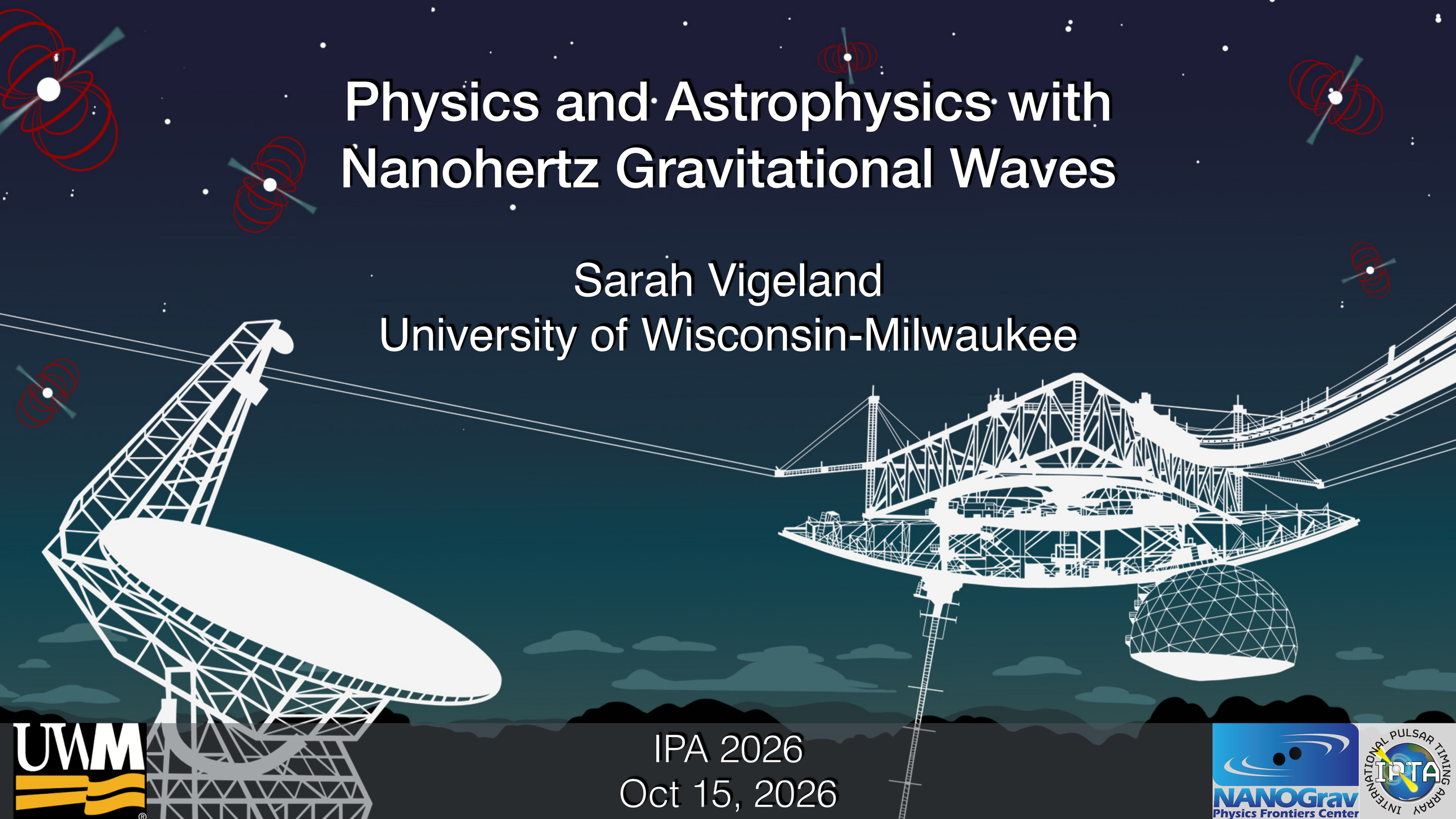
Physics and Astrophysics with Nanohertz Gravitational Waves

Sarah Vigeland
University of Wisconsin-Milwaukee



IPA 2026
Oct 15, 2026

Gravitational Wave Spectrum

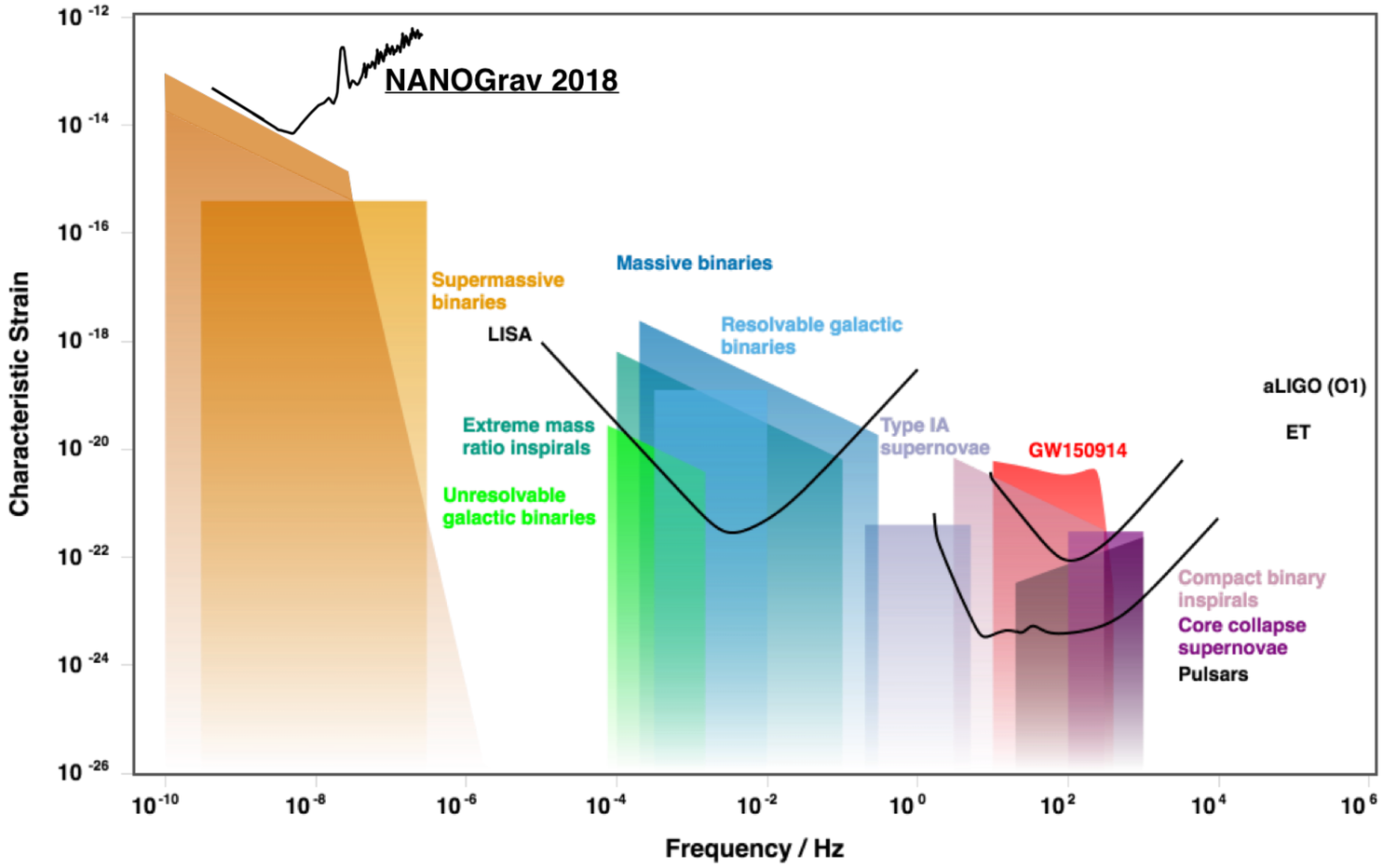
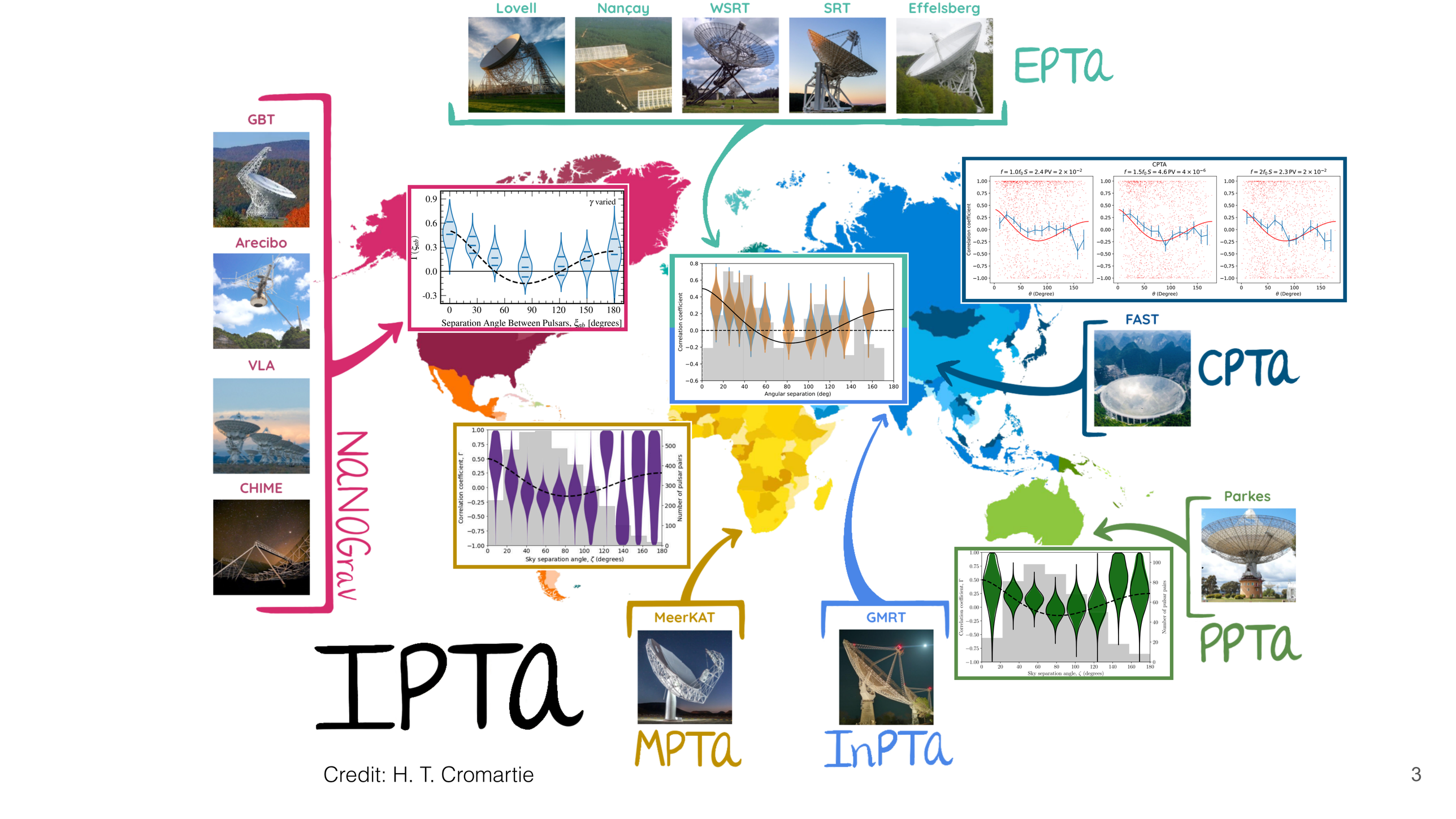


