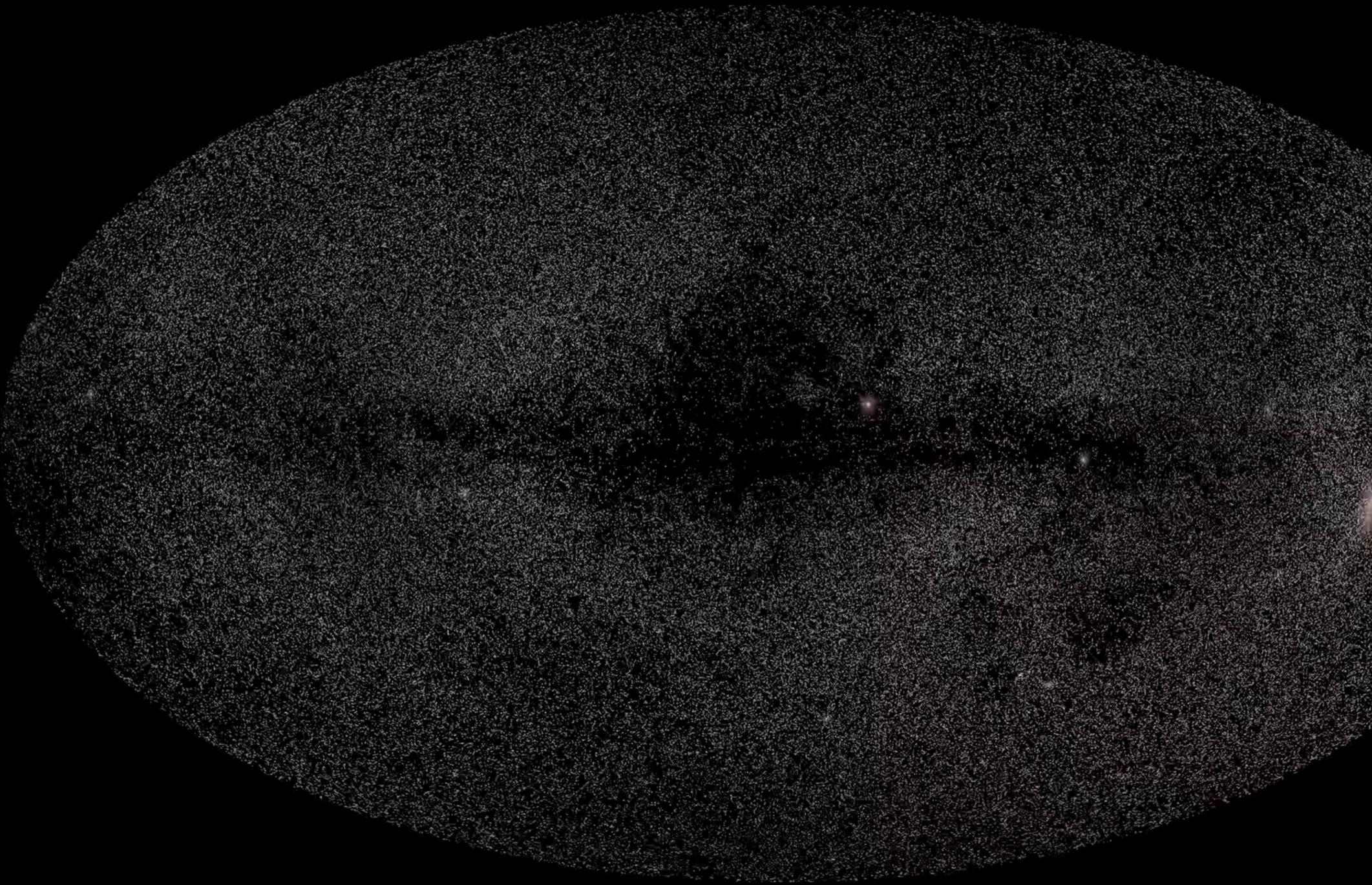


The velocity distribution of white dwarfs in Gaia EDR3

Daniel Mikkola



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY
MNRAS 000, 000–000 (2022)
Advance Access publication 2022 February 22

https://doi.org/10.1093/mnras/stz344

The velocity distribution of white dwarfs in *Gaia* EDR3

Daniel Mikkola,^{1*} Paul J. McMillan,² David Hobbs¹ and John Wimarsson^{1,2}

¹Lund Observatory, Department of Astronomy and Theoretical Physics, Lund University, Box 43, SE-22100 Lund, Sweden
²Space Research & Planetary Sciences, Physics Institute, University of Bern, Gesellschaftsstrasse 6, CH-3012 Bern, Switzerland

Accepted 2022 February 14; Received 2022 March 8; in original form 2021 October 25

ABSTRACT
Using a penalized maximum likelihood, we estimate, for the first time, the velocity distribution of white dwarfs in the solar neighbourhood. Our sample consists of 129 675 white dwarfs within 500 pc in *Gaia* Early Data Release 3. The white dwarf velocity distributions reveal a similar structure to the rest of the solar neighbourhood stars, reflecting that white dwarfs are subject to the same dynamical processes. In the velocity distribution for three magnitude-binned subsamples, we, however, find a novel structure at $(U, V) = (7, -19)$ km s⁻¹ in fainter samples, potentially related to the Coma Berenices stream. We also see a double-peaked feature in $U - W$ at $U \approx -30$ km s⁻¹ and in $V - W$ at $V \approx -20$ km s⁻¹ for fainter samples. We determine the velocity distribution and velocity moments as a function of absolute magnitude for two samples based on the bifurcation identified in *Gaia* Data Release 2 in the colour–magnitude diagram. The brighter, redder sequence has a larger velocity dispersion than the fainter, bluer sequence across all magnitudes. It is hard to reconcile this kinematic difference with a bifurcation caused purely by atmospheric composition, while it fits neatly with a significant age difference between the two sequences. Our results provide novel insights into the kinematic properties of white dwarfs and demonstrate the power of analytical techniques that work for the large fraction of stars that do not have measured radial velocities in the current era of large-scale astrometric surveys.

Key words: methods: data analysis – methods: statistical – stars: kinematics and dynamics – Galaxy: kinematics and dynamics – solar neighbourhood – Galaxy: structure.

1 INTRODUCTION

The present-day structure and the history of the Galaxy are encoded not just in the positions of its stars but also in their kinematics. It is well established that the present velocity distribution in the solar neighbourhood has a great deal of structure in it (e.g. *Gaia* Collaboration 2018c) for which there are multiple possible causes. Suggested origins for overdensities include dissolving open clusters, resonances from large-scale density waves such as the Galactic bar and spiral arms, accreted populations from galaxy mergers, and phase mixing from nearby satellite galaxies (e.g. Antoja et al. 2012; Kuchniruk, Schirmer & Bensby 2017). Understanding this substructure is a part of understanding the dynamical history of the Milky Way.

The phase-space distribution of stars within the Milky Way has been studied extensively over the last decades (see *Gaia* Collaboration 2018c and references therein) to reveal this complicated structure, especially since the *Hipparcos* mission (Perryman et al. 1997) and more so with its successor *Gaia*'s (*Gaia* Collaboration 2016) recent second and third data release (henceforth DR2 and EDR3, respectively; *Gaia* Collaboration 2018a, 2021a).

The astrometry of *Gaia* provides proper motions and positions for ~ 1.5 billion sources with great precision, which is an enormous leap forward from its predecessor, which observed $\sim 120\,000$ sources. The *Gaia* data have only been available for a few years but the potential for kinematic study has already been demonstrated. For example, Bovy (2017) accurately measured the Oort constants A and B as well as for the first time the non-axisymmetric constants C and K . In Monari et al. (2018), it was shown that the moving group Coma Berenices is limited to negative Galactic latitudes and likely has not undergone phase mixing in the Galactic potential. The kinematic structure of the solar neighbourhood has been studied in unprecedented detail to reveal many new and old structures (e.g. Kuchniruk et al. 2017; *Gaia* Collaboration 2018c) as well as arches (Antoja et al. 2018). Beyond velocity space, the solar neighbourhood has also been explored in orbit space (e.g. Trice, Cofino & Rix 2019; Trice et al. 2021; Trice 2022), showing ridges which can manifest themselves as streams and structures in velocity space. Understanding the kinematic substructure of the Galaxy will require exploration in both velocity and orbit space, which becomes far more accessible due to the wealth of data provided by missions such as *Gaia*.

Even though EDR3 provides accurate astrometry and photometry for a great number of sources, it does not contain full 3D phase-space information for all of them as some lack measured radial velocity. This means that for most individual stars only the position and proper motions are available as in the *Hipparcos* catalogue. In fact, the number of sources with radial velocities in *Gaia* EDR3, ~ 7.2 million, is dwarfed by the number of sources with at least position and proper motions, ~ 1.5 billion. This means that the radial

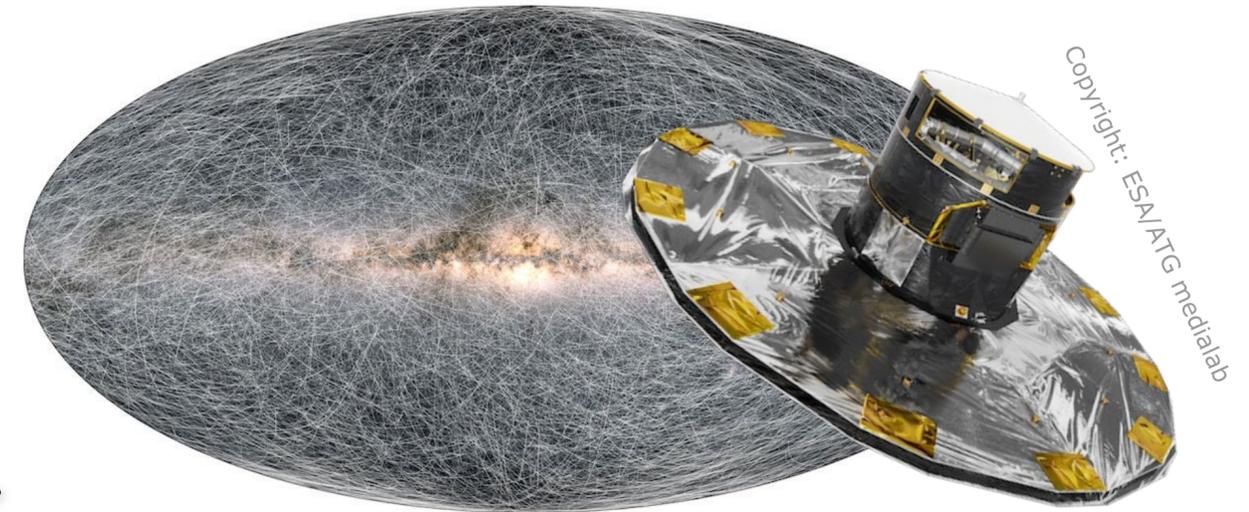
* E-mail: mikkola@astro.lu.se

© The Author(s) 2022.
Published by Oxford University Press on behalf of Royal Astronomical Society. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution, and reproduction in any medium, provided the original work is properly cited.

