Fitting the Milky Way with DES-DR1 data

and more...

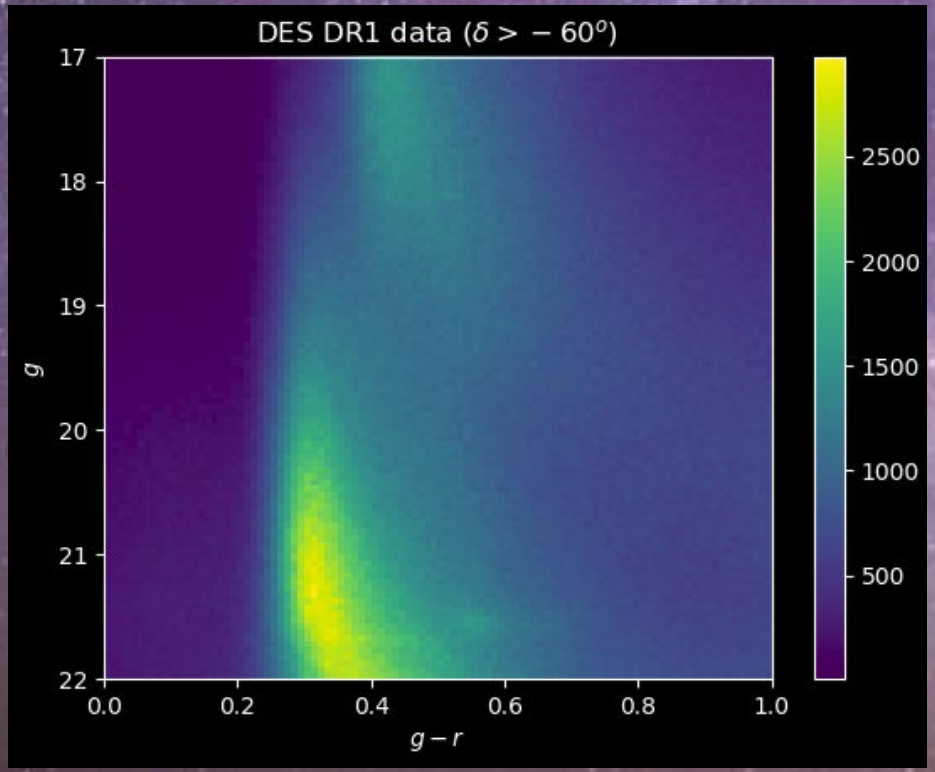
Adriano Pieres, Luiz da Costa,
Leo Girardi, Basílio Santiago

LIneA
Laboratório Interinstitucional de e-Astronomia

CAPES

INCT do e-Universo

DES-Brazil
Dark Energy Survey



Main aims:

- Fitting the main structures of the Milky Way focusing on the halo and disk (thick and thin) via population synthesis models;

- Using many colors, many regions and many surveys;

- Computationally as fast as possible;

- Generate reliable models and simulations for stellar fields;

Photo by Chris Bakley

Model for the Galaxy:

Thick disk: exponential model

Halo: power law

component & formula	parameter	meaning
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^{∞} $h_z^{\rm dust}$	total extinction at infinity dust scale heigth
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 $\int_{h=-\infty}^{+\infty}\rho^{\rm thin}{\rm d}z\Big\vert_{\odot} = \Sigma_{\odot}^{\rm thin}$	$\Sigma_{\odot}^{\rm thin}$ $h_R^{\rm thin}$ $R_{\rm max}^{\rm thin}$ $h_{z,0}^{\rm thin}$ $t_{\rm incr}^{\rm thin}$ α	local mass surface density thin disk scale length maximum radius scale height for youngest stars timescale for increase in h_z exponent for increase in h_z
Thick disk: $\rho^{\rm thick} = A^{\rm thick}\exp(h/h_z^{\rangle}\exp(R/h_R^{\rm thick})$ with $\int_{h=-\infty}^{+\infty}\rho^{\rm thick}{\rm d}z\Big\vert_{\odot} = \Sigma_{\odot}^{\rm thick}$	$\Sigma_{\odot}^{\rm thick}$ $h_R^{\rm thick}$ $R_{\rm max}^{\rm thick}$ $h_z^{\rm thick}$	local mass surface density thick disk scale length maximum radius (fixed) scale height
Halo: $\rho^{\rm halo} = A^{\rm halo}\left(\frac{r_{\odot}}{\sqrt{R^2+(z/q)^2}}\right)^n$ with $\rho^{\rm halo}(R_{\odot},0,z_{\odot}) = \rho_{\odot}^{\rm halo}$	$\rho_{\odot}^{\rm halo}$ q n	local mass space density axial ratio z''/x'' (or oblateness) exponent
Bulge $\rho^{\rm bulge} = A^{\rm bulge}\frac{\exp(-a^2/a_m^2)}{(1+a/a_0)^{1.8}}$ with $\rho^{\rm bulge}(0,0,0) = \rho_{\rm GC}^{\rm bulge}$ with $a = \left(x'^2 + y'^2/\eta^2 + z^2/\zeta^2\right)$ and x', y' rotated by ϕ_0. w.r.t. x, y	$\rho_{\rm GC}^{\rm bulge}$ $a_{\rm m}$ a_0 $\eta,\ \zeta$ ϕ_0	space density at GC scale length truncation scale length 1:η:ζ scale ratios angle w.r.t. Sun–GC line
Other	$R_{\odot}$ $z_{\odot}$	Sun's distance to the GC Sun's height above the plane

