Science from VPHAS+

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Talk outline:

1. Brief introduction to VPHAS+

2. ~one-slide overview of applications to date

3. Exploitation showcase: seeking out massive stars across the Galactic Plane

VPHAS+ Consortium credits:

Core functions:
University of Hertfordshire : VPHAS+ PI institution (Janet Drew)
University of Cambridge: CASU pipeline (Mike Irwin and others)

Other member institutions have included:
IAC, University of Graz, Radboud University Nijmegen, Warwick University, University College London, Tautenberg Observatory, Keele University, Imperial College London, University of Manchester, University of Bristol, Exeter University, Southampton University, Armagh Observatory, Harvard-Smithsonian CfA, ESO, Hong Kong University, Universidad de Valencia

Key individuals (variously, over the years): **Robert Greimel, Geert Barentsen, Jochen Eisloeffel**, **Nick Wright**, Hywel Farnhill, Mike Mohr-Smith, Maria Monguio, Roberto Raddi, Stuart Sale, Nic Walton, Nick Cross

VPHAS+ characteristics:

- Coverage of the southern Galactic Plane at $|b| < 5^o$, plus the bulge to $|b| < 10^o$.

- < 1 arcsec angular resolution, typically

- Reaches to at least 20^{th} mag (5σ) in the optical bands: u,g,r,i,Hα - deepest in g and r, reaching 21—22
- Bright limit of ~13^{th} mag typically

- Simultaneous acquisition of the filters making up the core colour-colour diagrams (u/g/r and r/i/Hα filter sets) ...minimises impact of stellar variability

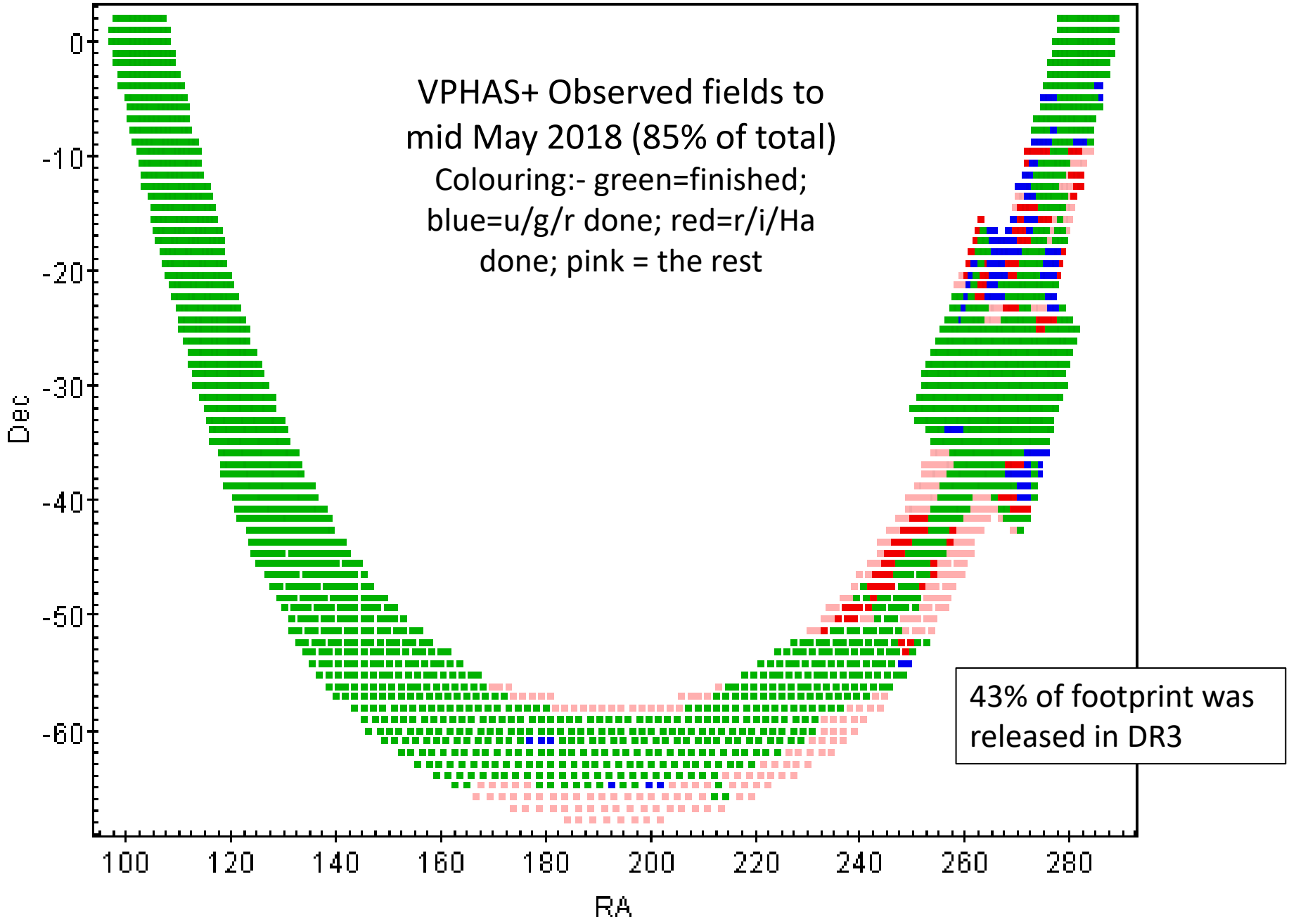
- u and Hα = scientifically-critical filters → dominate the telescope time requirement

- pointing overlap strategy → only ~0.03% of footprint unobserved.