Gaia (E)DR3

Gaia (2013 -): “An ambitious mission to chart a three-dimensional map of our Galaxy

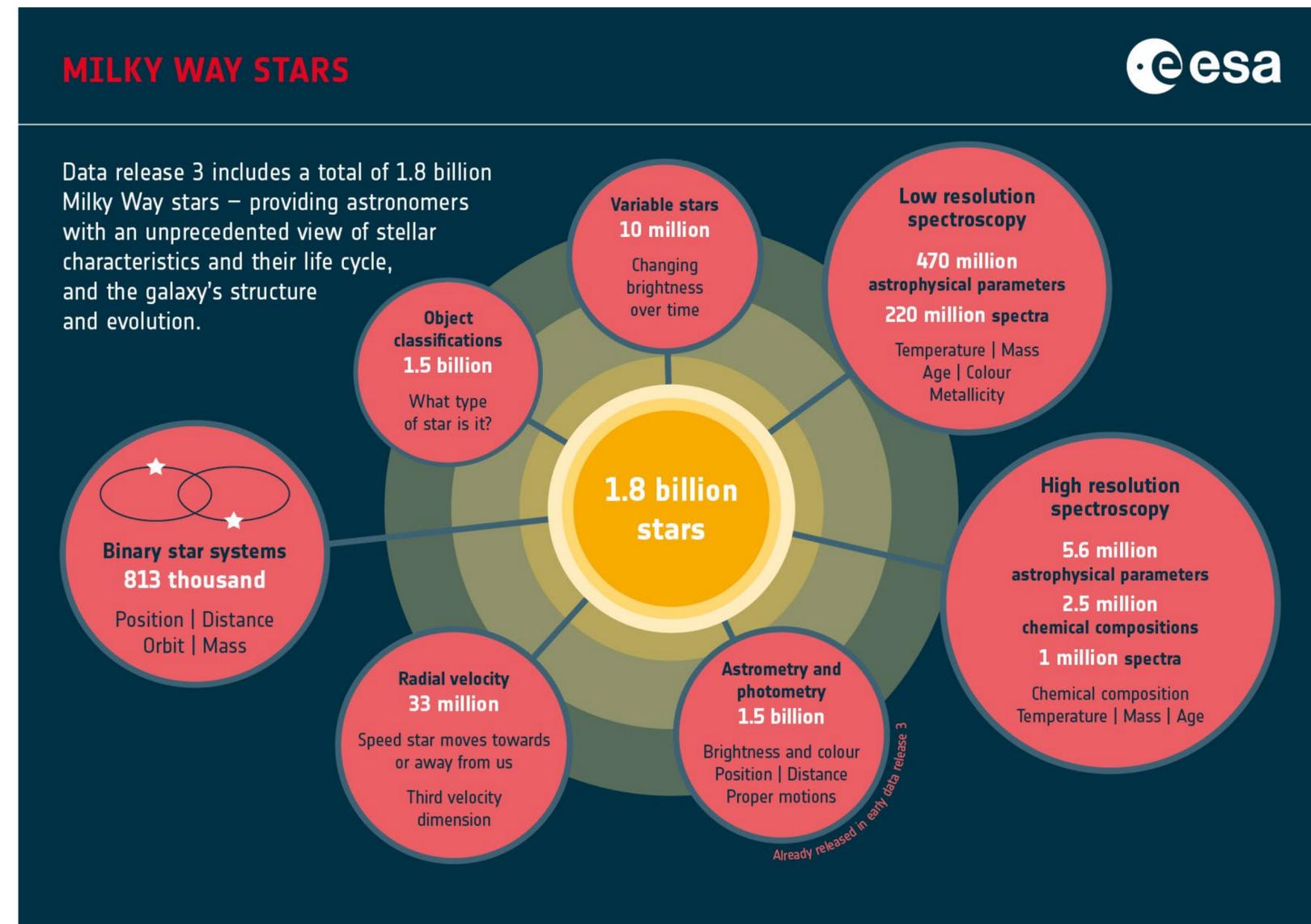
- In EDR3 ~1.5 billion sources with position, parallax and proper motion.
- ~7 million have radial velocities
- in DR3: ~34 million



Most sources lack 6D phase-space coordinates

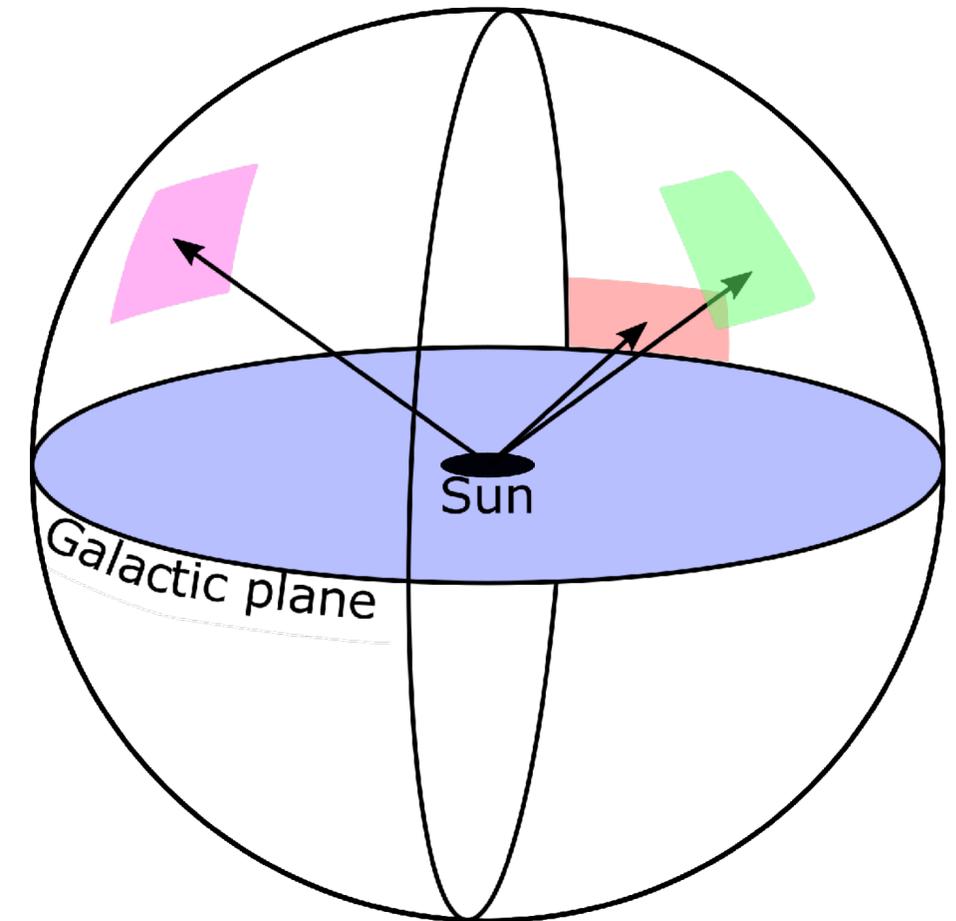
Useful to work with only the astrometry

See also: McMillan et al. (2022)

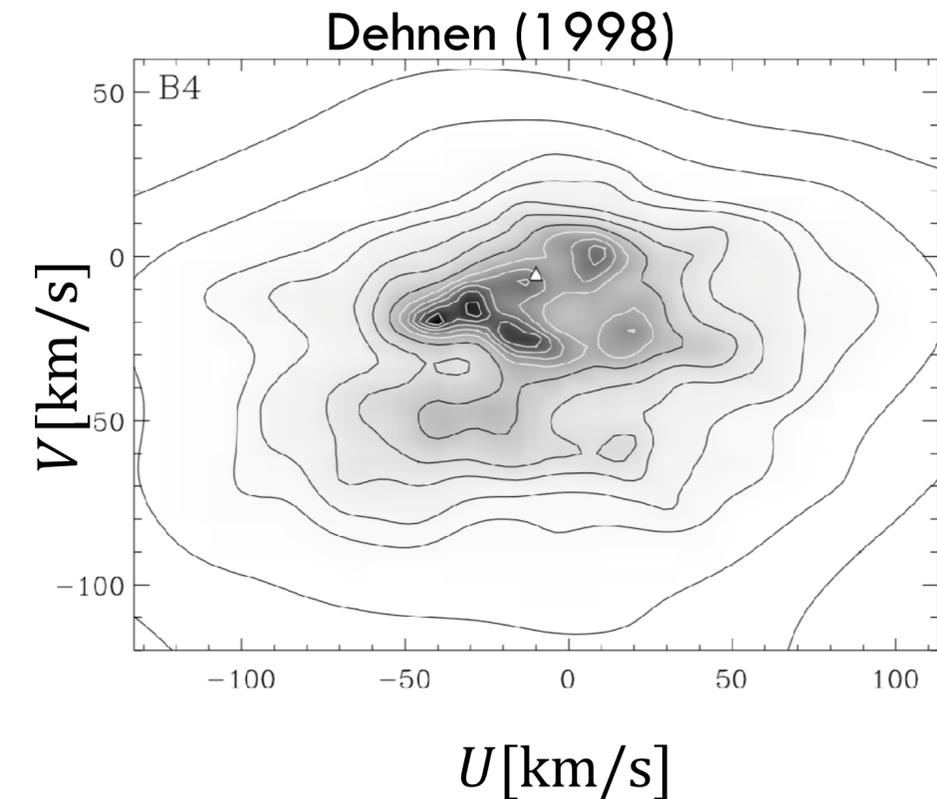


Working without RVs - What can we do?

