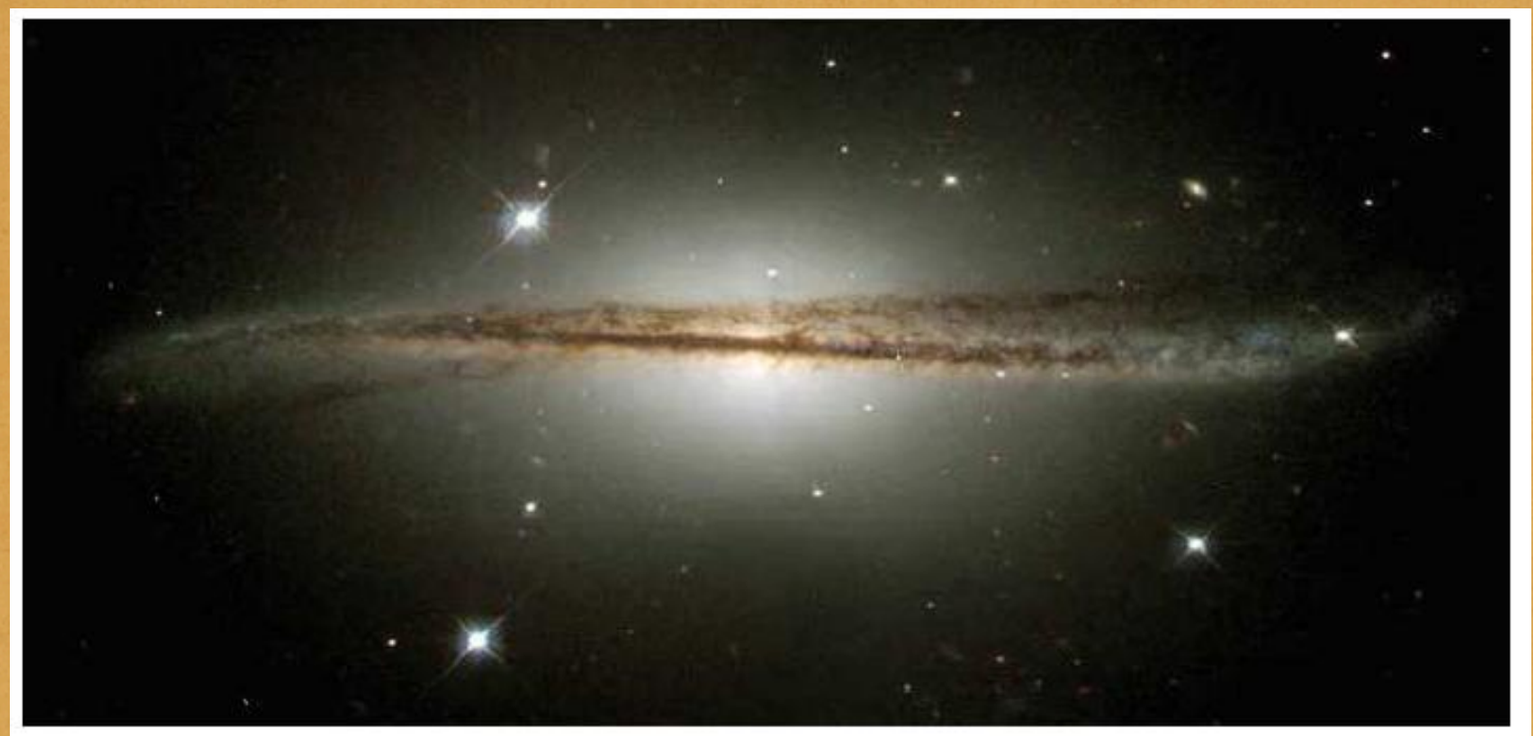
On the characterization of the Galactic warp in the Gaia era

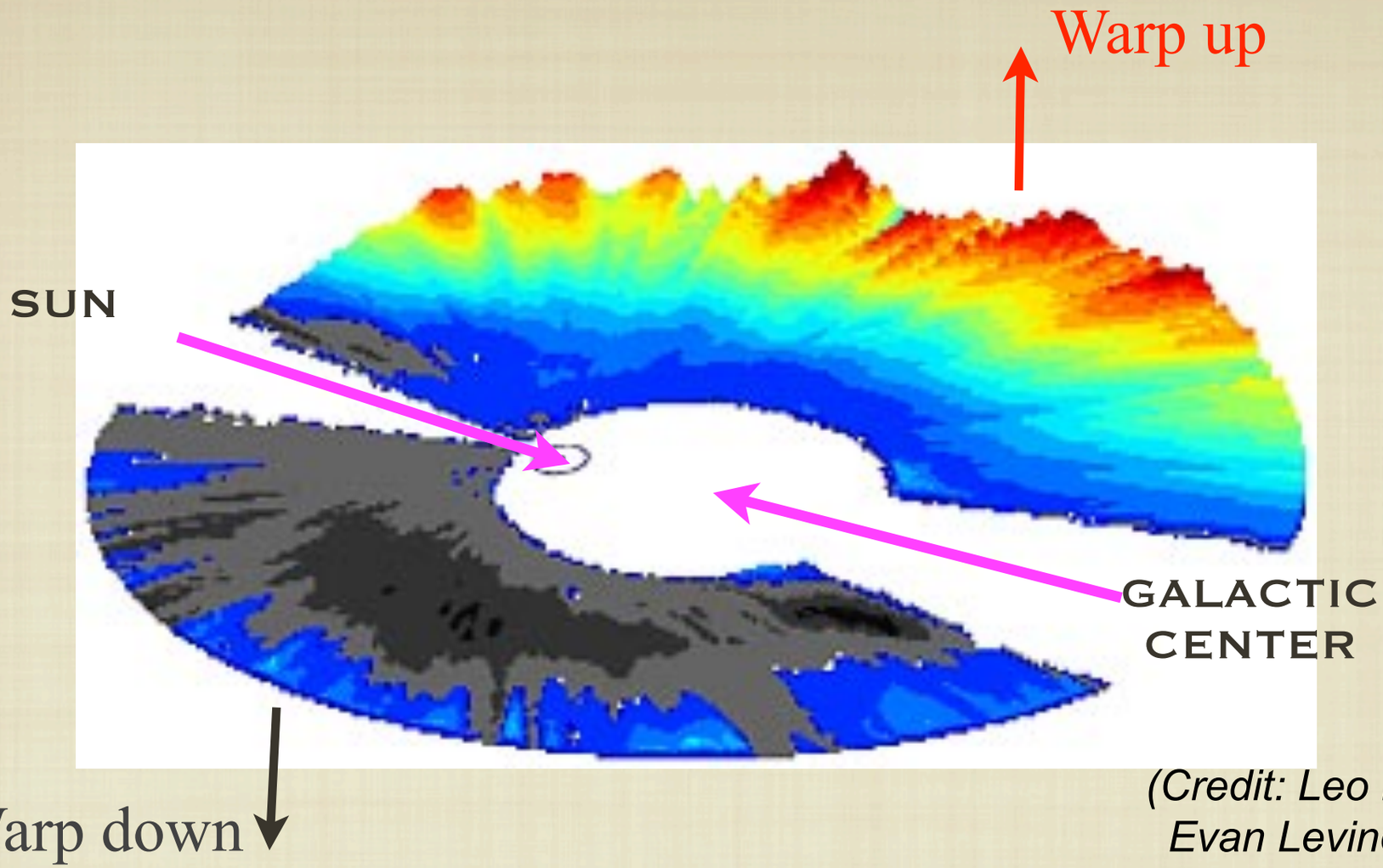


Hoda Abedi (icc-ub),
Francesca figueras (icc-ub),
Luis Aguilar (ia-unam),
Cecilia Mateu (ia- unam),
Merce Romero-Gomez (icc-ub),
Martin Lopez-Corredoira (IAC),
Francisco Garzon Lopez (IAC)

GREAT-ITN MARIECURIE ACTIONS

Universitat de Barcelona

The Galactic warp



(Credit: Leo Blitz/Carl Heiles/ Evan Levine-UC Berkeley)

- The disk of our Galaxy is known to have a warp in the ISM (Kerr, 1957; Hartmann & Burton, 1997) that is also seen in the stellar component (e.g. Lopez-Corredoira et al. 2002) .

- The line of nodes roughly coincides with the Galactic Center-Sun line.

TEST TOOL:
A Gaia mock catalogue of WARPED STELLAR POPULATIONS

Recipe for making a warped population in statistical equilibrium

Recipe for making a warped population in statistical equilibrium

- Choose the stellar population → We consider OB, A and RC stars. Take into consideration their velocity dispersion and local surface density

Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
- 3D Galactic potential

Recipe for making a warped population in statistical equilibrium

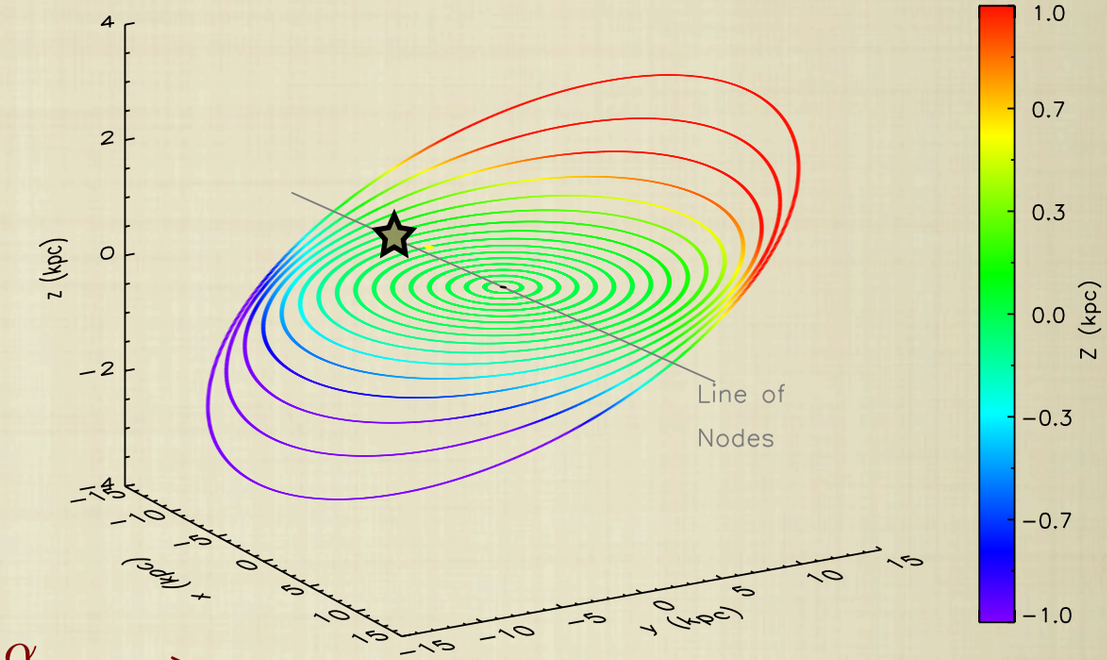
- Choose the stellar population
- 3D Galactic potential → Allen & Santillan (1991) potential consisting of a Miyamoto-Nagai disk, a spherical bulge and a massive spherical halo.

Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
- 3D Galactic potential
- A geometric warp model: tilted rings

Recipe for making a warped population in statistical equilibrium

- Choose the stellar population
- 3D Galactic potential
- A geometric warp model: tilted rings

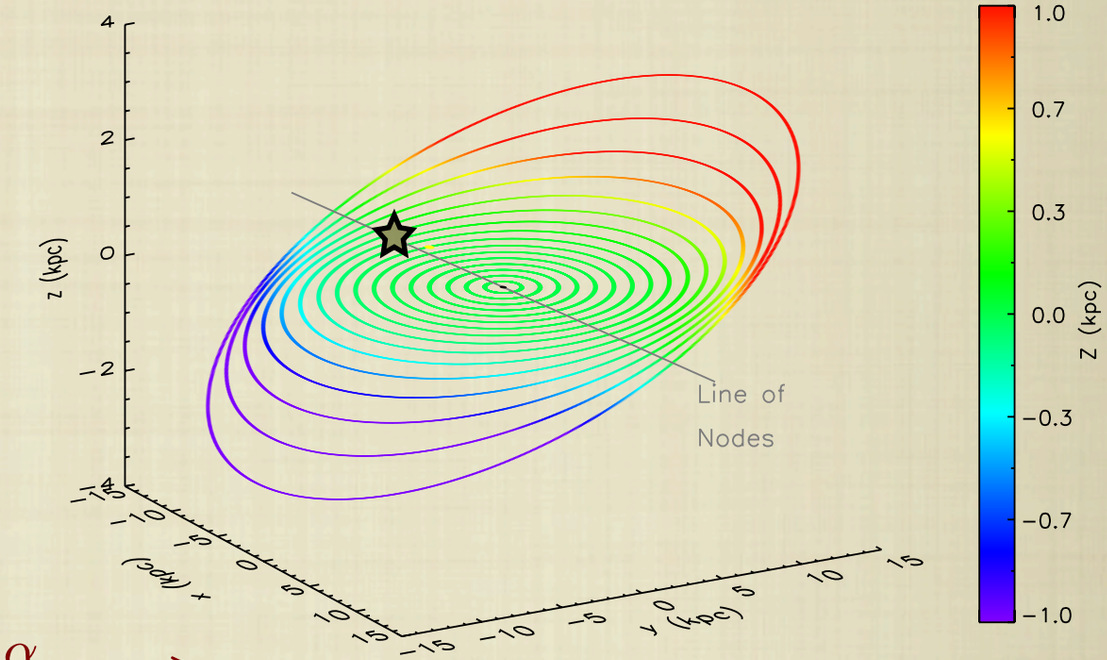


$$\Psi(r; r_1; r_2; \psi_{max}, \alpha) = \psi_2((r - r_1)/(r_2 - r_1))^{\alpha}, \;\; r > r_1$$

The tilt is applied beyond r_1. The resulting warp is such that the tilt angle increases as a power law whose exponent is α and such that at r_2 it has a value equal to Ψ_2.

