Variable Galactic Gamma-Ray Sources V

Barcelona, 4-6 September 2019

Searching for new gamma-ray binaries using Gaia DR2

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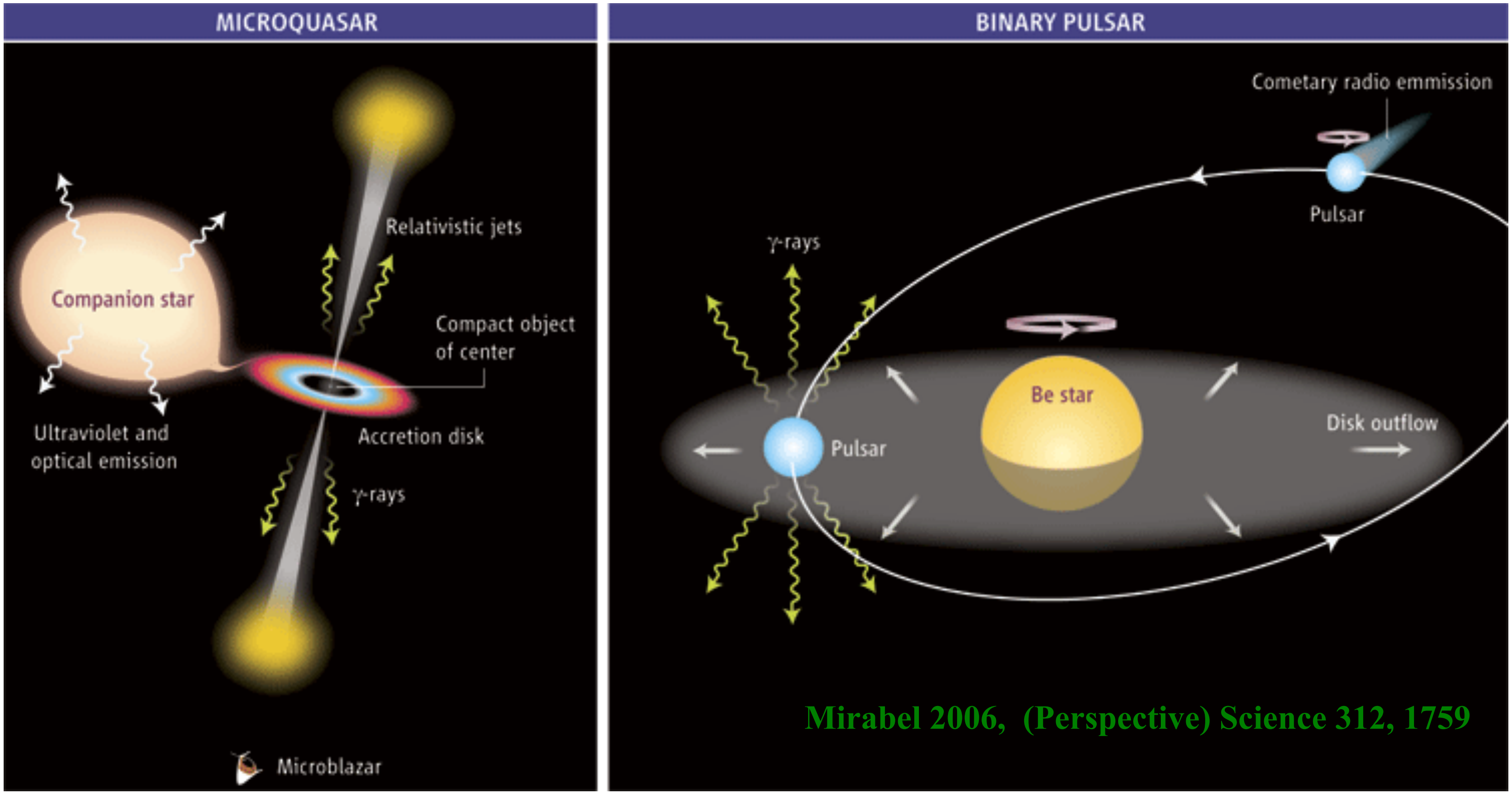
EXCELENCIA MARÍA DE MAEZTU

IEEC

OUTLINE

1. Introduction
2. Gaia DR2 and gamma-ray binaries
3. The GOSC and BeSS catalogs
4. The search for new gamma-ray binaries
5. Conclusions

Binary systems. X-ray binaries (microquasars) vs. gamma-ray binaries.



Cygnus X-3, Cygnus X-1

LS 5039 ?
LS I +61 303 ?
HESS J0632+057 ?
1FGL J1018.6−5856 ?
4FGL J1405.1-6119 ?
LMC P3 ?

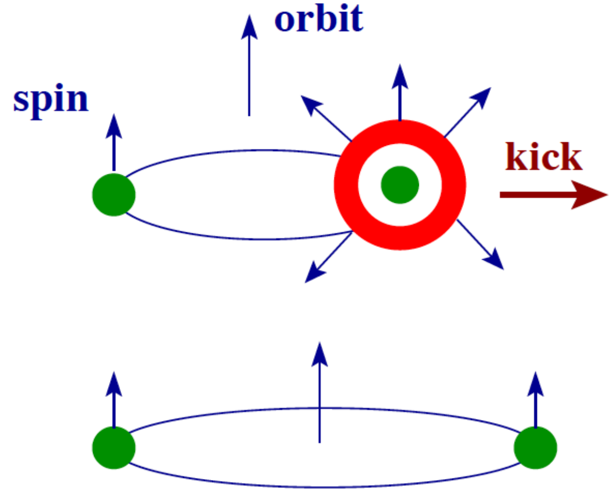
PSR B1259−63
PSR J2032+4127

Kicks during SN explosion (from Podsiadlowski).

Kicks and Binary Orbits

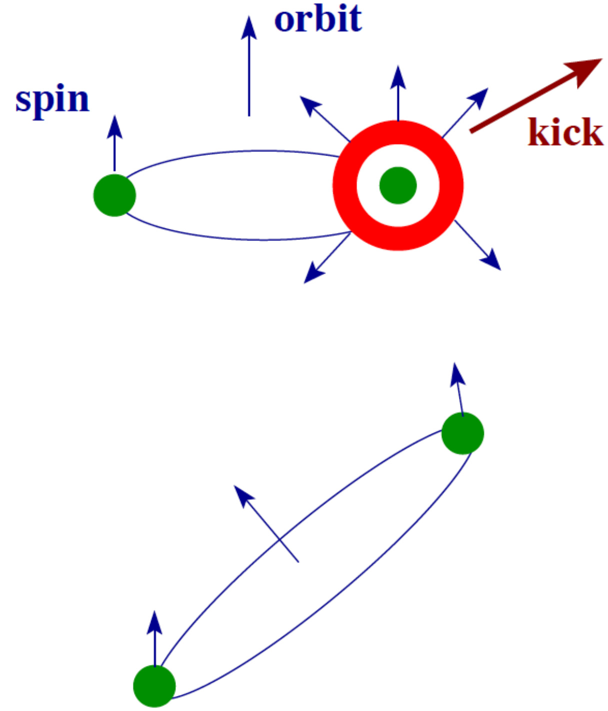
Blaauw Kick

- only due to supernova mass loss



- orbit increases
- spin + orbit remain aligned
- disruption if more than half the mass is lost

Asymmetric Explosion



- orbit increases or decreases
- spin/orbit misalignment (retrograde orbits possible)
- system can remain bound that could not otherwise

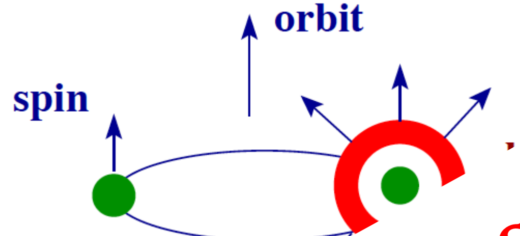
Note: if kick along spin axis → retrograde orbits impossible

Kicks during SN explosion (from Podsiadlowski).

Kicks and Binary Orbits

Blaauw Kick

- only due to supernova mass loss



- orbi
- spin ¬ remain aligned
- disruption if more than half the mass is lost

Asymmetric Explosion

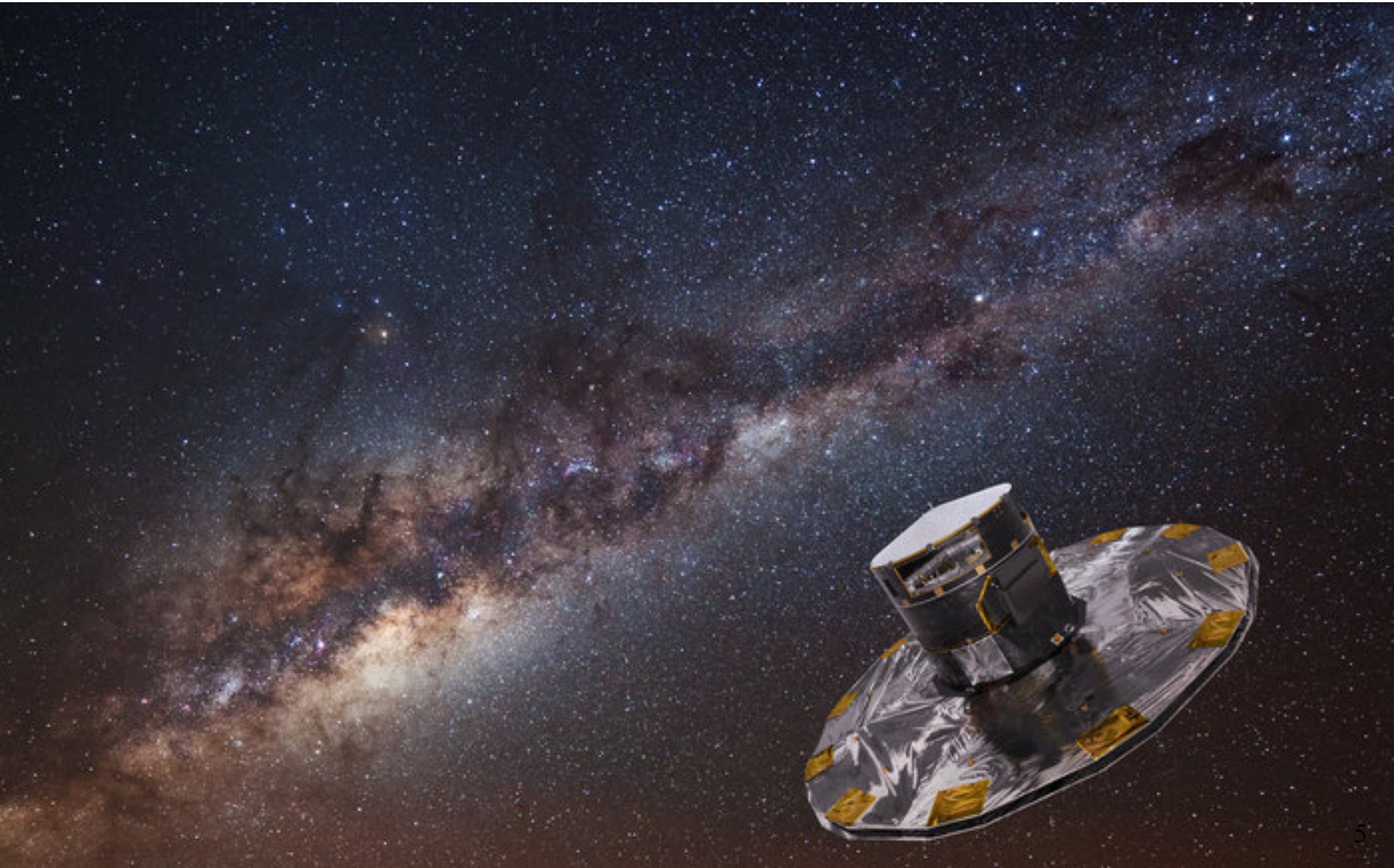
- orbit increases or decreases
- spin/orbit misalignment (retrograde orbits possible)
- system can remain bound that could not otherwise

