

Super-Eddington accretion and the formation of massive neutron stars

PULX and GW190425-like binaries

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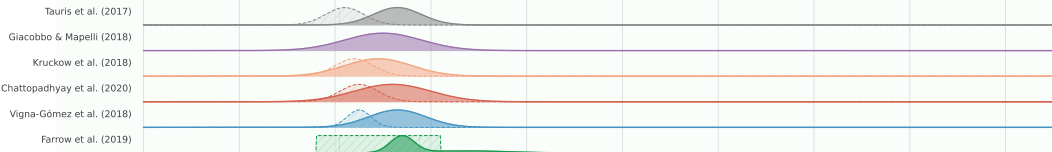
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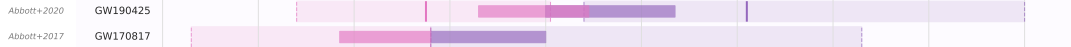
Neutron-star masses in DNS systems

● Recycled NS ◆ Second-born NS ■ GW m_1 ■ GW m_2 ■ Low spin ■ High spin — value

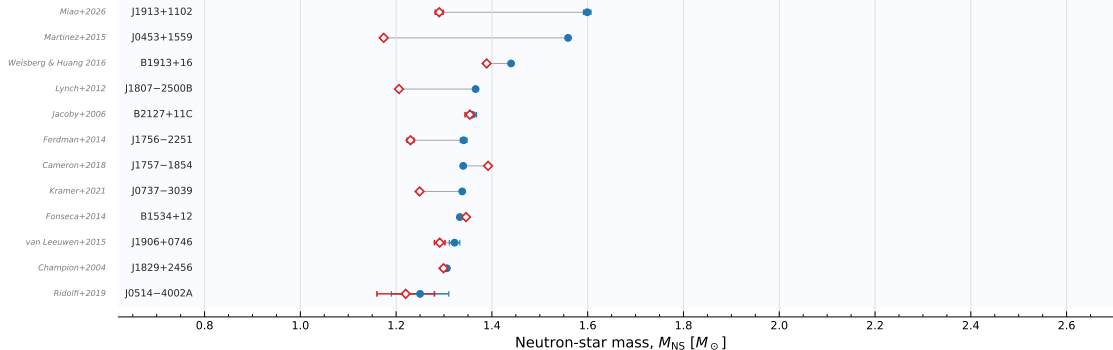
Mass distributions



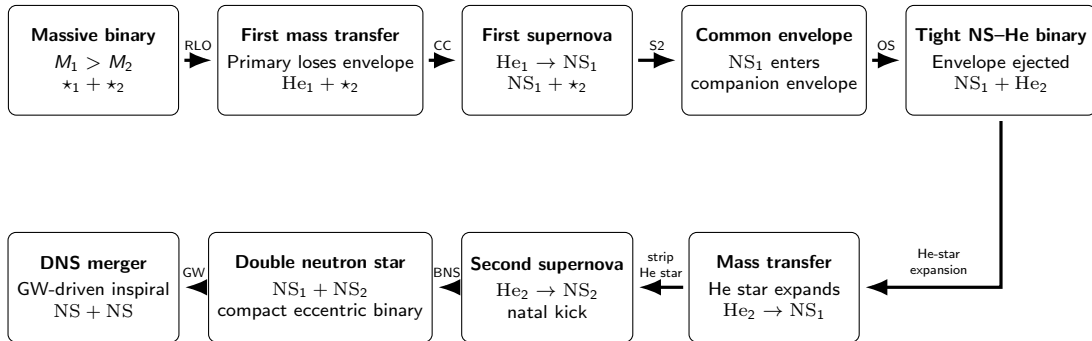
GW events



Galactic DNS



Formation of a Double Neutron-Star Binary



Method and Model Assumptions

Binary evolution and NS growth

He-star ZAMS $\rightarrow$ MESA He-star + NS grid $\rightarrow \dot{M}_{\text{tr}}(t) \rightarrow$ NS accretion model $\rightarrow$ second SN + DNS

$$M_{\text{He},i} = 2.2\text{--}4.2 M_{\odot}, \quad \log_{10}(P_{\text{orb},i}/\text{d}) = -1.3\text{--}0.7.$$

Super-Eddington disc

- MESA supplies $\dot{M}_{\text{tr}}(t)$
- Supercritical disc winds
- Spherization radius
- Magnetospheric truncation
-

$$\dot{M}(r) \propto r^p,$$

Spin + magnetic field

- Accretor / propeller / ejector
- Disc torque
- Magnetic-dipole spin-down
- Coupled evolution of M_{NS} , P_{spin} and B

