# Neutron star kicks by gravitational tug-boat mechanism

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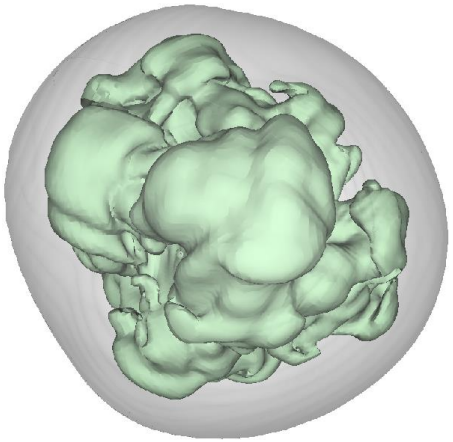

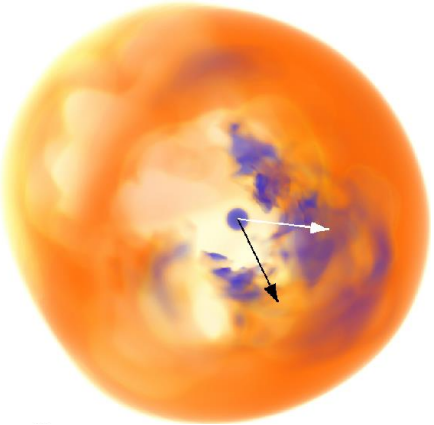

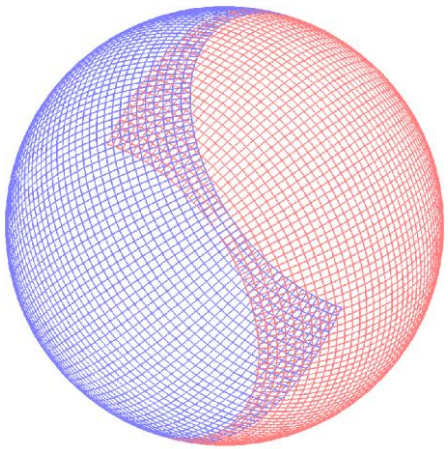

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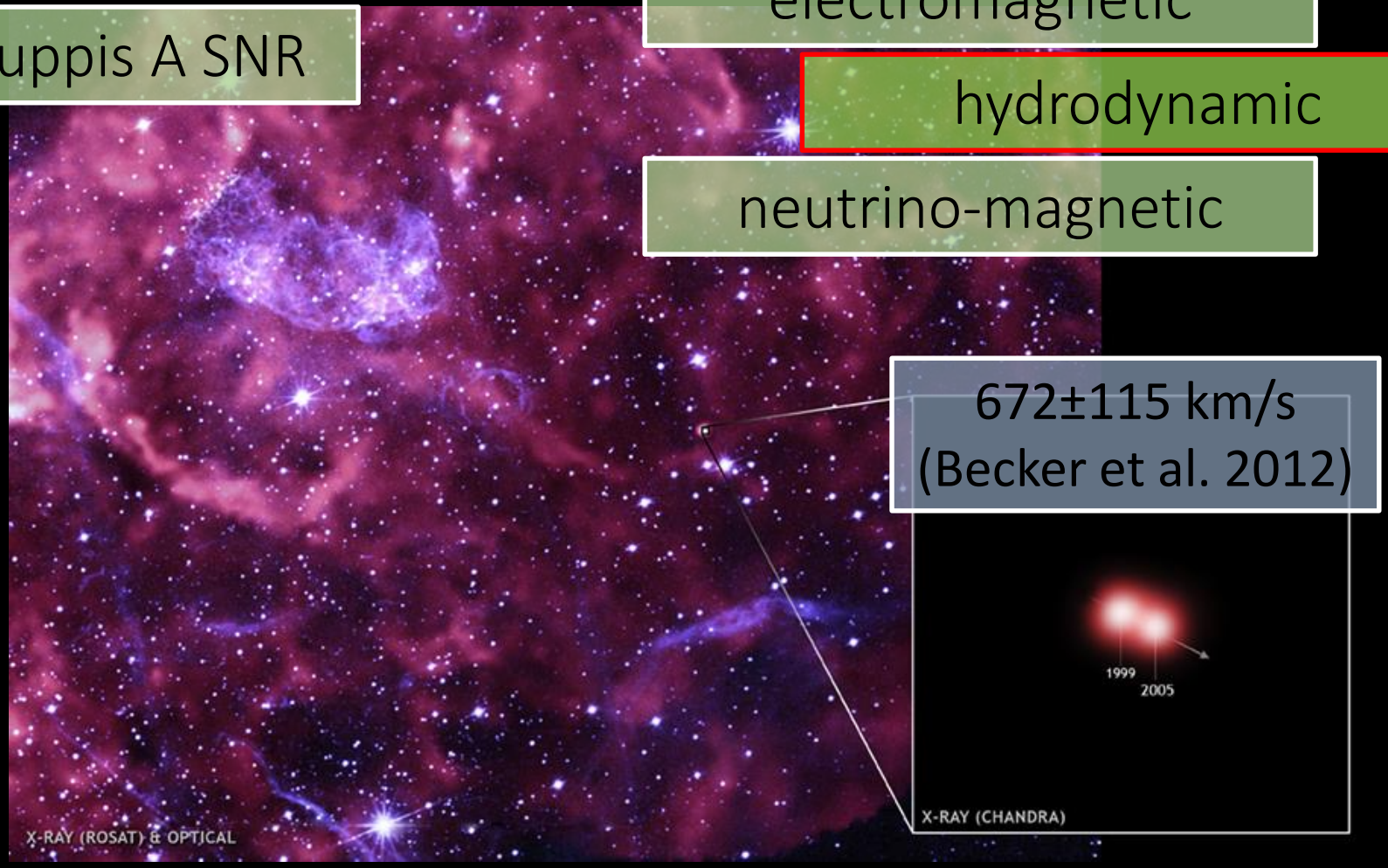
# Neutron star kicks

Kick mechanism??

- electromagnetic
- hydrodynamic
- neutrino-magnetic

Puppis A SNR




672±115 km/s
(Becker et al. 2012)

