# Measuring millisecond pulsar masses with radio Shapiro delay observations

**Thankful Cromartie**
Einstein Postdoctoral Fellow | Cornell University

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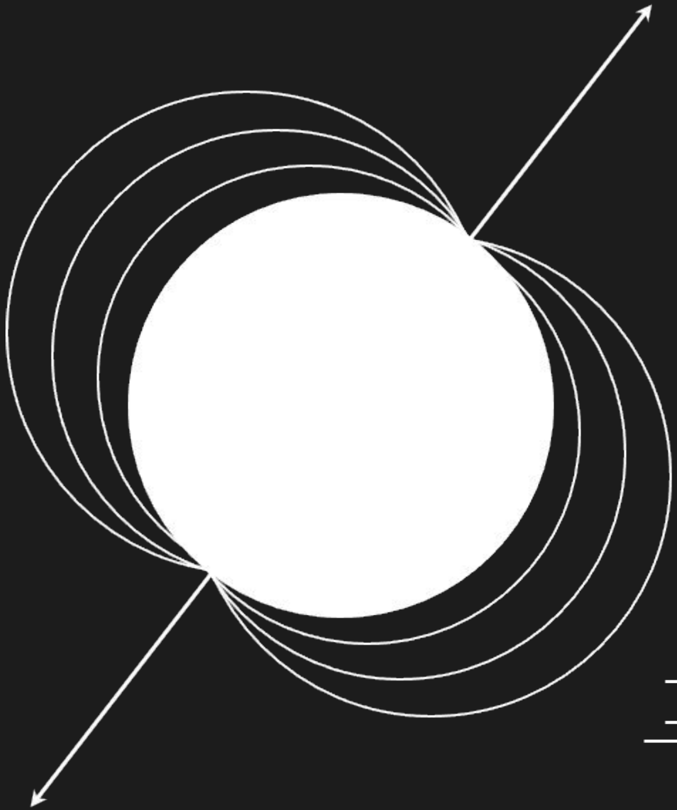
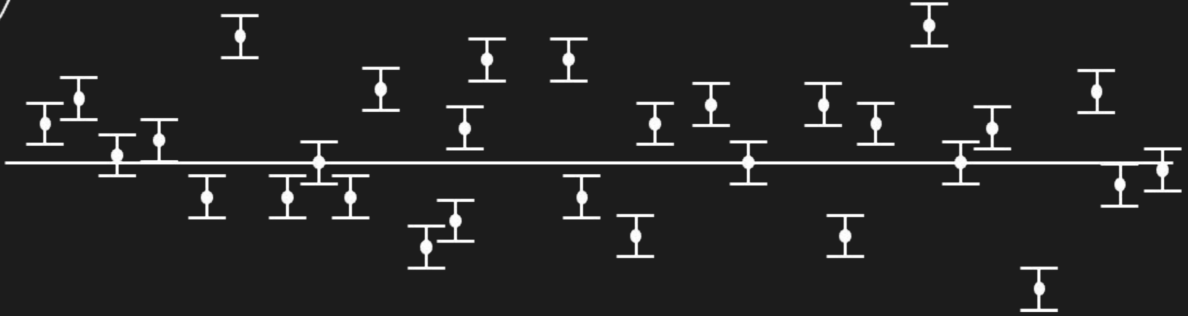
NANOGrav Physics Frontiers Center · Cornell University · NHFP NASA Hubble Fellowship Program

