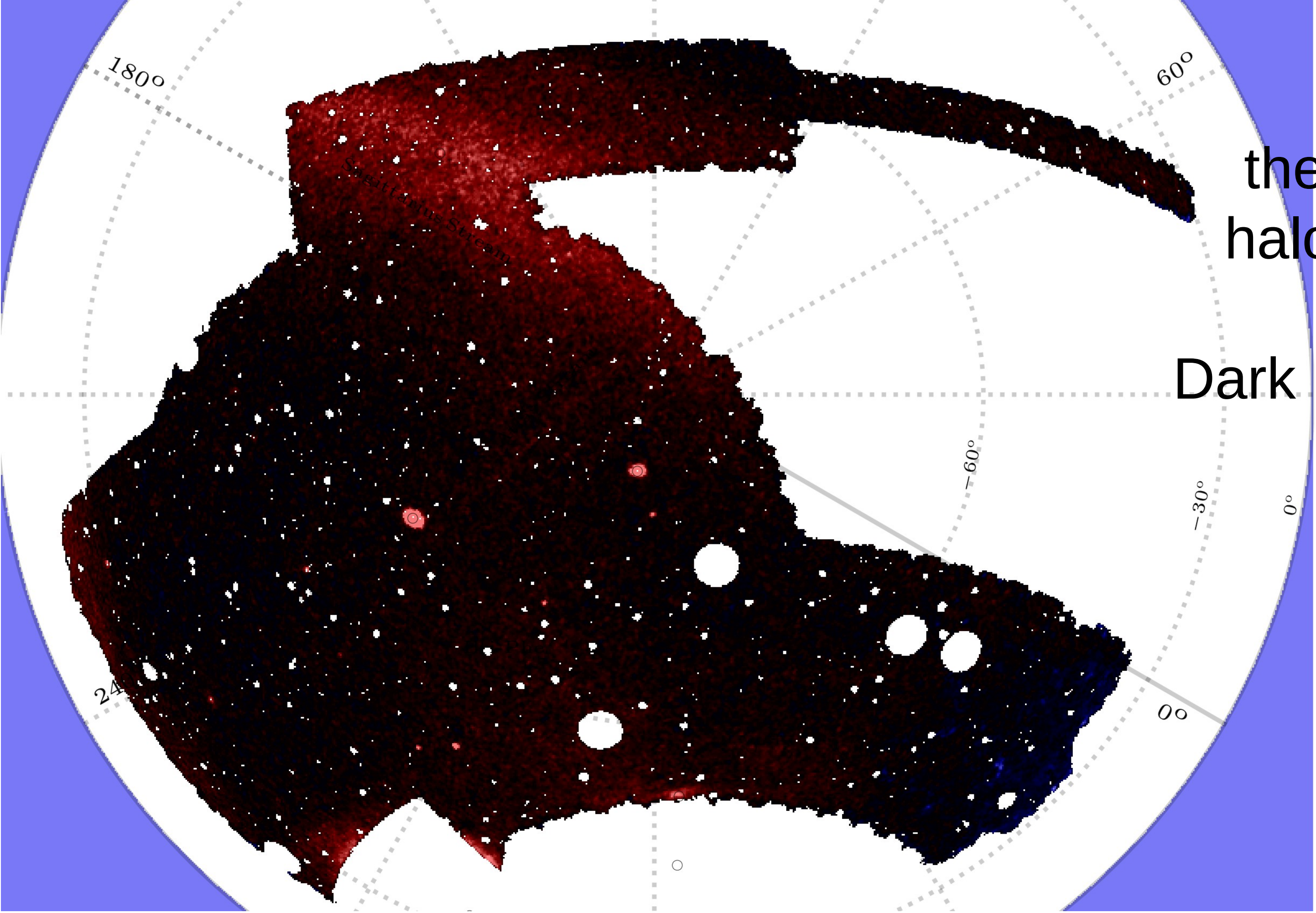


Describing the thick disk and halo of the Galaxy as seen by the Dark Energy Survey

Adriano Pieres
in collaboration with
L. Girardi, B. Santiago,
L. da Costa, E. Balbinot,
LineA IT team,
MWWG-DES

LineA Webinar - April 4, 2019

In this webinar

- I am going to discuss the work of comparing Hess diagrams (HDs) of TRILEGAL models to DES Y3 Gold 2.2 stellar sample;

- A bit of technical details about the comparisons;

- The MW model adopted and the best-fitting parameters of the thick disk and halo components with DES data;

- Perspectives about the future applications of the MWFitting pipeline (SDSS, GAIA);

Method and models

Aims and Methods

- Trilegal: Build the stellar content of each component of the MW;

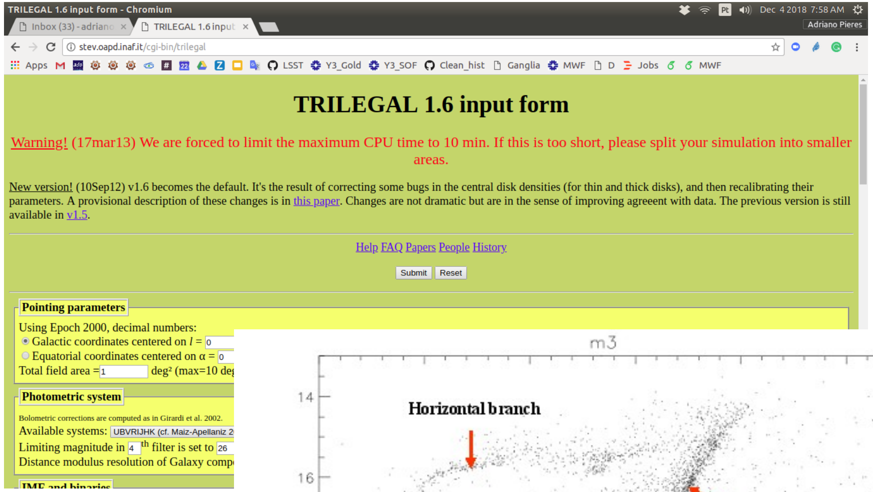
- Each MW component follows a model wrt density of stars;

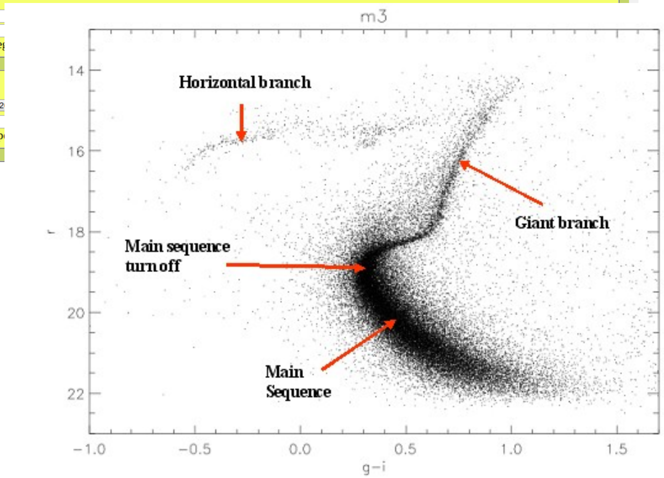
- IMF, SFH and AMR is set to each MW component (bulge, disks and halo);

- Projection of the field shows how it is seen from Sun position;

- Stellar evolutionary models are account;

- Similar to online version of Trilegal;



