Meeting new stellar and substellar neighbours with Gaia

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Milky Way and the Local Volume

Questions

♦ Why we need to know our neighbours ?
♠ Which neighbours are still hiding ?
♣ How can we find them ?
♥ Will *Gaia* provide the complete census ?

Topics

- Motivation to search for neighbours
- High proper motion (HPM) – a hint on short distance

- Targets: Ultracool dwarfs (UCDs) and white dwarfs (WDs)
- The growing 10 pc sample (pre-*Gaia)*
- New WD at 8.5 pc found with help of *Gaia* DR1

- Properties of *Gaia* DR2 subsamples of different quality
- *Gaia* DR2 colour-magnitude diagrams up to 100 pc
- Nearest extremely low-mass (ELM) WD at 72 pc
- Verification of *Gaia* parallaxes with HPM check
- New UCDs in *Gaia* DR2 20 pc sample

- Missing nearby binaries in *Gaia* DR2
- (Sub)stellar encounters

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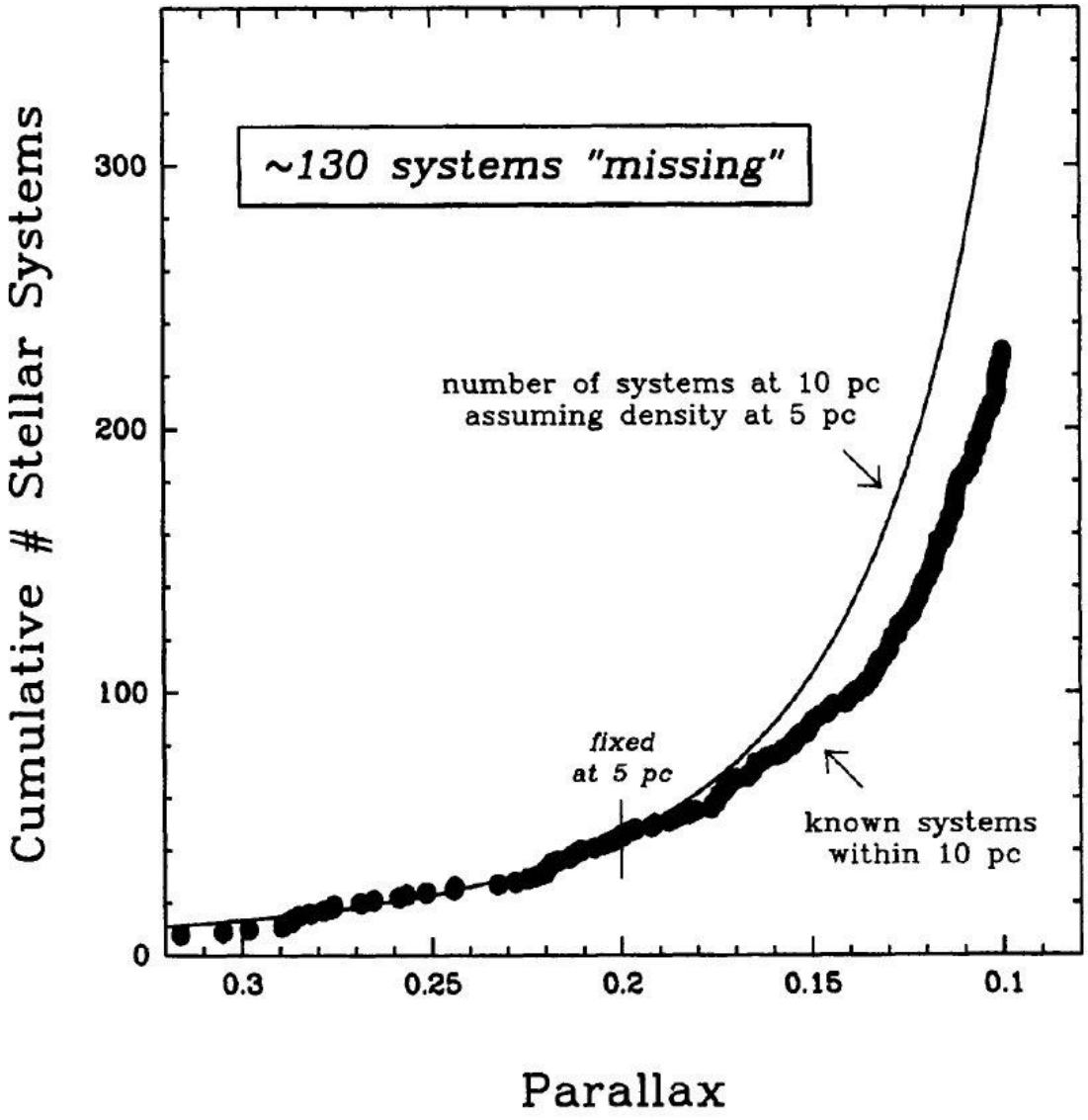
My motivation to search for nearby stars



Henry+97

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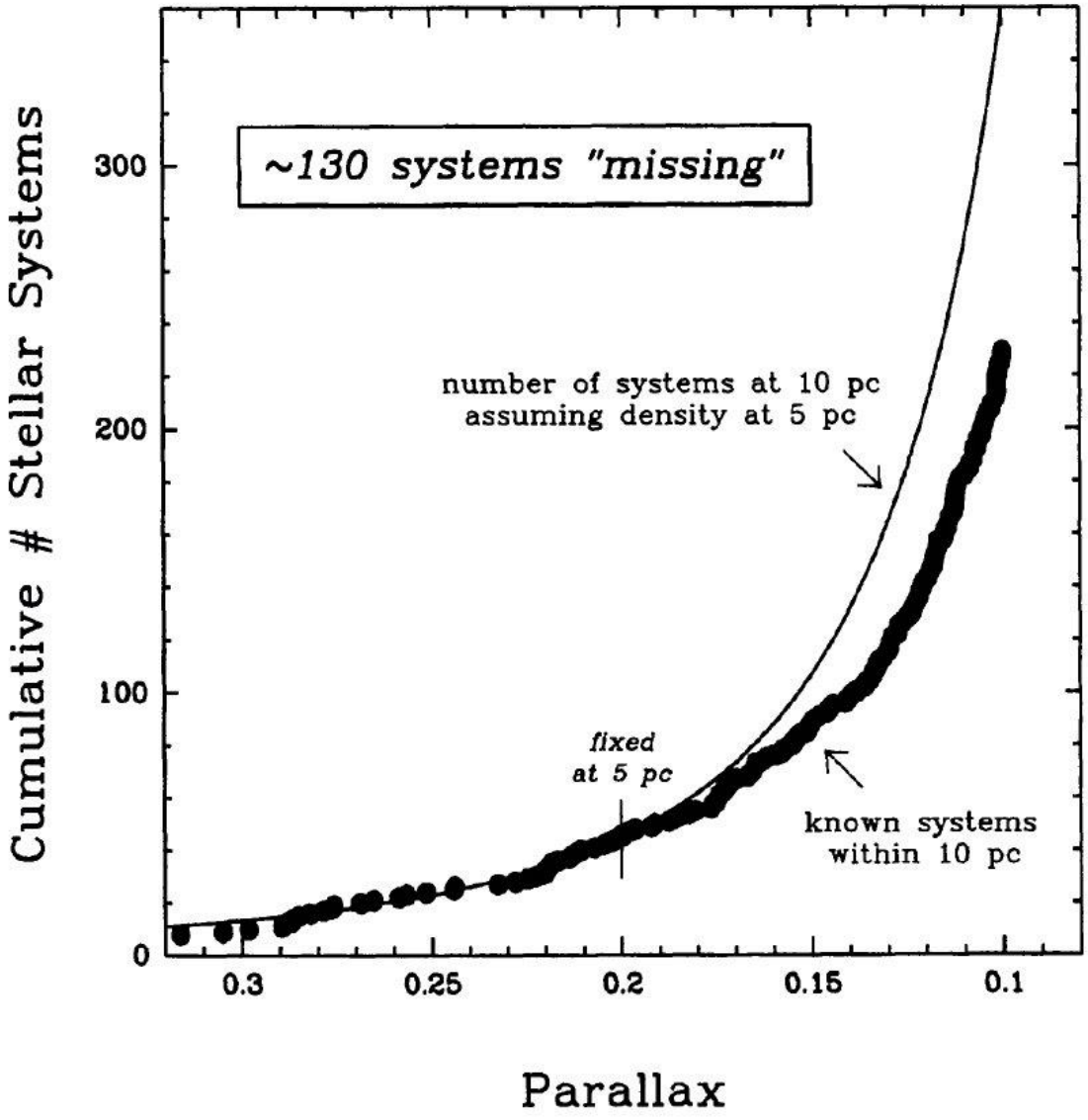


Many faint objects,

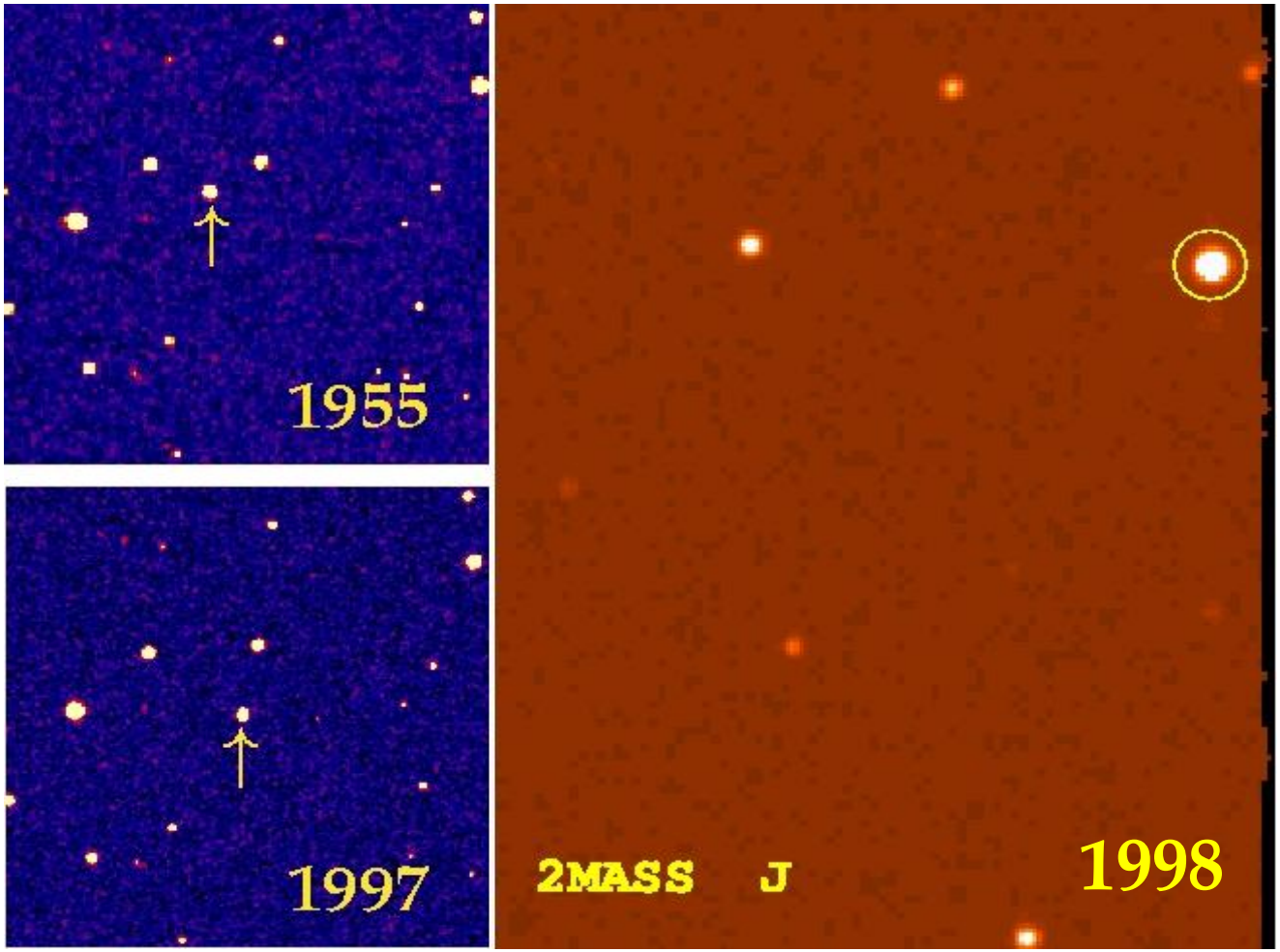
mainly
red dwarf stars
and brown dwarfs,

but also
white dwarfs,

awaited discovery!

Henry+97

Detection by high proper motion (HPM) and colour



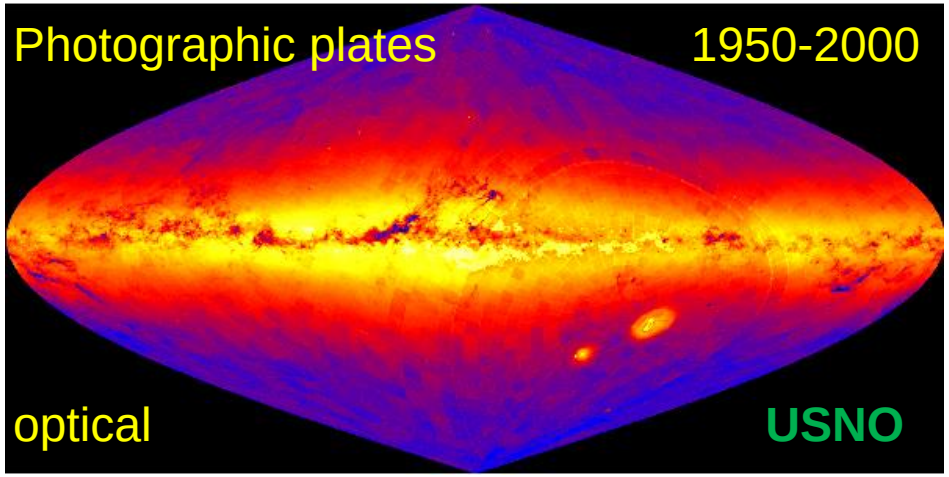
optical near-infrared

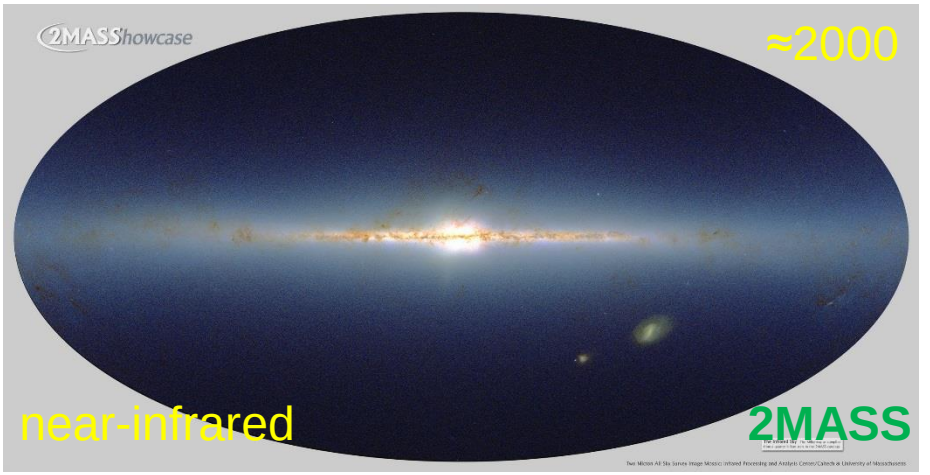
LHS 2090

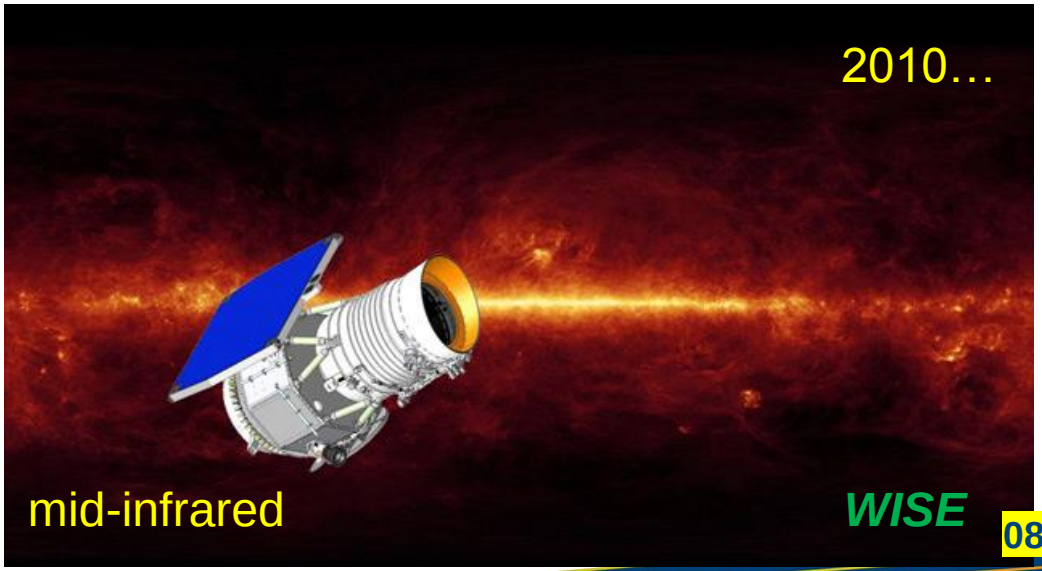
M6.5 dwarf
@ 6pc

Scholz+01

HPM surveys in multi-epoch & multi-colour data rely on correct object matching!







Why care about our nearest neighbours ?

a) Outcome of star formation

Kirkpatrick+19, Henry+19:
stars to brown dwarfs (BDs)
ratio ≈ 6-7 : 1

b) Space density, kinematics & stellar encounters

Bihain&Scholz16: nearest BDs unevenly distributed
Scholz14, Mamajek+15: WISE J0720-0846
Bailer-Jones15: GJ 710

c) Extrasolar planets

Anglada-Escudé+16: Proxima b
Jeffers+20: system of super-Earths around GJ 887

d) Follow-up of brightest benchmarks of different classes

Scholz+03, McCaughrean+04: ε Indi Ba,Bb (T1+T6)
Bihain+13: WISE J0521+1025 (nearest northern T dwarf)
Scholz+04a,b, Schilbach+09: latest M-type subdwarfs
Scholz18a: TYC 3980-1081-1 B (new WD within 10 pc)
Scholz18b, Kosakowski+20, Kawka+20: nearest extremely low-mass (ELM) white dwarf

e) Ages for members of nearby young moving groups (YMGs)

Aller+16, Gagné+17, Scholz20:
planetary-mass young BDs

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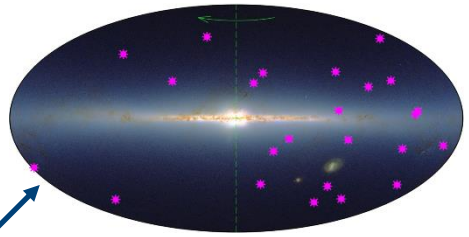

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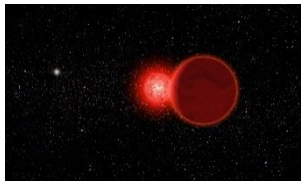

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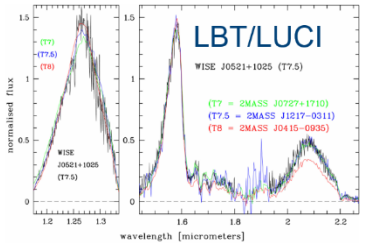

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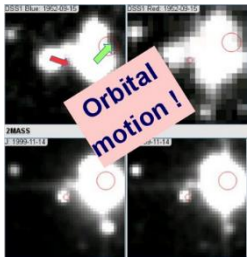

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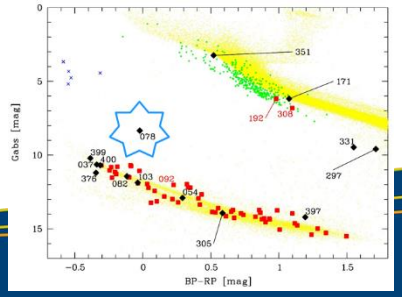
Aller+16, Gagné+17, Scholz20: planetary-mass young BDs



Ultracool dwarfs (UCDs) …

Dwarf stars of spectral types M7 and later were first called UCDs by **Kirkpatrick+97**

Increasingly cooler UCDs were discovered with time, and new spectral classes of L, T, and Y dwarfs were created (see review of **Cushing14**)

Spectral type of L4 and mass of 70 Jupiter masses ≈ hydrogen burning limit (**Dupuy&Liu17**), but boundary depends on age!
Brown dwarfs (BDs) change their spectral types as they cool down.

