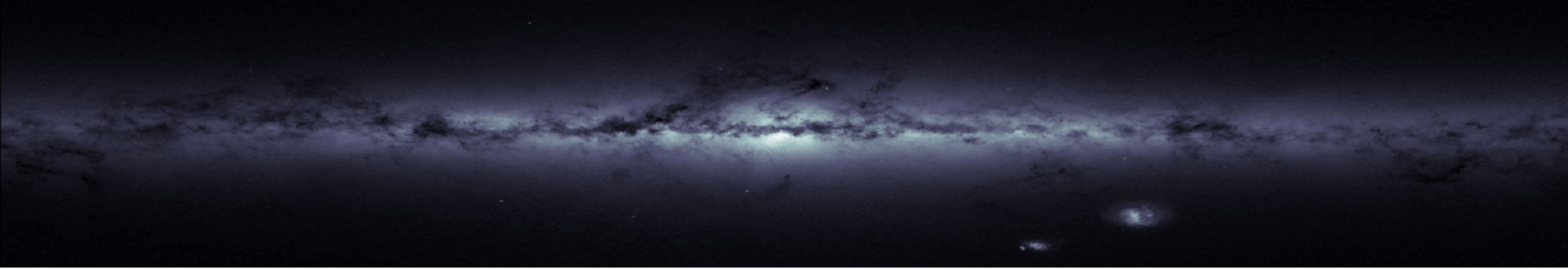
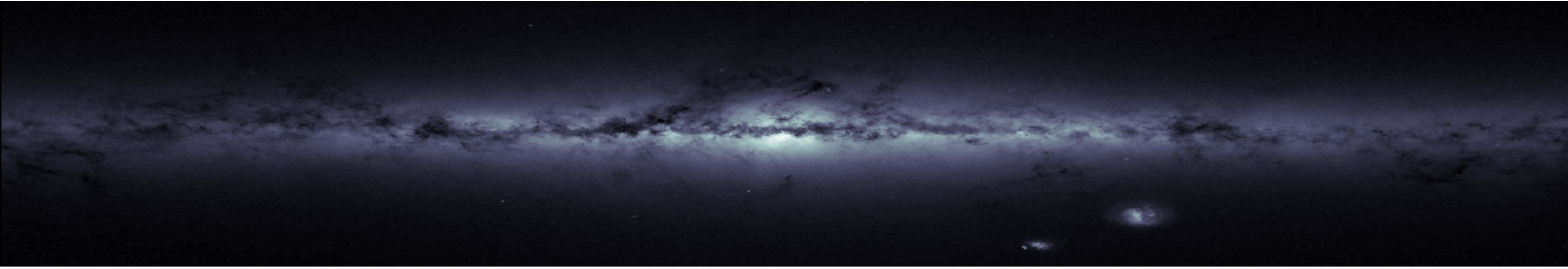


EXPLORING THE NATURE OF THE GALACTIC WARP

Eloisa Poggio
INAF - Osservatorio Astrofisico di Torino, Pino Torinese, Italy
Università degli Studi di Torino

Research group:
R. Drimmel
R. L. Smart
A. Spagna
M. G. Lattanzi



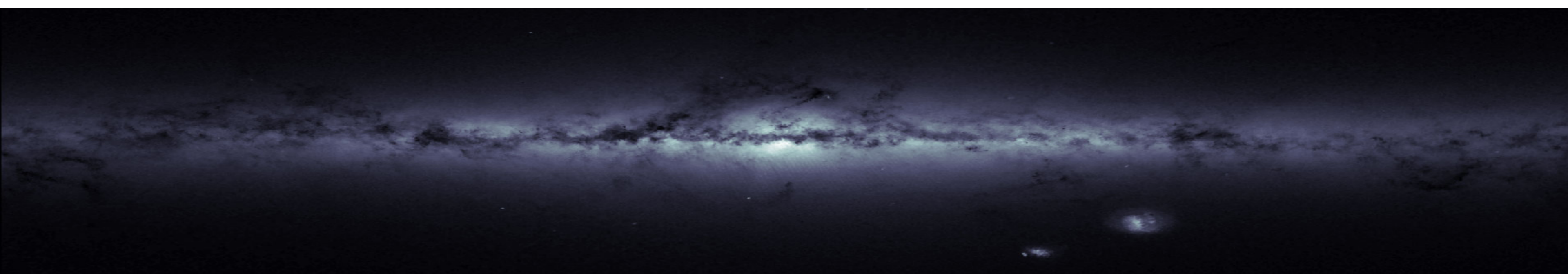
OUTLINE

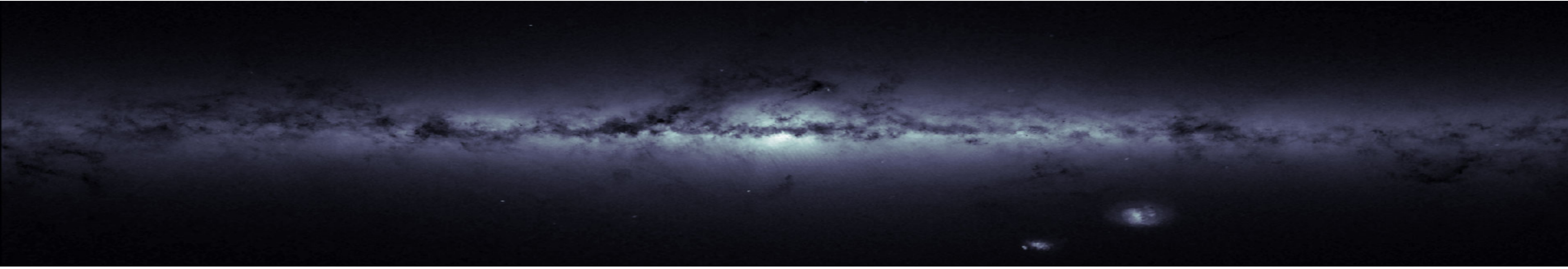
- **Section I**
  - Introduction
  - Motivation
- **Section II**
  - The model
- **Section III**
  - Data
  - Spectro-photometric distances
- **Section IV**
  - Results
  - Comparison with simulations
- **Conclusion and next steps**

Section I

Introduction

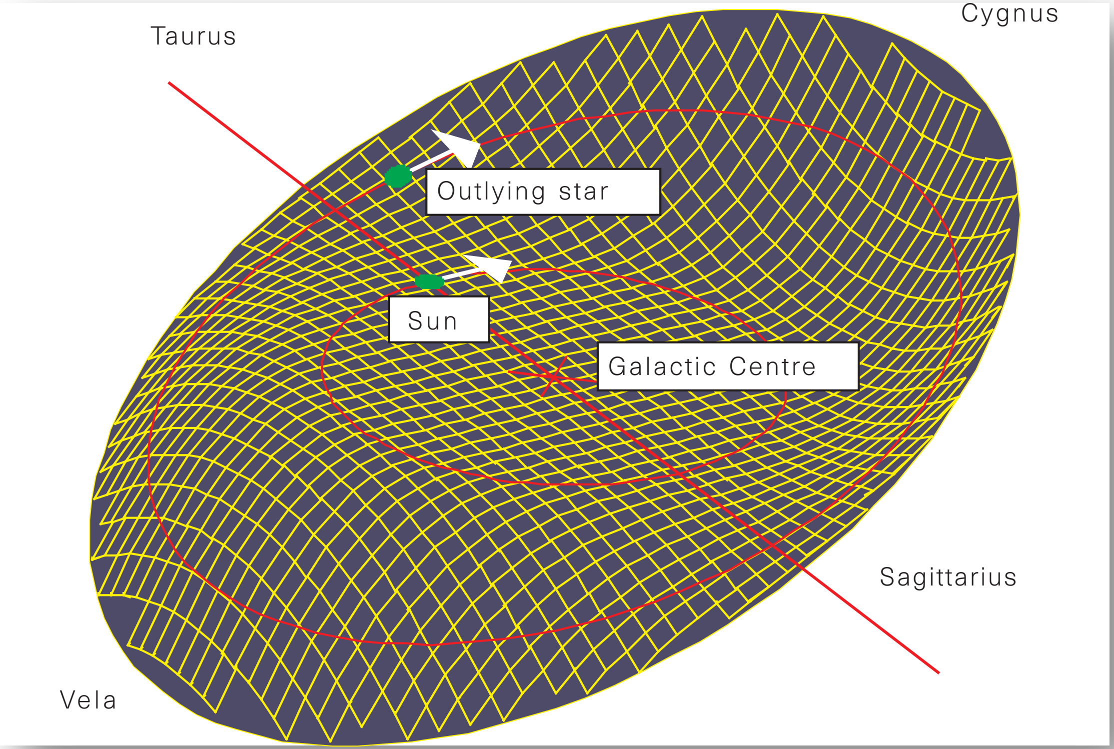
Motivation



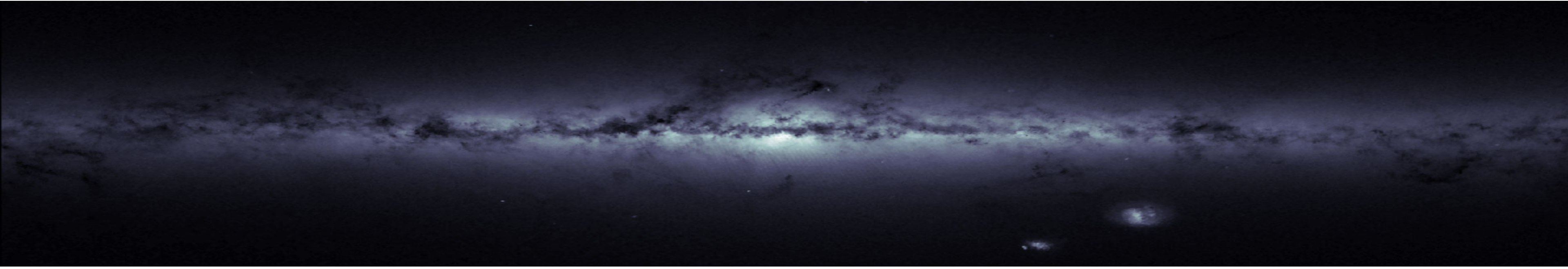


INTRODUCTION

- The Galactic warp



(R. L. Smart, R. Drimmel, M. G. Lattanzi & J. J. Binney, 1998)



SPATIAL WARP

- Galactic warp: first seen in HI observations (Burke 1957; Kerr et al. 1957; Westerhout 1957)

Warp in HI

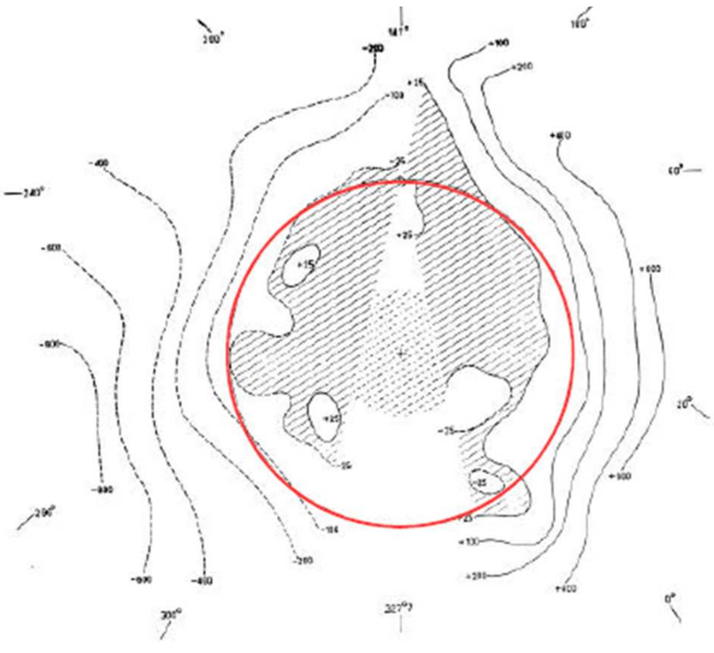
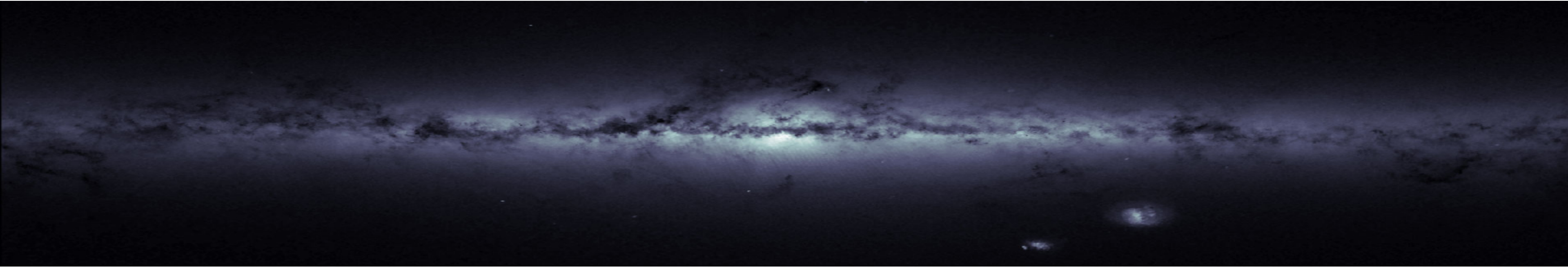


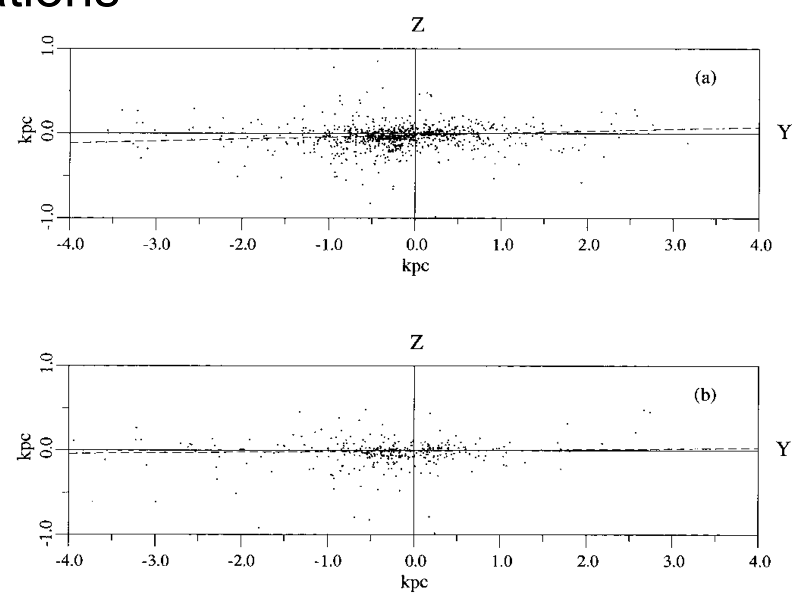
FIG. 1.—*Relief map showing the height z (pc) of the position of maximum hydrogen density above the new galactic plane. The distance scale is based on the Leiden velocity model (Westerhout 1957; Schmidt 1957).*

Gum, C. S.; Kerr, F. J.; Westerhout, G. 1960, MNRAS 121, 132



SPATIAL WARP

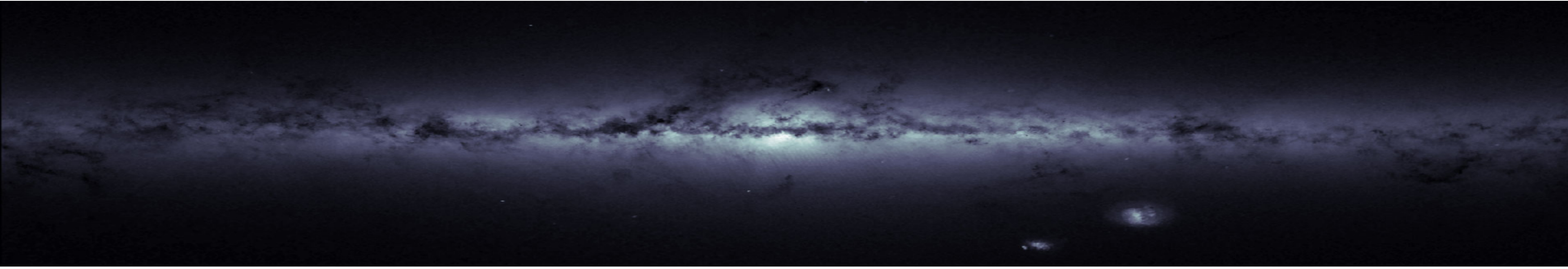
- Miyamoto et al. (1998), Smart et al. (1998), Drimmel et al. (2000) and Reed (1996) observed the warp in OB stars and found it to be consistent with HI observations



Miyamoto (1998)

FIG. 2.—Our 1523 O–B5 stars (other than the Gould belt stars) projected onto the *Y*-*Z* plane of Galactic rectangular coordinates. (*a*) Distribution of 823 O–B5 stars exterior to the solar circle. The dashed line indicates the mean plane of the distribution, which inclines with respect to the Galactic plane in the sense of the H I warp. (*b*) Distribution of 700 O–B5 stars interior to the solar circle. The mean plane of the distribution shows no meaningful inclination.