Recipe for making a warped population in statistical equilibrium

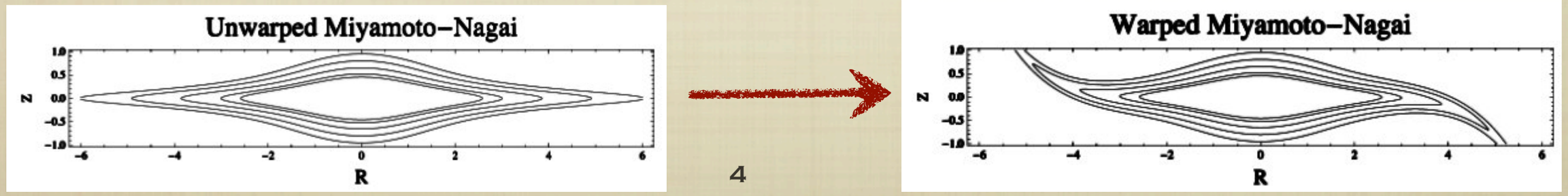
- Choose the stellar population
- 3D Galactic potential
- A geometric warp model: tilted rings



$$\Psi(r; r_1; r_2; \psi_{max}, \alpha) = \psi_2((r - r_1)/(r_2 - r_1))^{\alpha}, \;\; r > r_1$$

The tilt is applied beyond r_1. The resulting warp is such that the tilt angle increases as a power law whose exponent is α and such that at r_2 it has a value equal to Ψ_2.

This warp model is applied to the ***disc potential***

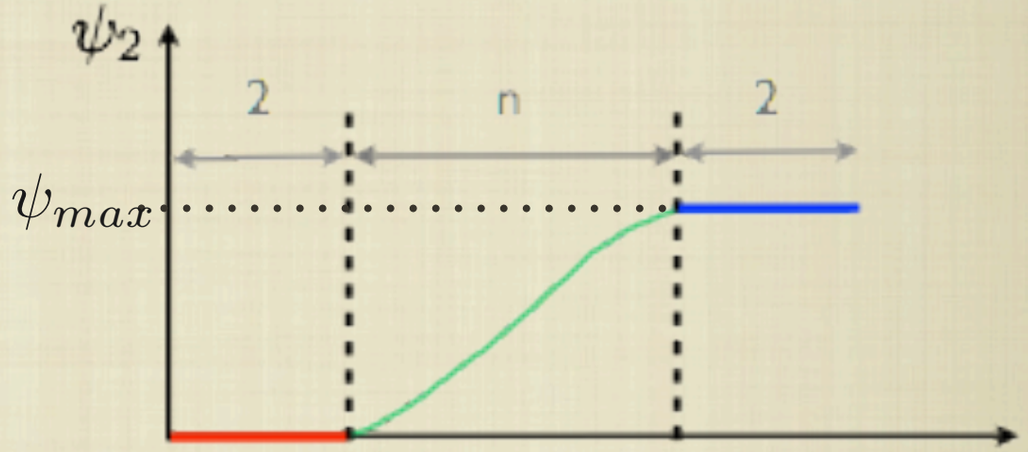


Recipe for making a warped population in statistical equilibrium

- Warp the Galactic disk potential adiabatically

Recipe for making a warped population in statistical equilibrium

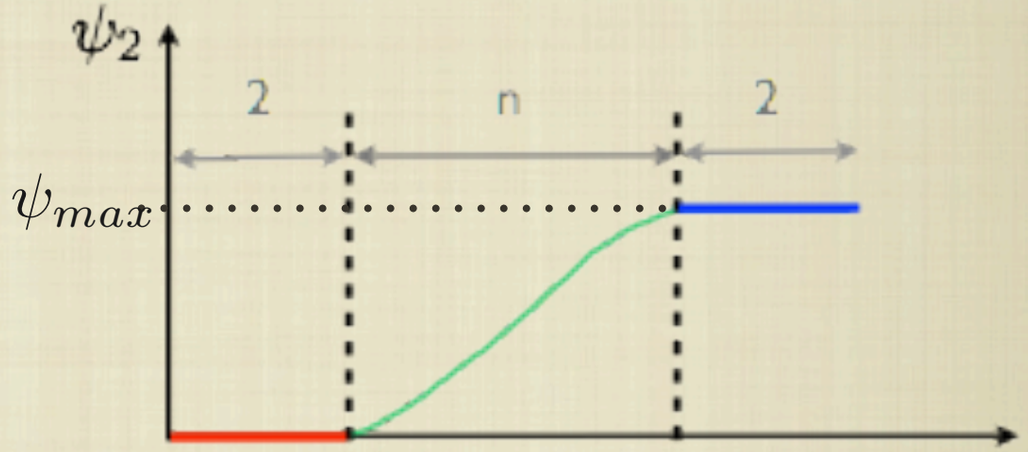
- Warp the Galactic disk potential adiabatically $\longrightarrow$ $\psi_2 = \psi_2(t)$



Recipe for making a warped population in statistical equilibrium

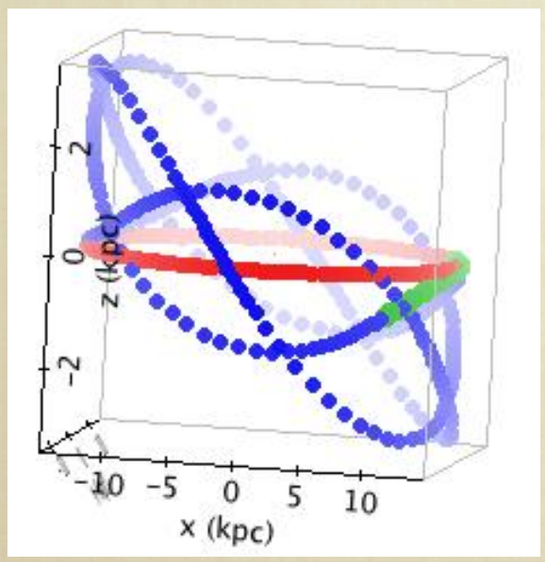
- Warp the Galactic disk potential adiabatically