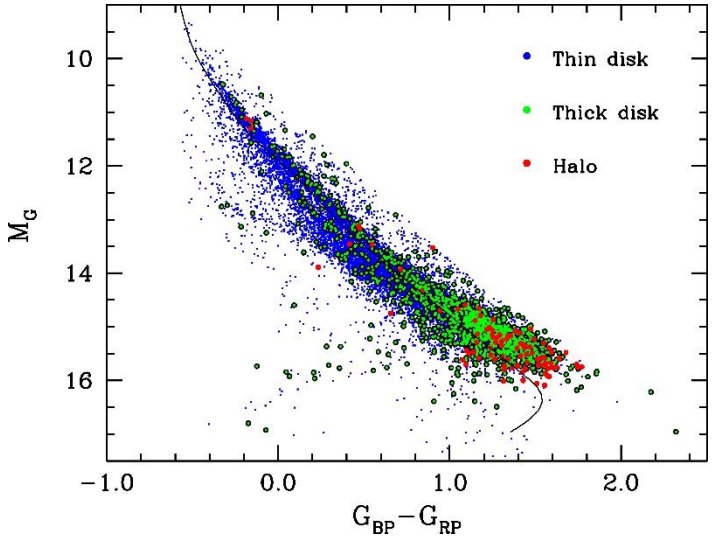
UCDs represent difficult (faint red) targets for *Gaia*: study of known UCDs in DR1 (**Smart+17**) and DR2 (**Smart+19, Bardalez+19**), and new photometric candidates in DR1 (**Scholz&Bell18**) and DR2 (**Reylé18**)

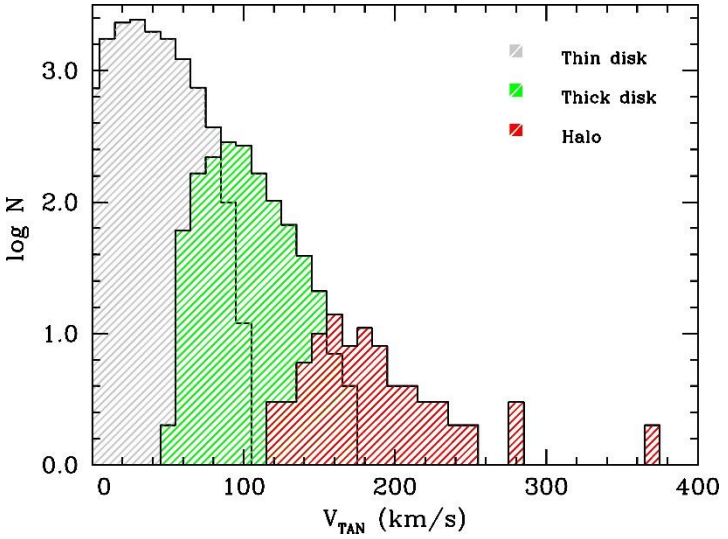
Scholz20: UCD candidates (mix of coolest dwarf stars and BDs) within 20 pc **selected by absolute magnitude M_G>14mag** in *Gaia* DR2

...and white dwarfs (WDs) as seen by *Gaia*

Gaia DR2 has substantially increased our knowledge on WDs, revealing fine structures in the WD sequence (***Gaia* Collaboration Babusiaux+18**), the Galactic halo age (**Kilic+19**), hypervelocity WD candidates (**Shen+18**), …

Torres+19: Random forest identification of different WD populations within 100 pc

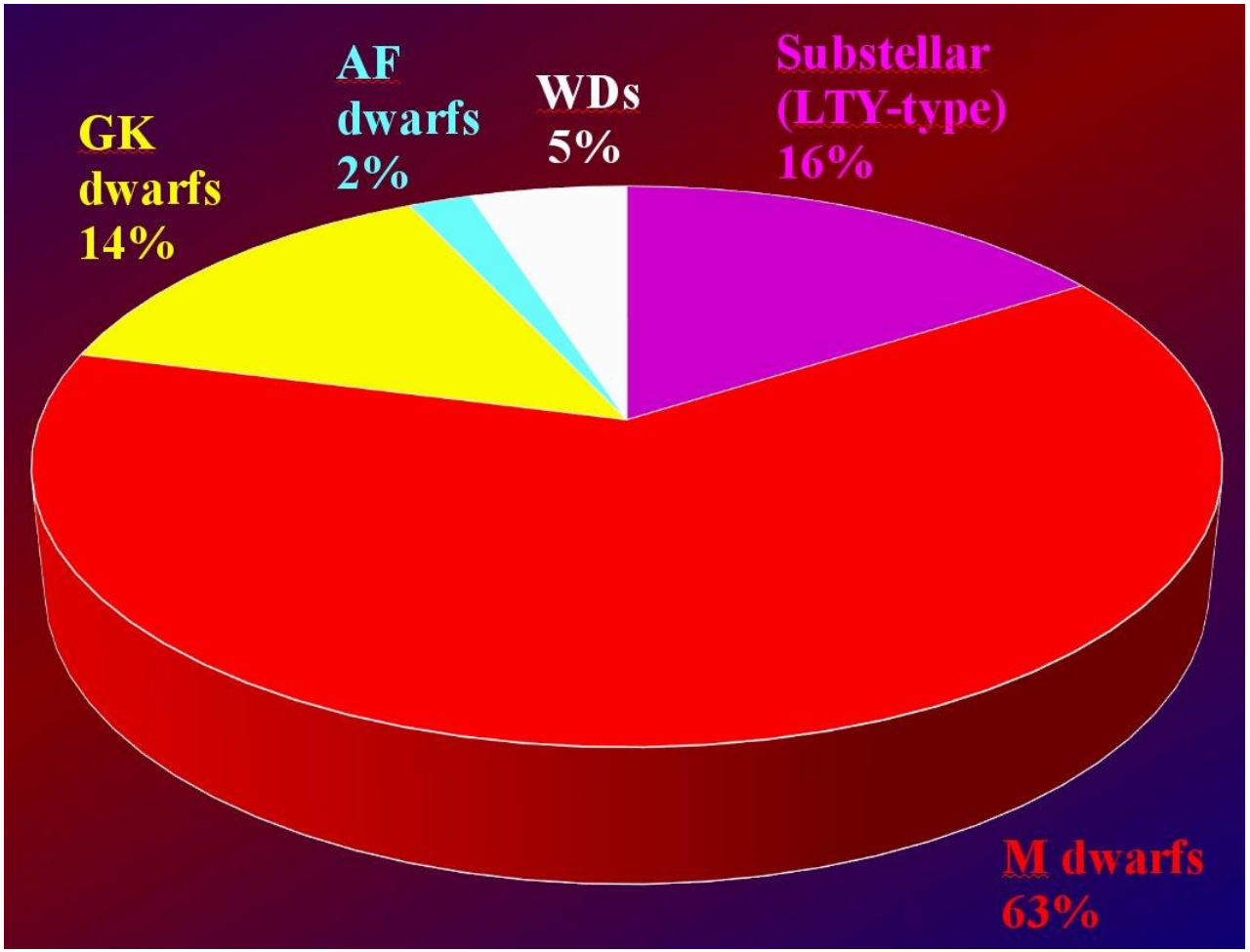




A new WD @ ≈8.5 pc (closer than completeness limit of 13 pc assumed by **Holberg+16** !) was found in *Gaia* DR1+UCAC5+URAT (**Scholz+18a**)

Within 20 pc, **Hollands+18** identified 139 WDs in *Gaia* DR2 (9 new WDs)
Scholz20 did not find additional new WDs in the *Gaia* DR2 20 pc sample

The nearest (*d*<6.5pc) census (166 objects)



based on:

REsearch Consortium On Nearby Stars (RECONS) **www.recons.org** (stellar) and **Bihain&Scholz16** (substellar)

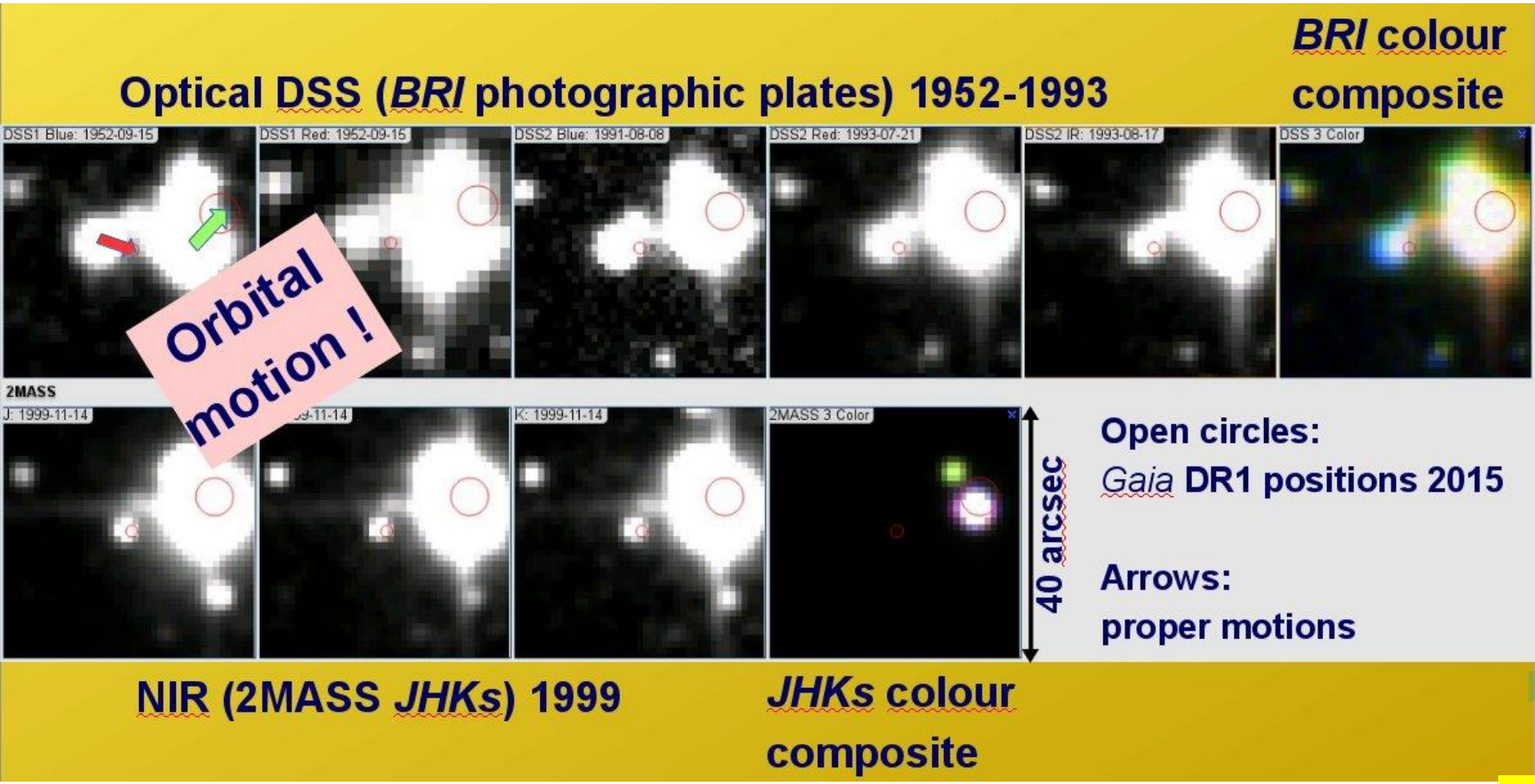
The solar neighbourhood within 10pc

No complete data bases available. **RECONS** gives only a TOP100 list and summarises the 10pc census (and history):

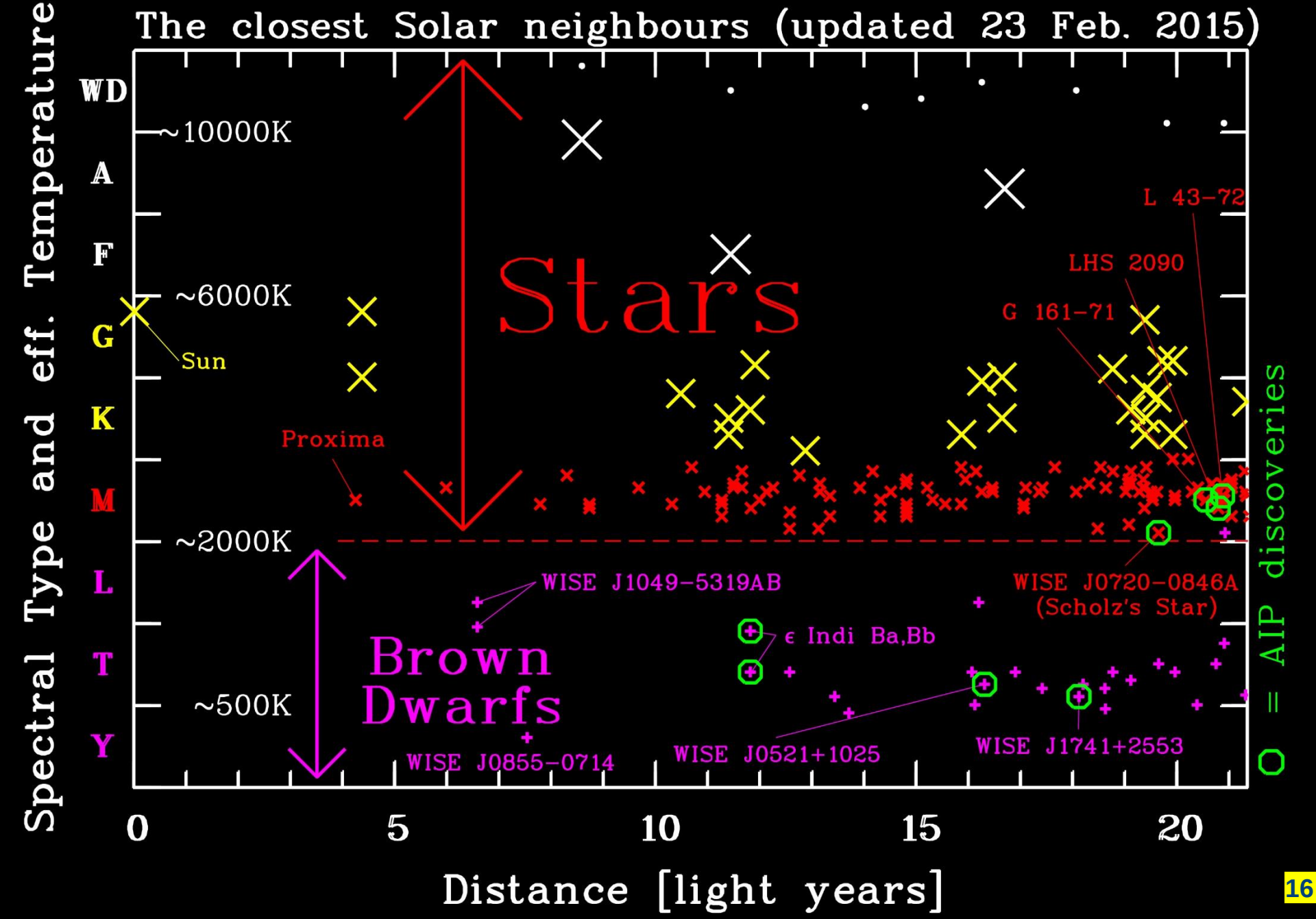
	2000.0	2010.0	2018.3	notes
total objects	293(+8)	366(+8)	462(+8)	58% increase since 2000
systems	213	256	317	49% increase since 2000
companions	78	97	111	42% increase since 2000 (stars+brown dwarfs)
planets	2(+8)	13(+8)	34(+8)	exoplanets (+8 Solar System planets)
white dwarfs	18	20	21	
O stars	0	0	0	
B stars	0	0	0	
A stars	4	4	4	
F stars	7	7	7	
G stars	19	19	19	
K stars	44	44	44	
M stars	198	246	283	43% increase since 2000
all stars	290	340	378	30% increase since 2000
brown dwarfs	1	13	50	
planets	2(+8)	13(+8)	34(+8)	

TYC 3980-1081-1 B = new WD within 10pc

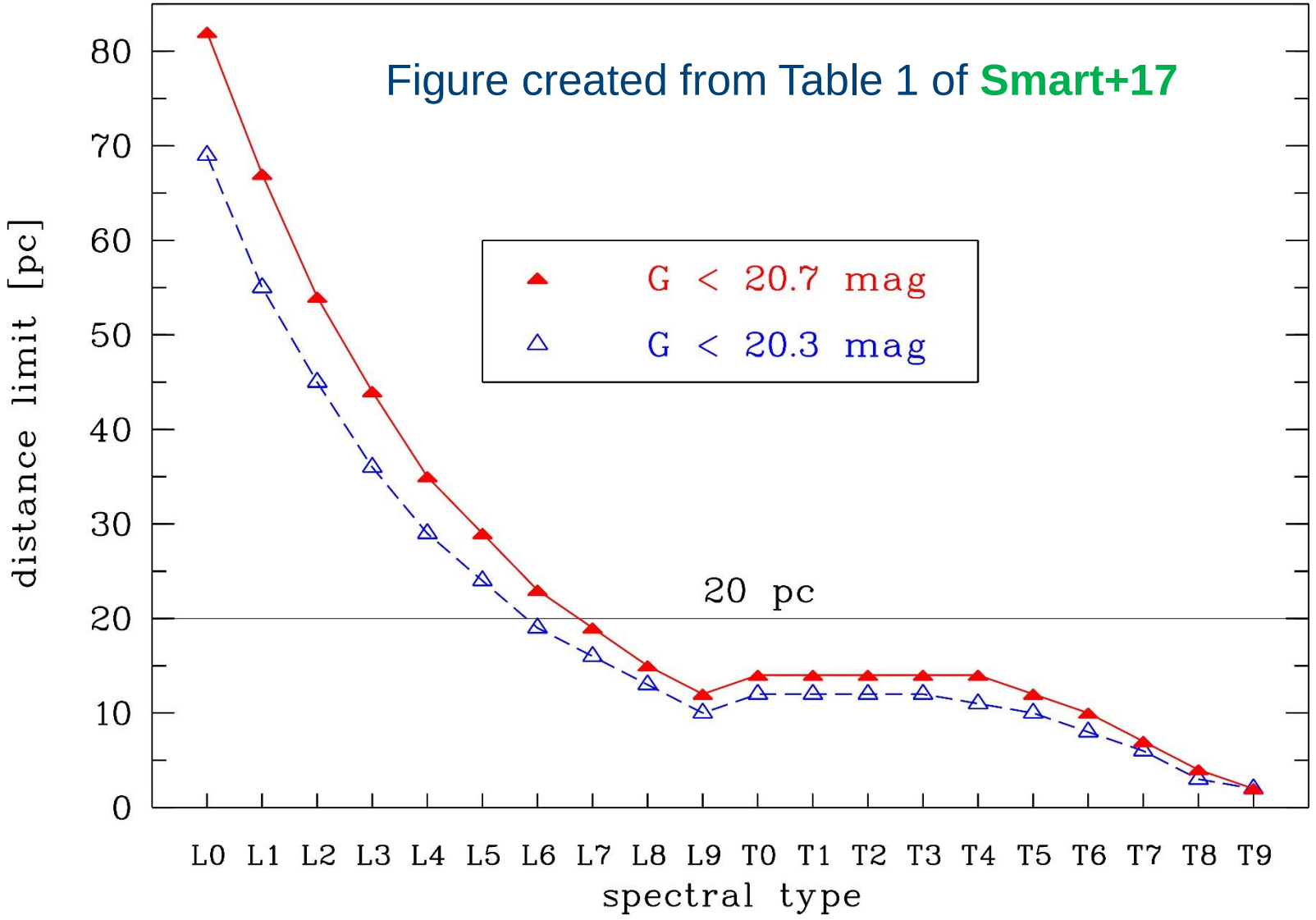
found as a common proper motion companion of a new nearby star (**Scholz+18a**) using *Gaia* DR1, UCAC5, and URAT1 catalogues



Finder charts from **Infrared Science Archive (IRSA)**


The closest Solar neighbours (updated 23 Feb. 2015)
Spectral Type and eff. Temperature
WD
A
F
G
K
M
L
T
Y
~10000K
~6000K
~2000K
~500K
Stars
Brown Dwarfs
Sun
Proxima
L 43-72
LHS 2090
G 161-71
WISE J1049-5319AB
ϵ Indi Ba,Bb
WISE J0720-0846A
(Scholz's Star)
WISE J0855-0714
WISE J0521+1025
WISE J1741+2553
= AIP discoveries
0
5
10
15
20
Distance [light years]

*Gaia´*s horizon for UCDs



Gaia DR2 10pc update + 20pc prediction

The pre-*Gaia* number of **428** (**378+50** stars+BDs) objects at <10pc was slightly reduced by **Henry+19** using *Gaia* DR2 to:

418 (**366+52** stars+BDs)

(only 8 new systems were so far added by *Gaia*,
but 47 of 305 systems =15% were missed)

Assuming constant space density, **Scholz20** expected within 20pc:

8 x 418 ≈ 3350 objects.

