Cepheids to trace the disc and the spiral arms of the Milky Way

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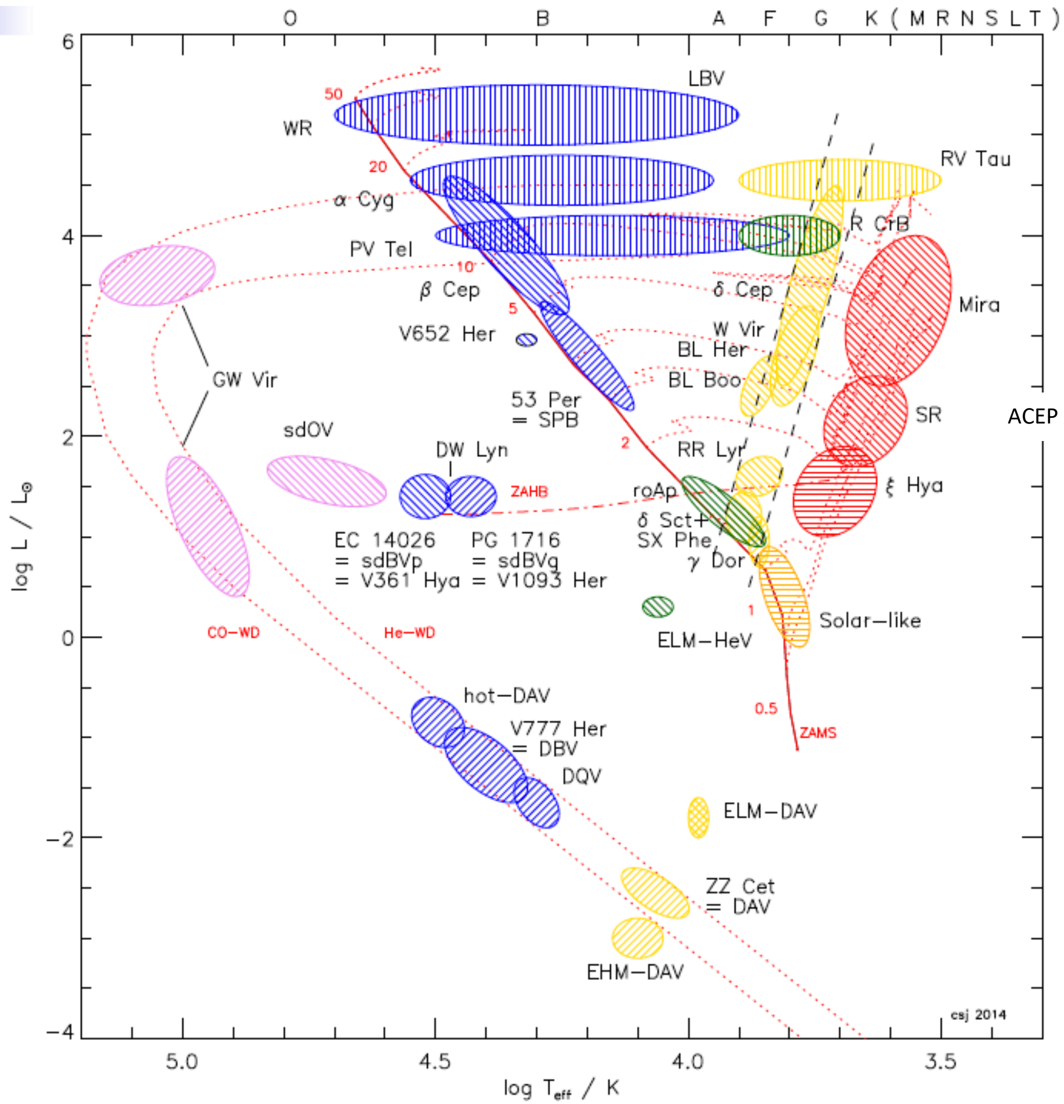
And Gaia DPAC

Outline

- Classical Cepheids as population tracers
- Literature results
- Gaia DR3 contribution for Cepheids in the MW
- Results from DR3 Performance Verification Paper GC, Drimmel+2023 and Drimmel+2023

Classical Cepheids



Jeffrey & Saio, 2016

Classical Cepheids: central helium burning stars

$M=3\div13M_\odot$

$M_V=$ -2÷- 7 mag

P=1÷100 d

Age=50÷400 Myrs

Pulsate in F, 1O, 2O, Multiple modes

Primary standard candles due to their PL relations

Classical Cepheids as population tracers in the MW

- Tracers of the young population of the Disc (50÷300 Myrs), Age can be estimated from period, colour and metallicity

- Marginally affected by radial mixing and migration (e.g. Minchev+2013) → close to their birth place

- Bright enough to be detected at large distances, even in rather obscured regions of the MW disc (beyond the Bulge using NIR photometry)

- Accurate distances over much of the Galactic disc

Classical Cepheids as population tracers in the MW

- Detailed abundance analysis possible for many elements (several well-defined absorption lines) and for a large number of objects (due to the intrinsic brightness)

- Accurate kinematic data PMs and RVs

- Greatly increased number of objects (> 3,500) in recent years, thanks to several surveys, OGLE IV, ASAS-SN, ATLAS, ZTF, Gaia DR2 and DR3

Recent researches using Cepheids to study MW's Disc

Skowron et al. (2019a,b) 2,390 stars

Optical data from OGLE, ASAS, ASAS-SN, ATLAS, GCVS,… + **mid-IR** WISE and Spitzer **+ mid-IR PL relations** from Wang et al. (2018) + **IR extinction maps** (Marshall+2006, Green+2015, Bovy+2016)

Chen et al. (2019) 1,339 stars

Mid-IR data from WISE + **optical data** from GCVS, ASAS, ASAS-SN, ATLAS, Gaia DR2 + **mid-IR PL relations** for WISE and Spitzer from Wang+2018

Minniti et al. (2020) 45 stars from near-IR

Near-IR data from VVV (verified with X-shooter spectra or OGLE) + **near-IR PL relations** Macri+2015 + **near-IR extinction**

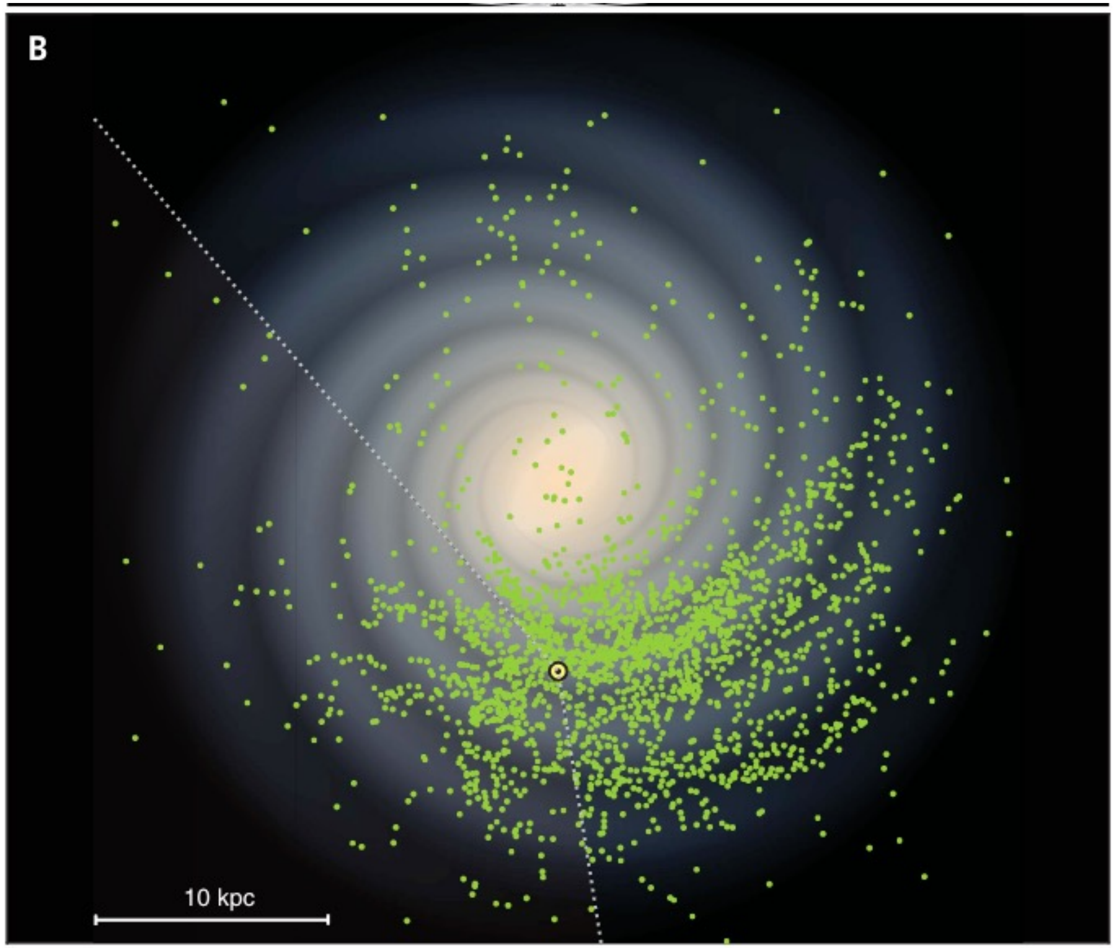
Lemasle et al. (2022) 2,684 stars (reduced taking only age < 150 Myr)

Optical data from OGLE, Gaia DR3, ASAS, ASAS-SN, ATLAS, ZTF, WISE, GCVS, + **mid-IR PW relations** for WISE + **Gaia EDR3 parallax**

None of these works takes into account the metallicity in deriving the distances or ages

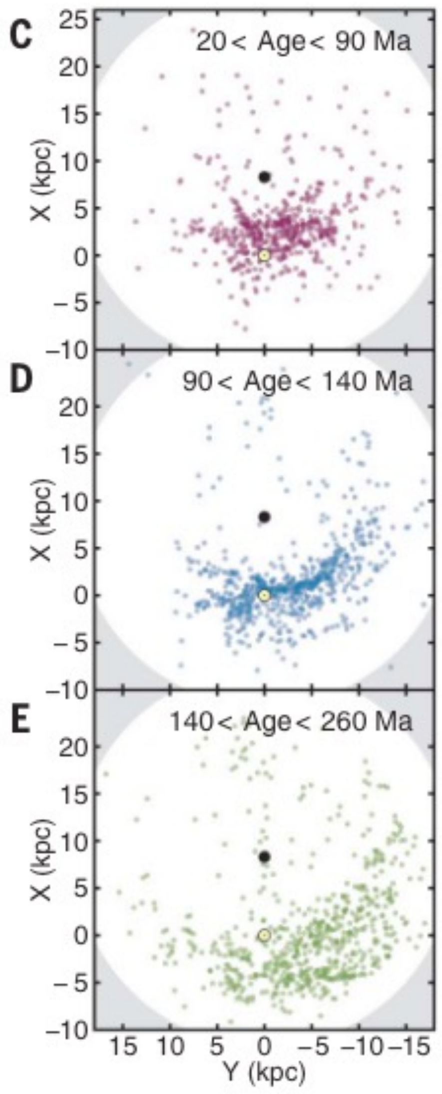
Adapted from D. Skowron talk at IAU 376

Tracing the spiral arms of the MW with Cepheids (2390 stars Skowron+2019a,b)



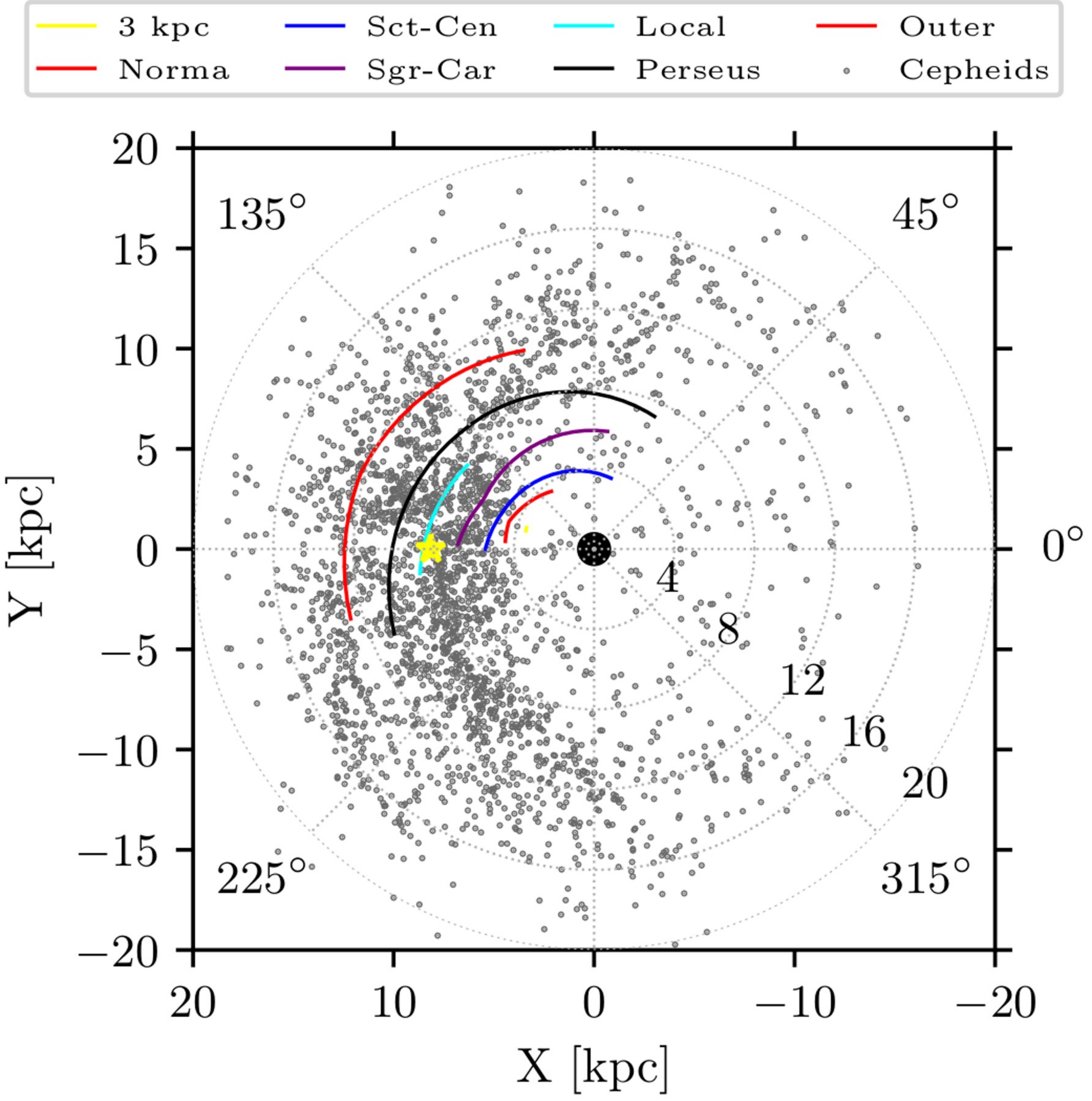
Cepheids roughly follow the spiral arm pattern based on HI (Levine+2006).