$$\psi_2 = \psi_2(t)$$

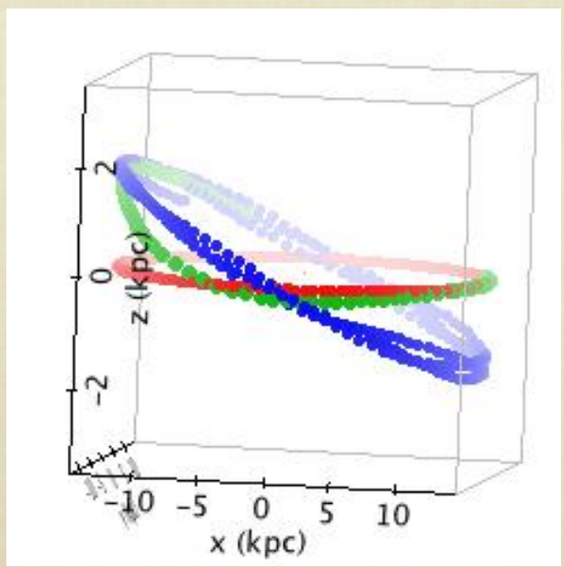


T/P

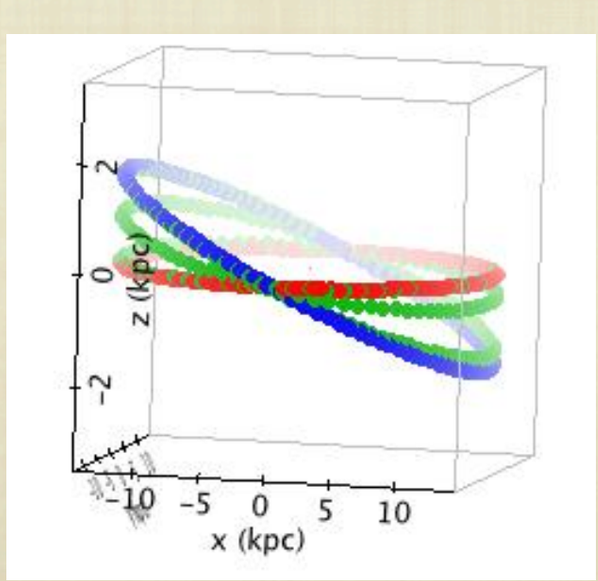
n =1/8



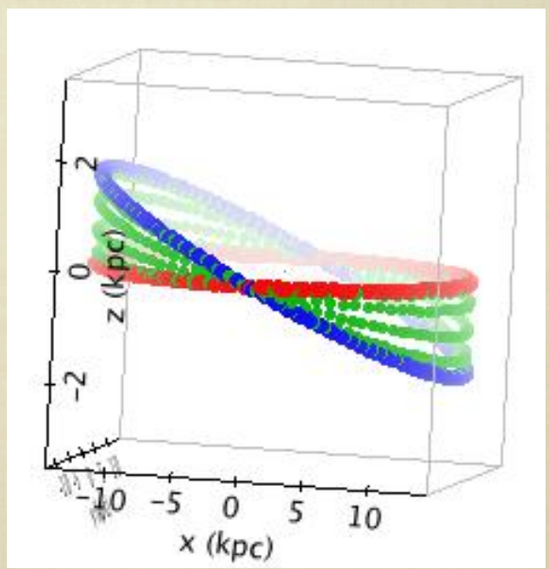
n =1/2



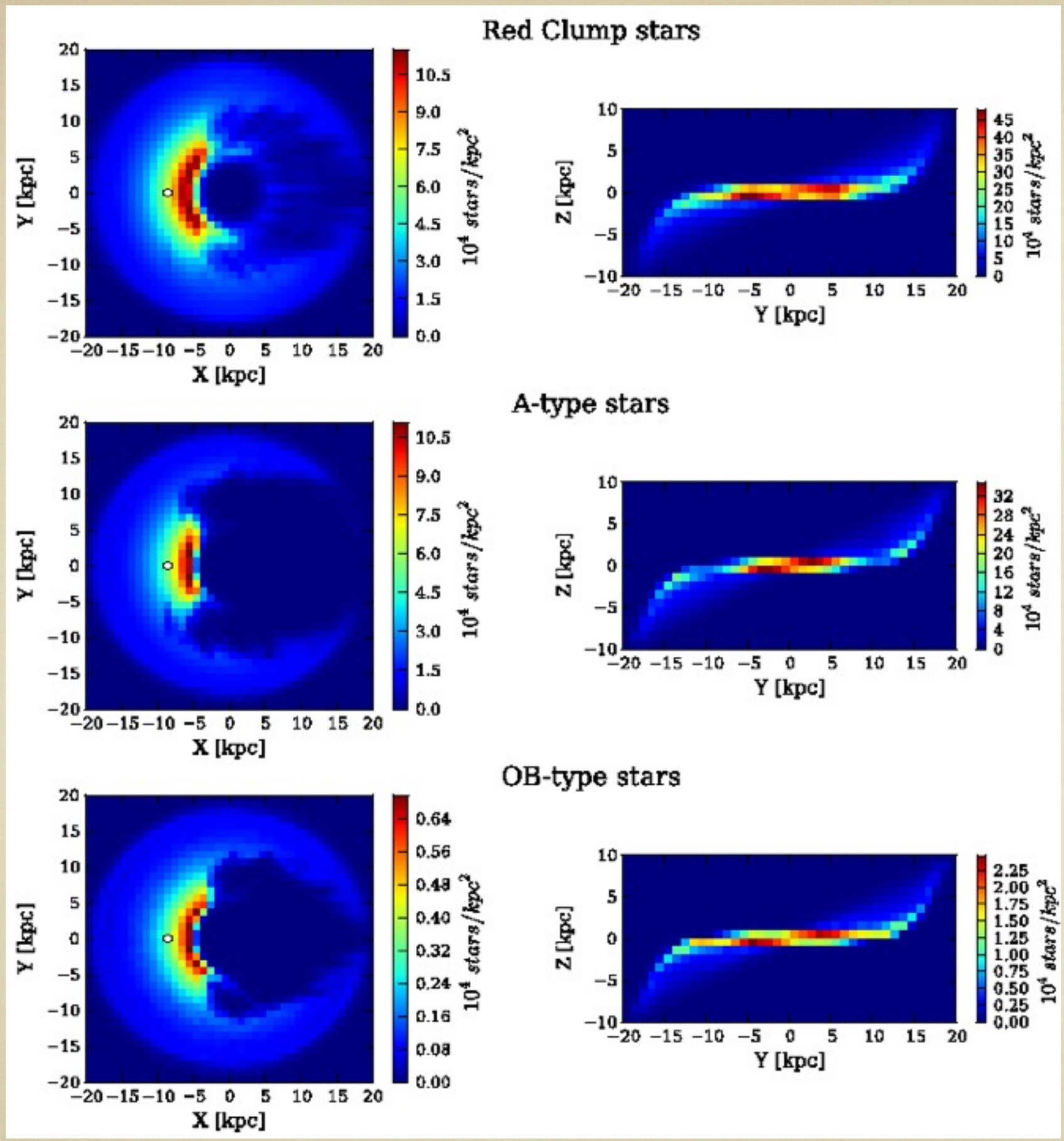
n =2



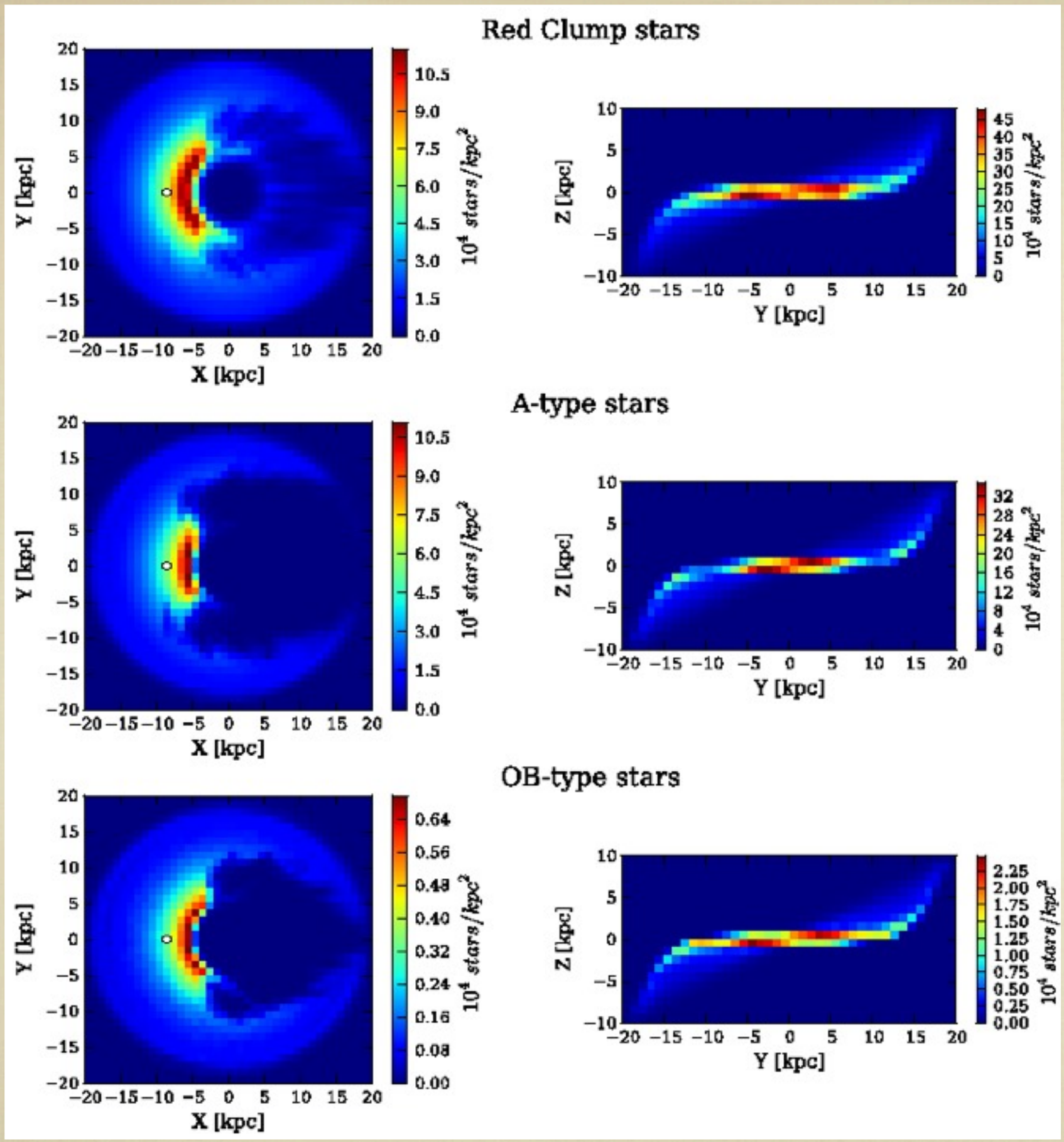
n =4



Impulsive ⟵ ⟶ Adiabatic



After considering Drimmel extinction map and Gaia selection function

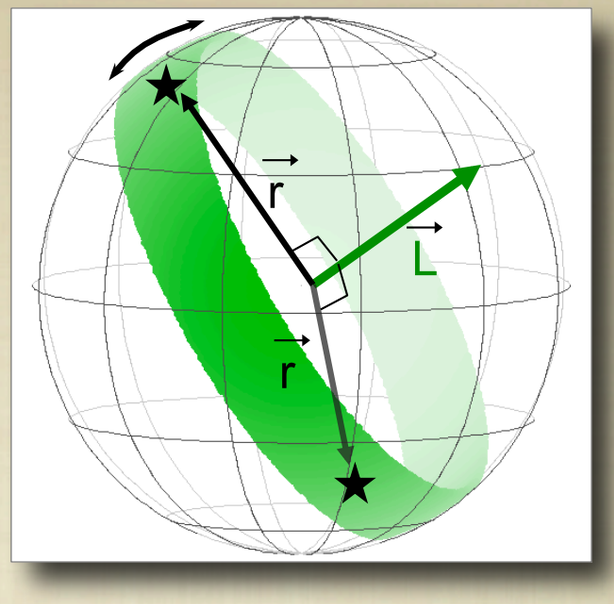


After considering Drimmel extinction map and Gaia selection function

What is the best way to detect and characterise the warp within the Gaia observational constrains?

Great Circle Cell Counts Methods

The GC3 methods



GC3: Great Circle Cell Counts Method
Johnston, Hernquist & Bolte, 1996, ApJ, 465, 278

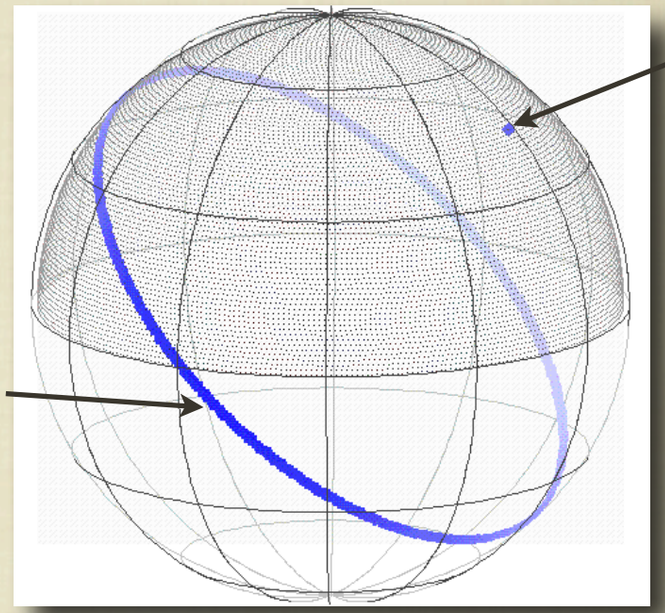
It relies on the fact that the orbits of stars in a stream in a spherical potential are confined to a plane that contains the galactic center.

$$|\hat{L} \cdot \hat{\mathbf{r}}_\star| \leq \delta_r$$

Pole vector: $\hat{L}$

Star position vector: $\hat{\mathbf{r}}_\star$

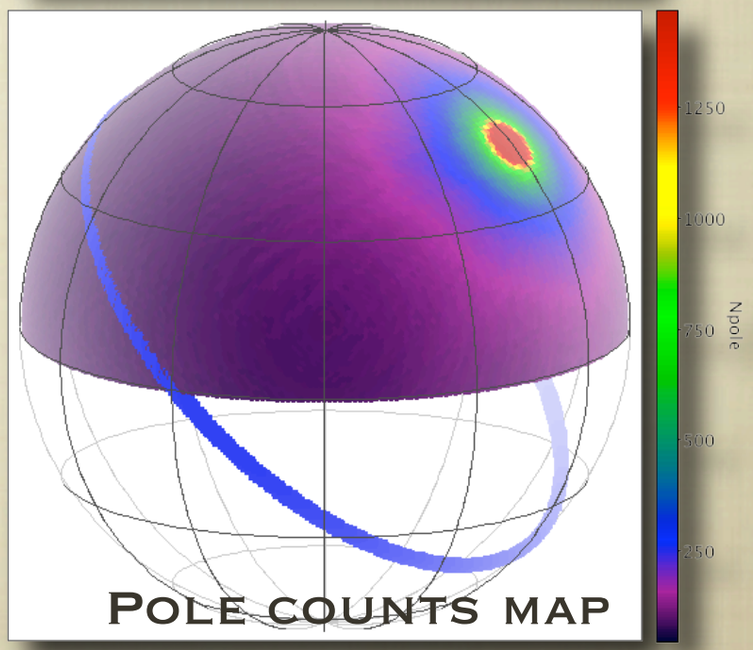
both unit vectors.



MGC3: Modified Great Circle Cell Counts
Mateu, et al., 2011, MNRAS, 415, 214.

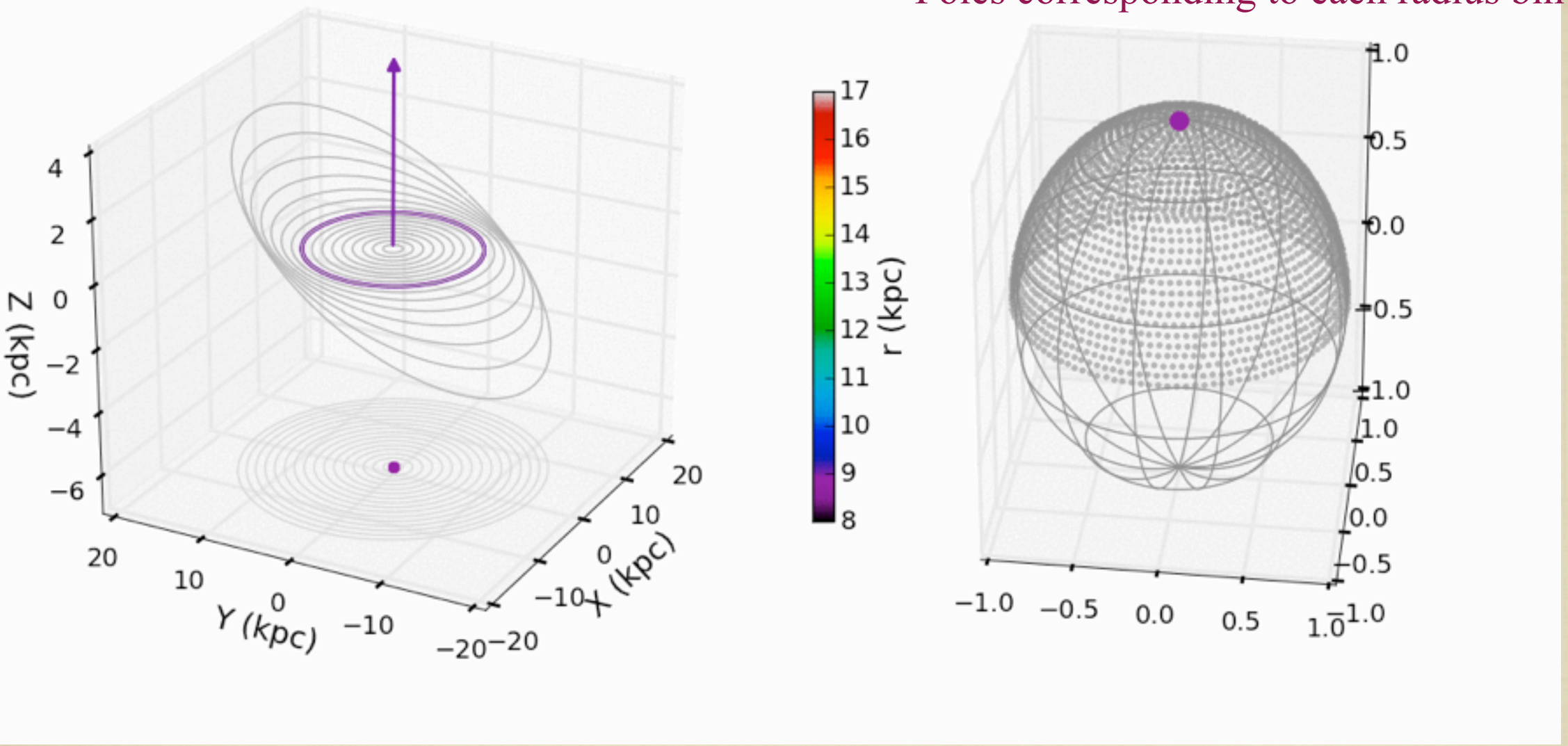
They add the extra requirement that the velocity vector lies within the great circle band.

