Observing Gravity and the (Invisible) Universe with Pulsar Timing Arrays

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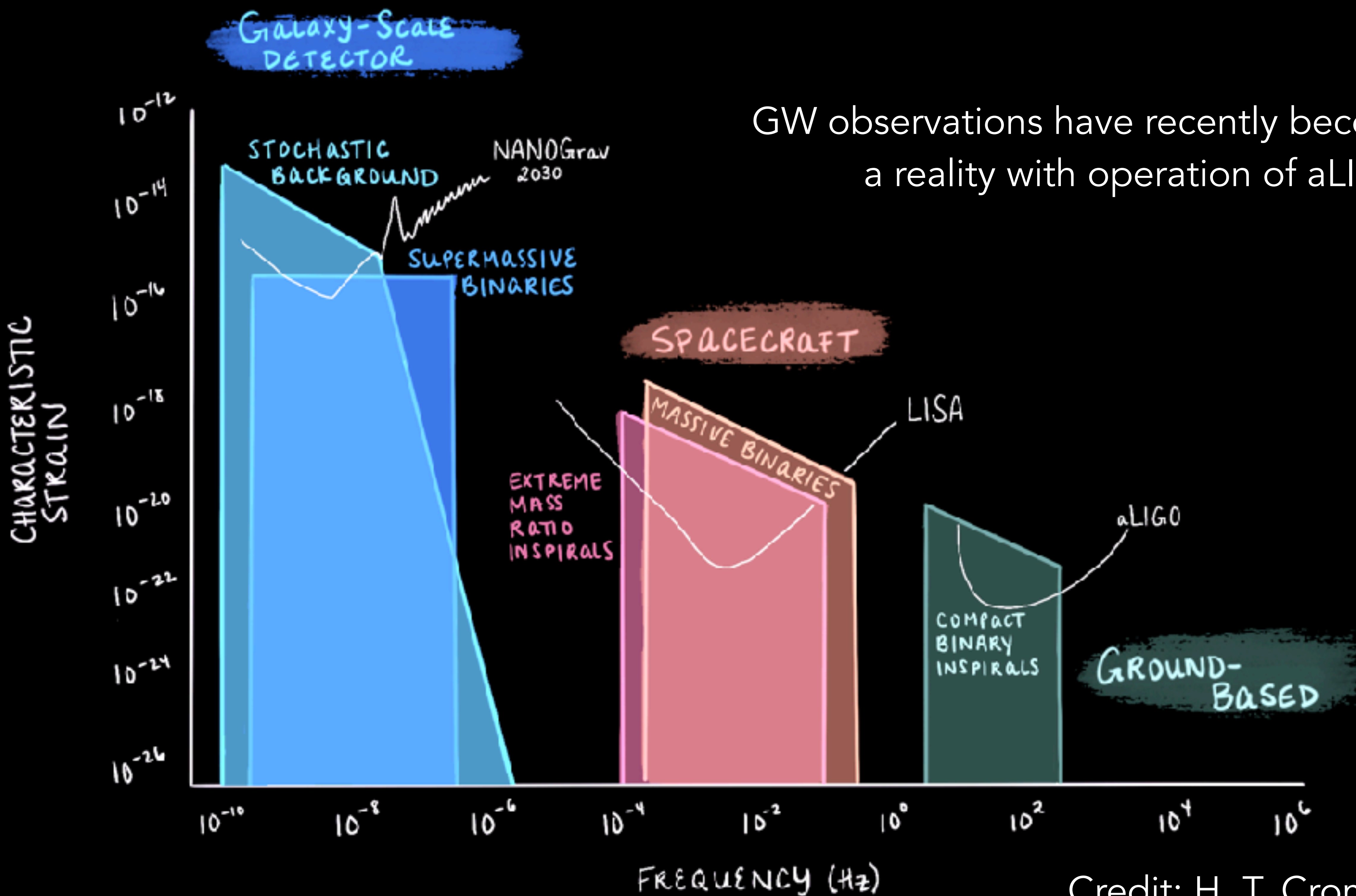
NANOGrav
Physics Frontiers Center

Gravitational-Wave Spectrum

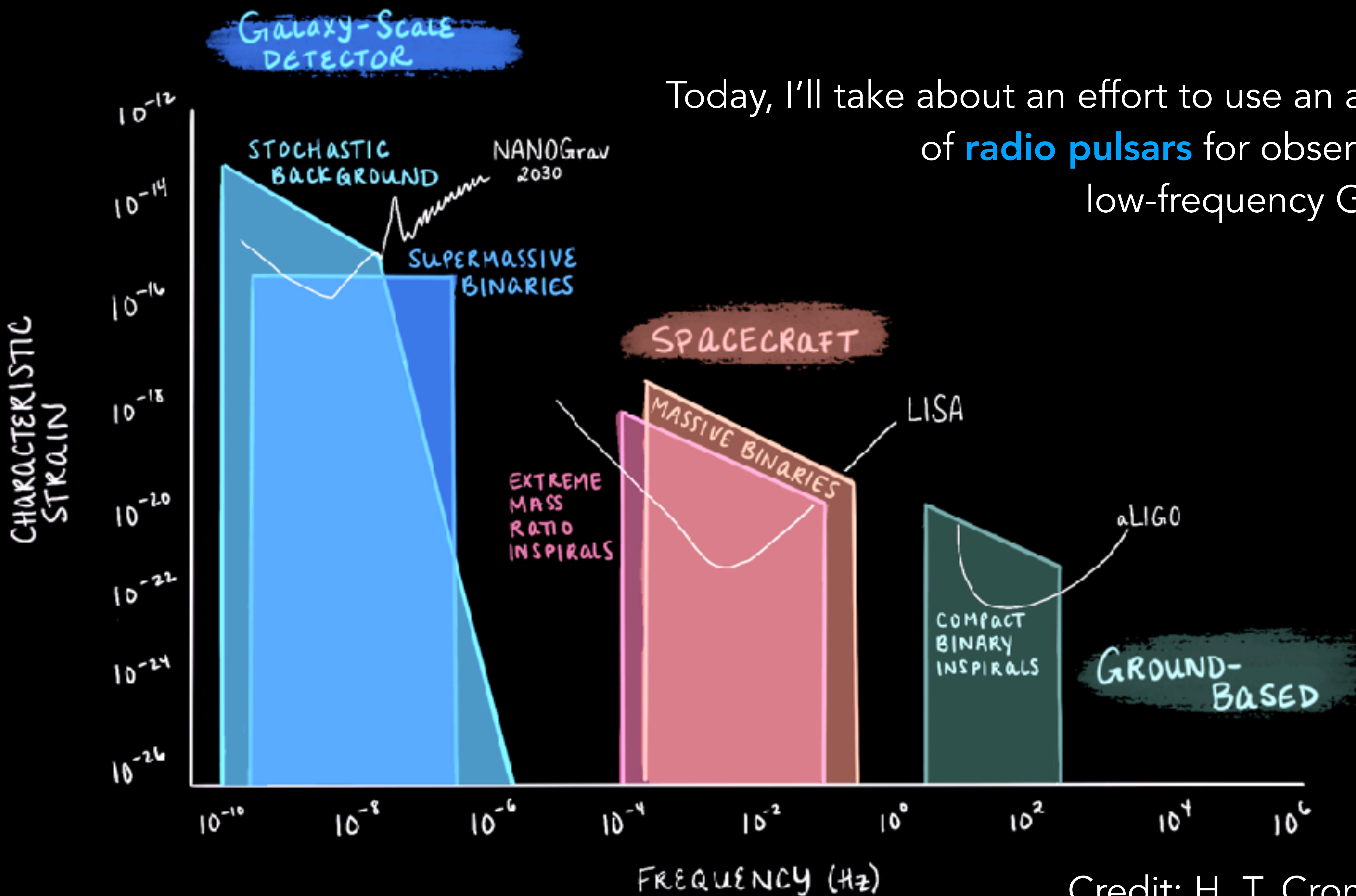
GW observations have recently become a reality with operation of aLIGO.



