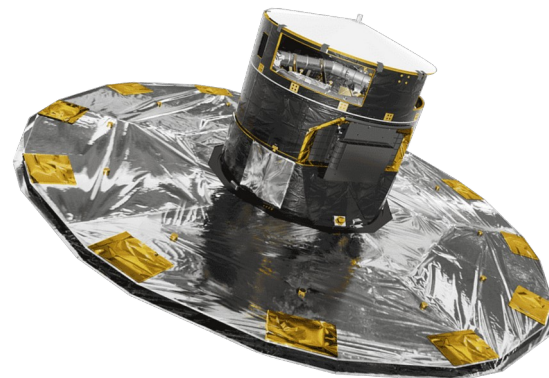
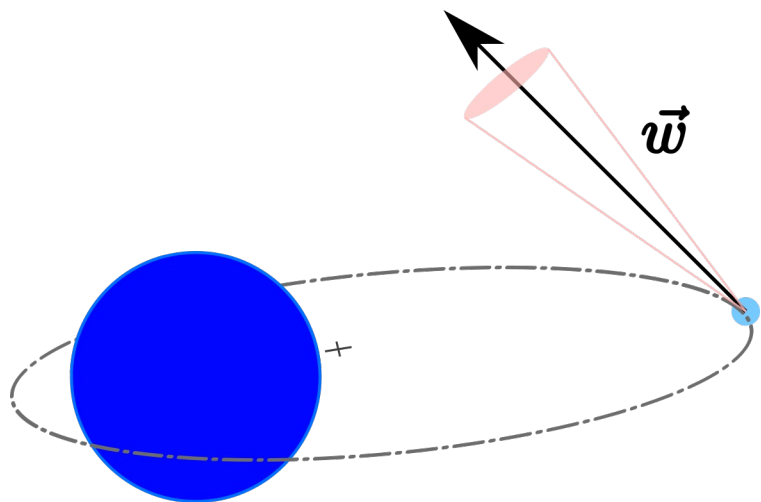
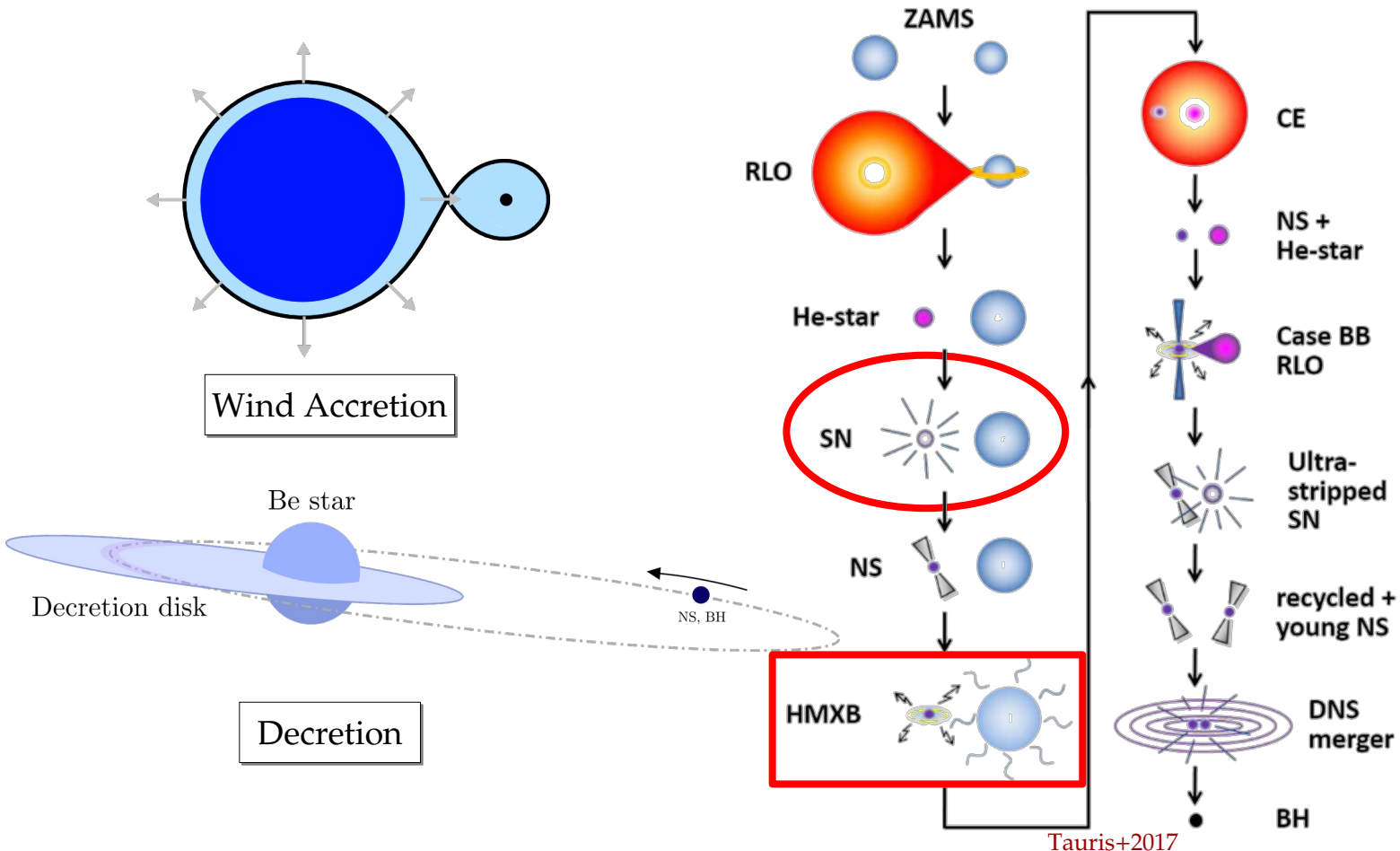