Note: if kick along spin axis → retrograde orbits impossible

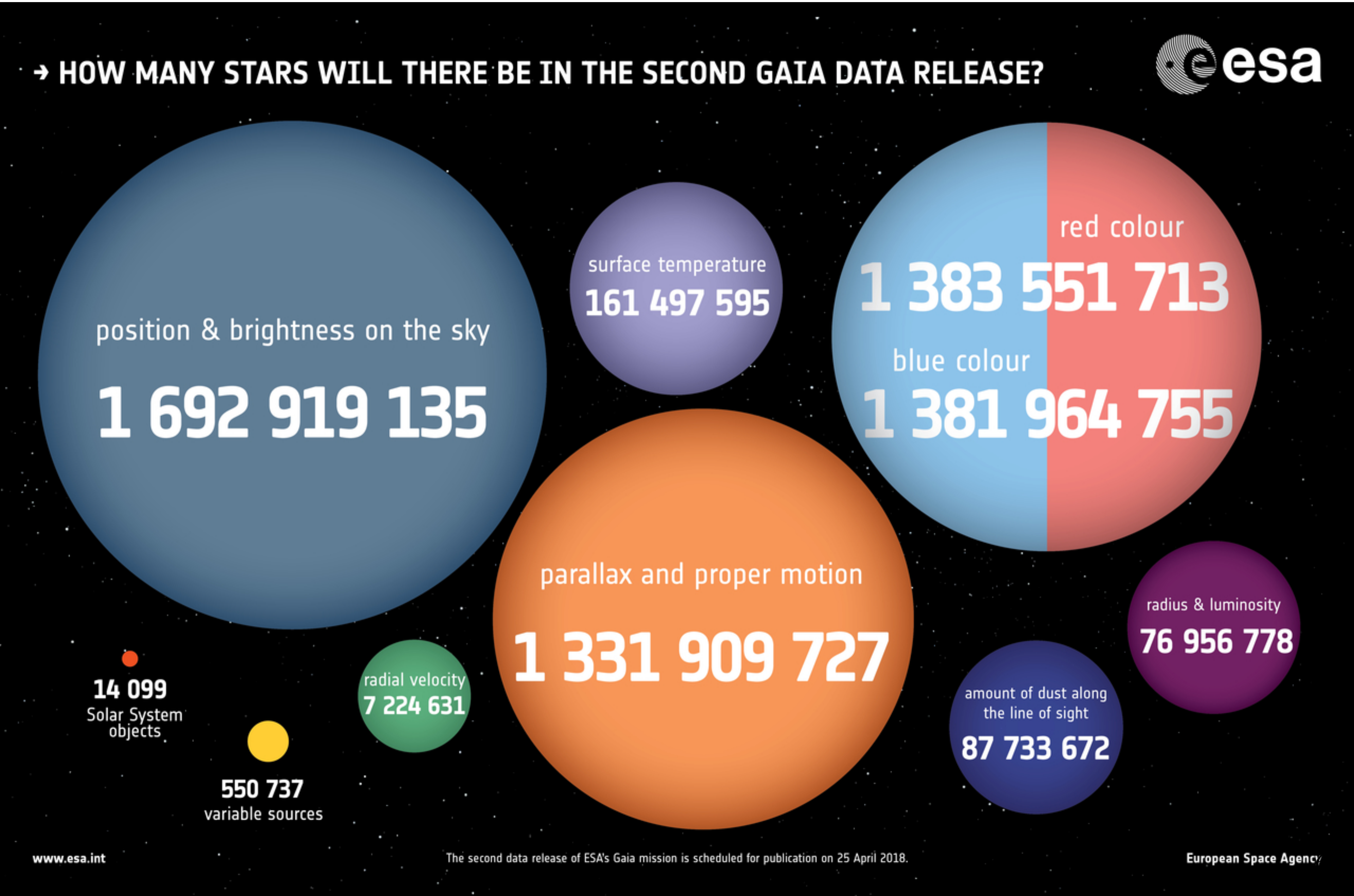
Some massive runaway stars might be in gamma-ray binaries

Gaia DR2.

2nd Data Release of the astrometric mission Gaia.

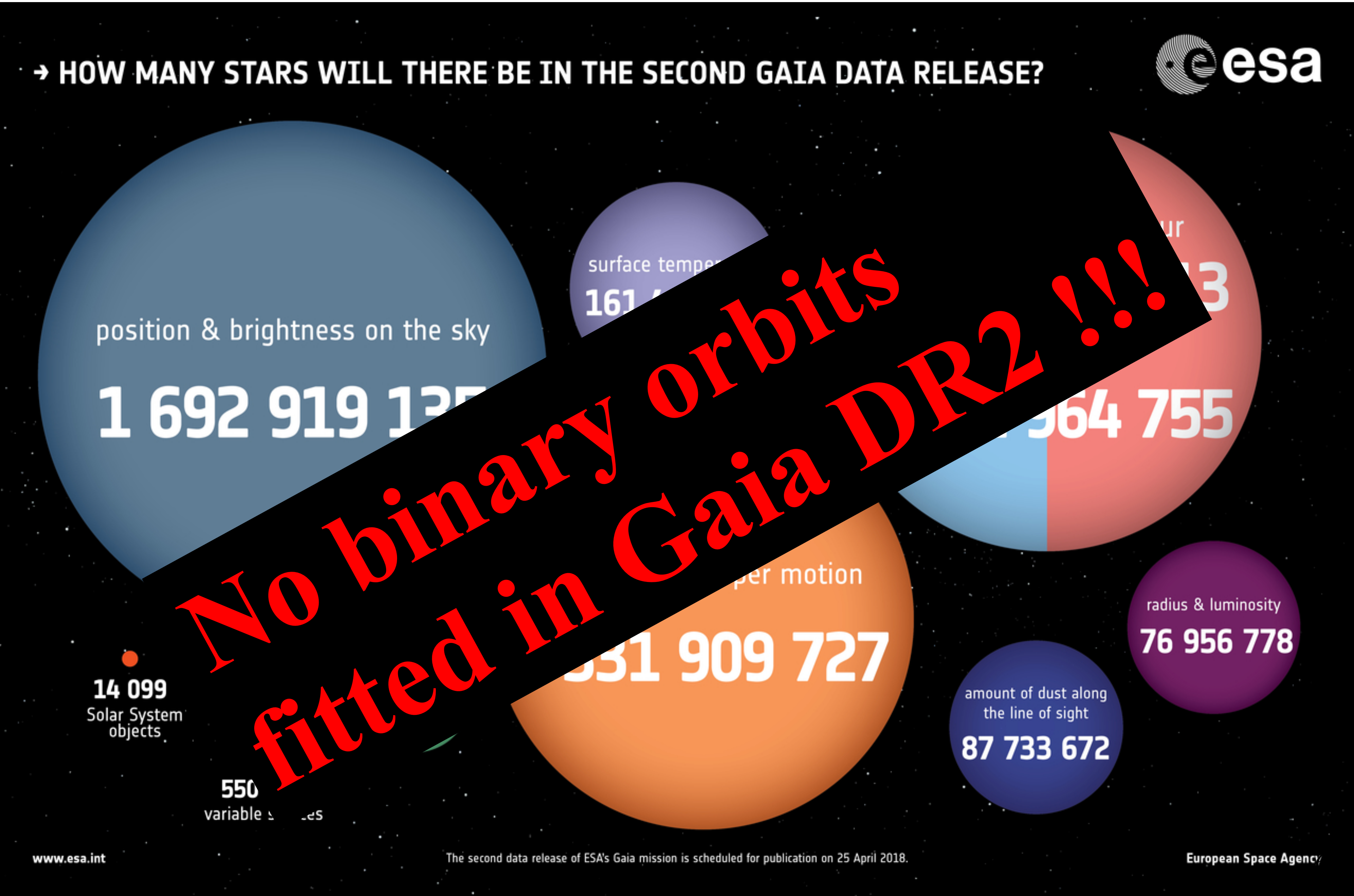


Gaia DR2.



→ HOW MANY STARS WILL THERE BE IN THE SECOND GAIA DATA RELEASE?
esa
position & brightness on the sky
1 692 919 135
surface temperature
161 497 595
red colour
1 383 551 713
blue colour
1 381 964 755
parallax and proper motion
1 331 909 727
radius & luminosity
76 956 778
amount of dust along the line of sight
87 733 672
radial velocity
7 224 631
14 099
Solar System objects
550 737
variable sources
www.esa.int
The second data release of ESA's Gaia mission is scheduled for publication on 25 April 2018.
European Space Agency

Gaia DR2.



No binary orbits fitted in Gaia DR2 !!!

Gaia DR2.

Astrometric indicators:

$\chi^2 = \texttt{astrometric\_chi2\_al}$

$N = \texttt{astrometric\_n\_good\_obs\_al}$

$G = \texttt{phot\_g\_mean\_mag}$

$C = \texttt{bp\_rp}$ (if available)

$\nu = N - 5$

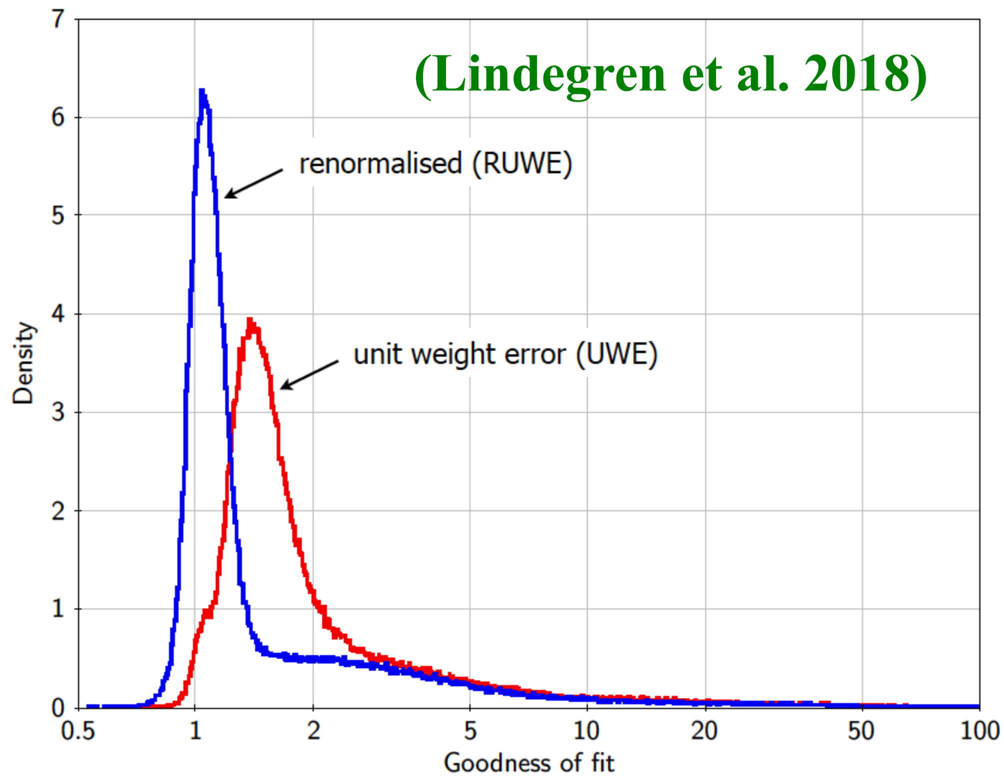
- Goodness of the fit (GOF):

$$\texttt{astrometric\_gof\_al} = \left(\frac{9\nu}{2}\right)^{1/2}\left[\left(\frac{\chi^2}{\nu}\right)^{1/3} + \frac{2}{9\nu} - 1\right]$$

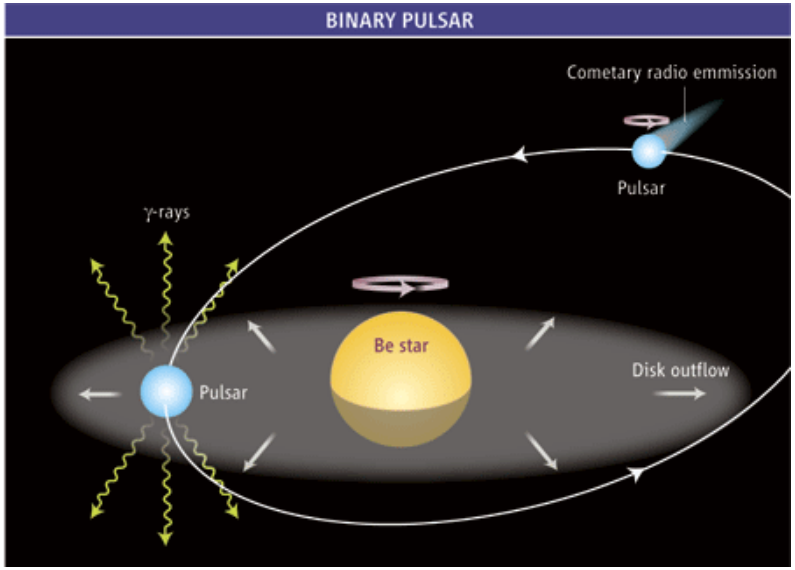
- Unit Weight Error (UWE):

