Current Status of Radio Pulsar Mass Measurements and Future Prospects

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NANOGrav

NASA Hubble Fellowship Program

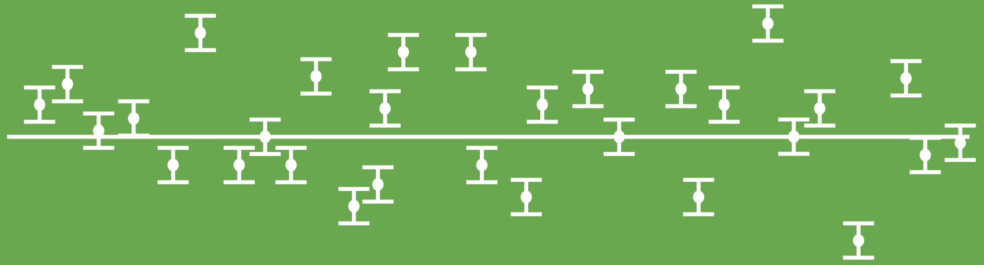
NSERC CRSNG

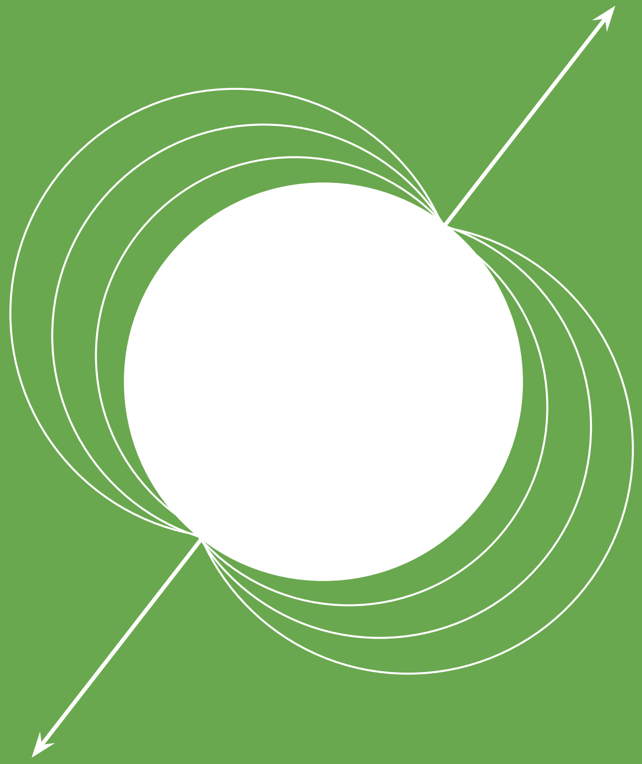
GREEN BANK OBSERVATORY

Outline

- Quick introduction to millisecond pulsars & pulsar timing (basic!)
- Pulsar timing to constrain NS masses
  - Techniques and notable examples
- Recent results from NANOGrav
- Prospects for the future

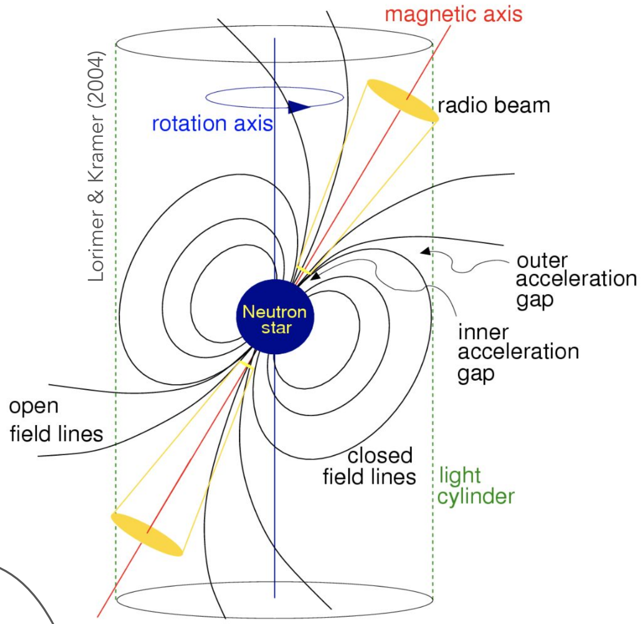
Millisecond pulsars & pulsar timing basics

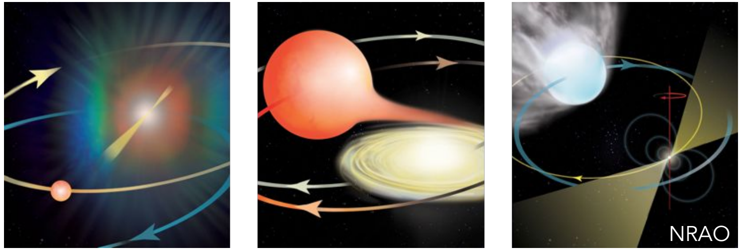




MSP Basics

- Pulsar: Jocelyn Bell-Burnell in 1967
- Don’t pulse, lighthouse-like
- ~10 km, 1-2 $M_\odot$
- MSPs rotate rapidly (fastest <1.5 ms) and have “weak” B-fields ~10^8-10^9 G
  - Spun up via recycling, mostly in binaries
- ~400 MSPs known (first in 1982)
- Observations between ~few hundred MHz and ~few GHz

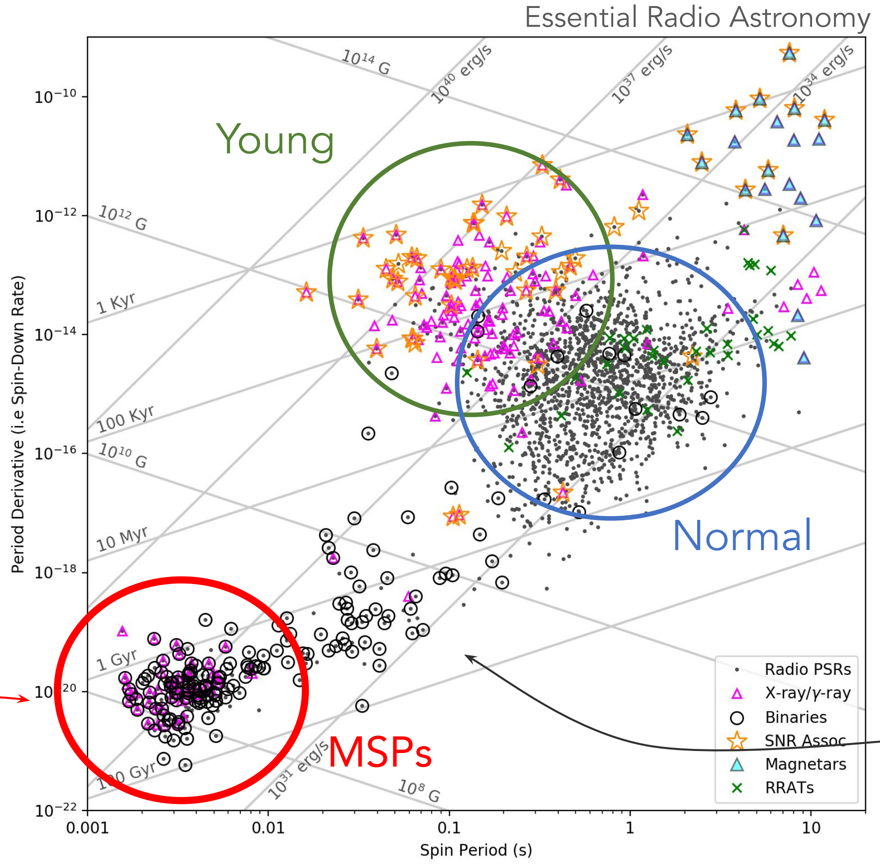




MSP Basics

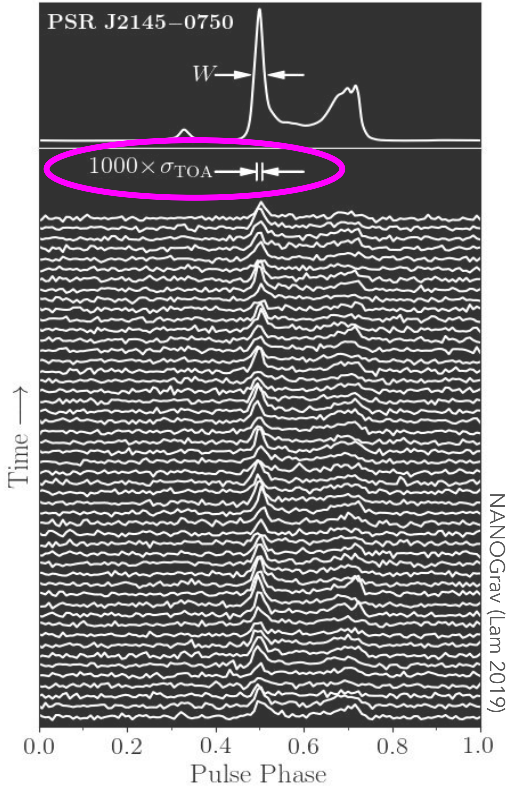
MSPs:
fully recycled,
low-e orbits,
stable, fast!

Low B

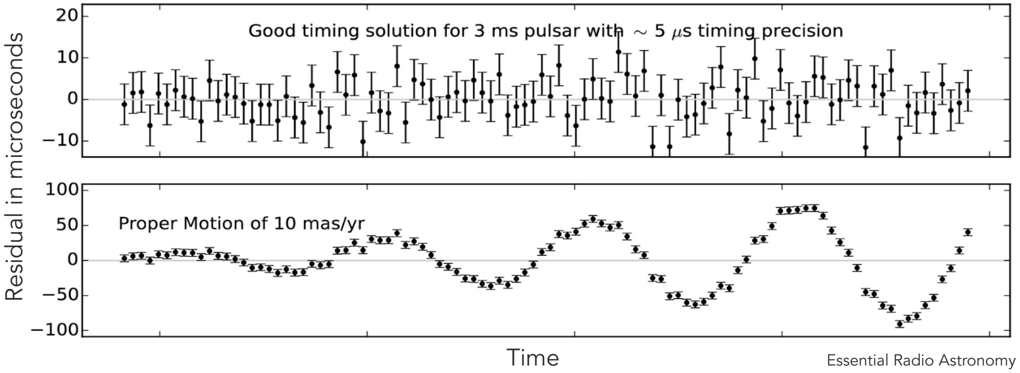


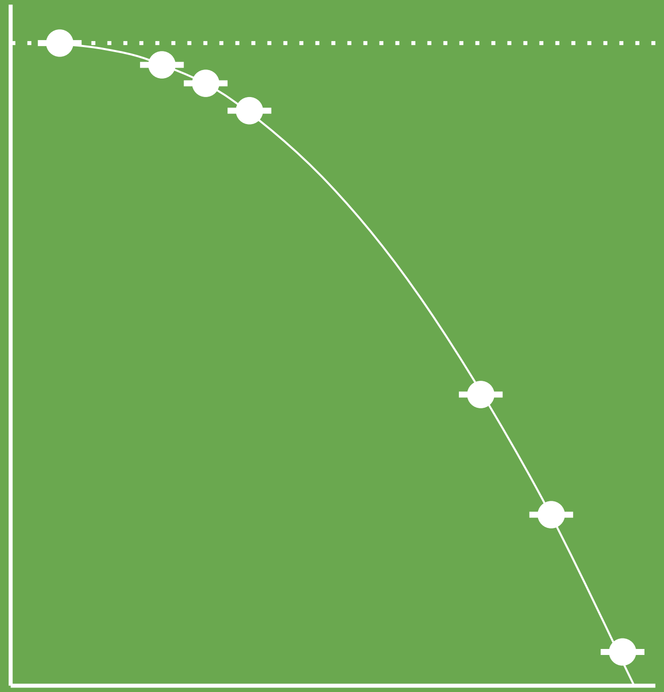
Double NS:
~17; mildly
recycled, high-e
orbits, good GR
tests