- Hipparcos kinematics (Dehnen & Binney 1998)
 - Mean velocities $\langle \mathbf{v} \rangle$
 - Velocity dispersions σ
- Hipparcos velocity distributions (Dehnen 1998)
 - Estimate $f(\mathbf{v})$ from position and tangential velocities

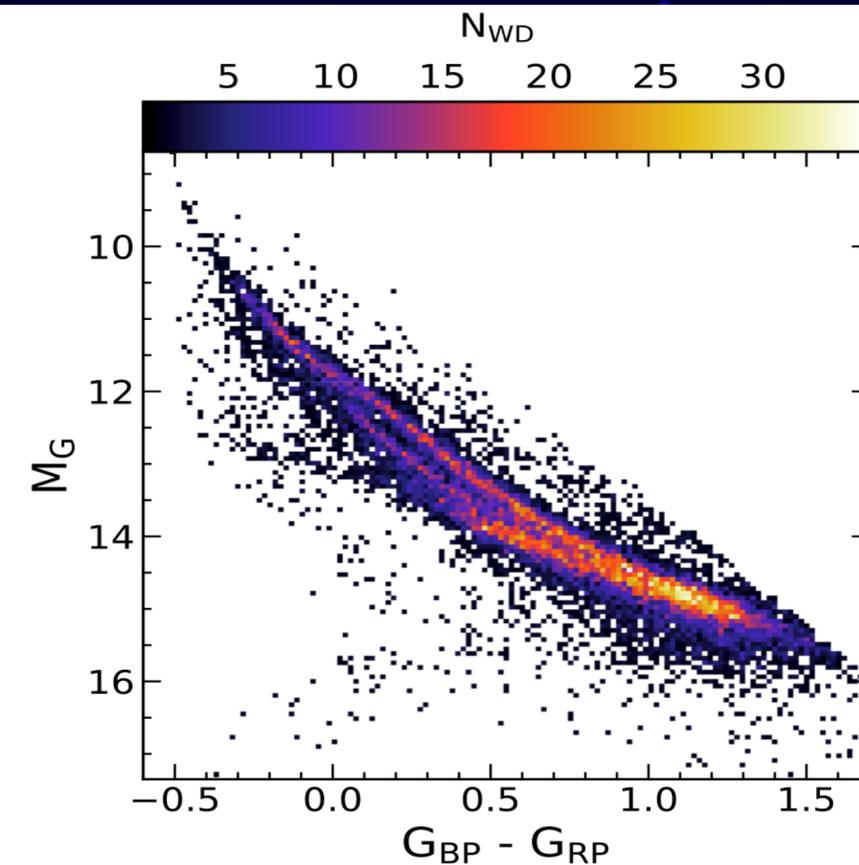
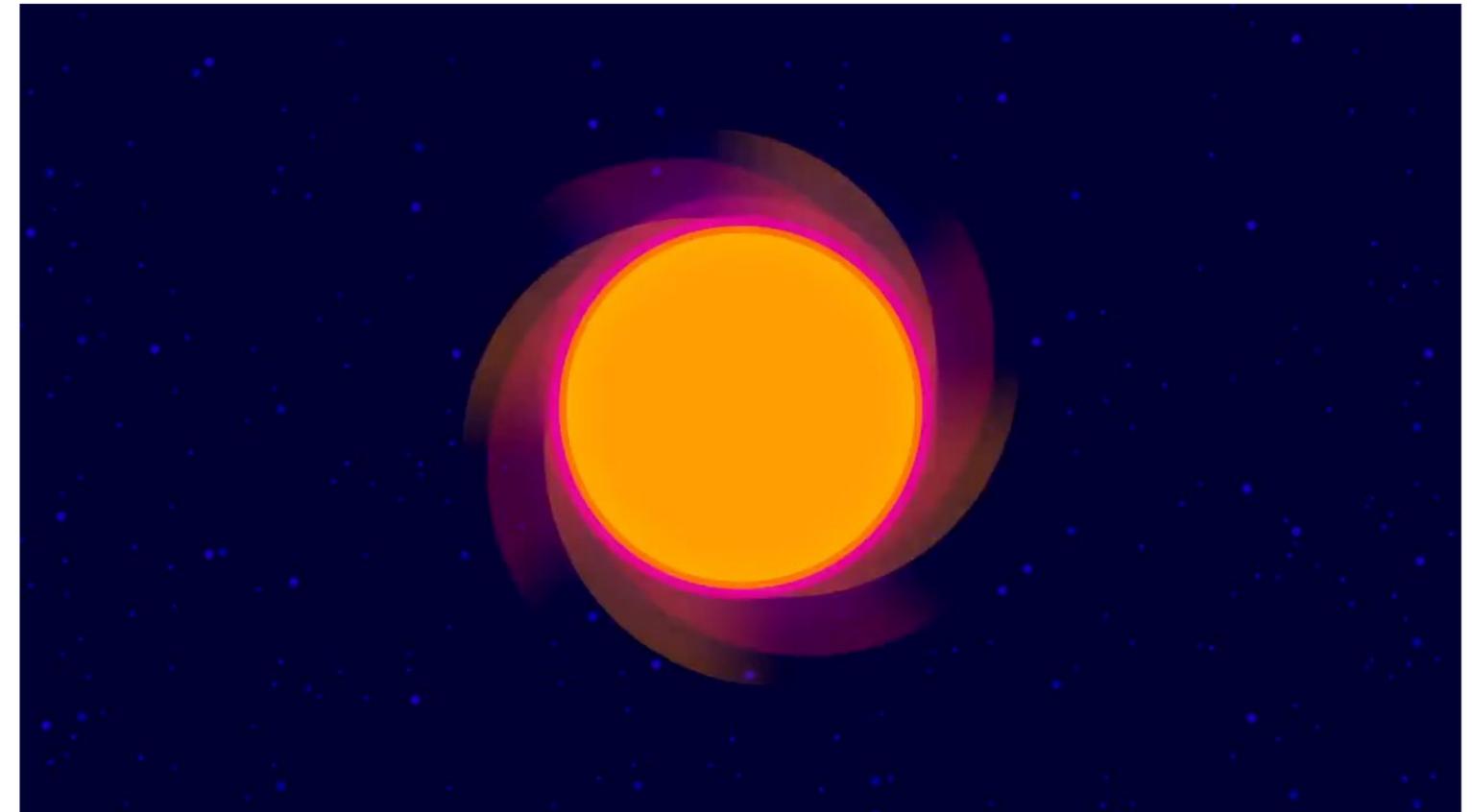


We must assume that $f(\mathbf{v})$ is constant across the volume in question
☞ local approximation

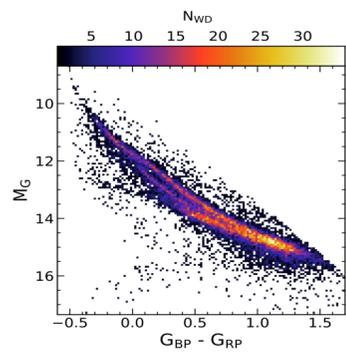


White dwarfs

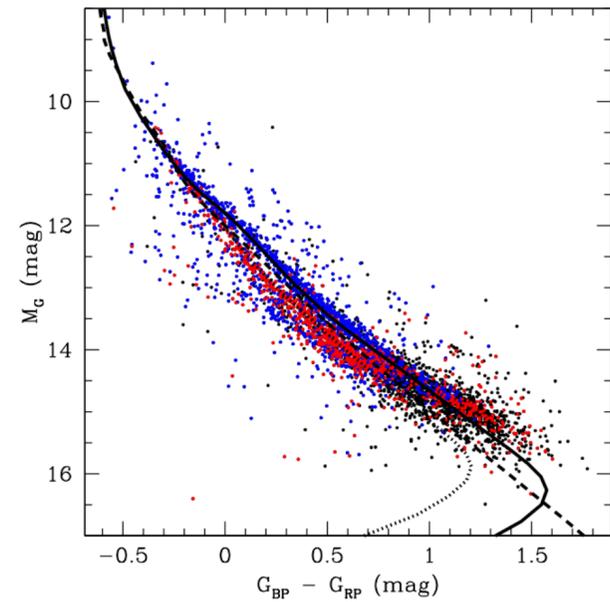
- WDs are faint and difficult to observe
 - Hard to measure radial velocities
 - Inferring $f(v)$ from astrometry provides the largest sample of WDs to date (1 29 675).
- WD CMD from Gaia DR2 shows bifurcation
 - between $M_G \sim 12 - 14$



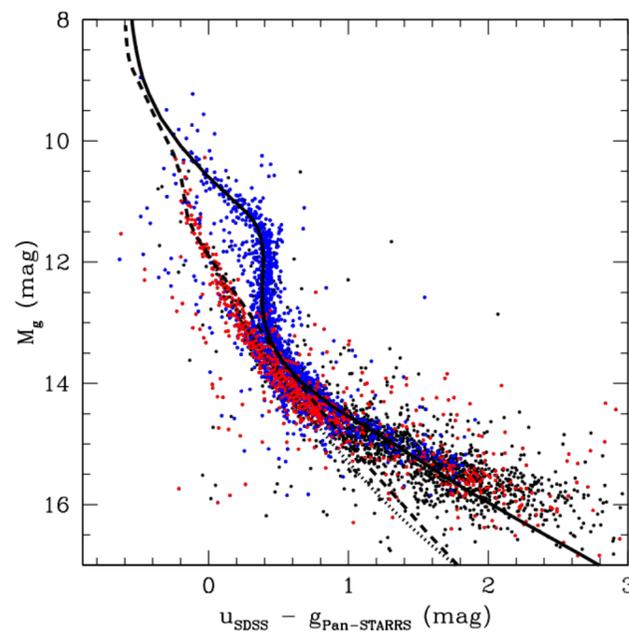
The bifurcation - explanations



Atmospheric composition

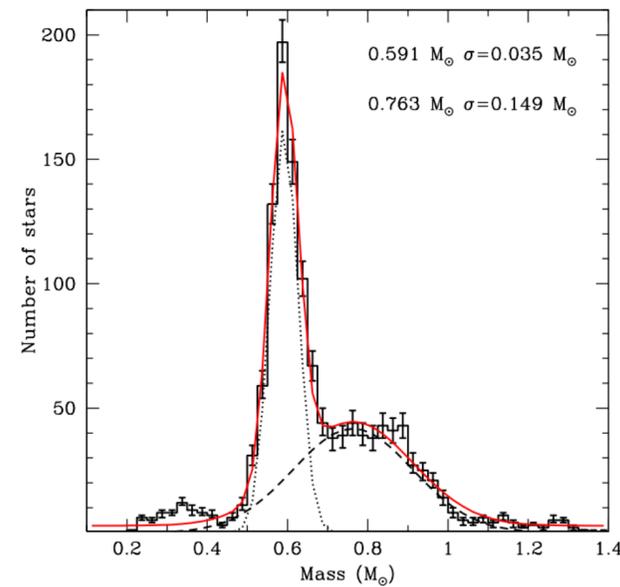


Kilic et al. (2020)