Constraints to neutron star kicks in High-Mass X-ray binaries with Gaia EDR3



F. Fortin, F. Garcia, S. Chaty, E. Chassande-Mottin, A. Simaz-Bunzel, A&A subm.

Evolution of High-Mass X-ray binaries




Supernova:
 - Blaauw kick
 - Asymetry

Survival rate ?
 Impact on orbit ?

Tauris+2017

Natal kicks – State of the art & Aims

- Analytical solution of its impact on orbital parameters in binaries (Kalogera 1996)
- Cir X-1 velocity & orbit explained by massive natal kick of ~ 500 km/s (Tauris+1999)
- Black Hole X-ray binary with high runaway velocity (Mirabel+2002)
- Isolated pulsars: preferential direction of the kick wrt spin ? (Ng & Romani 2013)
- Natal kick derived on an HMXB with the Australian LBA radio interferometer (Miller-Jones+2018)
- Radio interferometry + Gaia DR2  to derive kick on 16 BH X-ray binaries (Atri+2019)

Kicks are still misunderstood, most studies tackle a single source in the case of binaries

- **Infer the NS kick magnitude in known HMXBs of our Galaxy**
- **Use of astrometric data from Gaia EDR3**
- **Characterize the NS kick distributions across HMXB subtypes (Be, Oe, sg)**

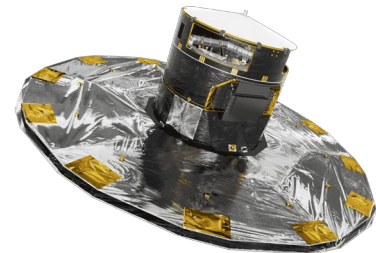
Pre-requisites

- i) build a list of HMXBs known in the Milky Way
 - cross-match between old HMXB catalogue (Liu+2006) with current INTEGRAL sources (Bird+2016)
 - cross-match with Simbad (Centre de Données astronomiques de Strasbourg)
 - some candidate HMXBs in previous catalogues are now confirmed/discarded
 - retrieve exact references for spectral type, mass, period, eccentricity, radial velocity (1D)

- ii) find the Gaia counterparts of those HMXBs & retrieve position (3D) and proper motion (2D)

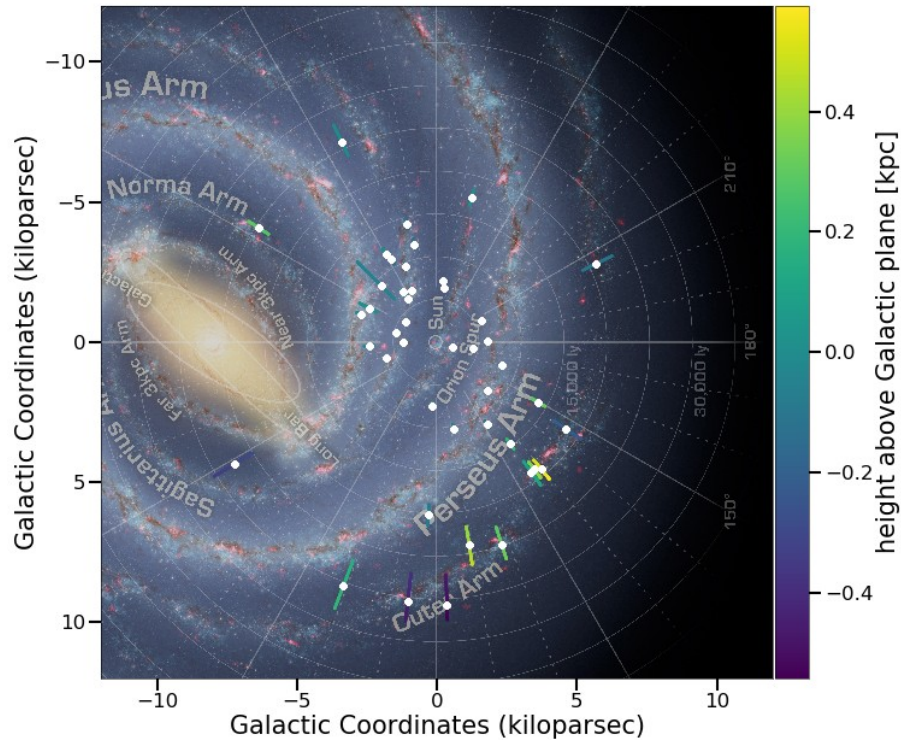
→ 6D data (position + proper motion + radial velocity)

