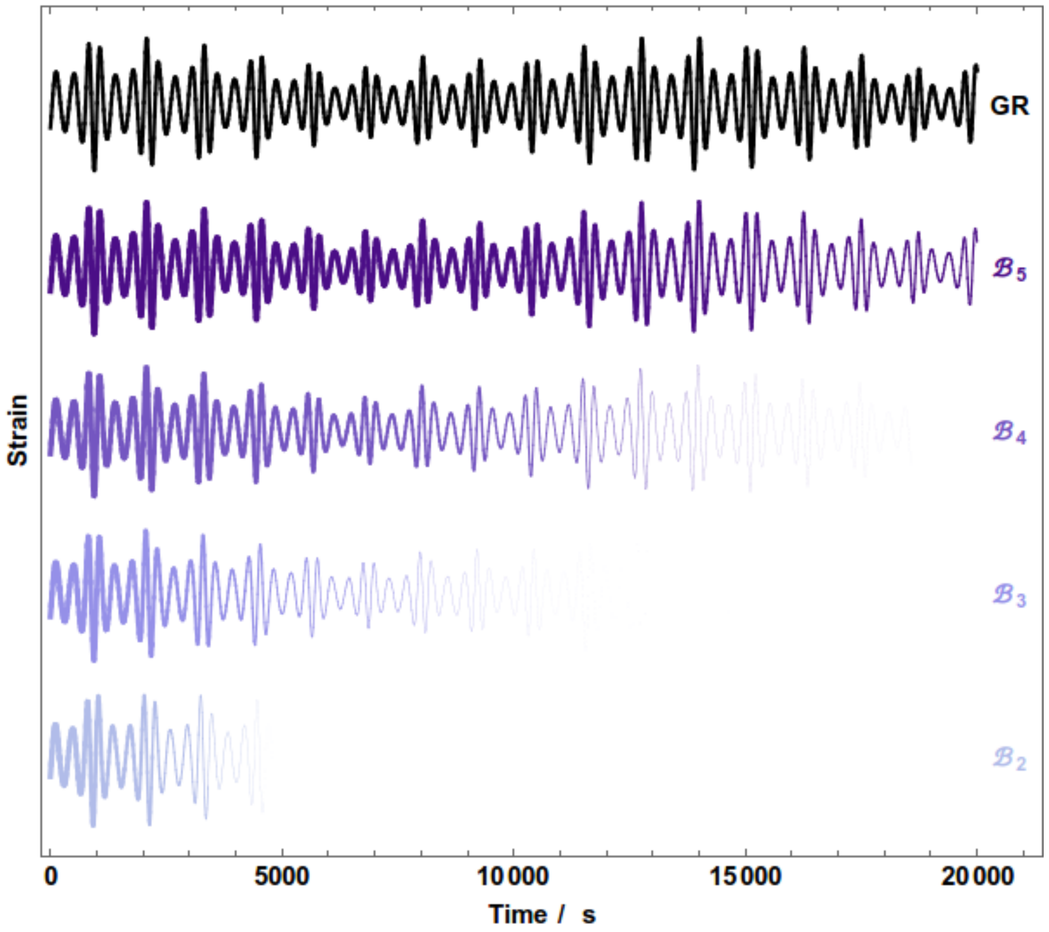
In GR, spacetime can be described in terms of mass moments and spin moments: $g_{\mu\nu} \to \{M_\ell, S_\ell\}$.

Kerr black holes are completely described by just two parameters ("no hair" theorem): $M_\ell + i\, S_\ell = M(ia)^\ell$.

For bumpy black holes, we relax this: $M_\ell + i\, S_\ell = M(ia)^\ell + \delta M_\ell + i\, \delta S_\ell$.

(Collins & Hughes 2004; Vigeland & Hughes 2010; Vigeland 2010; Vigeland, Yunes, and Stein 2011)

Bumpy Black Holes



Moore, Chua, Gair (2017)

Observations of GWs from EMRIs can be used to test the no hair theorem, since any “bumpiness” will alter the waveforms (Moore, Chua, Gair 2017; Chua, Hee, Handley, et al. 2018).

Conclusions

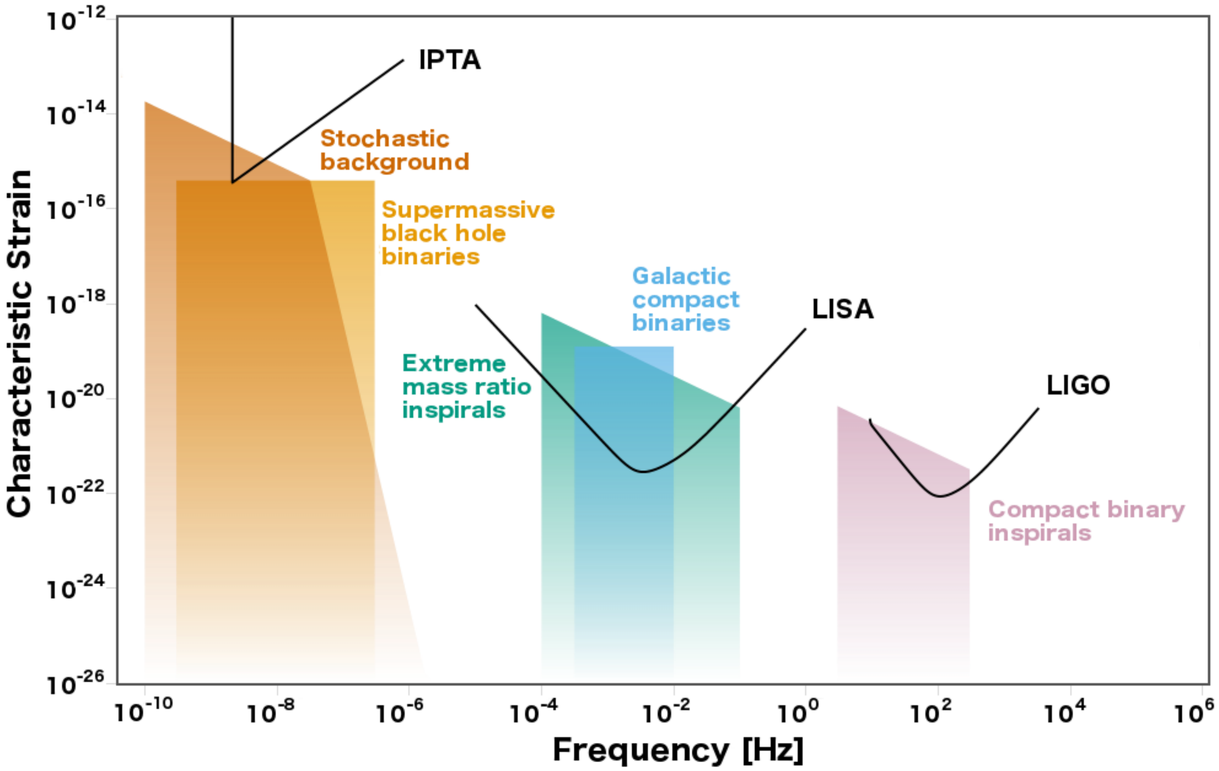


Figure credit: Moore, Cole, Berry 2014 (modified).

- Pulsar timing arrays are sensitive to nanohertz GWs, and are expected to detect GWs from SMBHBs within the next several years.
- Better measurements of the pulsars themselves improves the sensitivity of PTAs, and can be used to study binary evolution.
- LISA is scheduled to launch in 2034, and will open up the millihertz part of the GW spectrum.