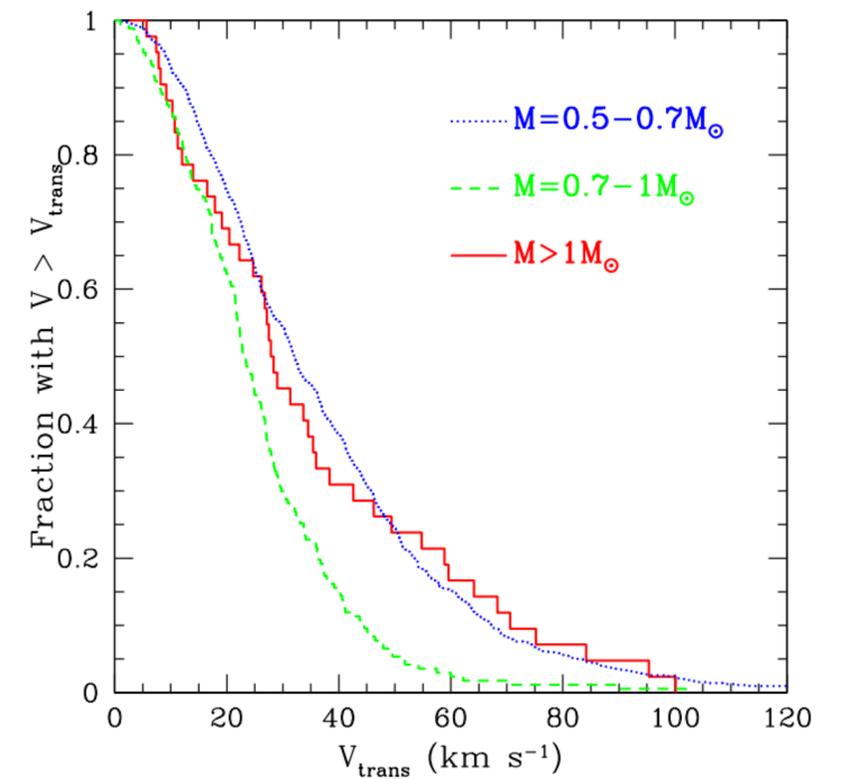
Bimodal masses

Kilic et al. (2020)

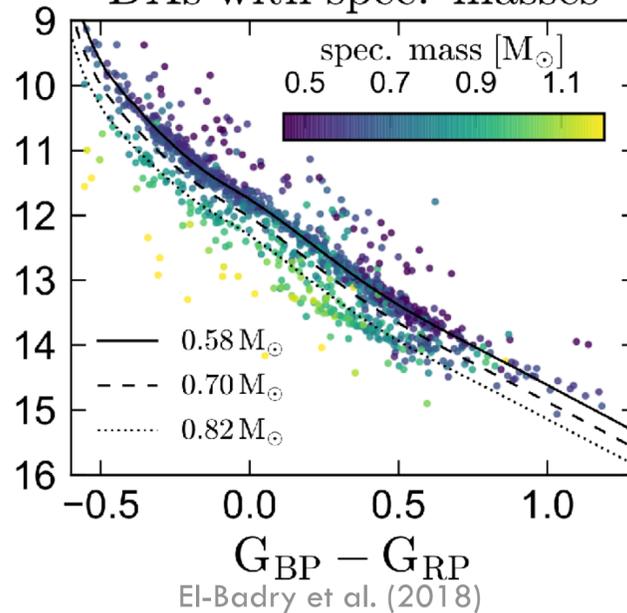


Mergers

Kilic et al. (2020)



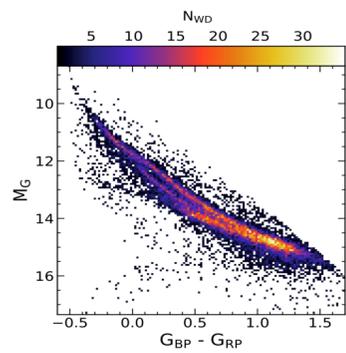
DAs with spec. masses



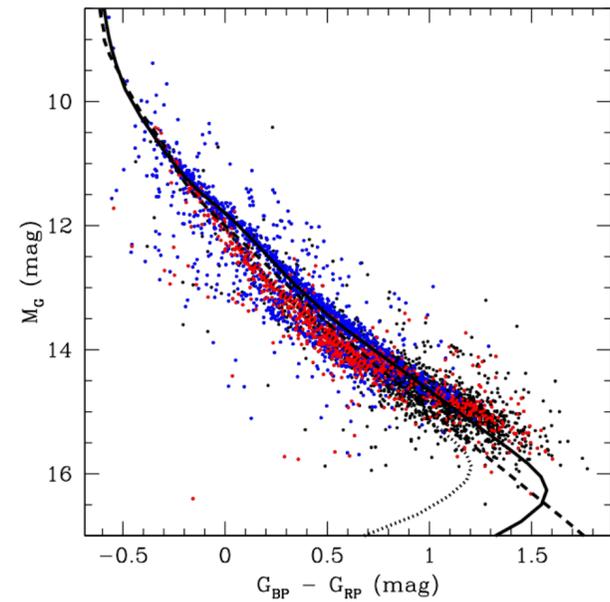
El-Badry et al. (2018)

IAUGA2022

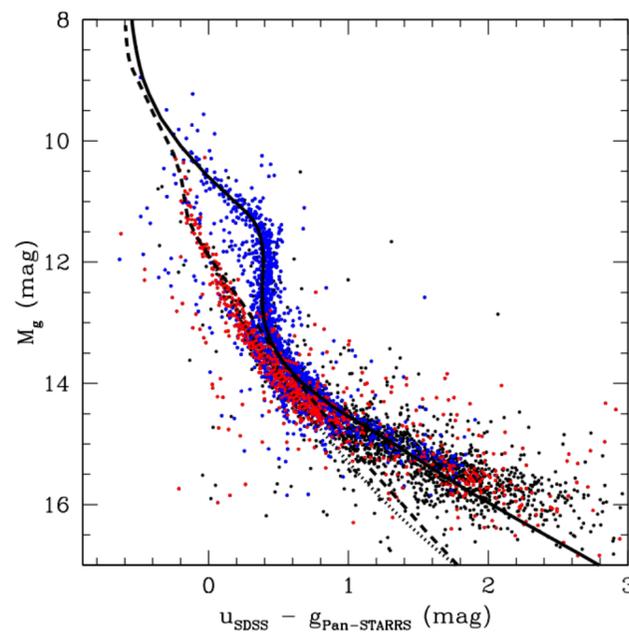
The bifurcation - explanations



Atmospheric composition

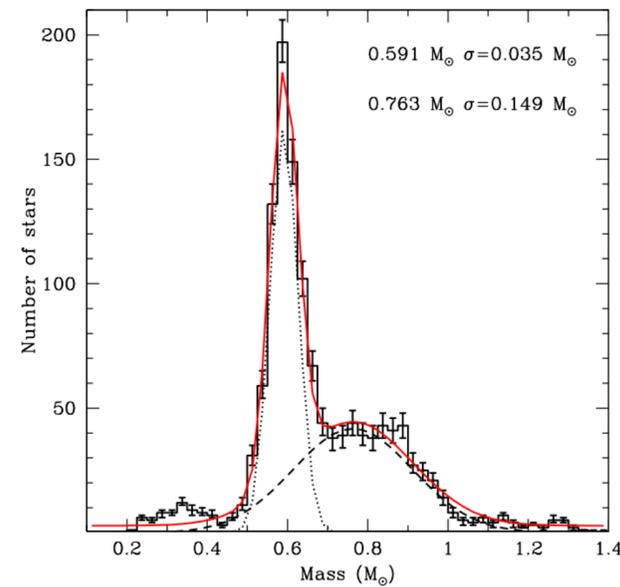


Kilic et al. (2020)

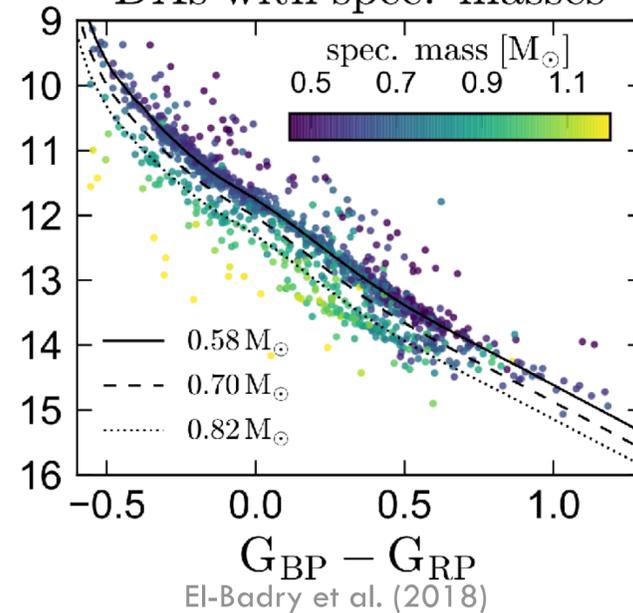


Bimodal masses

Kilic et al. (2020)