Tracing the spiral arms of the MW with Cepheids (2390 stars Skowron+2019a,b)



- Cepheids tend to be older at larger radii
- Youngest possibly associated with the inner Galaxy spiral arms (Norma-Cygnus, Scutum-CruxCentaurus, and Sagittarius-Carina)
- Oldest ones, possible associations with the Perseus and Norma-Cygnus/Outer arms are much less evident.
- Cepheids within individual overdensities have similar ages, suggesting a common origin in past star formation episodes.

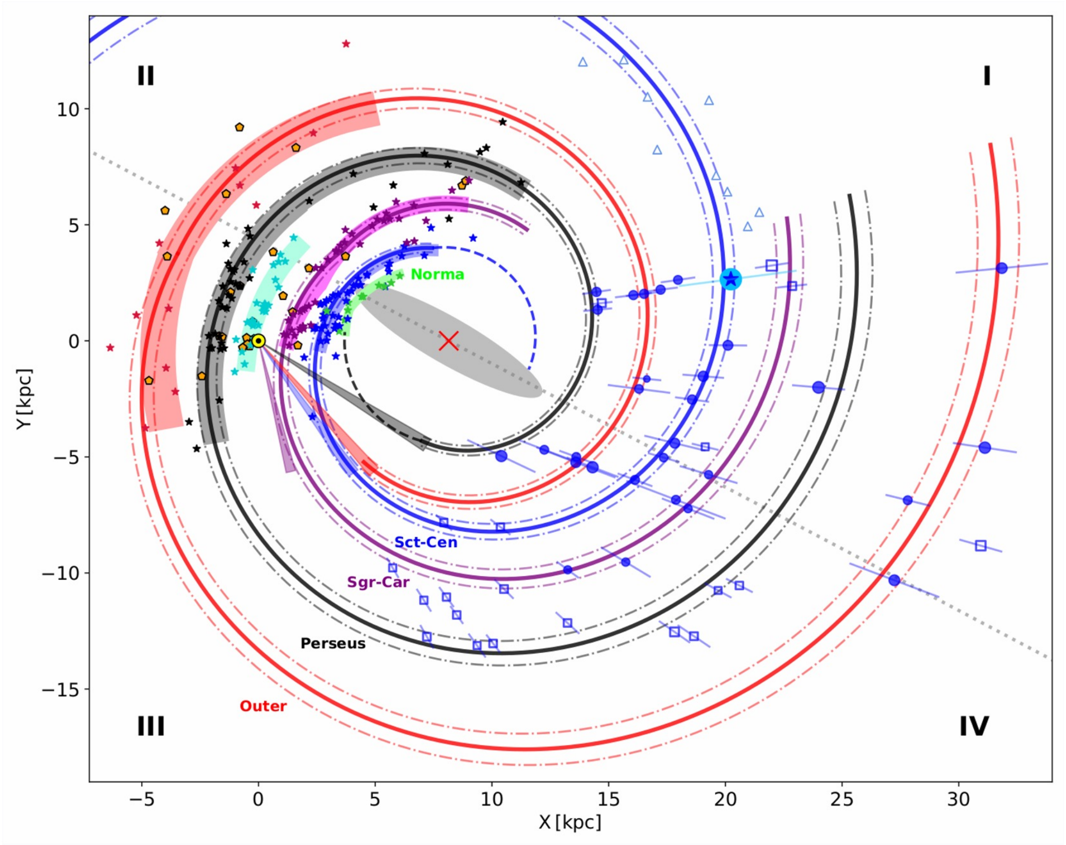
Tracing the spiral arms of the MW with Cepheids (<2684 stars Lemasle+2022)

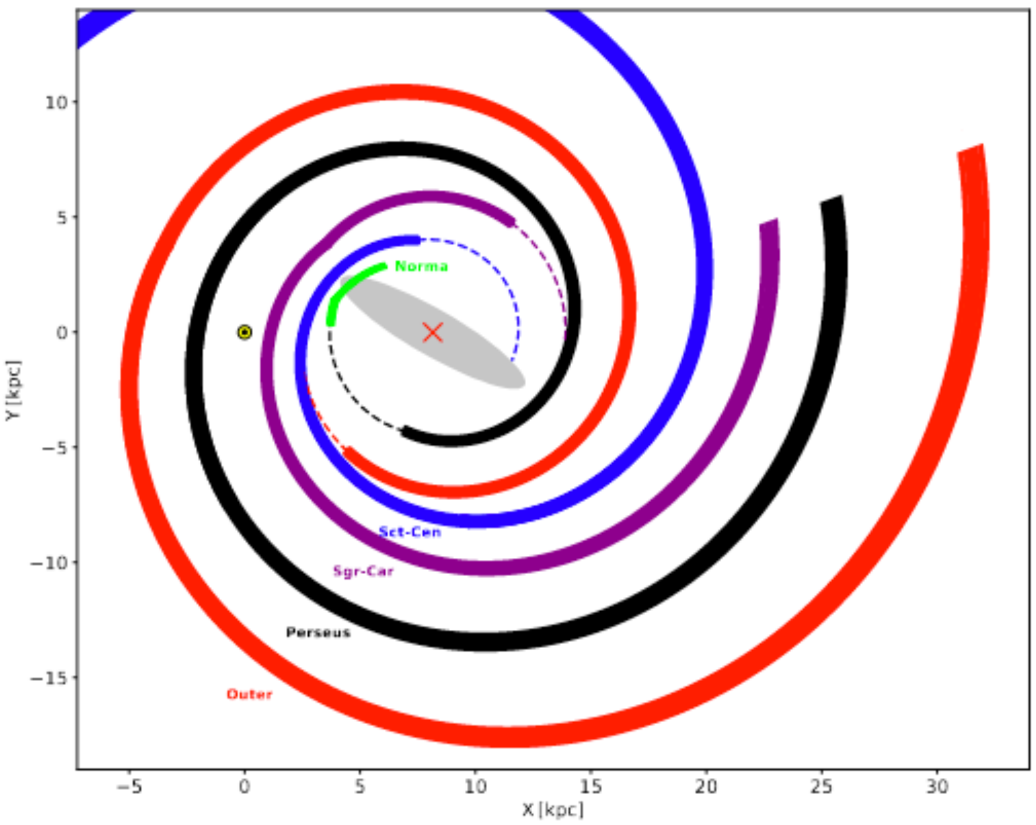


Agreement with the measured of Reid et al. (2019) based on masers

Spiral arms in the IV and I quadrants (VVV, Minniti+2021)

50 Cepheids from VVV, more stars already observed.

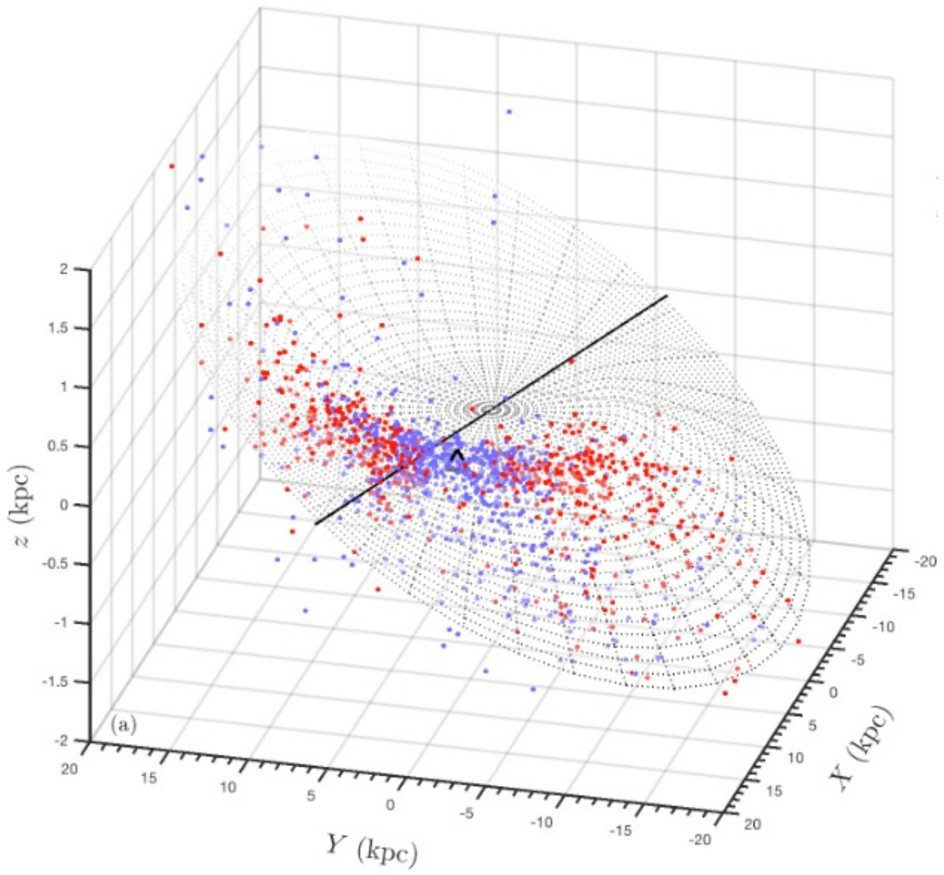




Norma Cygnus/Outer Scutum-Crux-Centaurus
Sagittarius-Carina Local Perseus

Spiral arm model with two main arms Perseus and Scutum-Centaurus that branch out into four arms.

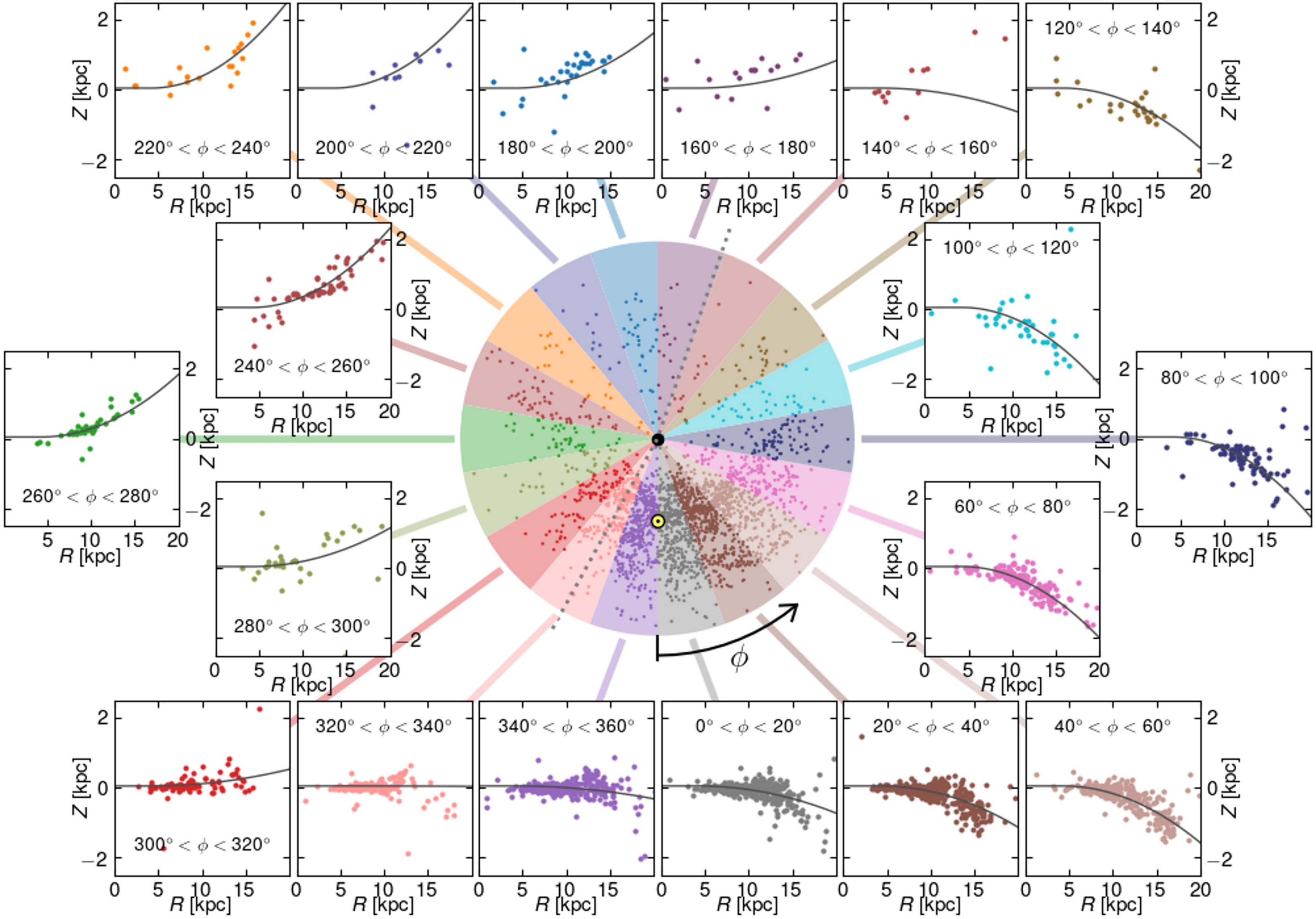
The Warp (1339 stars, Chen+2019)



- The warp's line of nodes is not oriented in the Galactic Center–Sun direction and subtends a mean angle of 17.5° ± 1° (formal) ±3° (systematic)
- The warp is associated with torques forced by the massive inner disc.

