Constraining mass of neutron star in compact binary with multi-messenger observations

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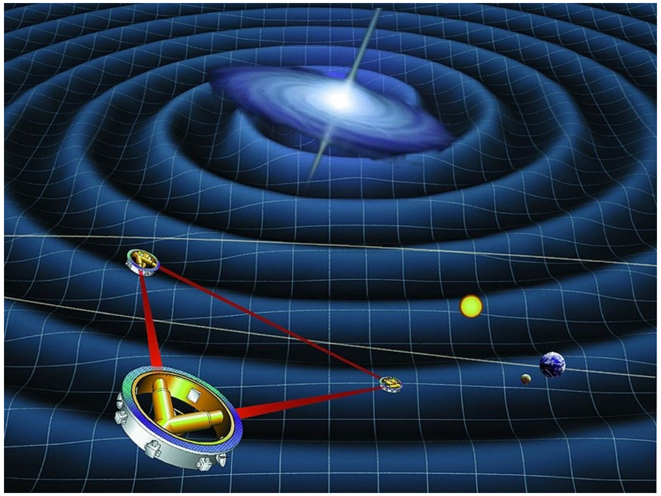
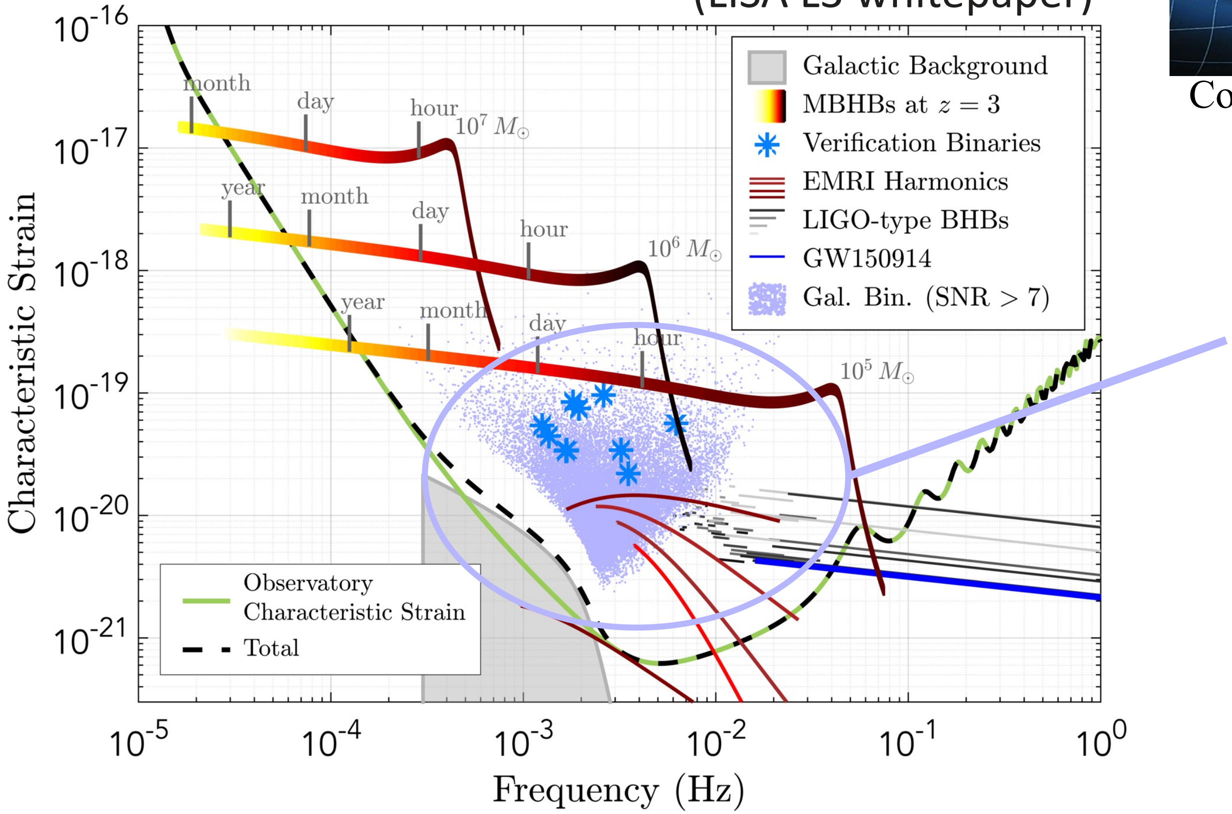
LISA mission

- Space-based mission
- Scheduled to launch in the early 2030s
- Three arms with length 3Gm



Concept of LISA (credit: ESA and NASA)

(LISA L3 whitepaper)