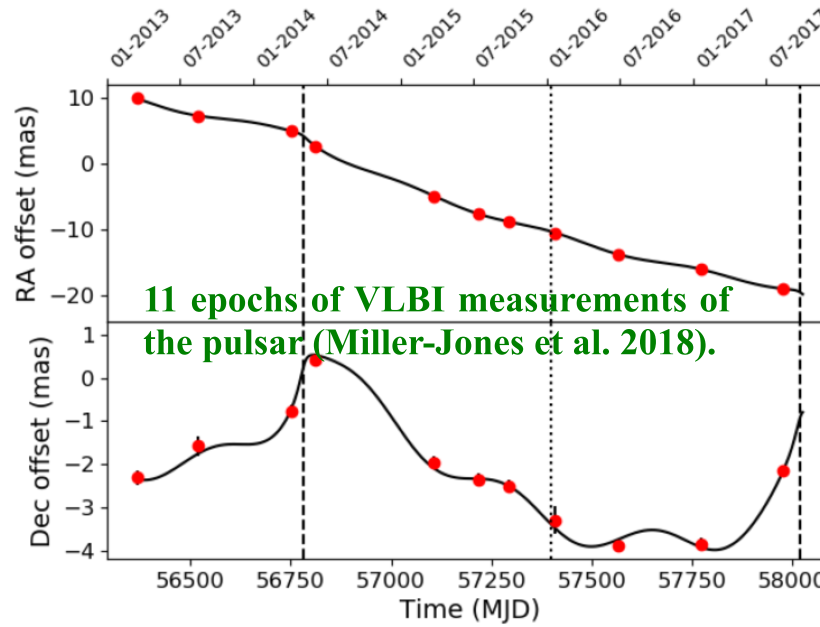
$$\mathrm{UWE} = \sqrt{\frac{\chi^2}{N-5}}$$

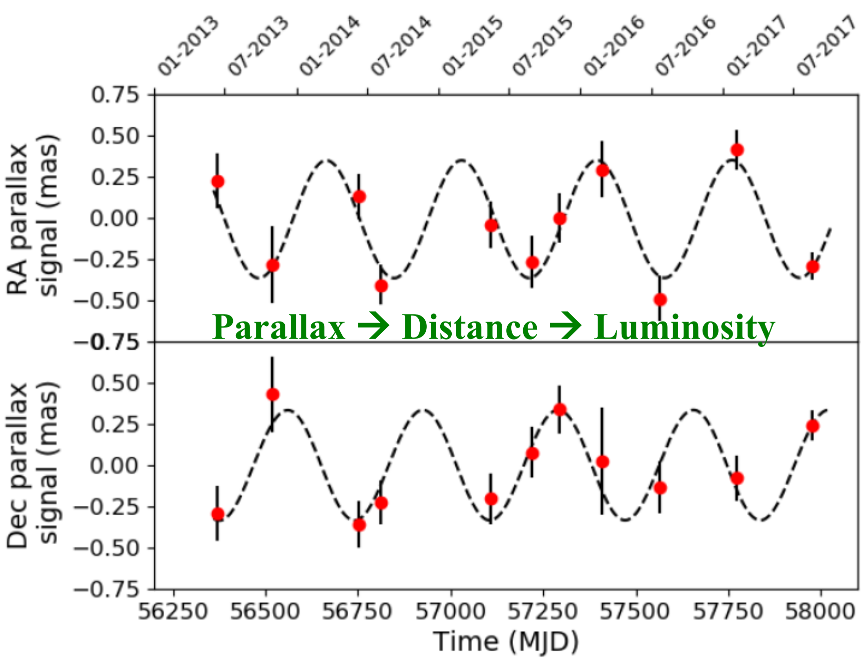
- Renormalized unit weight error RUWE = UWE/$u_0(G, C)$, where $u_0(G, C)$ is an empirical correction factor

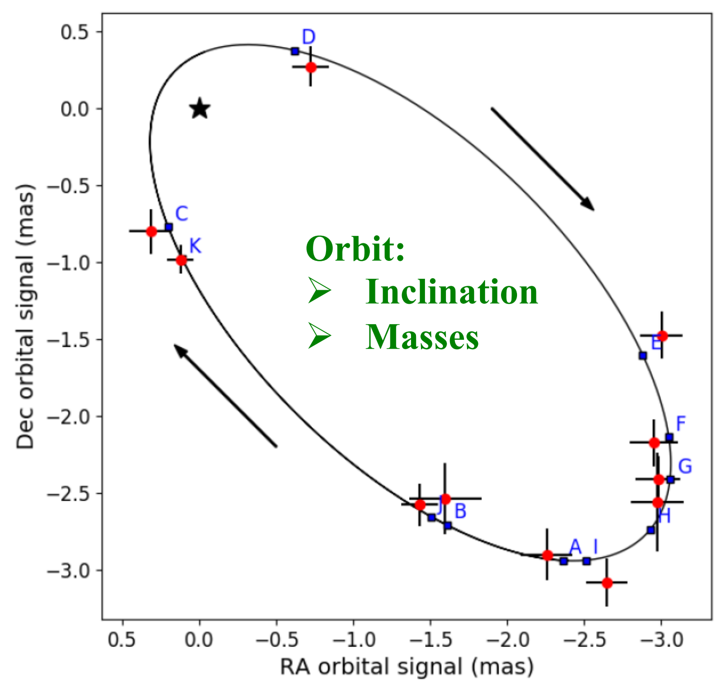


Gaia DR2 results on gamma-ray binaries. PSR B1259-63 (Miller-Jones et al. 2018).



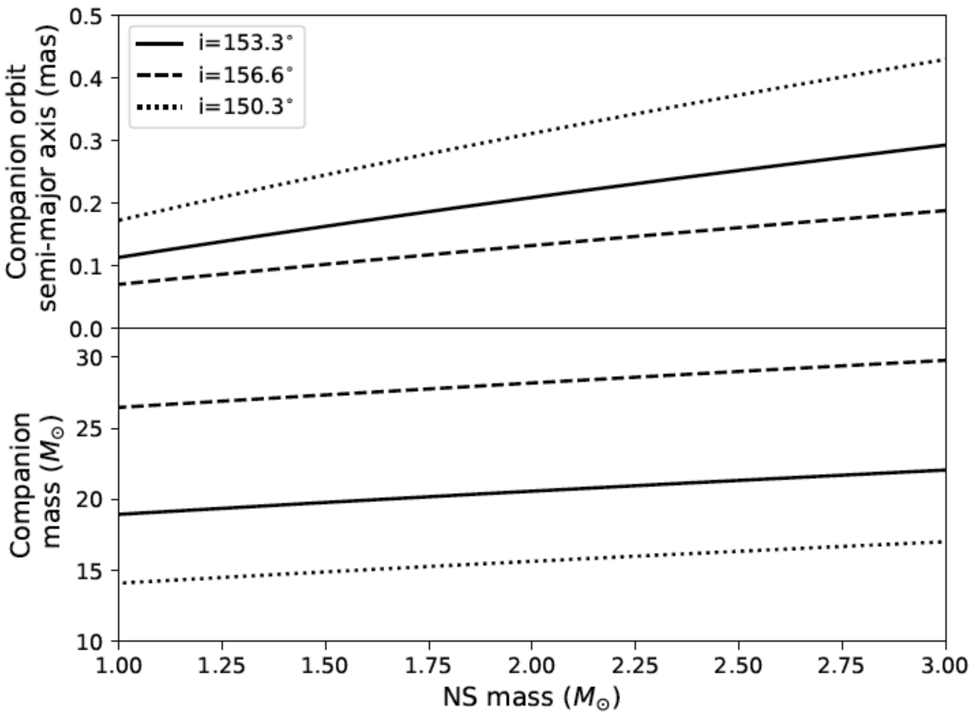


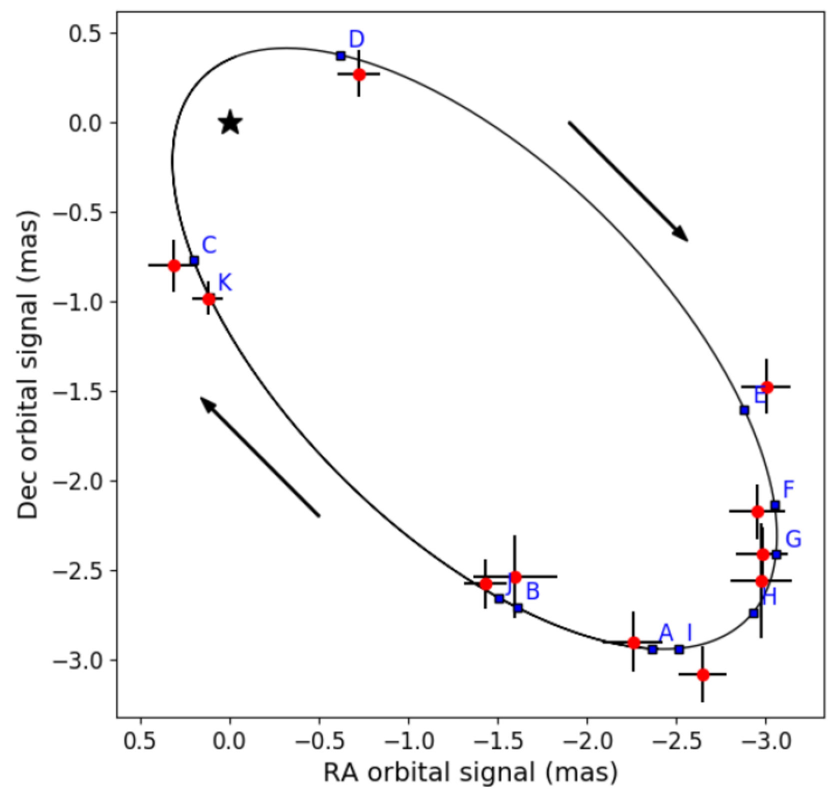




	Parameter	Symbol	Value
VLBI	Reference position in R.A. (J2000)	α_0	$13^{\rm h}02^{\rm m}47\overset{\rm s}{.}638337^{\rm s} \pm 0.000012$
	Reference position in Dec. (J2000)	δ_0	$-63°50'8.628585'' \pm 0.000008$
	Proper motion in R.A. (mas yr^{-1})	$\mu_\alpha \cos\delta$	-7.010 ± 0.030
	Proper motion in Dec. (mas yr^{-1})	μ_δ	$-0.532^{+0.033}_{-0.032}$
	Parallax (mas)	π	$0.387^{+0.047}_{-0.049}$
	Inclination angle (°)	i	$153\overset{\circ}{.}3^{+3\overset{\circ}{.}2}_{-3\overset{\circ}{.}0}$
	Longitude of the ascending node (° E of N)	Ω	$189\overset{\circ}{.}2 \pm 1.7$
Pulsar timing	Orbital period (days)	P	1236.724526 ± 0.000006
	Epoch of periastron (MJD)	T_0	$53071.2447290 \pm 0.0000007$
	Eccentricity	e	$0.86987970 \pm 0.00000006$
	Projected semi-major axis (lt-s)	$a \sin i$	1296.27448 ± 0.00014
	Argument of periastron	ω	$138\overset{\circ}{.}665013 \pm 0\overset{\circ}{.}000011$

(Miller-Jones et al. 2018)





