# SEARCH FOR GALACTIC WARP SIGNAL IN GAIA DR1 PROPER MOTIONS


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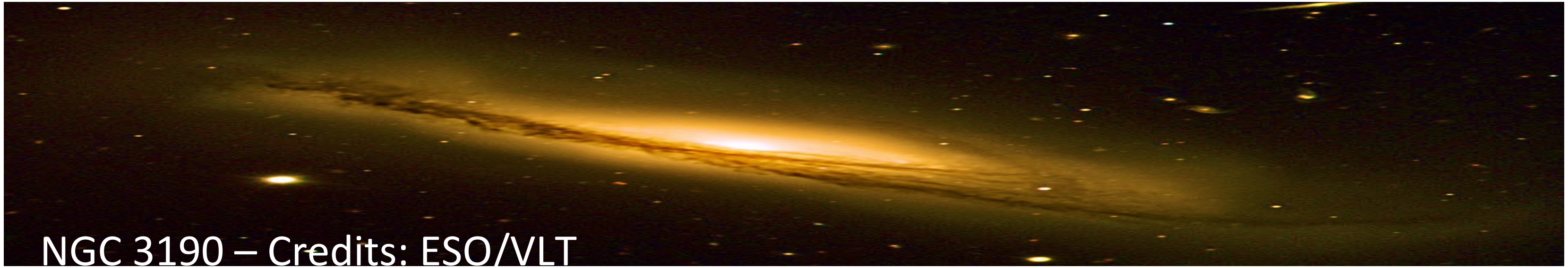

NGC 3190 – Credits: ESO/VLT

# Collaborators:

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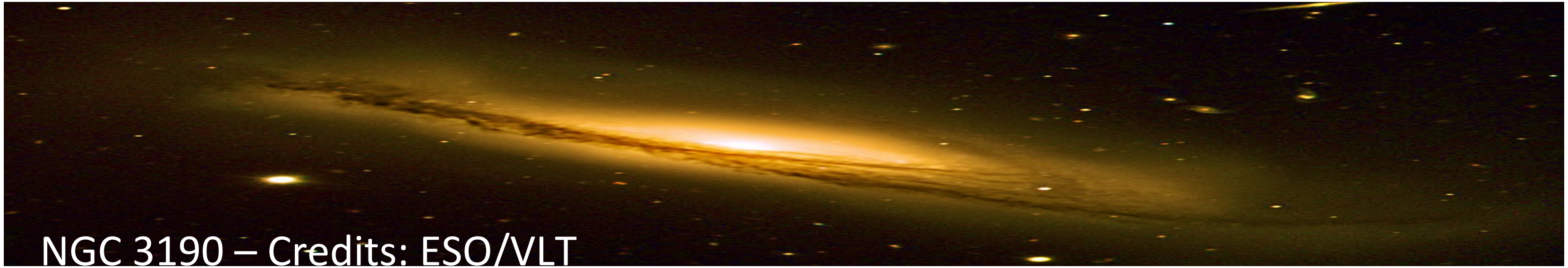
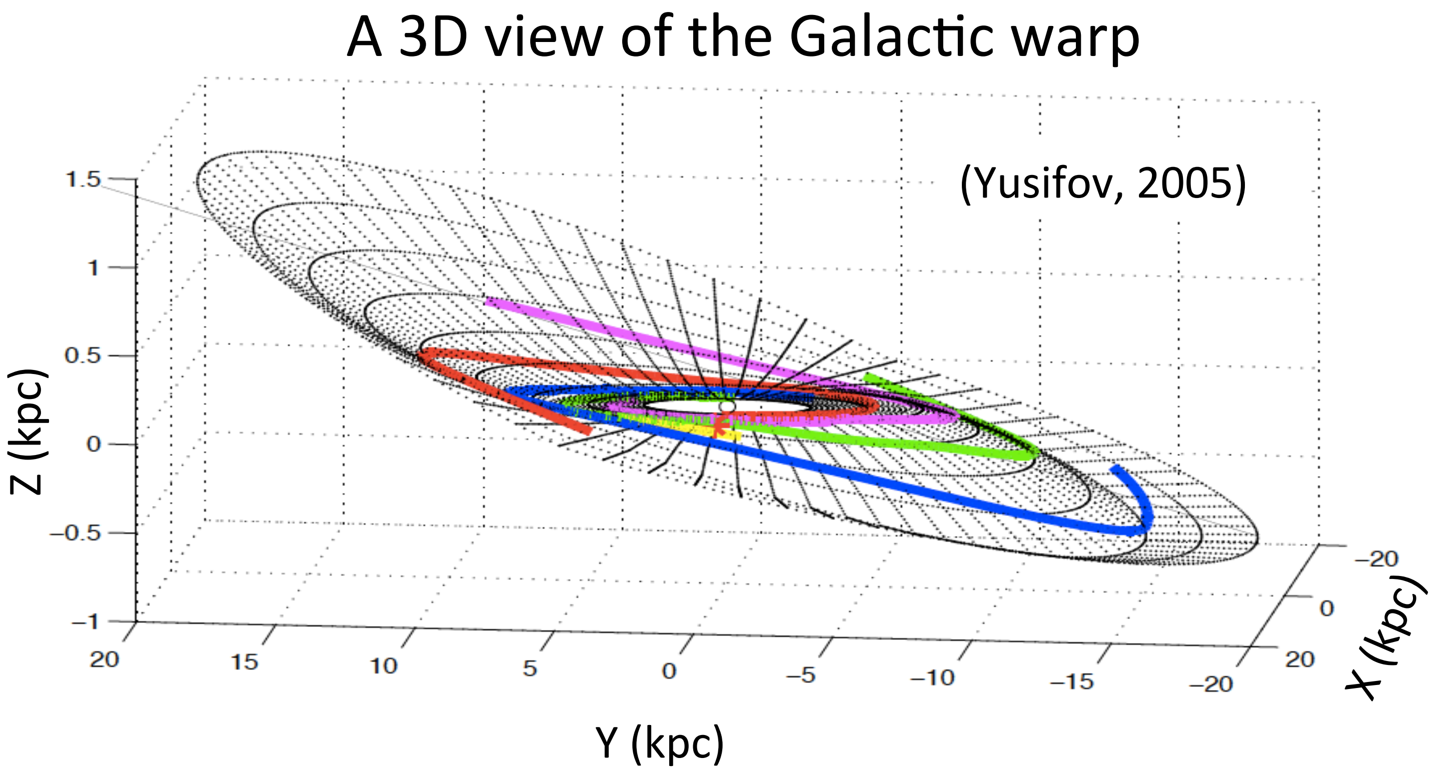
(MPIA, Heidelberg)



NGC 3190 – Credits: ESO/VLT

# The Galactic warp



# The Galactic warp

- **GAS**

  Burke (1957), Kerr et al. (1957), Westerhout (1957), Levine et al. (2006), Voskes & Butler Burton (2006), Kalberla et al. (2007)

- **DUST**

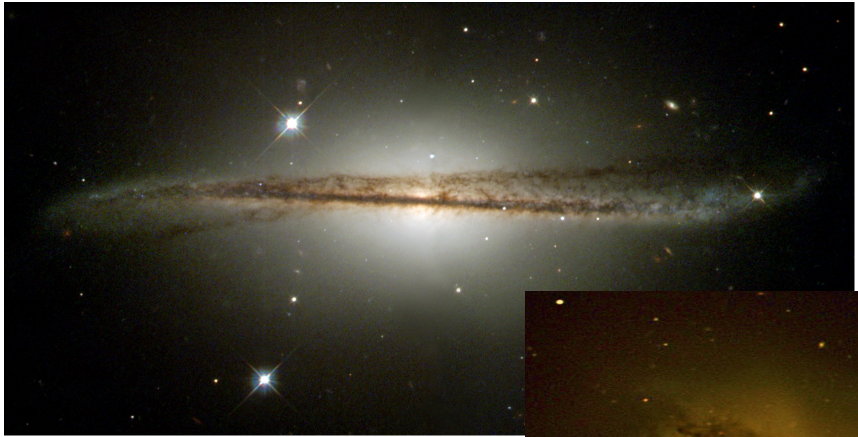
  Drimmel & Spergel (2001), Marshall et al. (2006)

- **STARS**

  Miyamoto et al. (1998), Smart et al. (1998), Drimmel et al. (2000), López-Corredoira et al. (2002), Yusifov (2005), Momany et al. (2006), Robin et al. (2008), Reylé et al. (2009)

# Motivation

- Warped disks: **common** feature in spiral galaxies



ESO 510-G13
Credits: NASA and The Hubble Heritage Team (STScI/AURA)

NGC 3190
Credits: ESO/VLT

# Motivation

- Warped disks: **common** feature in spiral galaxies
- Formation mechanism and dynamical nature: not clear
- In the Milky Way we can study the **stellar kinematics** associated with the warp
- Stars moving in a warped disk will have **systematic vertical velocities** with respect to the Galactic plane
- High precision astrometry will allow us to **constrain models** of the Galactic warp (transient vs. long-lived)

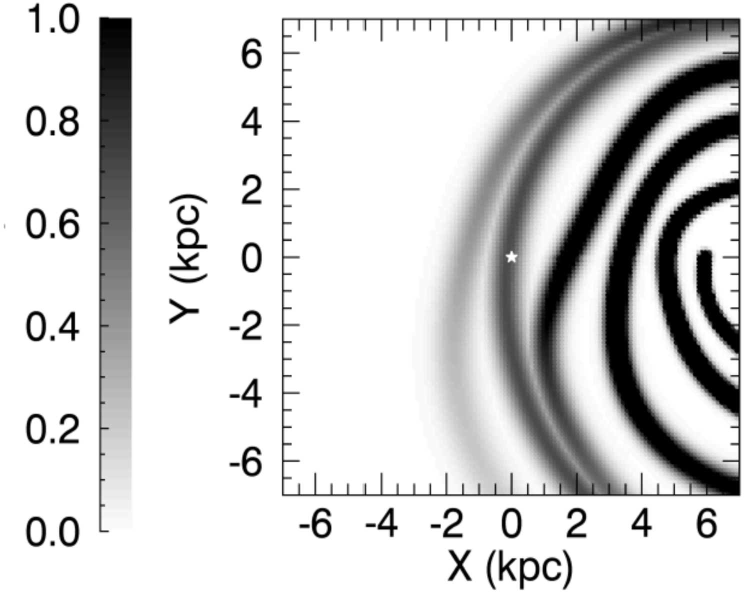
# Data selection

- OB stars, because:
  - they trace the gaseous disk
  - they can be seen to large distances
- Spectroscopically selected Hipparcos OB3 stars + parallax < 2 mas + mv < 8.5
- 989 Hipparcos OB3 stars (**HIP2 sample**, astrometry from van Leeuwen, 2007), of which
- 758 stars are also in the **Hipparcos subsample in Gaia DR1 (TGAS(HIP) sample**)