Peculiar Velocity = Velocity – Galactic orbital motion



Gaia counterparts to HMXBs

Gaia view of HMXBs in the Milky Way



Fortin et al. A&A subm.

- Position compatible with Spiral Arms (Coleiro & Chaty 2013)
 - Galactic warp (Romero-Gomez+2019)
 - parallax quality criteria (SNR & astrometric excess noise)
 - set of Gaia data, mass, spectral type, orbital parameters
- We can infer kicks on 35 known HMXBs.

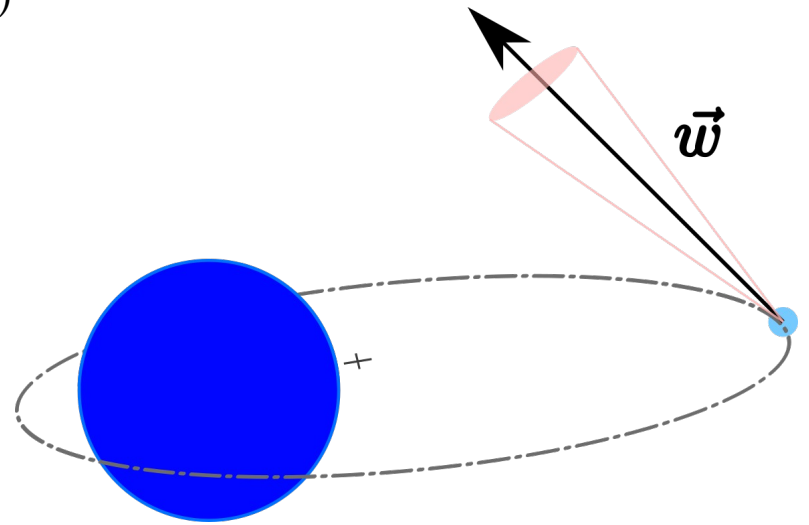
Deriving neutron star kicks

Analytical equation linking pre-SN to post-SN orbital parameters (Kalogera 1996), assuming an **isotropic probability of the kick direction**.

- Blaauw kick (spherically symmetric mass loss, Blaauw 1961)
- Asymmetric kick (random direction)

Hypotheses:

- circularized systems (initial mass transfer)
- fixed NS mass @ $1.4M_{\text{Sun}}$
- companion is unaffected by the supernova



