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Hypervelocity star candidates from Gaia DR2 and DR3 proper motions and parallaxes *

Ralf-Dieter Scholz / MWLV+DGGH meeting / 25 April 2024

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corresponding paper submitted to A&A on 30 October 2023,
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Structure of the paper

☀ = briefly discussed in this talk

HVS = hypervelocity stars
HPM = high proper motion

☀ 1. Introduction

2. Gaia HVS selection from tangential velocities

   2.1. Galactocentric tangential velocities

   2.2. Gaia DR2 candidates

☀ 2.3. Gaia DR3 candidates

☀ 2.4. Spurious HPMs in crowded regions

☀ 2.5. Trends from Gaia DR2 to DR3

   2.6. DR3 HVS selection effects with magnitude

☀ 2.7. Comparison with DR3 radial velocities

3. Verification of nearest extreme HVS candidates

   3.1. Close next neighbours (NNs)

☀ 3.2. DR3 astrometric quality parameters

   3.3. Local comparison of astrometric parameters

   3.4. Global comparison of astrometric parameters

☀ 3.5. No good candidates fulfilling all criteria

   3.6. Best candidates with relaxes criteria

☀ 4. Summary and conclusions

Hypervelocity stars (HVS) = unbound stars in the Galaxy

First theoretical predictions:

Hills (1988):
HVS formation = tidal disruption of tight binaries by supermassive black hole (SMBH)

Yu & Tremaine (2003): three scenarios of HVS ejection by (binary) SMBH in the Galactic centre (GC)

Some authors included these formation scenarios in the definition of HVS

First observations:

Brown et al. (2005, 2006, 2007):
B-type HVSs originating from GC (now >50 kpc away)

Hirsch et al. (2005), Edelman et al. (2005), Heber et al. (2008): different types, not all from GC

with new discoveries, in particular of exotic WDs (see next 2 slides), alternative scenarios were suggested

How a white dwarf (WD) may become a HVS:

for a complete overview see: **Igoshev et al. (2022)**, who list eight (!) scenarios

1) Dynamically Driven Double-Degenerate Double Detonation (D^6) scenario

proposed by **Shen et al. (2018)** for three exotic WDs found from Gaia DR2 tangential velocities

their Fig.1:

HVS = runaway *donor* of a WD+WD binary after double detonation (first helium, then carbon) of the more massive primary (*accretor*) in a SN Ia

Orbital (ejection) velocity 1000-2500 km/s

WD inflated possibly by tidal heating

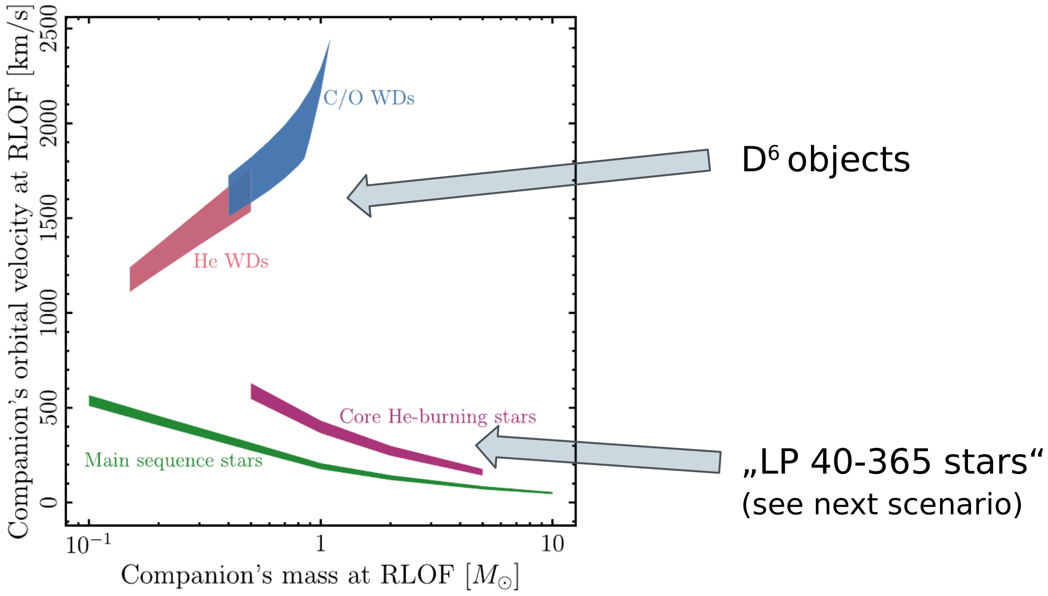


Figure 1. Companion's orbital velocity vs. mass at RLOF. The upper boundary of each region corresponds to a 1.1 $M_\odot$ primary WD; the lower boundary corresponds to a 0.85 $M_\odot$ primary.

How a white dwarf (WD) may become a HVS:

2) survivor of a thermonuclear explosion in a single-degenerate scenario

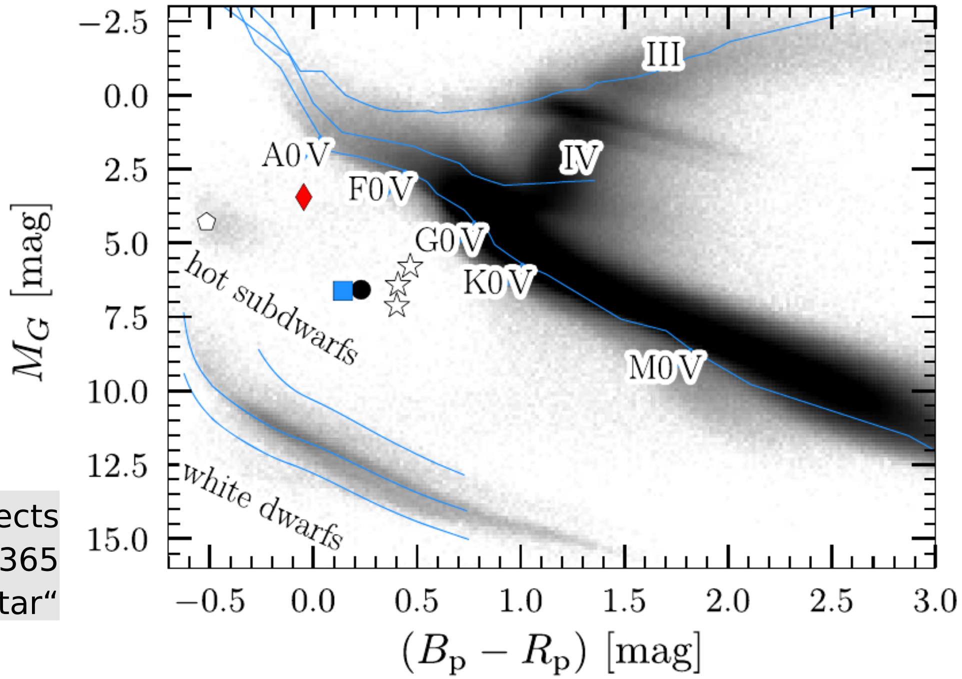
proposed by **Vennes et al. (2017)** for LP 40-365; + similar star found by **Raddi et al. (2019)**

their Fig.1:

HVS = partially burned runaway accretor from a single-degenerate binary in a SN Iax (the donor was a massive He-burning star)

Orbital (ejection) velocity ~600 km/s

WD inflated after supernova explosion



star-shaped symbols – D[6] objects
black circle – LP 40-365
blue square – J1603-6613, new „LP 40-365 star“

Astrometric selection of the nearest extreme HVS in DR2

Scholz (2018)