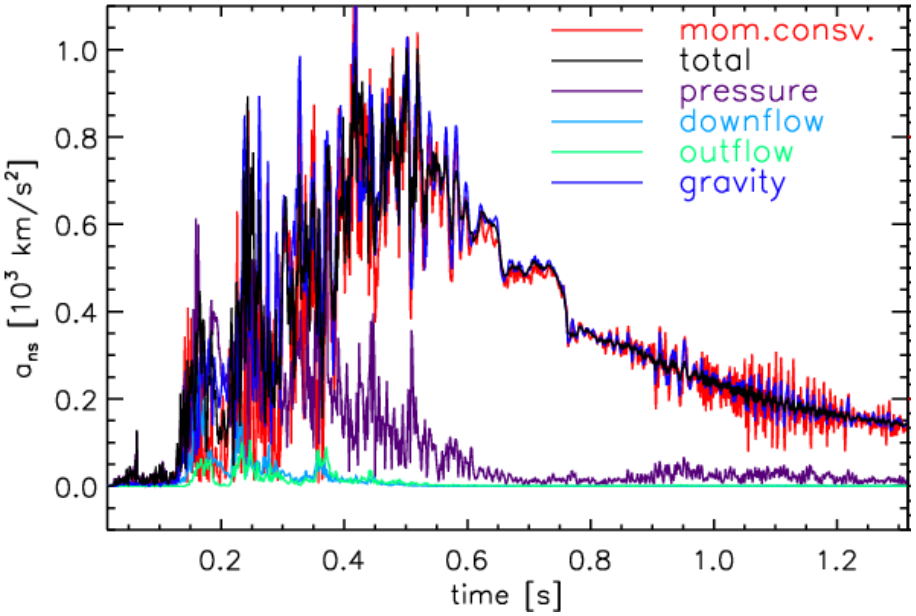
average pulsars velocity: 200-500 km/s

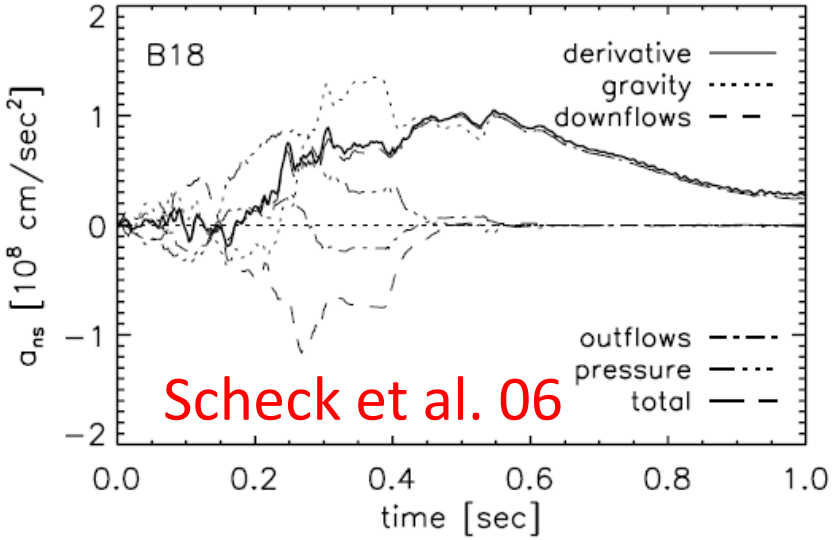
| Model | $M_{ns}$ [$M_\odot$] | $t_{exp}$ [ms] | $E_{exp}$ [B] | $v_{ns}$ [km s$^{-1}$] | $a_{ns}$ [km/s$^2$] | $v_{ns,\nu}$ [km s$^{-1}$] | $\alpha_{k\nu}$ [°] | $v_{ns}^{long}$ [km s$^{-1}$] | $a_{ns}^{long}$ [km/s$^2$] | $J_{ns,46}$ [$10^{46}$ g cm$^2$/s] | $\alpha_{sk}$ [°] | $T_{spin}$ [ms] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W15-1 | 1.37 | 246 | 1.12 | 331 | 167 | 2 | 151 | 524 | 44 | 1.51 | 117 | 652 |
| W15-2 | 1.37 | 248 | 1.13 | 405 | 133 | 1 | 126 | 575 | 49 | 1.56 | 58 | 632 |
| W15-3 | 1.36 | 250 | 1.11 | 267 | 102 | 1 | 160 | – | – | 1.13 | 105 | 864 |
| W15-4 | 1.38 | 272 | 0.94 | 262 | 111 | 4 | 162 | – | – | 1.27 | 43 | 785 |
| W15-5-lr | 1.41 | 289 | 0.83 | 373 | 165 | 2 | 129 | – | – | 1.63 | 28 | 625 |
| W15-6 | 1.39 | 272 | 0.90 | 437 | 222 | 2 | 136 | 704 | 71 | 0.97 | 127 | 1028 |
| W15-7 | 1.37 | 258 | 1.07 | 215 | 85 | 1 | 81 | – | – | 0.45 | 48 | 2189 |