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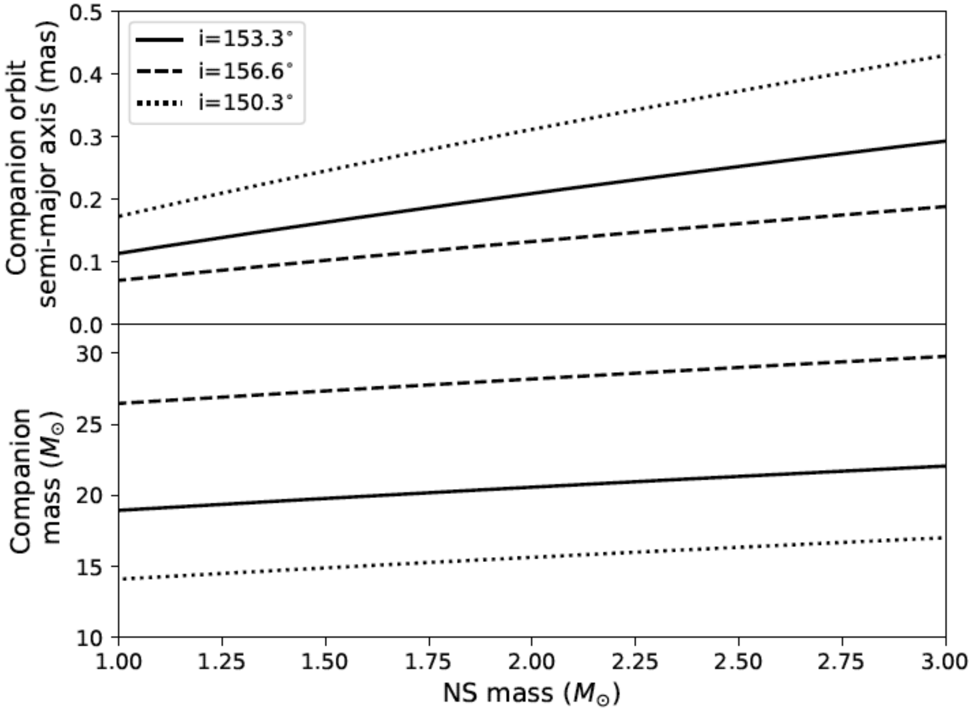

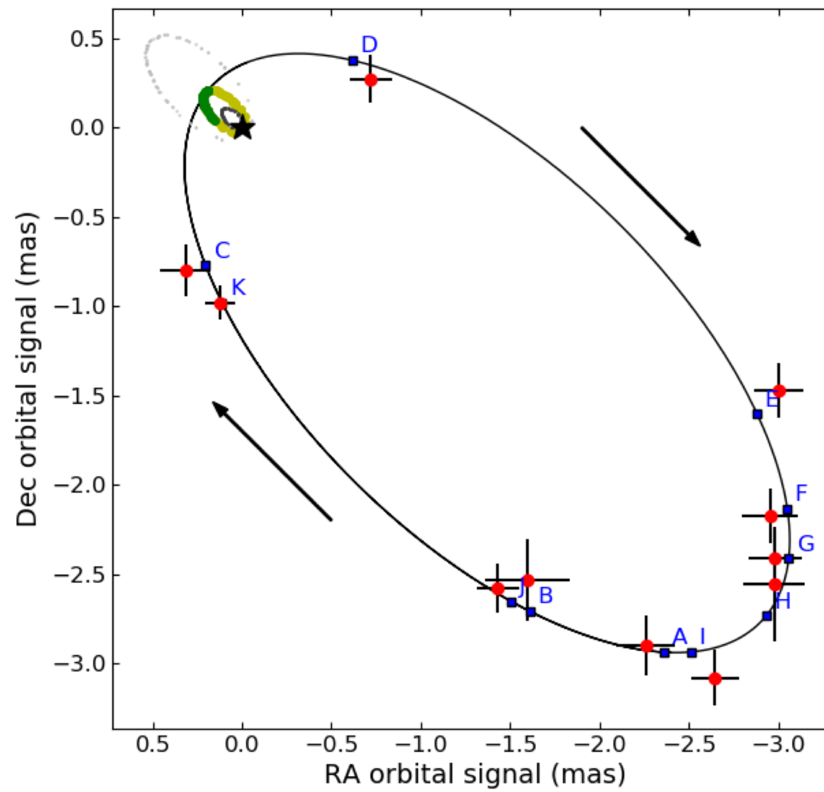

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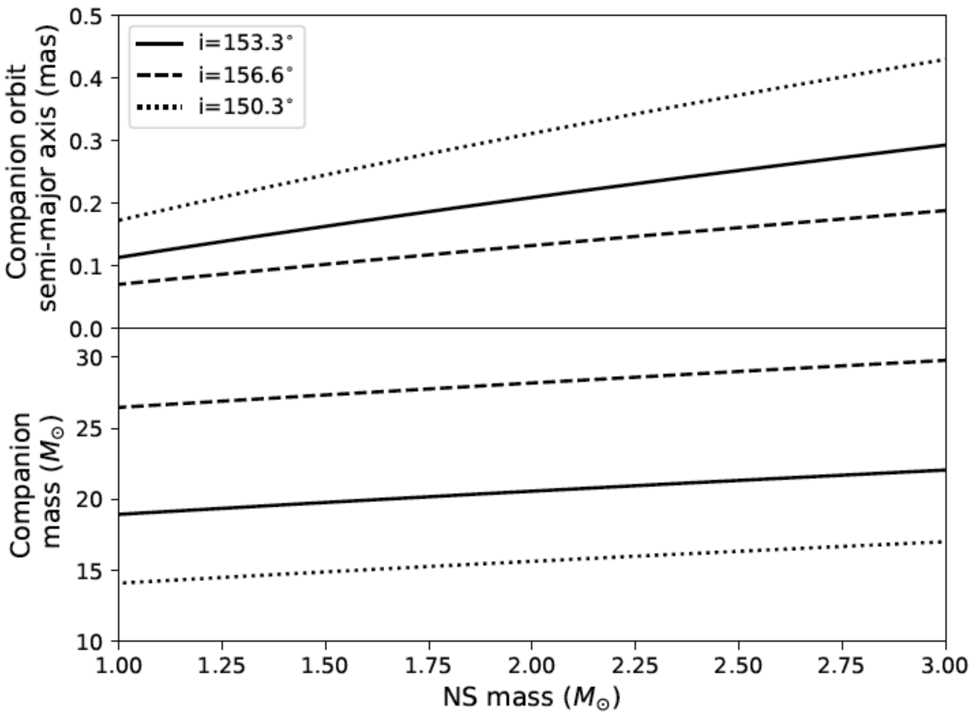
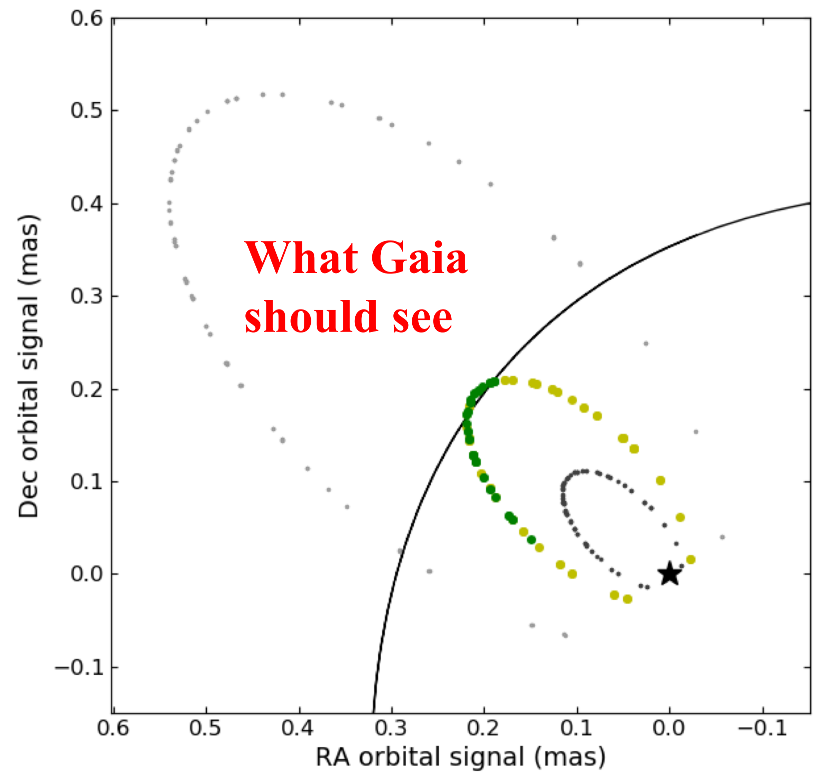
VLBI (reference position through longitude of the ascending node)

Pulsar timing (orbital period through argument of periastron)

Gaia DR2:
-6.986 +/- 0.043 mas/yr
-0.416 +/- 0.044 mas/yr
0.4181+/-0.0308

(Miller-Jones et al. 2018)





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VLBI (rows: reference position through longitude of the ascending node)

Pulsar timing (rows: orbital period through argument of periastron)

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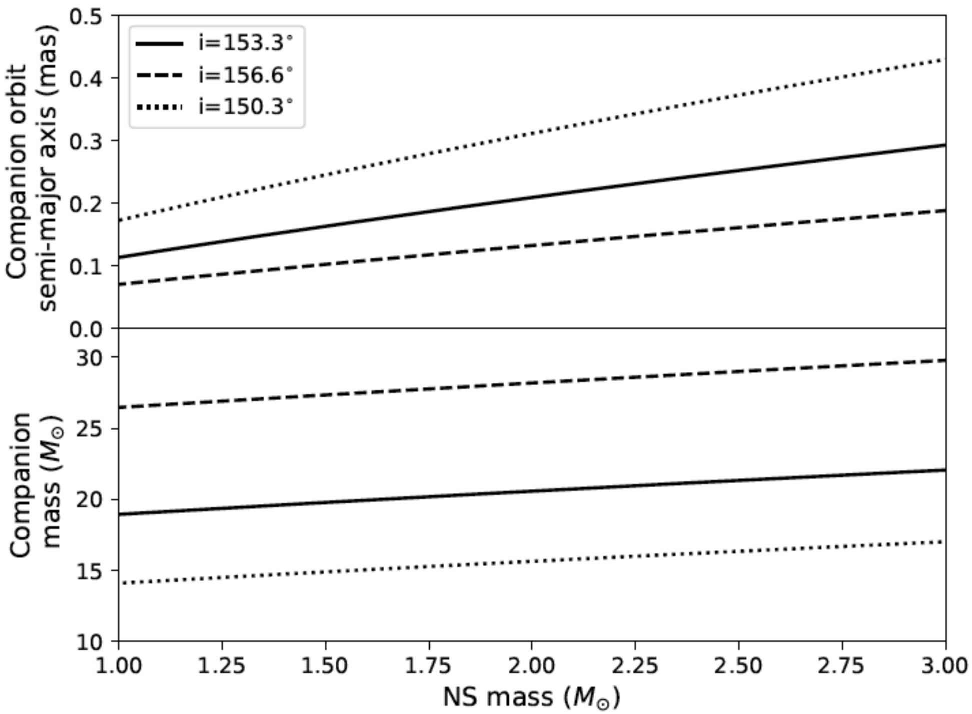
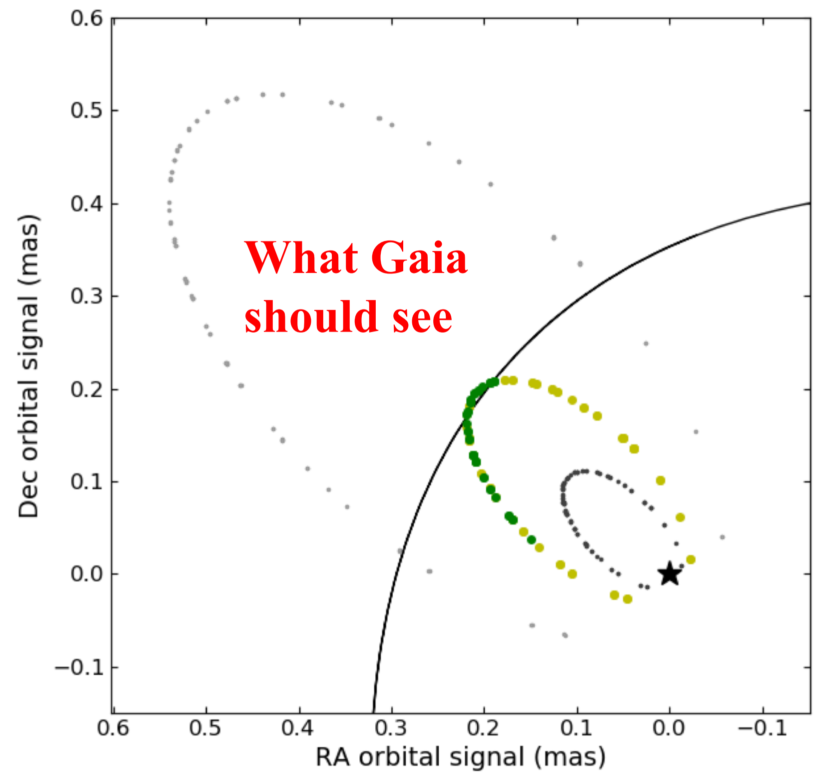
GOF of 8, bad !!