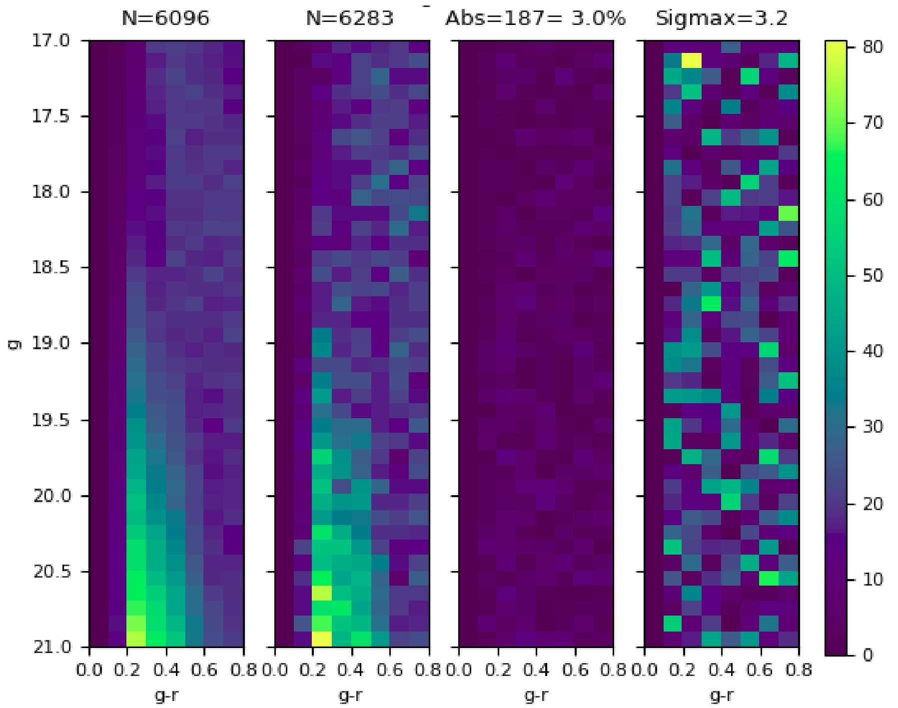


Hess Diagram

- The comparison model-data is made through Hess diagrams (figure);

- Figure: model (1), data (2), absolute difference (3), Poissonian significance of the bin (4);

- The MW model is accounted by the Hds of the cells (HealPix pixel in the sky);



Adopted models for MW components

Density (mass) profiles:

- Thin disk: sech² (h/hz), exp (R/Re);

- Thick disk: exp (R/Re), exp (h/hz);

- Halo: oblate power-law

$$\rho^{\rm halo} = \rho^{\rm halo}_{\odot} \left(\frac{r_{\odot}}{\sqrt{R^2 + (z/q)^2}} \right)^n$$
$$\text{with } \rho^{\rm halo}(R_{\odot}, 0, z_{\odot}) = \rho^{\rm halo}_{\odot}$$

Formula	Symbol	Meaning	Unit	Initial value	Final value*
Dust layer					
$\rho^{\rm dust} = A^{\rm dust}\exp(h/h_z^{\rm dust})$ with $\int_{\ell=0}^{+\infty} \rho^{\rm dust}{\rm d}\ell = A_V^{\infty}$	A_V^{∞}	total extinction at infinity	-	SFD value	fixed
	$h_z^{\rm dust}$	dust scale height	pc	110	fixed
Thin disk					
$\rho^{\rm thin} = A^{\rm thin}{\rm sech}^2(h/h_z^{\rm thin})\exp(R/h_R^{\rm thin})$ with $h_z^{\rm thin} = h_{z,0}^{\rm thin} + \left(1 + t/t_{\rm incr}^{\rm thin}\right)^{\alpha}$ and $\int_{h=-\infty}^{+\infty} \rho^{\rm thin}{\rm d}z \Big\vert_{\odot} = \Sigma_{\odot}^{\rm thin}$	$\Sigma_{\odot}^{\rm thin}$	local mass surface density	$M_{\odot}$ pc^{-2}	55.41	fixed
	$h_R^{\rm thin}$	thin disk scale length	pc	2913	fixed
	$R_{\rm max}^{\rm thin}$	maximum radius	kpc	15	fixed
	$h_{z,0}^{\rm thin}$	scale height for youngest stars	pc	94.7	fixed
	$t_{\rm incr}^{\rm thin}$	timescale for increase in h_z	Gyr	5.55	fixed
	α	exponent for increase in h_z	-	1.67	fixed
Thick disk					
$\rho^{\rm thick} = A^{\rm thick}\exp(h/h_z^{thick})\exp(R/h_R^{\rm thick})$ with $\int_{h=-\infty}^{+\infty} \rho^{\rm thick}{\rm d}z \Big\vert_{\odot} = \Sigma_{\odot}^{\rm thick}$	$\Sigma_{\odot}^{\rm thick}$	local mass surface density	$10^{-3}M_{\odot}$ pc^{-2}	4.98	4.08 ± 0.03
	$h_R^{\rm thick}$	thick disk scale length	pc	2163	2256 ± 5
	$R_{\rm max}^{\rm thick}$	maximum radius (fixed)	kpc	15	fixed
	$h_z^{\rm thick}$	scale height	pc	754.9	819.9 ± 2.0
Halo					
$\rho^{\rm halo} = \rho_{\odot}^{\rm halo}\left(\frac{r_{\odot}}{\sqrt{R^2+(z/q)^2}}\right)^n$ with $\rho^{\rm halo}(R_{\odot}, 0, z_{\odot}) = \rho_{\odot}^{\rm halo}$	$\rho_{\odot}^{\rm halo}$	local mass space density	$10^{-5}M_{\odot}$ pc^{-3}	4.36	5.35 ± 0.04
	q	axial ratio z/x (oblateness)	-	0.683	0.629 ± 0.002
	n	exponent	-	2.398	2.621 ± 0.006
Bulge					
$\rho^{\rm bulge} = \rho_{GC}^{\rm bulge}\frac{\exp(-a^2/a_m^2)}{(1+a/a_0)^{1.8}}$ with $\rho^{\rm bulge}(0,0,0) = \rho_{\rm GC}^{\rm bulge}$ with $a = \left(x'^2 + y'^2/\eta^2 + z^2/\zeta^2\right)^{1/2}$ and x', y' rotated by ϕ_0. w.r.t. x, y	$\rho_{GC}^{\rm bulge}$	space density at GC	$M_{\odot}$ pc^{-3}	406	fixed
	a_m	scale length	pc	2500	fixed
	a_0	truncation scale length	pc	95	fixed
	η, ζ	1:η:ζ scale ratios	-	0.68, 0.31	fixed
	ϕ_0	angle w.r.t. Sun–GC line	deg (°)	15	fixed

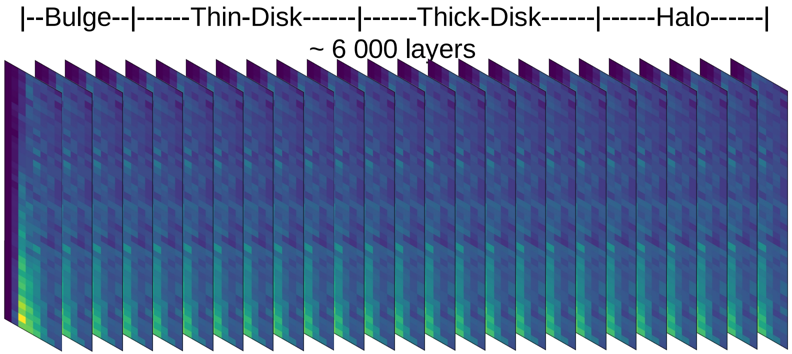
Method

- Comparing Hess Diagrams (HDs) from real data to models, guided by likelihood (Eidelman+2004);

$$-2\ln\lambda(\theta) = 2\sum_{i=1}^{N}\left(\nu_i(\theta) - n_i + n_i \ln\frac{n_i}{\nu_i(\theta)}\right)$$

- Extinction is applied in models using Schlegel maps (average and std. deviation) to each cell in the sky;

- Partial HDs (one to each cell) are carried out (with input MW parameters), each partial HD accounts the contribution of a bin in distance of each MW component (bulge, halo, thin and thick disks);



= Total Hess Diagram

Method (posterior likelihood)

1. The partial Hds are build as many layers of a FITS file → each layer is the contribution of a bin in distance of specific MW component;