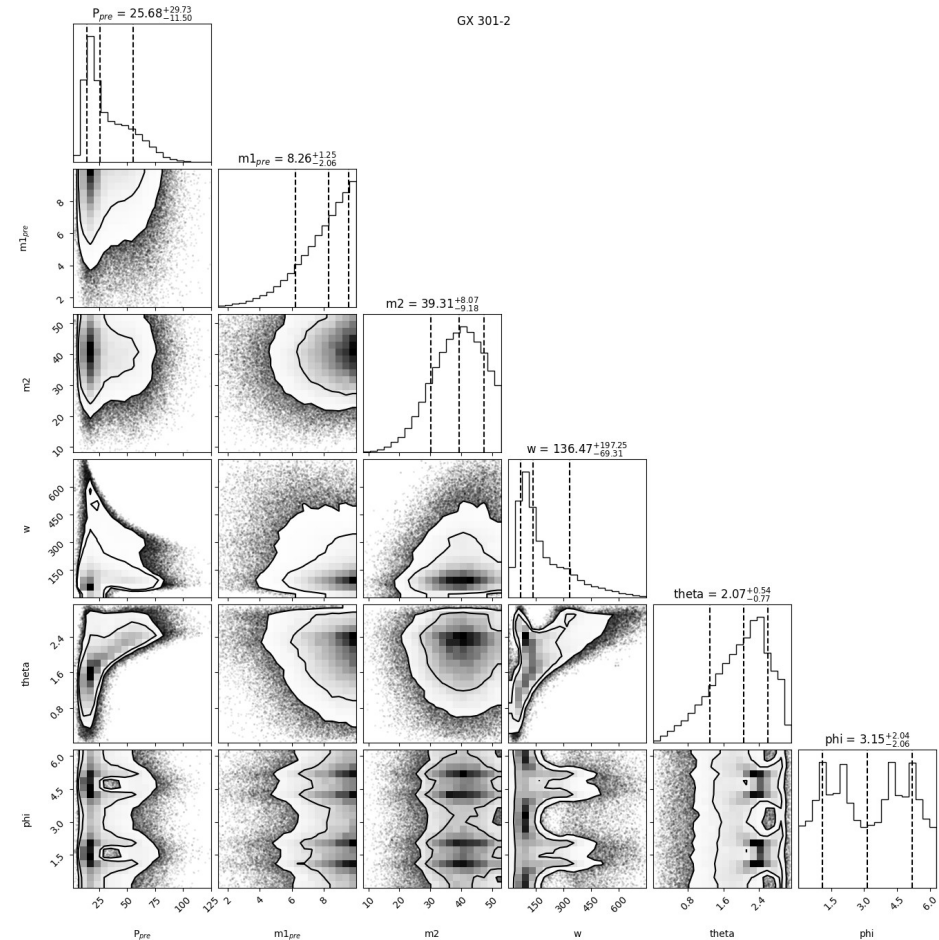
Deriving neutron star kicks

Bayesian approach:

- Priors on kick magnitude, initial P_{orb} and pre-SN mass

- Likelihoods: Gaia observables, companion mass, P_{orb} & eccentricity

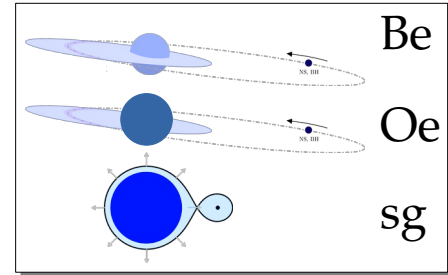
→ Explore the posterior distributions using Markov Chain Monte Carlo (MCMC)



Inferring kick distributions on HMXB subtypes

We have a posterior probability of kick velocities for each 35 HMXBs.

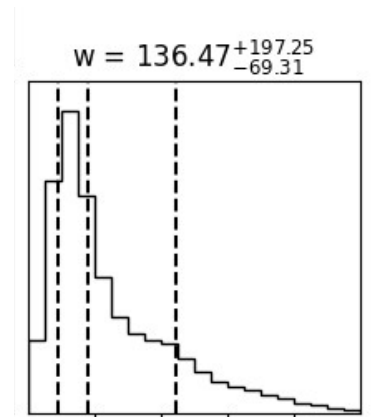
→ How can we characterize the kick distributions on each HMXB subtypes ?



To get a representative distribution, we use a bootstrap method:

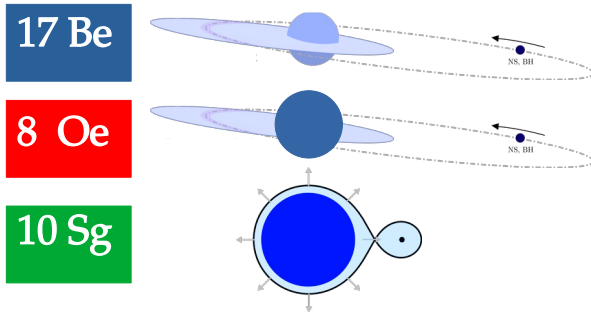
- for each HMXB, draw a random kick velocity according to its posterior probability
- 1 bootstrap iteration is a collection of those random draws, effectively one possible posterior for the whole HMXB subtype population in question
- iterate 1000 times

→ Fit each posteriors with a Gamma function, retrieve median parameters.



Results on kick distributions

Inferred kick magnitudes on 35 HMXB :