Figure credit: Moore, Cole, Berry (2014); modified by S. Taylor



Credit: H. T. Cromartie

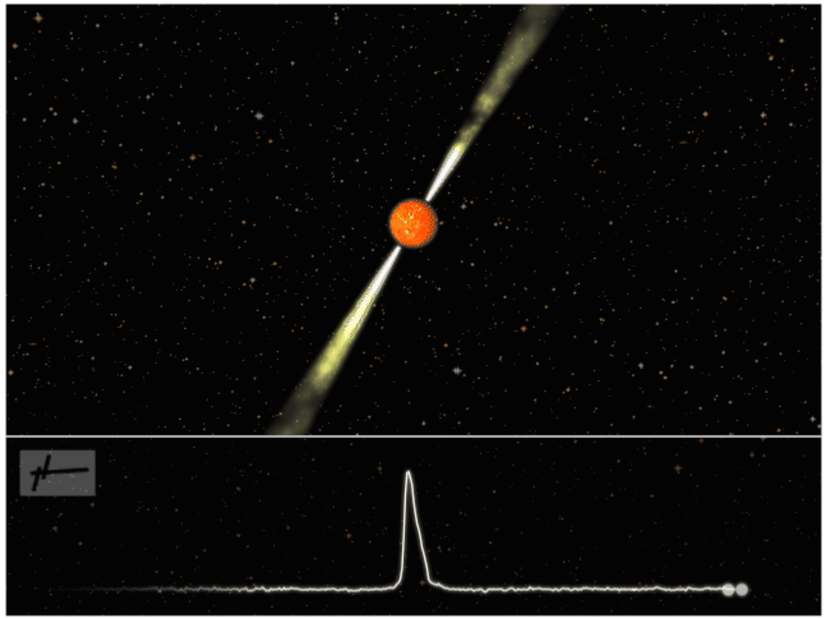


Credit: H. T. Cromartie

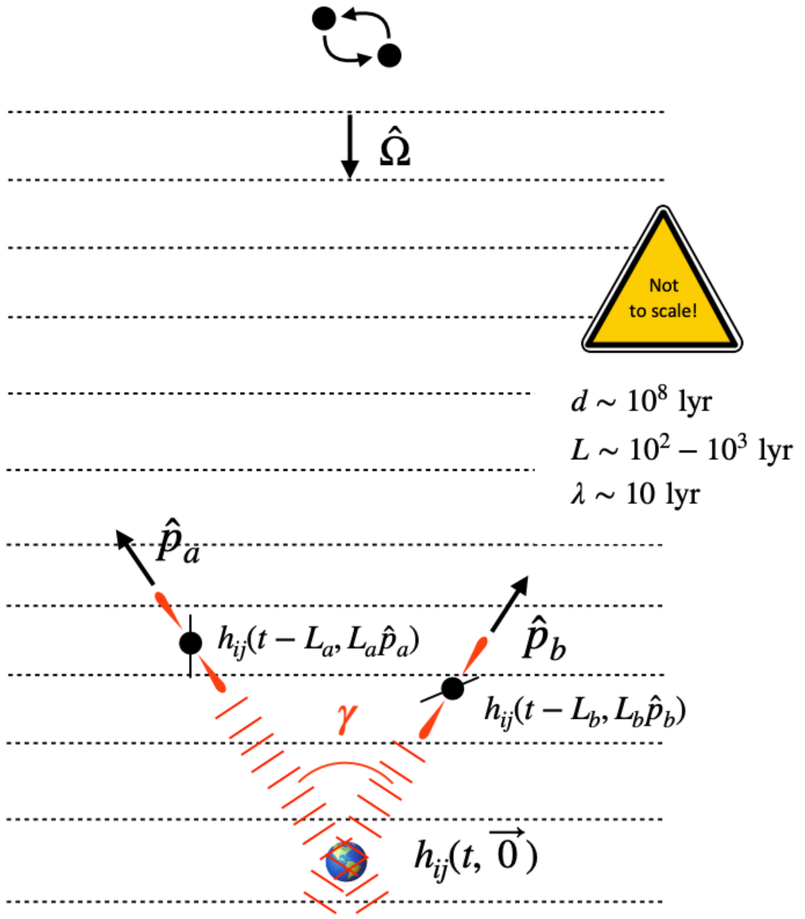
Pulsar Timing Arrays

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

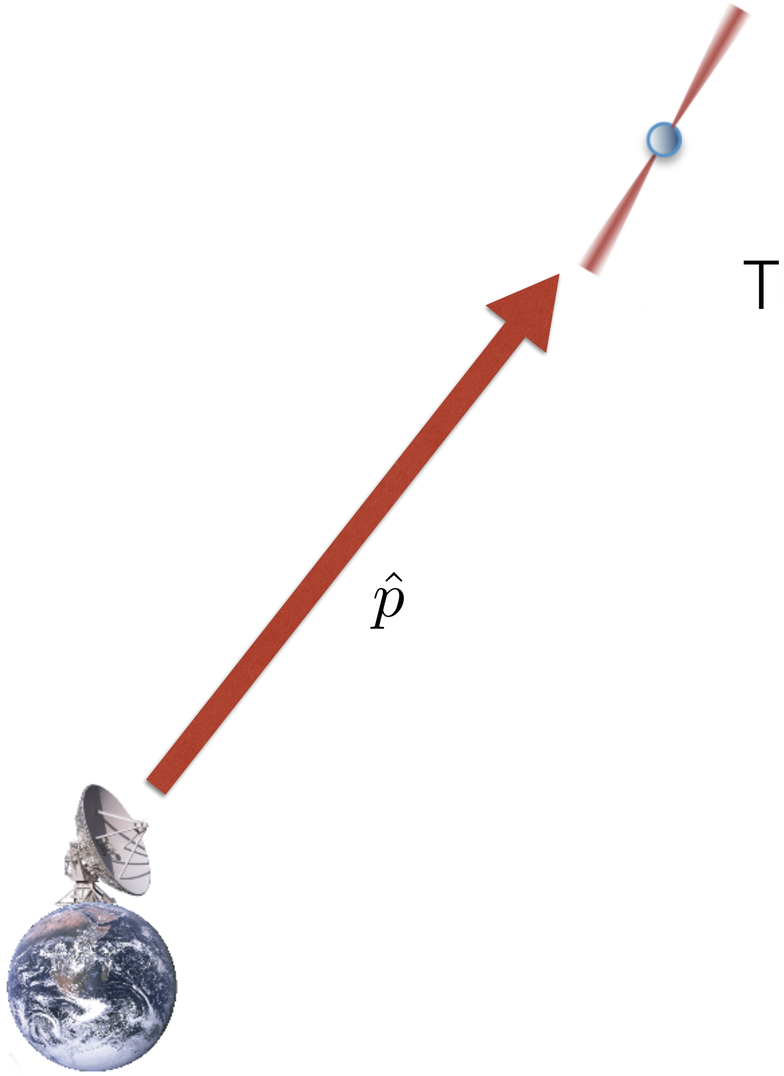
$$z(t,\hat{\Omega}) = \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\Delta h_{ij}$$

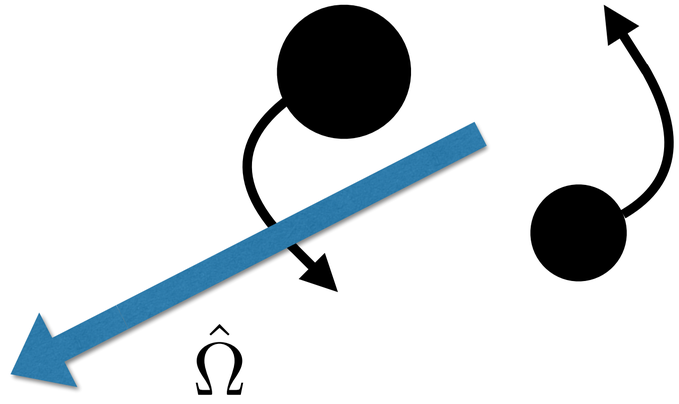


Credit: Joeri van Leeuwen



J. D. Romano and B. Allen, arXiv:2308.05847





The GW-induced residuals are

$$
\begin{aligned}
s(t,\hat{\Omega}) &= \int z(t,\hat{\Omega})\, dt \\
&= \sum_{A=+,\times} F^A(\hat{\Omega}) \int \Delta h_A(t)\, dt \\
&= \sum_{A=+,\times} F^A(\hat{\Omega}) \left[s_A(t) - s_A(t_p) \right]
\end{aligned}
$$

"Earth term" "pulsar term"

Averaging over an ensemble of gravitational wave sources gives us the **Hellings-Downs curve**: the average correlation in the timing residuals from a pair of pulsars.

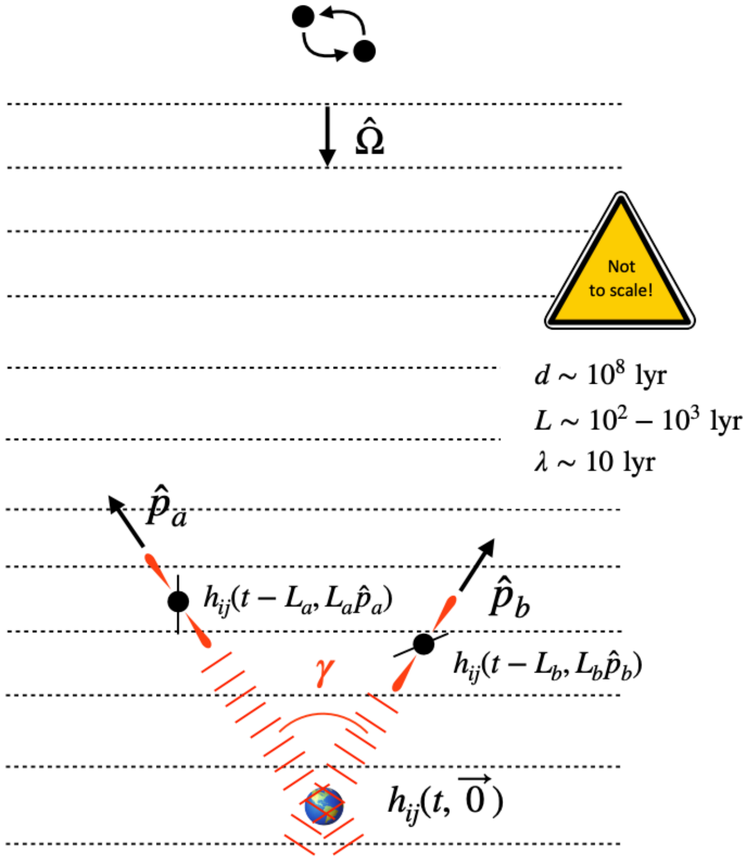
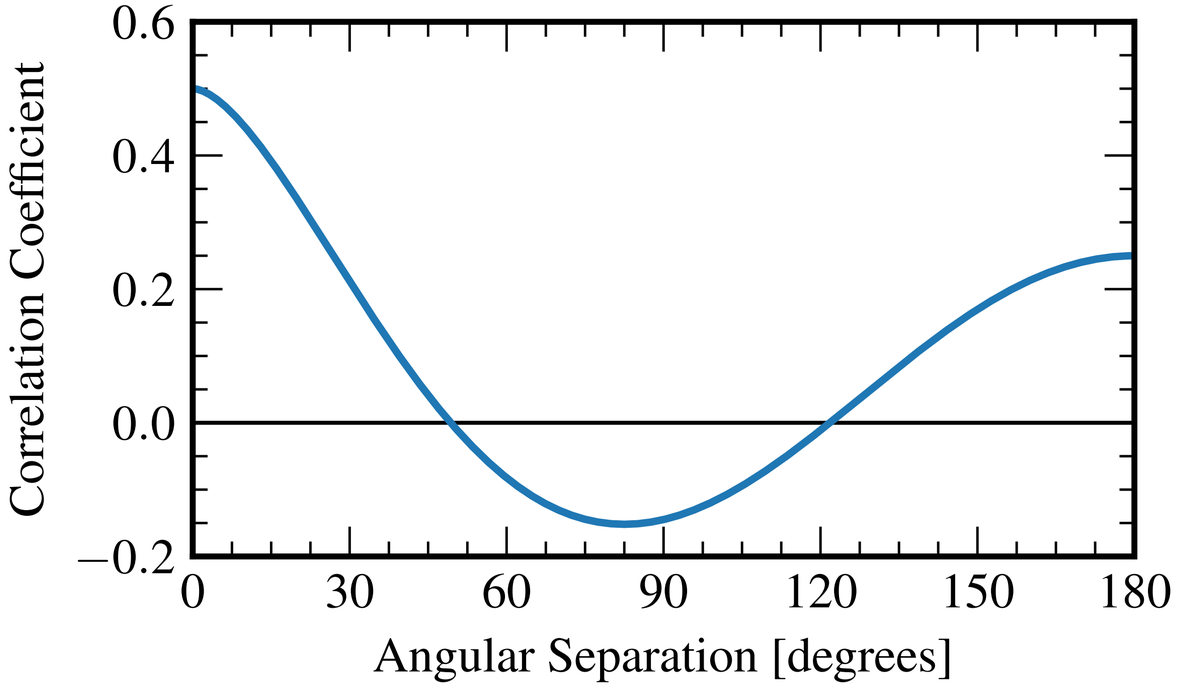