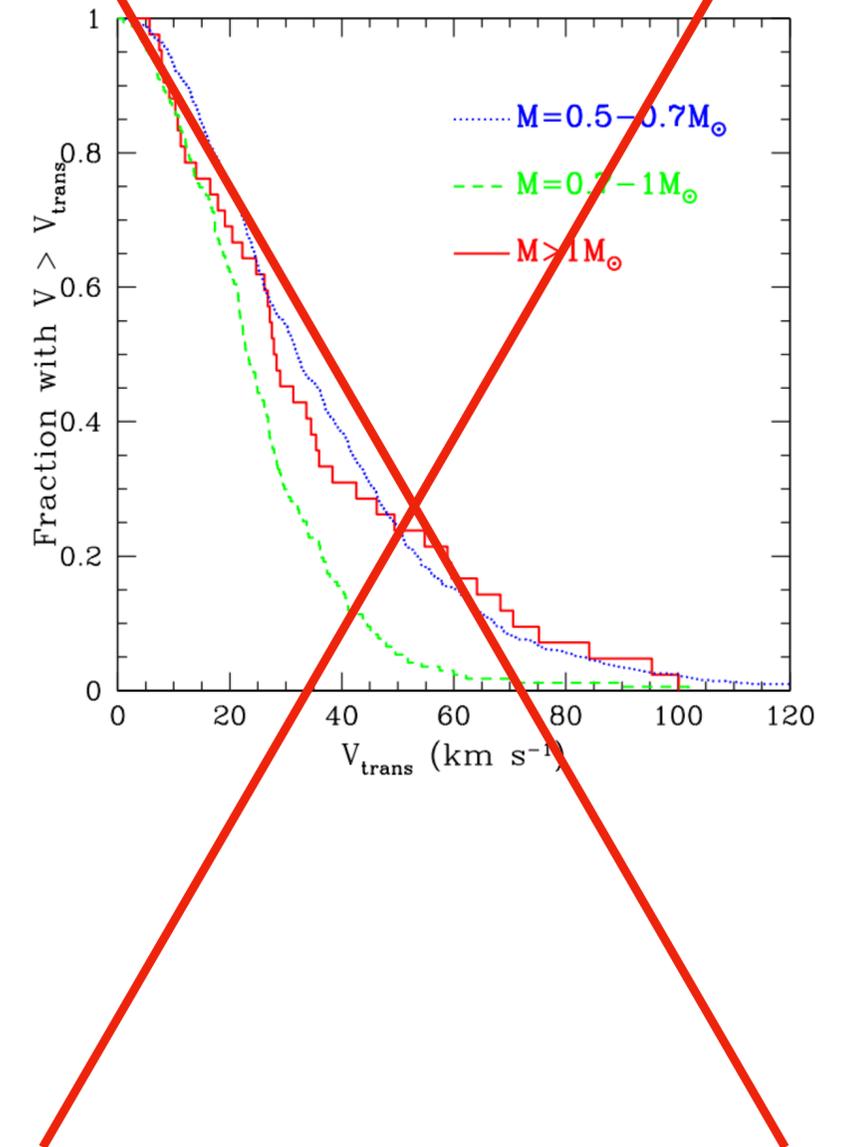
DAs with spec. masses



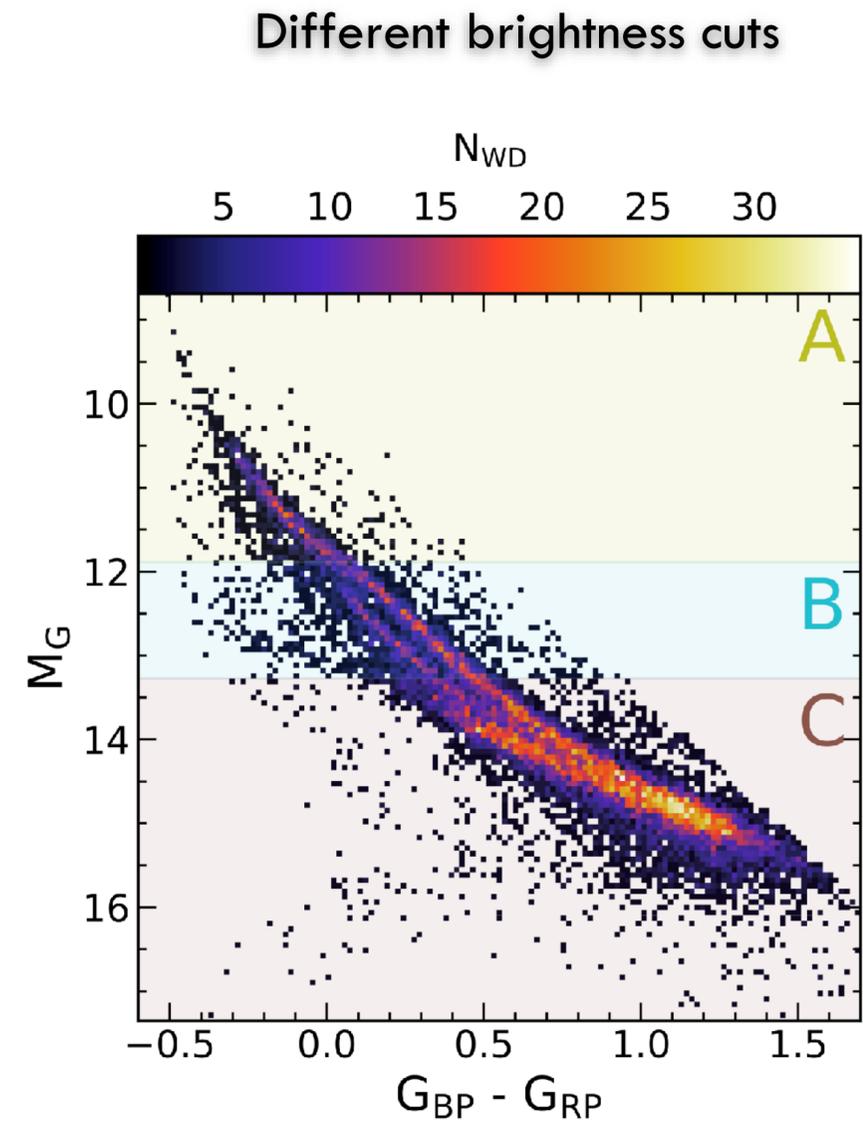
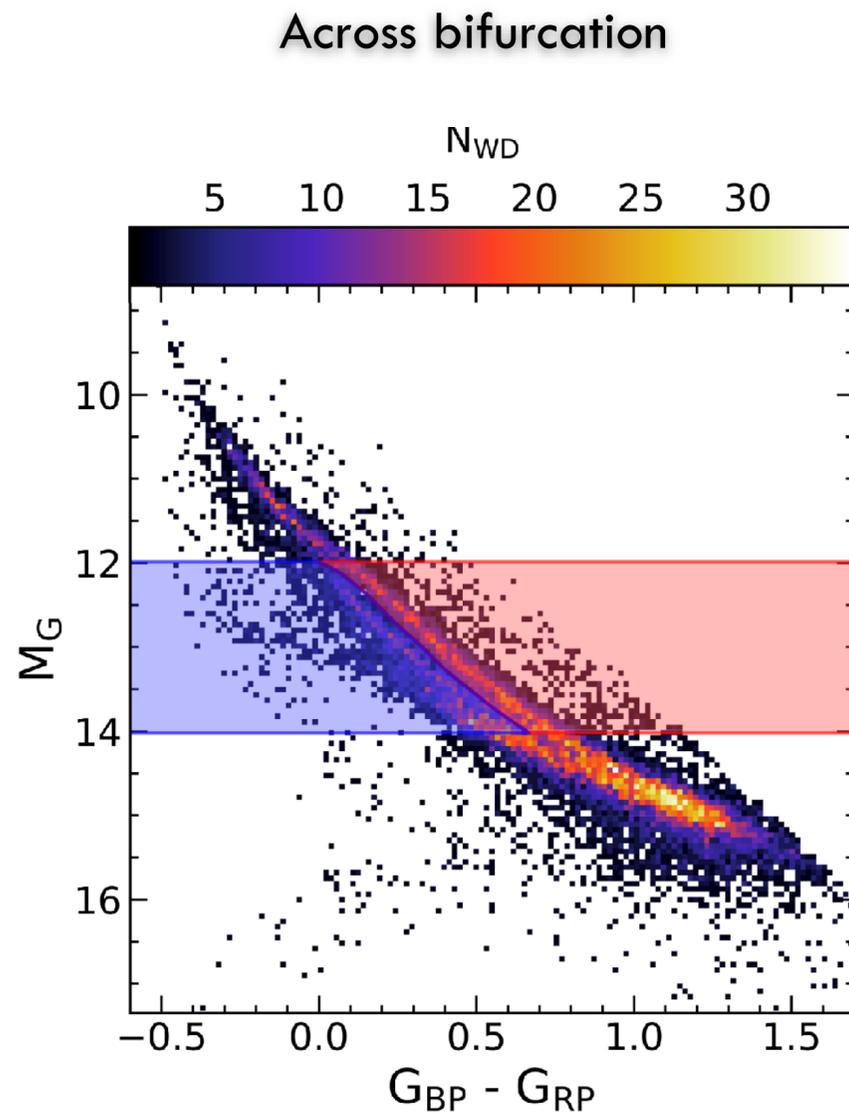
El-Badry et al. (2018)

Mergers

Kilic et al. (2020)



Our samples



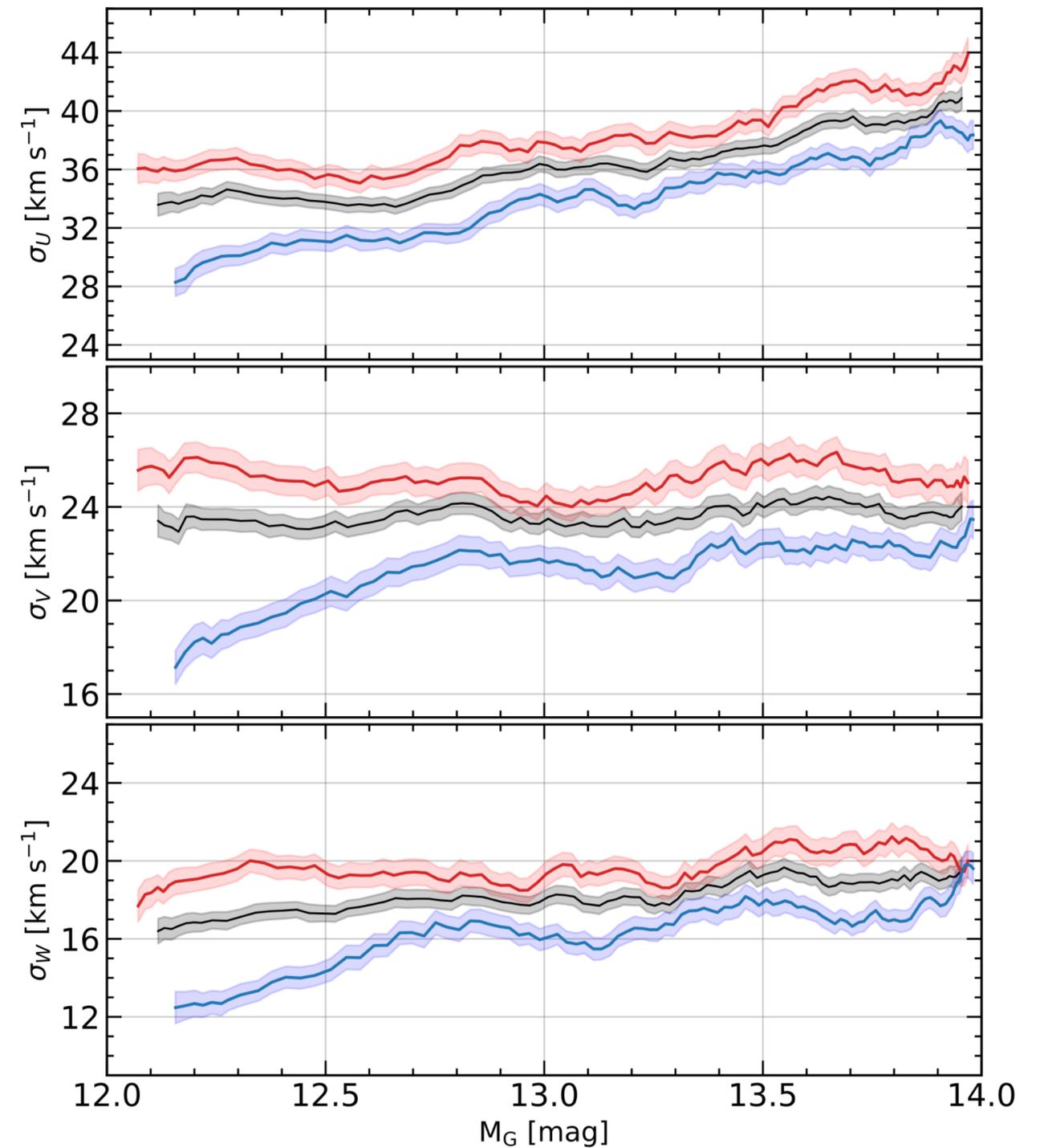
Velocity dispersions

$\sigma_U > \sigma_V$ for all three directions

$\sim 85\%$ DAs & $\sim 39\%$ DAs

There are two separate kinematic WD populations.