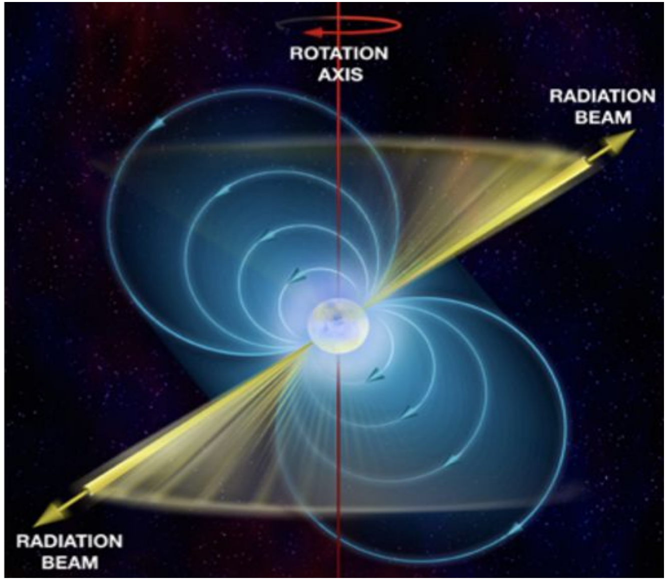
# Millisecond pulsar timing

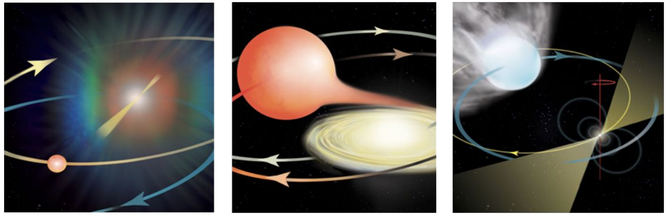




# Millisecond pulsars

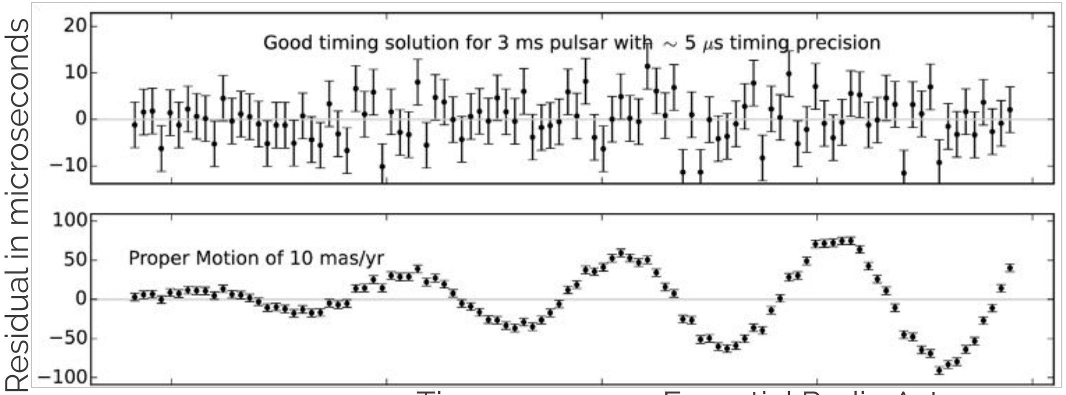
- Rapidly rotating (>700 Hz) highly magnetized neutron stars
- Beam radiation & spin, causing a "lighthouse" effect (don't pulse)
- ~10 km, 1.4 $M_\odot$
- Recycling process spins up MSPs; most in binary systems
- ~3,000 pulsars and ~400 MSPs known



# Pulsar timing in a nutshell

- Unambiguously account for every single rotation of a pulsar
- If we can predict times of arrival (TOAs), we know when external effects are interfering (ISM, ephemeris issues, relativistic effects, gravitational waves!)
- Deviations are timing residuals (measurement - model)



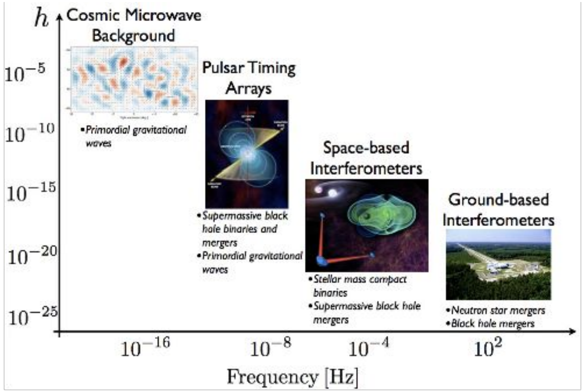

Essential Radio Astronomy

Responsible for some of the most accurate measurements ever

PSR J1737+0747:

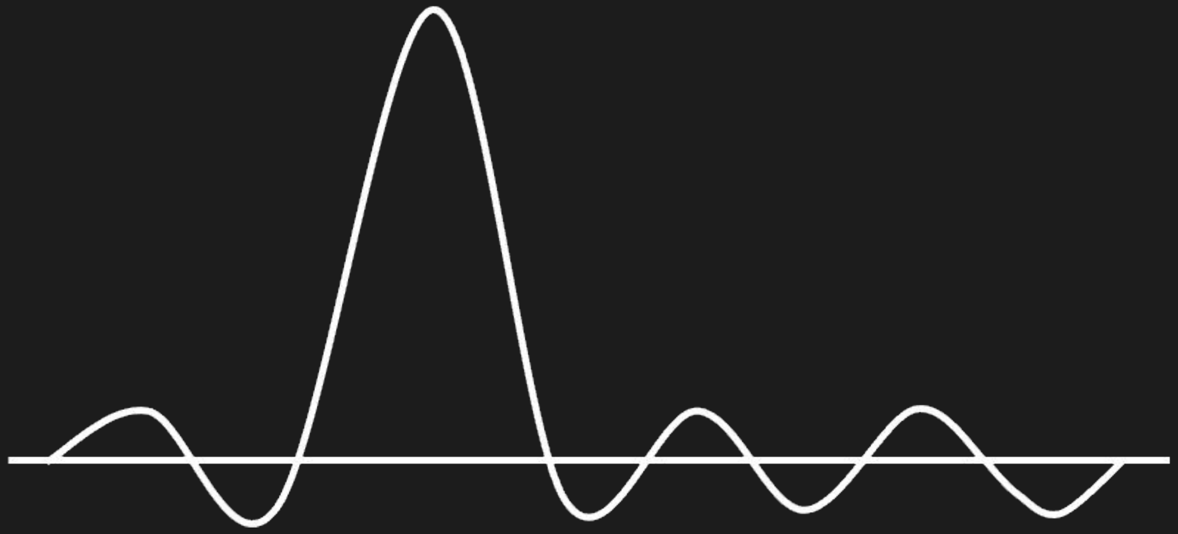
Period = 4.570136528819804 +/- 0.000000000000001 ms