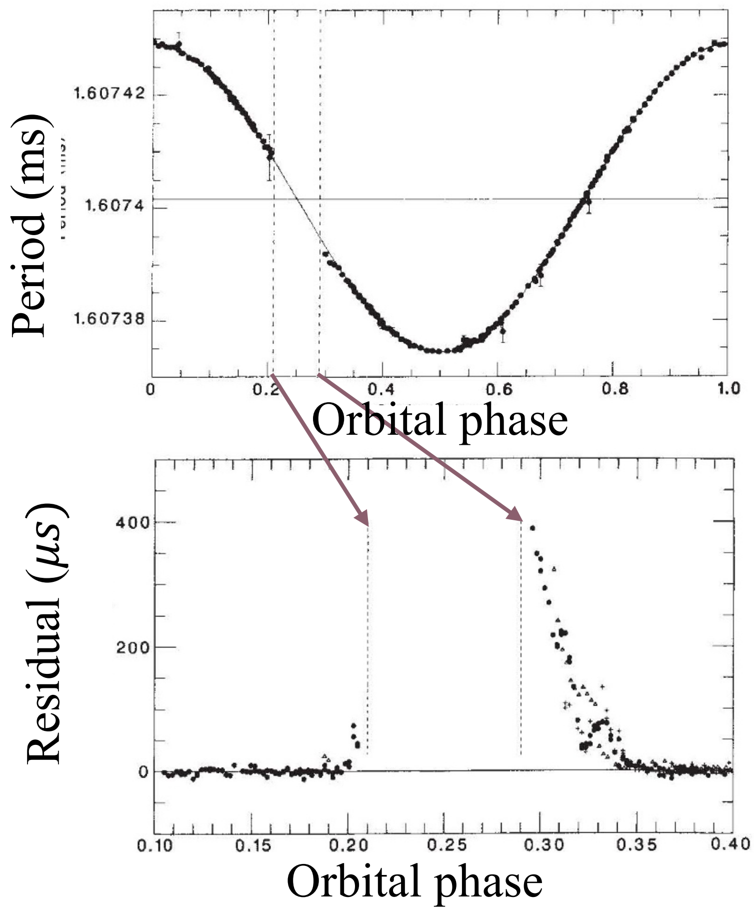


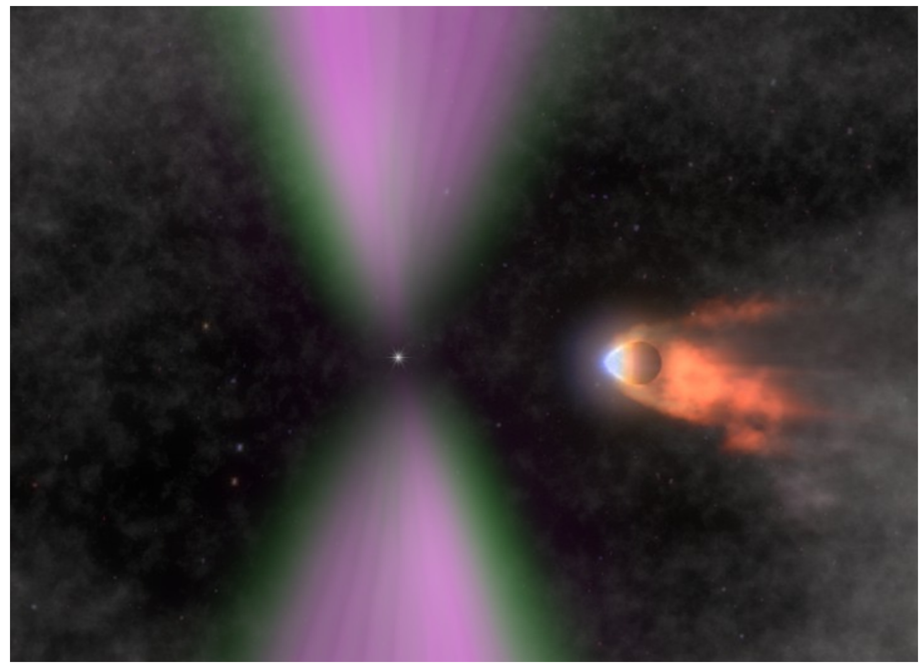
Galactic binaries

Compact millisecond pulsar binary: black widow system

- First system observed in 1988 with radio eclipse

(PSR1957+20) Fruchter, Stinebring and Taylor 1988





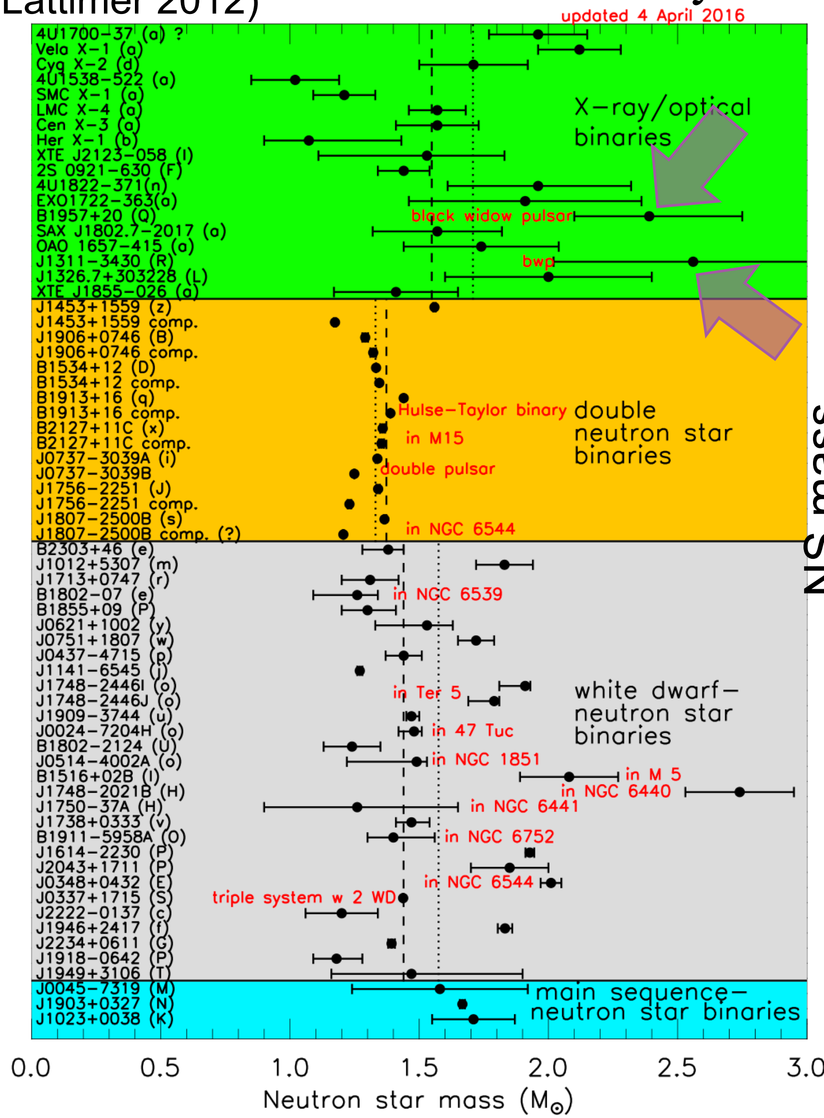