# The model

- Luminosity function + spatial distribution

✓ $N(M) \propto 10^{\alpha M}$
✓ Exponentially decreasing vertical distribution
✓ 4 major spiral arms + local arm
✓ Warp
✓ Vertical displacement of the local arm



# The model

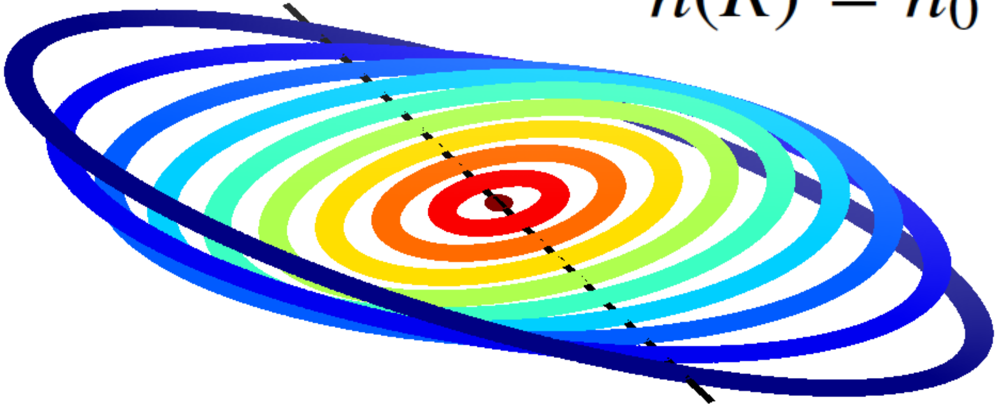
- Luminosity function + spatial distribution
- Kinematics (solar motion, Galactic rotation, velocity dispersions…)
- Astrometric errors (e.g. $\sigma_{\mu\alpha}$ (TGAS) $\propto$ $\sigma_{\alpha}$(HIP2)/$\Delta t$ )
- Completeness (Hipparcos and Hipparcos subset in TGAS)
- Add (or not) the warp systematic motions induced by the warp

Details in Poggio et al. (2017), 2017arXiv170204556P

# The warp model

$$z_w(R, \phi) = h(R)\ \sin(\phi + \phi_w)$$

$$h(R) = h_0\,(R - R_w)^{\alpha_w}$$

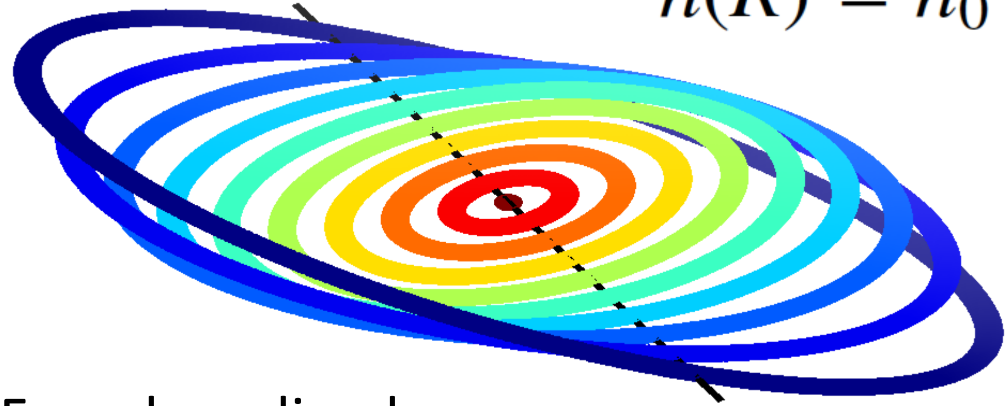


| | $R_w$ (kpc) | $\alpha_w$ | $h_0(\mathrm{kpc}^{\alpha_w - 1})$ | $\phi_w(°)$ |
|---|---|---|---|---|
| Drimmel & Spergel (2001), dust | 7 | 2 | 0.073 | 0 |
| Drimmel & Spergel (2001), stars | 7 | 2 | 0.027 | 0 |
| Yusifov (2004) | 6.27 | 1.4 | 0.037 | 14.5 |

# The warp model

$$z_w(R,\phi) = h(R)\ \sin\left(\phi + \phi_w\right)$$

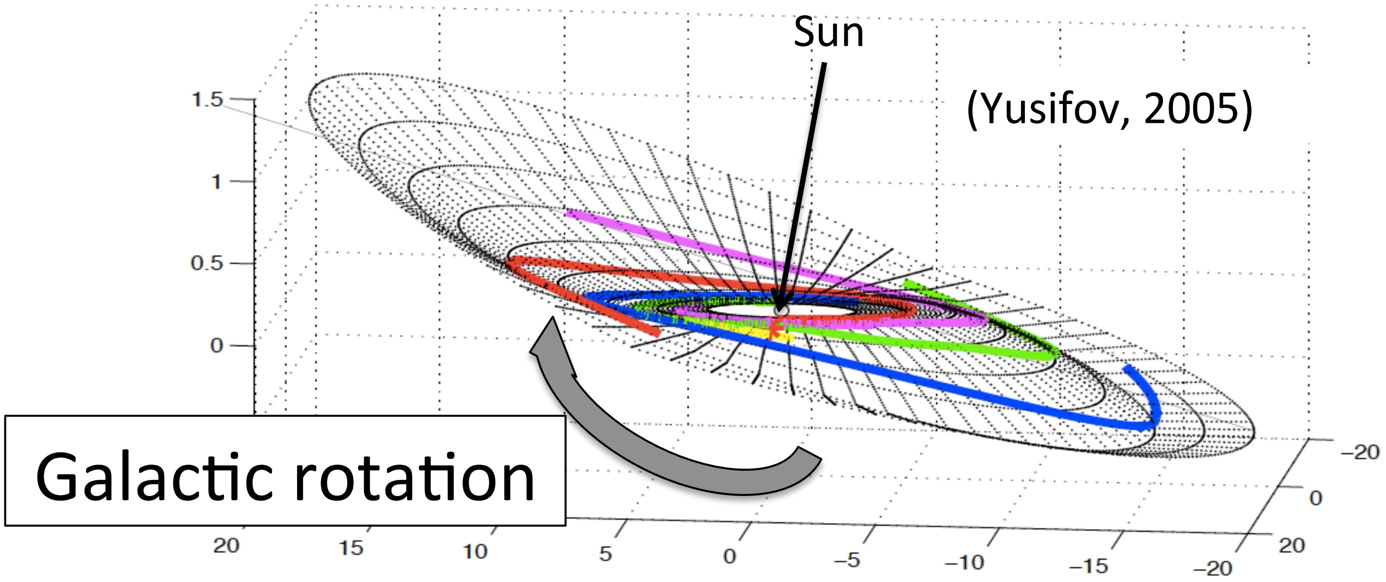
$$h(R) = h_0\left(R - R_w\right)^{\alpha_w}$$



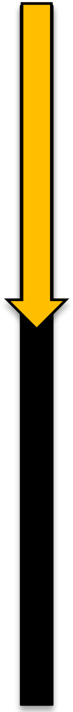
For a long-lived warp:

