SEARCHING FOR NEW GAMMA-RAY BINARIES USING *Gaia*

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IEEC Institut d'Estudis Espacials de Catalunya

OUTLINE

1. INTRODUCTION
2. MOTIVATION
3. METHODOLOGY
4. RESULTS
5. CONCLUSIONS AND OUTLOOK

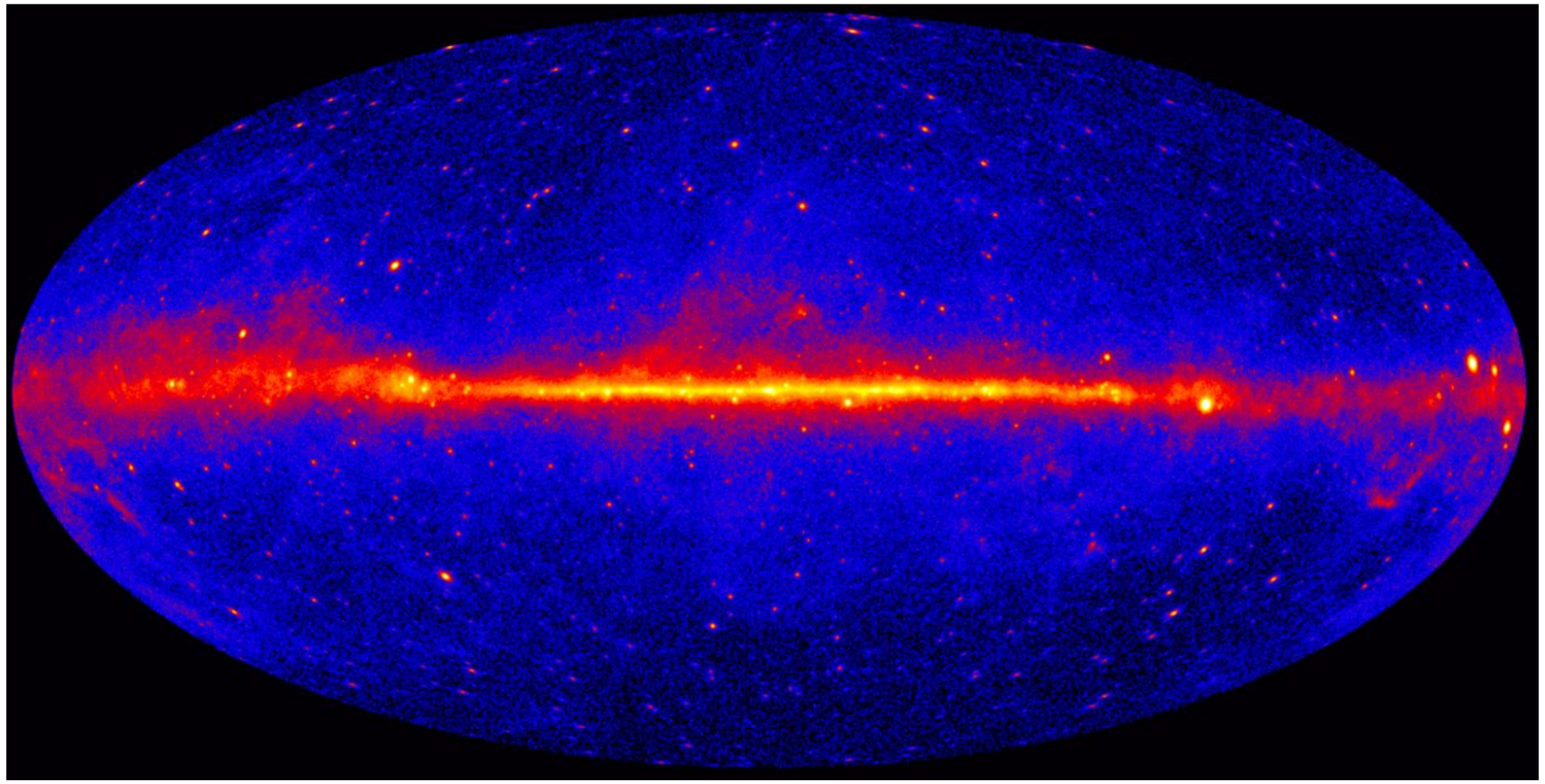
1. INTRODUCTION: THE GeV AND TeV SKY

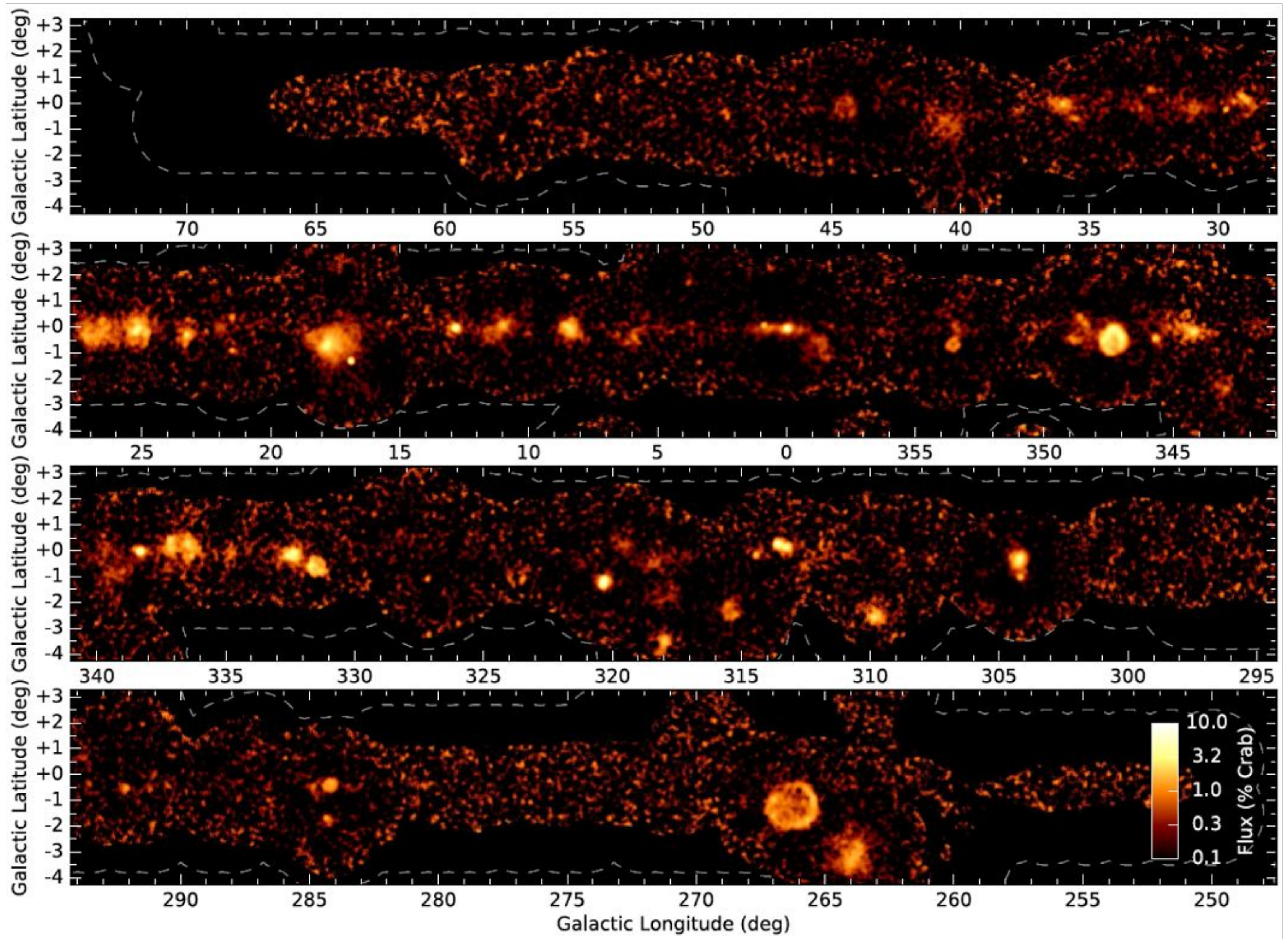
New facilities since 2005-2008

New facilities → new types of gamma-ray sources → gamma-ray binaries

HESS and MAGIC Cherenkov Telescopes (TeV)

Fermi/LAT satellite (GeV)

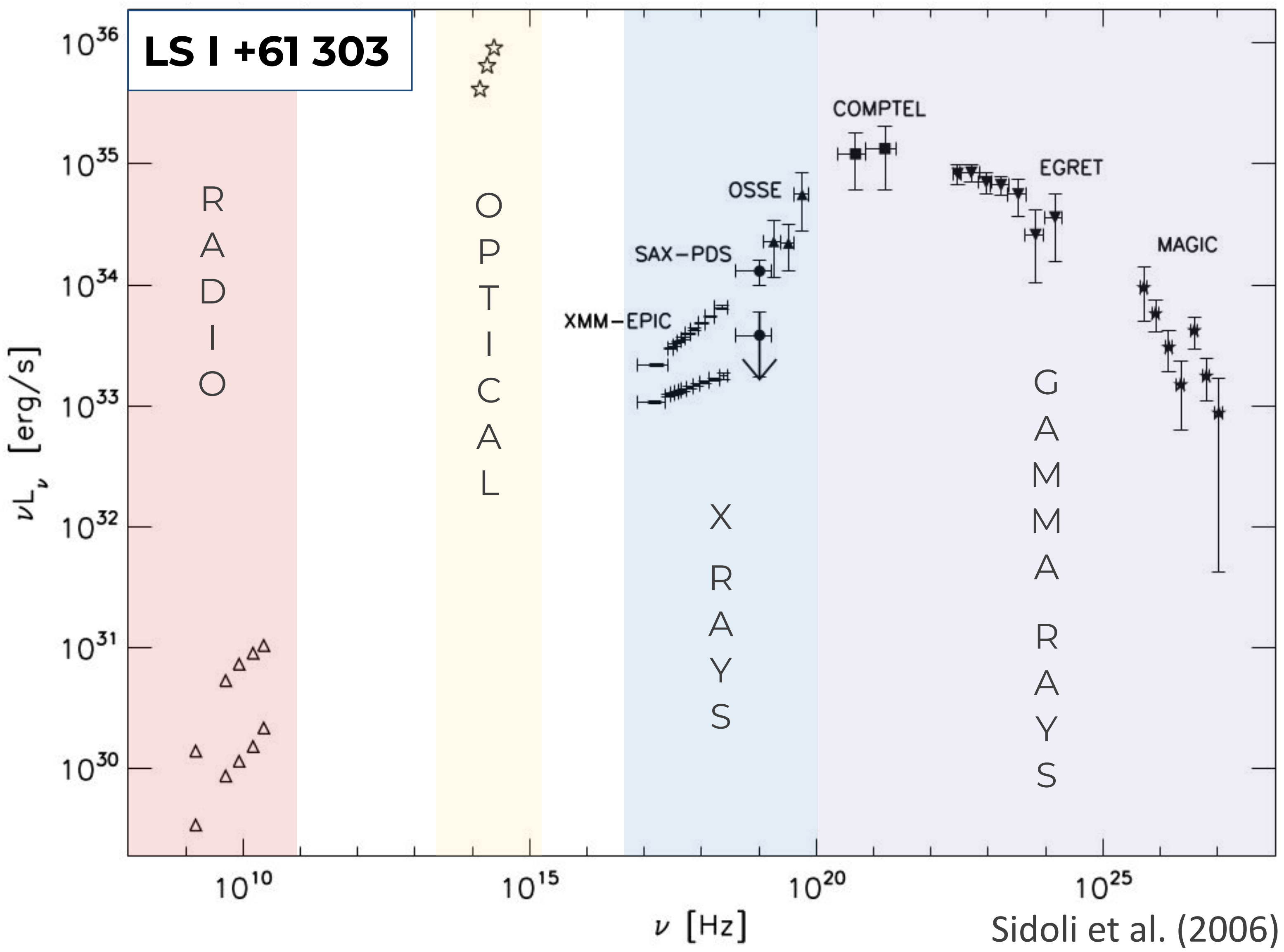




1. INTRODUCTION: GAMMA-RAY BINARIES

- Gamma-ray binaries:
  - consist of a **massive star** and a **compact object**
  - have the **maximum** of the non-thermal emission at **gamma-ray energies**

- Only **9** are known:
  - **two** of them have a confirmed **pulsar**
  - **no clear accretion signatures**
  - very **different orbital configurations** (*P*, *e*)



Sidoli et al. (2006)

Gamma-ray Binary System	Spectral Type	Orbital Period (days)	Distance (kpc)
LS 5039	O6.5V	3.9	2.0
LS I +61°303	B0Ve	26.5	2.7
PSR B1259−63	O9.5Ve	1236.7	2.3
HESS J0632+057	B0Vpe	315.0	1.9
1FGL J1018.6−5856	O6V	16.5	4.4
LMC P3	O5III	10.3	LMC
PSR J2032+4127	Be	17670.0	1.8
4FGL J1405−6119	O6III	13.7	–
HESS J1832−093	–	86.3	–

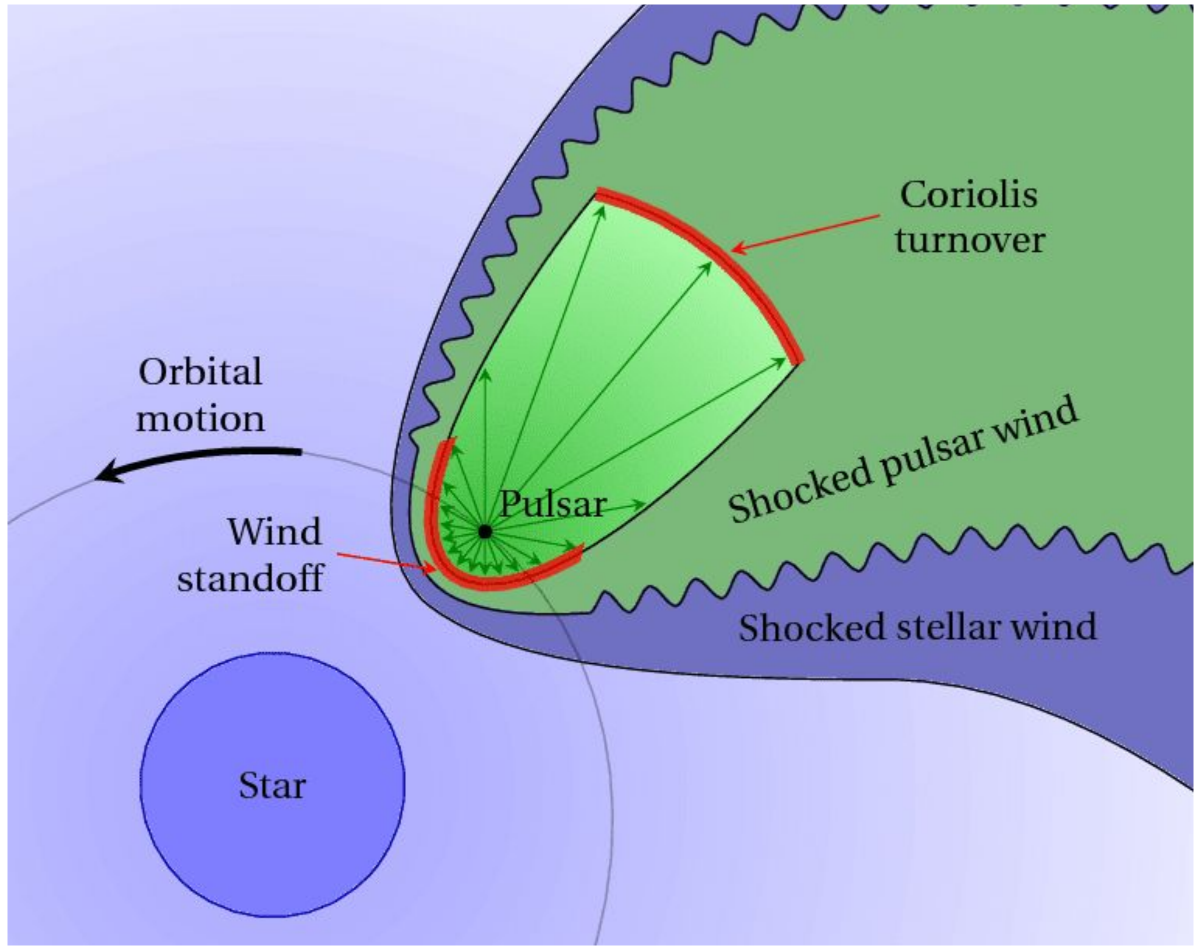
See Paredes & Bordas (2019) and references therein

1. INTRODUCTION: GAMMA-RAY BINARIES

- Physical scenario:

Non-accreting pulsar

- Young pulsar with a relativistic wind
- Particle acceleration: shock between the pulsar and stellar winds or the Coriolis shock (see Bosch-Ramon et al. 2015)
- Synchrotron radiation from radio to X-rays
- Gamma-ray emission: inverse Compton scattering



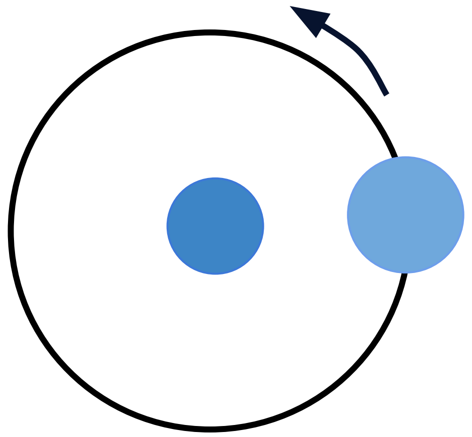
Zabalza et al. (2013)

Open questions

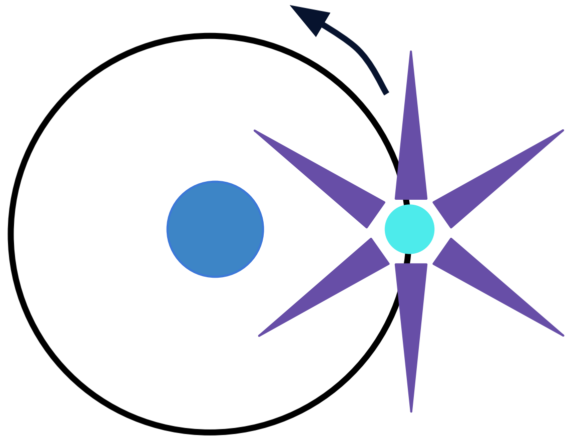
- Do all contain pulsars?
- Why only O and Be stars?
- What is the real population?
- Does it fit with binary stellar evolution?
- What will CTA see?
- Do we know all nearby objects or just the tip of the iceberg?
- Are the known ones representative of the population?
- Relevant physical parameters to produce GeV/TeV emission?