(PSR J1311-3430, credit: NASA)

- Millisecond pulsar with low mass companion
- Ablation of the companion
- Compact orbit (P<24 h)
- Negligible accretion

Constraining EOS model with massive neutron star

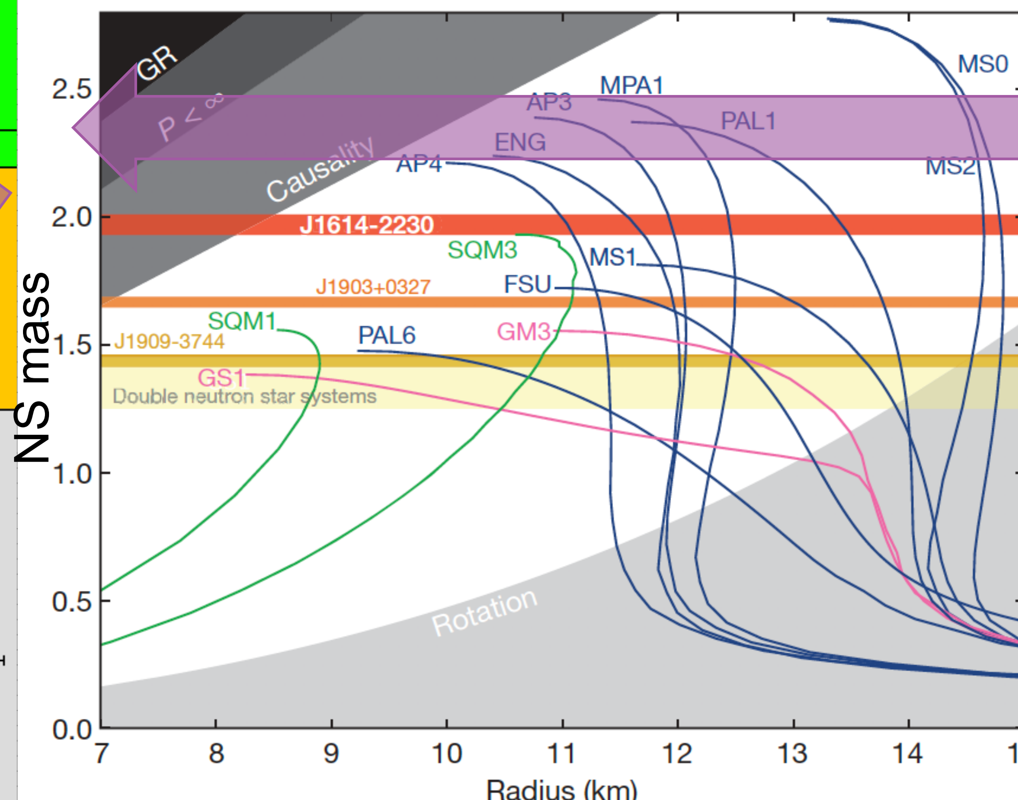
Black widow system host the most massive neutron stars?