Credit: H. T. Cromartie

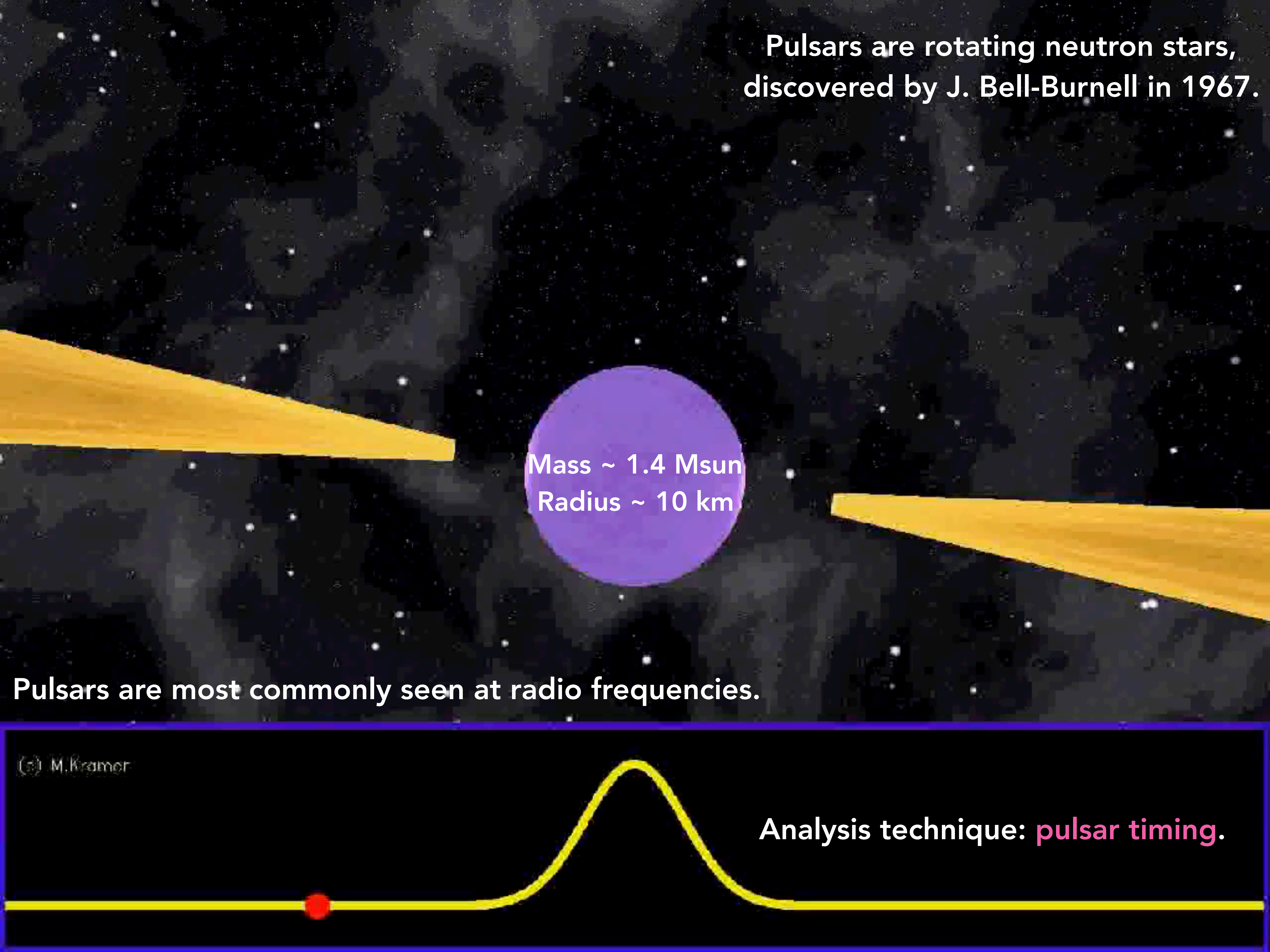
Gravitational-Wave Spectrum

Today, I'll take about an effort to use an array of **radio pulsars** for observing low-frequency GWs.



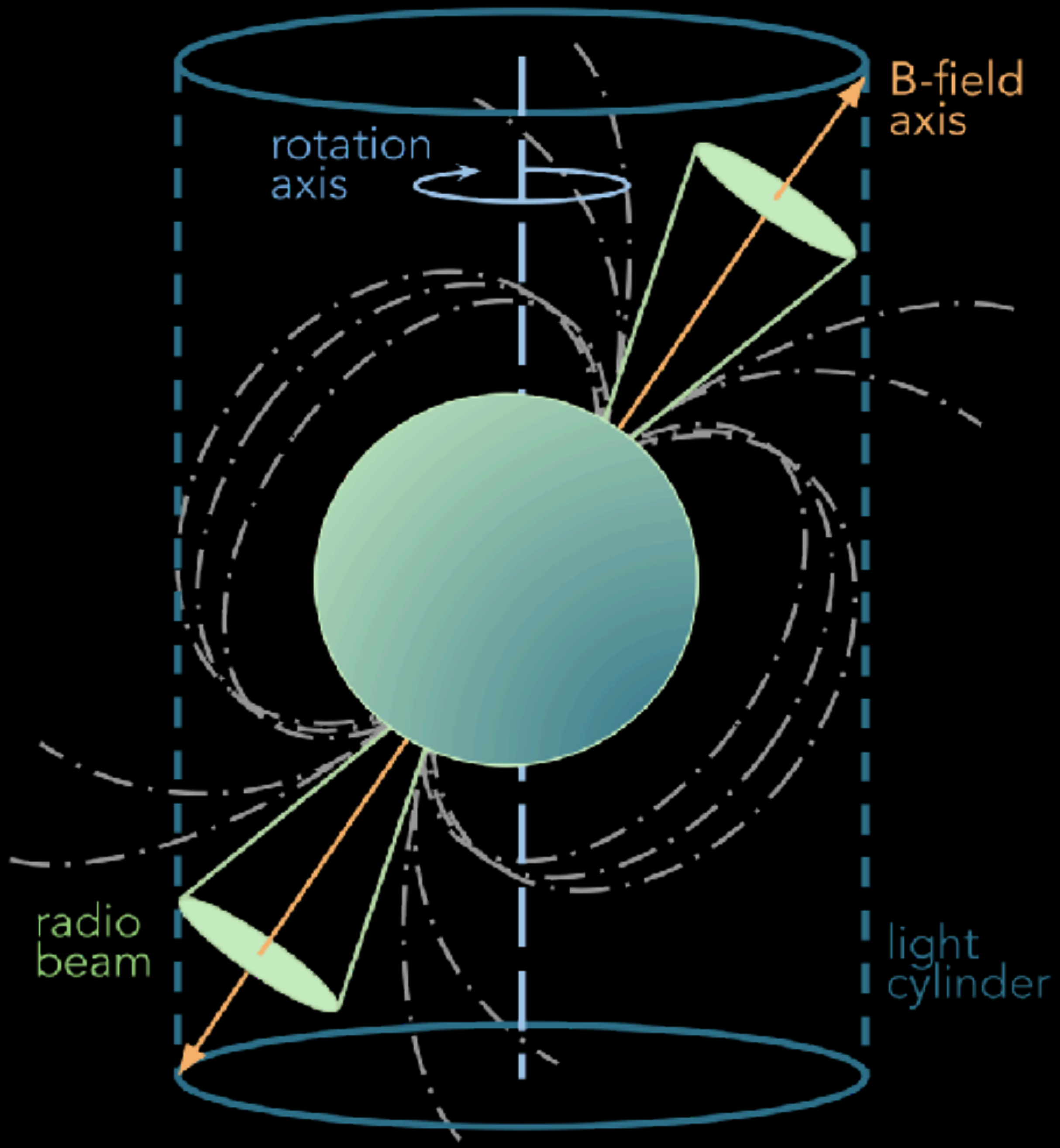
Credit: H. T. Cromartie

Part I: Pulsars


Pulsars are rotating neutron stars,
discovered by J. Bell-Burnell in 1967.
Mass ~ 1.4 Msun
Radius ~ 10 km
Pulsars are most commonly seen at radio frequencies.
(c) M.Kramer
Analysis technique: pulsar timing.

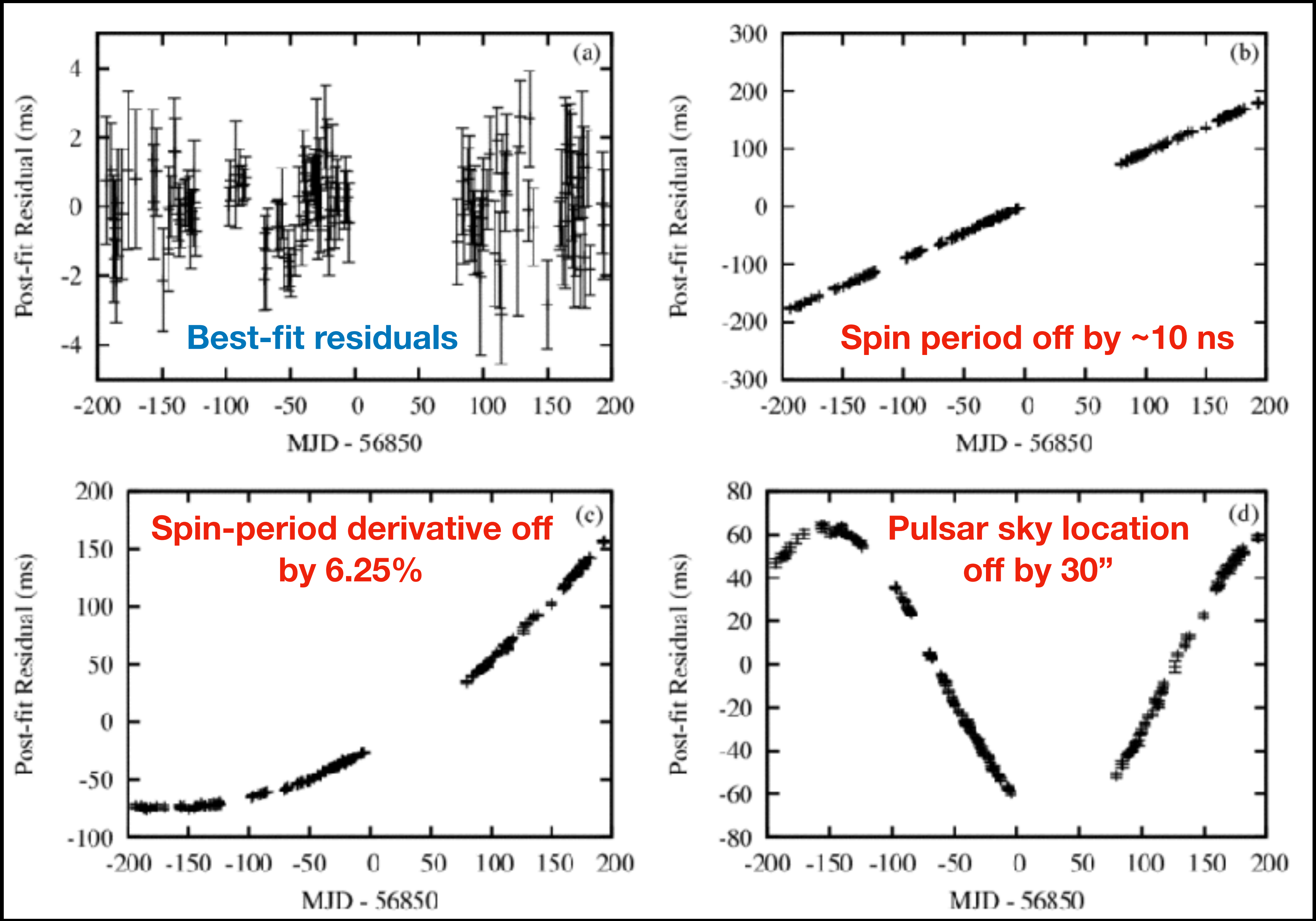
Pulsar Timing in a Nutshell

- For each pulsar, we derive a “time of arrival” (**TOA**) of an observed pulse and collect many TOAs over ~years.
- For millisecond pulsars (**MSPs**), TOAs typically have statistical uncertainties of ~0.1–1 us.
- As TOAs are collected, we model TOA variations in terms additive time delays associated with various physical phenomena.
- The end-products are a **timing model** and **TOA “residuals”** (i.e., data - model).