1. INTRODUCTION: KICKS AND BINARY ORBITS

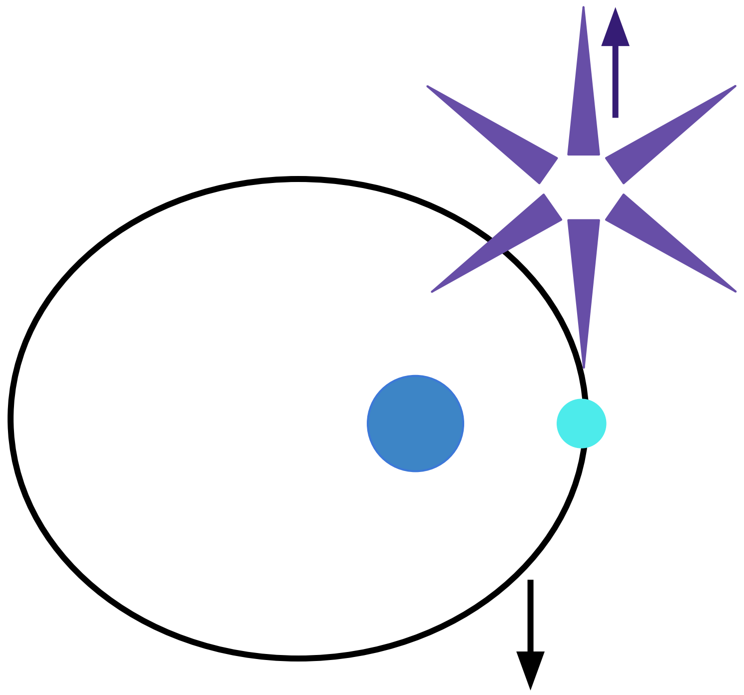
1. **Pre-supernova (SN) orbit**
   - Two massive stars in a binary system



2. **SN explosion**
   - Remains bound if less than half of the mass is lost



3. **Kick**
   - SN ejecta moving away
   - Binary system moving on the opposite direction
   - Orbit changes (P, e)



THE SYSTEM BECOMES RUNAWAY

$(30 - 200 \text{ km s}^{-1})$

2. MOTIVATION

- Some **gamma-ray binaries** have high to **extremely high peculiar velocities**
- Search for **runaways** among catalogs of **massive stars**

- Obtain a list of **gamma-ray binary candidates** to be further studied
- Should allow us to **discover additional gamma-ray binaries** with **different selection bias**

Gamma-ray Binary System	Spectral Type	Orbital Period (days)	Distance (kpc)	Peculiar Velocity ($km\ s^{-1}$)	
LS 5039	O6.5V	3.9	2.0	142 ± 40	(1)
LS I +61°303	B0Ve	26.5	2.7	16	(2)
PSR B1259−63	O9.5Ve	1236.7	2.3	26 ± 8	(3)
HESS J0632+057	B0Vpe	315.0	1.9	–	
1FGL J1018.6−5856	O6V	16.5	4.4	45^{+30}_{-9}	(4)
LMC P3	O5III	10.3	LMC	–	
PSR J2032+4127	Be	17670.0	1.8	–	
4FGL J1405−6119	O6III	13.7	–	–	
HESS J1832−093	–	86.3	–	–	

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

3. METHODOLOGY: GOSC-*Gaia* DR2 CROSS-MATCH

GOSC Catalog

- Catalog of Galactic O-type stars
- The current version lists 611 O stars and 32 B,A stars

***Gaia* DR2**

- 2nd Data Release of the astrometric mission *Gaia*
- 1,692,919,135 sources in *Gaia* DR2

$1''$

- 5 parameter solution
- $G > 6$
- visibility_periods_used > 10
- |parallax_over_error| > 5
- mean_varpi_factor_al ∊ [-0.23, 0.32]
- Negative parallax
- *RUWE* < 1.15