Survey description:
Drew et al 2014

Aims:

- *Comprehensive optical digital ~1 arcsec resolution imaging/photometric survey of the Galactic Plane within and inner Bulge*
  - → high resolution photometric imaging for nebular astrophysics, throughout the MW disk and bulge
  - → massive update of Hα emission line stars – young and evolved
  - → massive update of the UV-excess population – high-mass and evolved low-mass stars (OB stars , sub-dwarfs, WDs, compact binaries)
  - → map the 3D dust distribution across the Galactic disc
  - → bring the wider field to bear on star-cluster studies
  - → resource for photometric source selection for MOS surveys

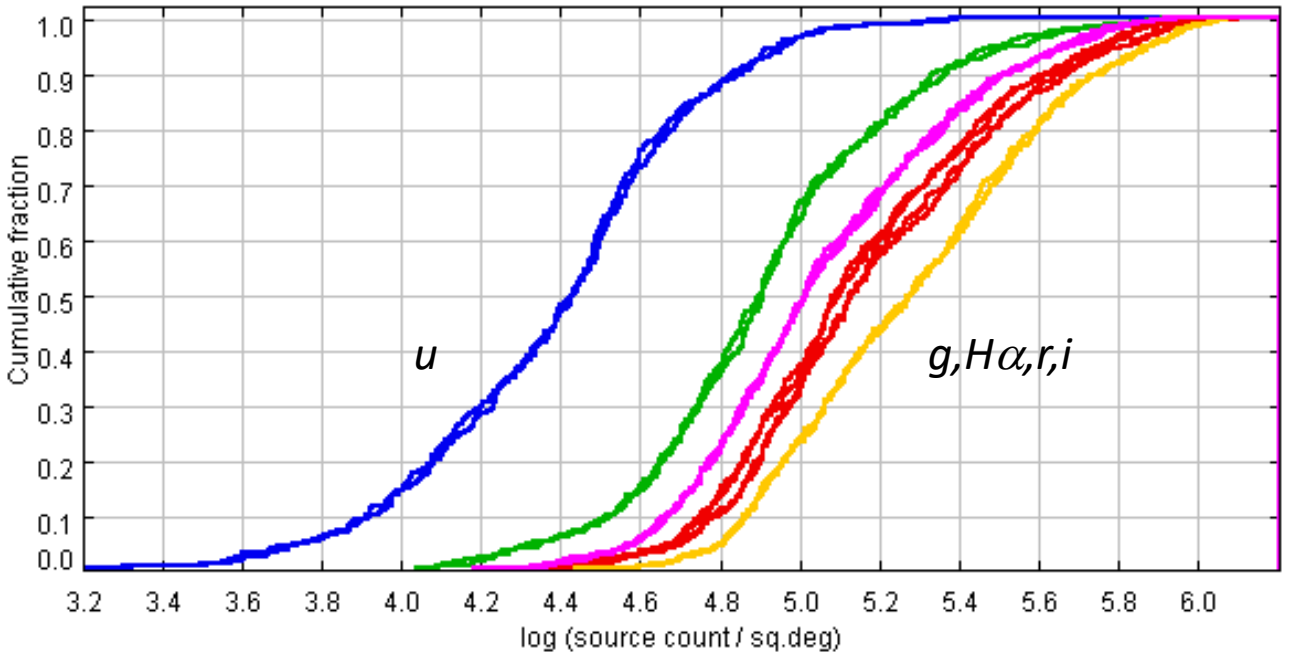


Observing started Dec 2011 – 4 phase-2 tranches to finish → 90% +

The VPHAS+ pattern of point-source counts, and depth ...a tensioning problem

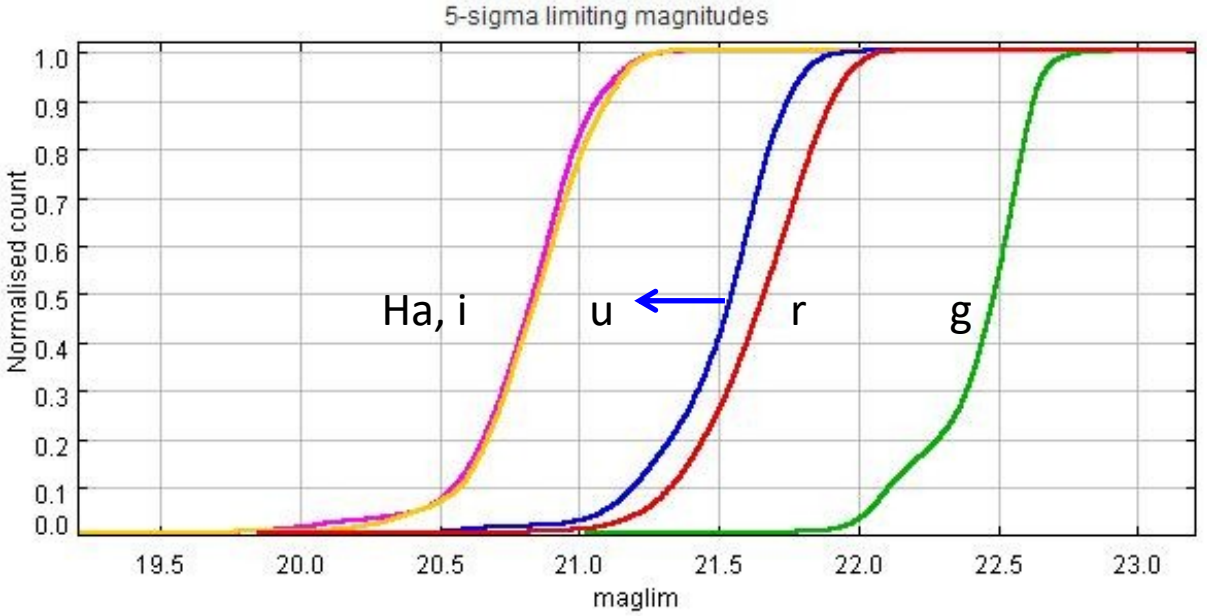
Log(source counts/sq.deg) across the 5 bands in single exposures.

