Precise Radio-Derived *(Neutron Star)* Mass Measurements from the NANOGrav 15-Year Data Set

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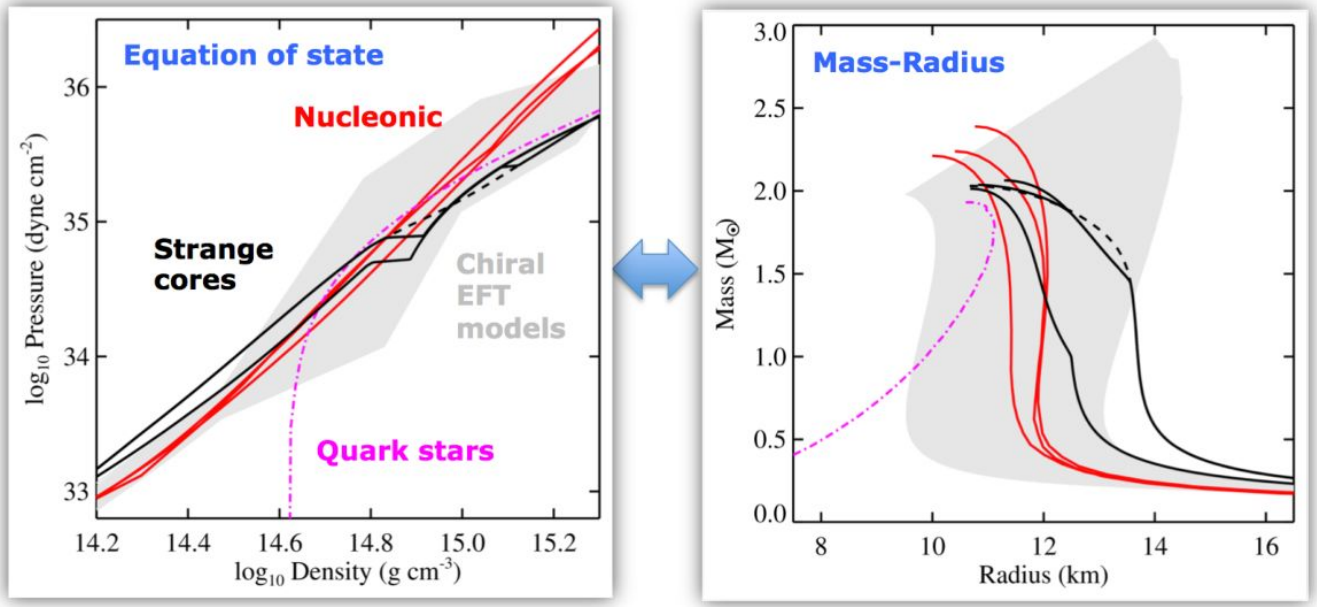
NASA Hubble Fellowship Program

Outline

- Motivation
- Quick introduction to pulsar timing & NANOGrav
- Comparing 15-year binary parameters
- “Advanced” analysis
- Future plans and prospects

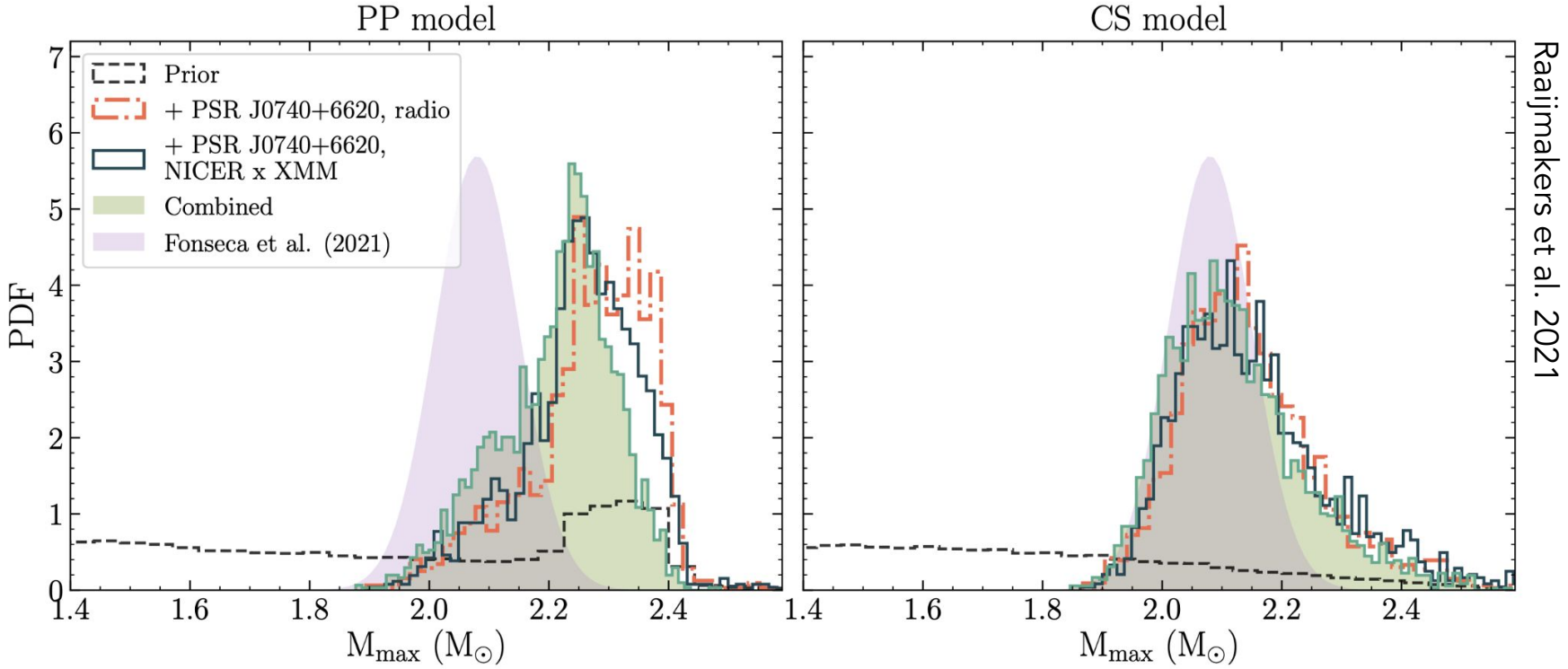
Disclaimer: this is all completely preliminary!