Pulsar Timing



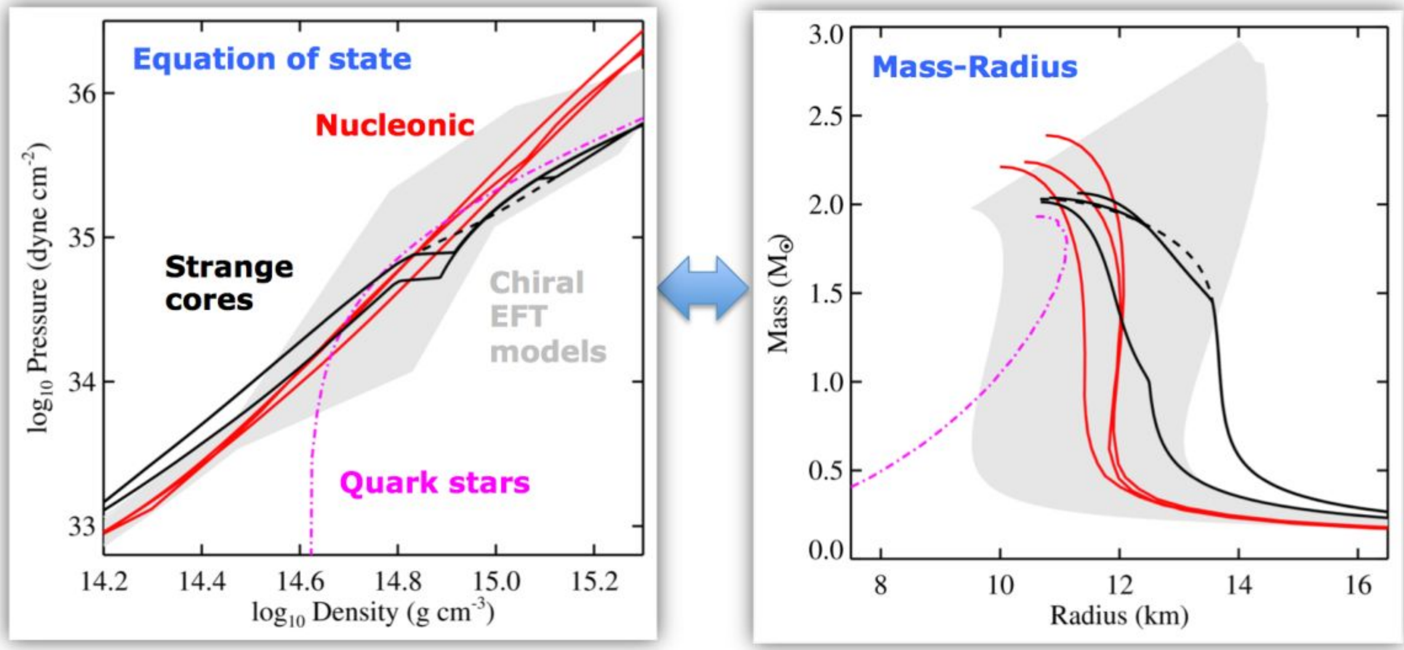
- Account for each rotation
- In addition to basic parameters, models account for ISM dispersion (DM), GR effects, ephemeris, etc.
- Deviations (measurement - model) = residuals
- Precision rivals atomic clocks





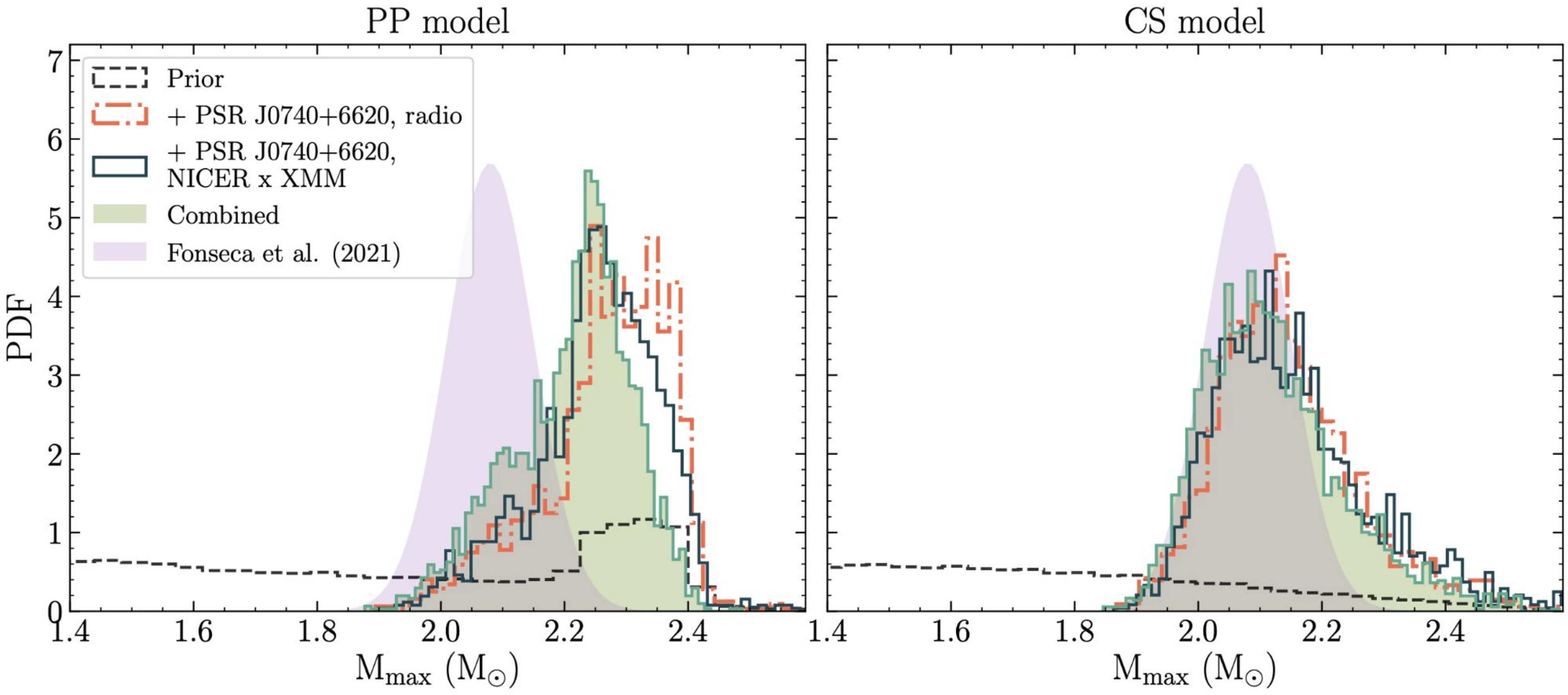
Pulsar mass measurement techniques

Motivation



Watts et al. 2016

Motivation



Raaijmakers et al. 2021

Overview: Radio Pulsar Mass Measurements

Five Keplerian parameters describe classical delay in binaries and can be measured:

- Projected semimajor axis: $x \equiv a \sin(i) / c$
- Longitude of periastron: ω
- Time of periastron passage: T_0
- Orbital period: P_b
- Orbital eccentricity: e

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

Overview: Radio Pulsar Mass Measurements

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

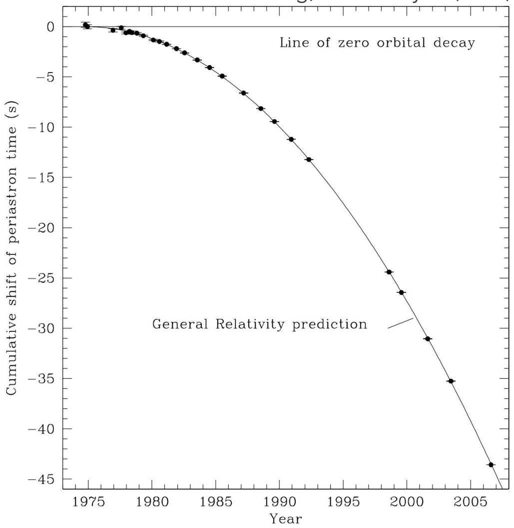
- Still don't have m_c, m_p, i → can't determine masses individually
- Break by measuring post-Keplerian parameters (only possible in a subset of systems):
  - Rate of periastron advance $\dot{\omega}$ and Einstein delay γ (eccentric)
  - Orbital period decay $\dot{P}_b$ (long timing baseline)
  - Shapiro delay parameters r, s (more on this later)

Overview: Radio Pulsar Mass Measurements

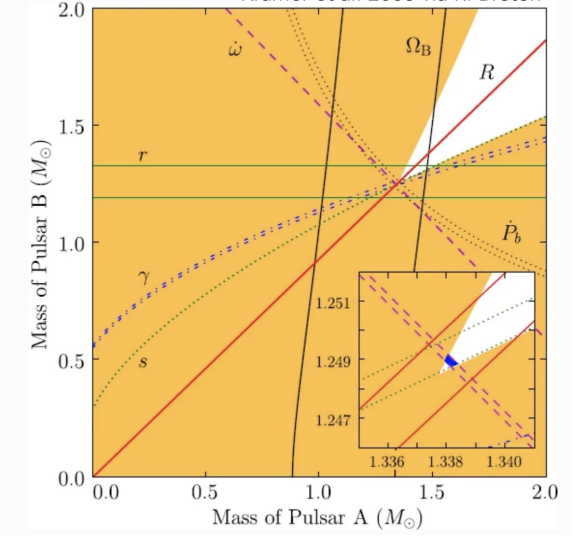
Notable PK measurements:

- B1913+16, the Hulse-Taylor DNS (1975):
  - Compact, eccentric (3 PK; GW energy loss)
- J0737-3039, the double pulsar (Burgay et al. 2003):
  - Most compact, highly inclined; seven measured parameters including M/R
  - Consistent independent of PK choice

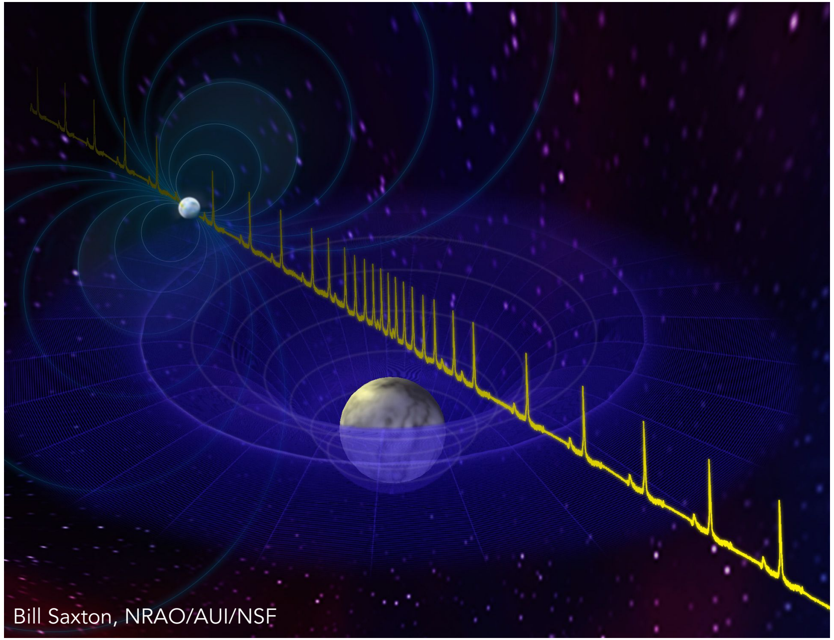
Weisberg, Nice & Taylor (2010)



Kramer et al. 2006 via R. Breton



Shapiro Delay



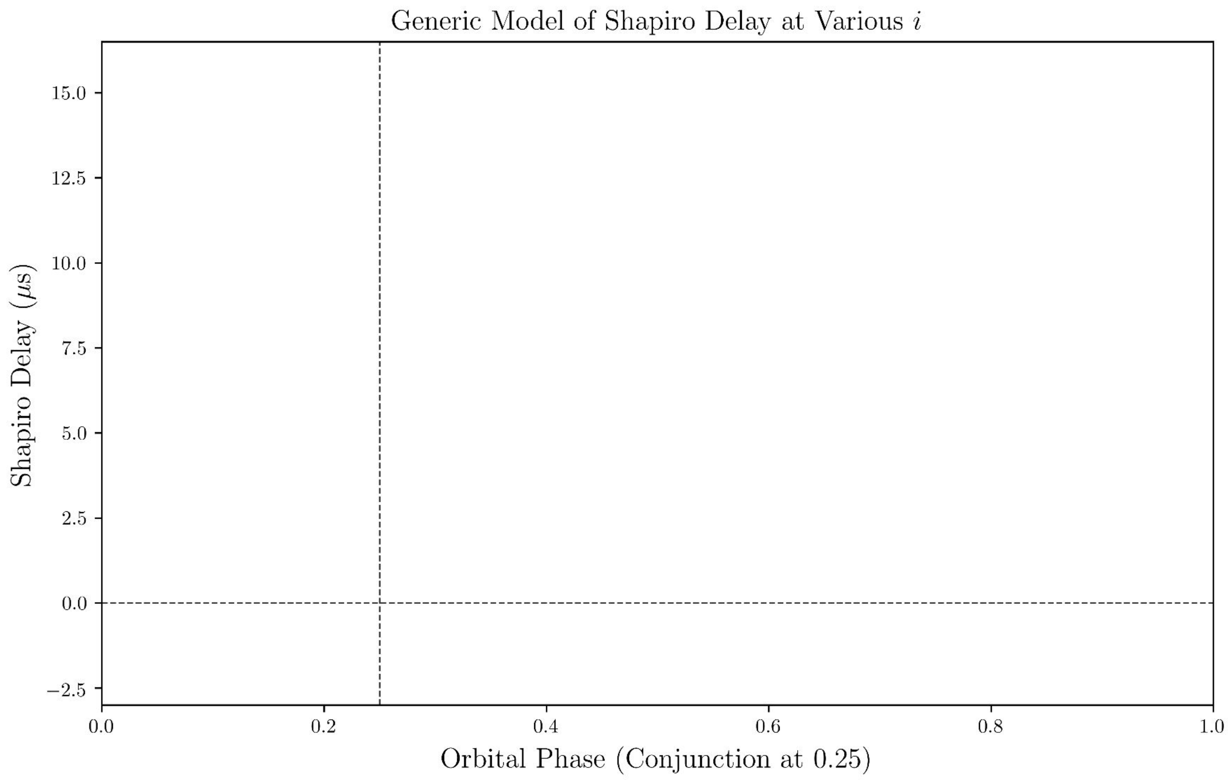
- Shapiro delay occurs at superior conjunction in edge-on binary systems
- "Range" and "shape" PK parameters are directly measurable:

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

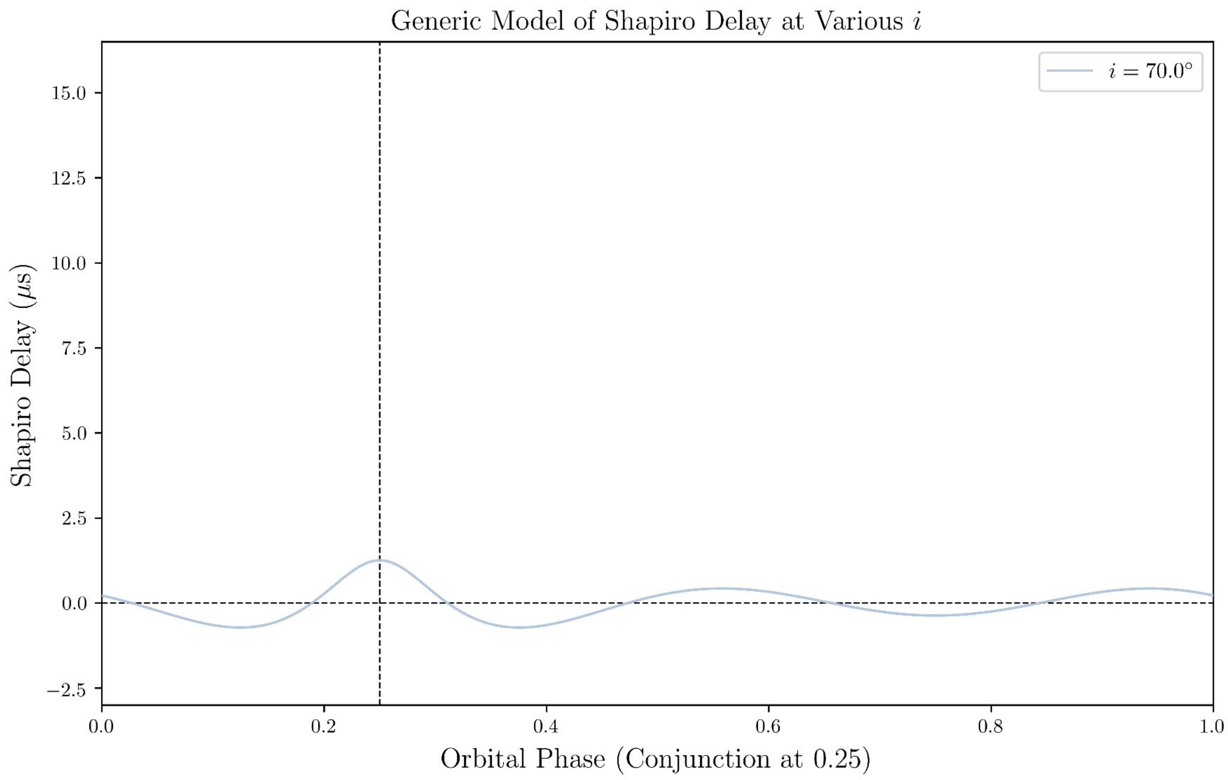
$$s = x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_2^{-1}$$