However, *Gaia* DR2 contains much higher numbers of objects:

5400 $Plx > 50\,\mathrm{mas}$

6105 $(Plx + 3 \times e\_Plx) > 50\,\mathrm{mas}$

Gaia DR2 quality criteria

Scholz20:

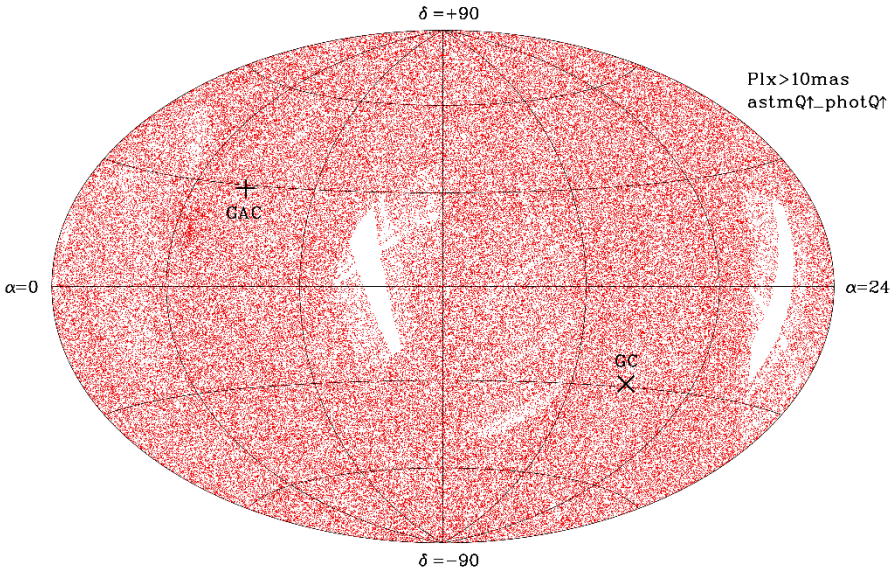
We considered the astrometry good when all of the following three criteria were fulfilled (otherwise, poor):

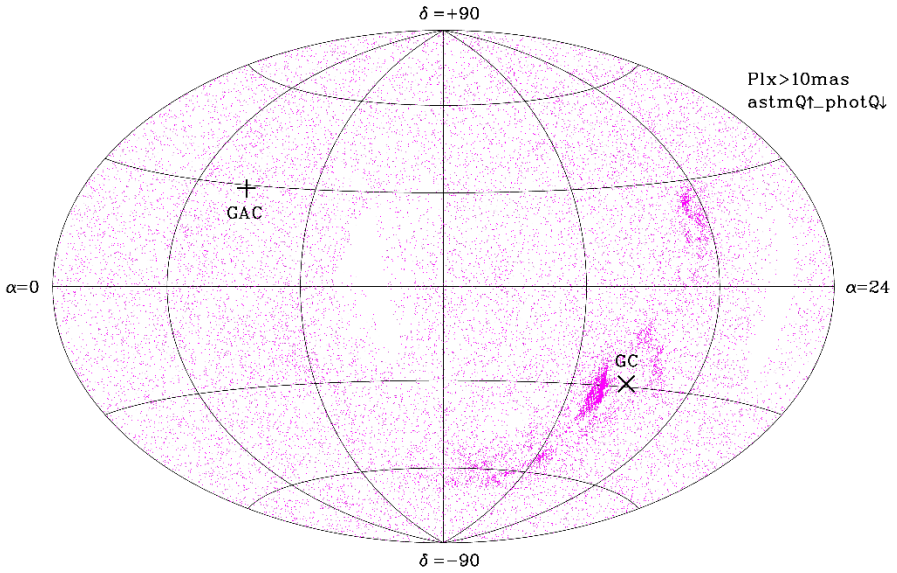
astm_q1 - $Plx/e\_Plx > 10$,
astm_q2 - $RUWE < 1.4$,
astm_q3 - visibility_periods_used> 8.

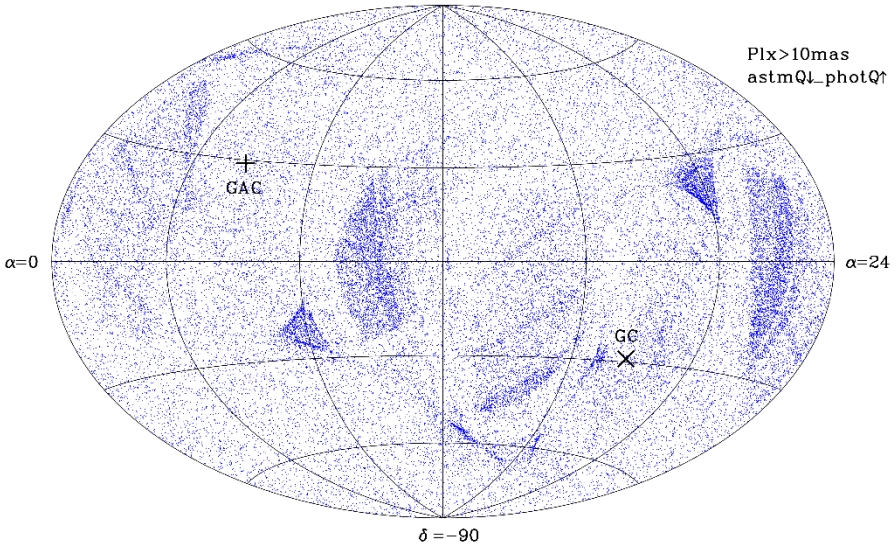
For good photometry, all of the following three criteria had to be fulfilled (otherwise, the photometry was considered poor):

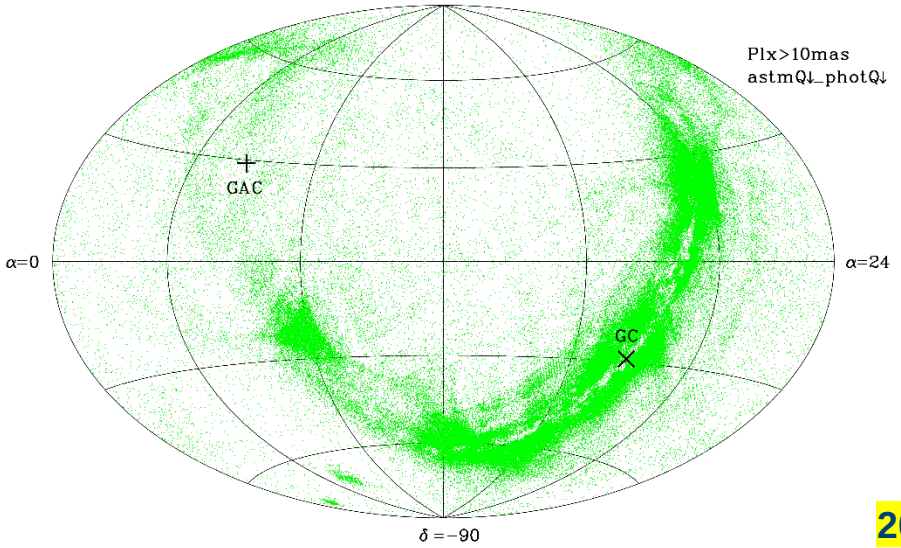
phot_q1 - phot_bp_mean_flux_over_error> 10,
phot_q2 - phot_rp_mean_flux_over_error> 10,
phot_q3 - phot_bp_rp_excess_factor $< 1.3+0.06\times(BP-RP)^2$,

Distribution of different *Gaia* DR2 100pc subsamples on the sky





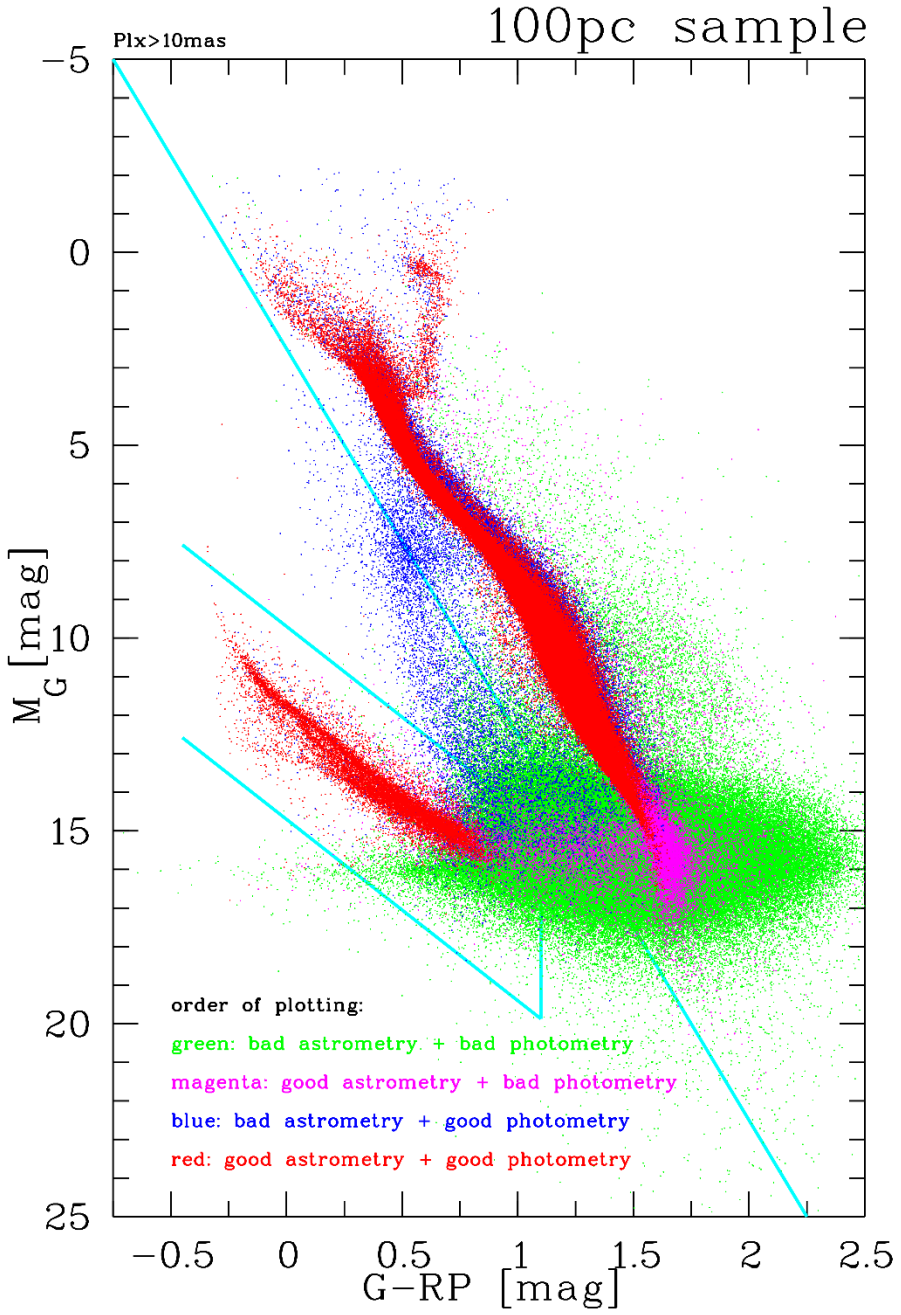




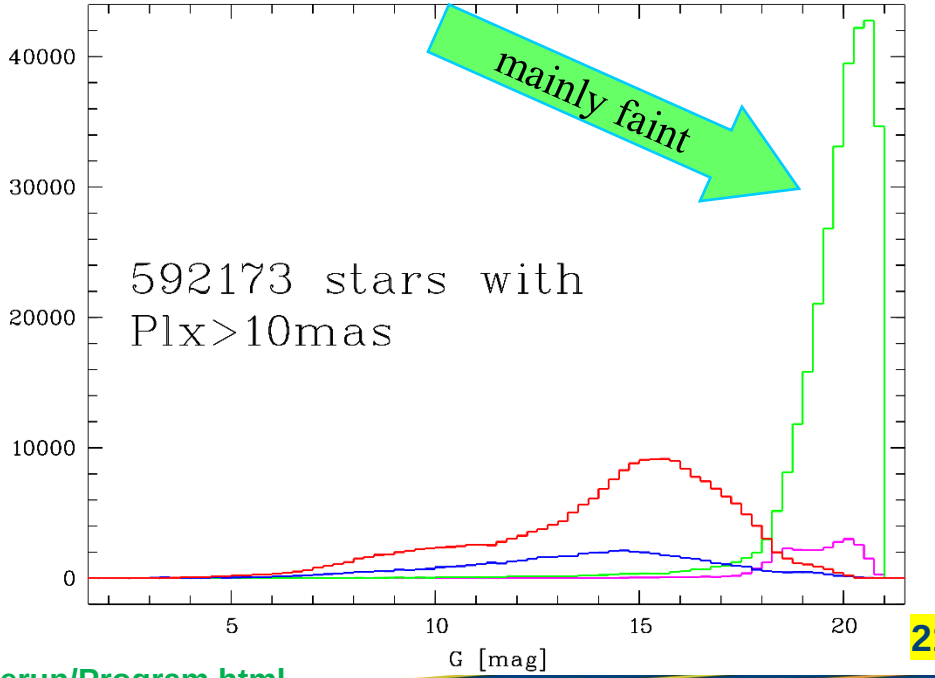
Scholz19: http://www.astro.physik.uni-potsdam.de/~starsontherun/Program.html

Gaia DR2 100pc horizon for WDs

- Of all reliable stars (red dots) 12821 WDs fall in **Hollands+18** colour box
  - ≈ 93% of 13732 WDs in **Torres+19**
  - = 6.11% of all 209793 stars
  - only 62 (0.03%) are not in WD colour box and below WD/MS+sd dividing line!