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

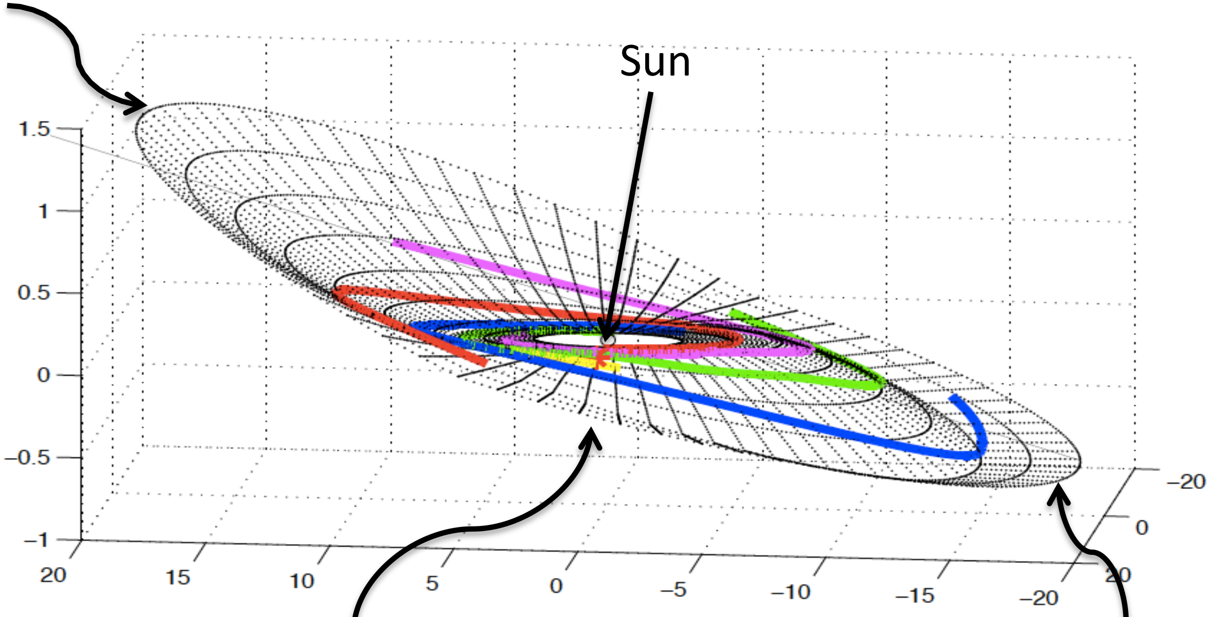
# The warp model



# The warp model



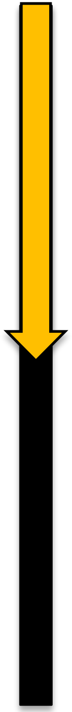
$\bar{v}_z(R,\phi)$ = 0

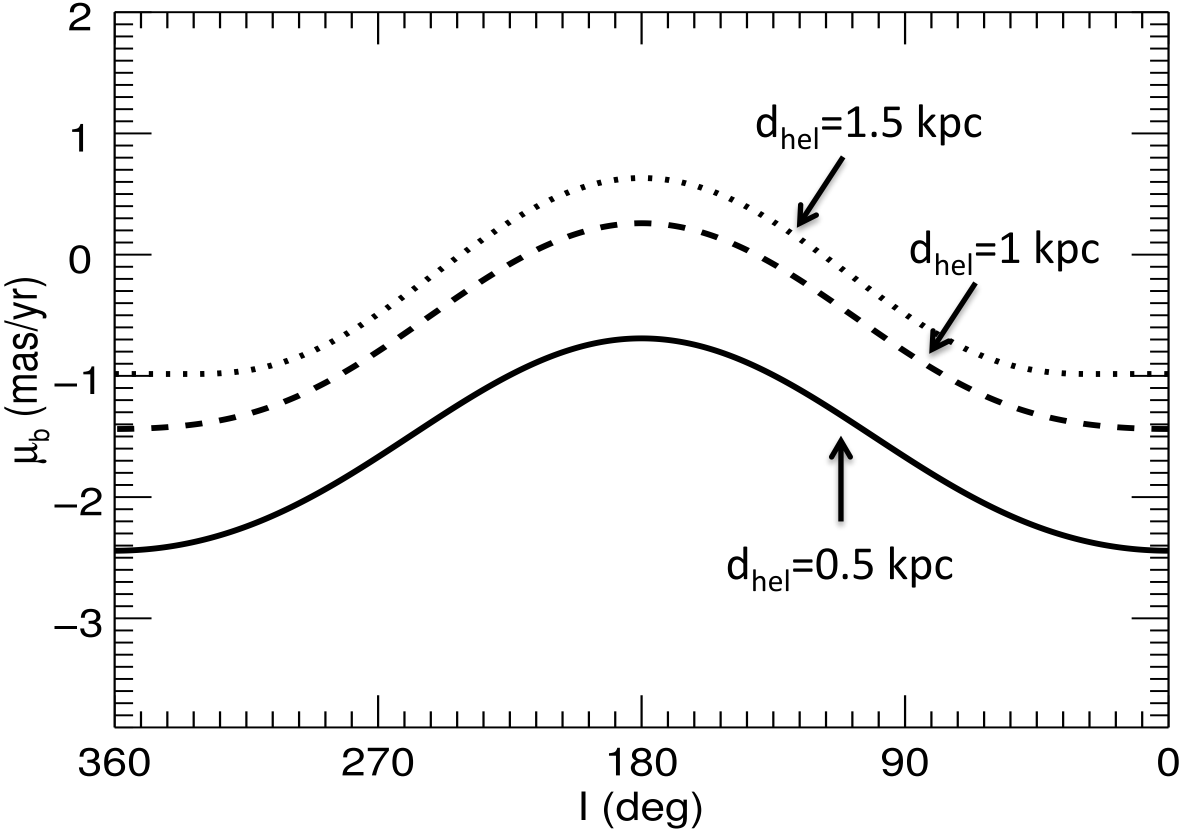



$\bar{v}_z(R,\phi)$ is maximum

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

# The warp model

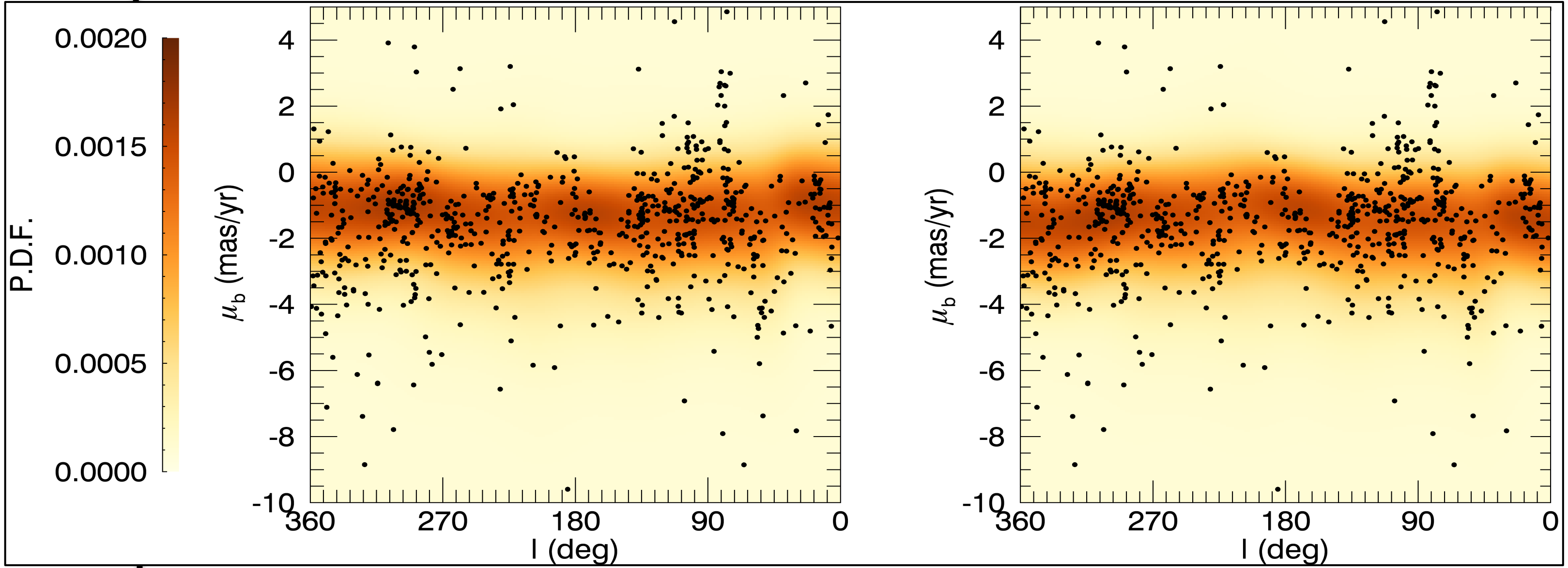




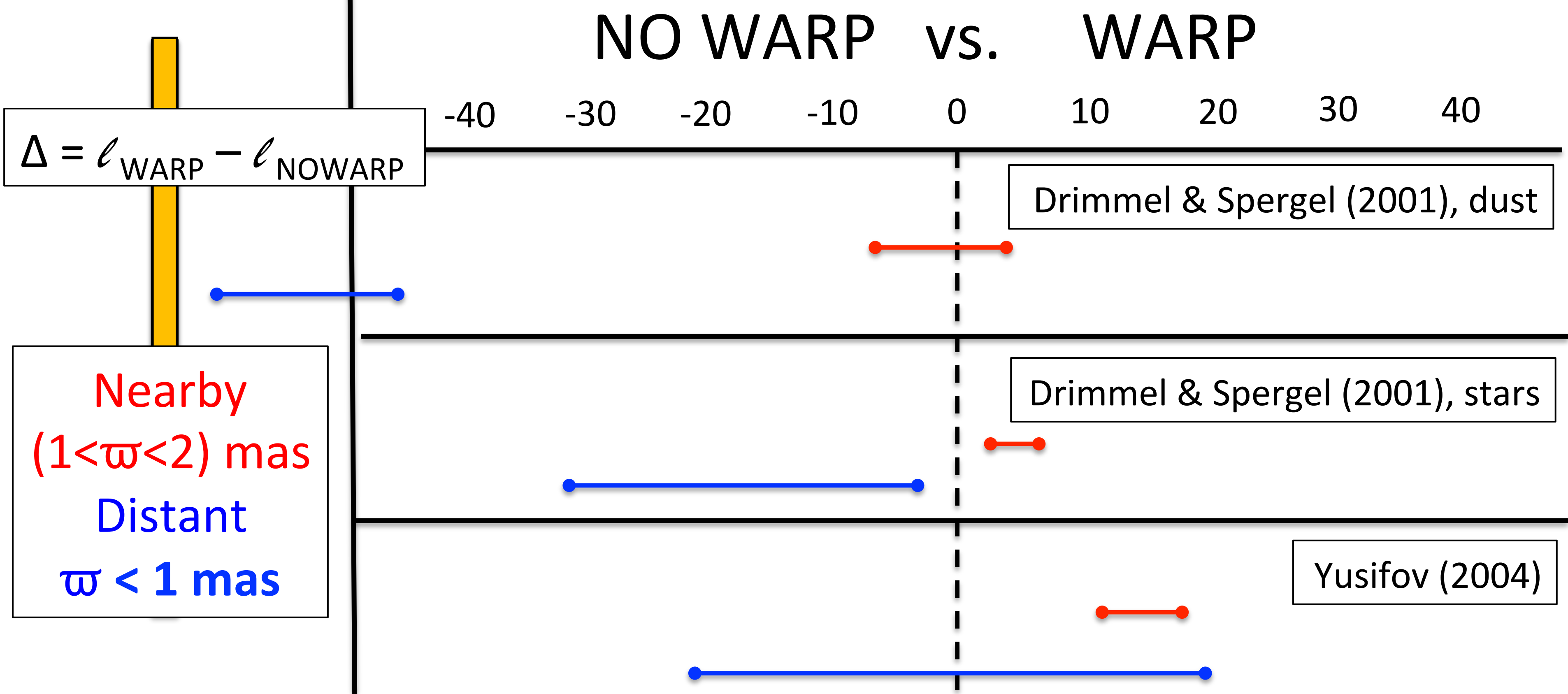
# Results

## NO WARP

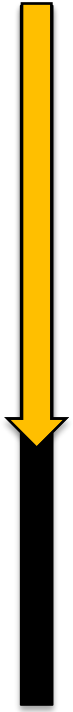
## WARP
Yusifov (2004)