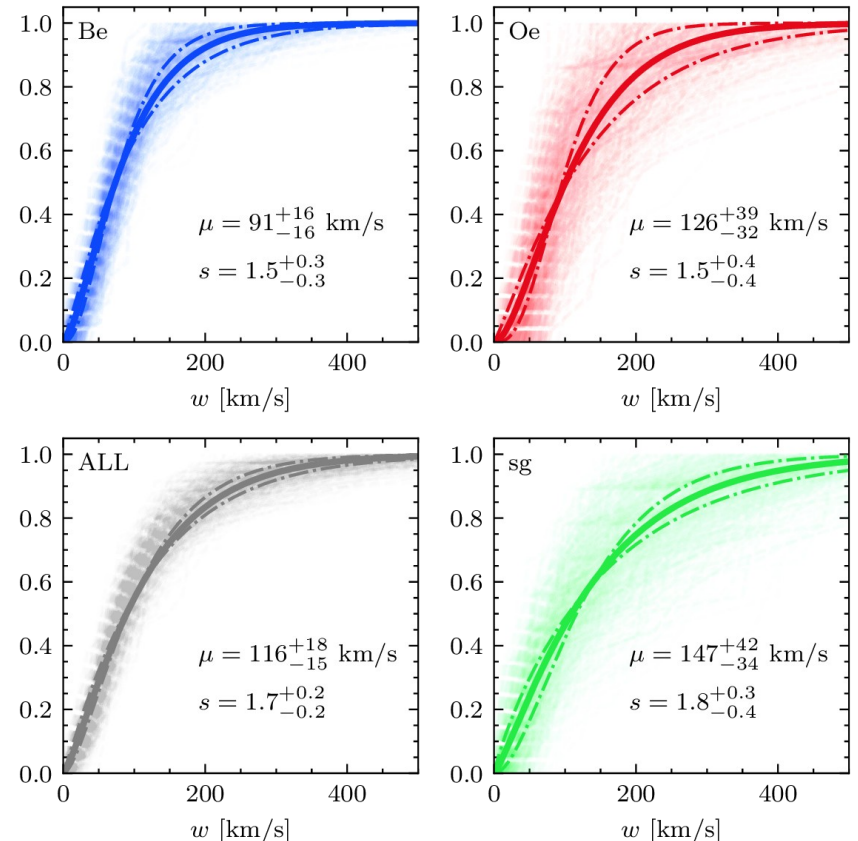


→ Kicks are reproduced with Gamma functions

(instead of the commonly used Maxwellian)

→ Can be confronted to population synthesis models
in order to constrain the physics behind NS kicks

Cumulative distributions of kicks



Prospects: Gaia DR3, HMXB birthplace, catalogue

- Upcoming release(s) of Gaia

- Gaia DR3 improvement over EDR3: addition of astrophysical parameters & some RVs
- No additional source, no improvement on astrometry
- Full release TBD, extra sources with more constrained astrometry.

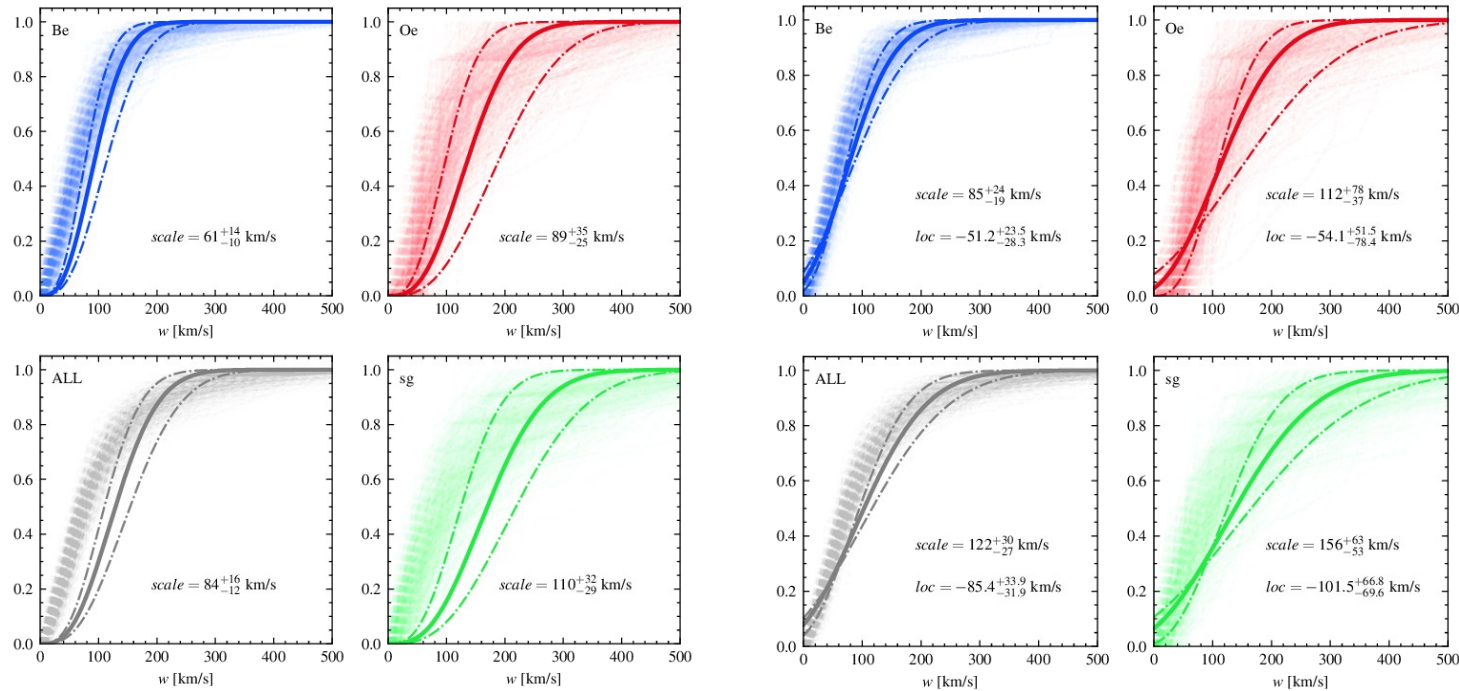
- Finding the birthplace of HMXBs in the Galaxy (Fortin et al. in prep)