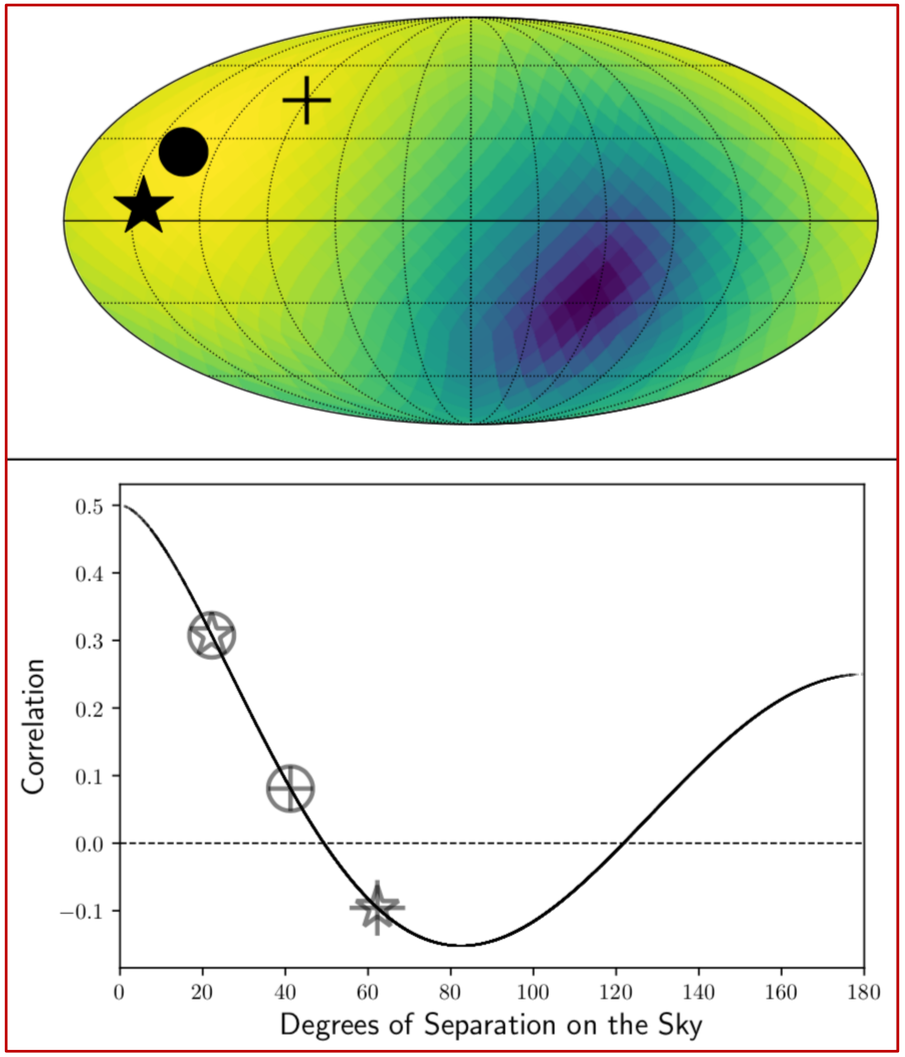
Figure credit: J. D. Romano and B. Allen, arXiv:2308.05847

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

$$F^A(\hat{\Omega}) = \frac{1}{2}\frac{\hat{p}^a\hat{p}^b}{1 + \hat{\Omega}\cdot\hat{p}}e^A_{ab}(\hat{\Omega})$$



GWB Signal Model



Gravitational waves induce correlated changes in the pulse times of arrival (Hellings & Downs, 1983).

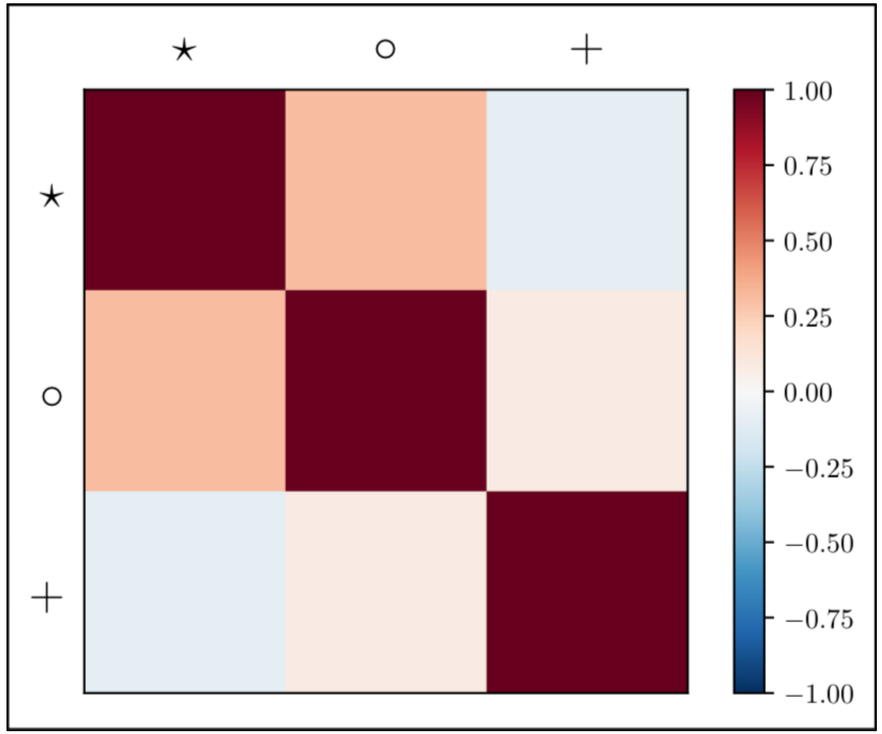
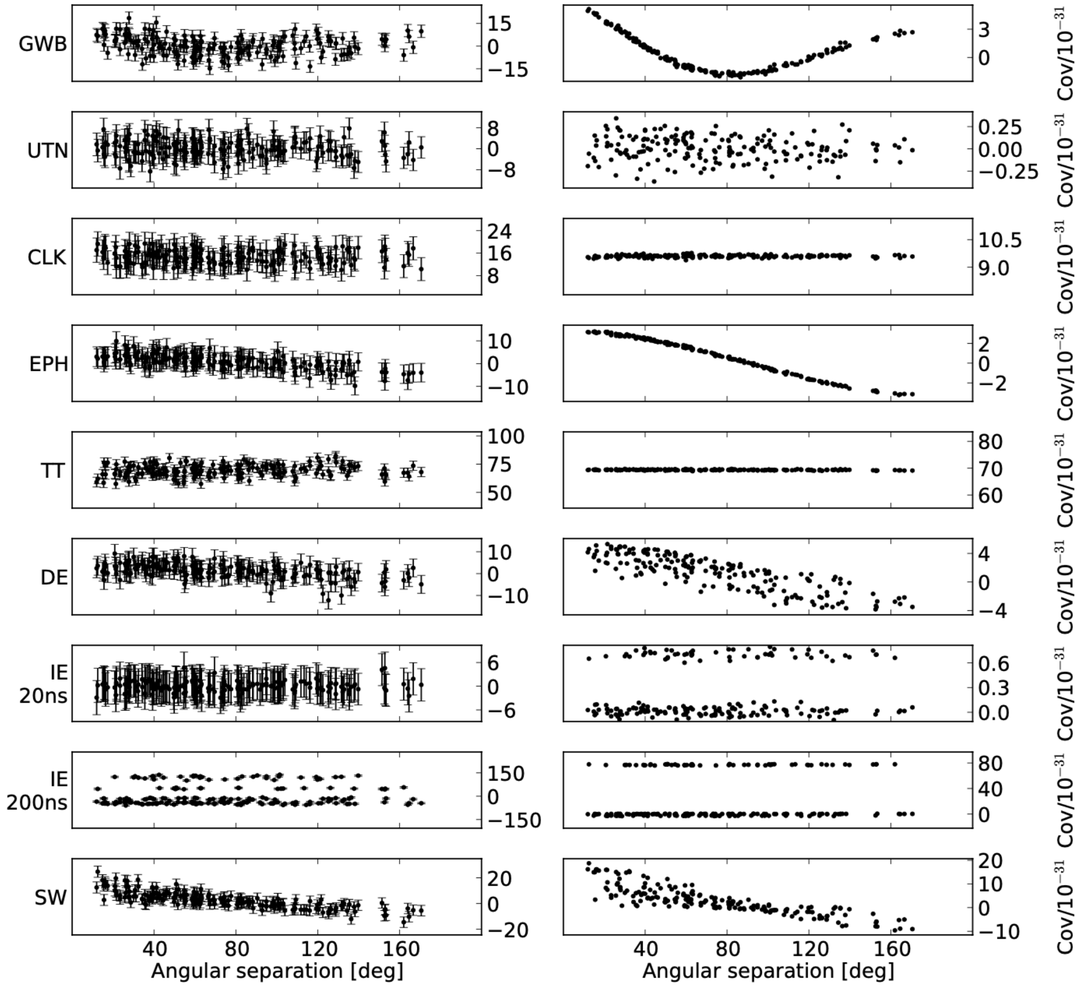


Figure credit: J. Hazboun

Correlated Noise Sources

Some noise sources can induce a common spatially-correlated signal (clock error, ephemeris error, etc.)

Tag	Simulated effect	GWB-like spectrum
S_{gwb}	GWB	Y
S_{utn}	Uncorrelated red noise	Y
S_{clk}	Stochastic clock-like errors	Y
S_{eph}	Stochastic ephemeris-like errors	Y
S_{tt}	Difference between TT(BIPM2013) and TT(TAI)	N
S_{de}	Difference between DE421 and DE414	N
S_{ie}	Instrumental errors	N
S_{sw}	Solar wind	N



Tiburzi et al., MNRAS 455, 4 (2015)

Pulsar timing array collaborations around the world have found evidence of a gravitational wave background at nanohertz frequencies.