$$|\hat{\mathbf{L}} \cdot \hat{\mathbf{v}}_\star| \leq \delta_v$$



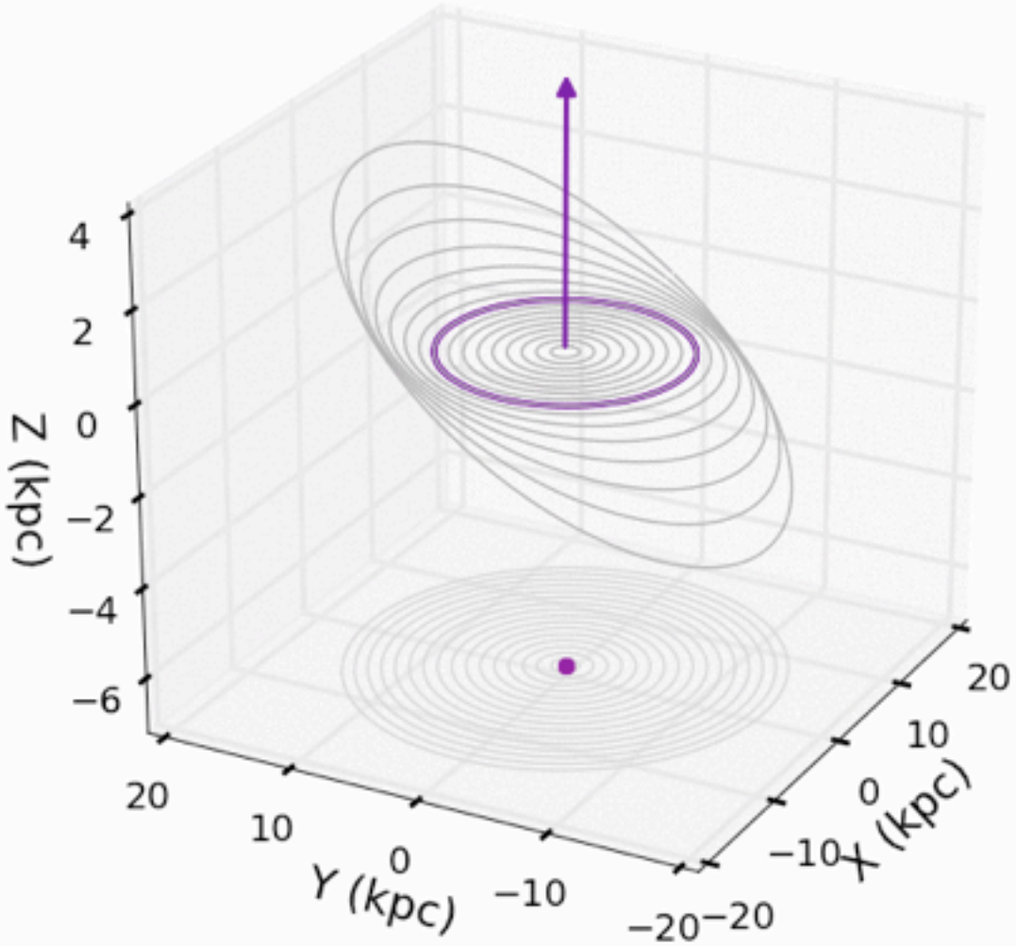
How this method is useful for detecting the warp?

Poles corresponding to each radius bin



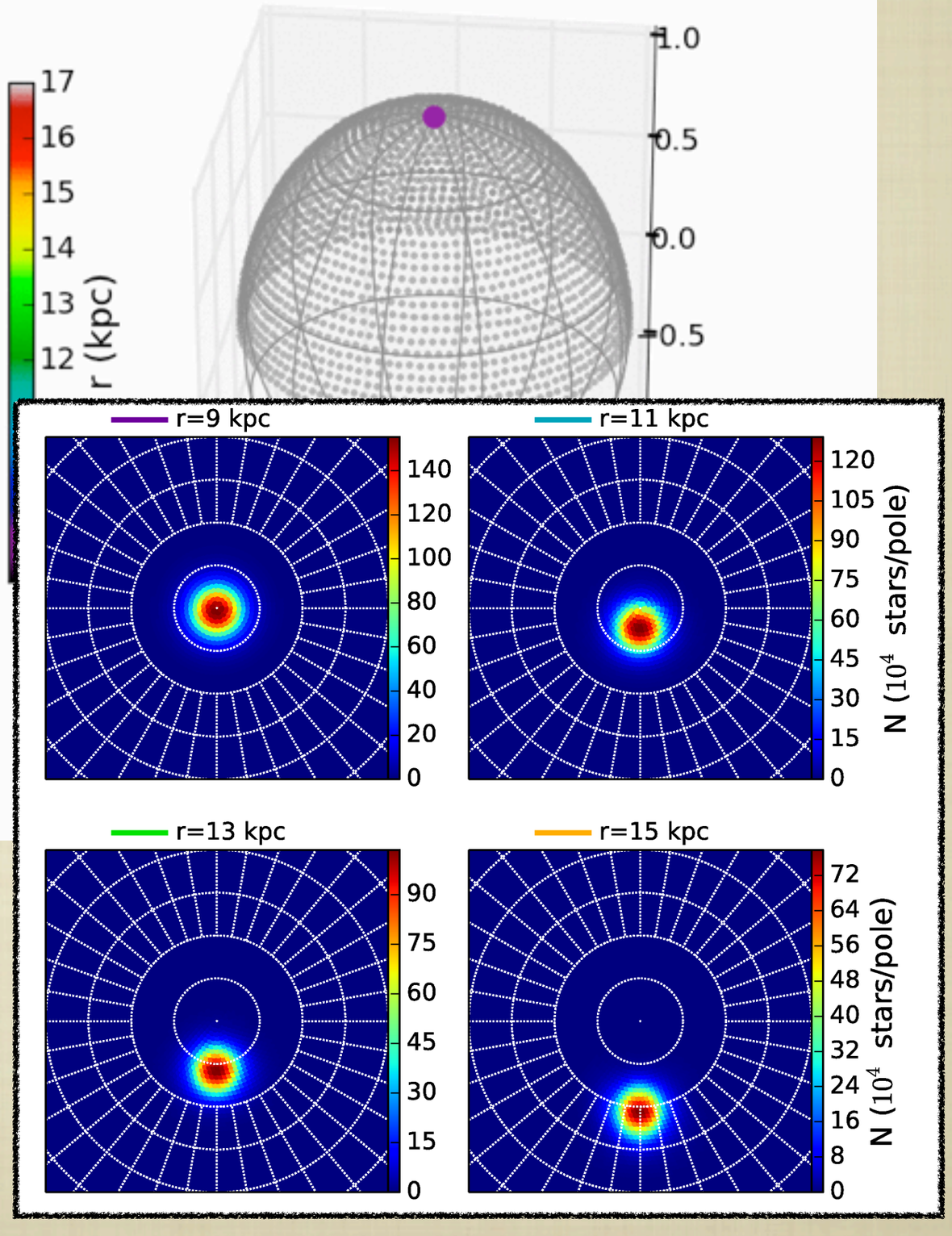
Courtesy of C. Mateu

How this method is useful for detecting the warp?