(Lattimer 2012)

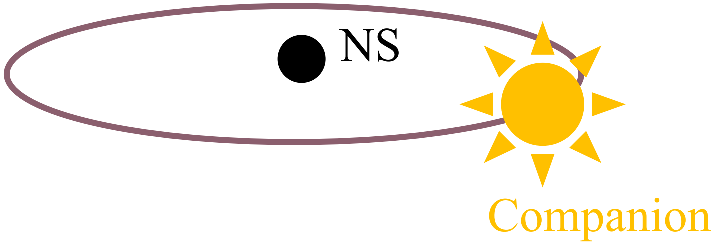


(Romani, APJ, 2022)

BW J0952: $2.33 M_\odot$

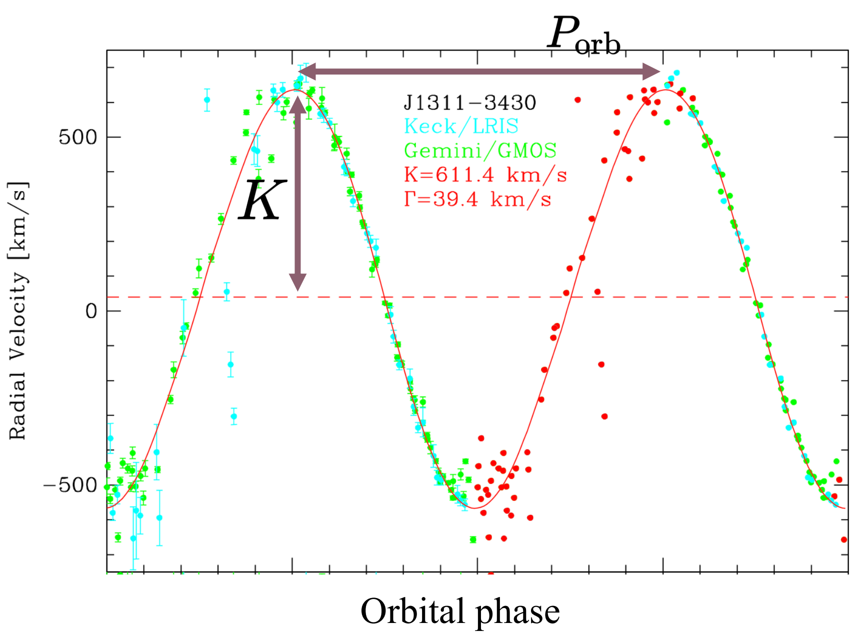


(Demorest, Nature, 2010)



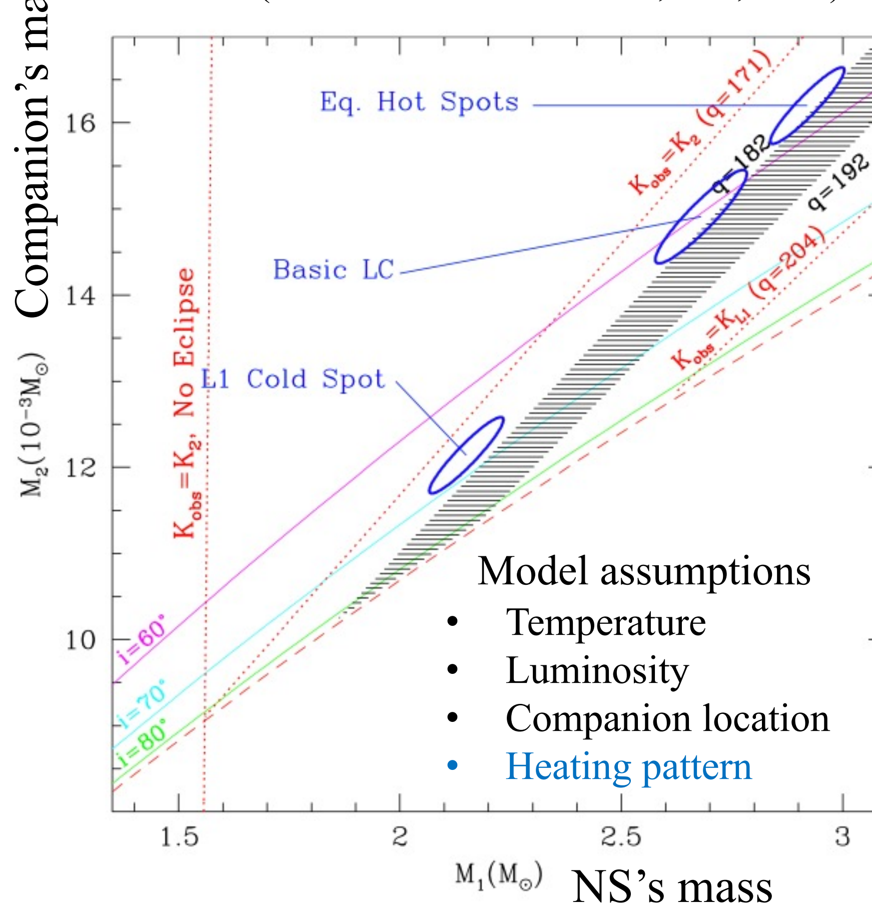
Mass function f(m)

$$f(m) = \frac{P_{\rm orb} K^3}{2\pi G}\left(1 - e^2\right)^{3/2} = \frac{{m_{\rm ns}}^3 \sin^3 \iota}{(m_{\rm ns} + m_{\rm c})^2}$$