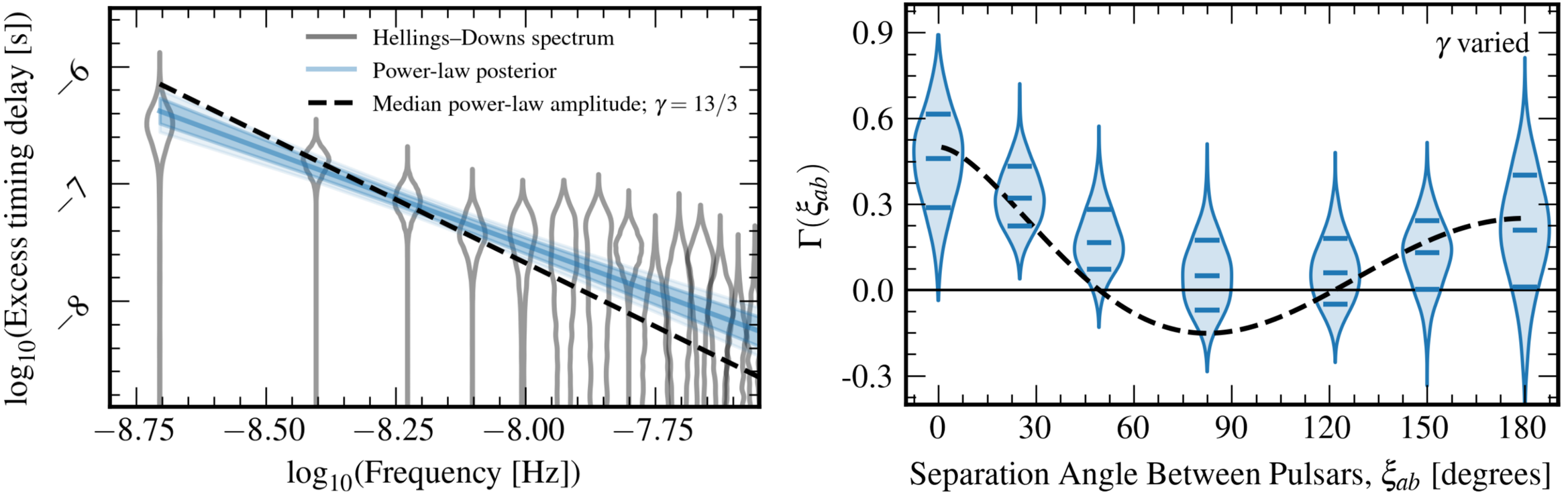
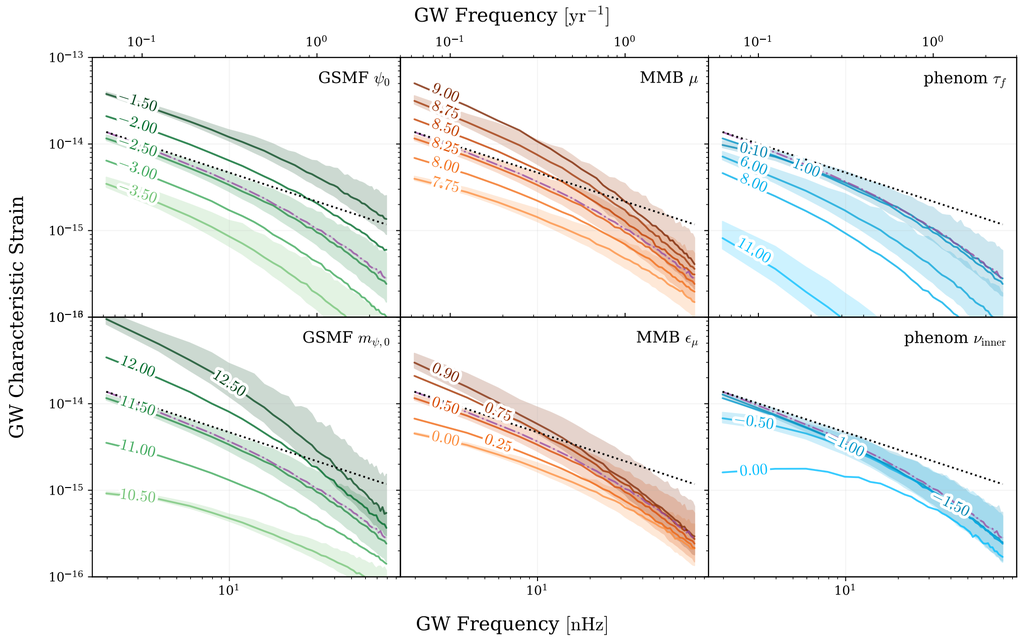


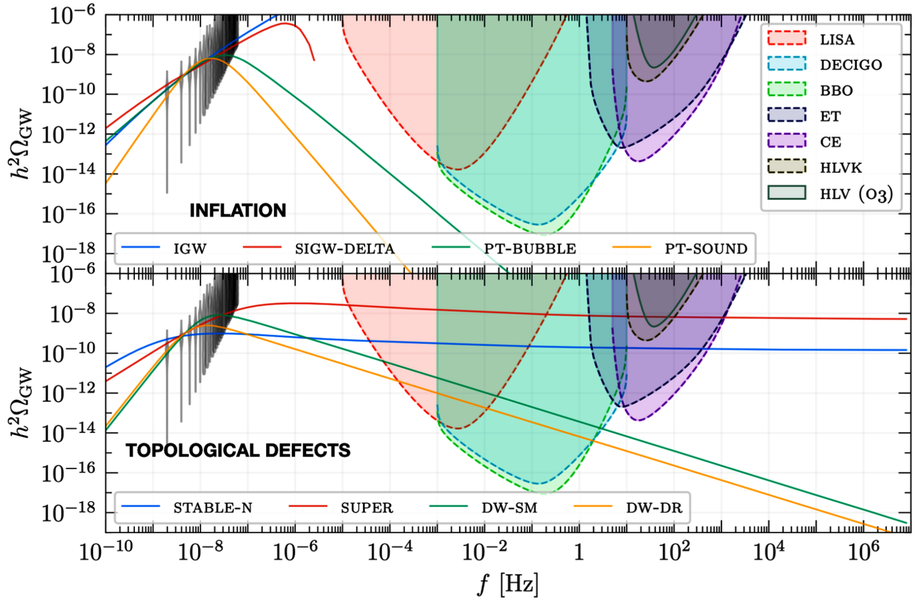
Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L8 (2023).

Major questions going forward:

- **What is the source of the GWB?** Is it supermassive binary black holes or something cosmological? Can we disentangle contributions to the GWB from different sources?



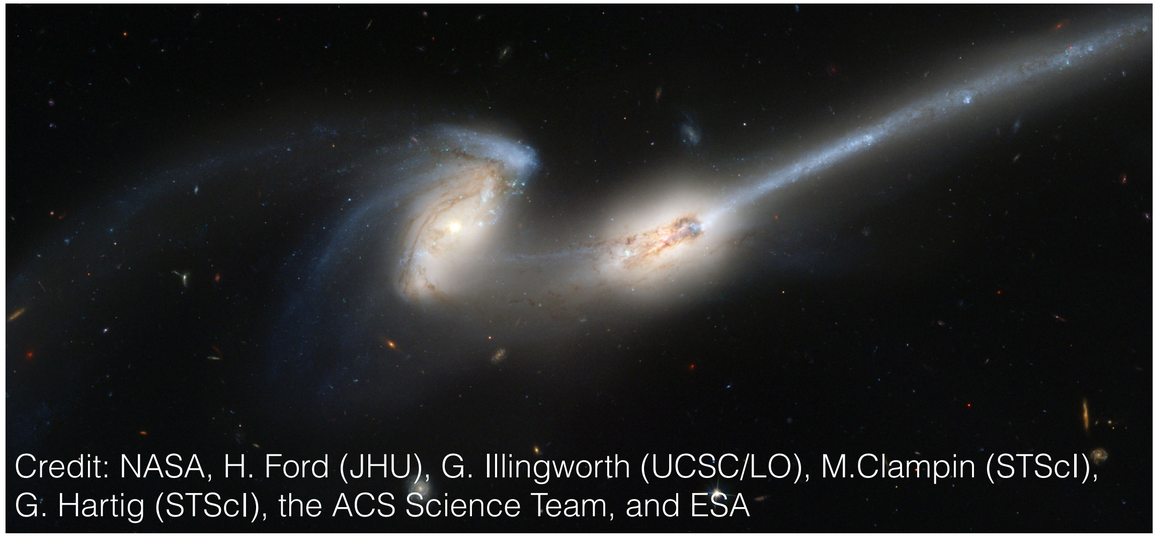
G. Agazie et al. (The NANOGrav Collaboration), ApJL 952, L37 (2023).



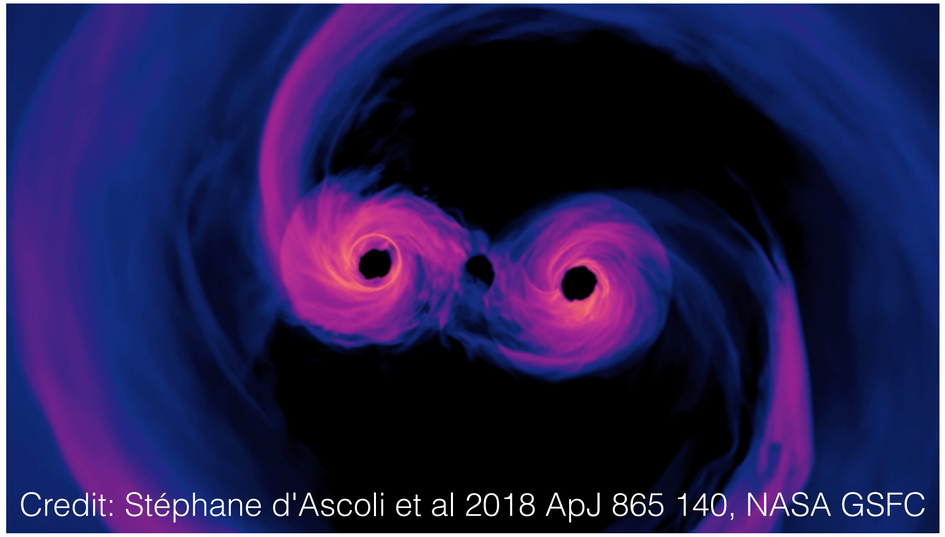
A. Afzal et al. (The NANOGrav Collaboration), ApJL 951, L11 (2023).

Major questions going forward:

- **What can we learn about supermassive black holes and galaxy evolution?** How massive are supermassive black holes? What is the galaxy merger rate? What are the environments around supermassive black holes like?



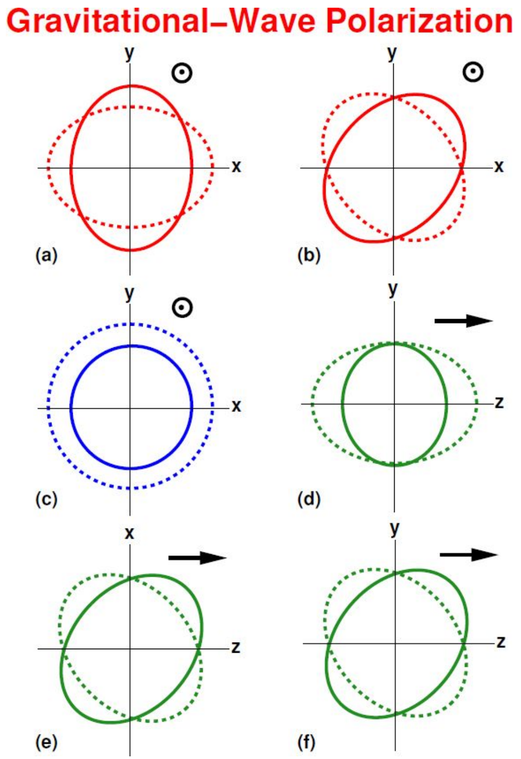
Credit: NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M.Clampin (STScI), G. Hartig (STScI), the ACS Science Team, and ESA



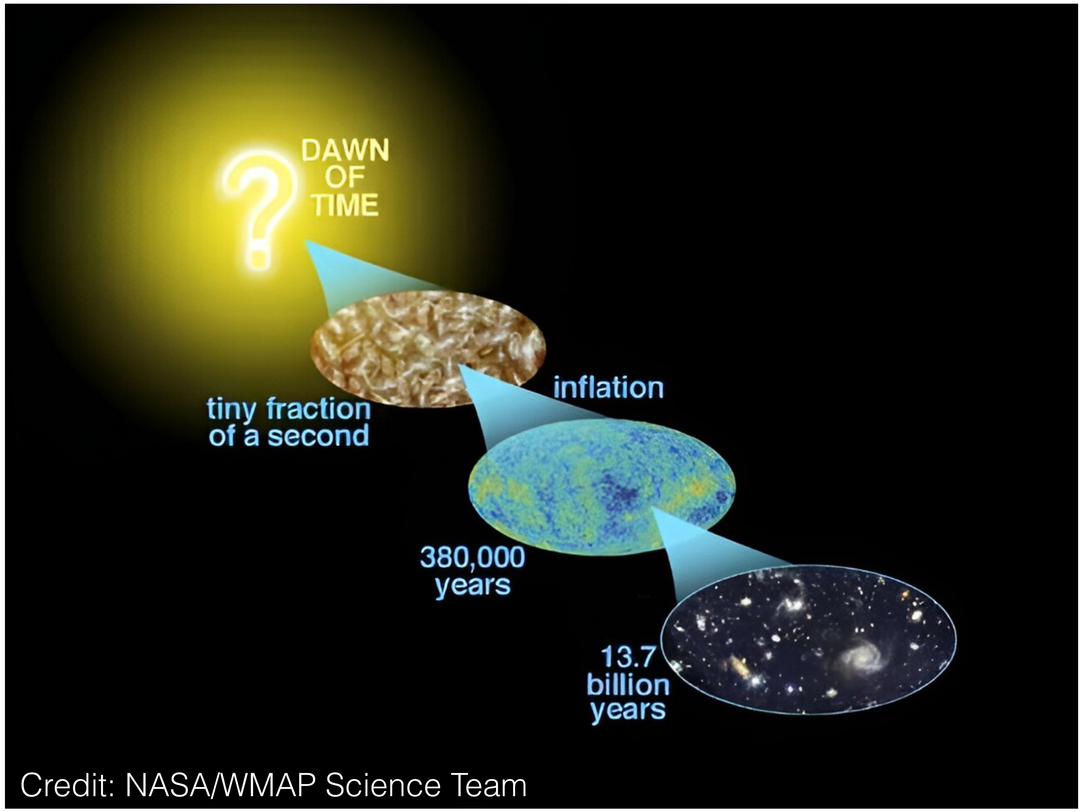
Credit: Stéphane d'Ascoli et al 2018 ApJ 865 140, NASA GSFC

Major questions going forward:

- **What can we learn about fundamental physics?** What kind of constraints can we put on alternative theories of gravity with PTAs? How well can we constrain new physics and cosmology?