main quality criterion:
Plx/ePlx>5

additional quality criteria:
UWE sepsi gofAL Nper

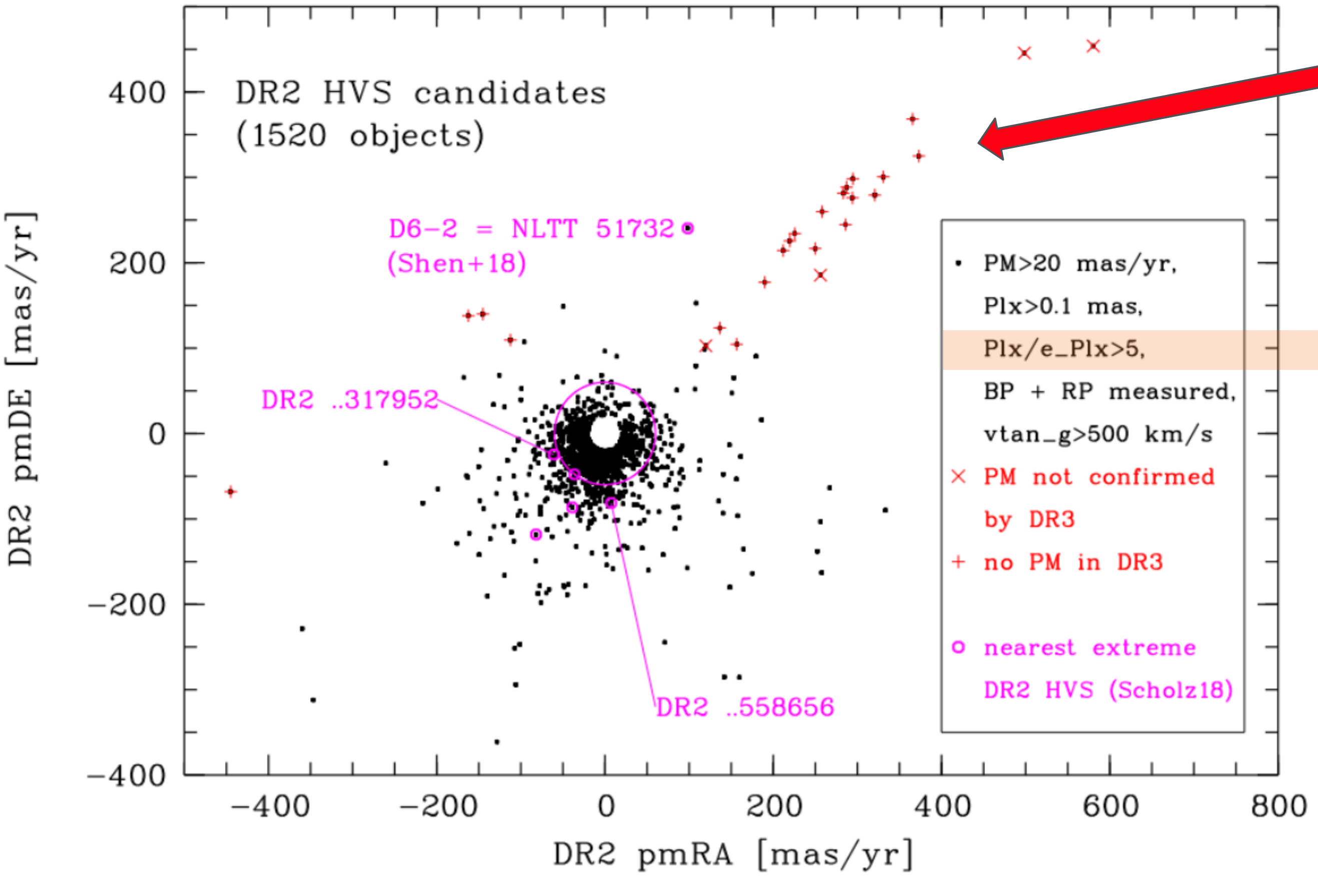
Table 1. Selected Gaia DR2 stars with proper motions μ>60 mas/yr and Galactocentric tangential velocities $v_{t,g}$>700 km/s

Gaia DR2 ID	G [mag]	$BP-RP$ [mag]	ϖ [mas]	$\mu_\alpha \cos\delta$ [mas/yr]	μ_δ [mas/yr]	u[1]	D[2]	gofAL[3]	vpu[4]	$v_{t,g}$ [km/s]
1798008584396457088[5]	17.02	0.40	1.05±0.11	+98.39±0.21	+240.35±0.17	1.13	1.8	2.7	9	1248±122
1540013339194597376[6]	15.96	1.01	0.59±0.05	−82.03±0.05	−118.29±0.05	0.98	0.0	−0.4	15	917±104
6698855754225352192[6]	15.39	0.81	0.47±0.05	−38.97±0.07	−86.57±0.05	1.02	0.0	0.3	13	733±99
3841458366321558656	15.89	0.86	0.33±0.06	+7.29±0.11	−81.39±0.11	0.92	0.0	−1.0	8	978±220
3593446274383096448	14.03	0.89	0.27±0.04	−36.35±0.06	−47.95±0.04	0.92	0.0	−1.2	9	855±156
6097052289696317952	13.53	0.60	0.17±0.03	−61.10±0.05	−24.73±0.05	1.02	0.0	0.3	9	1617±347

NOTE—[1]unit weight error, [2]astrometric_excess_noise_sig, [3]astrometric_gof_al, [4]visibility_periods_used, [5](= NLTT 51732) classified as hypervelocity white dwarf D6-2 (Shen et al. 2018), [6]previously found nearby high-speed star candidate (Bromley et al. 2018)

Only three out of six still have >700 km/s in Gaia DR3 !
(will be marked in the following plots)

Galactocentric tangential velocity
(cf. Hattori et al. 2018; Bromley et al. 2018)

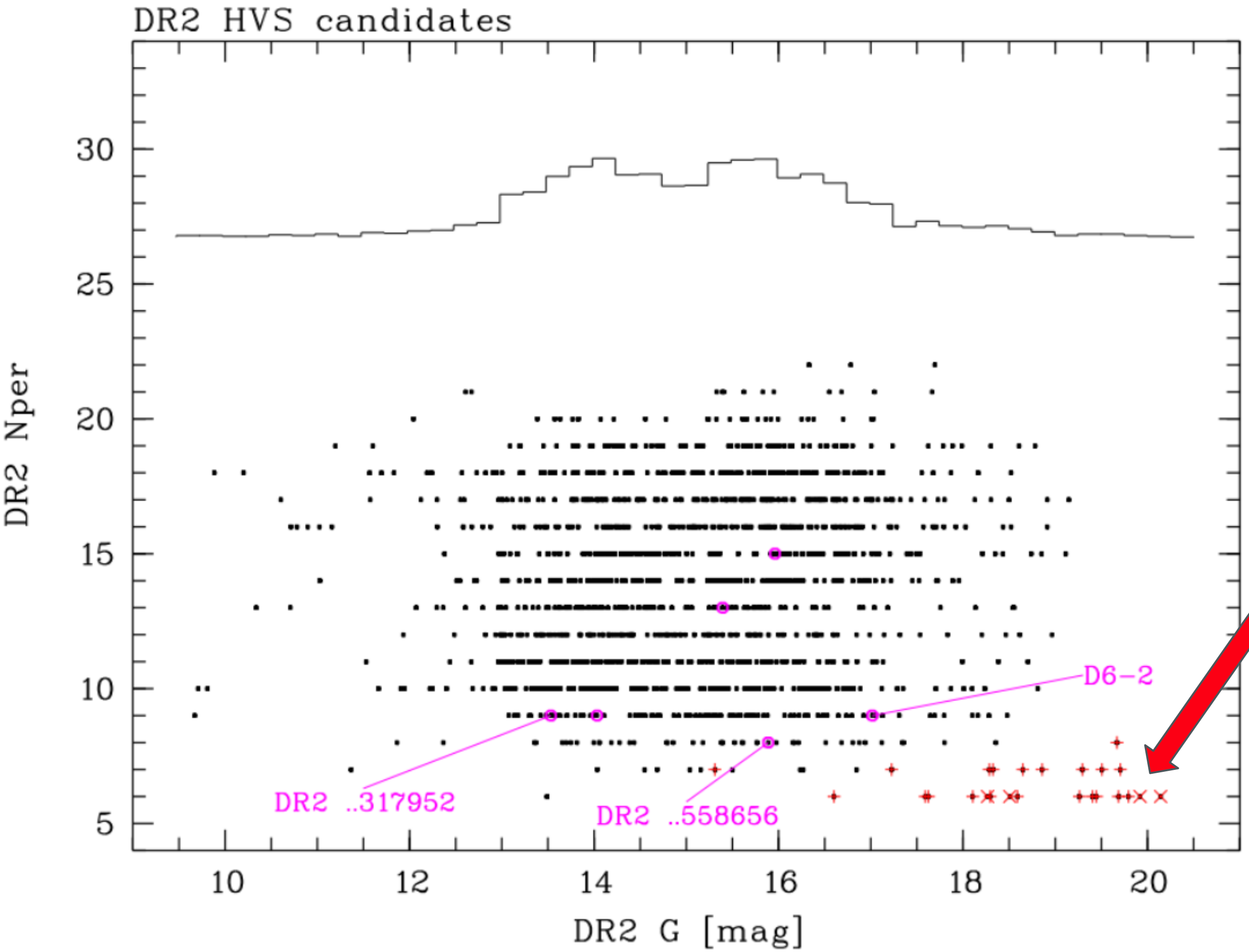


Spurious HPMs in Gaia DR2 a)