(Miller-Jones et al. 2018)





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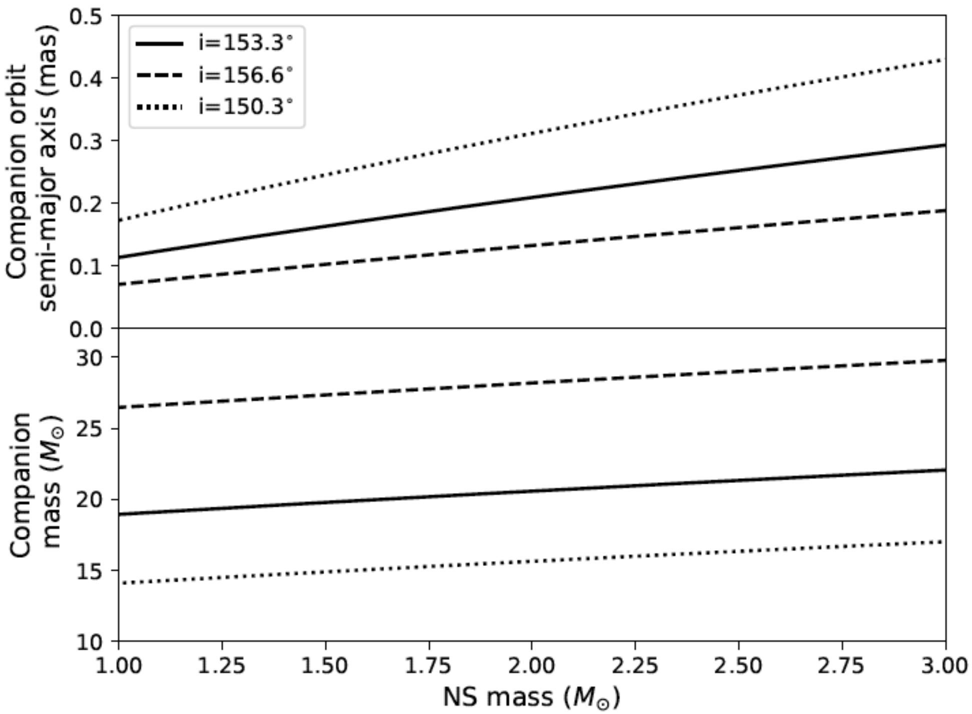
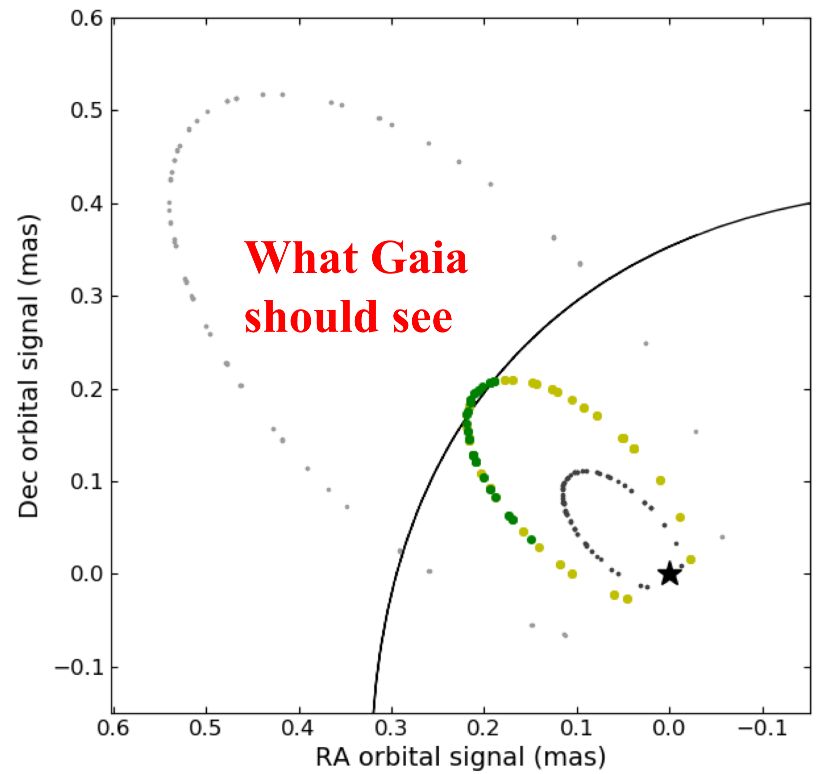
Gaia DR2:
-6.986 +/- 0.043 mas/yr
-0.416 +/- 0.044 mas/yr
Differences in pm:
0.024 +/- 0.052 mas/yr
0.116 +/- 0.055 mas/yr

Measuring a_* allows obtaining NS mass

Potential new targets for CTA, etc.

(Miller-Jones et al. 2018)





GOF, UWE and RUWE for gamma-ray binaries:

Most of the sources had a **bad GOF > 3** → **Promising discriminator** !!

After applying the recommended routines by **Lindegren et al. (2018)**, all of them turned out to have **"normal" values of UWE and RUWE around 1** !!!

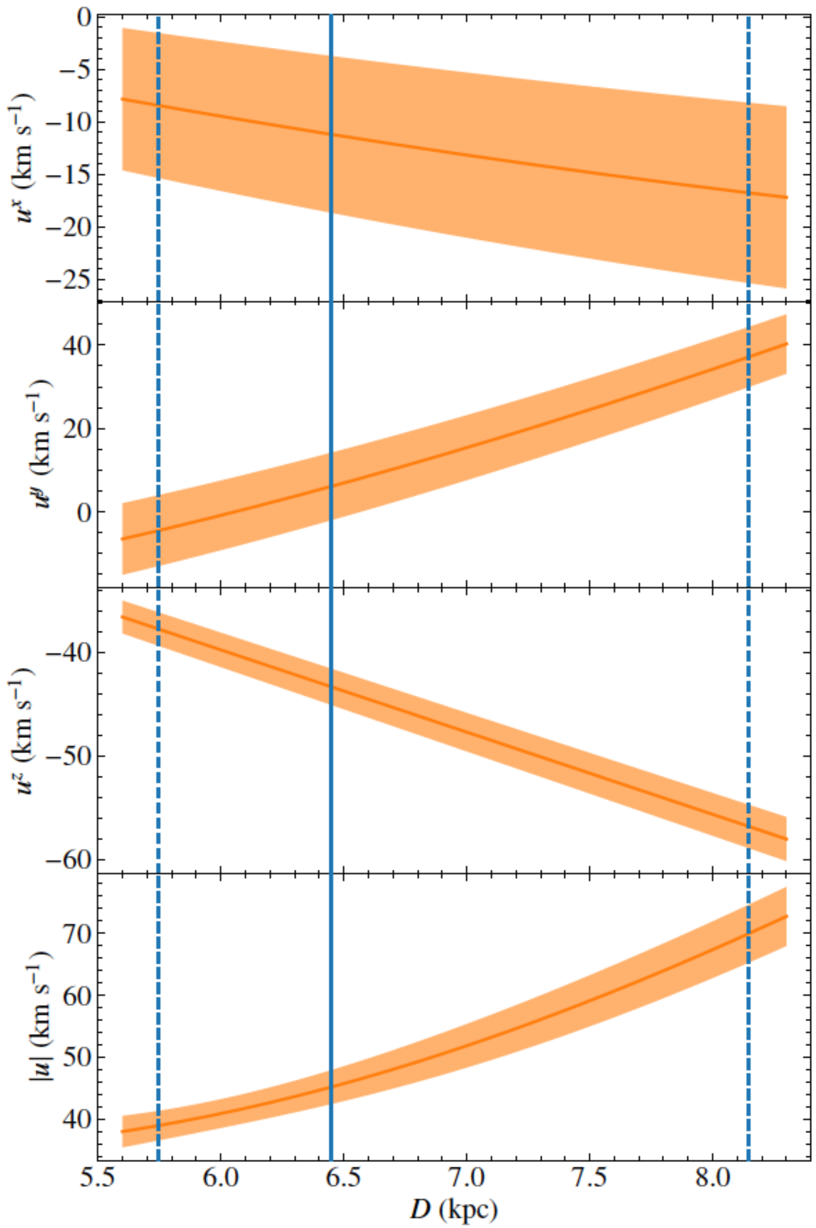
Gamma-ray Binary System	Spectral Type	Orbital Period (days)	G	$G_{BP} - G_{RP}$	GOF	UWE	$RUWE$	Peculiar Velocity (km s^{-1})
LS 5039	O6.5V	3.9	10.8	1.5	−2.64	0.85	0.69	142 ± 40 (1)
1FGL J1018.6−5856	O6V	16.58	12.3	1.4	0.10	1.00	0.94	45^{+30}_{-9} (2)
LS I +61 303	B0Ve	26.49	10.4	1.3	3.30	1.13	0.91	16 (3)
HESS J0632+057	B0Vpe	315	8.9	0.9	3.15	1.19	0.88	–
PSR B1259−63	O9.5Ve	1236.7	9.6	1.2	7.87	1.33	1.11	26 ± 8 (4)
MT91 213	Be	8578	11.4	1.6	9.26	1.48	1.05	–

(1) Moldón et al. 2012, (2) Marcote et al. 2012, (3) Wu et al. 2017, (4) Millor-Jones et al. 2018.

Gaia DR2 results on gamma-ray binaries.
1FGL J1018.6-5856 **(Marcote et al. 2018)**.

It is a runaway binary escaping from the Galactic Plane.

Similar to LS 5039
(Ribó et al. 2002, Moldón et al. 2012).



Goal:

- Search for new gamma-ray binaries using O and Be star catalogues

Methodology:

- Use Gaia DR2 on these stars to:

1. Search for **bad-behaved astrometric solutions**

2. Search for **runaway stars**

GOSC.

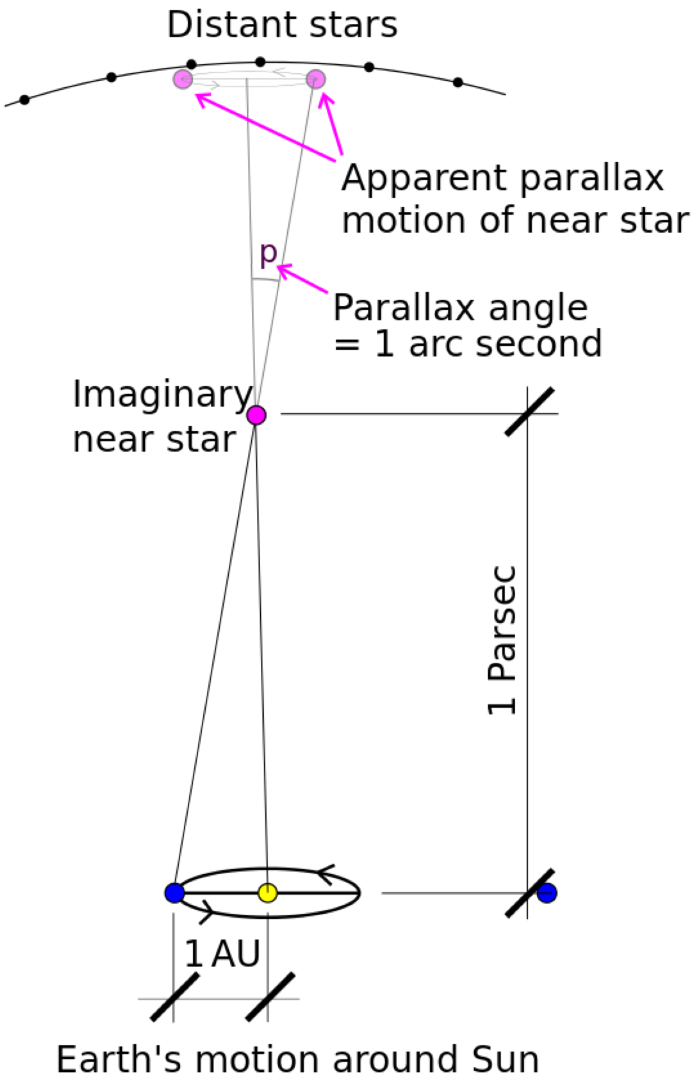
- Galactic O-Star Catalog **(Maíz Apellániz et al. 2004, 2013, 2018)**.
- Available at http://gosc.cab.inta-csic.es
- It contains **618** O and B0 stars.
- These authors detected 76 runaway stars (some of them not in GOSC).