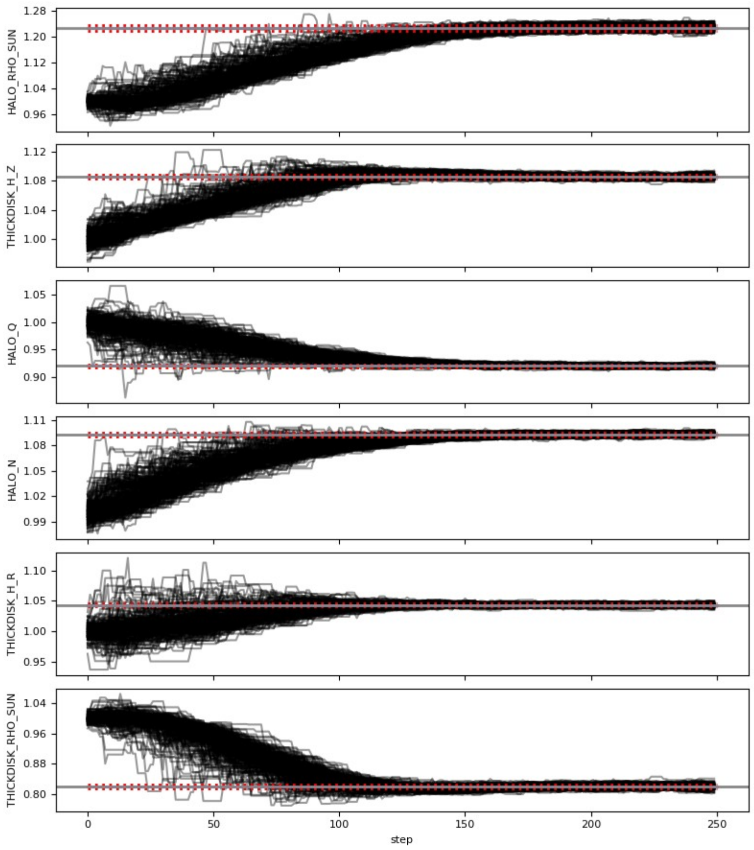
2. The MCMC approach asks a new model for the MW (by small changes in the 'main' model);

3. Based on the partial HD, Trilegal apply small changes in the partial Hess diagrams and sum all the partial Hds in a total HD (to each cell);

4. The likelihood of the MW model describes the data is given by the sum the likelihood to every cell;

5. Steps 1-4 are repeated until final step of MCMC;

- Convergence: Rc < 1.003 [1.00 (best) < Rc < 1.1 (acceptable)];



[DES-Y3 Gold 2.2] Data

[DES-Y3 Gold 2.2] Data

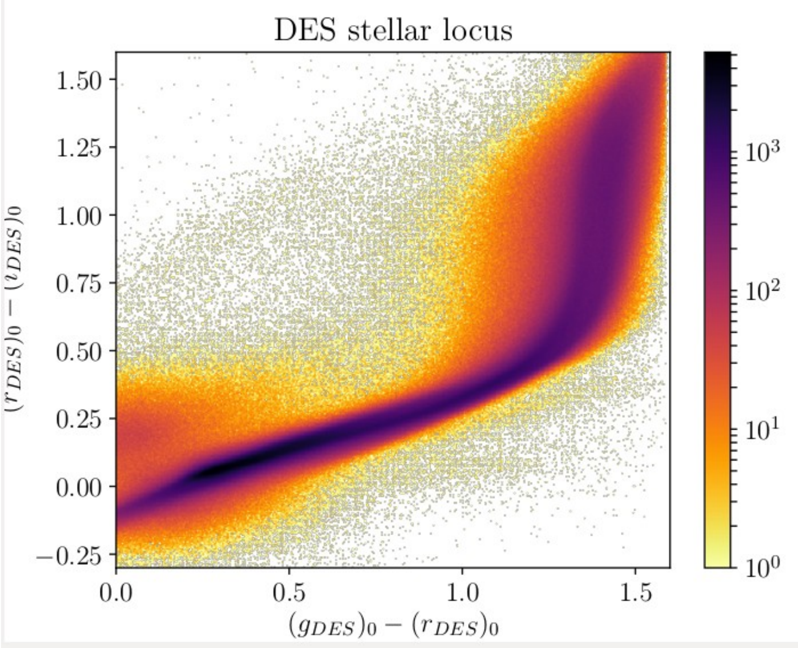
- DES-Y3 Gold 2.2 stars;

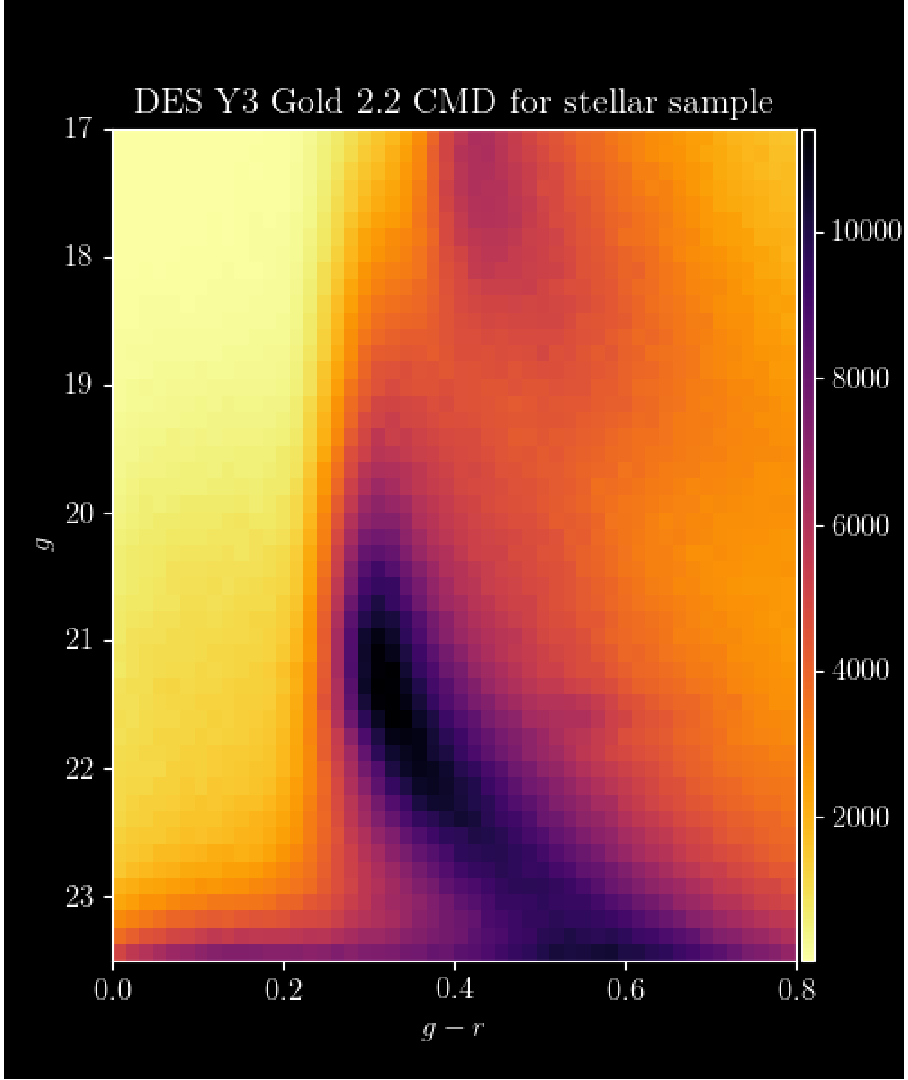
- S/G separation: EXTENDED_CLASS_MASH_SOF = 0 and 1 to the full range of magnitudes;

- SPREAD_MODEL (i) for bright stars (g<18);

