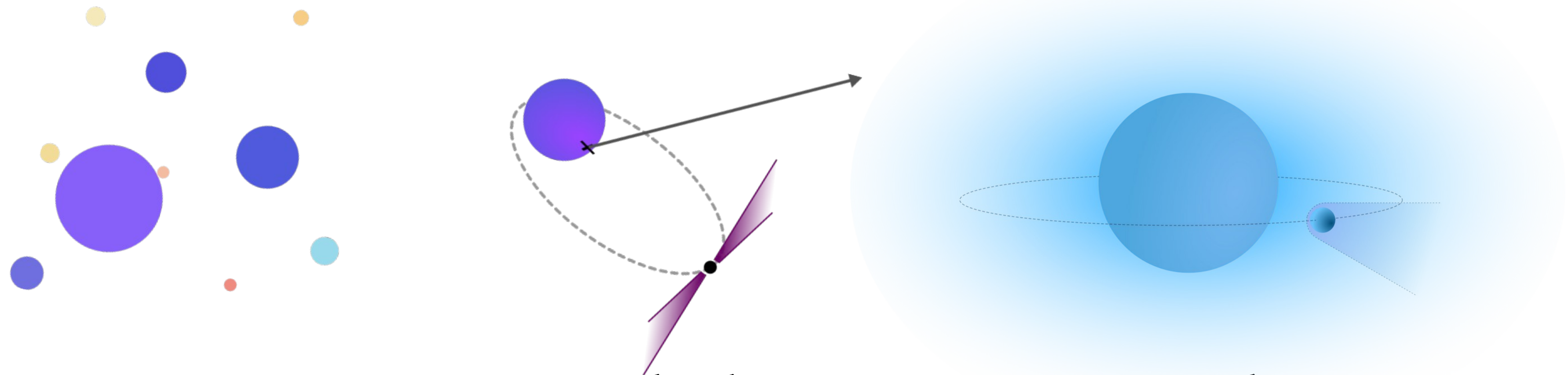
On the history of high-mass X-ray binaries through the Milky Way with Gaia



Francis Fortin – Postdoc LabEx UnivEarthS – APC

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

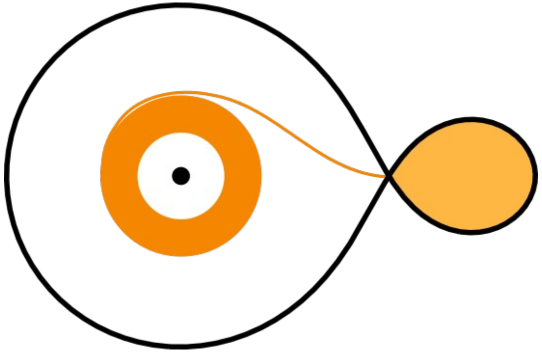
SF2A S02 – 23.06.2023

X-ray binaries cheat sheet

- Discovered in the 1960'
- Hard X-ray emission powered by accretion
- Transient or persistent
- Disks, jets, stellar winds...

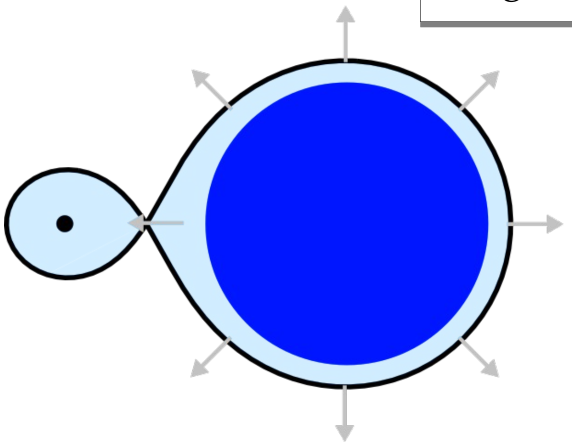
Companion star: low mass ($< 1\ M_\odot$) or high mass ($> 8\ M_\odot$)

Low Mass X-ray Binaries

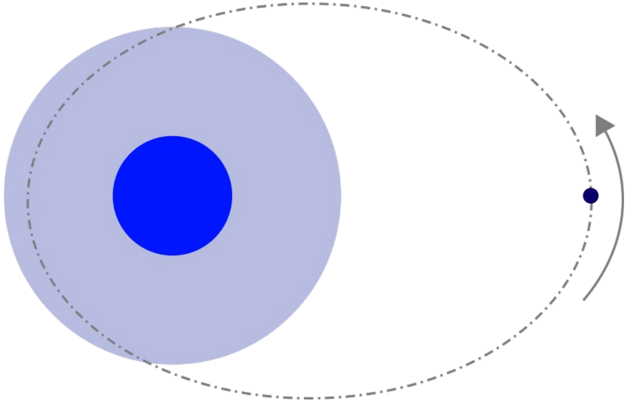


Roche lobe overflow

High Mass X-ray Binaries



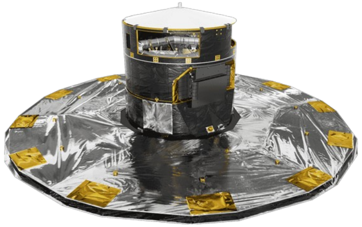
Wind accretion



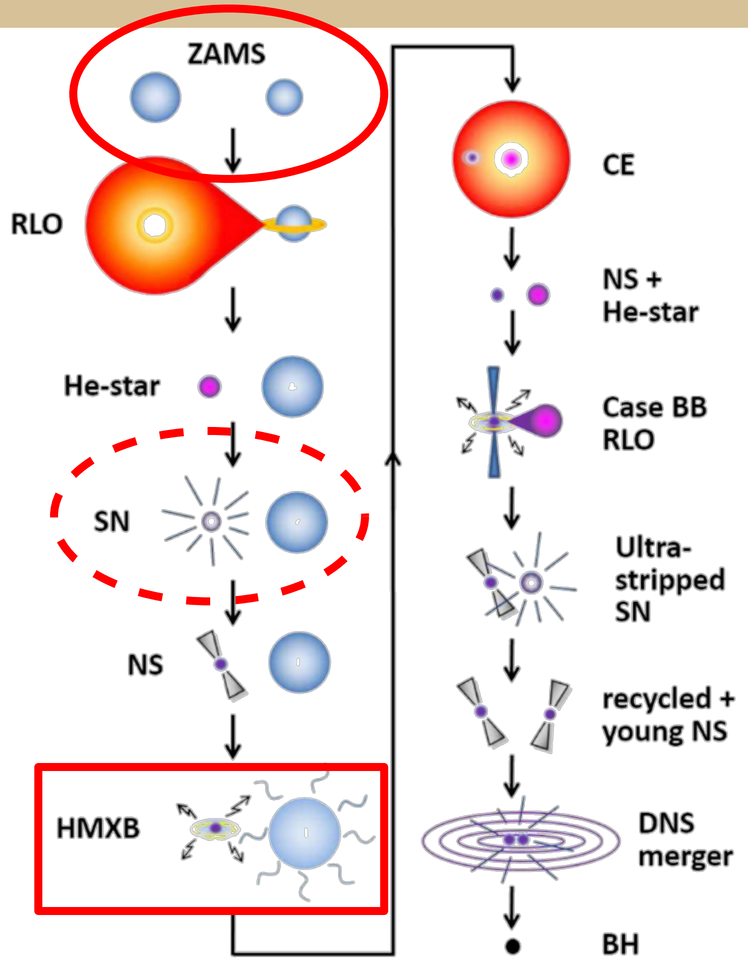
Decretion disk

Evolution of High-Mass X-ray Binaries (HMXBs)

- Can we infer the properties of past supernova events ?
- How old are HMXBs ?
- Where did their progenitors form in the Galaxy ?