Credit: H. T. Cromartie

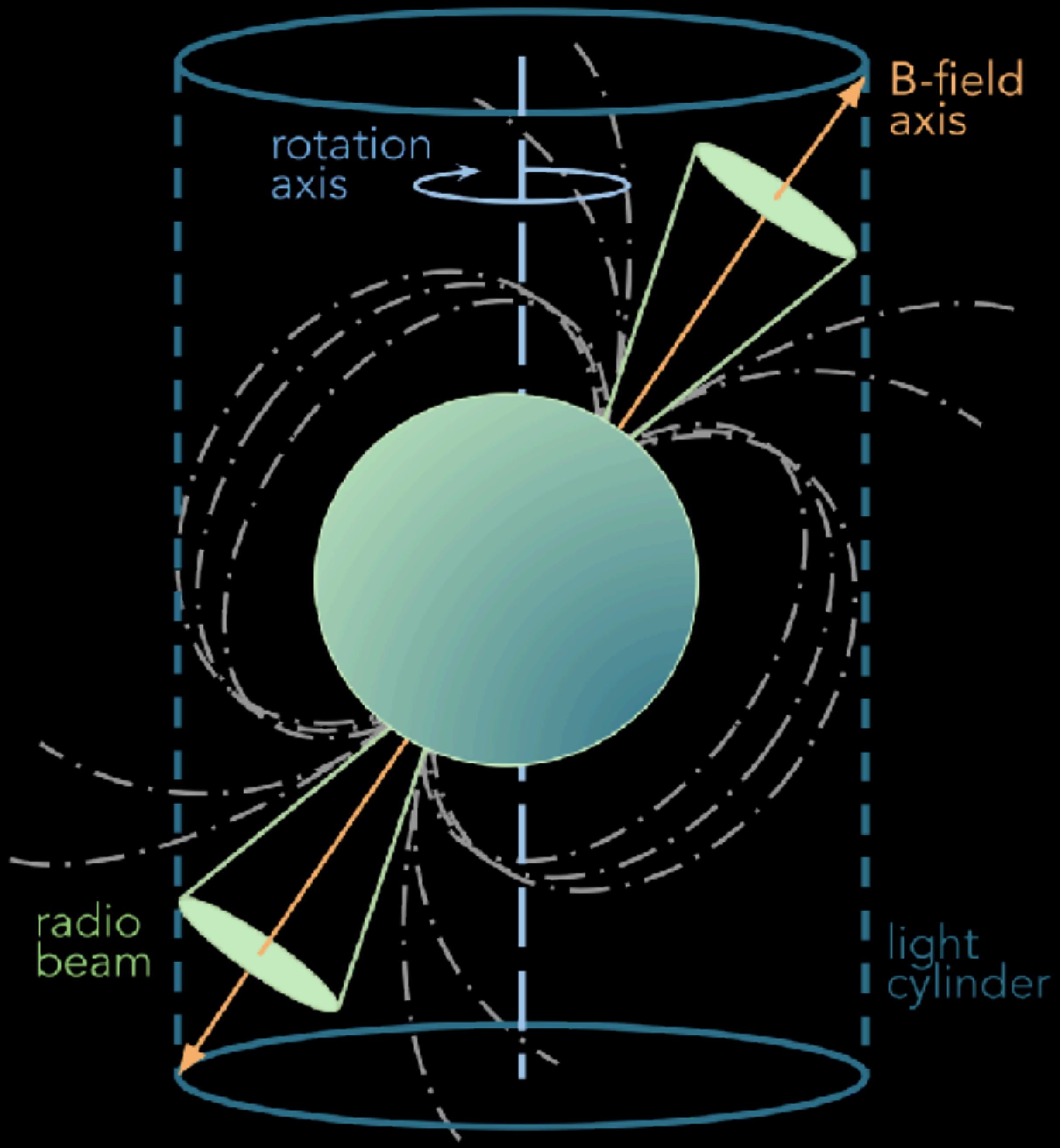
Pulsar Timing Examples



Credit: M. Surnis (2017, Ph. D. dissertation)

Pulsar Timing as a Tool

- There are **many applications** of pulsar timing, for example:
    - astrometry
    - "timing noise"
    - orbital motion
    - tests of general relativity and EOS physics
    - ISM structure
    - interstellar navigation
    - **direct detection of GWs**