2390 Cepheids

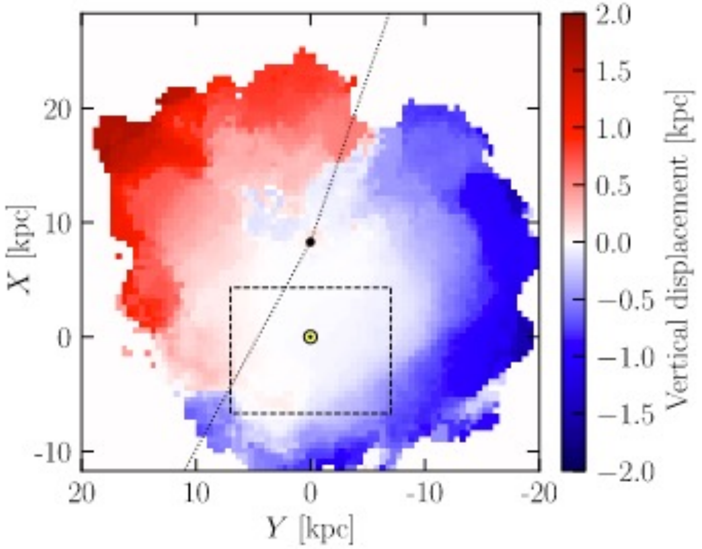
THE WARP

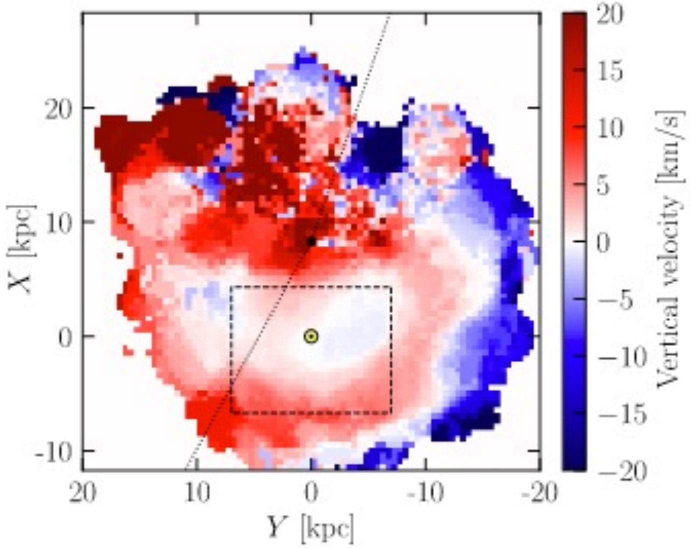


Skowron et al. (2019b)

Credits: D. Skowron, IAU 376

The Warp (Skowron+2019b)





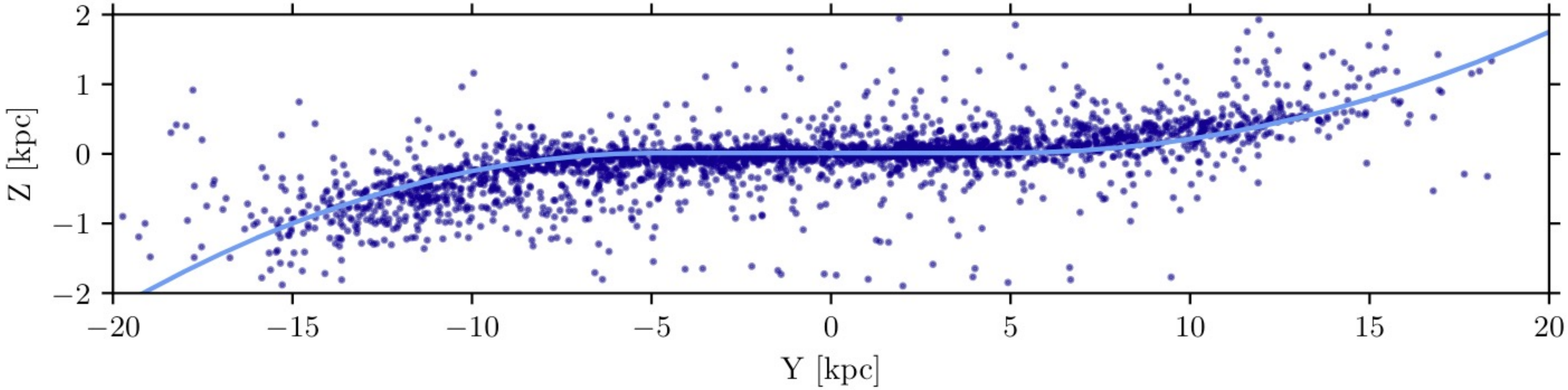
Northern part very prominent; its amplitude ~ 10% larger than that of the southern part.

Large-scale vertical motions with amplitudes of 10–20 km/s → Cepheids in the northern warp exhibit large positive vertical velocity (toward the north Galactic pole); those in the southern warp – negative vertical velocity (toward the south Galactic pole).

Possible signature of the impact with the Sagittarius dwarf galaxy

The Warp (2784 stars, Lemasle+2022)

$$z(R,\phi) = \begin{cases} z_0 & \text{for } R \leq R_d \\ z_0 + (R - R_d)^2 [z_1 \sin(\phi - \phi_1) + z_2 \sin(2(\phi - \phi_2))] & \text{for } R > R_d \end{cases}$$



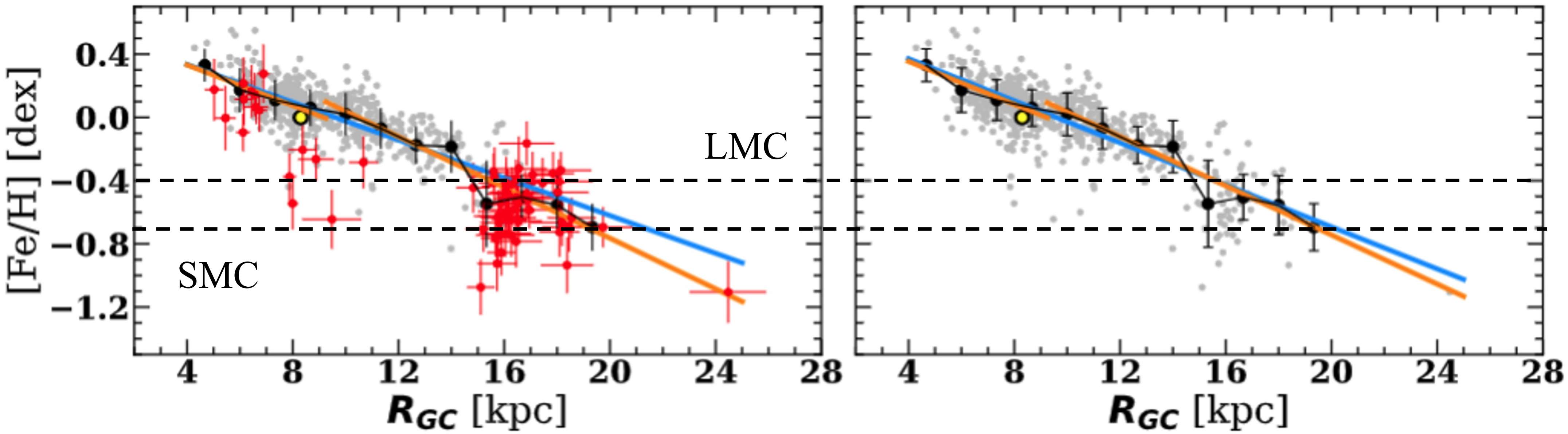
Results similar to Skowron+2019a,b

Metallicity gradient (Trentin+2023 – see also Lemasle+2022, Kovtyukh+2022)

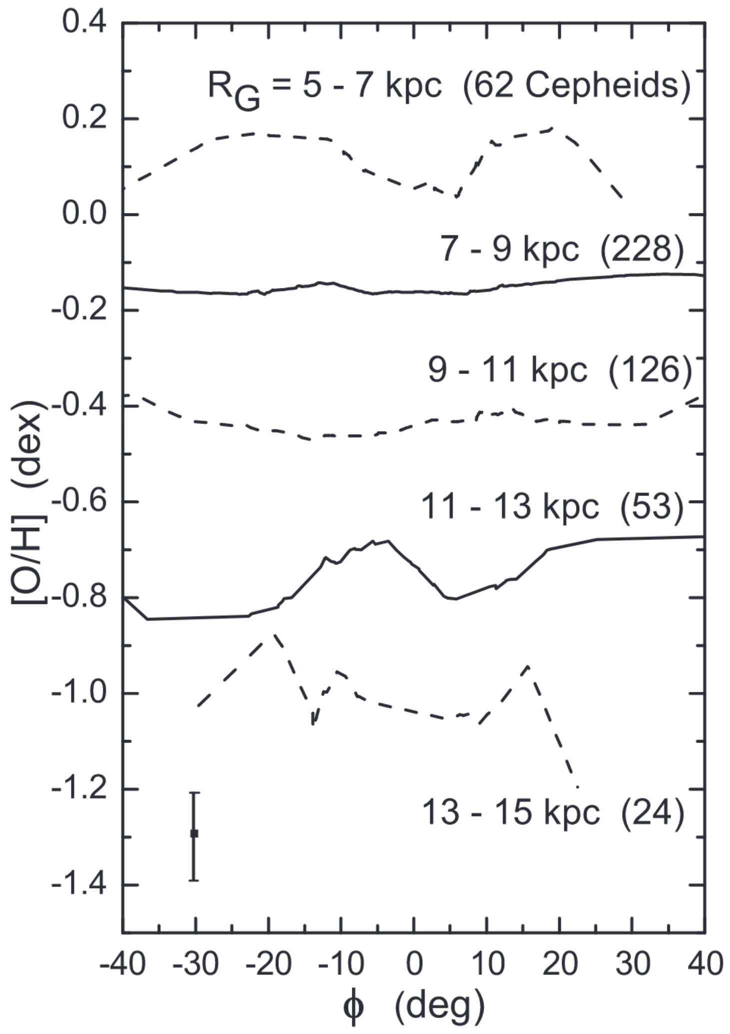
- Study of the metallicity gradient of the Galactic Disc up to a rather unexplored range of radii and metallicities.

- Statistical evidence of a possible break at ~9 kpc (already suggested in Genovali et al. 2014 and others). Steeper slope at super-solar metallicity → radial flows in the disc due to the Bar (Andrievski+2002)

- No flattening at large radii (found in the literature with – older – OC)



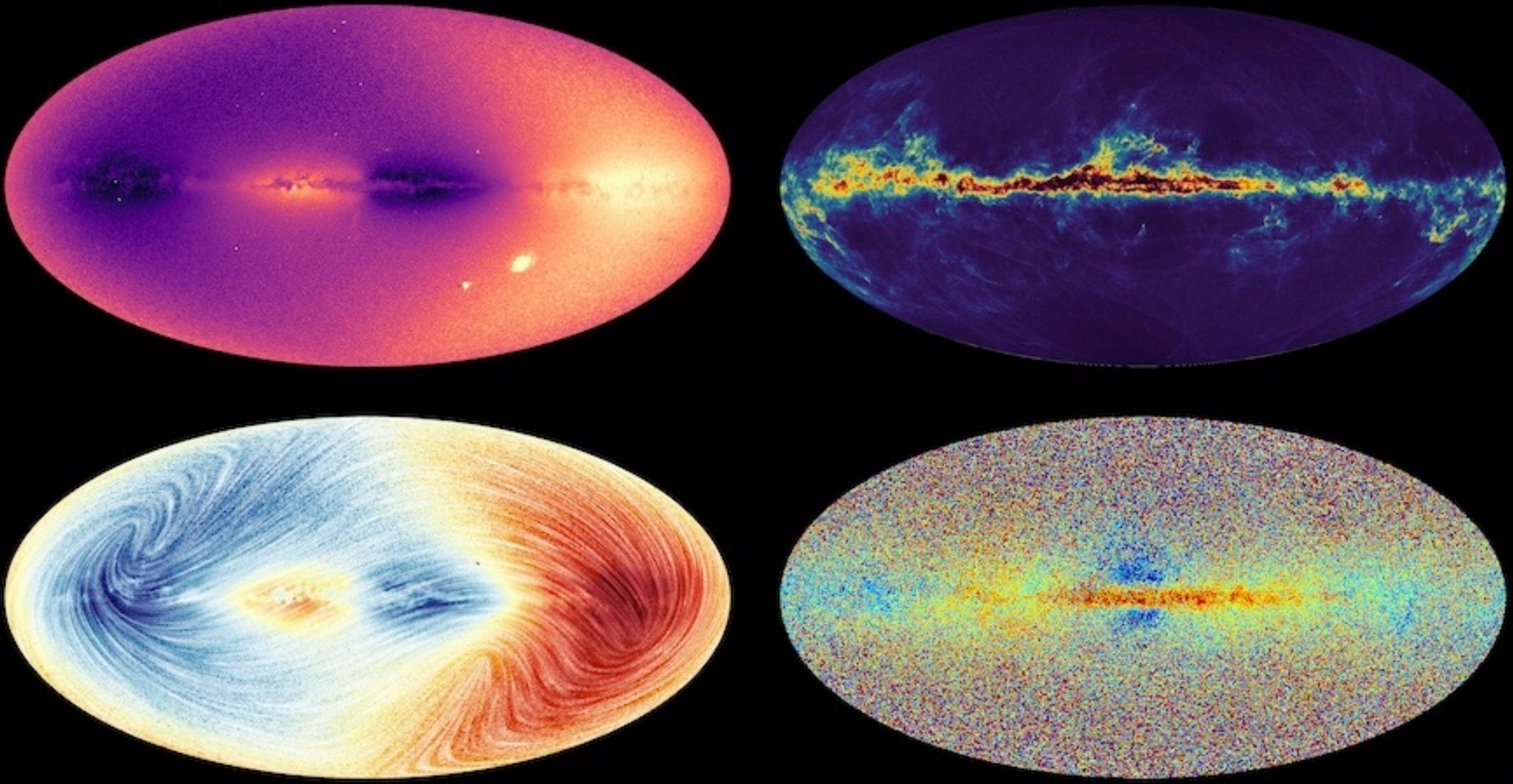
Metallcity gradient azimuthal variation (Kovtyukh+2022)



- [O/H] azimuthal asymmetries ≈0.2 dex in the inner Galaxy (perturbation by the Bar) and in the outer disc
- Similar findings for nearby spiral galaxies, as well as recent 2D chemo-dynamical models.