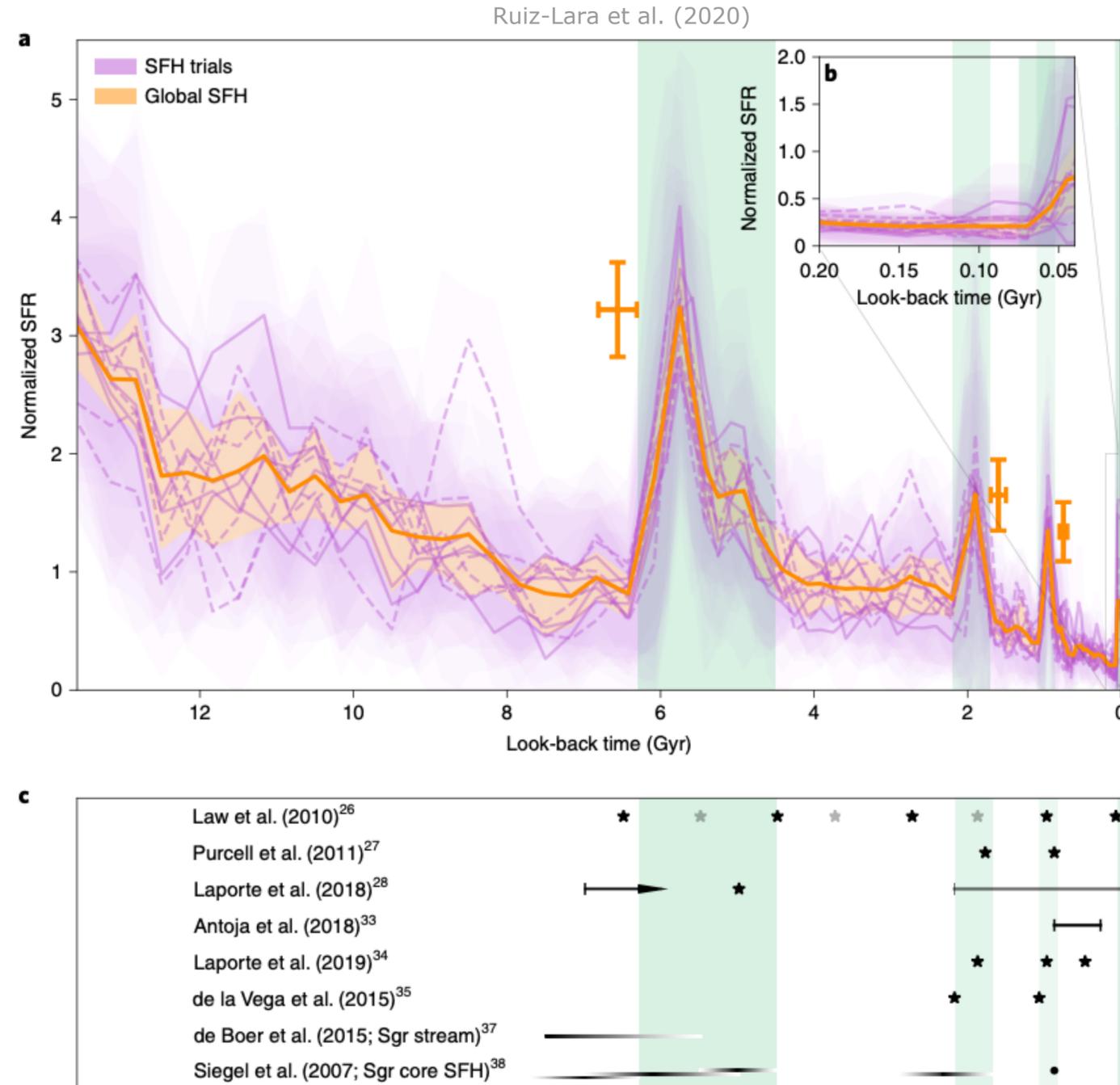
The kinematics cannot be explained purely by atmospheric composition. Most likely there are younger, massive WDs.



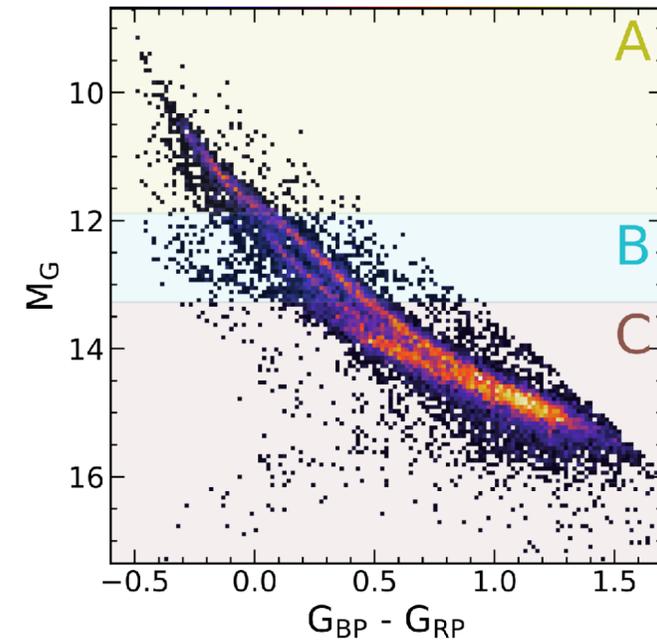
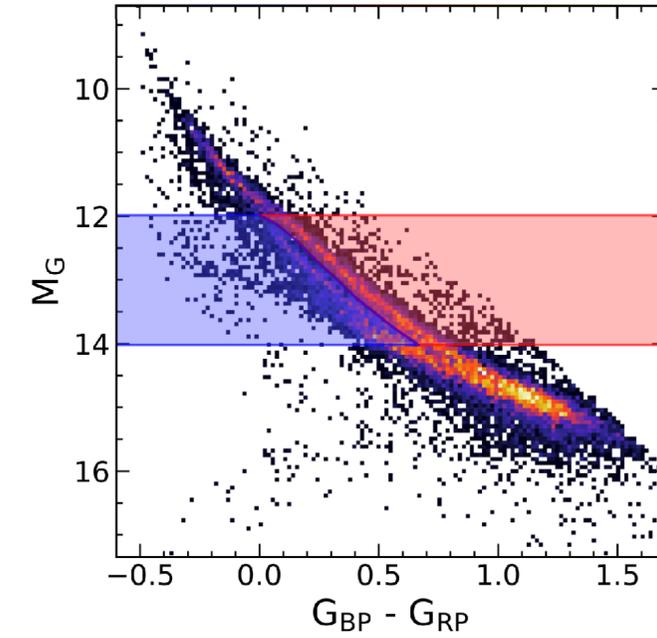
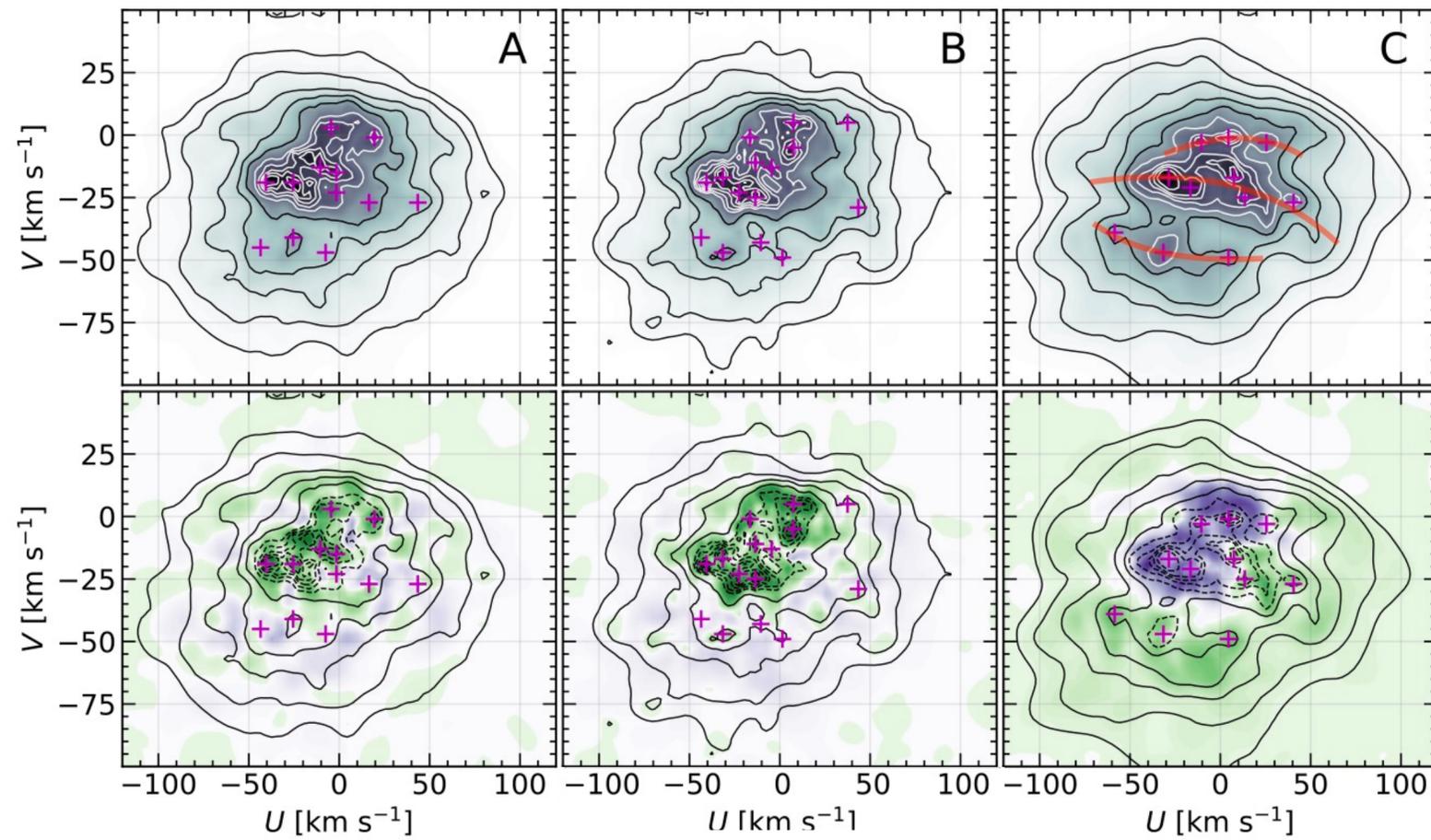
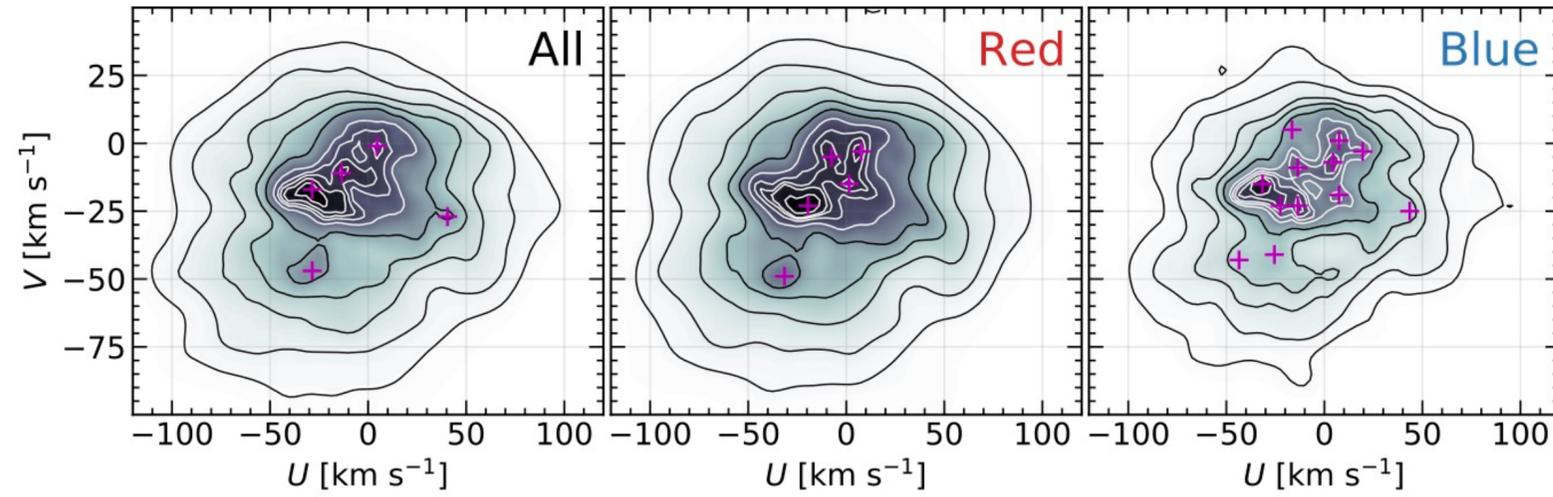
Young massive WDs