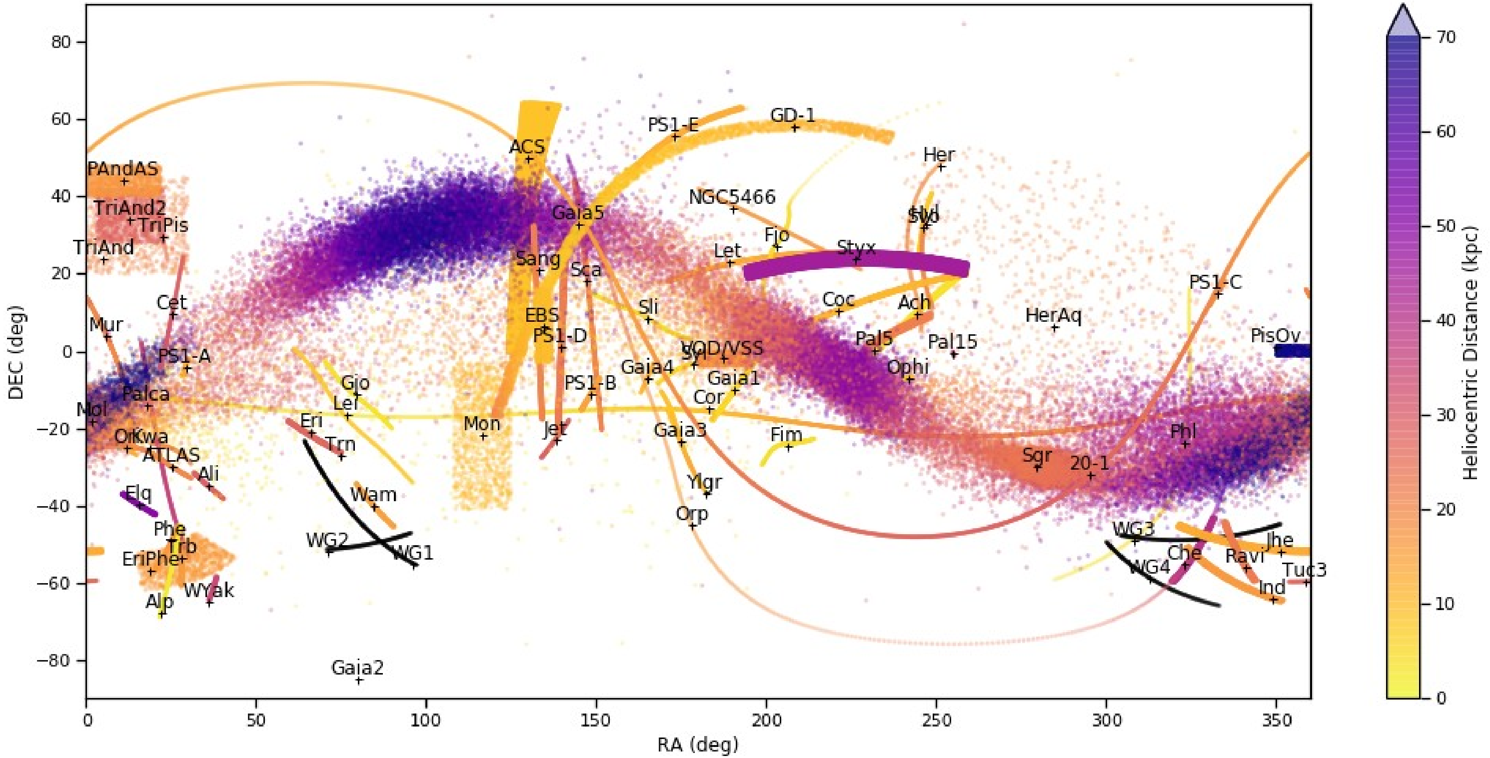
- Bright limit in the comparison: 17 < g < 21, 0 < g-r < 0.8;

- Color-color diagram for filtered in stars (right);



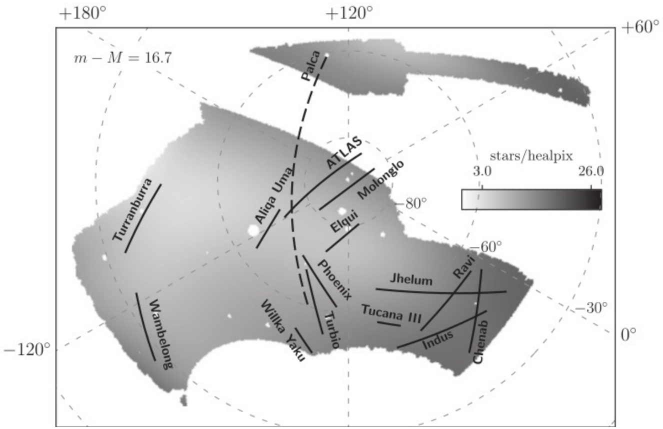

DES Y3 Gold 2.2 CMD for stellar sample
17
18
19
20
21
22
23
g
0.0
0.2
0.4
0.6
0.8
g − r
10000
8000
6000
4000
2000

[DES-Y3 Gold 2.2] Data



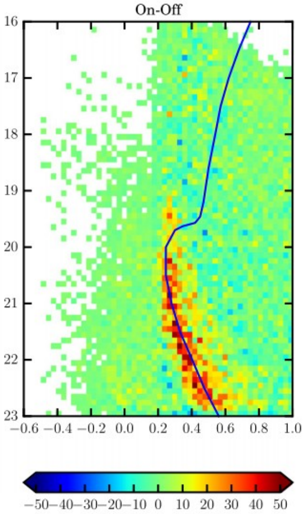
- Streams in the galstreams Python package (https://github.com/cmateu/galstreams);

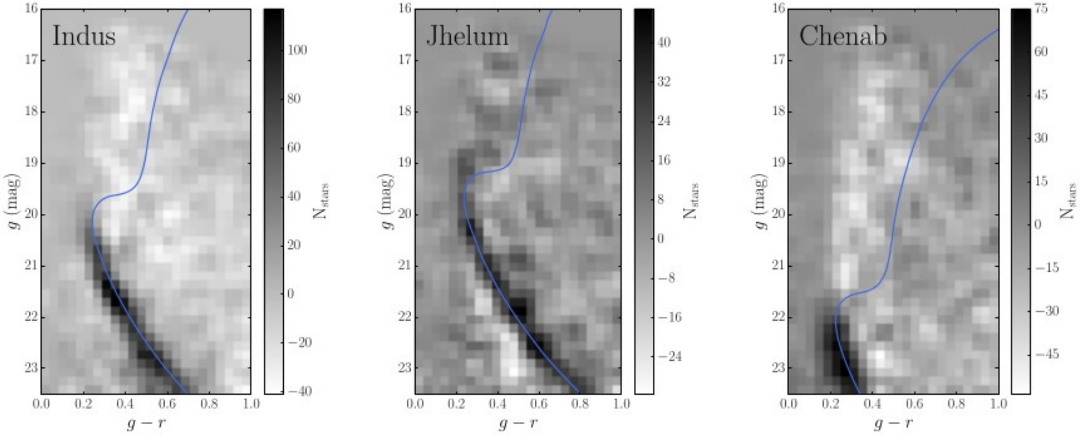
[DES-Y3 Gold 2.2] Data

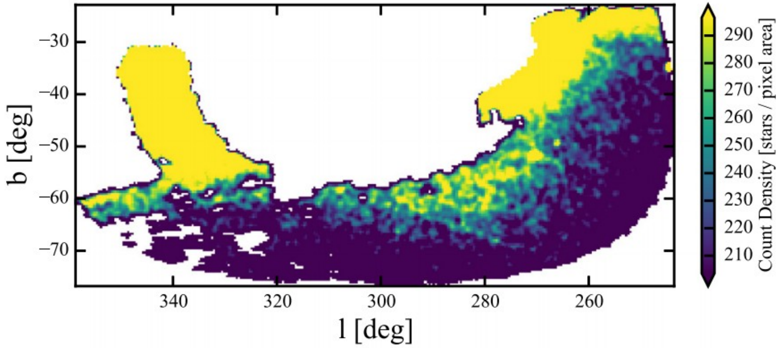


- Many streams have very-low densities (Shipp+2018, B&W figures) when compared to MW fields (~20k stars) and/or are very distant (g_{MSTO} > 21);

- Eri-Phe over density g_{MSTO}~20 (colored figures);