Longer 150-sec *u* exposure captures *u*-excess objects (low-reddening subluminous objects + reddened OB stars)



5-sigma limiting magnitudes delivered by the pipeline (Vega scale):

Hα, i reach to 20.5—21.0
u to > 21
r to 21.4—21.9
g reaches 22.5 (median)



VST/VPHAS+ PSF is generally **very good**: median in g,r,i,Hα ~0.8”, just under 1” in u.

2. Overview of use so far

- Early on, photometric data → GES for open-cluster target lists

- VPHAS+ DR2 (under ¼ of footprint): on Vizier > 10k successful queries per month

- papers on e.g.:

  - **M supergiant** ionized nebula in Wd 1 (Wright et al 2014)
  - **YSOs** in the Lagoon nebula cluster (Kalari et al 2015)
  - **White dwarfs** in clusters (Raddi et al 2016)
  - Searching for **PN central stars** (Barker et al 2018)
  - **OB stars** in Carina …next slides

  (ADS: "VPHAS" mentioned in full text of 124 publications)

3. Science exploitation

Seeking out the most massive (OB) stars in the Galactic disc

-- uses VPHAS+ and u band --

Why go searching for more/fainter OB stars in the Galaxy?

(a) Important for galactic ecology, up to and including products of SN explosions
(b) Intrinsically luminous stars → distant + simple spectra → great probes of extinction and the ISM
(c) …we still don't how and in what environments they form!
(d) Census so far only good to ~2 kpc …and not Gaia's strong point.

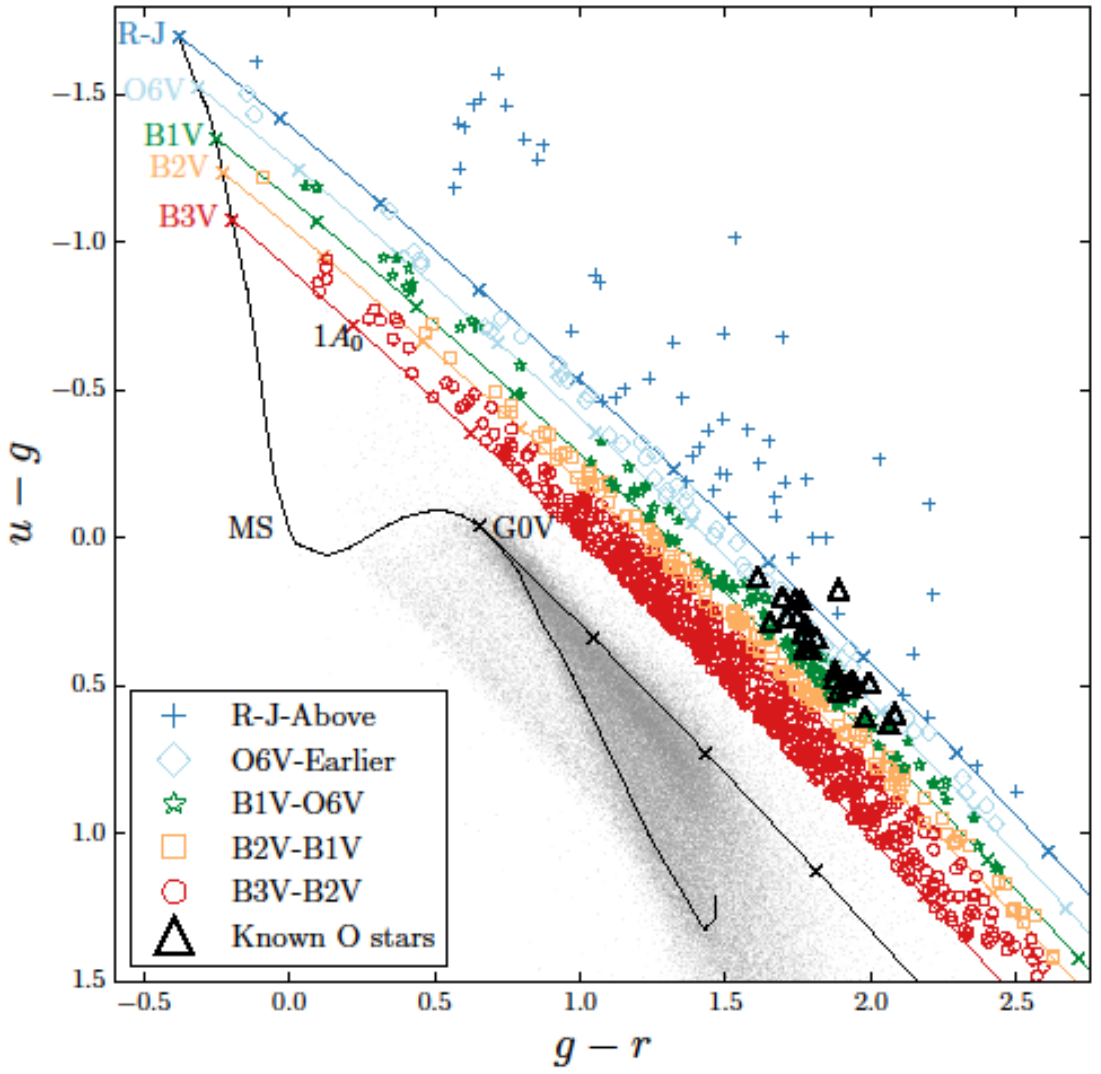
What VPHAS+ can do:

- photometry supports selections of different massive star sub-groups, e.g.
  - Hα excess → the emission-line Be/WR population
  - blue excess → mainly non-emission O—B3 stars

The colour-colour diagram, using the power of u

VPHAS+ u – g versus g – r:
pulls out blue excess objects:
unreddened WDs through to highly reddened OB stars

Right: the diagnostic diagram for ~2 sq.degs around the massive young cluster, Westerlund 2.