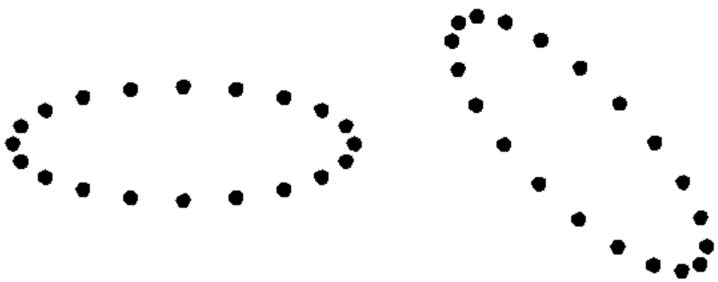


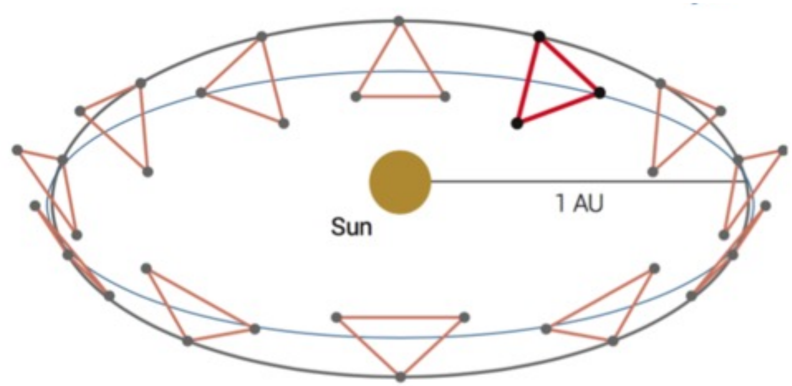
PSR J1311–3430 (Romani, APJ, 2015)

Model-dependent systematics
(PSR J1311−3430 Romani, APJ, 2013)



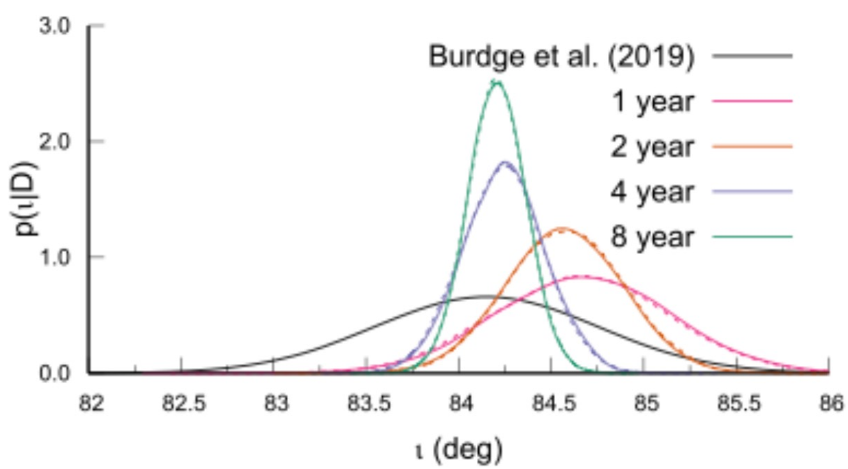
Determining the inclination angle from gravitational wave





$$h_+ = A\frac{1+\cos^2\iota}{2} \qquad h_\times = A\cos\iota$$

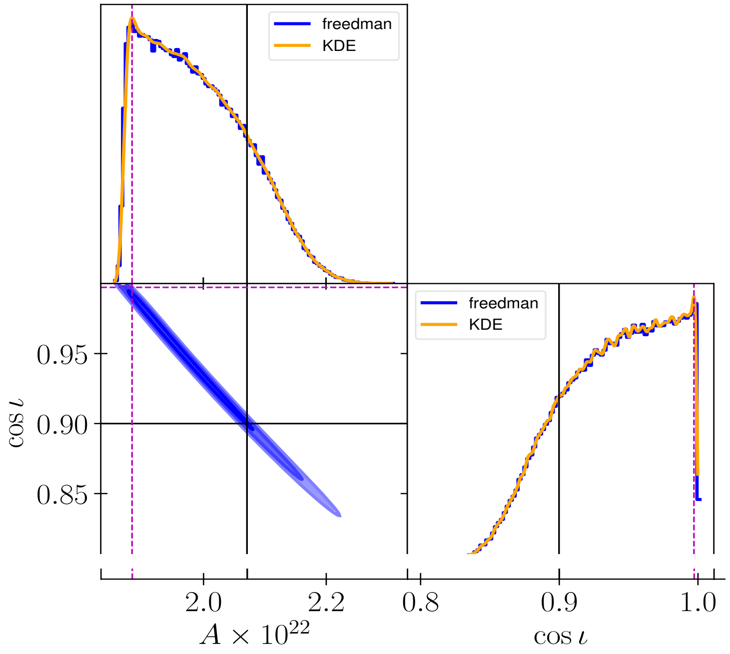
(credit: LISA Mission Consortium)