50% with astm_Q↓ and phot_Q↓



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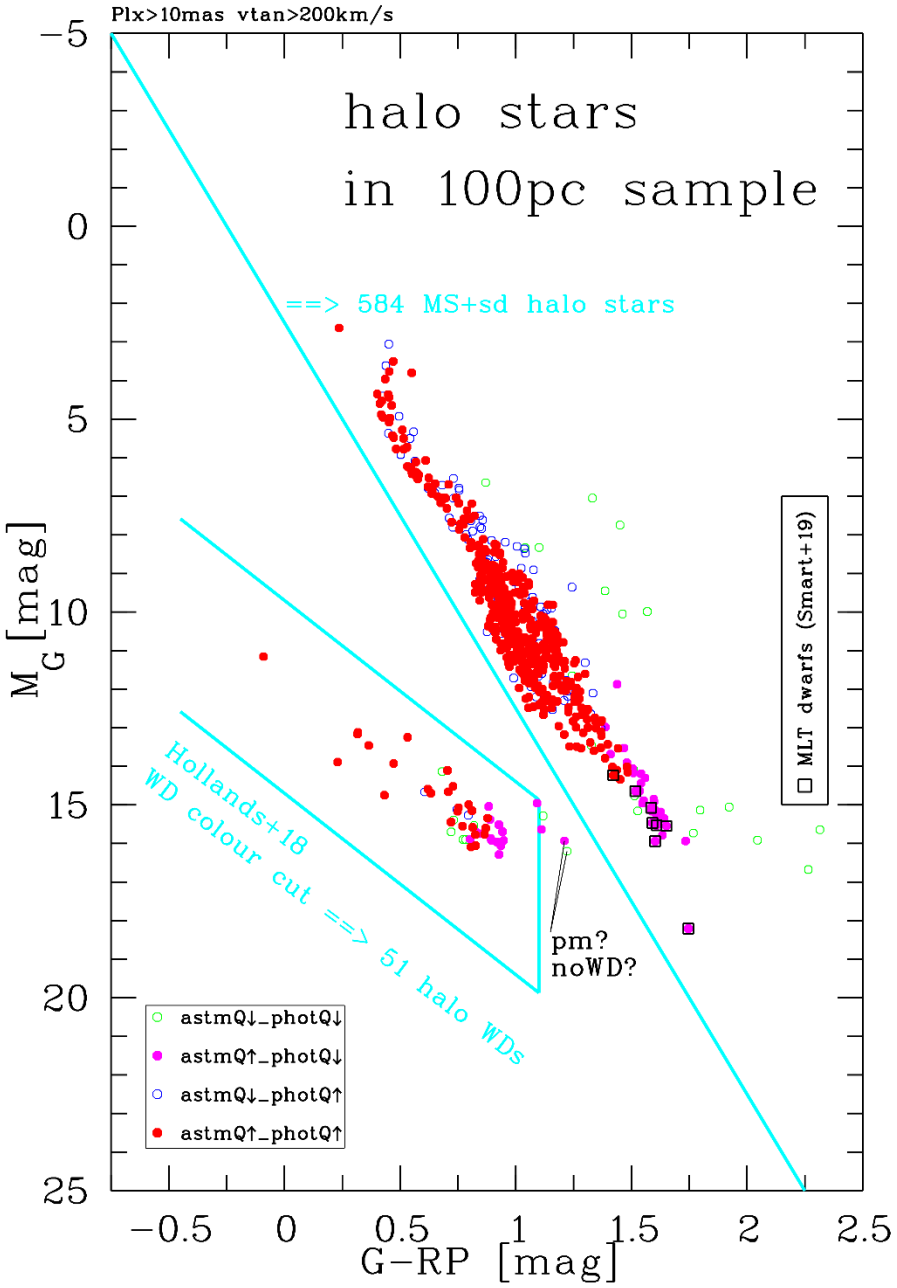
Kinematically defined halo stars (*Gaia* DR2 tangential velocities vtan>200km/s)



- Clear separation of WD sequence from other halo stars within 100pc
  - very small contamination by false pm objects (only 2 of 53 WD candidates)
  - most halo WDs are cool (see also **Torres+19**), some have G-RP>≈1.1, at the edge of the **Hollands+18** colour box
  - other halo stars seem to form two sequences: MS+sd
  - 51 halo WDs compared to 584 MS+sd → 8% of all halo stars are WDs

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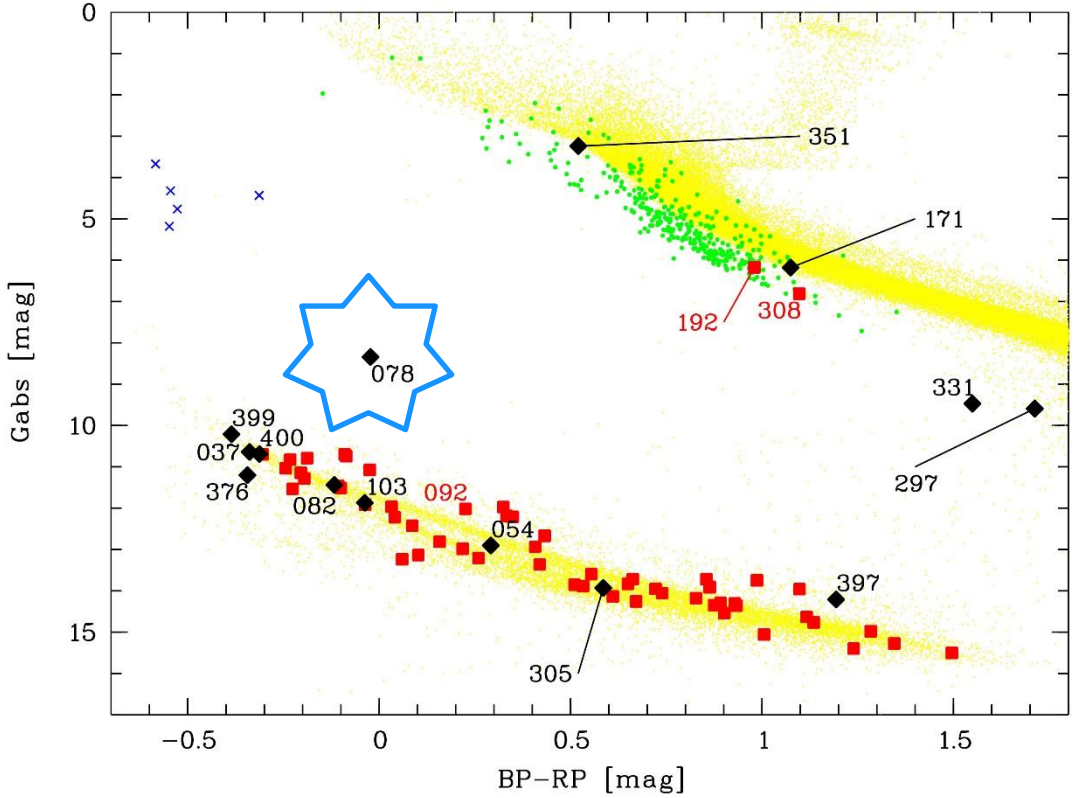
The nearest extremely low-mass WD ($d \approx 72$ pc)



Scholz+18b:
Spectroscopic classification + *Gaia* DR2 data of new WDs among blue HPM objects from LSPM (**Lépine&Shara05**) and UCAC2 (**Zacharias+04**)

078 = 2MASS J0500-0930
unusual WD, preliminarly classified as DA3.0 ± 1.5
log $g \approx 6$-6.5, $T_{eff} \approx 11{,}880 \pm 1100$ K

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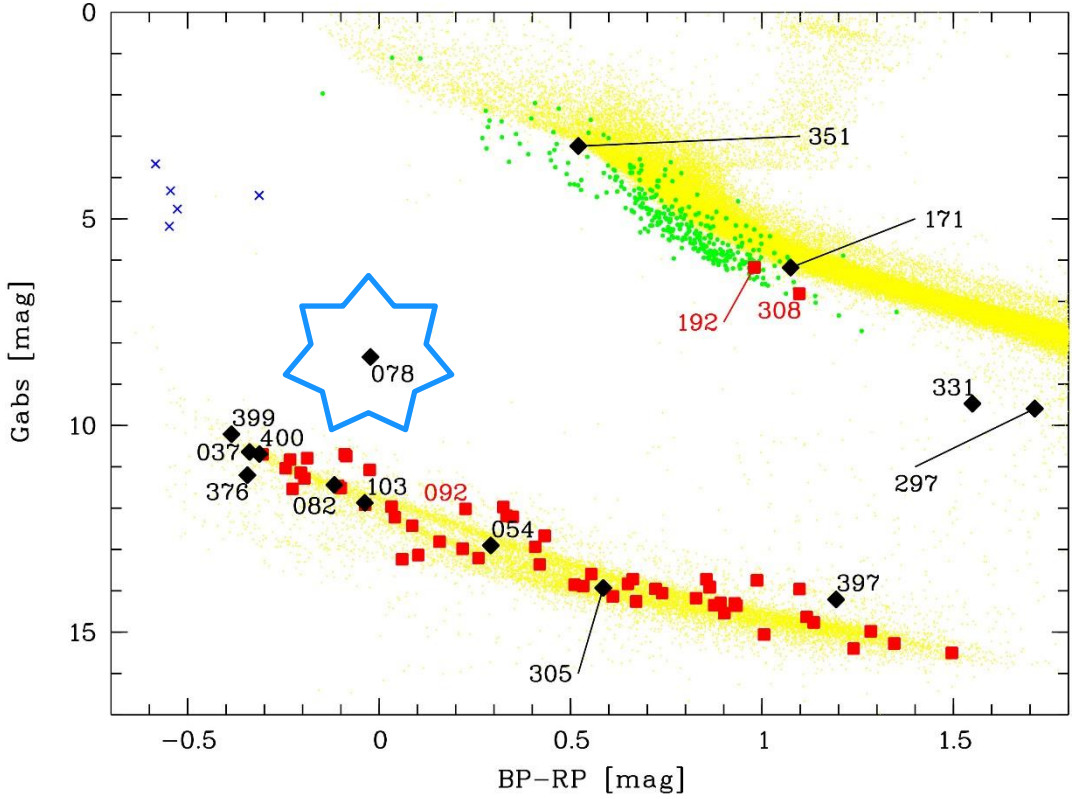

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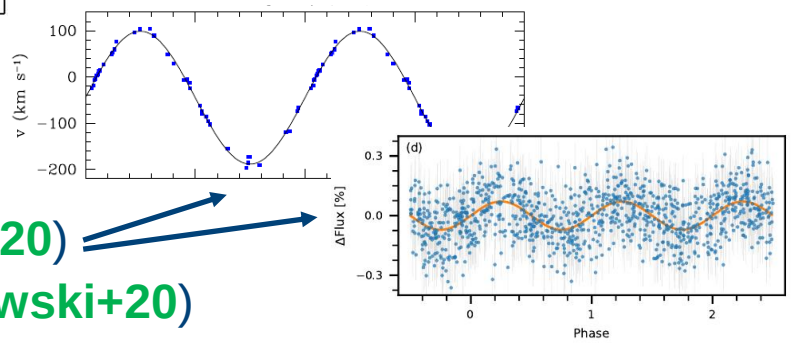
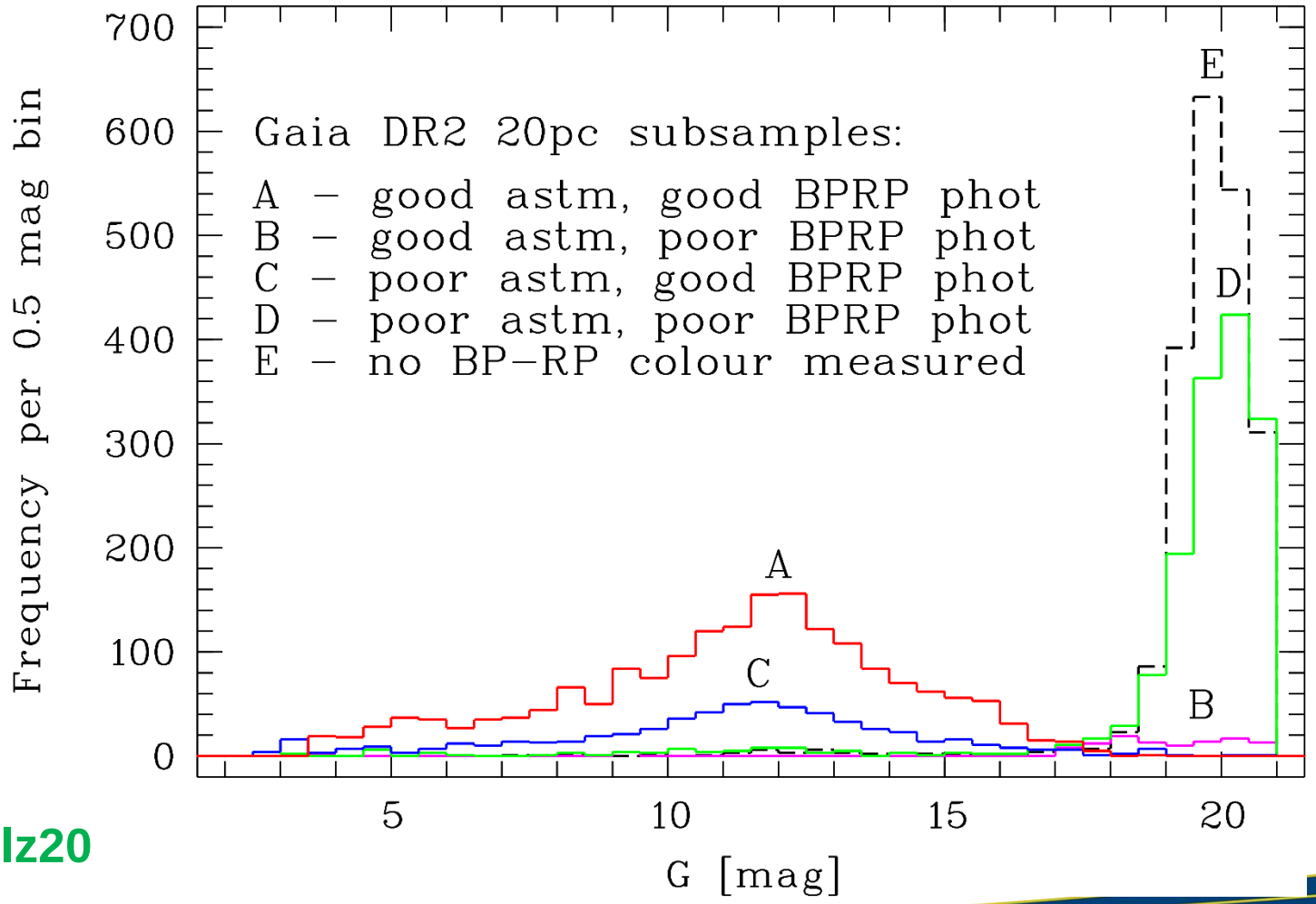
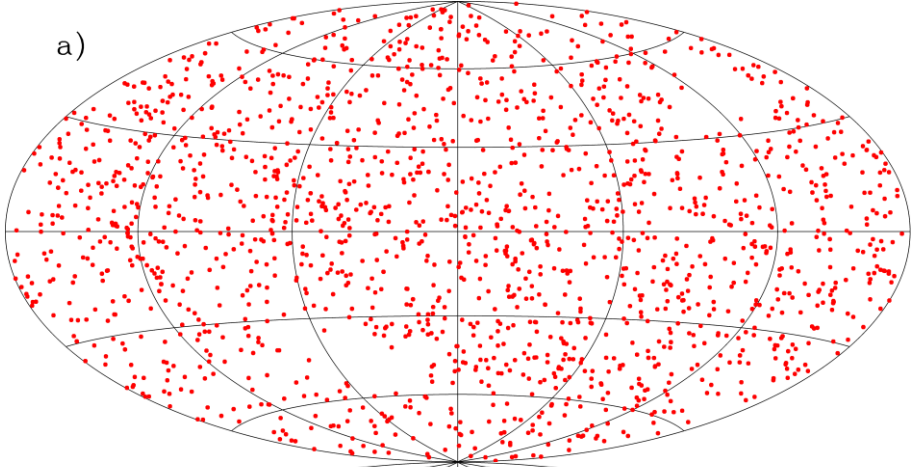


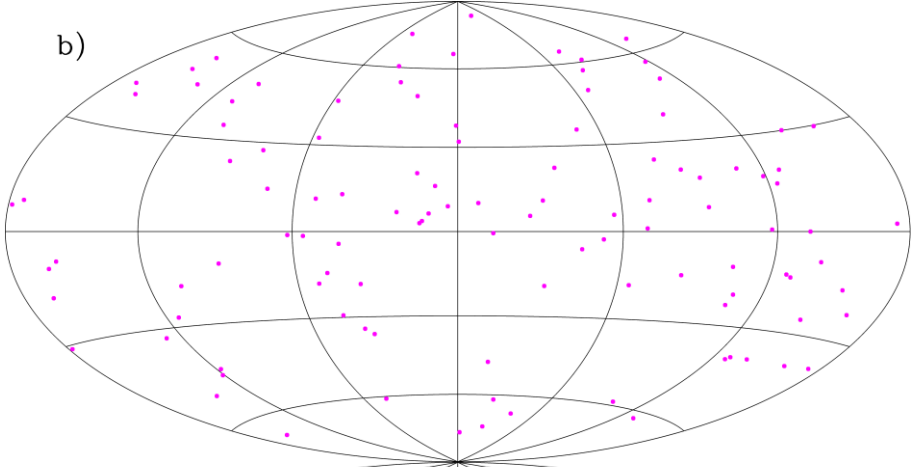
Confirmed as extremely low-mass (ELM) WD:
log g = 6.96 ± 0.01, T_{eff} = 10,536 ± 44 K (**Kawka+20**)
log g = 6.39 ± 0.02, T_{eff} = 10,810 ± 40 K (**Kosakowski+20**)
Both studies estimate a mass of 0.16-0.17 M_{solar} (and ≥0.3 M_{solar} for unseen cool WD companion) and measure P_{orb} = 9.5h from RV and TESS time series

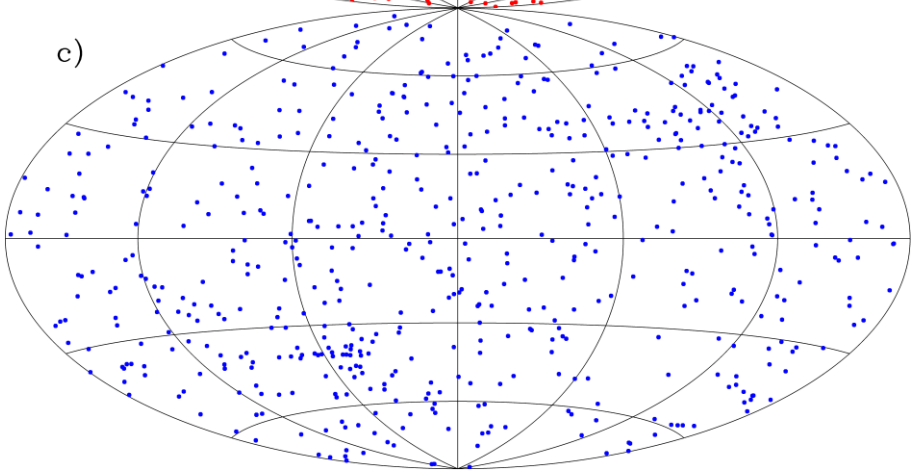
Magnitude distributions of 20pc subsamples of different quality