Our search for OB stars in Carina – including Westerlund 2.

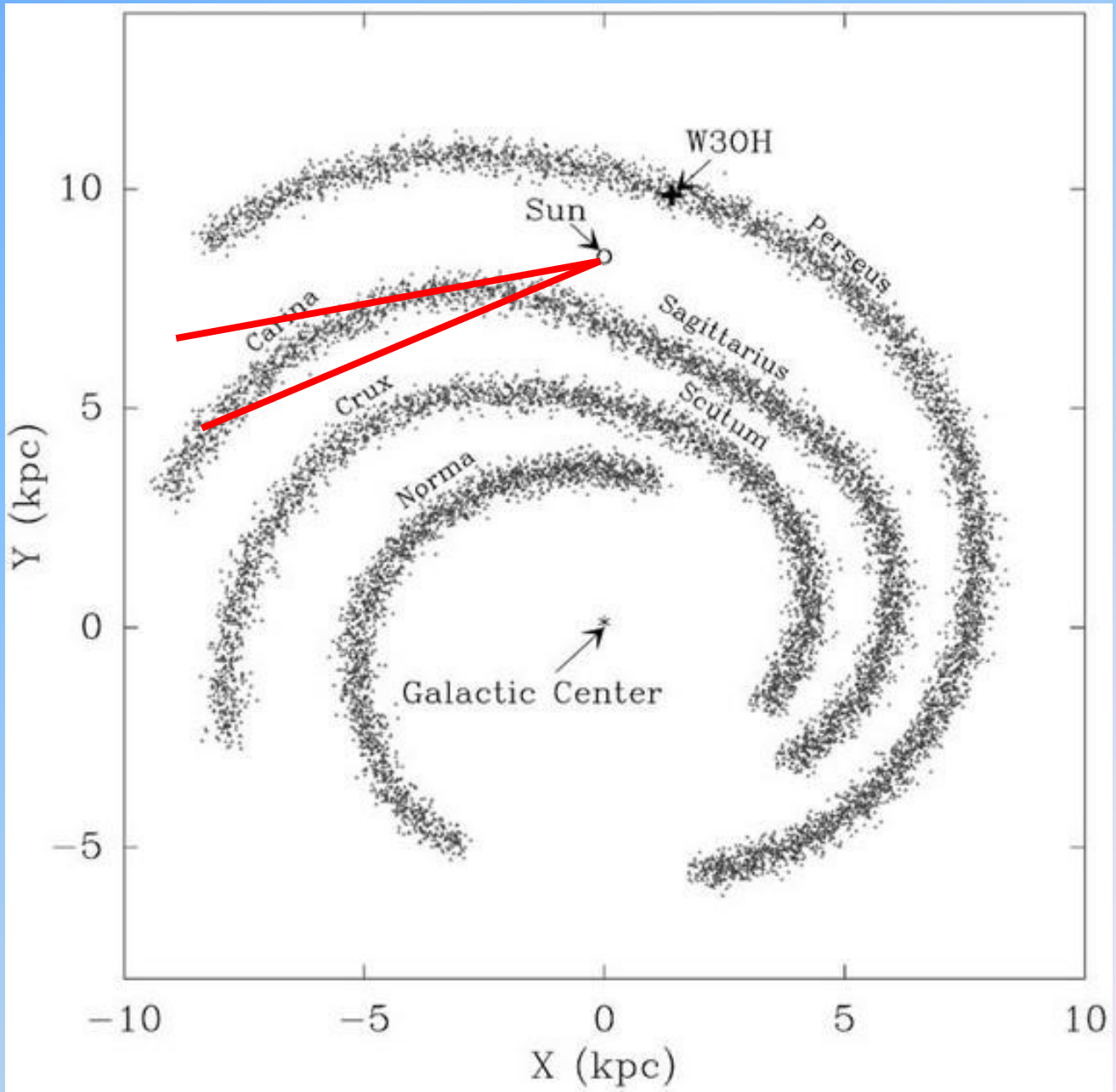
(Right: a simplified version of the 4-armed view of the MW disk.)

Steps on the way:

(i) Method validation, *Mohr-Smith et al 2015*

(ii) Carina Arm roll-out (red slice, right: 42 sq deg captured) *Mohr-Smith et al 2017*

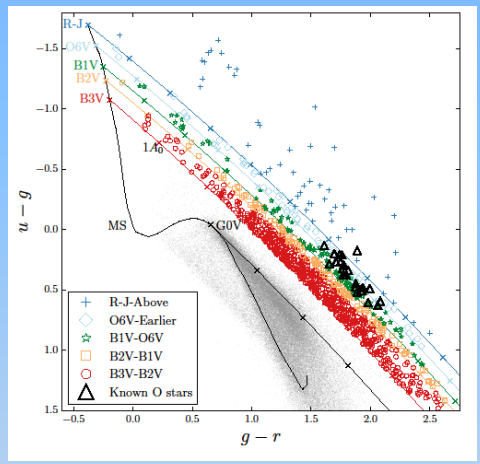
(iii) Westerlund 2 – analysis of 2 of the hottest 'hinterland' O stars + Gaia DR2 proper motion study *Drew et al submitted*