# The NANOGrav pulsar timing array

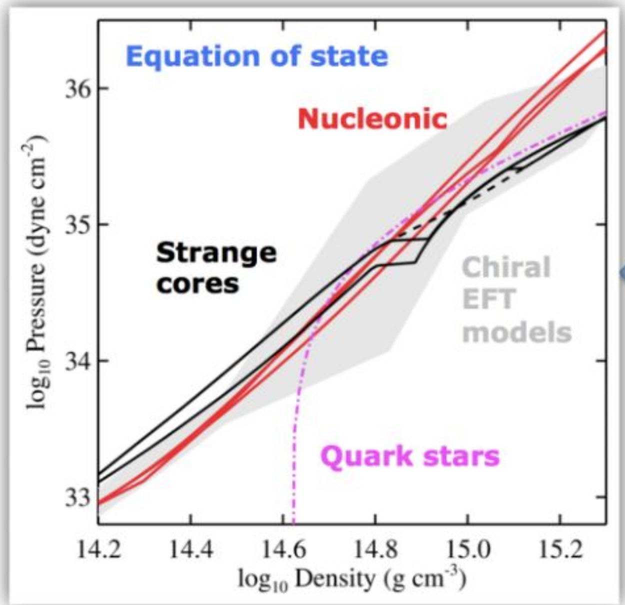


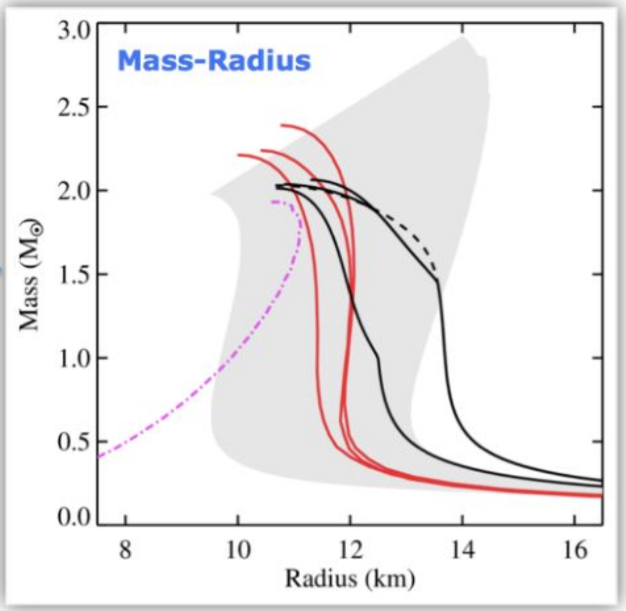

- Primary goal: detect the background of low-frequency gravitational waves from an ensemble of supermassive black hole inspirals
  - In effect, we are using a Galactic-scale gravitational wave detector to probe lower-frequency GWs (i.e. the MSPs *are* the detector)
- We currently time >75 MSPs using the GBT, VLA, CHIME, and until recently, Arecibo
  - (AO is a devastating loss; by no means the end of NANOGrav, but tragic for many reasons)
- Monthly dual-frequency observations of our MSPs spanning many years
- Many secondary science results!

# Relativistic Shapiro delay observations of J0740+6620



# The neutron star interior EoS



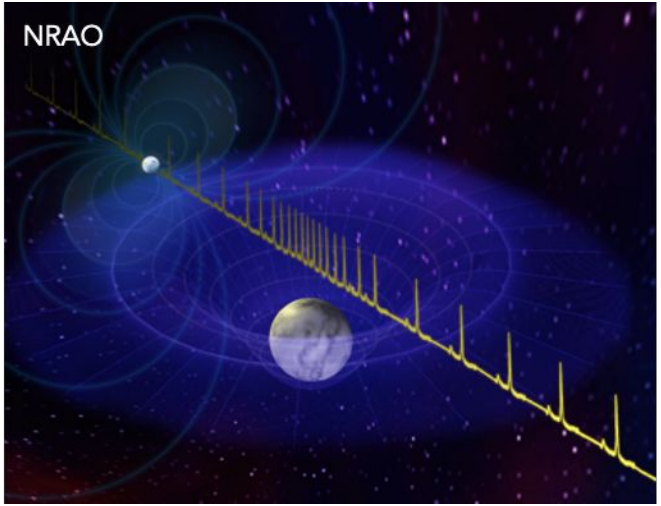

Watts et al. 2015

Observable! Maximum mass exists for every EoS where neutron star will collapse…

How do we measure NS masses precisely?

# Relativistic Shapiro delay

- Pulsar timing gives us 5 Keplerian parameters: among them PB, e, projected semi-major axis
- Shapiro delay occurs at superior conjunction in edge-on binary systems
- "Range" and "shape" PK parameters are directly measurable




$$r = T_{\odot} m_{\mathrm{c}}$$

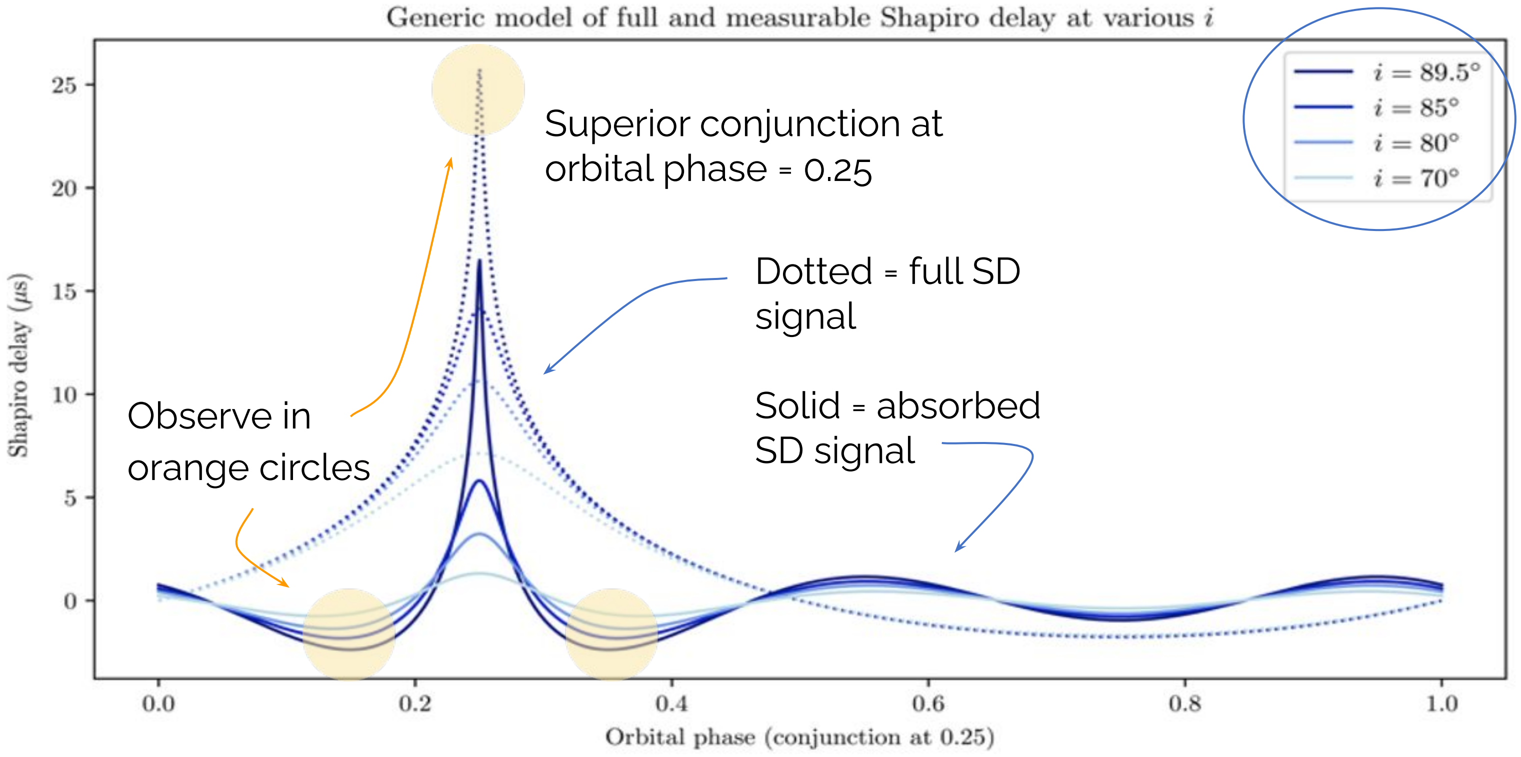
$$s = \sin(i) = x \left(\frac{P_{\mathrm{b}}}{2\pi}\right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_{\mathrm{c}}^{-1}$$