ZTF J1539+5027
SNR ~ 140 for 4 year
(Littenberg, APJ, 2019)

Mass-inclination degeneracy for gravitational wave

gbmcmc package: t Littenberg (https://github.com/tlittenberg/ldasoft)



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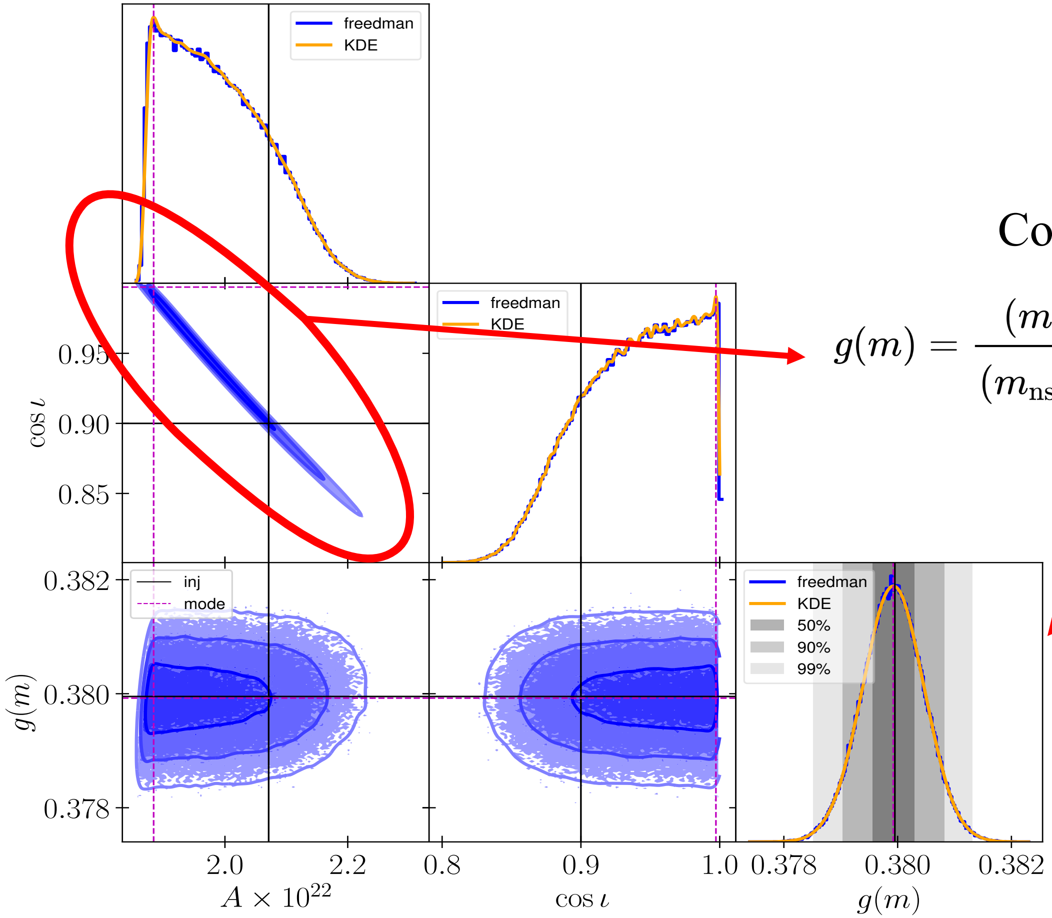
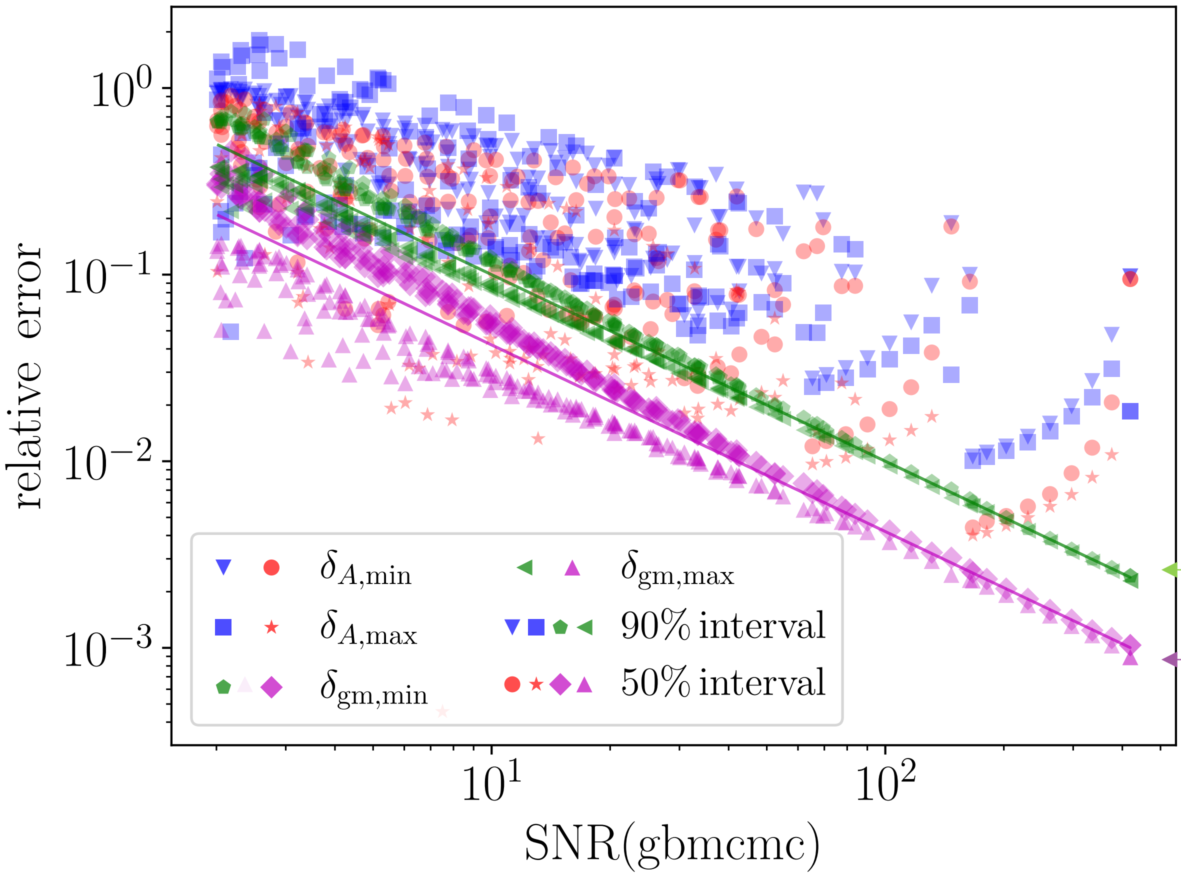


