Probing the Neutron-star Equation of State with Radio Pulsars

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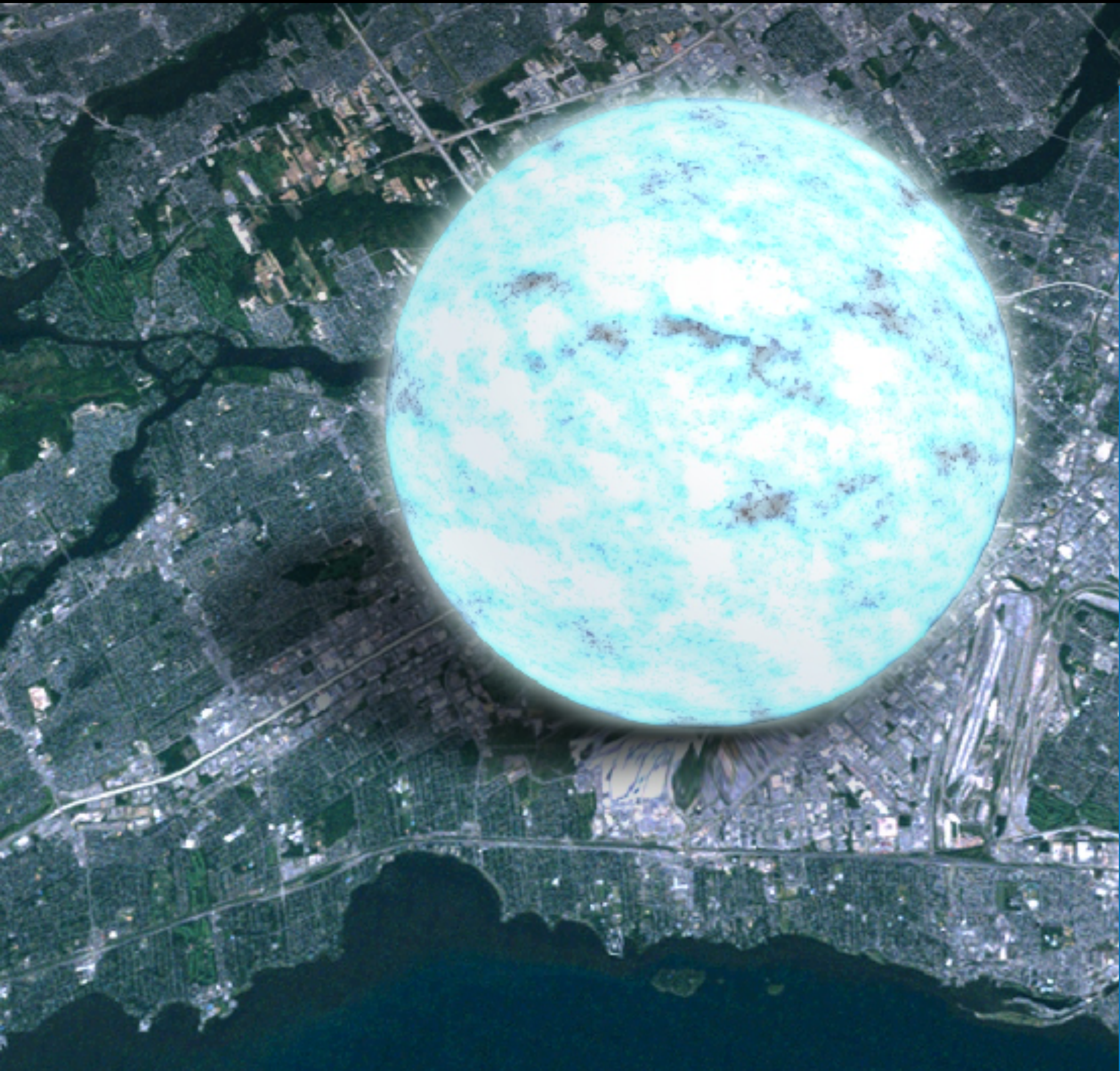
NANOGrav
Physics Frontiers Center


Credit: NASA GSFC



Credit: NASA GSFC

NANOGrav fundamentally relies on "pulsar timing" for its GW project.

Pulsar timing is "so good" that you can (and must!) study:

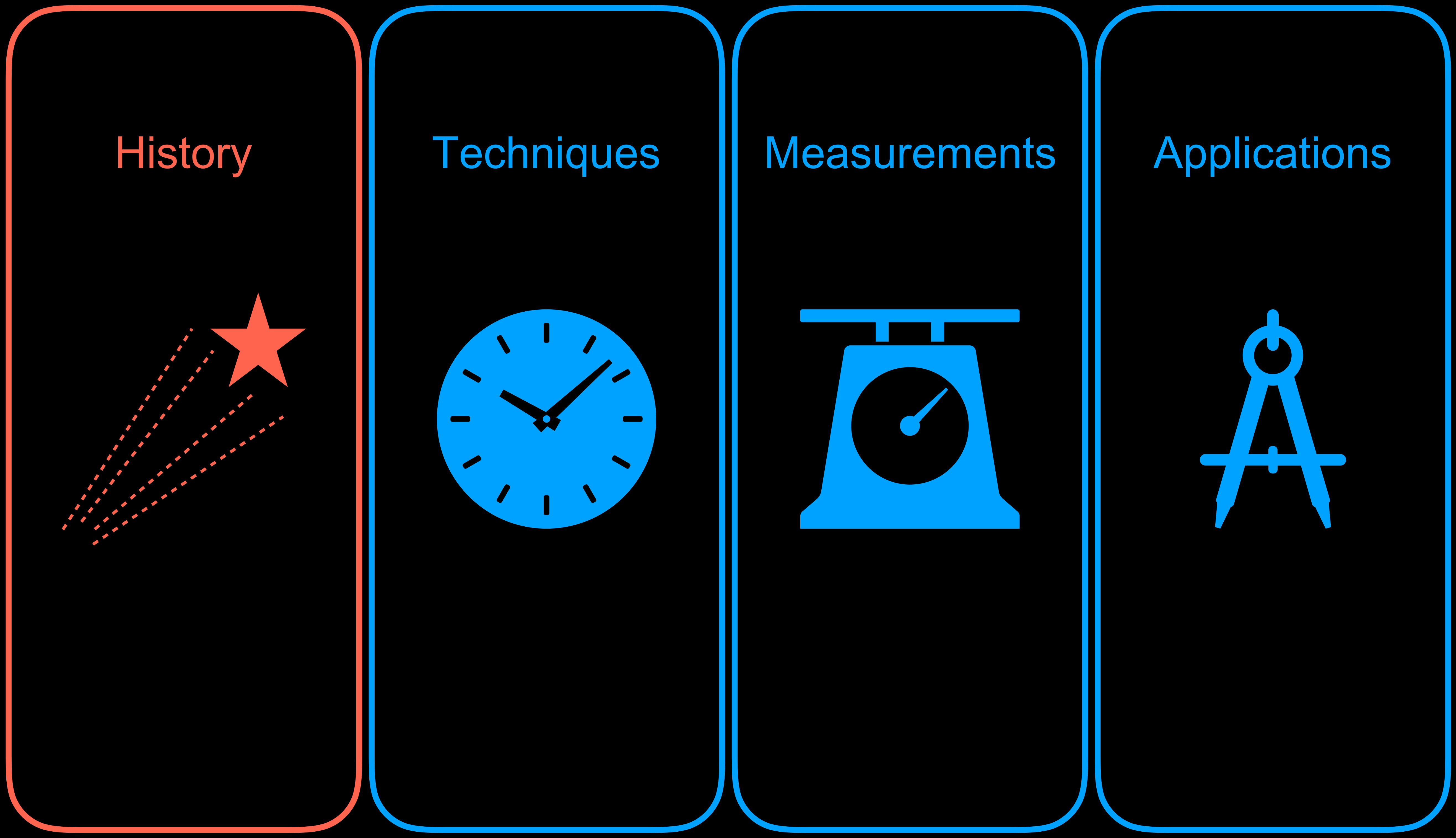
- astrometry
- irregularities in spin
- dispersion variations
- pulsar-based timescales
- strong-field gravity
- variations in radio polarization
- mass and geometric information

History

Techniques

Measurements

Applications


History
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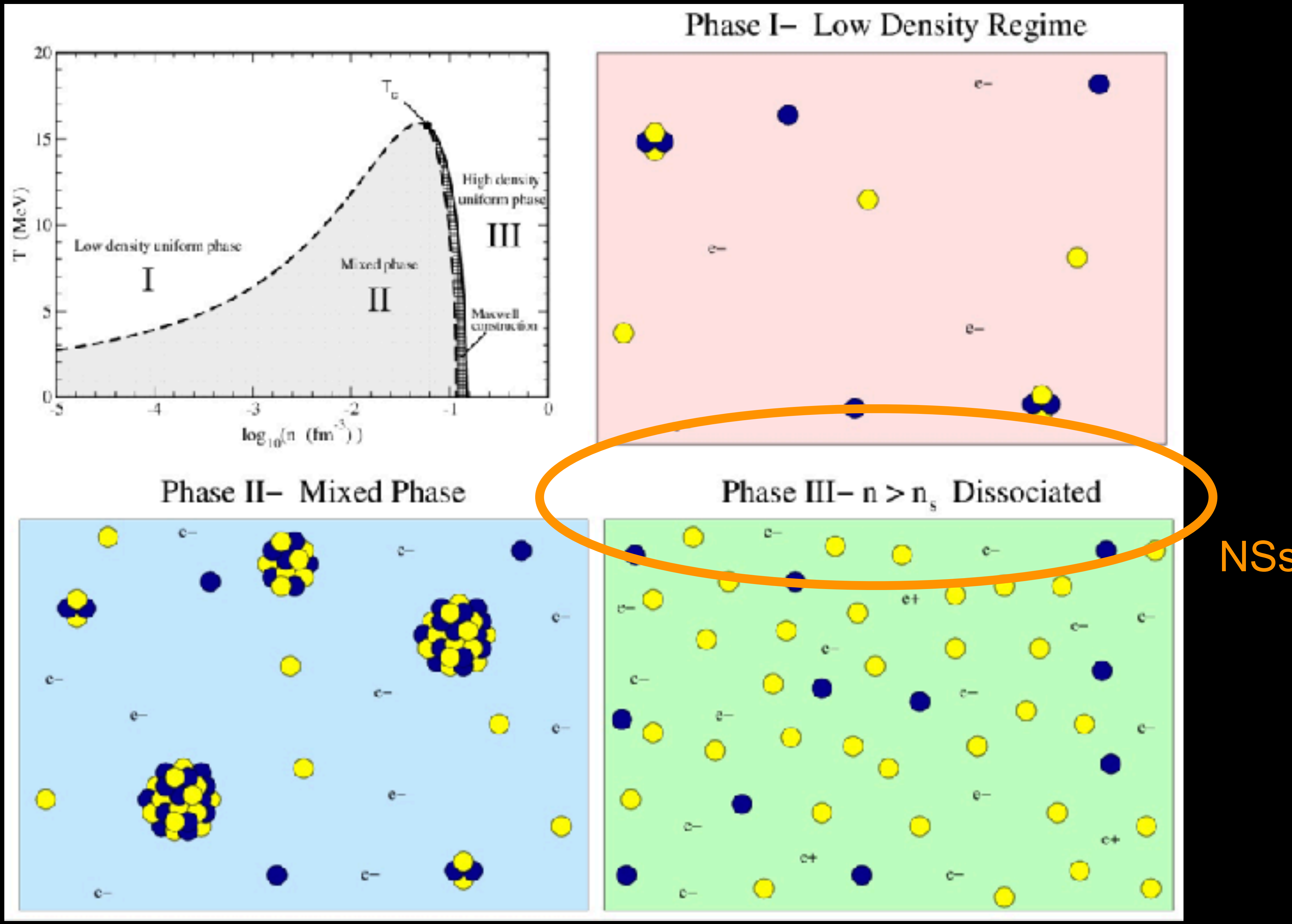
A Brief History of Neutron Stars

- Milestones for our understanding of neutron stars and their interiors:
  - 1933: neutron discovered (J. Chadwick)
  - 1934: neutron stars (NSs) proposed (W. Baade, F. Zwicky)
  - 1939: first equation of state (EoS) proposed (R. C. Tolman; J. R. Oppenheimer & G. M. Volkoff)
  - 1966: pre-observation summary of nuclear physics relevant to neutron stars (J. A. Wheeler)
  - 1967: first pulsar discovered! (J. Bell-Burnell, A. Hewish)