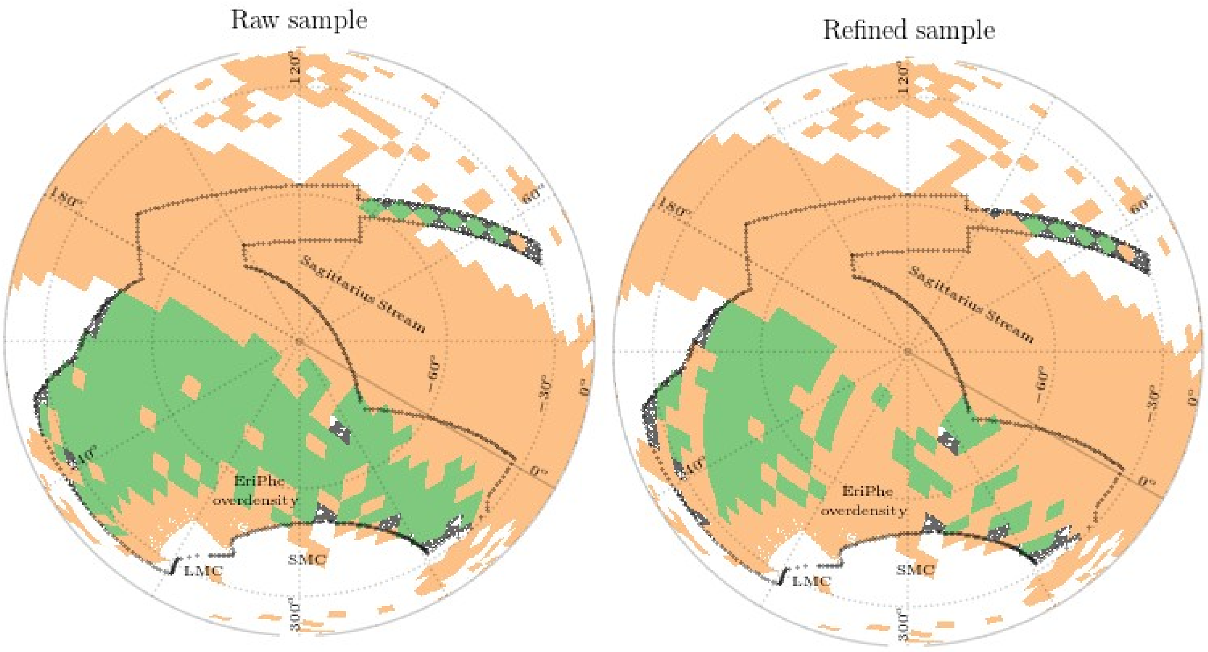
[DES-Y3 Gold 2.2] Data

- Two samples of DES data are compared to models;

- Raw sample: 2 315 sq. deg.;

- Refined sample: 1 256 sq. deg.;

- Green: cells applied in the comparison, orange: masked cells, white: cells not enough sampled (coverage < 50%);



Results with DES data

MWFitting results with DES data

Parameter	*Unit*	MWFITTING *Raw sample*	MWFITTING *Refined sample*	Jurić et al. 2008	de Jong et al. 2010
ThickDisk h_e	pc	$819.0 \pm 7.0 \pm 5.4$	$824.0 \pm 7.0 \pm 5.4$	743 ± 150	750 ± 70
ThickDisk R_e	pc	$2293 \pm 32 \pm 22$	$2284 \pm 166 \pm 22$	3261 ± 650	4100 ± 400
ThickDisk ρ (R=R$_\odot$)	$\times 10^{-3}$ M$_\odot$pc^{-2}	$4.16 \pm 0.10 \pm 0.12$	$4.02 \pm 0.15 \pm 0.12$	7.53 ± 0.75	5.01 ± 1.30
Halo n	-	$2.590 \pm 0.025 \pm 0.018$	$2.625 \pm 0.026 \pm 0.018$	2.77 ± 0.02	2.75 ± 0.07
Halo q	-	$0.637 \pm 0.009 \pm 0.009$	$0.618 \pm 0.014 \pm 0.009$	0.64 ± 0.01	0.88 ± 0.03
Halo ρ (R=R$_\odot$)	$\times 10^{-5}$M$_\odot$pc^{-3}	$5.25 \pm 0.10 \pm 0.12$	$5.54 \pm 0.12 \pm 0.12$	2.95 ± 0.74	6.31 ± 0.77

Radial scale for thick disk agrees to Bovy+2016 (2.2±0.2 kpc) using APOGEE stars;

Process takes ~30h in a single machine (MCMC takes 99% of time) via multiprocessing and ~23h in multiple machines/MPI parallelization;

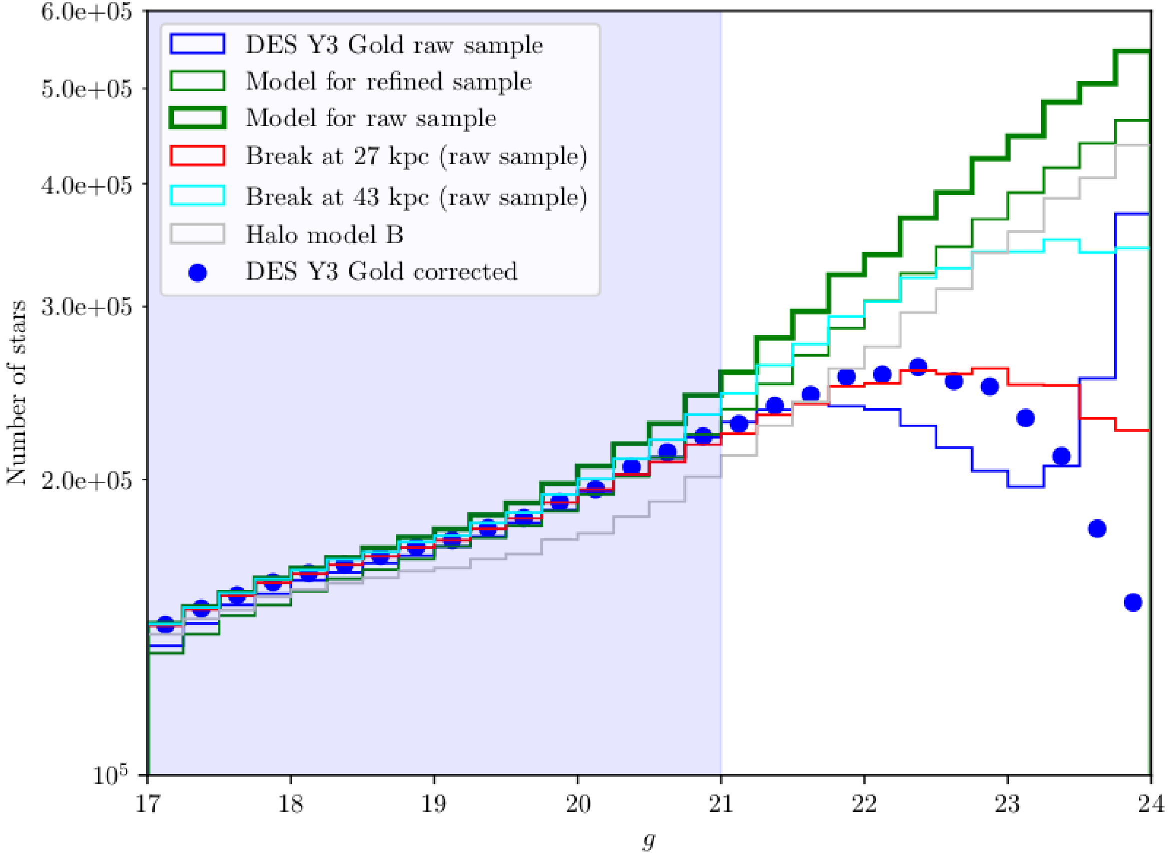
MWFitting results with DES data

- Statistical errors (dispersion of the sample of cells) from jackknife block method taking into account the standard deviation of the sample;