To guarantee good astrometric data

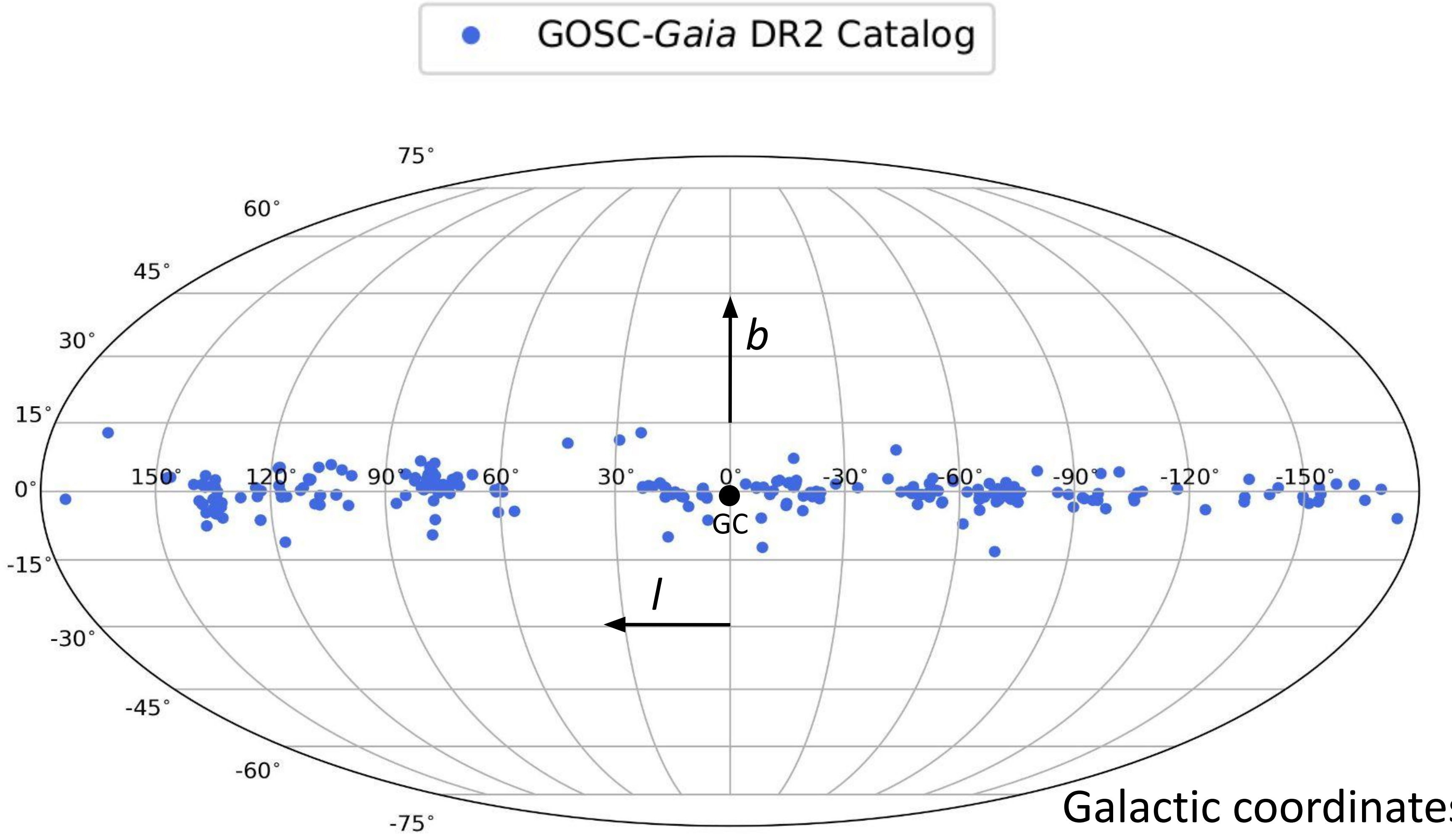
GOSC-*Gaia* DR2 Catalog

366 stars

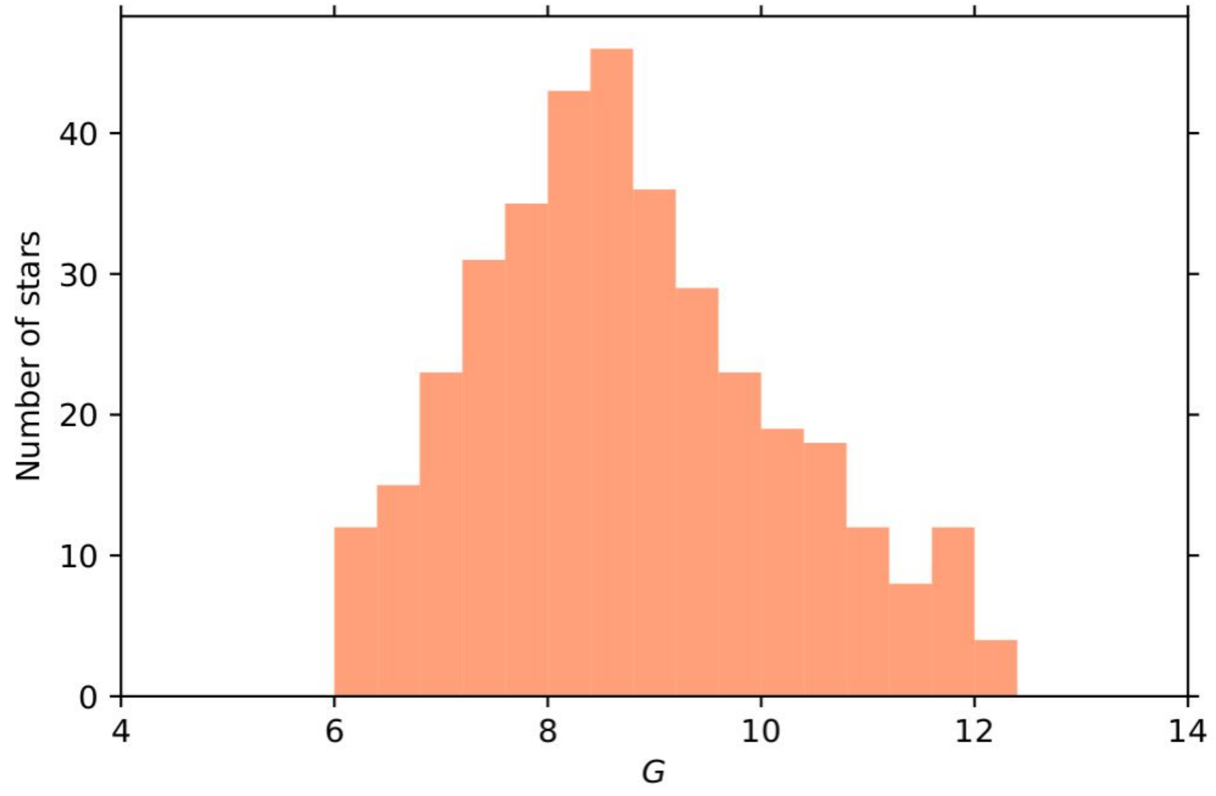
3. METHODOLOGY: GOSC-*Gaia* DR2 Catalog

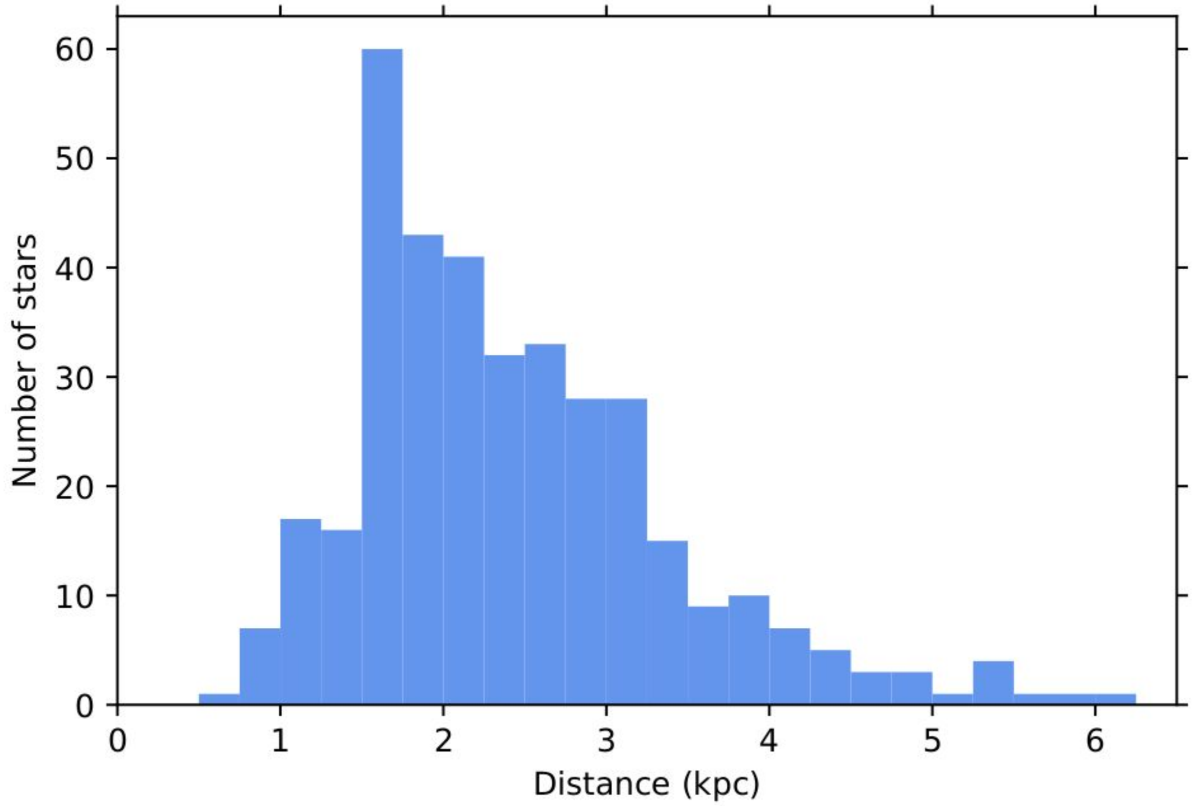
GOSC-*Gaia* DR2 Catalog

- *G* magnitude ranges from 6 to 12.5
- Distance ranges from 0.5 to 6.5 kpc



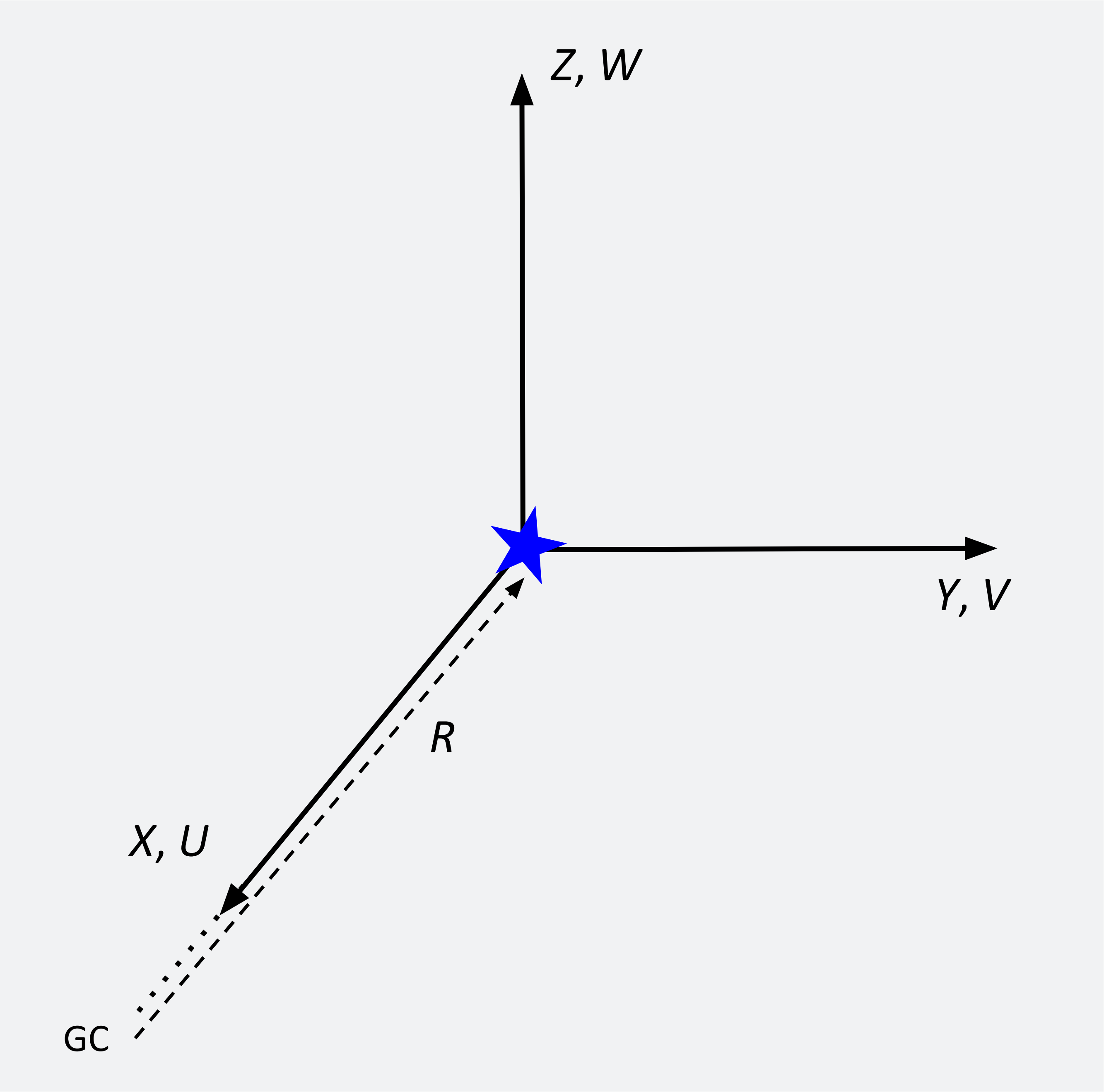
Galactic coordinates
(*l*, *b*)



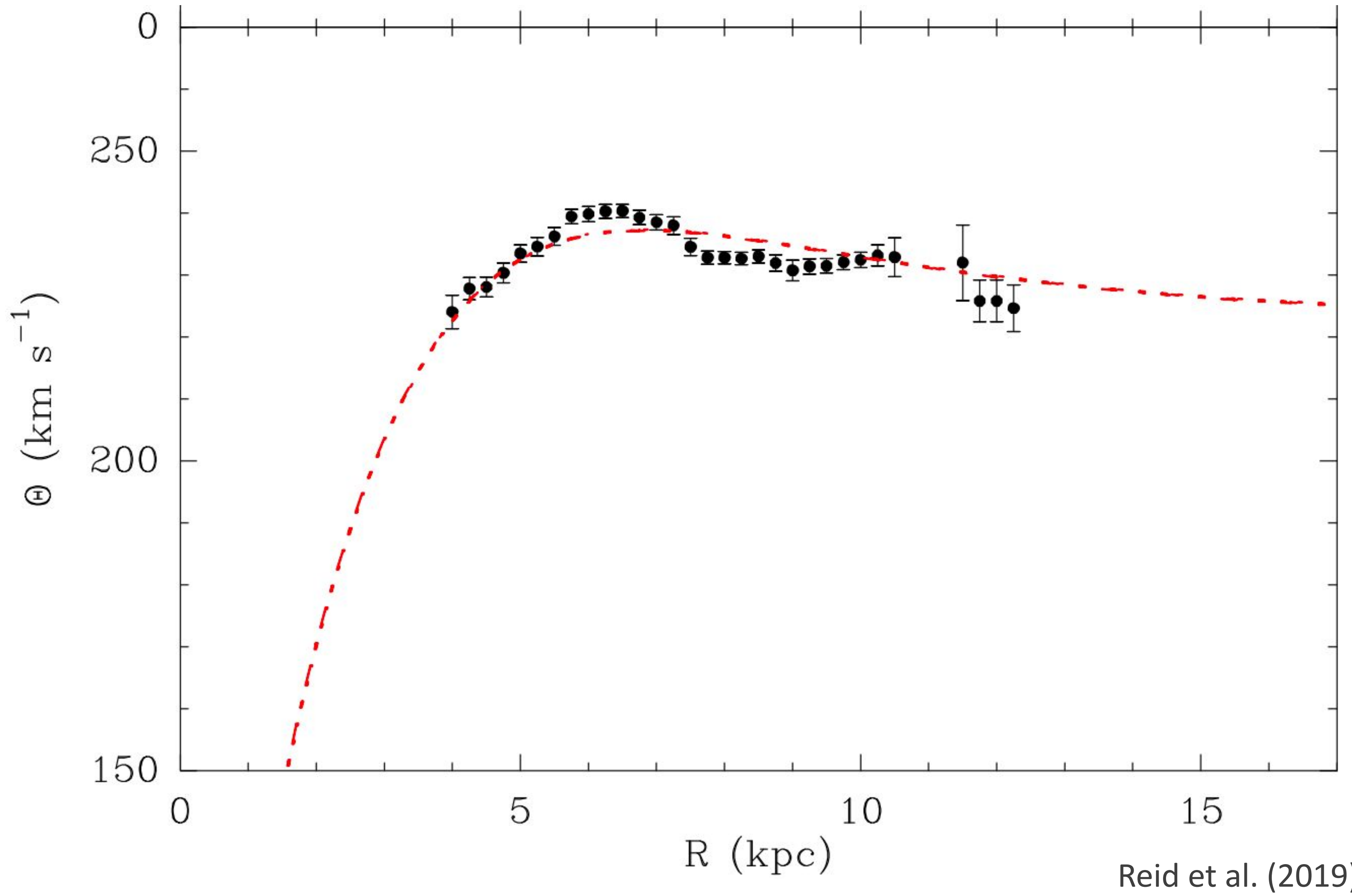


3. METHODOLOGY: Searching for runaway stars

Galactocentric coordinates

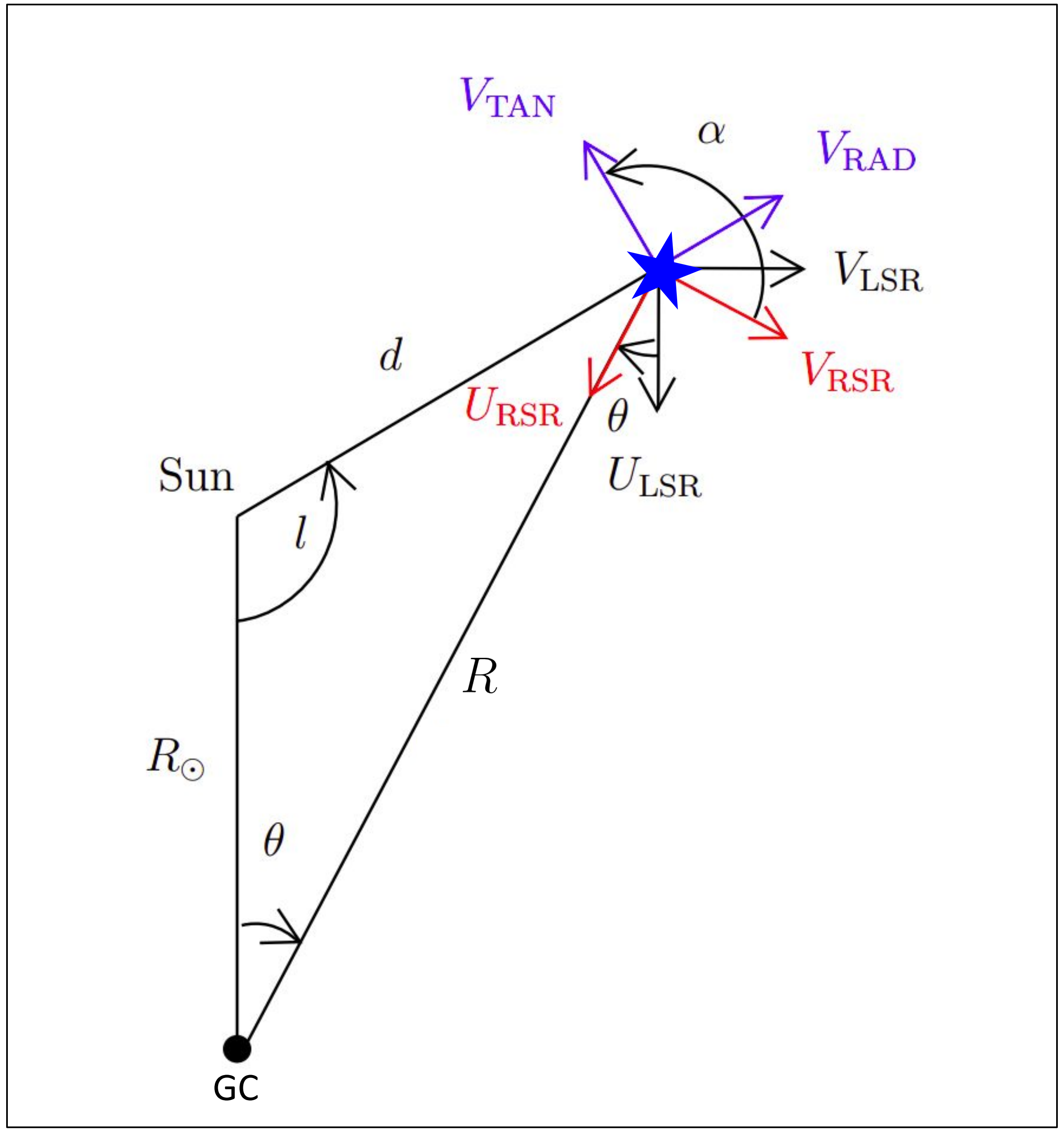


Galactic rotation curve



Reid et al. (2019)

3. METHODOLOGY: Searching for runaway stars



Local Standard of Rest

- At the position of the Sun
- $(U_{\rm LSR}, V_{\rm LSR}, W_{\rm LSR})$

Regional Standard of Rest ← Reid et al. (2019) Galactic rotation curve

- At the position of the star
- $(U_{\rm RSR}, V_{\rm RSR}, W_{\rm RSR})$

New Reference System

- To get rid of the radial velocity contribution
- $(V_{\rm TAN}, V_{\rm RAD}, W_{\rm RSR})$

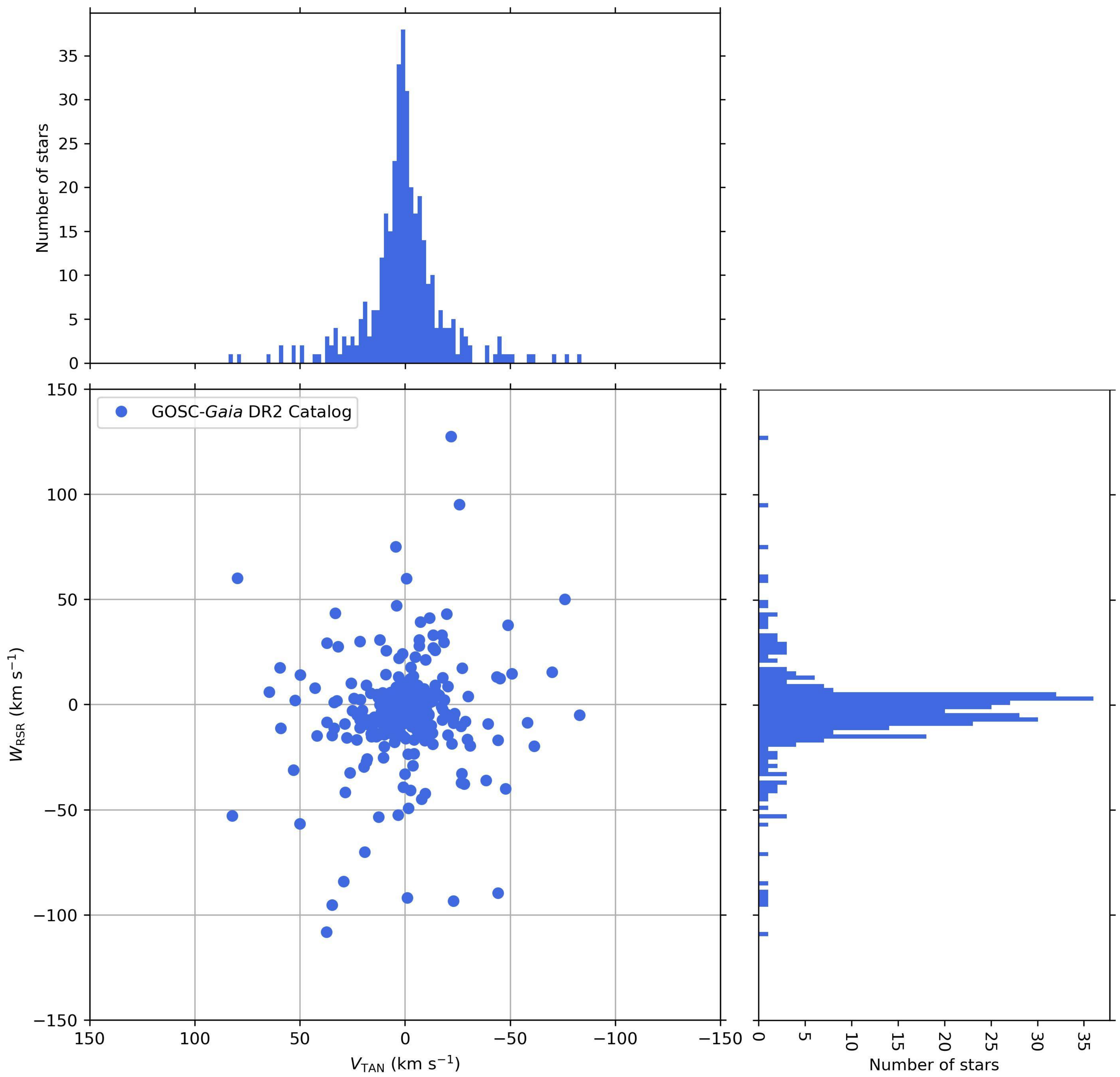
4. RESULTS:

New Reference System

- We have used the two velocity components:

$$(V_{\rm TAN}, W_{\rm RSR})$$

- Histogram with $2\ \mathrm{km\ s^{-1}}$ binning
- Most stars around (0,0) velocities, with some dispersion
- Other stars with clearly high velocities