SPATIAL WARP



- Using COBE near- and far-infrared data, Drimmel & Spergel (2001) found that the warp amplitude in the dust was larger than the one in the stars

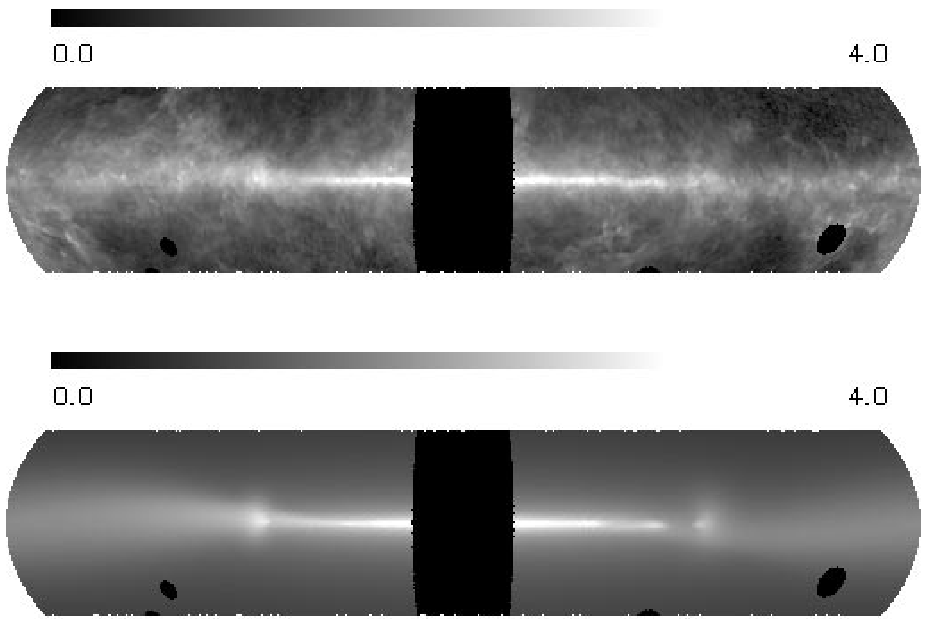
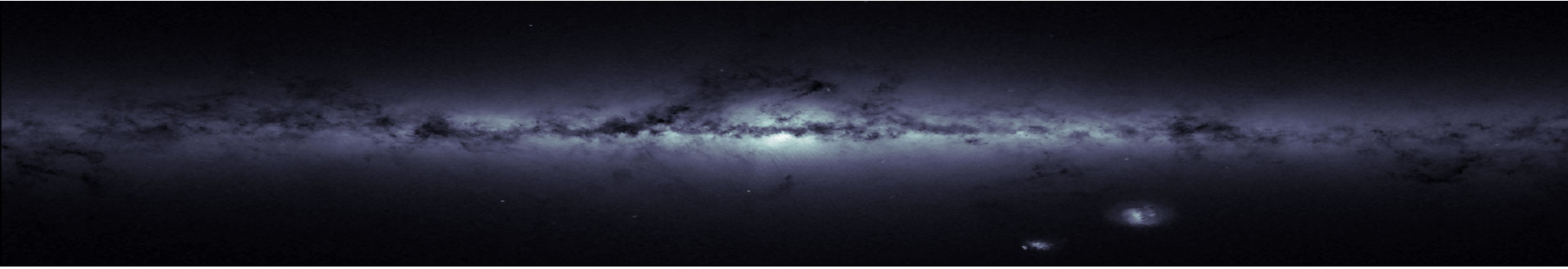


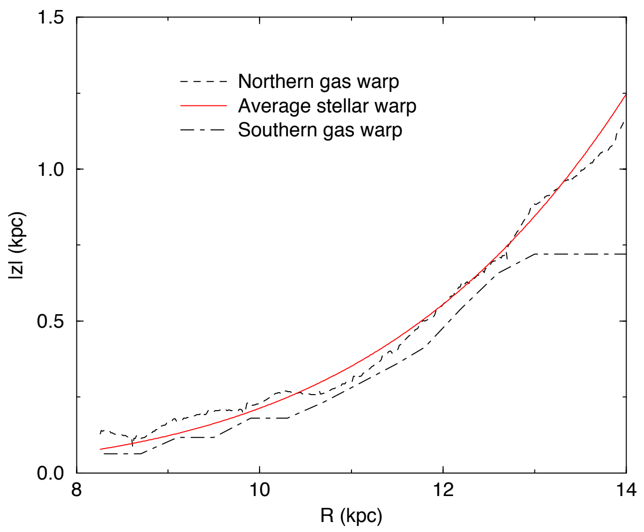
FIG. 4.—240 μm sky maps of the smoothed DIRBE data (*top*), the modeled emission (*middle*), and the relative difference between the modeled and served emission (*bottom*). The top two maps are on a logarithmic scale, while the bottom map is on a linear scale.

Drimmel & Spergel (2001)



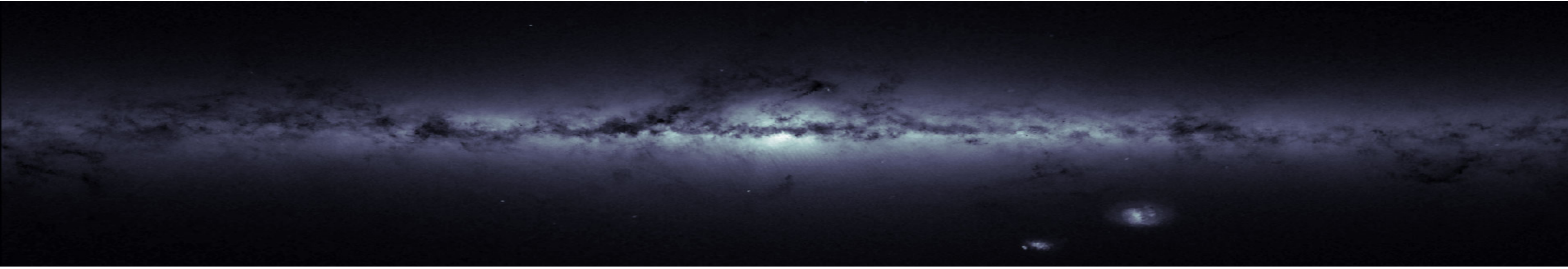
SPATIAL WARP

- López-Corredoira et al. (2002) and Momany et al. (2006) confirmed its presence in older stellar populations using 2MASS red clump stars



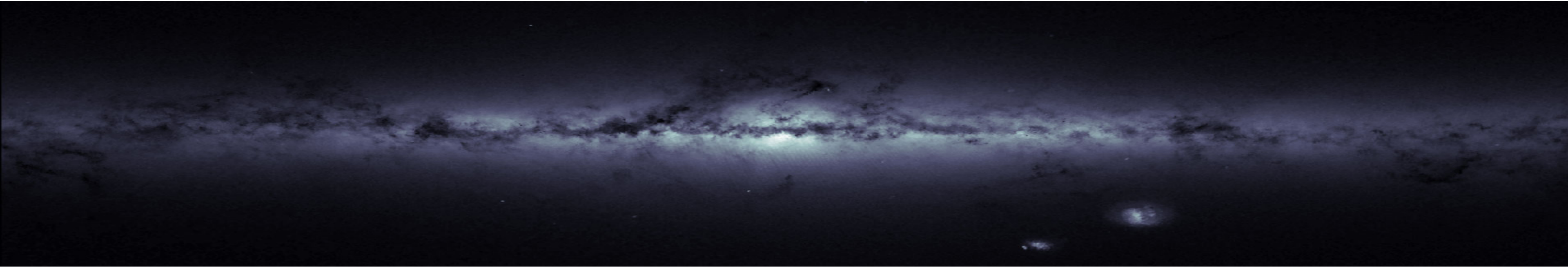
López-Corredoira (2002)

Fig. 18. Maximum amplitude of the stellar warp (solid line: $z_w = 2.1 \times 10^{-19} R(\mathrm{pc})^{5.25}$ pc, which is the best power-law fit to the data) in comparison with the one measured by Burton (1988) for the northern and southern warp gas scaled to $R_\odot = 7.9$ kpc (dashed and dot-dashed lines).

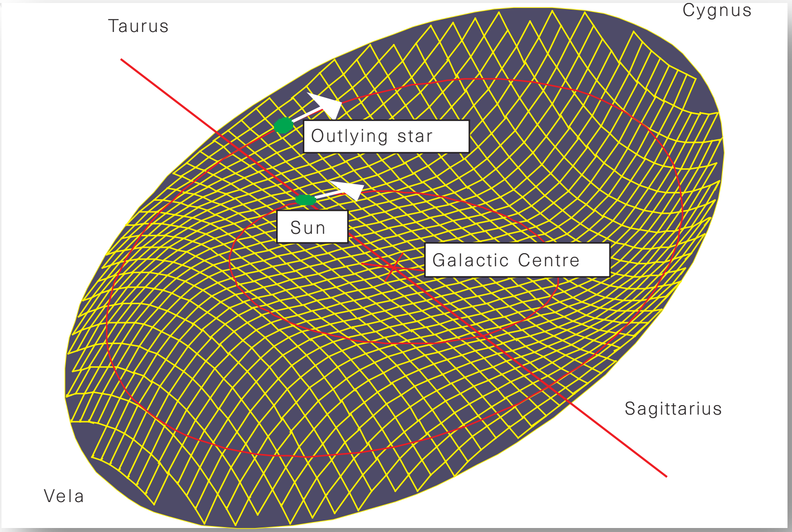


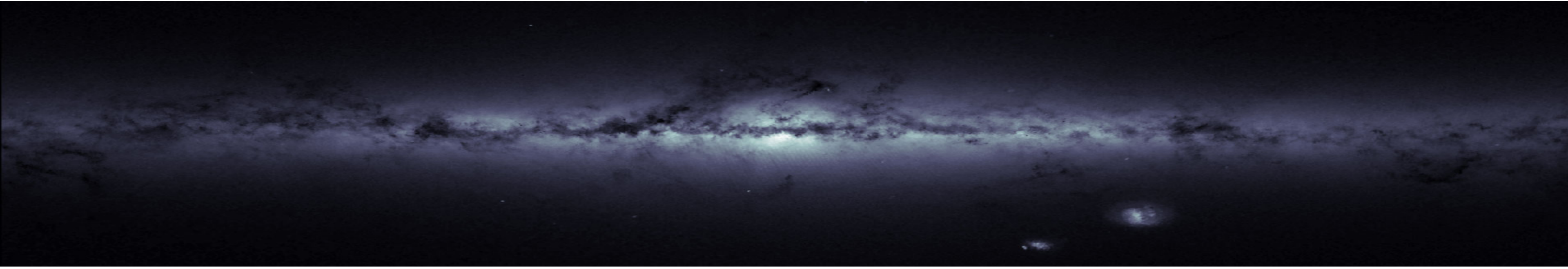
FORMATION

1. Interaction between the disk and a non spherical dark-matter halo (Sparke and Casertano 1988)
2. Gravitational influence of the Galaxy's nearest satellites (Bailin 2003)
3. Interaction with the intergalactic magnetic field (Battaner et al. 1990)
4. Interaction of the disk with a near-Galaxy flow formed by high-velocity hydrogen clouds that resulted from mass exchange between the Galaxy and the Magellanic clouds (Olano 2004)
5. An intergalactic flow (López-Corredoira 2002)



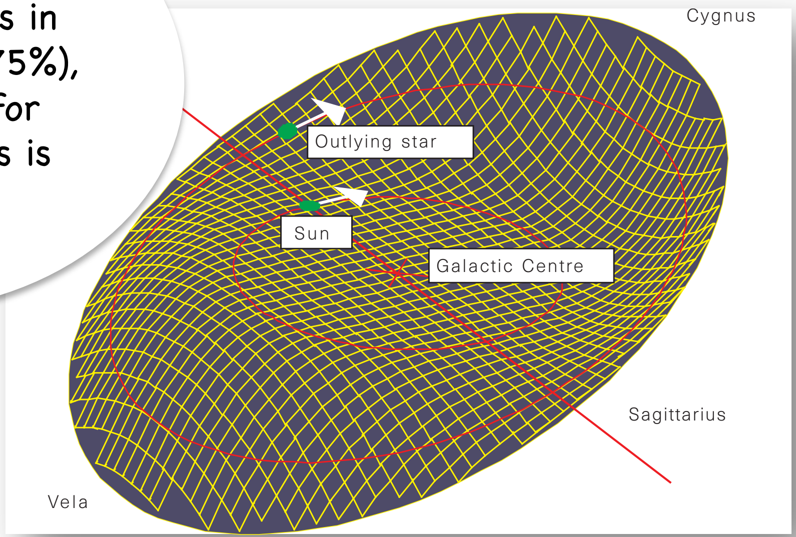
MOTIVATION

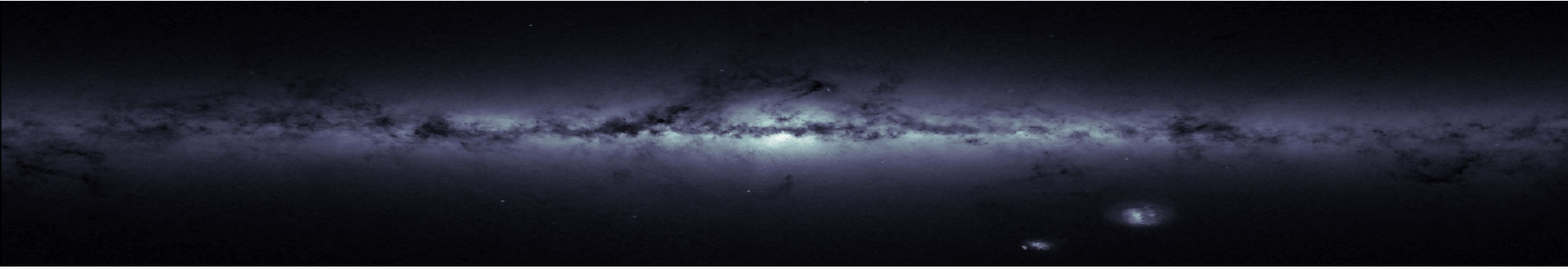

Taurus
Cygnus
Outlying star
Sun
Galactic Centre
Sagittarius
Vela



MOTIVATION

Warped disks are **common** features in spiral galaxies (~75%), but the cause for these structures is still unclear.





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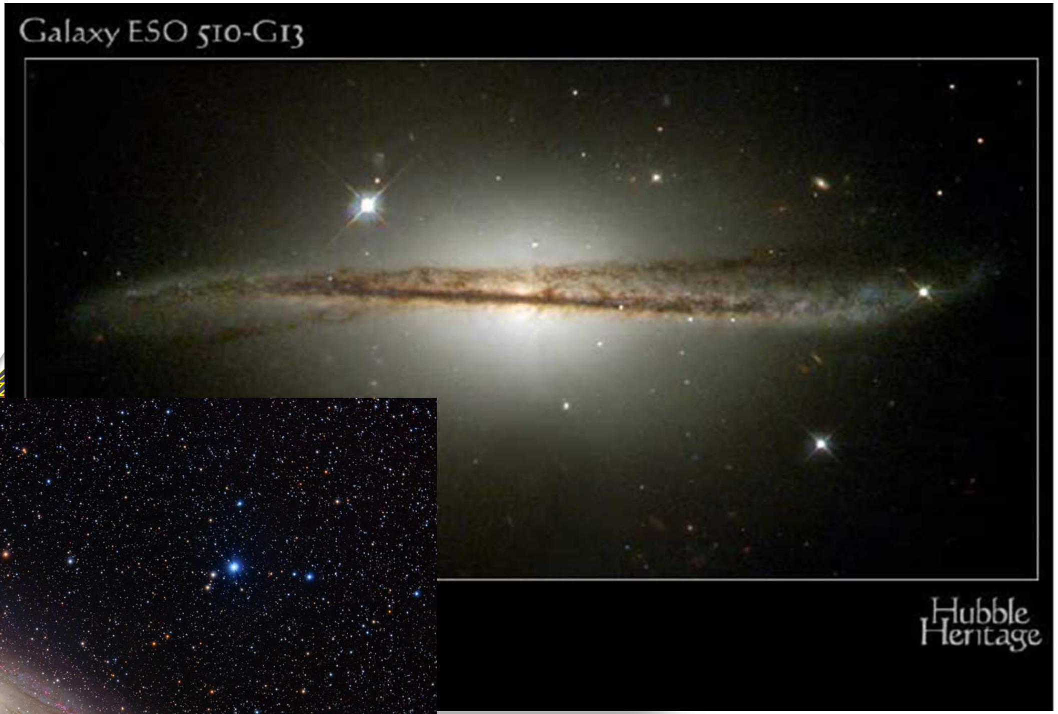

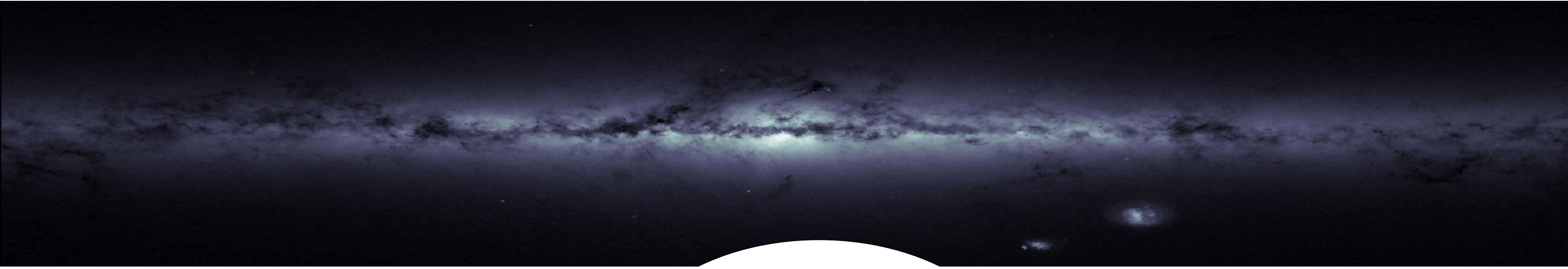

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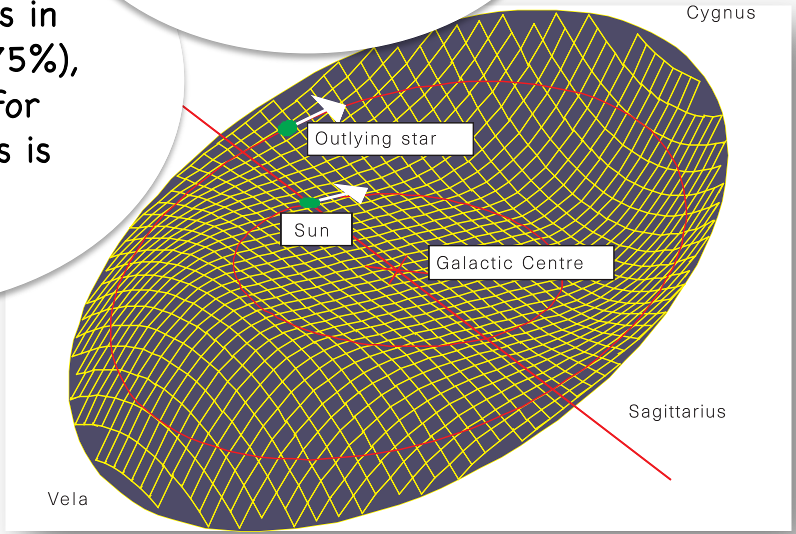
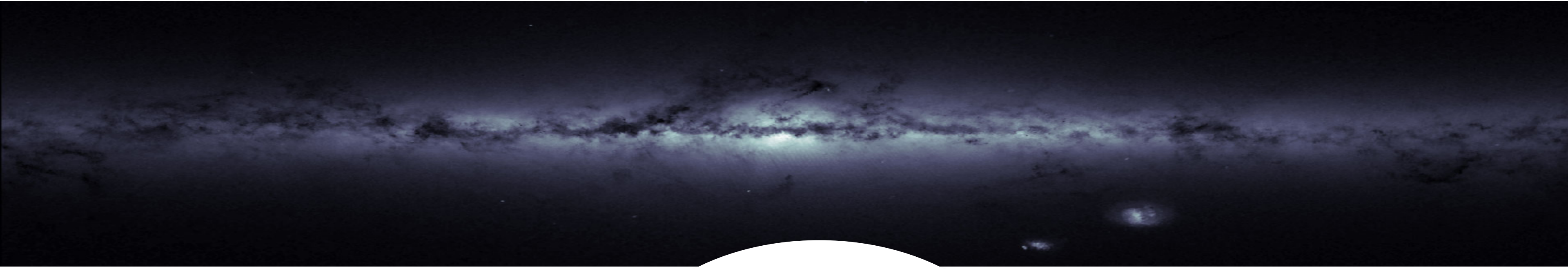
Warped disks are **common** features in spiral galaxies (~75%), but the cause for these structures is still unclear.