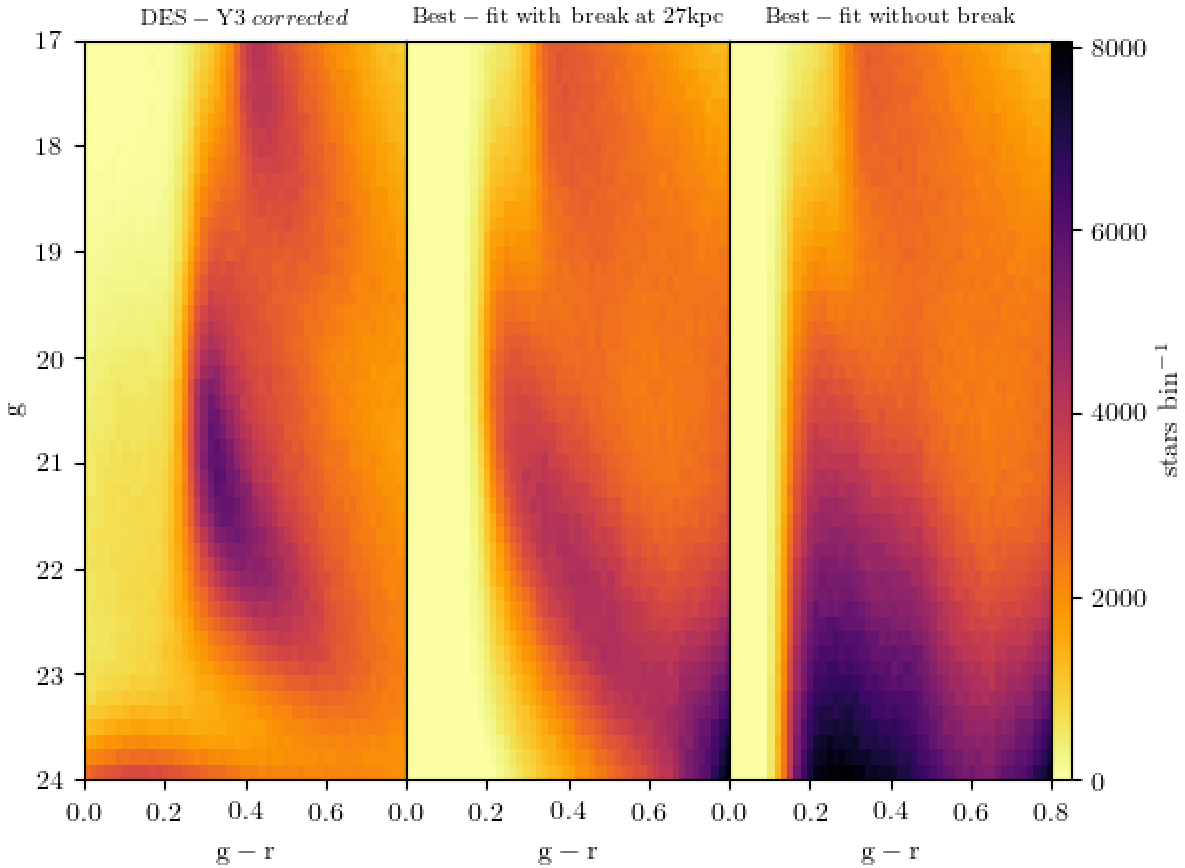
- Systematic errors (errors in recovering the model) from validation tests (below);

Parameter	*Unit*	*True Value*	*Initial Guess* A	*Initial Guess* B	*Best-fitting* A	*Best-fitting* B	$\frac{\|Best-True\|}{True}$ (%) A	$\frac{\|Best-True\|}{True}$ (%) B	$\frac{Best-True}{\sigma}$ A	$\frac{Best-True}{\sigma}$ B
ThickDisk h_e	pc	754.9	1123.4	512.1	$750.7^{+1.8}_{-1.8}$	$748.9^{+1.7}_{-1.9}$	0.6	0.8	-2.3	-3.0
ThickDisk R_e	pc	2163	2722	1613	2156^{+12}_{-6}	2157^{+6}_{-6}	0.3	0.3	-0.7	-1.0
ThickDisk ρ ($R=R_\odot$)	$\times10^{-3}M_\odot pc^{-2}$	4.98	6.16	6.76	$5.07^{+0.04}_{-0.04}$	$5.08^{+0.04}_{-0.03}$	1.9	2.1	+2.3	+2.7
Halo n	-	2.398	3.168	2.715	$2.411^{+0.008}_{-0.006}$	$2.415^{+0.006}_{-0.006}$	0.5	0.7	+1.9	+2.8
Halo q	-	0.683	0.820	0.519	$0.687^{+0.005}_{-0.003}$	$0.680^{+0.002}_{-0.002}$	0.6	0.4	+1.0	-1.5
Halo ρ ($R=R_\odot$)	$\times10^{-5}\ M_\odot pc^{-3}$	4.36	5.96	3.81	$4.41^{+0.03}_{-0.04}$	$4.49^{+0.05}_{-0.04}$	1.1	3.0	+1.4	+2.6