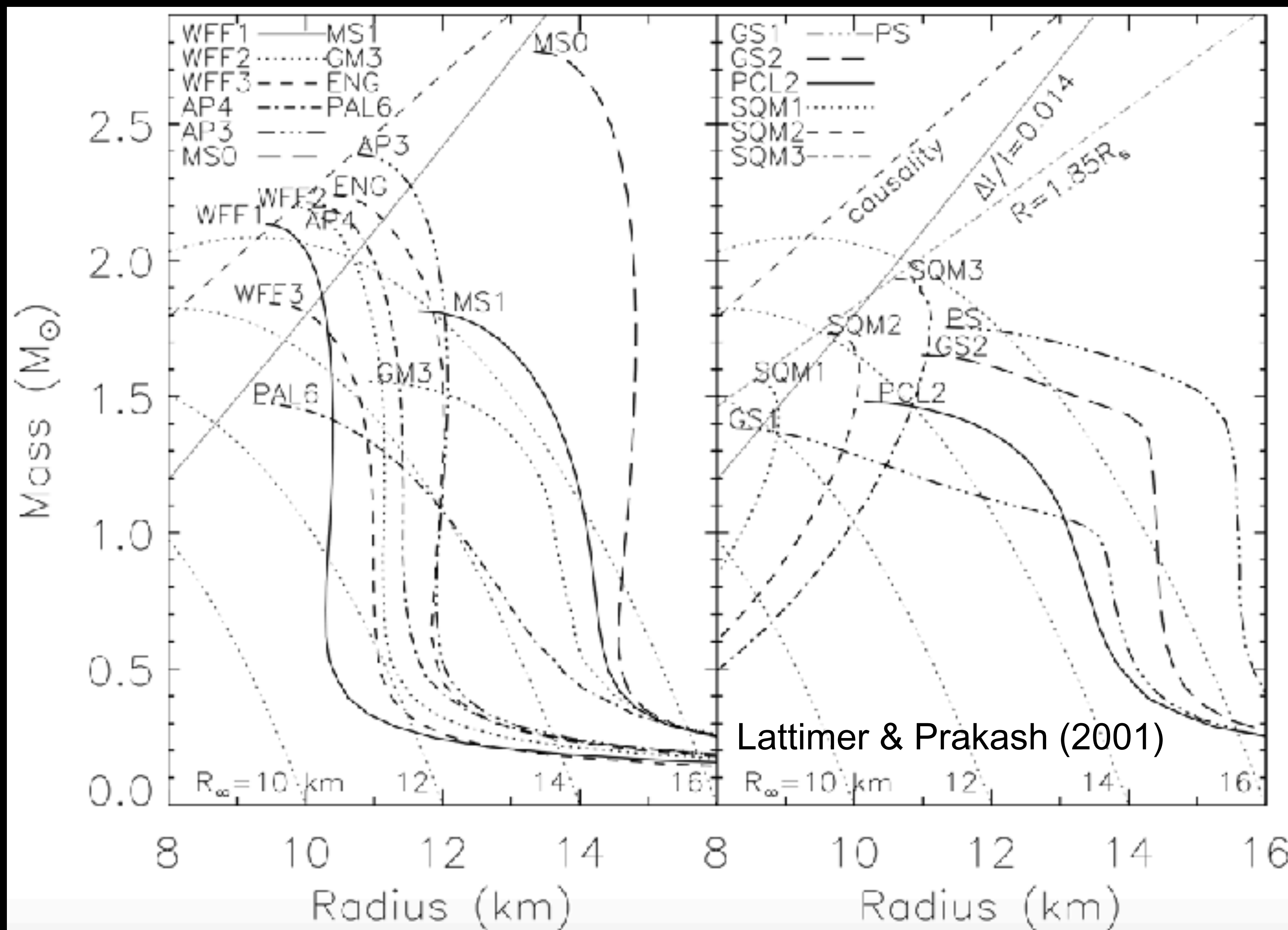
Supernova in NGC4157, discovered by F. Zwicky in 1937
(Credit: CalTech / Palomar)

History of NS-EoS Theory, I



At supra-nuclear densities (III above), NSs are believed to consist of: unbound nucleons, strange-carrying baryons (e.g., hyperons), quarks, Bose-Einstein condensates, etc. (Credit: M. Carmell.)

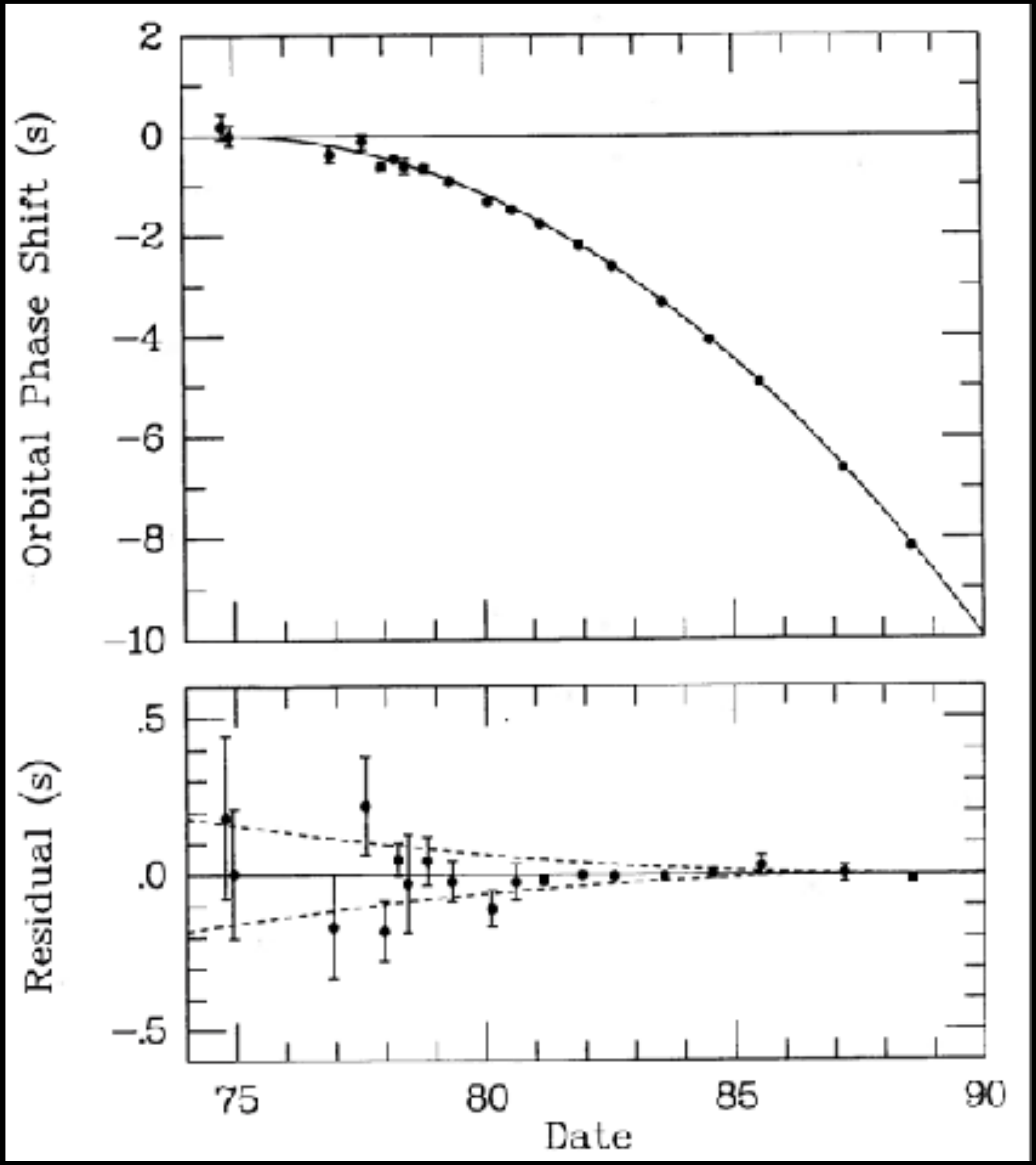
History of NS-EoS Theory, II



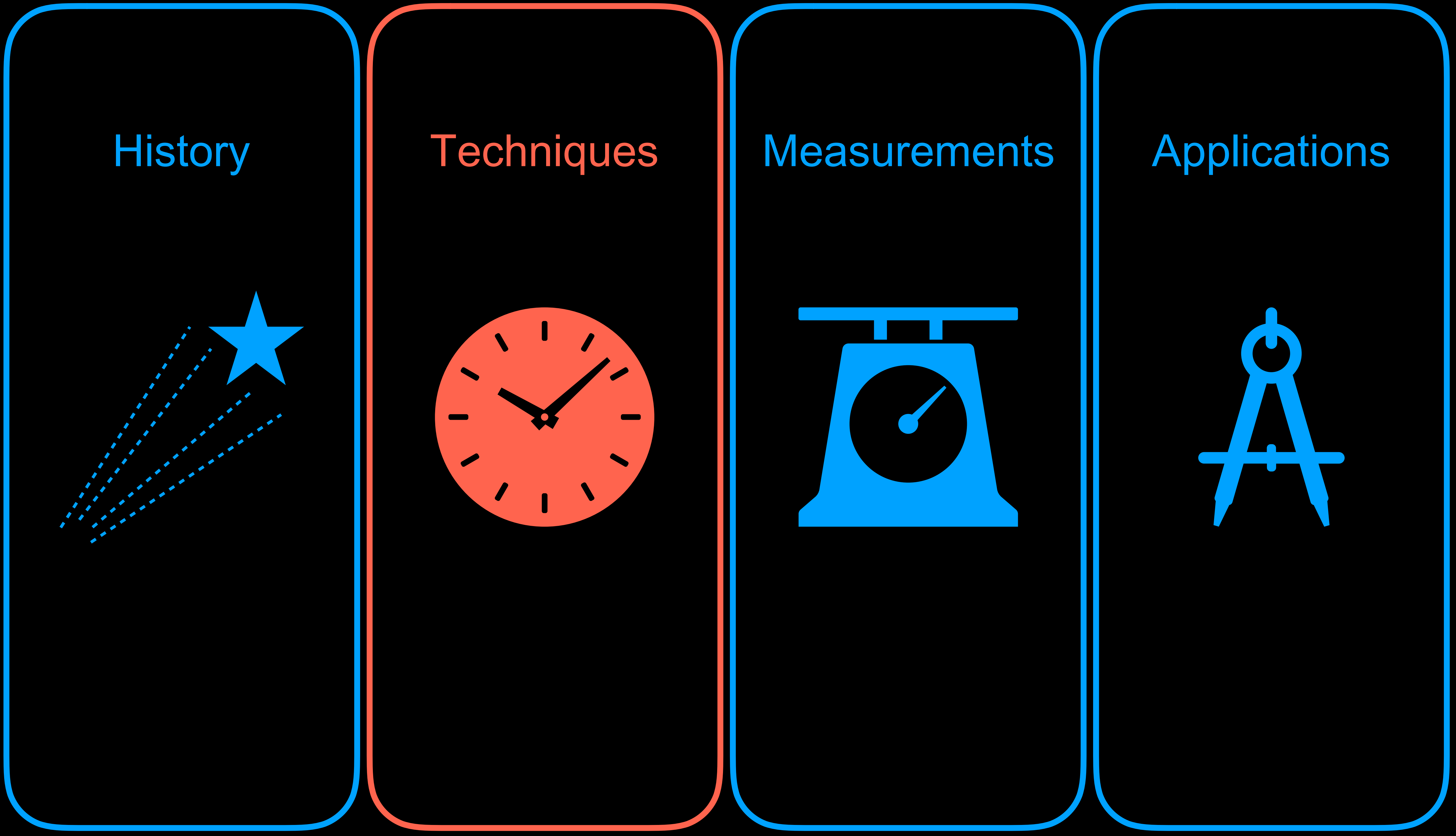
Development of particle physics and QCD led to a diverse range of possibilities for NS compositions, due to uncertainties in strong, many-body interactions.

History of NS Observations

- The first binary pulsar, PSR B1913+16, found by Hulse & Taylor (1975) to orbit another NS.
- Timing measurements yielded orbital deviations explained by general relativity (Taylor & Weisberg, 1982).
- Masses of both neutron stars determined down to 0.003 solar masses.



Orbital decay in PSR B1913+16
(Taylor & Weisberg, 1982)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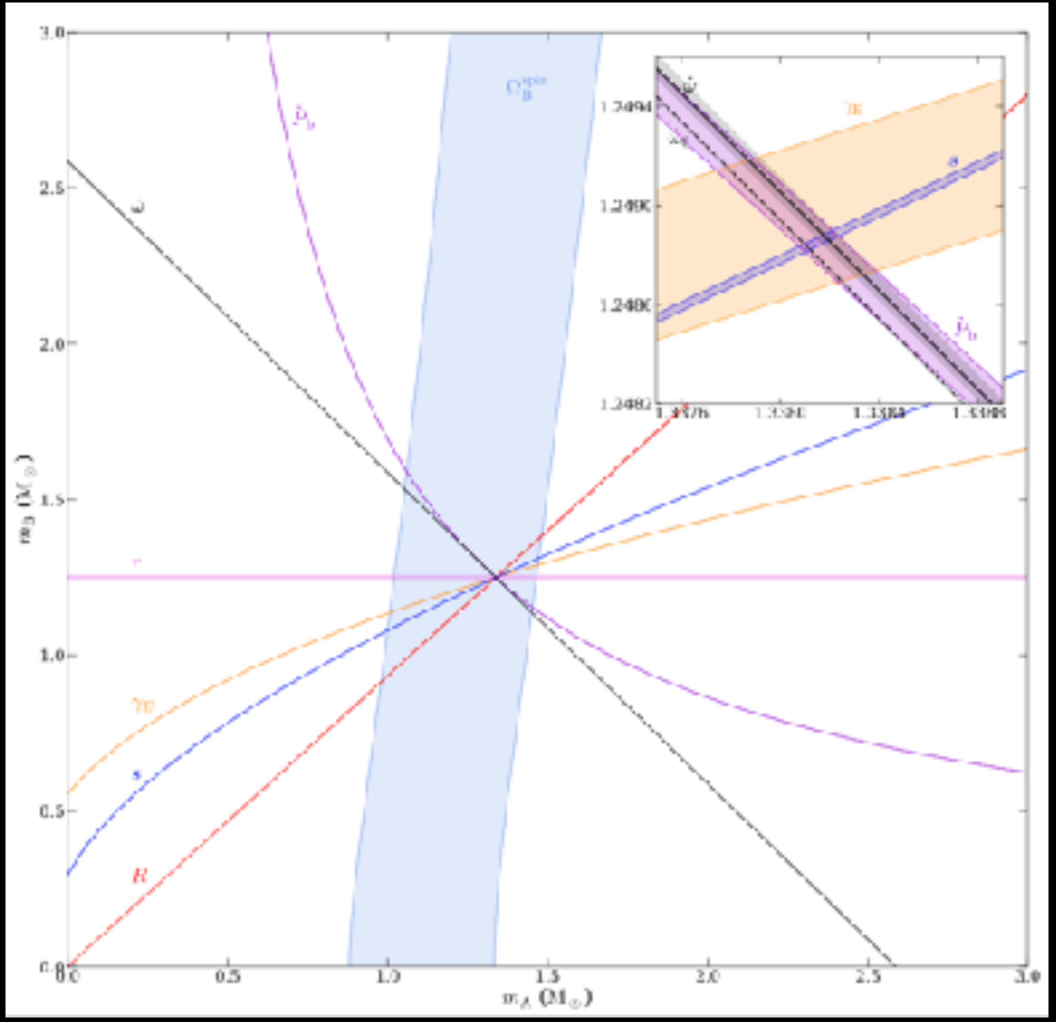
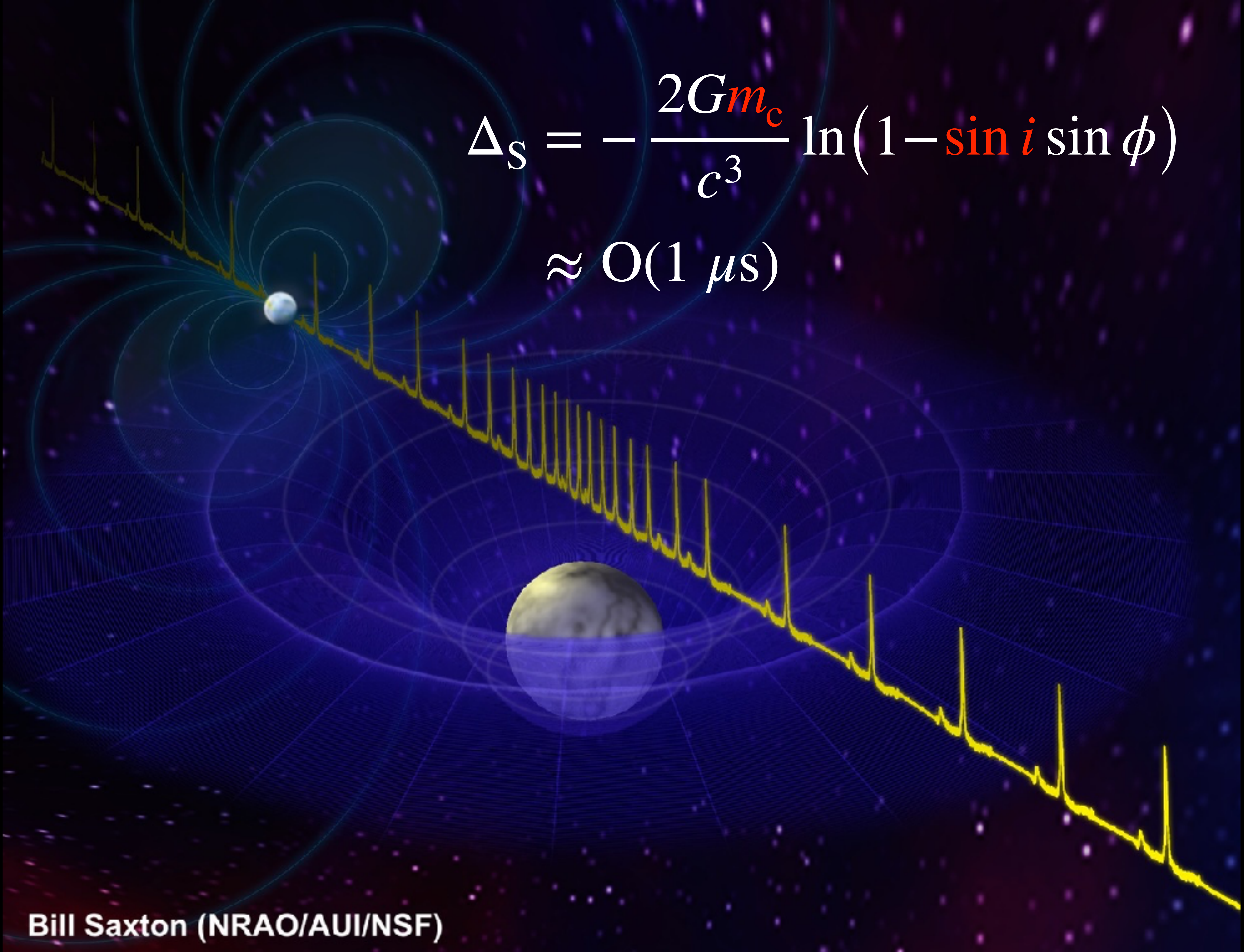
Radio Timing of Binary Pulsars