Field position, photosys

Sun position IMF and binaries

Extinction

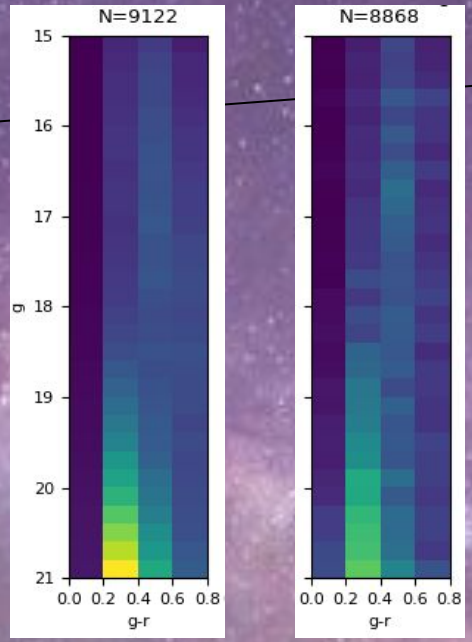
MW disk, halo and bulge

Object inserted and output

```
COORD_SYSTEM COORD_ALPHA COORD_DELTA FIELD_AREA   # 1: galactic l, b (deg), field_area (deg2)
FILE_PHOTOSYS    # kind_mag file_photsys
MAG_NUM MAG_MIN:MAG_MAX MAG_RES MAG_BLUE MAG_RED C_MIN:C_MAX C_RES # magnitude columns and limits

R_SUN Z_SUN      # r_sun, z_sun: sun radius and height on disk (in pc)
FILE_IMF         # file for imf
BIN_KIND         # binary_kind: 0=none, 1=yes
BIN_FRAC         # binary fraction
BIN_MRINF BIN_MRSUP # binary_mrinf, binary_mrsup: limits of mass ratios if binary_kind=1

EXT_KIND         # extinction kind: 0=none, 1=exp with local calibration, 2=exp with calibration at infty
EXT_RHO_SUN      # extinction_rho_sun: local extinction density Av, in mag/pc
EXT_INF EXT_INF_DISP    # extinction_infty: extinction Av at infinity in mag, dispersion
EXT_H_R EXT_H_Z # extinction_h_r, extinction_h_z: radial and vertical scales

THINDISK_KIND    # thindisk kind: 0=none, 1=z_exp, 2=z_sech, 3=z_sech2
THINDISK_RHO_SUN        # thindisk_rho_sun: local thindisk surface density, in stars formed/pc2
THINDISK_H_R THINDISK_R_MIN THINDISK_R_MAX      # thindisk_h_r, thindisk_r_min,max: radial scale, truncation radii
THINDISK_H_Z0 THINDISK_HZ_TAU0 THINDISK_HZ_ALPHA THINDISK_NS # thindisk_h_z0, thindisk_hz_tau0, thindisk_hz_alpha
THINDISK_FILE THINDISK_A THINDISK_B # File with (t, SFR, Z), factors A, B (from A*t + B)
THICKDISK_KIND          # thickdisk kind: 0=none, 1=z_exp, 2=z_sech2
THICKDISK_RHO_SUN       # rho_thickdisk_sun: local thickdisk volume density, in stars formed/pc3
THICKDISK_H_R THICKDISK_R_MIN THICKDISK_R_MAX   # thickdisk_h_r, thickdisk_r_min,max: radial scale, truncation radii
THICKDISK_H_Z   # thickdisk_h_z: scale heigth (a single value)
THICKDISK_FILE THICKDISK_A THICKDISK_B  # File with (t, SFR, Z), factors A, B
HALO_KIND       # halo kind: 0=none, 1=1/r^4 cf Young 76, 2=oblate cf Gilmore, 3=power-law
HALO_RHO_SUN    # 0.0001731 0.0001154 halo_rho_sun: local halo volume density, to be done later: 0.001 for 1
HALO_R_EFF HALO_Q HALO_N # halo_r_eff, halo_q: effective radius on plane (about r_sun/3.0), oblateness and exponent
HALO_FILE HALO_A HALO_B # File with (t, SFR, Z), factors A, B
BULGE_KIND      # bulge kind: 0=none, 1=cf. Bahcall 86, 2=cf. Binney et al. 97
BULGE_RHO_CENTRAL       # bulge_rho_central: central bulge volume density, unrelated to solar position
BULGE_AM BULGE_A0       # bulge_am, bulge_a0: scale length and truncation scale length
BULGE_ETA BULGE_CSI BULGE_PHI0  # bulge_eta, bulge_csi, bulge_phi0
BULGE_CUTOFFMASS        # bulge_cutoffmass: (Msun) masses lower than this will be ignored
BULGE_FILE BULGE_A BULGE_B      # File with (t, SFR, Z), factors A, B

OBJECT_KIND     # object kind: 0=none, 1=at fixed distance
OBJECT_MASS OBJECT_DIST # object_mass, object_dist: total mass inside field, distance
OBJECT_AVKIND OBJECT_AVT        # object_avkind, object_av: Av added to foreground if =0, not added if =1,
OBJECT_CUTOFFMASS       # object_cutoffmass: (Msun) masses lower than this will be ignored
OBJECT_FILE OBJECT_A OBJECT_B   # File with (t, SFR, Z), factors A, B
OUT_TYPE        # output file: 1=data points 2=Hess 3=Partial Hess
```

1. MWFitting Method

MW model yields same sky region



Sky region from survey

Convert to a Hess diagram (Hd) within specific limits

The best Milky Way model

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

n: data (star counts)
v: expected values (model)
N: Hd bins
θ: fitting parameters
λ: likelihood
(from Eidelman+2004)