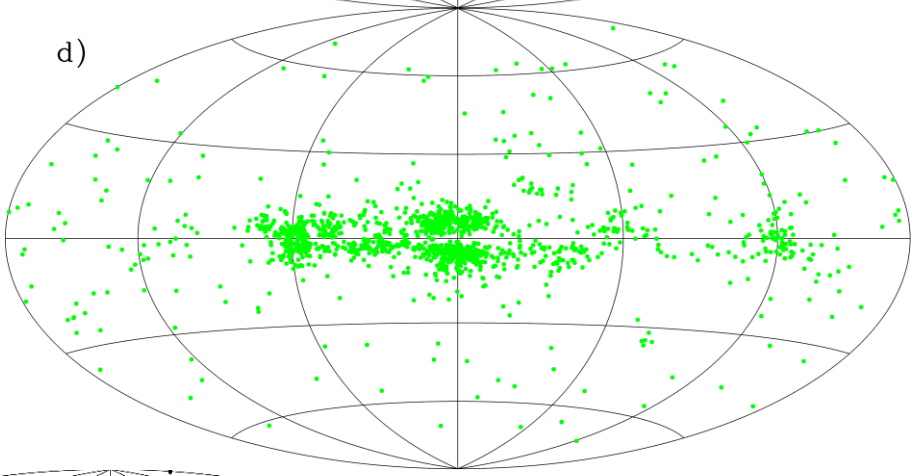


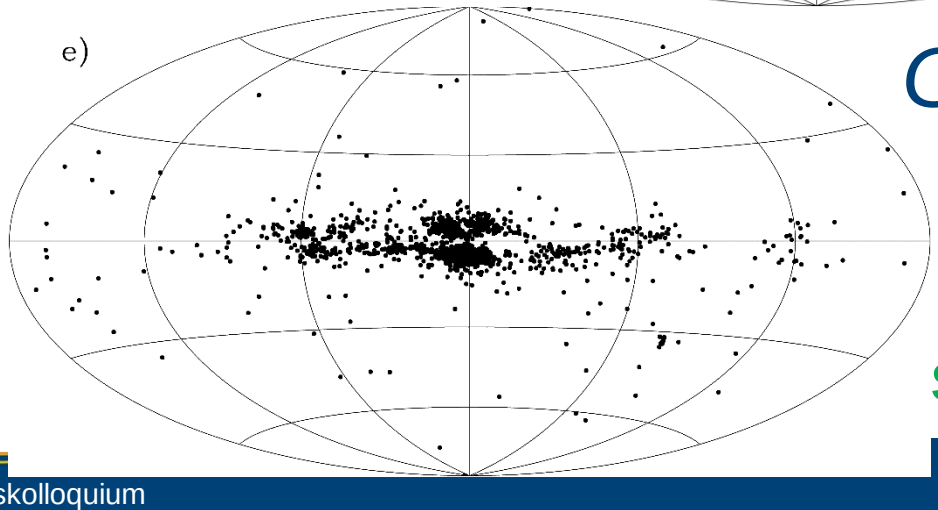
Scholz20







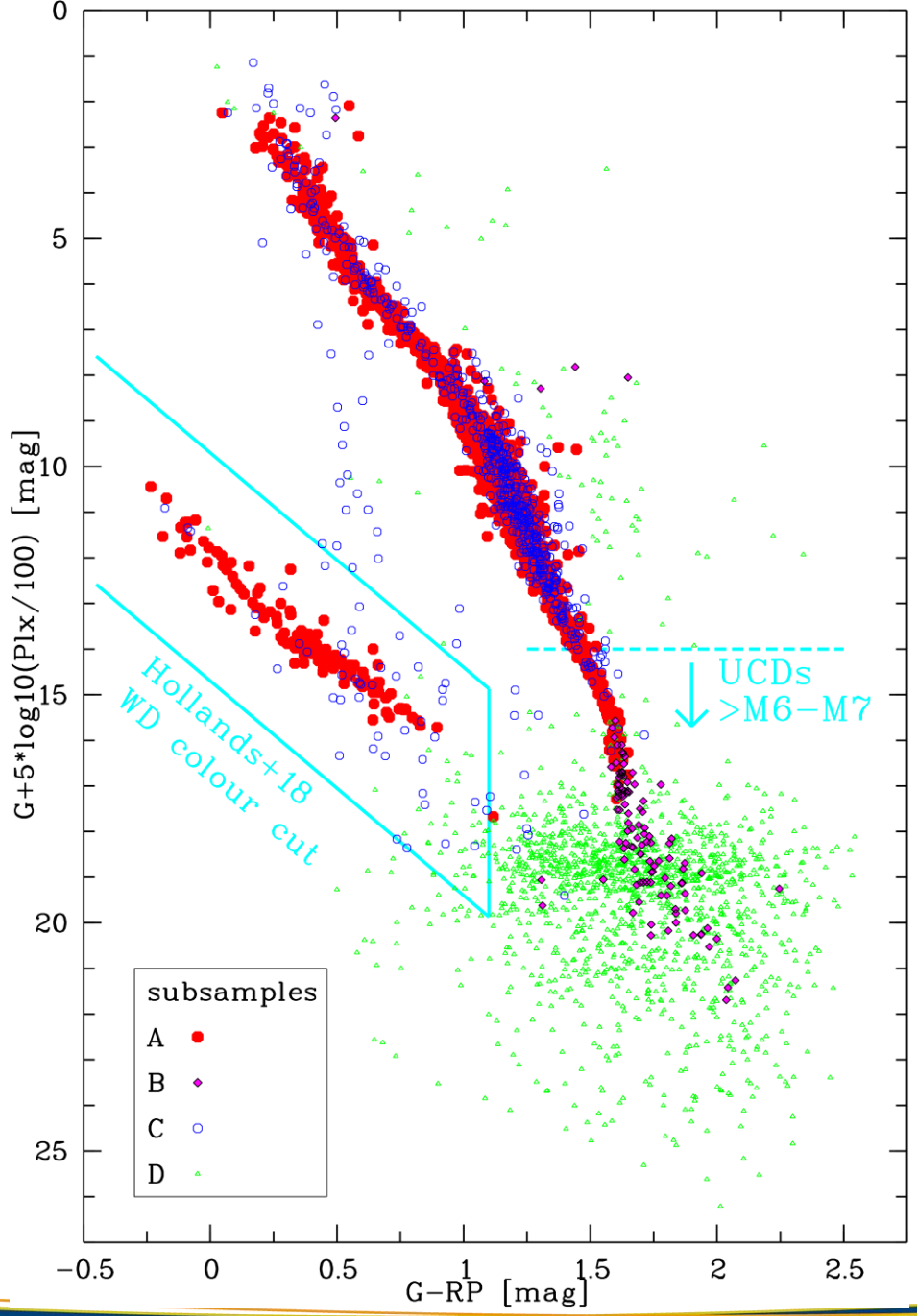




Distributions in Galactic coordinates

Gaia DR2 20pc

Scholz20



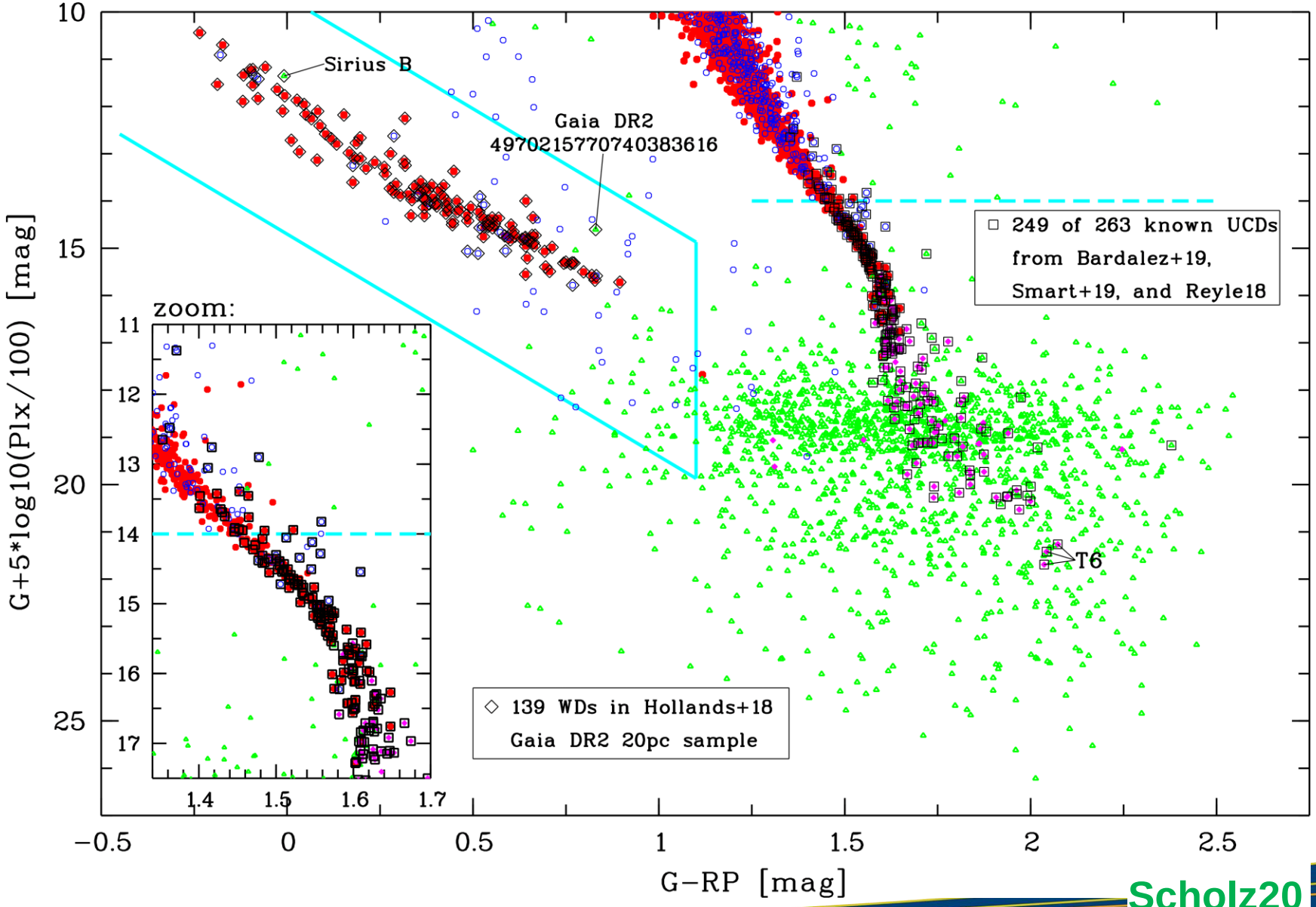
Colour-magnitude diagram (CMD) of full *Gaia* DR2 20pc sample

$$(Plx + 3 \times e\_Plx) > 50\,\mathrm{mas}$$

Only ≈4100 of ≈6100 objects have *G-RP* colour information

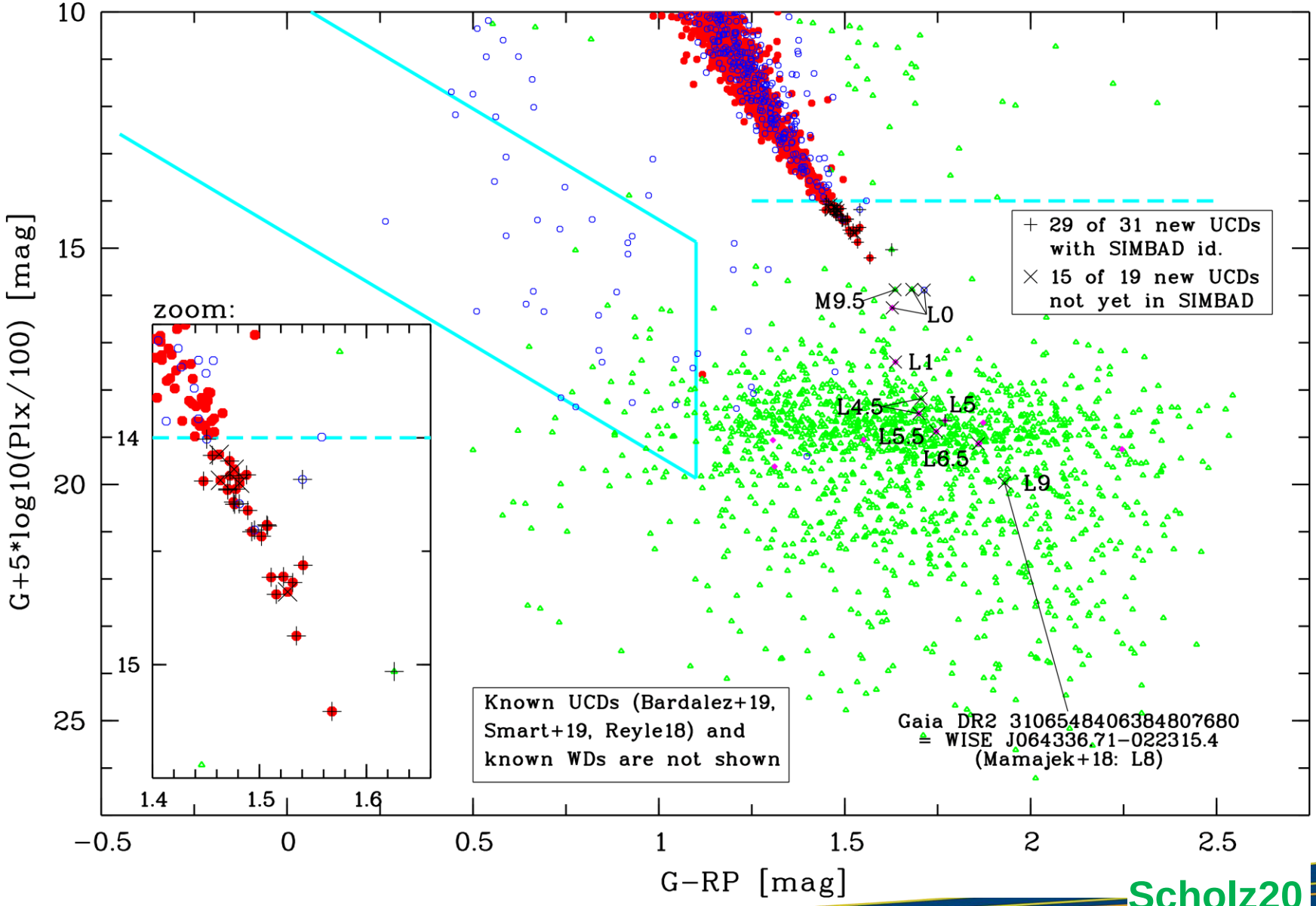
Scholz20

Zoom to faint part of *Gaia* CMD @ *d*<20pc



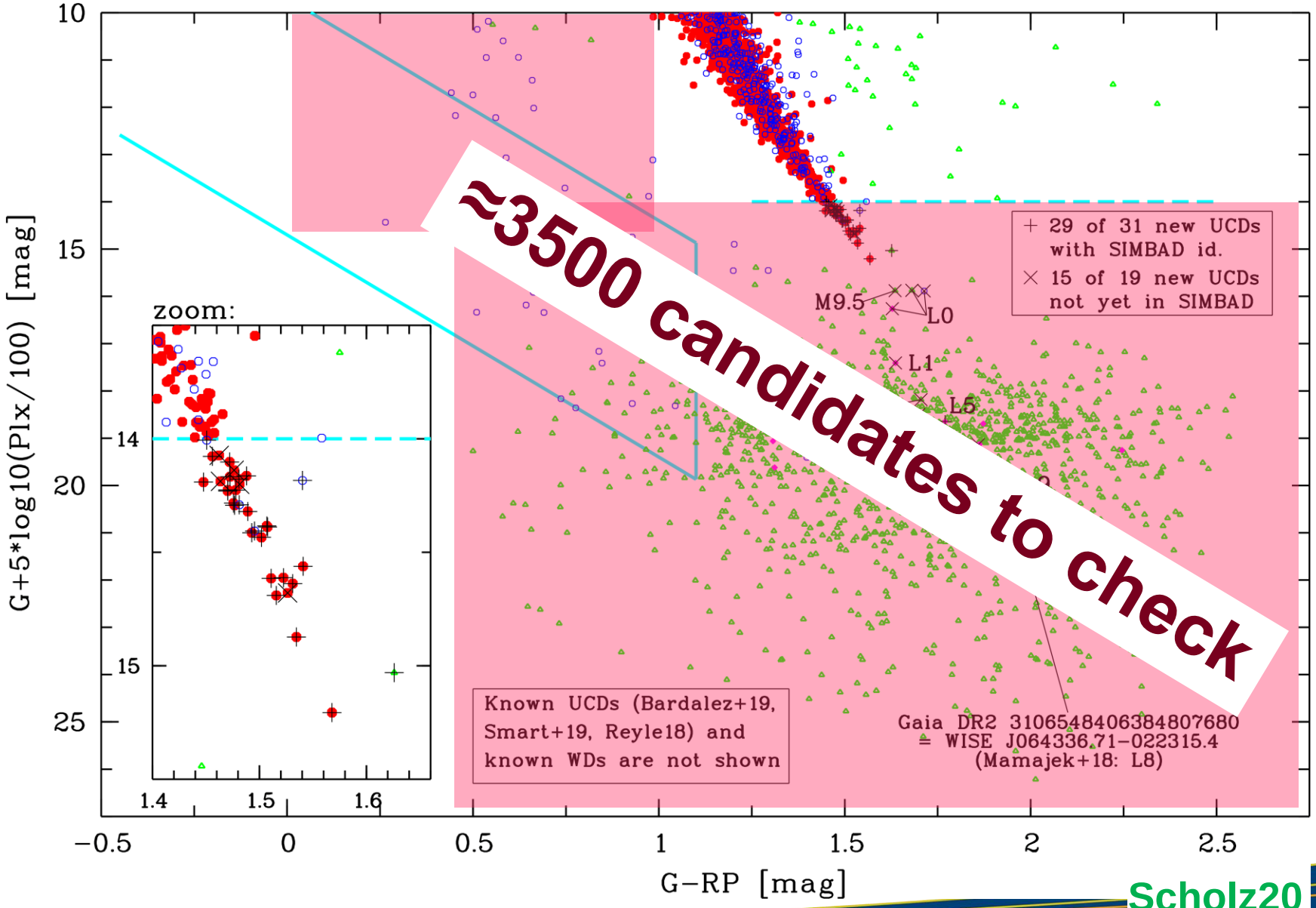
Scholz20

after excluding known WDs+UCDs *d*<20pc



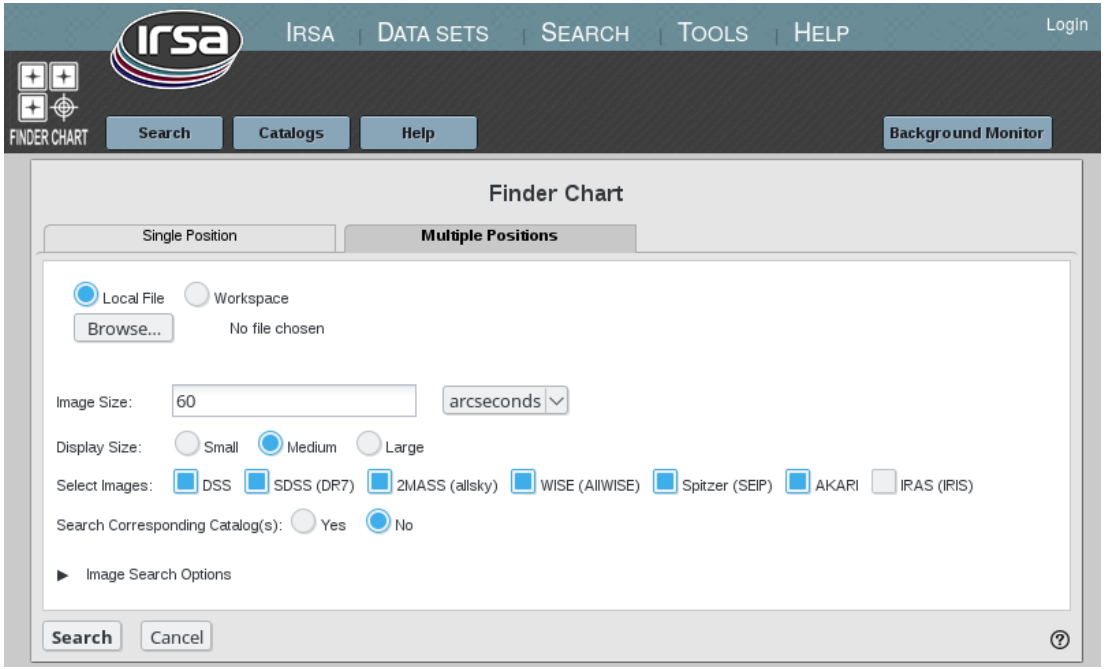
Scholz20

after excluding known WDs+UCDs *d*<20pc



Scholz20

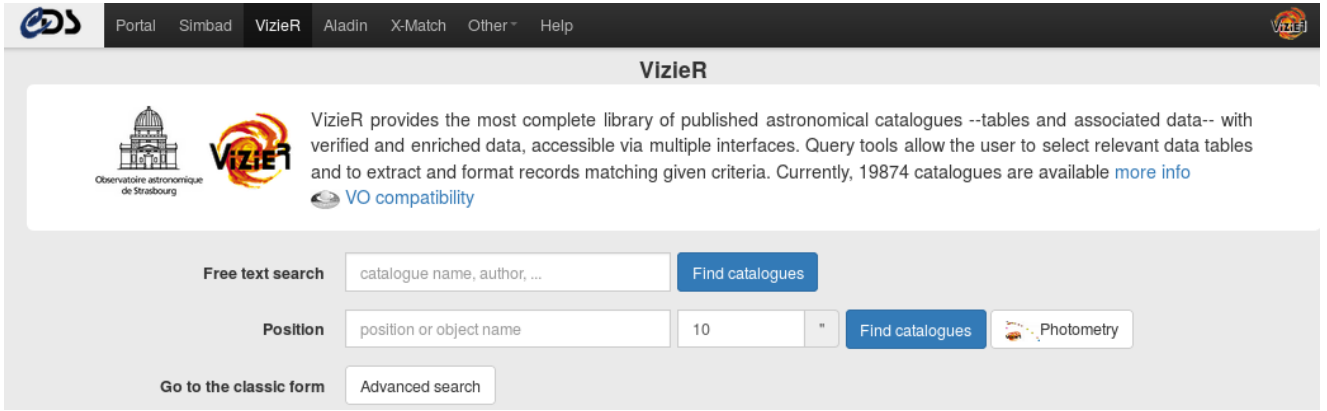
Check *Gaia* DR2 proper motions



Step 1:

IRSA finder charts

irsa.ipac.caltech.edu/applications/finderchart/



Step 2:

Other proper motion catalogues in **VizieR**

vizier.u-strasbg.fr

Step 3:

Own proper motion determination

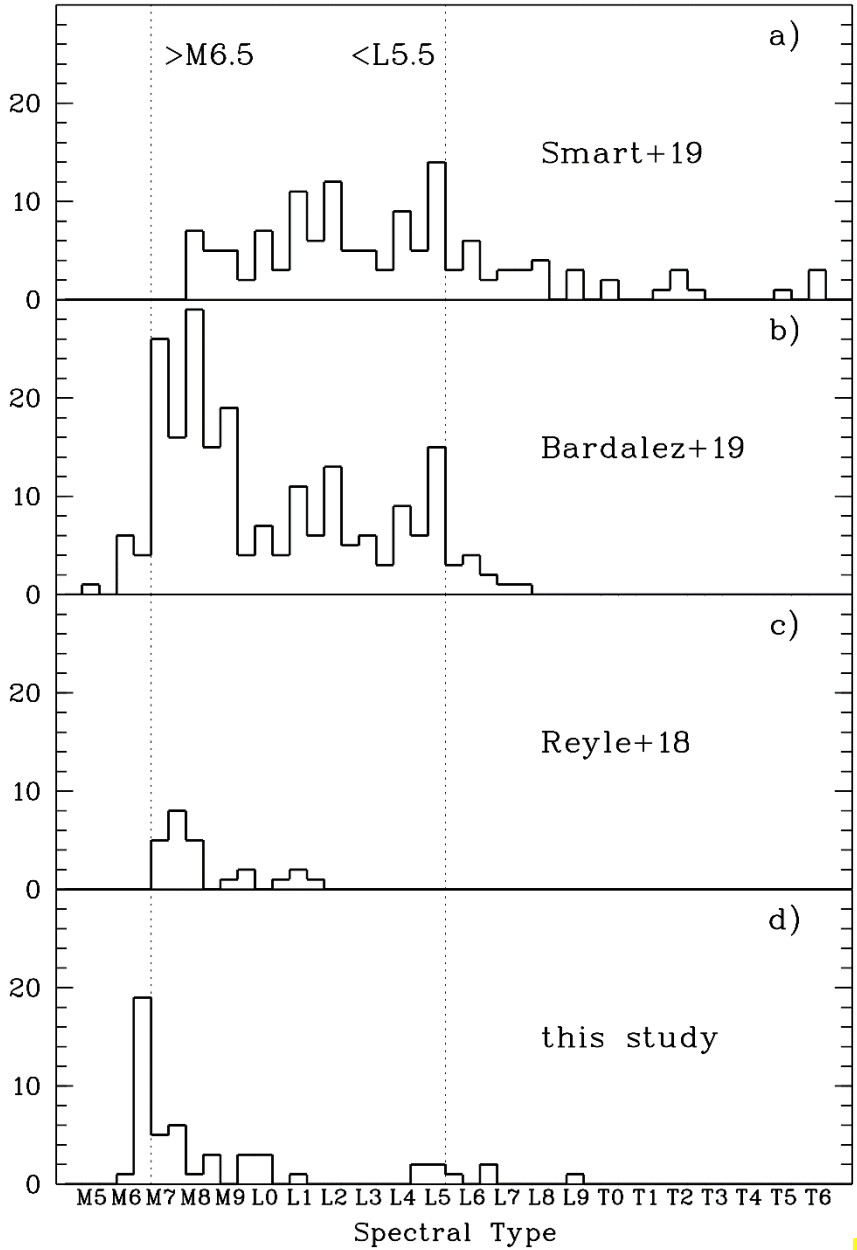
Comparison with UCD spectral types in three previous *Gaia* DR2 studies

(d < 20 pc)

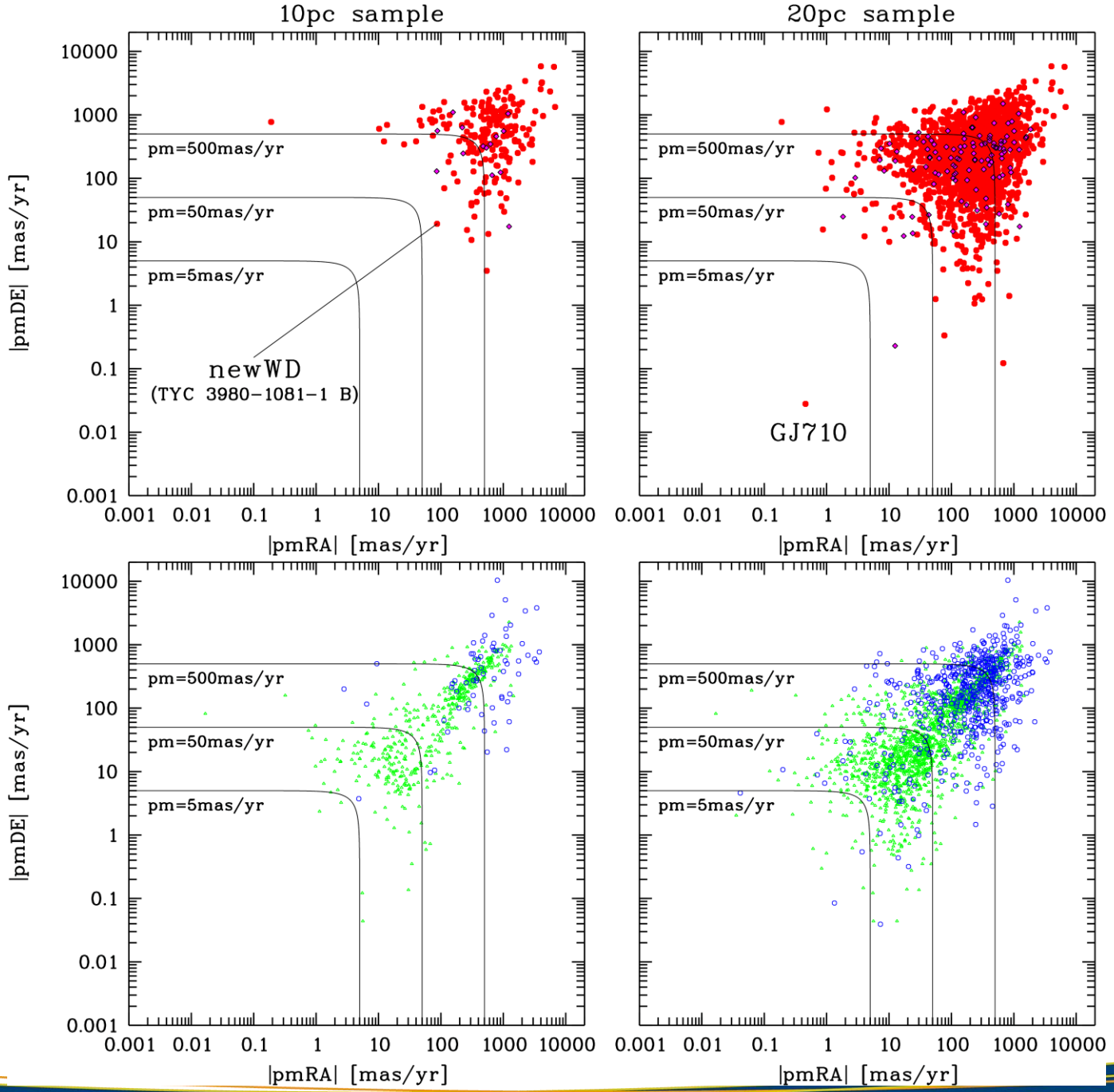
Compared to **263** UCDs
in three previous studies:

50 new objects
(only 30 of which match
classical UCD definition
by spectral type >M6.5)

spectroscopic ↔ photometric



Scholz20



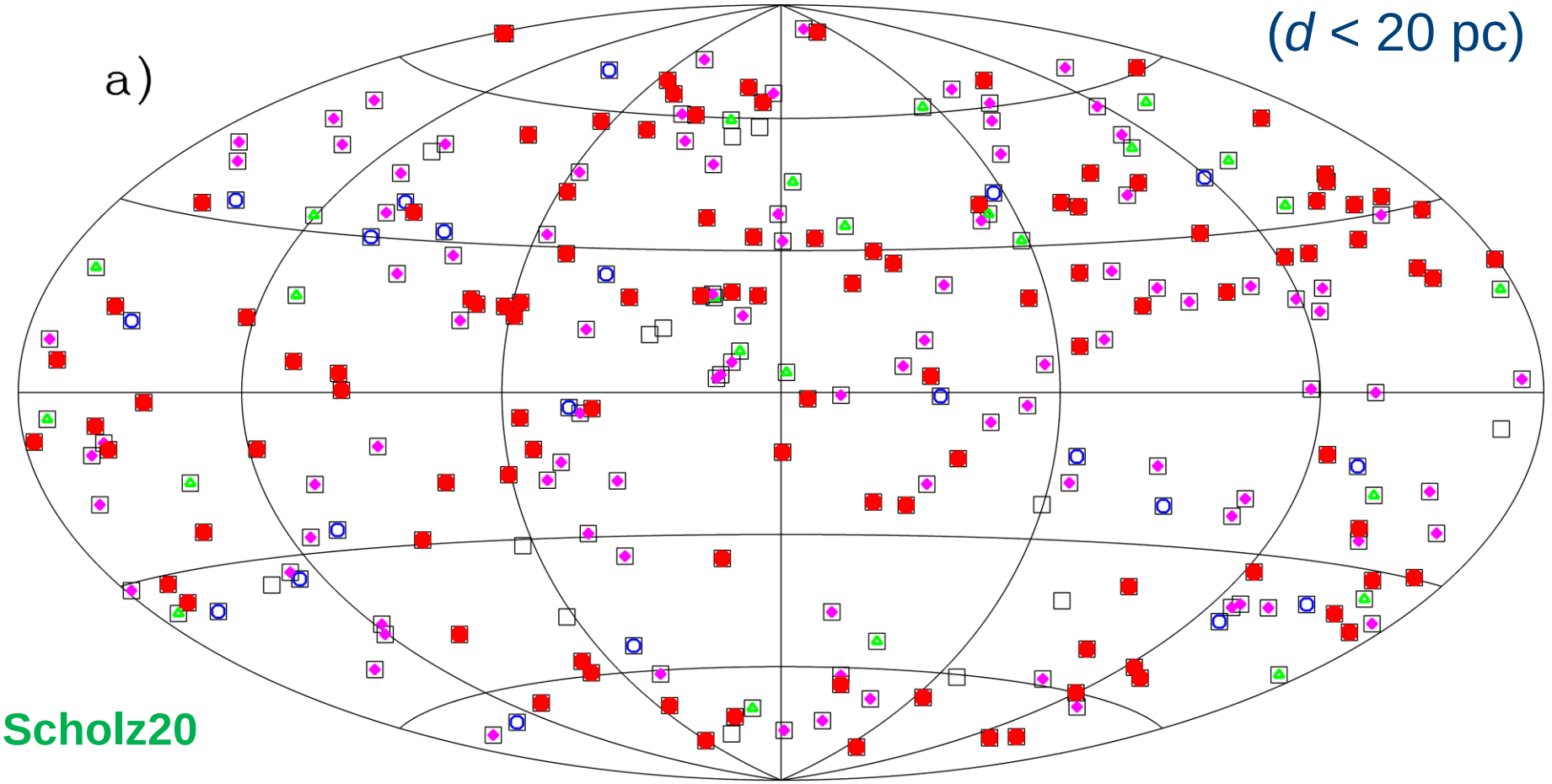
Real and doubtful proper motions of nearby stars

Scholz20

➔ cf. more distant wrong high proper motion (HPM) hypervelocity candidates (**Du+19**)

Non-uniform distribution of known UCDs

(d < 20 pc)



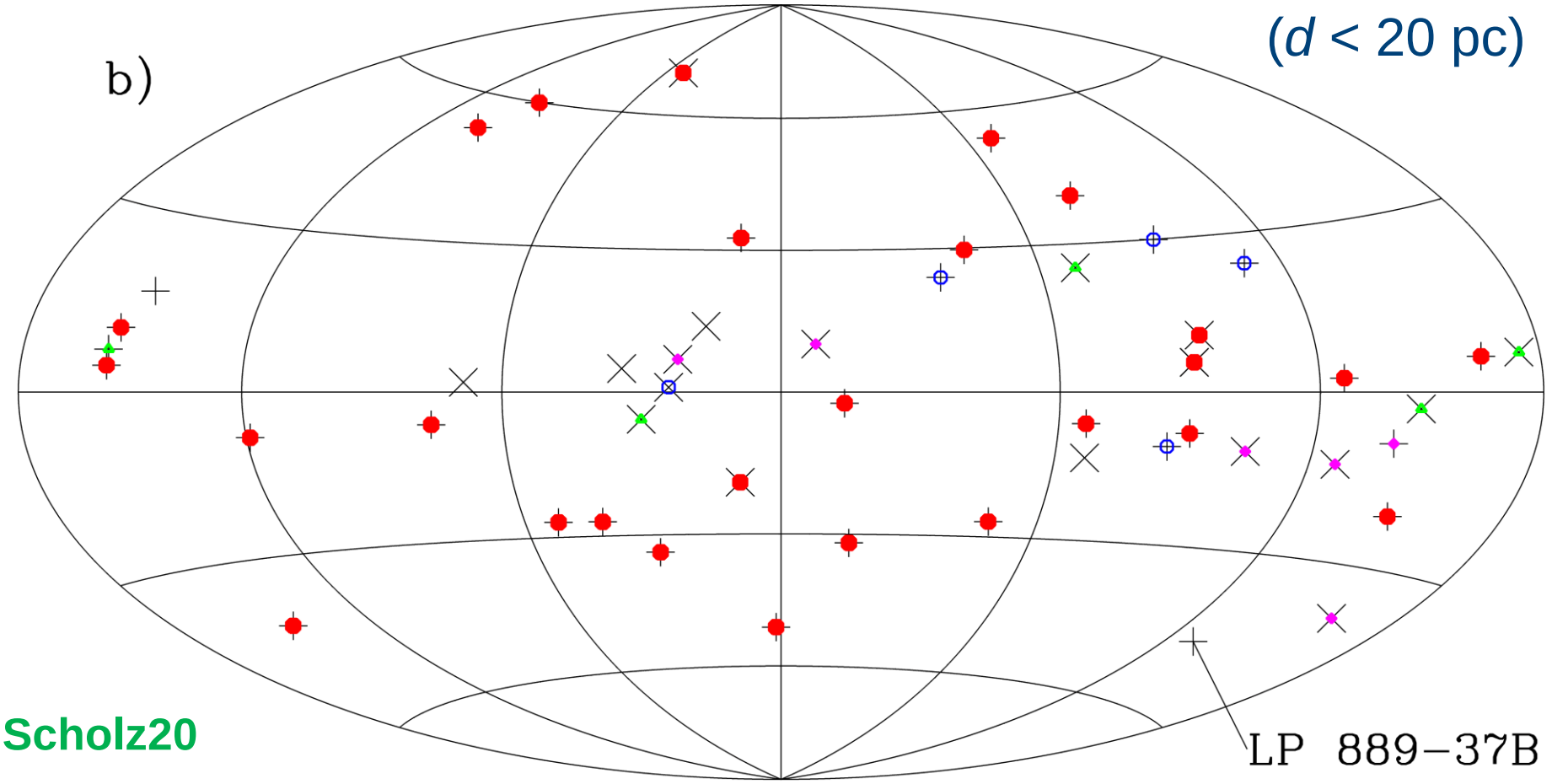
Scholz20

Deficit in Galactic plane (|b|<15°): 21% instead of expected 26%

Galactic north-south asymmetry 148:115

Most new UCDs close to Galactic plane

(d < 20 pc)

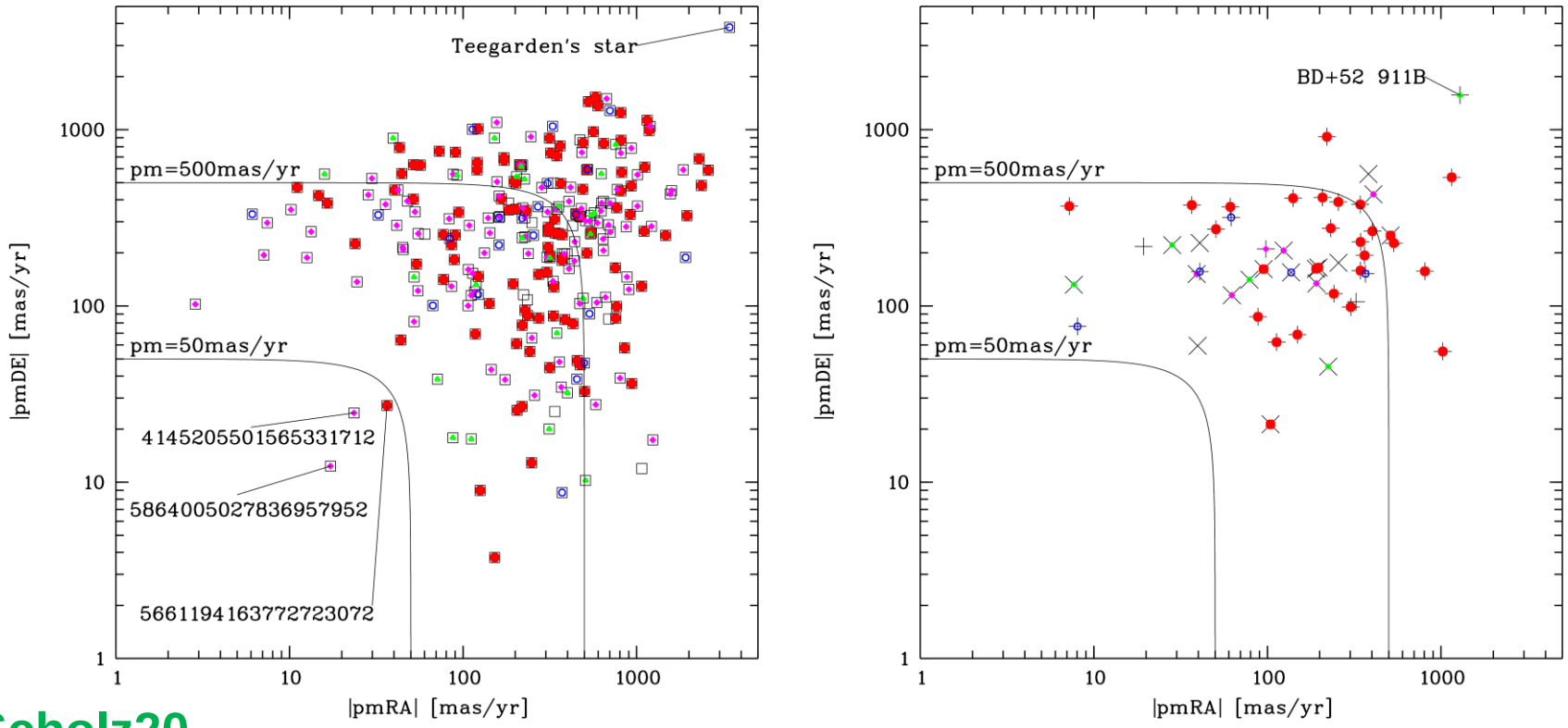


Scholz20

pluses – identified in SIMBAD, crosses – not found in SIMBAD,
56% in Galactic plane (|b|<15°)! Outside plane mostly good astm,
mild Galactic north-south asymmetry 27:23