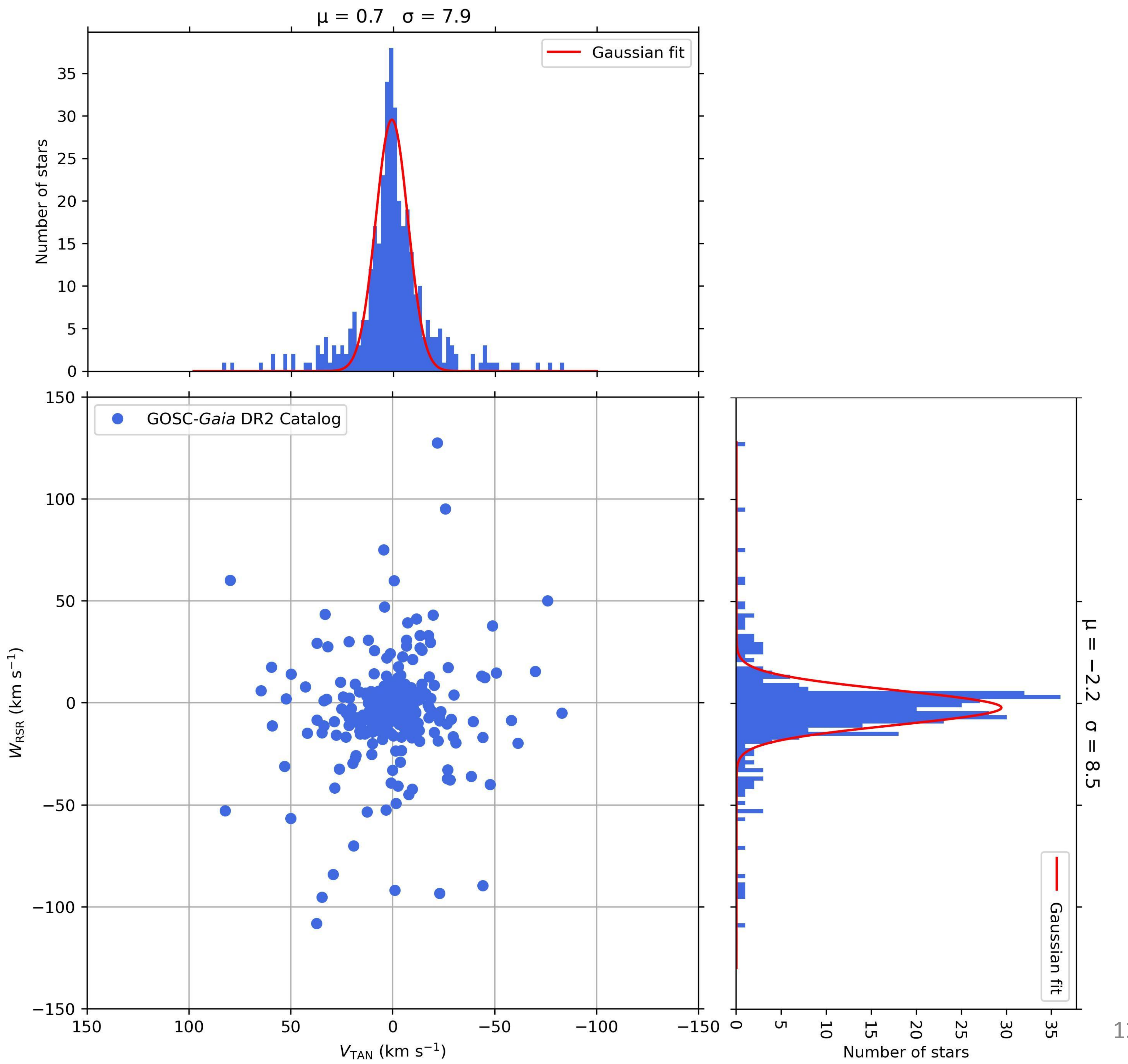


4. RESULTS:

Gaussian fit

- Gaussian fitting to the histograms
- Standard deviations ($\sim 9 \text{ km s}^{-1}$) have typical values for young stars

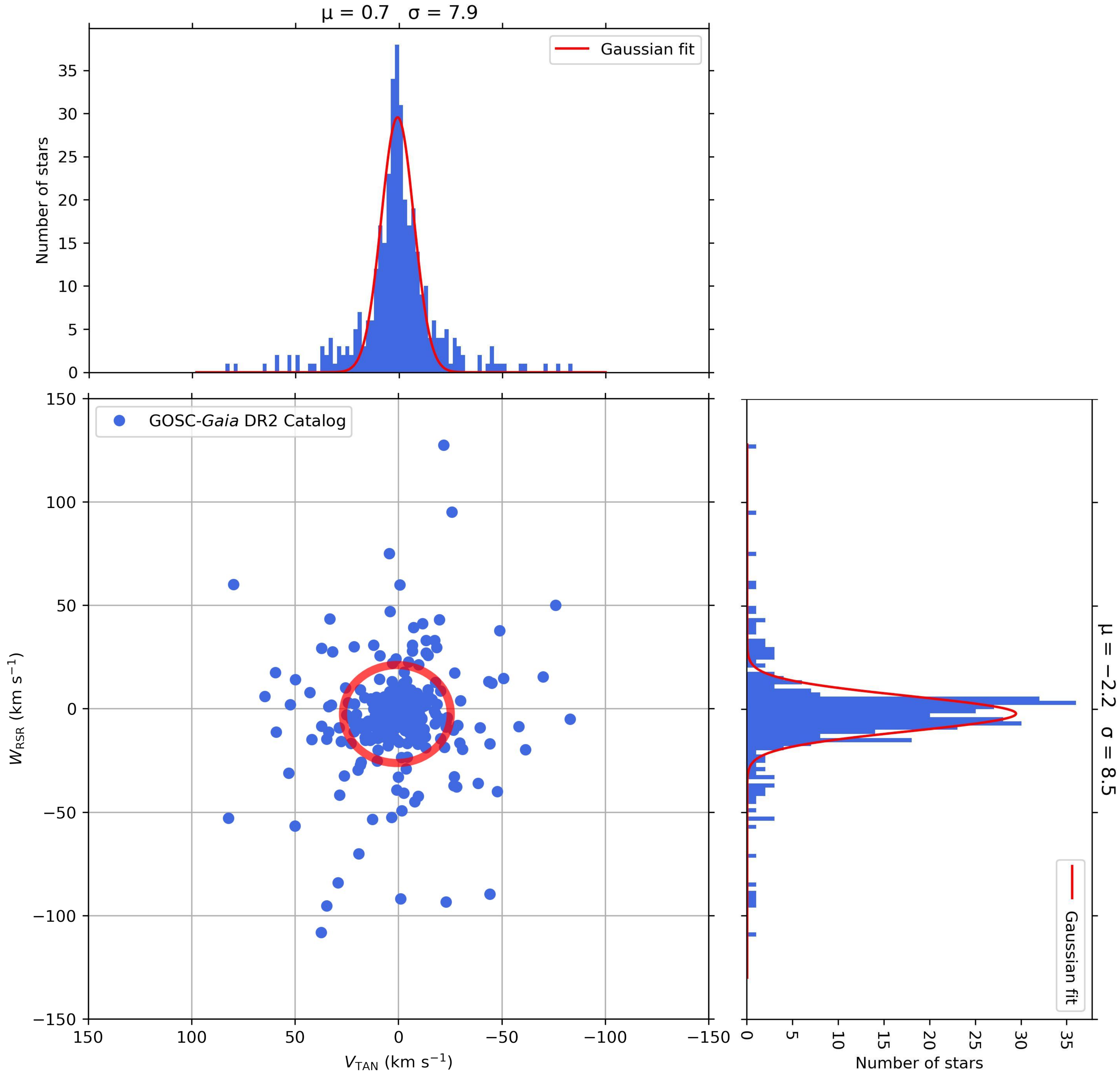
(Torra et al. 2000)



4. RESULTS:

Criterion for determining runaway stars

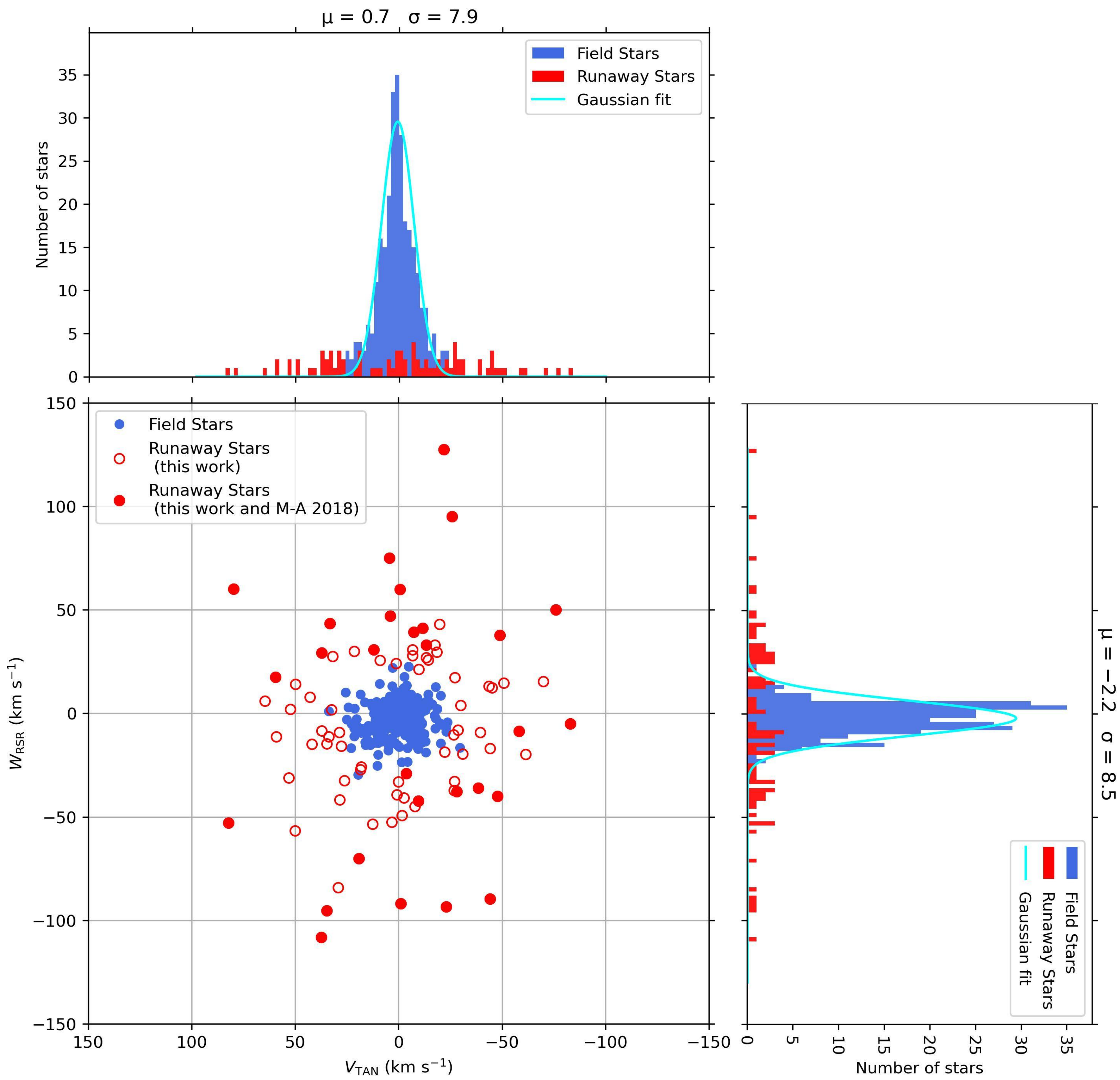
- **3σ** ellipse
- Stars inside this ellipse will be classified as field stars
- **Stars outside** this **ellipse** will be classified as **runaways**
- **82** runaway stars



4. RESULTS:

Gaussian fit

- The Gaussian fit is affected by the runaway stars

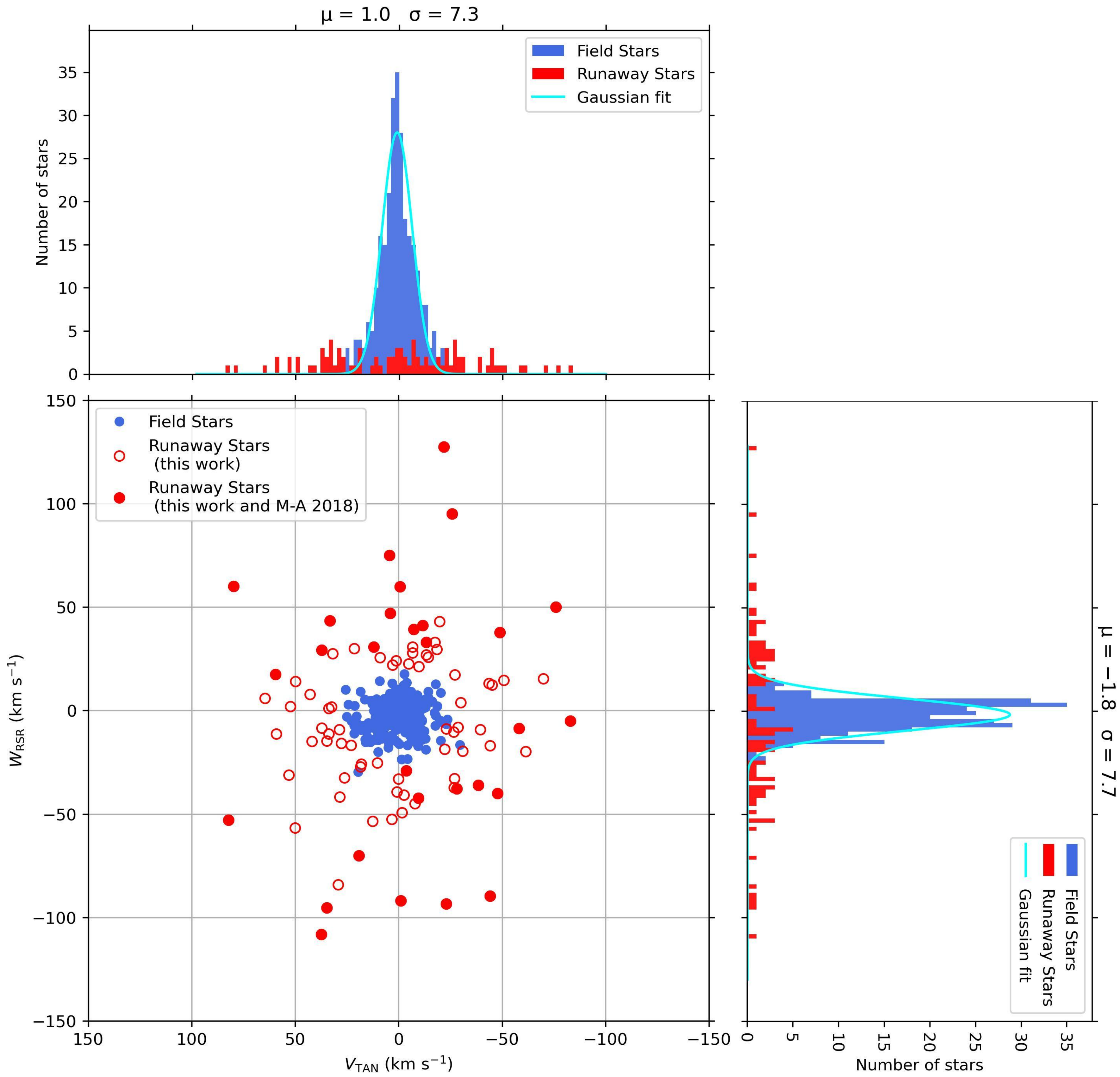


4. RESULTS:

Clipping

- Gaussian fit has improved
- Standard deviations have decreased
- After clipping, we obtained **6** more **runaway stars**

Iteration	$\mu_{V_{\mathrm{TAN}}}$	$\sigma_{V_{\mathrm{TAN}}}$	$\mu_{W_{\mathrm{RSR}}}$	$\mu_{W_{\mathrm{RSR}}}$	Excluded stars
1	0.66	7.88	−2.23	8.46	82
2	0.98	7.31	−1.87	7.79	5
3	1.00	7.33	−1.83	7.75	1
4	0.96	7.27	−1.82	7.74	0