Photo by Chris Bakley

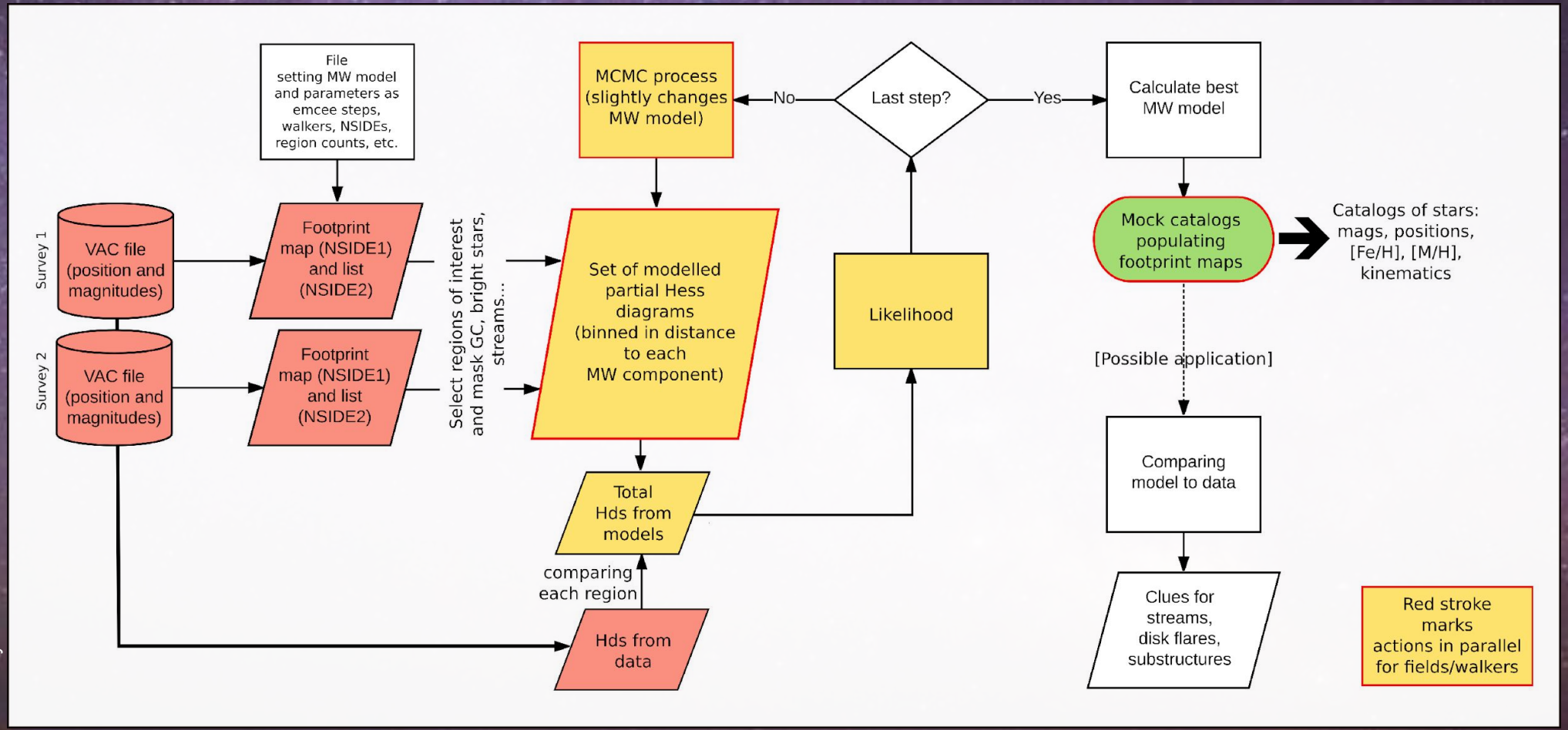


Photo by Chris Bakley

MWFitting main inputs:

Input data:

- Generate simulations? [True, False]
- Footprint Nside [Ex.: 4096],
- Input as simulations? [True, False]
- Factor, seed for input simulations [Ex.: 2, 4]

Mock catalogs:

- Build mock catalogs? [True, False]

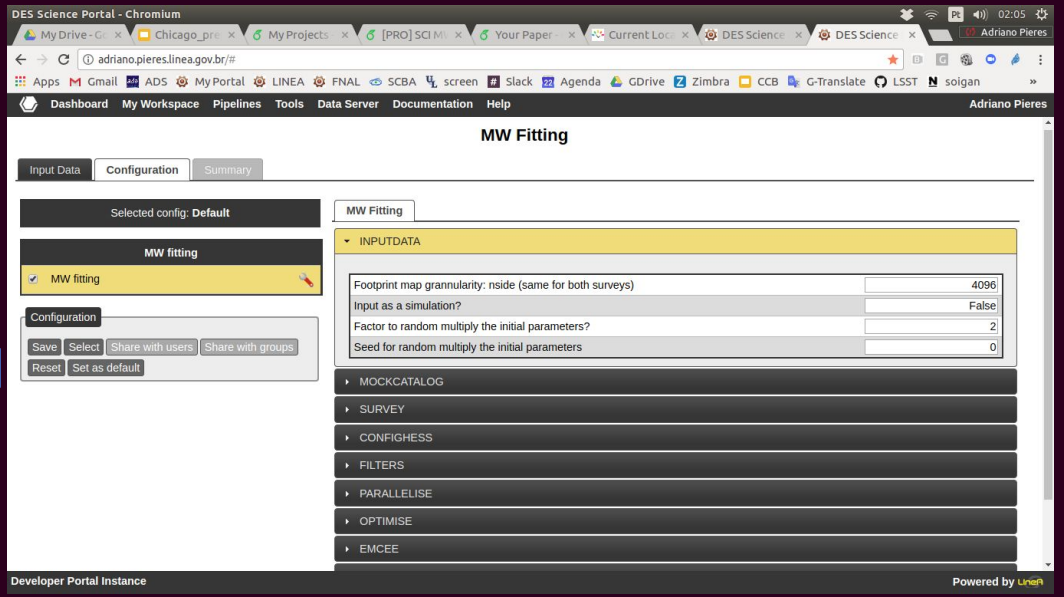
Surveys sampled:

- Surveys data [DES;SDSS]

Filters:

- Sigmas to extract streams along its perpendicular axis [Ex.: 2.]
- Absolute value for the lowest Galactic field (deg) [Ex.: 30]
- Overfactor (how many times models are oversampled) [Ex.: 50]

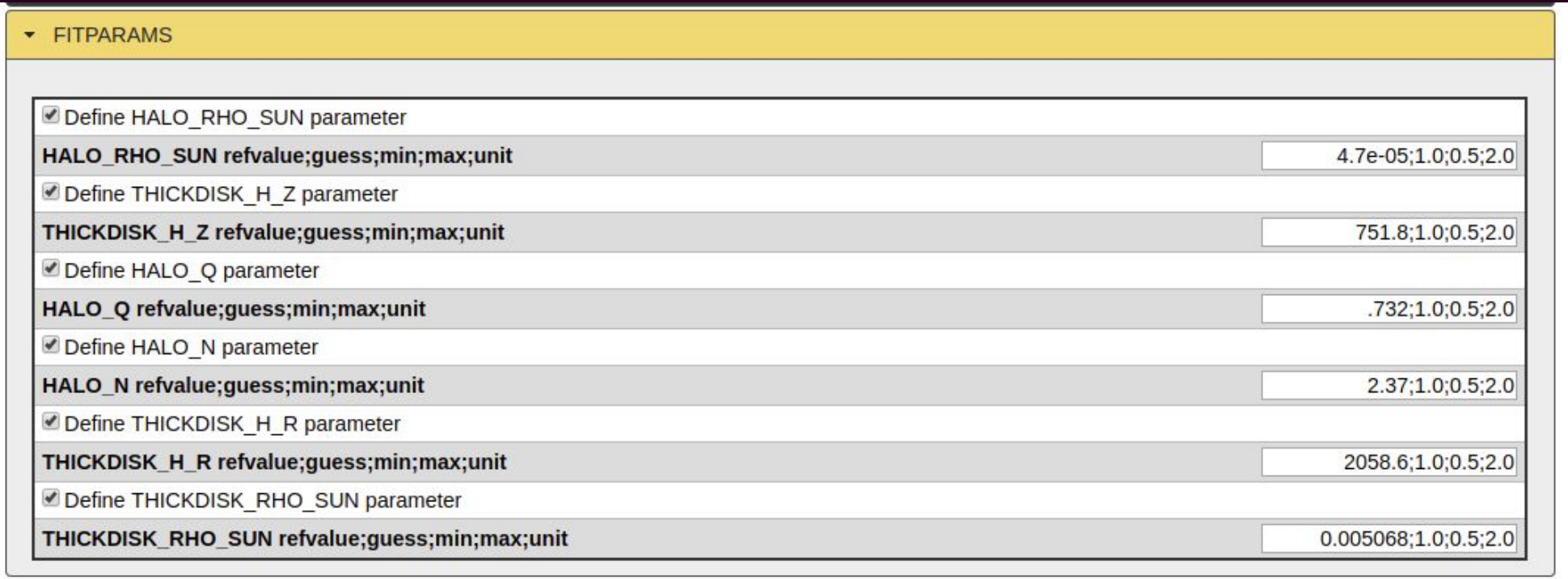
Emcee parameters: (walkers, steps, temperature)...