Motivation



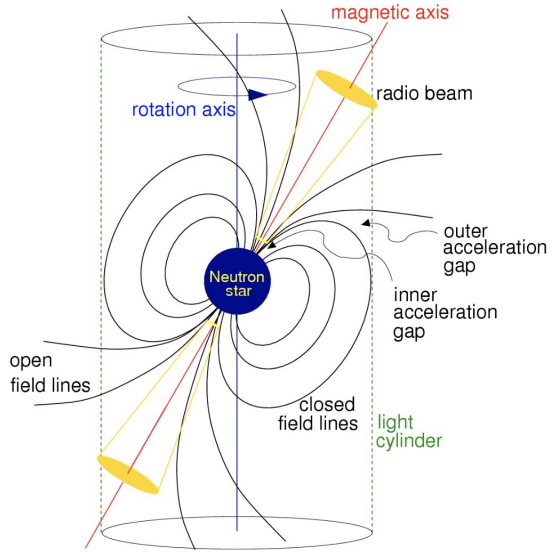
Watts et al. 2016

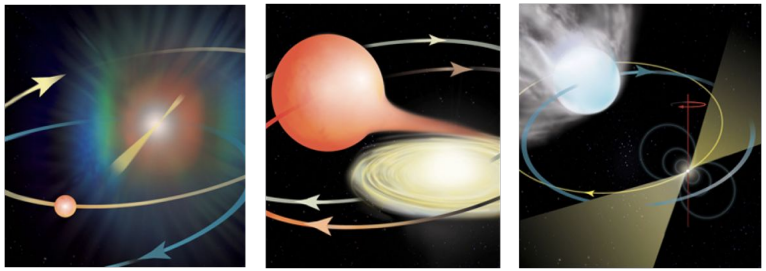
Motivation


PP model
CS model
Prior
+ PSR J0740+6620, radio
+ PSR J0740+6620, NICER x XMM
Combined
Fonseca et al. (2021)
PDF
M_{max} ($M_\odot$)
M_{max} ($M_\odot$)
Raaijmakers et al. 2021

Millisecond pulsars

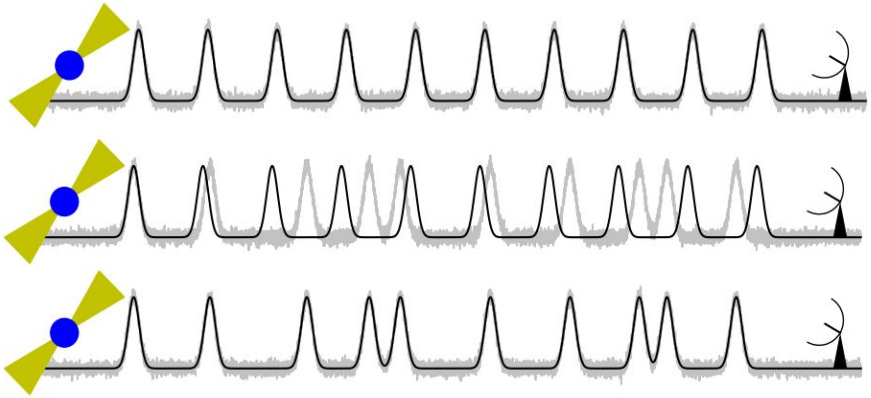
- Rapidly rotating (>700 Hz), highly magnetized neutron stars
- Beam radiation & spin, causing a "lighthouse" effect
- ~10 km, 1.4 $M_{\odot}$
- Recycling process spins up MSPs; most in binary systems
- ~400 MSPs known

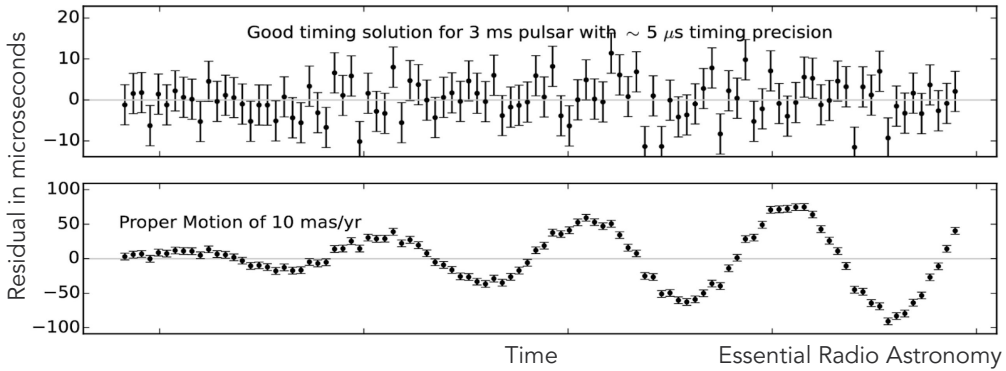




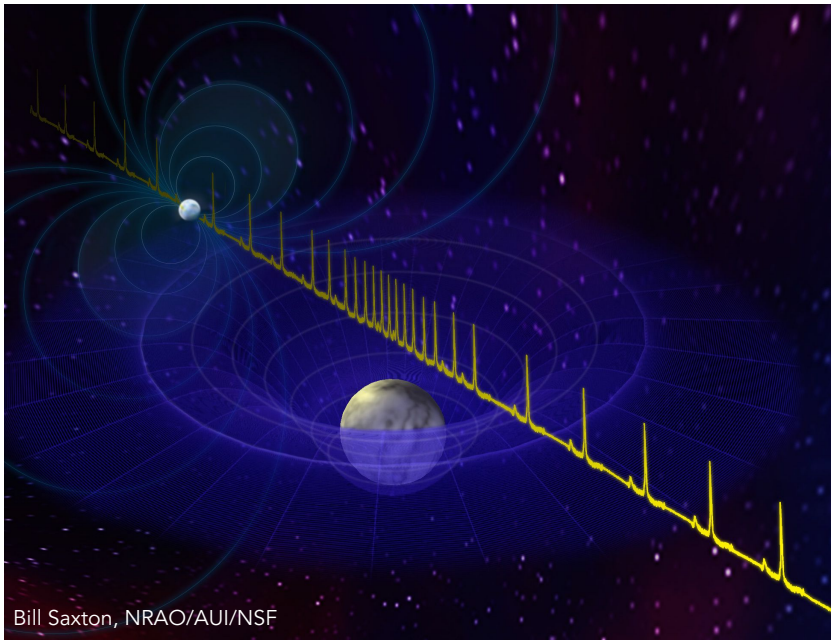
Lorimer & Kramer 2004 (top), Bill Saxton (NRAO/AUI/NSF, bottom)