How the Carina list of candidate OB stars from VPHAS+ was built:

(i) Region uniformly calibrated (including u, ‘astrophysically’)

(ii) Long list extracted from u-g,g-r diagram



(iii) For each candidate: u,g,r,i + 2MASS J,H,K magnitudes fit to reddened OB theoretical magnitudes

→ Goodness of fit (accept/reject?);

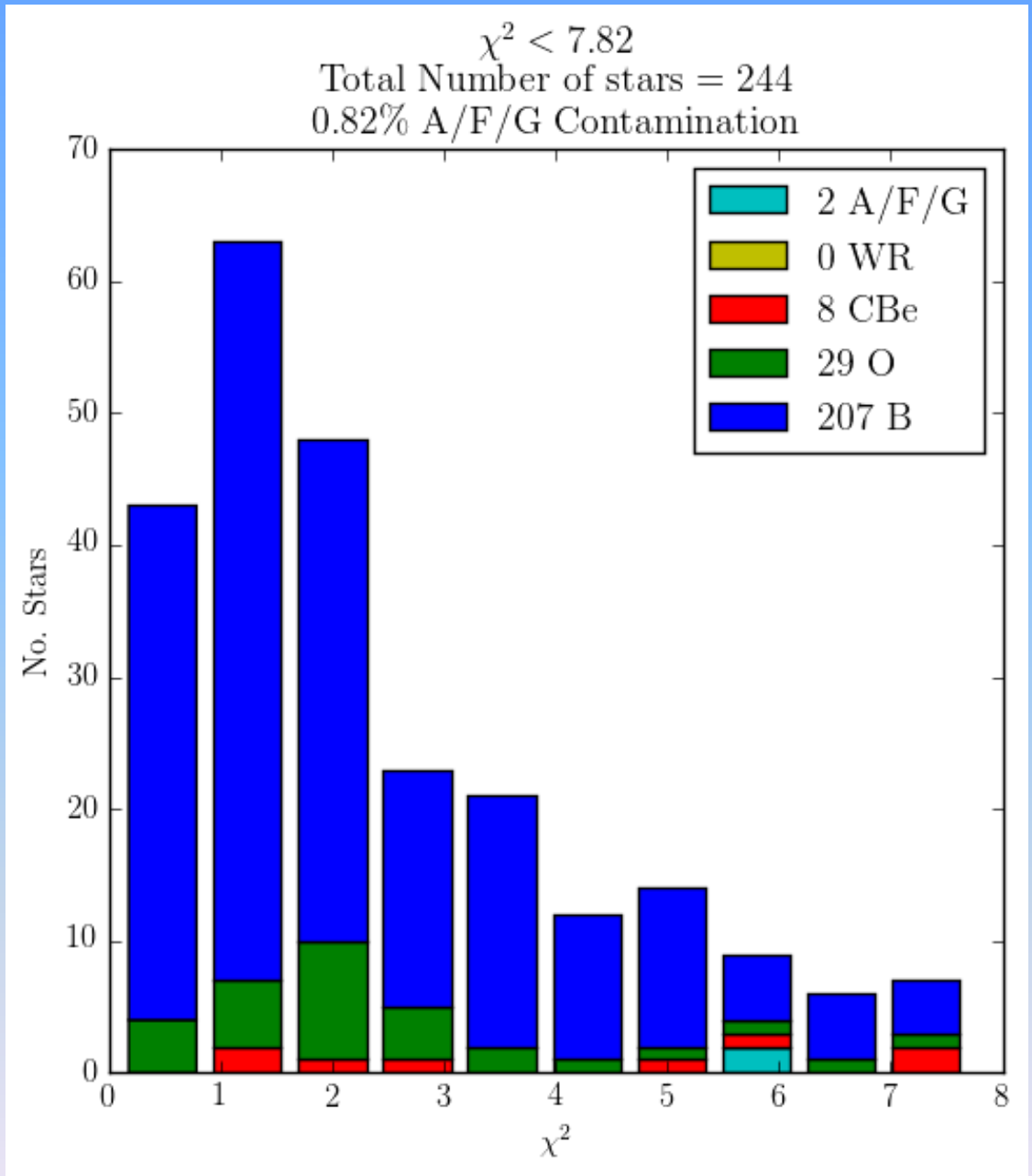
→ **precise extinction** (A_0, R_v to better than 0.1)

→ first estimate of sp.type/T_{eff}

…and spectroscopy confirmed the selection was ~99% successful:

Right: histogram wrt χ^2, with 7.82 as cut off (3 d.o.f.).