C.M. Will, LRR 17, 4 (2014)



Credit: NASA/WMAP Science Team

Non-Einsteinian Polarization Modes

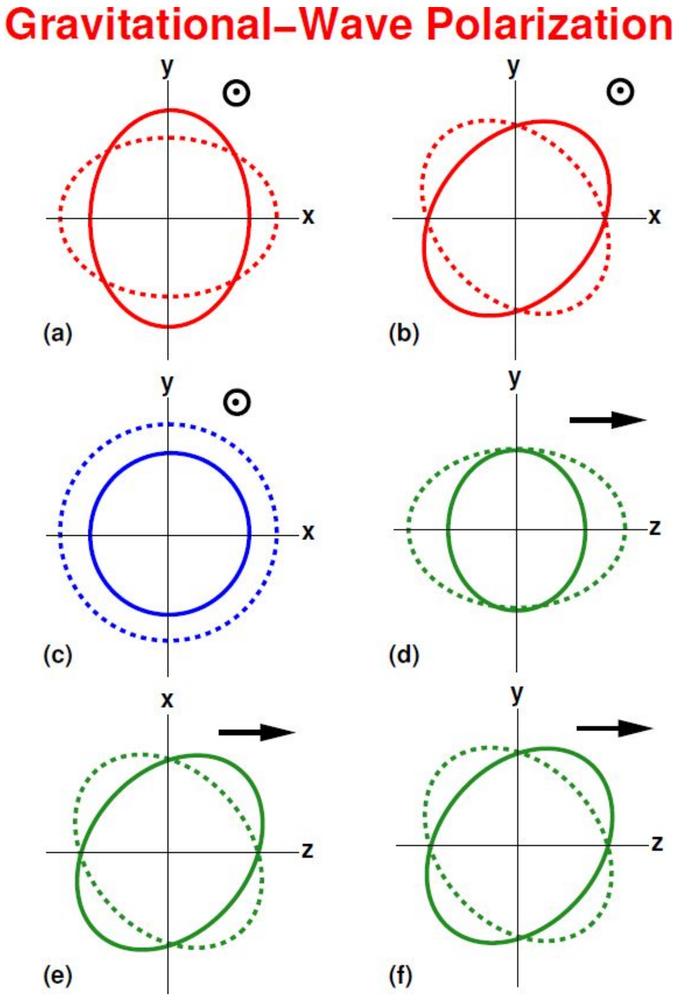


Figure credit: C. Will (2014)

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)

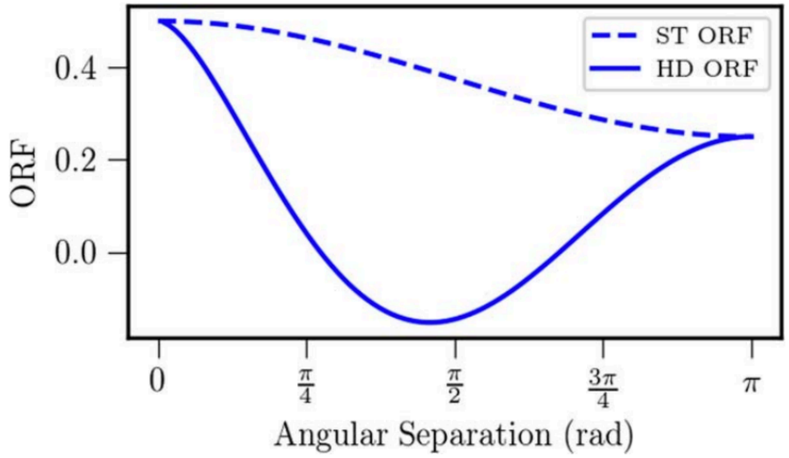
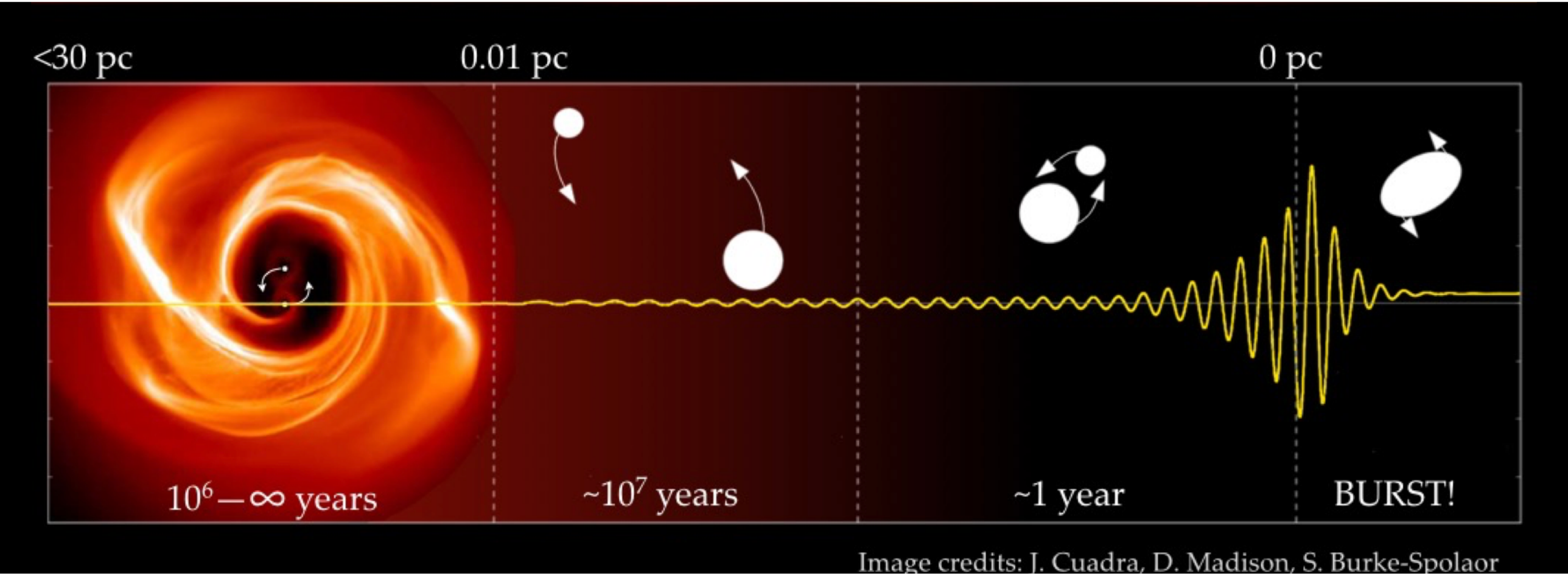
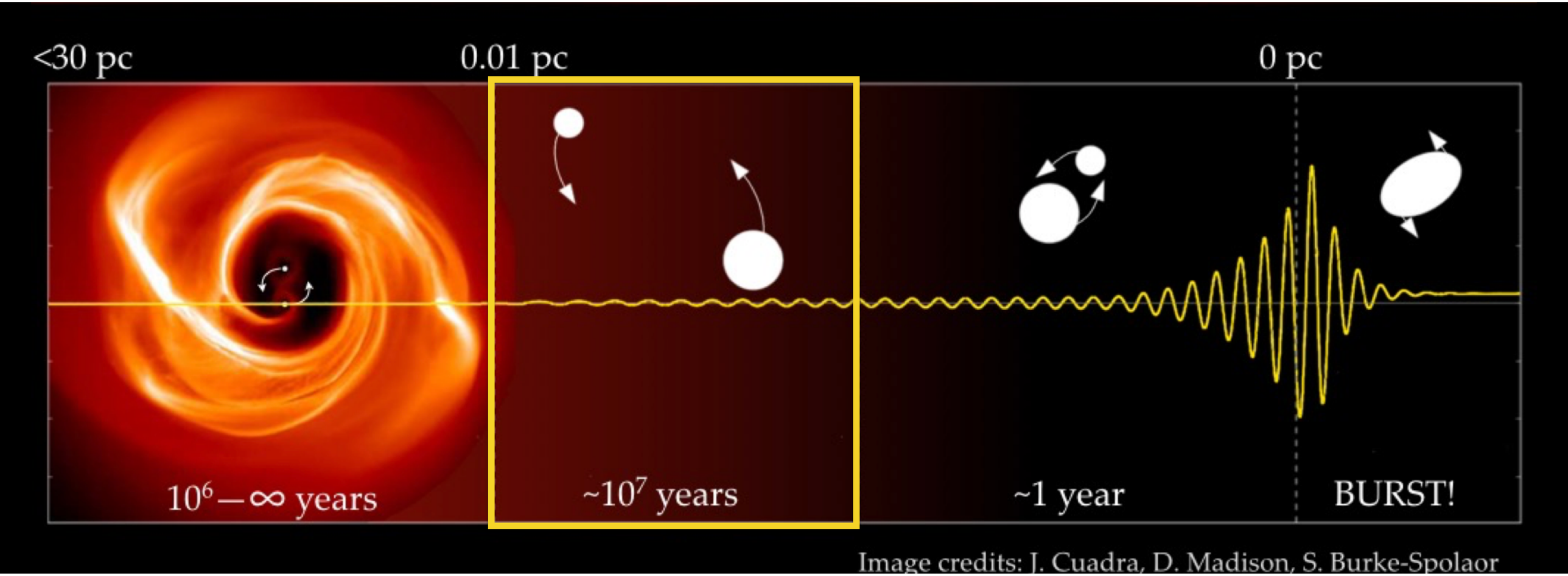


Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 923, L2 (2021).