→ Gaia can help.



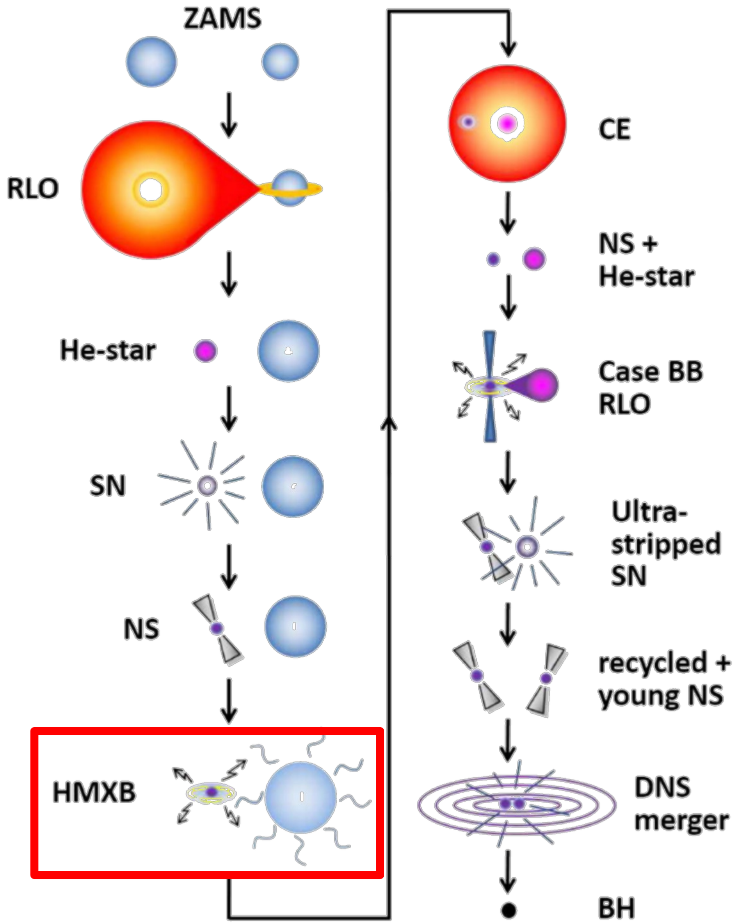
Tauris+2017

Observing the history of binary star systems

I – A catalogue of HMXBs in the Galaxy

II – Properties of the natal kick in binaries

III – Finding the birthplace of stellar systems

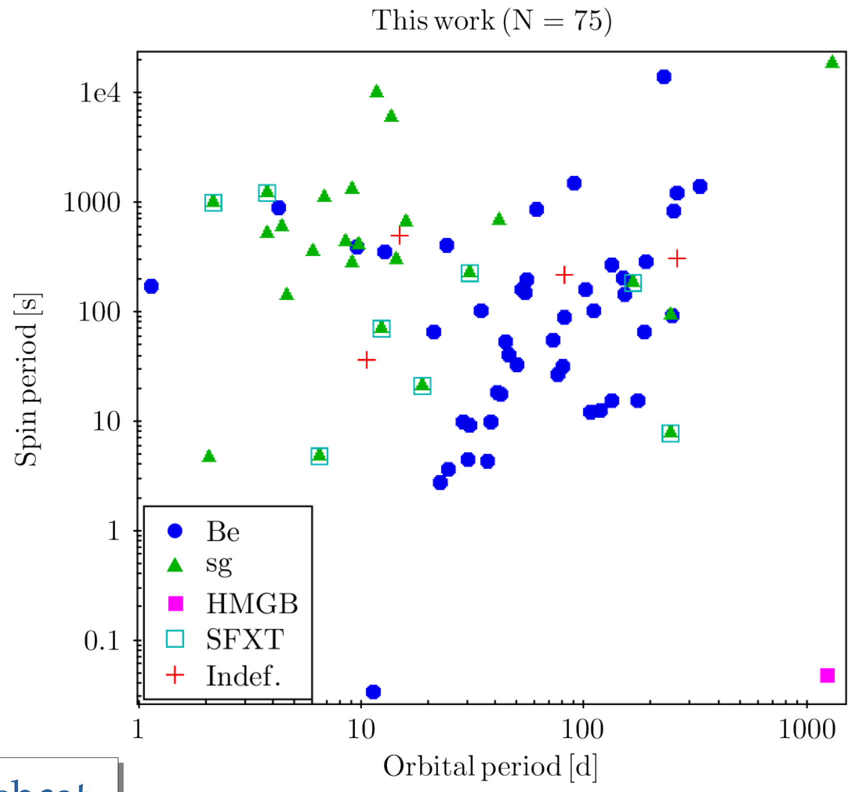


The new catalogue of HMXBs in the Galaxy

New catalogue of HMXBs : Fortin et al. 2023 [N=154]

→ automated search for multi-wavelength counterparts

→ manual search for spectral types, orbital parameters...