→

$$f(m_{\mathrm{p}}, m_{\mathrm{c}}) = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_{\mathrm{b}}^2} = \frac{(m_{\mathrm{c}} \sin i)^3}{M^2}$$

# Relativistic Shapiro delay

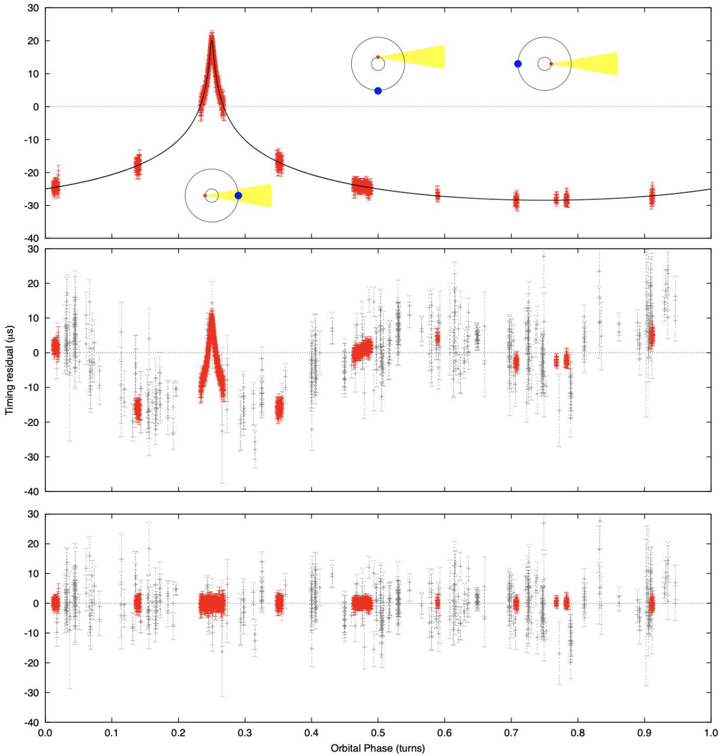
Strongly dependent on *i*



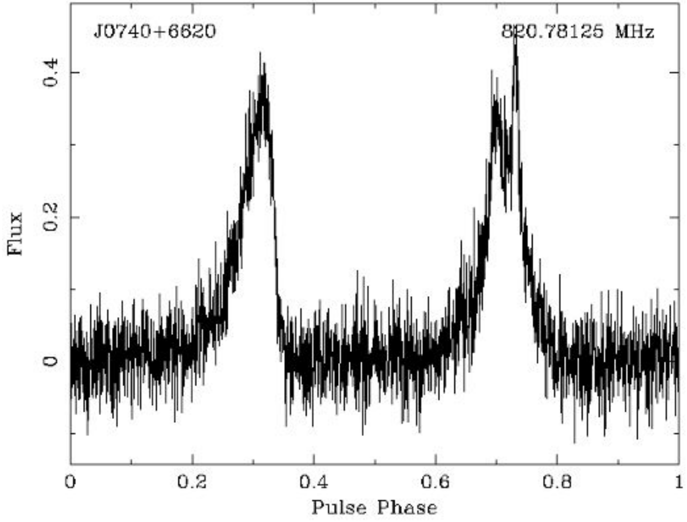
# The first ~2 $M_\odot$ neutron star(s)

- Demorest et al. 2010: J1614-2230 mass = 1.97 ± 0.04 $M_\odot$. Included in NANOGrav data set; measured mass now ~1.93 $M_\odot$
- Ruled out many “exotic” EoS (hyperons, kaon condensates at ~few times nuclear saturation density)
- Next massive NS from Antoniadis et al. 2013 (~2.01 $M_\odot$)
- Fonseca et al. 2016 (NANOGrav): 14 significant SD measurements from 1.18 to 1.93 $M_\odot$