MWFitting main inputs:

...AND Galactic initial pars ('fitparams' - all of them are normalized when compared to data)

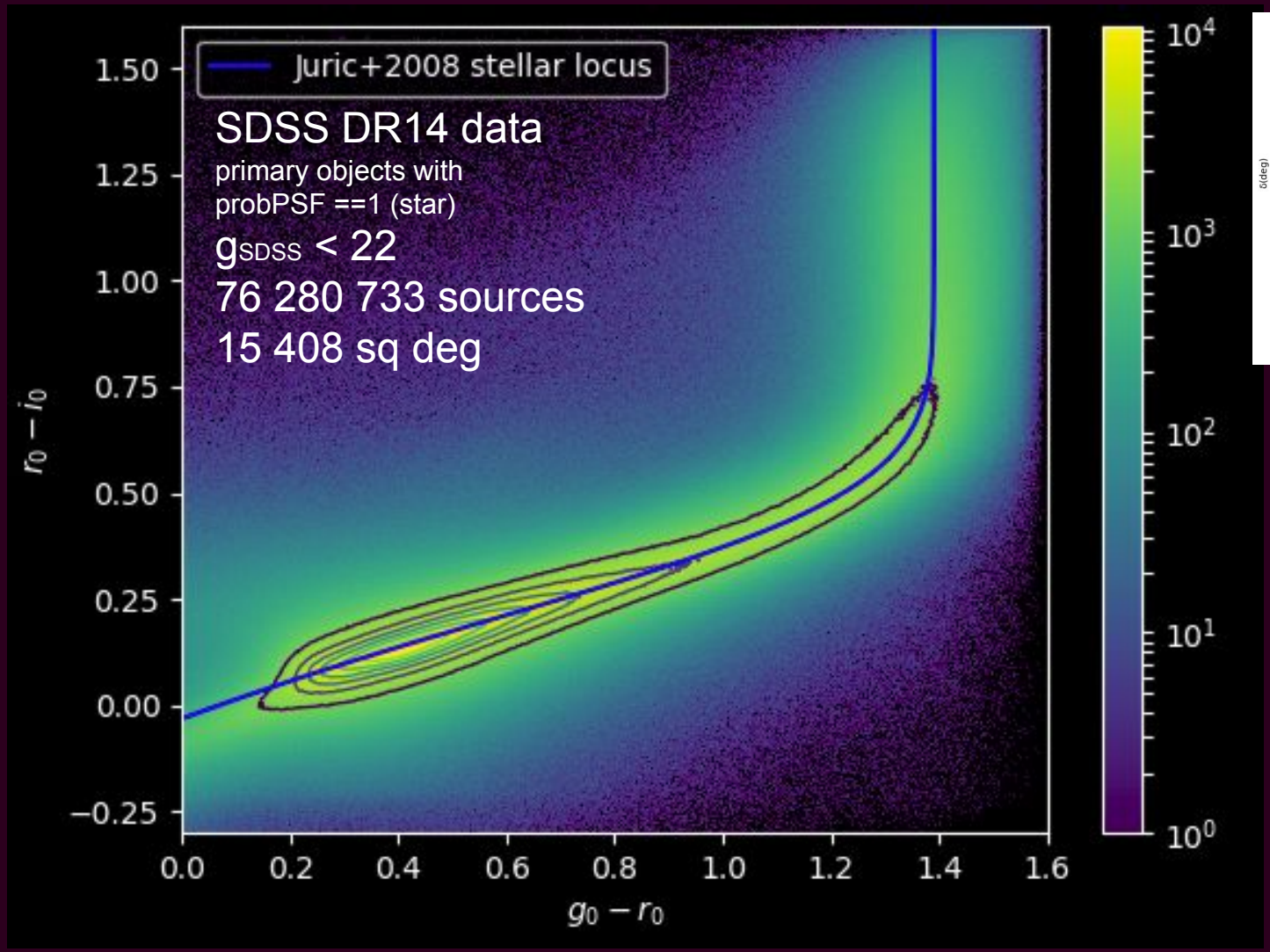
- *Thickdisk_rho_sun, thickdisk_h_z, thickdisk_h_r;*
- *Halo_rho_sun, halo_q, halo_n;*
  [initial value, factor to multiply, lower limit, upper limit]

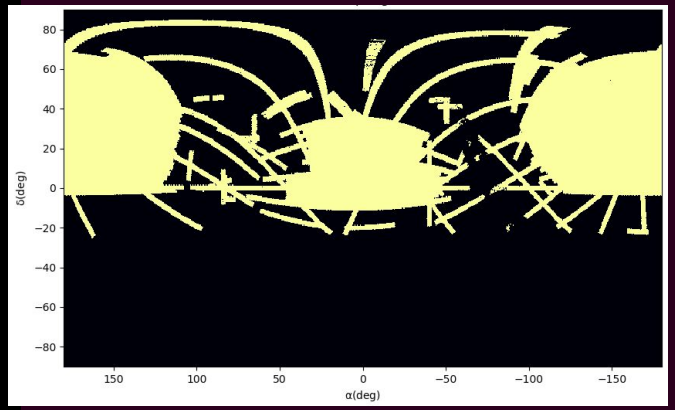


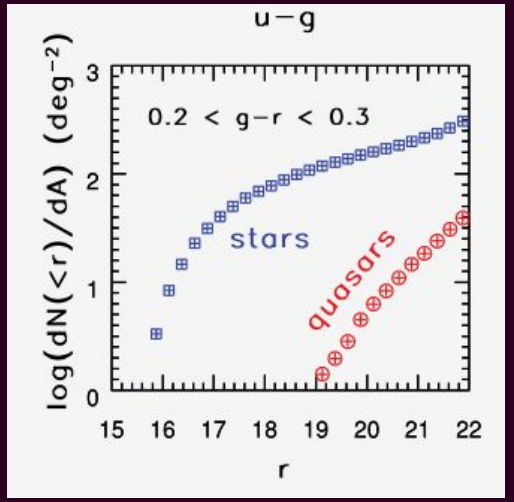
MWFitting main features:

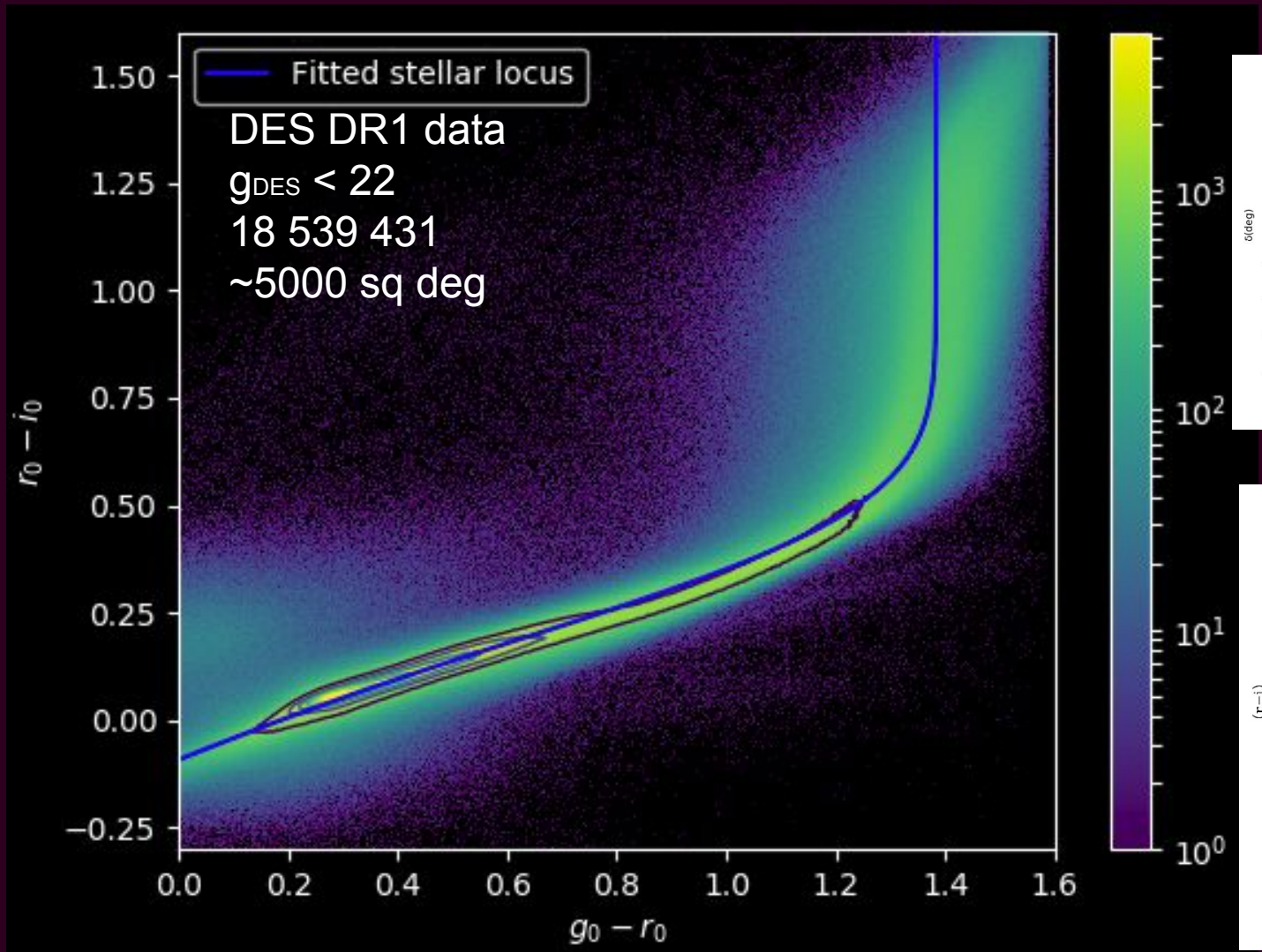
- MWFitting uses TRILEGAL [updated] models (Girardi+2005);
- For speed, instead fitting the entire footprint the set of comparing fields is limited;
- The code is being entirely developed in the LIneA environment (provenance, reproducibility and sharing with users): des-portal.linea.gov.br;
- Changes in code (user portal) -> tests -> commit -> lead changes to shared portal;
- Extinction to each field is made sampling points in the selected region and calculating mean and dispersion for A_V;
- Positions for mock stars are randomly sorted using footprint map (but restricted to pixel of comparison);
- Typical run for DES Stripe-82 and SDSS DR14 (including simulations) takes 4-20h;

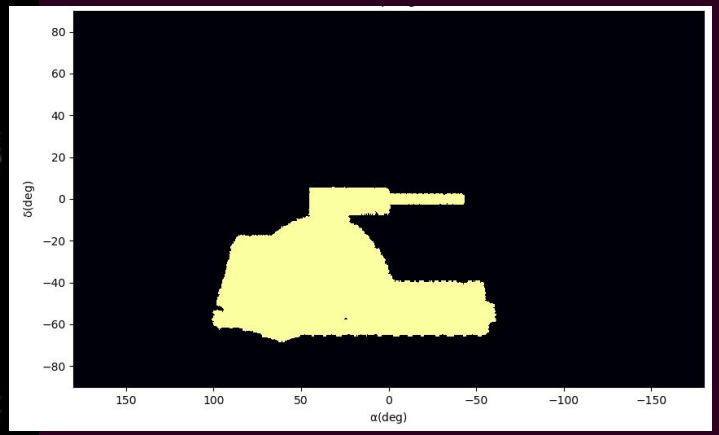
Photo by Chris Bakley

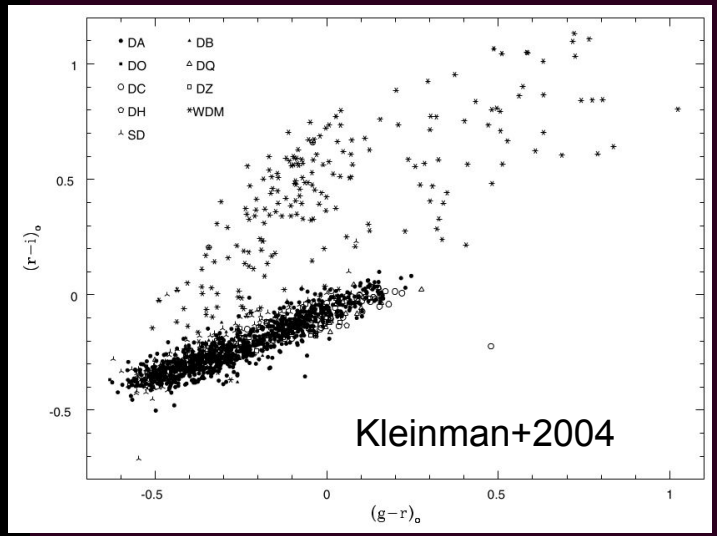

Juric+2008 stellar locus
SDSS DR14 data
primary objects with
probPSF ==1 (star)
g_{SDSS} < 22
76 280 733 sources
15 408 sq deg
$r_0 - i_0$
$g_0 - r_0$
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
10^4
10^3
10^2
10^1
10^0