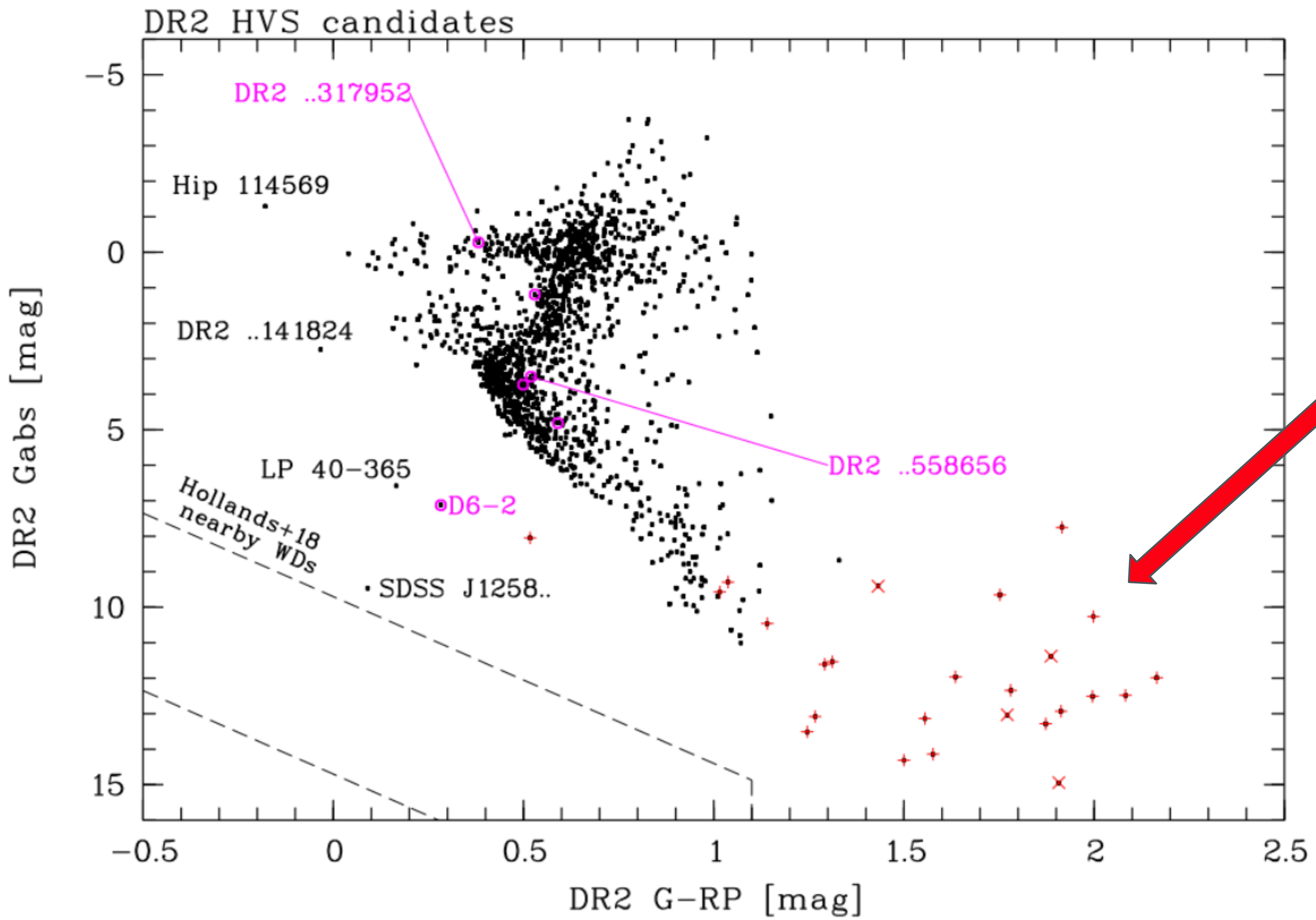
No further quality criteria

vtan_g = Galactocentric tangential velocity

Spurious HPMs in Gaia DR2 b)

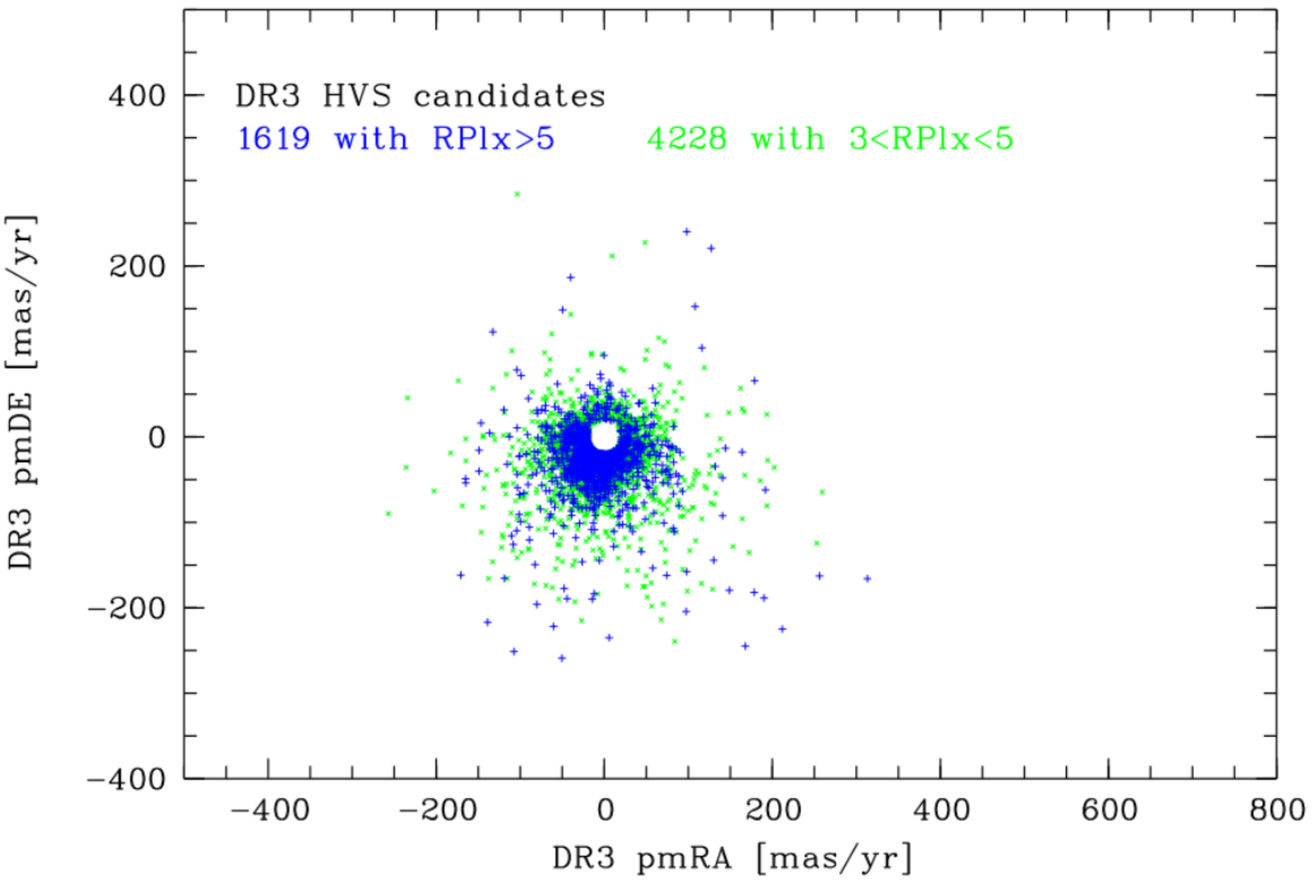


insufficient number of epochs
+
faint objects



Spurious HPMs

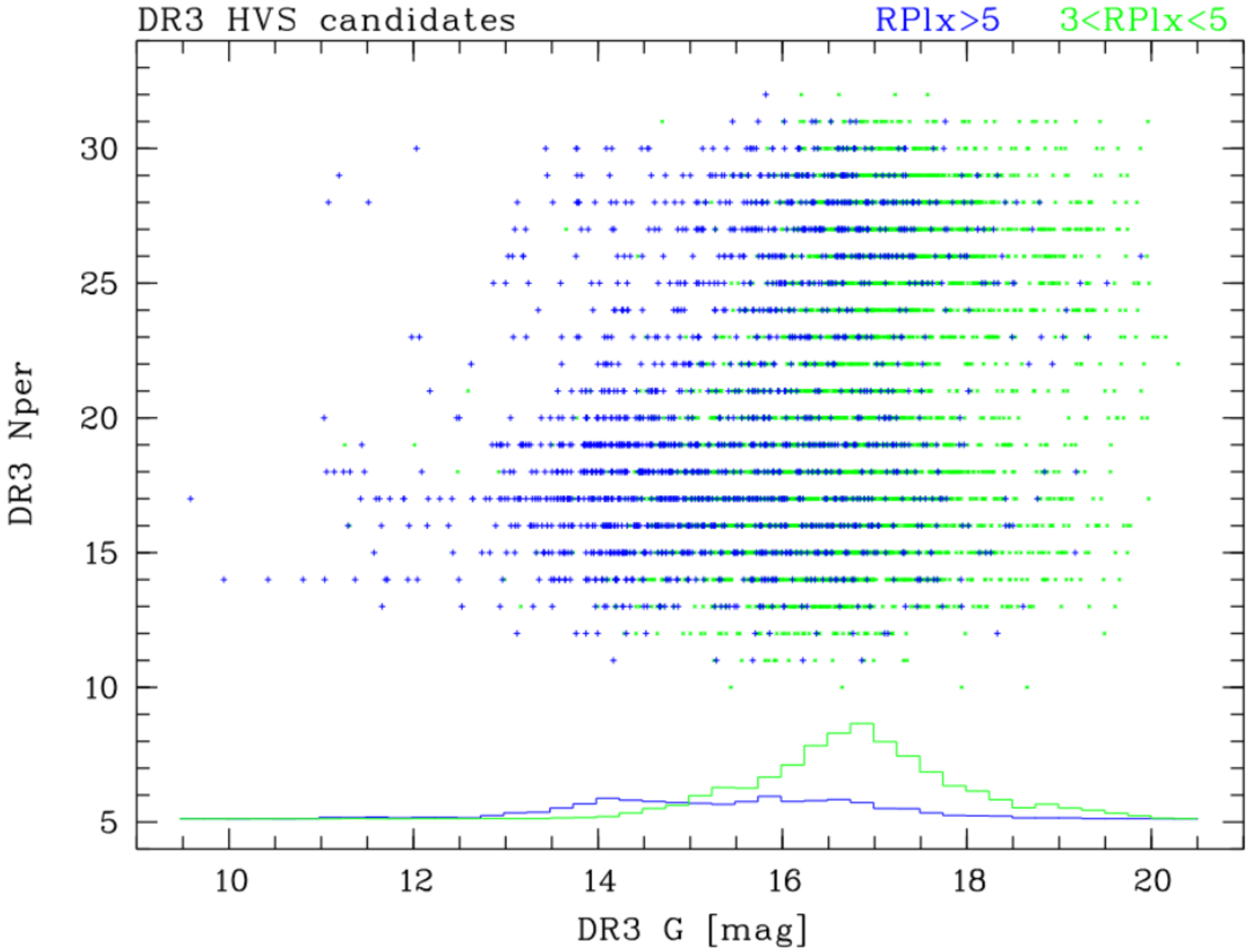
in Gaia DR2 c)