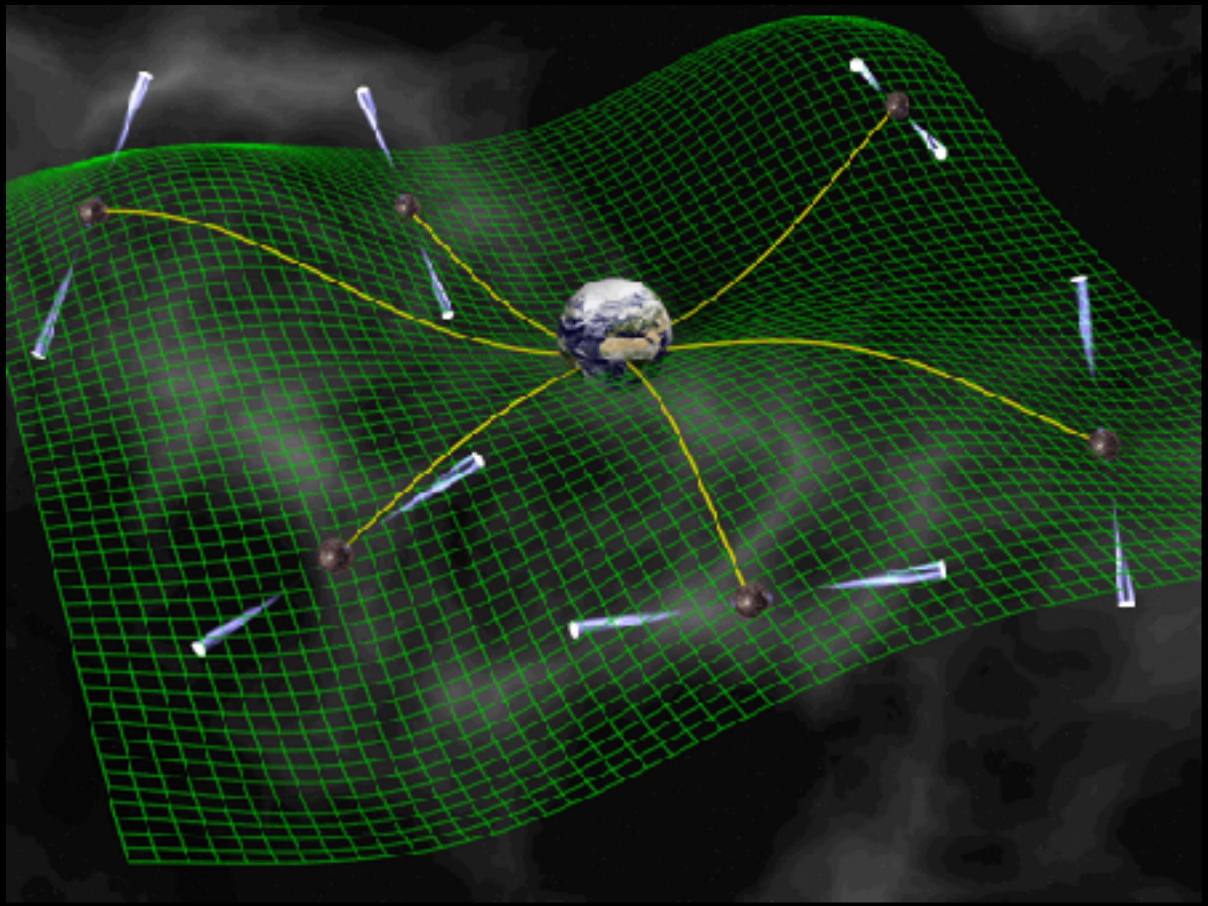


Credit: H. T. Cromartie

Part II: PTAs

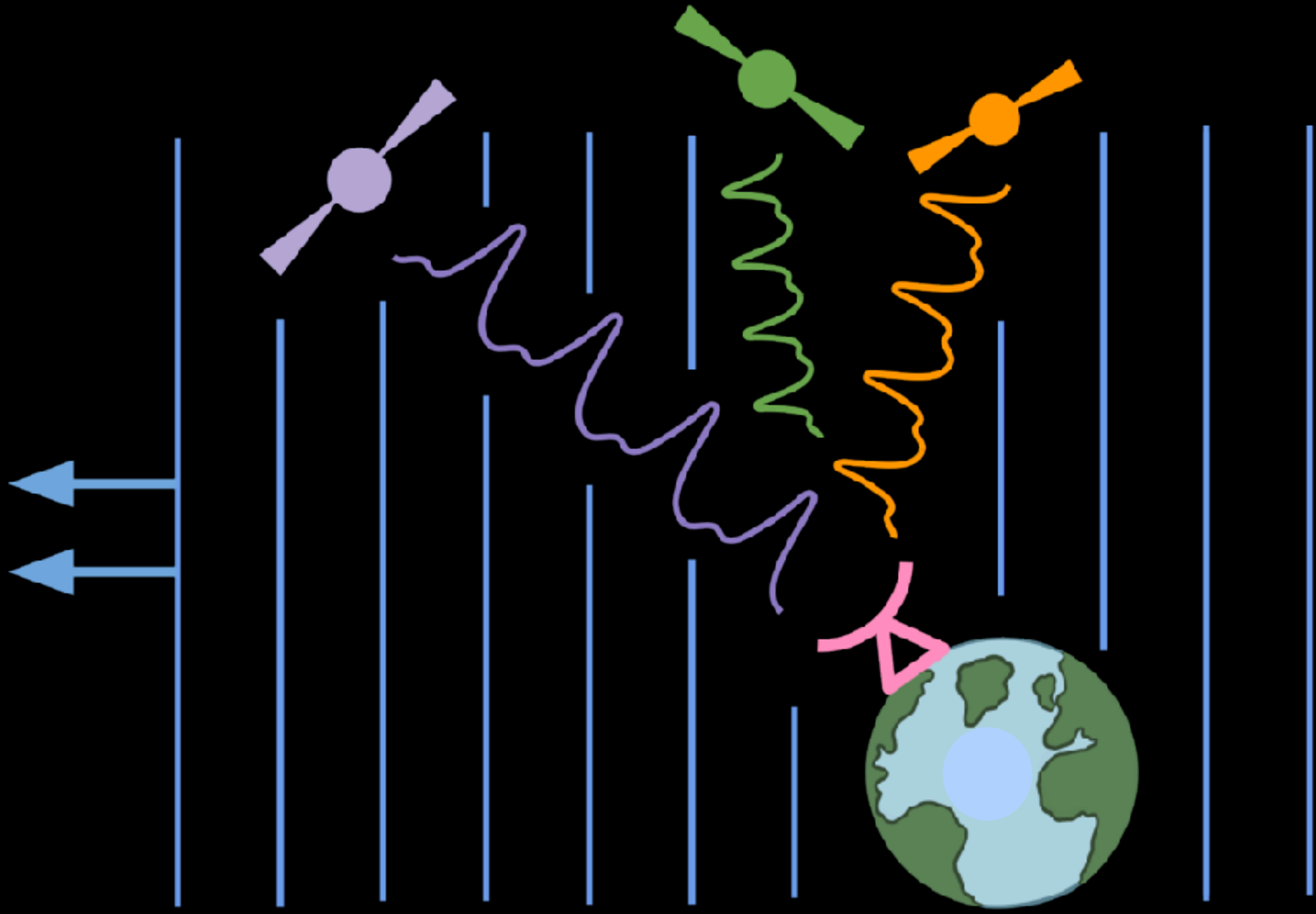
Pulsars Can Directly Detect GWs

- Each pulsar is unique in its timing properties, but all are observed using observatories on Earth.
- GWs that affect the observer therefore impact all pulsar data in the same way.
- In theory, we can construct a "**pulsar timing array**" and search for correlated timing features the TOA residuals for all pulsars.