HMXBs → bright optical counterparts

→ more than 110 detected by Gaia

→ unprecedented sample of parallax measurements

→ an opportunity for massive stars & Galactic ecology

→ GitHub/HMXBwebcat

Observing the history of binary star systems

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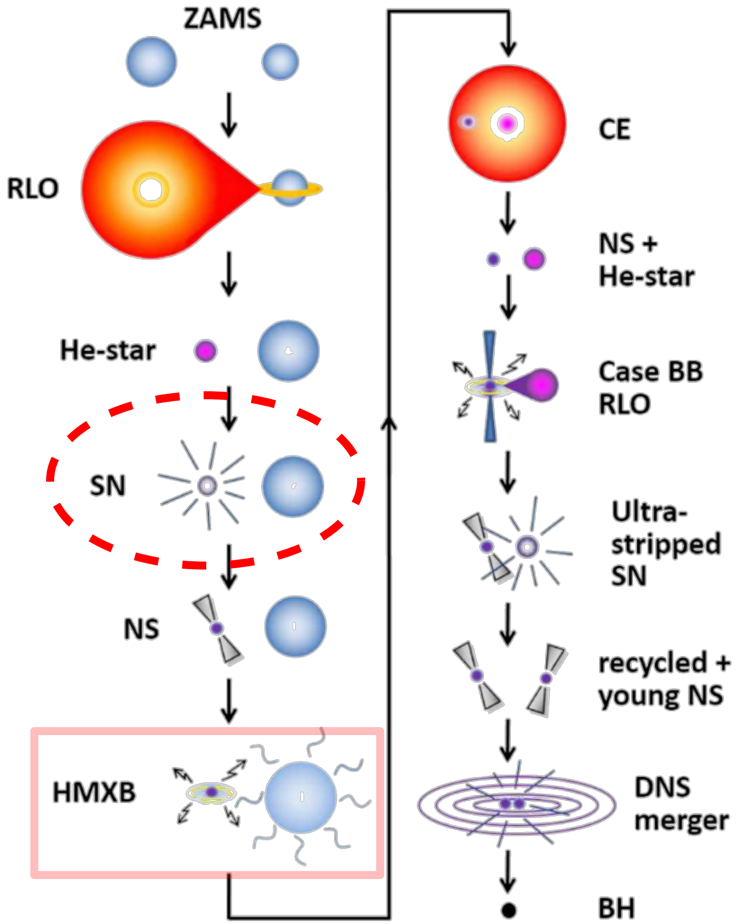
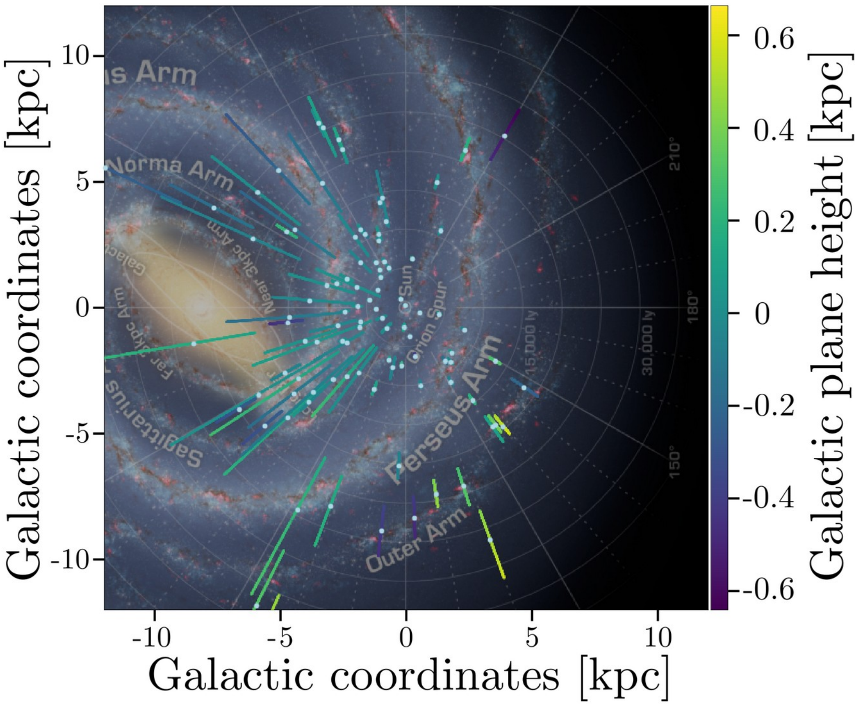


Pre-requisites

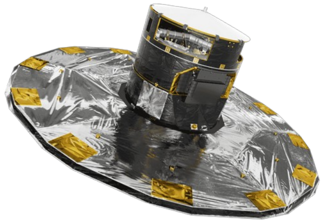
i) Have a catalogue of HMXBs (done !)

ii) Compute their peculiar velocity



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

Peculiar Velocity = Velocity – Galactic orbital motion



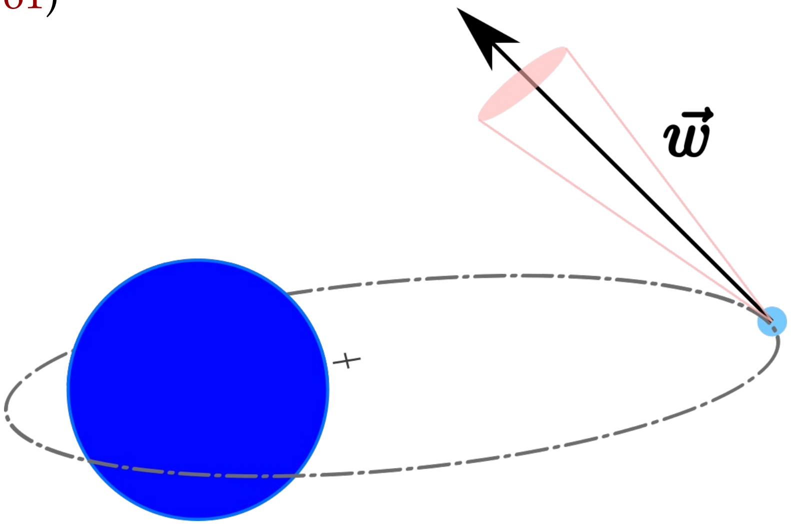
Gaia: astrometric optical survey

→ sky position + distance + proper motion

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 Dosopoulou & Kalogera 2016
- fixed NS mass @ 1.4M_{Sun} Kiziltan+2013
- companion is unaffected by the supernova Liu+2015

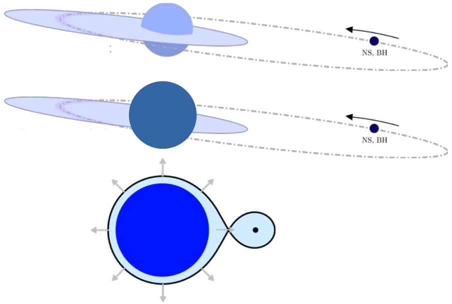
Results on kick distributions

Inferred kick magnitudes on 35 HMXB :