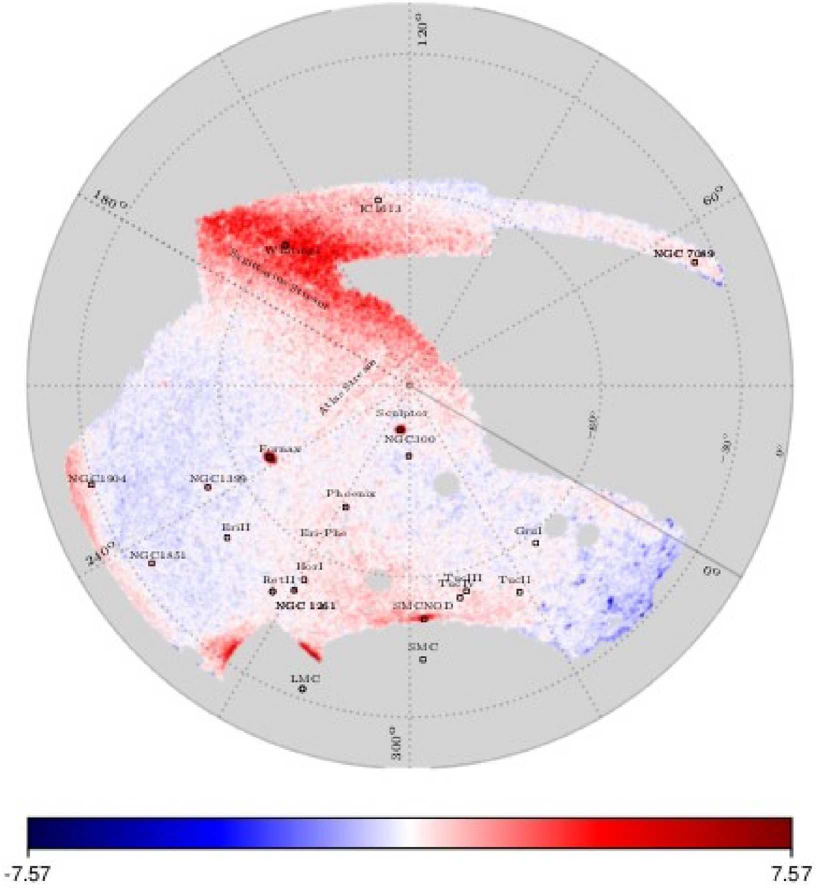
MWFitting results

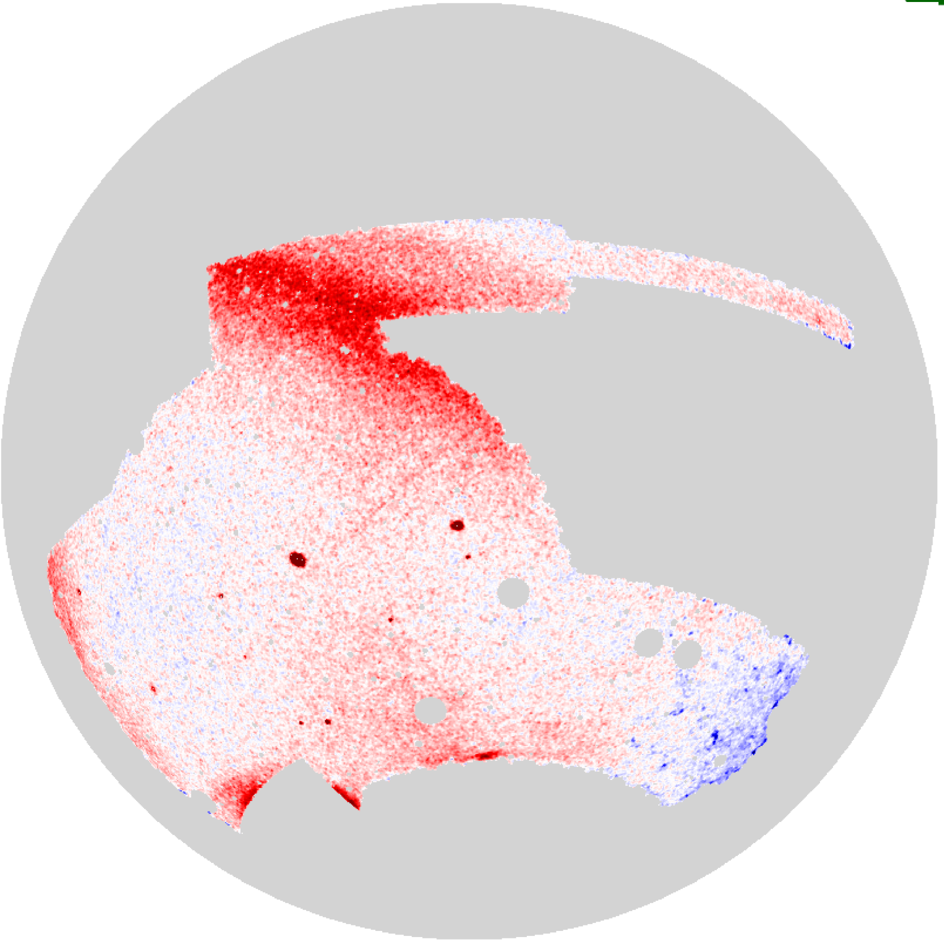


MWFitting results



Simulations for raw and refined models





Concluding remarks regarding DES data

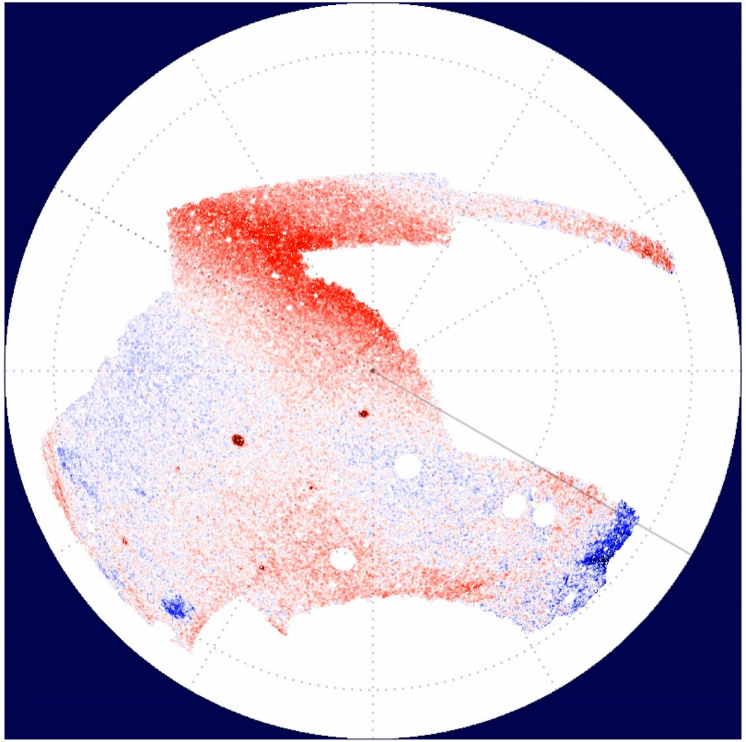
- MWFitting effectively offers a robust way to fit and simulate the Galactic components;

- Evidence for a power-law with break in index ~27kpc to describe halo density profile;

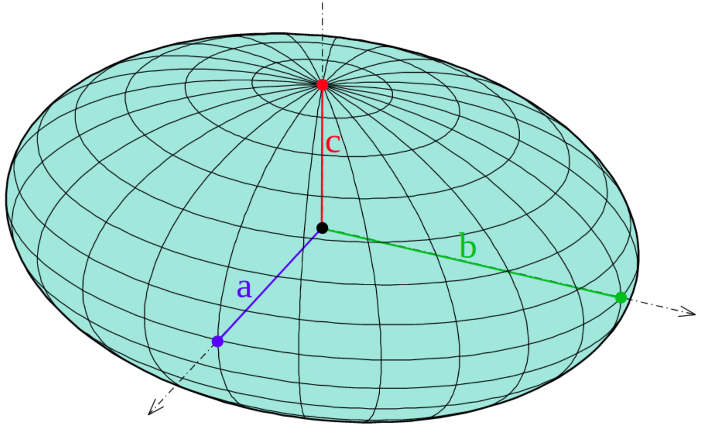
- Code is able to fit (tested and working!) more than one survey, more than one color, more halo models...

- The draft is in the (DES) final reader stage;