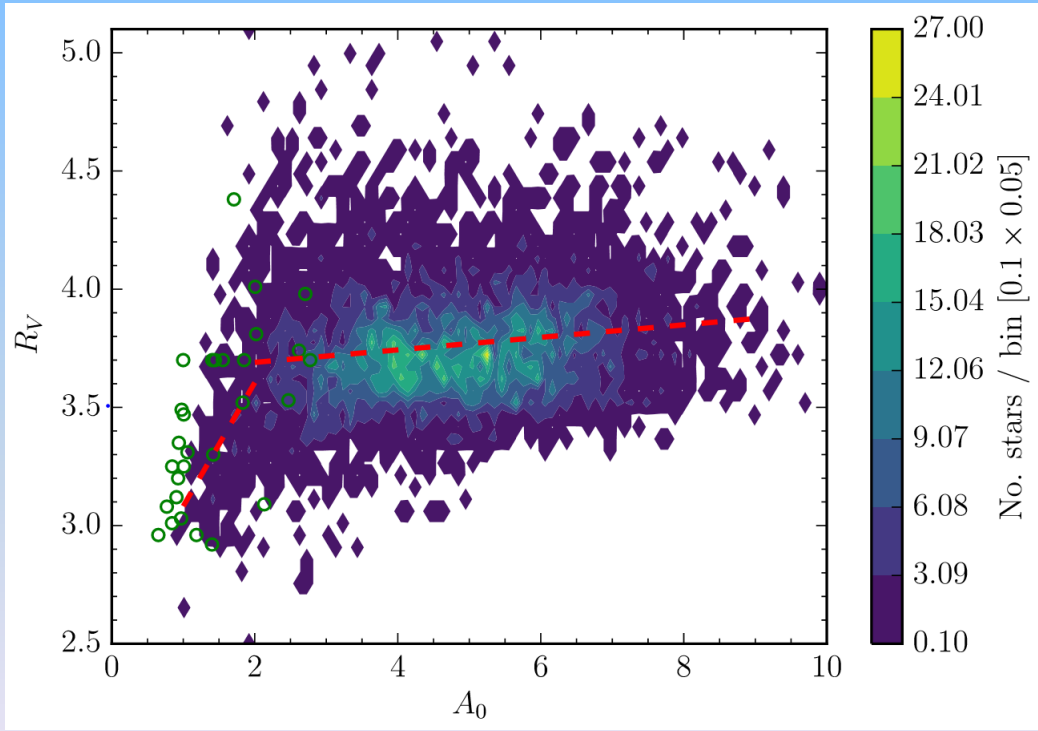
(…but repels WR stars!)

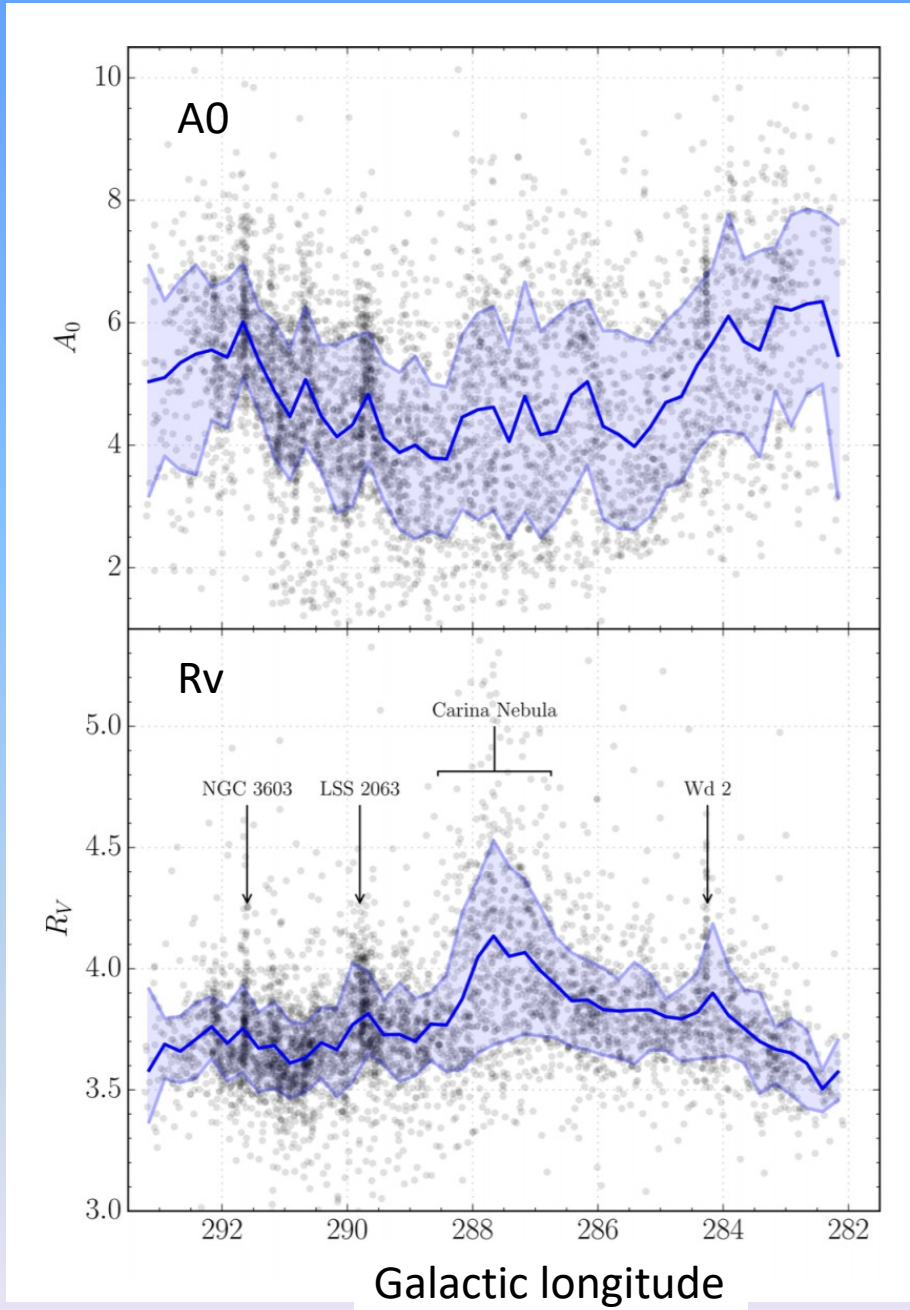


Carina Region – overview of extinction (A_0 and R_v)

Right: trends with Galactic longitude from Mohr-Smith et al 2017

Below: Rv versus A0, with green circles from Fitzpatrick & Massa (2007) dataset.