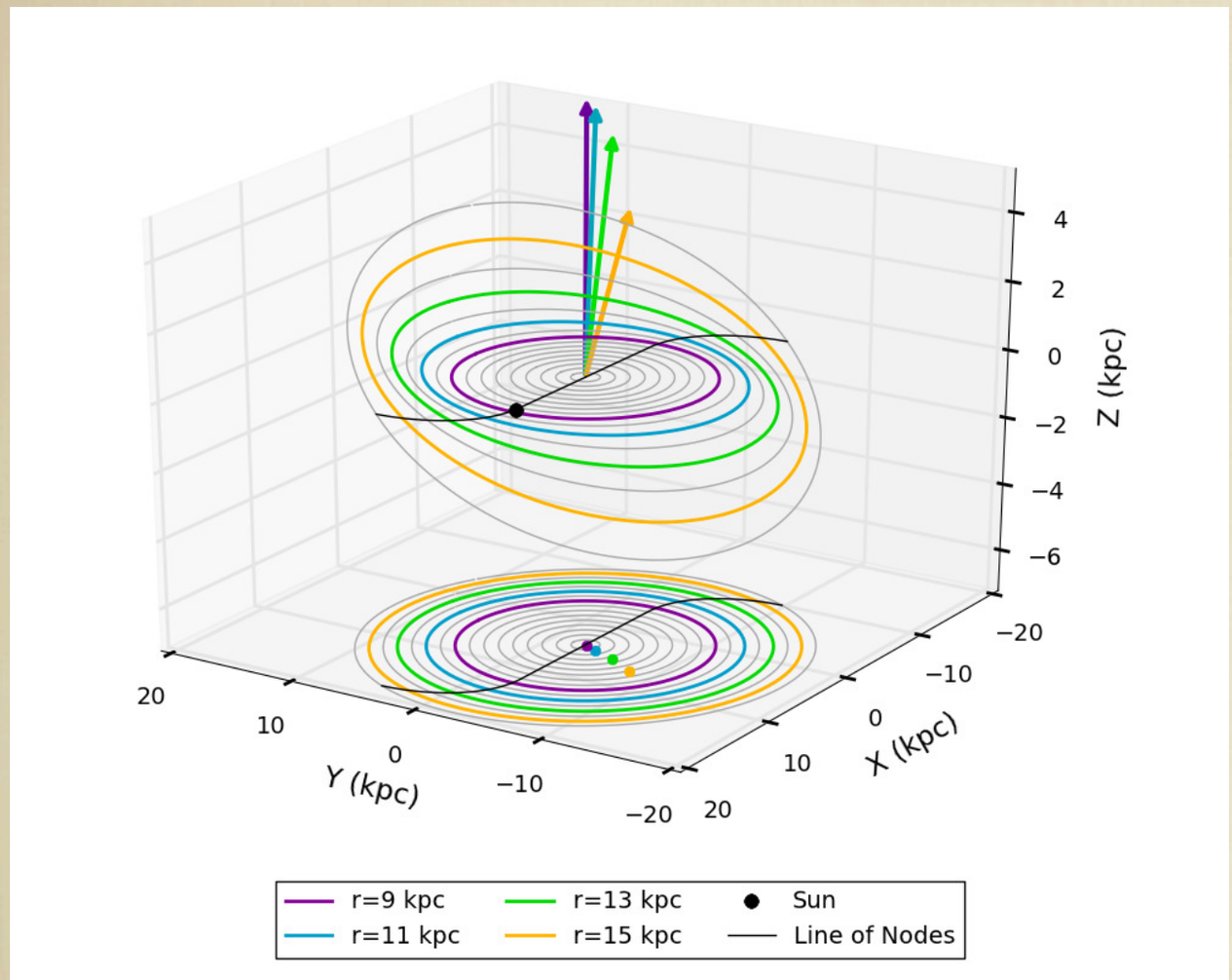


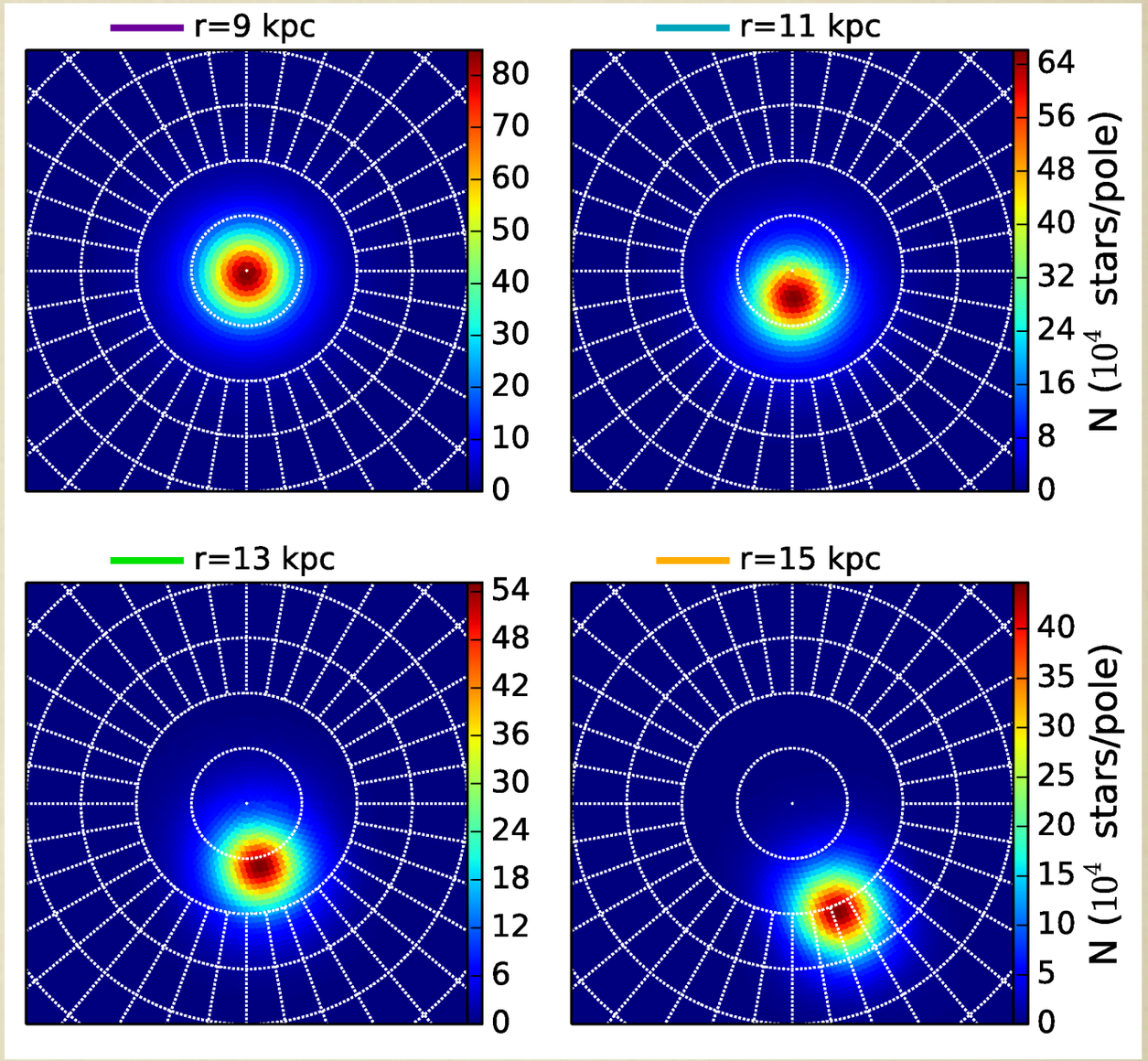
Courtesy of C. Mateu

Poles corresponding to each radius bin

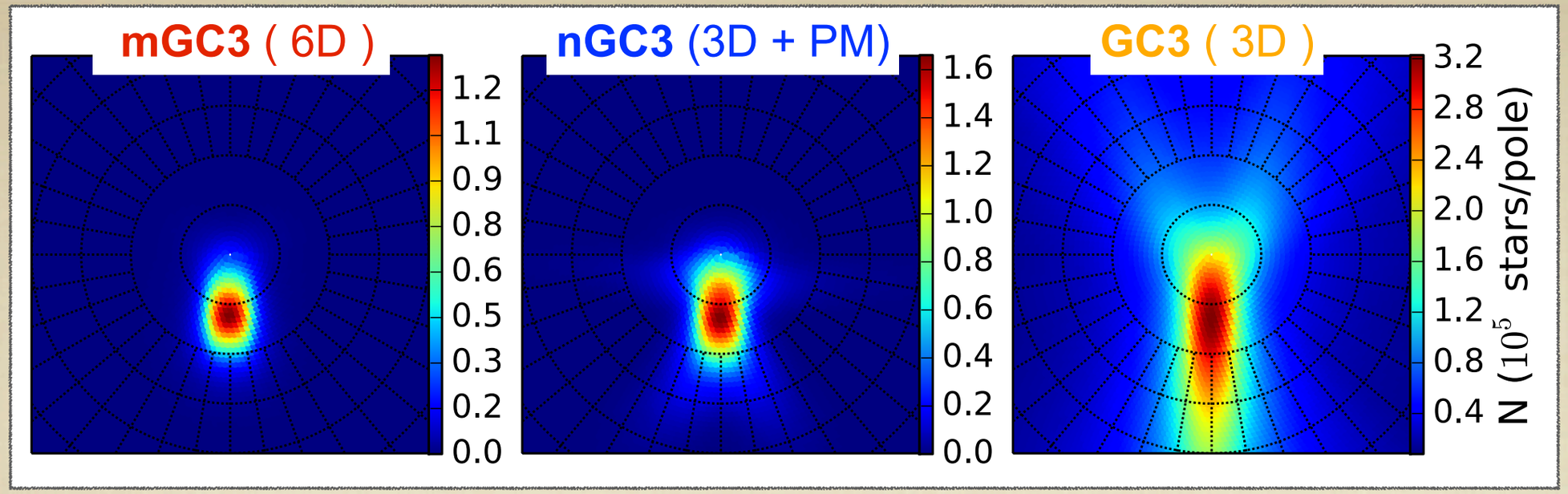


How this method is useful for detecting the warp?