Quick introduction to MSP timing





Shapiro delay



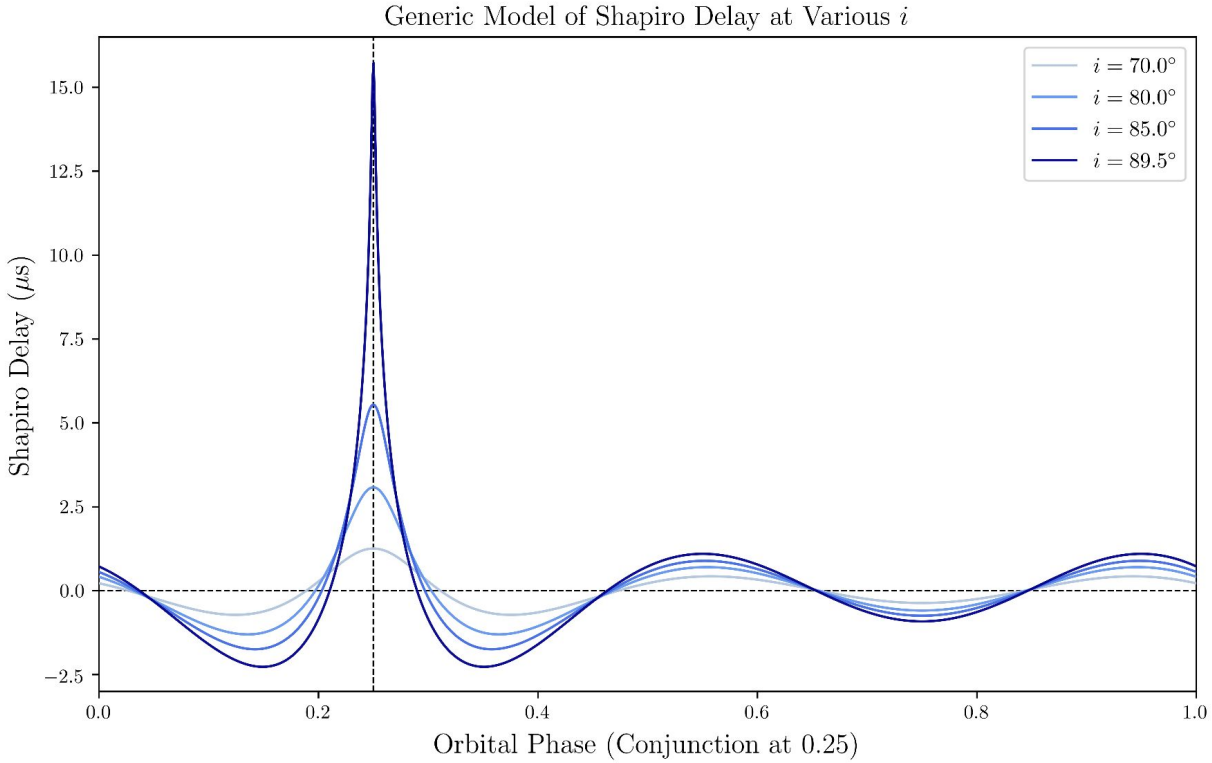
- Pulsar timing → 5 Keplerian parameters
- Shapiro delay occurs at superior conjunction in edge-on binary systems
- "Range" and "shape" PK parameters are directly measurable:

$$r = T_{\odot} m_2$$

$$s = x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_2^{-1}$$

$$f(m_p, m_c) = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}$$

Shapiro delay



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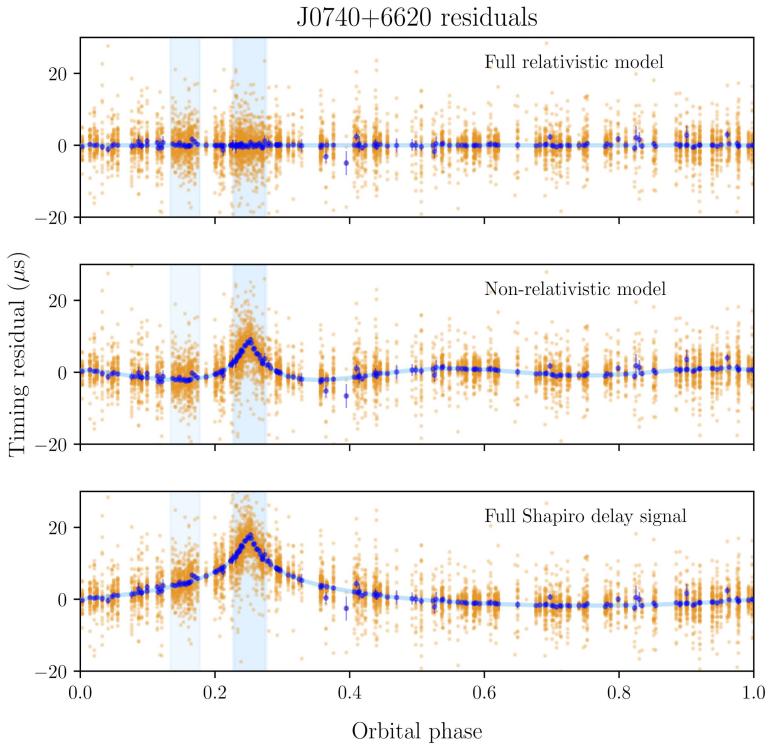
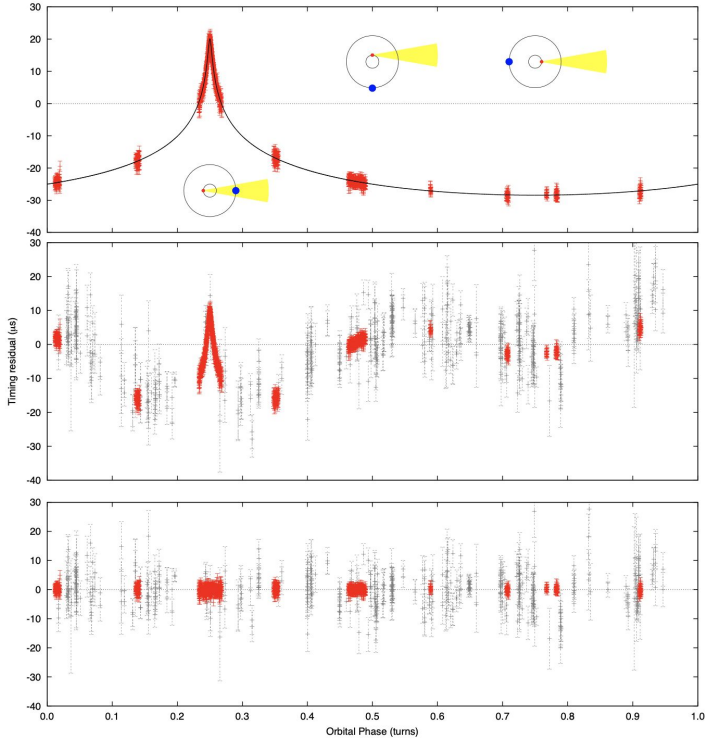
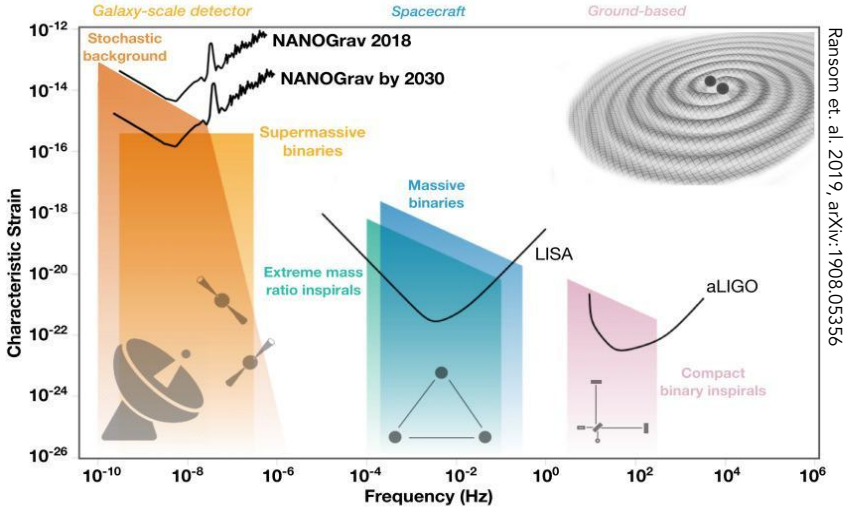