Massive young WDs require recent source of star formation

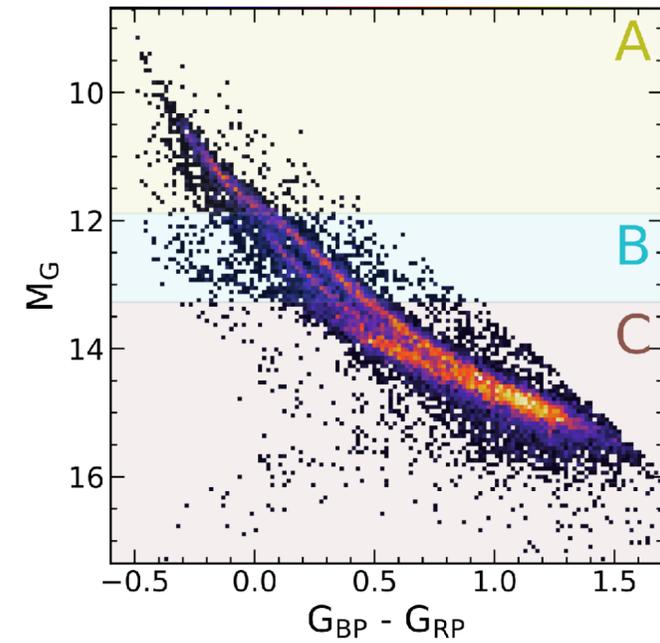
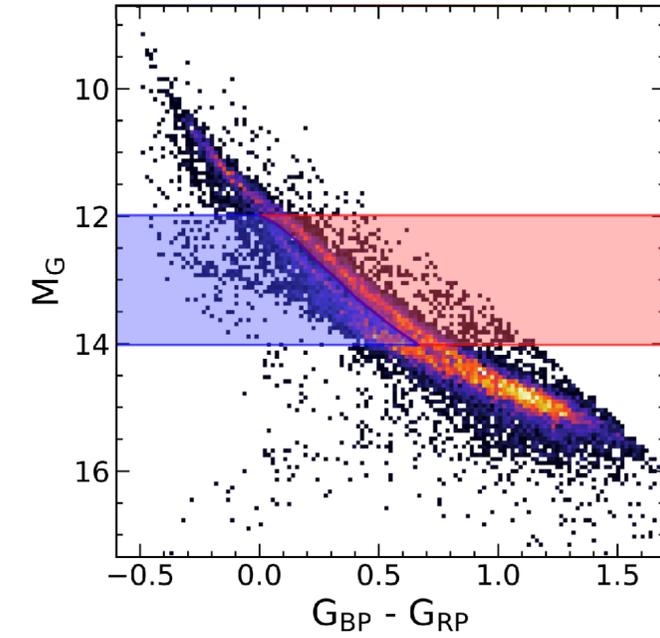
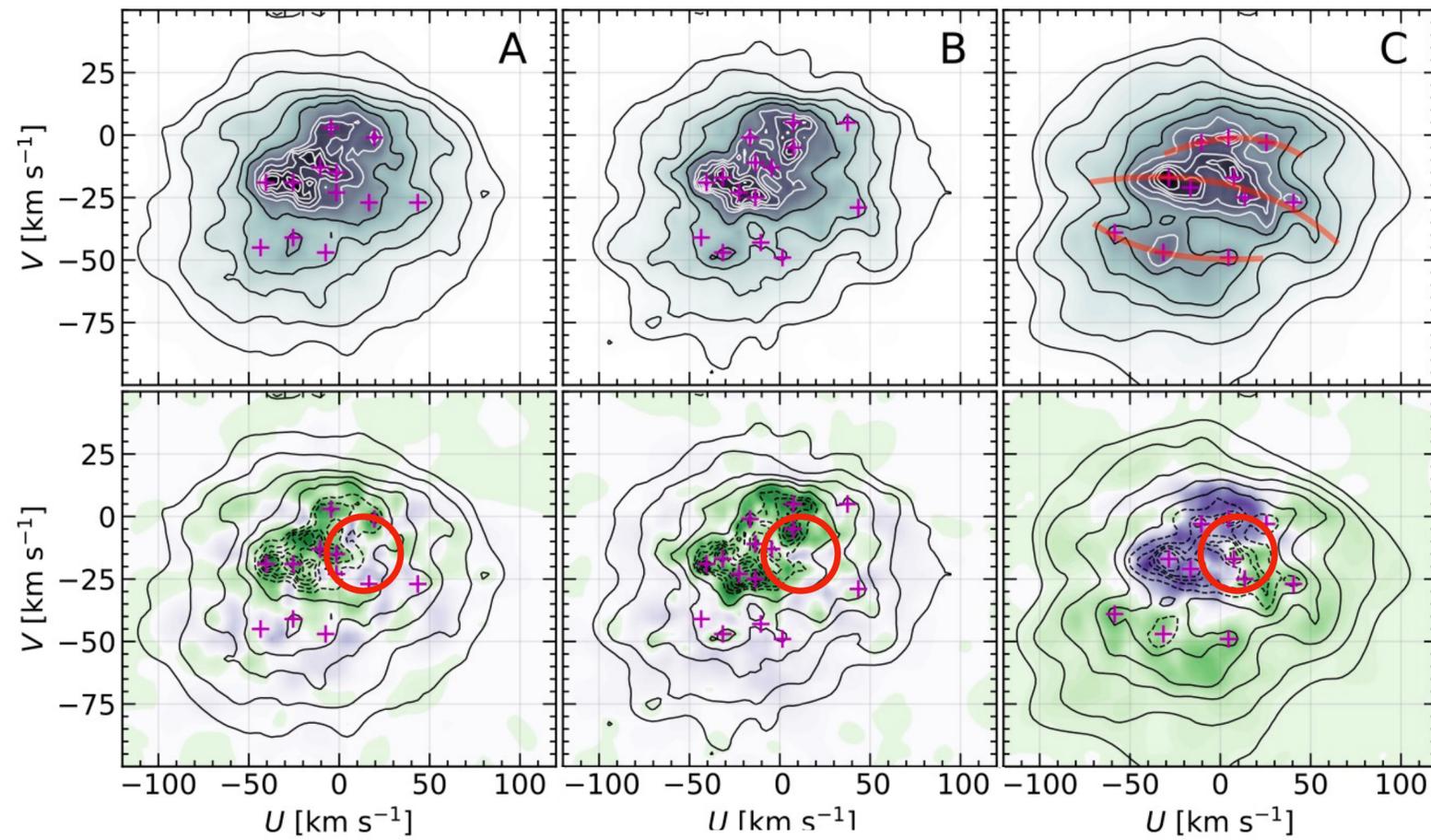
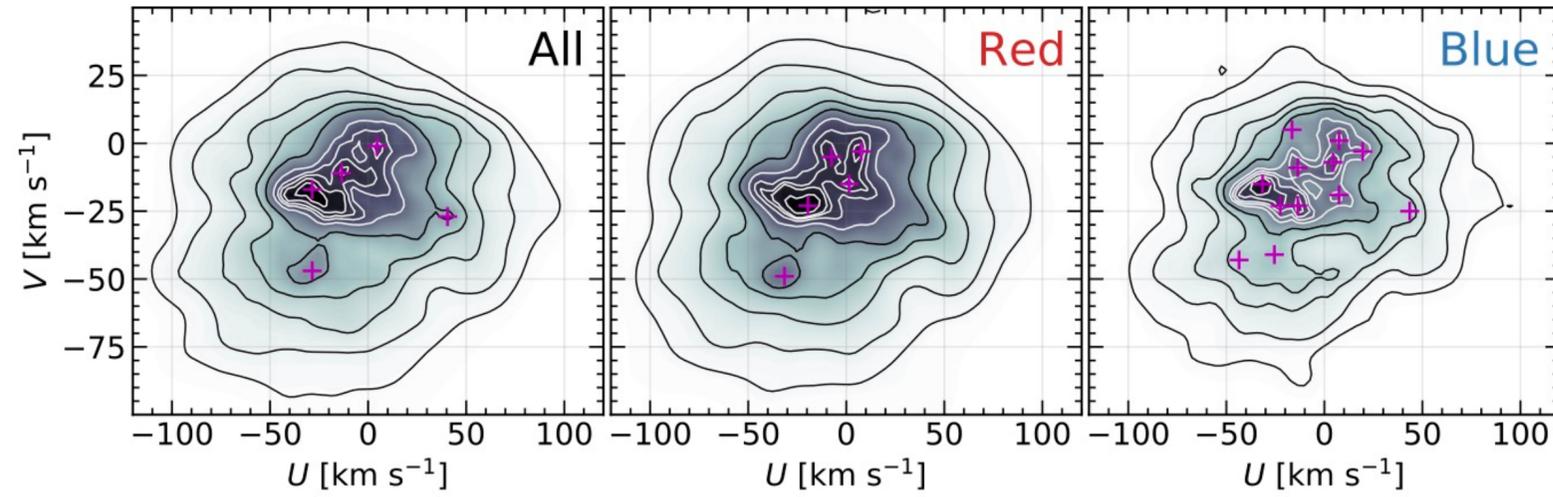
Could be linked to Sagittarius dwarf passing