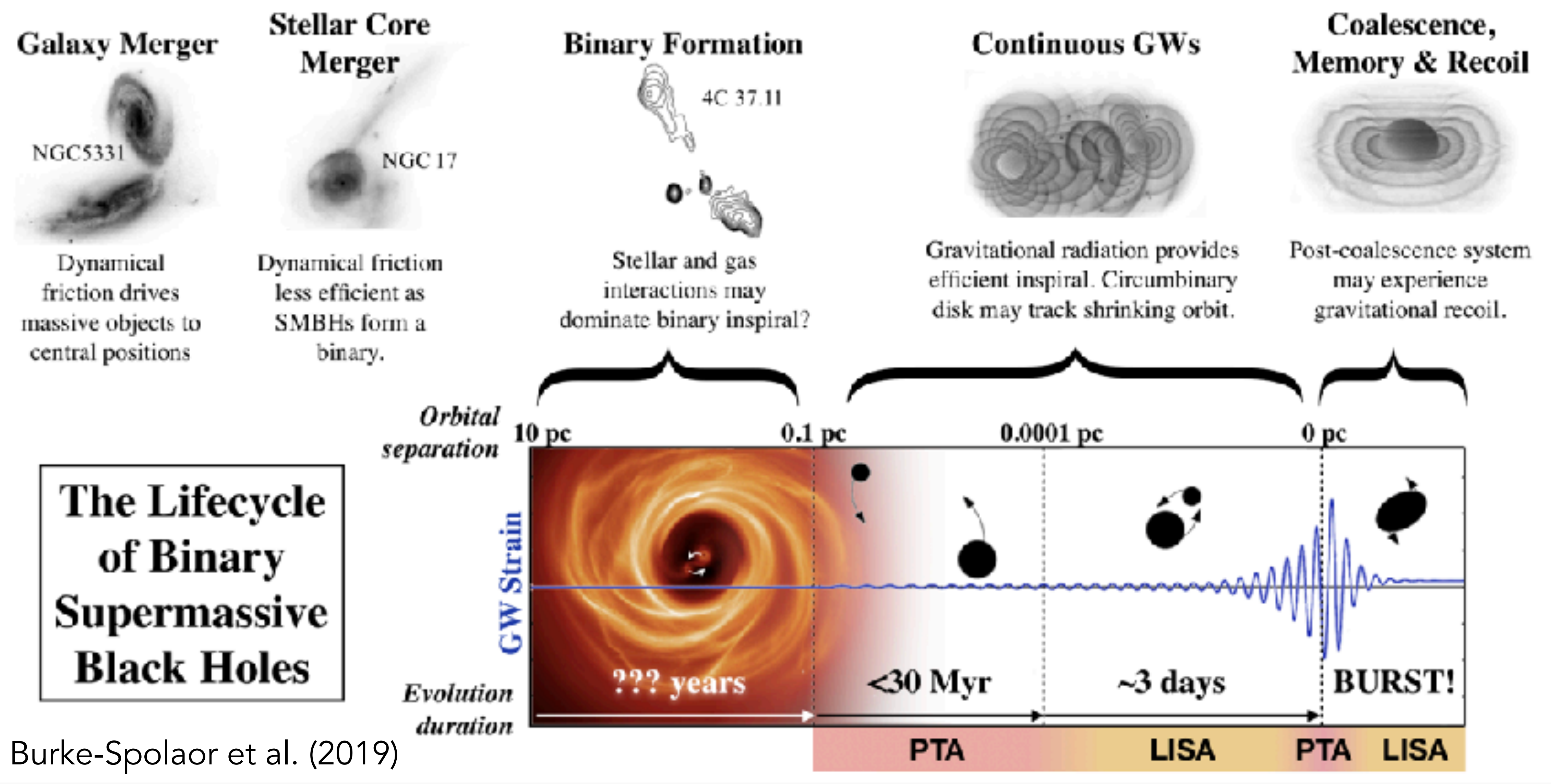
Credit: D. Champion

A Toy PTA



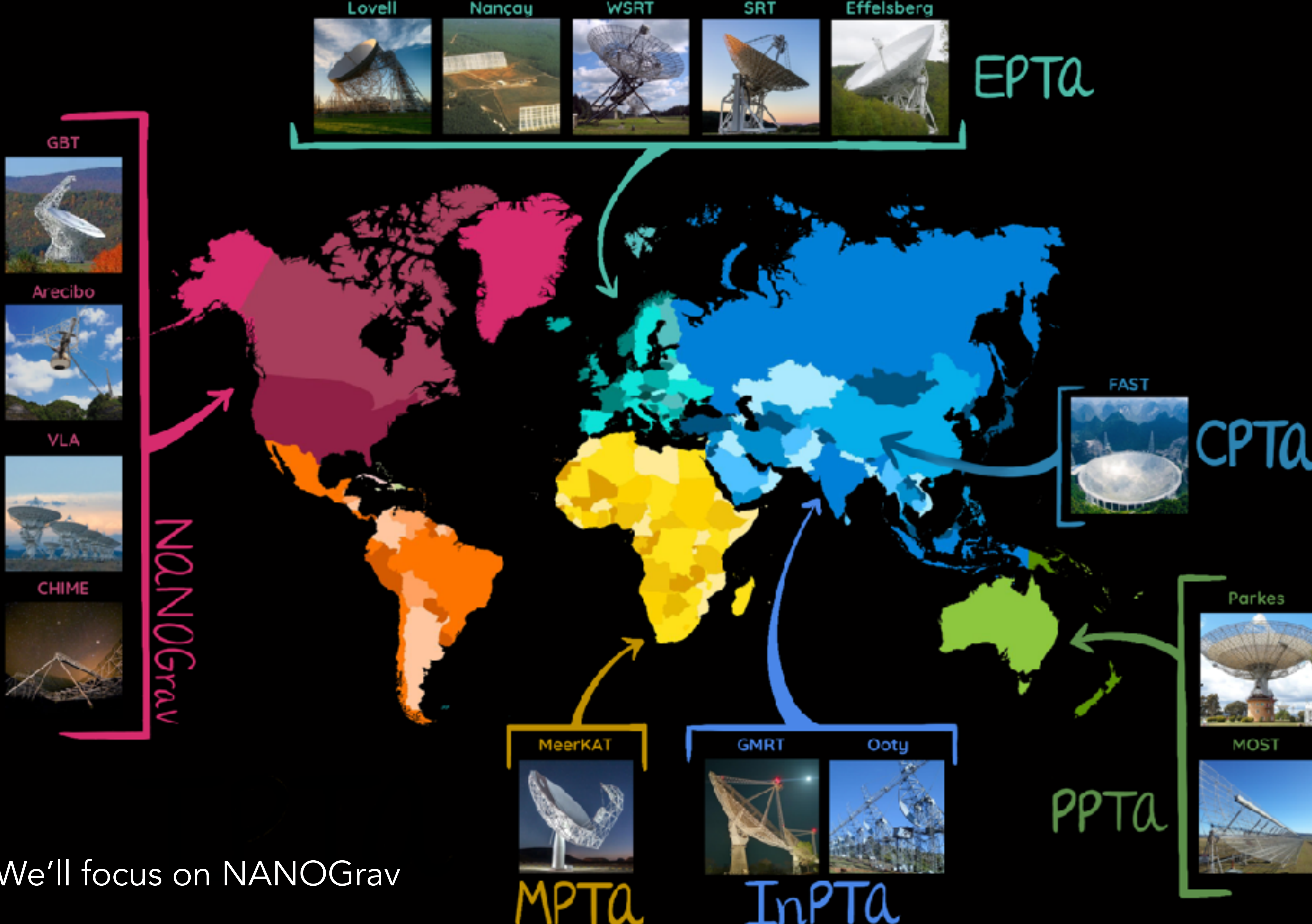
Credit: H. T. Cromartie

Source(s) of GWs for PTAs



Burke-Spolaor et al. (2019)

The expected source of nHz-freq. GWs for PTAs is a population of merging supermassive-black-hole binary systems, though PTAs can also place limits on GWs from, e.g., cosmic strings (e.g. Siemens et al., 2007).



We'll focus on NANOGrav

Credit: H. T. Cromartie

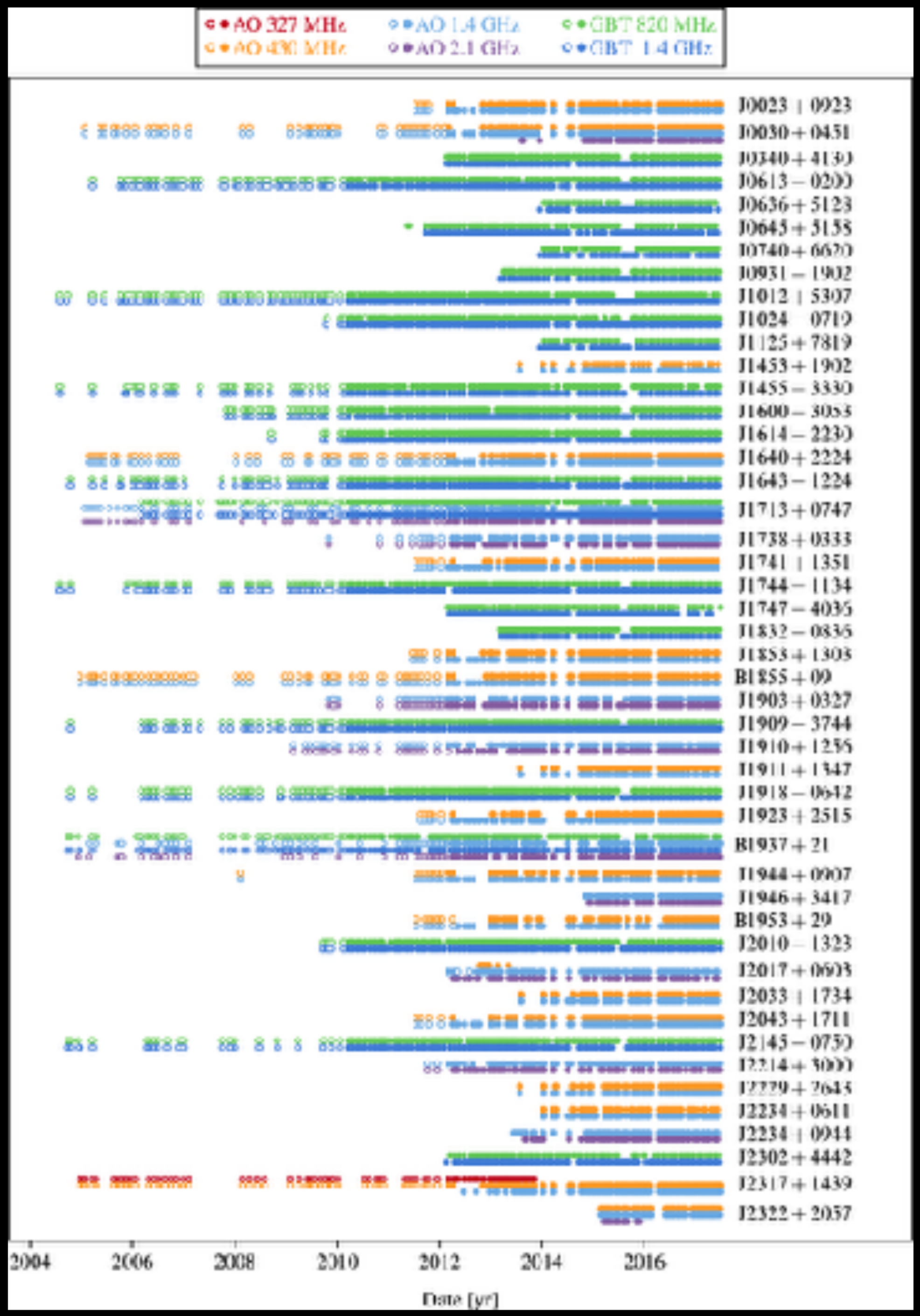
Part III: NANOGrav

The NANOGrav Collaboration

- NANOGrav = **N**orth **A**merican **N**anohertz **O**bservatory for **Grav**itational Waves.

- NANOGrav performs high-precision timing analyses of 70+ MSPs, with the key goal of detecting nHz-freq. GWs.

- `https://nanograv.org/`



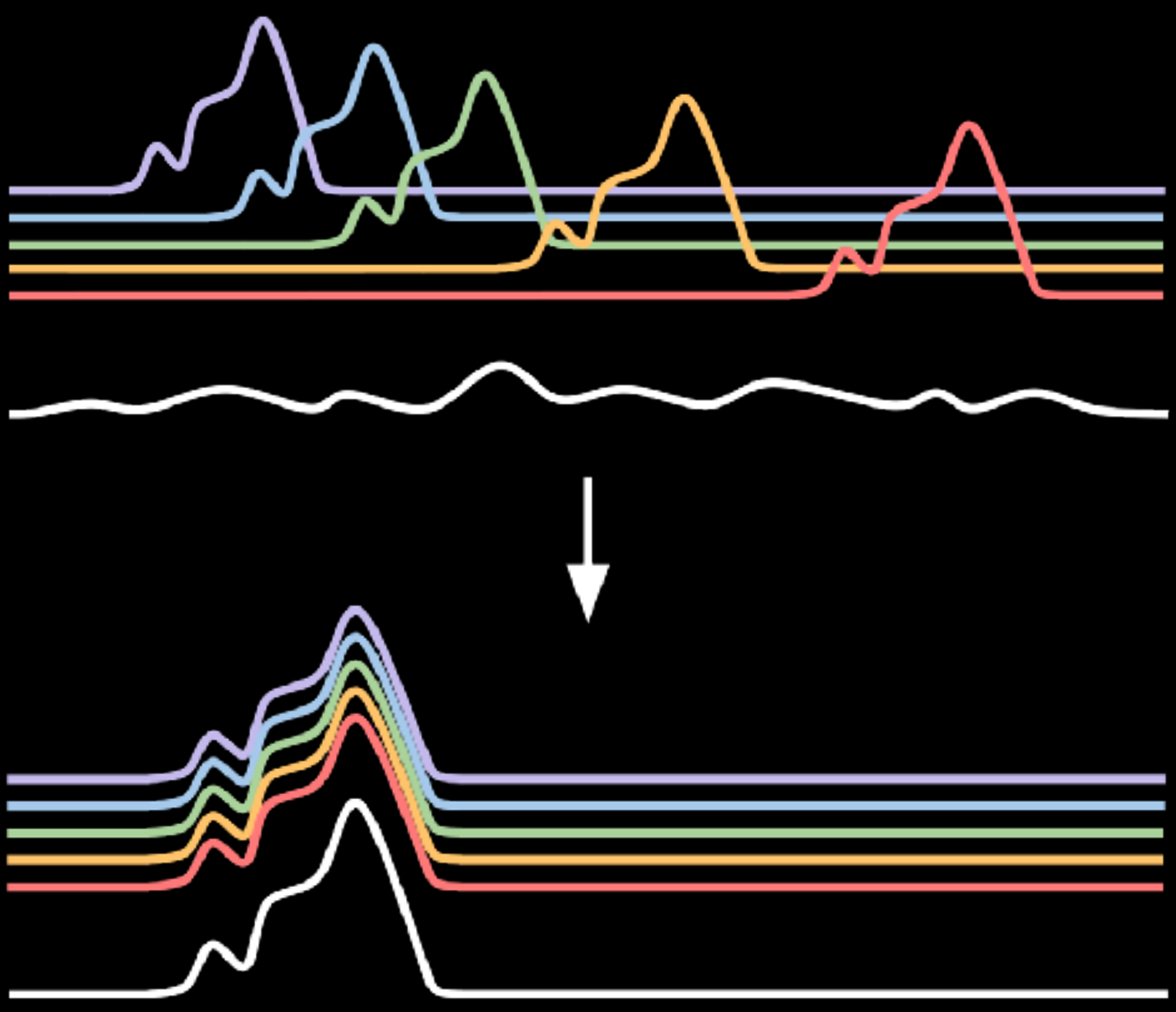
Alam et al. (2021a)