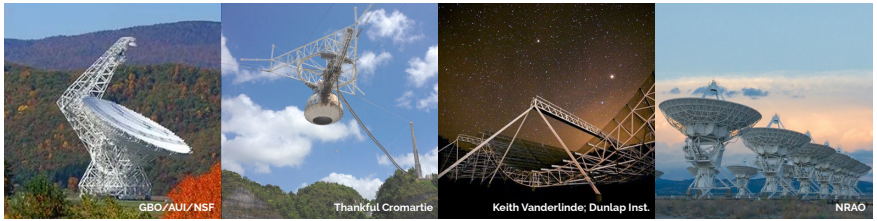


Cromartie et al. 2020 (left), Demorest et al. 2010 (right)

NANOGrav

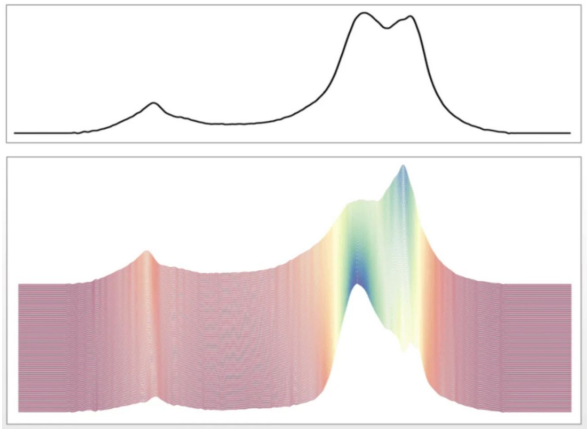
- Characterize the nanohertz gravitational wave (GW) universe through high-precision radio timing of millisecond pulsars
  - Supermassive black hole binaries: stochastic background, continuous wave (CW) signals, bursts with memory
  - Last parsec problem, merger rates, SMBHB populations
  - Exotic sources and gravity beyond GR
- Interesting secondary science = free! (NS masses, ISM studies, profile variation, etc.)

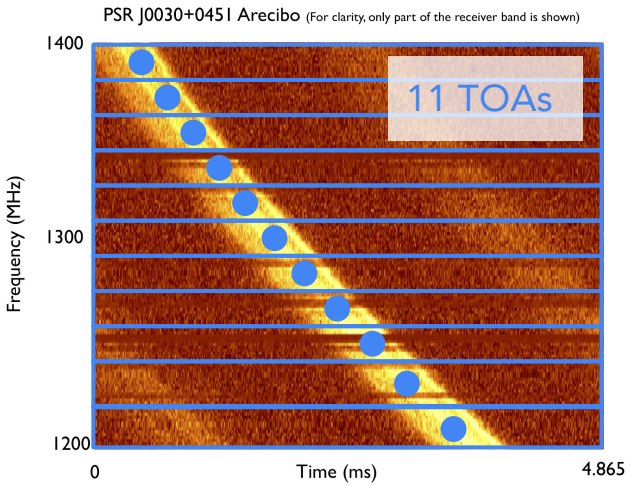


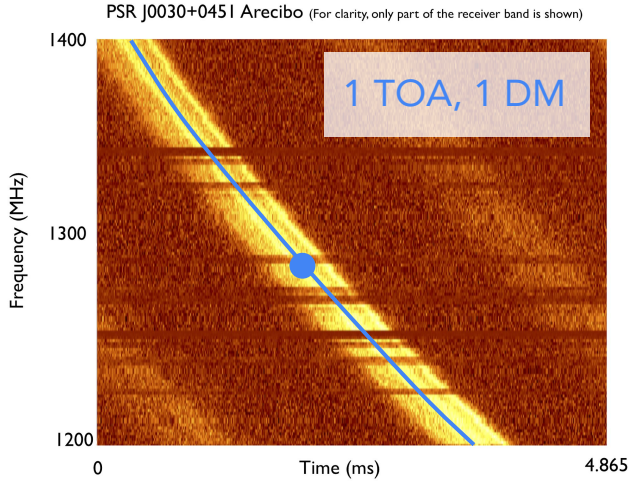


NANOGrav 12.5-year data set (WB timing)

- Narrowband and wideband data releases (Alam et al. 2021a+b) for 47 MSPs over ~13 years
- Wideband = data volume reduction by >30x!