Velocity distributions

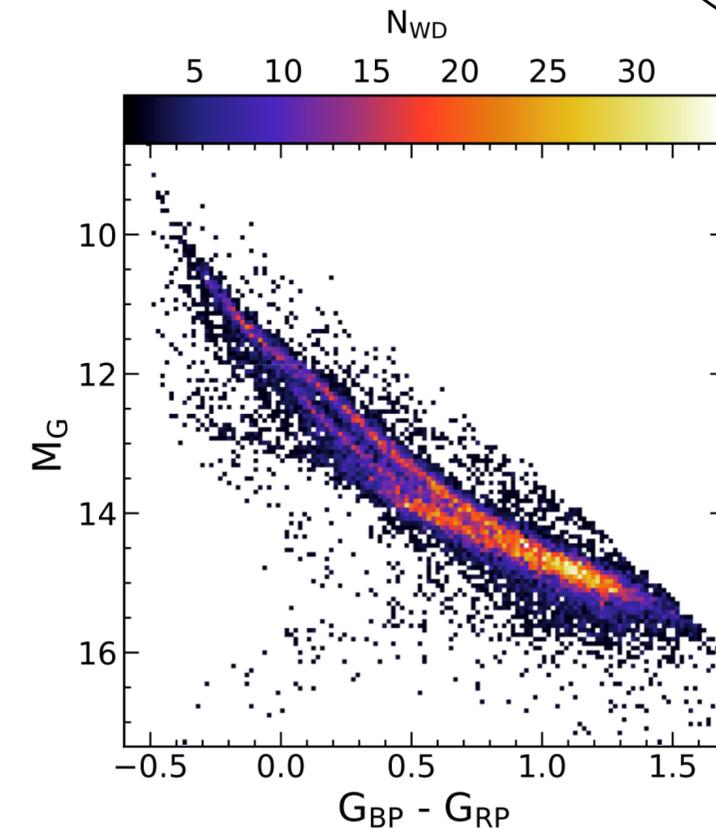
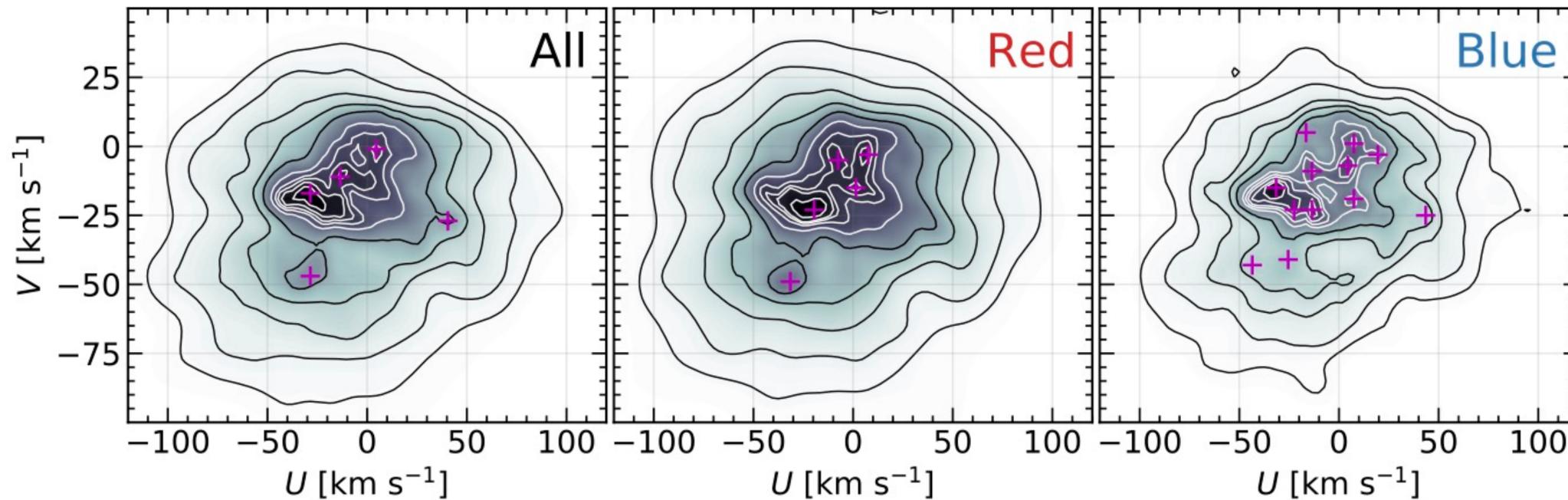
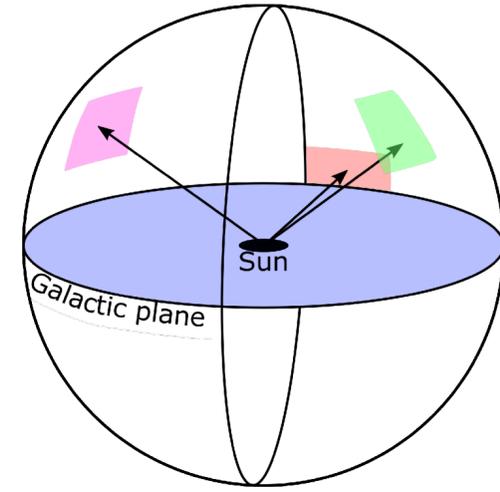
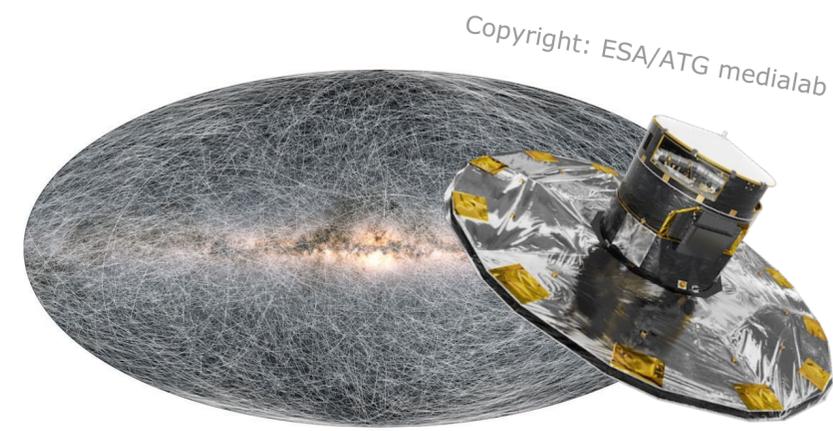


Velocity distributions



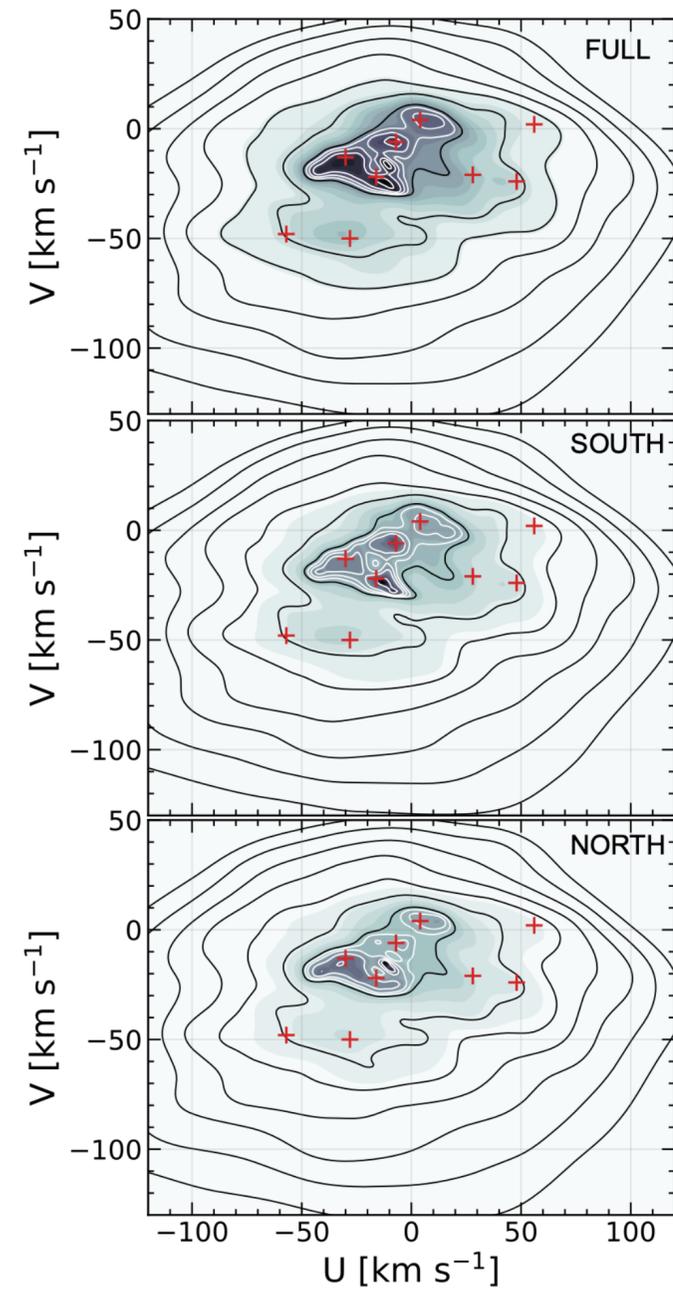
Conclusions

- Using statistical methods (Dehnen 1998) we can infer $f(\mathbf{v})$ of WDs and determine σ .
- σ suggests there are young, massive WDs.
- These massive WDs could be formed with recent star formation
- We present full 3D velocity distributions of WDs in unprecedented detail and find some novel structures.



What's next?

Entire SNBH



Local stellar halo