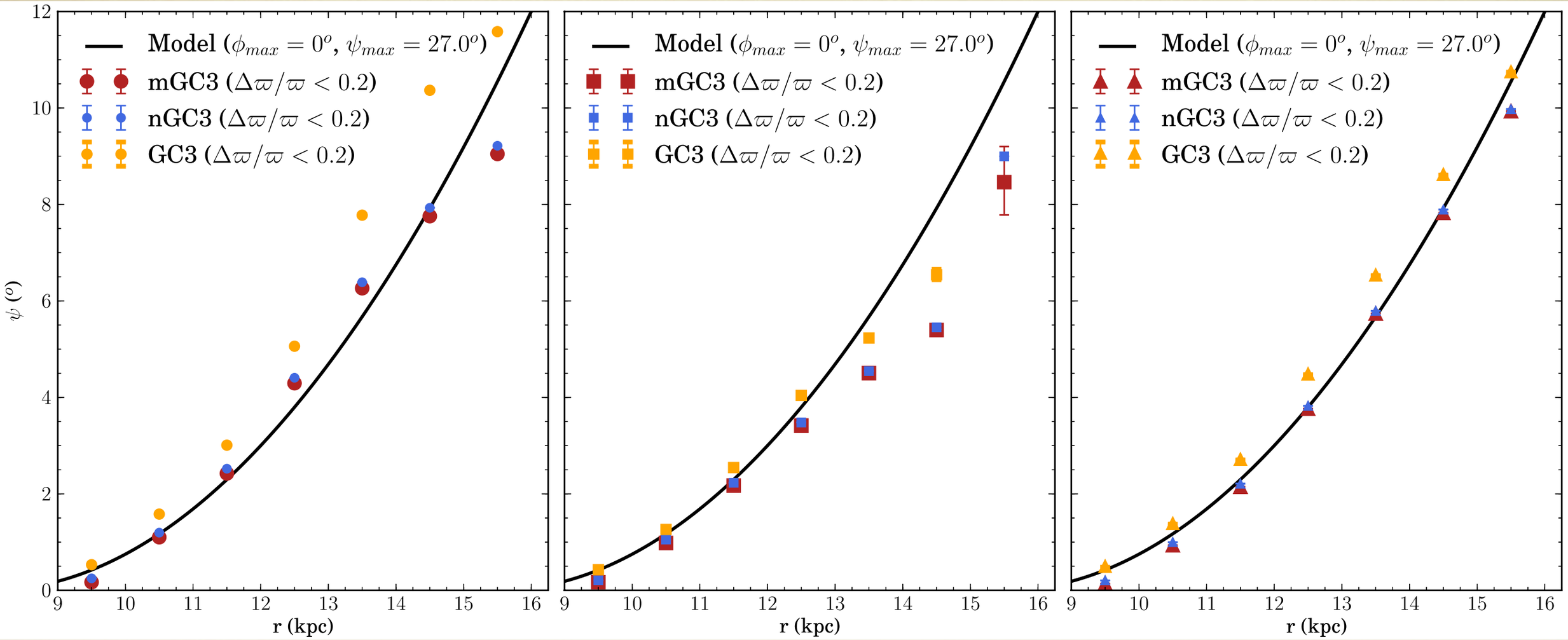
Results



RC stars

A stars

OB stars

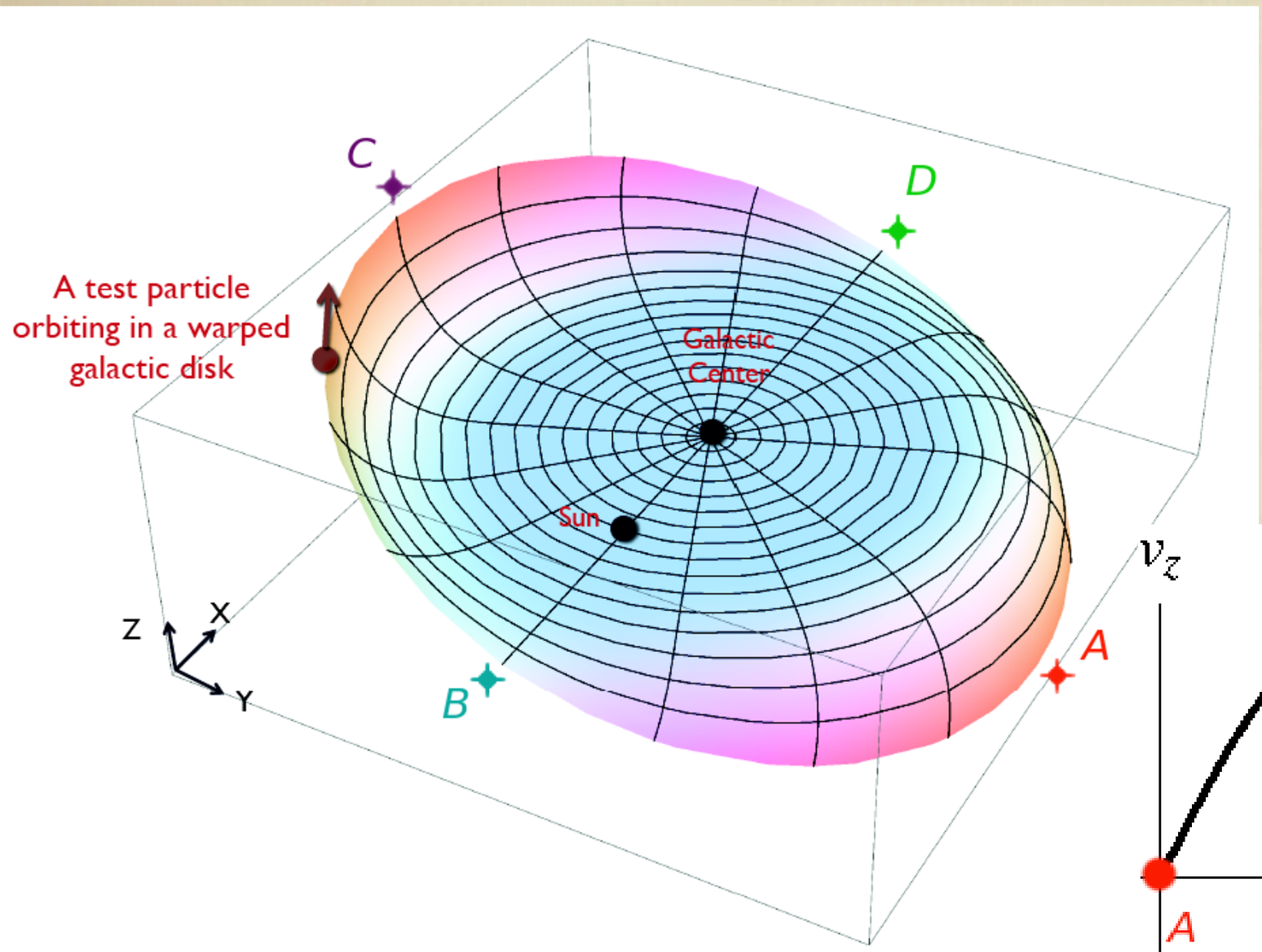


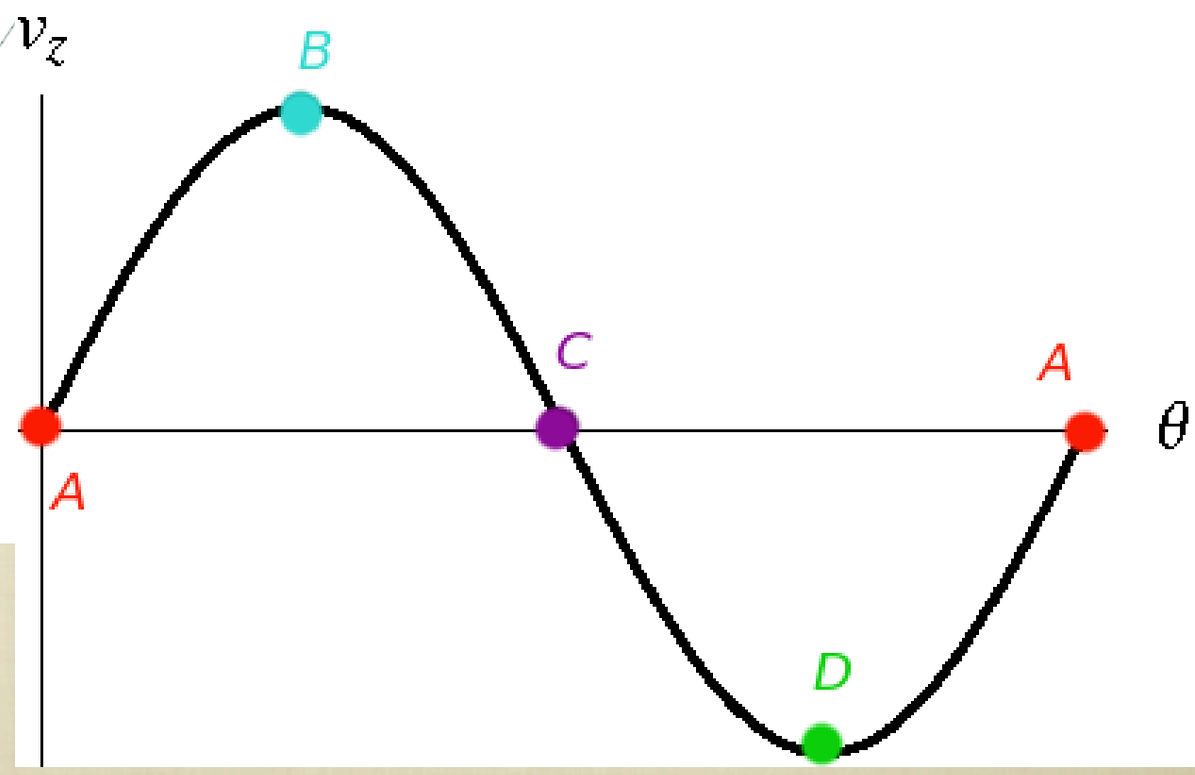
Results after Applying Gaia selection function and Gaia errors

Abedi et al. 2014 (*MNRAS.442.3627A*)

KINEMATIC SIGNATURE OF THE WARP

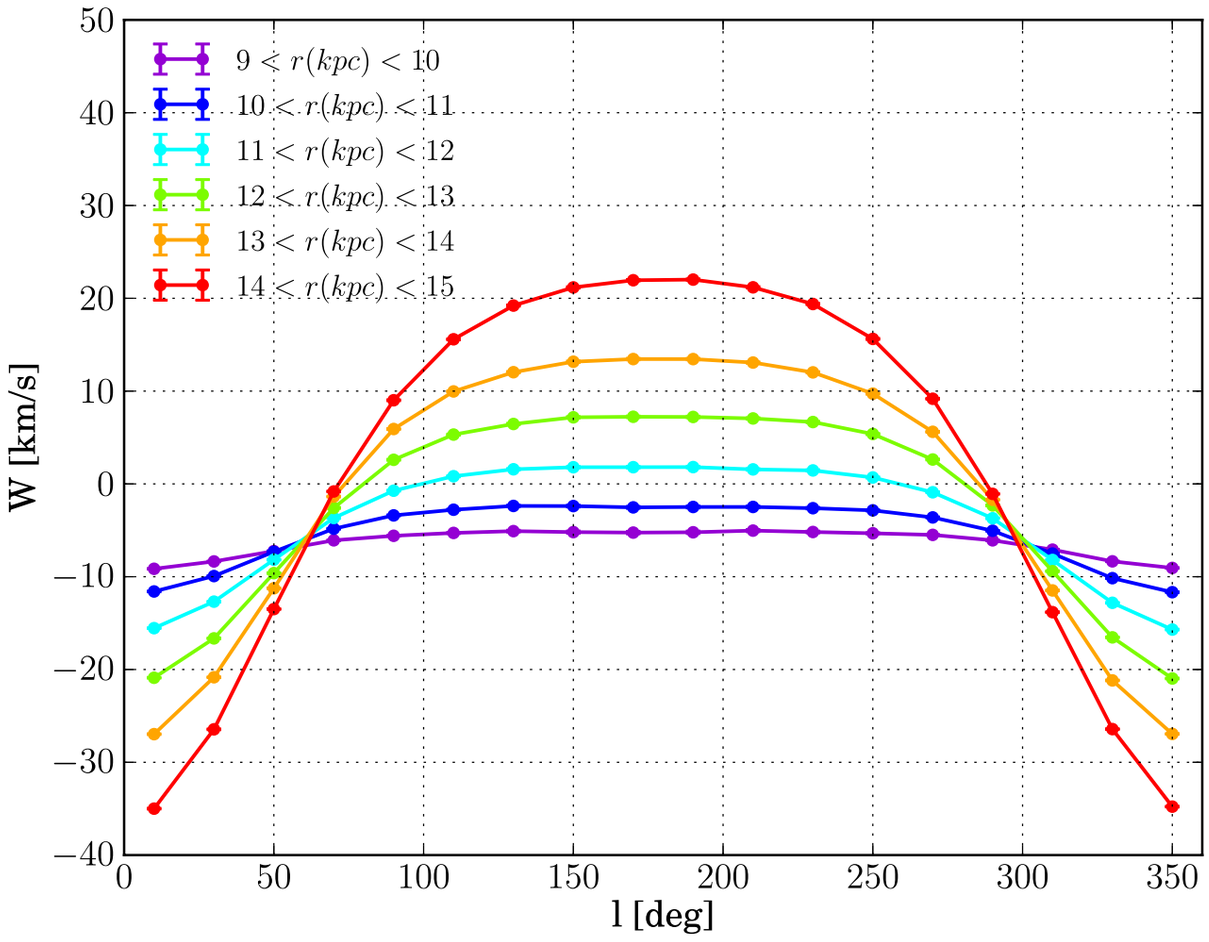
Looking at the vertical velocities



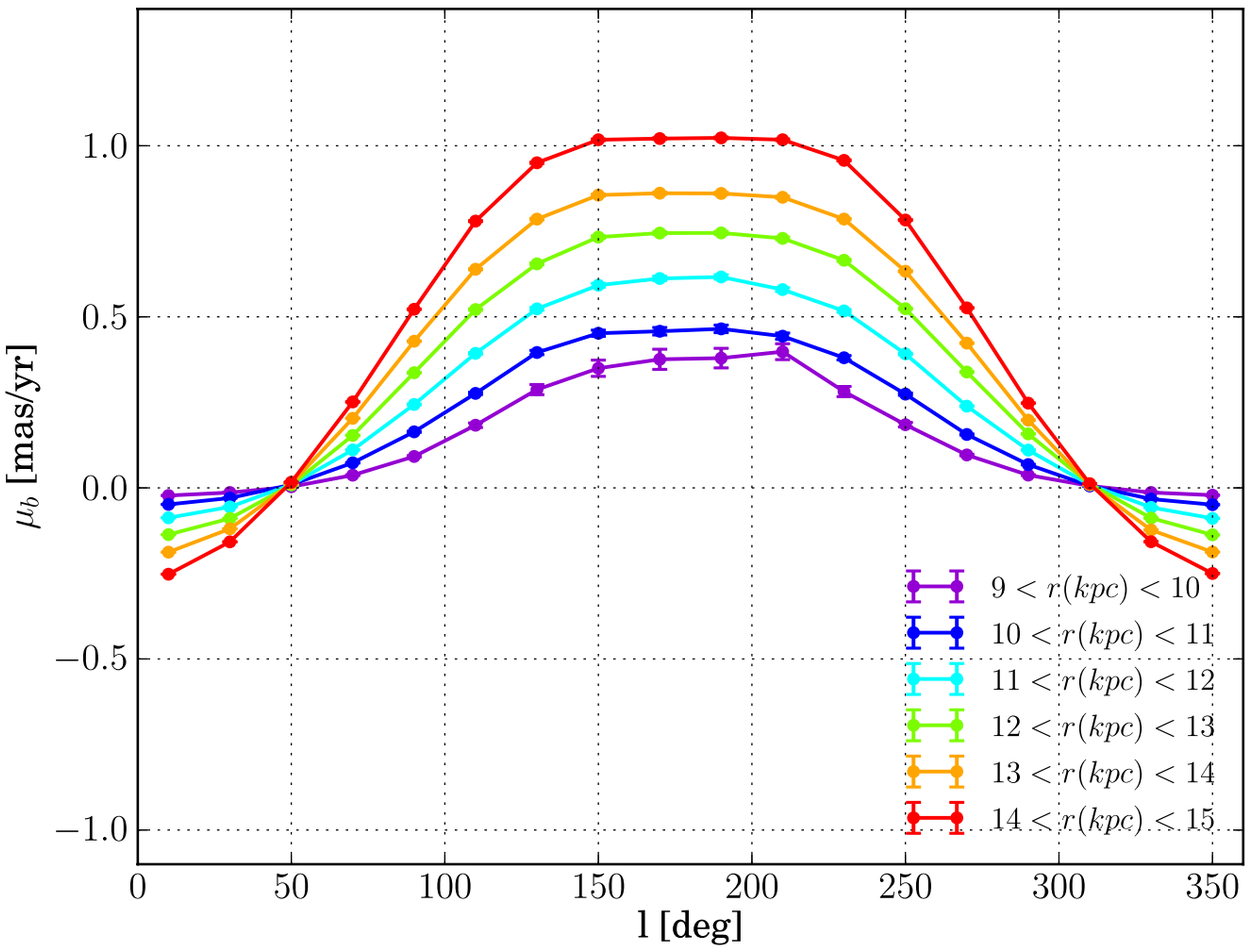


Kinematic signature of the warp

W velocity component



$\mu_b(mas/yr)$



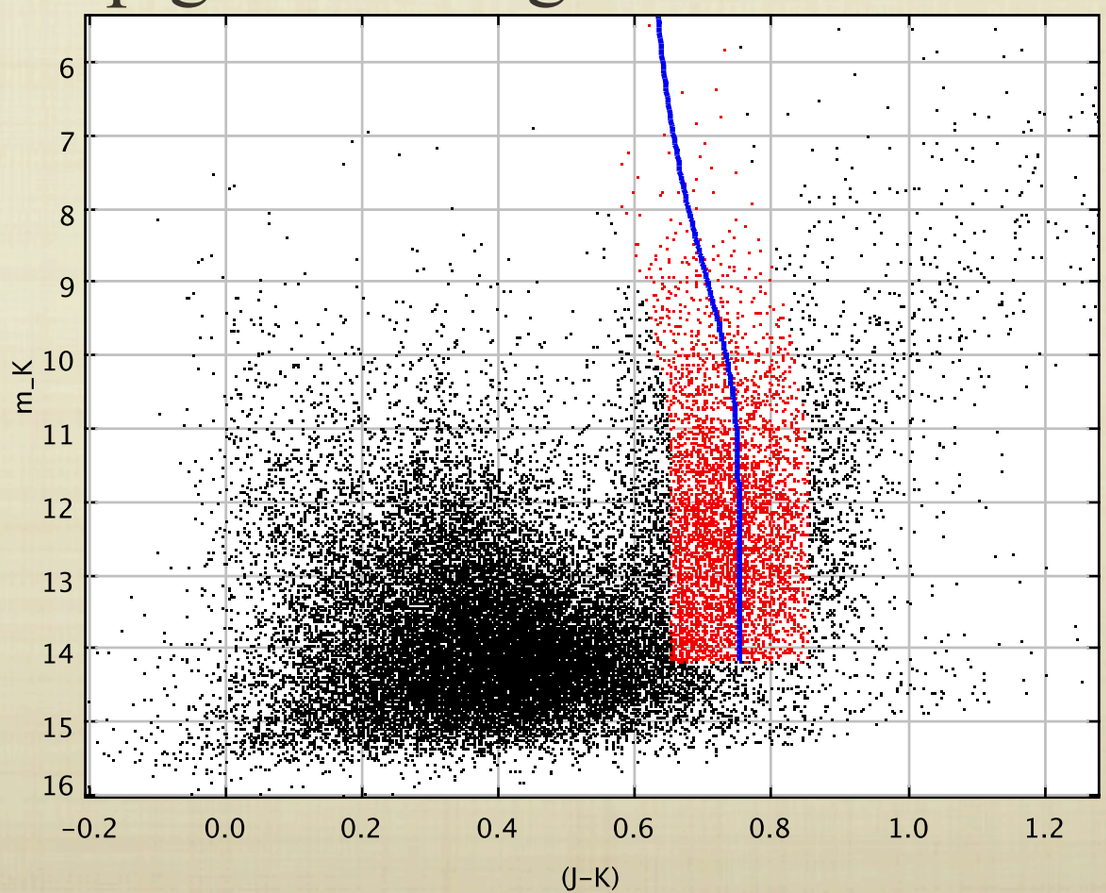
Both are corrected for the vertical motion of the Sun

SIMULATIONS VS. OBSERVATIONS I : UCAC4 CATALOG

SIMULATIONS VS. OBSERVATIONS I : UCAC4 CATALOG

- The fourth United States Naval Observatory (USNO) CCD Astrograph Catalog, UCAC4, is an all-sky astrometric catalog with more than 105 million of stars with proper motions. It is complete to R=16. It also contains 2MASS magnitudes (Zacharias et al. 2013).