Gaia DR*3*

GAIA: EXPLORING THE MULTI-DIMENSIONAL MILKY WAY

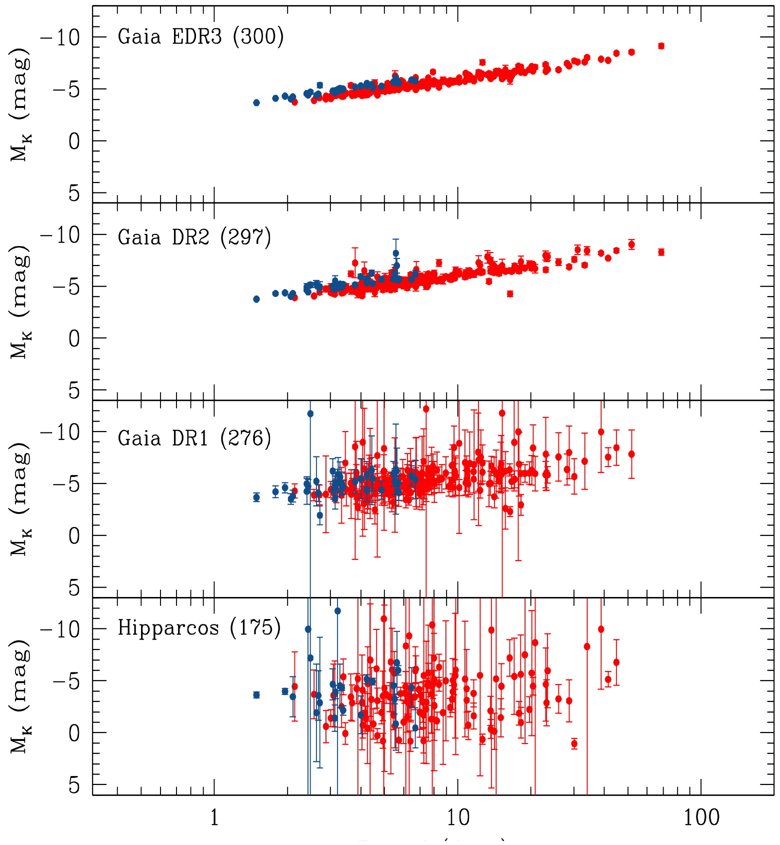


Gaia: 3 "Instruments" in 1

Astrometry, (Spectro)Photometry, Spectroscopy

Ra,Dec,PMs,Plx — G, G_{BP}, G_{RP} — BP, RP, RVS

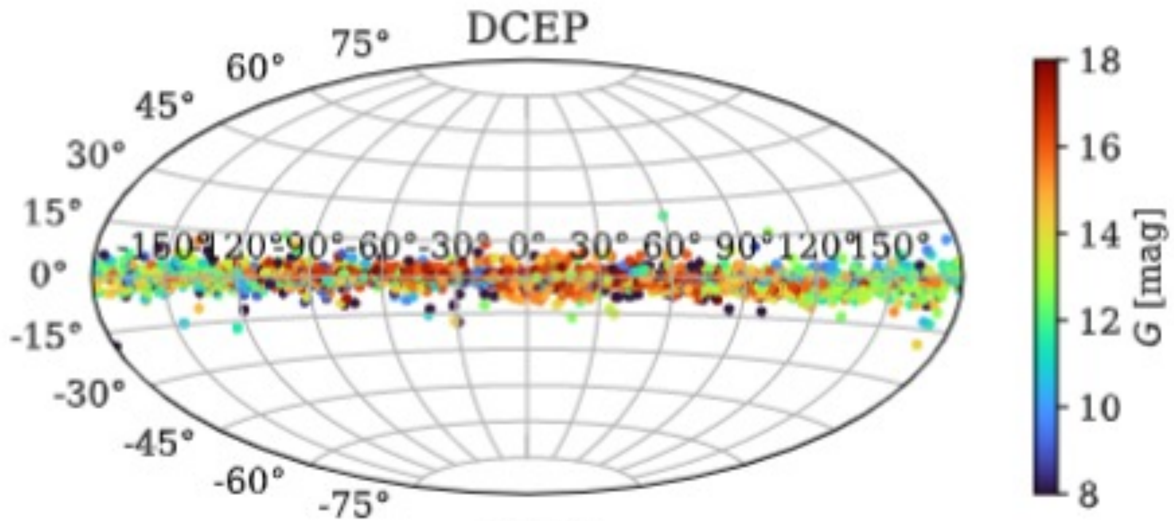
Cepheids

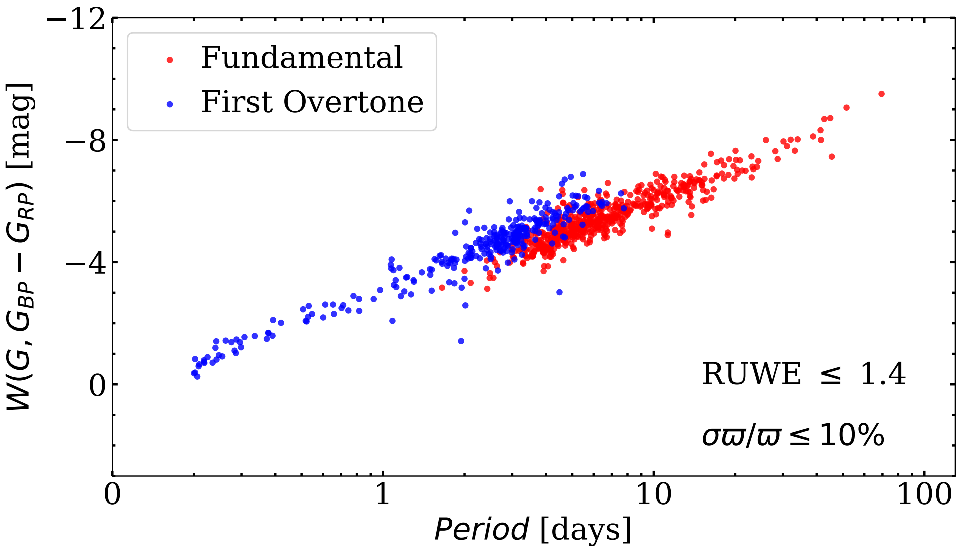


Credit: ESA/Gaia/DPAC, created by: V. Ripepi

- Repeated observations → time series
- Unprecedented astrometry
- High photometric precision up to G~21 mag
- All sky
- **HOMOGENEITY for all the derived observables**

Cepheids in the MW in Gaia DR3





~1060 Cepheids in Gaia DR3 with high-precision parallaxes (distances)

- 3,434 MW **Classical Cepheids** in Gaia DR3 → largest homogeneous dataset published so far
- Period, mode of pulsation, mean magnitudes and amplitudes in three photometric bands G, G_{BP}, G_{RP} Fourier parameters in G
- Radial velocities curves for 729 MW Cepheids (largest dataset ever)
- Mean radial velocity for > 2000 Cepheids
- Parallax (1/3 with err < 10%) and PM for all Cepheids
- Atmospheric parameters (effective temperature, gravity etc. from gsp_spec) and chemical abundances for about 900 Cepheids

Ripepi et al. 2023, A&A, in press

Classical Cepheids

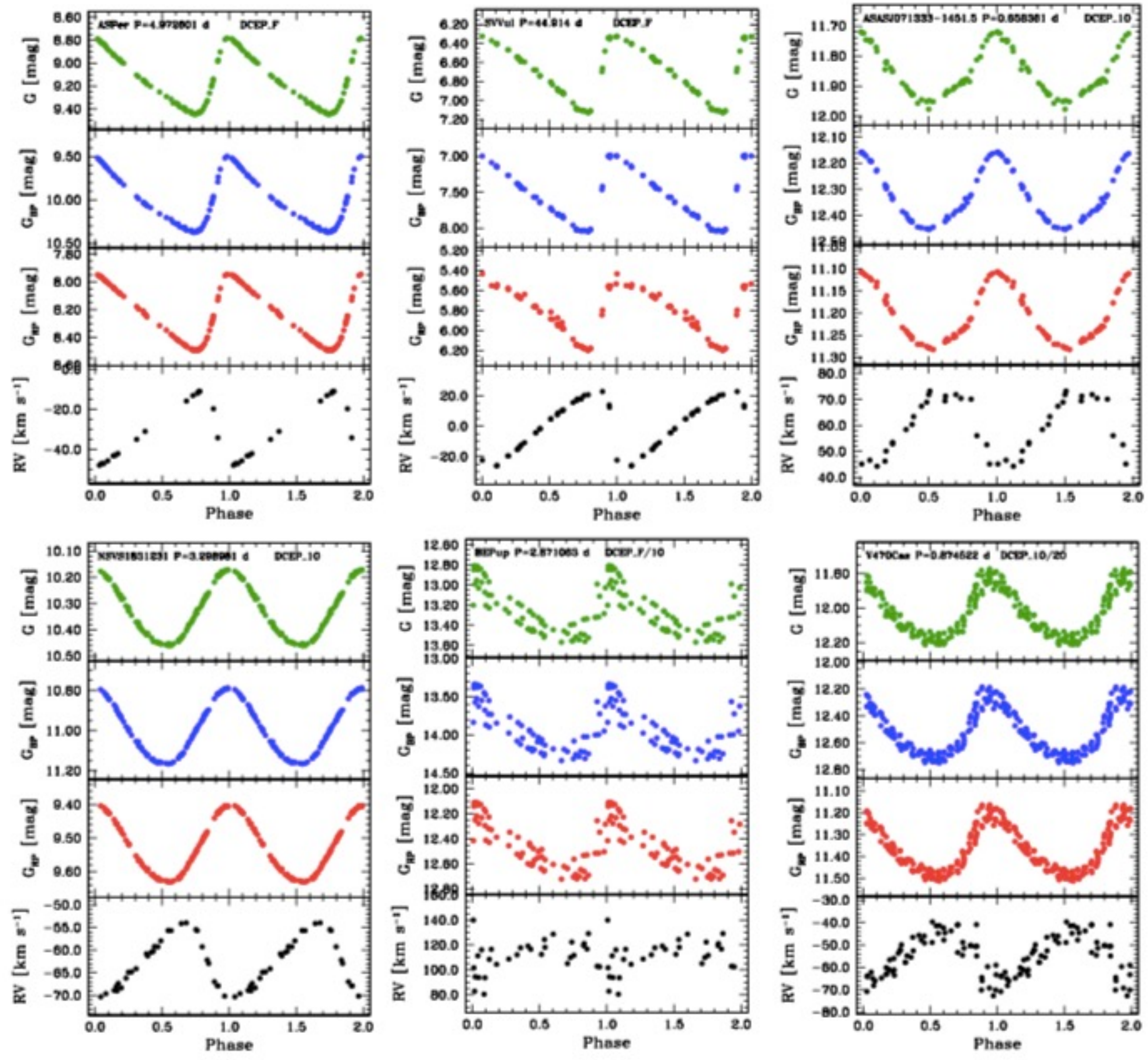


Fig. A.1. Light and RV curves for a selected sample of DCEPs of different modes.

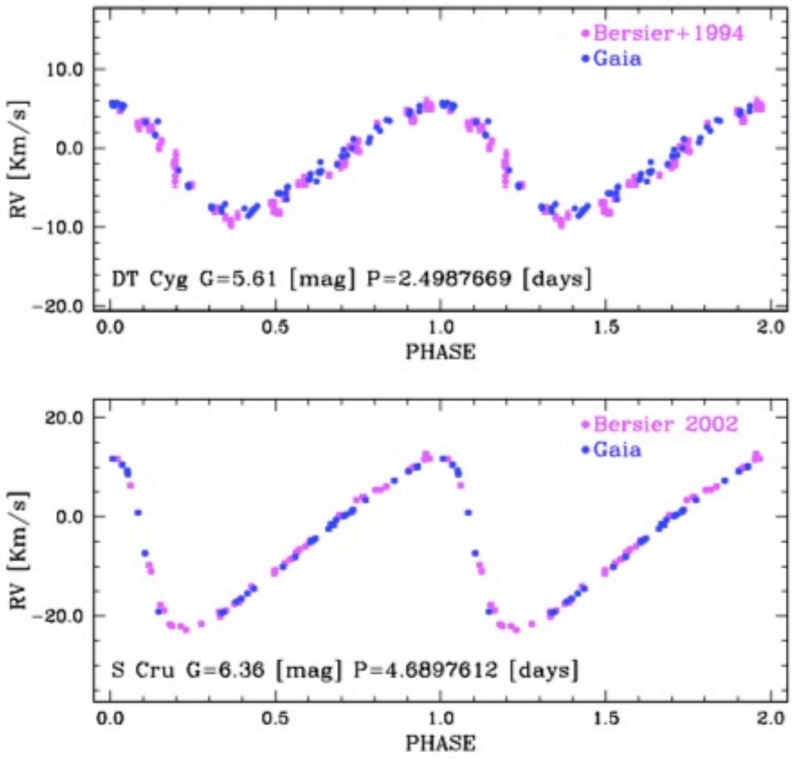


Fig. 37. Examples of the comparison between the *Gaia* and the literature RV curves for a DCEP_1O (DT Cyg) and a DCEP_F (S Cru)

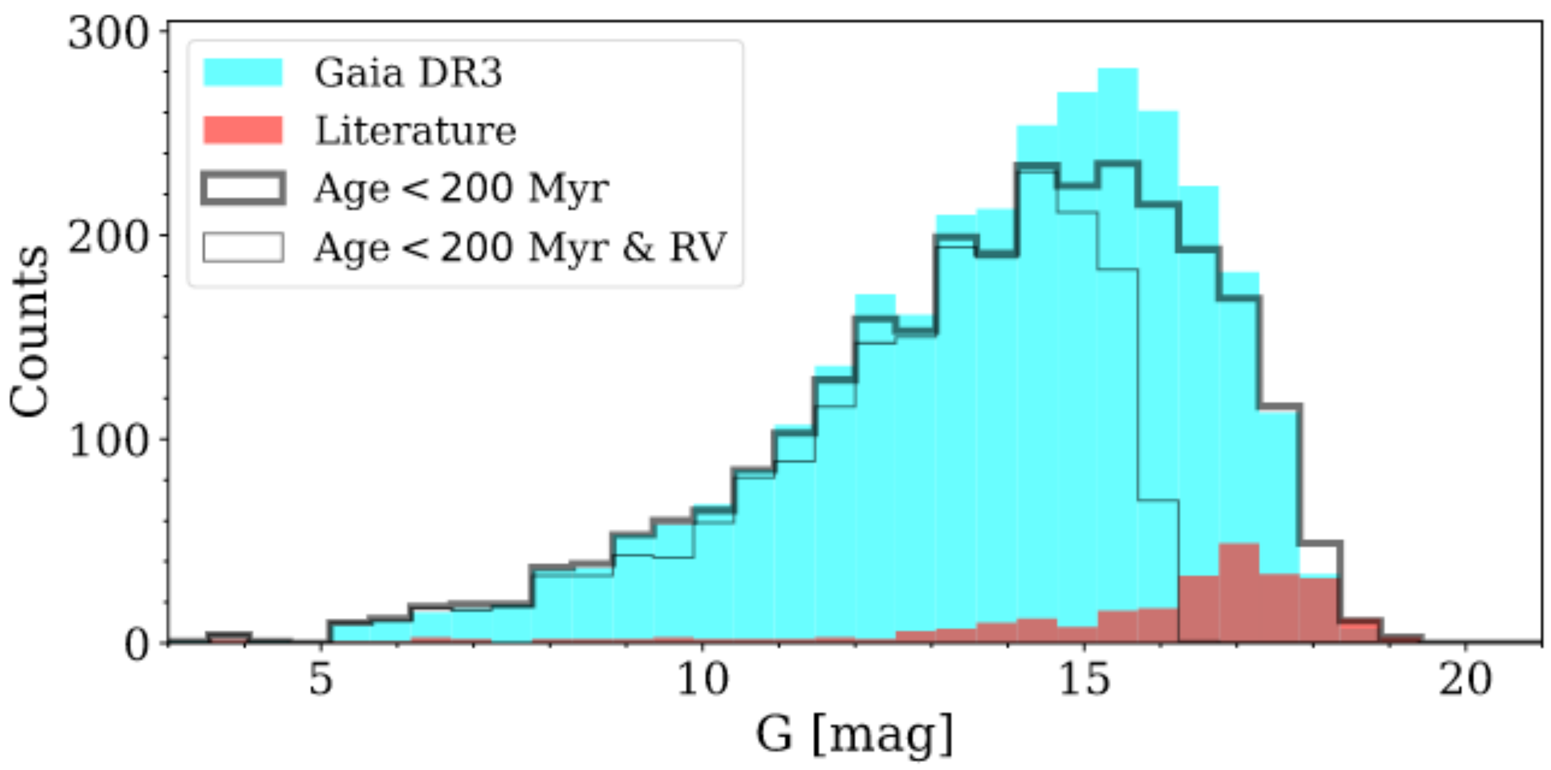
Ripepi et al. 2023, A&A, in press

Cepheid data used for the Performance Verification Paper GC, Drimmel+2023 “Mapping the asymmetric disc of the Milky Way”

- Cepheids inventory
- Distances → Photometry (periods) → PL relations
- Ages (Period-Age relations)
- Kinematics → PMs, RVs
- Metallicities (Spectroscopy)