# Results

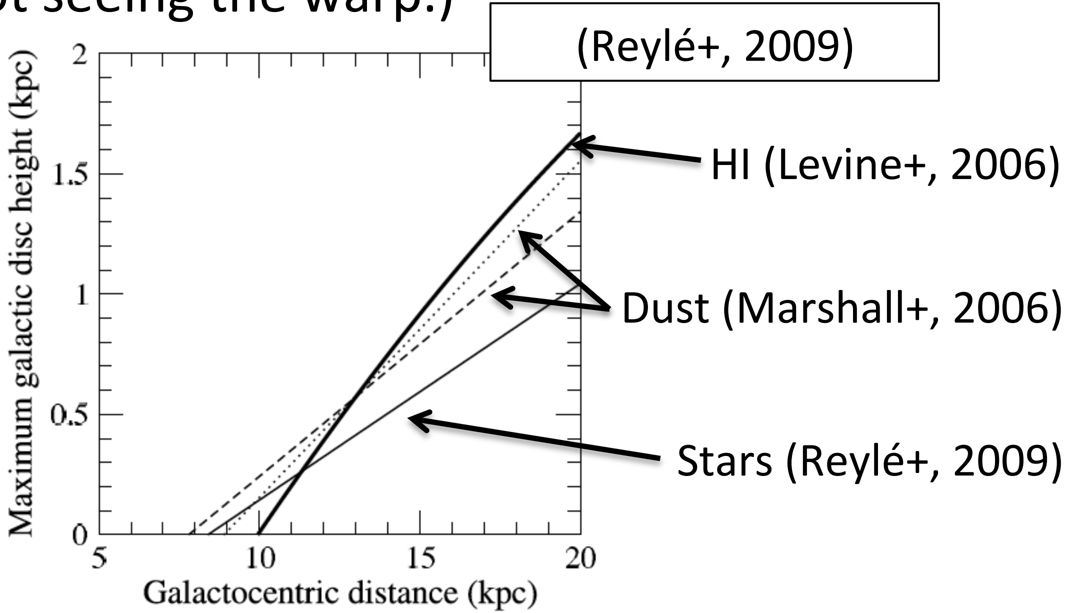

NO WARP vs. WARP
-40 -30 -20 -10 0 10 20 30 40
Δ = ℓ_WARP − ℓ_NOWARP
Drimmel & Spergel (2001), dust
Drimmel & Spergel (2001), stars
Yusifov (2004)
Nearby
(1<ϖ<2) mas
Distant
ϖ < 1 mas

# Possible interpretations



1. The warp in the gas starts well beyond the Solar Circle.

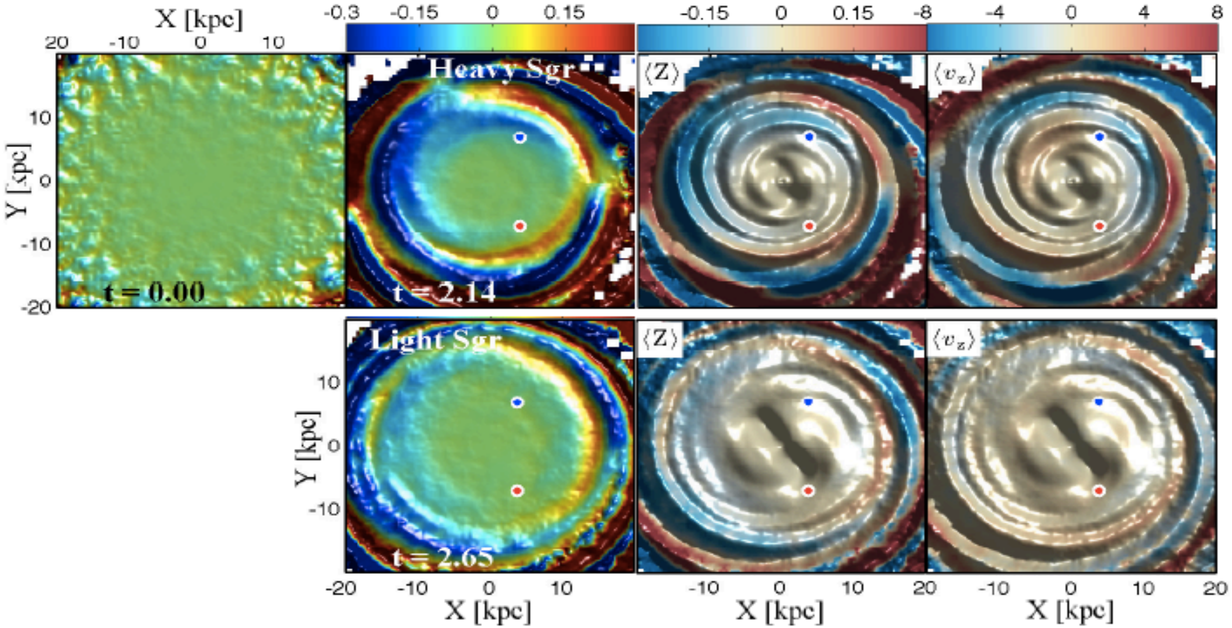
   (We're not seeing the warp.)



# Possible interpretations

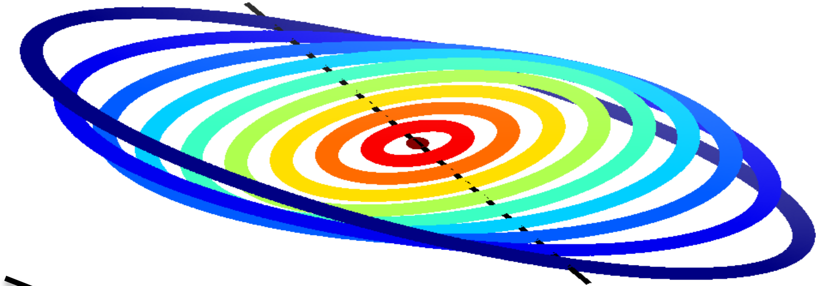
2. The warp kinematic signal is overwhelmed by other vertical motions.

(Gómez et al., 2013)



# Possible interpretations

3. The warp is short-lived / transient.
(Our model is wrong.)



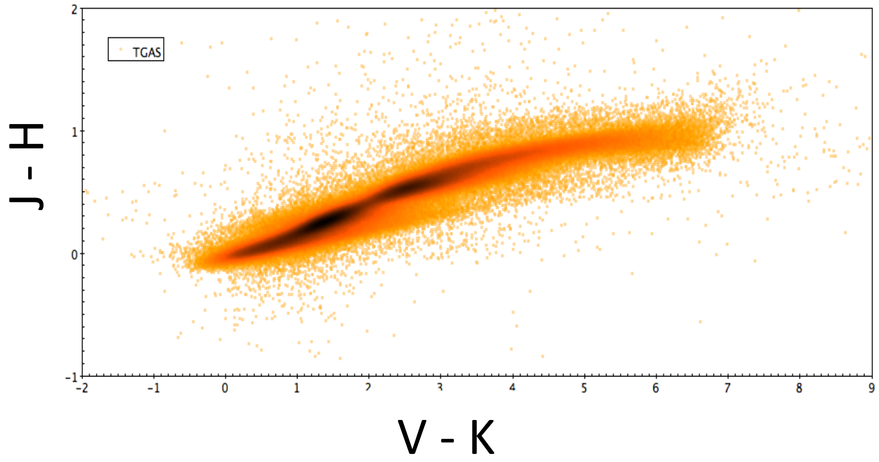
$$z_w(R,\phi) = h(R)\ \sin(\phi + \phi_w)$$

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

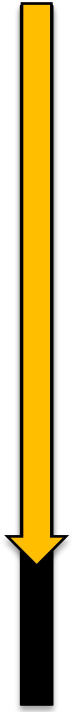
# First results with TGAS (1)

**TGAS in DR1:**

- Selection of ≈37000 OB star candidates in TGAS



# First results with TGAS (1)



**TGAS in DR1:**

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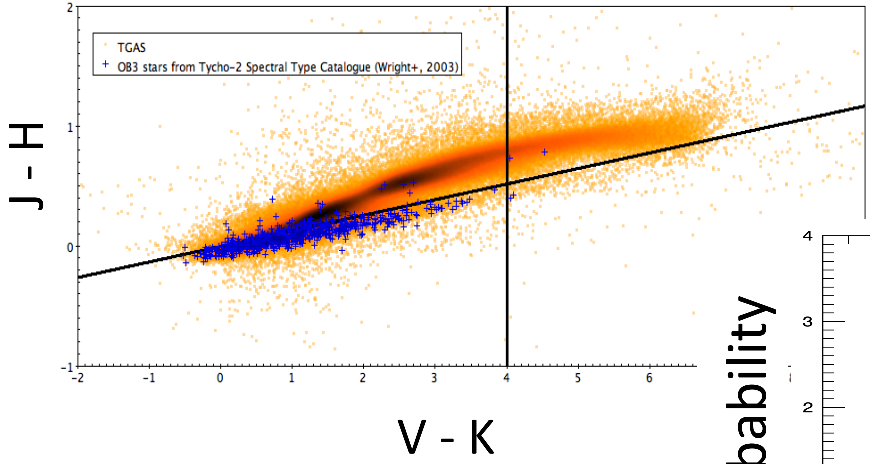
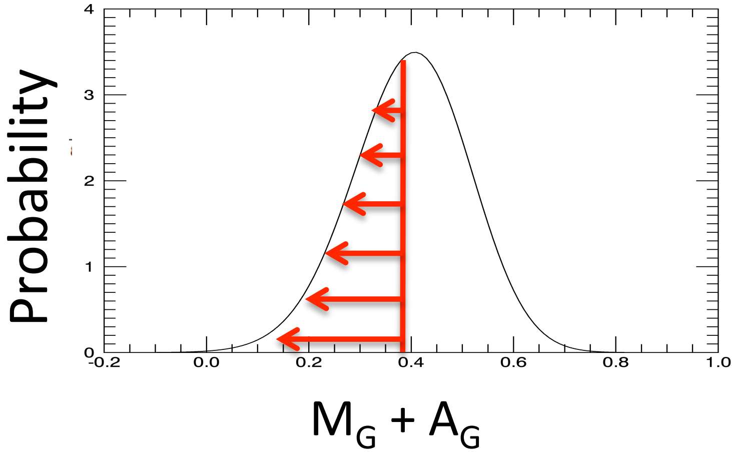