BeSS.

- Catalog of Be stars.
- Available at http://basebe.obspm.fr/basebe/
- It contains **2251** classical Be stars.

Filters applied in Gaia DR2 data.

- *G* magnitude > 6 to avoid saturation.
- 5 parameters solutions: position, proper motion and parallax.
- Parallax over error > 5 to have distance uncertainties smaller than 20%.
- Visibility periods > 10 to avoid bad solutions or large uncertainties.



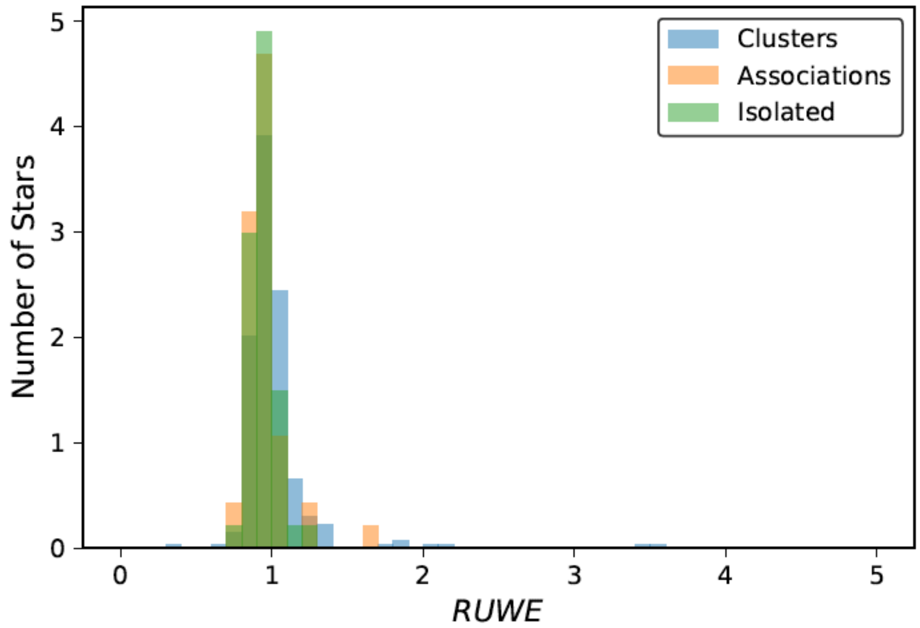
GOSC.

- Galactic O-Star Catalog **(Maíz Apellániz et al. 2004, 2013, 2018)**.
- Available at http://gosc.cab.inta-csic.es
- It contains **618** O and B0 stars.
- These authors detected 76 runaway stars (some of them not in GOSC).
- After several filters we work with an O-Gaia DR2 catalog of **370** objects.

BeSS.

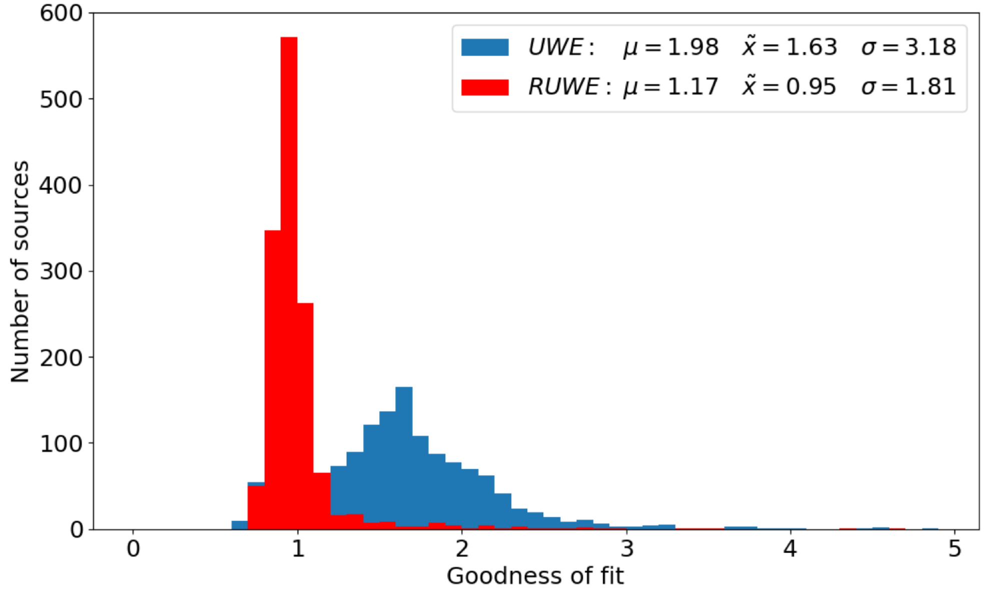
- Catalog of Be stars.
- Available at http://basebe.obspm.fr/basebe/
- It contains **2251** classical Be stars.
- After several filters we work with a BeSS-Gaia DR2 catalog of **1399** objects.

Astrometric goodness-of-fits.



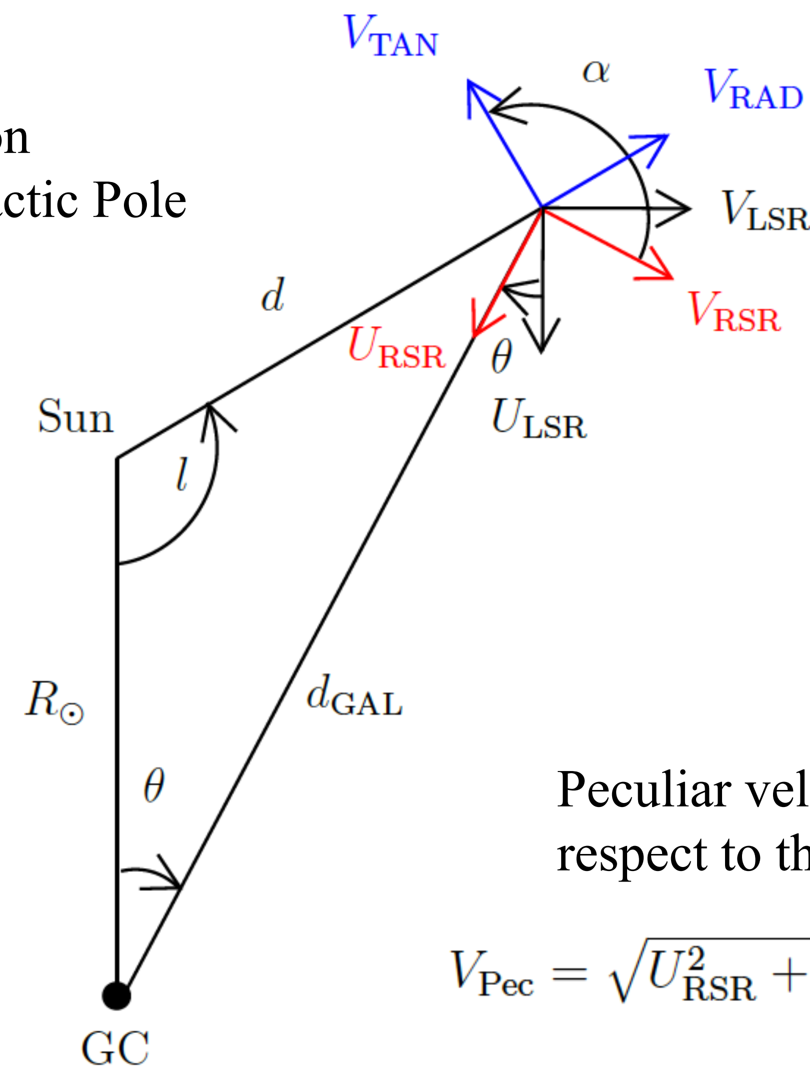
GOSC.
36 stars (~10%) with "bad-behaved solutions" (*RUWE*>1.15).
Gamma-ray binary candidates.

BeSS.
144 stars (~10%) with "bad-behaved solutions" (*RUWE*>1.12).
Gamma-ray binary candidates.



The Local Standard of Rest and the Regional Standard of Rest.

Galactic velocities:
U towards the GC.
V towards Galactic rotation
W towards the North Galactic Pole

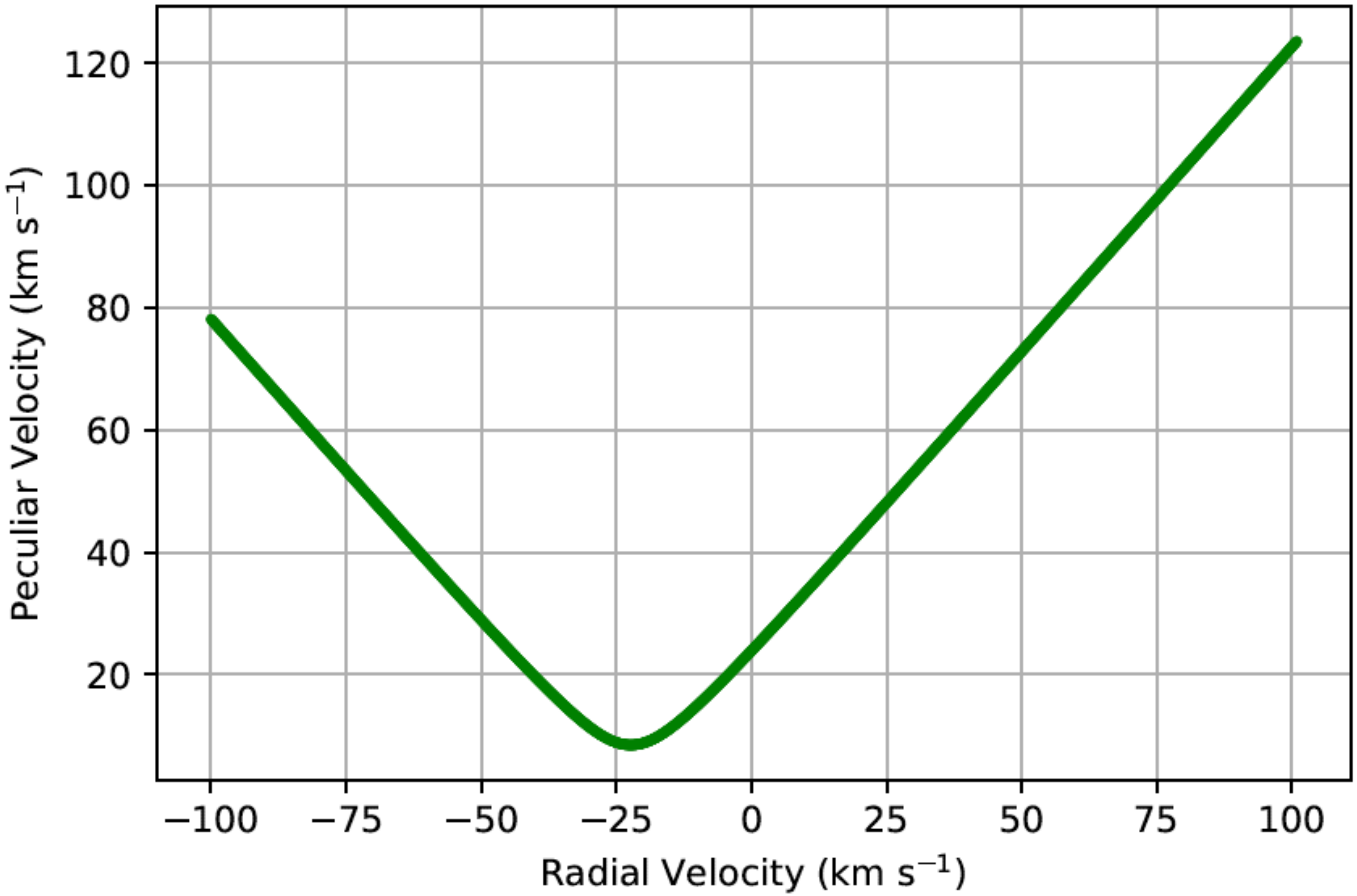


We use the Galactic rotation model of **Reid et al. (2014)**.