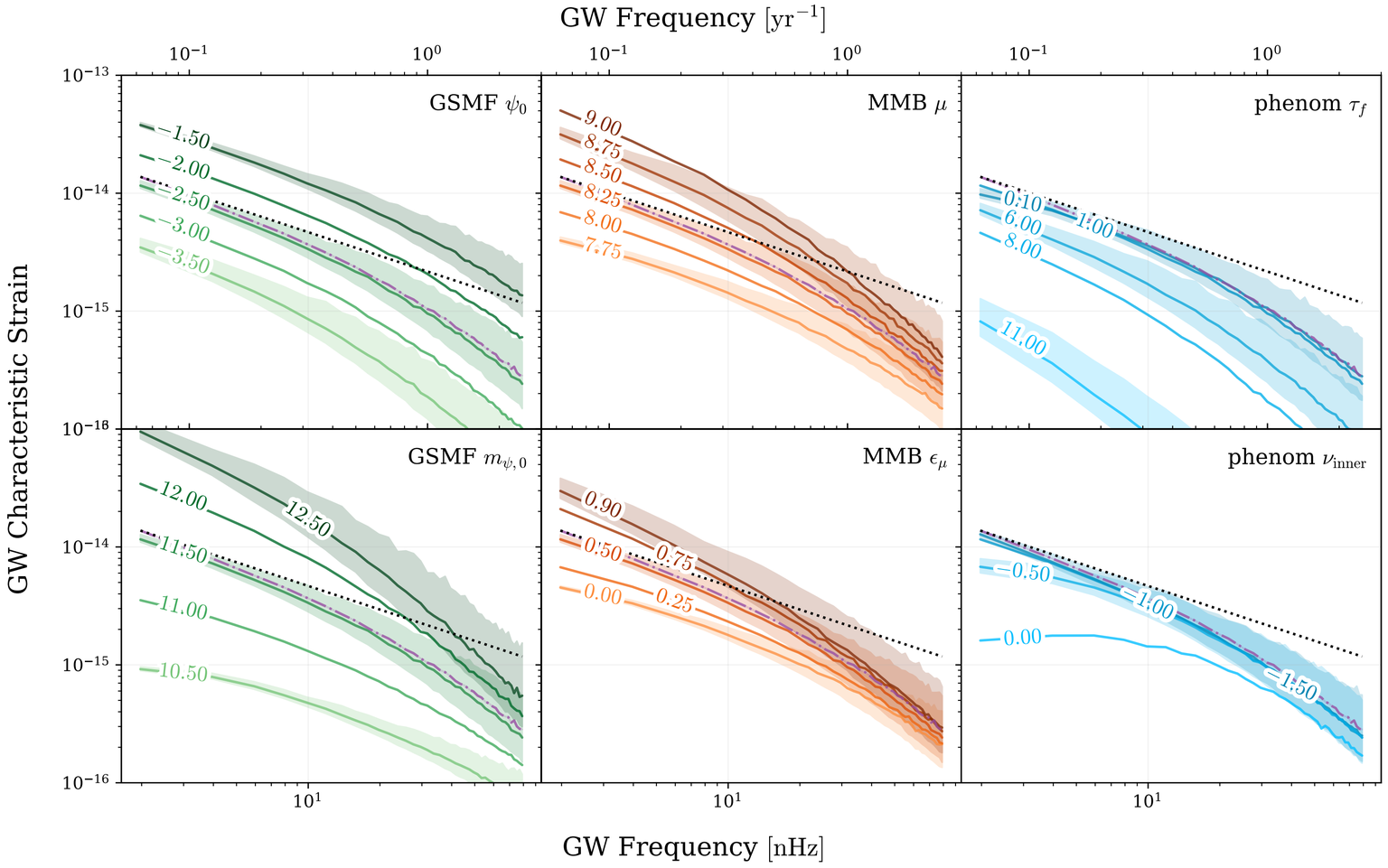
Supermassive Binary Black Holes



Supermassive Binary Black Holes



The incoherent superposition of GWs from a population of supermassive binary black holes produces a **gravitational wave background** (GWB).

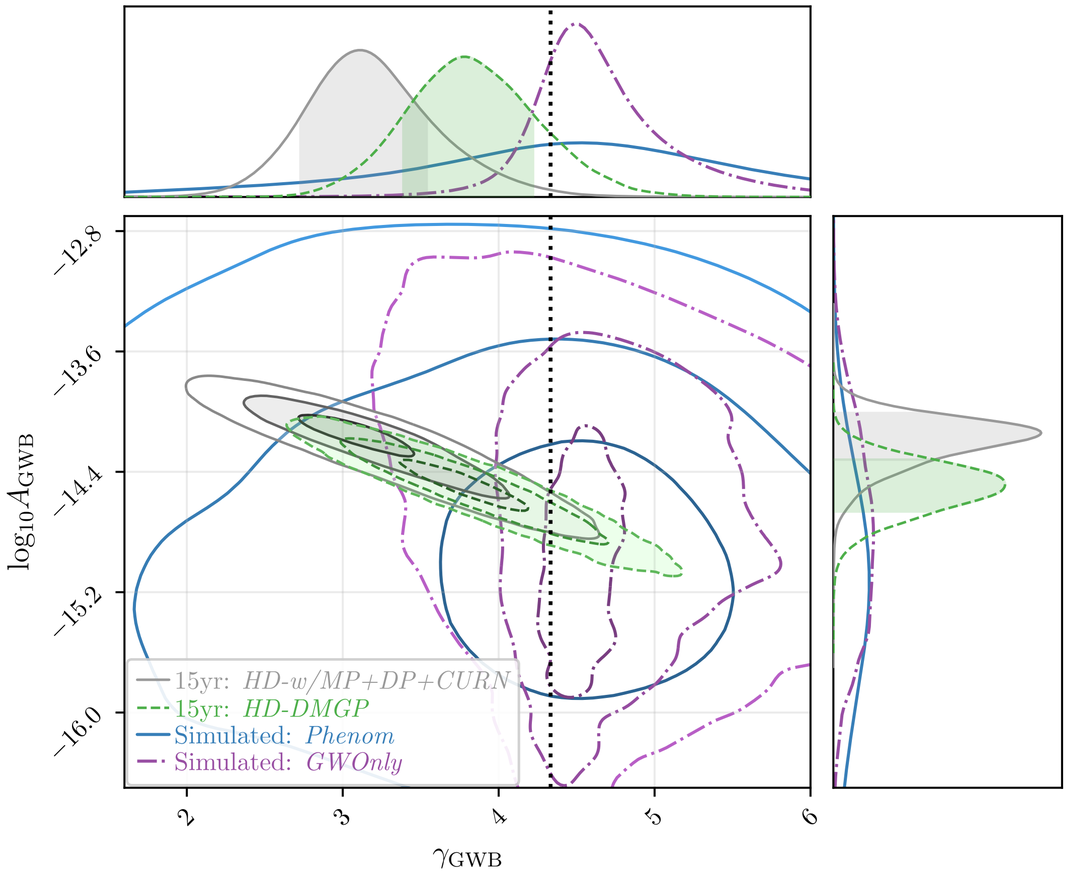


GWB amplitude is most sensitive to SMBH mass parameters and galaxy number density.

GWB spectral shape mostly depends on the binary hardening rate.

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 952, L37 (2023).

Implications for SMBBHs



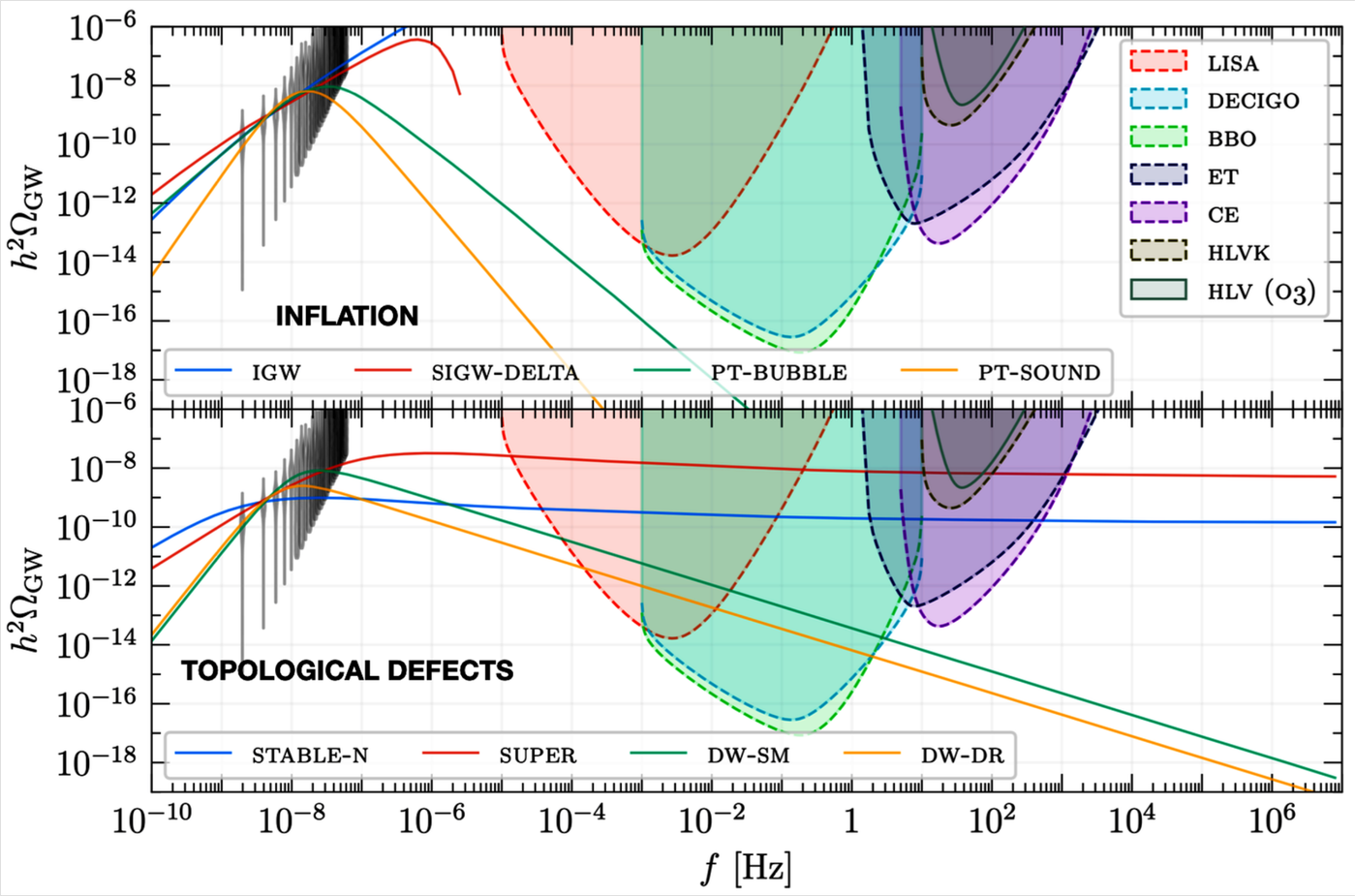
Observed PSD is consistent with a GWB produced by SMBBHs

Some preference for interacting models versus GW-only evolution models

Amplitude is high, but within the range of expectations. Implies some combination of relatively high masses, high rates of galaxy mergers, and efficient binary inspiral

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 952, L37 (2023).

Implications for New Physics



Processes in the early universe can also generate nanohertz gravitational waves.

Observed PSD is also consistent with GWB produced by cosmic inflation, scalar-induced GWs, first-order phase transitions, and domain walls. Stable cosmic strings are disfavored.

A. Afzal et al. (The NANOGrav Collaboration), ApJL 951, L11 (2023).

Searching for Anisotropy

If the GWB is being produced by SMBBHs, then it is composed of GWs from a finite number of individual sources and therefore will not be perfectly isotropic.

Simulations suggest future PTA data sets with ~20 years of data will be able to detect anisotropy in the GWB (Pol, Taylor, and Romano 2022).

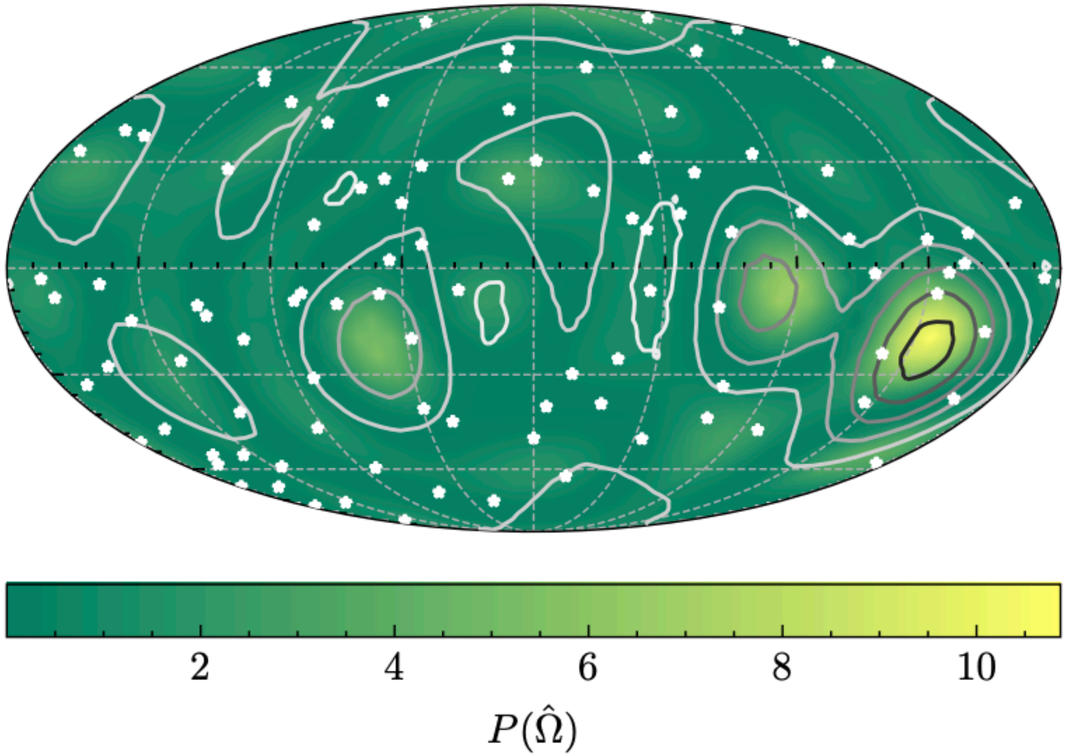


Figure credit: Pol, Taylor, and Romano, ApJ 940, 173 (2022).