# First results with TGAS (2)

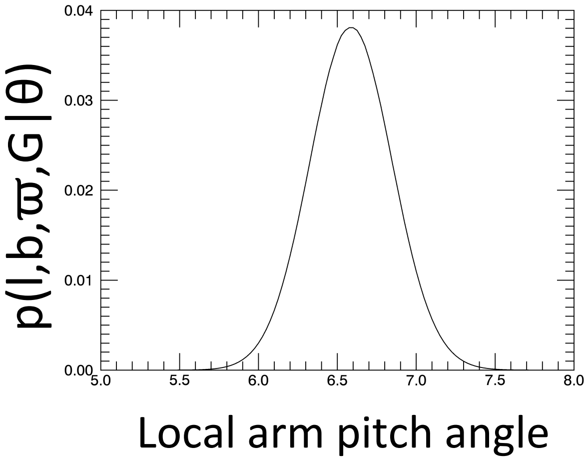
**TGAS in DR1:**

- Simplified model: spatial model + CMD + cut at G < 11.5 (no uncertainties)

$$p(\Theta_{model} \,|\, l, b, \varpi, G) = \frac{p(l, b, \varpi, G \,|\, \Theta_{model})\, p(\Theta_{model})}{p(l, b, \varpi, G)}$$

- Test: mock catalogue with local arm pitch angle = 6.5 deg

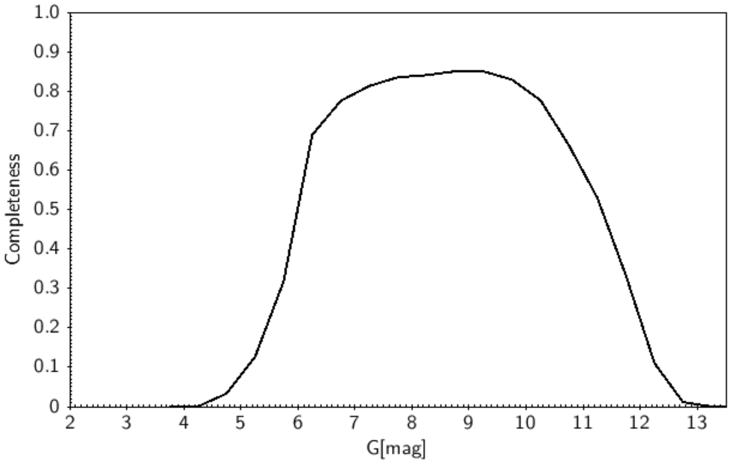
Recovered value = (6.58 ± 0.26) deg

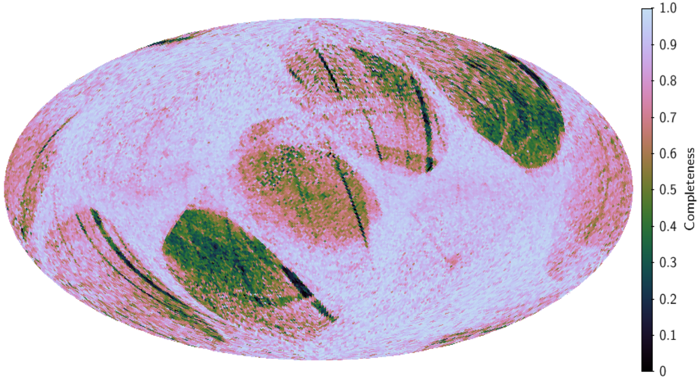


# Next steps with TGAS

**TGAS in DR1:**

- Uncertainties
- Selection function: TGAS completeness and target selection
- Kinematics




(Drimmel et al., in preparation)

# Summary

**Hipparcos subsample in DR1:**

- The observed kinematic trends in young OB stars cannot be be explained by a simple model of a stable long-lived warp

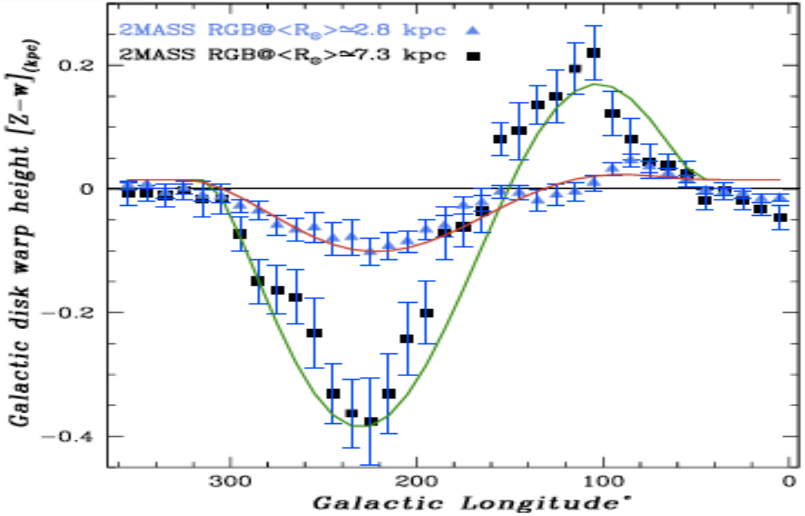
Poggio et al. (2017), “The kinematic signature of the Galactic warp in Gaia DR1 – I. The Hipparcos subsample”, 2017arXiv170204556P

**TGAS in DR1:**

- Selection of OB star candidates
- Working on the model

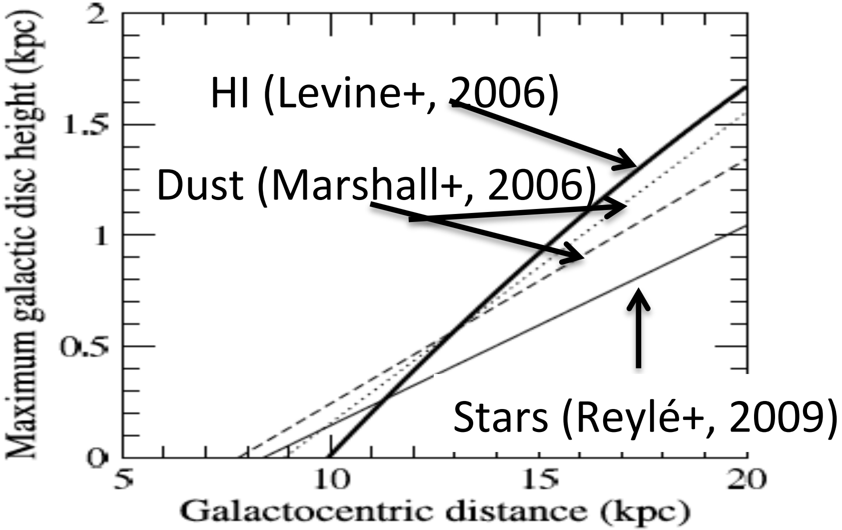
# BACK-UP SLIDES

# The Galactic warp

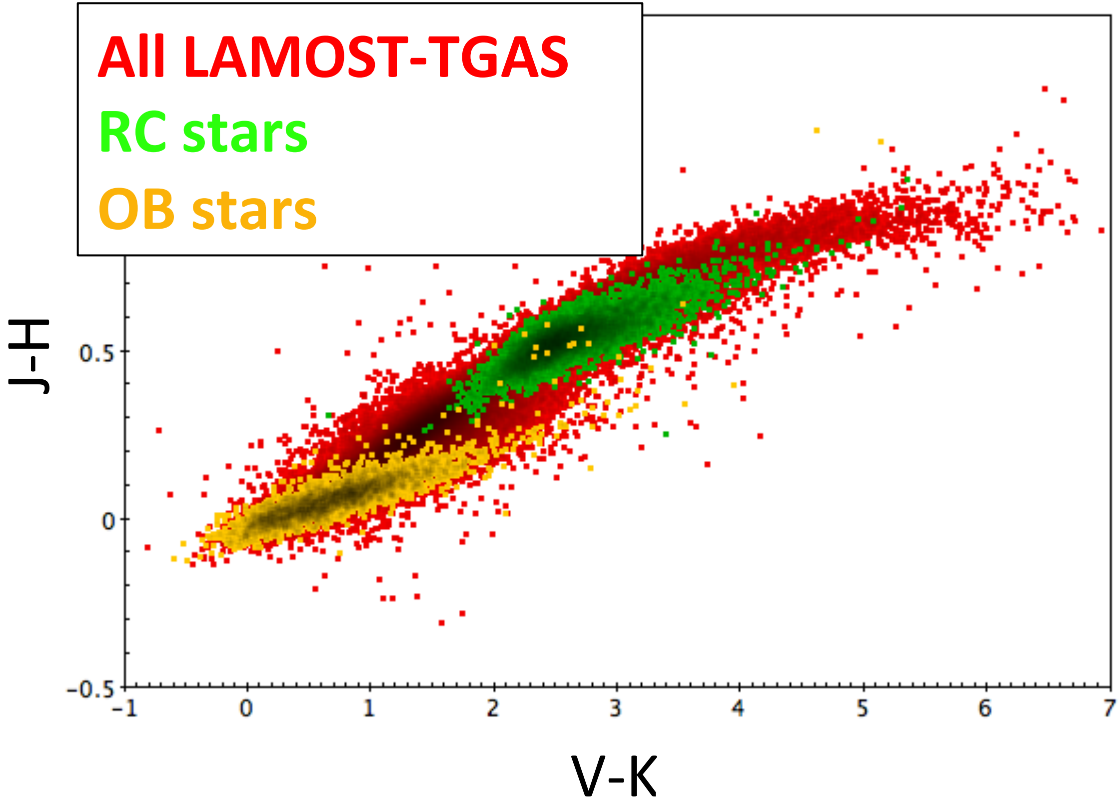



(Momany et al., 2006)

(Reylé et al., 2009)