Selecting HVS based on Gaia DR3

a) proper motions

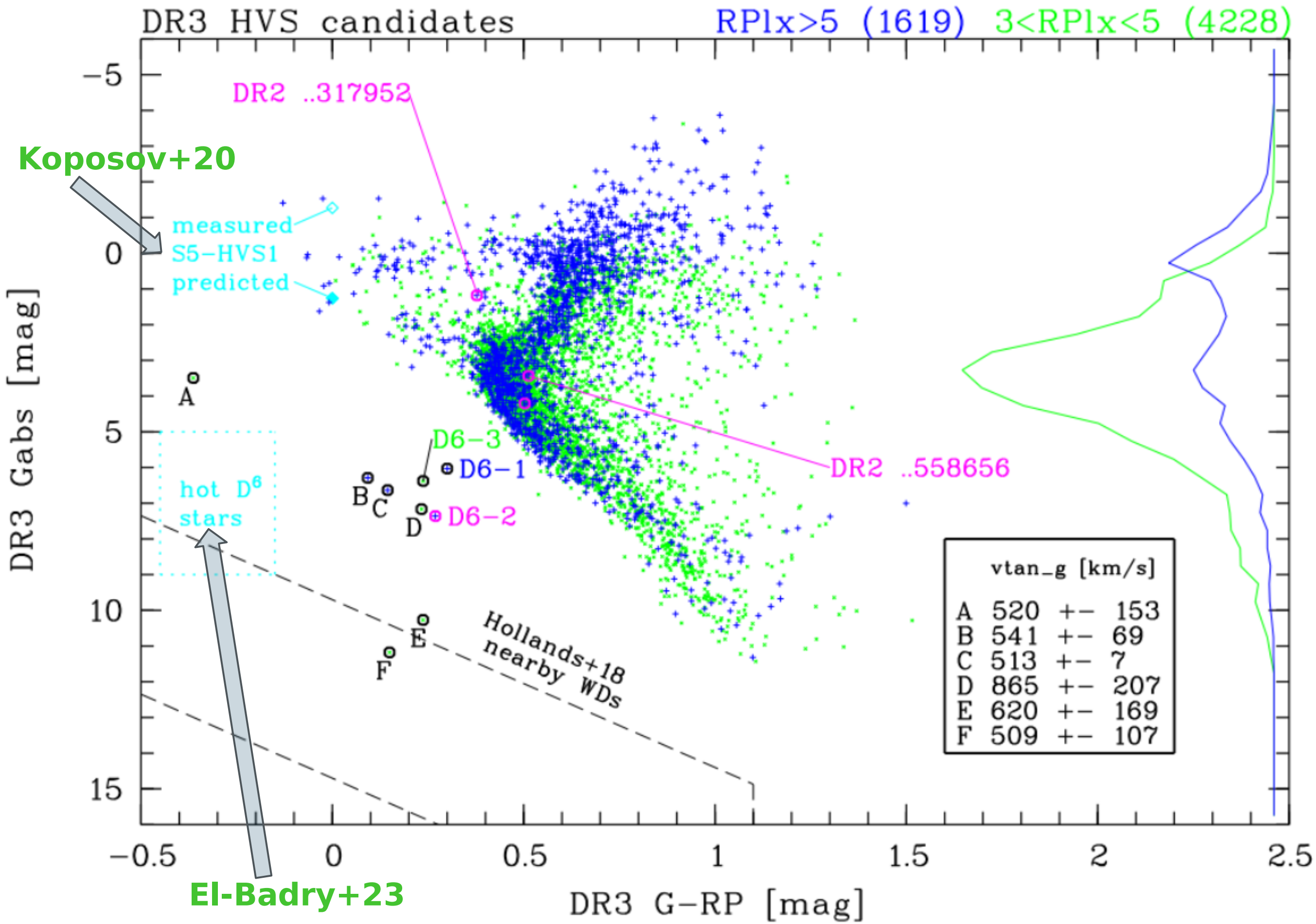
Incl. low-priority candidates:
3<Plx/ePlx<5 (green crosses)



Selecting HVS based on Gaia DR3

b)
N visibility periods vs. magnitudes

Incl. low-priority candidates:
3<Plx/ePlx<5 (green crosses)



Selecting HVS based on Gaia DR3

c) CMD

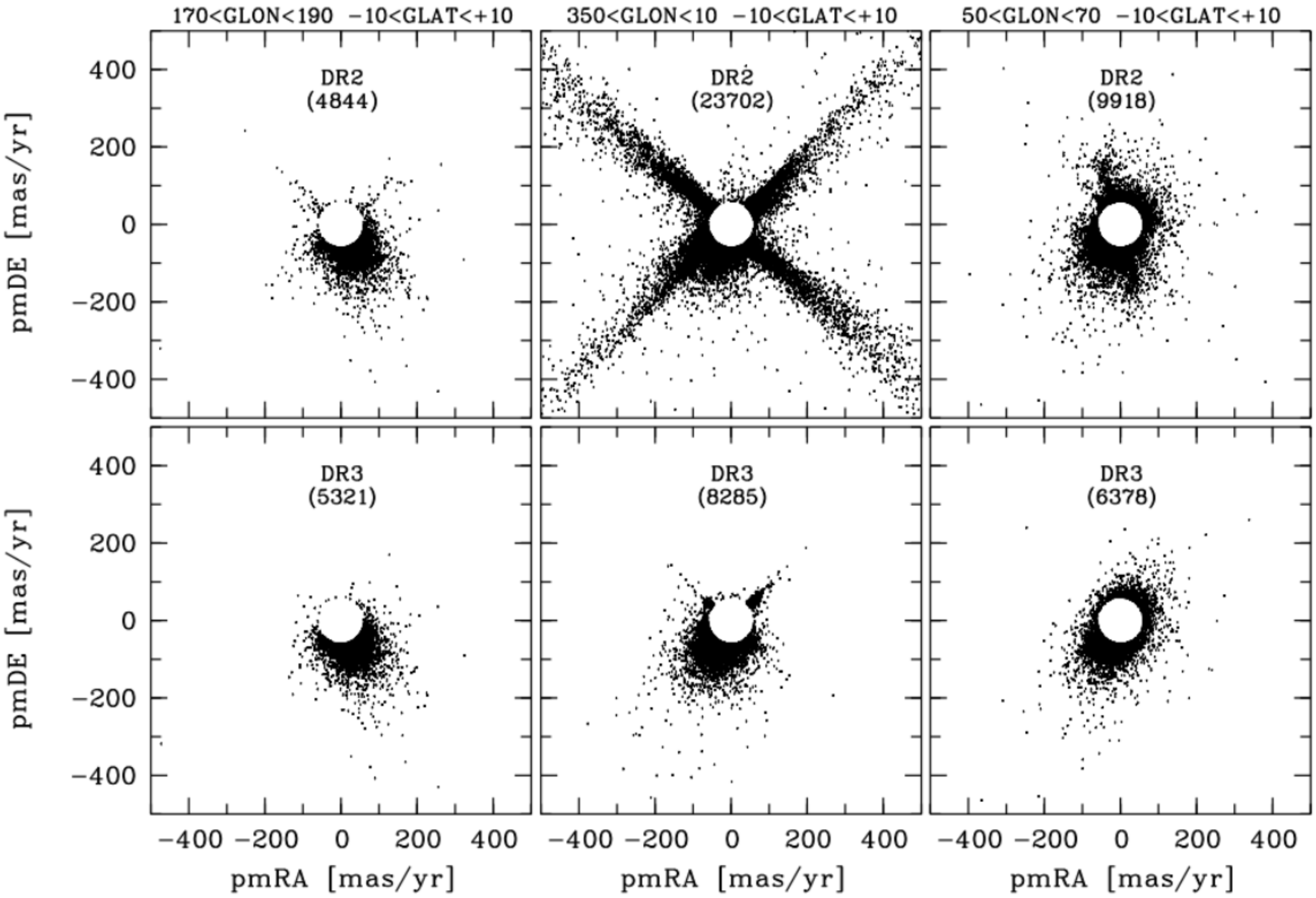
Incl. low-priority candidates: 3<Plx/ePlx<5 (green crosses and green histogram)