(Most of) The NANOGrav Collaboration

Telescopes Used by NANOGrav

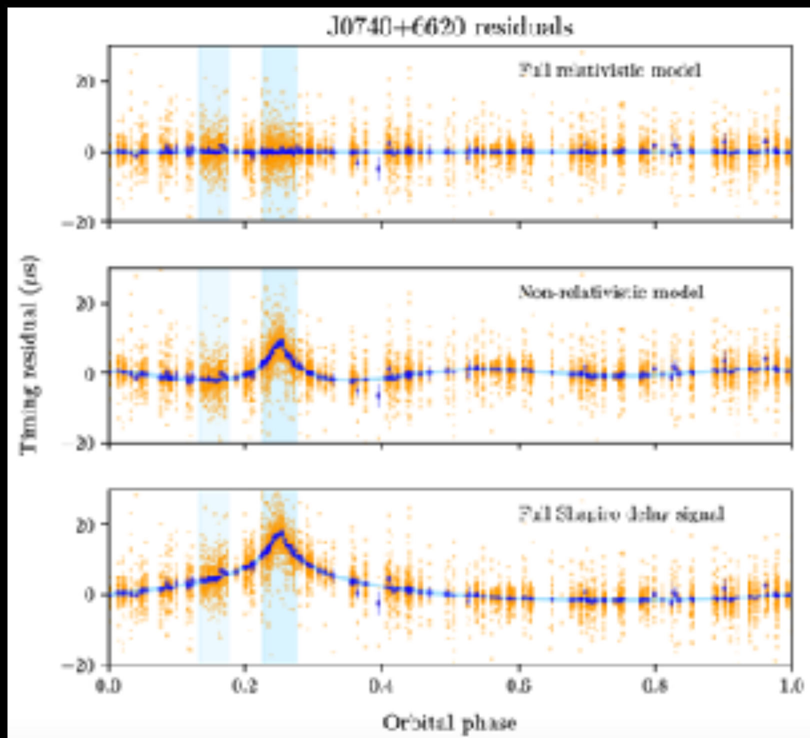
NANOGrav Data/Noise Analysis

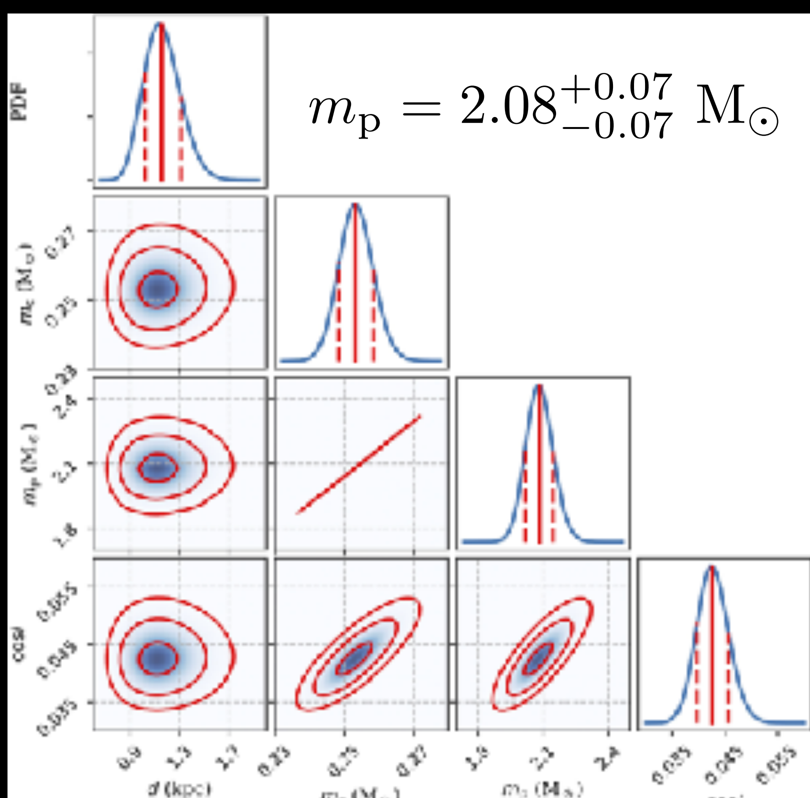
- NANOGrav uses methods discussed in **Part I** to obtain timing models and TOA residuals for all MSPs.
- NANOGrav also employs analysis methods to model all possible sources of stochastic "timing noise", e.g., variations in dispersion (right).
- See Lam et al. (2017, 2019) for discussions on noise sources and their mitigation.

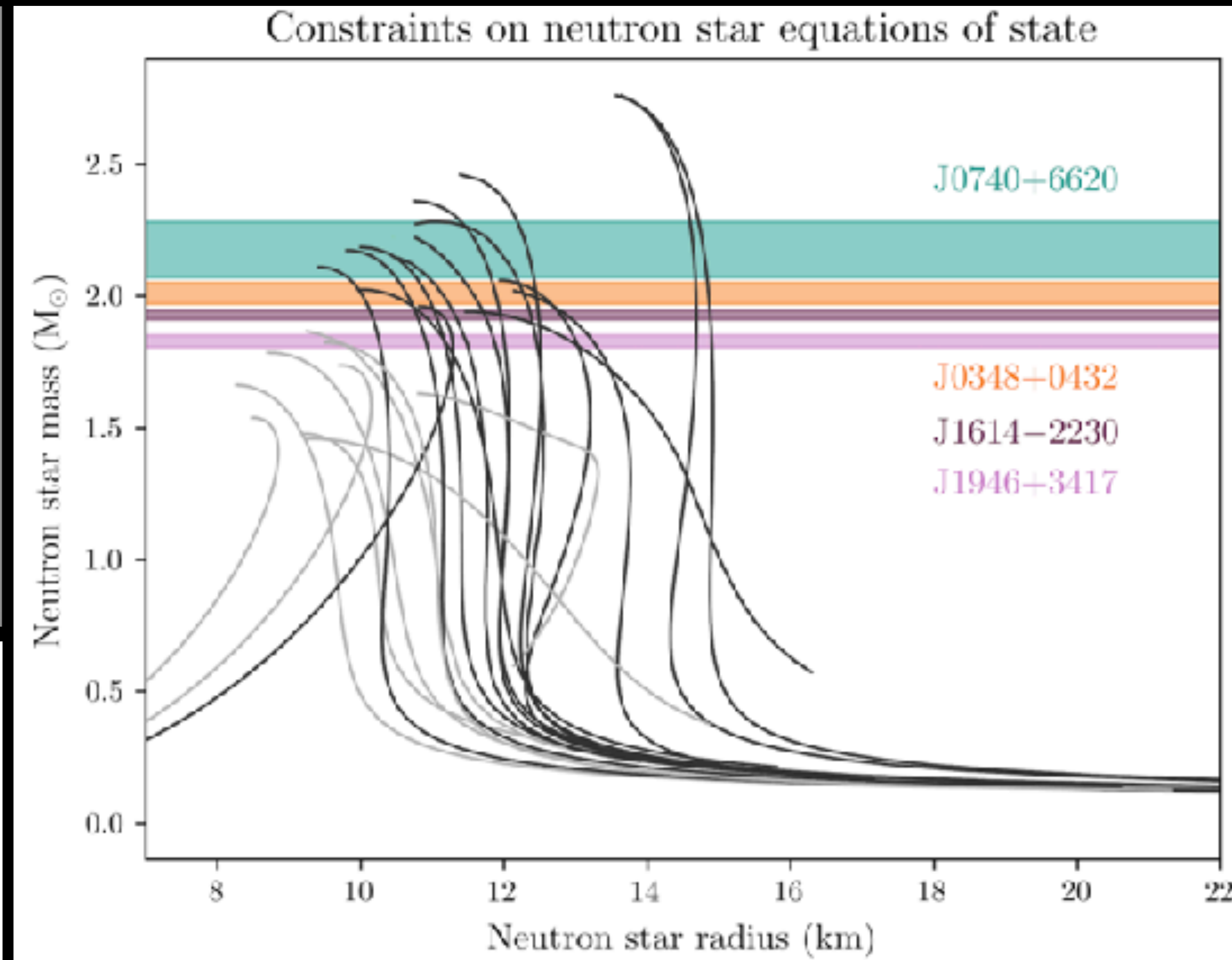


Credit: H. T. Cromartie

Sidenote: Ancillary Science with J0740+6620







The NANOGrav data set for PSR J0740+6620 yields a significant measurement of the Shapiro time delay, which itself is related to the mass and geometry of the system —> **highest mass NS known**!

See Cromartie et al. (2019) and Fonseca et al. (2021).