Demorest et al. 2010

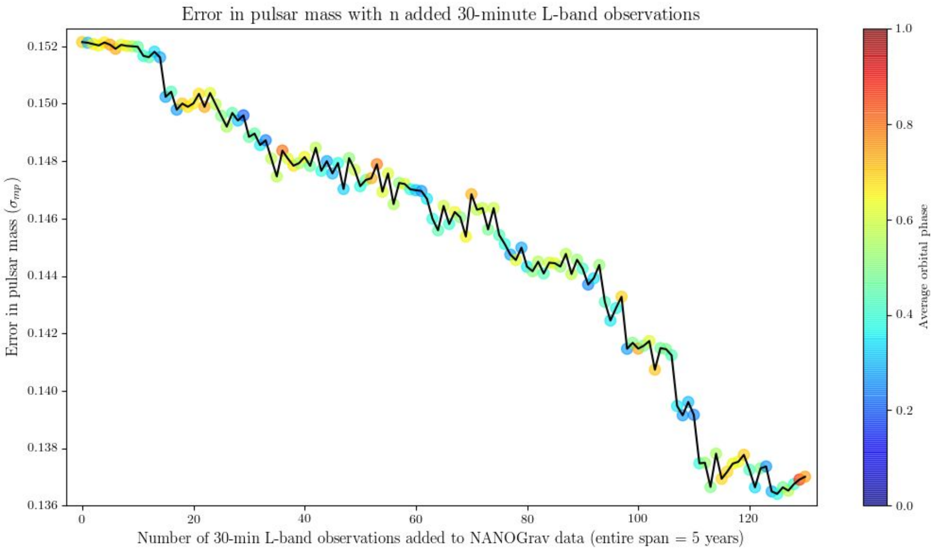


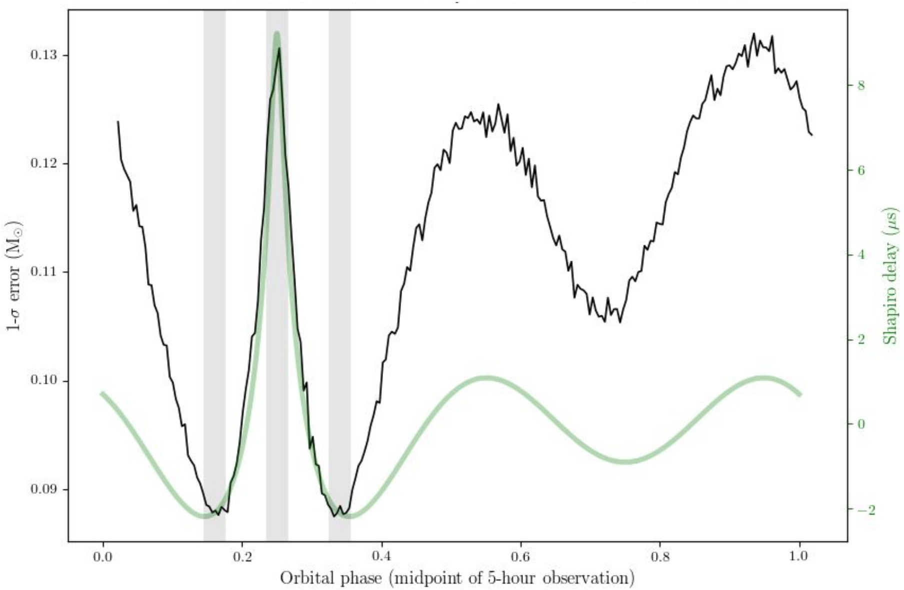
# The MSP J0740+6620




- Found in 2014 GBT survey
- P = 2.9 ms, Pb = 4.8 days
- NANOGrav MSP since 2014 that showed hint of Shapiro delay (2.0 ± 0.2 $M_\odot$)
- First supplemental campaign at the GBT targeted conjunction; saw significant Shapiro delay (yielded 2.18 ± 0.15 $M_\odot$ combined with NANOGrav data)

# How to efficiently observe J0740+6620?



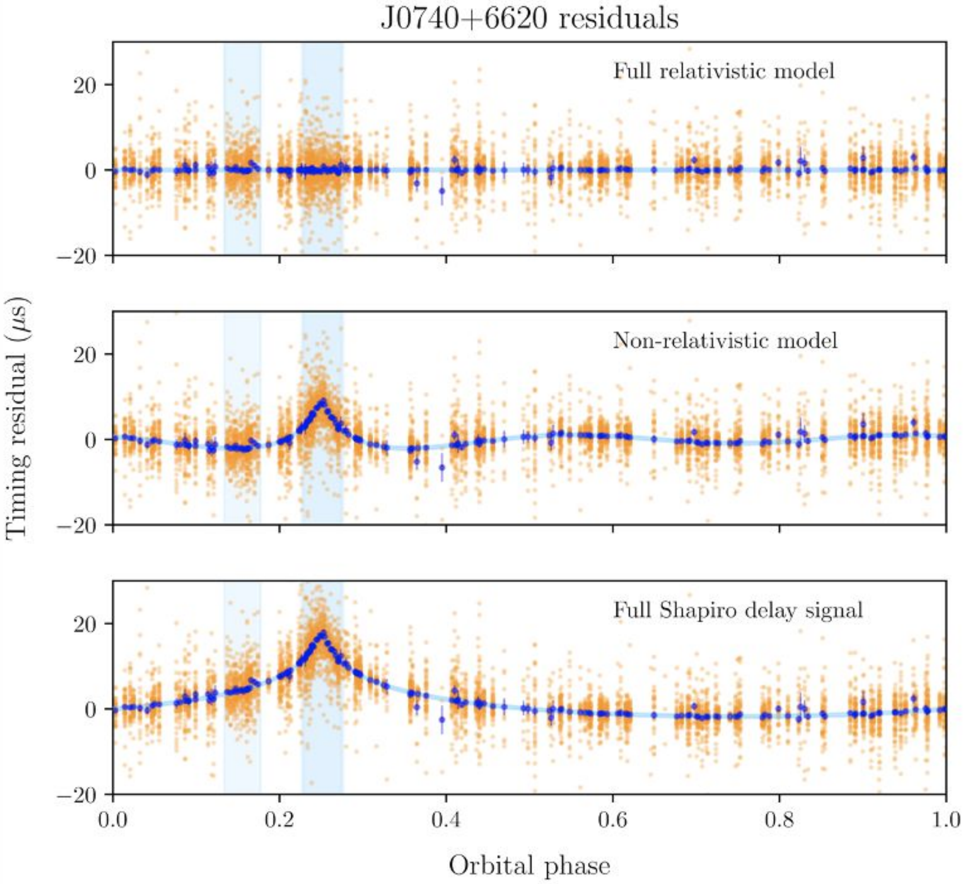




Left: only a small improvement over 5 years with NANOGrav. Right: observing during the SD "troughs" is indeed the right approach.