- Pulsar timing: see talk by R. Jennings!
- “Most robust” method of obtaining macroscopic NS parameters.
- mass uncertainties ~ 0.00001—0.1 solar masses.
- Common post-Keplerian effects:
  - orbital decay
  - apsidal motion
  - time dilation + gravitational redshift
  - the Shapiro time delay



Measurement of 6 PK effects in the double-pulsar system (Kramer et al., 2021)



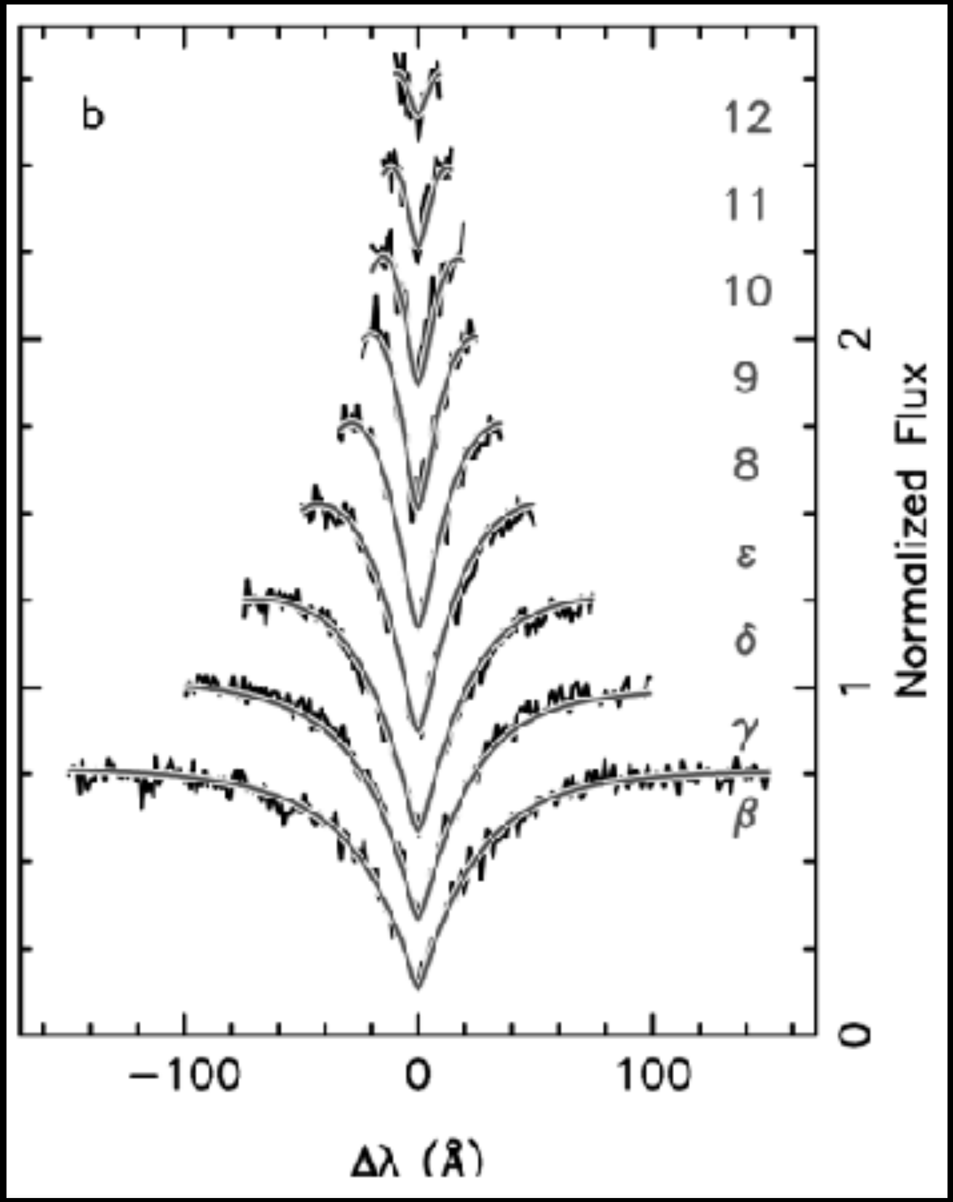
$$\Delta_S = -\frac{2Gm_c}{c^3}\ln\left(1 - \sin i \sin\phi\right)$$

$$\approx O(1\ \mu s)$$

Bill Saxton (NRAO/AUI/NSF)

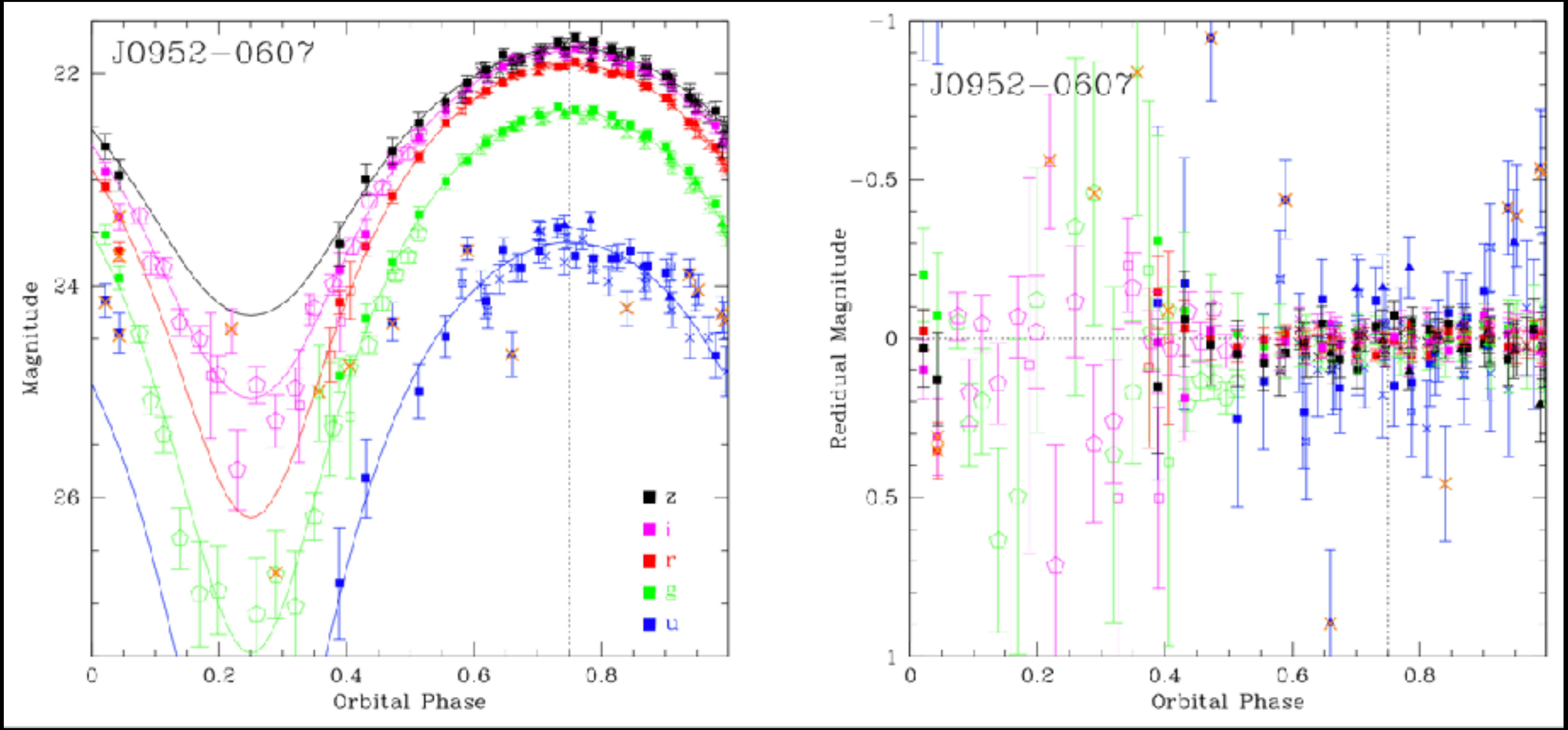
Optical Spectroscopy of WD Companions to Binary Pulsars

- White dwarfs (WDs) that are bright enough (magnitude < 23) can be observed with spectrographs.
- Doppler shift of emission lines —> projected radial velocity —> mass ratio (when combined with radio timing).
- Additional WD parameters (e.g., surface gravity and temperature from shape of spectral features, radius from WD-EoS models) can be obtained, but these are model-dependent.
- NS mass uncertainties ~ 0.1 Msun or larger.



Observed and models hydrogen Balmer lines in the WD companion to PSR J1911-5958A (Bassa et al., 2006c)

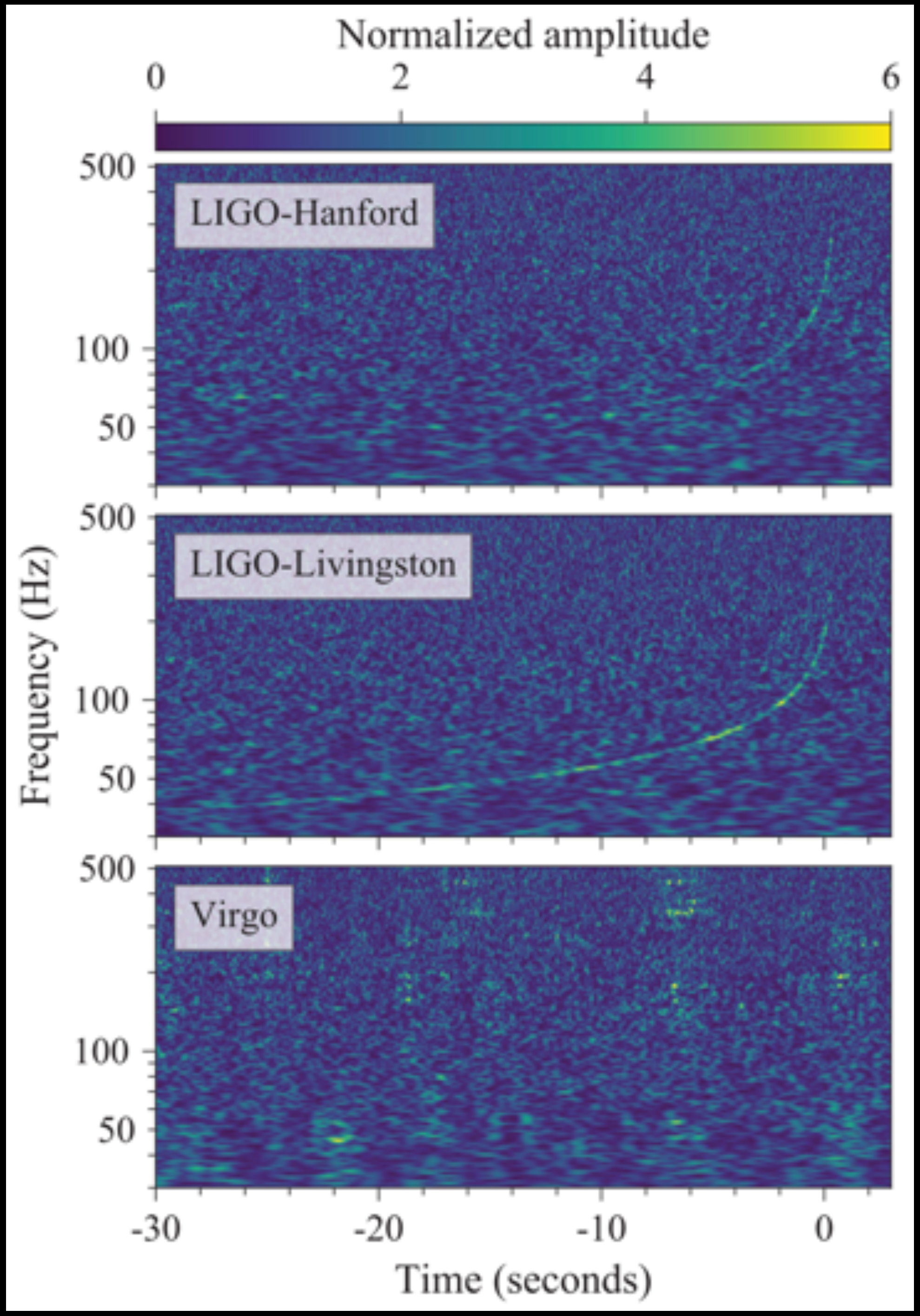
Optical Modeling of “Black Widow” Pulsars



Similar observations can be conducted for “black-widow” pulsars, where modeling of spectral features and light-curve variations (the latter being model-dependent) have been shown to yield mass and geometric information. (Above: Romani et al., 2022.)