δ(deg)
α(deg)
80
60
40
20
0
−20
−40
−60
−80
150
100
50
0
−50
−100
−150

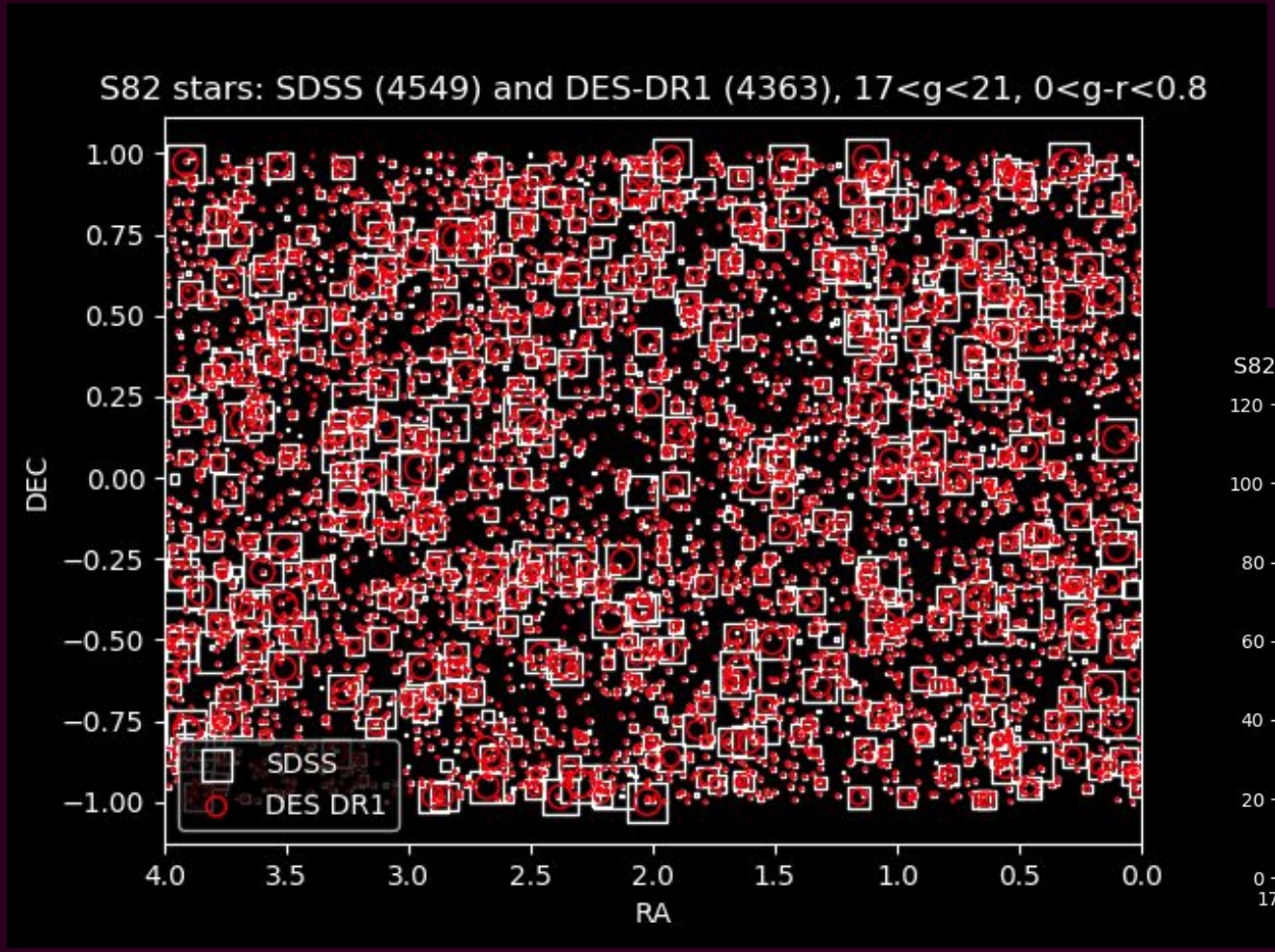

u − g
0.2 < g−r < 0.3
stars
quasars
log(dN(<r)/dA) (deg⁻²)
r
0
1
2
3
15
16
17
18
19
20
21
22

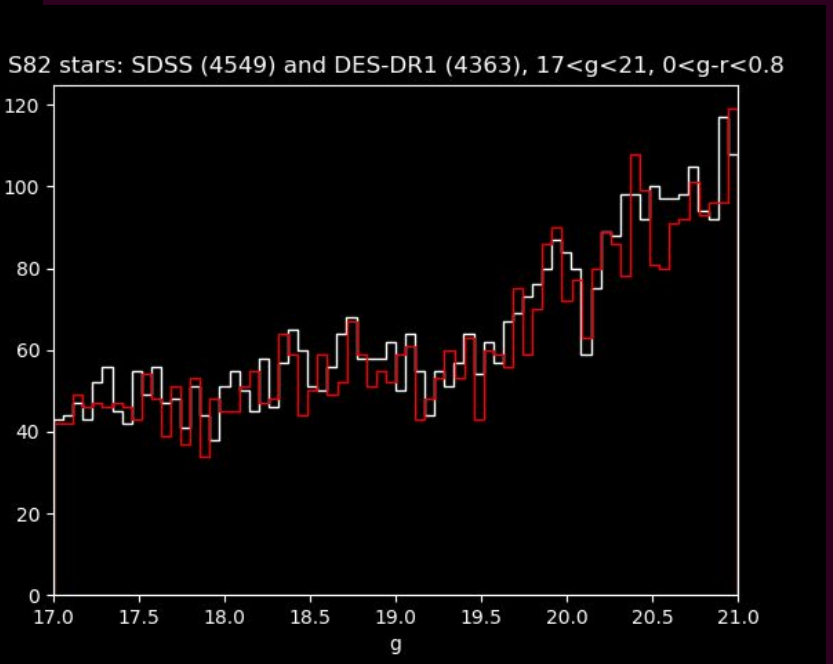

Fitted stellar locus
DES DR1 data
$g_{DES} < 22$
18 539 431
~5000 sq deg
$r_0 - i_0$
$g_0 - r_0$
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
10^3
10^2
10^1
10^0


δ(deg)
α(deg)
80
60
40
20
0
−20
−40
−60
−80
150
100
50
0
−50
−100
−150


DA
DB
DO
DQ
DC
DZ
DH
*WDM
SD
$(r-i)_o$
$(g-r)_o$
1
0.5
0
-0.5
-0.5
0
0.5
1
Kleinman+2004