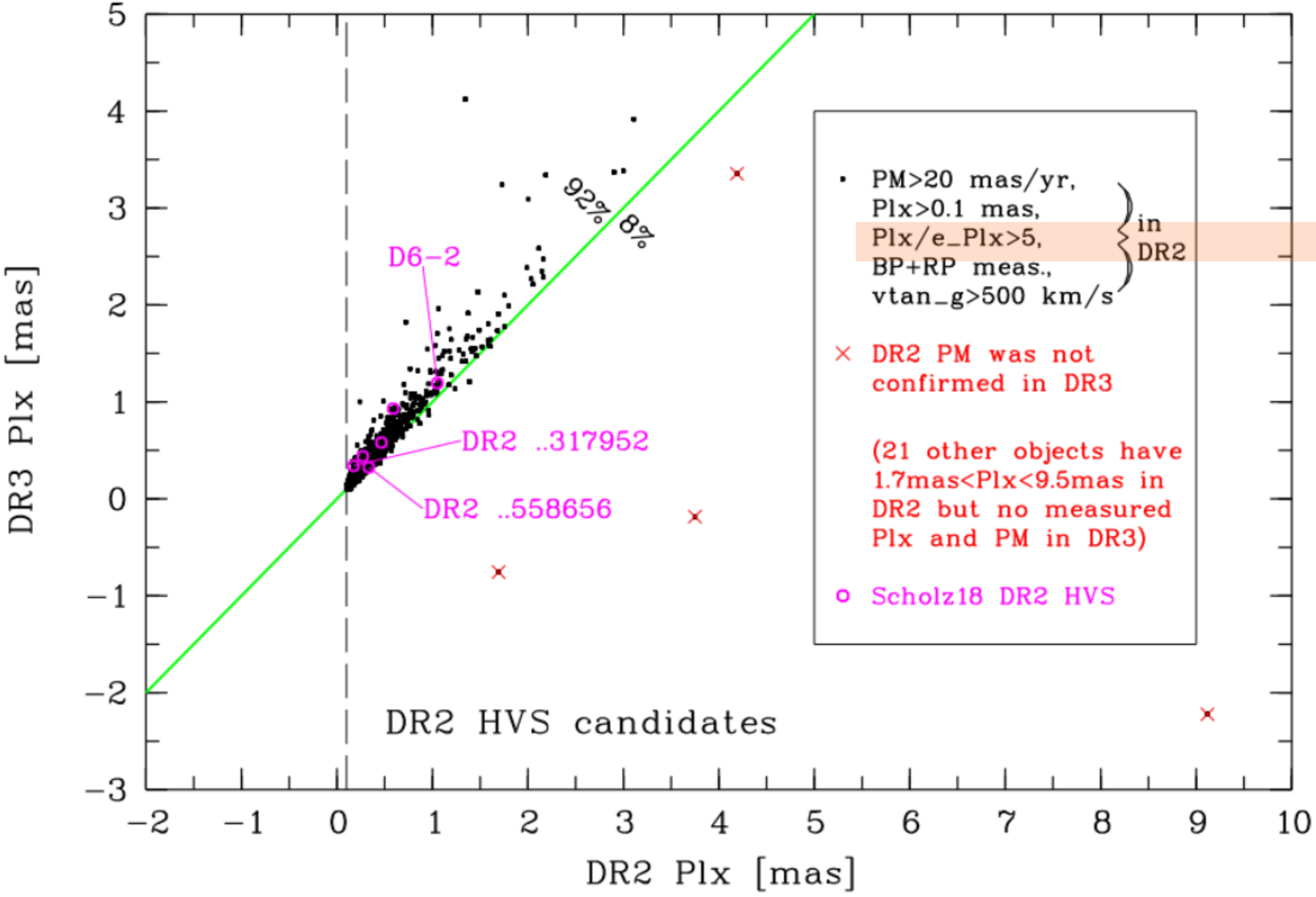
A = known hot subdwarf (**Green+86, …, Geier+20**)
B = J1603, new „LP 40-365 star“ and HVS (**Raddi+19**)
C = LP 40-365 = known HVS (**Vennes+17, …, Lach+22**)
E, F = new WDs from Gaia (**Gentile Fusillo+19**)
D = new extreme HVS/WD ?

False DR2 and DR3 HPMs in Galactic plane

Shown are all faint (*G*>18mag) HPM stars (PM>60mas/yr)
in Galactic anti-centre (left),
Galactic centre (middle),
and at GLON=60deg

Much less problems in DR3,
but still visible
in Galactic centre !



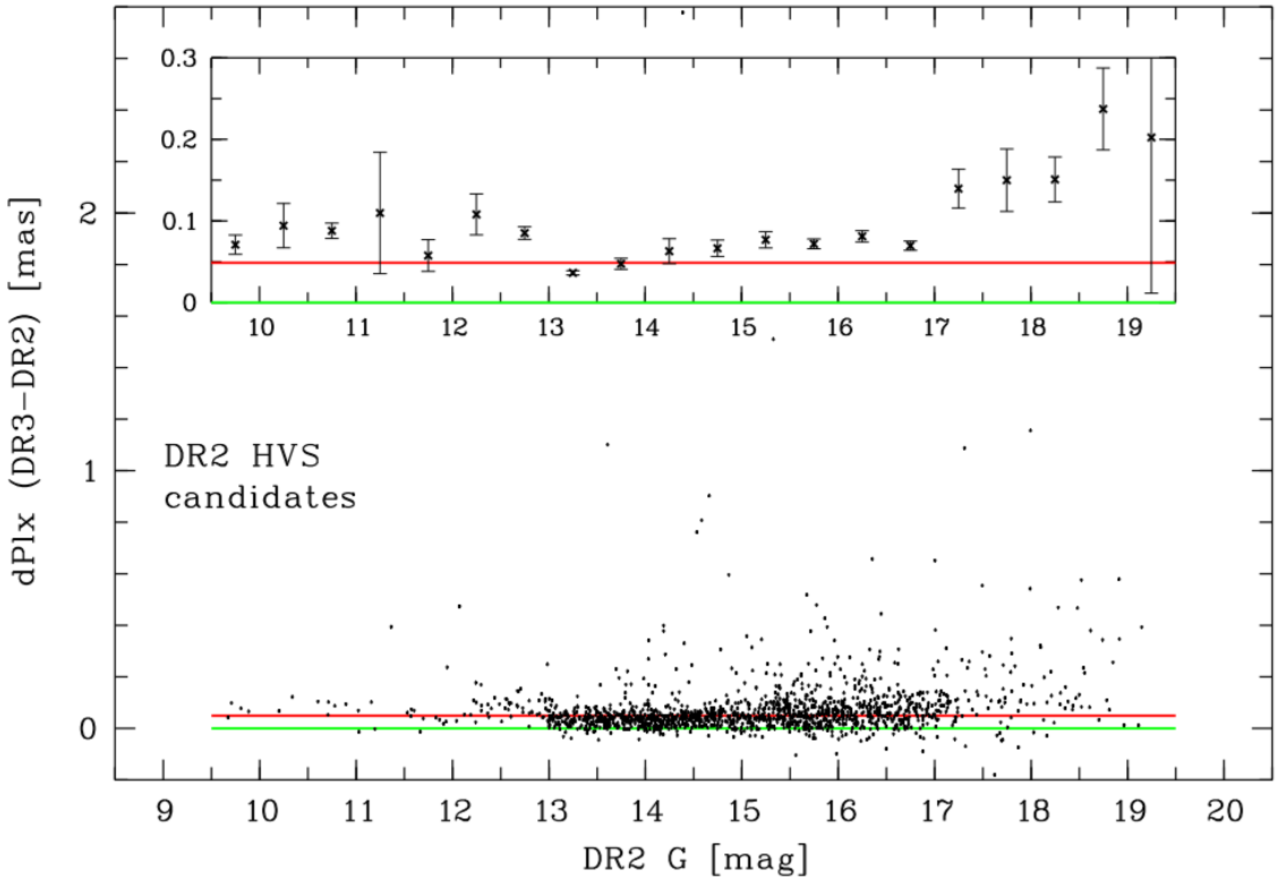


DR2 HVS have larger parallaxes in DR3

No further quality criteria

(when we exclude spurious DR2 HPM objects)

Plx differences DR3-DR2



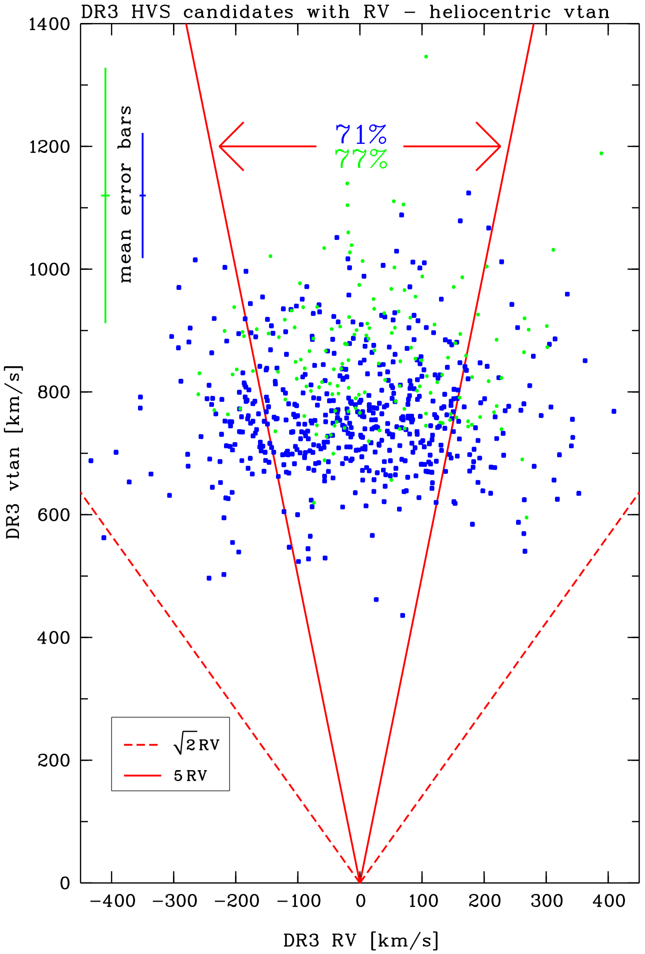
Black crosses with error bars (insert):
mean parallax differences and standard deviations in 0.5mag bins