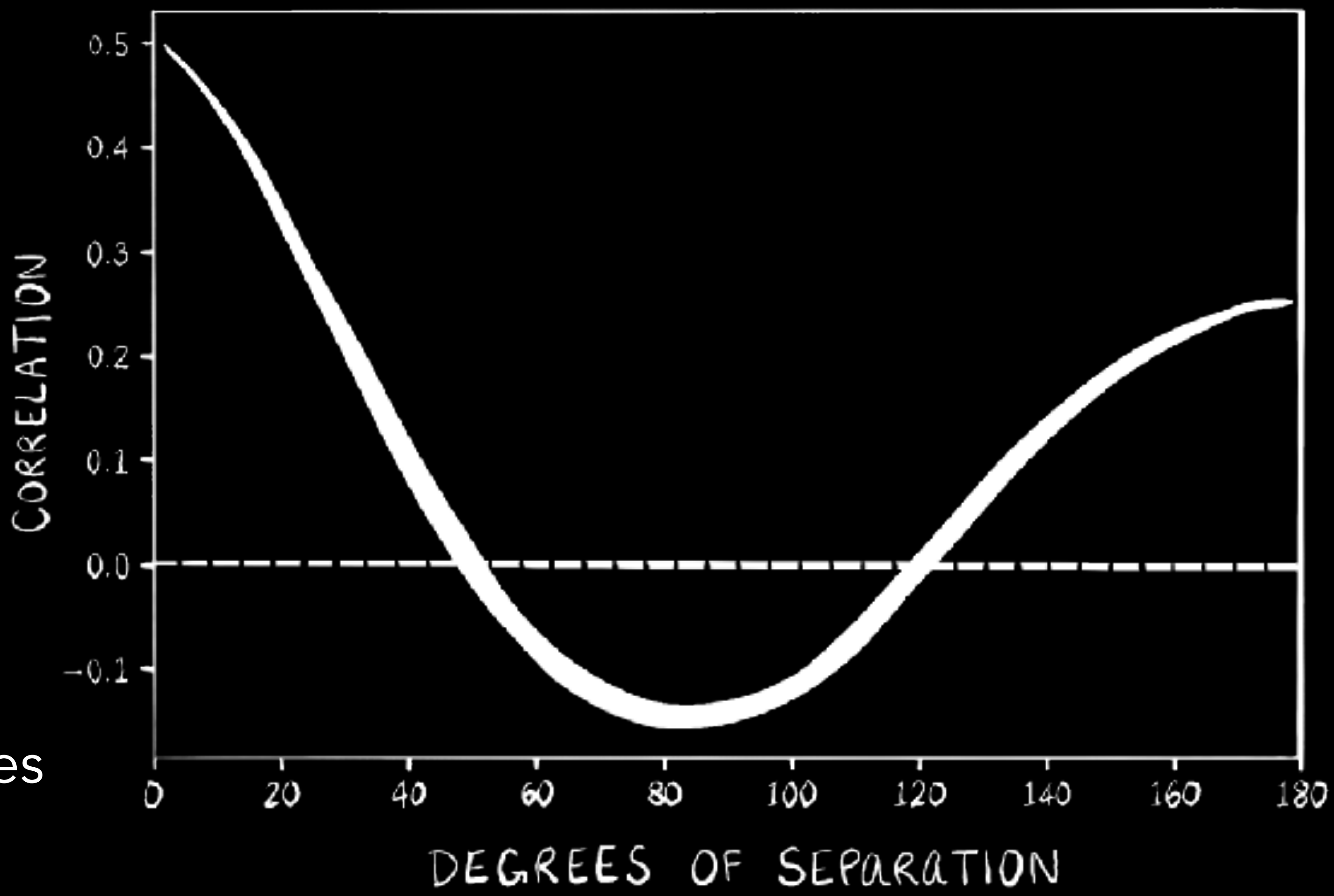
Searching for GWs in the NANOGrav Data Set, I

The residuals induced by a stochastic GW background is given by

$$S_{ab}(f) = \Gamma_{ab}(f)\frac{h_c^2(f)}{12\pi^2 f^3}$$

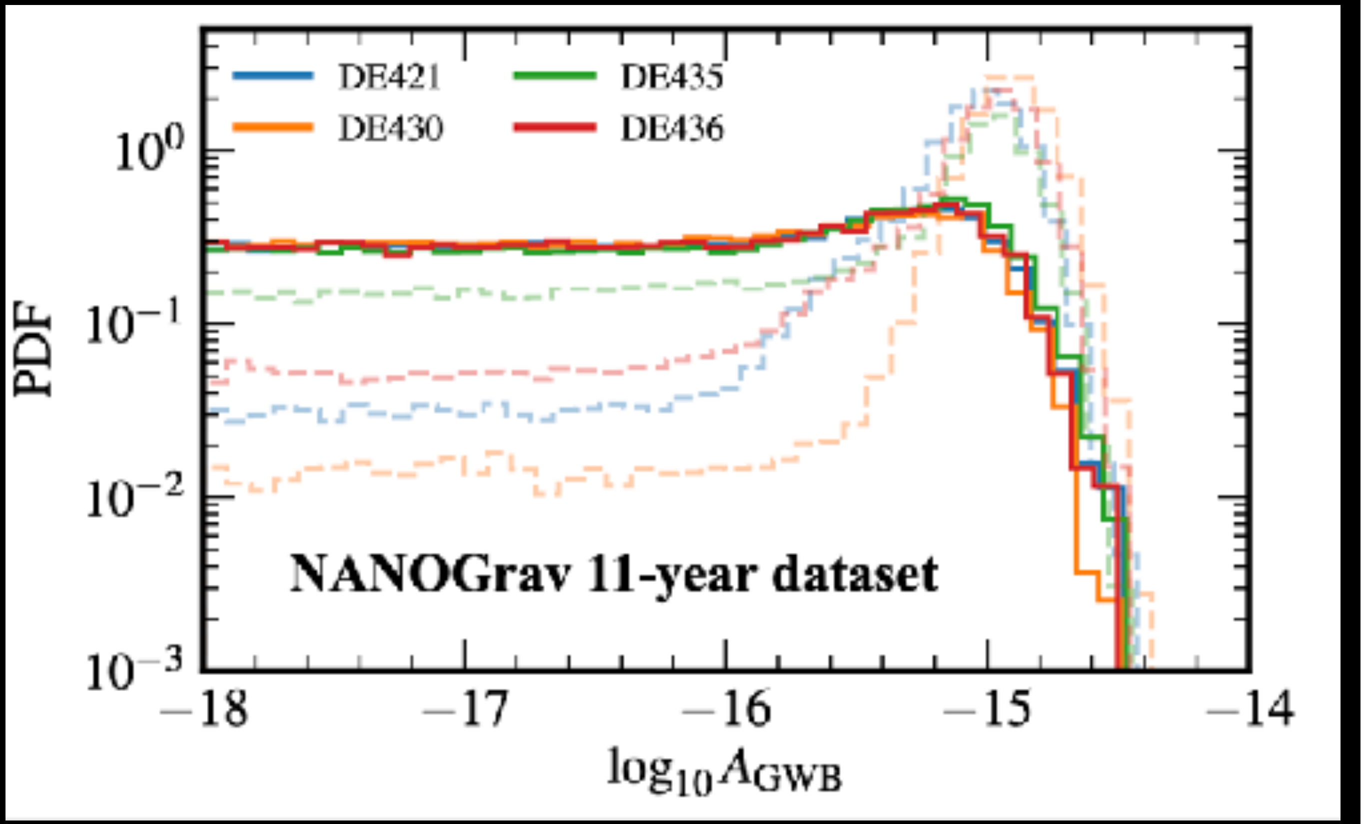
where:

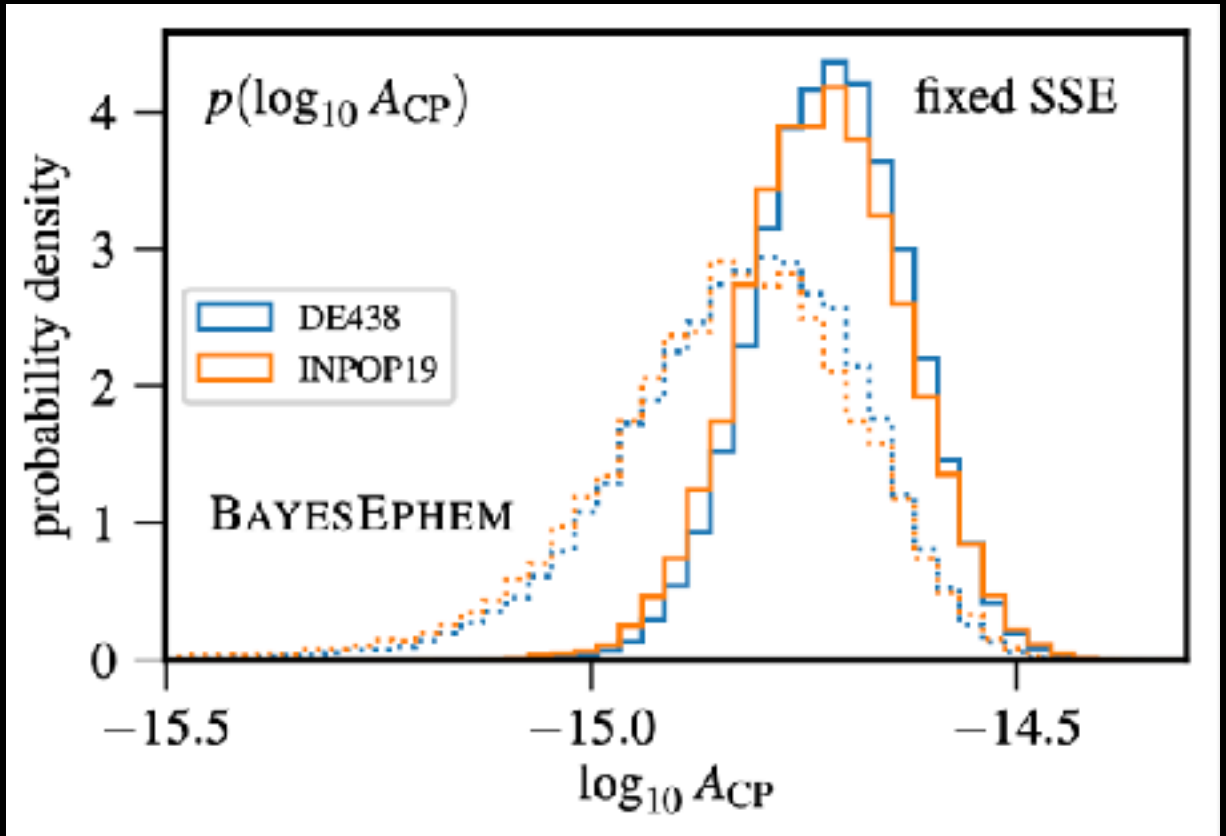
- "ab" denotes a pair of pulsar baselines
- "h_c" is the GW "strain" amplitude
- Γ is the degree of correlation between "ab" pulsars (Hellings-Downs curve; right)