17 Be

8 Oe

10 Sg

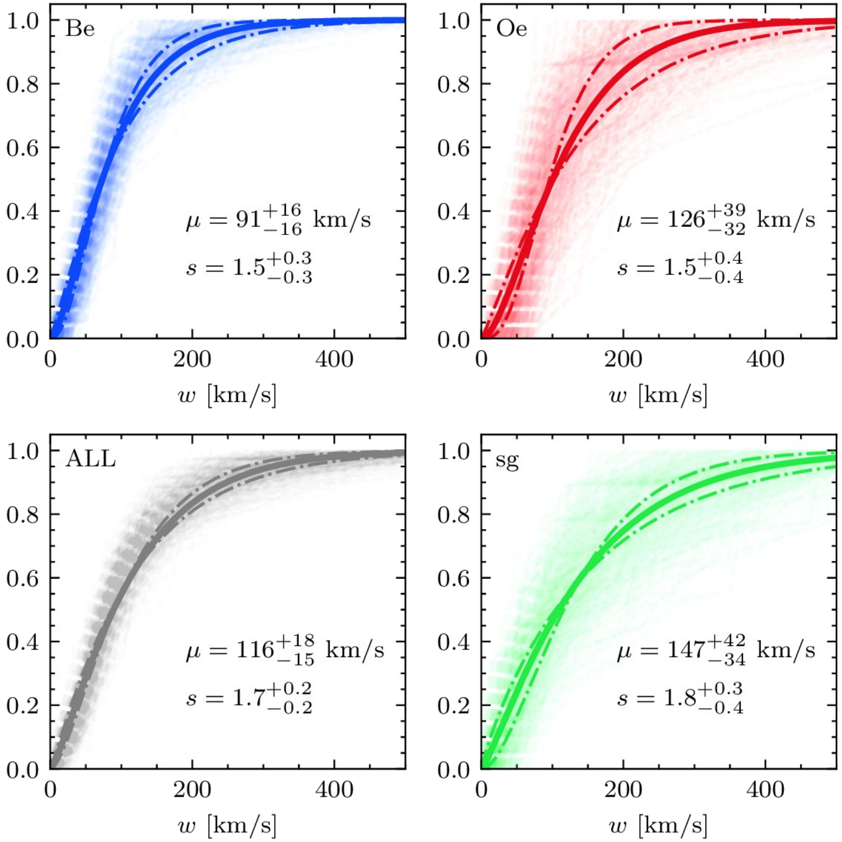


Kick magnitude + pre-SN mass + disrupted fraction

Low natal kicks: stripped SN events

→ useful for population synthesis models ?

Cumulative distributions of kicks



Observing the history of binary star systems

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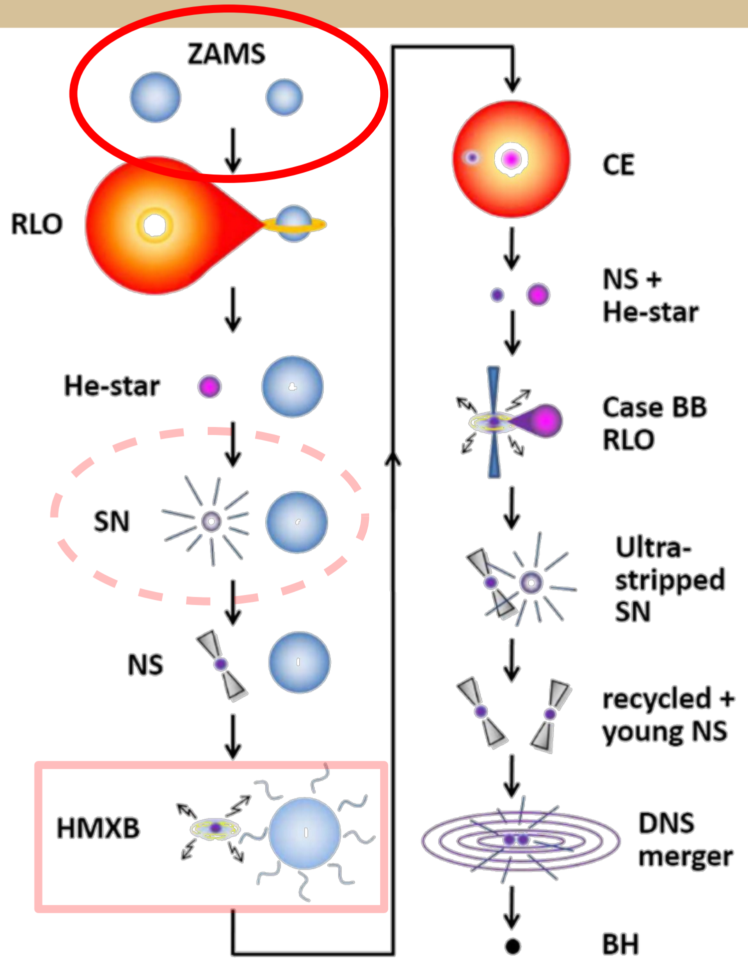
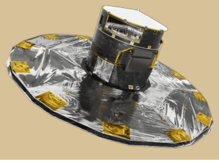


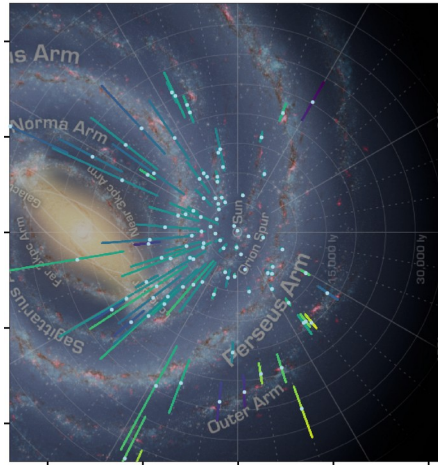
Astrometry from Gaia EDR3



High-Mass X-ray Binaries

Fortin+2022b,2023

- 94 confirmed in Milky Way
- 80 observed by Gaia
- **26 with full 6-D astrometry**

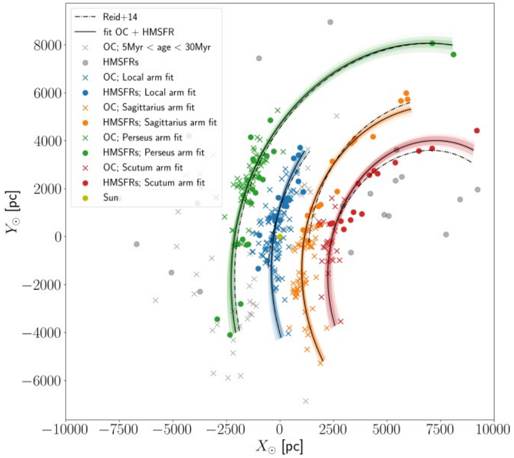


Galactic spiral arms

Castro-Ginard+2021

- Local, Sagittarius, Perseus, Scutum
- shape + motion

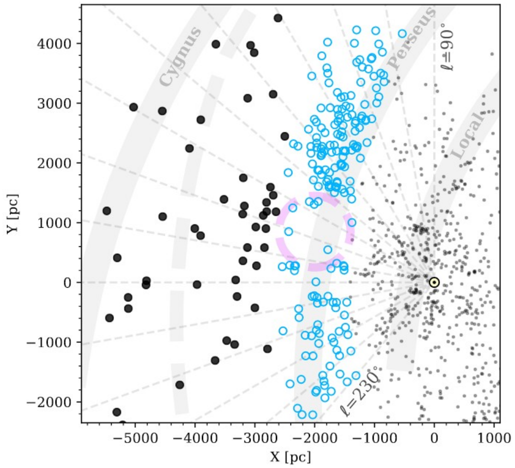
$$\ln \frac{R_G}{R_{G,ref}} = -(\theta_G - \theta_{G,ref}) \tan \psi$$