| W15-8 | 1.41 | 289 | 0.72 | 336 | 168 | 3 | 160 | – | – | 4.33 | 104 | 235 |
| L15-1 | 1.58 | 422 | 1.13 | 161 | 69 | 5 | 135 | 227 | 16 | 1.89 | 148 | 604 |
| L15-2 | 1.51 | 382 | 1.74 | 78 | 14 | 1 | 150 | 95 | 4 | 1.04 | 62 | 1041 |
| L15-3 | 1.62 | 478 | 0.84 | 31 | 27 | 1 | 51 | – | – | 1.55 | 123 | 750 |
| L15-4-lr | 1.64 | 502 | 0.75 | 199 | 123 | 4 | 120 | – | – | 1.39 | 93 | 846 |
| L15-5 | 1.66 | 516 | 0.62 | 267 | 209 | 3 | 147 | 542 | 106 | 1.72 | 65 | 695 |
| N20-1-lr | 1.40 | 311 | 1.93 | 157 | 42 | 7 | 118 | – | – | 5.30 | 122 | 190 |
| N20-2 | 1.28 | 276 | 3.12 | 101 | 12 | 4 | 159 | – | – | 7.26 | 43 | 127 |
| N20-3 | 1.38 | 299 | 1.98 | 125 | 15 | 5 | 138 | – | – | 4.42 | 54 | 225 |
| N20-4 | 1.45 | 334 | 1.35 | 98 | 18 | 1 | 98 | 125 | 9 | 2.04 | 45 | 512 |
| B15-1 | 1.24 | 164 | 1.25 | 92 | 16 | 1 | 97 | 102 | 1 | 1.03 | 155 | 866 |
| B15-2 | 1.24 | 162 | 1.25 | 143 | 37 | 1 | 140 | – | – | 0.12 | 162 | 7753 |
| B15-3 | 1.26 | 175 | 1.04 | 85 | 19 | 1 | 24 | 99 | 3 | 0.44 | 148 | 2050 |