- We have the peculiar velocity of HMXBs
- If they are born within clusters, we could find them in Gaia → get their peculiar velocity
- Integrate orbits over \sim Myr to find candidate birthplaces for Galactic HMXBs.

- Catalogue of High-Mass X-ray Binaries in the Milky Way

Extra: Maxwellian vs. Gamma

Maxwellian is historically used to model kicks in isolated pulsars (Hobbs+2005, Ng & Romani 2007, Noutsos+2013)



Unbound systems ?

→ observed vs. pop synth.

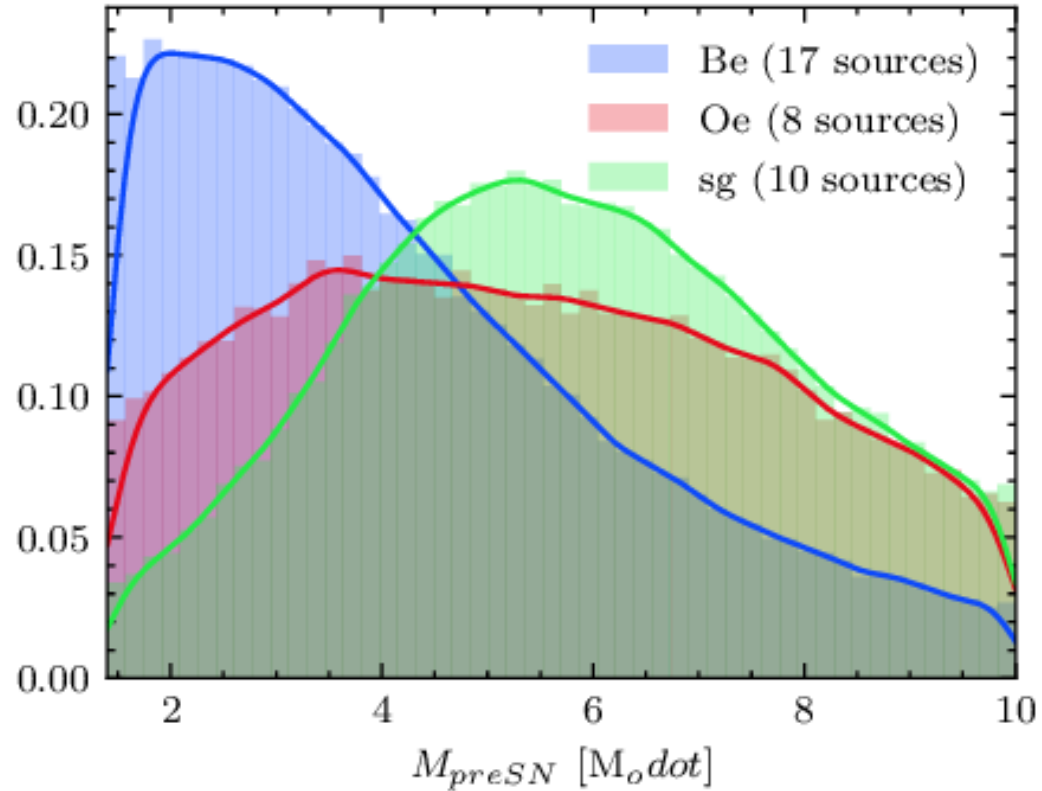
Stripped progenitors ?