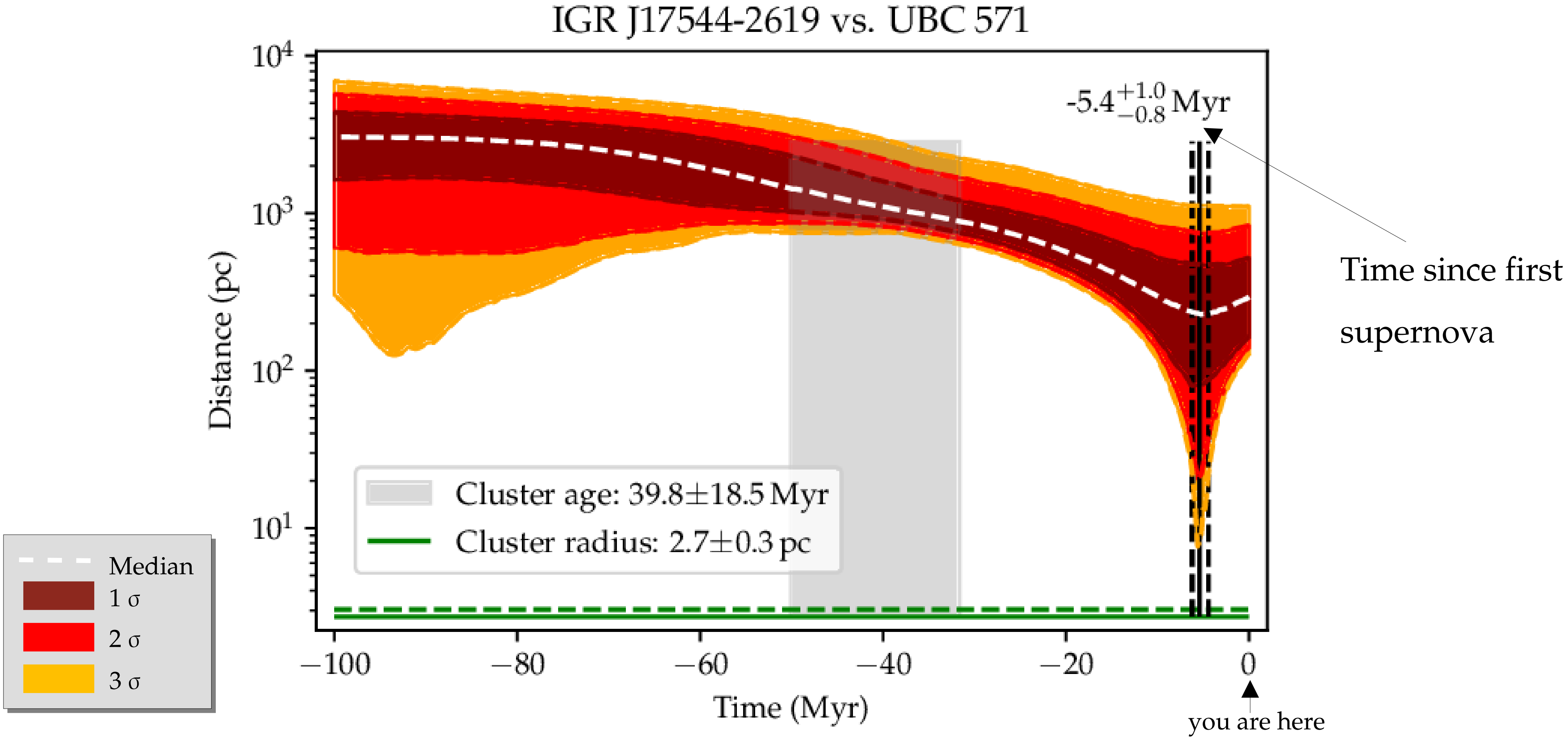
Open stellar clusters

Cantat-Gaudin+2020

- 2017 within ~5kpc
- age from HR isochrone fitting
- **1381 with full 6-D astrometry**



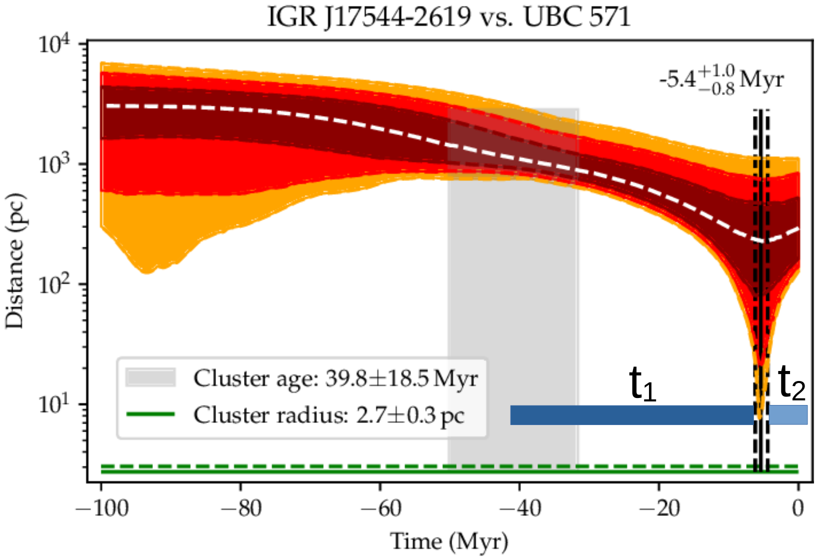
Encounter detection: time-distance histograms



Actual results : ZAMS masses, and more

Mass – Age relation for massive stars (10 – 60 M⊙) : $\frac{M}{M\odot} = \left[10^{-4}\left(\frac{t_{ZAMS}}{Myr}\right)\right]^{\frac{1}{1-\alpha}}$; $\alpha = 3.125$ (Figueiredo+1991)

Cluster encounters give primary star lifetime (**t_1**) and age since supernova (**t_2**) :



$t_1 \rightarrow M_{1,i} = 14.4$ +/- 0.2 M⊙ — Primary ZAMS mass

$t_1 + t_2 \rightarrow M_{2,i} \leqslant 13.5$ +/- 1.8 M⊙ — Secondary ZAMS mass (upper limit)

$M_{2,f} = 23$ M⊙ $\rightarrow M_{acc} \geqslant 9.5$ M⊙ — Initial mass transfer (lower limit)

$M_{1,\,pre\text{-}SN} \leqslant 4.9$ M⊙ — Pre-supernova mass (upper limit)

→ Binary evolution through kinematics

Conclusion & Prospects

- X-ray binaries are challenging to observe

→ the latest catalogue updates the INTEGRAL – Gaia era

- We can observe their past using current optical/IR facilities

→ constraining impact of first supernova

→ date & place of birth : binary evolution history

- Gaia : astrophysical parameters, upcoming releases 4 & 5
- Gravitational waves: probing the future of X-ray binaries