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

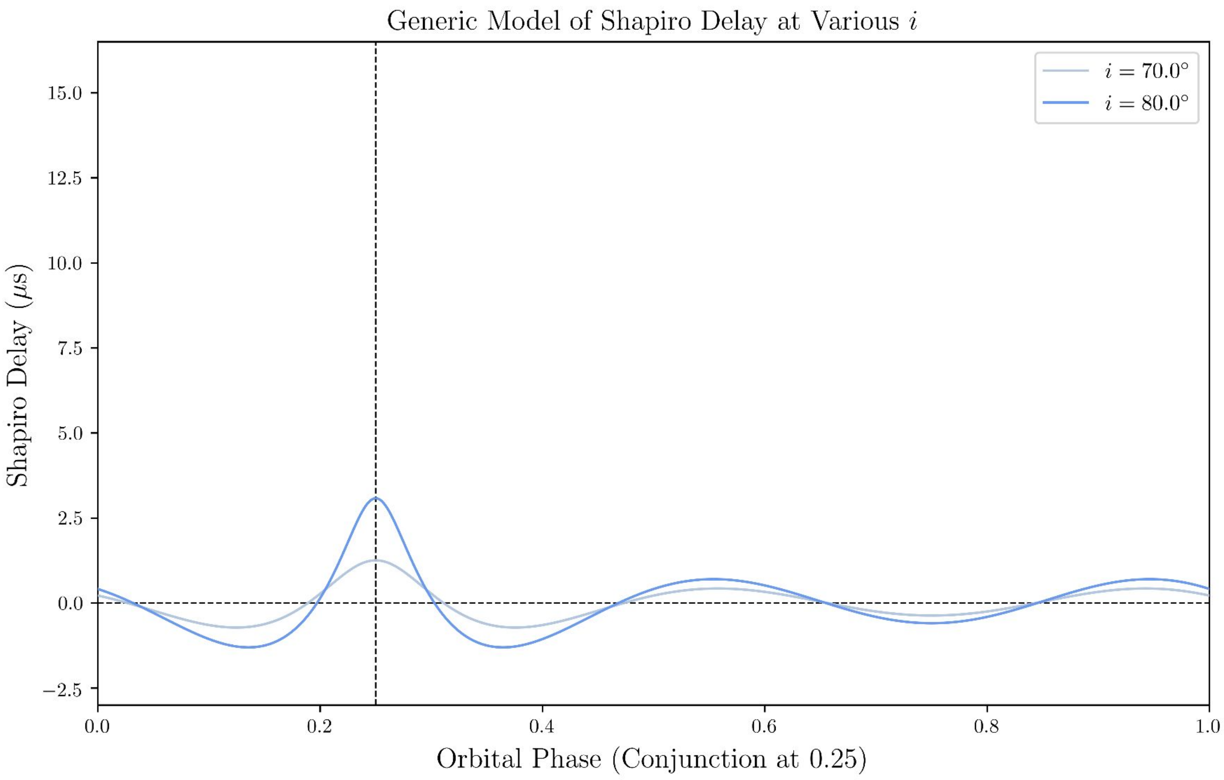
Shapiro Delay



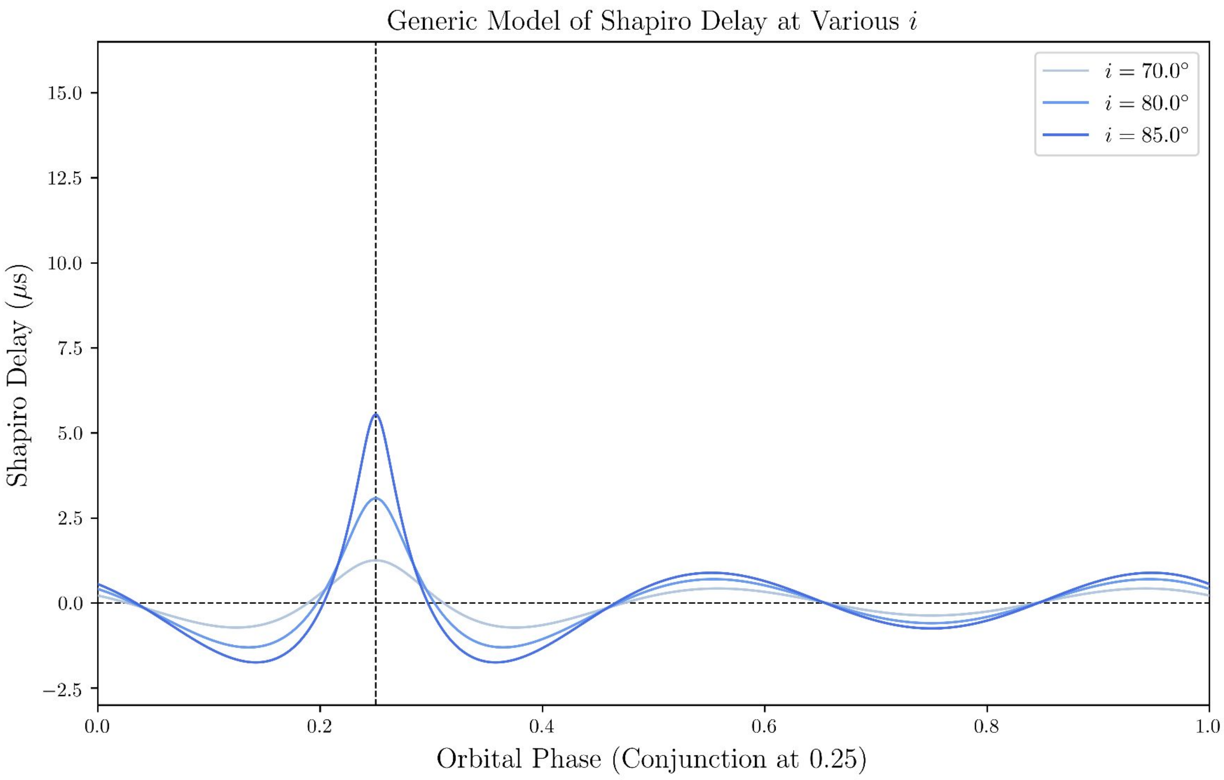
Shapiro Delay



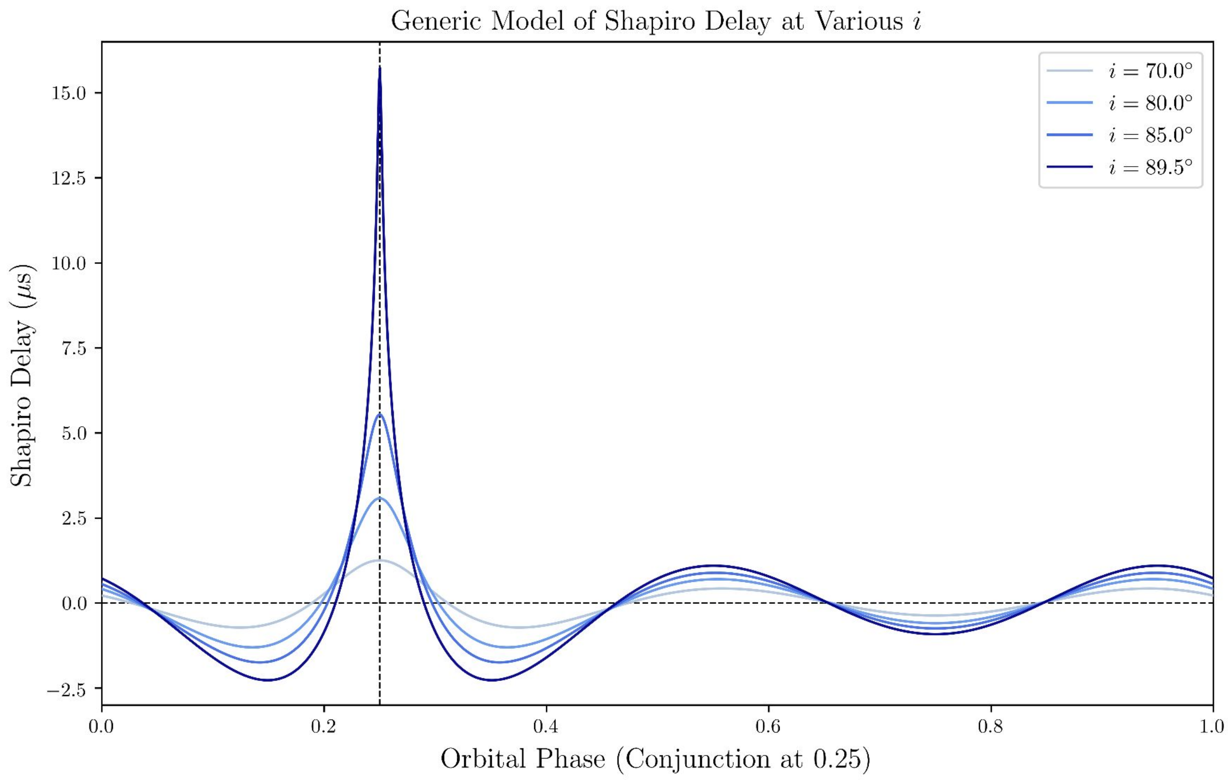
Shapiro Delay



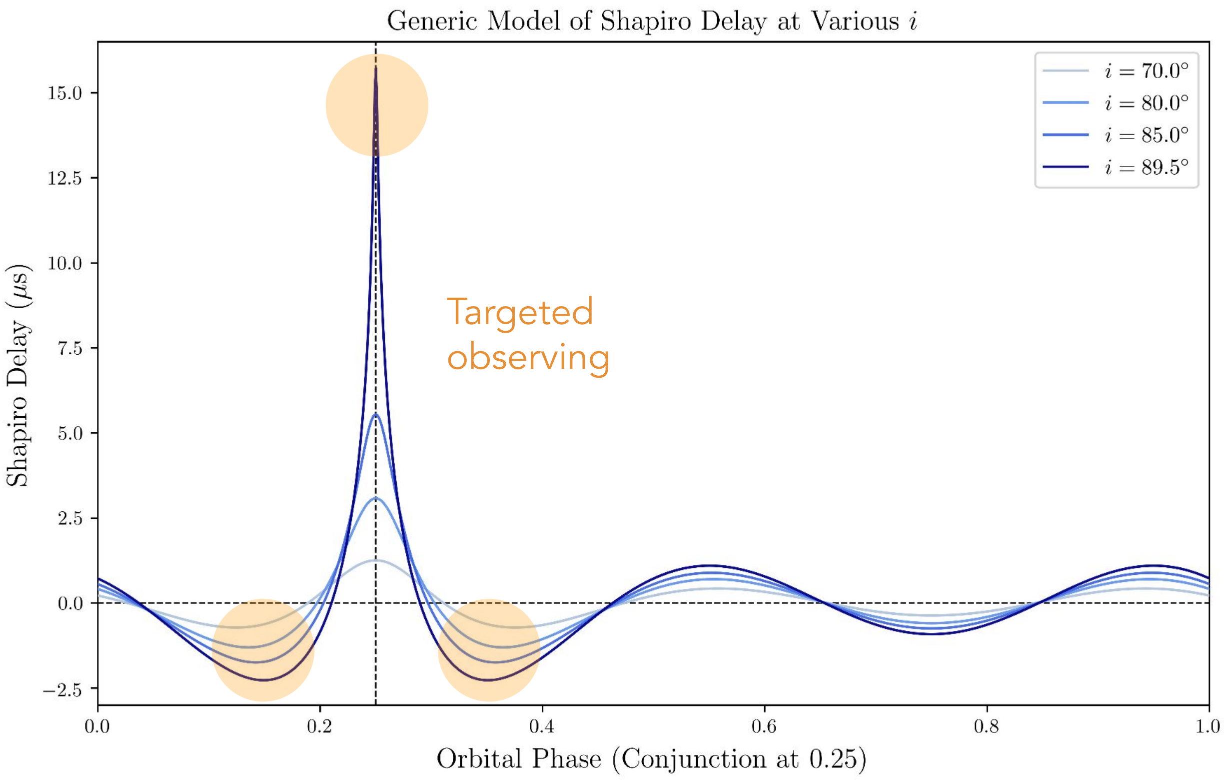
Shapiro Delay

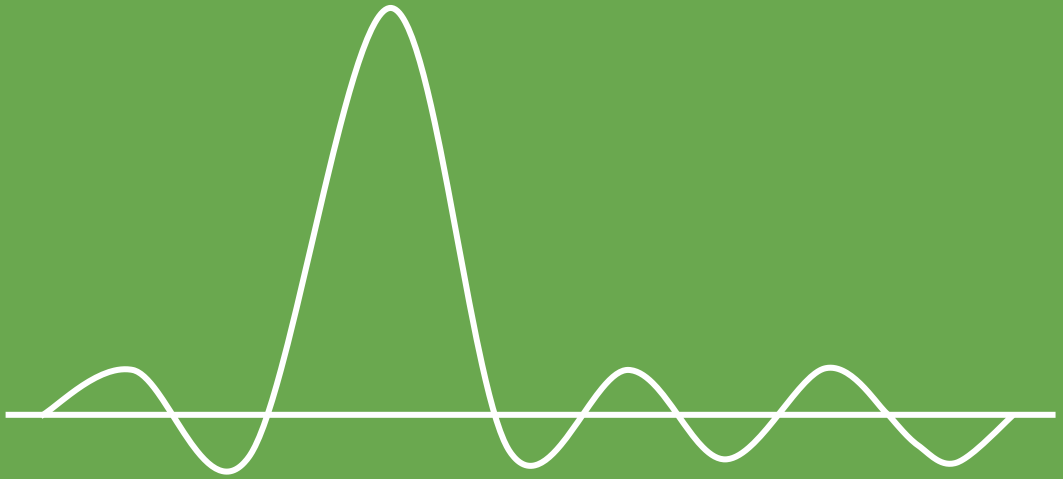


Shapiro Delay



Shapiro Delay





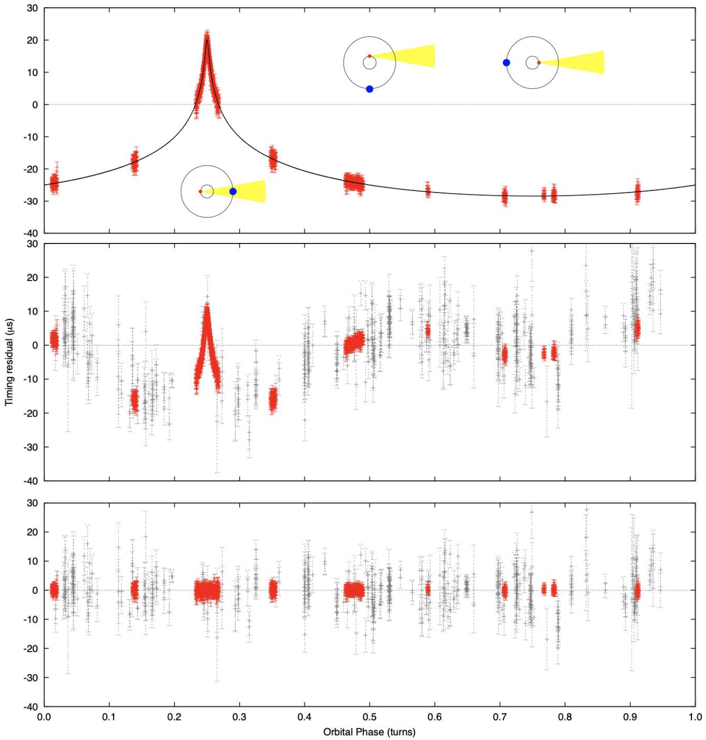
Recent radio Shapiro delay results (and more!)

Massive NS via Shapiro Delay (J1614-2230)

Demorest et al. 2010:

- Long-term timing + phase-targeted campaign
- 1.97 ± 0.04 $M_\odot$
- (Fonseca et al. 2016): 1.928 ± 0.017 $M_\odot$
- First ~2 $M_\odot$ NS rules out softer EoS (hyperons, kaon condensates, etc.)

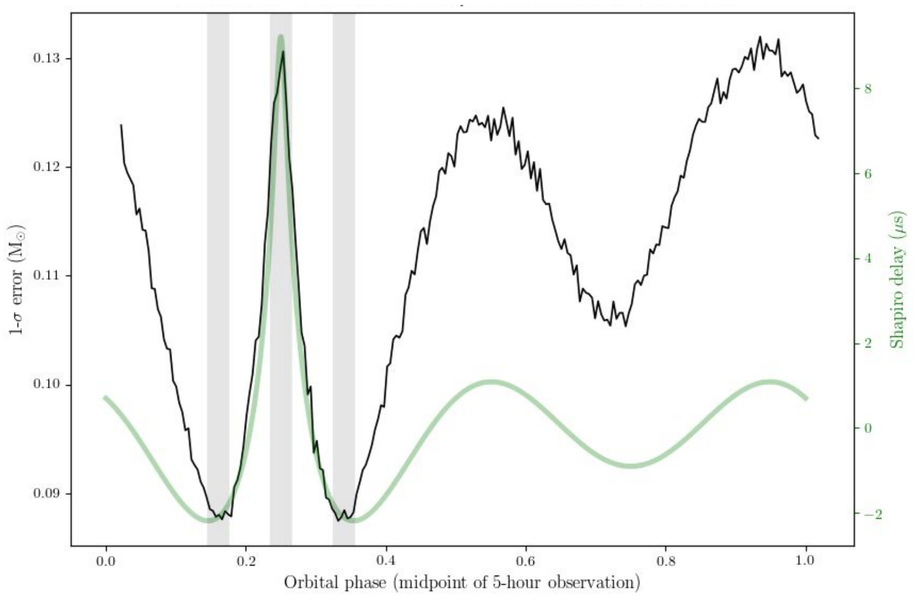
Demorest et al. 2010



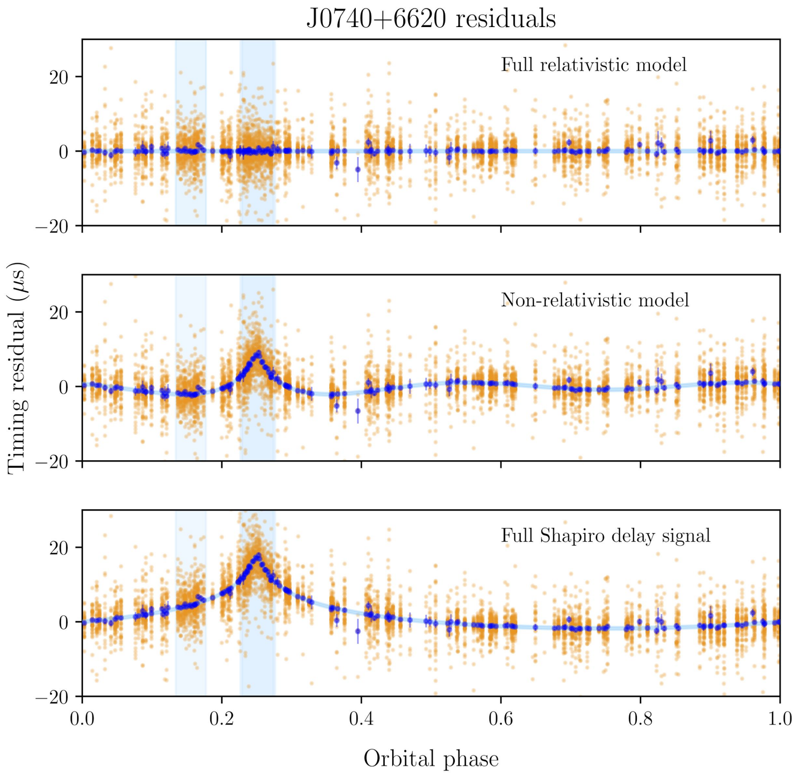
Massive NS via Shapiro Delay (J0740+6620)

MSP J0740+6620:

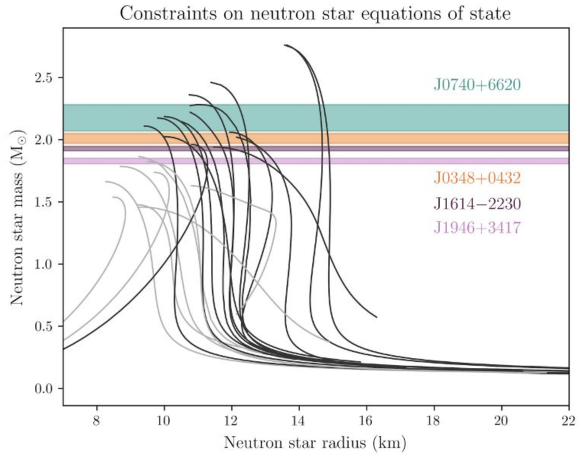
- Found in GBNCC survey (Stovall et al. 2014)
- $P = 2.9$ ms, $P_b = 4.8$ days
- NANOGrav MSP since 2014 that showed hint of Shapiro delay ($2.0 \pm 0.2\ M_\odot$)
- GBT 6-hr supplemental campaign targeted conjunction; saw significant Shapiro delay (yielded $2.18 \pm 0.15\ M_\odot$ combined with NANOGrav data)
- Random orbital sampling wasn't enough



Massive NS via Shapiro Delay (J0740+6620)



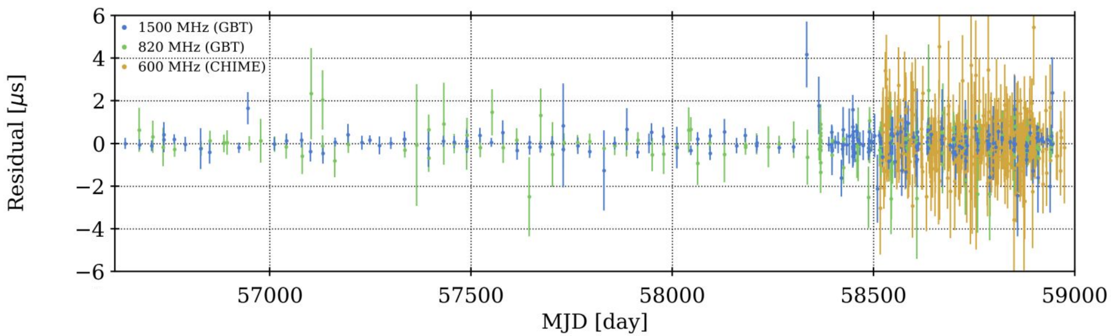
- NANOGrav + targeted campaigns → m_p ~2.14 ± 0.09 $M_\odot$ (then the most massive NS; Cromartie et al. 2020)
- Higher mass → also in tension with "exotic" theories (quark matter, hyperons, meson condensates, etc.)
- See fully recycled MSPs < 1.4 $M_\odot$ → born massive?