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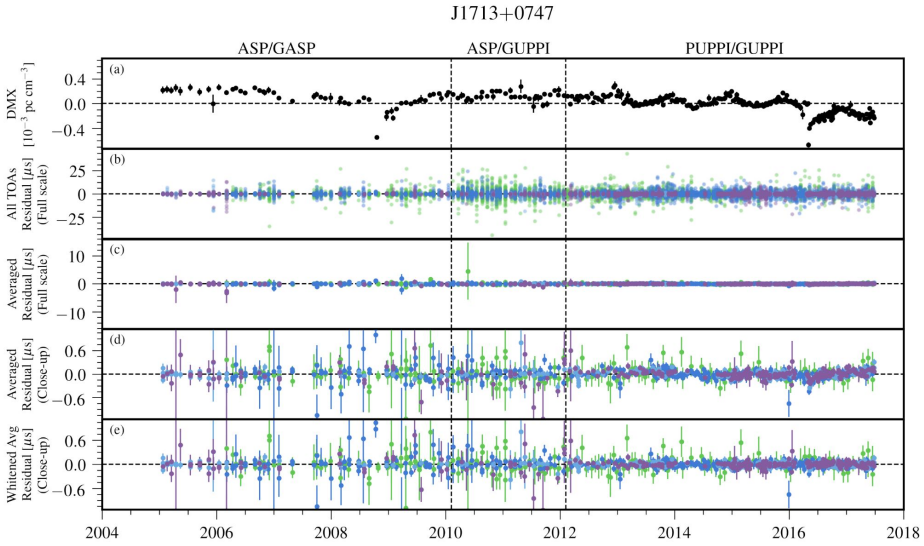
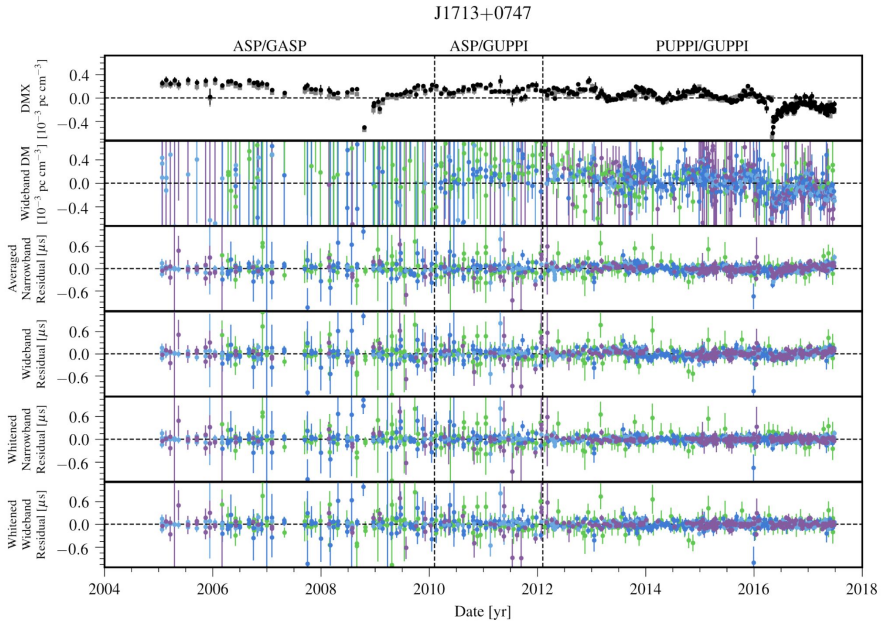
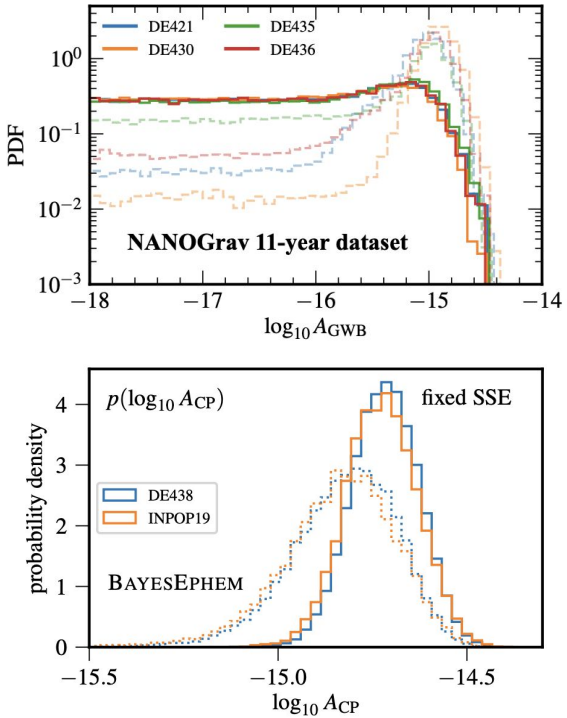




NANOGrav 12.5-year GW search results



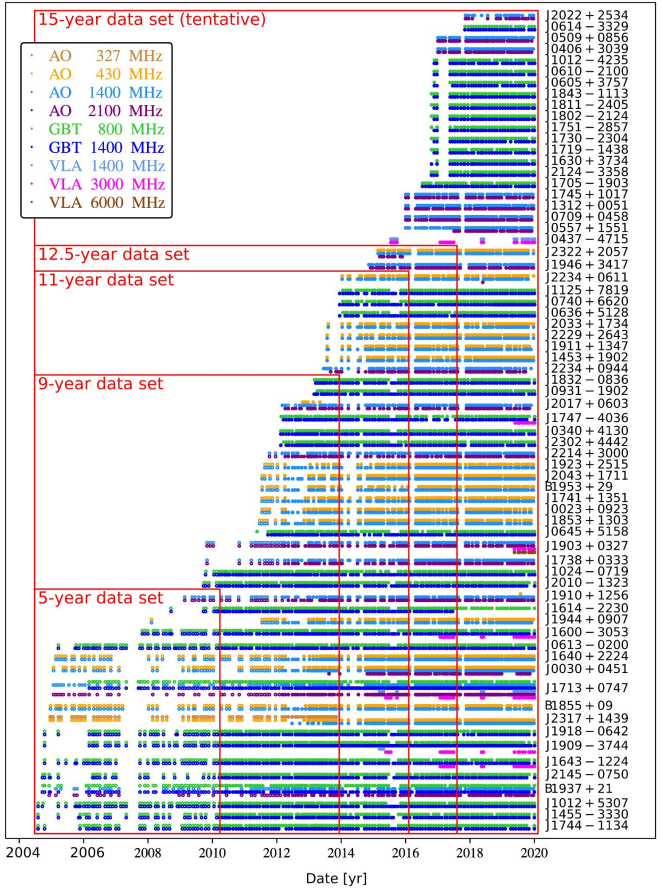
Arzoumanian et al. 2018 (top), 2020 (bottom)

- GWB analysis (Arzoumanian+21) finds:
  - Strong evidence for γ = 13/3 common red process
  - No strong evidence for HD correlations; evidence against monopolar and dipolar correlations
- Findings from other PTAs and the IPTA in agreement