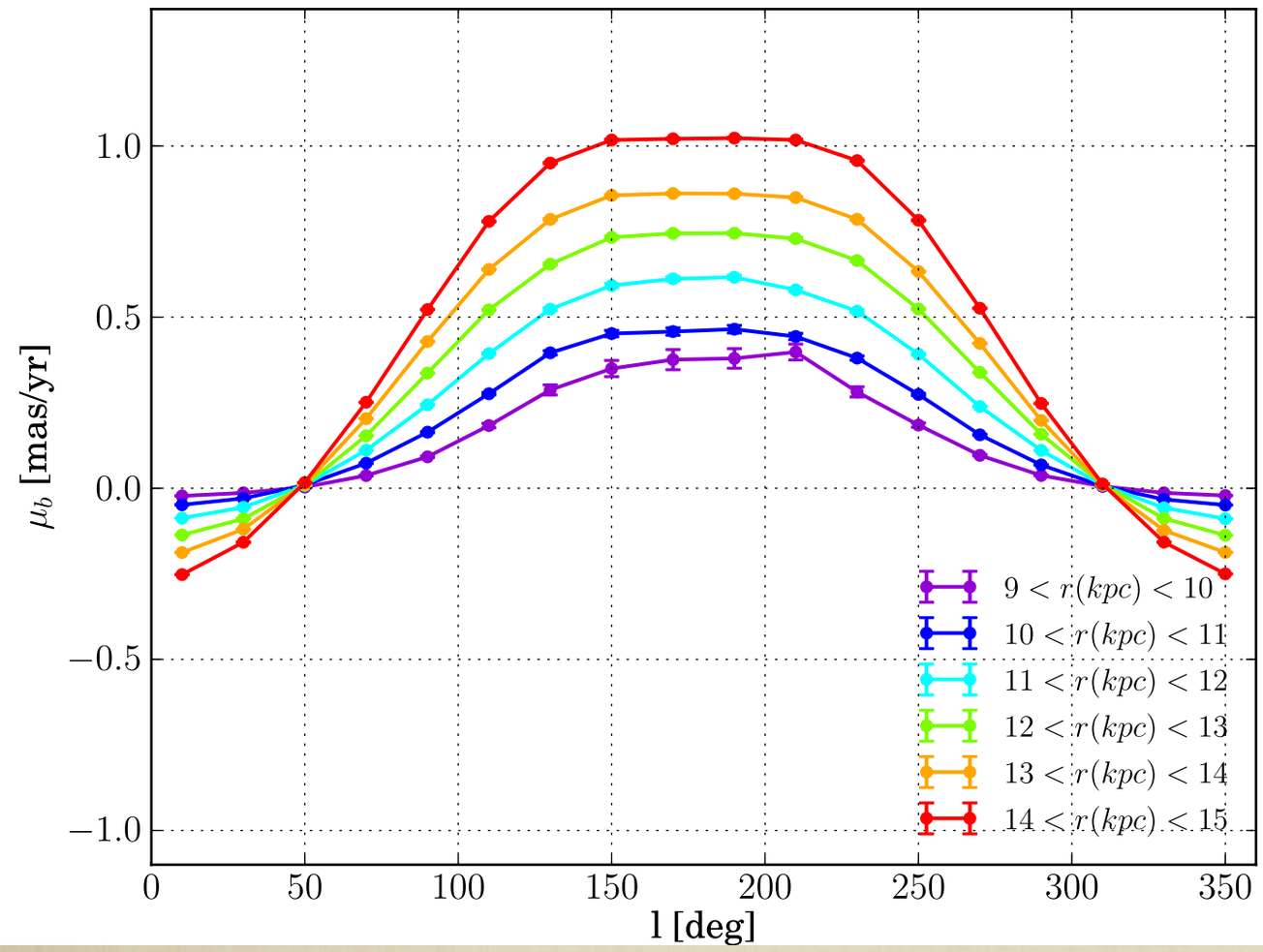
- We choose the Red clump giants using the method from Cabrera-Lavers et al. 2007.



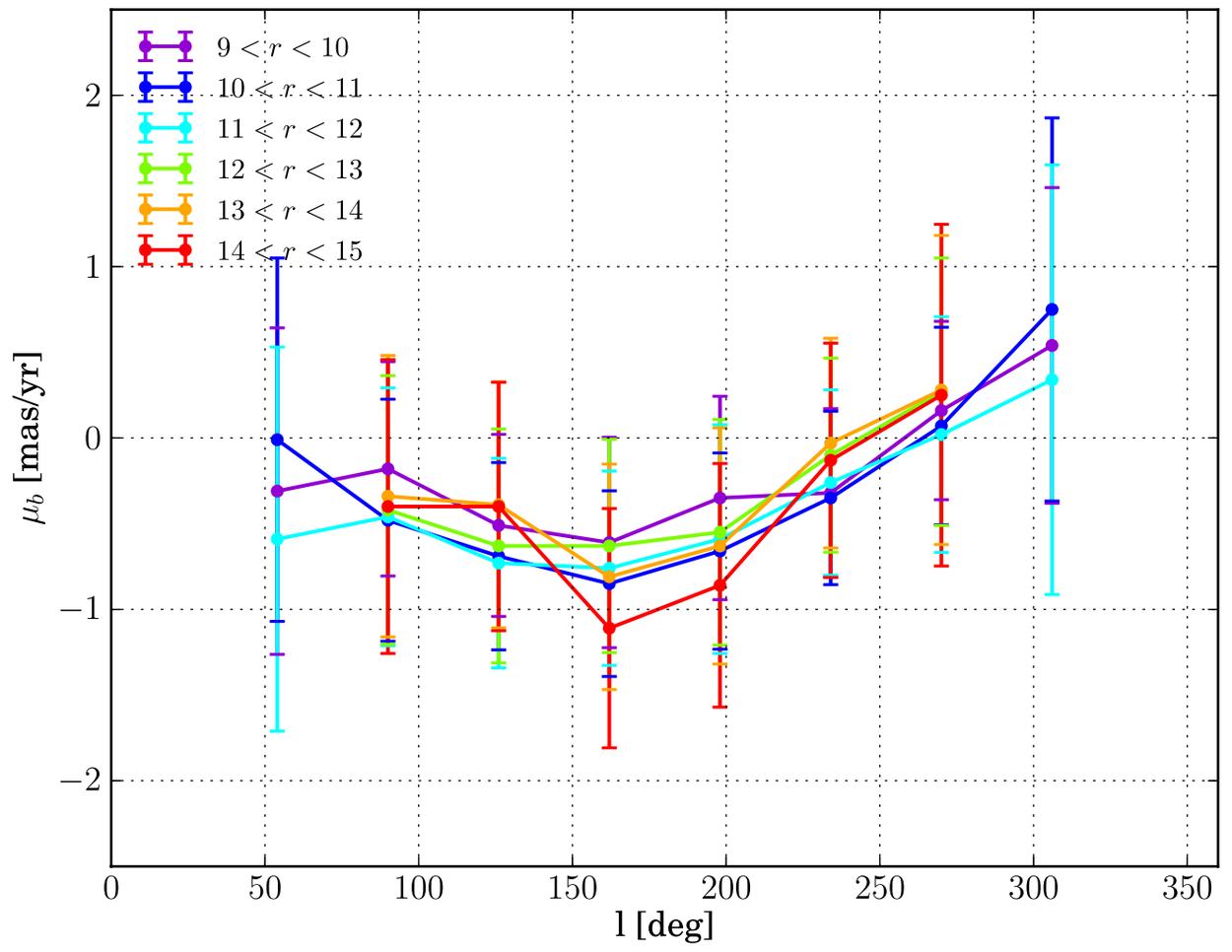
SIMULATIONS VS. OBSERVATIONS

Our warp model

(affected by Gaia selection function)

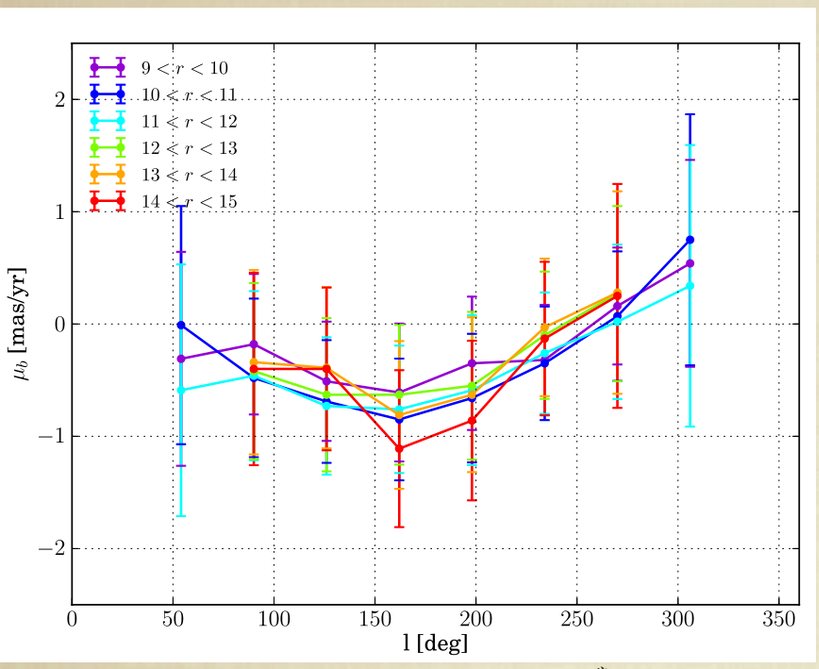


UCAC4



Note that the μ_b is corrected for the vertical motion of the Sun.

Residual spin of Hipparcos/Tycho-2 system wrt extragalactic inertial reference frame