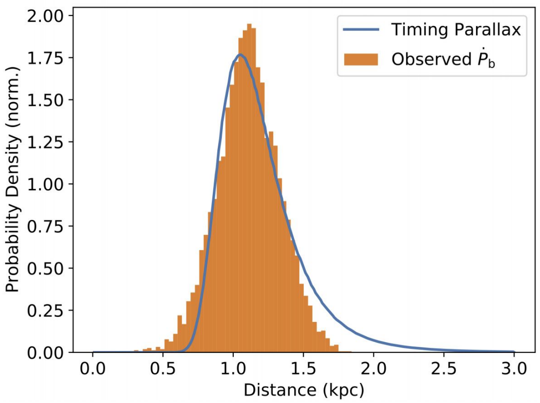


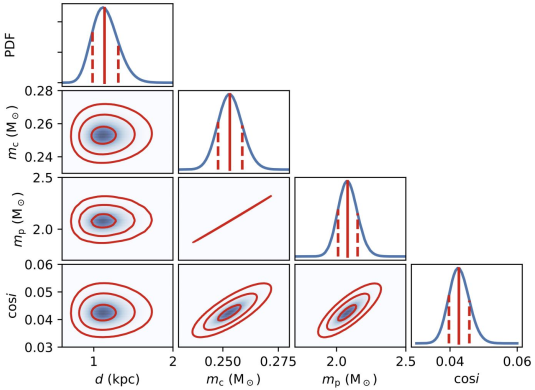
Fonseca & Cromartie based on Özel & Freire 2016

Massive NS via Shapiro Delay (J0740+6620)

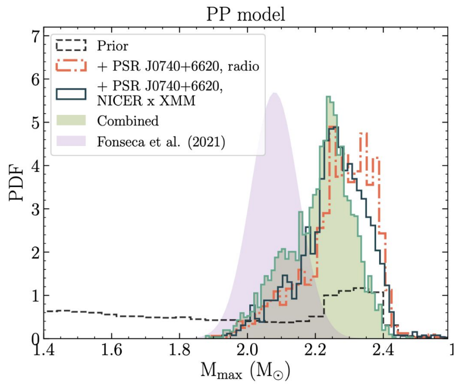
- Updated in Fonseca et al. 2021
- Additional 1.5 years of GBT w/NANOGrav at high cadence
- 1.5 years daily CHIME observations
- 2.08 ± 0.07 $M_\odot$
- Lower limit on max. mass unchanged from Cromartie et al.
- First measurement of $\dot{P}_b$ (consistency check w/parallax d)

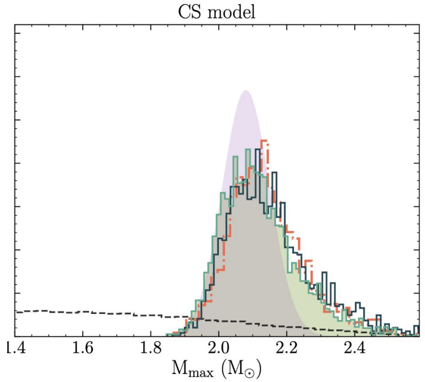






Massive NS via Shapiro Delay (J0740+6620)

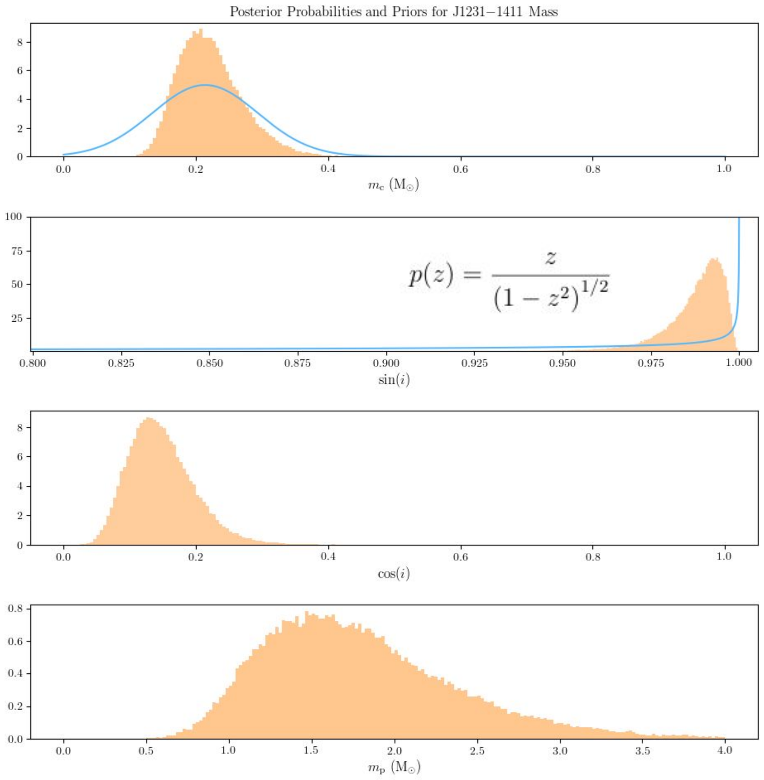




NICER + NANOGrav + XMM:

- Riley et al. 2021:
  - R = 11.29 (+1.20, -0.81) km
- Miller et al. 2021:
  - R = 11.51 (+1.87, -1.13) km
- These analyses significantly constrain the EoS (Raaijmakers et al. 2021)

Not-So-Massive NS via Shapiro Delay (J1231-1411)

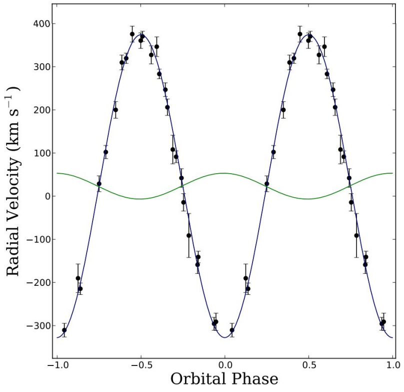


- Brightest gamma-ray MSP, NICER target
- 22 additional hours (incl. 2x6 hr conjunction) w/GBT to obtain Shapiro delay measurement; combined with Nançay and archival GBT
- emcee-based MCMC in `PINT`:
  - Tauris & Savonije 1999 (TS99) prior on M2
  - Flat-in-cos(i) prior on sin(i)
- Radio Shapiro delay 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) $M_\odot$

Massive NS via Companion Observations

Antoniadis et al. 2013 (J0348+0432):

- 39-ms PSR, 2.5-hour P_b
- APO & VLT spectroscopy of WD → folded RV → mass ratio; WD cooling curves → WD mass
- $m_p = 2.01 \pm 0.04\ M_\odot$



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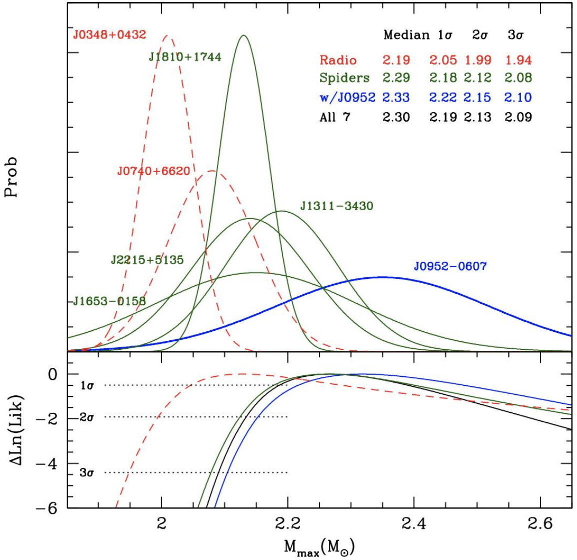
Massive NS via Companion Observations

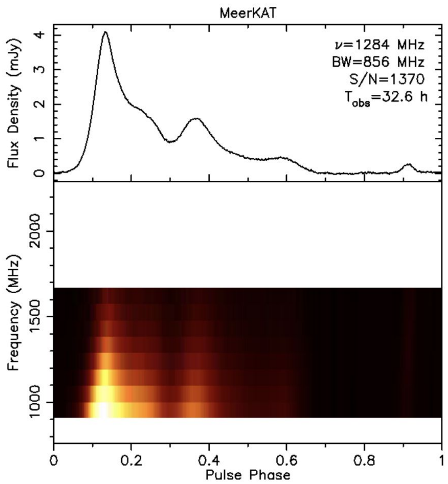
"PSR J0952-0607: The Fastest and Heaviest Known Galactic Neutron Star" (Romani et al. 2022):

- Black widow discovered with LOFAR; fastest Galactic MSP (1.41 ms)
- Spiders likely have long accreting phases before ablation → massive
- Optical counterpart was thought to be too faint
  - 2x two-color imaging campaigns, six spectroscopic observations
- $m_p = 2.34 \pm 0.17\ M_\odot$ (1σ)
- "Cleaner" BW system but complicated by large brightness drops
- 10-30 m class telescopes will help improve precision



Other New (Selected) Mass Measurements

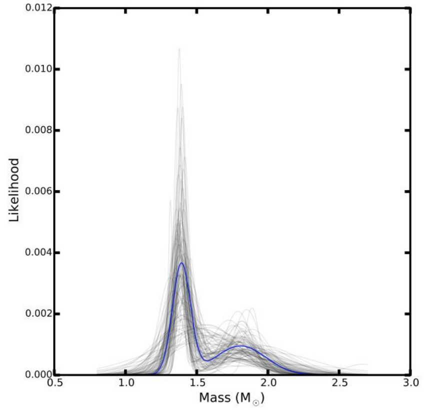
- J0955-6150 (Serylak et al. 2022):
  - Very eccentric (e = 0.11), significant $\dot{\omega}$ and SD
  - Vastly improved timing precision with MeerKAT
  - $m_p \sim 1.71\ M_\odot$



- MeerKAT RelBin program (Kramer et al. 2021):
  - New SD measurements for several sources, ongoing observations
- Combined results for J2045+3633 (~1.251 $M_\odot$ in McKee et al. 2020)
- New masses from FAST, CHIME, etc.
  - FAST: sensitivity, CHIME: cadence
- These are important for binary evolution, X-ray priors, population studies

Constraining the Mass Distribution

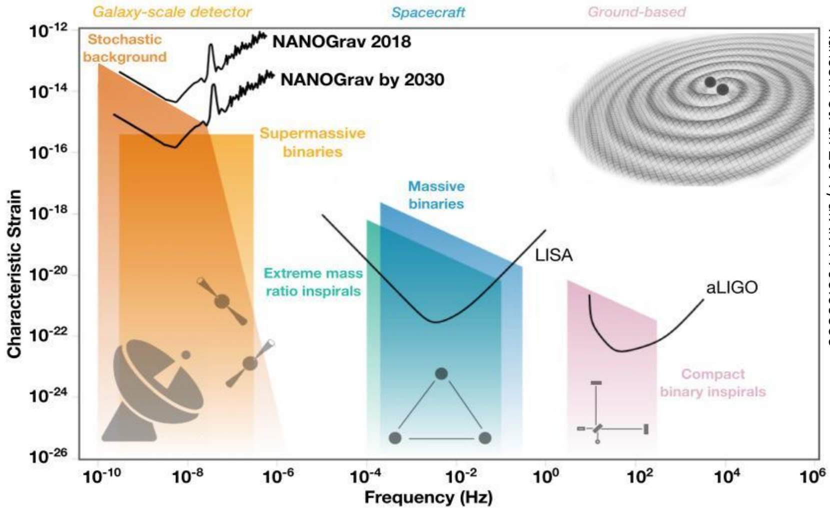
- As more masses are measured precisely, we get a better idea of what the overall NS population looks like
- ~20% with mass > 1.8 $M_\odot$; bimodal w/ peaks at ~1.4 and ~1.8 $M_\odot$ (Antoniadis et al. 2016) → SN physics, birth masses



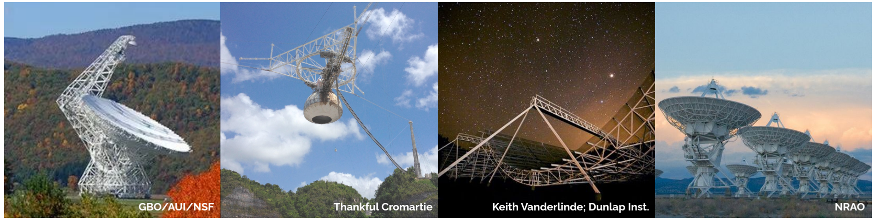
Recent results from NANOGrav

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.)