# Target selection




Data from dr. Chao Liu

# Target selection

## Color-color selection + parallax criterium

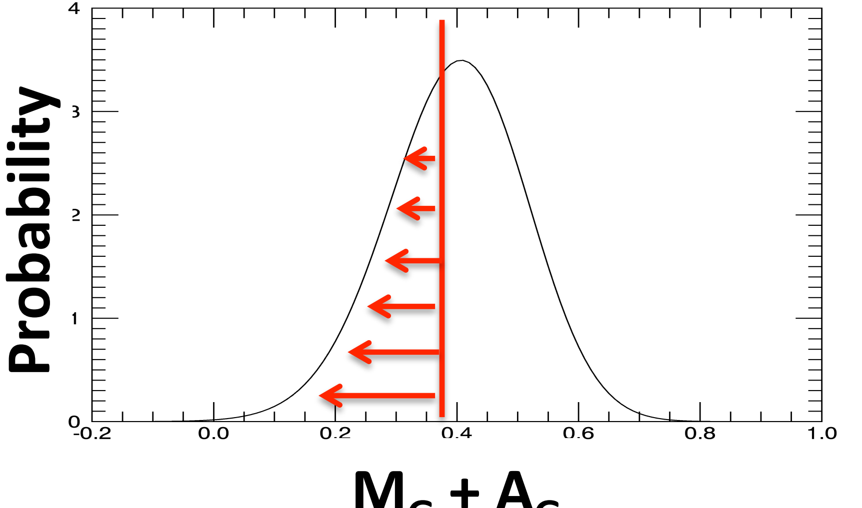
- Given G, $\varpi$ and $\sigma_{\varpi}$, calculate the probability of each star of $M_G + A_G$ being brighter than a fixed limit
- The limit is -1 for $A_G$=0 and corrected for extiction

Prior similar to Bailer-Jones, 2015:

$$P(d) \propto \begin{cases} d^2\, e^{-|z|/h_z}\, e^{-r_{GP}/L}, & \text{if } d > 0 \\ 0, & \text{otherwise} \end{cases}$$

$$z = d \sin b$$

$$r_{GP} = d \cos b$$

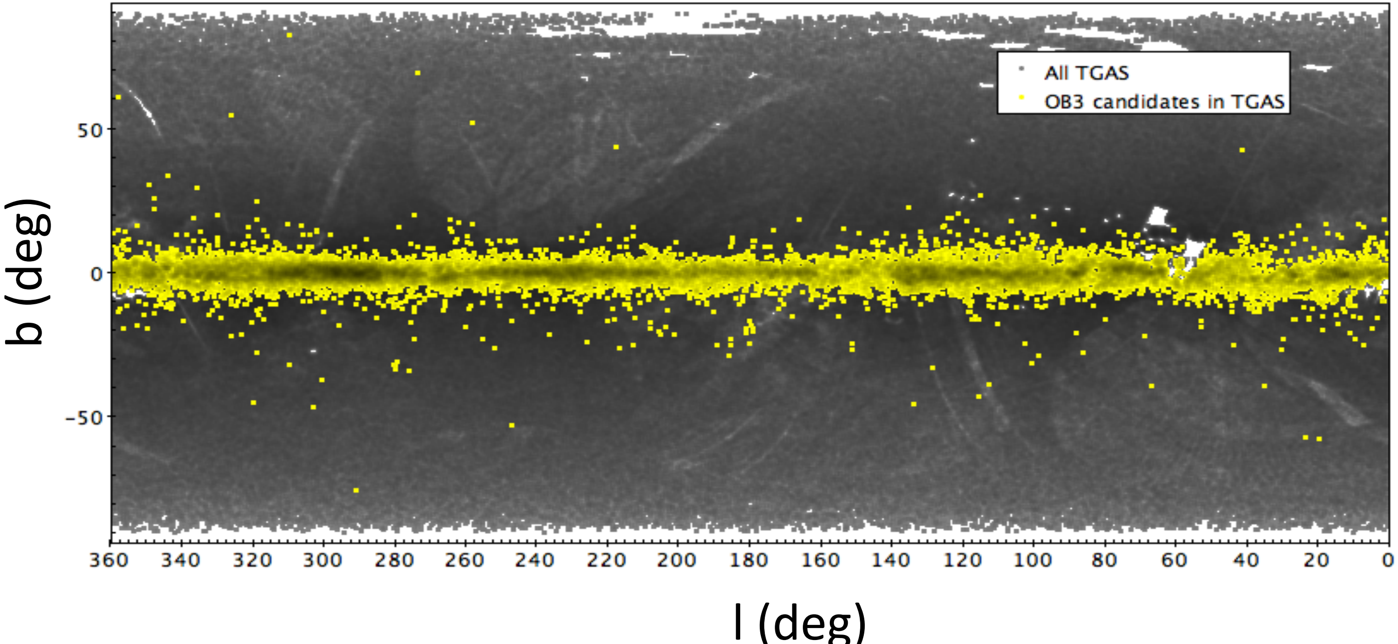


# Target selection

Color-color selection + parallax criterium

↓

≈37000 OB3 candidates



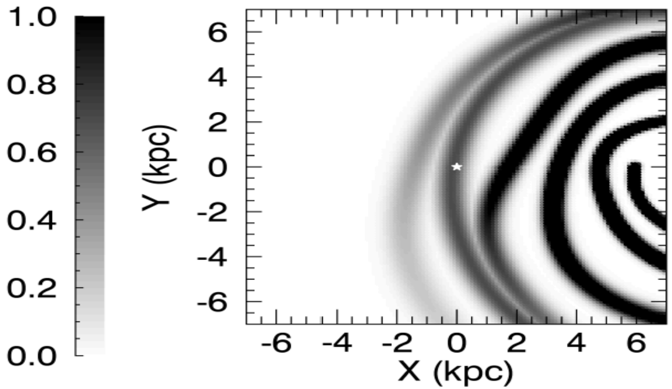
# The model

## SIMPLIFIED MODEL: no errors, no selection function

- Assume that we have one star with l, b, ϖ and G
- No errors, no selection function: only cut al G = 11.5
- Given one model with a set of parameters $\theta_i$, we calculate:

$$p(l,b,\varpi|\theta_i)$$

Spatial model
(described in Section I)

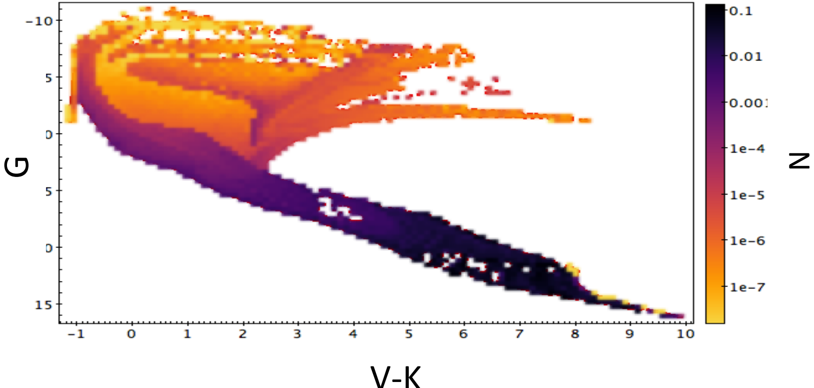


# The model

## SIMPLIFIED MODEL: no errors, no selection function

- Assume that we have one star with l, b, ϖ and G
- No errors, no selection function (only cut at G = 11.5)
- Given one model with a set of parameters $\theta_i$, we calculate:

$$p(G|\theta_i, l, b, \varpi, A_V)$$




Observed CMD:

- ✓ IMF (Kroupa 2001, 2002)
- ✓ SFH (const in log($t_{age}$), to be modified)
- ✓ Parsec isochrones (http://stev.oapd.inaf.it/cgi-bin/cmd)
- ✓ Extinction map from Drimmel et al. (2003)
- ✓ Solar metallicity

# The model

## SIMPLIFIED MODEL: no errors, no selection function

TEST WITH A MOCK CATALOGUE:

(m=mock)

- Generate one mock catalogue $(l,b,\varpi,Gmag)_m$ from model $\theta_0$
- The likelihood $\ell_i$ of the model $\theta_i$ given the mock data
- Expectation: $\ell_0 > \ell_{1,}\ \ell_{2,}\ \ell_3 \ldots$

$$\ell_i = p((l,b,\varpi)_m \,|\, \theta_i) * p((G)_m \,|\, \theta_{i,}(l,b,\varpi)_m, A_v)$$

# The model

## SIMPLIFIED MODEL: no errors, no selection function

TEST WITH A MOCK CATALOGUE:

(m=mock)

- Generate one mock catalogue $(l,b,\varpi,Gmag)_m$ from model $\theta_0$
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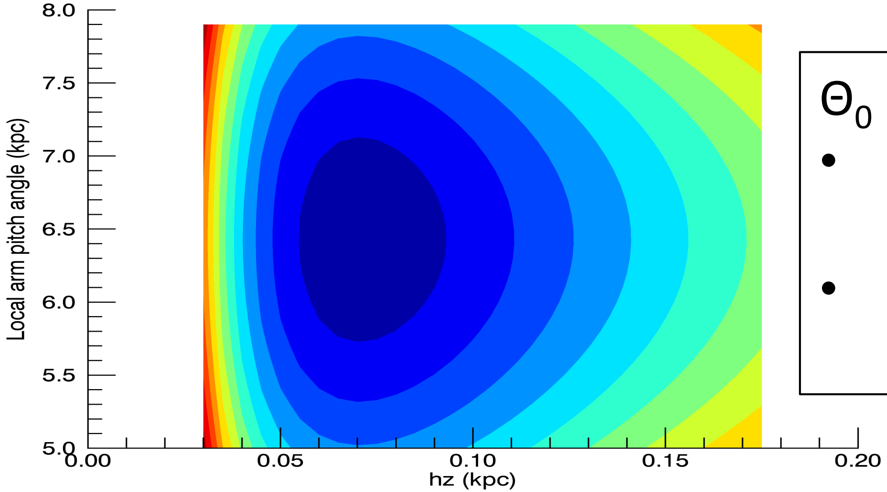
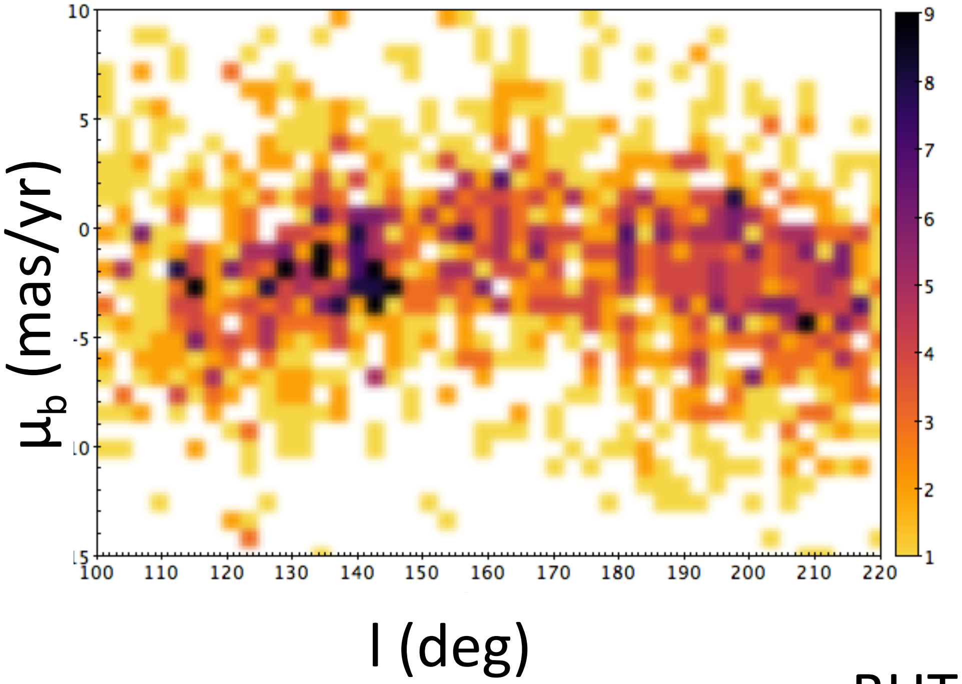