LIGO/Virgo/KAGRA O4 started on May 24th for 18 months,

hopefully lots of neutron star merger events like 17/08/2017

Attendance reward

Ringed teal, Orsay (FR)

Disrupted systems, isolated NS velocities

Tauris & Takens 1998 : equations for velocity of a NS kicked-out of the binary after the SN event

Observed velocity distribution of isolated radio pulsars :

Hobbs+2005 → **265 km/s**

Igoshev 2020 → **230 km/s** (or 146 + 317 km/s)

We keep track of disrupted systems (5 to 50% of simulation outcomes depending on the binary)

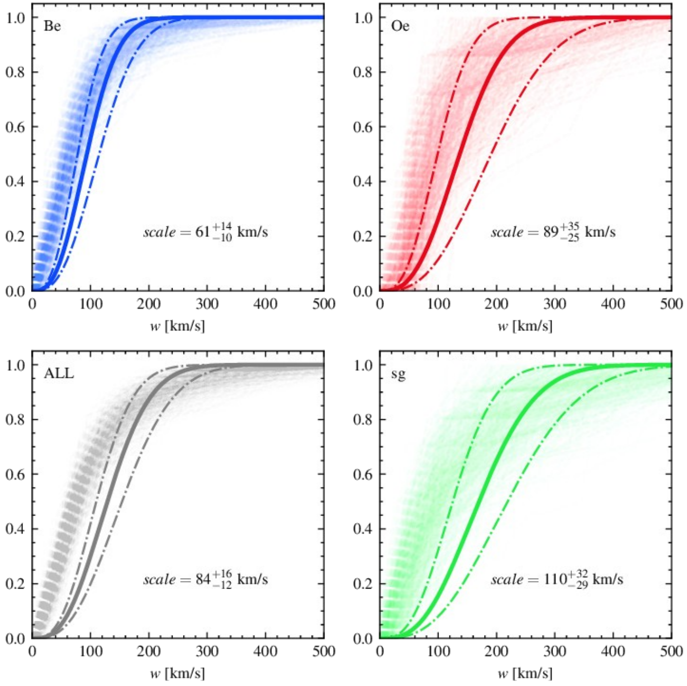
→ NS velocity from disrupted systems in our sample : **110 km/s**

→ In case of disruption, < 3% result in fast pulsars (> 500 km/s, large initial period > 1000 d required)

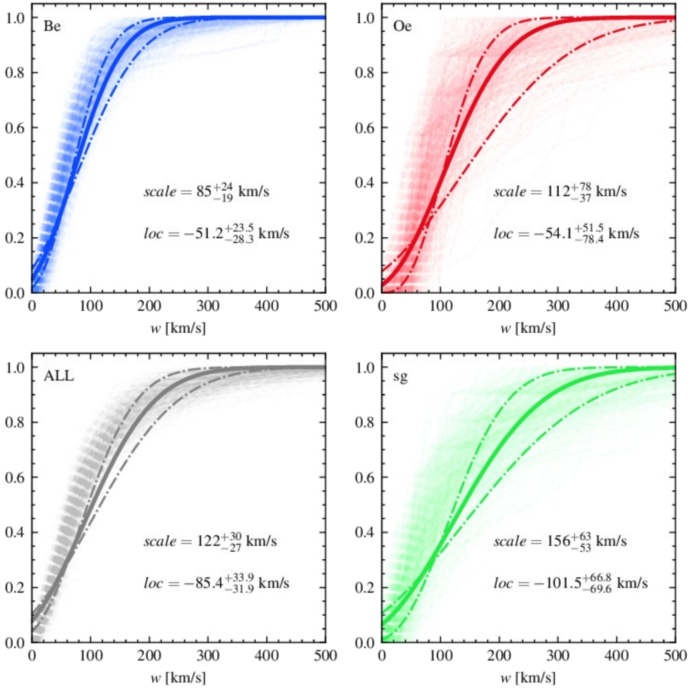
→ Binary evolution unlikely to be a formation channel for fast isolated NS.

Extra: Maxwellian vs. Gamma

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



Classical Maxwellian



Shifted Maxwellian

Unbound systems ?

→ observed vs. pop synth.

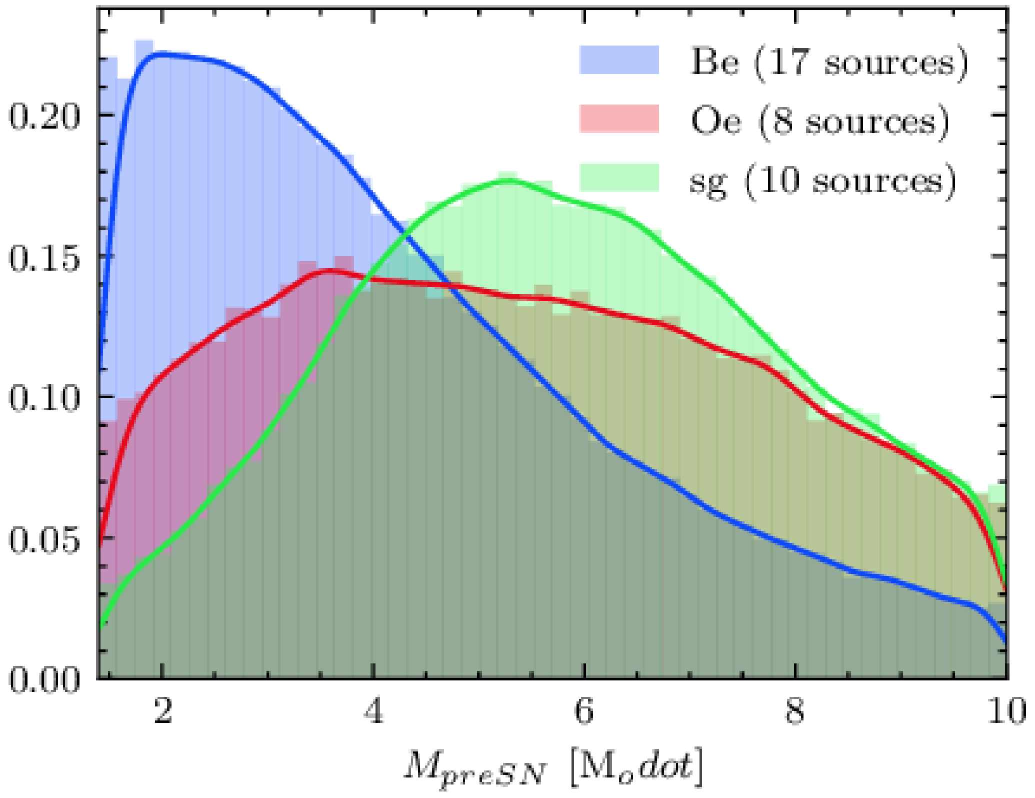
Stripped progenitors ?