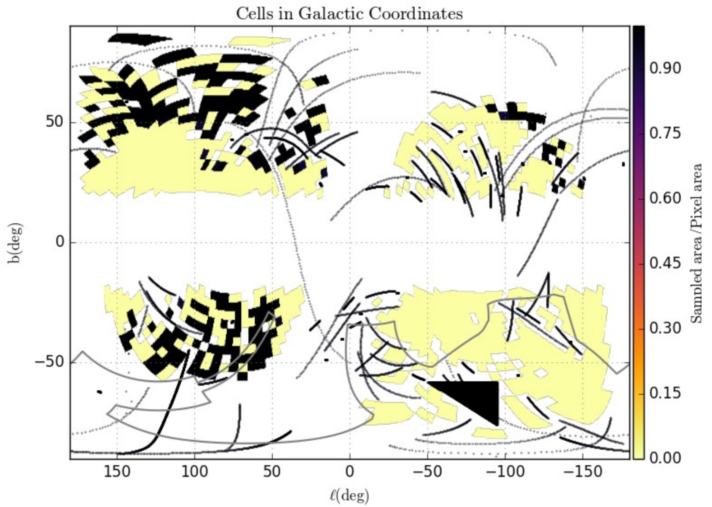
DES data – model for $(m-M)_0 = 16.3$

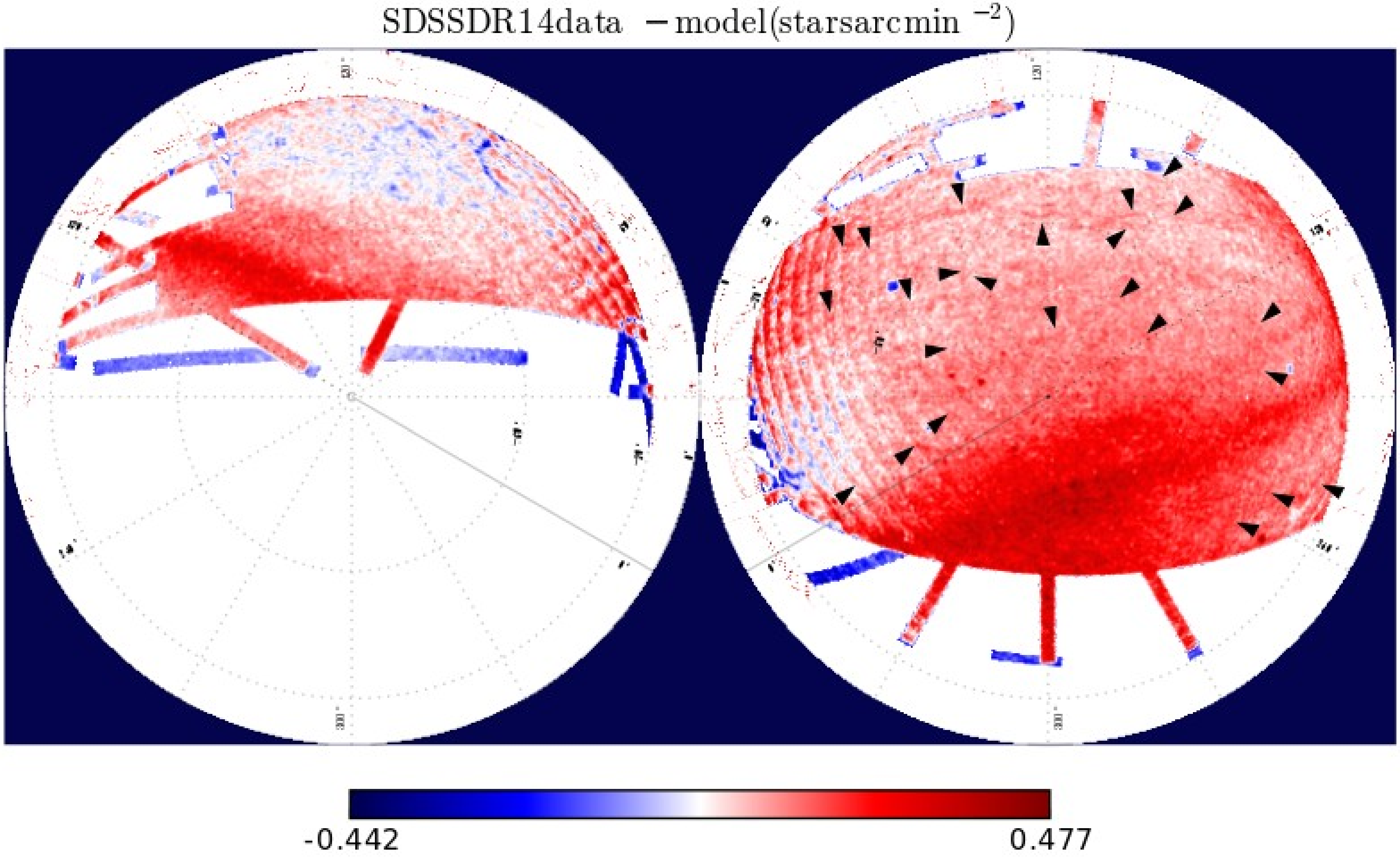


Preliminary tests with SDSS data



- SDSS covers Northern and Southern Galactic hemispheres;
- Halo modelled by triaxial spheroid (a, b and c) with the ***a*** axis displaced by phi (azimuthal angle, counterclockwise) and delta (towards north pole) regarding the Sun position;
- Fig. (bottom): 2600 square degrees compared to Trilegal models;
- Low triaxiality (a/b = 1.05±0.02);
- Phi and theta angles indicate major axis points to a region between LMC and SMC;
- Similarity to Gaia-Enceladus galaxy?





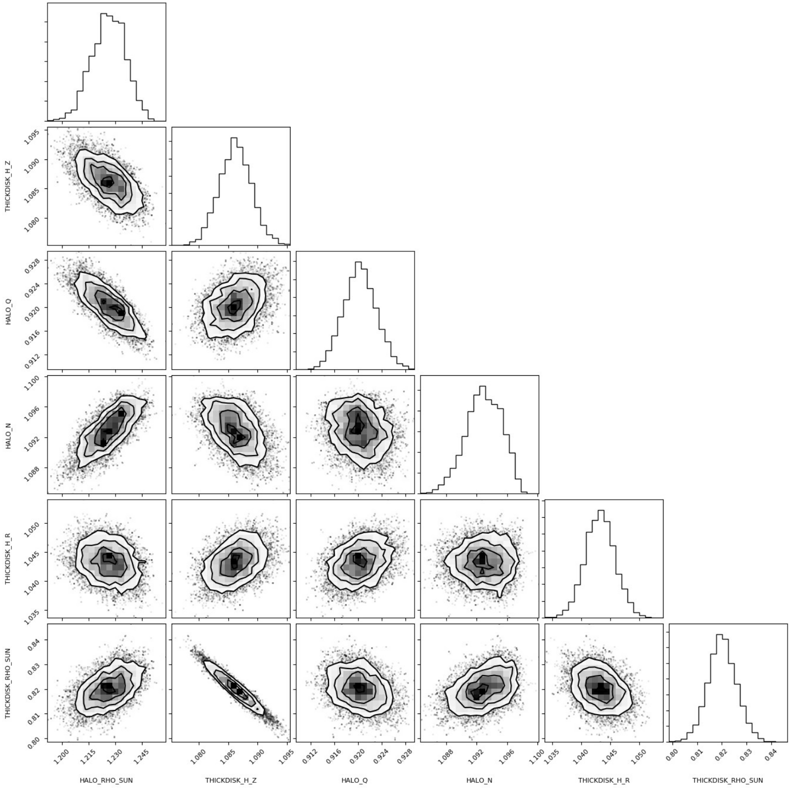
SDSSDR14data −model(starsarcmin $^{-2}$)
-0.442
0.477

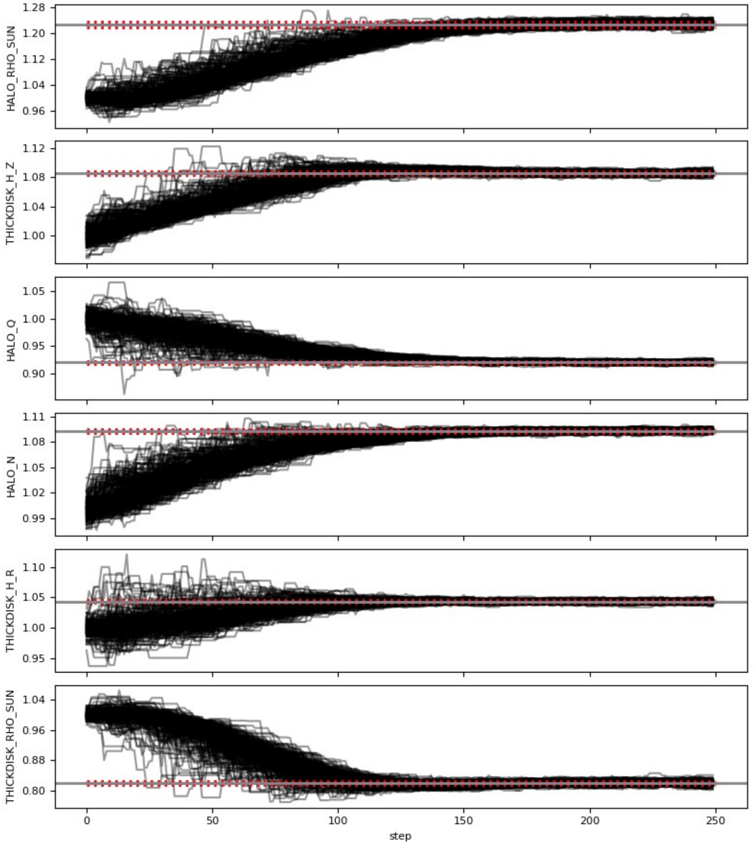
Perspective and concluding remarks

- First paper presenting the pipeline is ready (with DES comparison)!
- Break in the power law index is a need;
- Pan-STARRS and 2MASS are two examples of available data in LineA archives;
- SDSS comparison would provide a simulation down to g=23 as a public deliverable product;
- Gaia stars present information in 7D (position, velocities and metalicity) and down to G ~ 21;
- Trilegal provides kinematic information about stars and that is very useful to detect substructures even in the position-velocity space;

Thank you!

Questions?


HALO_RHO_SUN
THICKDISK_H_Z
HALO_Q
HALO_N
THICKDISK_H_R
THICKDISK_RHO_SUN


HALO_RHO_SUN
THICKDISK_H_Z
HALO_Q
HALO_N
THICKDISK_H_R
THICKDISK_RHO_SUN
step