Peculiar velocity with respect to the RSR.

$$V_{\mathrm{Pec}} = \sqrt{U_{\mathrm{RSR}}^2 + V_{\mathrm{RSR}}^2 + W_{\mathrm{RSR}}^2}$$

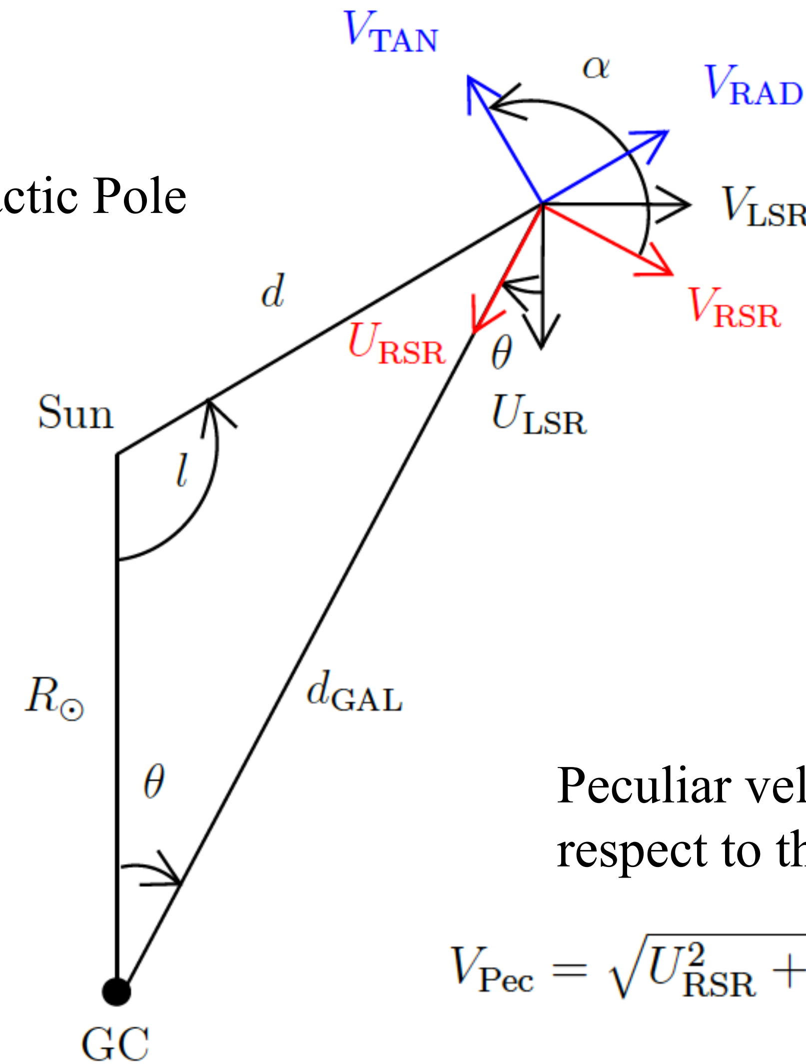
Lack of radial velocity.



We estimate the radial velocity of the RSR, which provides minimum V_{Pec}

The new velocities V_{RAD} and V_{TAN}.

Galactic velocities:
V_{RAD} is not relevant
V_{TAN} is relevant
W towards the North Galactic Pole



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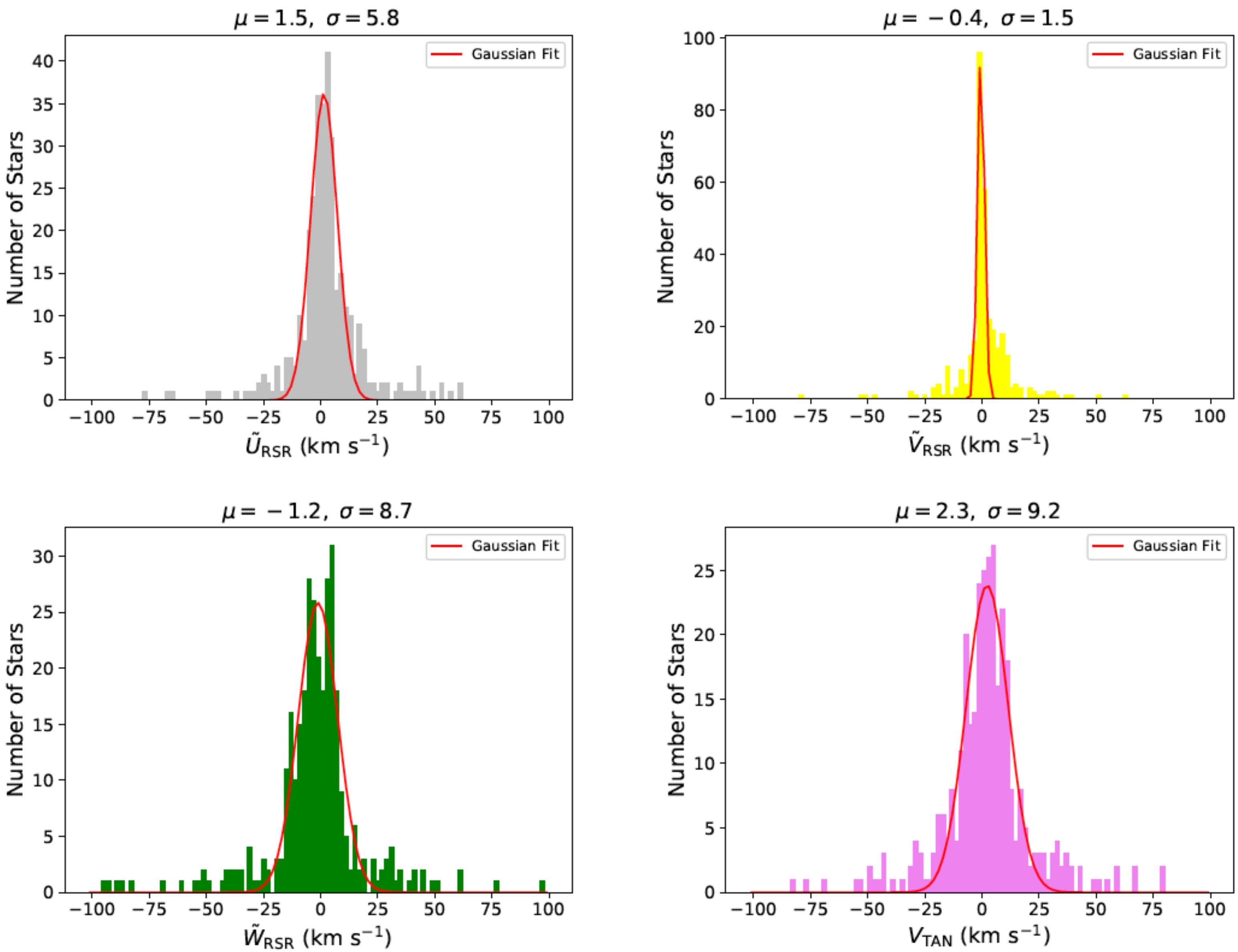
Runaways in GOSC.



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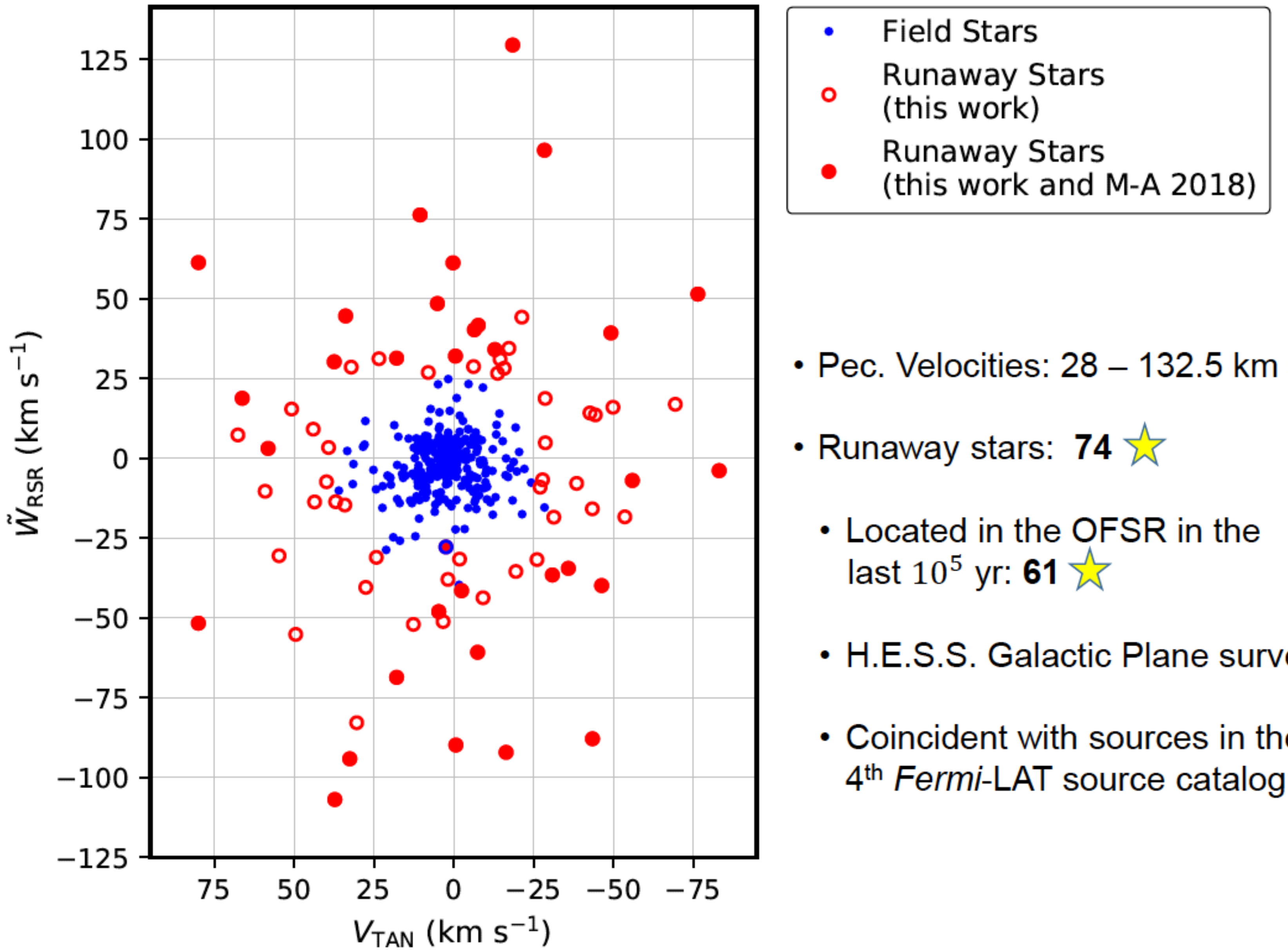
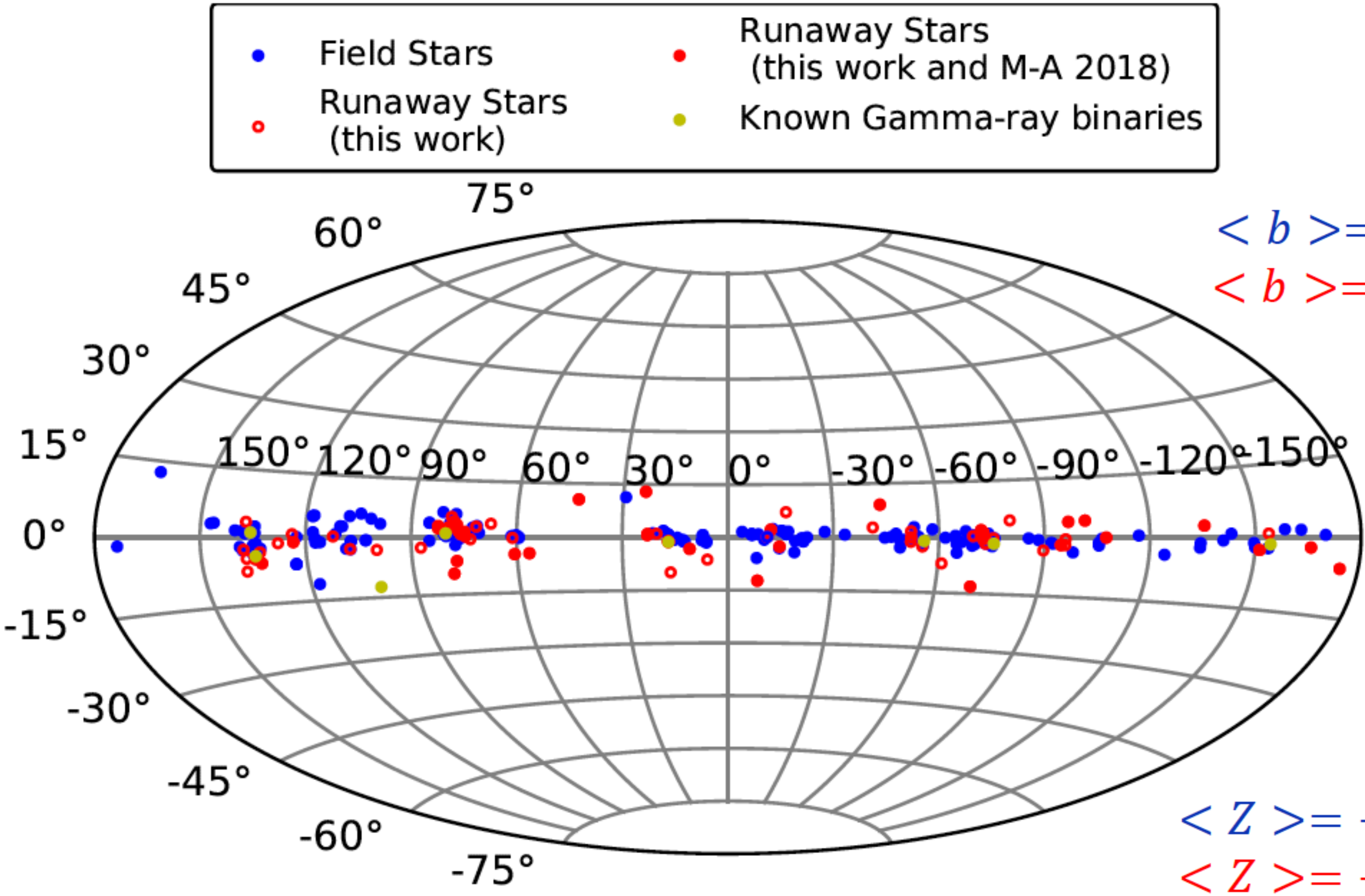