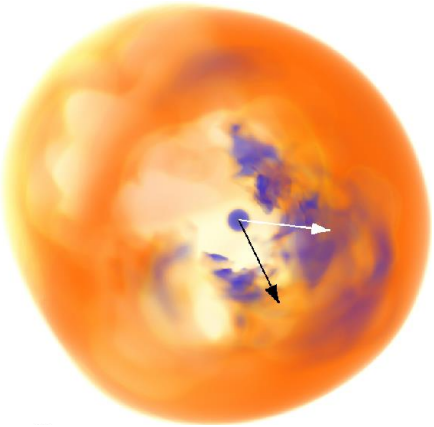
$v_{ns}$ from 31-437 km/s

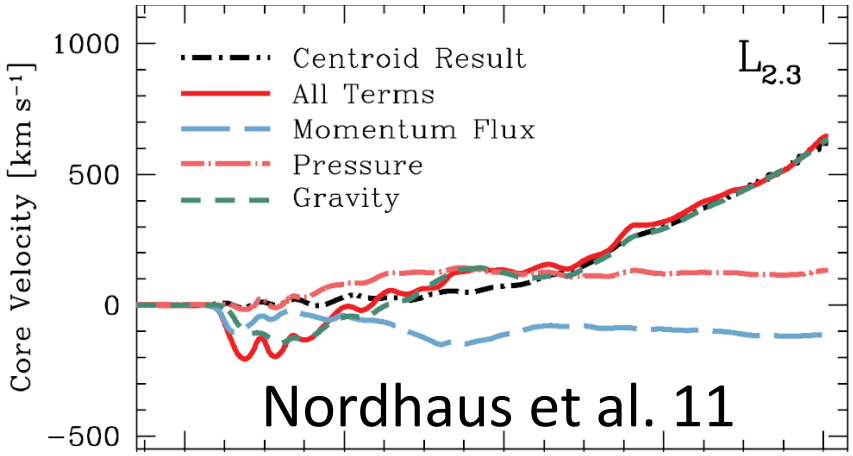
700 km/s later

$$\dot{\vec{P}}_{ns} \approx -\oint_{r=r_0} P\, d\vec{S} - \oint_{r=r_0} \rho \vec{v} v_r dS + \int_{r>r_0} \frac{G M_{ns} \vec{r}}{r^3}\, dm$$






gravitational drag term is dominant