Credit: H. T. Cromartie

Searching for GWs in the NANOGrav Data Set, II



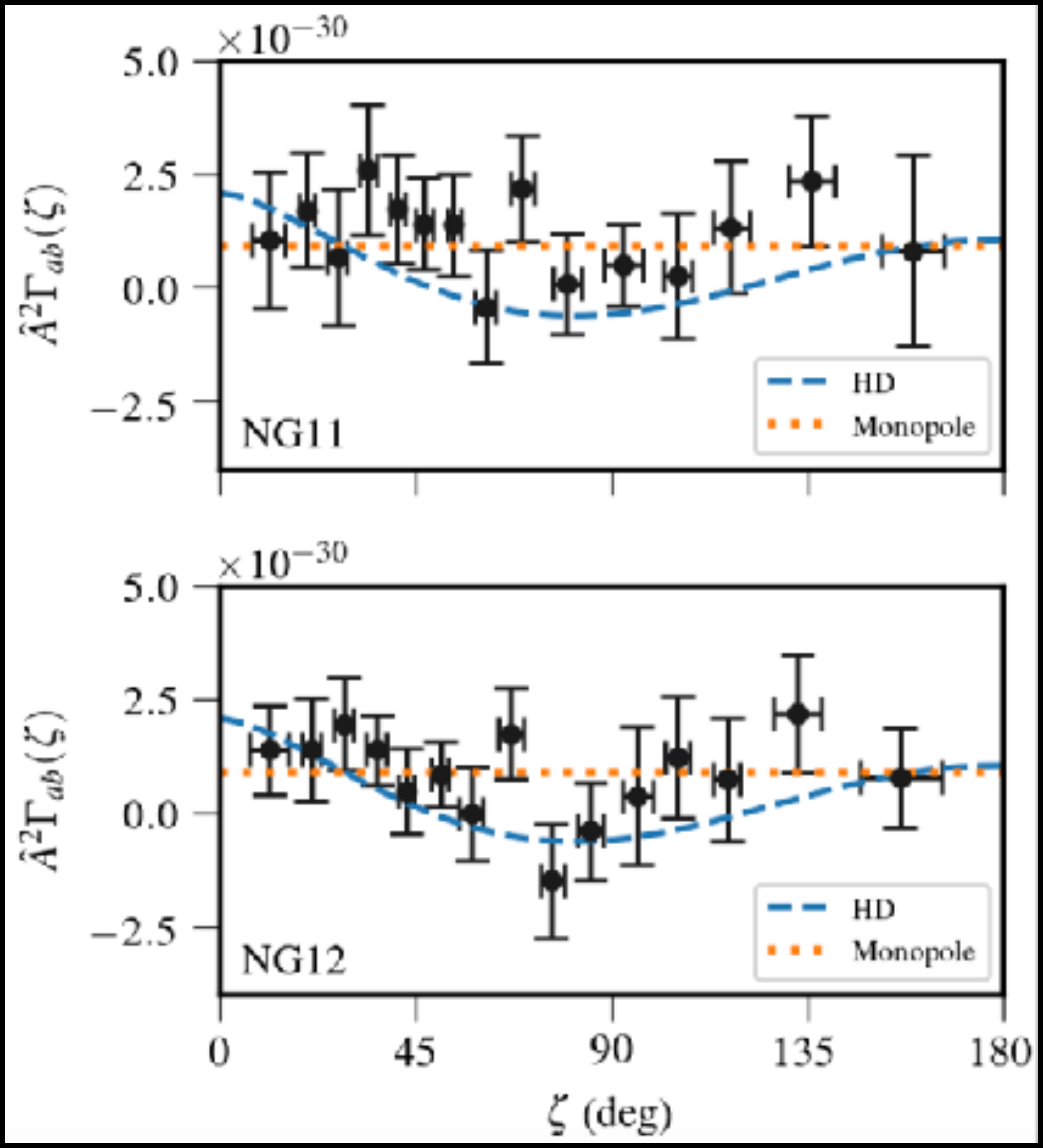


Correlations of the NANOGrav best-fit TOA residuals were producing improved upper limits on the GW amplitude (e.g., Arzoumanian et al., 2018; left) **until recently**, when the NANOGrav 12.5-yr data set showed significant signs of a common stochastic process in all TOA data (Arzoumanian et al., 2021c; **right**).

The signal remains significant even when using different Solar-System ephermides (“DE”, “INPOP”) to model planetary impacts on our pulsar-timing data.

Did NANOGrav Detect GWs??

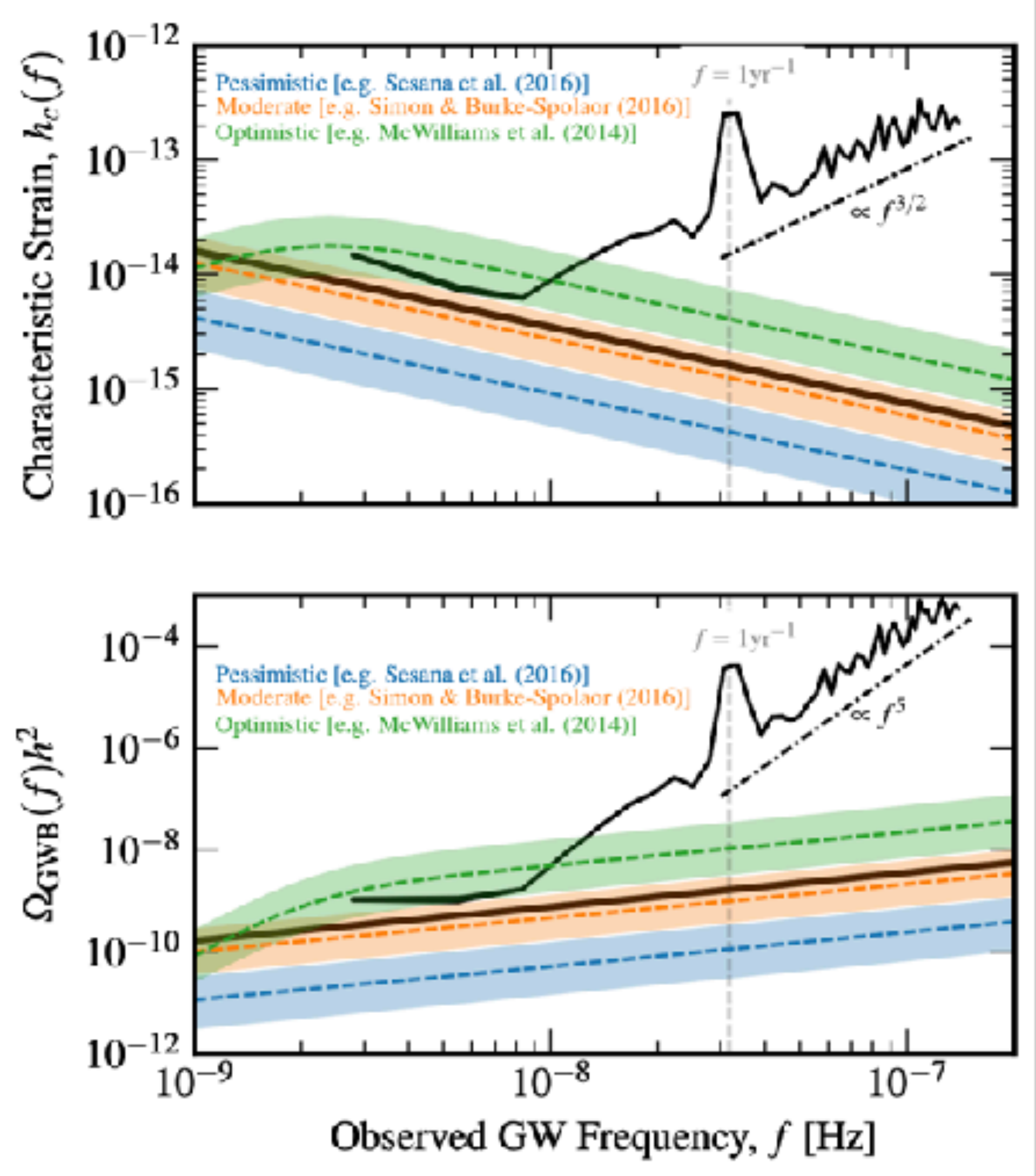
- NANOGrav sees a common process, but is this due to a GW background?
- Reconstruction of the correlation curve cannot differentiate between Hellings-Downs (i.e., GW) and non-GW correlations, but constraints are improving between data releases.
- **Long story short**: we cannot say that we've detected the expected GW background (**yet**).
- See Allen et al. (2023) for a thorough "detection checklist" for IPTA groups.



Arzoumanian et al. (2021c)

Ongoing and Future Work for NANOGrav

- NANOGrav is currently finalizing its **15-yr data set**.
- The NANOGrav data set will be publicly released within the next ~2 months.
- Major effort ongoing with other IPTA groups to publish independent+joint analyses of all PTA data sets on a similar timescale.
- Stay tuned!



Arzoumanian et al., 2018