→ lower pre-SN mass

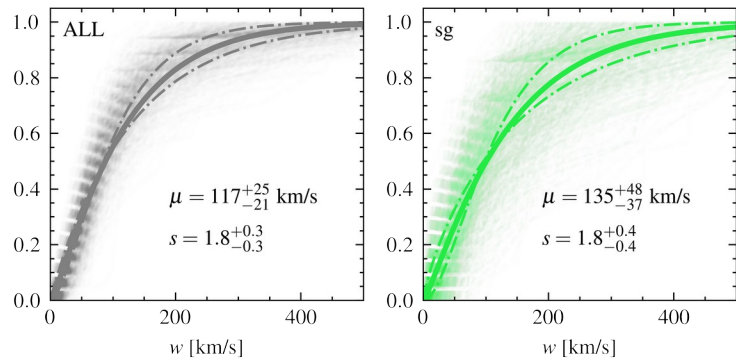
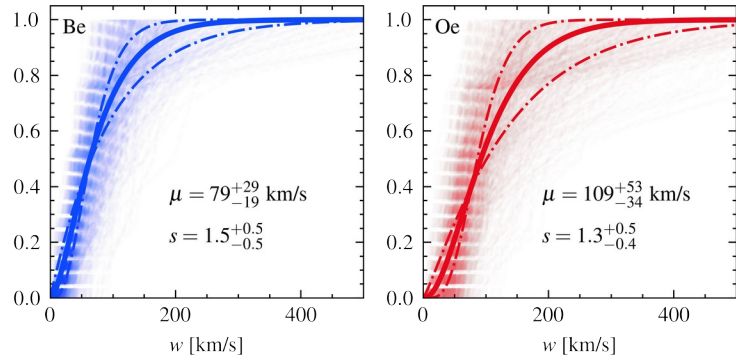
Kick isotropy ?

→ NS spin axis

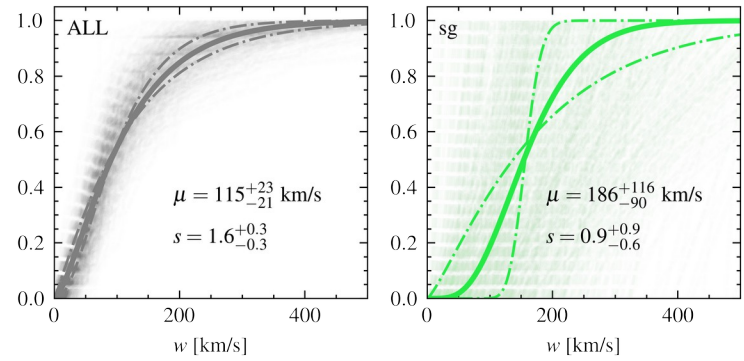
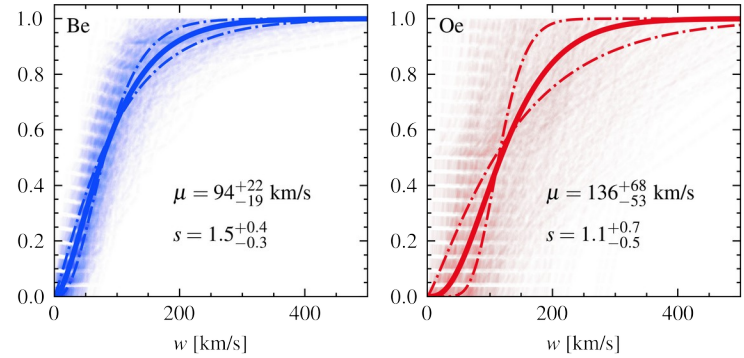
Extra: $M_{\text{pre-SN}}$ distribution