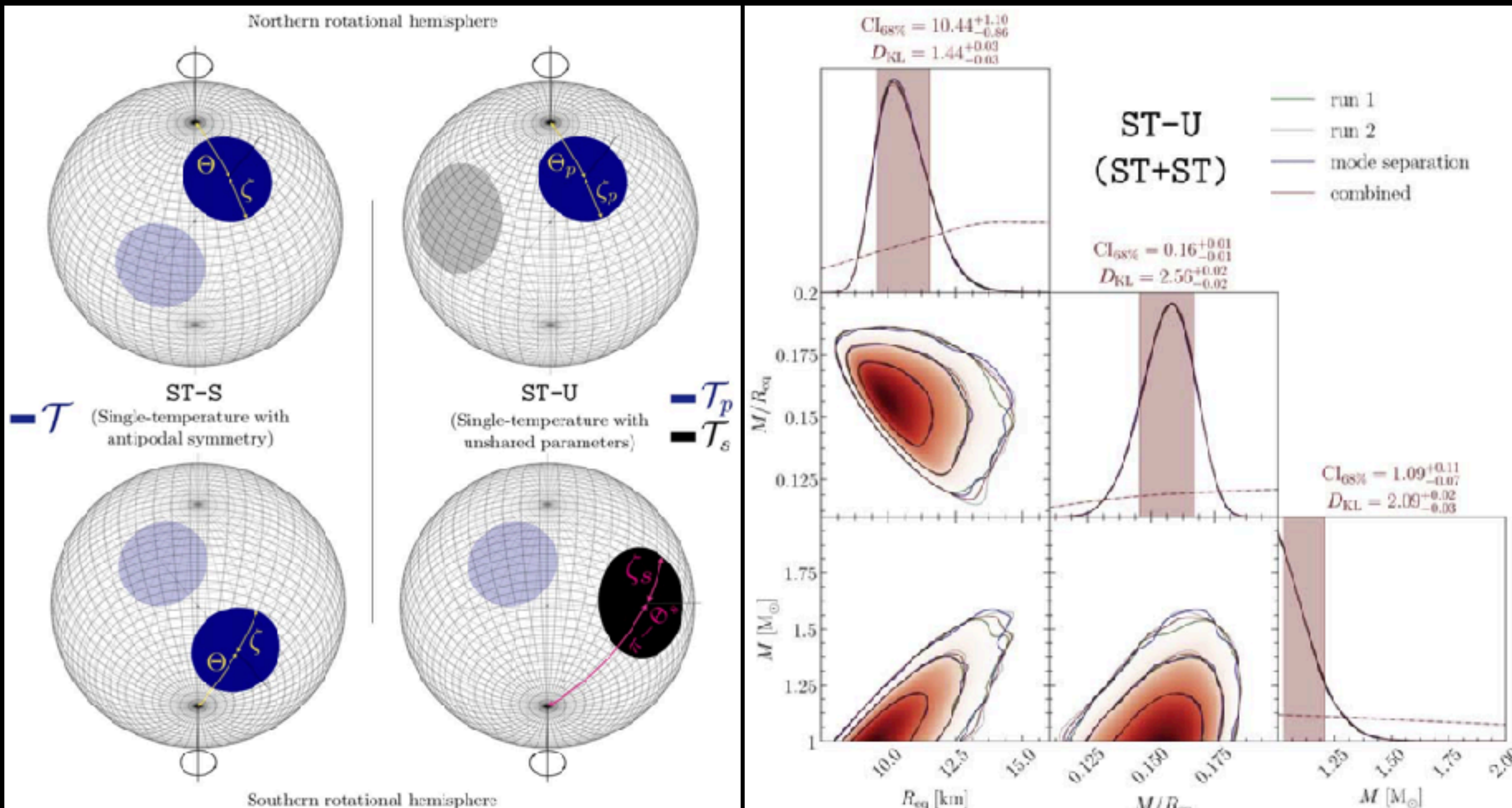
Modeling GW Waveforms

- Gravitational waves (GWs) have been detectable with LVK as of 2015.
- Waveform modeling can account for point-particle and spin effects to measure component masses.
- Tidal deformability can be observed as departure in late-time orbital decay of inspiral —> direct constraint on radius.

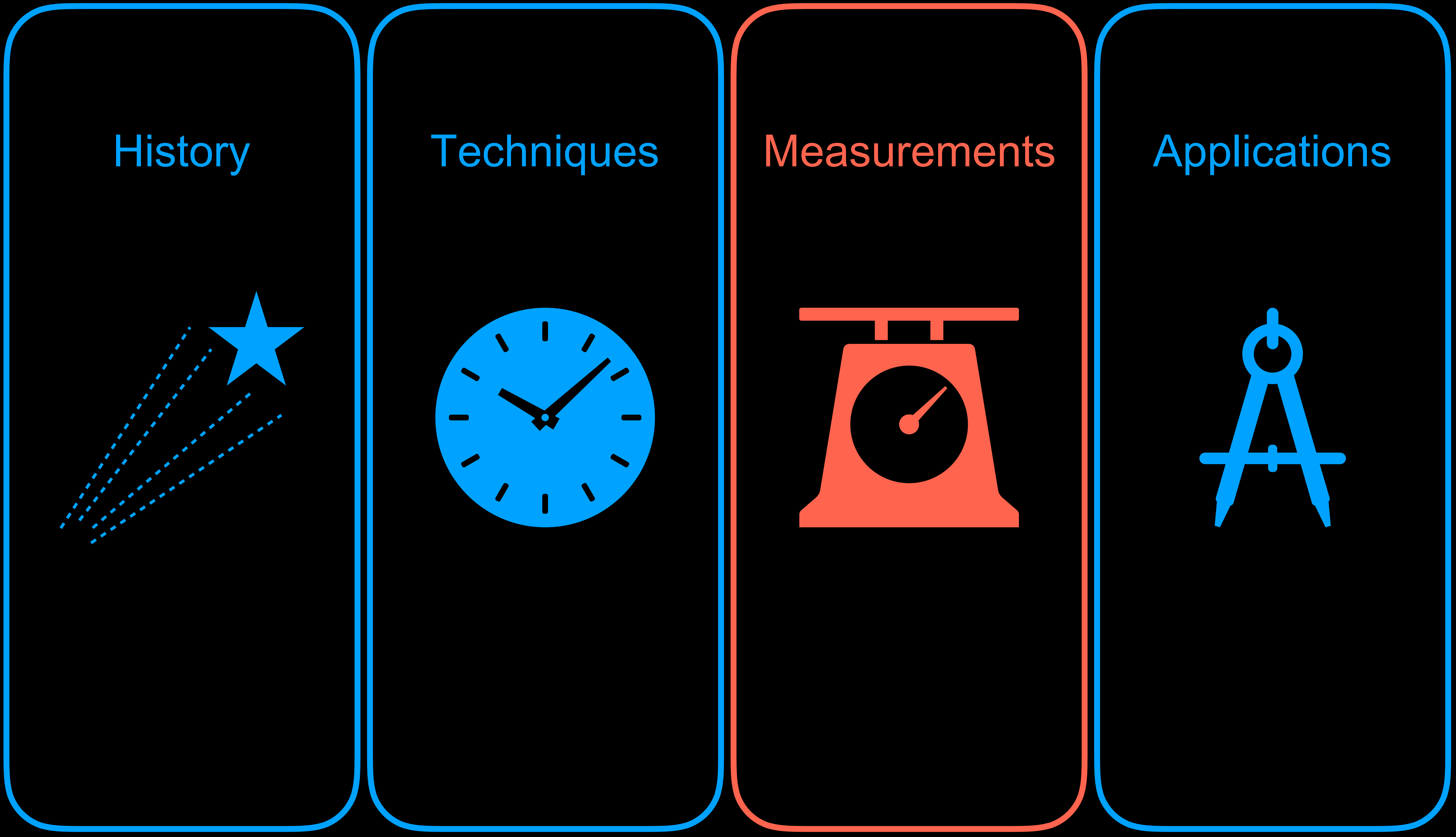


Detection of GW170817 (Abbott et al., 2017a)

X-ray Measurement of NS Radii



The Neutron Star Interior Composition Explorer (NICER) recently measured the mass and radius of PSR J0030+0451 - an isolated pulsar! - through X-ray lightcurve modeling (e.g., Miller et al., 2019; Riley et al., 2019).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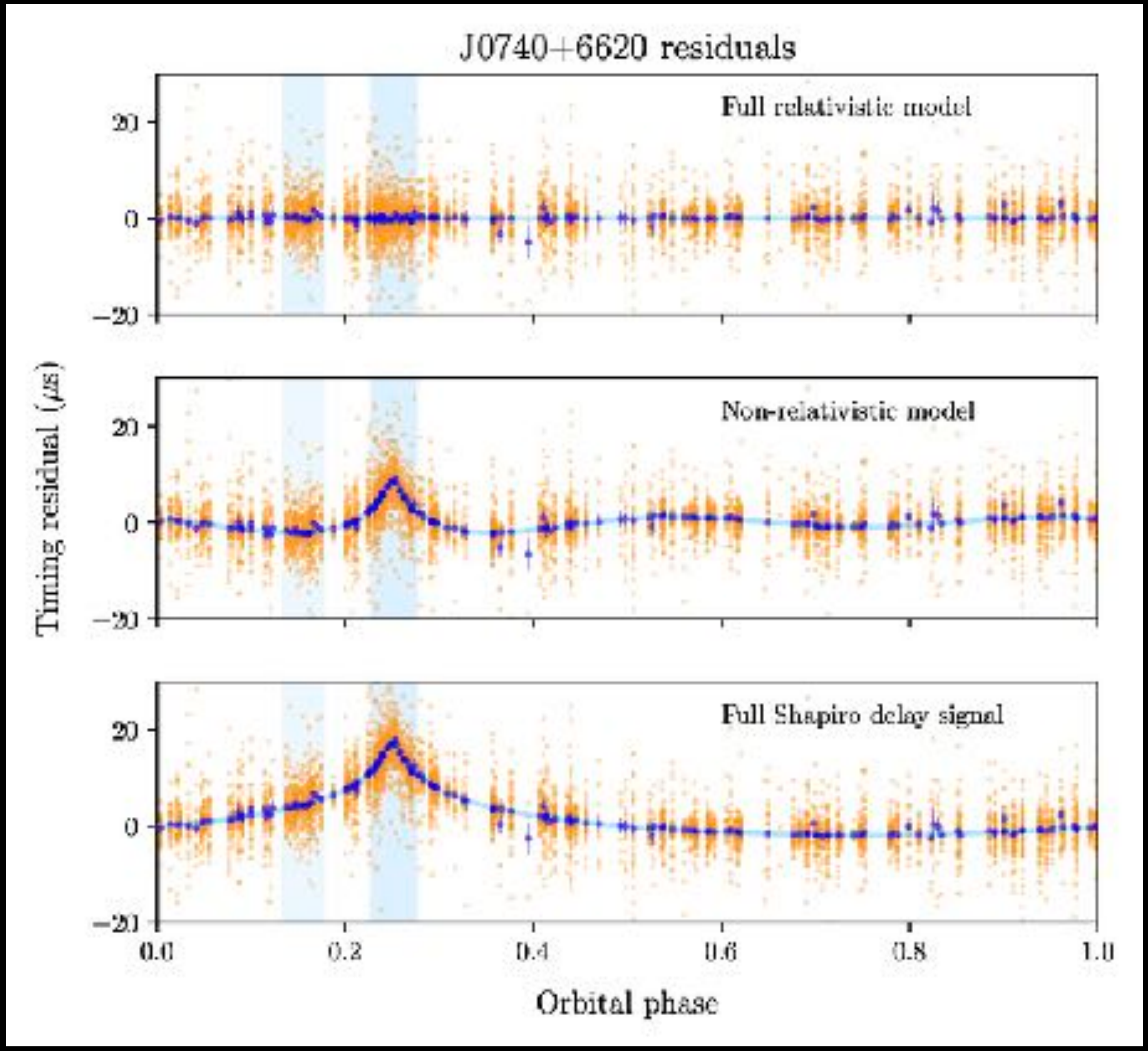
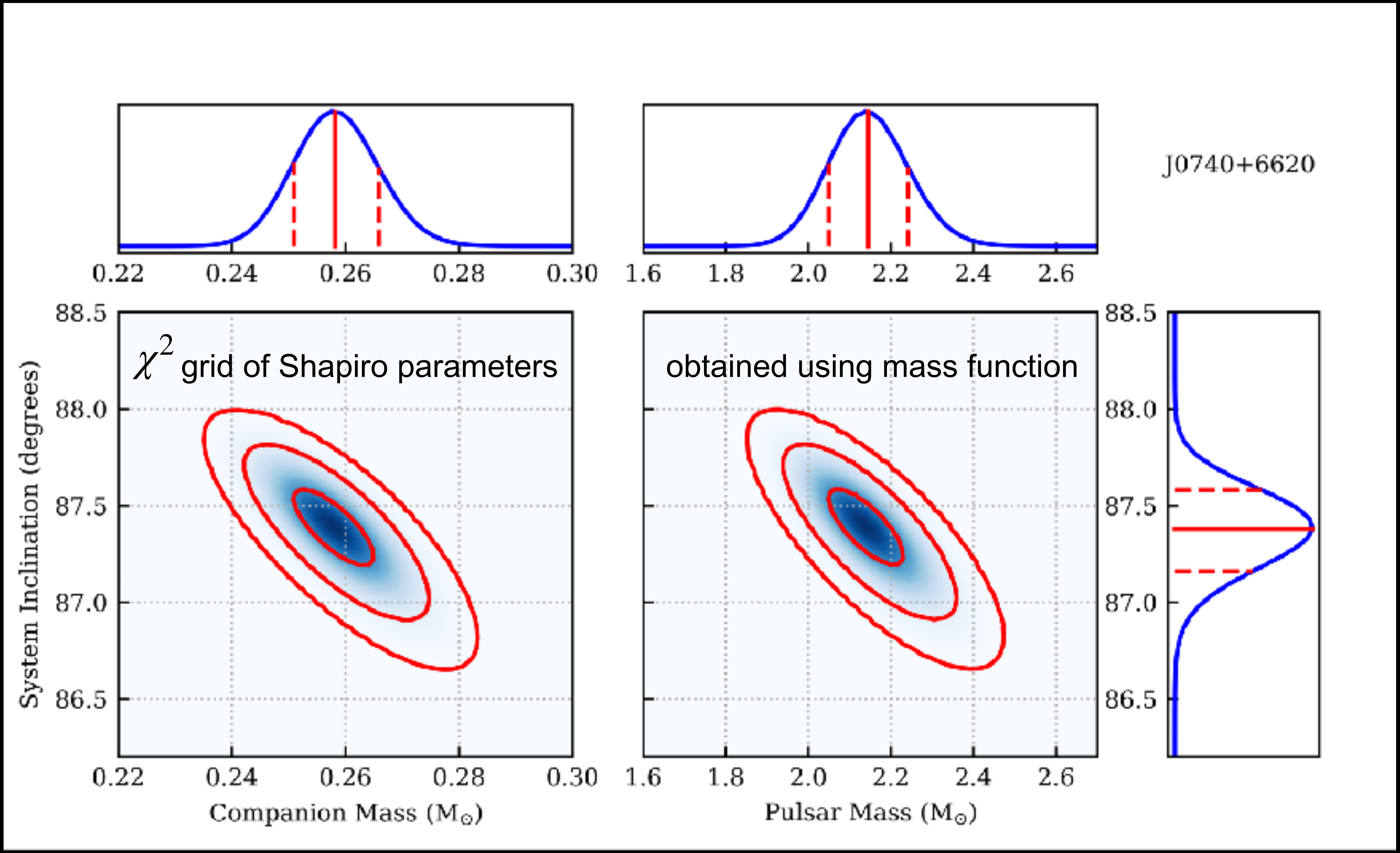
NS-Mass Summary & Statistics