→ lower pre-SN mass

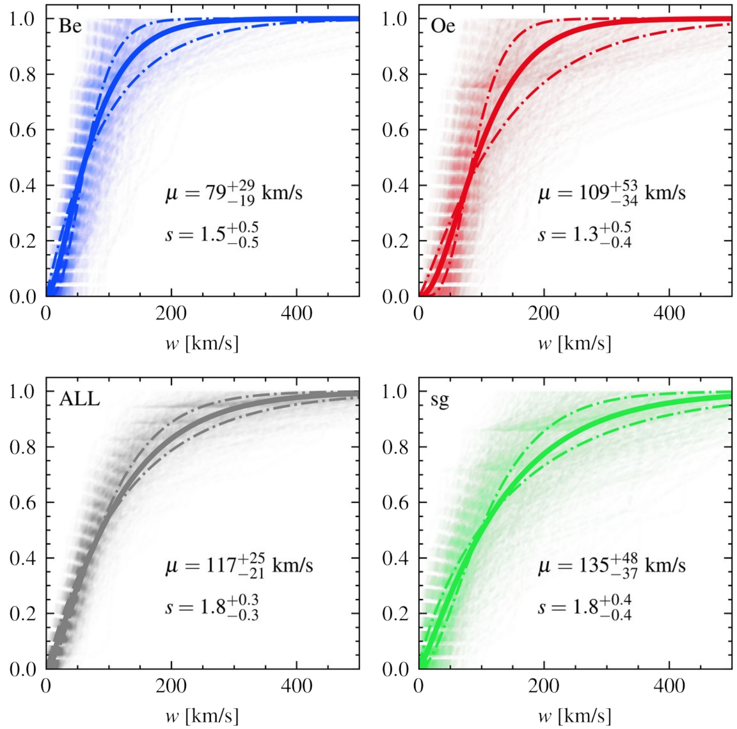
Kick isotropy ?