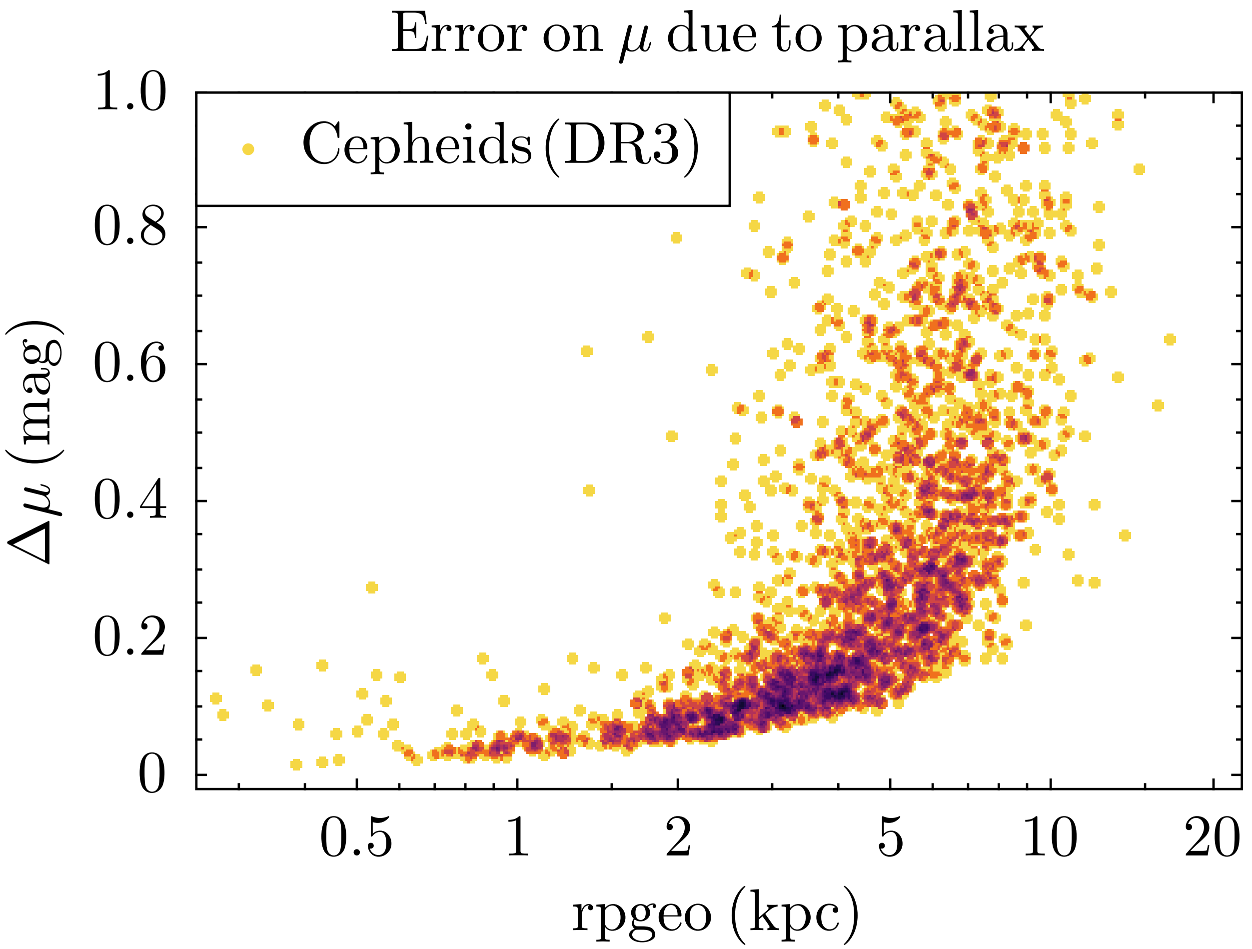
Inventory of Cepheids used in the Gaia PVP paper

- Gaia DR3 +~480 objects from Pietrukowicz et al. (2021) and Inno et al. (2021) → 3785 DCEPs, reduced to 3306 (due to photometry quality cuts etc.)
- Includes most of the OGLE IV and ZTF DCEPs



Other recent DCEP compilations: 3666 objects in the Pietrukowicz list at http://www.astrouw.edu.pl/ogle/ogle4/OCVS/allGalCep.listID

Distances

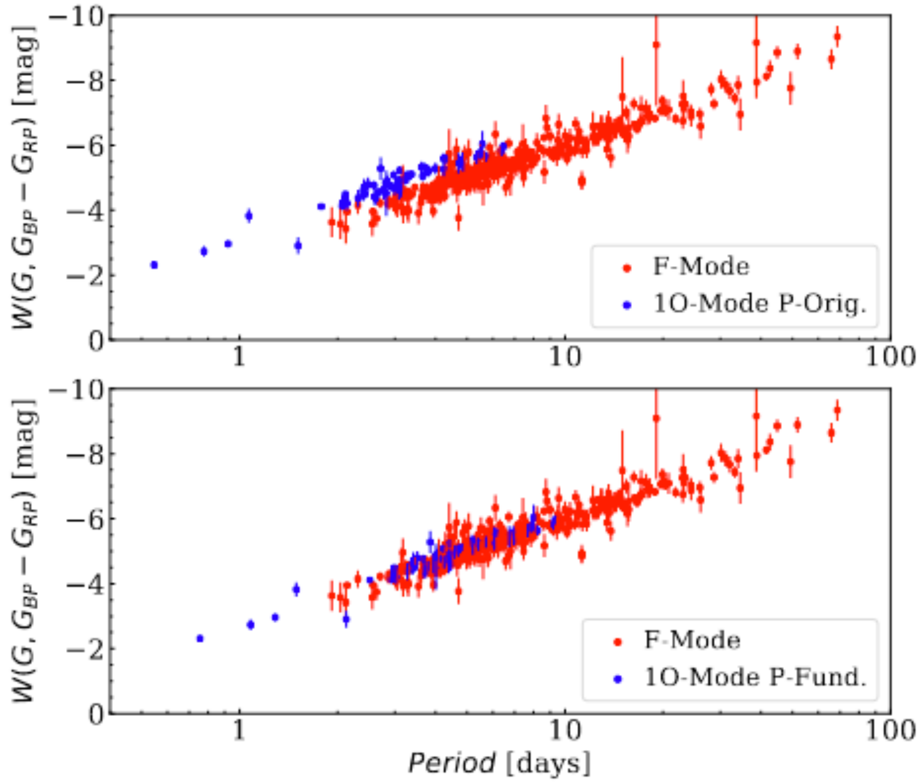


Gaia-parallax based distances become uninformative beyond ~ 5-6 kpc

To study the MW disc with Cepheids → more accurate distances → PL relations

Sample of Cepheids from GC-Drimmel+2023
rpgeo-distances from Bayler-Jones+2021

Distances: Period-Wesenheit-Metallicity in the Gaia bands (Ripepi+2022)



- Sample of 372 F- and 63 1O-mode DCEPs with good astrometry and metallicity from high-resolution spectroscopy from the literature.
- Wesenheit magnitude $w_{Gaia} = G-1.90\,(G_{BP}-G_{RP})$ from Ripepi+2019 (reddening-free by construction, Madore 1982)
- Adopted Astrometric-Based-Luminosity (ABL) to use correctly the parallaxes

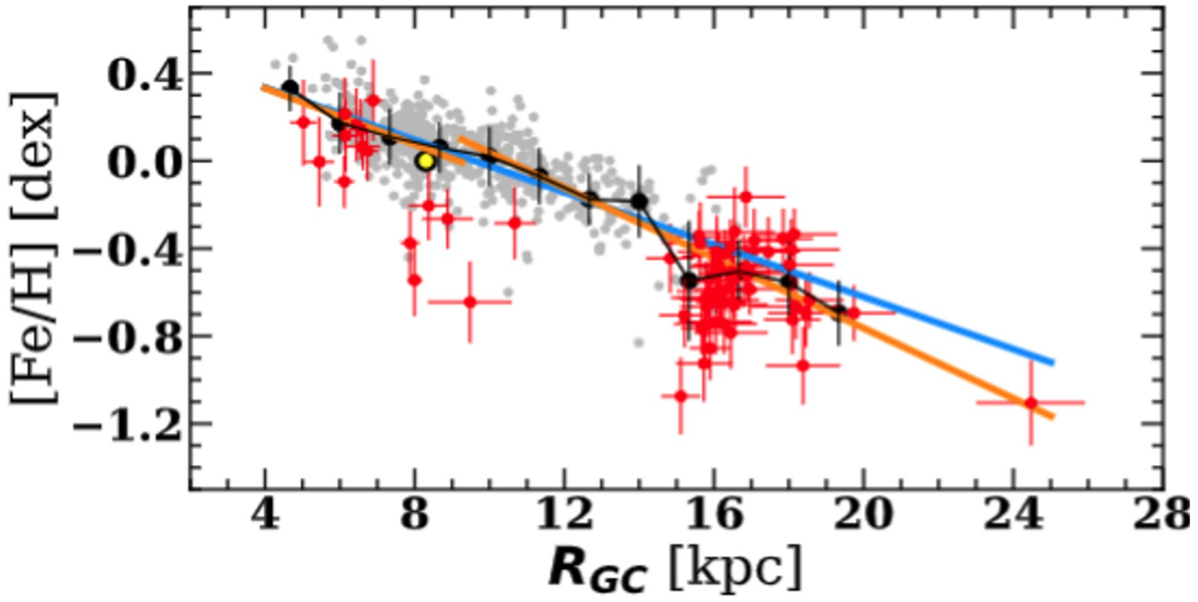
$$ABL = 10^{0.2W} = 10^{0.2(\alpha+\beta \log P+\gamma[Fe/H])} = \varpi 10^{0.2w-2},$$

$$W_{Gaia} = -5.988 \pm 0.018 - (3.176 \pm 0.044)(\text{LogP}-1.0) - (0.520 \pm 0.090)[Fe/H]$$

Metallicity is a fundamental quantity!

Distances: Metallicity is a fundamental quantity!

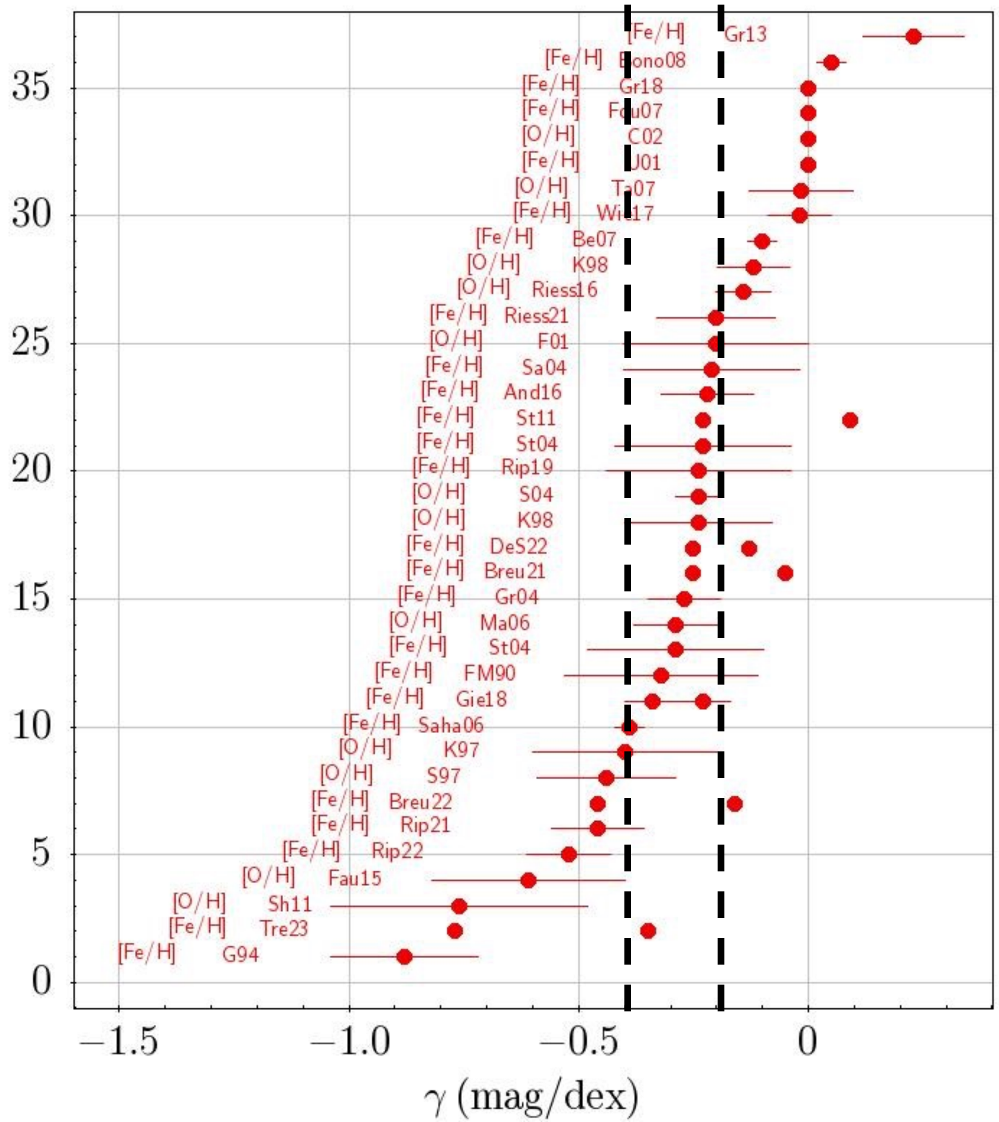
- Metallicity gradient of the Galactic Disc → [Fe/H] varies over 1 dex!