- There are ~60 NS masses measured (53 come from radio-timing / WD modeling).
- All precise measurements (5% or better) come from timing.
    - ★ majority of these come from the Shapiro time delay.
- There are clear trends that correlate with companion types (and therefore evolutionary history).



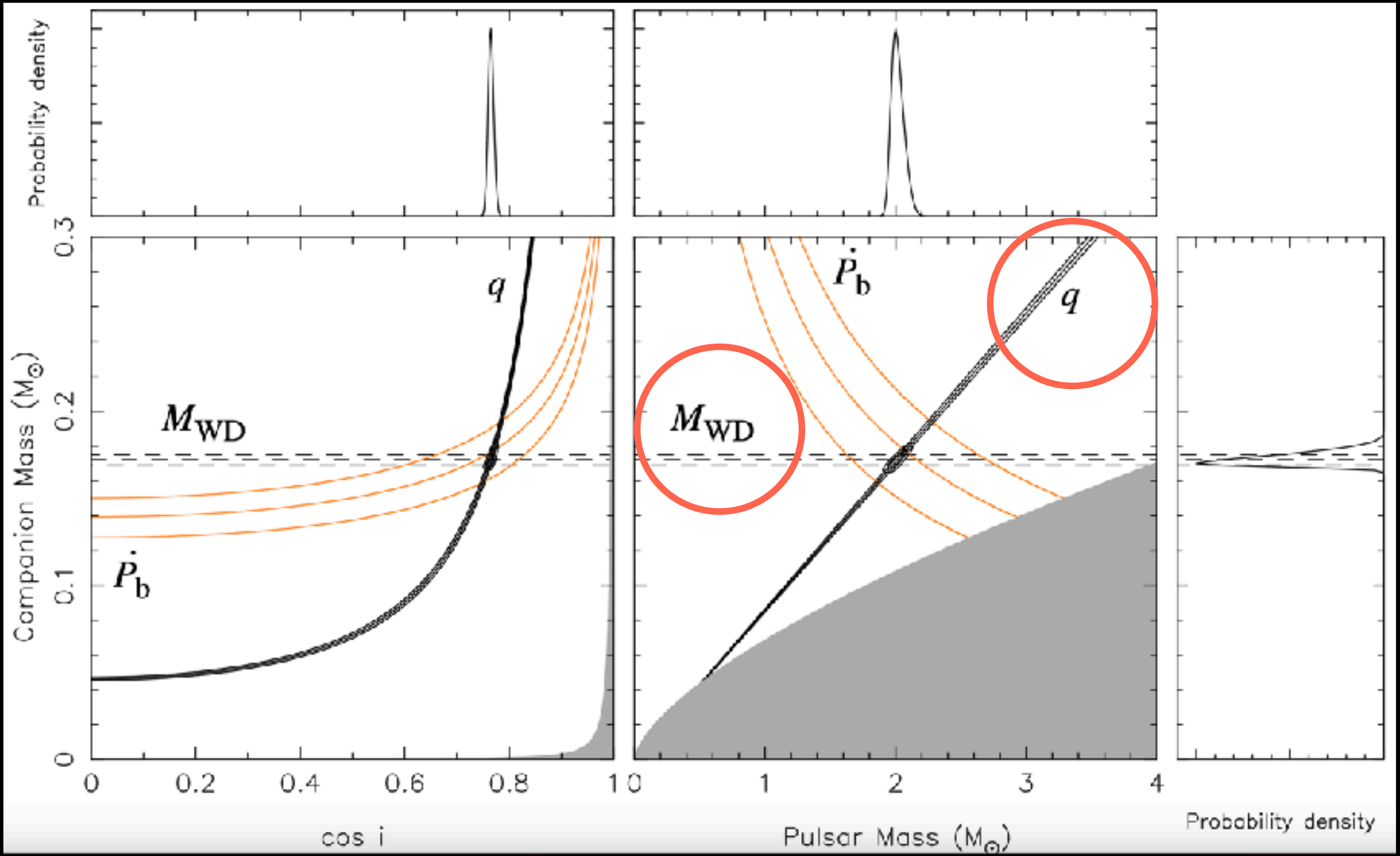
Shapiro delay in the PSR J0740+6620 binary system (Cromartie et al., 2020; Fonseca et al., 2021).

NS Masses from Timing



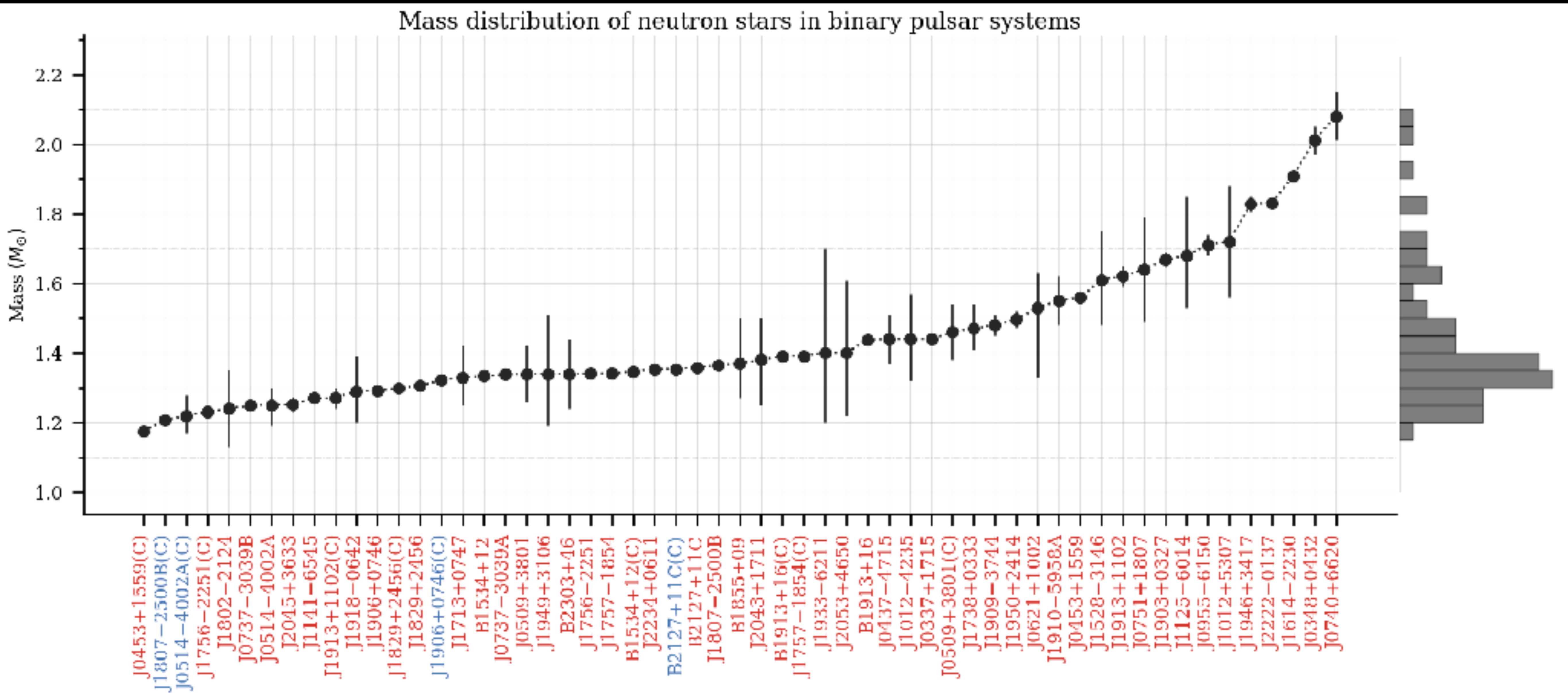
Mass and geometry from the Shapiro time delay in PSR J0747+6620
(Cromartie et al., 2020)

NS Masses from Optical Modeling of WD Companions



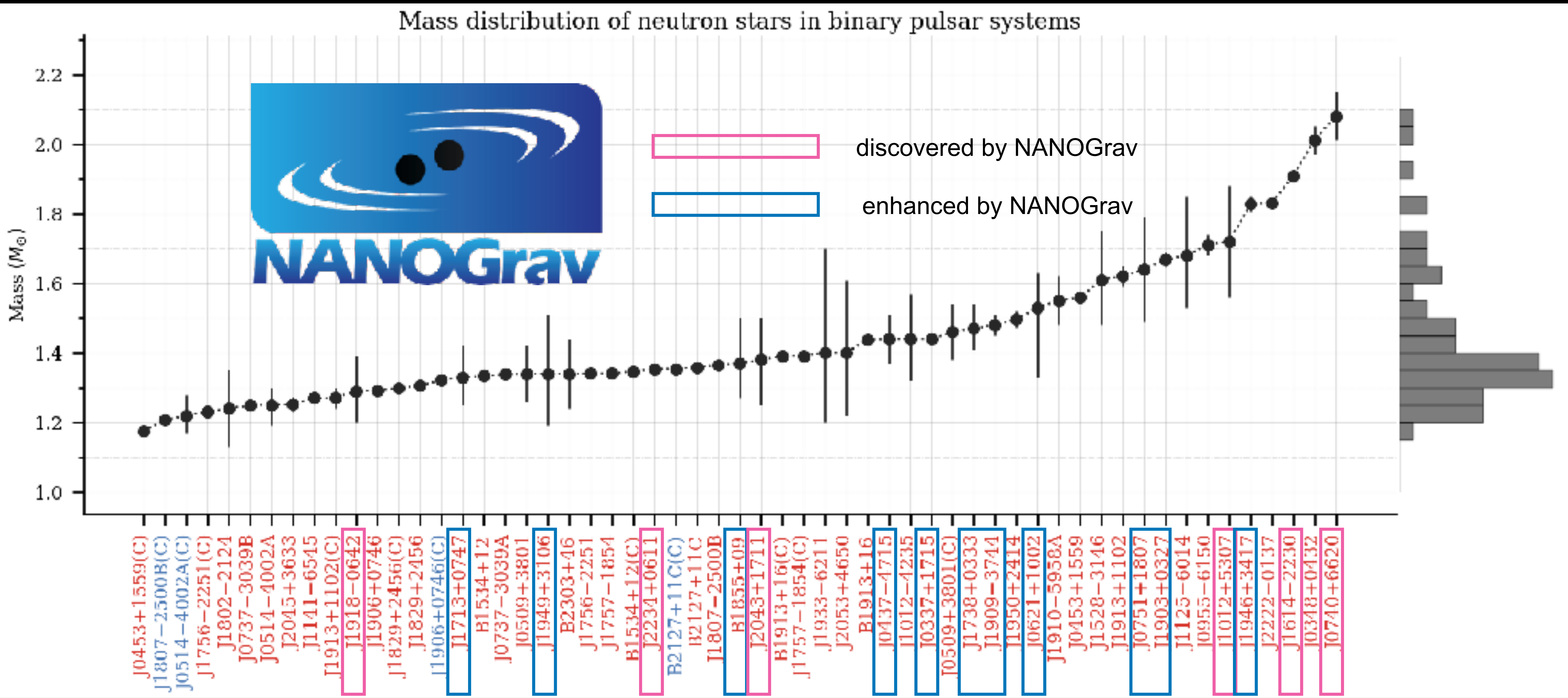
Constraints from spectroscopic measurements (red circles) for WD companion to PSR J0348+0432 (Antoniadis et al., 2013)