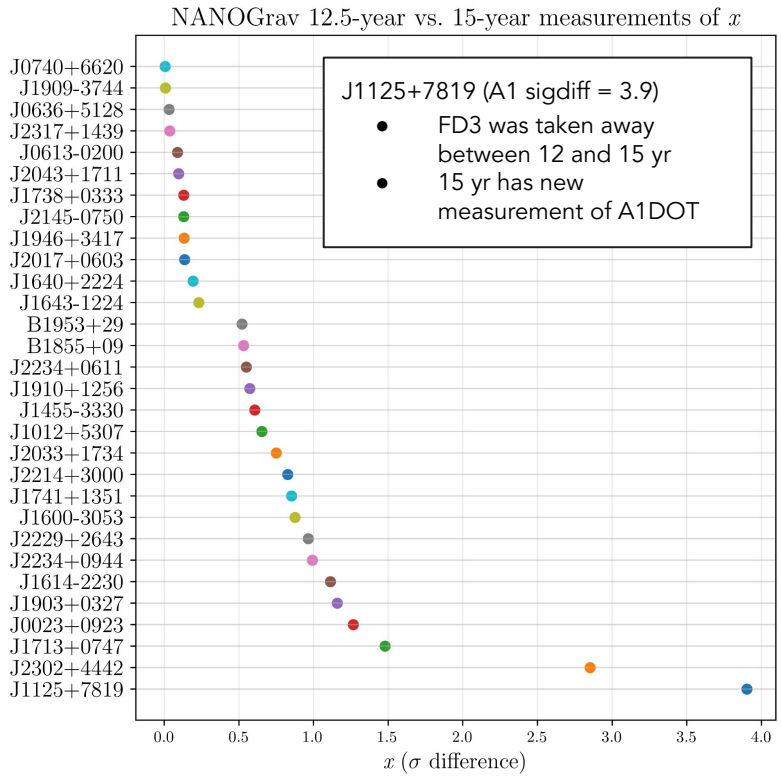
NANOGrav 15-year data set

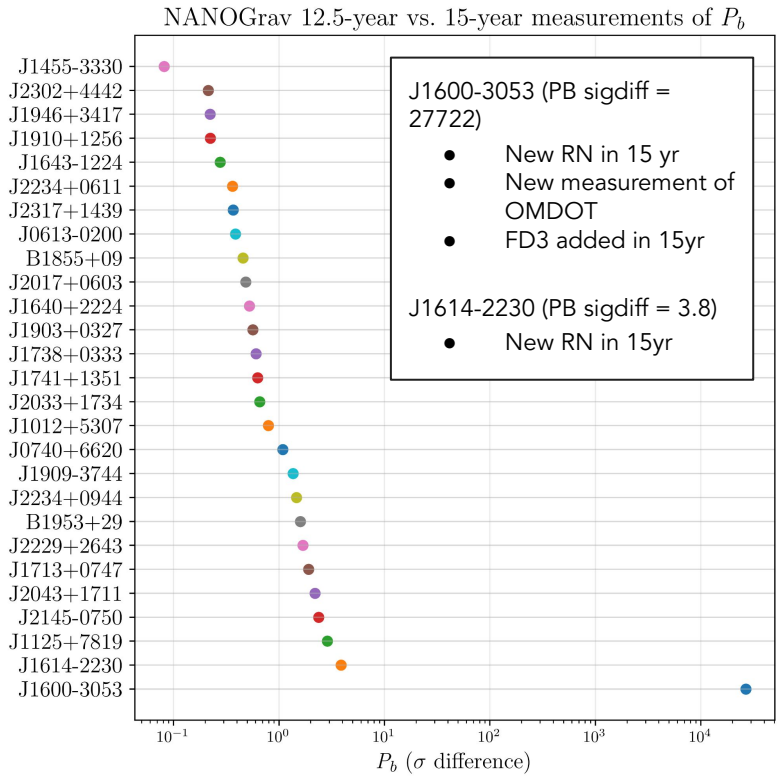
- 15-year data set adds 21 MSPs and ~3 years; GWB analysis is underway
- `PINT`-based timing in new pipeline
  - Transparency and accessibility
- VLA data and J0437-4715
- NB and WB timing, but WB issues under investigation

Courtesy David Nice



Comparing the 12.5-year and 15-year data sets





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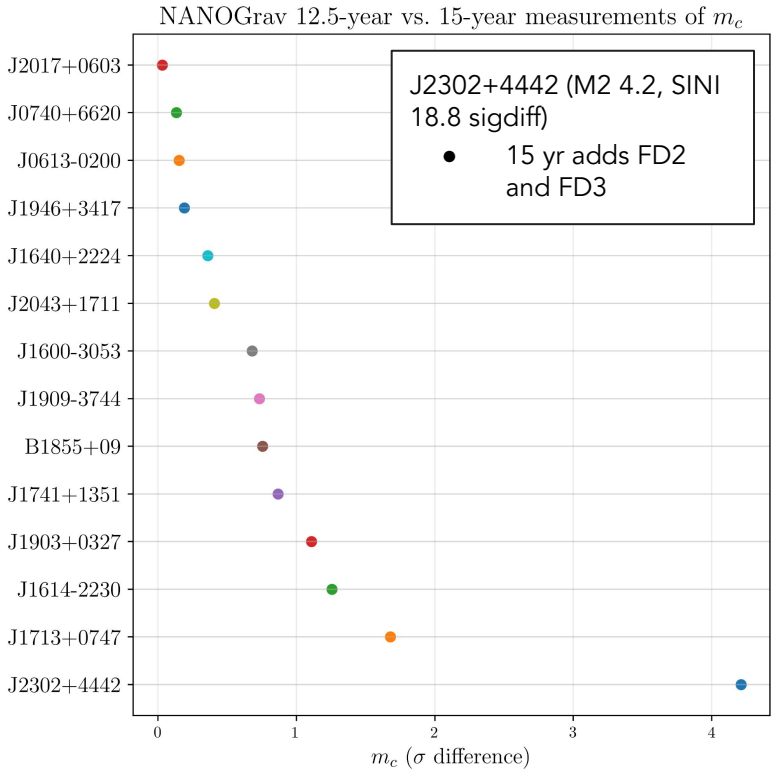