Prospects for Detecting Individual SMBBHs

If the GWB is produced by SMBBHs, at some frequencies the GWB will be dominated by a few or a single loud source.

We expect to be able to resolve a handful of signals from individual binaries.

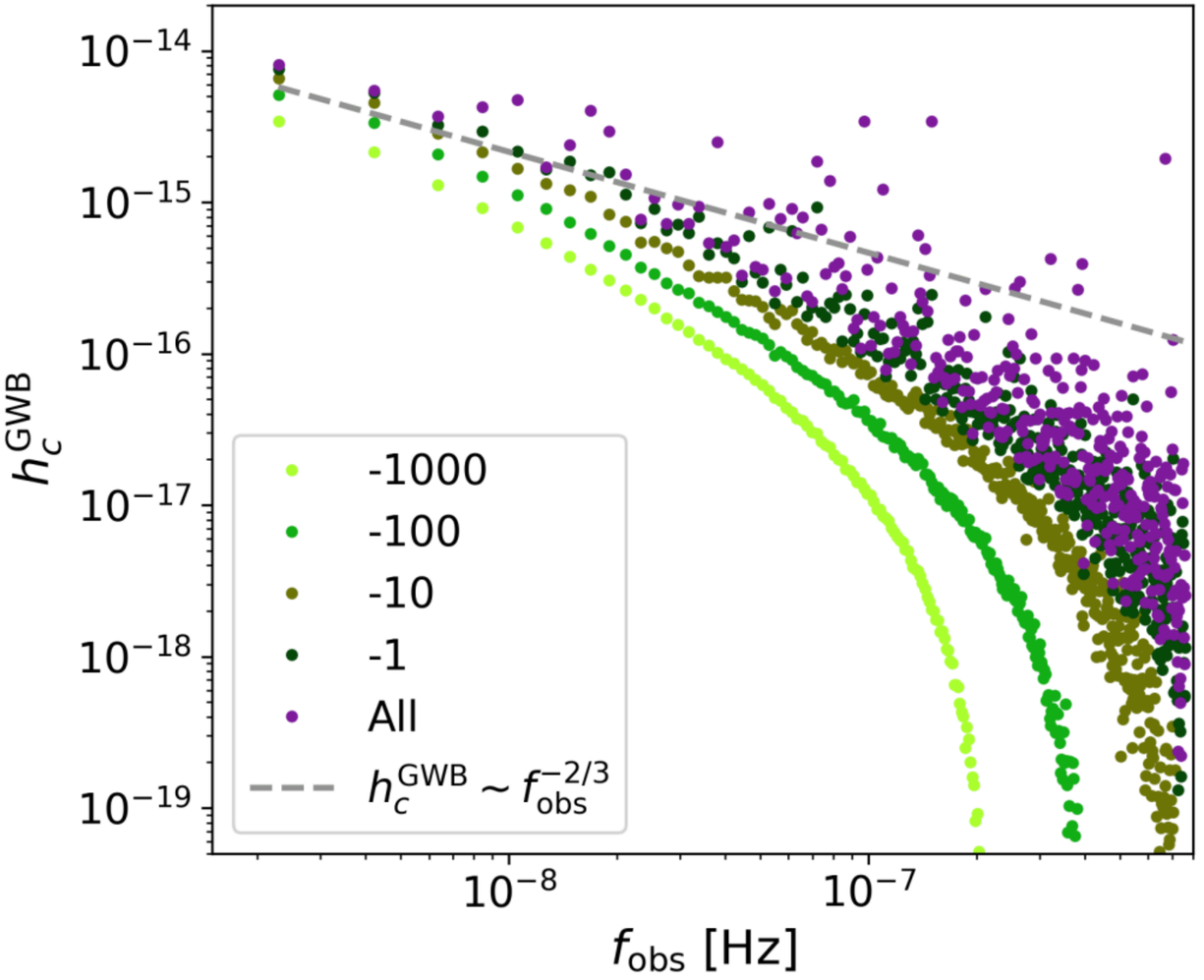
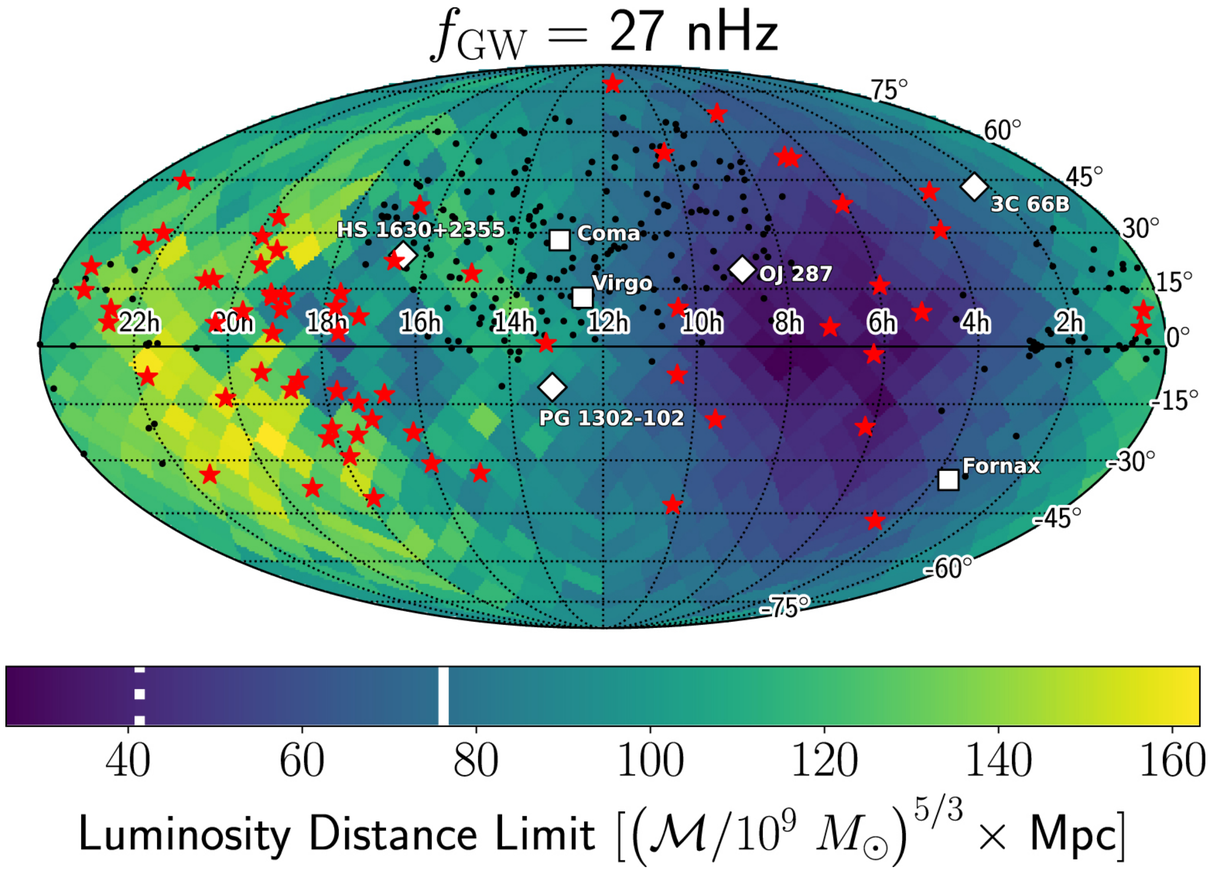


Figure credit: Becsy, Cornish, and Kelley, ApJ 941, 119 (2022).