Pulsar Mass Summary



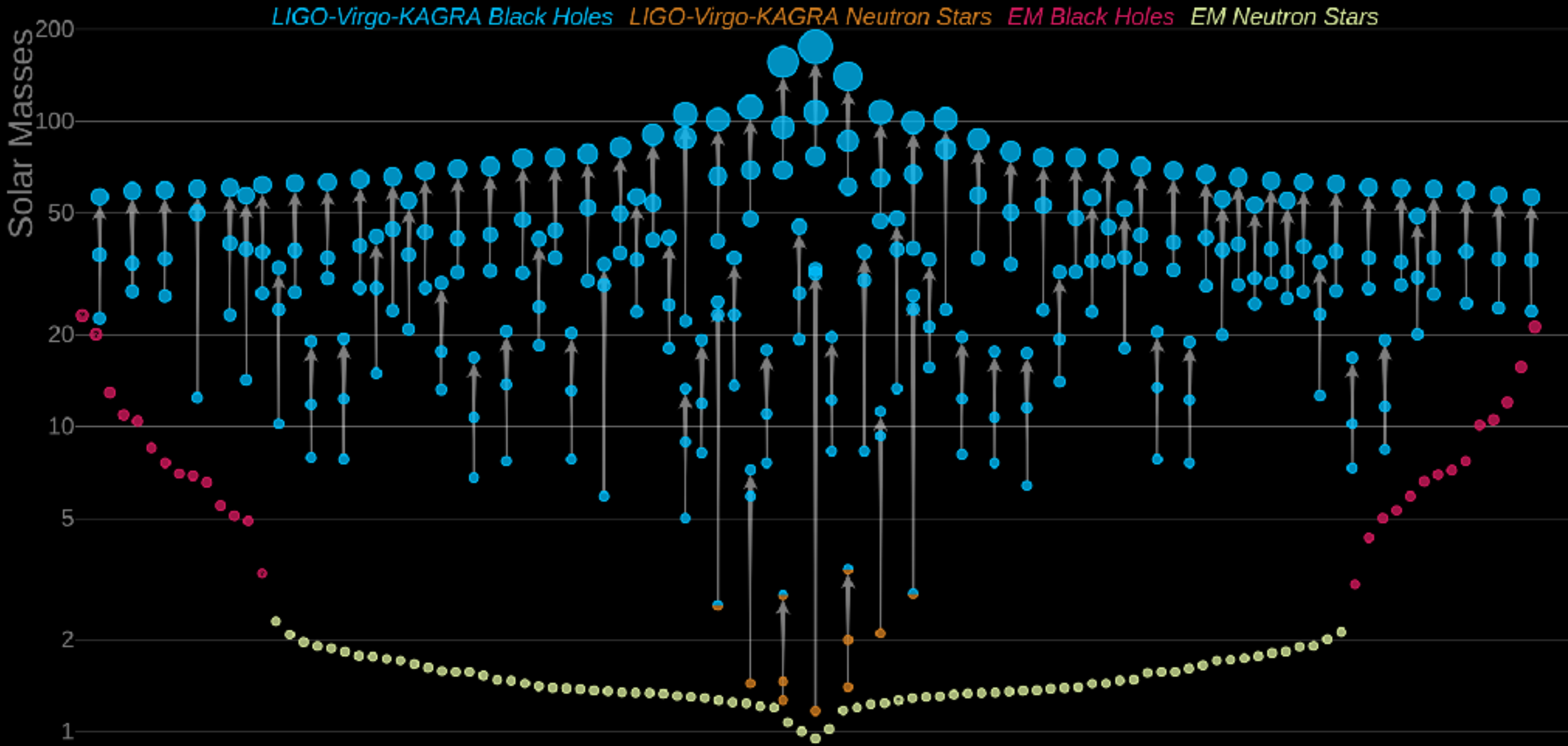
Credit: V. V. Krishnan, P. C. C. Freire

Pulsar Mass Summary



Credit: V. V. Krishnan, P. C. C. Freire

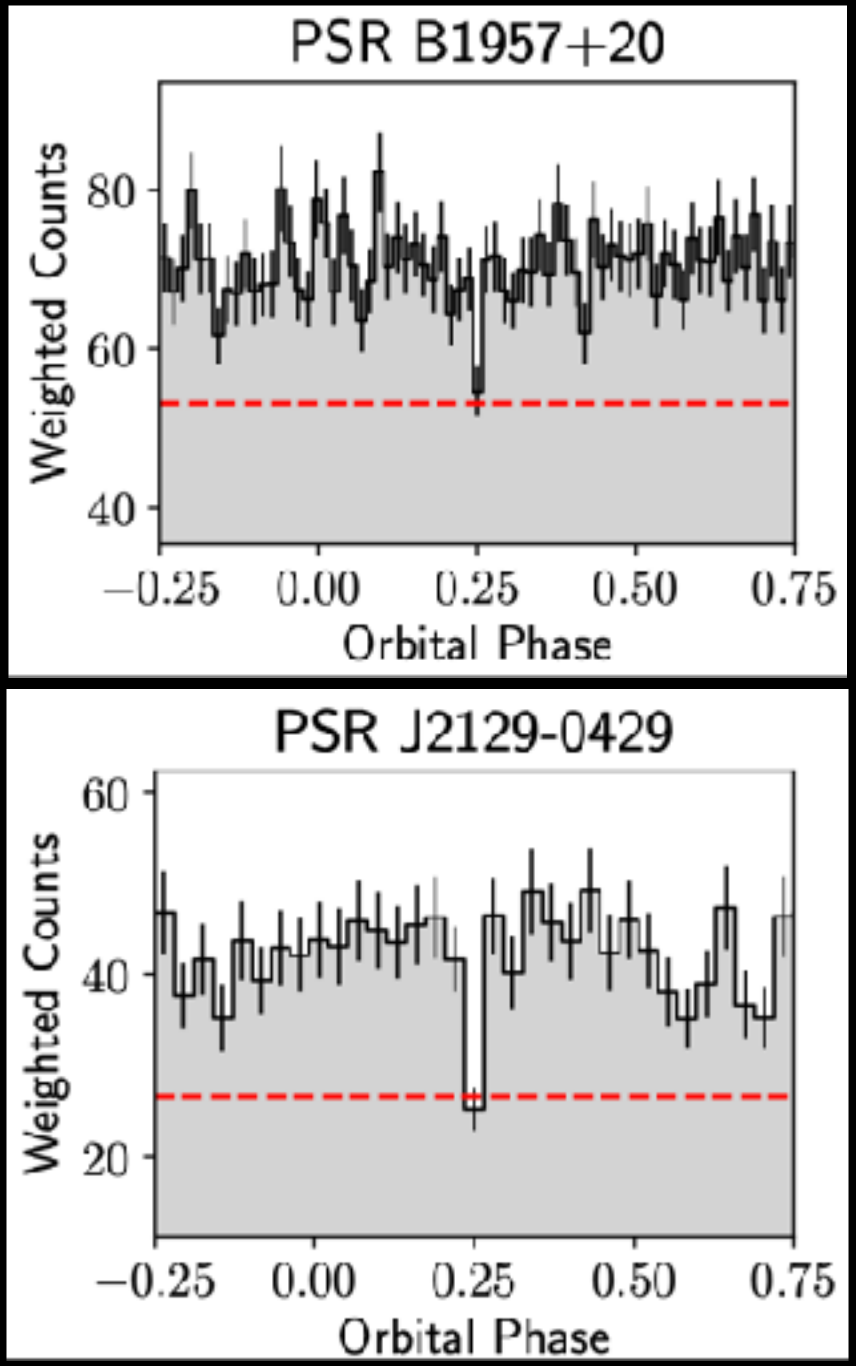
Masses in the Stellar Graveyard



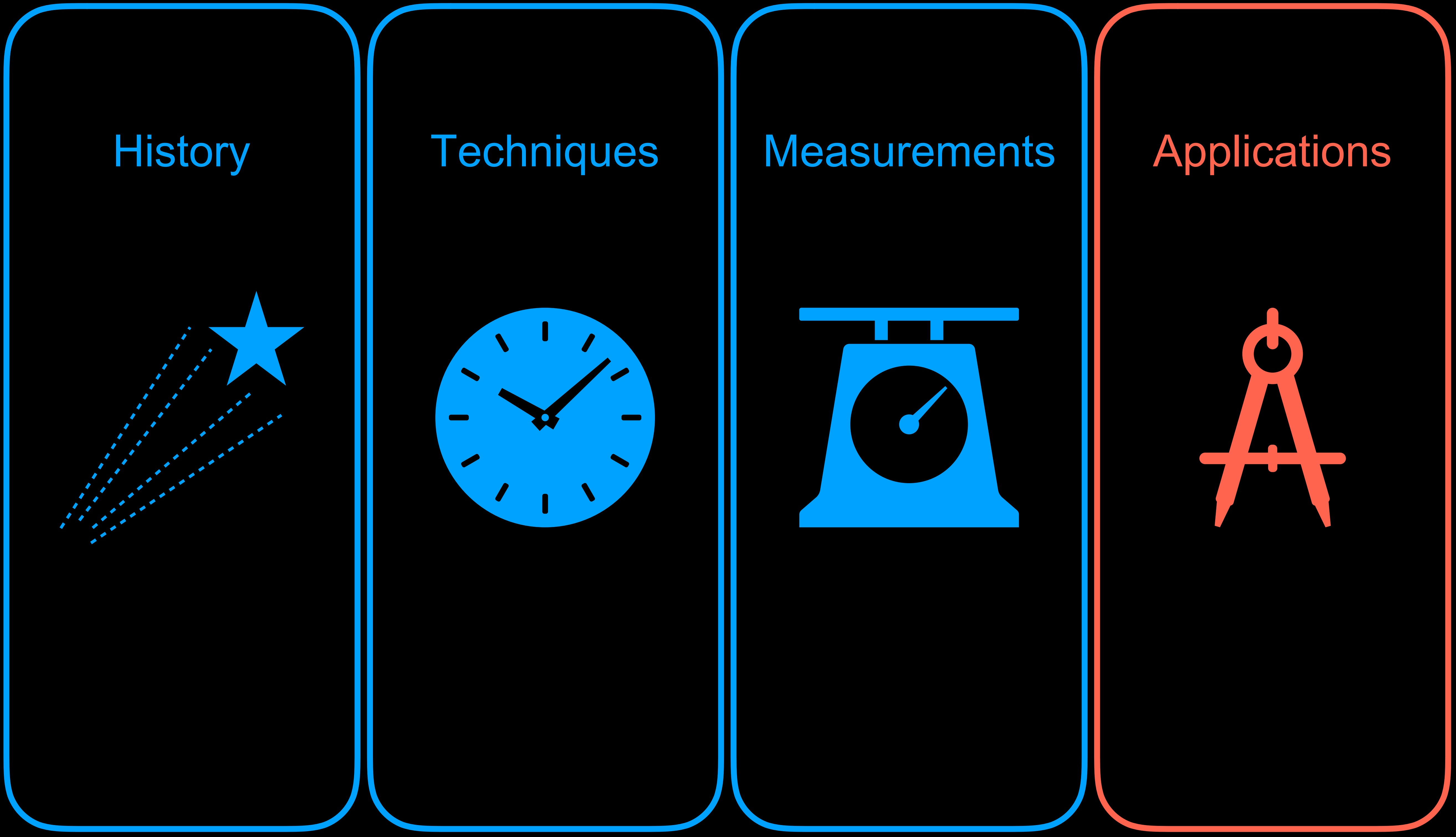
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Black-Widow Masses

- Black-widow masses from radio+optical measurements:
  - B1957+20: (2.4 +/- 0.1) $\mathbf{M_\odot}$ [van Kerkwijk et al., 2011]
  - J2215+5135: (2.3 +/- 0.15) $\mathbf{M_\odot}$ [Linares et al., 2018]
- Recent work indicates that gamma-ray constraints on inclination in these systems produce inconsistent results:
  - B1957+20: (1.81 +/- 0.04) $\mathbf{M_\odot}$