Metallicity gradient for a sample of about 640 DCEPs with HiRes spectroscopy, after Trentin+2023

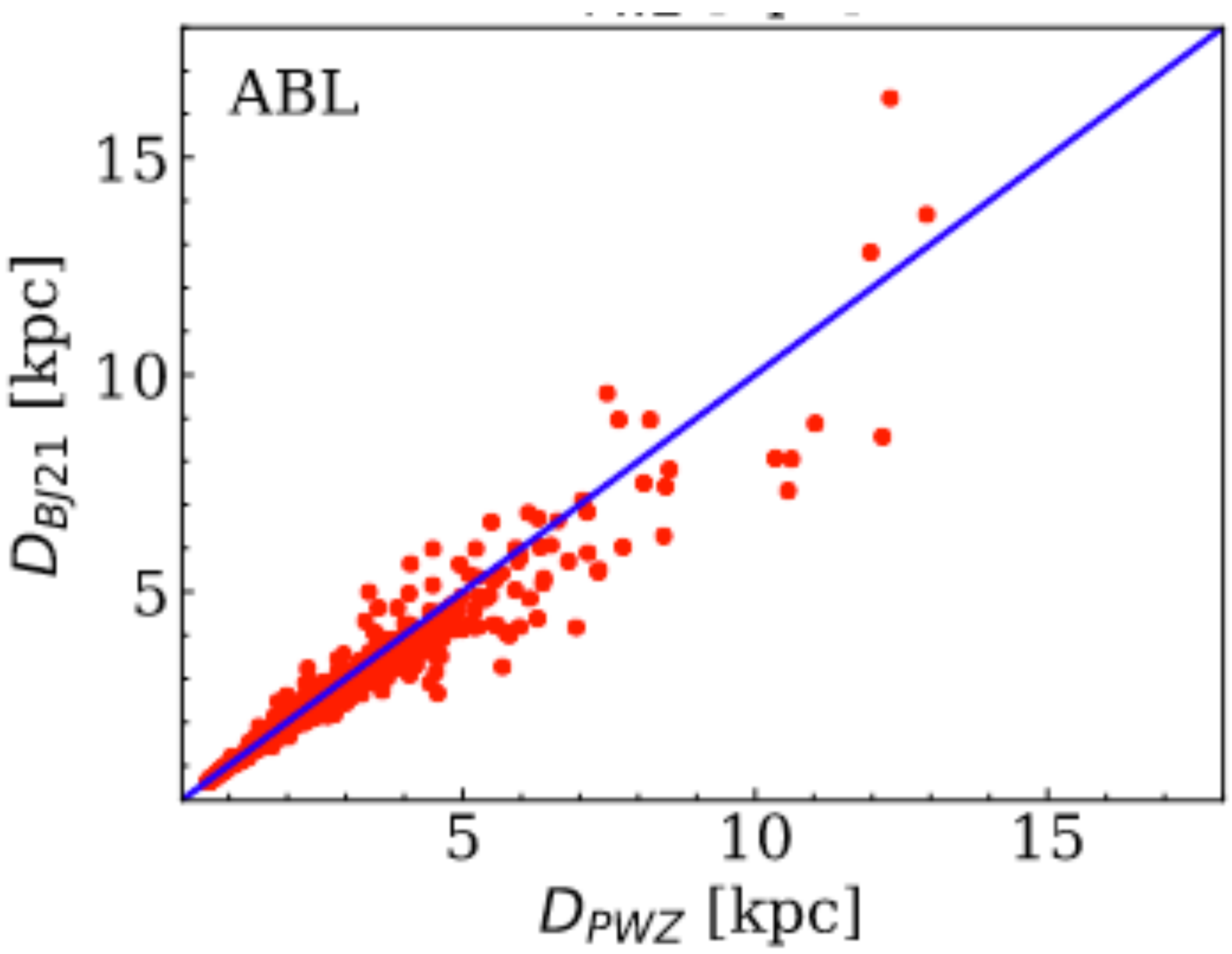
Distances: Metallicity is a fundamental quantity!

- Metallicity gradient of the Galactic Disc → [Fe/H] varies over 1 dex!
- All the recent studies → metallicity term ~ -0.2 : -0.4 mag/dex ALSO in Mid-IR (Breuval+2022)
- If neglected in PLs, the metallicity alone can introduce relative errors on distance up to 10%-20% (e.g. at R_{GC} ~ 15 kpc, where <[Fe/H> ~ -0.4 dex)
- To calculate the distances from the PWZ relation: i) Gaia metallicities from RVS spectra when available; ii) estimated from the metallicity gradient for the other



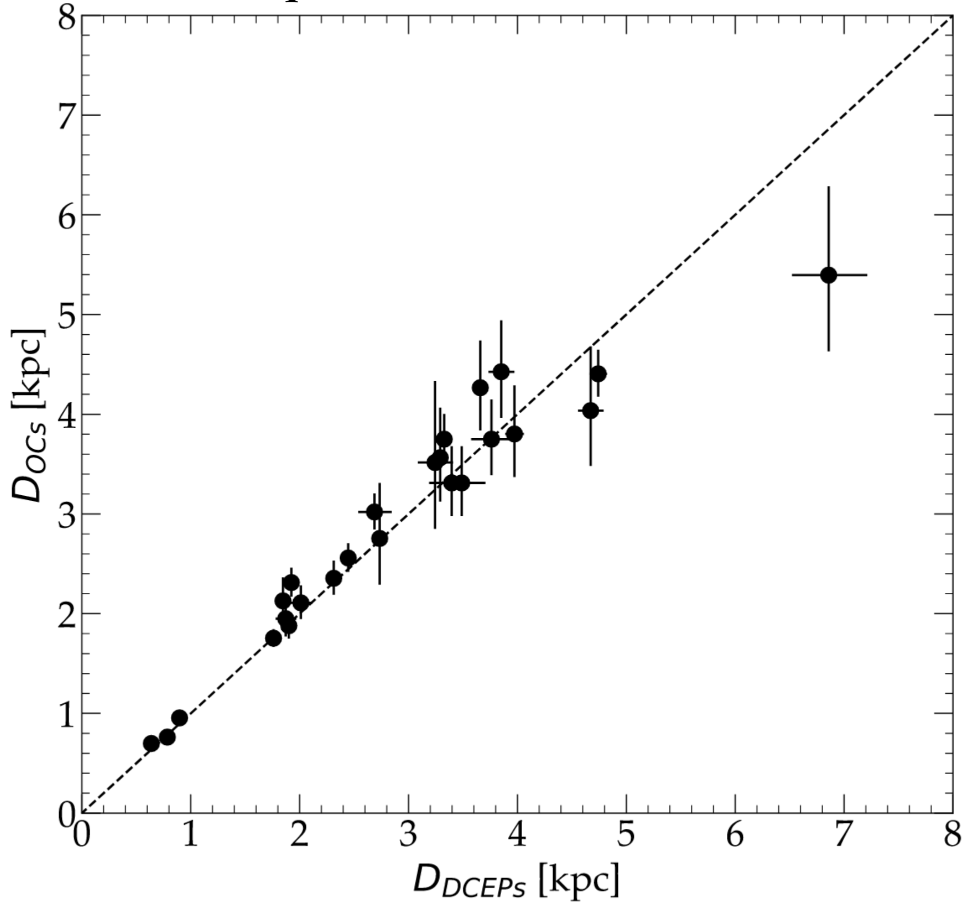
Distance validation

Comparison between distances from PWZ relation and Bayler-Jones+2022



Ripepi+2022

Comparison between distances from PWZ relation and OC (Cantat-Gaudin+2020) for 25 Cepheids in OC



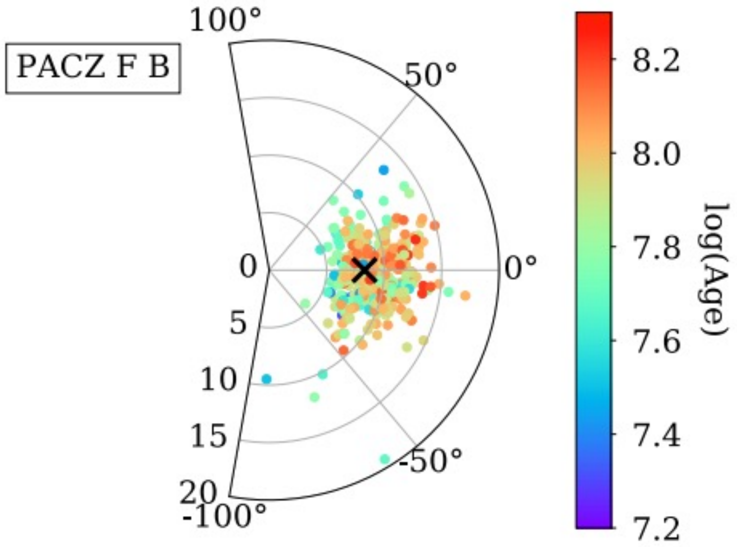
GC, Drimmel+2023

Period-Age-Metallicity and Period-Age-Color-Metallicity relations for Classical Cepheids (De Somma+2021, Marconi's talk)

Evolutionary times inside the predicted instability strip + period-luminosity-mass-temperature relations

→ Period-Age and Period-Age-Color relations, for each Z, Y

Period-Age-[Fe/H] and Period-Age-Color-[Fe/H] (PACZ) relations



Ages for 416 F-mode and 56 FO-mode pulsators with metallicities from literature, after De Somma+2021

→ $\log t = (8.423 \pm 0.006) - (0.642 \pm 0.004) \log P - (0.067 \pm 0.006)[Fe/H]$

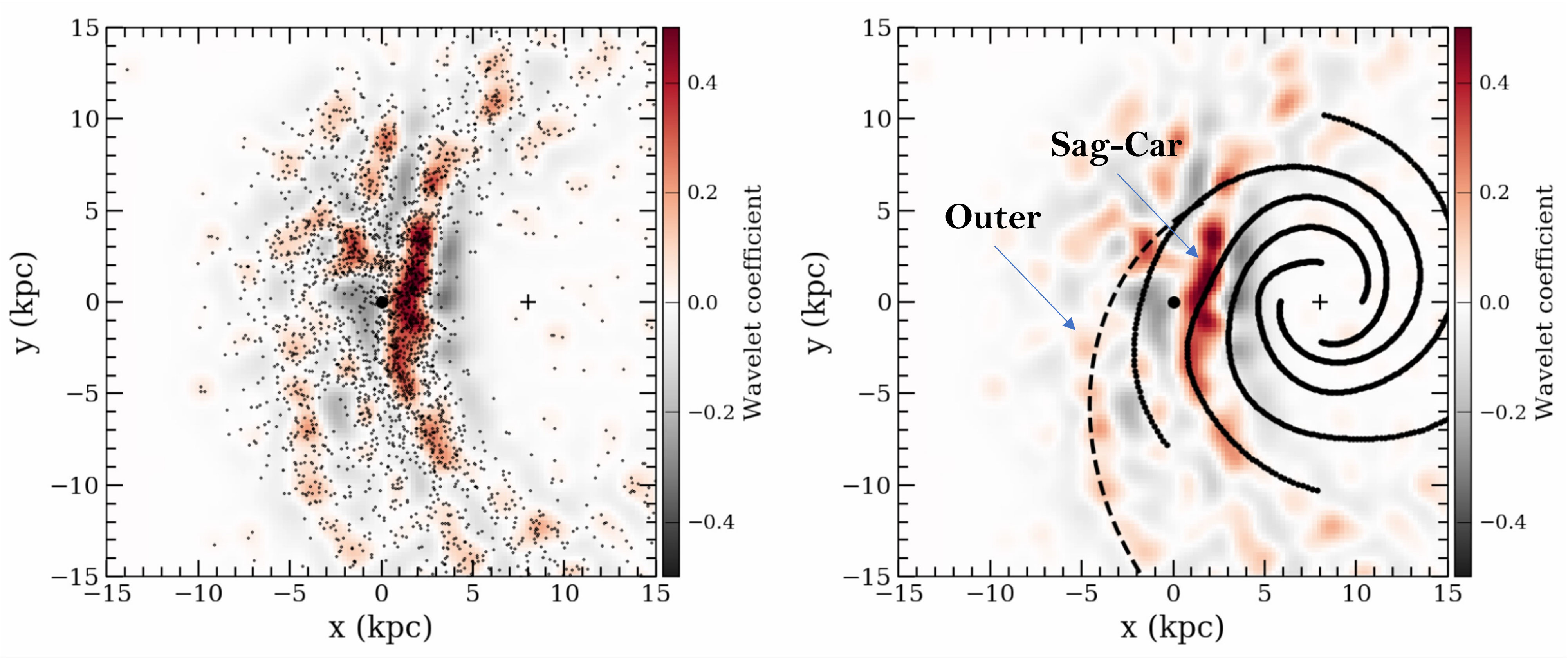
$\Delta\,[Fe/H] \sim 0.4$ dex ($R_{GC} \sim 15$ kpc) → $\Delta\,logt \sim 0.027$ → +6% at 150 Myrs → possible bias when cutting the sample on age (e.g at 150 Myrs as in recent papers).

Classical Cepheid sample in the MW in DR3 used in GC, Drimmel+2023

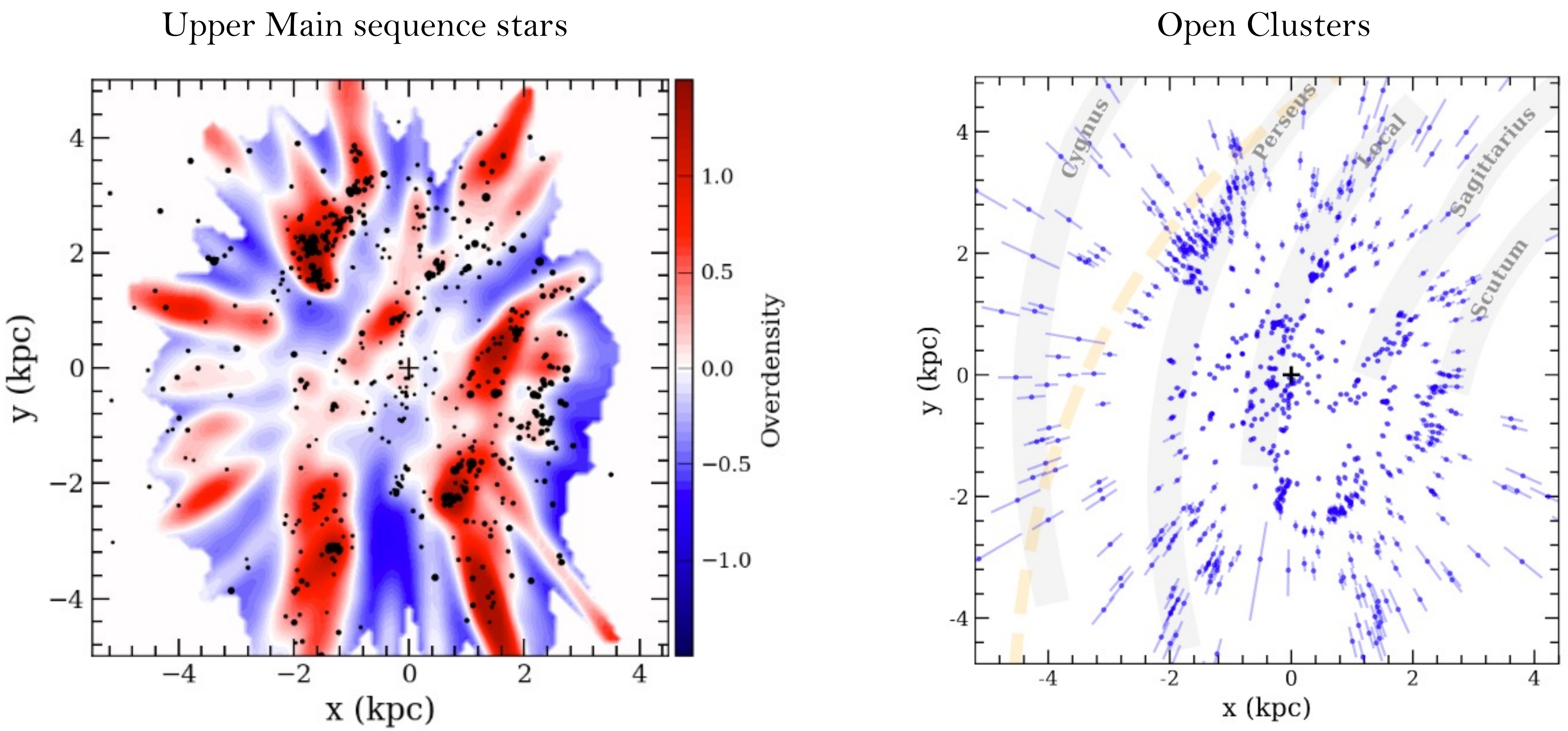
- 3306 in total, 2808 with ages<200 Myr to trace the spiral arms
- 1948 DCEPs with ages<200 Myr and RV measurements for the kinematics
- Distances from period-Wesenheit-metallicity relation (Ripepi+2022).
- The relative distance errors less than 6.25% for 90% of this sample → uncertainties in the velocities perpendicular to the line of sight, derived from the proper motions and distances < 10 km/s for 90% of our sample to a distance of 6 kpc.
- Median uncertainty in RV < 5 km/s at all distances.
- The resulting uncertainties in the galactocentric azimuthal velocity are less than 10 km/s for 90% of our sample to a distance of at least 9 kpc from the Sun.