Red line: median difference
Green line: equal parallaxes

Heliocentric vtan can be expected to be only slightly higher than the RV, if one assumes for simplicity an isotropic stellar distribution (cf. Fig.1 in **Palladino+14**)

Palladino+14 found large transverse-to-radial velocity ratios in their sample because of large proper motion errors (confirmed by **Ziegerer+15**).

Our sample is likely not affected by proper motion errors but underestimated parallaxes!

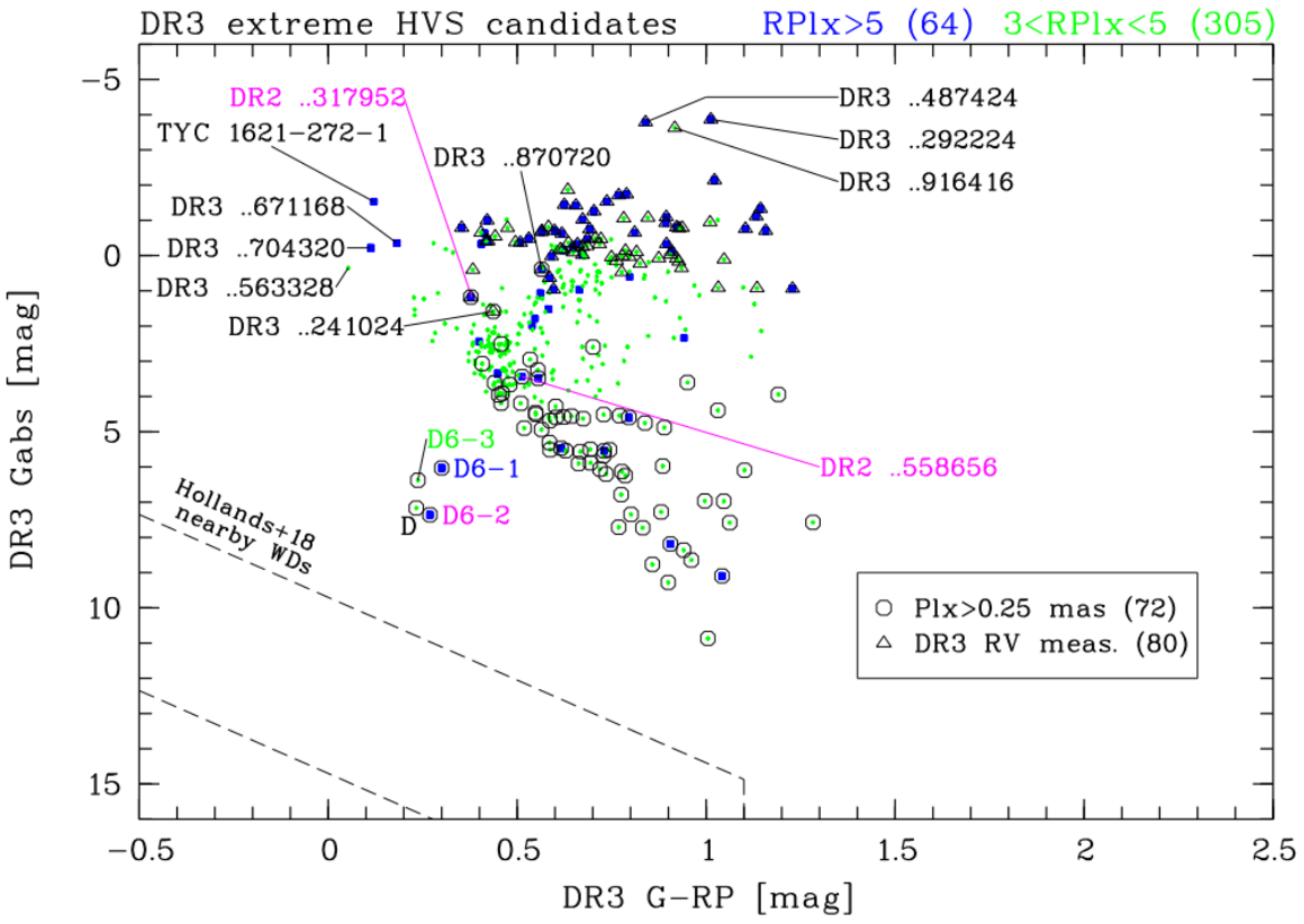


DR3 HVS (vtan_g>500km/s) with RV measurements

Incl. low-priority candidates: 3<Plx/ePlx<5 (green symbols and error bars)

Formal RV errors are
20 x smaller (high-priority HVS)
30 x smaller (low-priority HVS)
than tangential velocity errors

>70% have more than 5 times higher heliocentric vtan than absolute RV



Extreme HVS
(vtan_g>700km/s)
selected in Gaia DR3

Incl. low-priority candidates:
3<Plx/ePlx<5 (green symbols)

Except for the bluest, bright stars have DR3 RV measured

72 nearest candidates (within 4kpc) are mainly dwarfs of low priority (only 11 have RPlx>5)

DR3 quality criteria for 72 nearest extreme HVS candidates

Quantity/ criterion	DR3 column	Critical values (? among 72)	Remark
	throughout the paper:		
RPlx	parallax_over_error	>5 (11)	high priority
		3-5 (61)	low priority
	Sect. 3.1:		
close NNs	n/a	(11)	own NN search in DR3
IPDfmp	ipd_frac_multi_peak	>0 (18)	
IPDfow	ipd_frac_odd_win	>0 (5)	
Solved	astrometric_params_solved	=95 (10)	six-parameter solution
Dup	duplicated_source	>0 (1)	
	Sects. 3.3; 3.4:		
Nper	visibility_periods_used	<*med* (22; 41)	
e_Plx	parallax_error	>*q*75 (15; 26)	in [mas]
e_pmRA	pmra_error	>*q*75 (15; 25)	in [mas/yr]
e_pmDE	pmdec_error	>*q*75 (15; 26)	in [mas/yr]
gofAL	astrometric_gof_al	>*q*75 (36; 36)	can be <0
epsi	astrometric_excess_noise	>*q*75 (33; 28)	≧0; in [mas]
sepsi	astrometric_excess_noise_sig	>*q*75 (35; 29)	≧0
amax	astrometric_sigma5d_max	>*q*75 (16; 23)	in [mas]
IPDgofha	ipd_gof_harmonic_amplitude	>*q*75 (16; 18)	
RUWE	ruwe	>*q*75 (37; 37)	