Proper motions of known and new UCDs

(d < 20 pc)

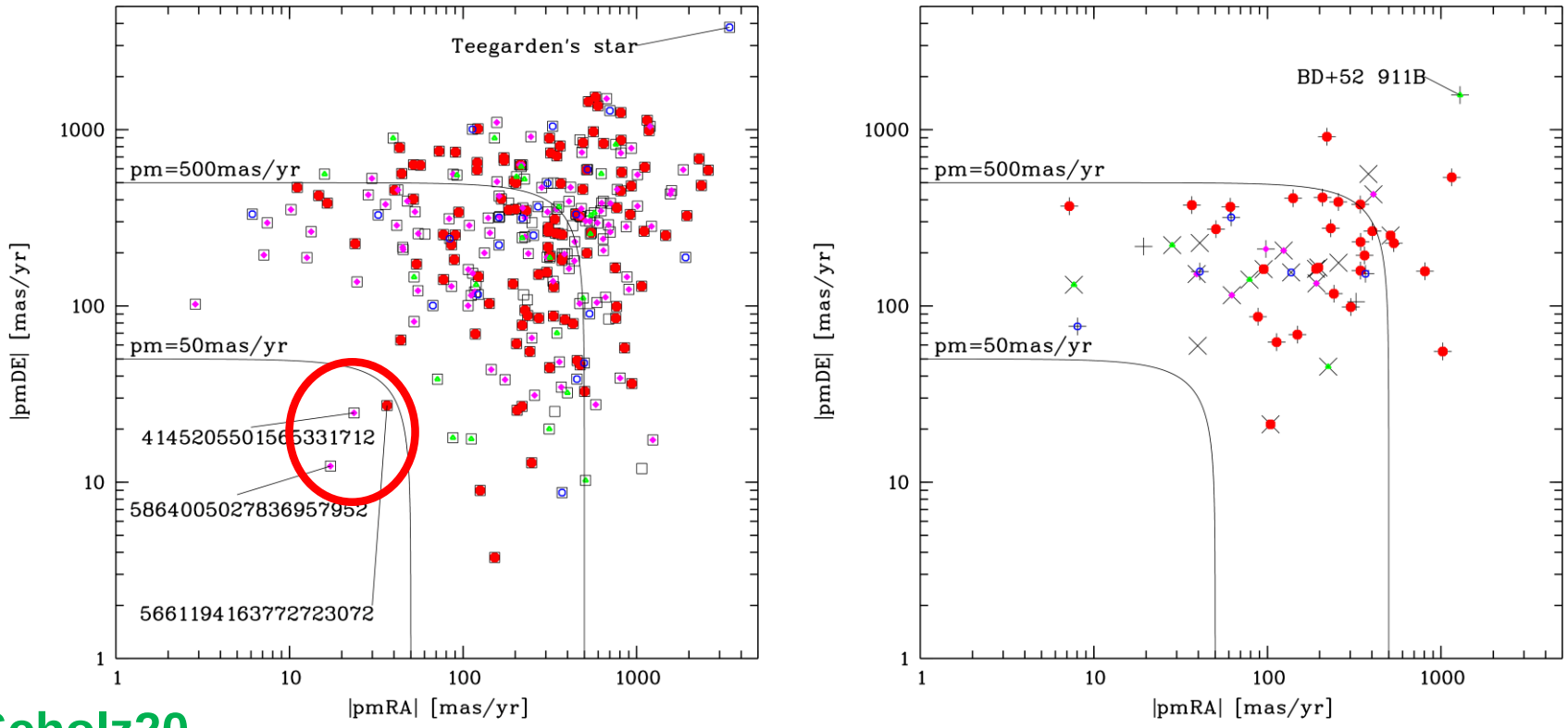


Scholz20

New UCDs (right), especially those not yet in SIMBAD (crosses), have smaller proper motions than previously known ones (left), but not so small as those labelled on the left (from **Reylé18**).

Proper motions of known and new UCDs

(d < 20 pc)



Scholz20

New UCDs (right), especially those not yet in SIMBAD (crosses), have smaller proper motions than previously known ones (left), but not so small as those labelled on the left (from **Reylé18**).

close flyby candidates!

Members of young moving groups (YMGs)?

Table 3. YMG membership probabilities of new UCDs **(Scholz20)**

	Object name	ABDMG (%)	CARN (%)	COL (%)	ARG (%)	Field (%)
M6.5	NLTT 14748	2.4	95.4	0.1	0.1	2.0
M6.5	LP 675-7	99.6	-	-	-	0.4
M6.5	SIPS J1848-8214	2.3	-	-	-	97.7
M6.5	2MASS J20021341-5425558	64.2	-	-	-	35.8
L4.5	Gaia DR2 3432218798435750016	-	0.2	-	99.0	0.8
L9.0 #	Gaia DR2 3106548406384807680	-	-	2.4	-	97.6
L6.5	Gaia DR2 5535283658436274944	-	0.3	-	5.5	94.2
M6.5	Gaia DR2 5424690587034891264	-	-	-	40.8	59.2
M6.5	Gaia DR2 5424690587034982144	-	-	-	71.4	28.5
L4.5	Gaia DR2 6031367499416648192	-	-	-	71.0	29.0

Notes. Only non-zero YMG membership probabilities and the corresponding field membership probabilities are listed as computed using BANYAN (Gagné et al. 2018).

already discovered and spectroscopically classified as L8 by **Mamajek+18** (also close flyby !)

YMG ages ➔ young (low-mass) BDs!

AB Doradus moving group (ABDMG; **Zuckerman+04**): 125 Myr (**Luhman+05, Barenfeld+13**) similar to Pleiades age (!)

Carina Near (CARN; **Zuckerman+06**): ≈200 Myr

Columba (COL; Torres et al. 2008): 42 Myr (**Bell+15**)

Argus (ARG; **Makarov&Urban00**): 40-50 Myr (**Zuckerman19**)

M-type UCDs of Pleiades age are likely BDs.

Mid-L UCDs of ≈50 Myr may be planetary-mass BDs!

Missing in *Gaia* DR2 (no Plx, pmRA, pmDE)

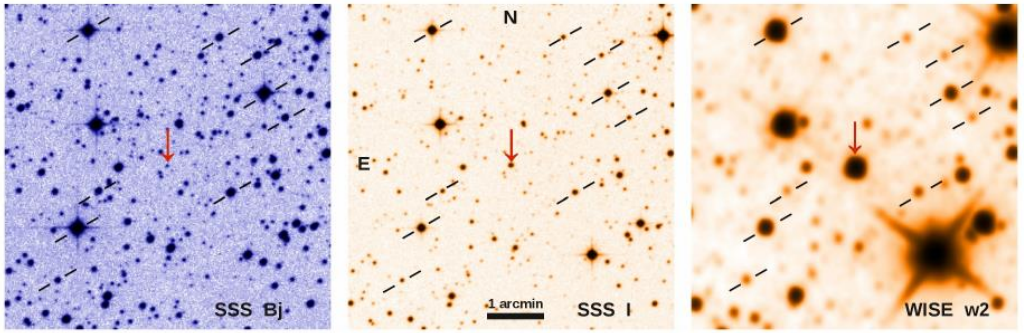
Four well-known WDs within 10 pc, probably because of saturation & matching problems (**Hollands+18**)

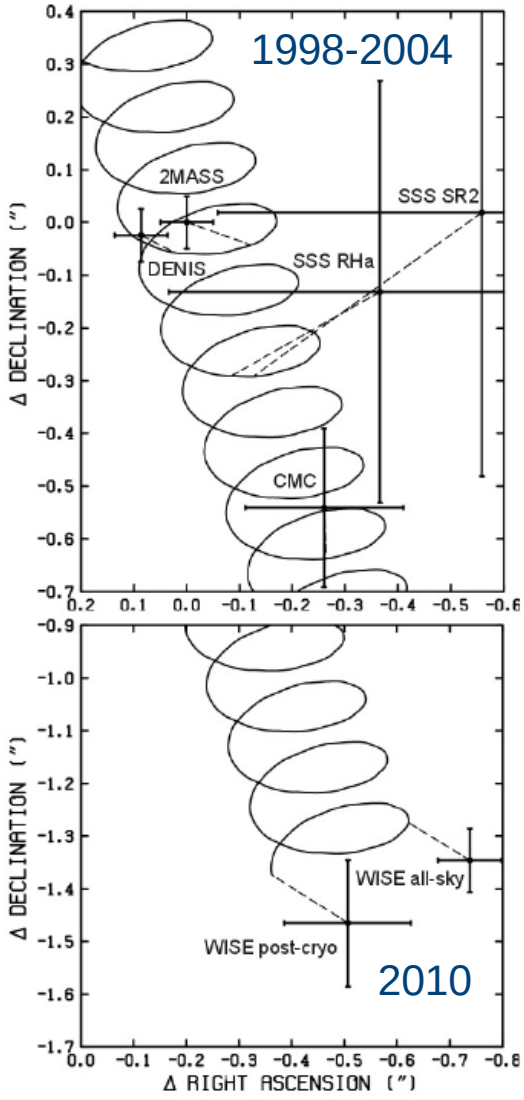
Procyon B (DQZ7.7, separation ≈ 4 arcsec)
40 Eri B (DA2.9, separation ≈ 8 arcsec)
Wolf 489 (DZ9, HPM ≈ 4 arcsec/yr !)
G 99-47 (DA8, not known as binary)

Three nearest UCD (close) binaries including L and T dwarfs:

WISE J1049-5319 AB (L7.5+T0.5@2.0pc; **Luhman13, Burgasser+13**),
eps Indi Ba,Bb (T1+T6@3.6pc; **Scholz+03, McCaughrean+04**),
SCR J1845-6357 AB (M8.5+T6.0@3.9pc; **Hambly+04, Biller+06**)
…
WISE J0720-0846 AB (M9.5+T5.5@6.8pc; **Scholz14, Burgasser+15, Dupuy+19**)

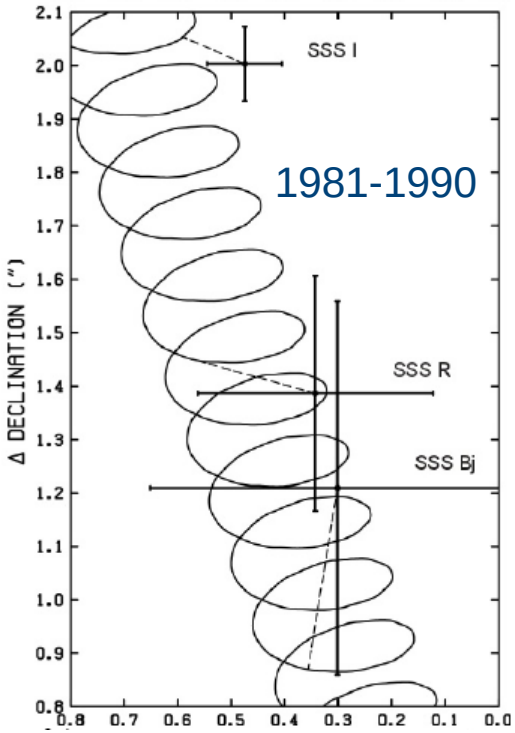
A new cool neighbour discovered in 2014…



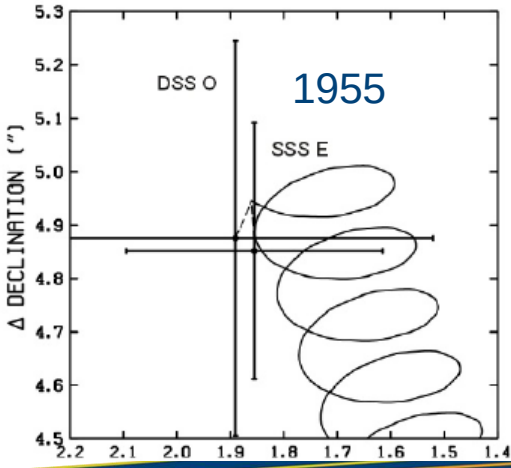


Scholz14

WISE J0720-0846



M9±1(phot) @ 7.0±1.9 pc
in Galactic plane b=+2° with
moderately HPM 120 mas/yr

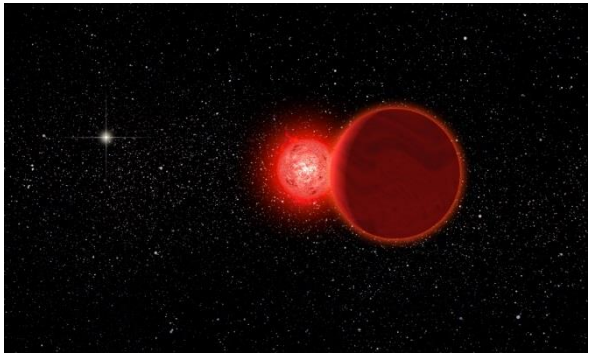


… is the closest known flyby in the past !

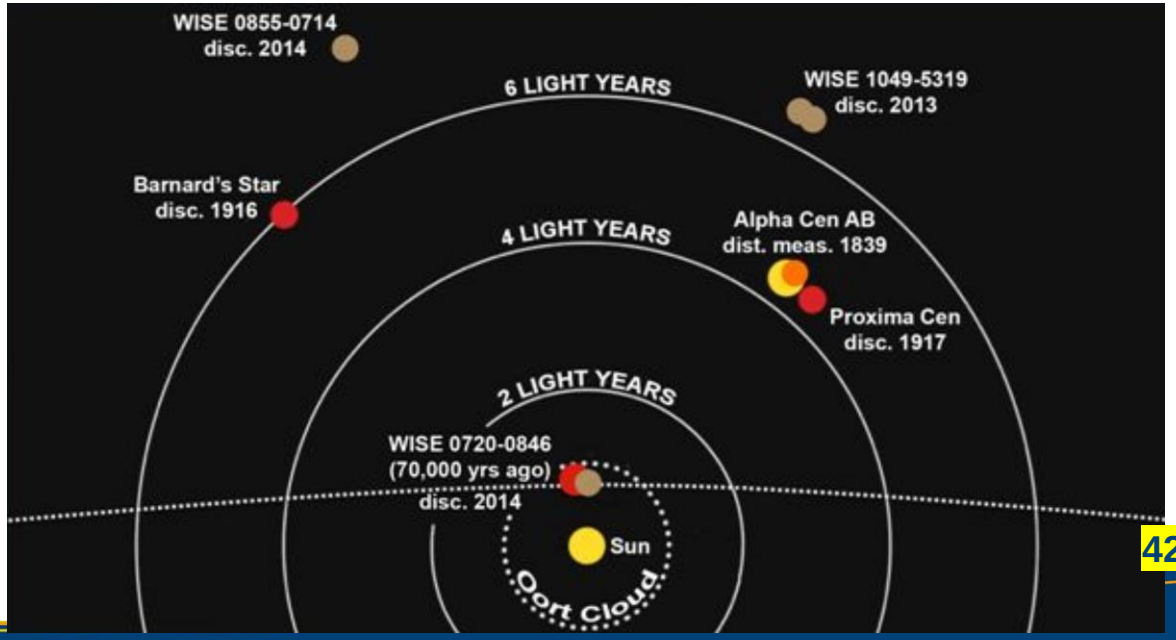
Burgasser+15: binary M9.5+T5.5 (spec), radial velocity +83.8±0.3 km/s

Mamajek+15 (calling WISE J0720-0846 Scholz´s star):
52+23-14 kAU from the Sun 70,000 years ago (in Oort cloud!)

Dupuy+19: 69±2 kAU from the Sun 80,000 years ago, based on more accurate trigonometric distance of 6.80±0.06 pc, binary with P_{orb} = 8 years, 0.2 arcsec separation (no parallax in Gaia DR2)



University of Rochester



NASA Astrophysics Forum (Penn State University and P. Eisenhardt)

José A. Peñas / SINC - image used in PR on study of de la Fuente Marcos+18

GJ 710 – the closest flyby

in the future

Bailer-Jones15,
Bailer-Jones+18
Videos from
ESA/Gaia/DPAC

95% probability of coming closer than 17 kAU (4 times closer than Scholz´s star)

Summary

Close binaries and overlapping background objects, especially in crowded regions, caused problems in *Gaia* DR2 measurements of nearby stars

The impact of *Gaia´s* optical survey is higher for WDs than for UCDs

This concerns not only the whole 100 pc sample, but also the nearest WDs within 10 pc and the nearest representatives of rare ELM WDs at ≈70 pc

Nevertheless, inspecting *Gaia* DR2 data helped to detect >10 new L dwarfs, including some very low-mass BD members of YMGs within 20 pc

No new T dwarfs found within expected *Gaia* distance limits

Galactic plane region no longer incomplete with respect to nearby UCDs

Without any pre-selection of HPM objects, Gaia will provide more close flyby candidates with radial velocities >> tangential velocities

New UCDs need spectroscopic follow-up

European Organisation for Astronomical Research in the Southern Hemisphere

Observing Programmes Office • Karl-Schwarzschild-Strasse 2 • D-85748 Garching bei München • email: opo@eso.org • Tel: +49 89 3200 6473

Cycle: P106
Type: Normal
Status: Submitted
Printed: 22 Apr 2020

APPLICATION FOR OBSERVING TIME 106.214E

IMPORTANT NOTICE

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

Completing the nearby census at the star/substellar boundary: characterization of new objects revealed by Gaia DR2

ABSTRACT

The local census of very low-mass stars and brown dwarfs is critical for measuring the stellar mass function and star formation history across the hydrogen-fusion limit, and for searches for potentially habitable terrestrial exoplanets. While hundreds of these dwarfs have been uncovered in large sky surveys, this population remains incomplete even nearby due to their faint magnitude and color selection biases. The Gaia mission provides a means of uncovering them through astrometry, making possible a volume-complete sample. Recently, Gaia DR2 revealed over 200 of these objects with a parallactic distance <30 pc. As part of an international collaboration using multiple facilities, we propose to complete the spectroscopic follow-up of these candidates to obtain classification and diagnostics of metallicity, and surface gravity. This program will significantly improve our census of the local low-mass population, which will serve as key probes in various Galactic and exoplanet studies.