P=10 min, d=1 kpc, cosi=0.9

Complementary mass function

$$g(m) = \frac{(m_c m_{ns})^{3/5}}{(m_{ns} + m_c)^{1/5}} \left[\cos^2\iota + \left(\frac{1+\cos^2\iota}{2}\right)^2\right]^{3/10}$$

A handy relation with SNR



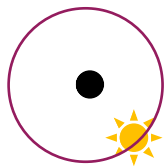
Once the GW SNR is known, we can use g(m) to infer the NS's mass

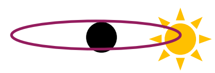
$$\left(\frac{\Delta g(m)}{g(m)}\right)_{90\%} \approx 0.2\left(\frac{10}{\mathrm{SNR}}\right) .$$

$$\left(\frac{\Delta g(m)}{g(m)}\right)_{50\%} \approx 0.09\left(\frac{10}{\mathrm{SNR}}\right) ,$$

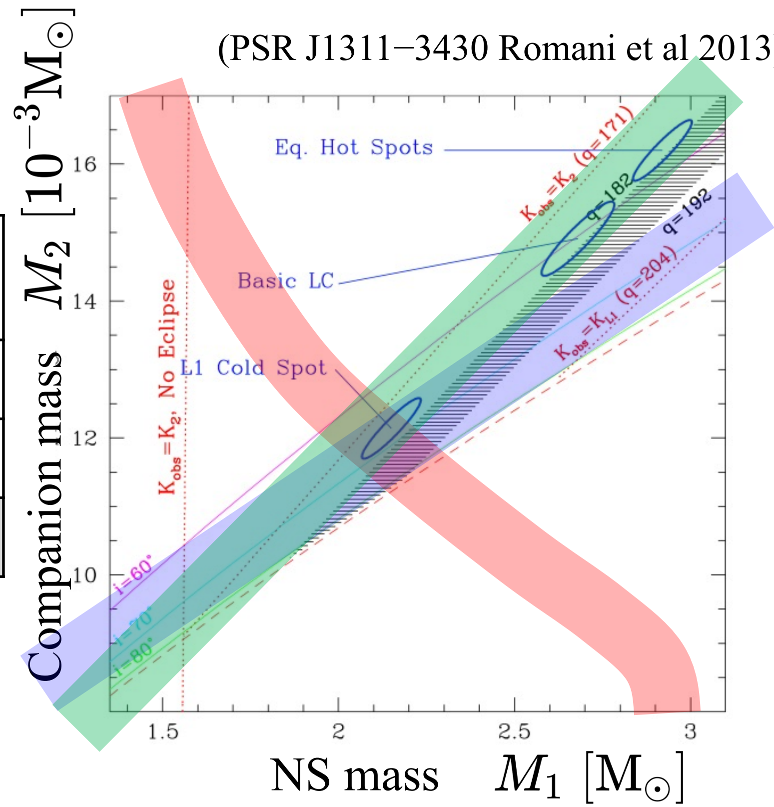
~200 systems, P_b: 10-30 min, d: 1-30 kpc, cosi: 0.1-0.9, $m_{ns} = 2.0\ M_\odot$, $m_c = 0.1 M_\odot$