$\Theta_0$ :

- local arm pitch angle = 6.5 deg
- Scale height of the disk hz = 0.07 kpc

# On the importance of the selection function

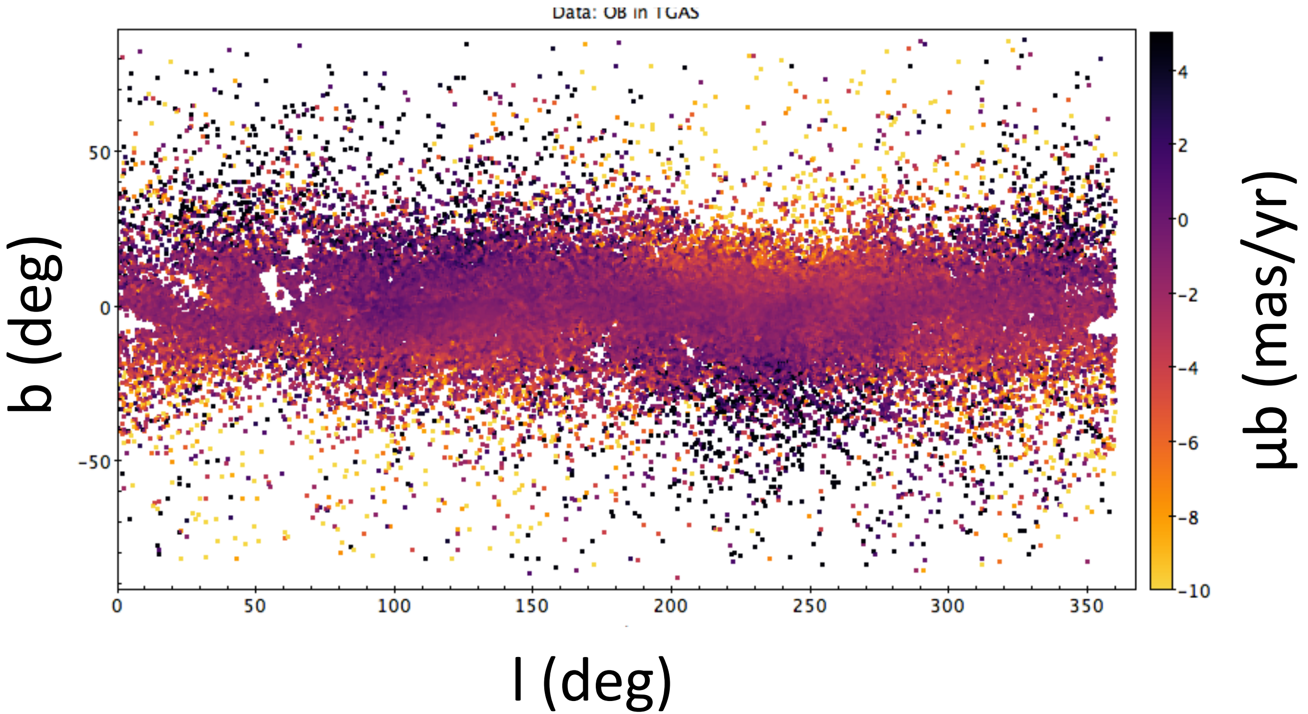
K-giants in LAMOST-TGAS with parallax < 0.5




BUT…

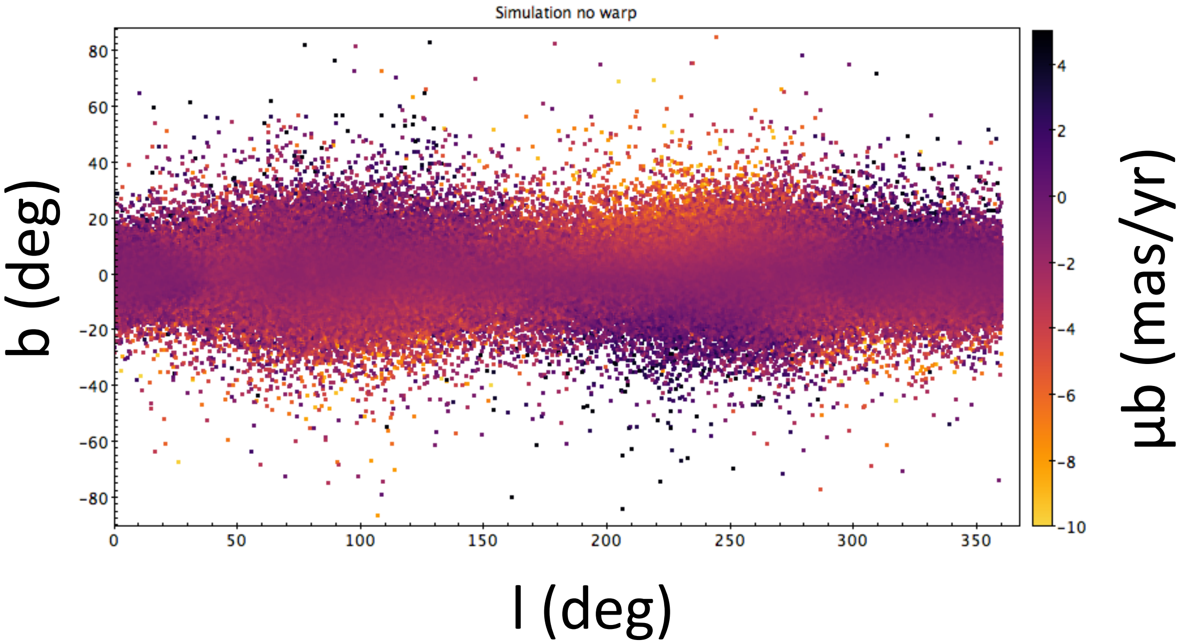
# On the importance of the selection function

## DATA: selected OB in TGAS



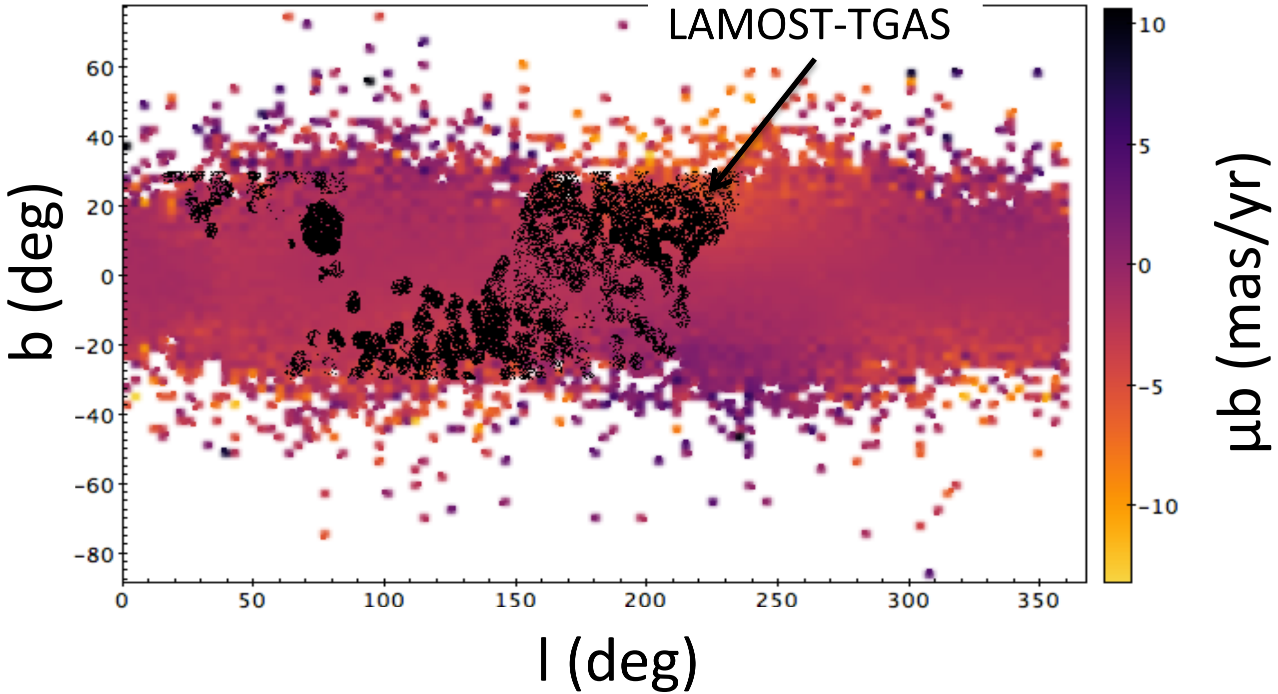
# On the importance of the selection function