Ransom et. al. 2019, arXiv:1908.05356



This is NANOGrav-centric; other PTAs are doing GW searches and NS mass constraints, too! (Including the IPTA)

NANOGrav

- Proven strategy: both J0740+6620 and J1614-2230 are NANOGrav MSPs
- Successive data releases improve measurement precision
  - Fonseca et al. 2016: 24 binaries w/ 14 significant SD measurements
  - This was for the 9-year data set

Table 3

Estimates of Shapiro-delay Parameters from χ^2-grid Analyses

PSR	Pulsar Mass ($M_\odot$)		Companion Mass ($M_\odot$)		System Inclination (deg)	
	Trad	Ortho	Trad	Ortho	Trad	Ortho
J0613–0200	$2.3^{+2.7}_{-1.1}$	$2.1^{+2.1}_{-1.0}$	$0.21^{+0.23}_{-0.10}$	$0.19^{+0.15}_{-0.07}$	66^{+8}_{-12}	68^{+7}_{-10}
J1600–3053[a]	$2.4^{+1.5}_{-0.9}$	$2.4^{+1.3}_{-0.8}$	$0.33^{+0.14}_{-0.10}$	$0.33^{+0.13}_{-0.08}$	63^{+5}_{-5}	64^{+4}_{-5}
J1614–2230	$1.928^{+0.017}_{-0.017}$	$1.928^{+0.017}_{-0.017}$	$0.493^{+0.003}_{-0.003}$	$0.493^{+0.003}_{-0.003}$	$89.189^{+0.014}_{-0.014}$	$89.188^{+0.014}_{-0.014}$
J1640+2224	$4.4^{+2.9}_{-2.0}$	$5.2^{+2.6}_{-2.0}$	$0.6^{+0.4}_{-0.2}$	$0.7^{+0.3}_{-0.2}$	60^{+6}_{-6}	58^{+6}_{-6}
J1713+0747[a,b]	$1.31^{+0.11}_{-0.11}$	$1.31^{+0.11}_{-0.11}$	$0.286^{+0.012}_{-0.012}$	$0.286^{+0.012}_{-0.012}$	$71.9^{+0.7}_{-0.7}$	$71.9^{+0.7}_{-0.7}$
J1741+1351[a]	$1.87^{+1.26}_{-0.69}$	$1.78^{1.08}_{-0.63}$	$0.32^{+0.15}_{-0.09}$	$0.31^{+0.13}_{-0.08}$	66^{+5}_{-6}	66^{+5}_{-6}
B1855+09	$1.30^{+0.11}_{-0.10}$	$1.31^{+0.12}_{-0.10}$	$0.236^{+0.013}_{-0.011}$	$0.238^{+0.013}_{-0.012}$	$88.0^{+0.3}_{-0.4}$	$88.0^{+0.3}_{-0.4}$
J1903+0327[a]	$1.65^{+0.02}_{-0.02}$	$1.65^{+0.02}_{-0.03}$	$1.06^{+0.02}_{-0.02}$	$1.06^{+0.02}_{-0.02}$	72^{+2}_{-3}	72^{+2}_{-3}
J1909–3744	$1.55^{+0.03}_{-0.03}$	$1.55^{+0.03}_{-0.03}$	$0.214^{+0.003}_{-0.003}$	$0.214^{+0.003}_{-0.003}$	$86.33^{+0.09}_{-0.10}$	$86.33^{+0.09}_{-0.10}$
J1918–0642	$1.18^{+0.10}_{-0.09}$	$1.19^{+0.10}_{-0.09}$	$0.219^{+0.012}_{-0.011}$	$0.219^{+0.012}_{-0.011}$	$85.0^{+0.5}_{-0.5}$	$85.0^{+0.5}_{-0.5}$
J1949+3106	$4.0^{+3.6}_{-2.5}$	$4.0^{+3.4}_{-2.3}$	$2.1^{+1.6}_{-1.0}$	$1.9^{+1.5}_{-0.9}$	67^{+9}_{-8}	68^{+8}_{-8}
J2017+0603	$2.4^{+3.4}_{-1.4}$	$2.0^{+2.8}_{-1.1}$	$0.32^{+0.44}_{-0.16}$	$0.27^{+0.30}_{-0.12}$	62^{+9}_{-12}	65^{+7}_{-11}
J2043+1711	$1.41^{+0.20}_{-0.18}$	$1.43^{+0.21}_{-0.18}$	$0.175^{+0.016}_{-0.015}$	$0.177^{+0.017}_{-0.015}$	$83.2^{+0.8}_{-0.9}$	$83.1^{+0.8}_{-0.9}$
J2302+4442	$5.3^{+3.2}_{-3.6}$	$5.5^{+3.0}_{-3.2}$	$2.3^{+1.7}_{-1.3}$	$1.8^{+1.6}_{-1.0}$	54^{+12}_{-7}	57^{+11}_{-9}
J2317+1439	$4.7^{+3.4}_{-2.8}$	$4.1^{+3.5}_{-2.4}$	$0.7^{+0.5}_{-0.4}$	$0.5^{+0.5}_{-0.3}$	47^{+10}_{-7}	51^{+10}_{10}

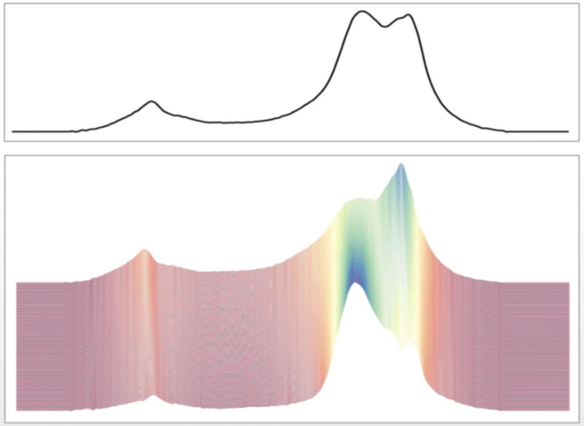
Note. — All uncertainties reflect 68.3% credible intervals. "Trad" refers to estimates made with the traditional (m_c, sin i) Shapiro-delay model, while "Ortho" refers to those made with the orthometric (h_3, ς) model. Difference in median values and credible intervals reflect the consequence in choosing uniform prior PDFs on the (m_c, sin i) or (h_3, ς) parameters for weak measurements of Δ_S.

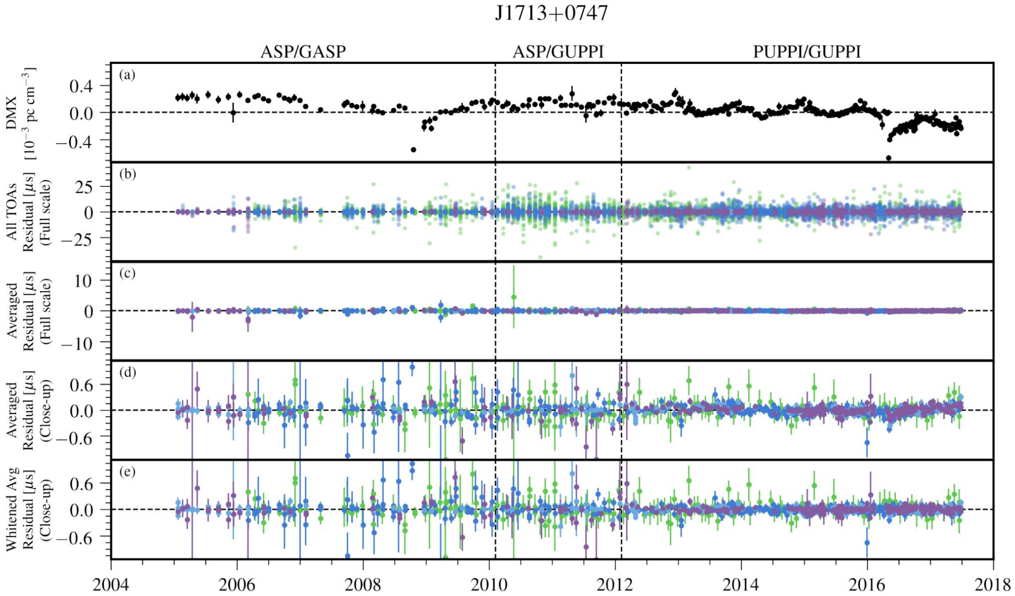
[a] The observed secular variations in this system were used to constrain the Shapiro-delay parameters.

[b] The Shapiro-delay estimates for PSR J1713+0747 were taken from Zhu et al. (2015), which used the NANOGrav nine-year data set as well as historical TOAs collected for previous studies.

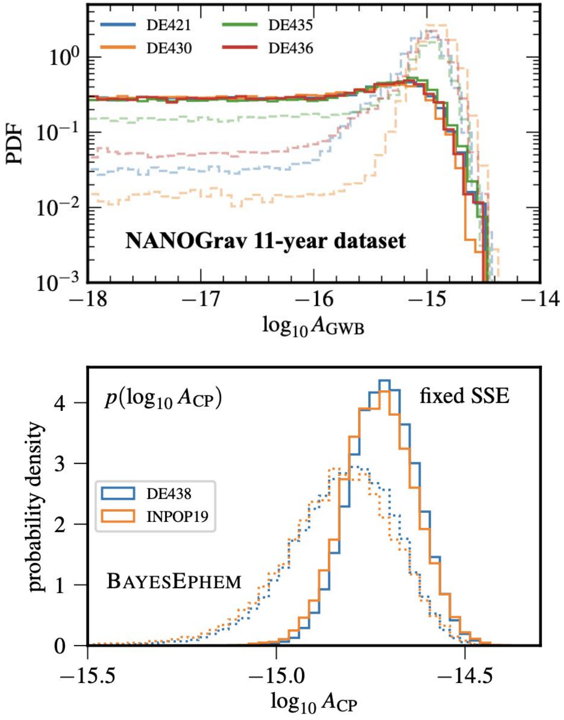
NANOGrav 12.5-Year Data Set

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





Advertisement: NANOGrav 12.5-Year GW Results



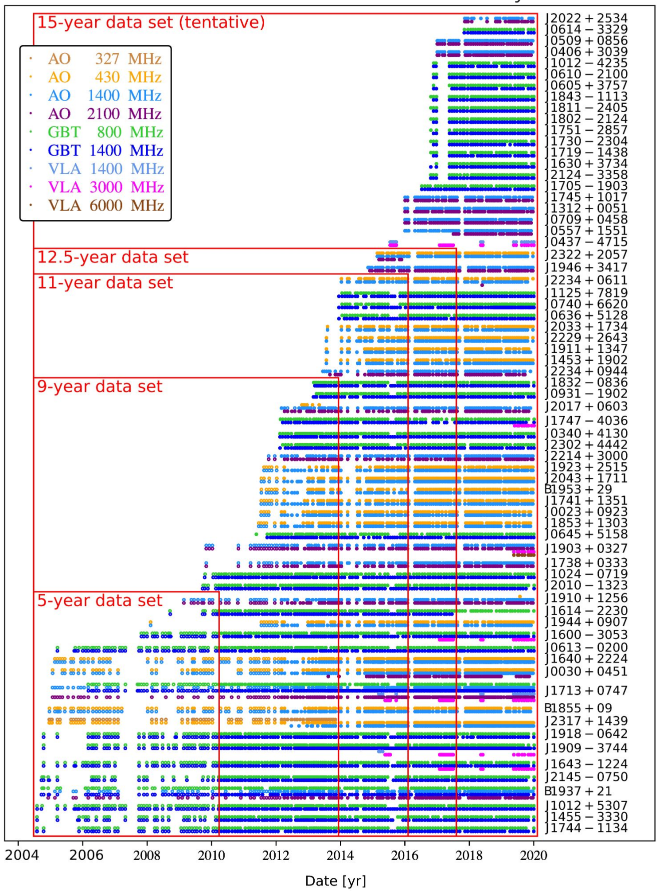
Arzoumanian et al. 2018 (top), 2020 (bottom)