# J0740+6620 results

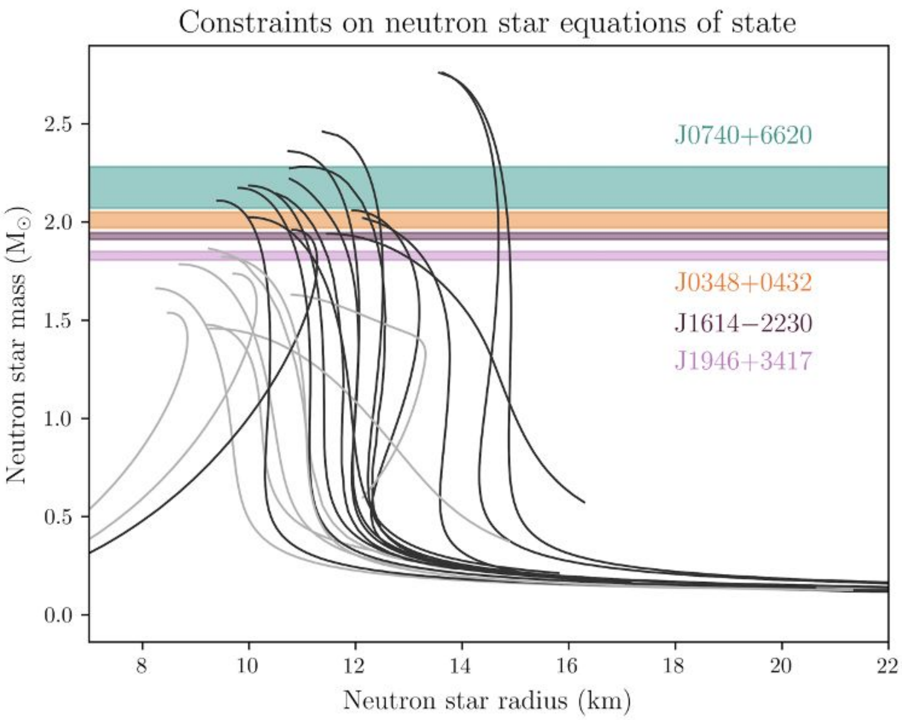
- DDT time for a second supplementary campaign
- NANOGrav + two targeted campaigns eventually yielded 2.14 ± 0.09* $M_\odot$ (1 sigma; the most massive NS known to date)
- Cromartie et al. 2020, Nature Astronomy

*(2.14 +0.10, -0.09 $M_\odot$)



# J0740+6620 results

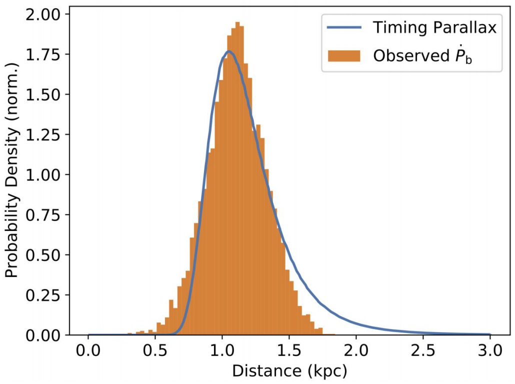
- Higher mass → similarly in tension with exotic theories (quark matter, hyperons, meson condensates, etc.)
- See fully recycled MSPs < 1.4 $M_\odot$ → some born massive?
- Slight tension with TS99 prediction; high $m_c$ → low Z?
- Must improve uncertainty...

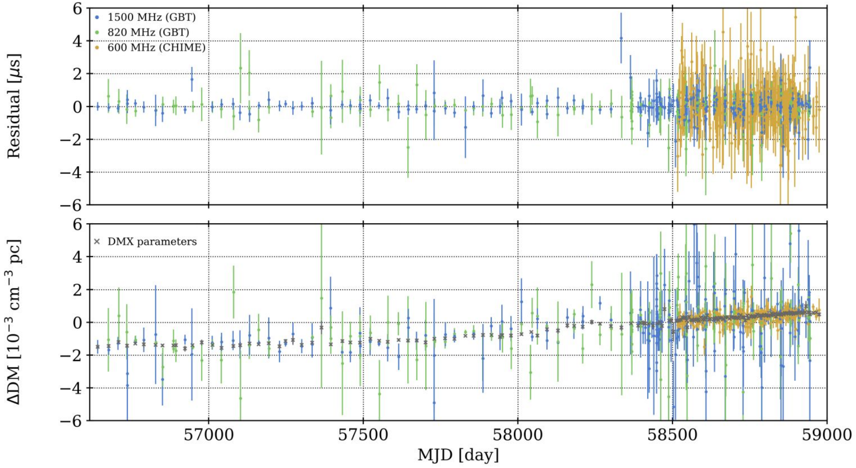



Fonseca & Cromartie based on Özel & Freire 2016

# J0740+6620 update

- Fonseca, Cromartie et al. 2021
  - Additional 1.5 years of GBT w/NANOGrav at high cadence
  - 1.5 years daily CHIME observations
- First measurement of PB-dot
- Consistency check with parallax d