Extra: impact of missing radial velocity



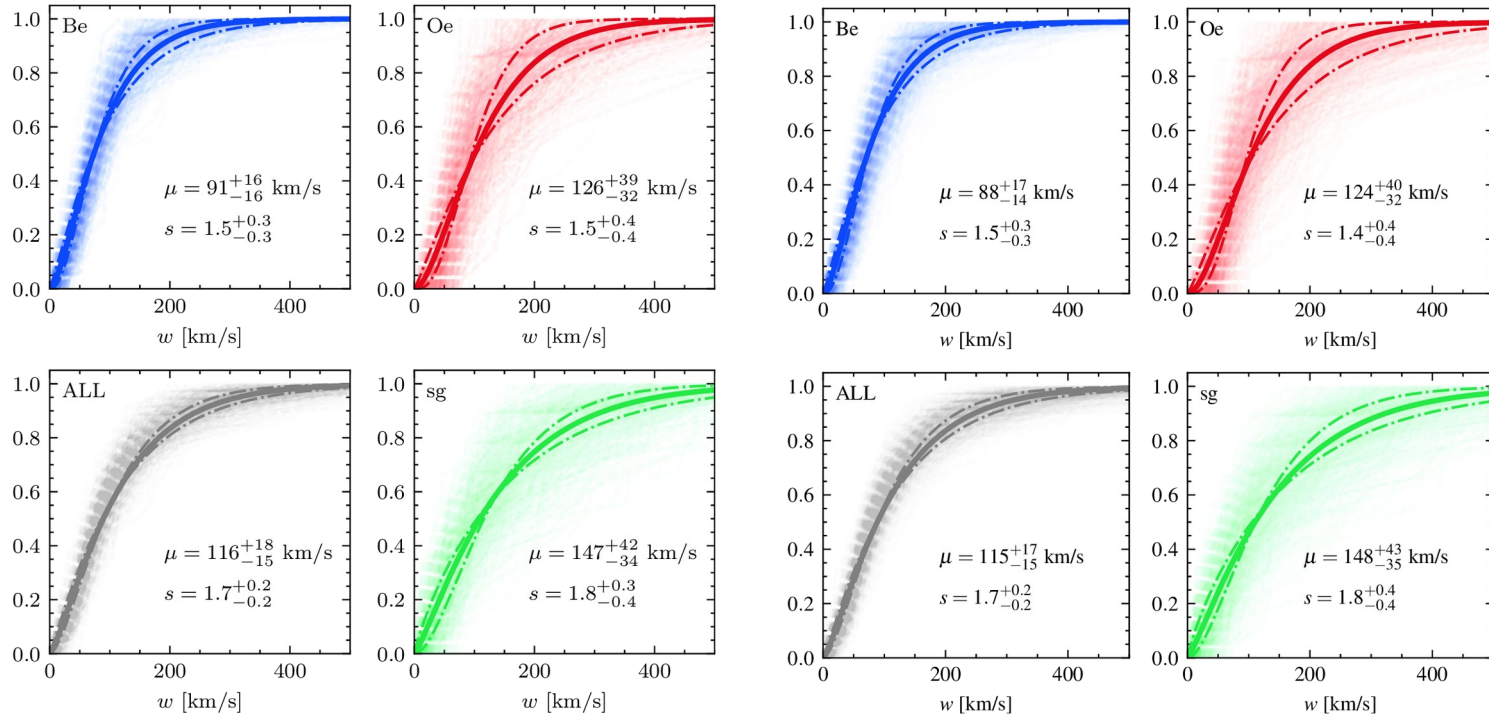
With RV only



Without RV only

Extra: impact of neutron star mass

→ Assumed constant NS mass of 1.4 Msun, what about more massive NSs ?



$M_{\text{NS}} = 1.4 M_{\text{Sun}}$

$M_{\text{NS}} = 1.8 M_{\text{Sun}}$

No notable difference
on the fitted
parameters

→ NS mass variation
are much smaller
than $M_{\text{pre-SN}}$
uncertainty

Extra: building the list of HMXBs

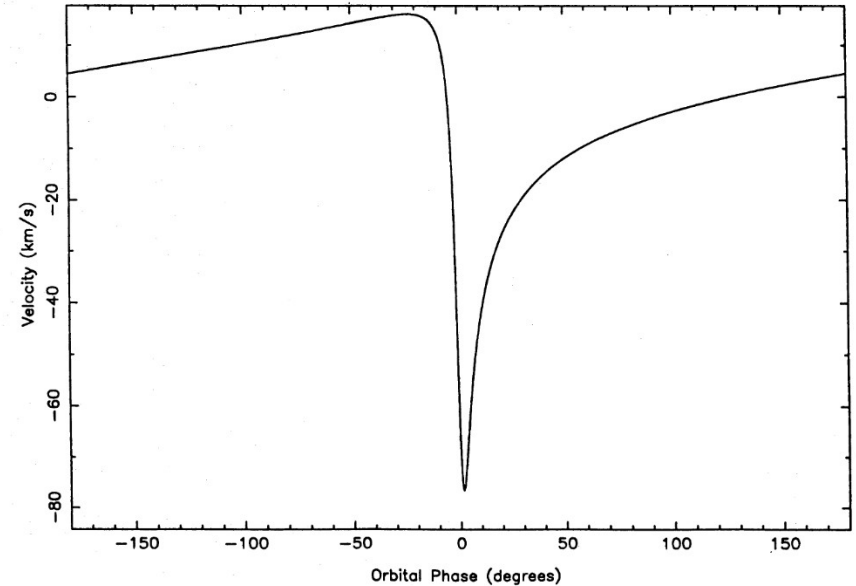
Example: PSR B1259-63

Radial velocity followup of the Oe companion star

→ Curve is presented but no value of the systemic velocity is given in the paper !

→ WebPlotDigitizer: we retrieved the data from the plot and fitted the systemic velocity

→ Do that for 130 HMXBs in the Galaxy.



Radial velocity of PSR B1259-63 (Johnston+1994)