Warps are either **long-lived features** or frequently regenerated.





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Warped disks are **common** features in spiral galaxies (~75%), but the cause for these structures is still unclear.

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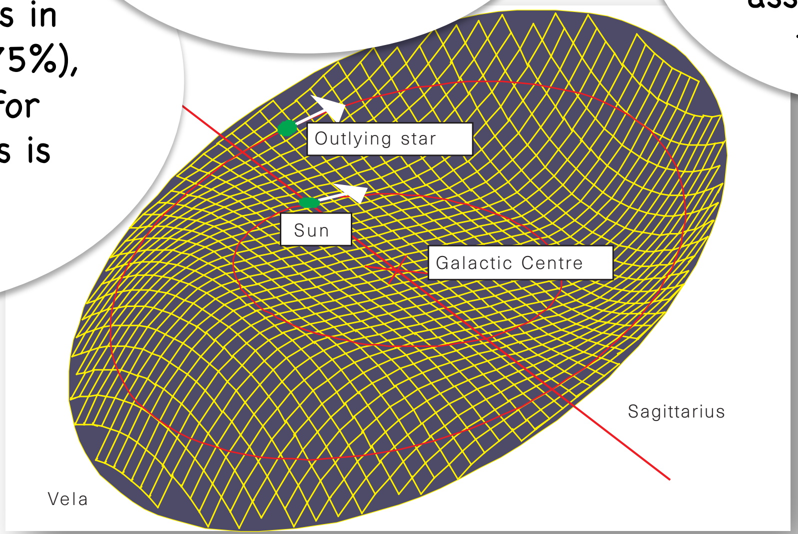
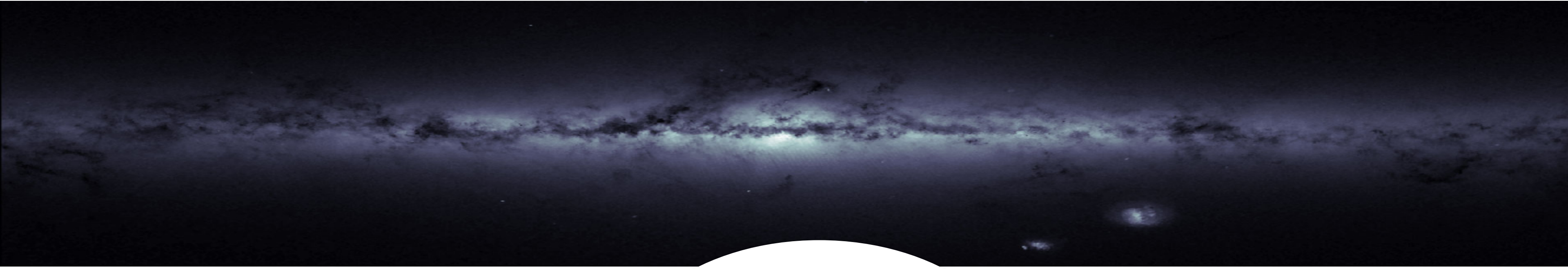
In the Milky Way we can study the **stellar kinematics** associated with the warp.





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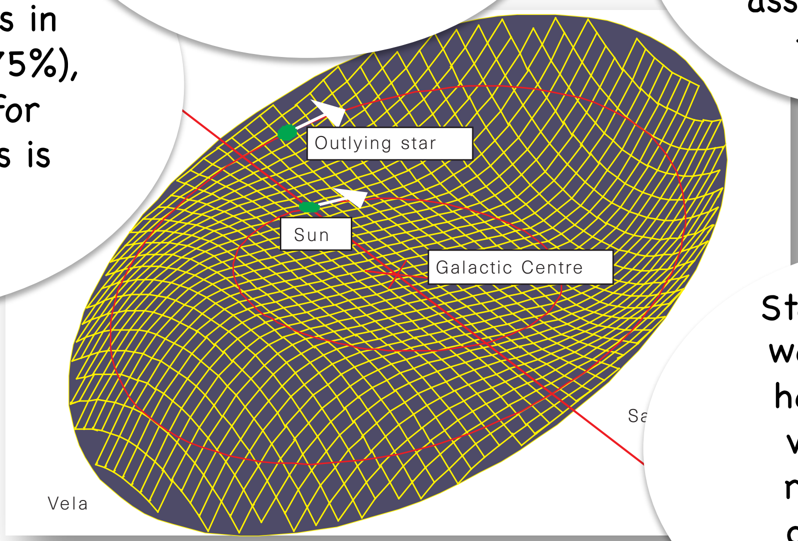
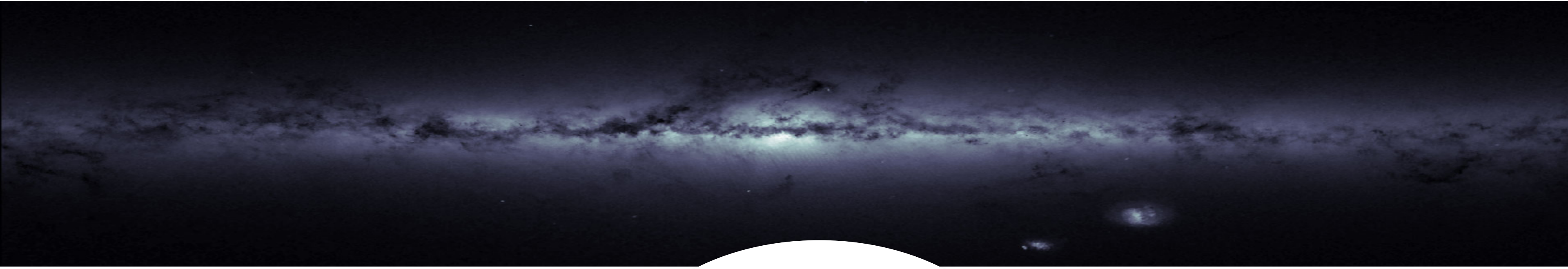


Stars moving in a warped disk will have systematic velocities with respect to the galactic plane: μ_b .



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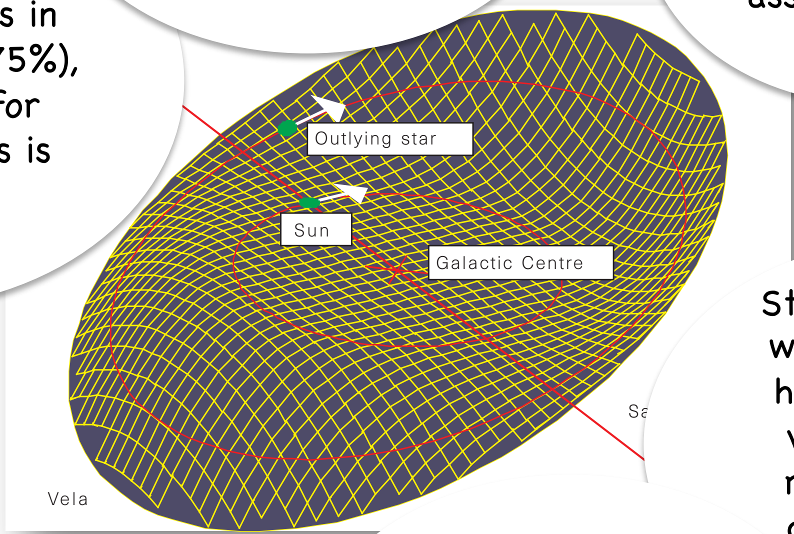
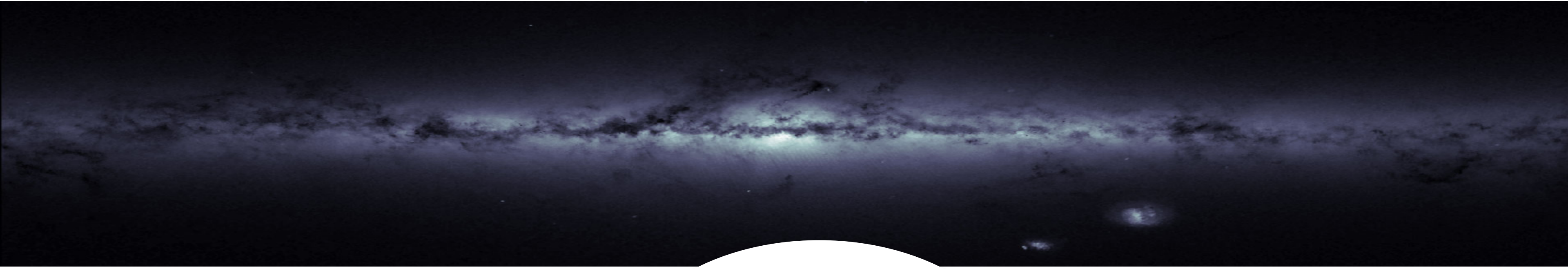


Stars moving in a warped disk will have systematic velocities with respect to the galactic plane: μ_b .

High precision astrometry will allow us to constrain models of the **Galactic warp.**



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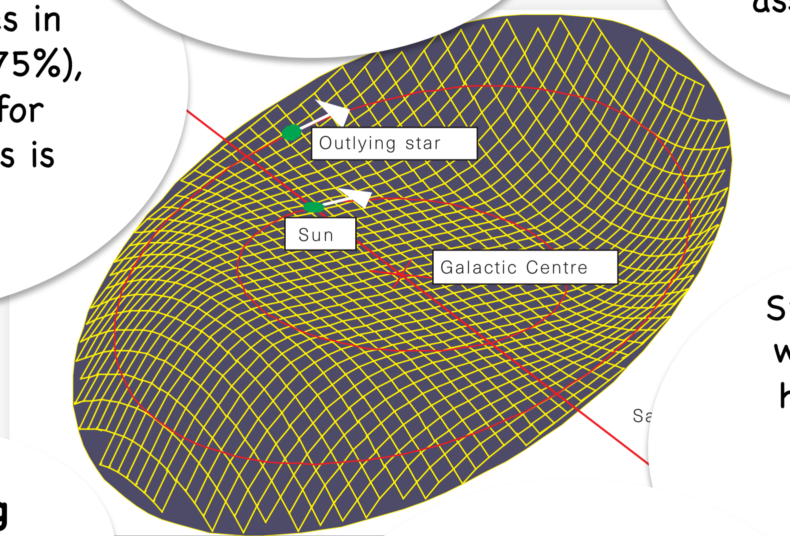


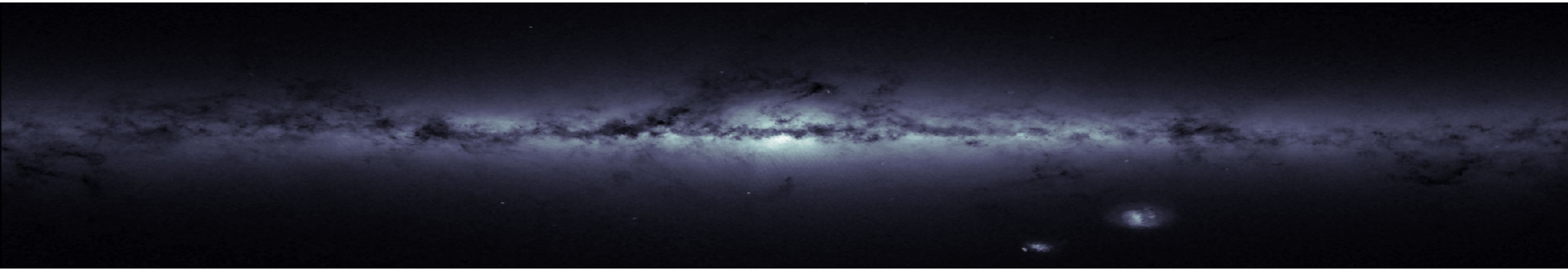
Stars moving in a warped disk will have systematic velocities with respect to the galactic plane: μ_b .

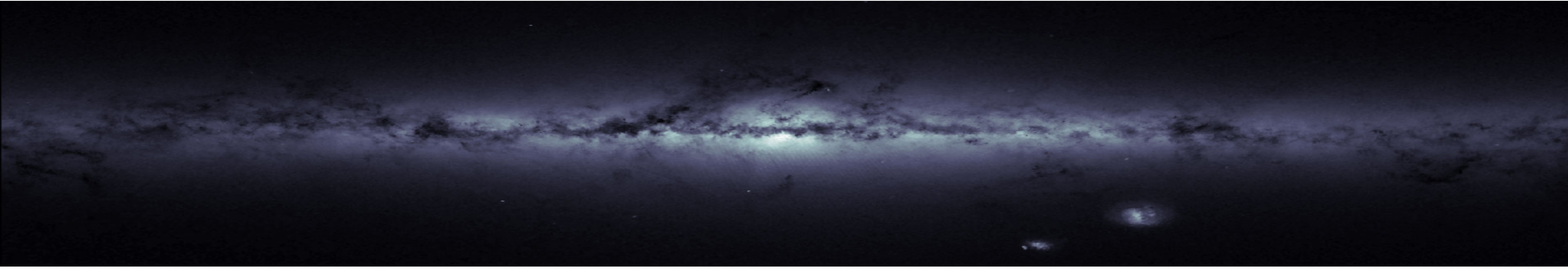
Getting ready for Gaia...

High precision astrometry will allow us to constrain models of the **Galactic warp.**

Section II

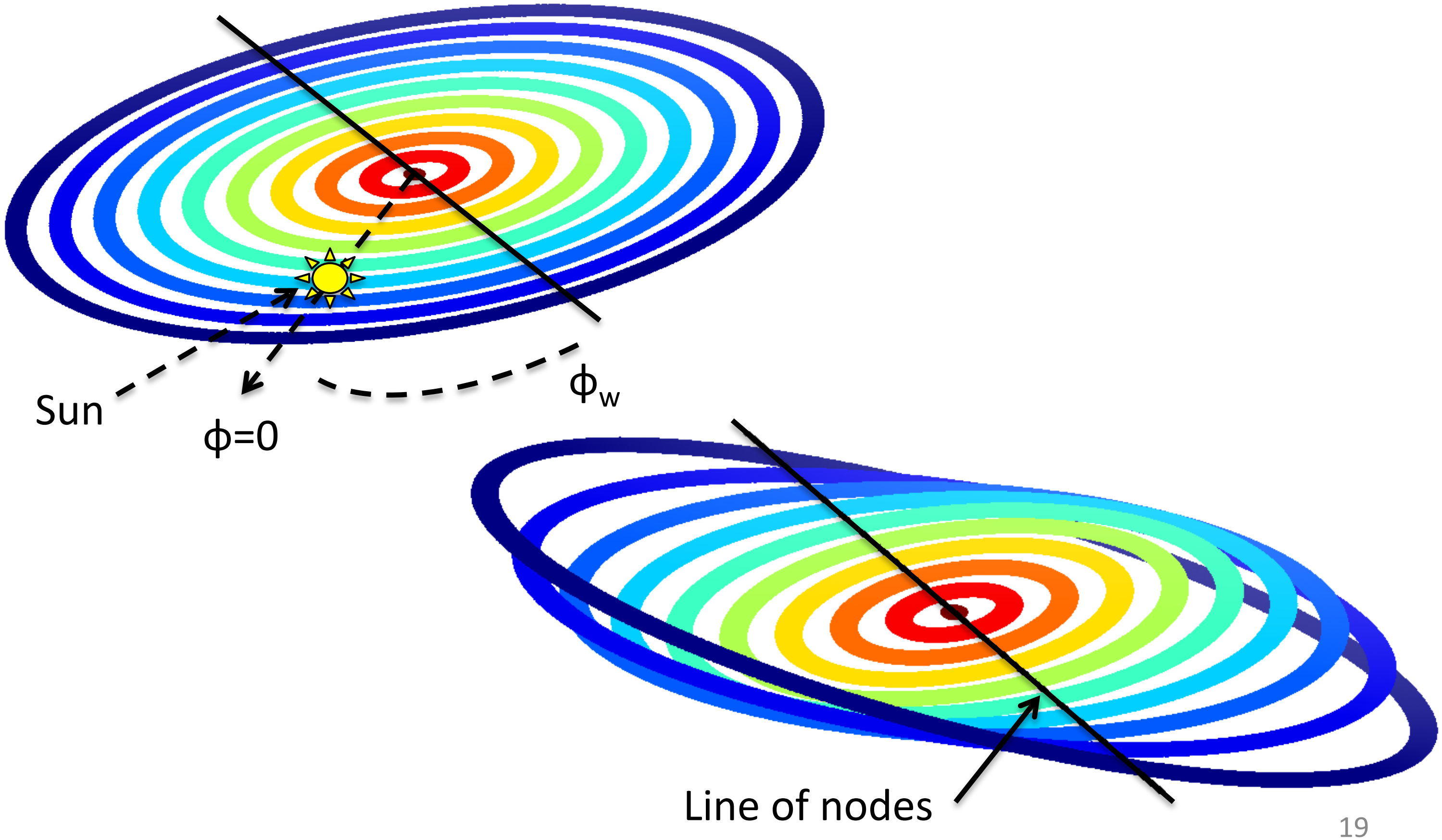
The model

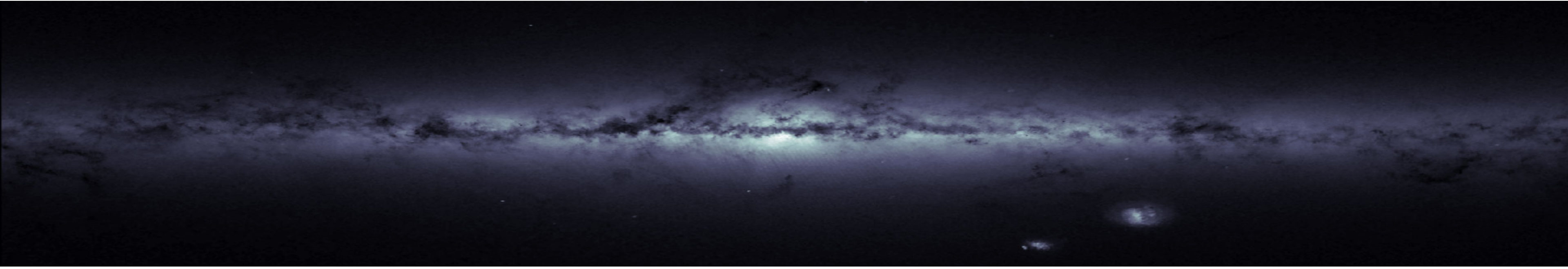




THE MODEL

Let’s warp the Galactic disk!