- 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

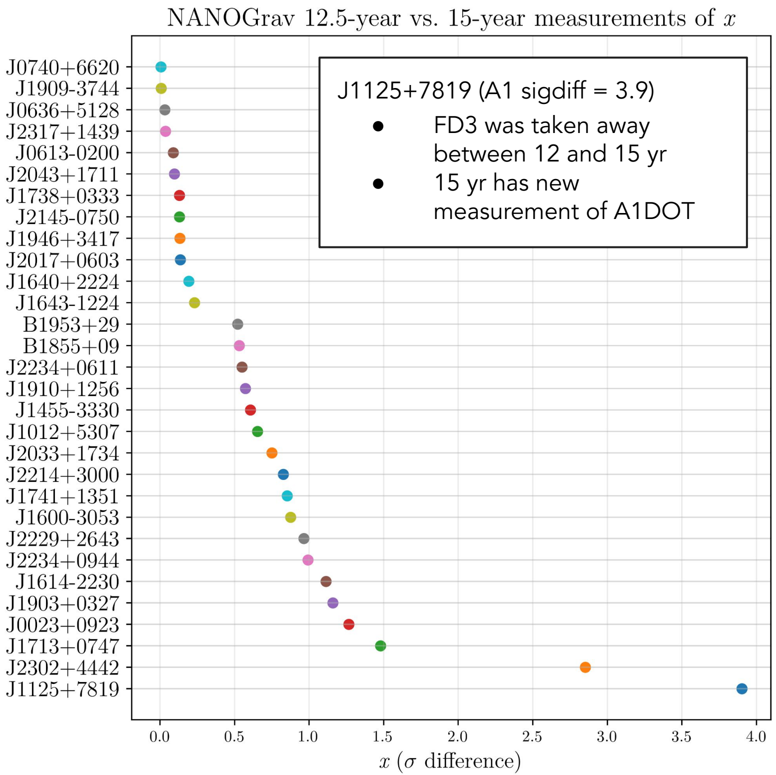
- 15-year data set adds 21 MSPs and ~3 years; GWB analysis is underway
- `PINT`-based timing in new pipeline
  - Transparency and accessibility
- VLA data and J0437-4715
- NB and WB timing, but WB issues under investigation

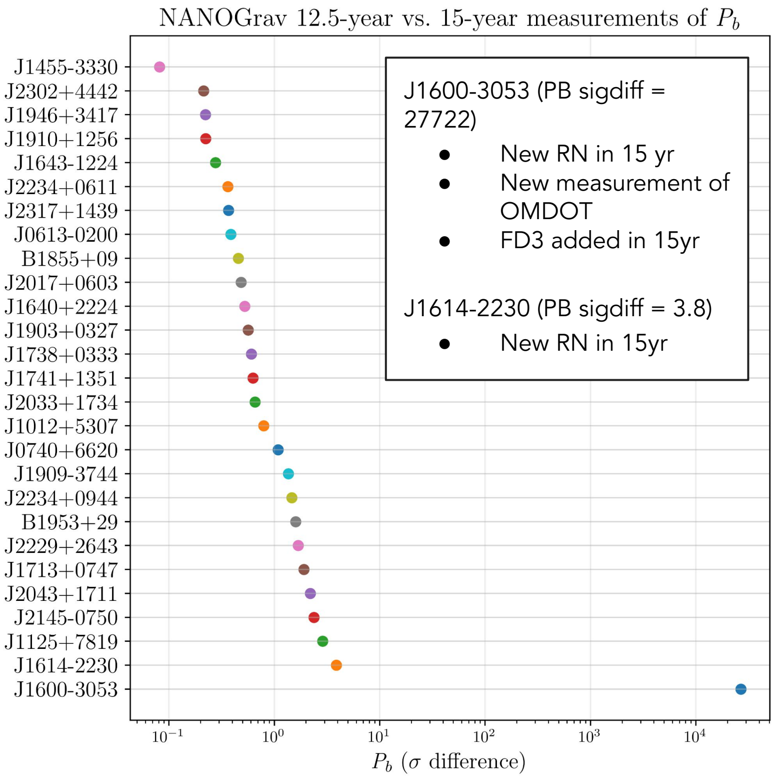
Courtesy David Nice



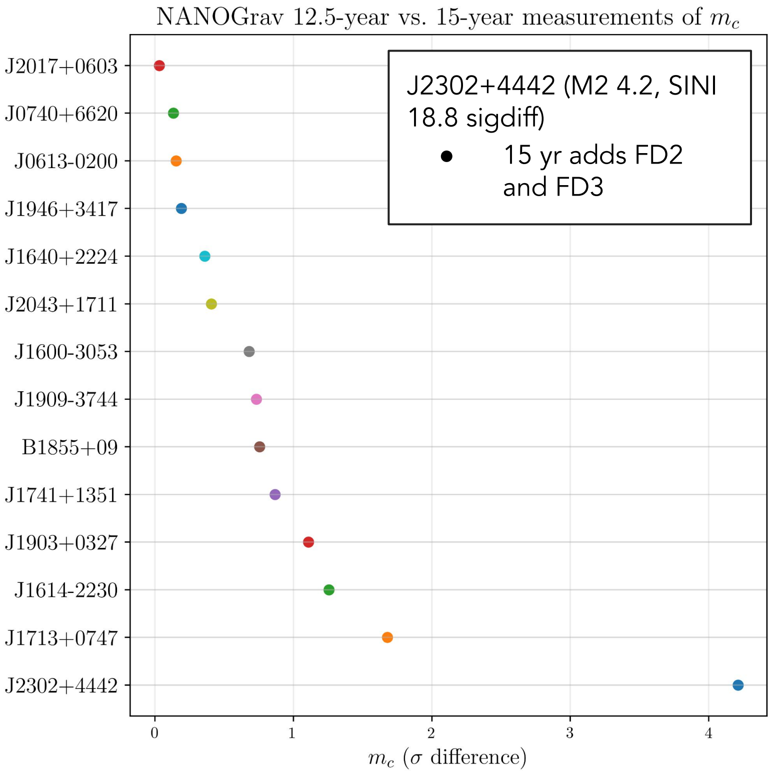
NANOGrav Physics Frontiers Center

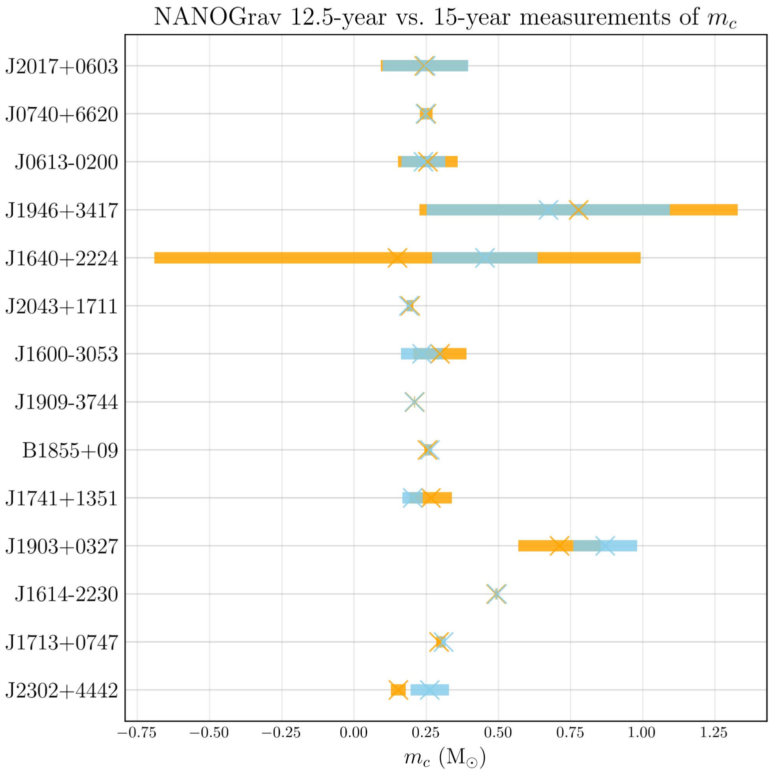
Comparing the 12.5 and 15-Year Data Sets



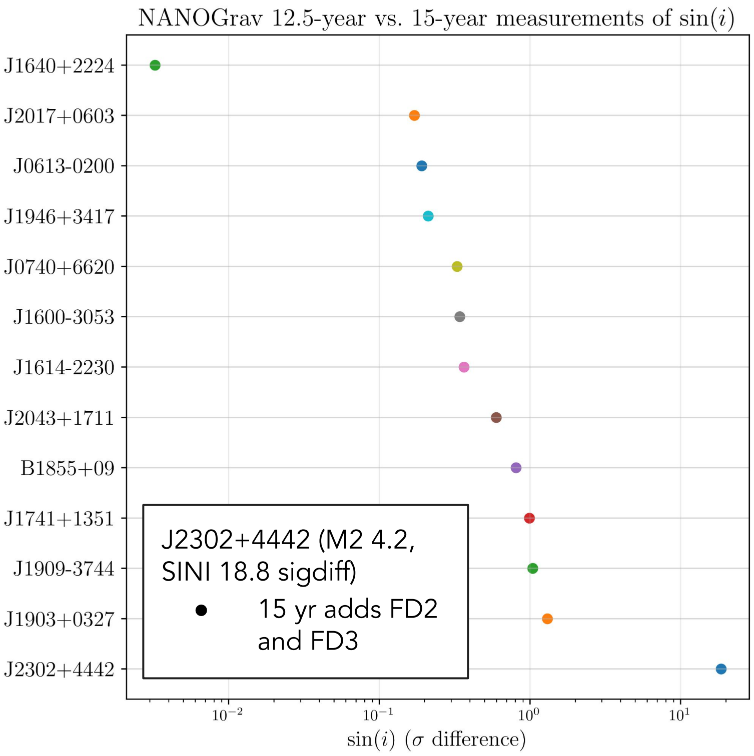


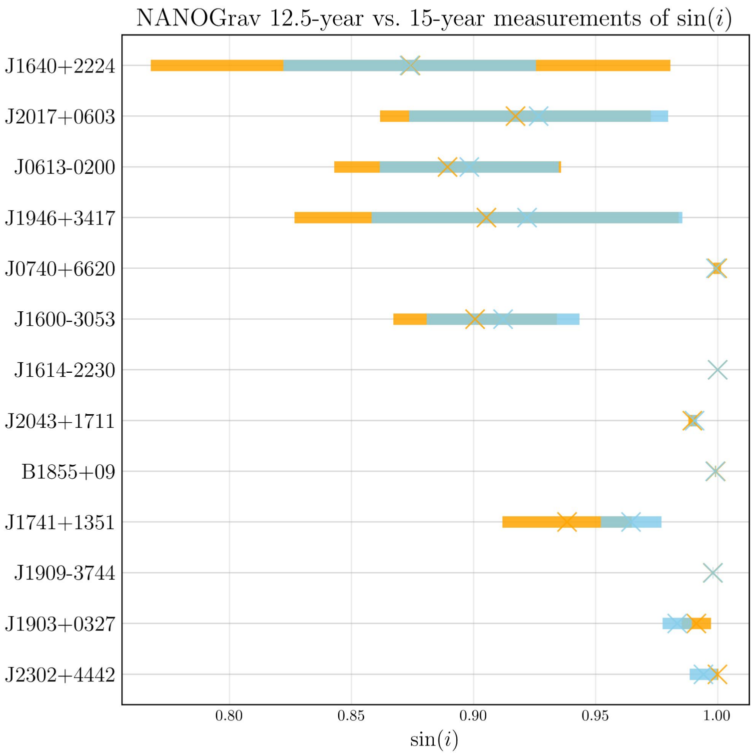
Comparing the 12.5 and 15-Year Data Sets





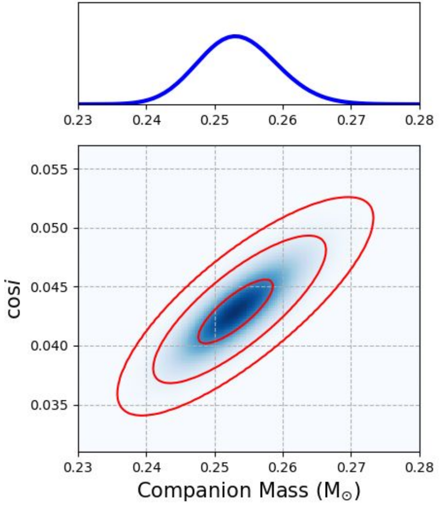
Comparing the 12.5 and 15-Year Data Sets