- Pec. Velocities: 28 – 132.5 km s^{-1}
- Runaway stars: **74** ☆
  - Located in the OFSR in the last 10^5 yr: **61** ☆
  - H.E.S.S. Galactic Plane survey : **24** ☆
  - Coincident with sources in the 4th *Fermi*-LAT source catalog: **2** ☆

Runaways in GOSC.



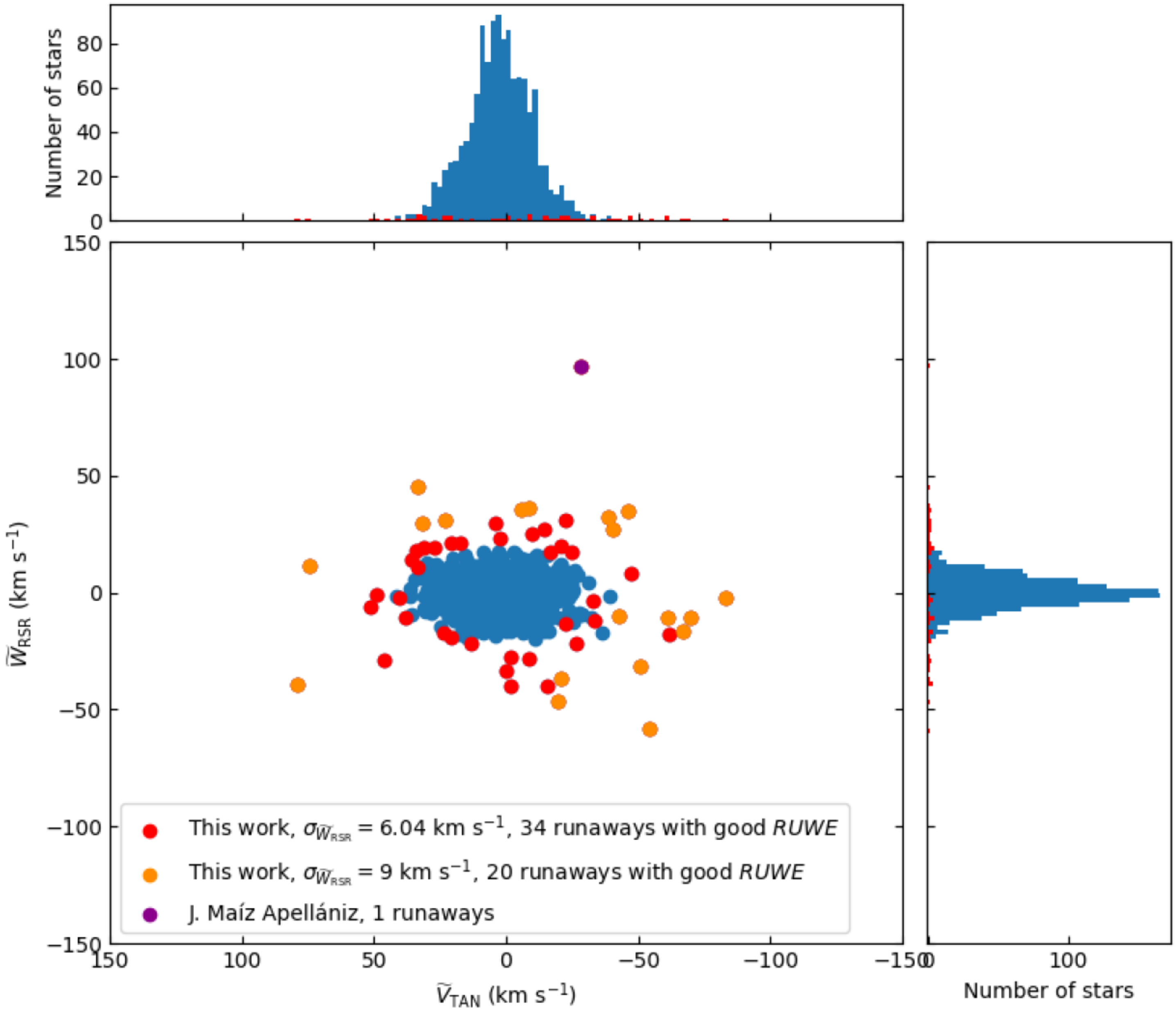
$< b >= 0.1 \pm 2.3$ º

$< b >= -0.6 \pm 4.6$ º

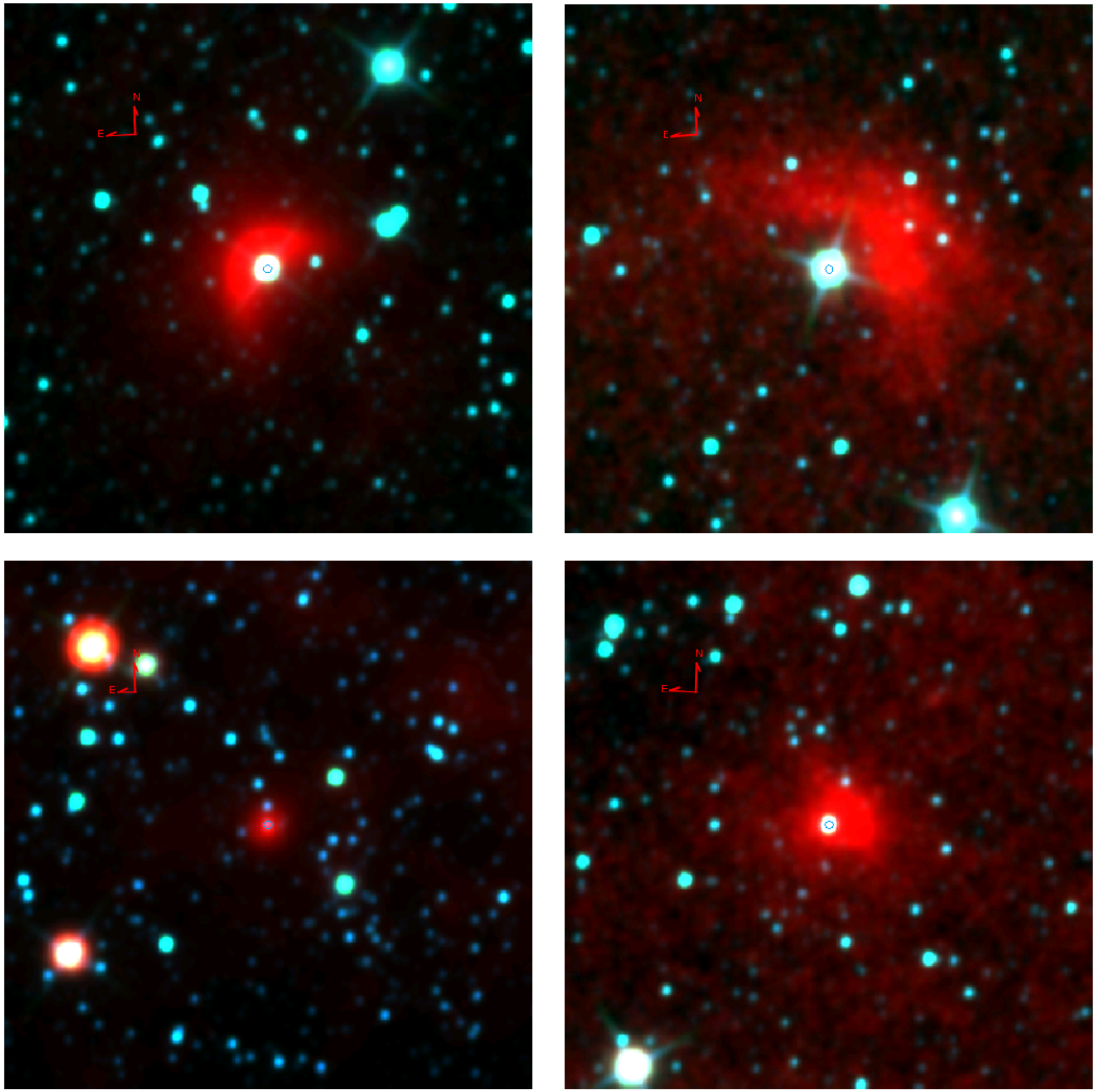
$< Z >= -6 \pm 89$ pc

$< Z >= -33 \pm 194$ pc

Runaways in BeSS.



Runaways in BeSS.



Gamma-ray binary candidates.

GOSC.

- Galactic O-Star Catalog **(Maíz Apellániz et al. 2004, 2013, 2018)**.
- Available at http://gosc.cab.inta-csic.es
- It contains **618** O and B0 stars.
- These authors detected 76 runaway stars (some of them not in GOSC).
- After several filters we work with an O-Gaia DR2 catalog of **370** objects.
- **36** stars (~10%) with "bad-behaved solutions" (*RUWE*>1.15).
- We have found **76 runaways, 42 more than Maíz Apellániz et al. (2018)**.
- 24 are in positions covered by the HESS GPS, 2 are 4th *Fermi*-LAT sources.

BeSS.

- Catalog of Be stars.
- Available at http://basebe.obspm.fr/basebe/
- It contains **2251** classical Be stars.
- After several filters we work with a BeSS-Gaia DR2 catalog of **1399** objects.
- **144** stars (~10%) with "bad-behaved solutions" (*RUWE*>1.12).
- We have found **54 new runaway stars**.
- Only 5 are in positions covered by the HESS GPS.

Future work.

- Make deep searches in MW catalogues.
- Conduct radial velocity studies to constrain 3-D velocities and search for binarity!
- Conduct a systematic search for bow shocks around the stars.

Conclusions

- Gamma-ray binaries are **unique laboratories** to test particle acceleration and radiation and absorption mechanisms in repeatable geometric configurations.
- Available models do not fully explain the observations available so far.
- We only know a **very reduced population of 8 sources** (4 O stars, 4 Be stars), with only 2 with confirmed young non-accreting pulsars with Be stars.
- **Enlarging the population** could allow us to to disentangle between the typical behavior and deviations from it in particular sources.
- A search for new gamma-ray binaries using astrometric data from Gaia DR2 reveals **42 new runaway O stars and 54 new runaway Be stars**.
- Spectroscopic observations needed to unveil their **possible binary nature**.
- These are targets for **future studies with IACTs**.