Spiral Arms GC,Drimmel+2023

- Age < 200 Myr
- 4-arms models of Taylor & Cordes+1993 + Levine+2006 → Sag-Car arm partially well defined; Local arm barely visible; Outer arm from Levine+2006: perfect agreement

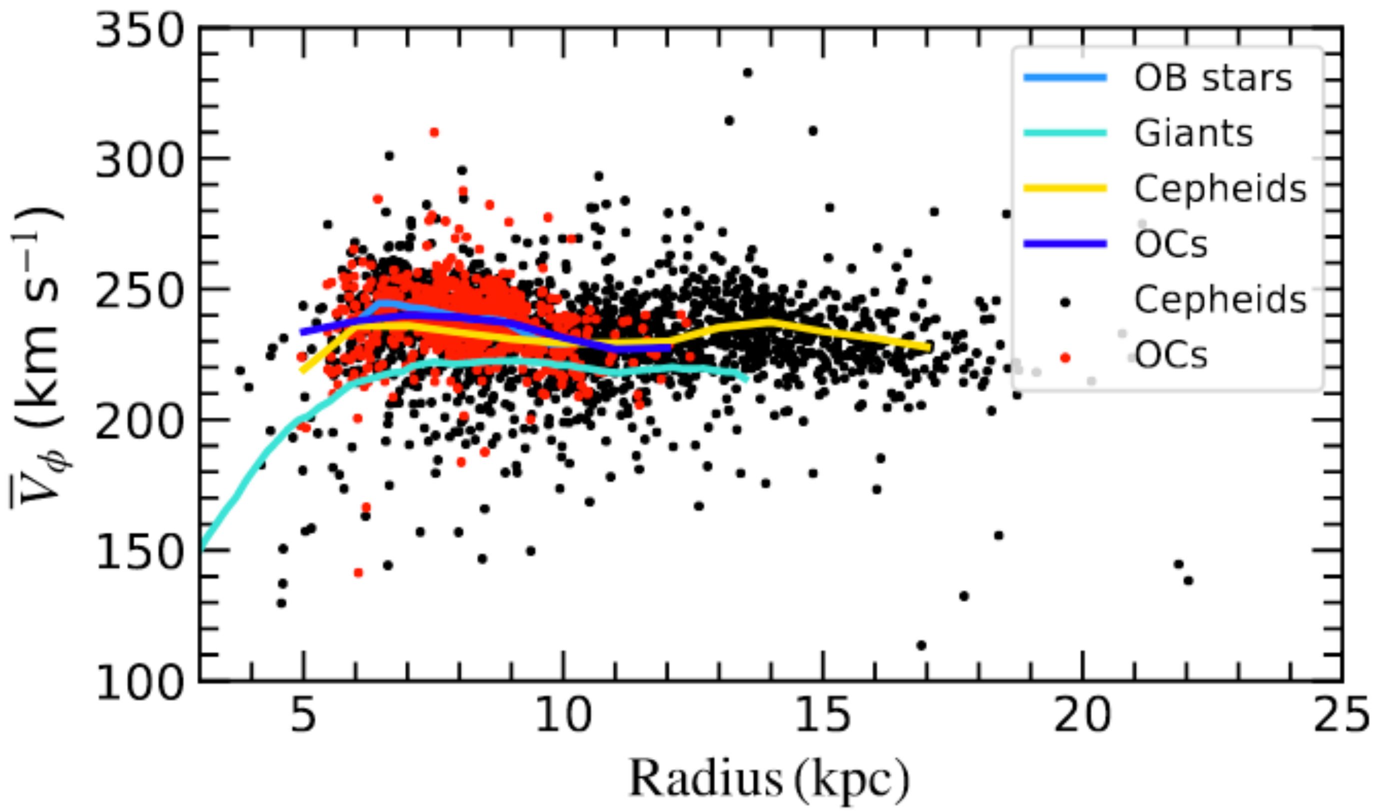


Spiral Arms GC,Drimmel+2023



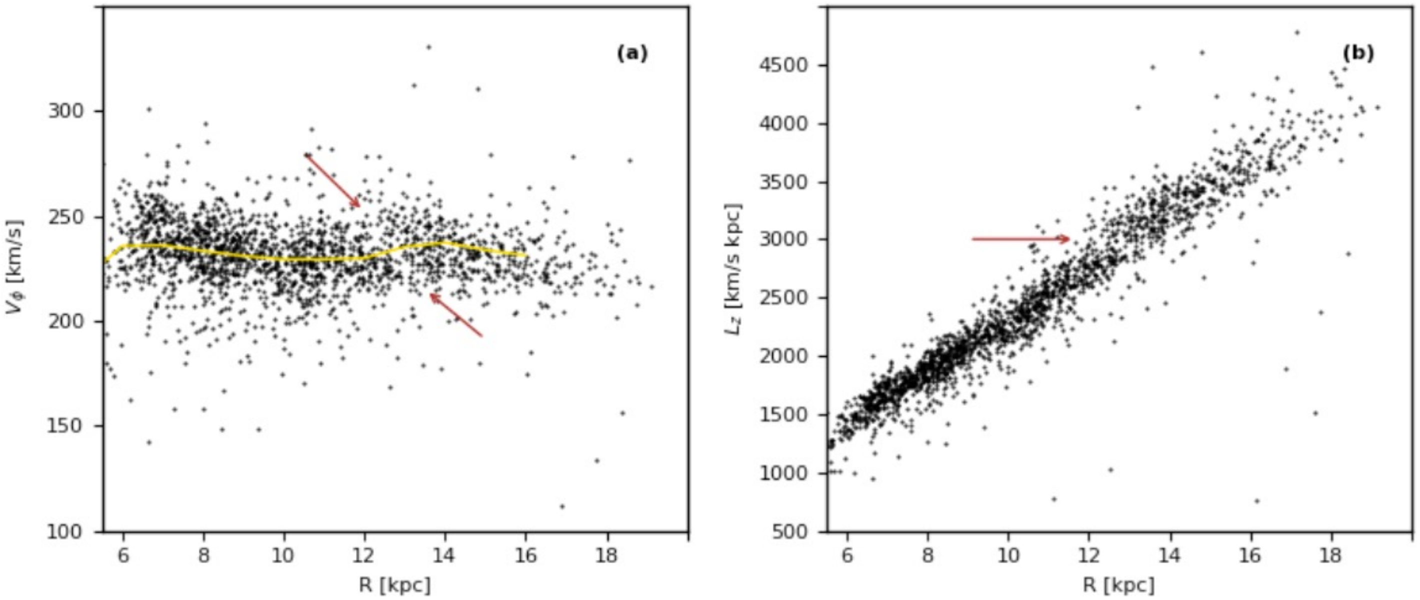
DCEPs allows us to trace the spiral arms a much larger distances than other tracers of the young stellar populations.

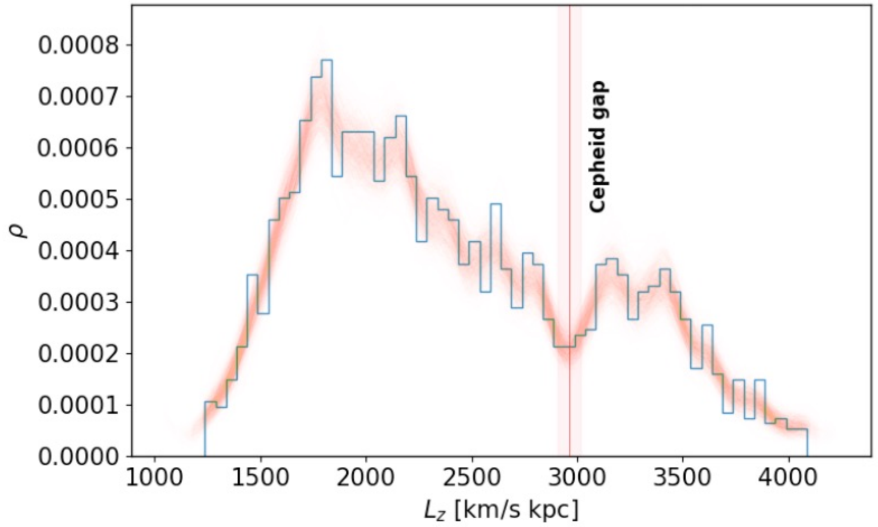
Rotation curve (GC, Drimmel+2023)



The Cepheids exhibit a mean azimuthal velocity similar, but slightly slower, to the OB and the open clusters,

Resonant feature in the Cepheids' rotation curve (Drimmel+2023)

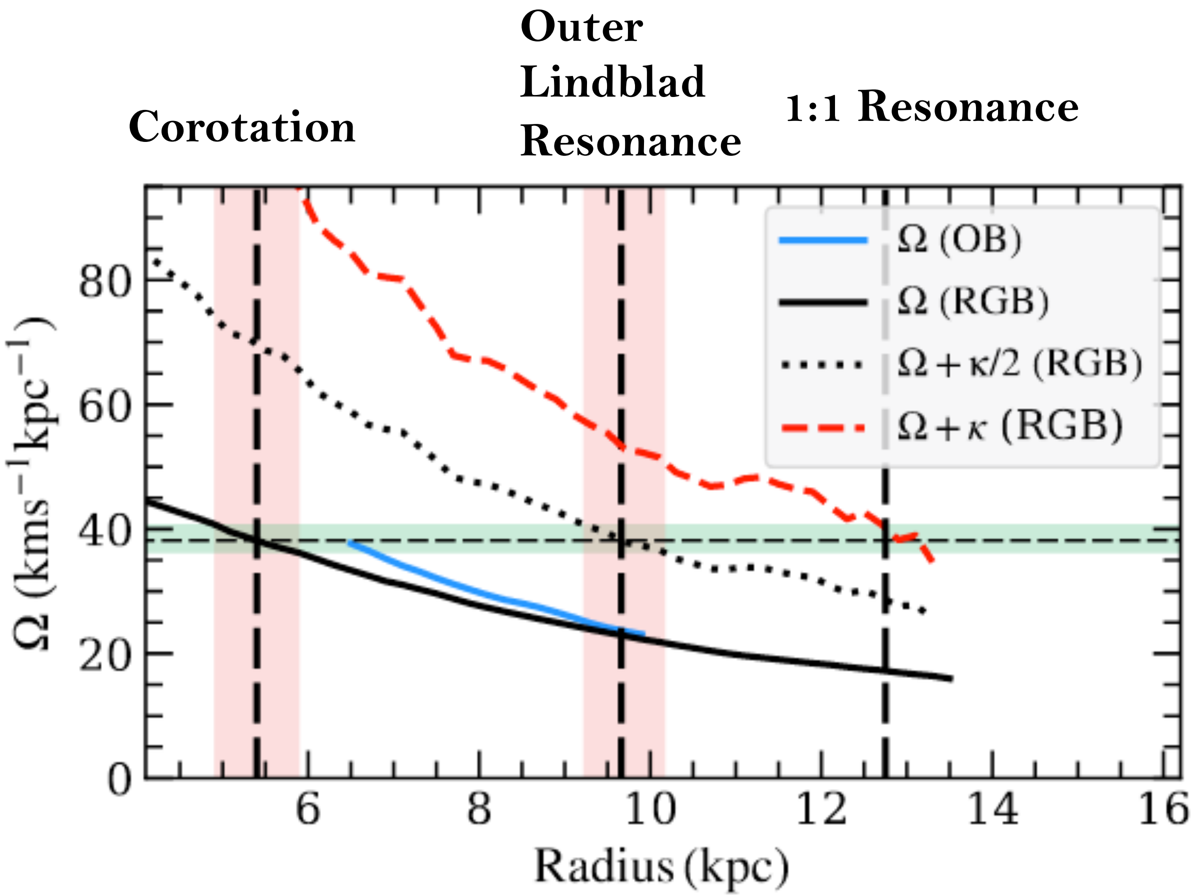




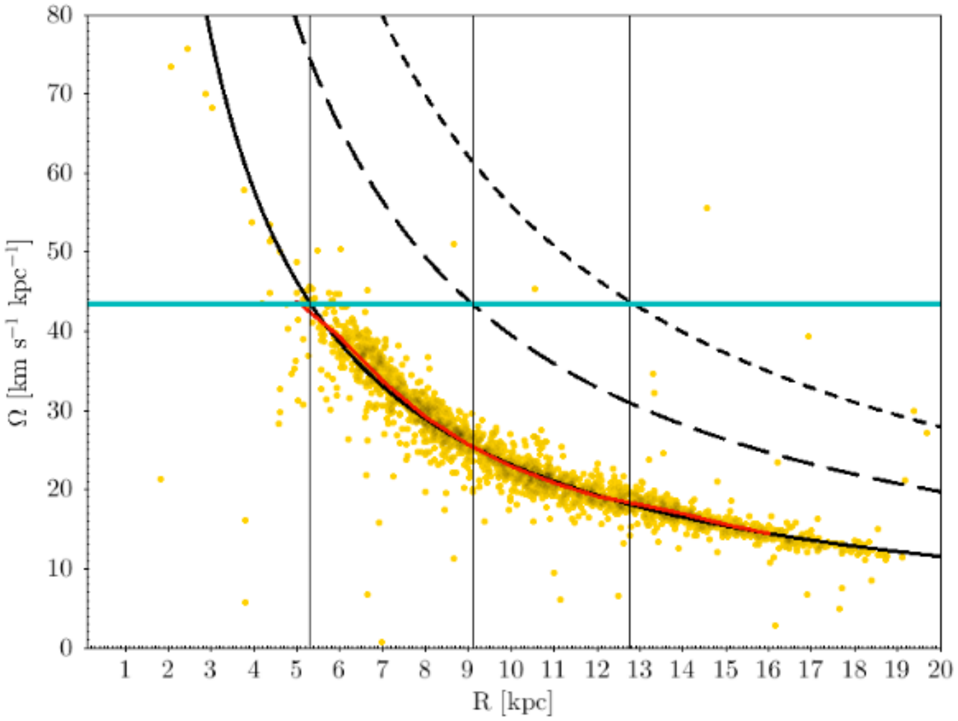
- Unexpected feature in the rotation curve of DCEPs: gap around R_{GC}~12.75 kpc
- Visible in Lz, which has a dip at Lz = 2950 ± 46 km s^{-1} kpc
- → resonance?