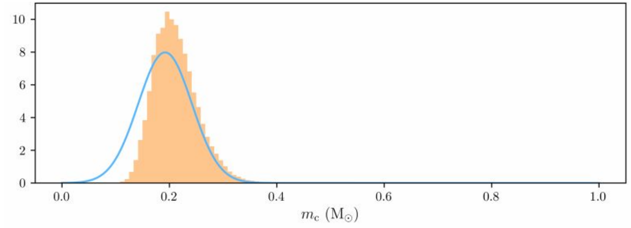




Advanced Techniques

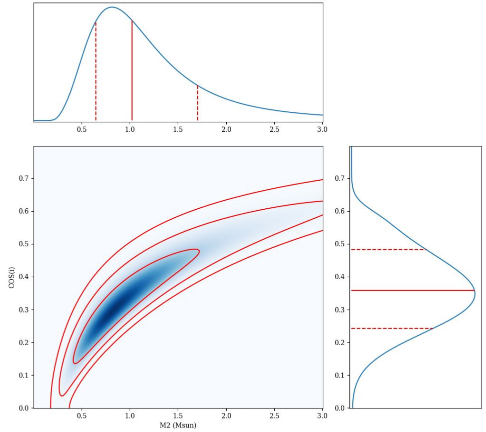
- Bayesian radio timing:
  - **Uncertainty:** parameters and correlations; model non-linear dependence
  - **Priors:** use physical information
  - **Model comparison:** compare models with different parameters (Vigeland & Vallisneri 2014)
- Implemented in `PINT` as `MCMCFitter`
- For now, χ^2 gridding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



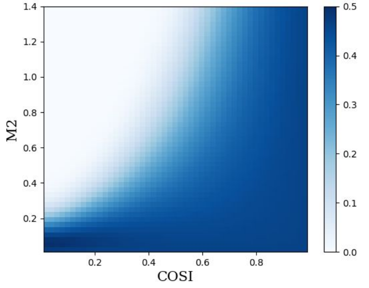


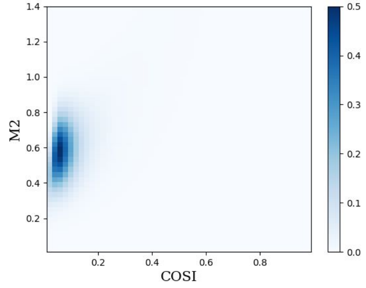
Selected Gridding Results

- *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 $M_\odot$:

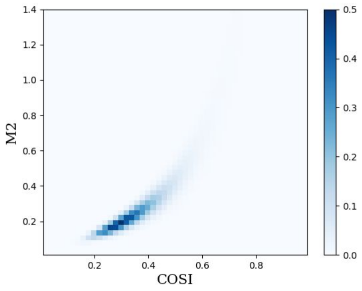


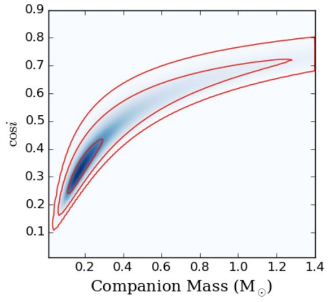
New for 15-year: J1312+0051, J1012-4235, and more





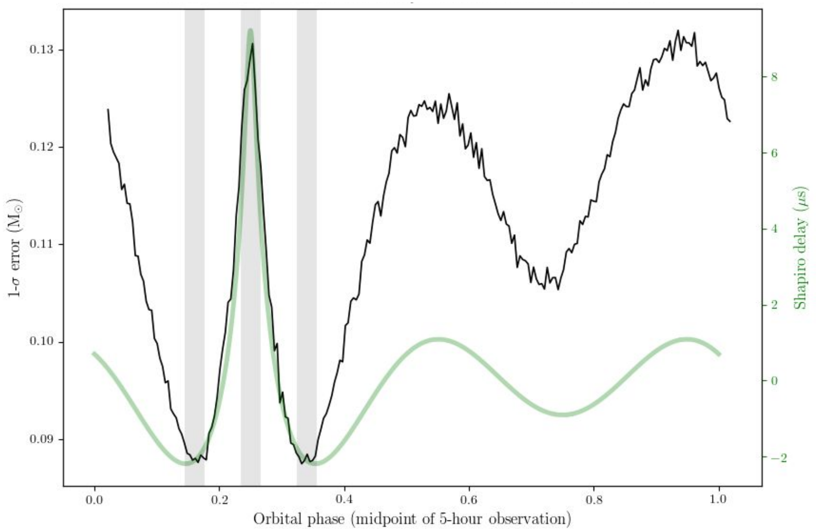
Significant improvements, like J2017+0603: 1.7718 + 1.8218 - 0.8208 $M_\odot$





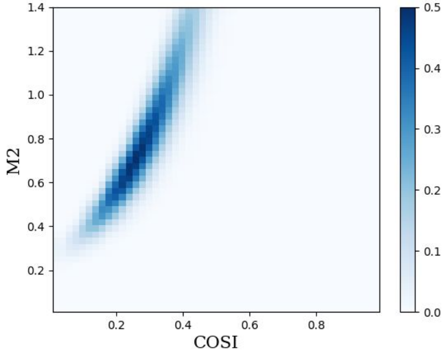
Selected Gridding Results

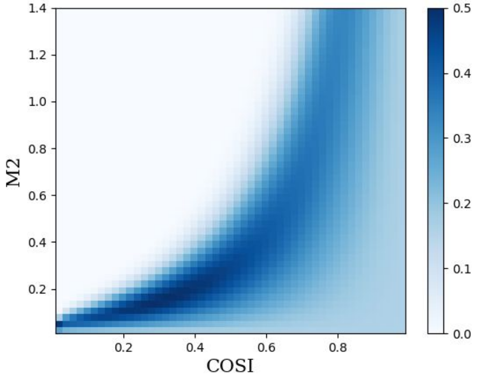
Incomplete and preliminary!




```
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)
```

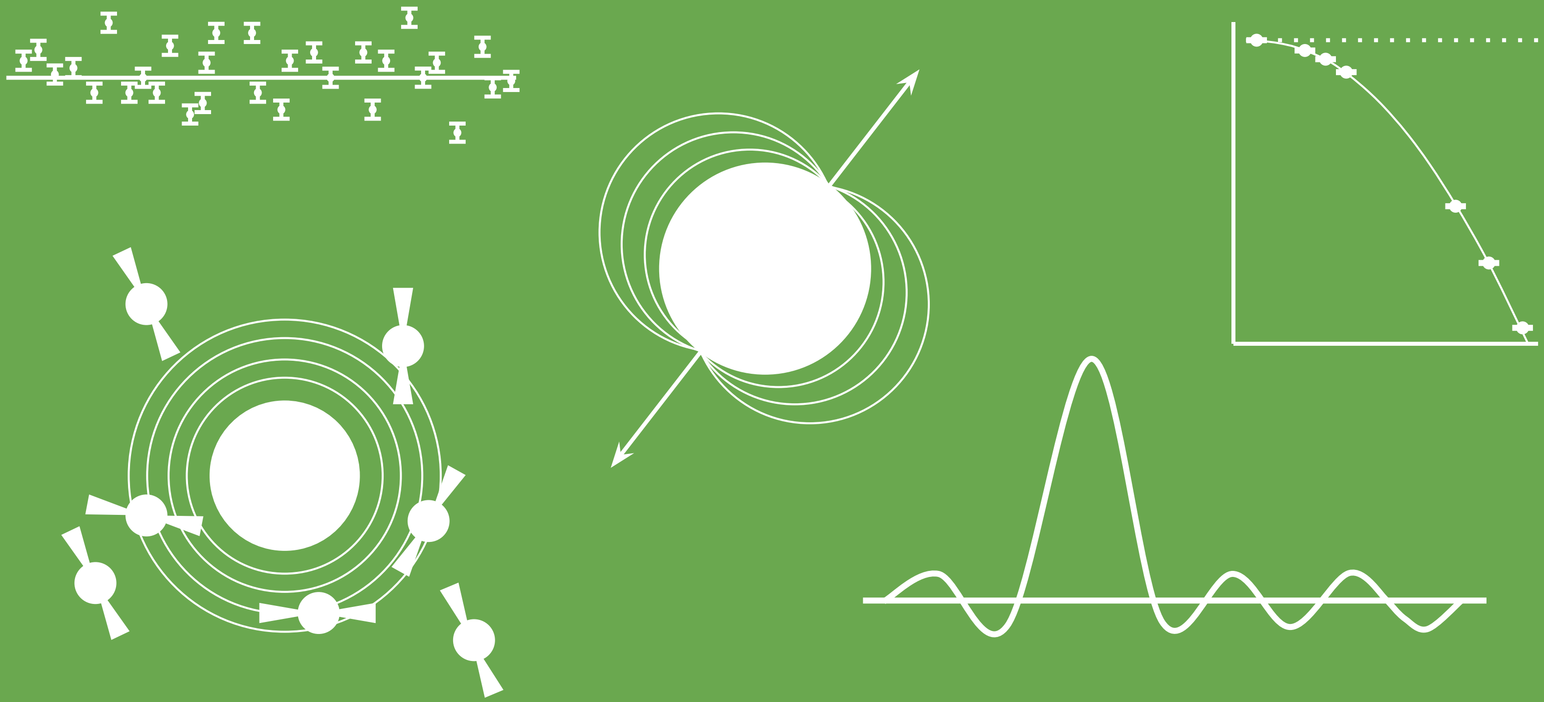
- GBT 22A-399 (+J0125-2327, J1853+1303)





- Older targeted GBT campaign… another?

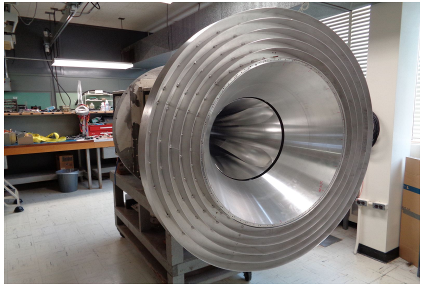
Currently combining recent targeted results with NANOGrav 15-year data set



Looking forward

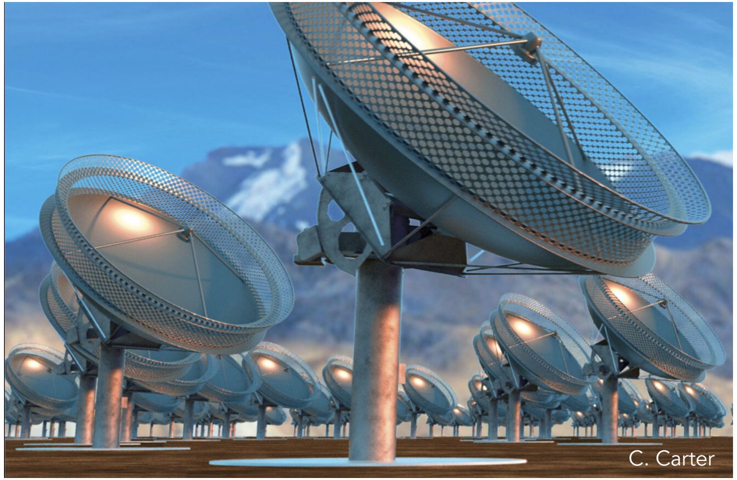
The Future of SD Mass Measurements

- Targeted campaigns help constrain masses
- Some systems simply show weak SD, or don't time "well"
  - Proven limit to improving constraint
- Improving TOA precision can happen in a number of ways:
  - Increasing sensitivity (new & planned facilities)
  - Increasing bandwidth (Parkes, GBT)
- Long-term and high-cadence observing projects are great for orbital phase coverage (CHIME/NANOGrav, MeerKAT timing projects, other PTAs, etc.)
- Searches! Better telescopes, better algorithms / compute power



Near Future for This Work

- NANOGrav 15-year data set (WB+NB), GWB search, noise budget, astrophysics will be released together in early 2023
    - Full binary analysis
- WB Bayesian constraints, `PINT`-based gridding for all binaries
- "SD masses over time" assessment
- GBT UWB receiver, DSA-2000, SKA, etc.
- Continuing to collaborate with NICER folks!


C. Carter

Summary

- Measurements of post-Keplerian parameters for radio MSPs has been — and remains — one of the best ways to precisely measure NS masses
  - Carefully planned observational campaigns improve constraints
- New facilities (MeerKAT, FAST, CHIME, etc.) are key for these observations
- Optical observations of a WD companion have (very) recently revealed a high (>2.35 $M_\odot$) mass NS, but improved precision is important
- NANOGrav's growing data set brings newly significant NS masses