4. RESULTS:

- **88** runaway stars, **24%** of the GOSC-*Gaia* DR2 catalog

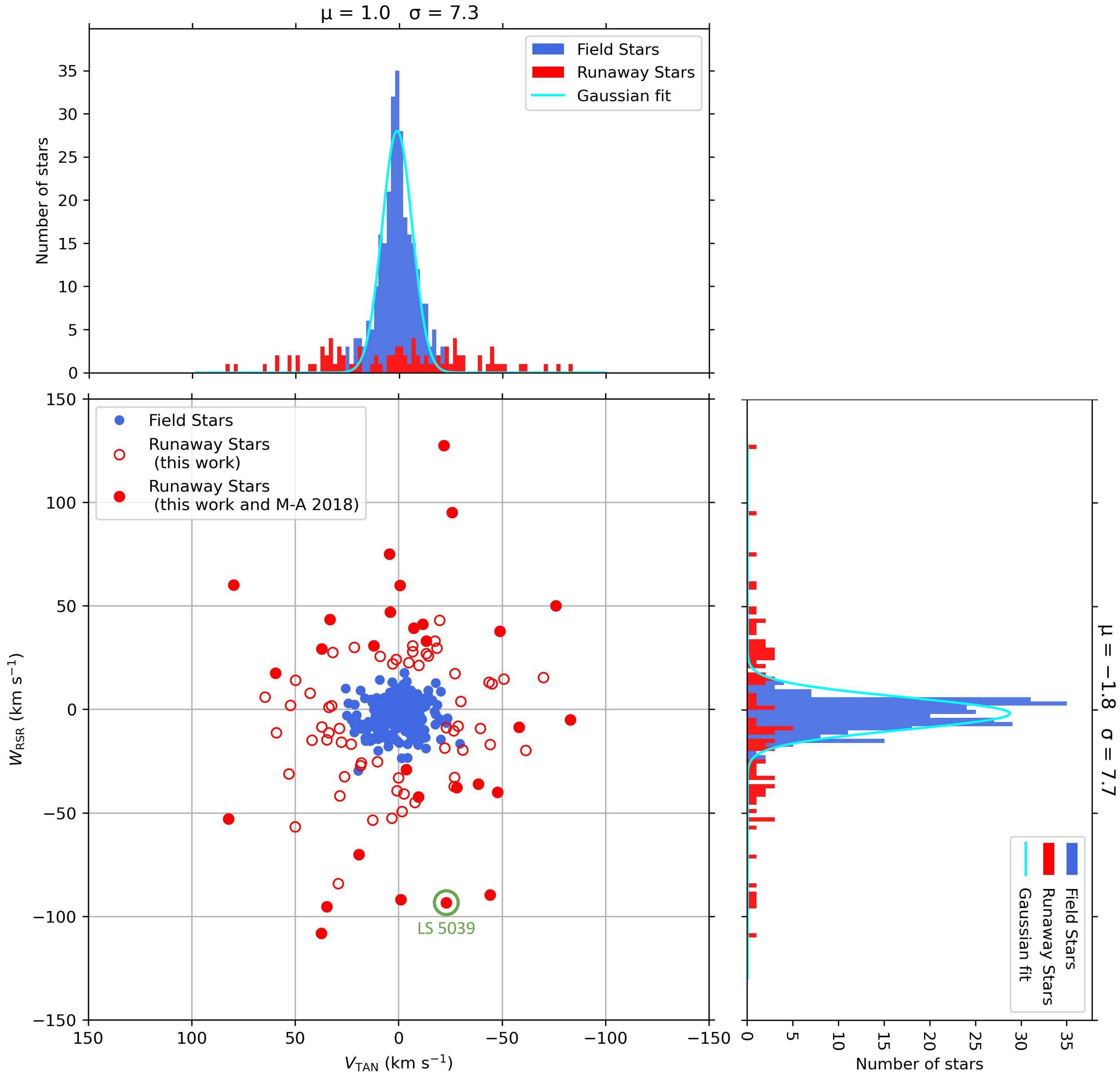
- Peculiar velocities:

$$30 - 131 \text{ km s}^{-1}$$

- Peculiar velocities of runaway gamma-ray binaries:

$$26 - 142 \text{ km s}^{-1}$$

Gamma-ray Binary System	GOSC Catalog	GOSC-*Gaia* DR2 Catalog	Classified as
LS 5039	✓	✓	Runaway
PSR B1259−63	✗	–	–
1FGL J1018.6−5856	✗	–	–

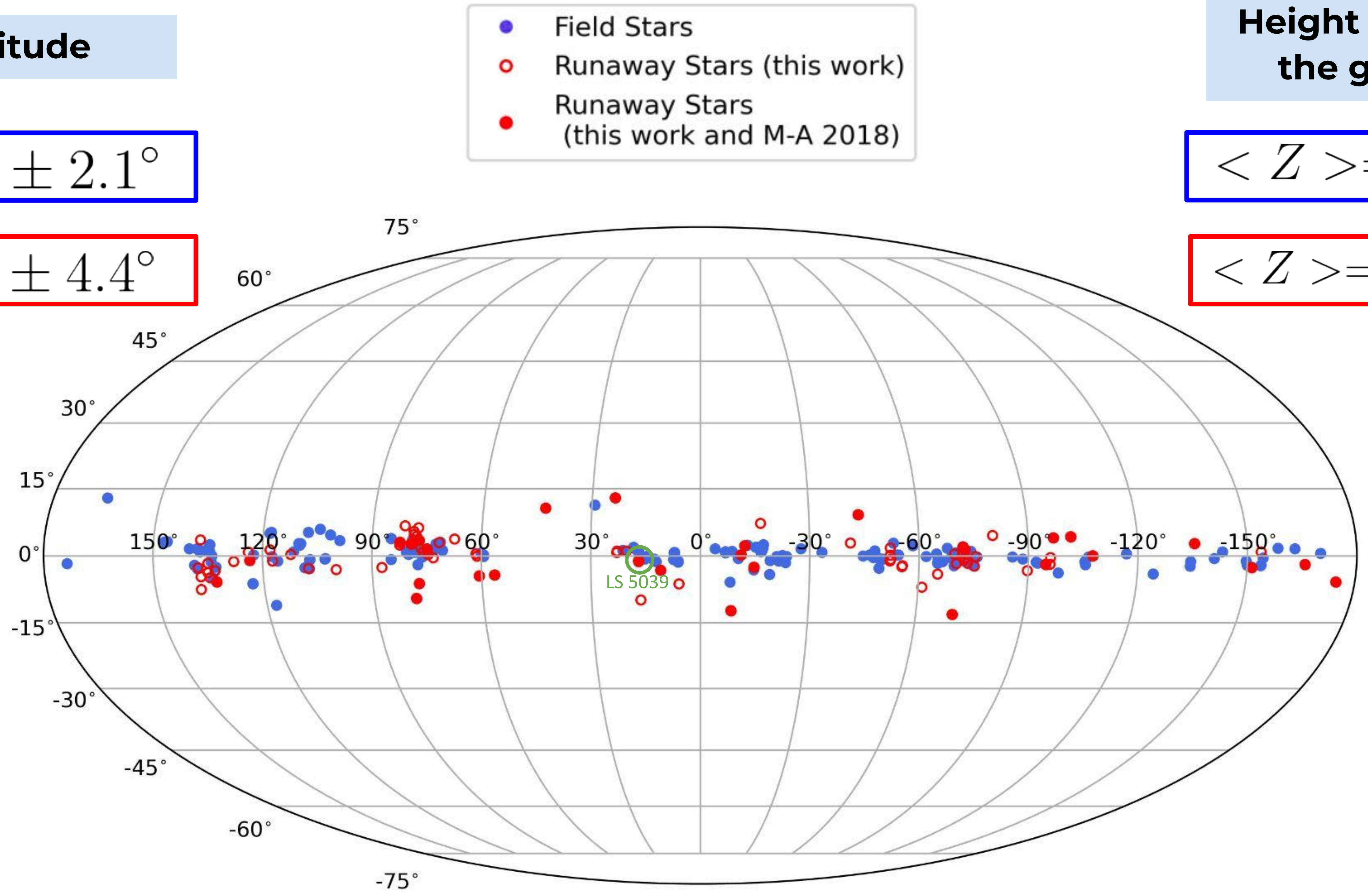


4. RESULTS:

Galactic latitude

$$< b >= 0.2 \pm 2.1^\circ$$

$$< b >= 0.5 \pm 4.4^\circ$$



Height with respect to the galactic plane

$$< Z >= -3 \pm 79 \text{ pc}$$

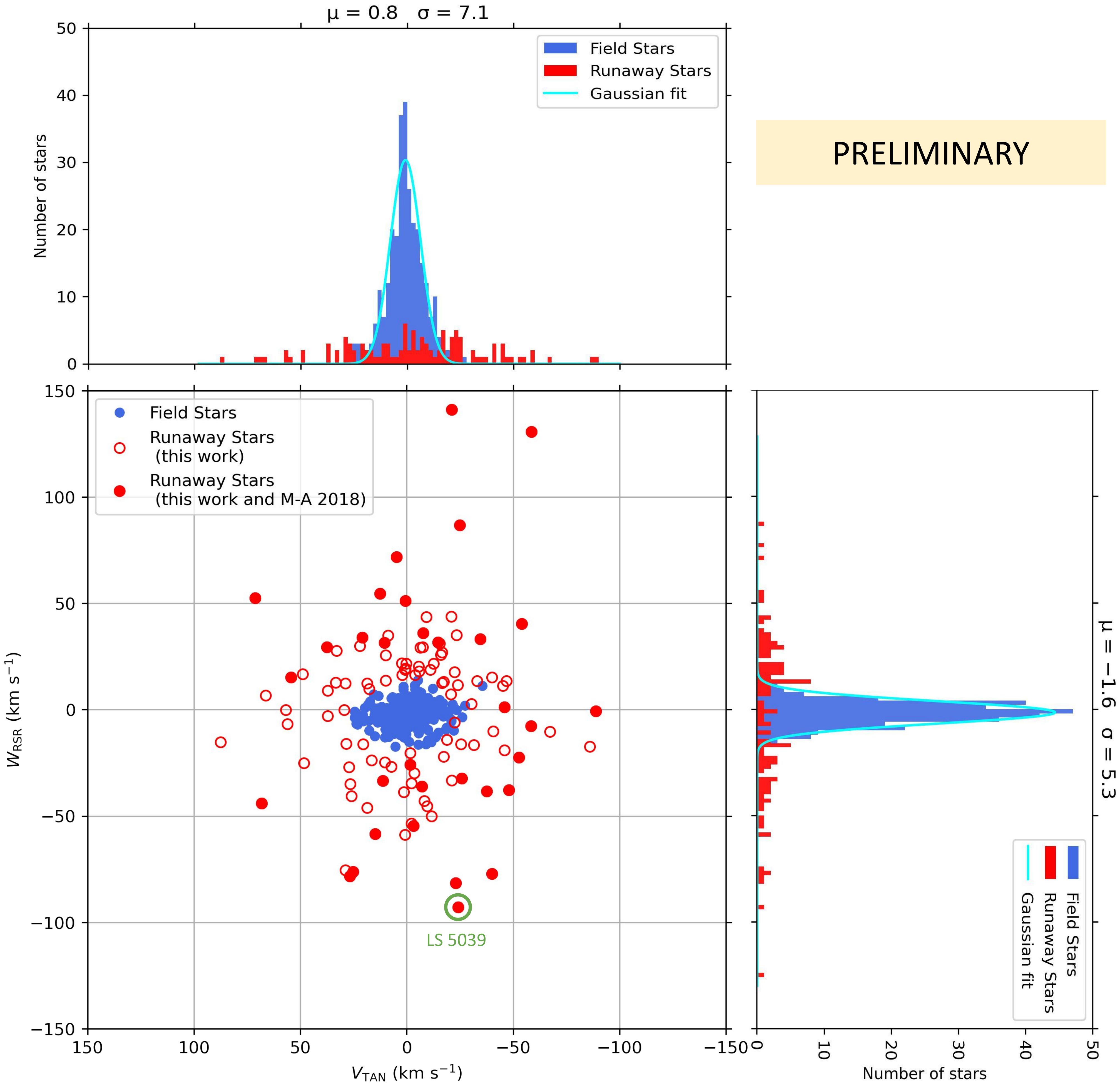
$$< Z >= -30 \pm 187 \text{ pc}$$

4. RESULTS: EDR3

- GOSC-*Gaia* EDR3 catalog consists of **407** stars
- Errors and W_{RSR}-standard deviation have decreased
- **111** runaway stars, **27%** of the GOSC-*Gaia* EDR3 catalog
- Peculiar velocities:

$$16 - 290 \text{ km s}^{-1}$$

(3-4 stars outside the plot range)



PRELIMINARY

5. CONCLUSIONS AND OUTLOOK

- Gamma-ray binaries with an O-type star present high peculiar velocities
- We have analyzed a sample of **643 early-type stars** to search for new gamma-ray binaries
- We have found **88** runaway stars with Gaia DR2 data
- **111** runaways with Gaia EDR3 data
- Some of them could be gamma-ray binaries

- Conduct a similar study with a Be-star catalog
- Publish the methodology and the obtained results with both catalogs
- Search for non-thermal emission in other catalogs
- Prepare future observations of selected sources (radial velocities, photometry, radio, X-rays, etc.)
- Conduct MAGIC and CTA observations

TAKE HOME MESSAGES

Searching for **runaway stars** → **discover new gamma-ray binaries**

111 **runaways** with Gaia EDR3 data → ❓ **new gamma-ray binaries**

Currently only **9** are **known**

THANK YOU FOR YOUR ATTENTION!

ANY QUESTIONS?