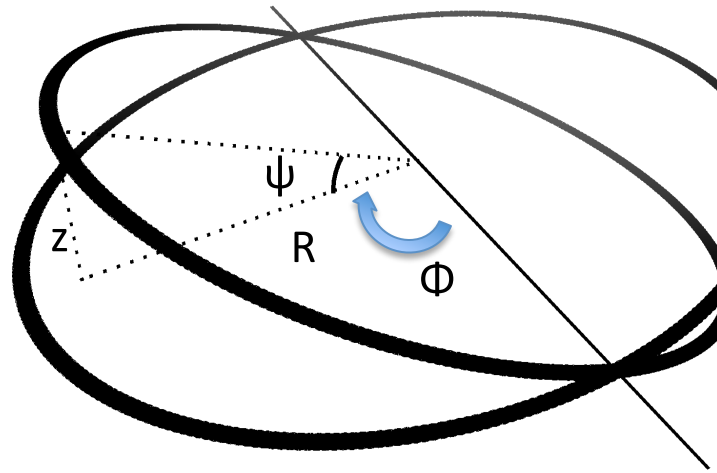
THE MODEL

- Spatial warp:

$$z(\phi) = z_{max}\, sin(\phi)$$

$$\Downarrow$$

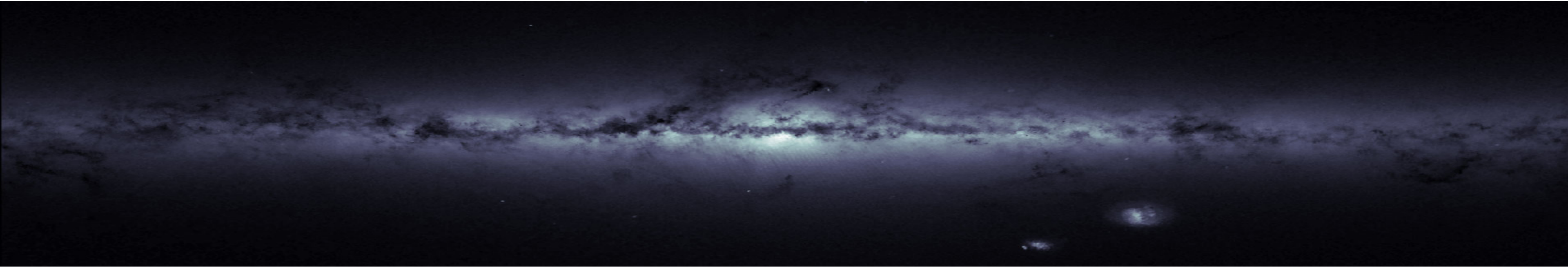
$$h(R)$$



Height function $h(R) = \begin{cases} 0, & \text{if } R < R_w \\ (R - R_w)^2/R_h, & \text{if } R < R_w \end{cases}$

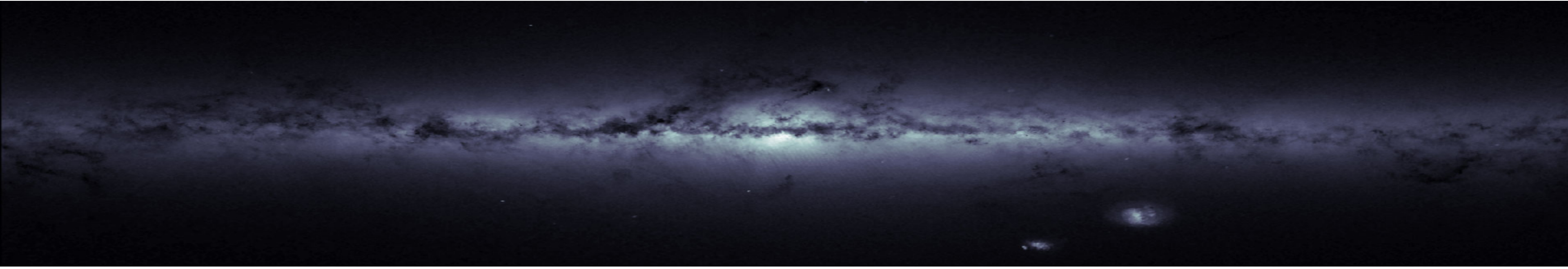
$$z(t, R, \phi) = h(R)\, sin(\phi + \phi_w + \omega_p t)$$

From observations: $\phi_w \cong 0$



THE MODEL

- Kinematics is the key element for determining the nature of the Galactic warp (i.e. stable or transient feature)
- It is convenient to study the vertical component of the velocity $\bar{v}_z(R, \phi)$
- Galaxy: collisionless system, stars moving under the influence of a smooth potential
- Apply the collisionless boltzmann equation to a warped disk

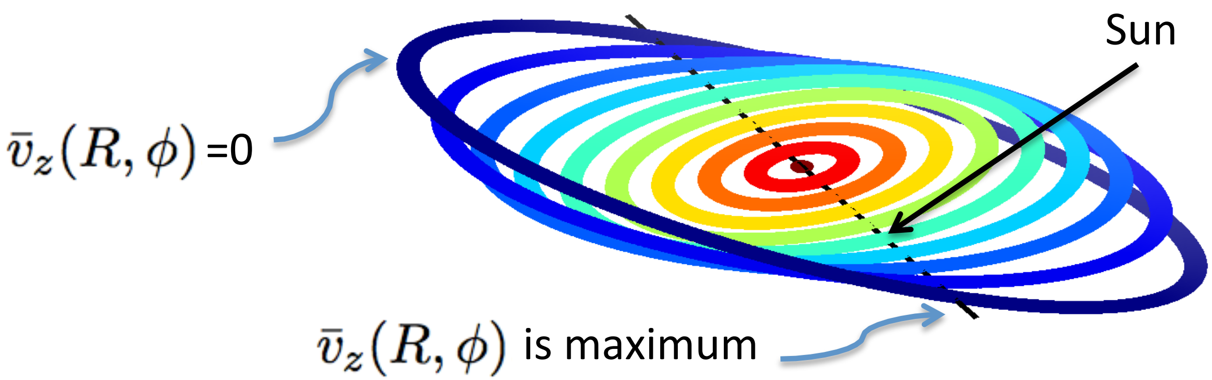


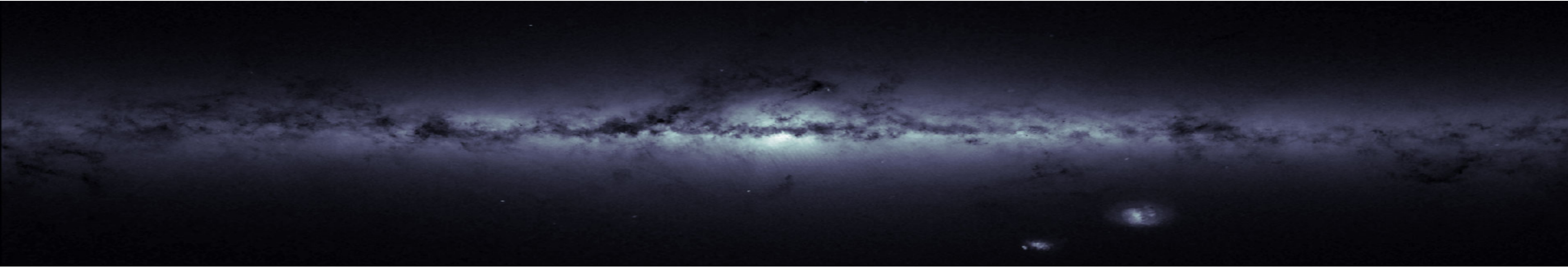
THE MODEL

- For $\omega_p = \text{const}$ we obtain:

$$\bar{v}_z(t, R, \phi) = \left(\frac{\bar{v}_\phi}{R} + \omega_p\right) h(R)\, cos(\phi + \phi_w + \omega_p t)$$

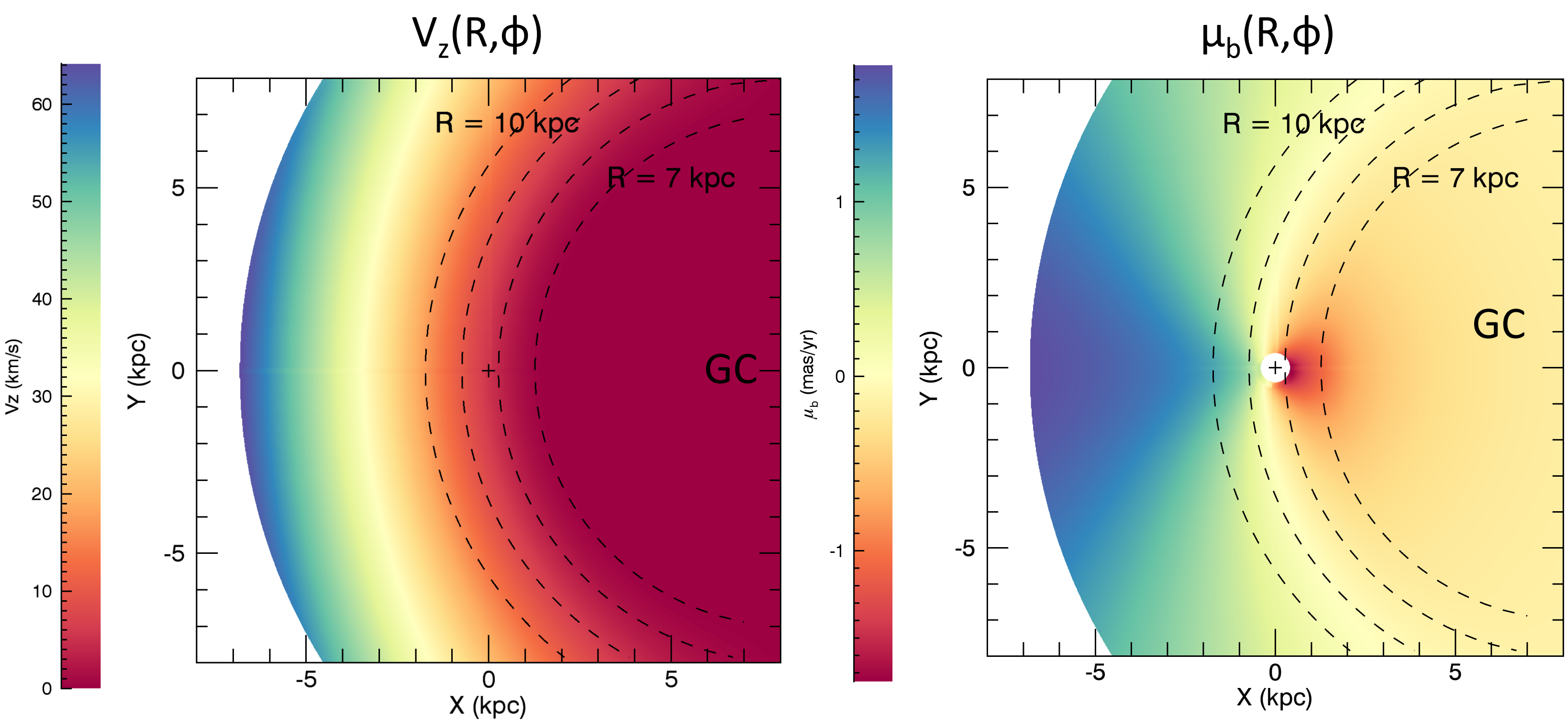
- For a long-lived warp:





Expectation for a long-lived non-precessing warp

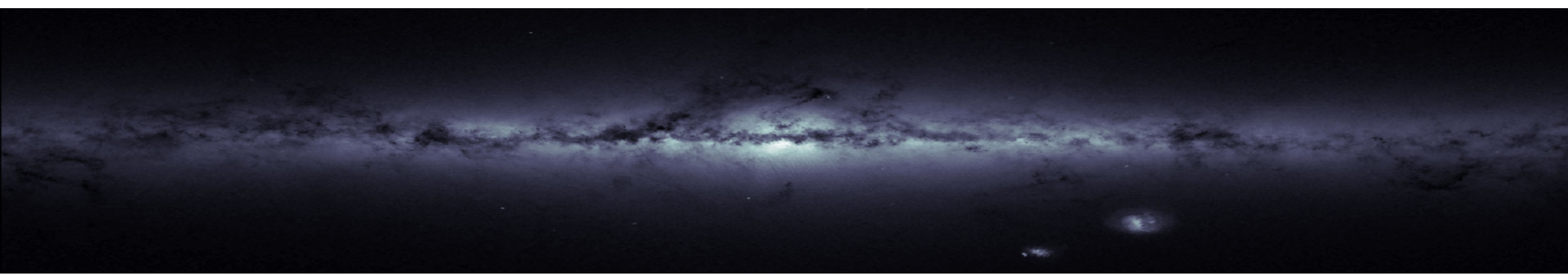
THE MODEL

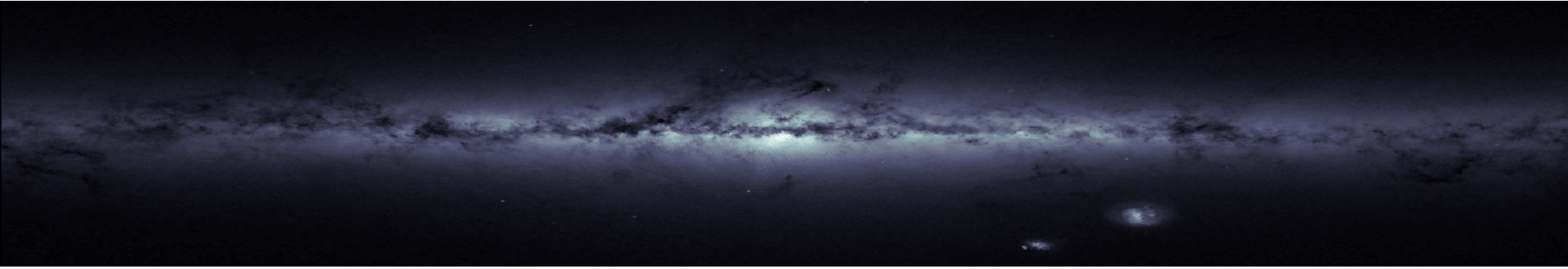


Section III

Data

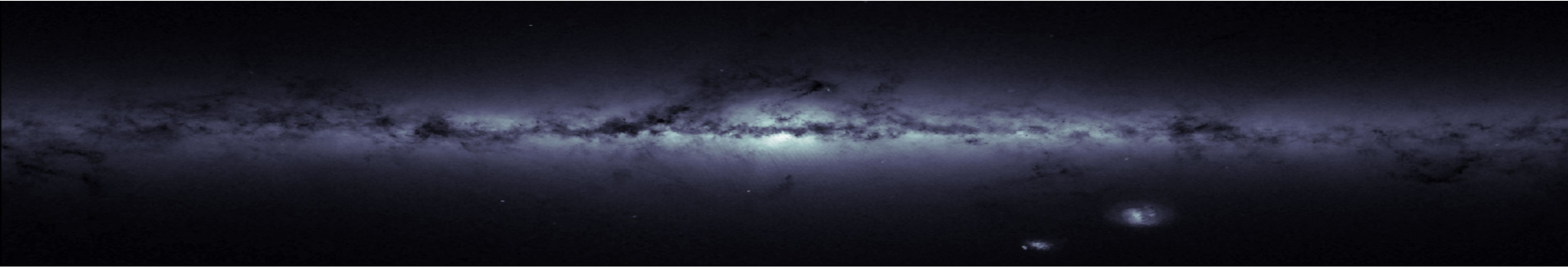
Distance errors



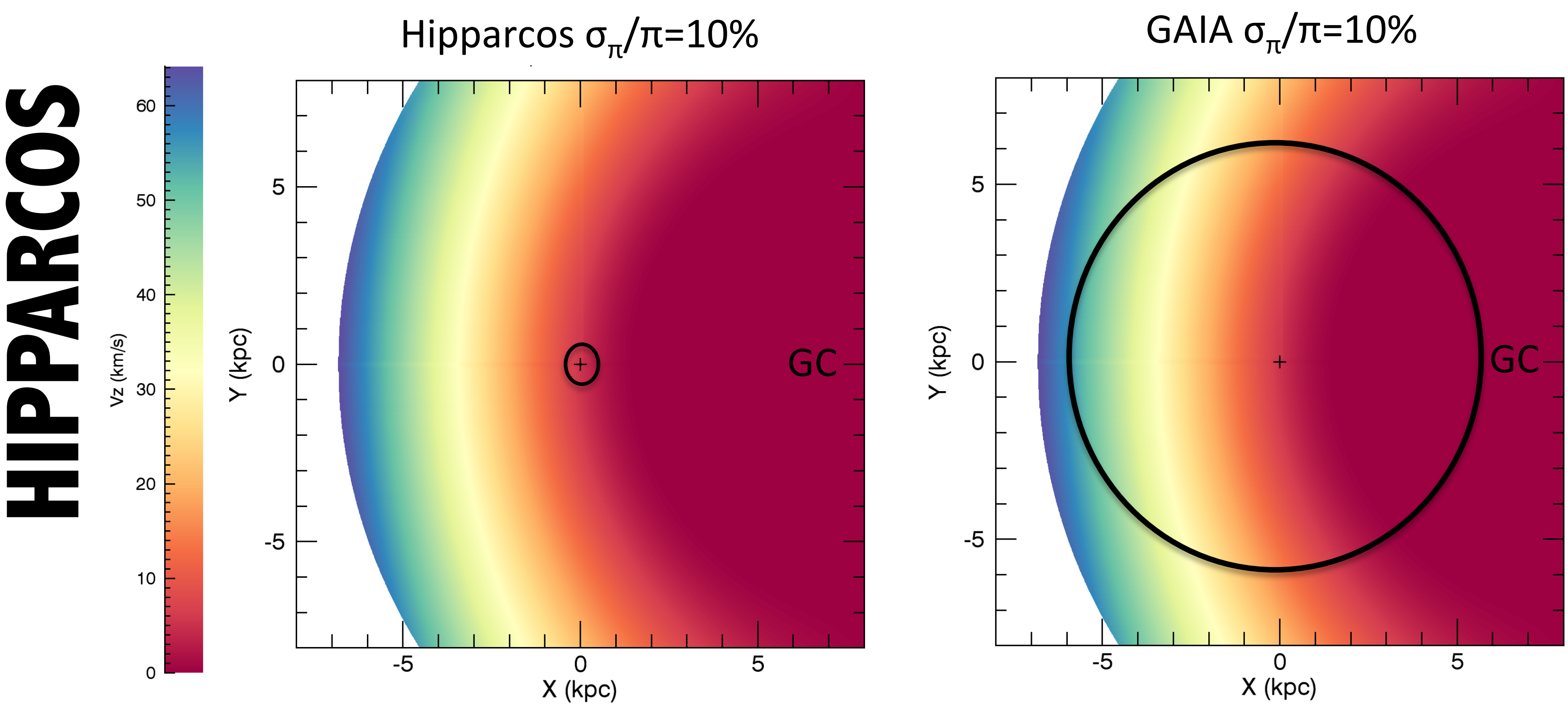


DATA

- Hipparcos catalogue, the New Reduction (Van Leeuwen, 2007)
- Same approach as Smart et al. (1998) and Drimmel (2000) with new data
- OB3 stars were selected, because:
  - they trace the gaseous disk
  - they can be seen to large distances
- For distances beyond 500 pc, Hipparcos parallaxes are not sufficiently precise: we use spectro-photometric distances
- Parallaxes are only used to remove nearby objects