Breaking the mass-inclination angle degeneracy with multi-messenger method





Orbital modulation	Face-on	Edge-on
Optical light curve	Min	Max
Radial velocity	Min	Max
Gravitational wave	Max	Min



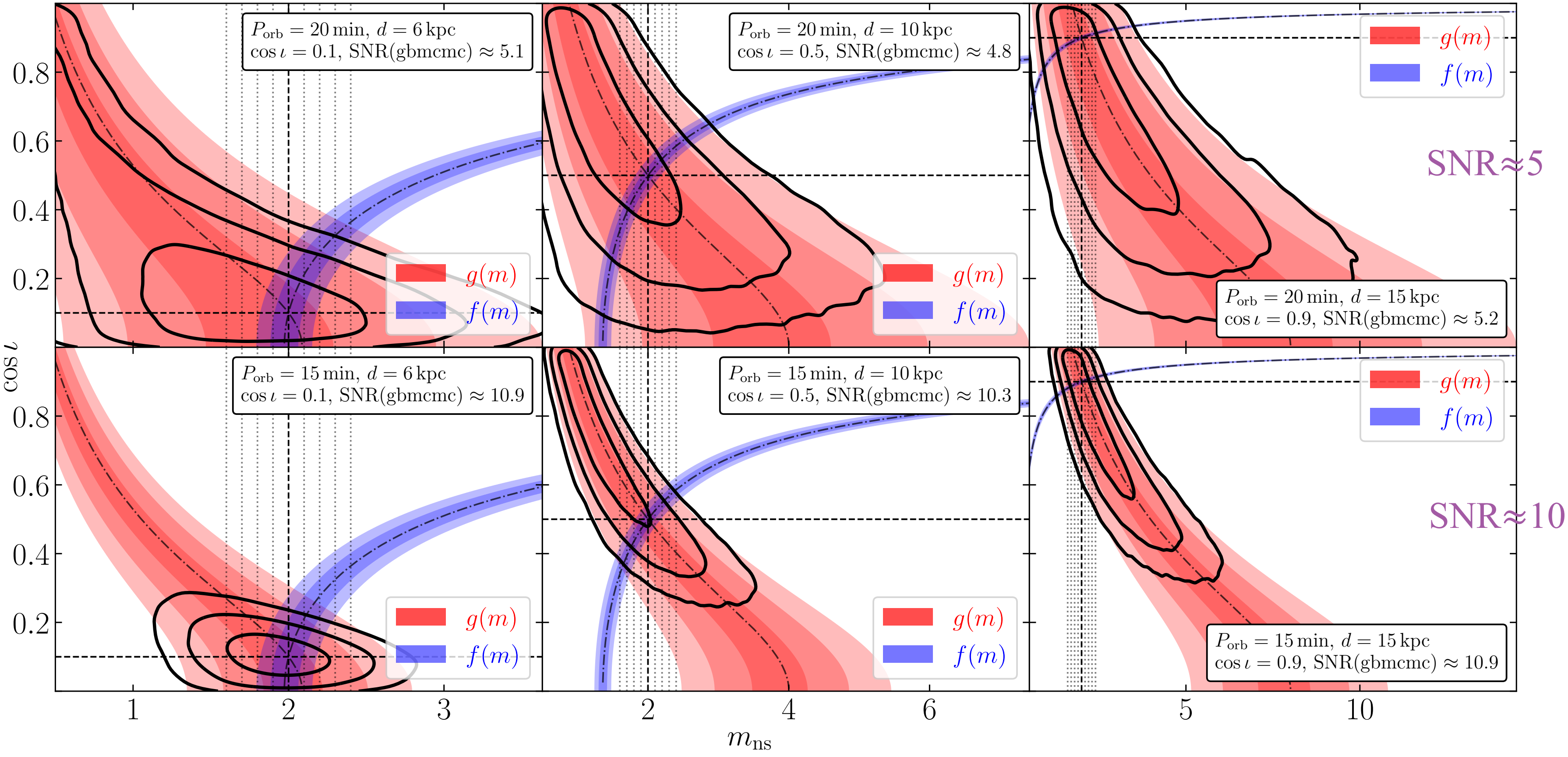
(PSR J1311−3430 Romani et al 2013)

2D confidence interval + g(m) + f(m)

(Long, **Li**, Wu, Kong 2023 submitted)

Other injected value: $m_{ns} = 2.0\ M_\odot$, $m_c = 0.1 M_\odot$

gbmcmc/g(m): 50%, 90%, 99%; f(m): 5%, 10%



Summary

- Mass-inclination degeneracy is the major problem in constraining the pulsar's mass in optical observation
- Gravitational wave observation (complementary mass function) helps break the degeneracy
- Combining gravitational wave and optical observation could help us to constrain the EOS of pulsar