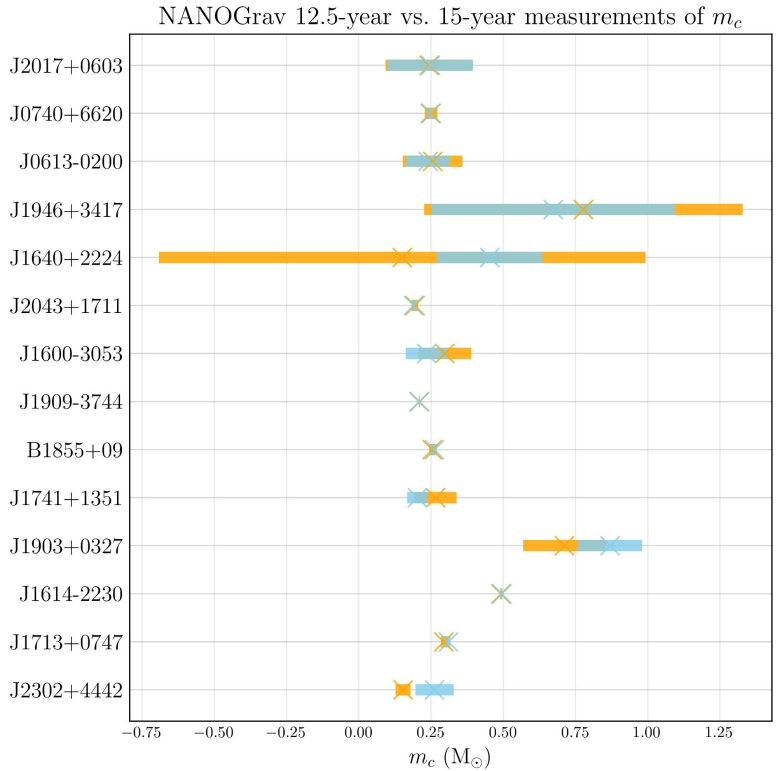

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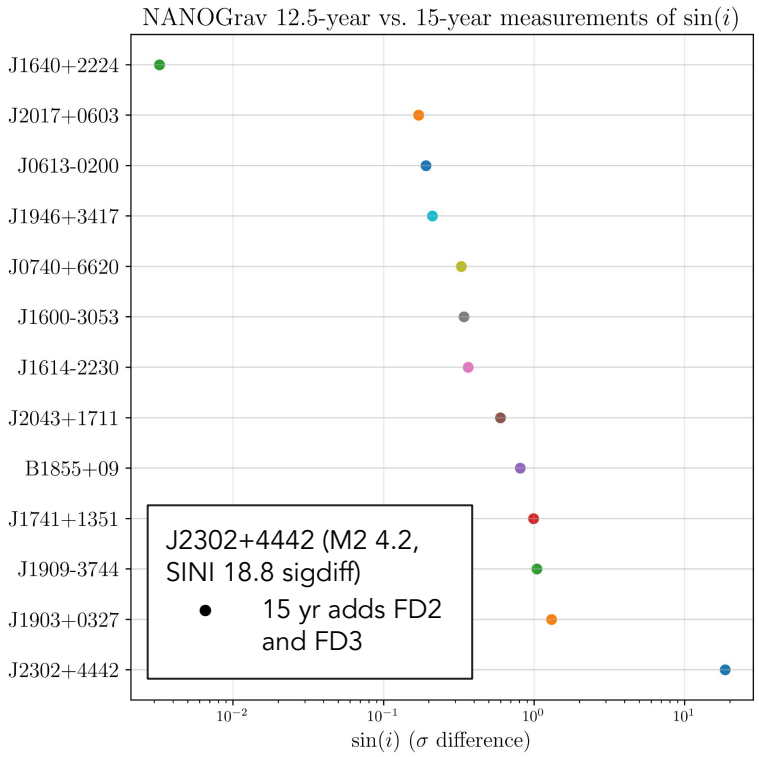
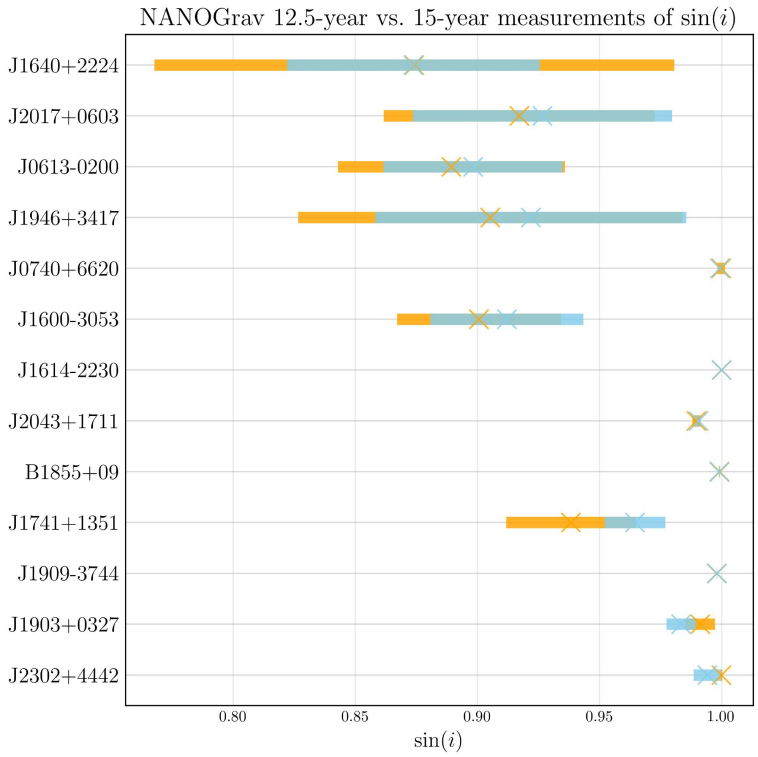
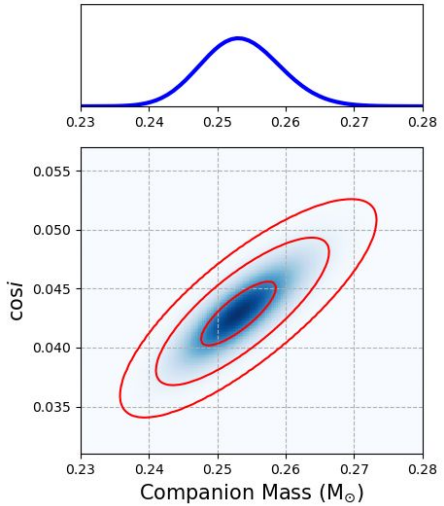
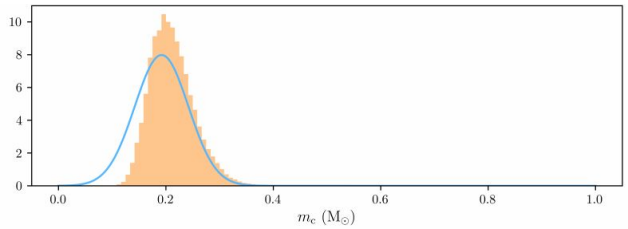




Advanced techniques

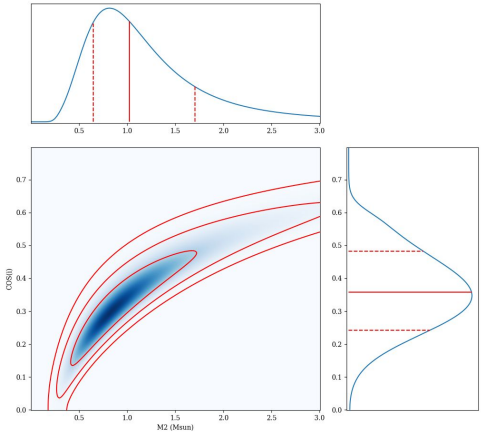
- Bayesian radio timing:
  - **Uncertainty:** parameters and correlations; model non-linear dependence
  - **Priors:** use physical information
  - **Model comparison:** compare models with different parameters (Vigeland & Vallisneri 2014)
- Implemented in `PINT` as `MCMCFitter`
- For now, χ^2 gridding (Fonseca et al. 2016) in `TEMPO(2)/PINT` helps; implementing in pipeline
- *WB data set makes Bayesian timing feasible*



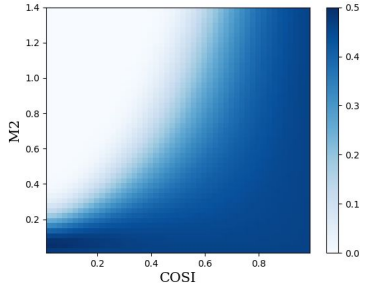


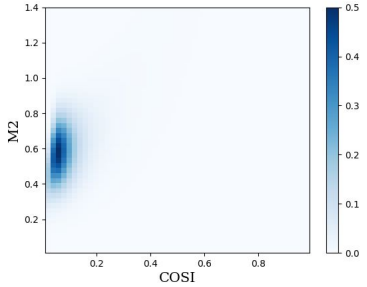
Selected gridding results

- *Incomplete and preliminary!*
- All 15yr pulsar masses (so far; vast majority done) consistent with 12.5-year results
- Some interesting new results: J1630+3734: low CI (2-sigma) > 2.1 $M_\odot$:

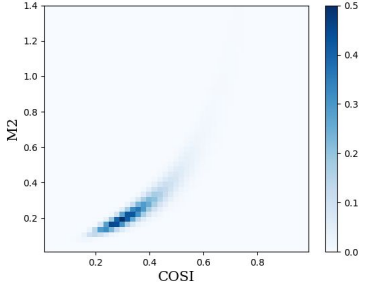


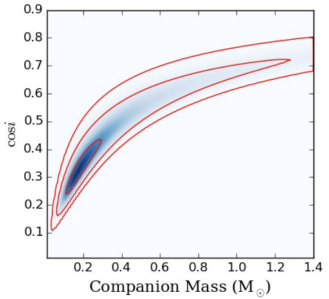
New for 15-year: J1312+0051, J1012-4235, and more