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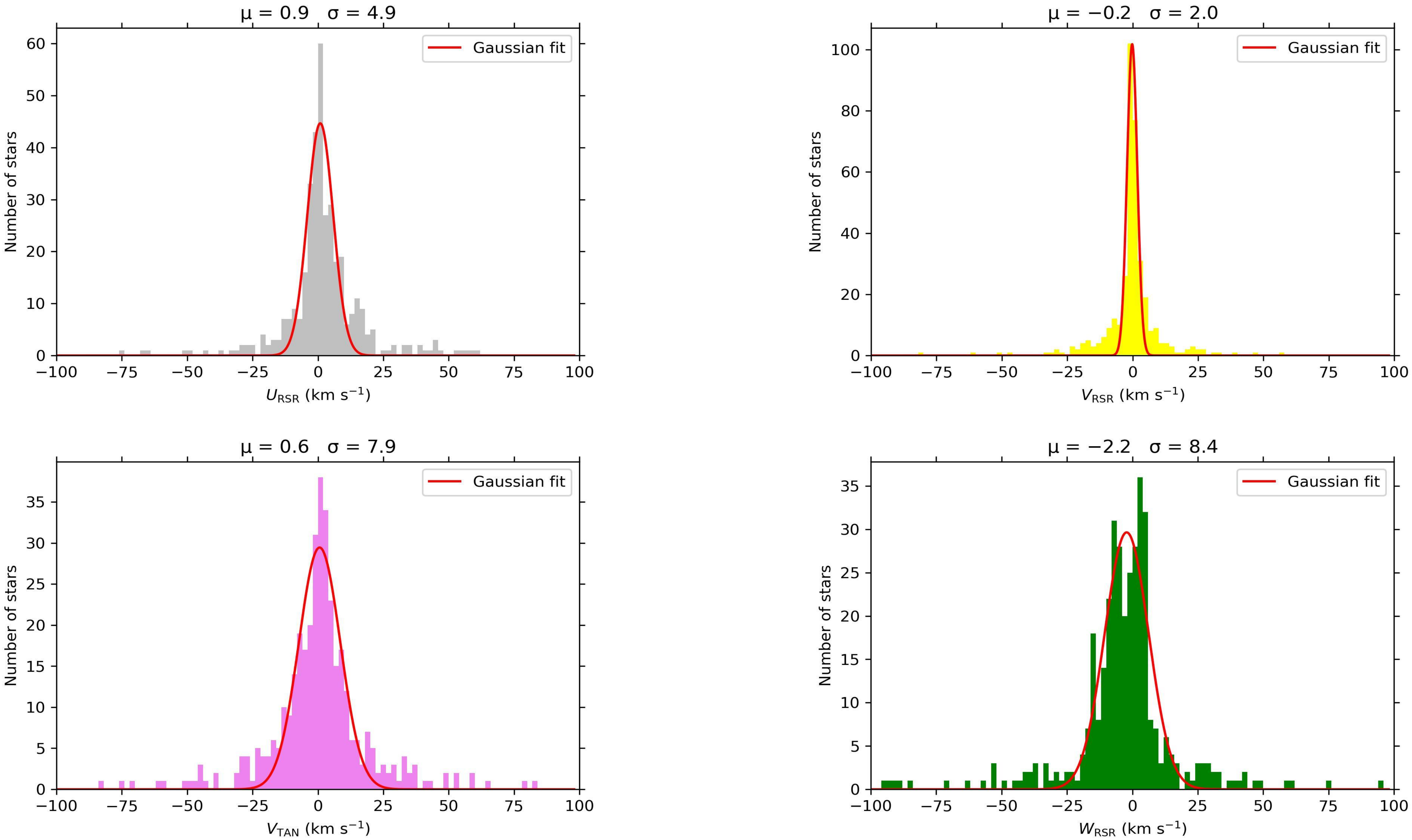
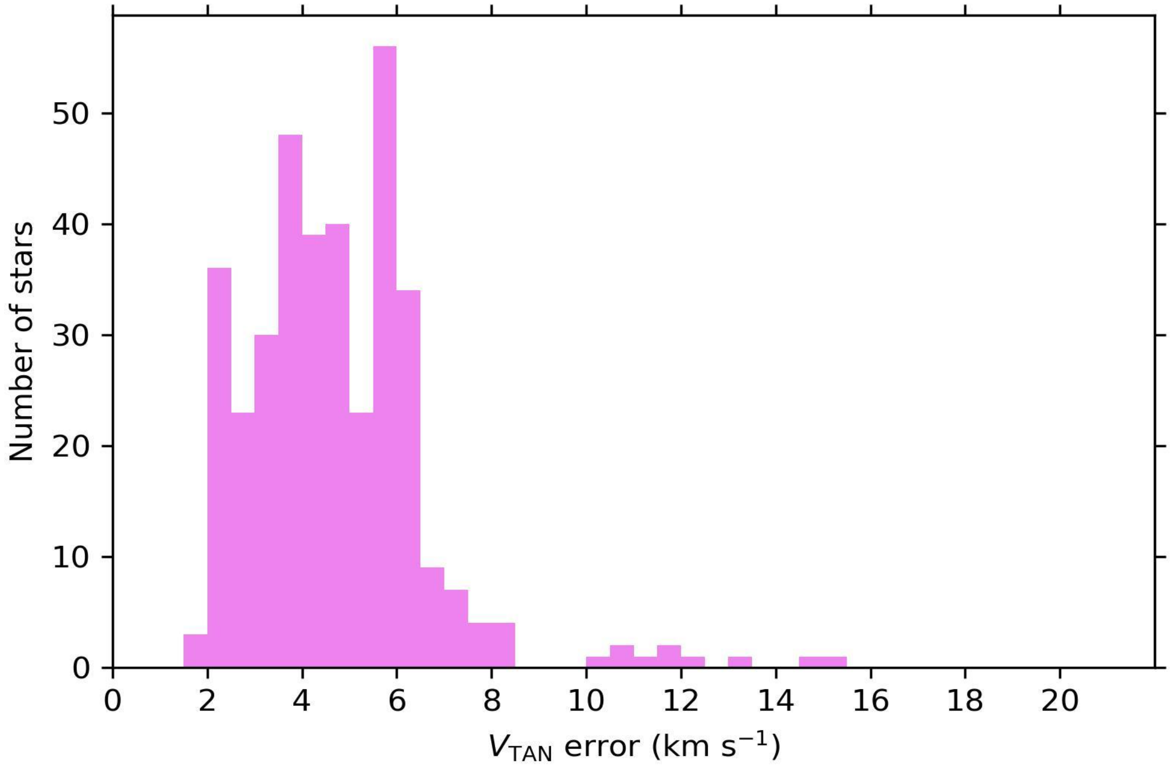
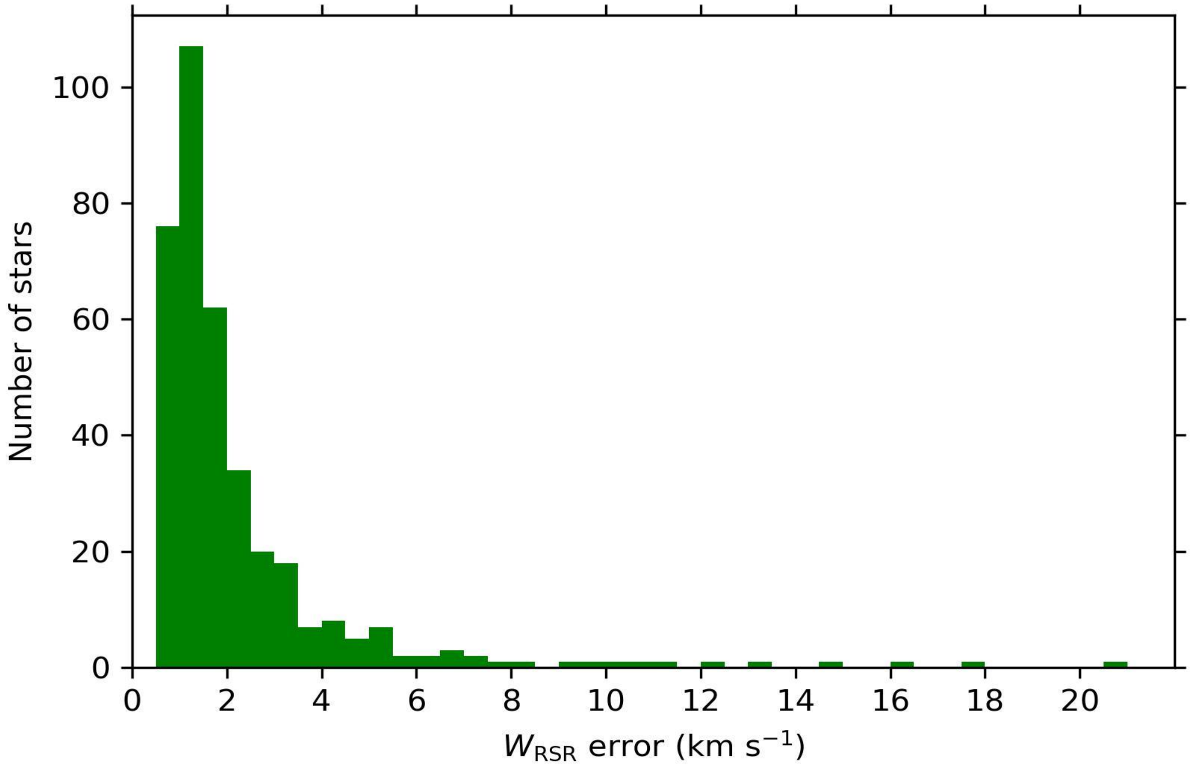
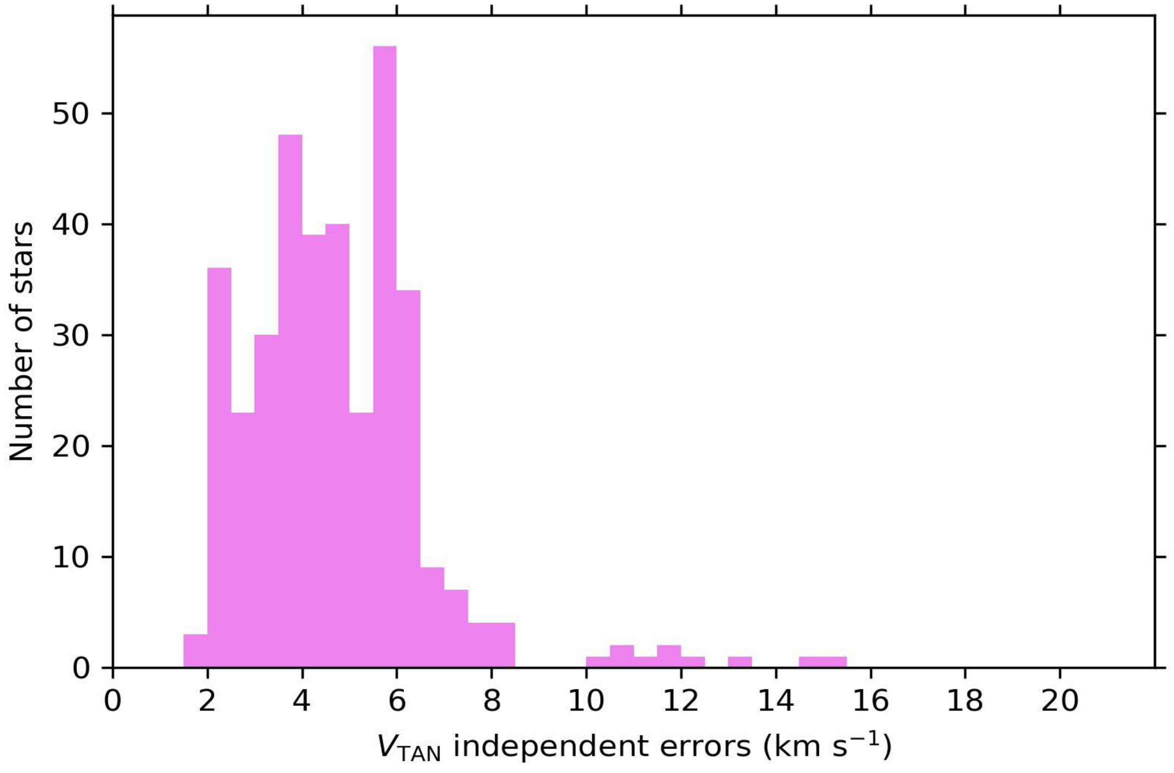
BACKUP

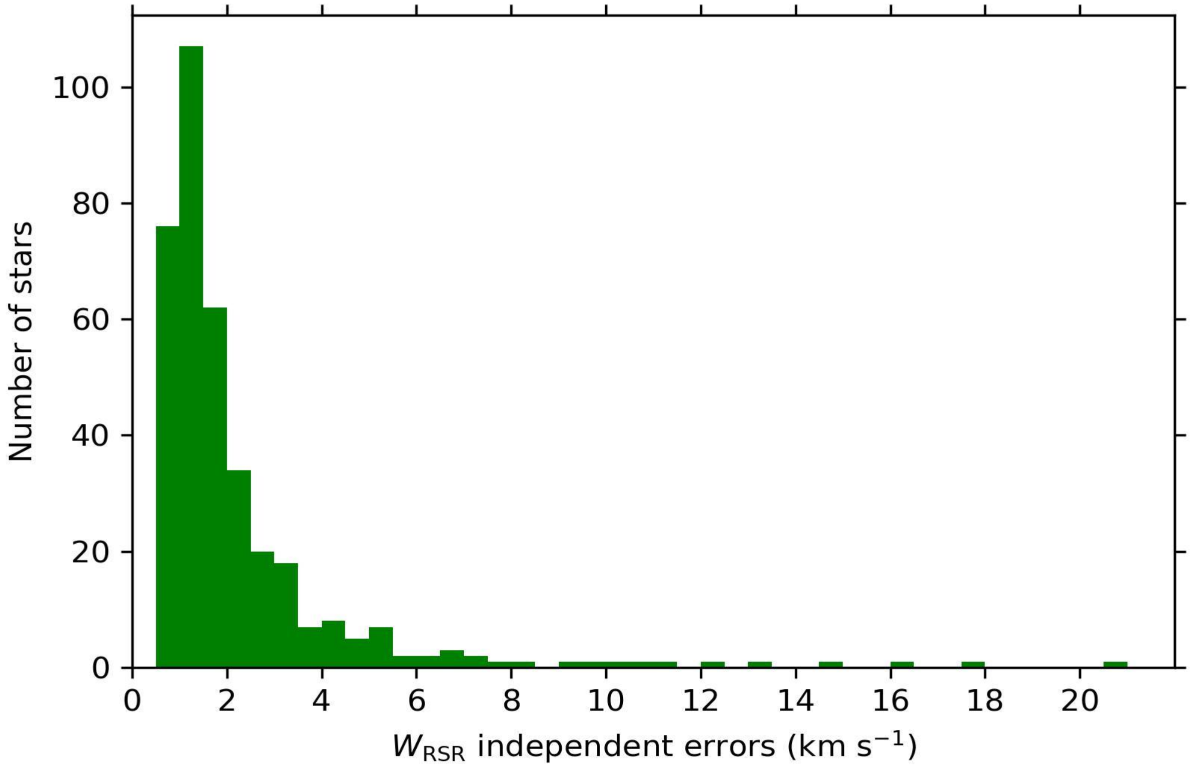

μ = 0.9 σ = 4.9
Gaussian fit
Number of stars
U_RSR (km s⁻¹)
μ = −0.2 σ = 2.0
Gaussian fit
Number of stars
V_RSR (km s⁻¹)
μ = 0.6 σ = 7.9
Gaussian fit
Number of stars
V_TAN (km s⁻¹)
μ = −2.2 σ = 8.4
Gaussian fit
Number of stars
W_RSR (km s⁻¹)

BACKUP

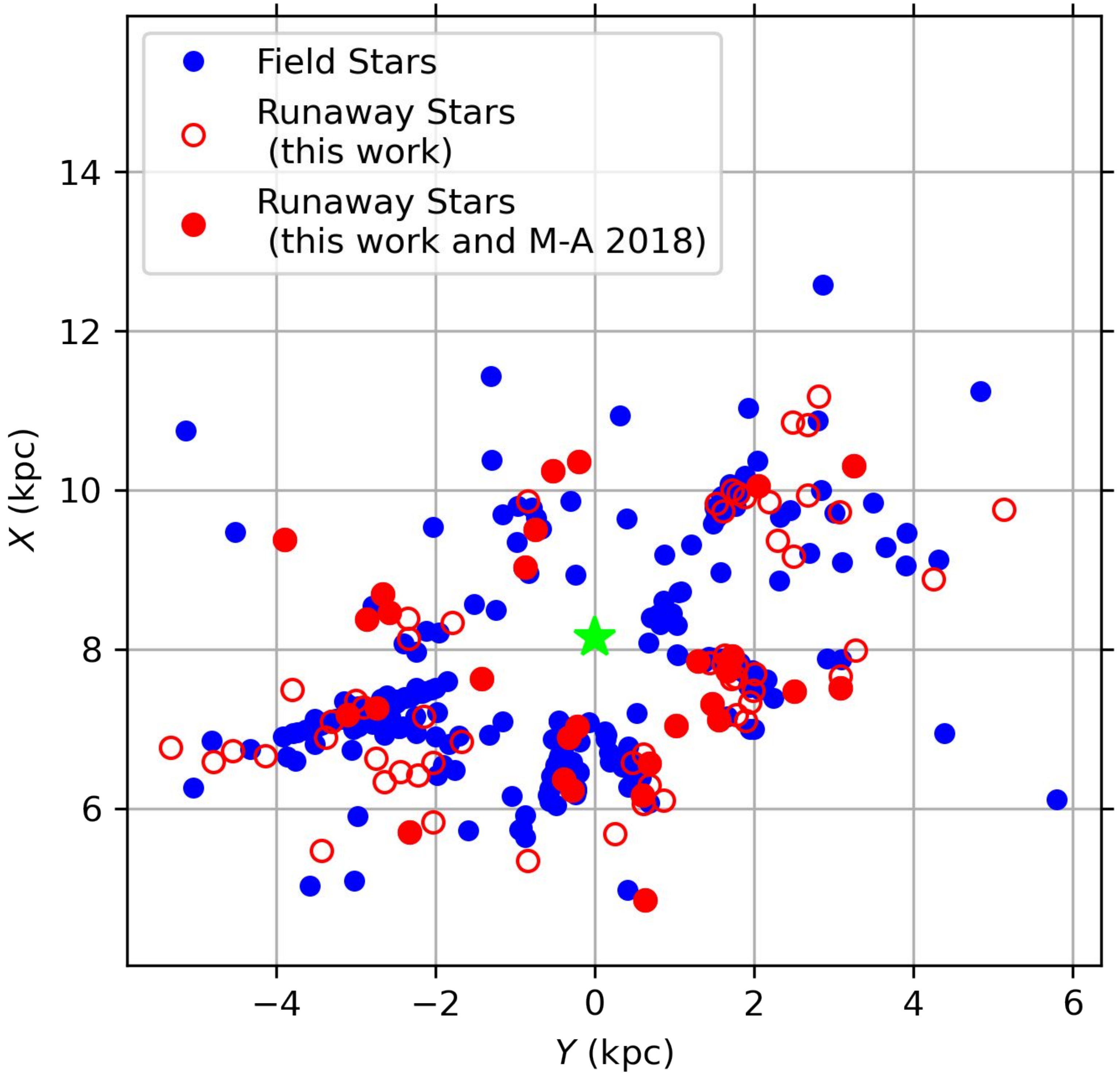

Number of stars
0
10
20
30
40
50
0 2 4 6 8 10 12 14 16 18 20
V_{TAN} error (km s^{-1})


Number of stars
0
20
40
60
80
100
0 2 4 6 8 10 12 14 16 18 20
W_{RSR} error (km s^{-1})