used as most important criterion

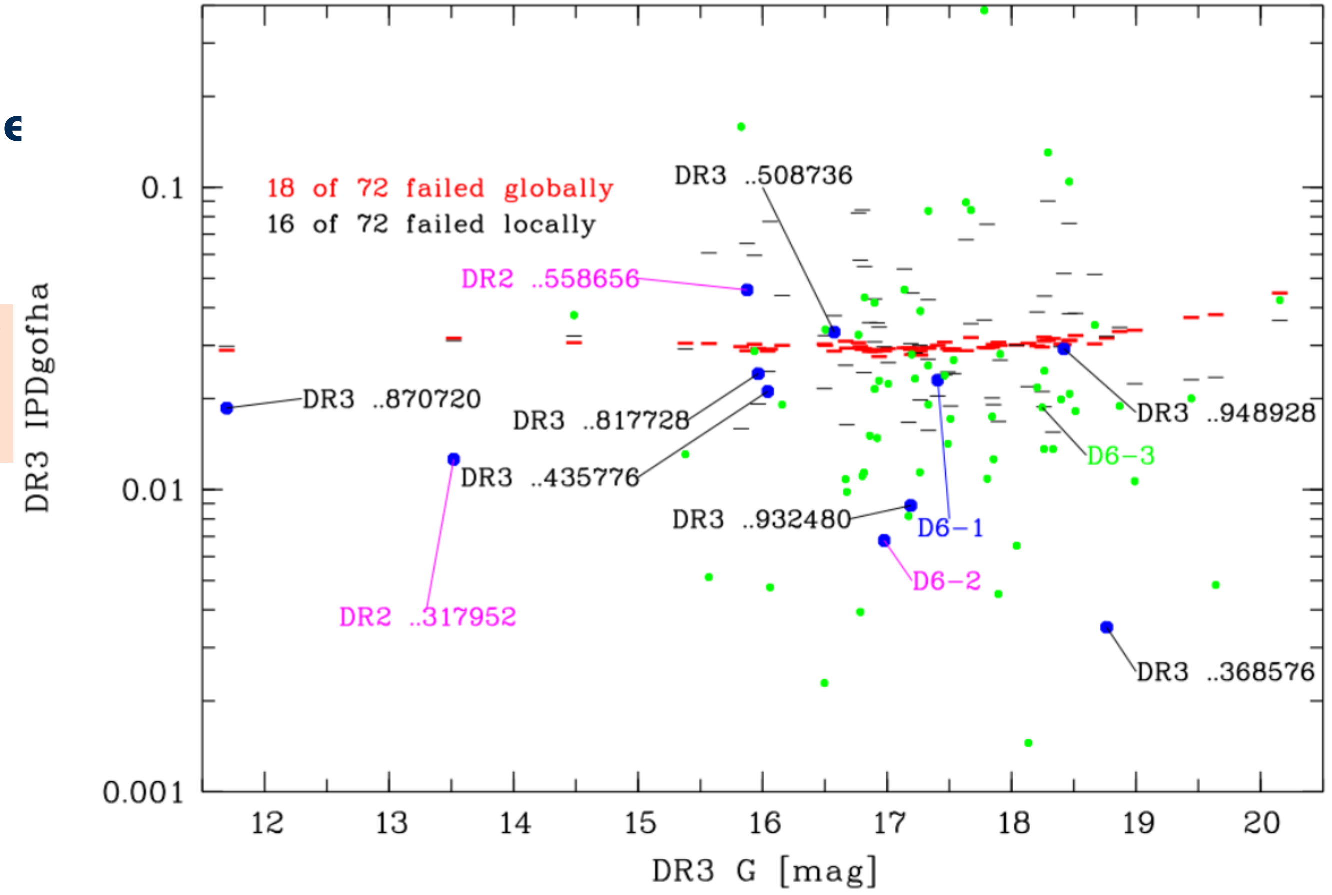
flags and parameters indicating binarity

Checked both locally and globally using comparison objects of similar magnitudes

Check of parameter IPDgofha for 72 nearest extreme HVS candidates

high-priority candidates (Plx/ePlx>5) are labelled: **blue symbols**
low-priority candidates (3<Plx/ePlx<5): **green symbols**

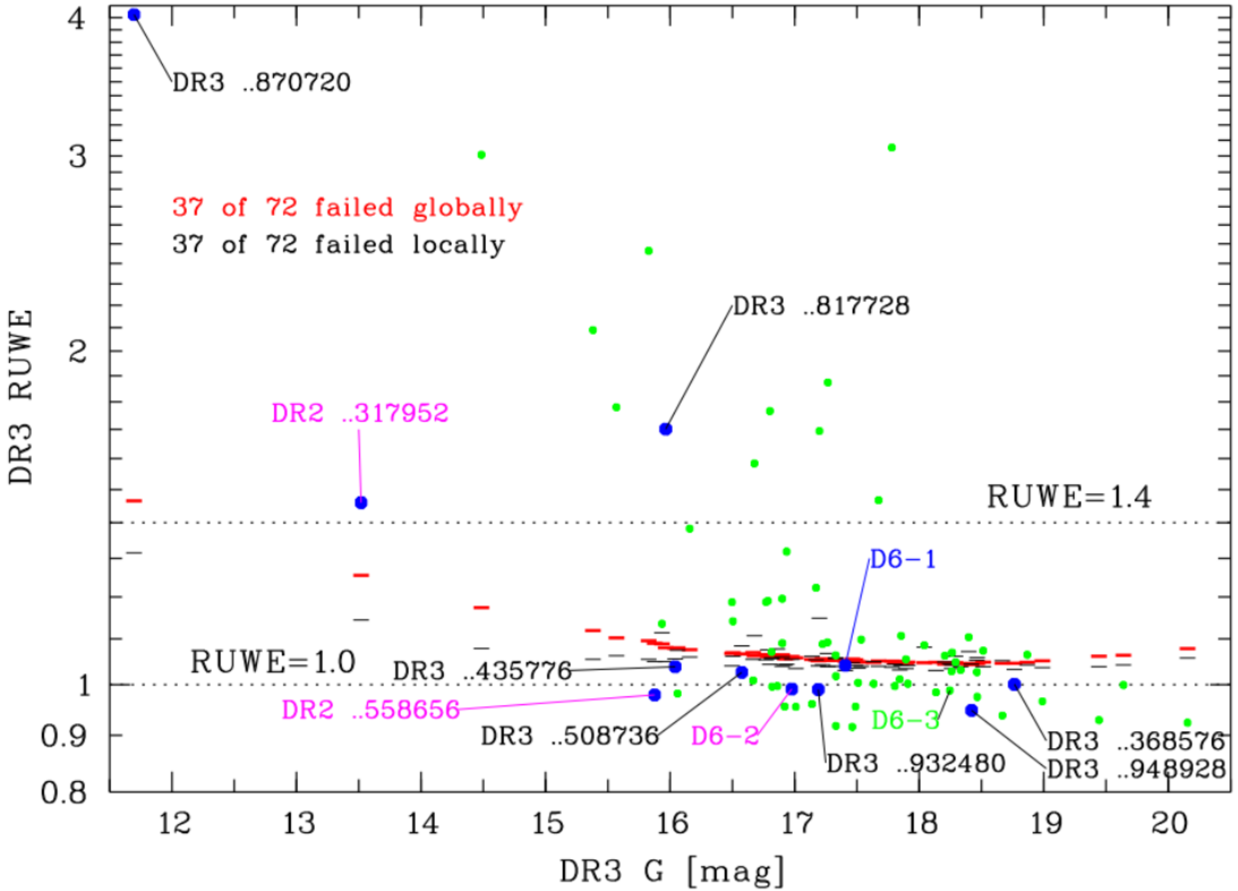
Horizontal bars show 0.75 quantiles of objects with similar magnitudes in local (thin black) and **global (thick red)** comparisons



Check of parameter RUWE for 72 nearest extreme HVS candidates

high-priority candidates (Plx/ePlx>5) are labelled: **blue symbols**
low-priority candidates (3<Plx/ePlx<5): **green symbols**

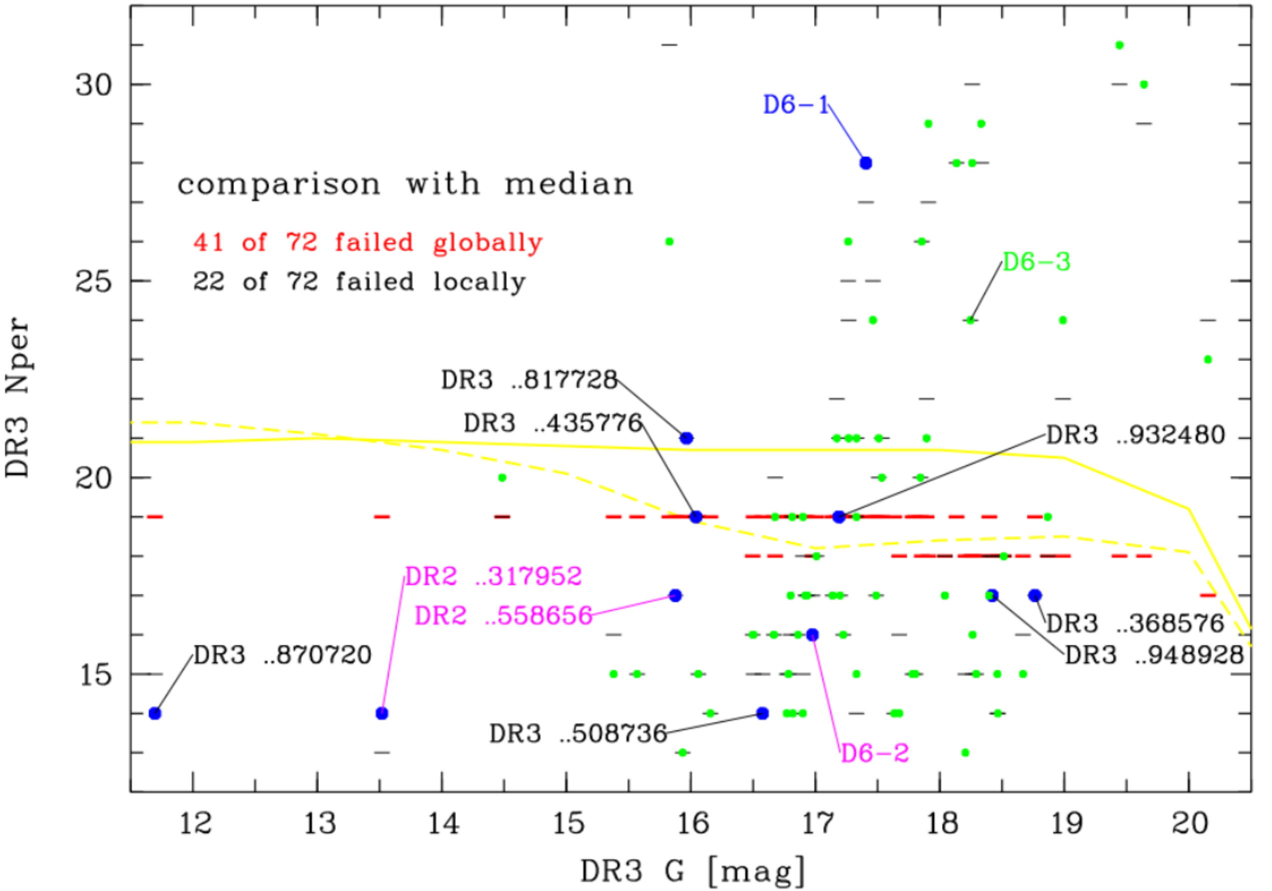
Horizontal bars show 0.75 quantiles of objects with similar magnitudes in local (thin black) and **global (thick red)** comparisons