## Simulated OB in TGAS



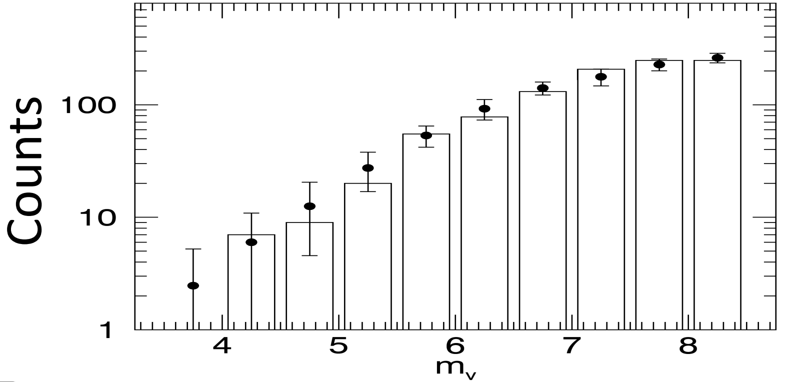
# On the importance of the selection function

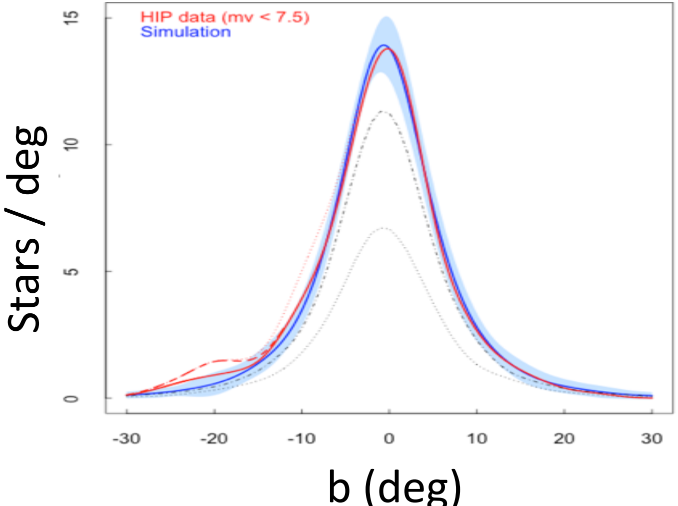
## Simulated OB in TGAS

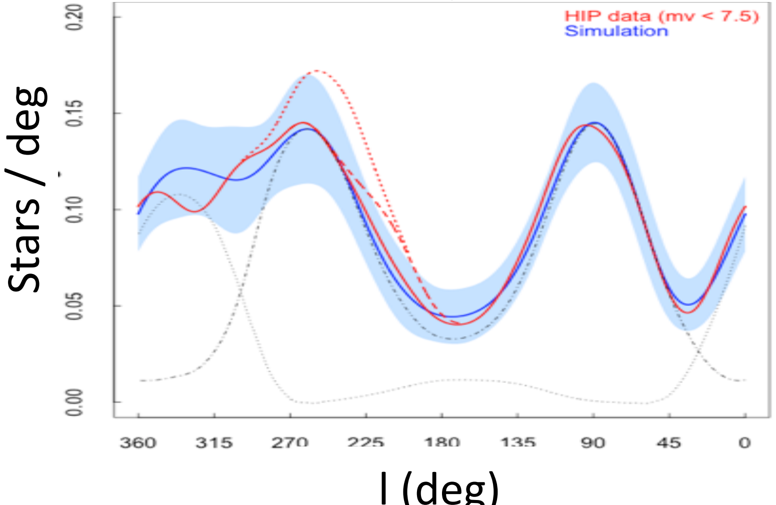


# The model

- Luminosity function + spatial distribution

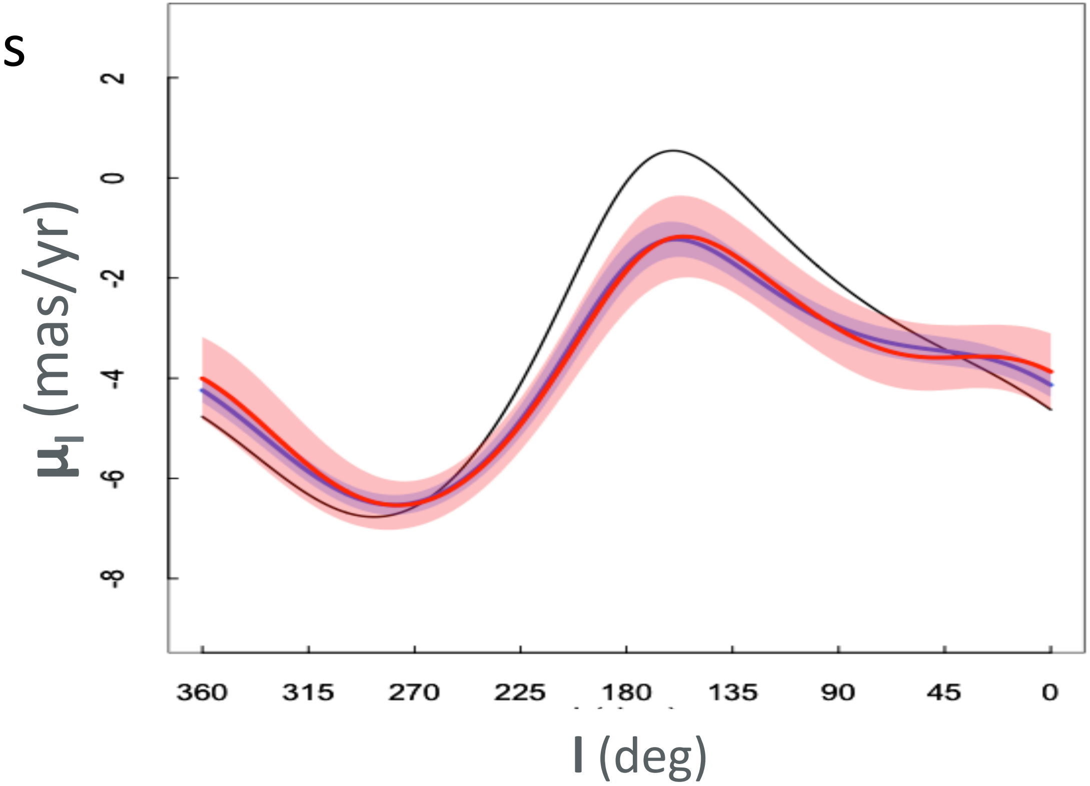


# The model

- Kinematics

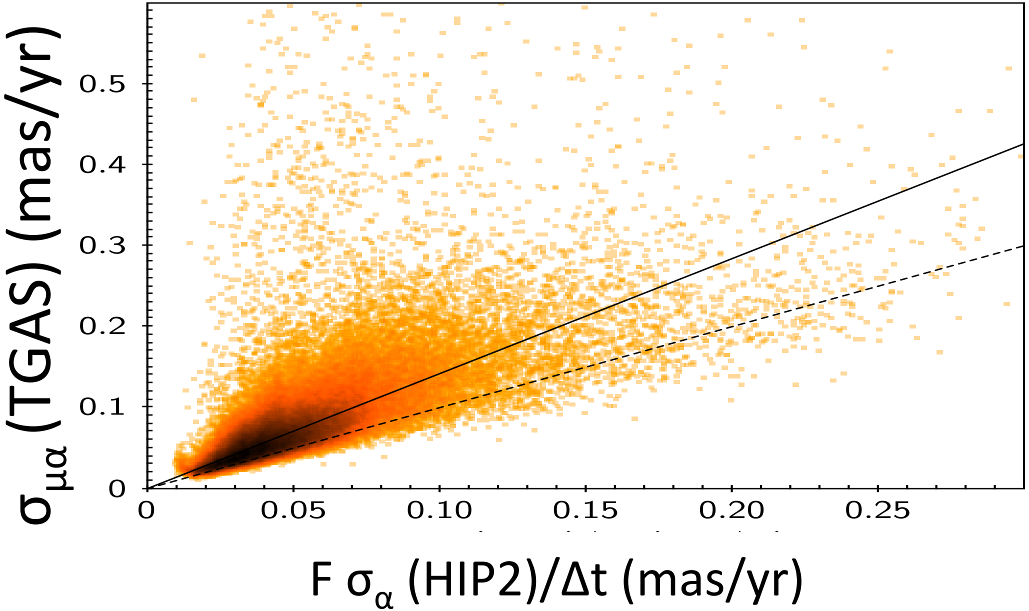



$\Theta$=238 ± 15 km/s
(Bland-Hawthorn & Gerhard, 2016)

$(U_\odot,V_\odot,W_\odot)$=(11.1,12.24,7.25) km/s
(Schoenrich et al., 2010)

# The model

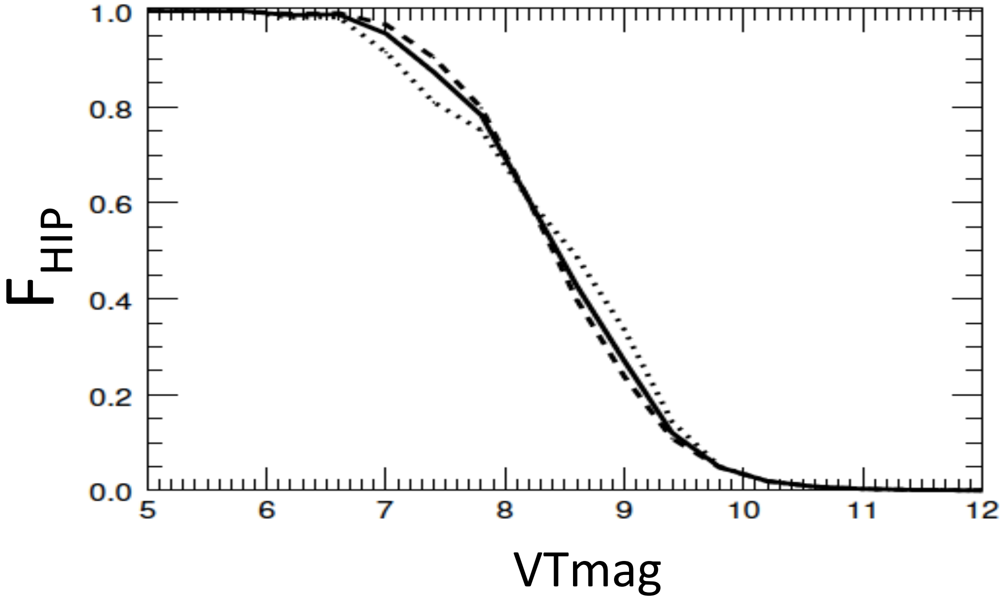
- Astrometric errors



# The model

- Completeness

Hipparcos catalogue



# The model

- Completeness

Hipparcos subset in Gaia DR1