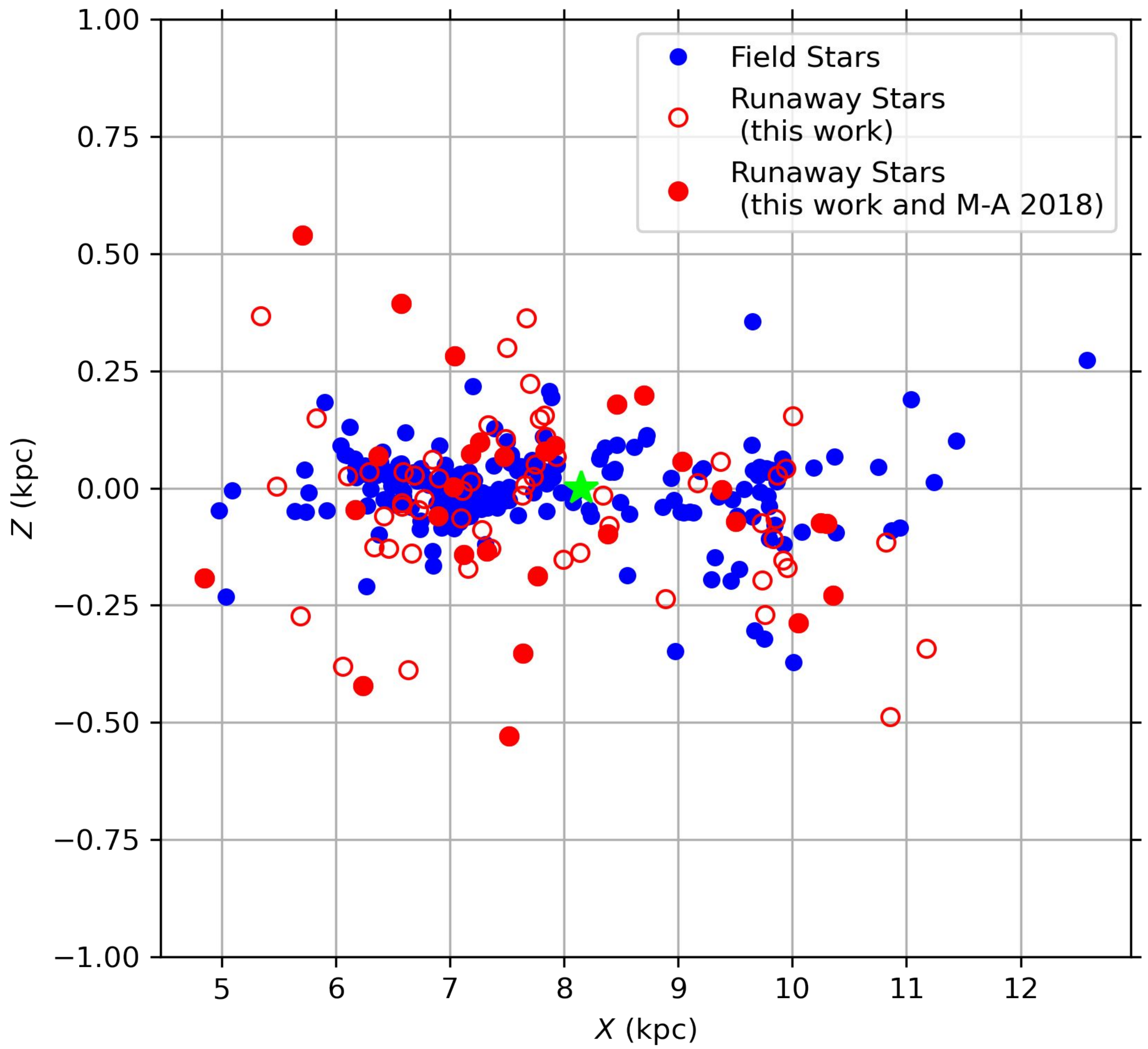

Number of stars
0
10
20
30
40
50
0 2 4 6 8 10 12 14 16 18 20
V_{TAN} independent errors (km s^{-1})

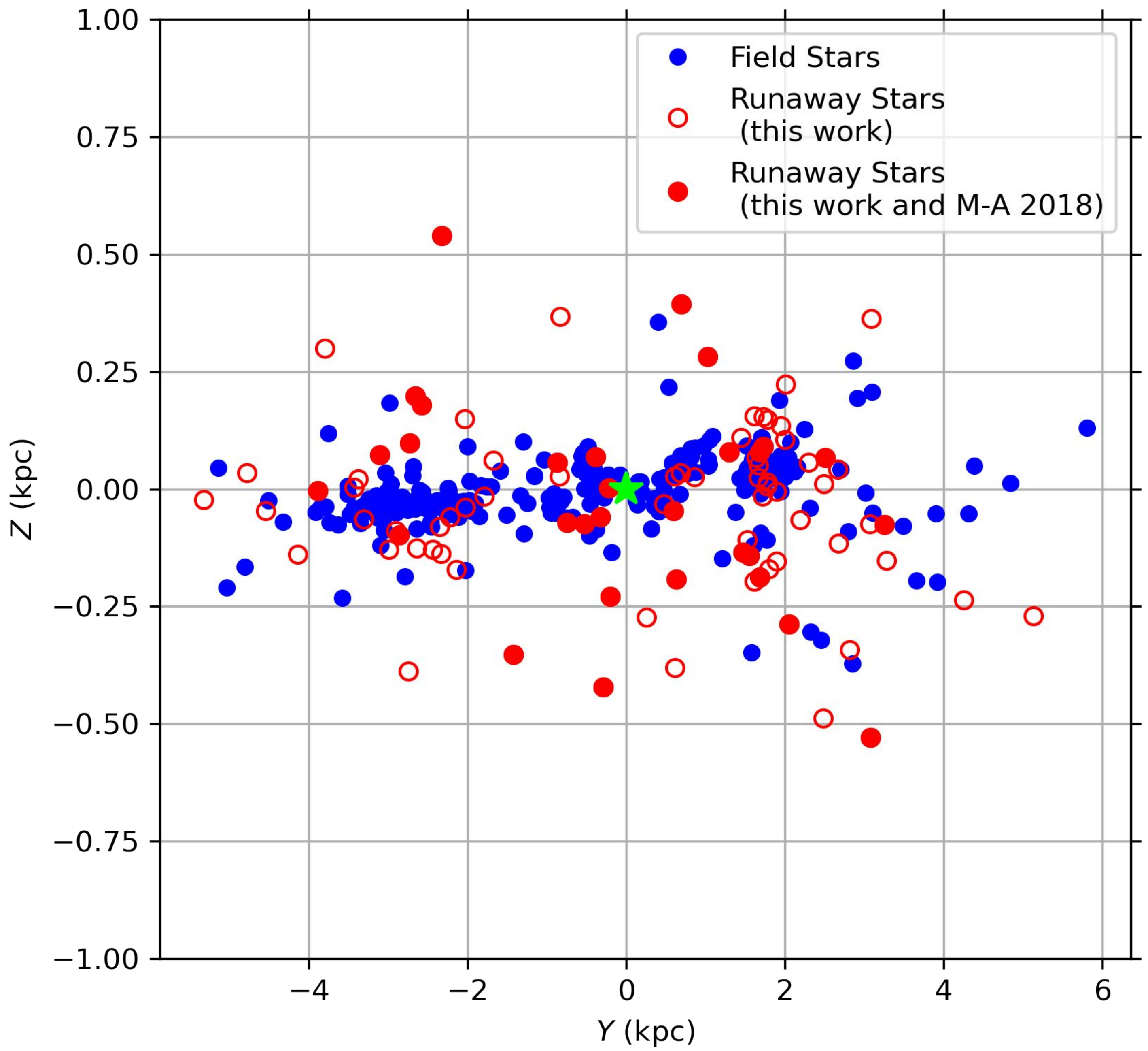

Number of stars
0
20
40
60
80
100
0 2 4 6 8 10 12 14 16 18 20
W_{RSR} independent errors (km s^{-1})

BACKUP

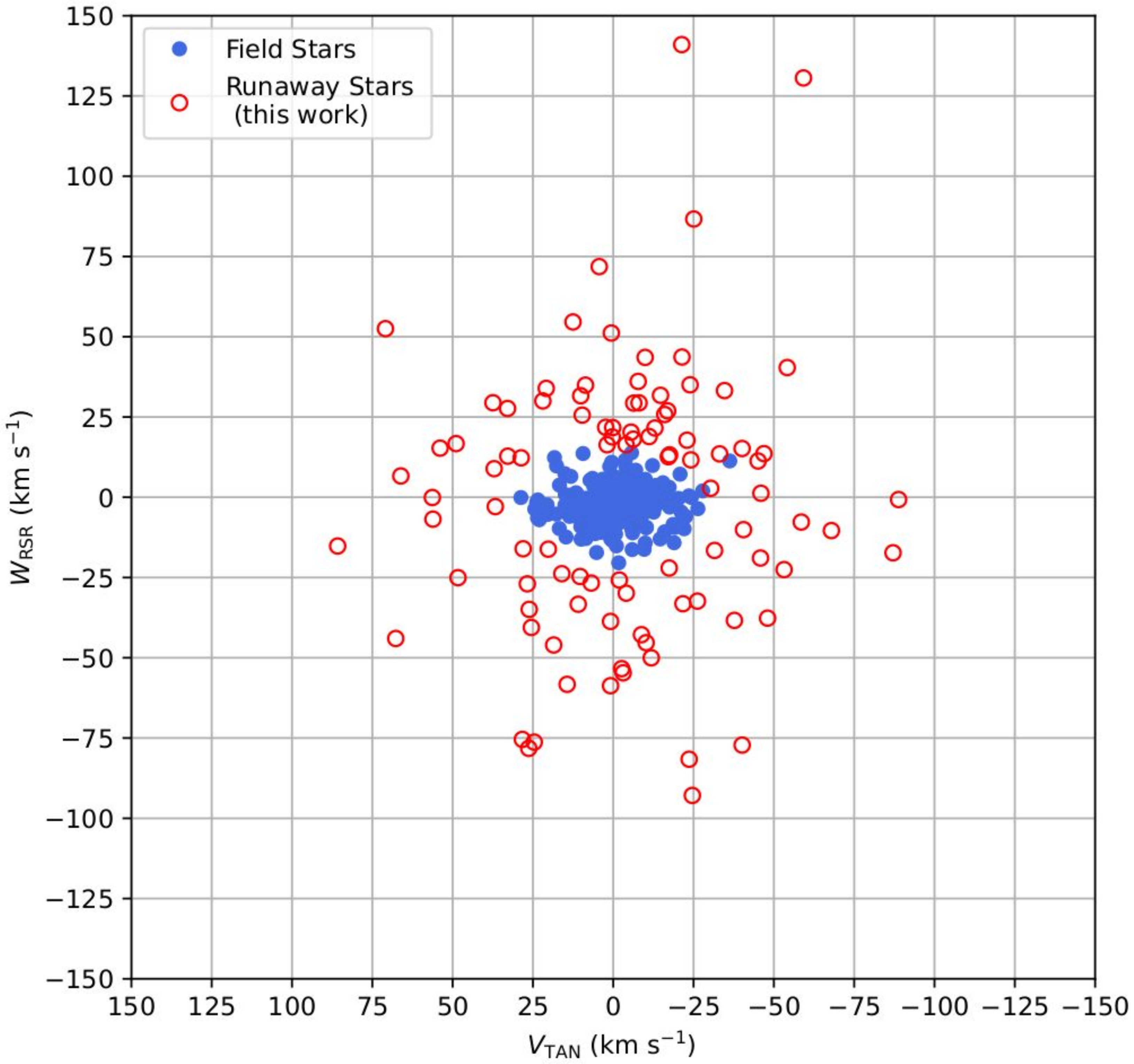

Field Stars
Runaway Stars
(this work)
Runaway Stars
(this work and M-A 2018)
14
12
10
8
6
−4
−2
0
2
4
6
X (kpc)
Y (kpc)

BACKUP

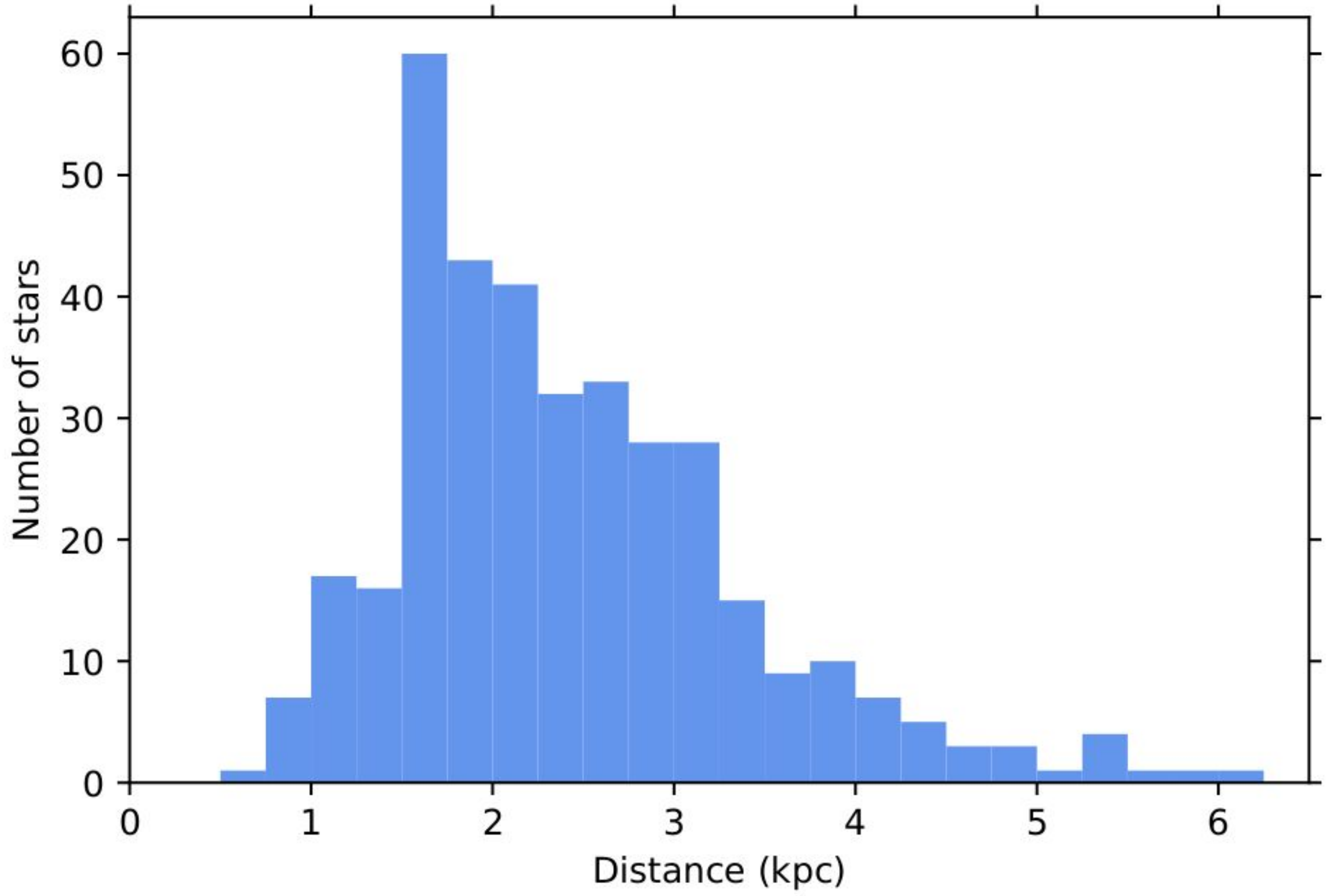

Field Stars
Runaway Stars
(this work)
Runaway Stars
(this work and M-A 2018)
Z (kpc)
X (kpc)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
5
6
7
8
9
10
11
12