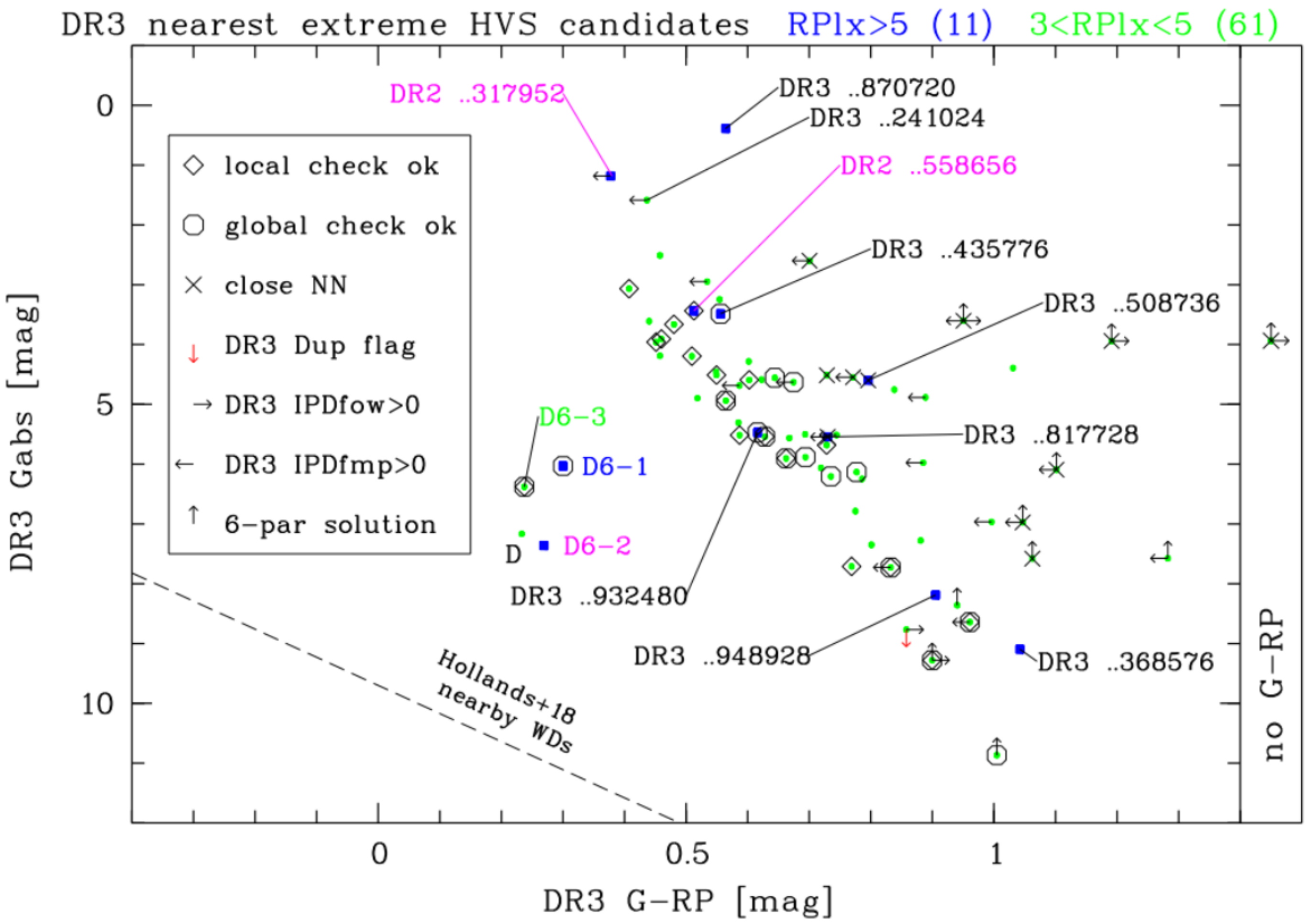


Check of parameter Nper for 72 nearest extreme HVS candidates

high-priority candidates (Plx/ePlx>5) are labelled: **blue symbols**
low-priority candidates (3<Plx/ePlx<5): **green symbols**

Horizontal bars show median values of objects with similar magnitudes in local (thin black) and **global (thick red)** comparisons. **Yellow solid and dashed lines**: mean Nper of all five- and six-parameter solutions **(Lindegren+21)**





Zoomed CMD of 72 nearest extreme HVS in Gaia DR3

local & global parameter comparison and check of IPD and other (binarity) flags

Incl. low-priority candidates: 3<Plx/ePlx<5 (green symbols)

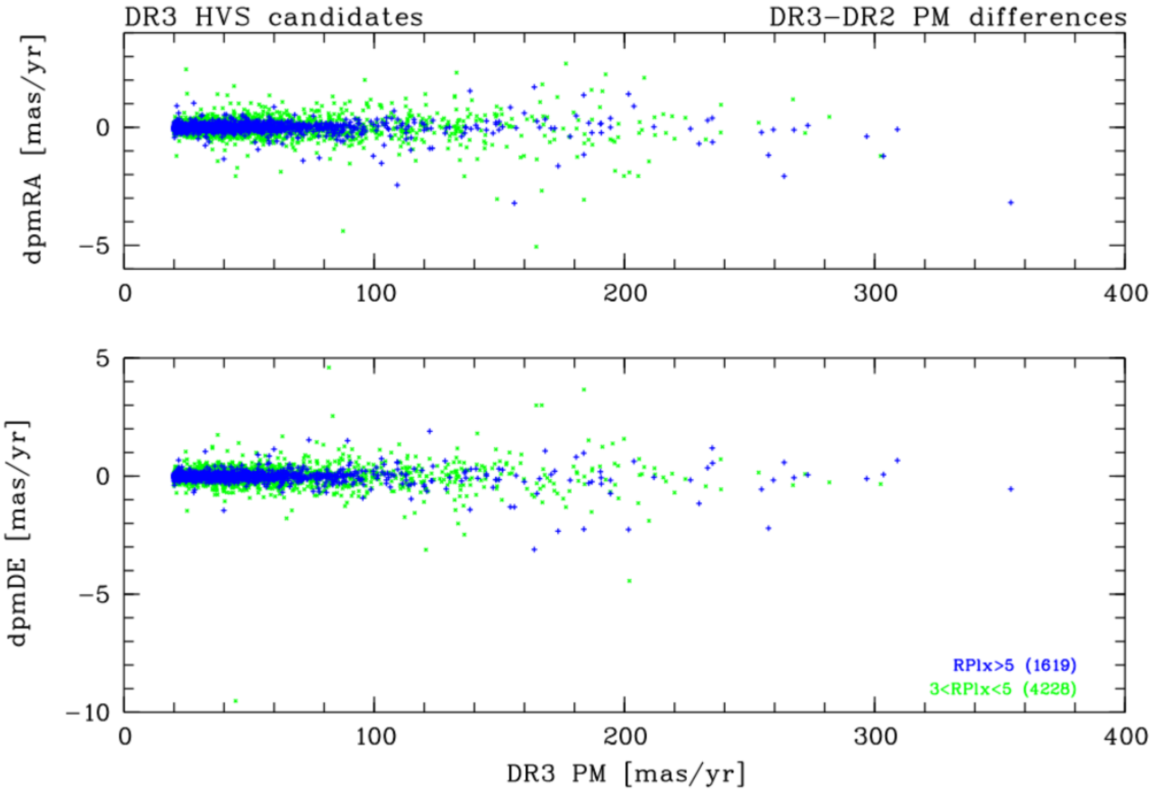
Most of apparently too red candidates have flags hinting at binarity

None of 11 high-priority candidates passed both global and local quality checks !

Conclusions

- New HVS candidates found and known ones reviewed using Gaia astrometry
- Spurious HPMs in Galactic plane/centre led to false HVS interpretations in Gaia DR2 and are still present in DR3, although to a lesser extent.
- HPMs of DR3 HVS candidates agree with DR2 values and are highly significant
- However, HVS candidates selected from DR2 tend to have larger parallaxes hence lower tangential velocities in DR3
- Most DR3 RVs are much lower than heliocentric tangential velocities, indicating that DR3 HVS candidates are still affected by underestimated parallaxes
- None of 72 extreme (vtan_g>700km/s) and nearby (d<4kpc) DR3 HVS candidates, incl. three D^6 stars, passed all quality checks of many astrometric parameters+flags

Proper motion differences (DR3-DR2) for HVS candidates selected with DR3



Incl. low-priority candidates:
3<Plx/ePlx<5 (green crosses)