Resonant feature in the Cepheids' rotation curve (Drimmel+2023)

Expected 1:1 resonance location according to GC, Drimmel+2023 results for the pattern speed of the Bar derived with RGB stars



New Bar pattern velocity calculated from DCEPs in case of 1:1 resonance → agreement within errors with GC, Drimmel+2023

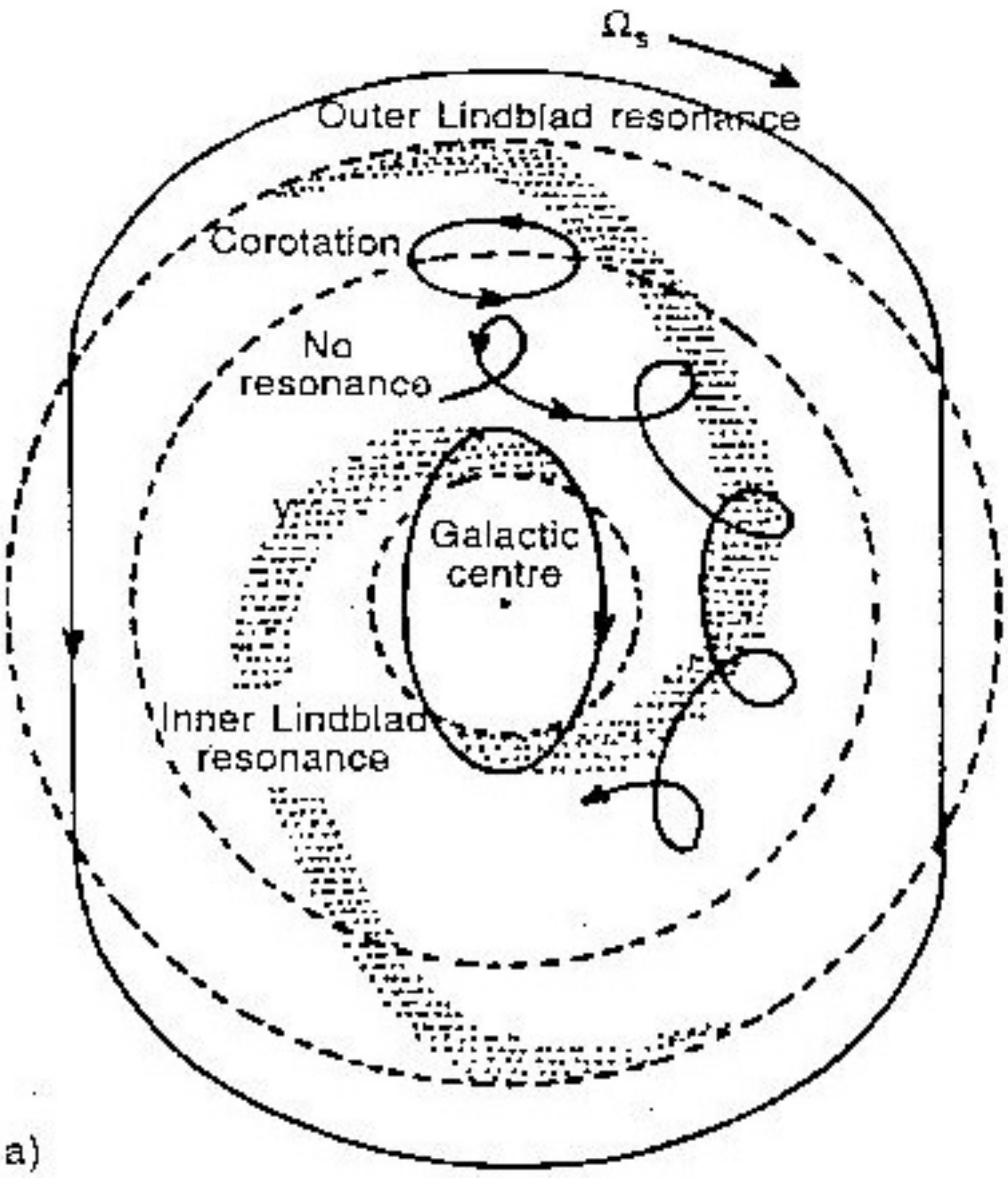


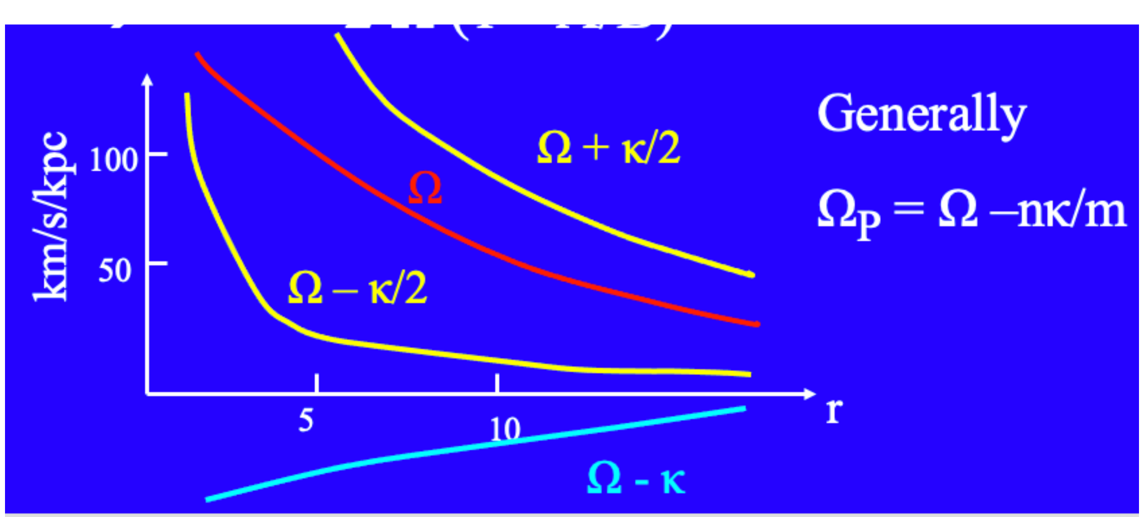
Problems with the Bar resonance interoperation (Drimmel+2023)

- The Bar quadrupole potential ~ R^{-3} → no significant influence beyond OLR
- Why we do not see a similar feature at the OLR of the bar?
- Resonance from spiral arms developing from the Bar? Possibly, but pattern speed of spiral arms uncertain.
- Hole provoked by the impact of Sgr dSph? Fully reasonable based on models, but the orbit of Sgr put the impact much farther than the observed hole in Cepheids Lz distribution.
- Open problem and opportunity to better understand the MW disc

Conclusions

- Cepheid variables are important tracers of the MW disc and spiral arms up to large distances and beyond the Bulge/Bar.
- Despite the small consistency of the Cepheid sample, the accuracy of the distance determinations allows us to reveal small features
- Great advancements can be expected from Gaia DR4, which will provide accurate and homogeneous astrometry, photometry, kinematics and spectroscopy for thousands of Cepheids.


Ωs
Outer Lindblad resonance
Corotation
No resonance
Galactic centre
Inner Lindblad resonance
a)


Generally
$\Omega_P = \Omega - n\kappa/m$
km/s/kpc
100
50
5
10
r
Ω + κ/2
Ω
Ω – κ/2
Ω - κ

Orbit resonance

An orbital resonance occurs in galaxies when an orbit's epicyclic frequency —the frequency of an orbit's radial motion—is a simple multiple of a forcing frequency. The forcing frequency can be the rate at which an object encounters successive crests of spiral waves or the influence of a rotating central bar. In these cases the spiral pattern or the rotating bar can be characterized by a pattern frequency Ω_b. If an orbit's angular frequency is Ω then a resonance (in the limit of a circular orbit) occurs when the rate at which an object encounters the forcing, $\Omega - \Omega_b$, is commensurate with the epicycle frequency κ:

$$m(\Omega - \Omega_b) = \kappa$$

$$\kappa^2(R) = \left(R \frac{d\Omega^2}{dR} + 4\Omega^2 \right)_{R_g} .$$

Taking $\Omega^2 = V_\phi^2/R^2 = L_Z^2/R^4$

The features seen in the rotation curve and overall pattern are then

(1) Pattern Speed Ω_P

(2) Physical Rotation $\Omega(R)$

(3) Co-rotation Radius R_c, $\Omega_P = \Omega(R_C)$

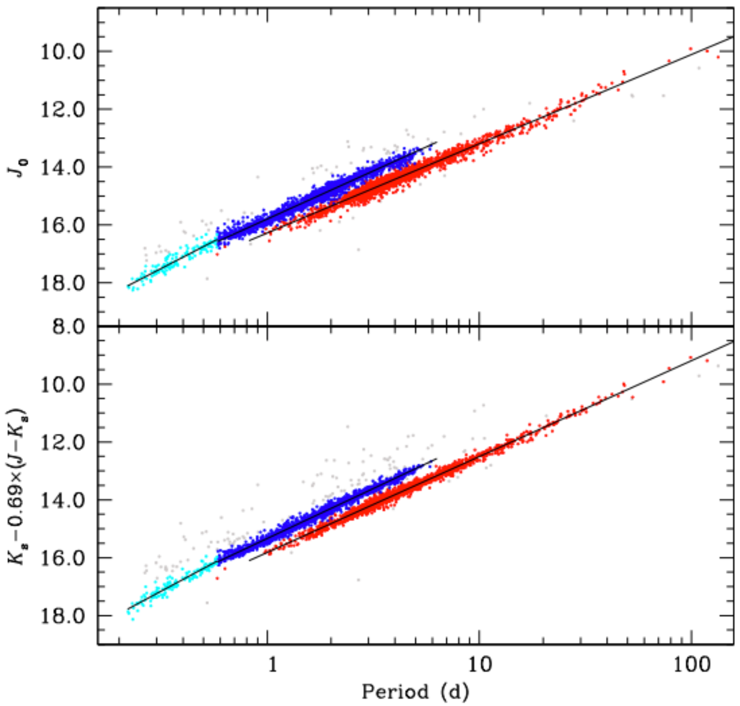
(4) Inner and Outer Lindblad Resonances

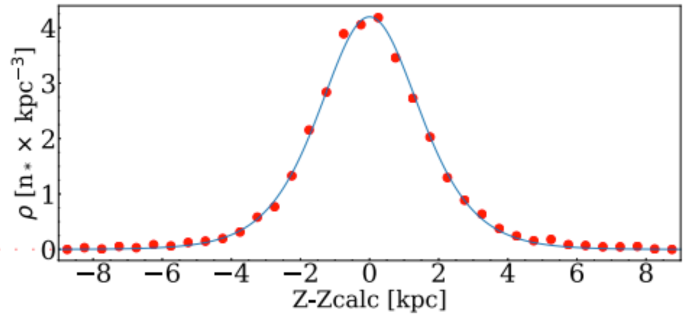
corresponding to closed orbits at the pattern speed ---

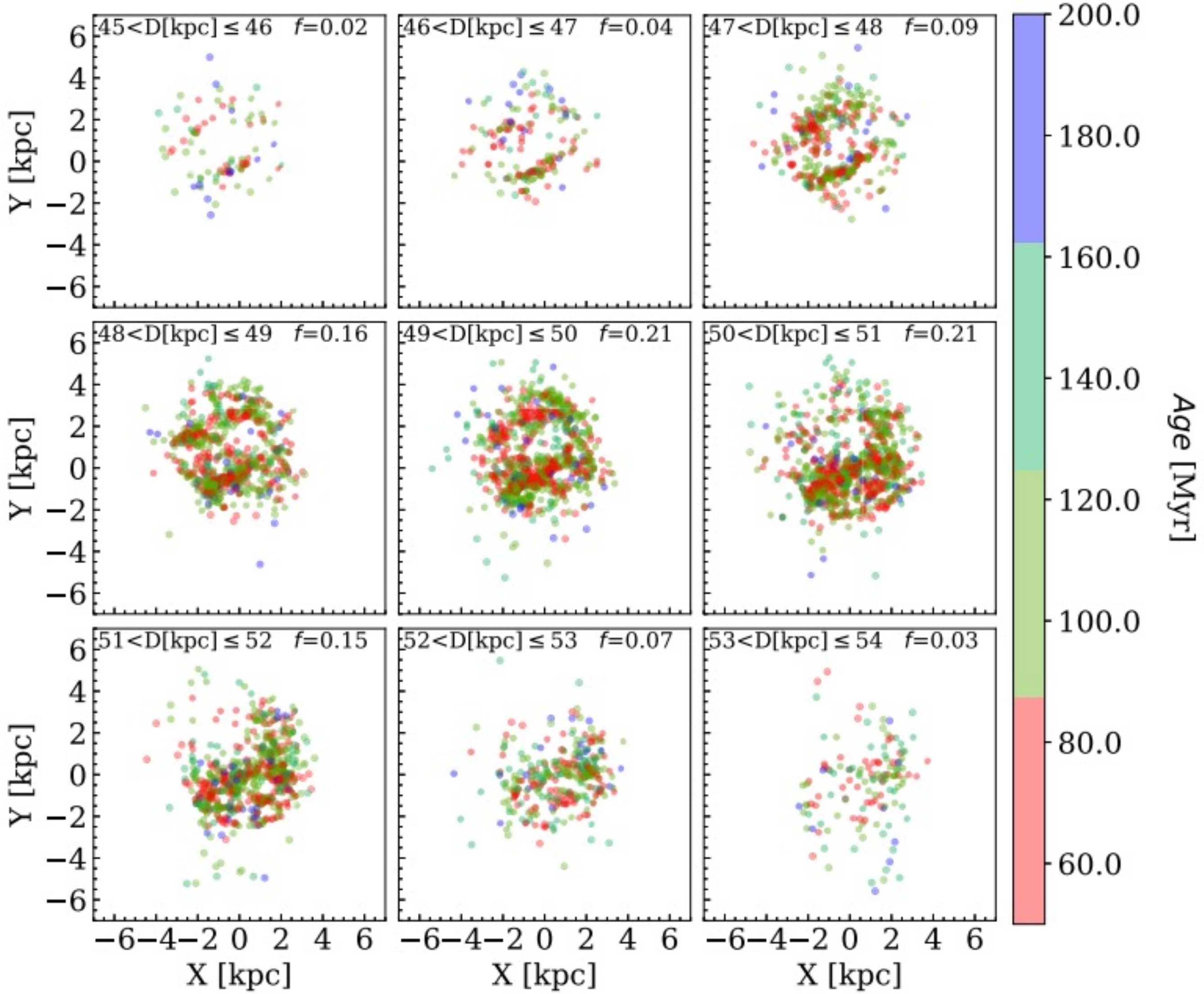
$$\Omega_P = \Omega(R) \pm \kappa/m$$

Cepheids as (relative) distance indicators → 3D structure

Using the PW relations in the NIR
→ 3D structure of the LMC







→ scale height of the LMC disc
Z0 = 1.94 ± 0.02 kpc

Ripepi et al. 2022 MNRAS