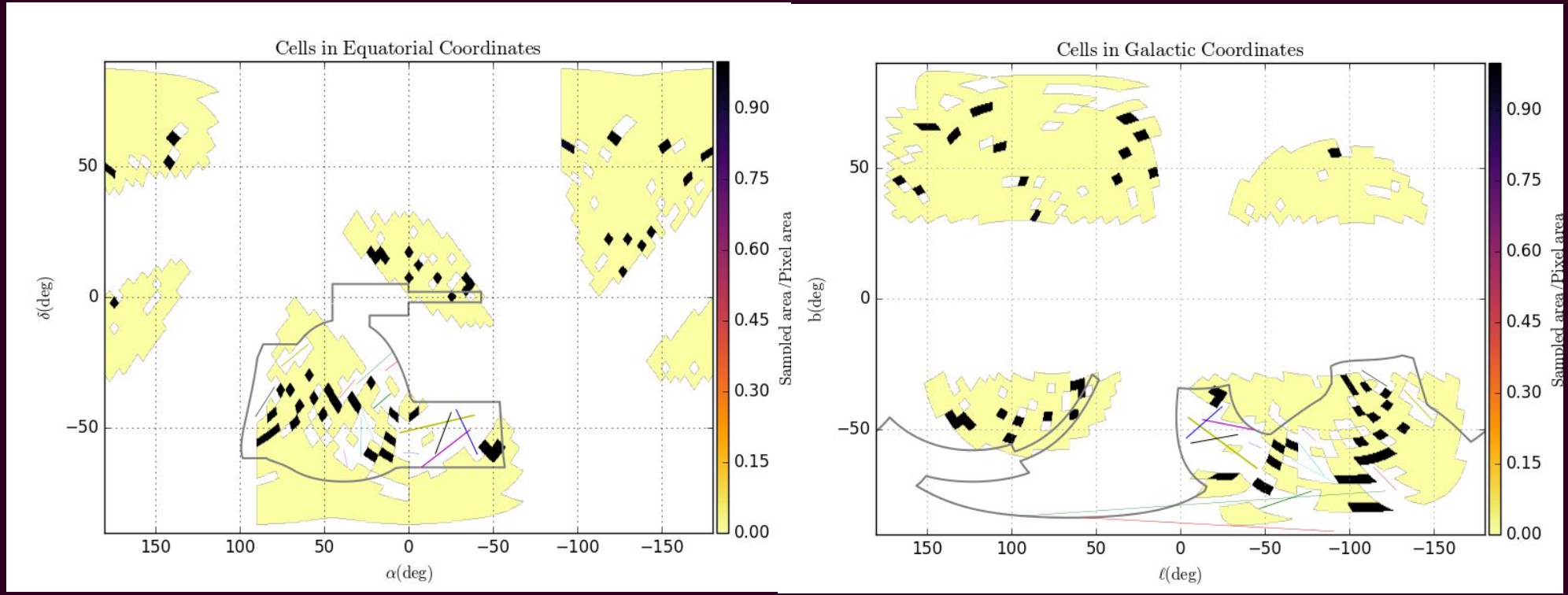
Good agreement and matching for SDSS DR14 and DES DR1 stars in part of Stripe 82