Constraints on Individual SMBHBs

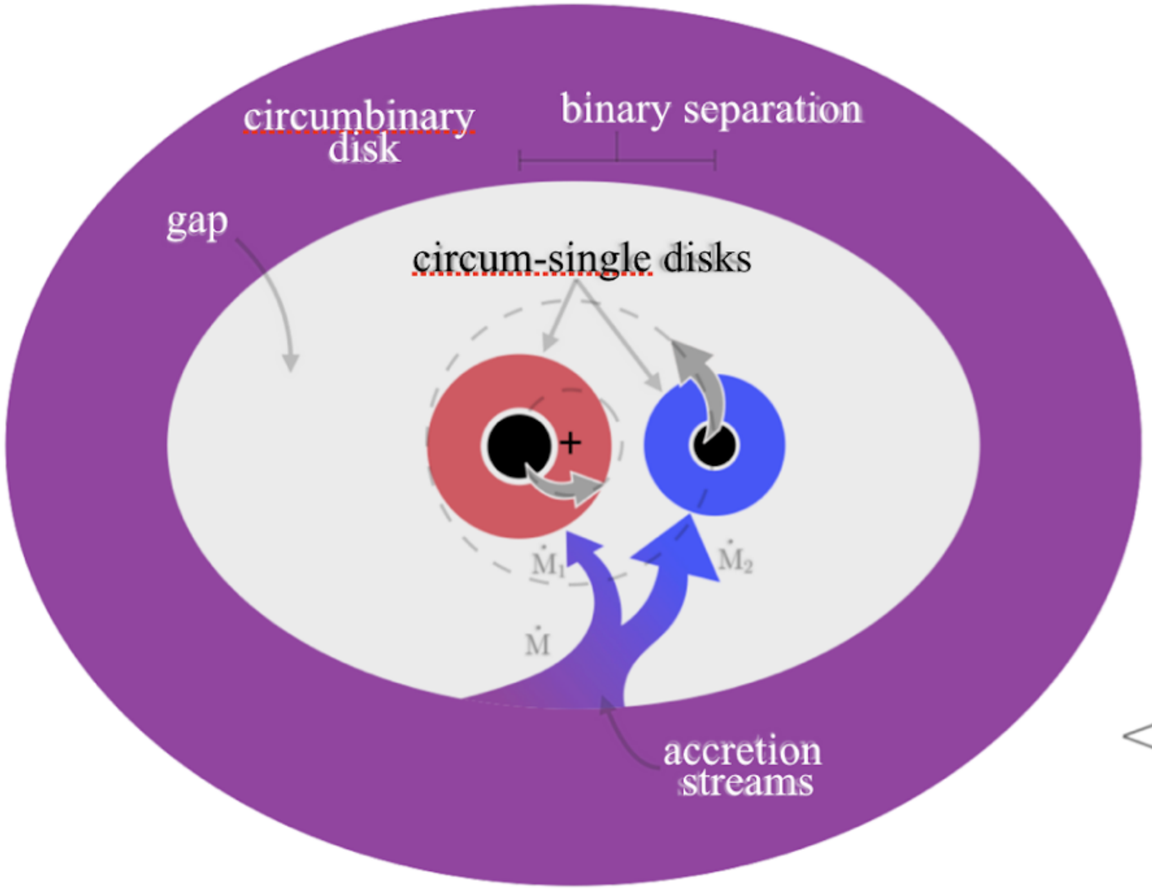


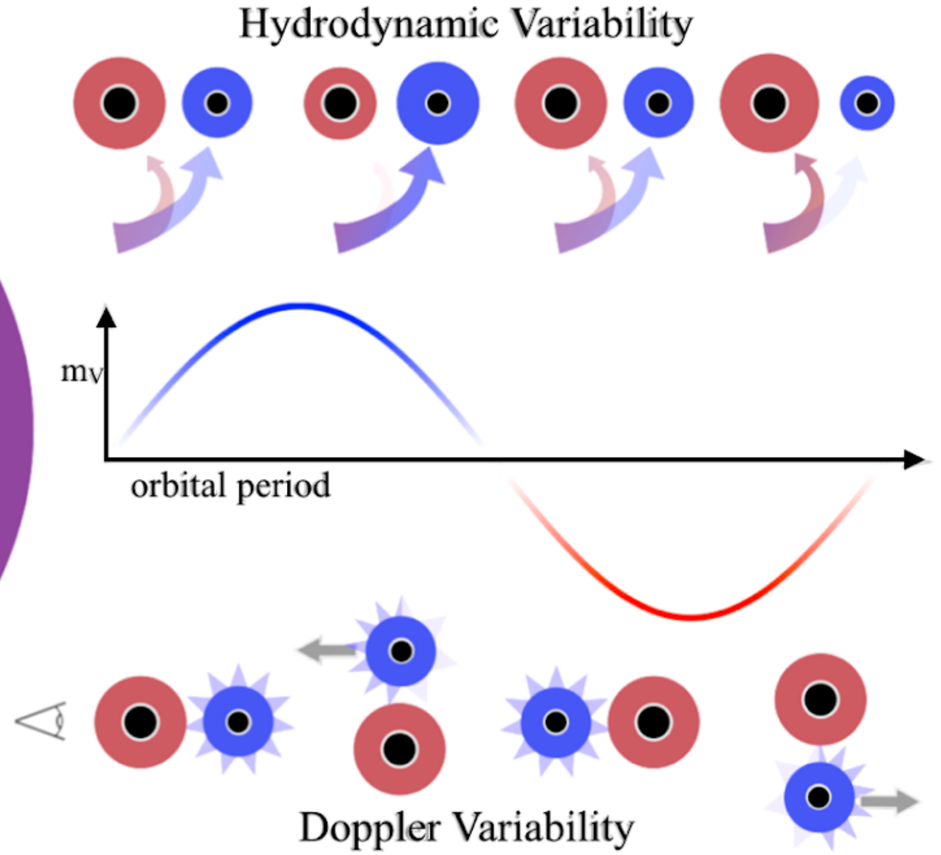
No significant evidence for GWs from individual SMBHBs in addition to a GWB

We can place lower limits on the distance to individual SMBHBs based on sky location and GW frequency

Figure credit: G. Agazie et al. (The NANOGrav Collaboration), ApJL 951, L50 (2023).

Prospects for Multimessenger Astrophysics





Kelley et al. (2018), arXiv:1809.02138

Prospects for Multimessenger Astrophysics

HS 1630 is a periodic quasar identified by CRTS (Graham et al. 2015)

Identified as a promising GW source with frequency of 11.3 nHz and distance of 5.26 Gpc (Xin et al. 2021)

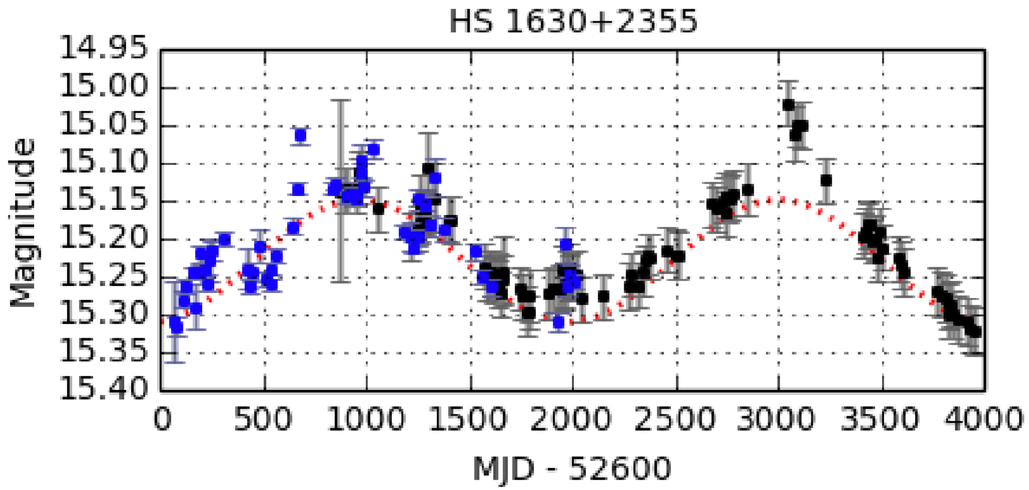


Figure credit: M. Graham et al., MNRAS 453, 2 (2015).

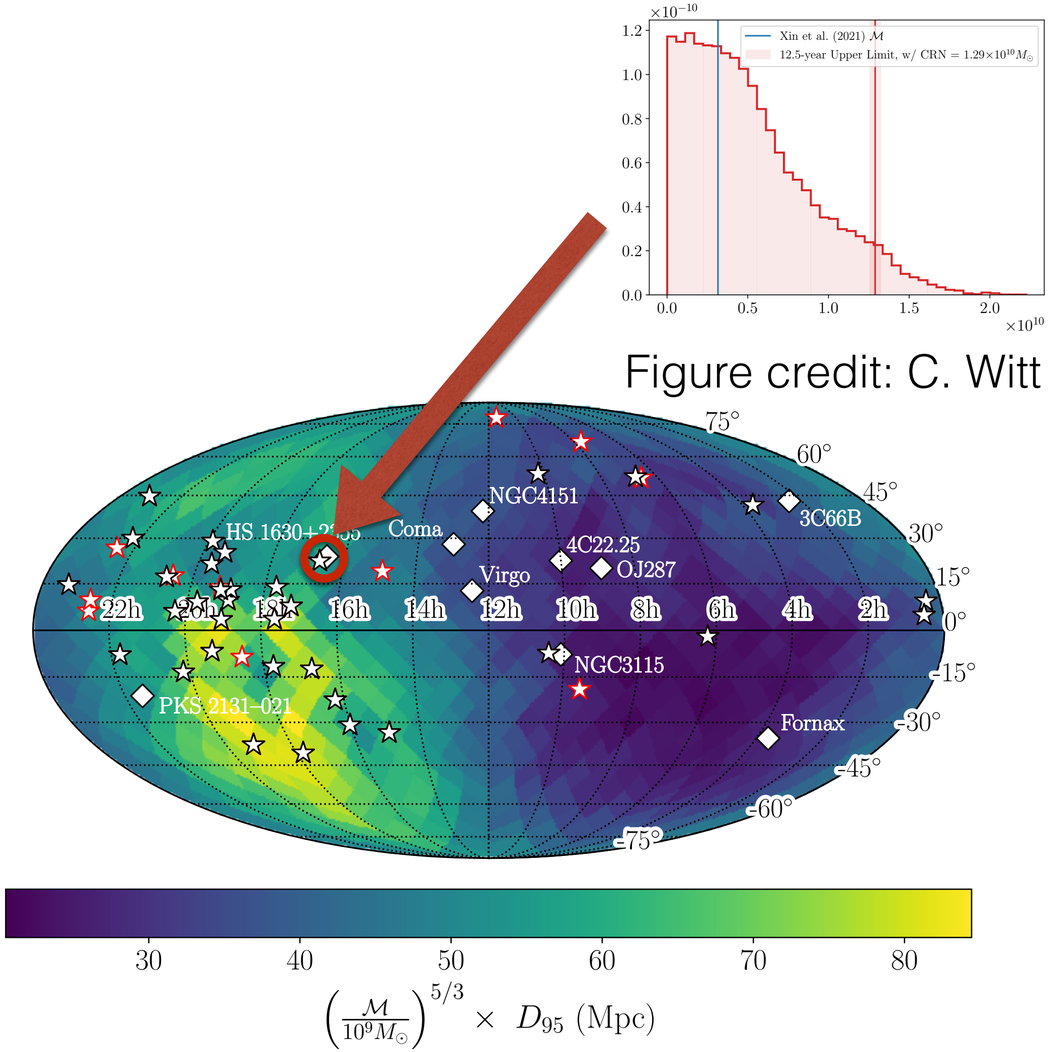
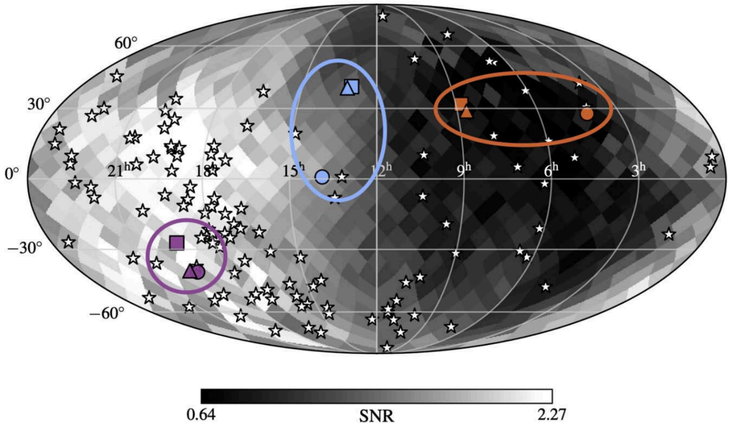


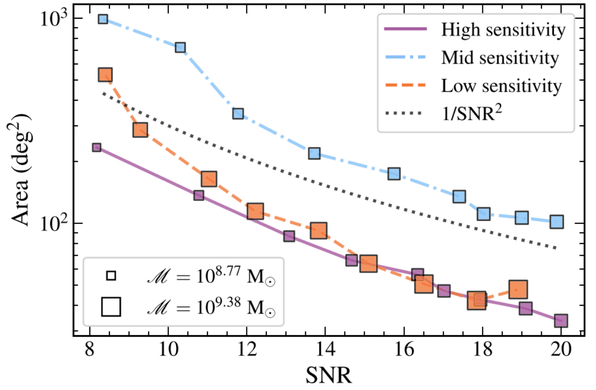
Figure credit: C. Witt

Figure credit: Z. Arzoumanian et al. (The NANOGrav Collaboration), ApJL 951, L2 (2023).

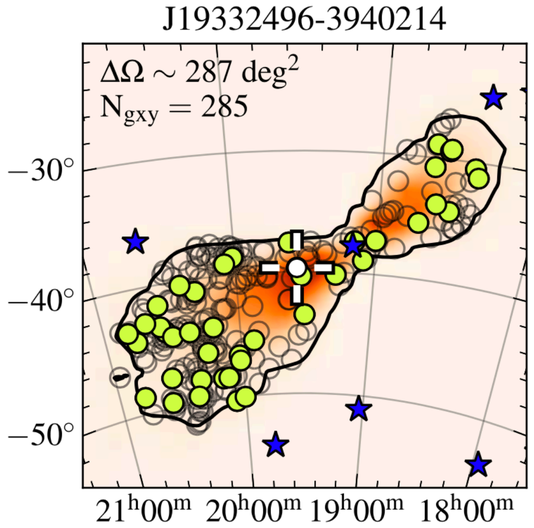
Host Galaxy Identification

Our ability to localize the source on the sky depends strongly on its sky location, especially how close the nearest pulsars are.





Within a localization area, we can use mass and distance cuts to narrow down potential host galaxies.



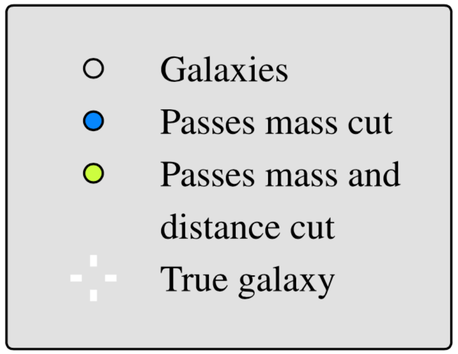


Figure credit: P. Petrov, S. Taylor, M. Charisi, C-P Ma, ApJ 976, 1 (2024).



Image credit: H. T. Cromartie

IPTA DR3 currently underway

Will contain data from GBT, Arecibo, **VLA**, **CHIME**, Lovell, Nancay, WSRT, **SRT**, Effelsberg, **LOFAR**, **MeerKAT**, **GMRT**, **FAST**, Parkes

Full data set will contain observations of **121 pulsars**, with a baseline of **25 years**

Conclusions



Pulsar timing array collaborations have recently published evidence for a gravitational wave background at nanohertz frequencies.

This signal is likely coming from a population of supermassive binary black holes, but it could also be produced by a number of cosmological sources (e.g., cosmic strings, phase transitions).

Longer pulsar timing baselines and more pulsars will give us better measurement of the GWB power spectrum (—> source of the GWB) and the interpulsar correlations (—> GW polarizations).