DNS formation

- Evolve donor to C depletion
- Second NS from final CO core
- Natal kick at second SN
- Post-SN orbit
- GW merger time

Magnetic-field model :

$$B = B_0 \exp\left(-\frac{\Delta M_{\text{acc}}}{\Delta M_c}\right), \quad \Delta M_c = 0.05 M_{\odot},$$

Accretion model

Spherization radius, R_{sph}

$$R_{\text{sph}} \simeq \frac{27}{4} \frac{\dot{M}_{\text{tr}}}{\dot{M}_{\text{Edd}}} R_{\text{g}}, \quad R_{\text{g}} = \frac{GM_{\text{NS}}}{c^2}.$$

- Supercritical region of the disc.
- Inside R_{sph} , winds reduce the inflow:

$$\dot{M}(r) = \dot{M}_{\text{tr}} \left(\frac{r}{R_{\text{sph}}} \right)^p.$$

Magnetospheric radius, R_{m}

$$R_{\text{m}} = \xi \left(\frac{\mu^4}{2GM_{\text{NS}} \dot{M}_{\text{in}}^2} \right)^{1/7}.$$

- Disc truncated by the NS magnetic field.
- $\xi = 0.5$ in this work.

$$\dot{M}_{\text{tr}} \longrightarrow R_{\text{sph}} \text{ (wind)} \longrightarrow R_{\text{m}} \text{ (magnetic)} \longrightarrow R_{\text{co}} \text{ (gate)} \longrightarrow \dot{M}_{\text{acc}}$$

Corotation radius, R_{co}

$$R_{\text{co}} = \left(\frac{GM_{\text{NS}} P_{\text{spin}}^2}{4\pi^2} \right)^{1/3}.$$

- Radius where the disc rotates at the NS spin frequency.

Accretion

$$R_{\text{m}} < R_{\text{co}}$$

Propeller

$$R_{\text{m}} > R_{\text{co}}$$

Accretion model: main assumptions

Neutron star

- Initial gravitational mass:

$$M_{\text{NS},0} = 1.4 M_{\odot}$$

- Radius:

$$R_{\text{NS}} = 12 \text{ km}$$

- Initial spin:

$$P_0 = 0.1, 1 \text{ s}$$

- Maximum NS mass:

$$M_{\text{NS,max}} = 2.5 M_{\odot}$$

Magnetic field & disc wind

- Two initial magnetic moments:

$$\mu_0 = 10^{30}, 10^{32} \text{ G cm}^3$$

- Supercritical disc-wind models:

$$p = 0.05, 0.20, 0.50$$

- Helium-rich transferred material:

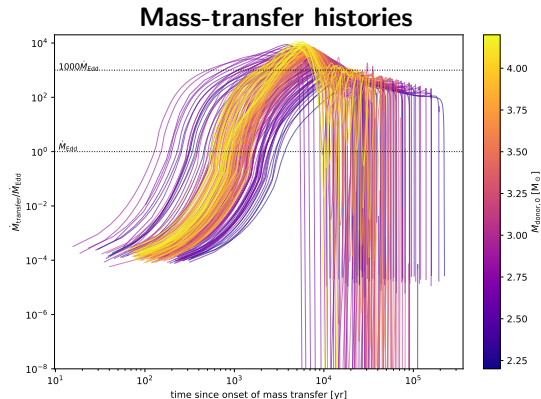
$$X = 0$$

- Exponential magnetic-field burial as mass is accreted

Role of the wind parameter

Smaller $p \Rightarrow$ weaker disc mass loss $\Rightarrow$ more material available for NS accretion.

Results (MESA): Mass transfer History

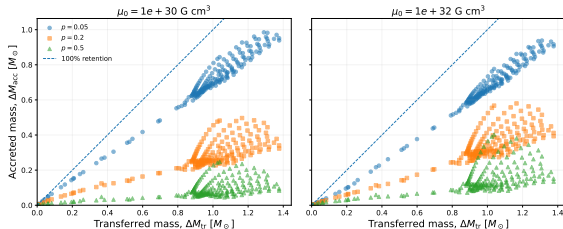


Mass transfer reaches strongly super-Eddington rates.
 $\dot{M}_{\text{tr}} \rightarrow R_{\text{sph}} \text{ (wind)} \rightarrow R_{\text{m}} \text{ (magnetic)} \rightarrow R_{\text{co}} \text{ (gate)} \rightarrow \dot{M}_{\text{acc}}.$

Results: Does the initial NS spin affect mass retention?