SCIENTIFIC CATEGORY

D1 Main sequence stars

RUNS

Run	Period	Instrument	Tel. Setup	Constraints	Mode	Type	Propr. Time	Time Constr.	Req. Time
1. Run 1	106	SOFI	NTT	FLI: 100% • Turb.: 60% • Sky: Clear	VM	Normal	12m	×	34h14m

PI: C. Reylé
3 nights with ESO SOFI@NTT
in December 2020 (?)
+
A. Burgasser
Dick Kast@3 m telescope
this week (!)
+
R. Smart
IRTF and TripleSpec@SOAR

Outlook (work in progress)

Search for extremely wide (angular separation ≥0.5°) HPM (>200mas/yr) UCD companions of nearby stars (**Scholz, in prep.**)

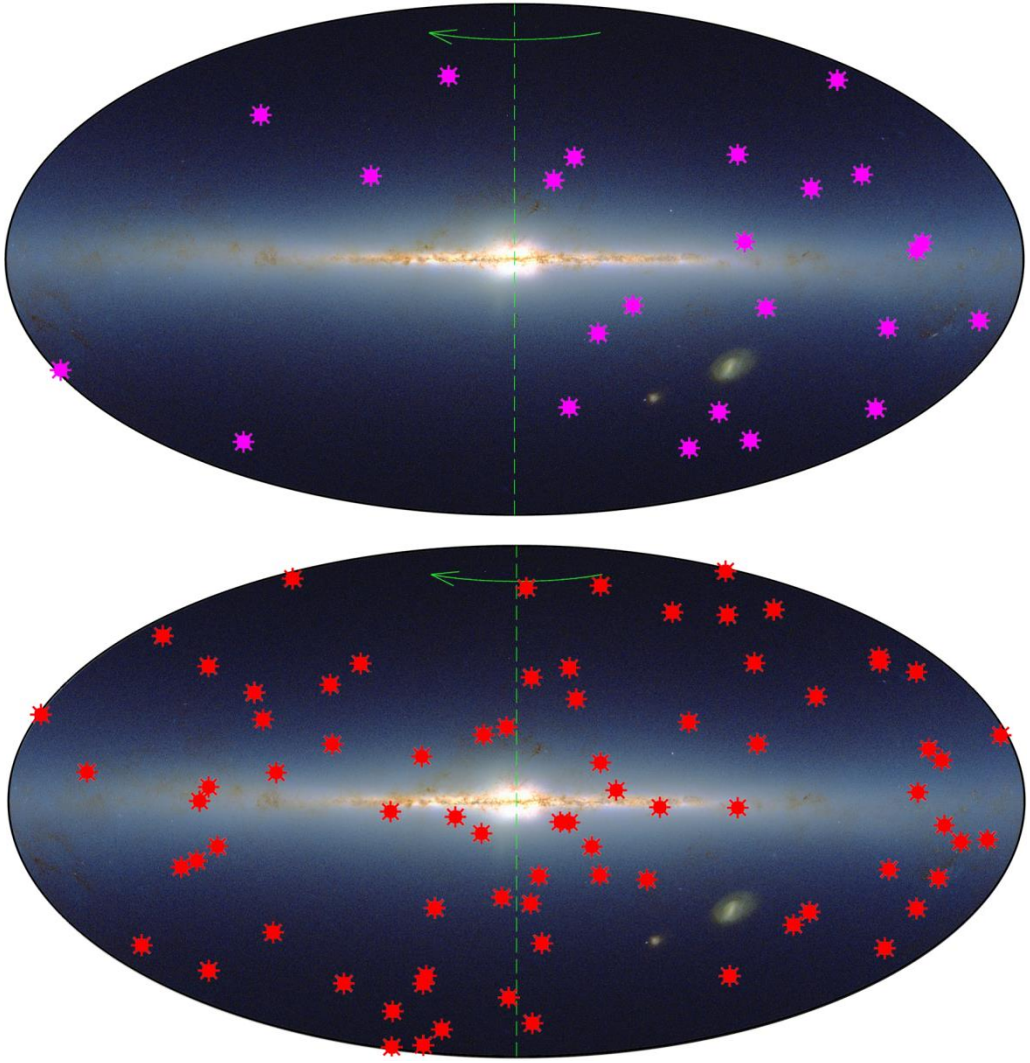
Two previous *Gaia* DR2 based catalogues of wide binaries:
El-Badry&Rix18 and **Hartman&Lepine20**,
multiple systems containing *Gaia* DR2 UCDs: **Marocco+20**

Verify *Gaia* astrometry with new proper motion catalogues, e.g. the extended *Gaia*-PS1-SDSS catalogue (GPS1+; **Tian+20**)

New quality parameters will be defined and recommended for *Gaia* DR3, but **checking the proper motions by finder charts, other catalogues, and own determination will still be useful !**

Appendix A: BD distribution @ d<6.5pc

Bihain&Scholz16



Brown dwarfs

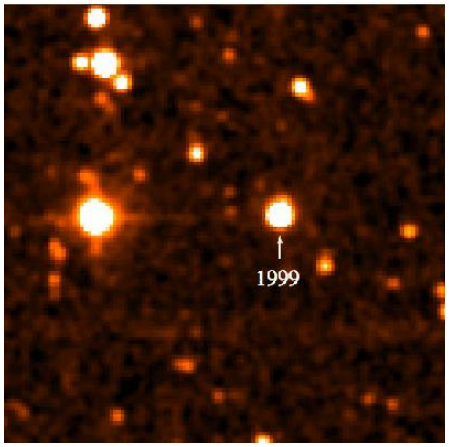
Red dwarf stars

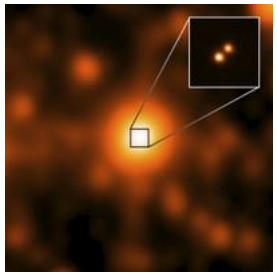
AIP PR 2016 with 2MASS sky background

Appendix B: the nearest BD systems

WISE J1049-5319 AB
L7.5+T0.5 @ 2.0 pc

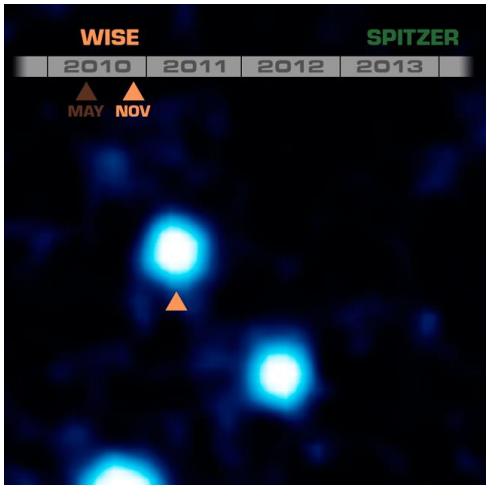
Luhman13, Burgaser+13





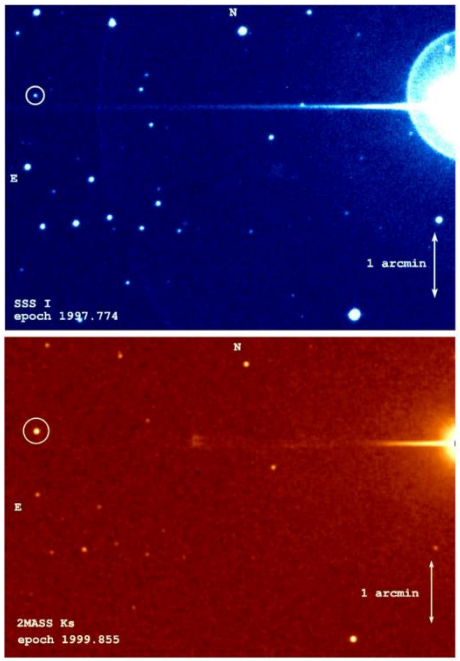
WISE J0855-0714
>Y2 @ 2.2 pc

Luhman&Esplin14, Leggett+15



ε Indi Ba, Bb
T1+T6 @ 3.622 pc (known K4 primary)

Scholz+03, McCaughrean+04



AIP

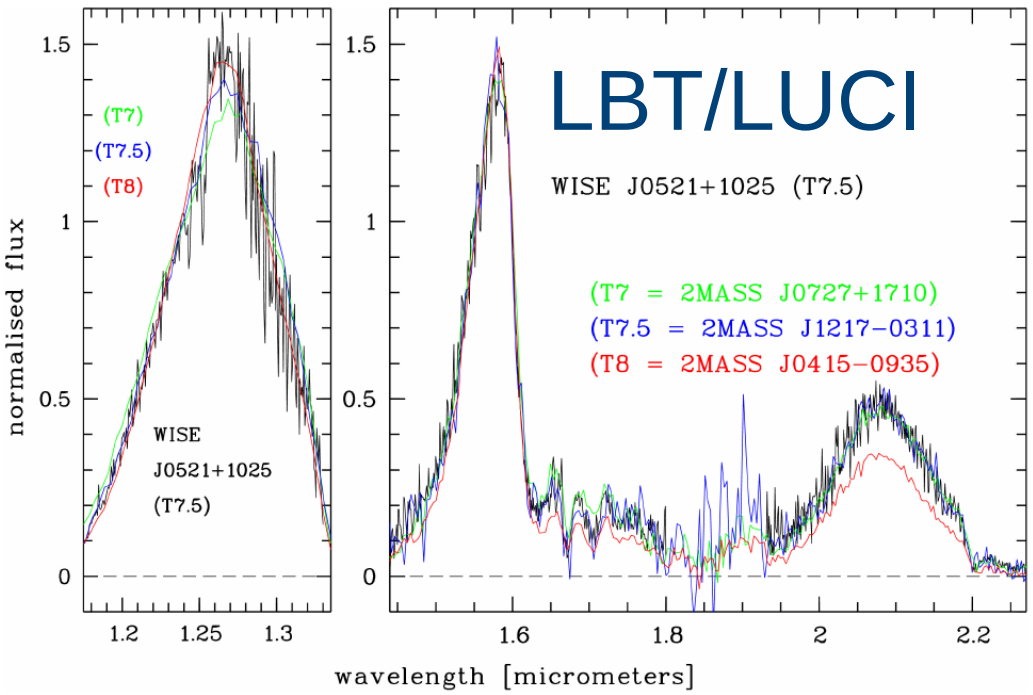
Appendix C: Nearest T dwarf in the north

Bihain+13

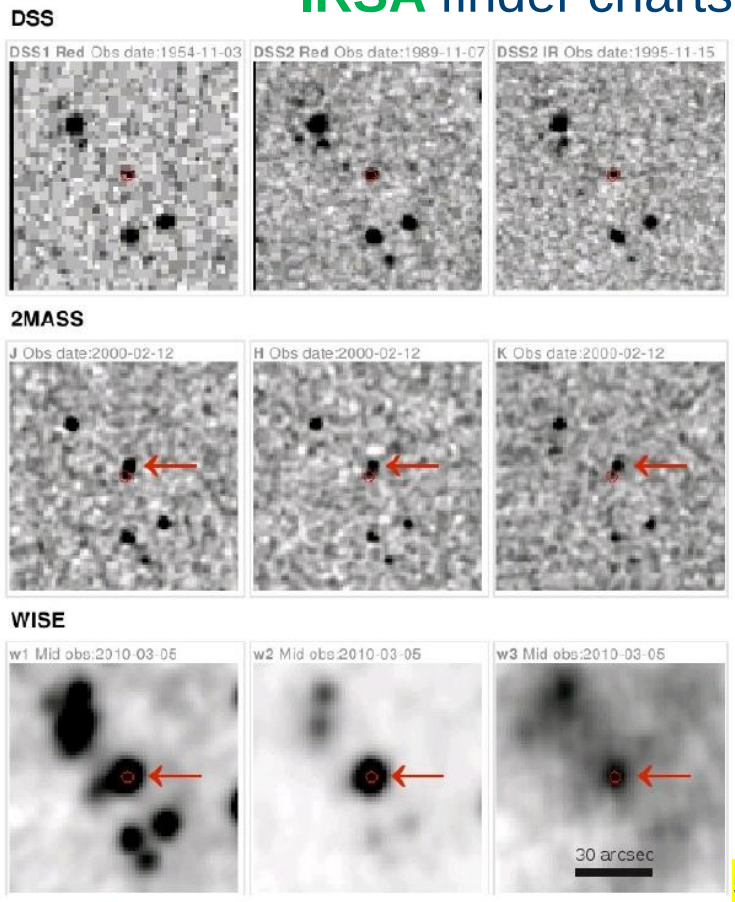
Previously overlooked because of overlap with background object

WISE J0521+1025 (T7.5@5pc):

not in *Gaia* DR2

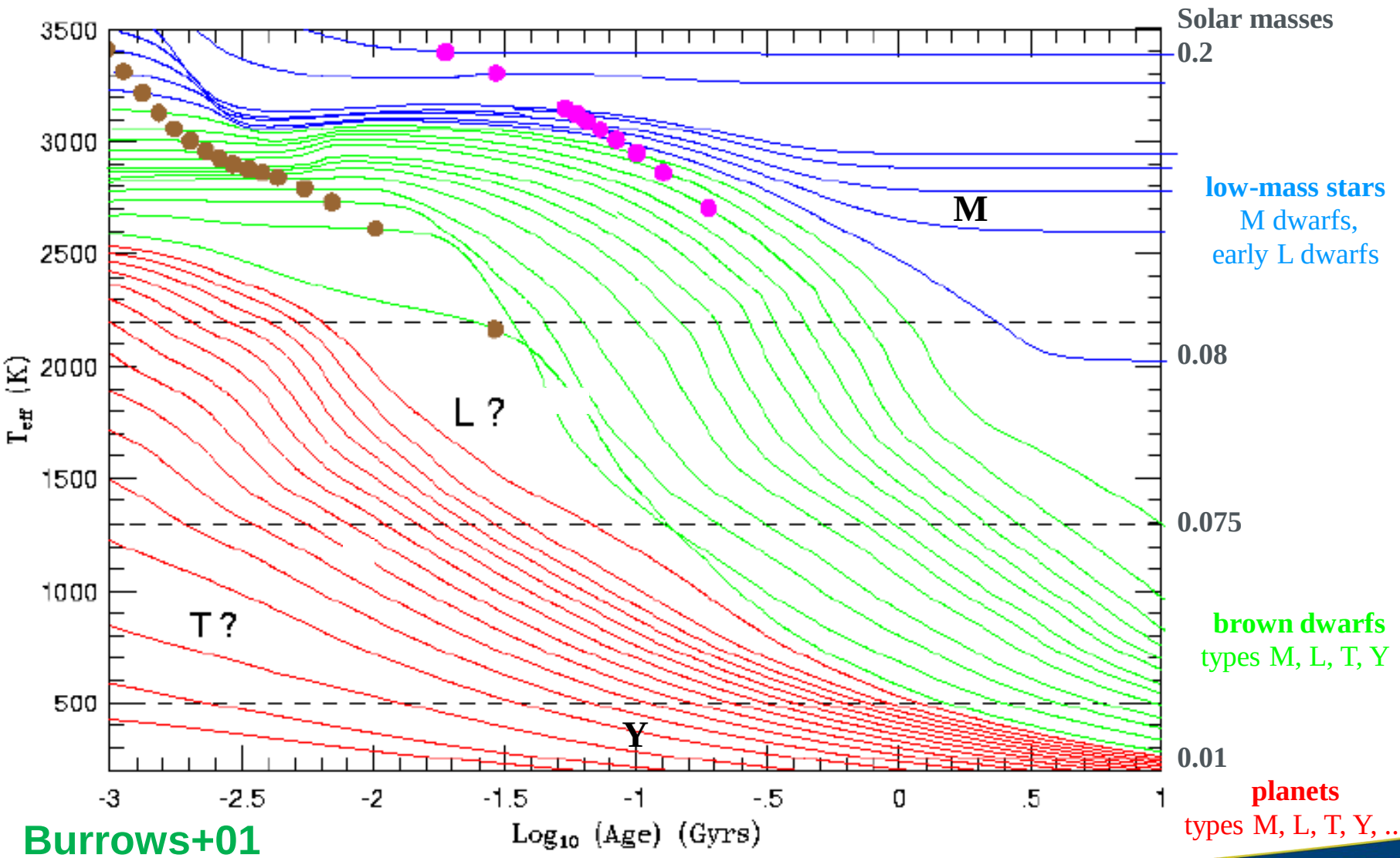


IRSA finder charts



Trigonometric parallax of **Best+20** confirmed its distance of 5 pc

Appendix D: low-mass star and BD tracks



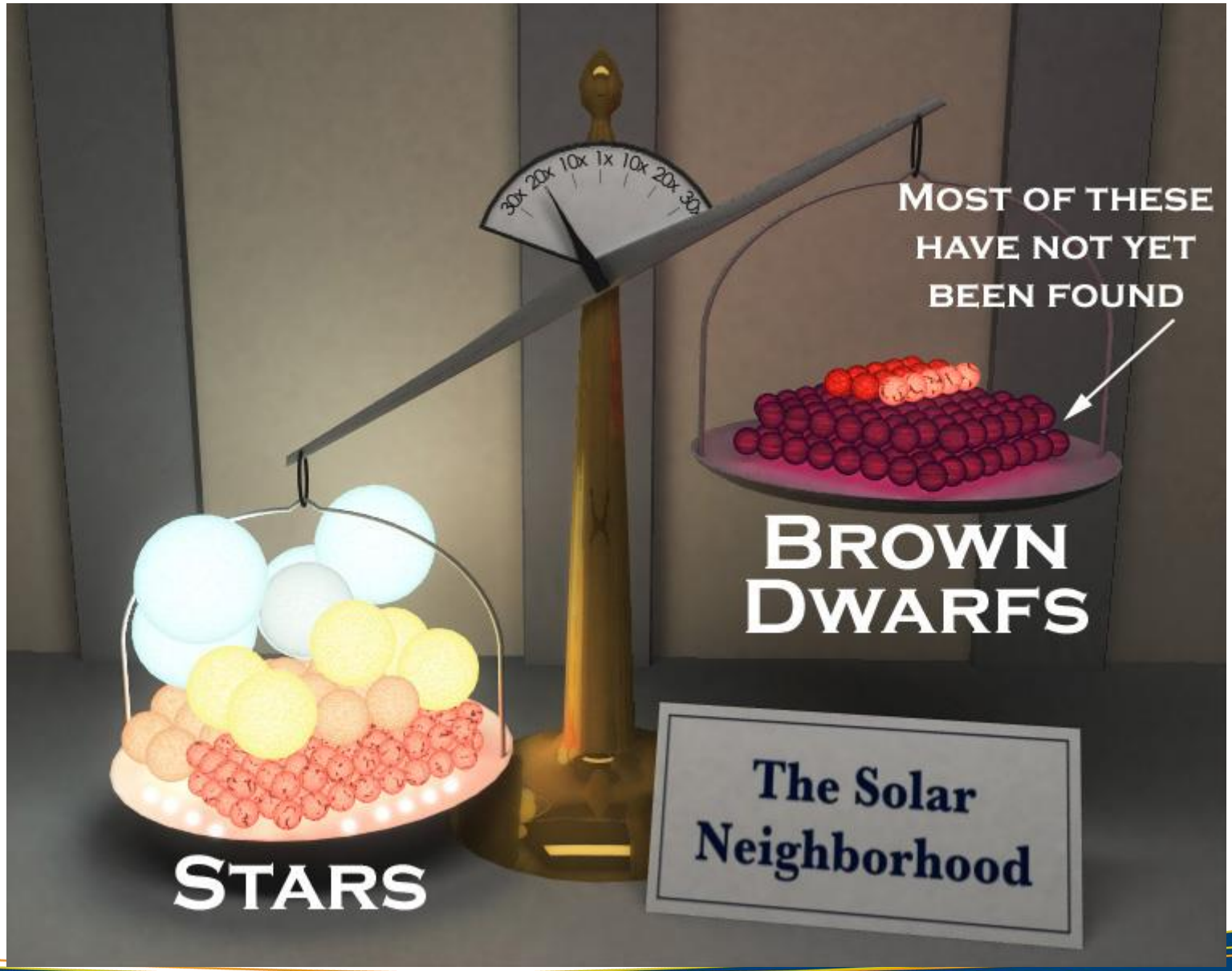
low-mass stars
M dwarfs,
early L dwarfs

brown dwarfs
types M, L, T, Y

planets
types M, L, T, Y, ...

Burrows+01

Appendix E: mass of BDs << M(dark matter)



RECONS