Clark et al. (2023)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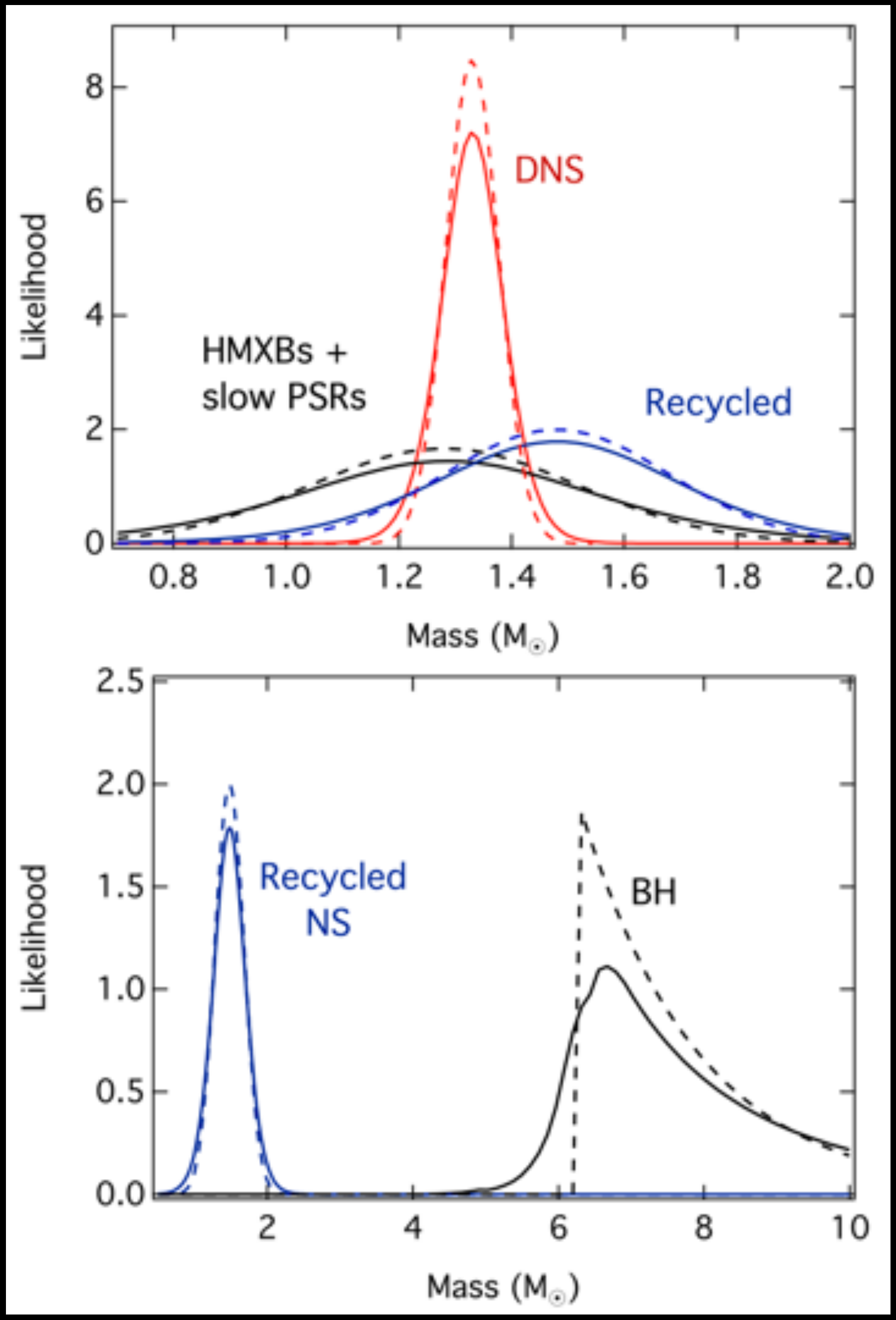
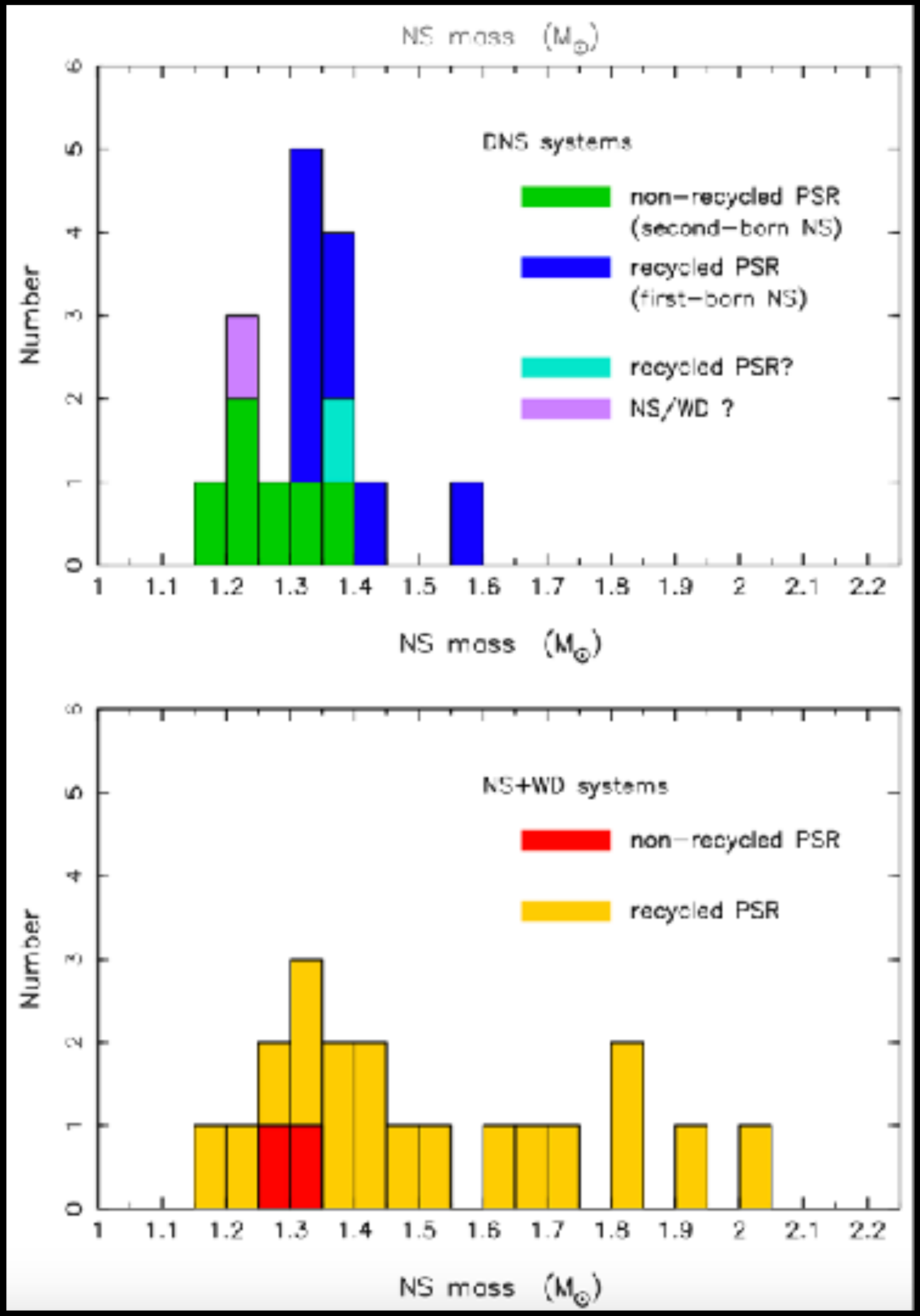
Census of Pulsar Masses

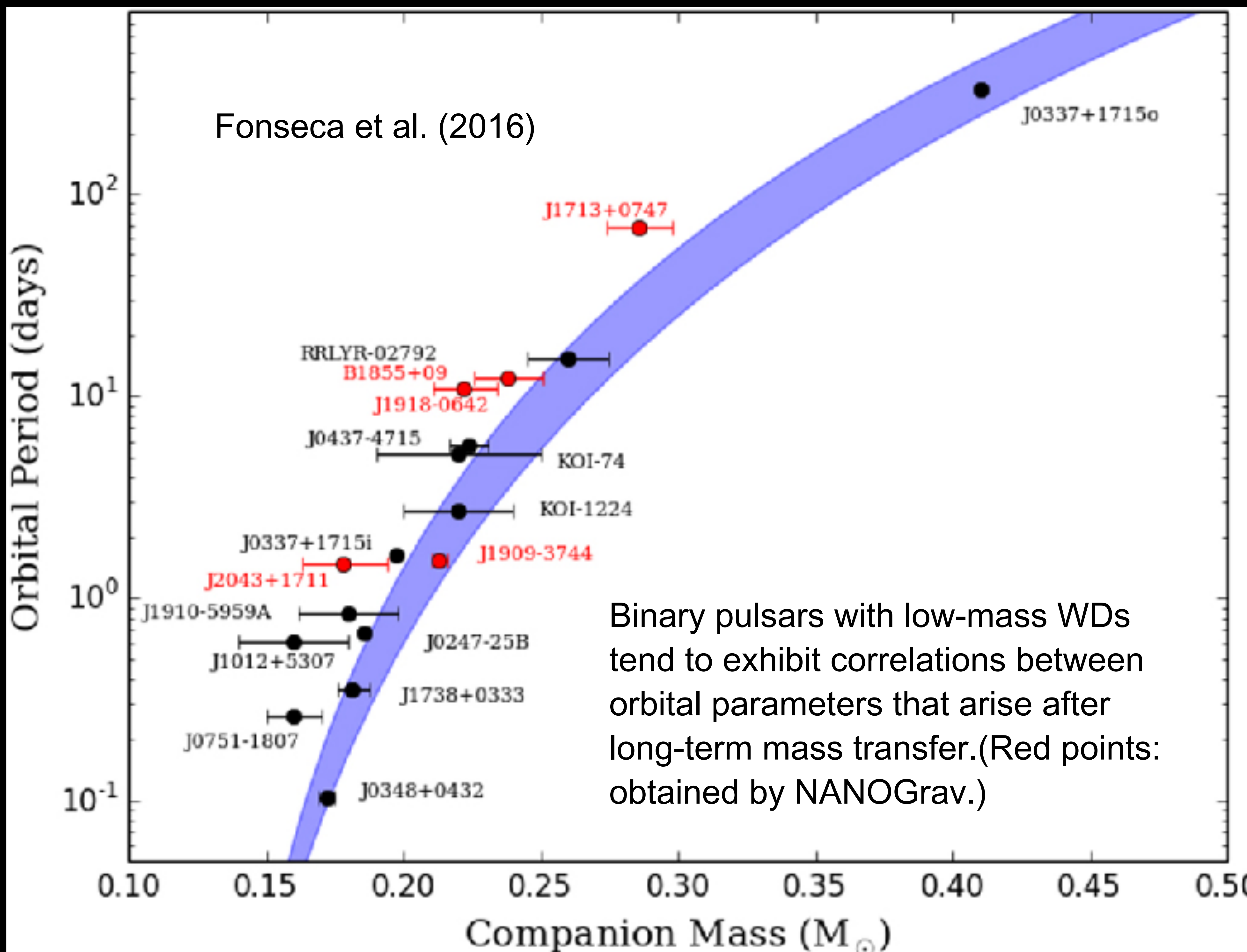


Özel et al. (2012)



Tauris et al. (2017)

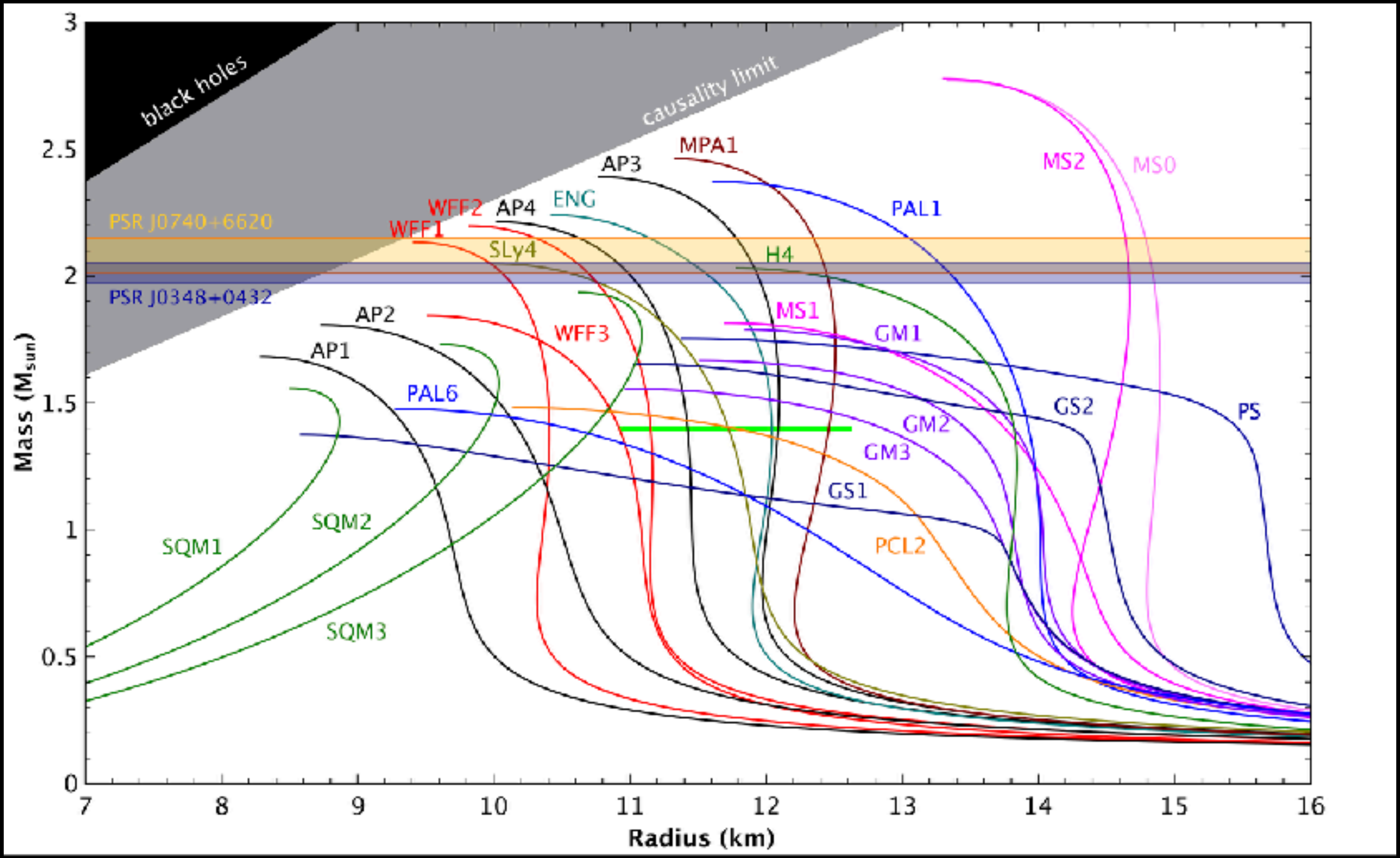
NS/WD Masses & Correlations



Fonseca et al. (2016)