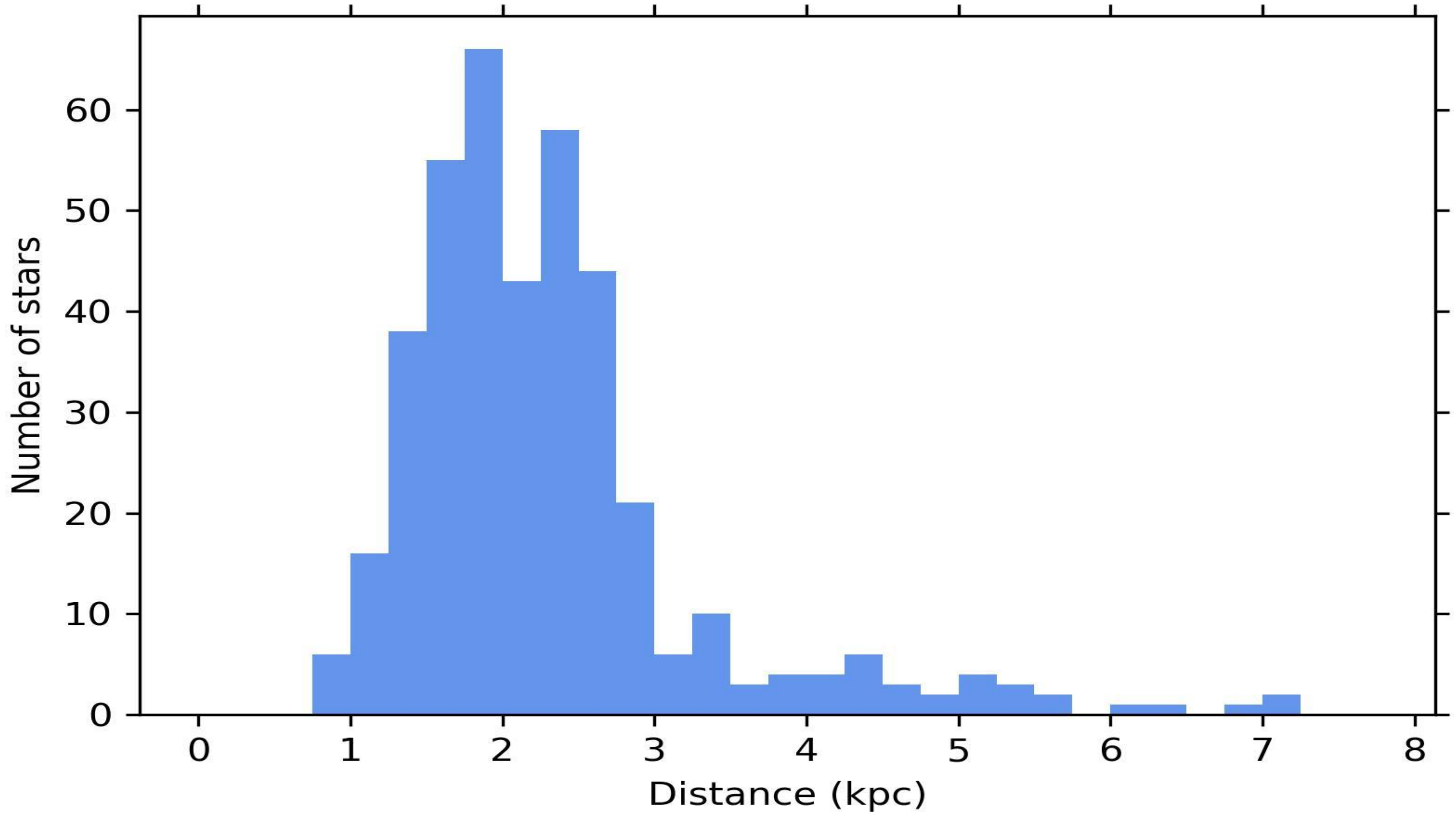

Field Stars
Runaway Stars
(this work)
Runaway Stars
(this work and M-A 2018)
Z (kpc)
Y (kpc)
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
−4
−2
0
2
4
6

BACKUP - EDR3


Field Stars
Runaway Stars
(this work)
W_{RSR} (km s^{-1})
V_{TAN} (km s^{-1})
150
125
100
75
50
25
0
−25
−50
−75
−100
−125
−150

BACKUP - GOSC-Gaia DR2 vs. GOSC-Gaia EDR3





BACKUP - DISCOVERY METHODS

Source	Discovery
PSR B1259-63	HESS periastron
PSR J2032+4127	MAGIC/VERITAS periastron
LS 5039	HESS GPS
LS I + 61 303	MAGIC targeted
HESS J0632+057	HESS GPS
1FGL J1018.6-5856	*Fermi*/LAT periodicity search
4FGL J1405.1-6119	*Fermi*/LAT periodicity search
HESS J1832-093	HESS GPS
LMC P3	*Fermi*/LAT periodicity search

5. PhD THESIS GOALS

SEARCH FOR NEW GAMMA-RAY BINARIES

- Search for runaway massive stars
- Search for non-thermal emission of the selected sources
- Multi-wavelength observations of the selected sources

MAGIC COLLABORATION

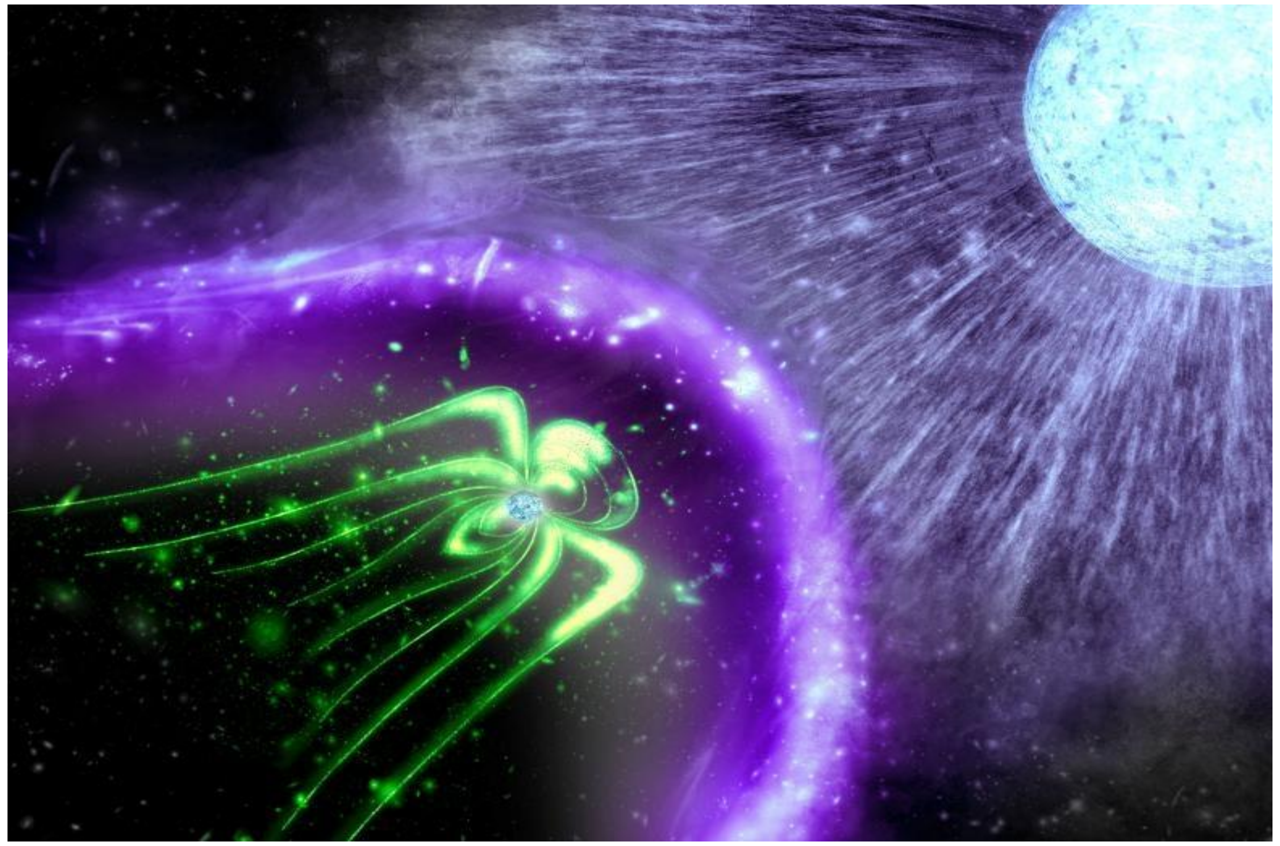
- Observations of transients phenomena
- TeV-detection of microquasars during the flaring state
- Analysis of Gamma-Ray Bursts (GRBs) data (eventually VLBI observations)
- Contributions to the MAGIC Flare Advocate Team

1. INTRODUCTION: GAMMA-RAY BINARIES

- Physical scenario:

Non-accreting pulsar

  - Young pulsar with a relativistic wind
  - Particle acceleration: shock between the pulsar and stellar winds or the Coriolis shock (see Bosch-Ramon et al. 2015)
  - Gamma-ray emission: inverse Compton scattering



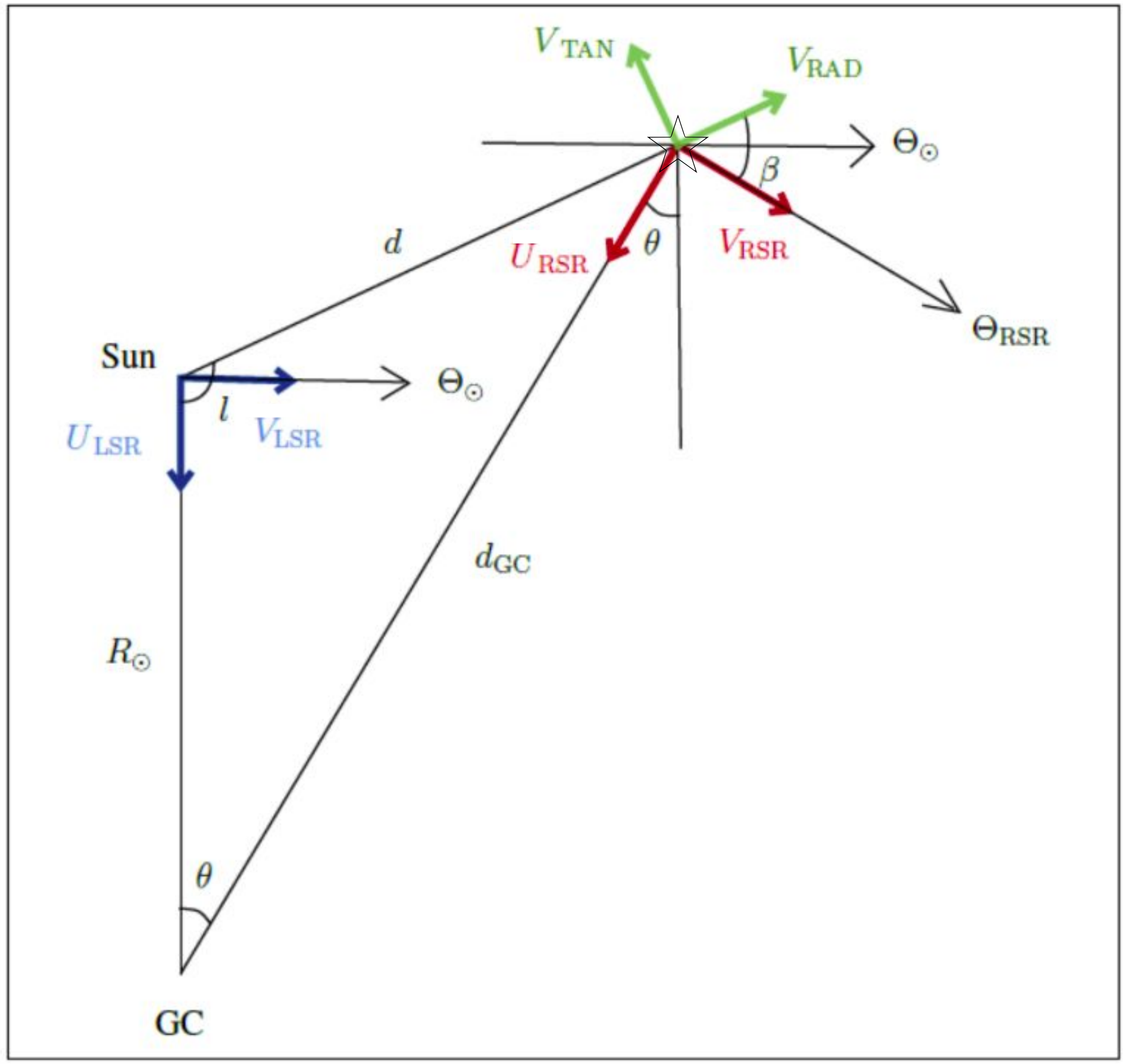
Credit: Kavli IPMU

Open questions

- Do all gamma-ray binaries contain pulsars?
- What are the relevant physical parameters?
- What is the actual population?
- Does it fit with the predictions of binary stellar evolution?
- Where and how is the GeV/TeV emission produced?
- …

3. METHODOLOGY: Searching for runaway stars

resolució imatge



Local Standard of Rest

- At the position of the Sun
- $(U_{\rm LSR}, V_{\rm LSR}, W_{\rm LSR})$

Regional Standard of Rest ← Reid et al. (2019) Galactic rotation curve

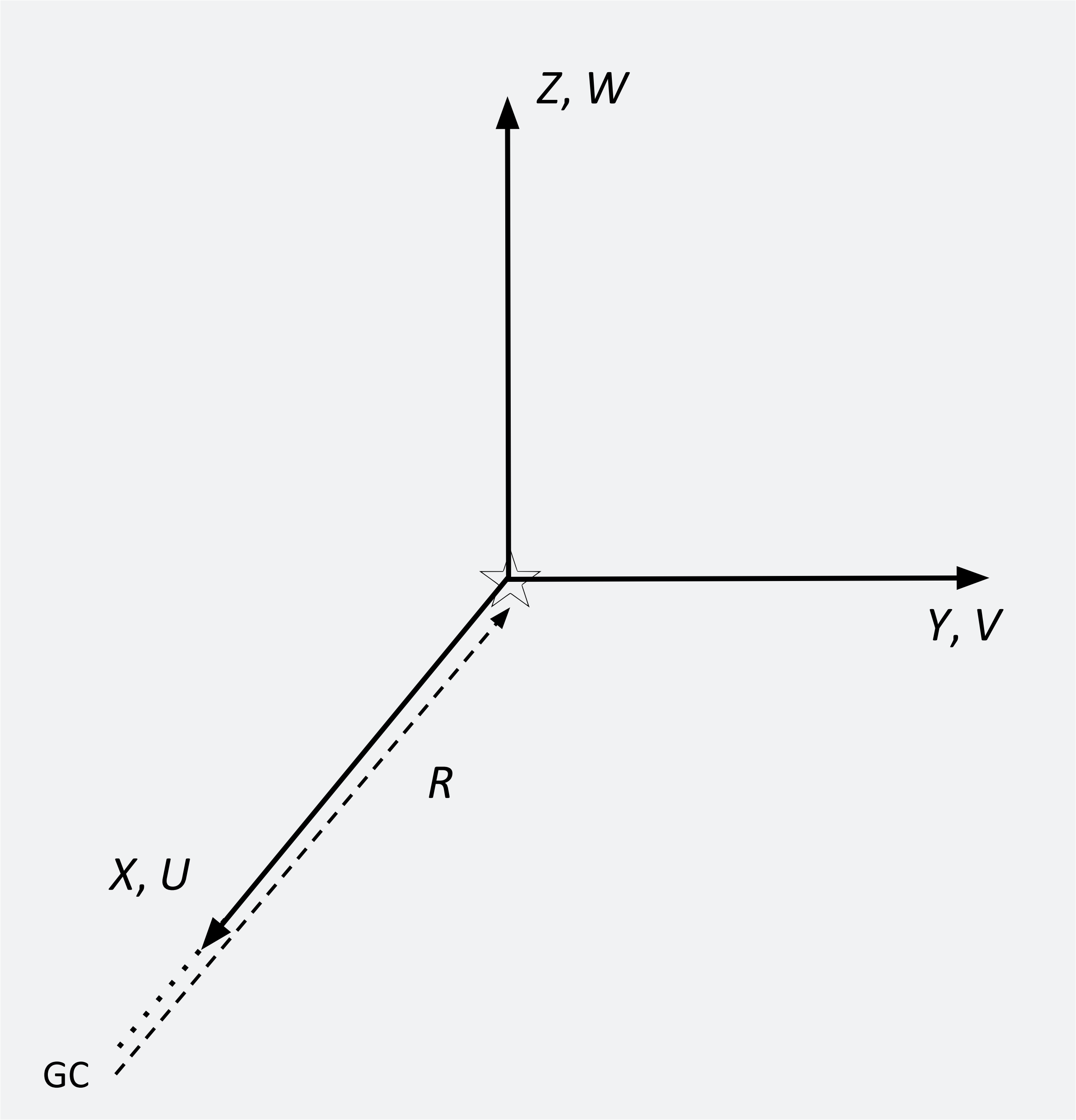
- At the position of the star
- $(U_{\rm RSR}, V_{\rm RSR}, W_{\rm RSR})$

New Reference System

- To separate the radial velocity contribution
- $(V_{\rm TAN}, V_{\rm RAD}, W_{\rm RSR})$

3. METHODOLOGY: Searching for runaway stars

Galactocentric coordinates



Galactic rotation curve

Reid et al. (2019)