Significant improvements, like J2017+0603: 1.7718 + 1.8218 - 0.8208 $M_\odot$

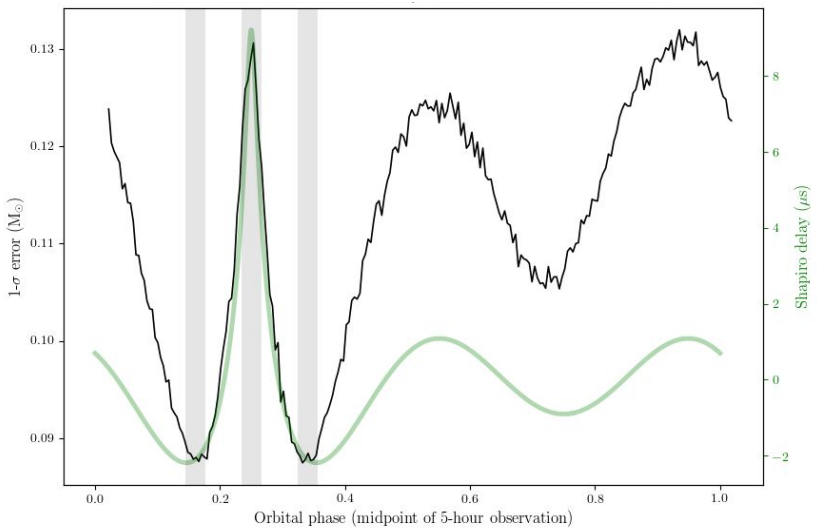




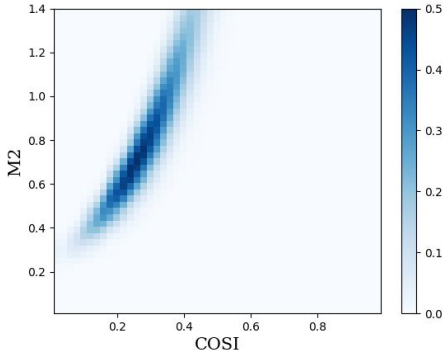
Selected gridding results

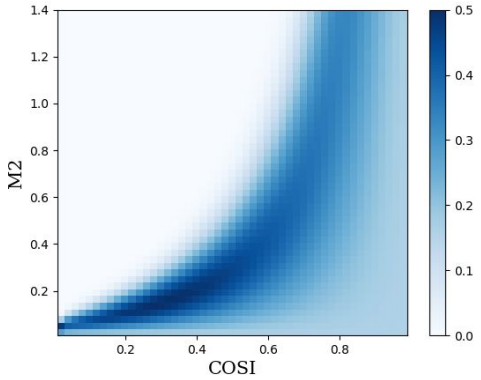
Incomplete and preliminary!

```
M1 for J0614-3329: 1.9119 + 3.2432 - 1.1612 (Msun)
M1 for J1125+7819: 1.4314 + 2.8629 - 1.1812 (Msun)
M1 for J1630+3734: 6.2763 + 2.4024 - 2.5025 (Msun)
M1 for J1811-2405: 2.4324 + 1.7818 - 0.9209 (Msun)
```



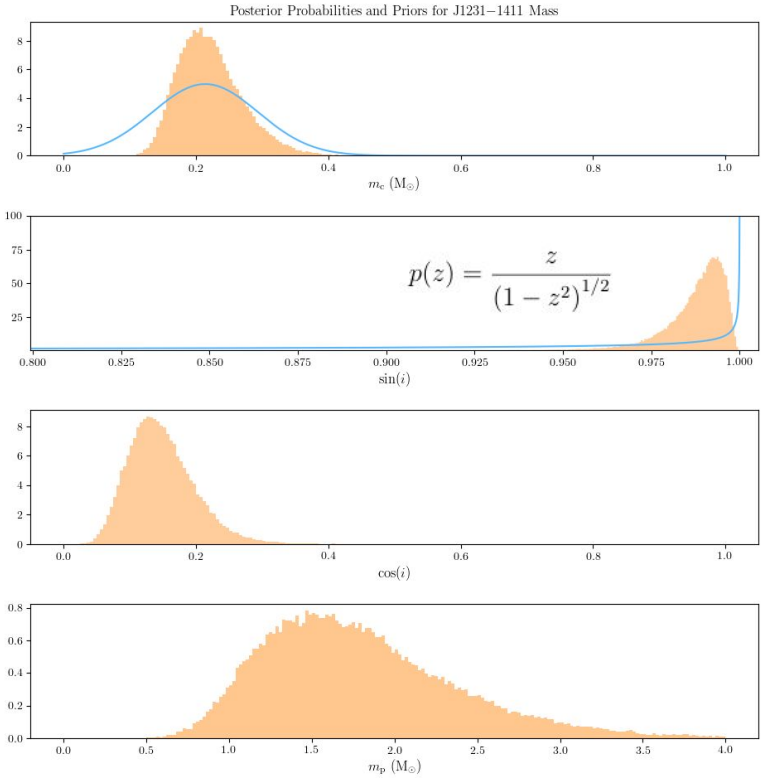
- GBT 22A-399 (+J0125-2327, J1853+1303)





- Older targeted GBT campaign… another?

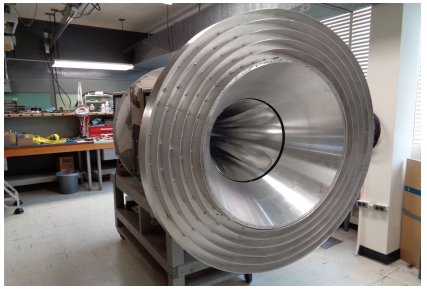
(Non-NANOGrav) J1231-1411



- 22 additional hours (incl. 2x6 hr conjunction) w/GBT to obtain Shapiro delay measurement; combined with Nançay and archival GBT
- Tauris & Savonije 1999 (TS99) prior on M2
- Flat-in-cos(i) prior on sin(i)
- Radio Shapiro delay is significant; not *Fermi*
- 1-sig results:
  - M_c = 0.216 (-0.042, + 0.053) $M_\odot$
  - sin(i) = 0.990 (-0.009, +0.005) ~82 deg
  - M_p = 1.707 (-0.475, +0.661) $M_\odot$

On the horizon

- NANOGrav 15-year data set (WB+NB), GWB search, noise budget, astrophysics will be released together in early 2023
- Fully binary analysis
- Combining supplemental observations with 15-year
- WB bayesian constraints
- `PINT`-based gridding for all binaries
- “SD masses over time” assessment
- GBT UWB receiver, DSA-2000
- Continuing to collaborate with NICER folks!



Summary

- The NANOGrav 15-year data set adds 21 MSPs and 3 years of data
- Comparisons between 12.5-year data set and 15-year data set for pulsar masses shows consistency; anomalous orbital parameter changes are explained
- Some new SD constraints, including intriguing mass for J1630
- Final results will be published with 15-year analysis in early 2023
- Ongoing efforts to integrate advanced techniques (and simple ones!) into the soon-to-be-public pipeline