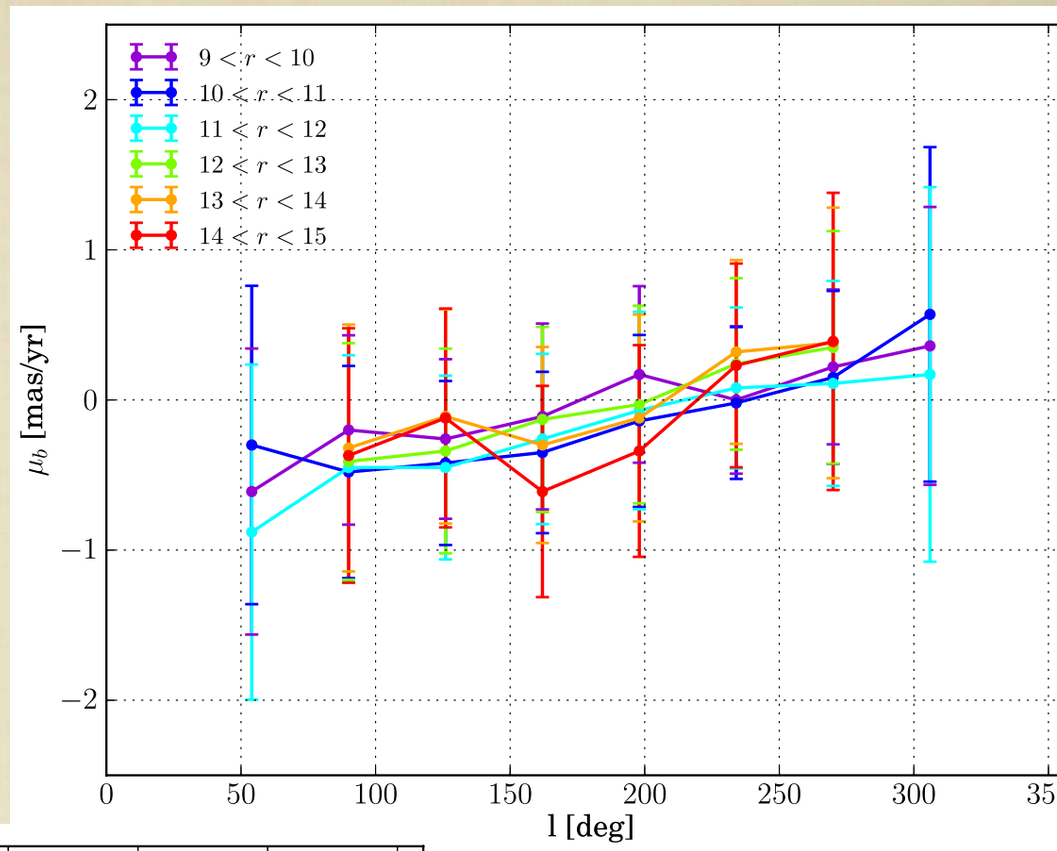


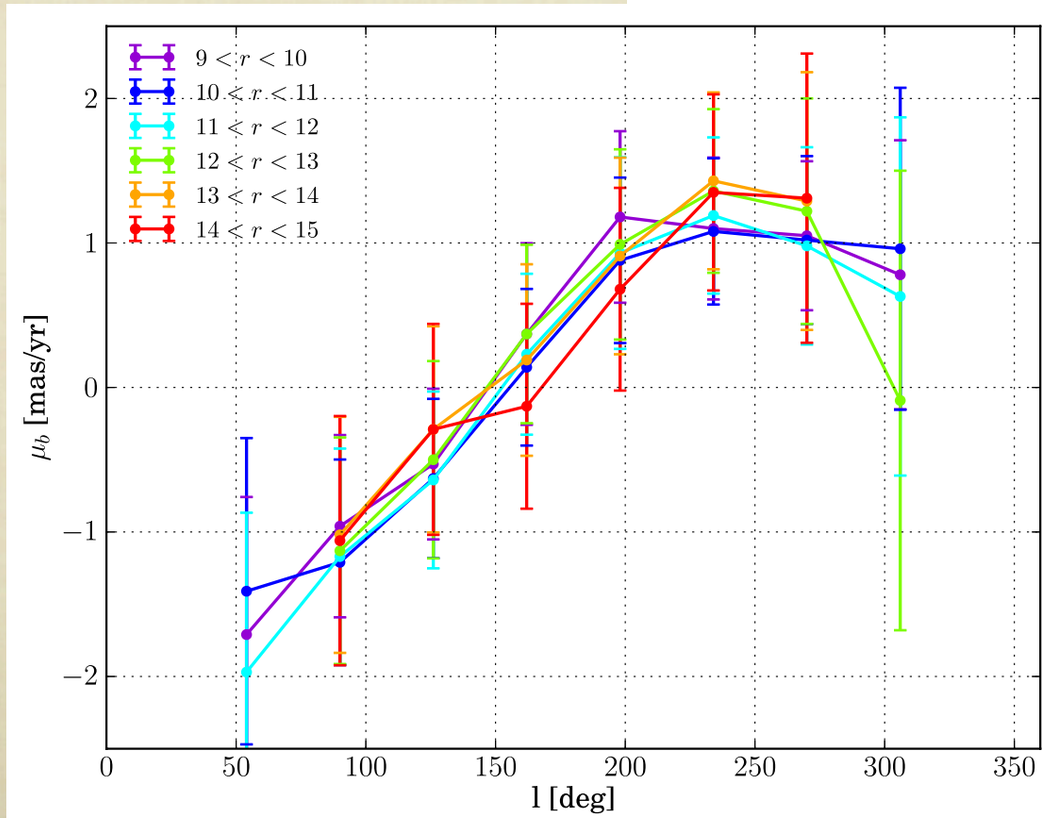
$$(\omega_1, \omega_2, \omega_3) = (-0.11, 0.24, -0.52)\, mas/yr$$

Bobylev (2010)

$$(\omega_1, \omega_2, \omega_3) = (0, 0, -1.8)\, mas/yr$$

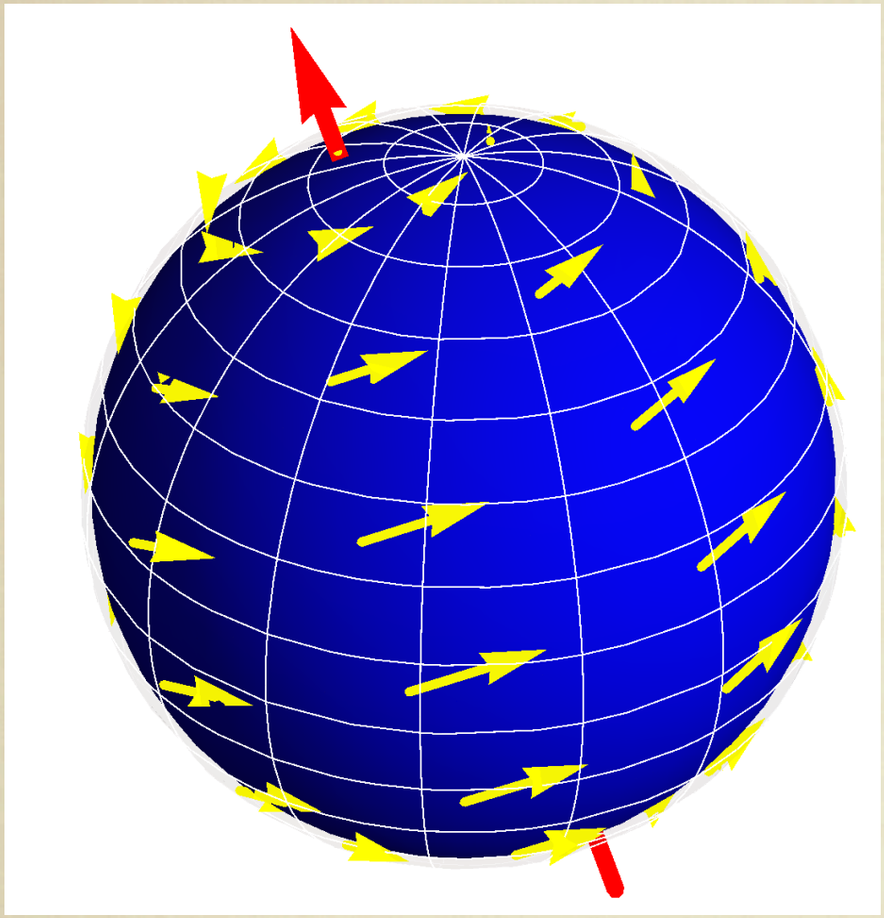
Federov et al. (2011)

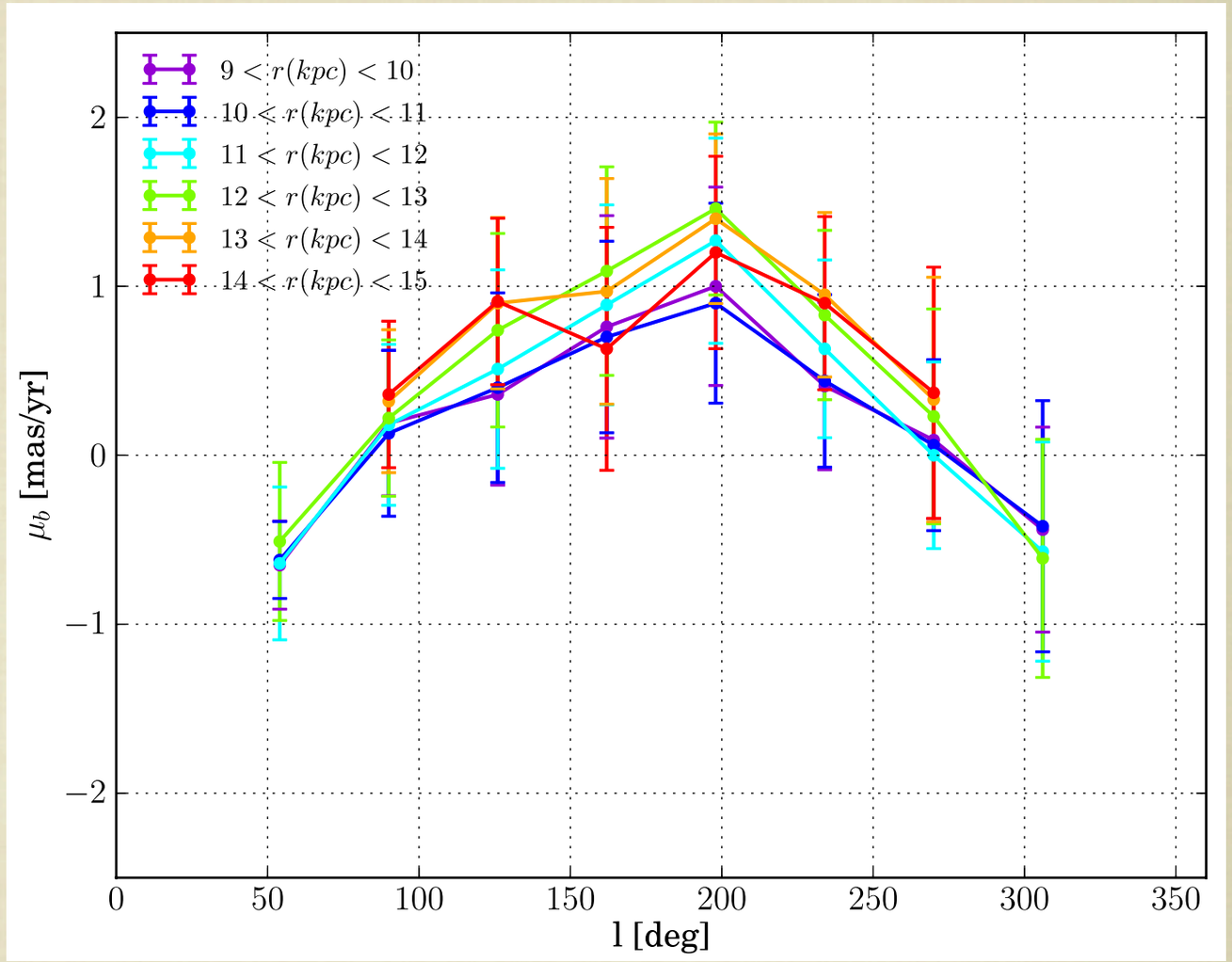




What should be the spin axis for which the observations match with the model?

Least squares fit





$$(\omega_{1g}, \omega_{2g}) =$$

$$(-0.09, -1.55)\ \mathrm{mas\,yr^{-1}}$$

Residual rotation of Hipparcos/Tycho-2 system wrt extragalactic inertial reference frame

Spin vector in Equatorial coordinates

Spin vector in Galactic coordinates

Method/Solution	ω_1	ω_2	ω_3	ω_{1g}	ω_{2g}	ω_{3g}	σ
Bobylev (2010)	-0.11 ± 0.14	0.24 ± 0.10	-0.52 ± 0.16	0.05	-0.55	-0.19	-
Fedorov et al. (2011)	~ 0	~ 0	-1.8 ± 0.16	0.87	-1.34	-0.82	-
LSF	-	-	-	-0.129 ± 0.009	-1.92 ± 0.012	-	10.6
LSF, outliers removed	-	-	-	-0.09 ± 0.003	-1.55 ± 0.005	-	3.96
QSO	0.73	0.91	-1.05	-0.34 ± 0.51	-0.83 ± 0.52	-1.29 ± 0.72	9.8

Residual rotation of Hipparcos/Tycho-2 system wrt extragalactic inertial reference frame

Spin vector in Equatorial coordinates

Spin vector in Galactic coordinates

Method/Solution	ω_1	ω_2	ω_3	ω_{1g}	ω_{2g}	ω_{3g}	σ
Bobylev (2010)	-0.11 ± 0.14	0.24 ± 0.10	-0.52 ± 0.16	0.05	-0.55	-0.19	-
Fedorov et al. (2011)	~ 0	~ 0	-1.8 ± 0.16	0.87	-1.34	-0.82	-
LSF	-	-	-	-0.129 ± 0.009	-1.92 ± 0.012	-	10.6
LSF, outliers removed	-	-	-	-0.09 ± 0.003	-1.55 ± 0.005	-	3.96
QSO	0.73	0.91	-1.05	-0.34 ± 0.51	-0.83 ± 0.52	-1.29 ± 0.72	9.8

Conclusions

* We have made a kinematical model for the Galactic warp.

* We have used the GC3 methods to search for and characterise the warp. We find that it is a very efficient and robust method.

* We look for the kinematic signature of the warp in real data using UCAC4 proper motion catalogs. Correcting for the rotation of the inertial reference frame and any other systematics is very crucial for our work.

Abedi et al. 2014 (*MNRAS.442.3627A*)