The ~8000 O/early B stars found, coloured according to best-fit extinction (rough proxy for distance)

(deleted movie)

underlying image: VPHAS+ Ha

Focus on Westerlund 2 – a great 'lab rat':

(i) Massive young cluster – and relatively isolated → good for figuring out relation to cluster-field relations
(ii) Our Carina census showed a scatter of ~early O stars within ~1 degree… runaways or formed in situ?

Relevant points:
• Threshold relative space velocity for runaway status: Blaauw's 30 km/s, revised down to 25 km/s by Portegies Zwart
• SMC work by Lamb et al 2016 on 399 field O stars → ~one-third are runaways and up to ~one-half are 'isolated'
• Rosslowe & Crowther 2018 → only one-quarter of WR stars in Scutum-Crux co-locate with HII regions/clusters
• Roman-Lopes et al 2011 proposed WR20c and WR20aa as Westerlund 2 ejections (based on on-sky geometry)

Westerlund 2

Hubble 2x3 arcmin^2 image of massive star cluster, Westerlund 2

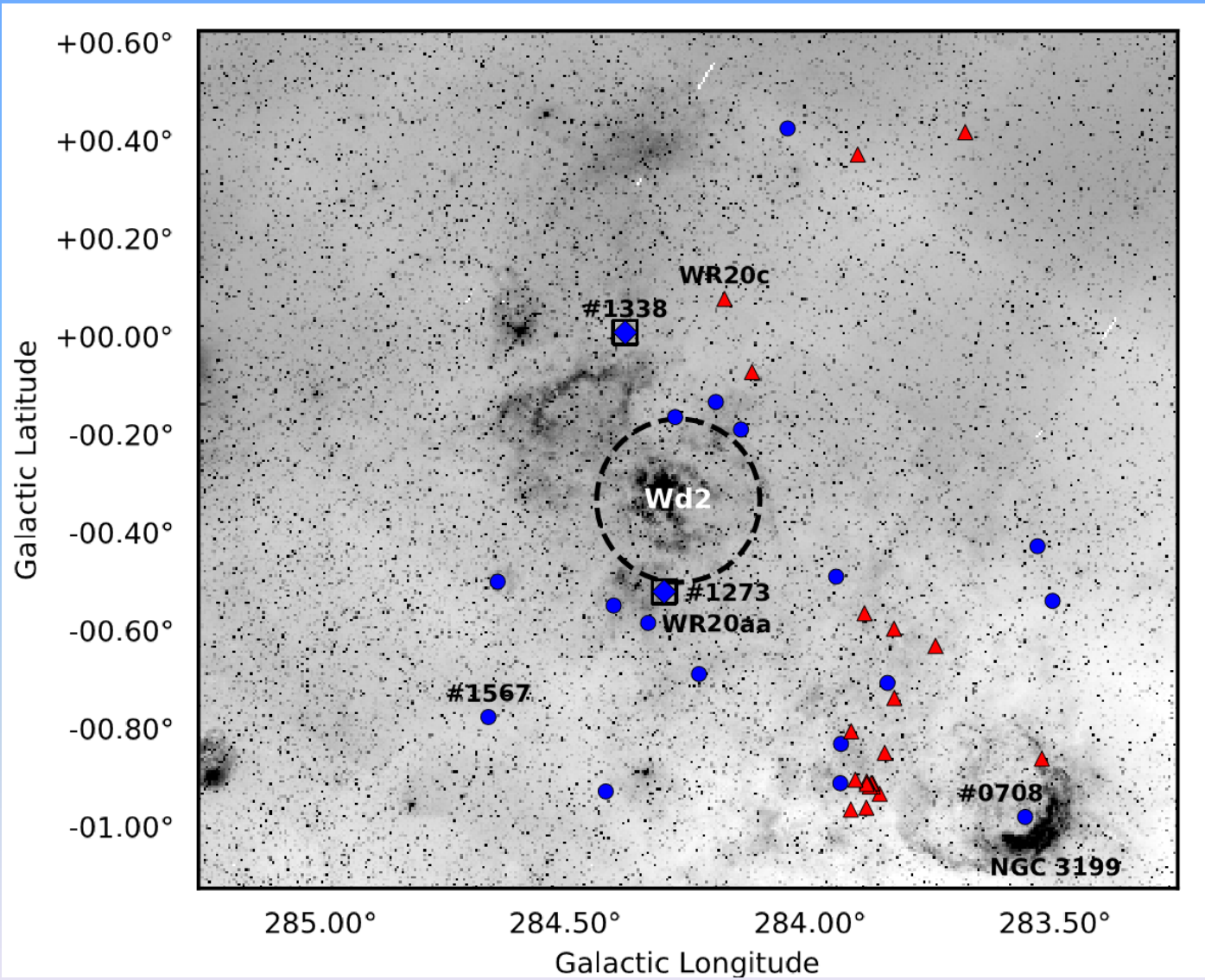
5+ kpc distant, on the sky near the Carina Arm tangent

Study region around Westerlund 2:
90x90 sq.arcmin → 130x130 sq.pc for D = 5 kpc

- 10 arcmin/15 pc radius circle around cluster core (dashed line) excluded

- 19 objects in blue = O star candidates, with $5.5 < A_0 < 7.5$. cf. Wd2 cluster $6 < A_0 < 7$
  - Multi-epoch X-shooter data obtained for the 2 stars in boxes
    → Good stellar parameters, precise radial velocities (wrt Westerlund 2)
    → both O4 V, M ~ $50M_\odot$
    RVs of –29 and –14 km/s

- 21 objects in red – more reddened ($A_0 > 7.5$)
  → likely background.