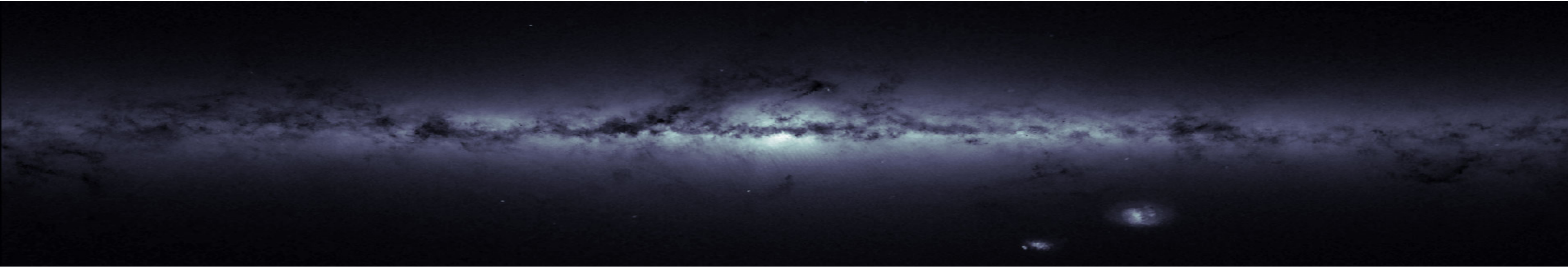


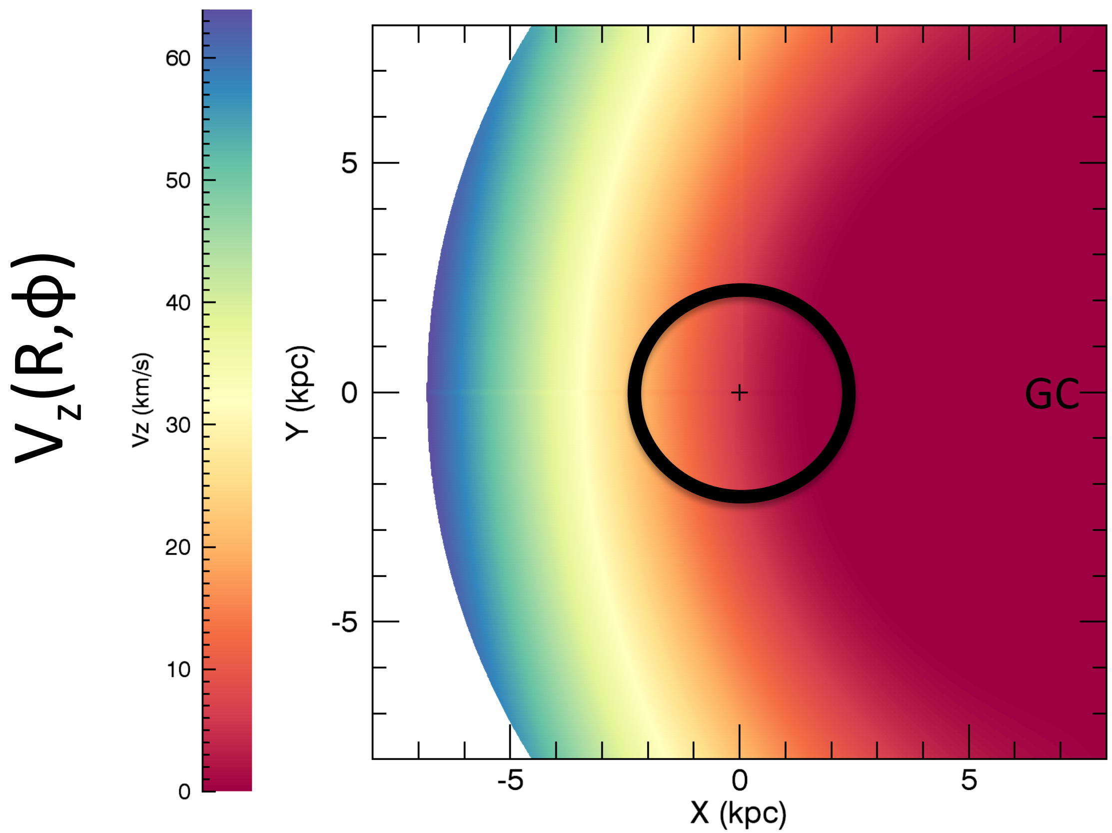
Trigonometric parallax

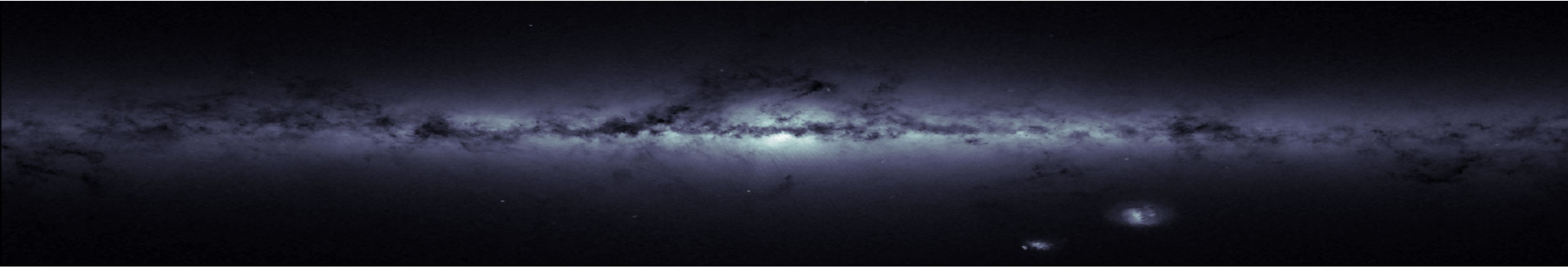


HIPPARCOS

Spectroscopic parallax







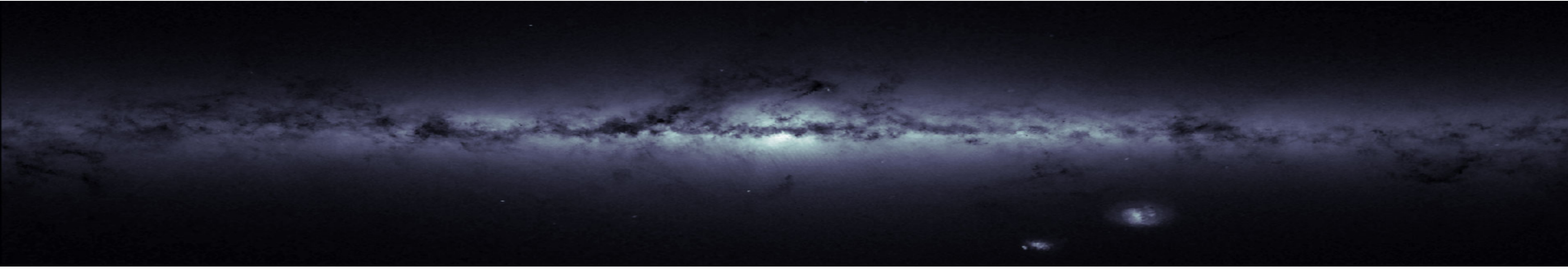
SPECTRO-PHOTOMETRIC DISTANCES

- The uncertainties on distance estimates give the largest contribution to the uncertainties in velocity

- To minimize errors, the most homogeneous and recent available spectral classification are needed

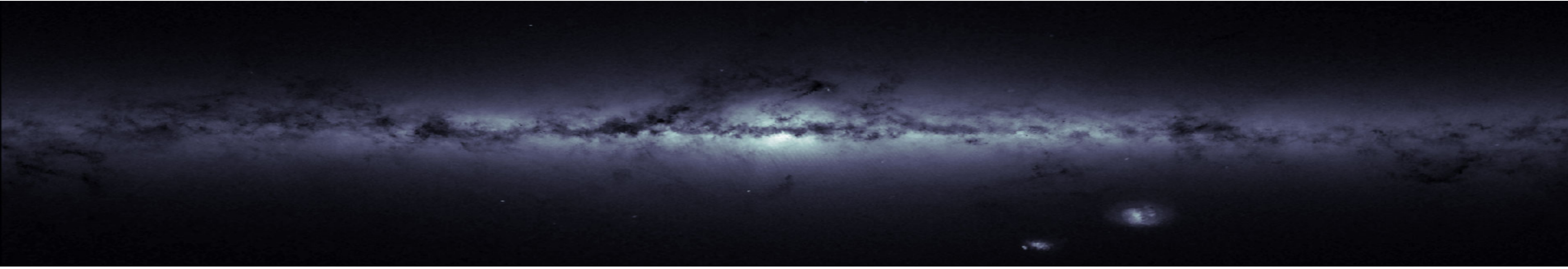
- Sources for spectral classification, in order of preference:

1. The Galactic O-Star Spectroscopic Survey (GOSSS) (Sota, 2014)
2. the Michigan Catalogue of HD stars (Houk, 1999)
3. the most recent classification furnished by Catalogue of Stellar Spectral Classification (Skiff, 2009).



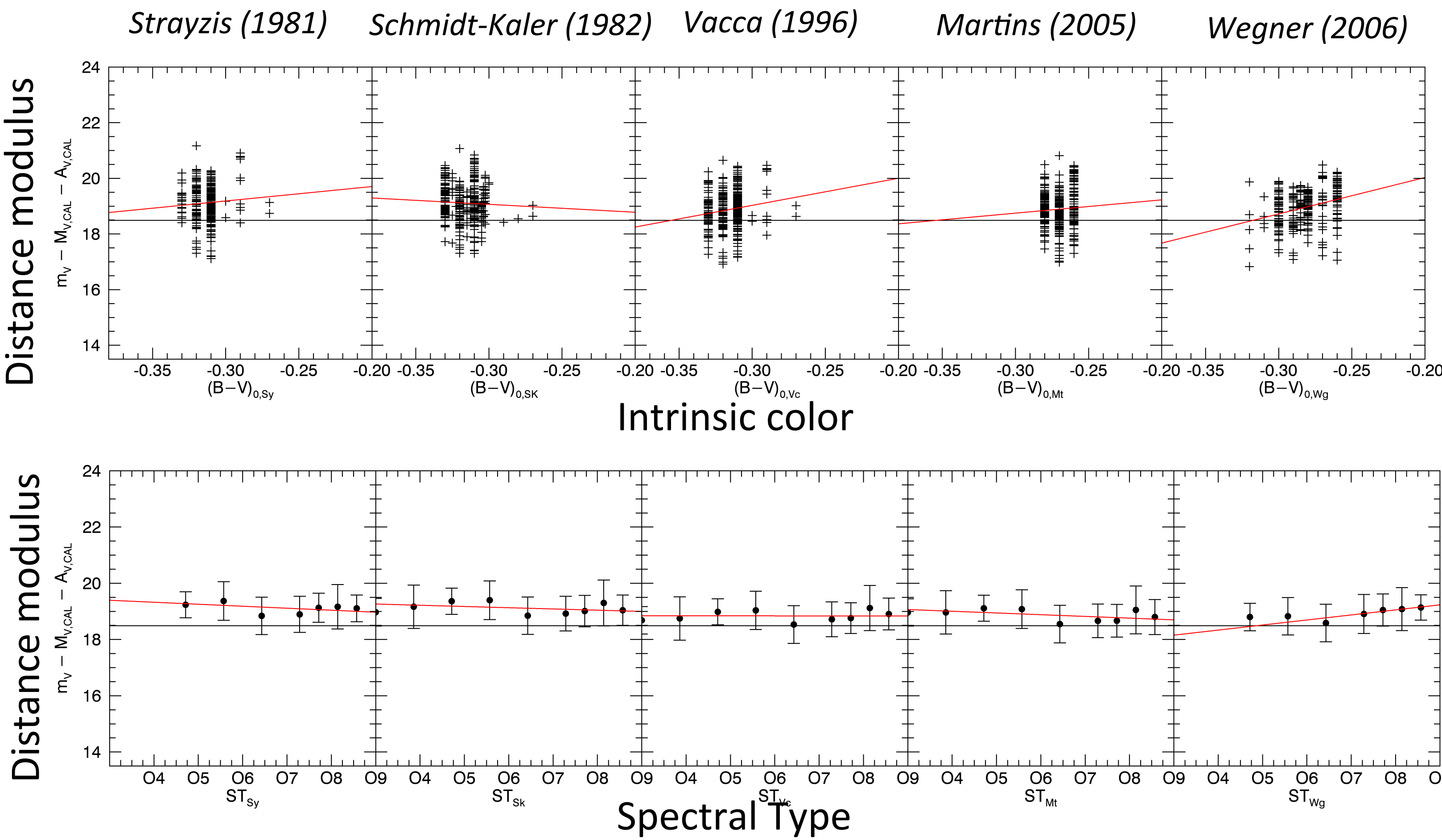
SPECTRO-PHOTOMETRIC DISTANCES

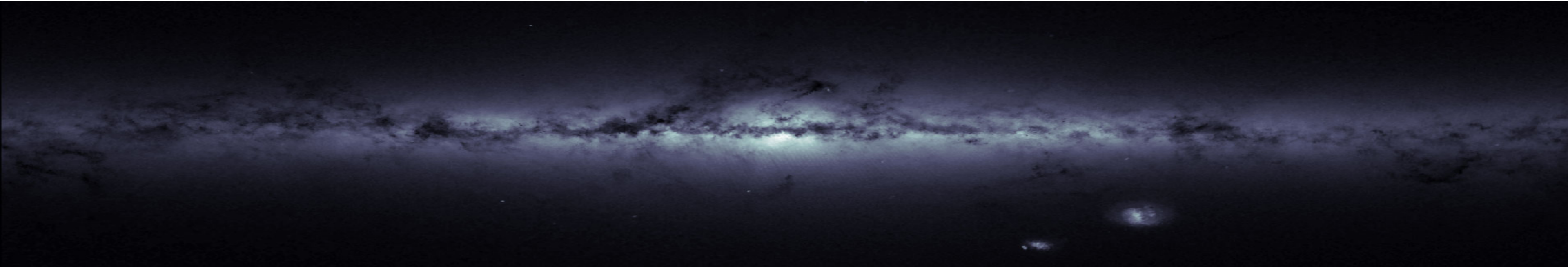
- We performed a test to study absolute magnitude and intrinsic color calibrations
- We used the Tarantula nebula (NGC 2070, 30 Doradus) in the LMC as laboratory to work with a copious number of massive stars located with good approximation at the same distance from the Sun
- The VLT-Flames Tarantula Survey ESO Large Programme (Evans,2011)



- 352 O stars, spectral classification from Doran (2013)