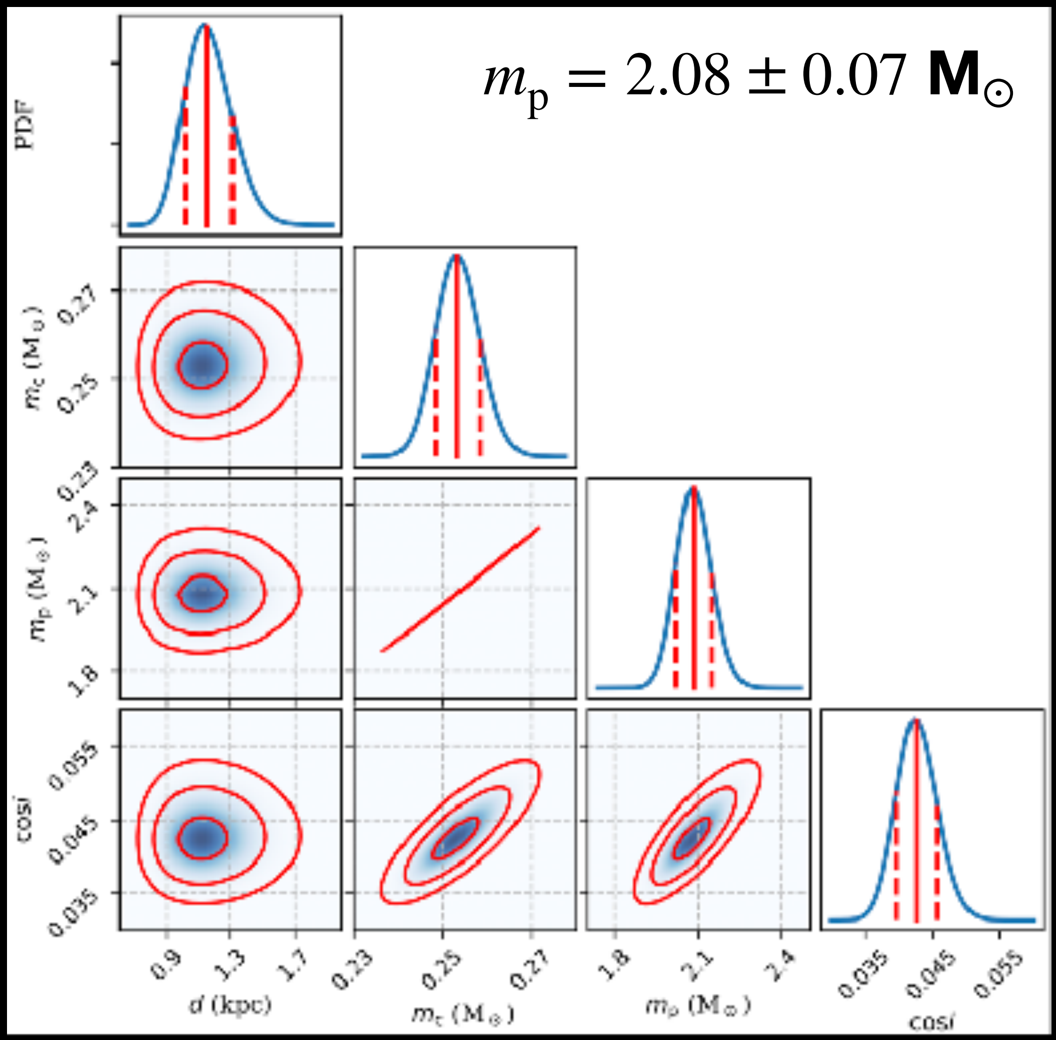
Binary pulsars with low-mass WDs tend to exhibit correlations between orbital parameters that arise after long-term mass transfer.(Red points: obtained by NANOGrav.)

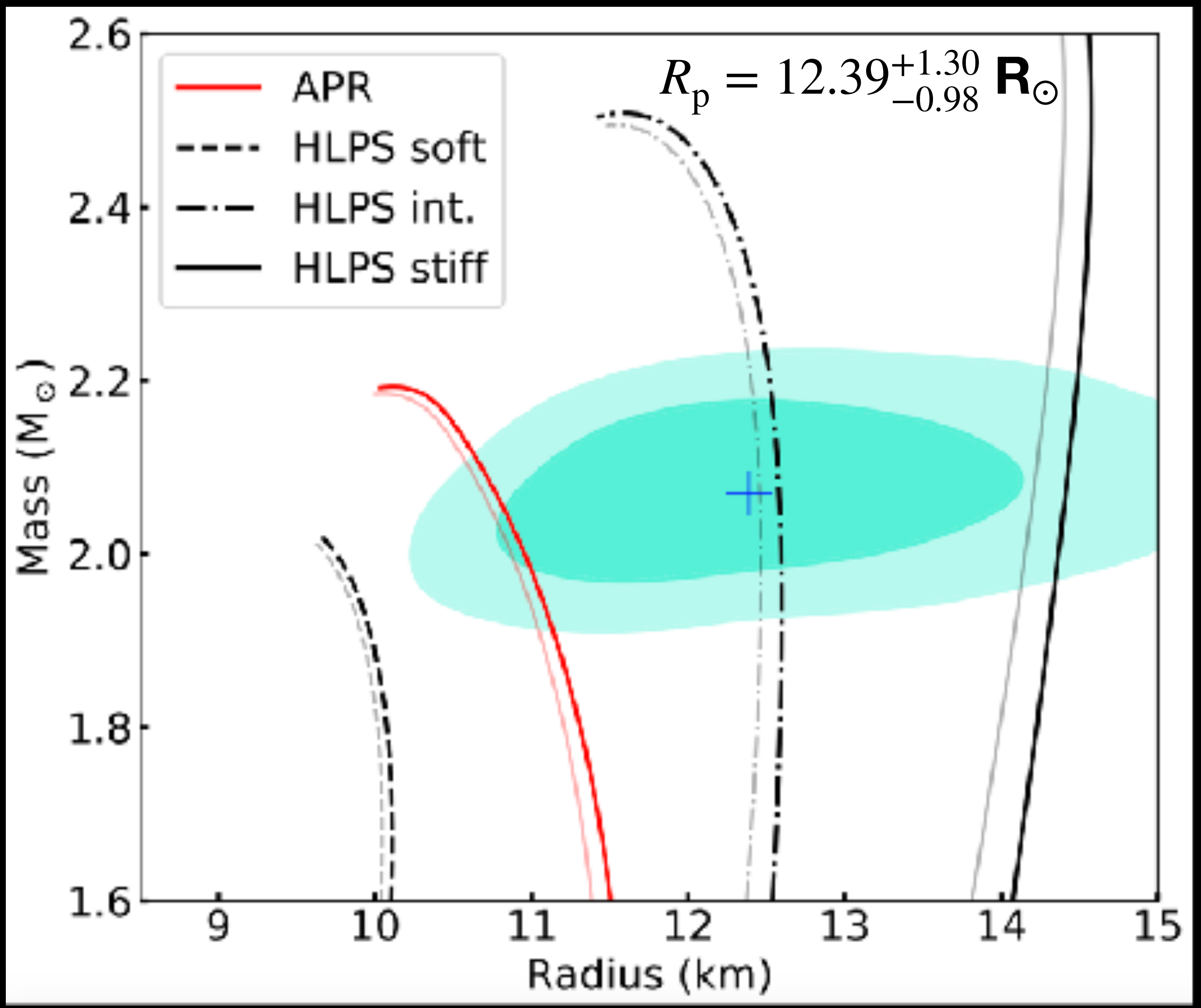
High-mass NSs Constrain EoSs



High-mass NSs are most valuable for EoS science since all EoSs terminate at a specific, maximum NS mass. (Credit: N. Wex, P. C. C. Freire.)

NANOGrav+NICER Constraint on the Radius for PSR J0740+6620

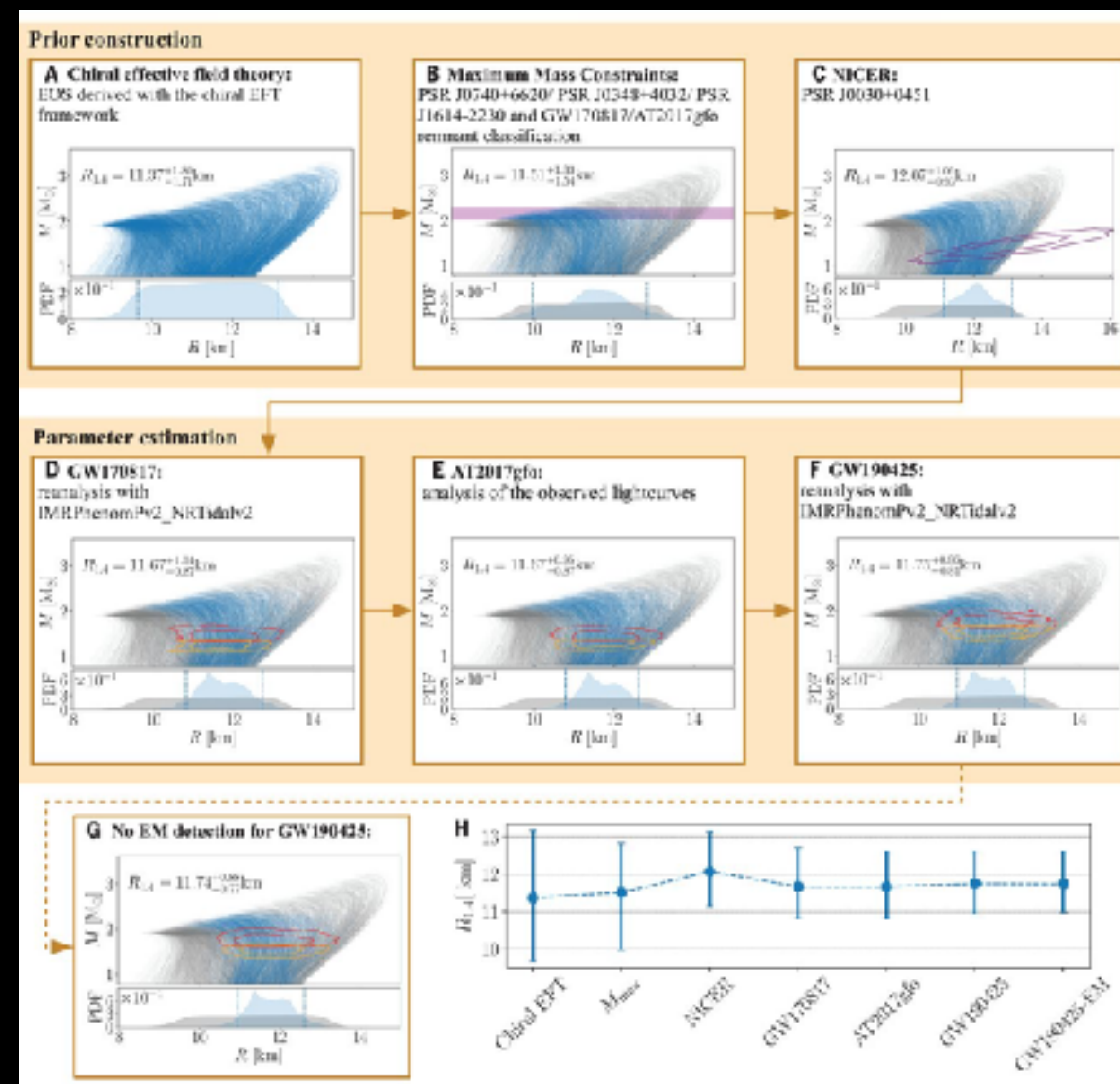




NANOGrav measured the mass of PSR J0740+6620 to ~4% (left; Fonseca et al., 2021), which was then used by NICER to directly measure the radius to ~10% (right; Riley et al., 2021).

Multi-Messenger EoS Constraints

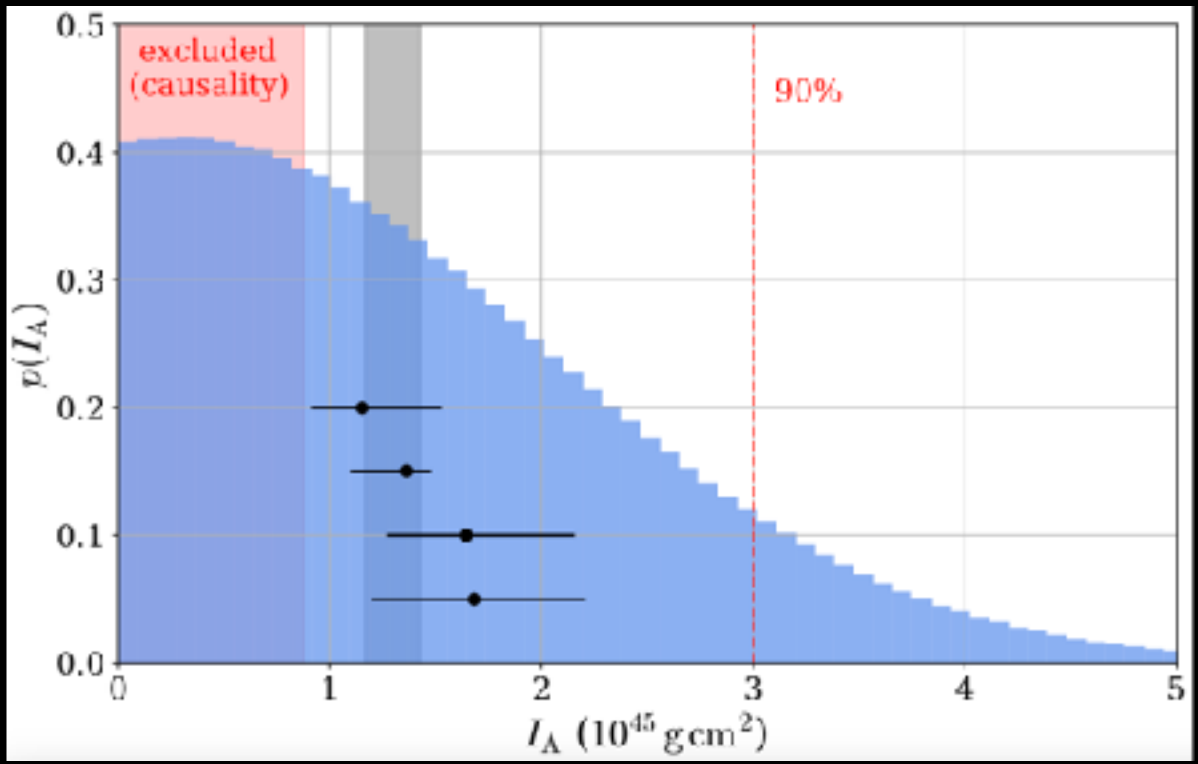
- NS-mass measurements are growing in number due to multi-messenger opportunities.
- The union of high-mass outliers and radii measurements allow for unprecedented EoS tests (see right).



Use of radio-timing/X-ray/GW measurements or limits on NS mass/radius to constrain EoS (Dietrich et al., 2020)

Conclusion & Future Prospects

- NANOGrav will produce more Shapiro-delay measurements, fold in non-timing constraints on companion mass and inclination (e.g., scintillation).
- Next-generation radio observatories will yield 50-100 more Shapiro-delay measurements.
- Long-term timing of DNS systems will yield first measurement of NS moment of inertia (e.g., Kramer et al., 2021).
- Next-generation X-ray observatories expected to yield ~20 NS radii.



Constraint on the moment of inertia for PSR J0737-3039A (Kramer et al., 2021).