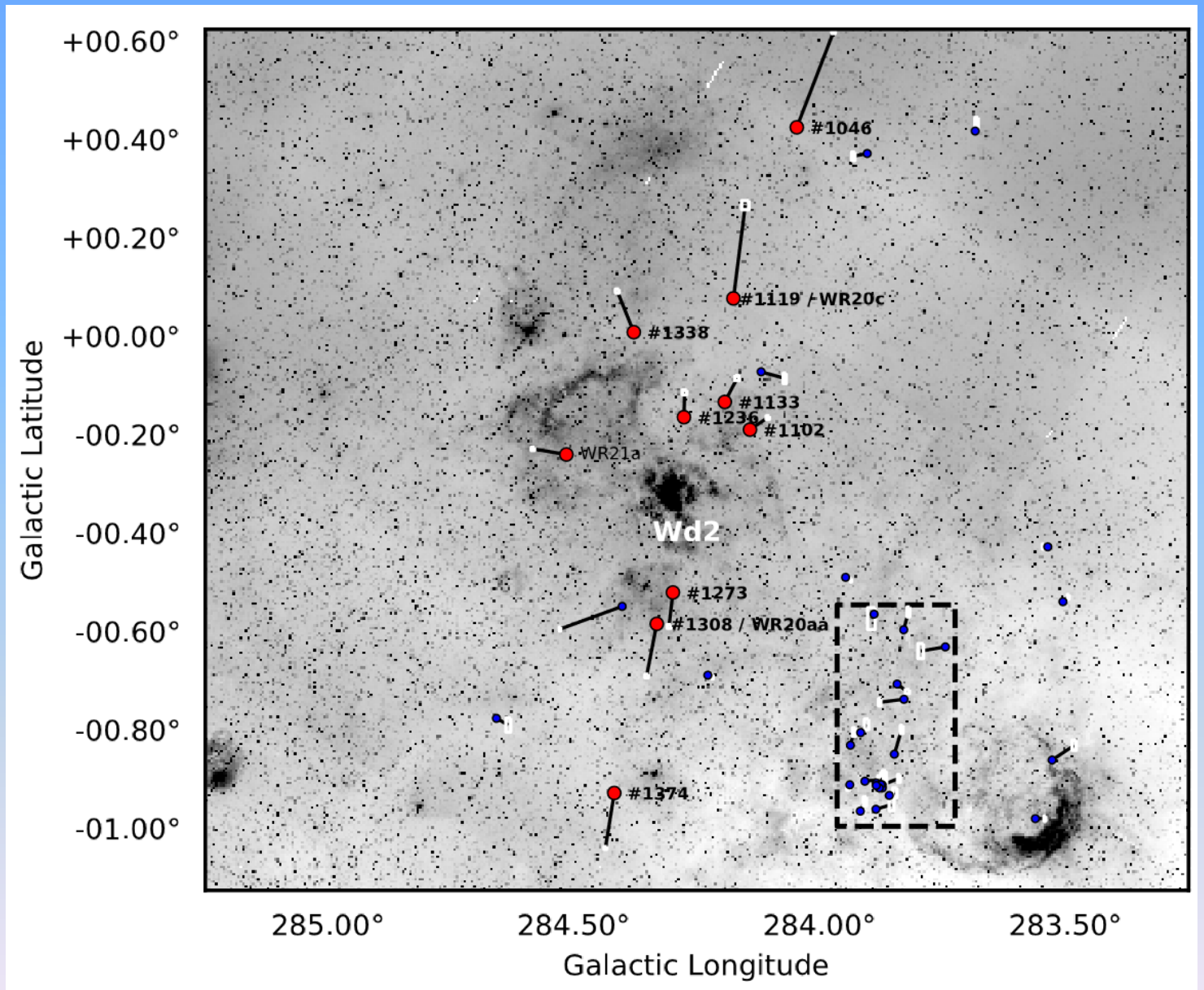
Gaia DR2 relative proper motions

Of the 40 objects in our search list
…9 have relative PM clearly directed away from Wd2

Transverse velocities at D=5 kpc:
#1273 29 km/s
#1338 38 km/s
WR 20aa 46 km/s
WR 20c 82 km/s

MSP 18, MSP 171 (in cluster), WR 21a need to be added to the list

→ 12 ejected stars
→ travel times < 1 Myr in every case



Where does this leave things:

…with at least 12 runaways:

- #1338 (O4V) is a ~50 km/s runaway
- #1273 (O4V) is too, at the low end: ~30 km/s
- 10 more (including MSPs 18 and 171, and THREE WR stars)

→ a ~25% cluster ejection efficiency at high O-star masses
cf. 10% from 'bully binary' dynamical models (Fujii & Portegies Zwart 2011)
cf. 15—20% from 'bully binary' + sub-cluster merging (Fujii et al 2012)
cf. W. Lucas et al 2018

N-S alignment seen ~ N-S placing of Wd2 sub-clusters, now

…there are examples of 'in situ' formation here

- one of them has linked cluster? → the stochastic picture of cluster building described by Parker/Goodwin (2007) might suit
- 4 more O star candidates with ~zero relative proper motion, and no evident associated clusters → isolated formation?

Concluding remarks:

VPHAS+ observations ending soon

The survey offers

- high quality < 1 arcsec PSF imaging,
- calibrated multi-band photometry down to > 20th magnitude.

Practically speaking, DR4 should be the last release

→Flexible options for 'global' Galactic Plane science (~degree scale to 100s of degrees)
→ u, Ha discrimination
→ Great search lists for Gaia
→ Complementary to NIR and longer wavelength surveys.


\Thank you for listening