O STARS





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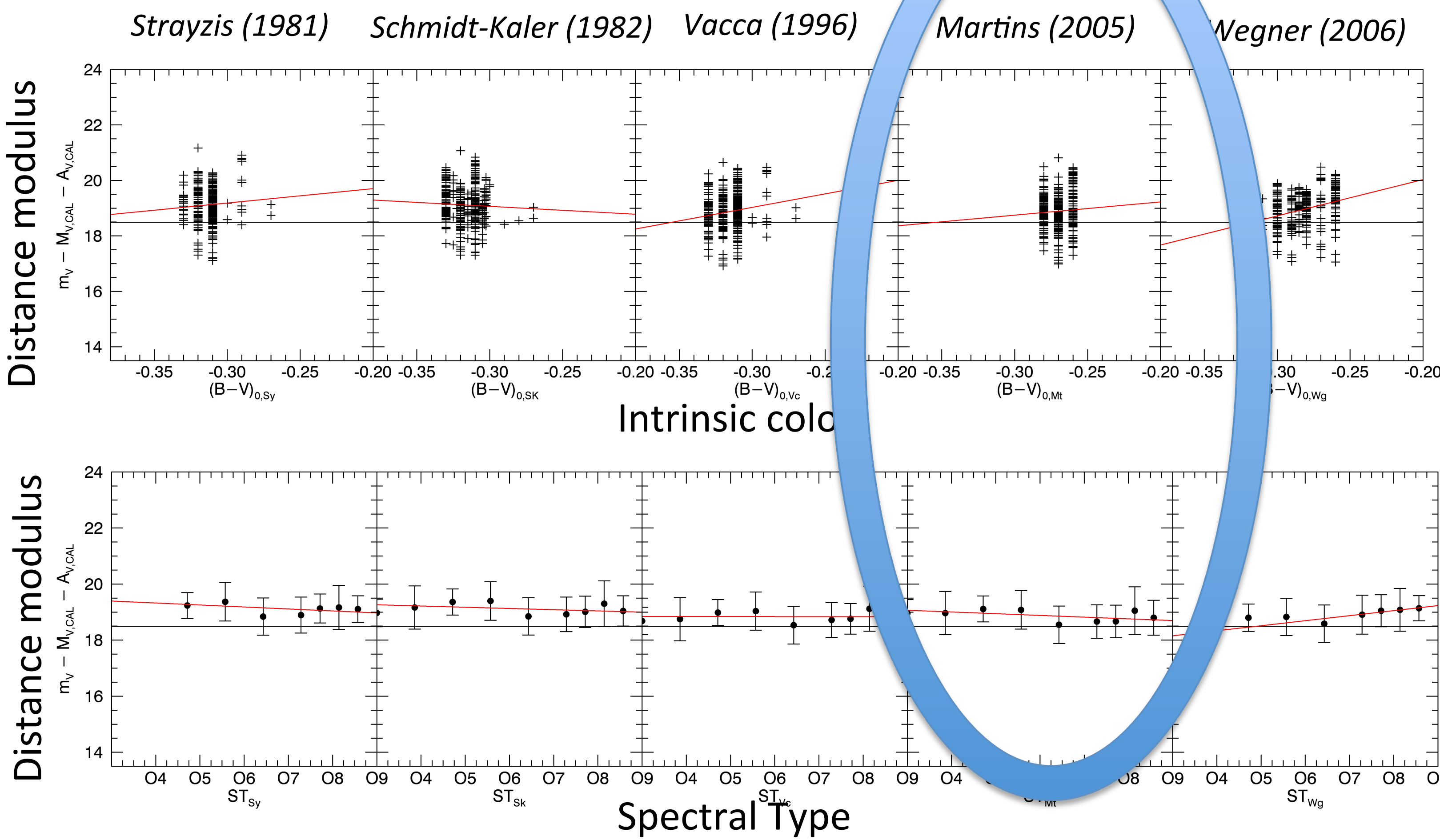
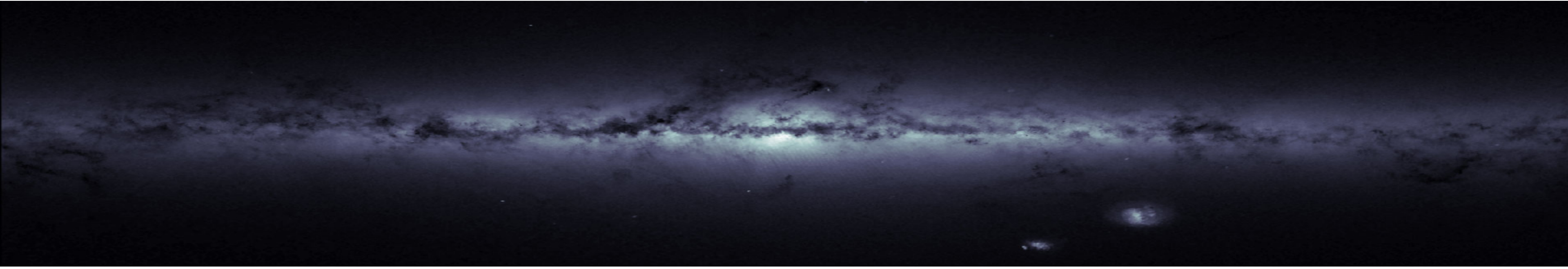
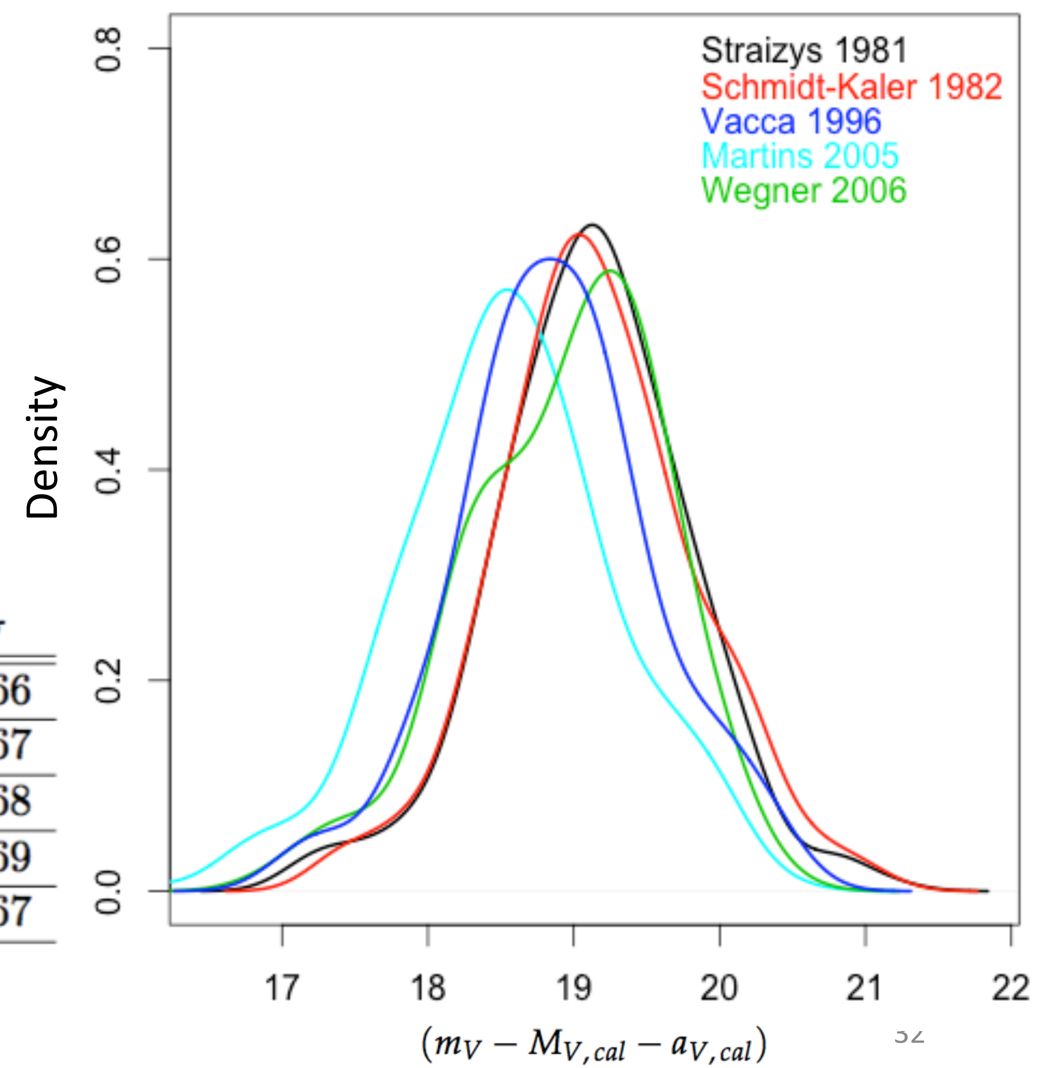
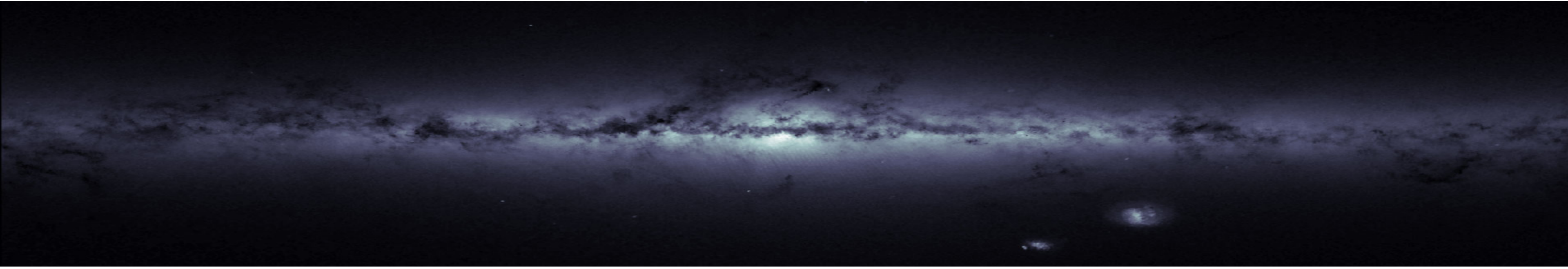




O STARS

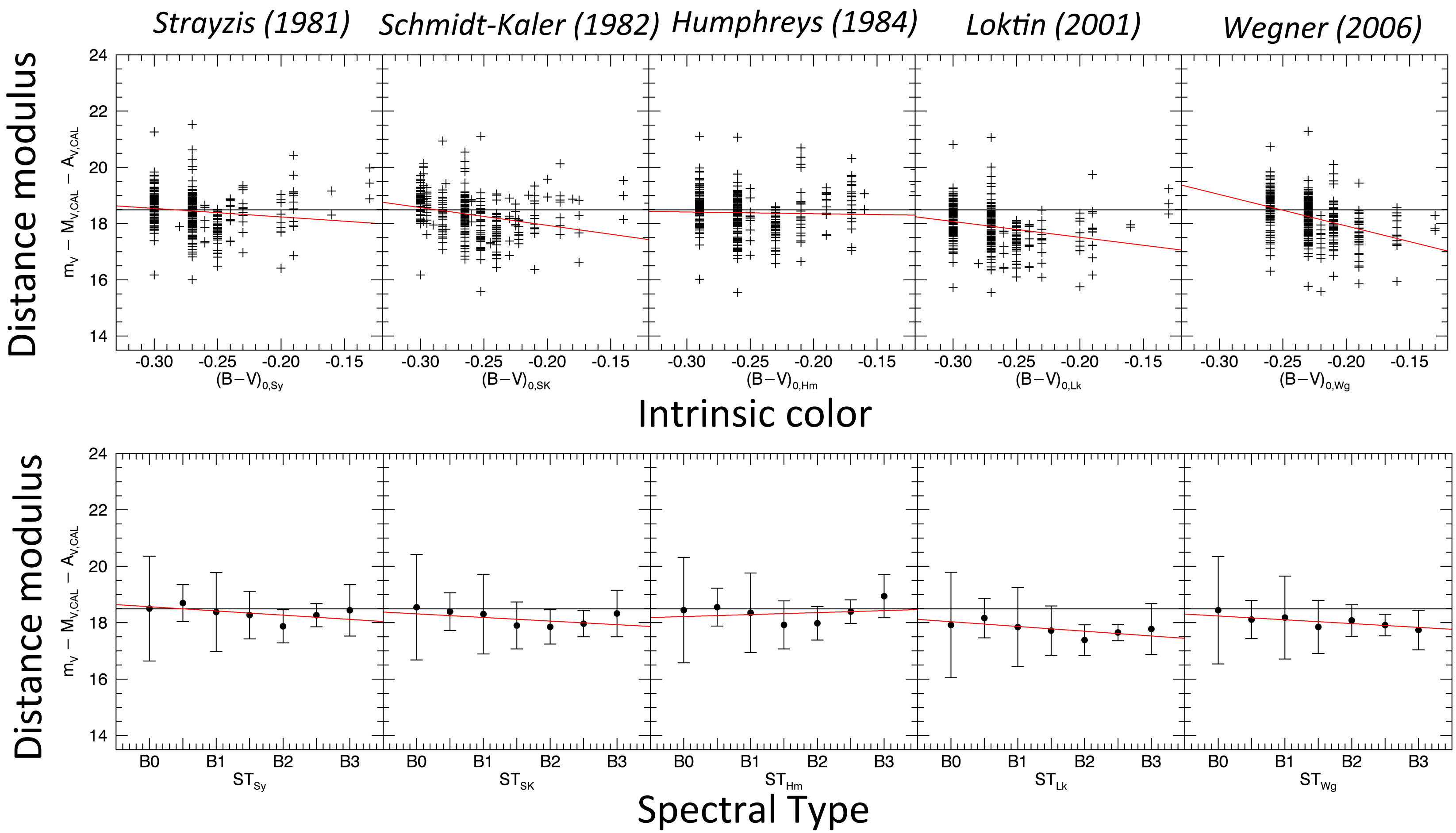
	$\overline{(m-M)}$	σ
Strayzis (1981)	19.12	0.66
Schmidt-Kaler (1982)	19.15	0.67
Vacca (1996)	18.87	0.68
Martins (2005)	18.54	0.69
Wegner (2006)	18.94	0.67

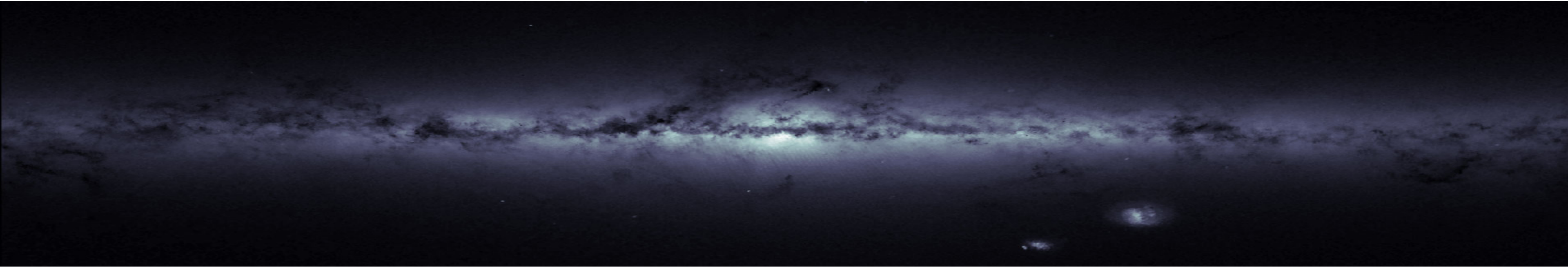




B STARS

- 416 B stars, spectral classification from Evans (2015)





B STARS

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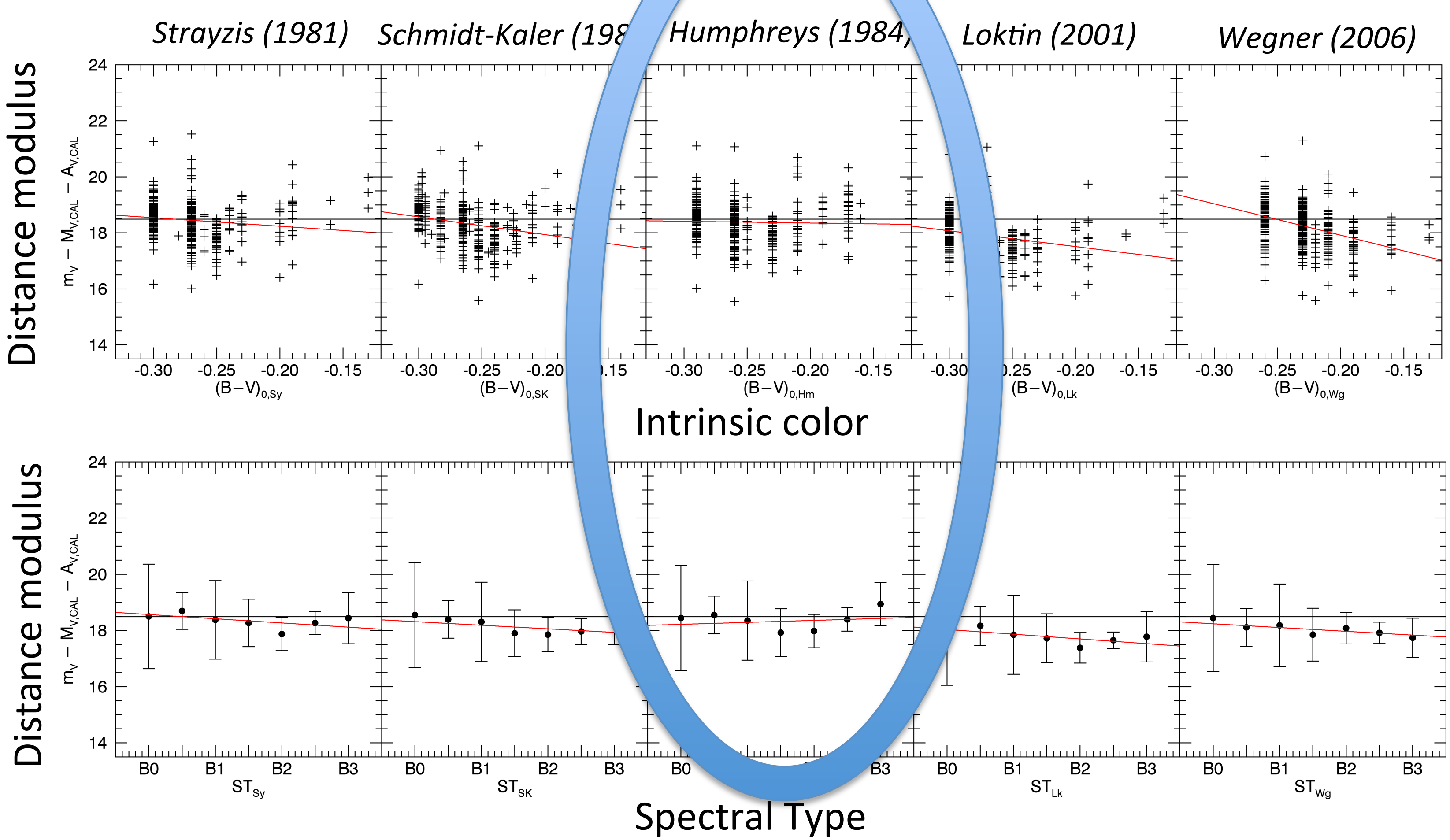
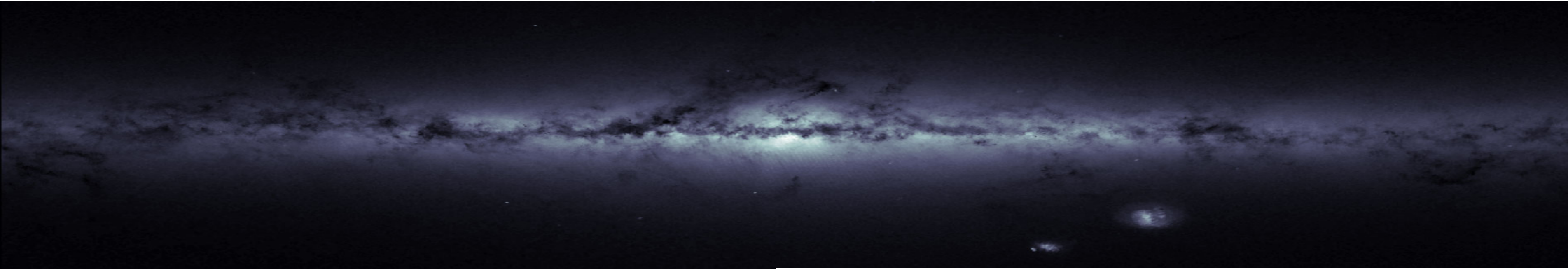
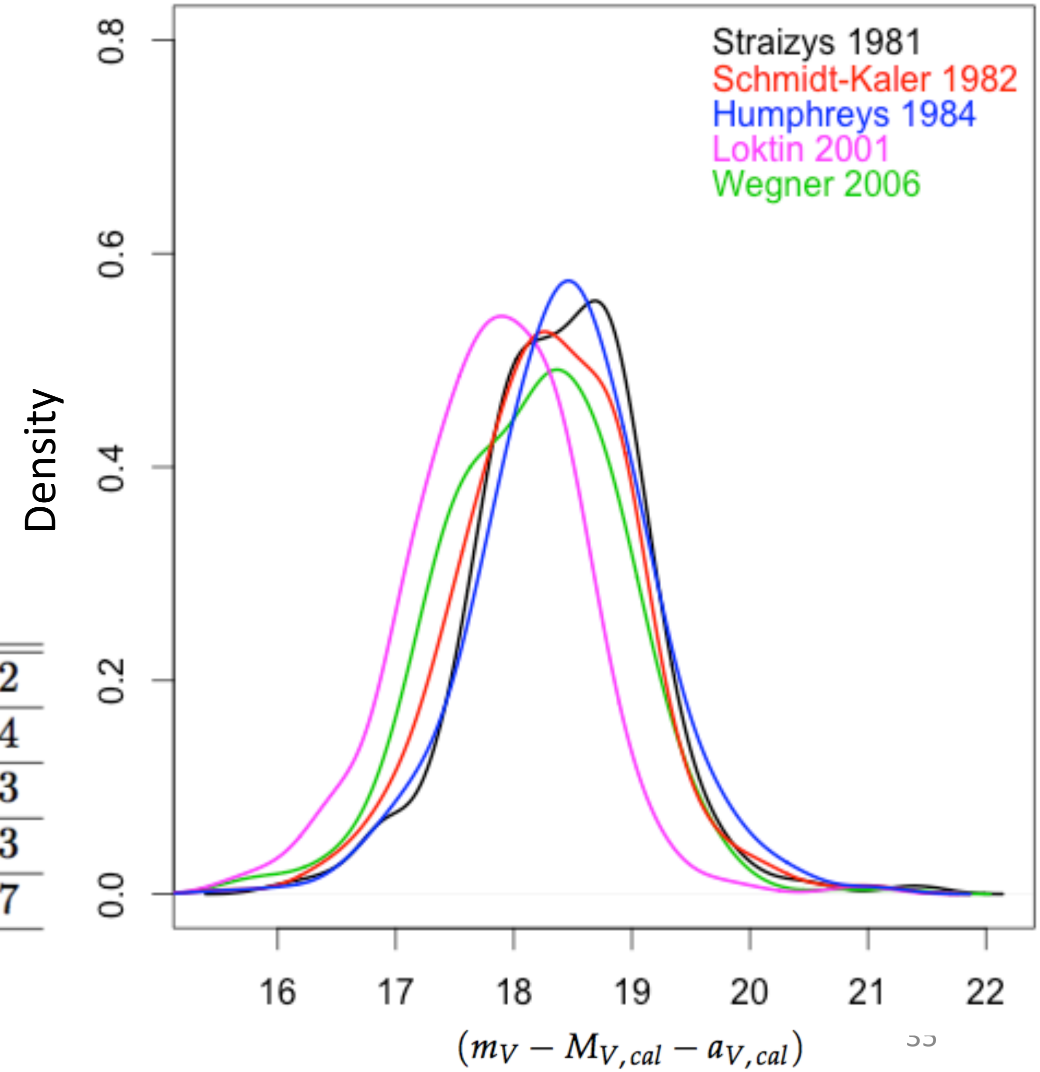
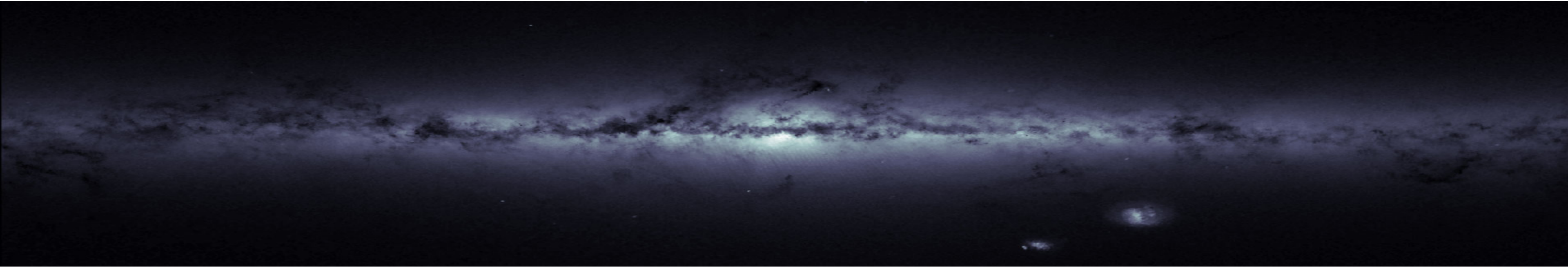