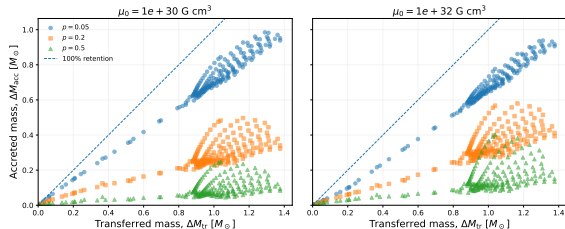
$$P_0 = 0.1 \text{ s}$$

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$$P_0 = 1 \text{ s}$$

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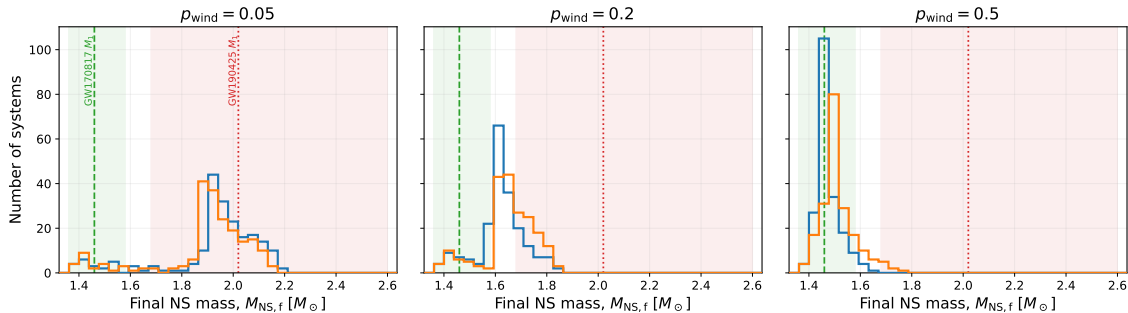


Changing P_0 from 0.1 to 1 s produces little visible change in the integrated accreted mass. The dominant difference is instead set by the disc-wind parameter p .

Final neutron-star mass distribution

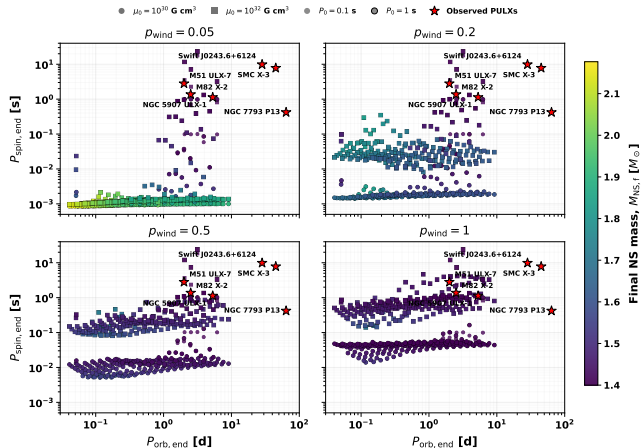
Final neutron-star mass distribution, $P_0 = 1$ s

$\mu_0 = 1e+30$ G cm³ $\mu_0 = 1e+32$ G cm³



- **Weak winds favour massive NS formation:** $\rho_{wind} = 0.05$ produces a broad high-mass population, extending beyond $2 M_\odot$.
- The two initial magnetic moments give broadly similar mass distributions; the stronger dependence is on ρ_{wind} .

Results: Spin-orbit distribution and observed PULXs



- **Weak winds:** strong spin-up to millisecond periods.
- Known PULXs have spin periods of $\sim 0.4\text{--}10 \text{ s}$ and span orbital periods from a few to tens of days (Bachetti et al. 2014, Furst et al. 2016, Israel et al. 2017)

Modelling approach: Zhang et al. 2023 vs. this work

Zhang et al.

Prescribed accretion efficiency

$$\dot{M}_{\text{acc}} = 1, 10, 100, 1000 \dot{M}_{\text{Edd}}$$

- Fixed multiples of the Eddington rate
- NS growth determined by the adopted accretion limit

This work

Flow-dependent accretion

$$\dot{M}_{\text{tr}} \rightarrow R_{\text{sph}} \rightarrow R_{\text{m}} \rightarrow \dot{M}_{\text{acc}}$$

- $\dot{M}_{\text{tr}}(t)$ taken from MESA binaries
- Disc winds: $p_{\text{wind}} = 0.05, 0.2, 0.5$
- Magnetic truncation and propeller included
- NS mass, spin and magnetic field evolve together

Formation of the second-born neutron star



Evolution of the resulting binary neutron star



Gravitational-wave study and comparison with GW observations

Thank you