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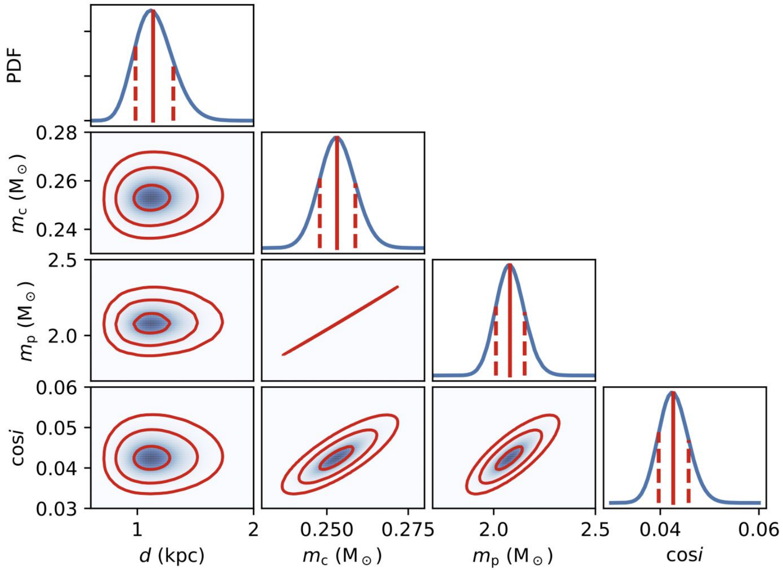
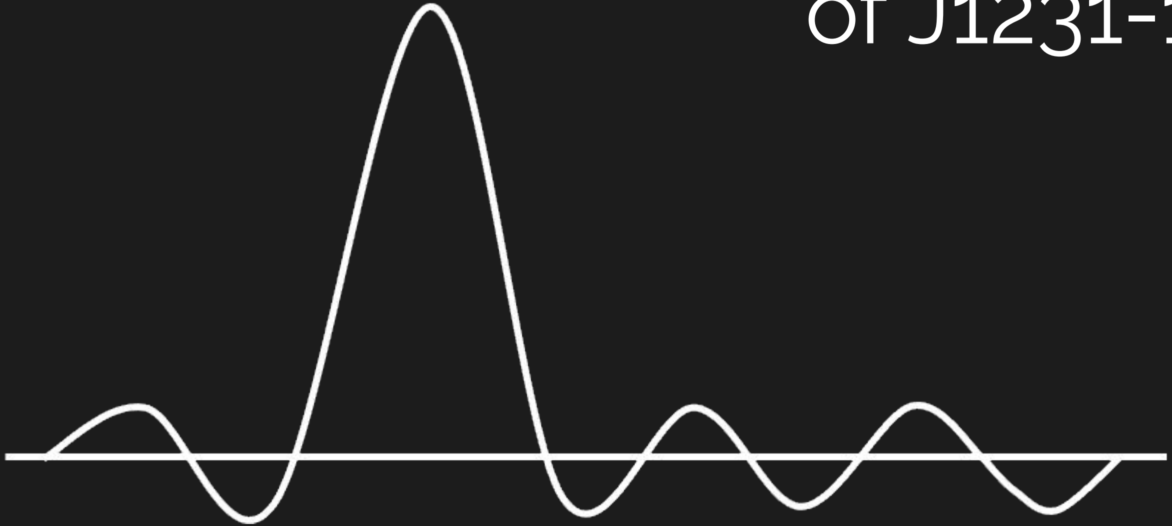
# J0740+6620 update

- Bayesian model averaging over DMX models (incl. hybrid)
- 2.08 ± 0.07 $M_\odot$
  - Lower limit on max. mass ~unchanged from Cromartie et al.
- Improved distance → white dwarf cooling curves; agree with both analyses (0.2-0.3 $M_\odot$)
- These updated measurements inform NICER studies — more on that later!