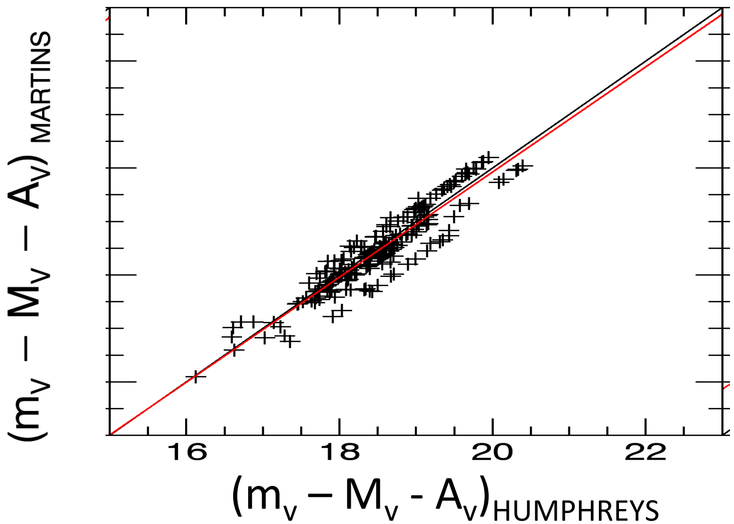
B STARS

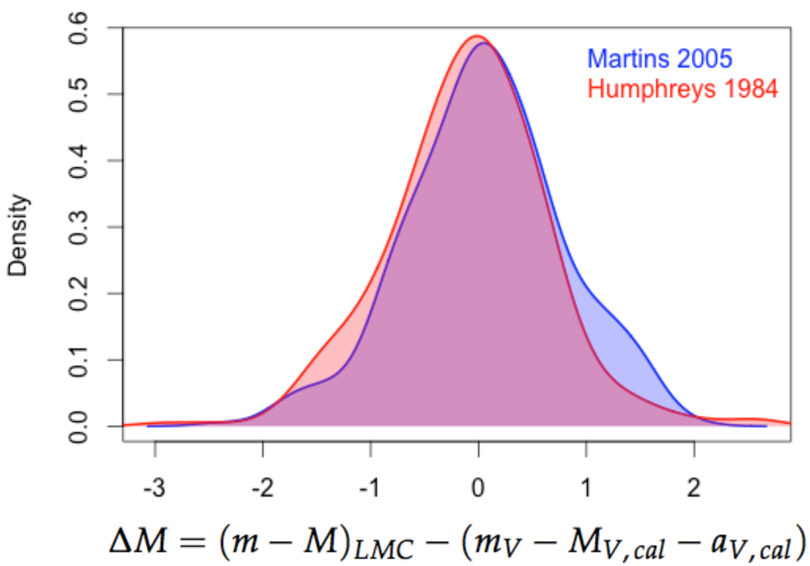
	$\overline{(m-M)}$	σ
Strayzis (1981)	18.40	0.72
Schmidt-Kaler (1982)	18.29	0.74
Humphreys (1984)	18.44	0.73
Loktin (2001)	17.84	0.73
Wegner (2006)	18.16	0.77





CALIBRATION





- In the following, Martins and Humphreys calibration are adopted (for the O and for the B0-B3 stars respectively)
- With this exercise, we can estimate the error on distance modulus as

$\sigma_{m\text{-}M} = 0.7$ mag

$$(m - M)_{LMC,MT} = 18.54 \pm 0.69$$
$$(m - M)_{LMC,HM} = 18.44 \pm 0.72$$

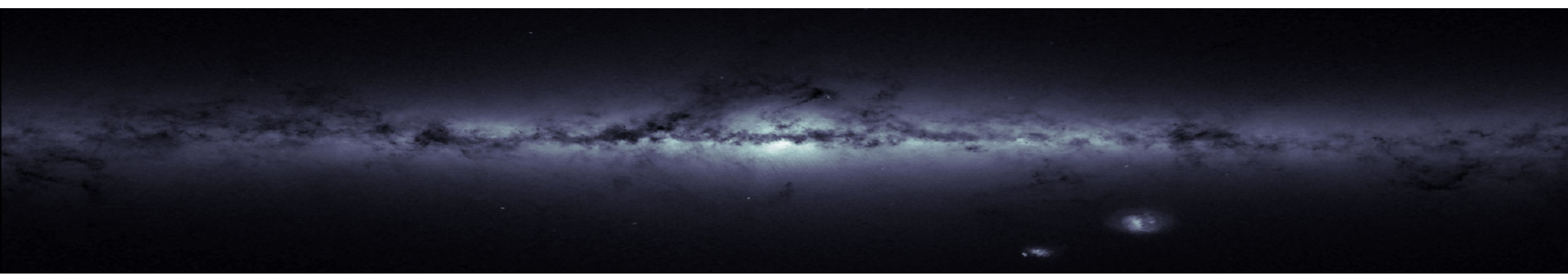
$$(m - M)_{LMC} = 18.49 \pm 0.13$$

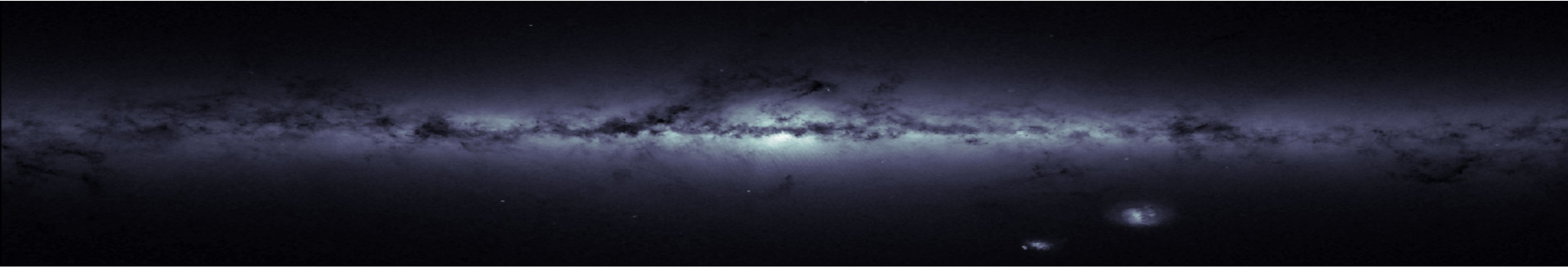
Grijs et al. (2014)

Section IV

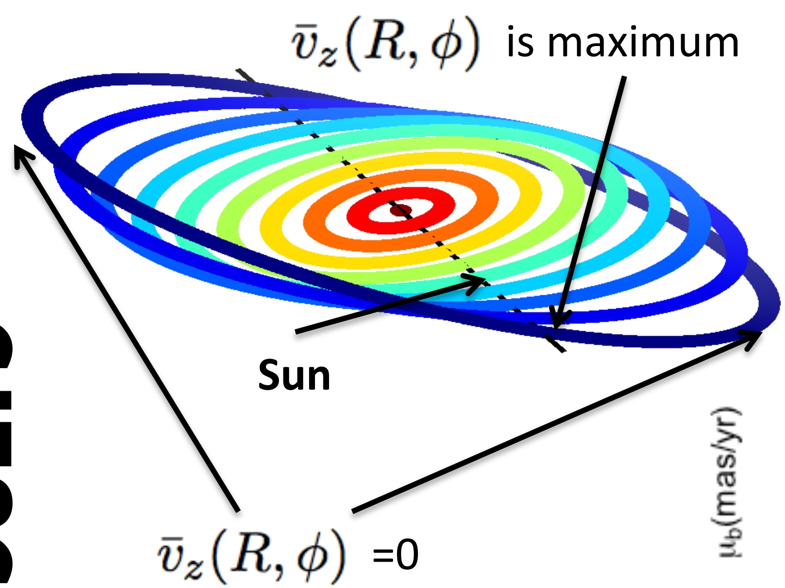
Results

Comparison with simulations

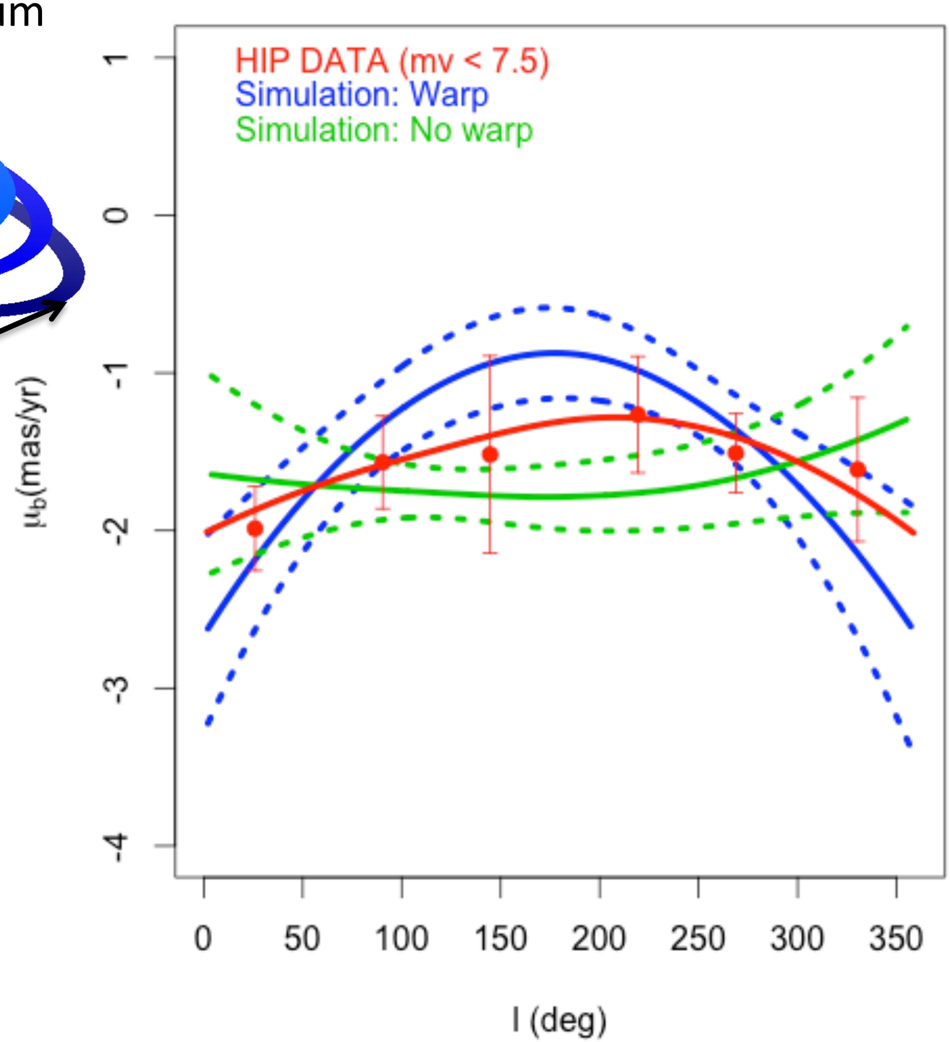




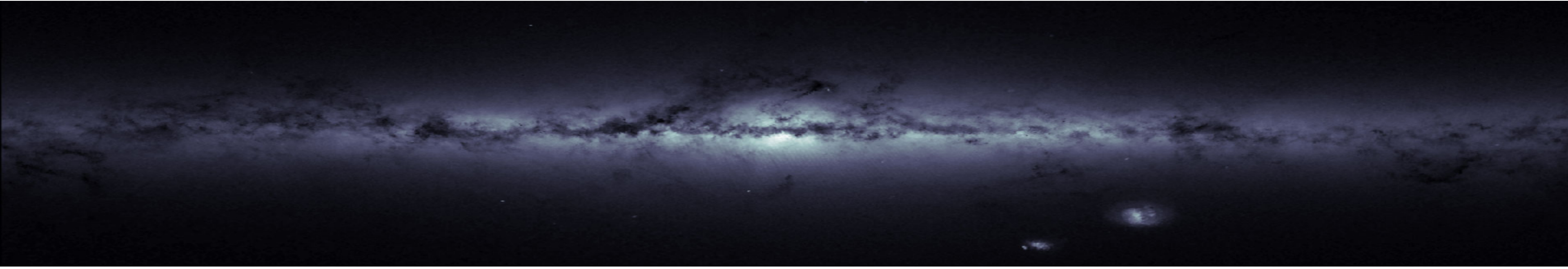
RESULTS



$\bar{v}_z(R, \phi)$ is maximum
Sun
$\bar{v}_z(R, \phi)$ =0

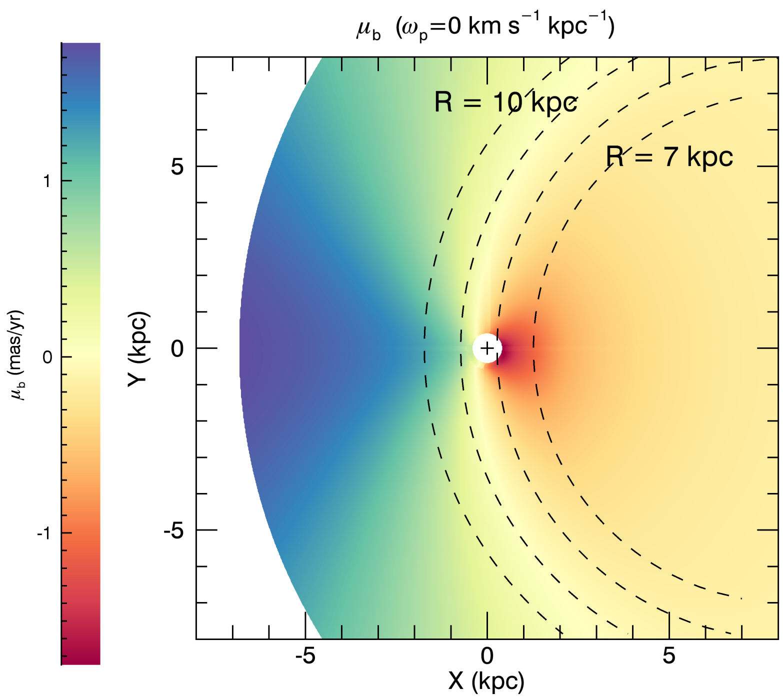


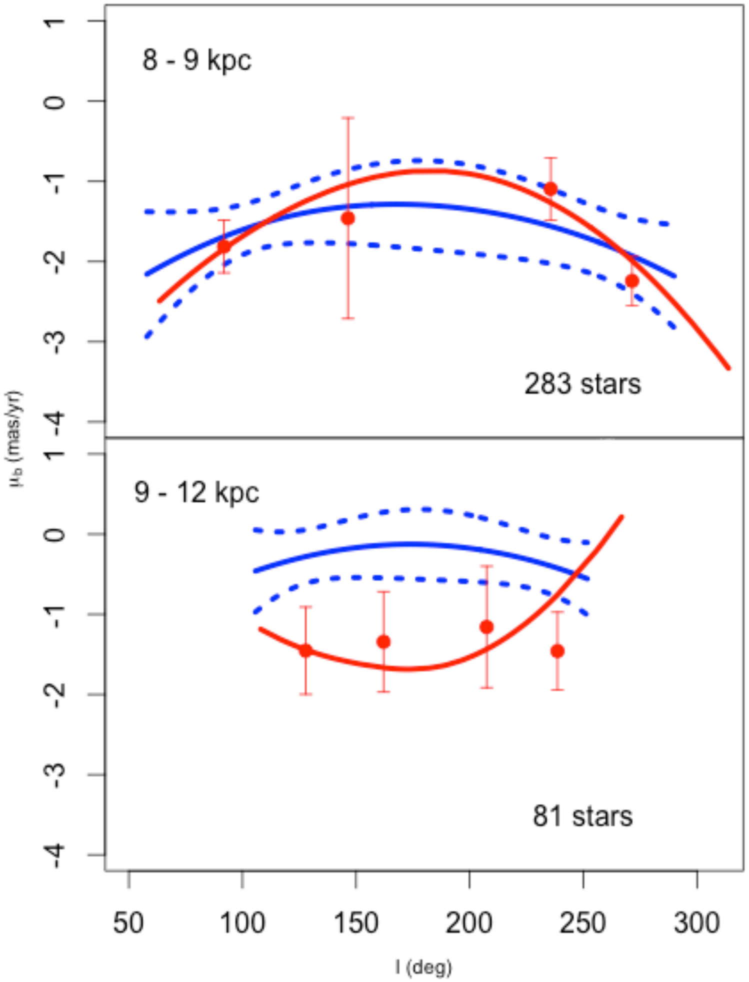
HIP DATA (mv < 7.5)
Simulation: Warp
Simulation: No warp
μ_b(mas/yr)
l (deg)
1
0
-1
-2
-3
-4
0
50
100
150
200
250
300
350