→ NS spin axis

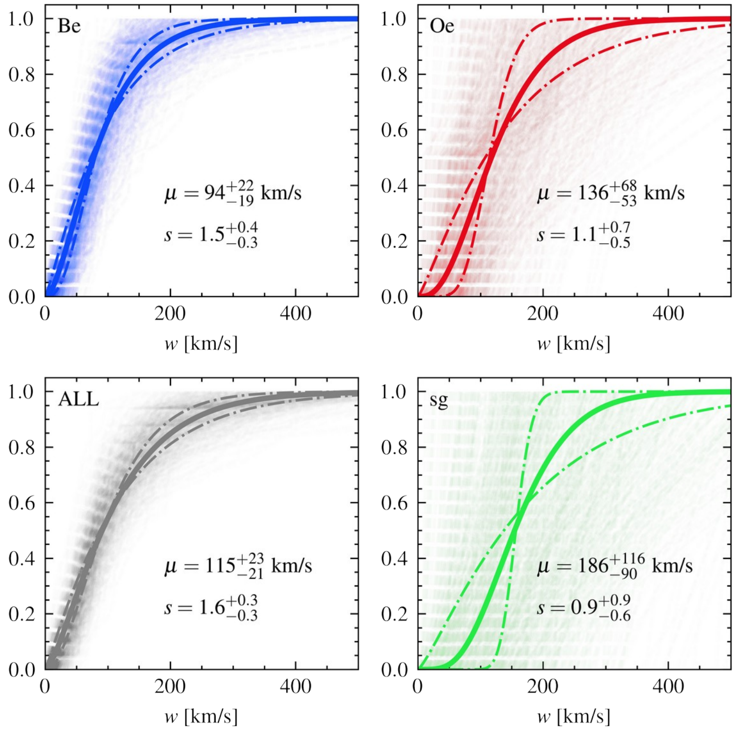
Extra: M_{pre-SN} distribution



Extra: impact of missing radial velocity



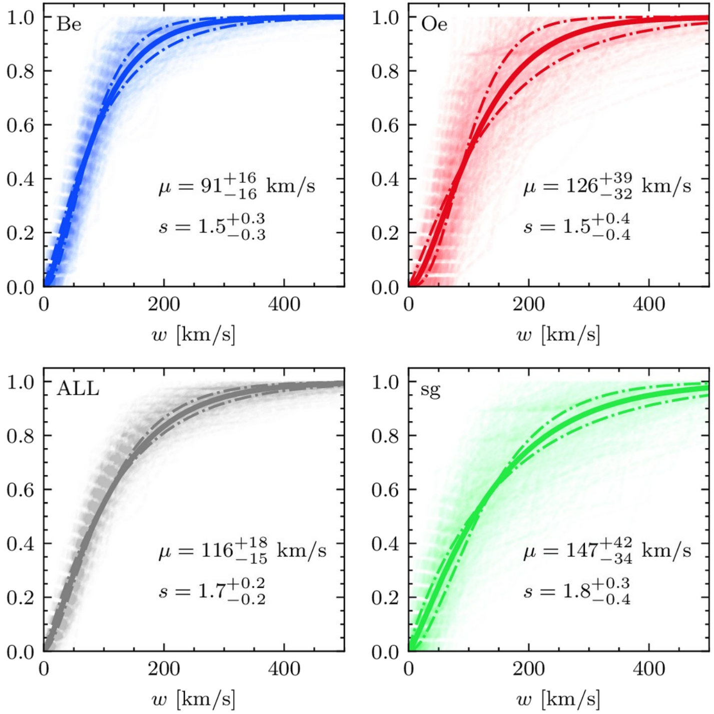
With RV only



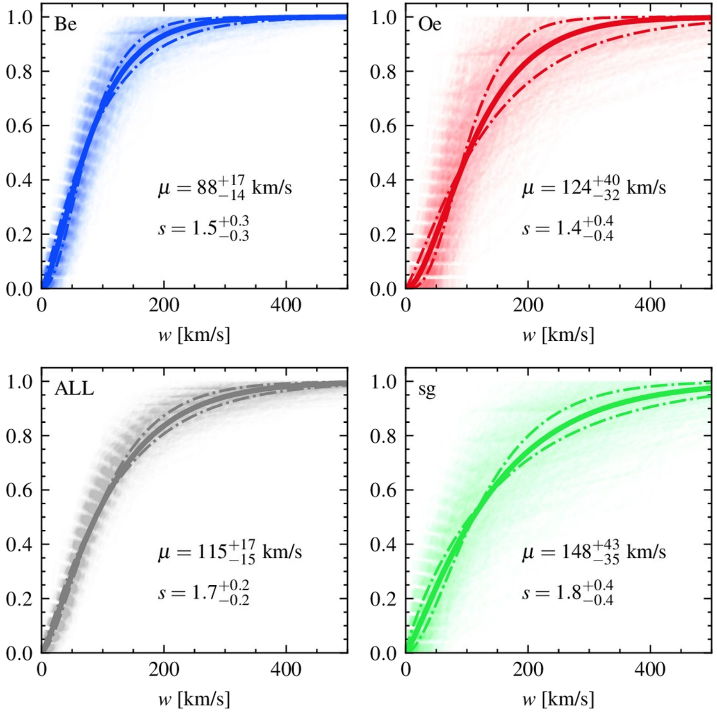
Without RV only

Extra: impact of neutron star mass

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



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



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

No notable difference on the fitted parameters

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

Extra: building the list of HMXBs

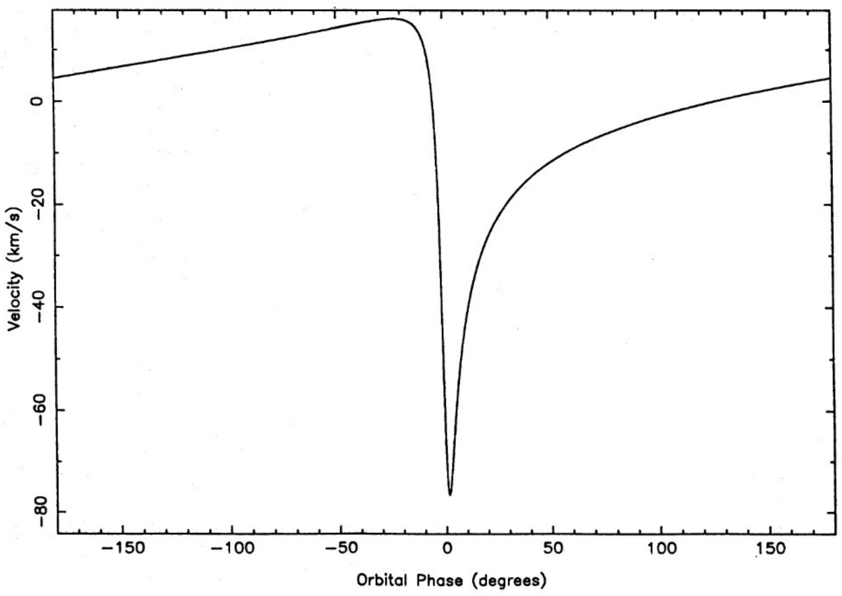
Example: PSR B1259-63

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.



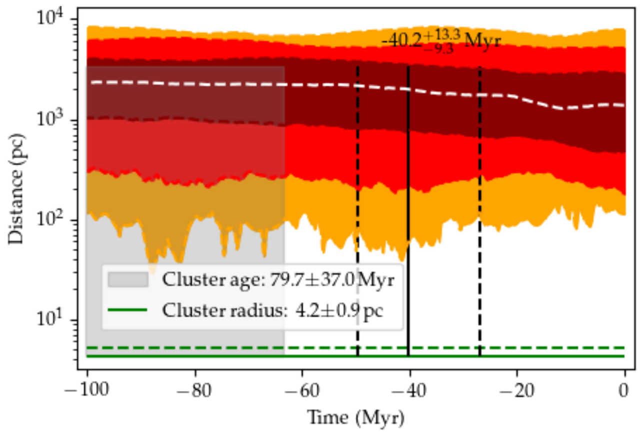
Radial velocity of PSR B1259-63 (Johnston+1994)

Encounter detection : validity of the method

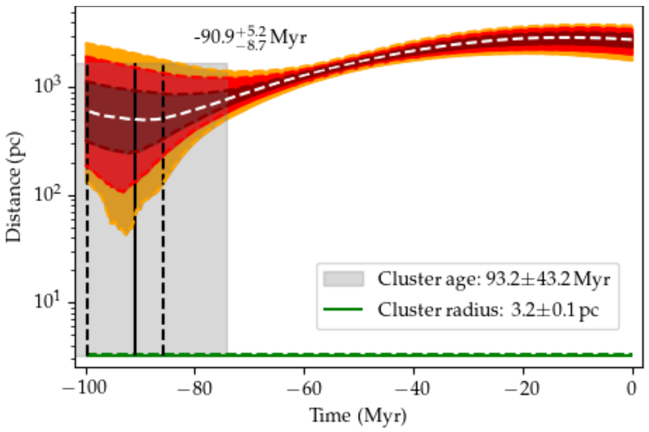
→ Simulations over randomly generated HMXBs and clusters to test the ability to find a birthplace

- chose a random birth date in [1 : 100] Myr
- initialize a birth cluster at a random position + velocity
- initialize HMXB born somewhere near the cluster
- apply random natal kick to HMXB
- integrate both orbits up until today
- generate dummy Gaia astrometry for HMXB & cluster of random quality (according to real data)
- look for an encounter

Encounter detection : validity of the method

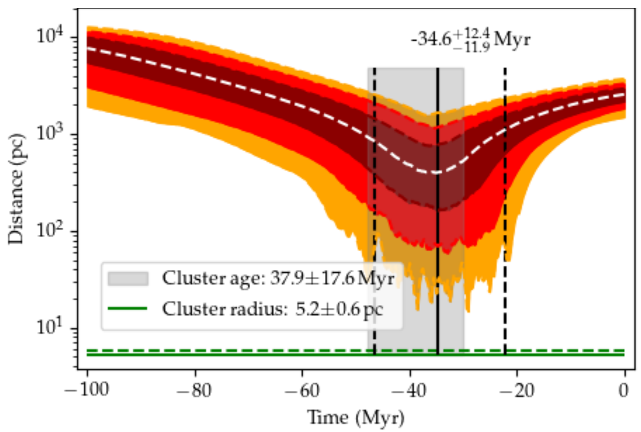


← Bad astrometry : 10% failed cases



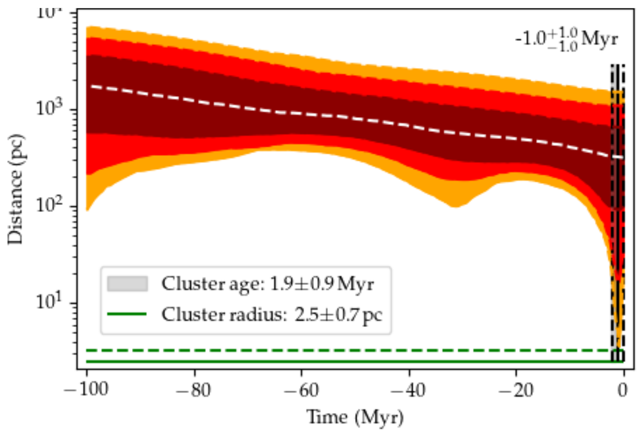
Good astrometry →

retrieve old encounters



produce both sharp →

← and wide distributions



Galactic distribution of Gaia clusters & HMXBs

- Gaia parallax → distances $\lesssim$ 5kpc

→ drastic decrease in known clusters with distance