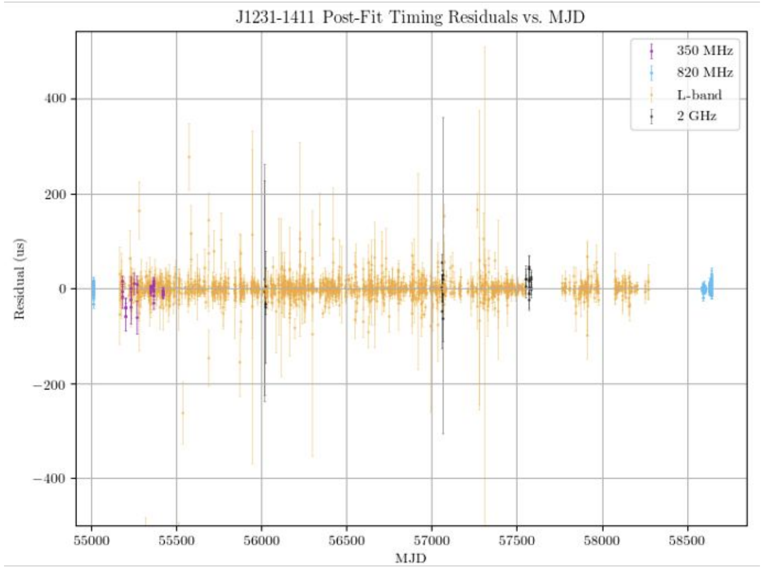


# Relativistic Shapiro delay observations of J1231-1411



# The MSP J1231-1411

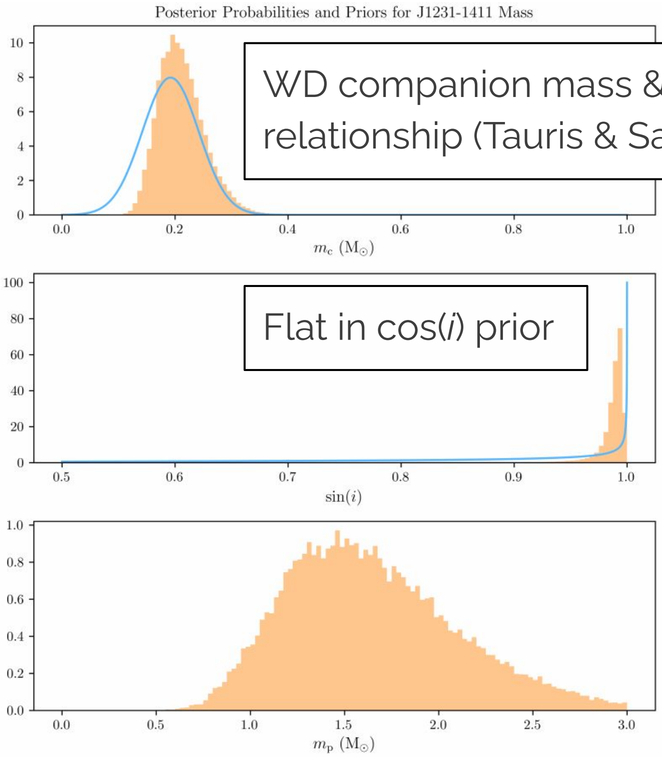
- Discovered in *Fermi* unidentified source search
- Target of interest for NICER (also brightest MSP in gamma-rays)
  - X-ray light curve suggests source is less massive
  - Use SD-derived mass to improve NICER radius measurement
- 22 additional hours (incl. 2x6 hr conjunction) w/GBT to obtain Shapiro delay measurement; combined with Nançay and archival GBT



# The MSP J1231-1411

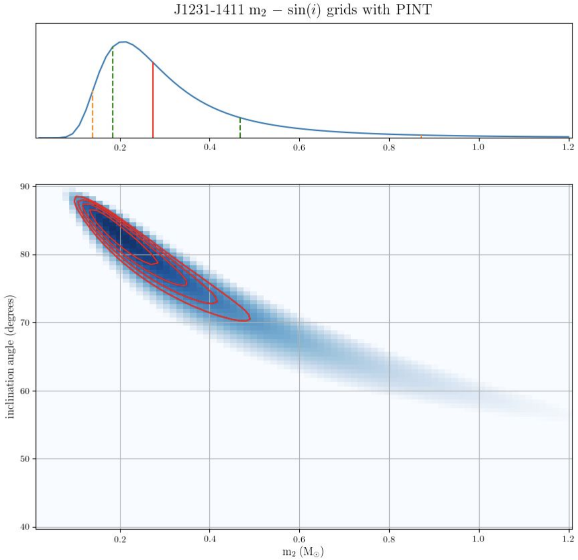
$m_c$ ~ 0.22 ± 0.04, $m_p$ ~ 1.7 ± 0.5

- Grids and MCMC for combined data set prefer low $m_c$, high inclination (~82°)
- Despite low mass, studying these sources is important



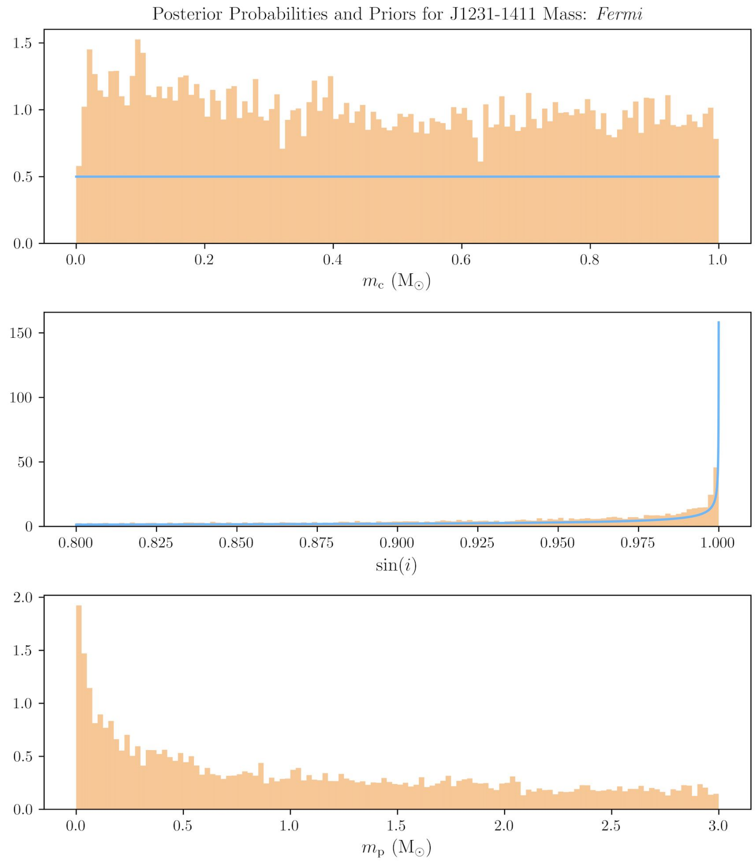

WD companion mass & binary orbital period relationship (Tauris & Savonije 1999)

Flat in cos($i$) prior



# The MSP J1231-1411 (*Fermi*)

- With Gamma-ray MSPs, detect as few as 1-2 photons per day
- Single-photon timing: technique yields timing solutions similar to those in radio
- Companion mass not constrained, result is uninformative
- Radio results will still inform NICER analysis!



# Summary

- The NANOGrav pulsar timing array observes many binary MSPs with measurable Shapiro delay
  - By combining NANOGrav data for the MSP J0740+6620 with targeted observations, the pulsar's measured mass was 2.14 ± 0.09 $M_{\odot}$
  - Update by Fonseca et al. adds CHIME data, yields 2.08 ± 0.07 $M_{\odot}$
  - Lower limit ~equal to Cromartie et al. 2020 result
  - Still very likely to be most massive NS known; significant constraint of EoS
- J1231-1411 is another MSP with significant radio Shapiro delay
  - Its mass is ~1.7 ± 0.5 $M_{\odot}$ (more poorly constrained), but may still help with NICER analysis

Questions? thankful.cromartie@cornell.edu

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