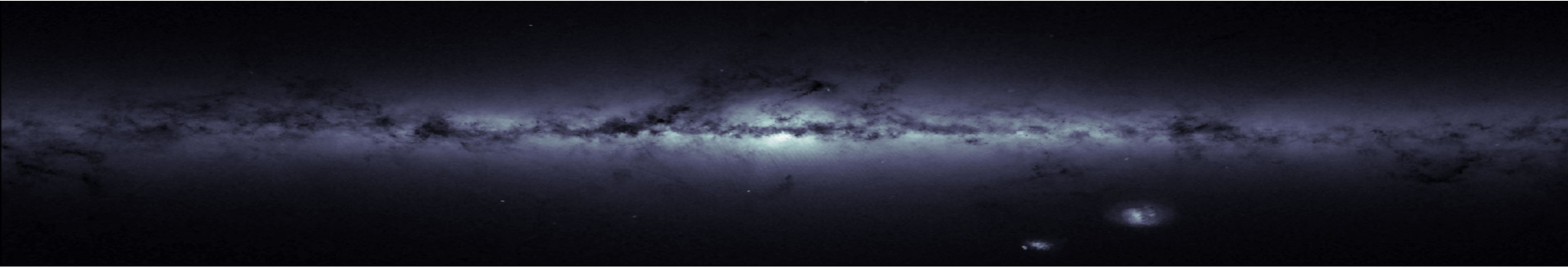


RESULTS

- Binning in Galactocentric radius:







RESULTS

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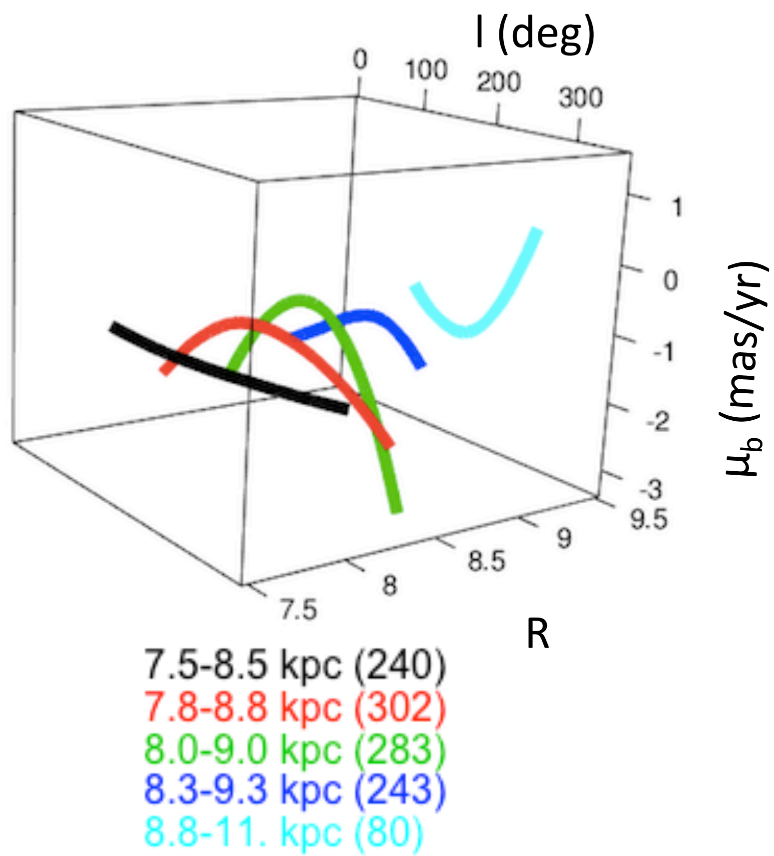
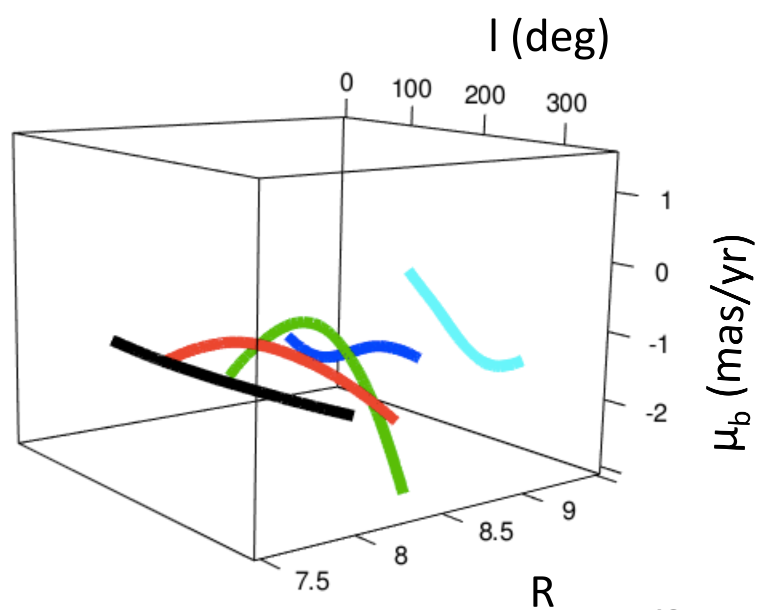
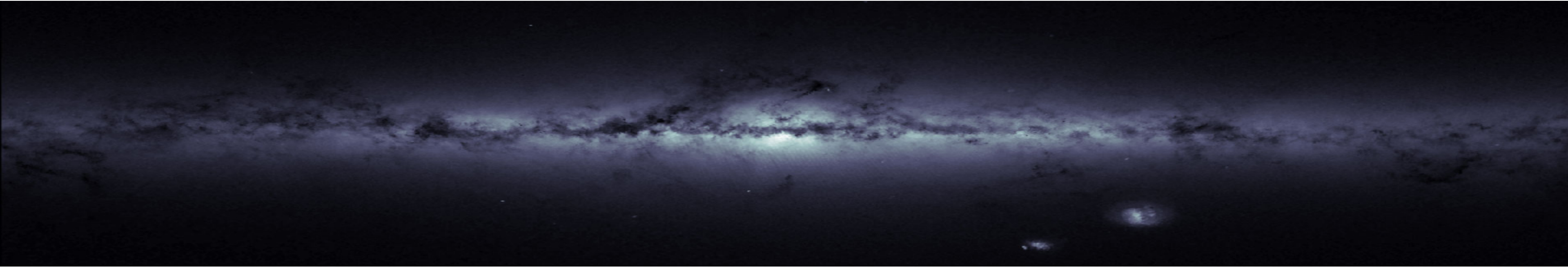


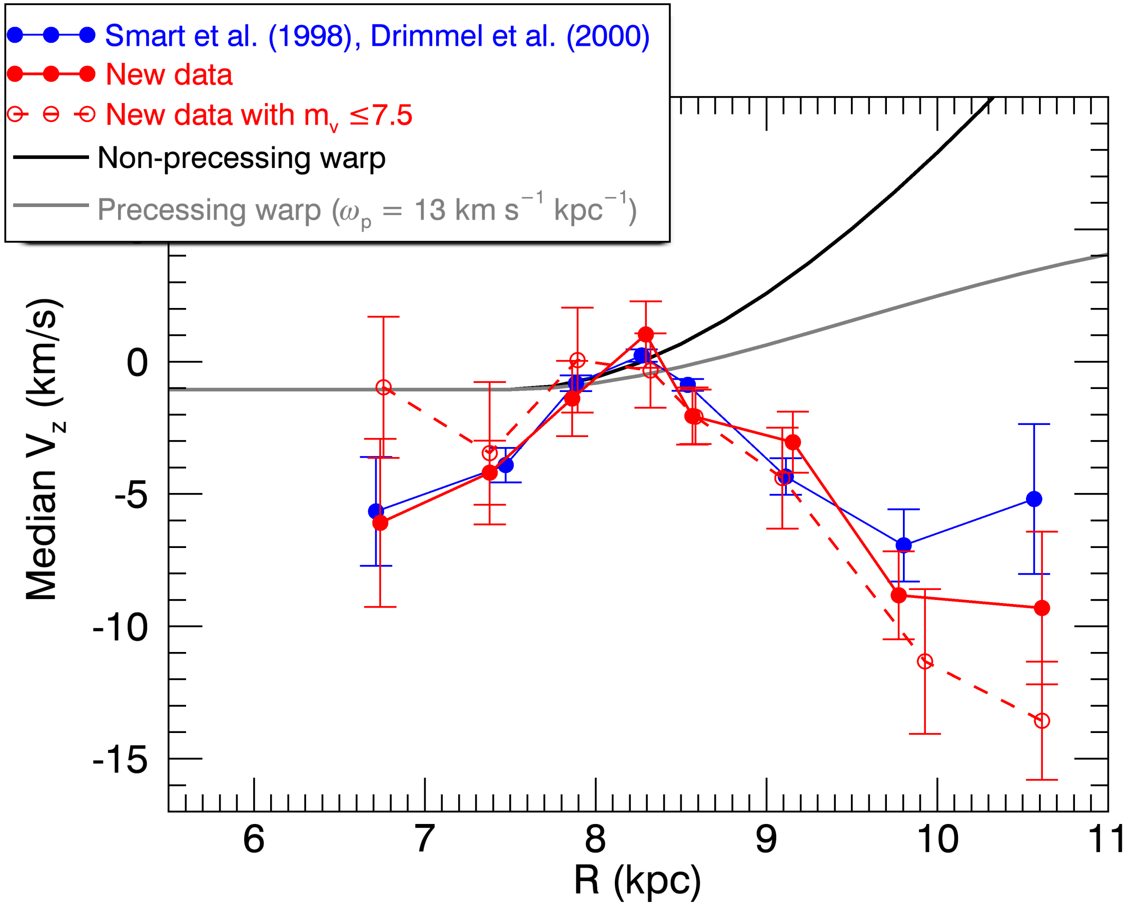
Cut on vertical velocity (50 km/s) to remove 6 runaway stars

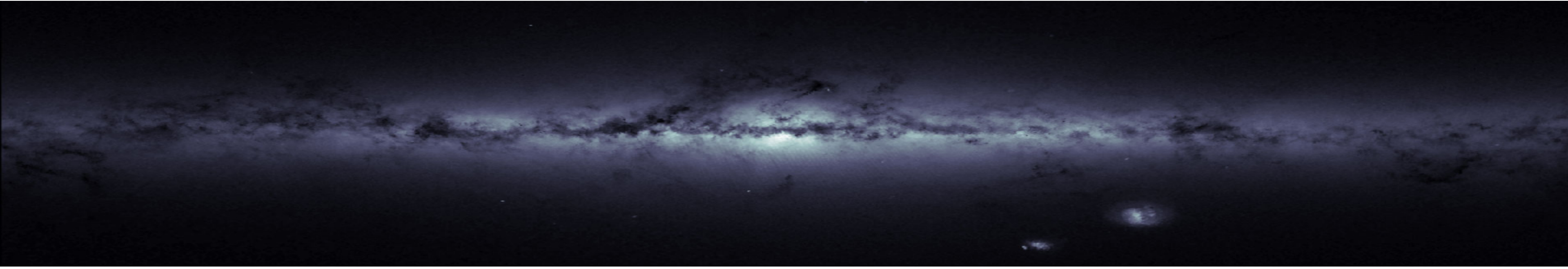




RESULTS

- Vertical velocity:





RESULTS

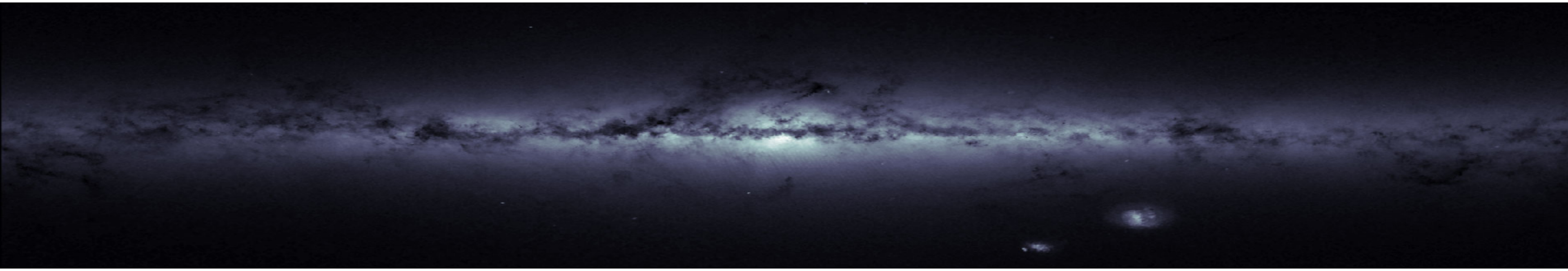
Possible interpretations:

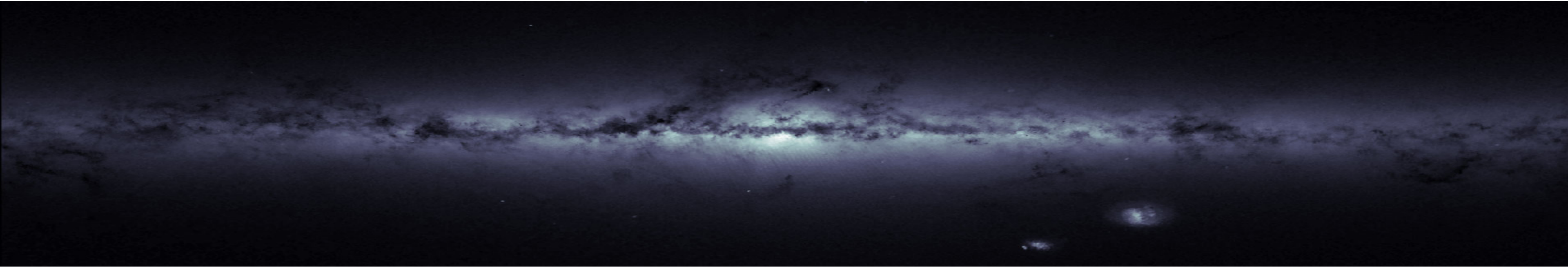
1. The Galactic warp is a transient feature

2. The warp signature is overwhelmed by other "local" systematic vertical motions.

3. There are systematic errors in the Hipparcos proper motions at a level of 1 mas/yr.

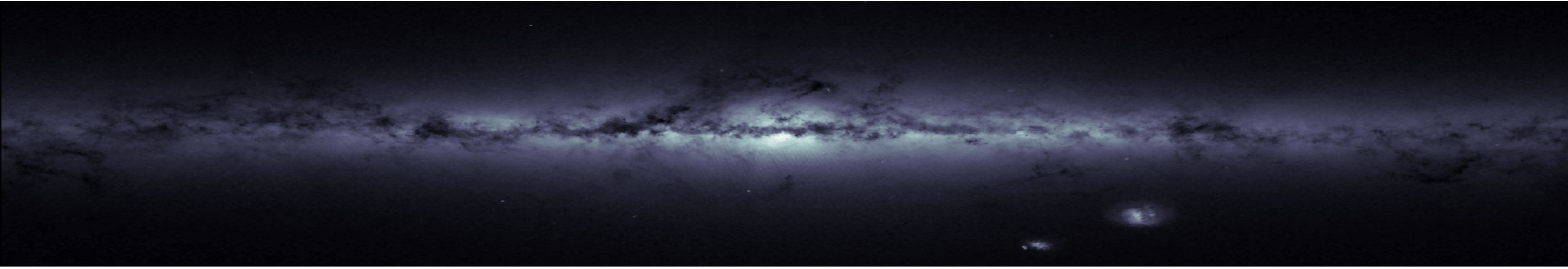
Conclusion and next steps





SUMMARY

- ✓ If the warp is a long-lived feature, we are able to predict the expected trend for the mean vertical velocity
- ✓ We performed a test to study absolute magnitude calibrations and spectro-photometric distances
- ✓ Here **we confirm the previous results** obtained with Hipparcos (Smart et al. 1998; Drimmel et al. 2000) using **new data** and a **different luminosity calibration**



NEXT STEPS

Getting ready for the first Gaia release, which will likely include the TGAS (Tycho-GAIA Astrometric Solution, Michalik, 2015):

- Comparing kinematics of the young stars to old stars.
- Improved modeling of the observations, including possible systematic errors.
- Deriving better distances by combining the astrometric and photometric data.