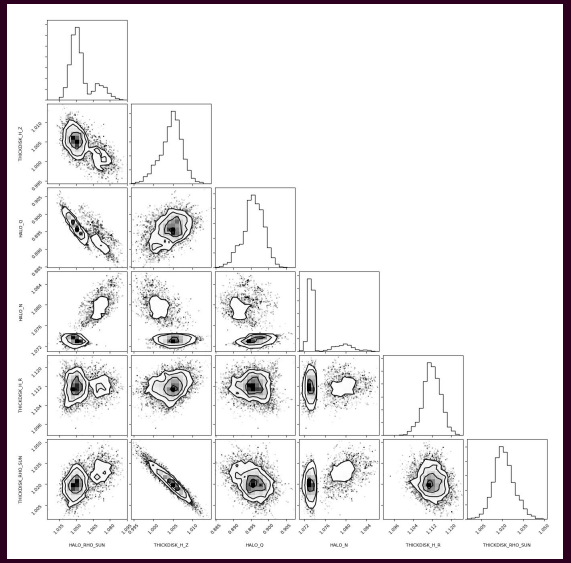


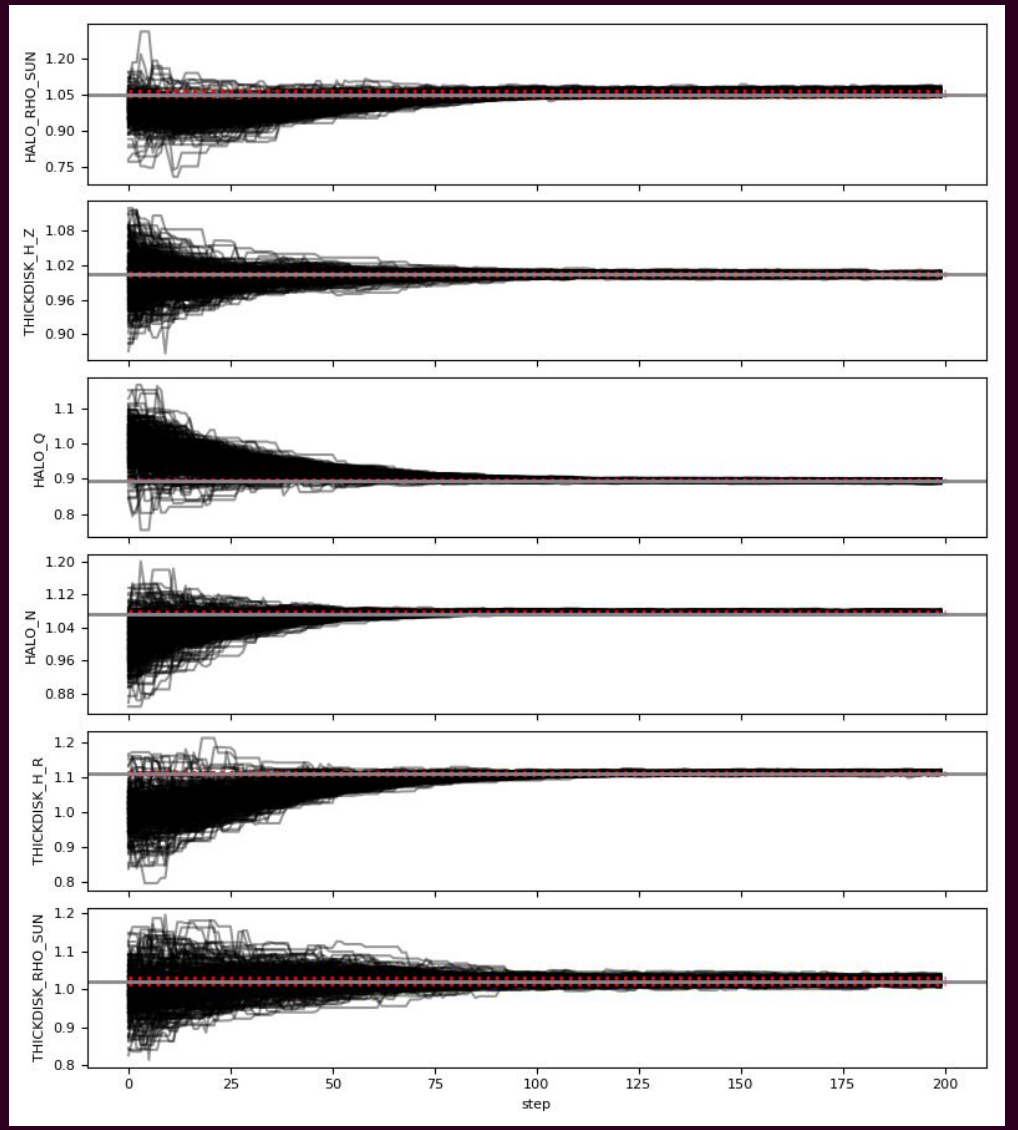

3. [Unpublished] results
Photo by Chris Bakley

Example of MWFitting run for [25 SDSS + 25 DES DR1] fields (each field ~13 sq. deg), masking low Galactic latitude fields, Sagittarius Stream and ‘DES’ streams (*Shipp+2018*), and coverage > 90%

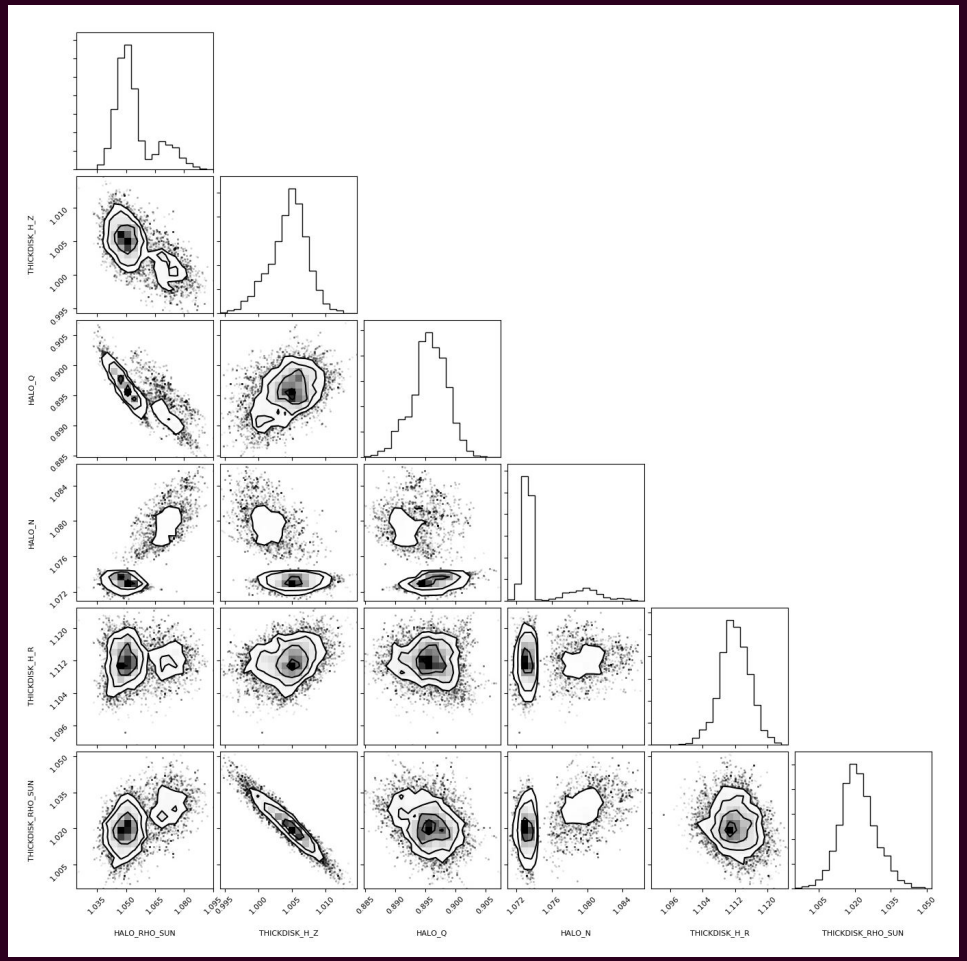


Parameter description	Our work (DES+SDSS)	Juric+2008 (SDSS)	de Jong+2010 (SEGUE)
Halo exponent	2.544±0.012	2.77±0.02	2.75±0.07
Halo oblateness	0.656±0.002	0.64±0.01	0.88±0.03
Halo density at R=$R_\odot$ (10^{-5} $M_\odot/pc^3$)	4.94±0.08	2.95±0.74	6.31±0.77
Thick Disk scale radius (pc)	2289±8	3261±650	4100±400
Thick Disk vertical scale (pc)	755±2	743±150	750±70
TD density at R=$R_\odot$ (10^{-3} $M_\odot/pc^{-3}$)	5.17±0.04	7.53±0.75	5.01±1.30

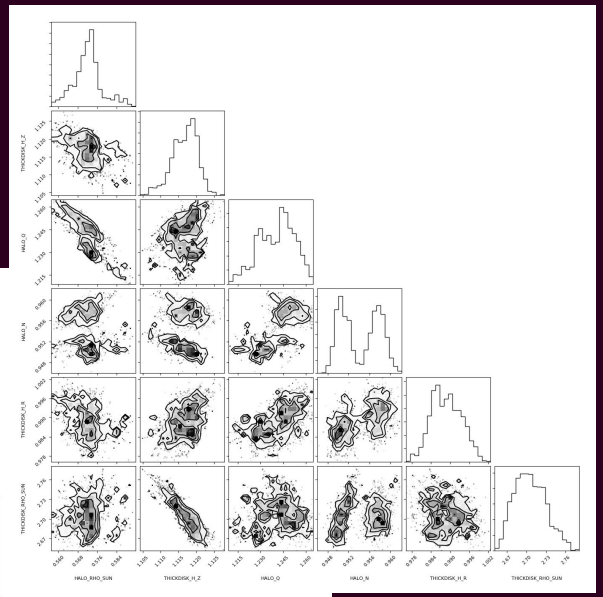




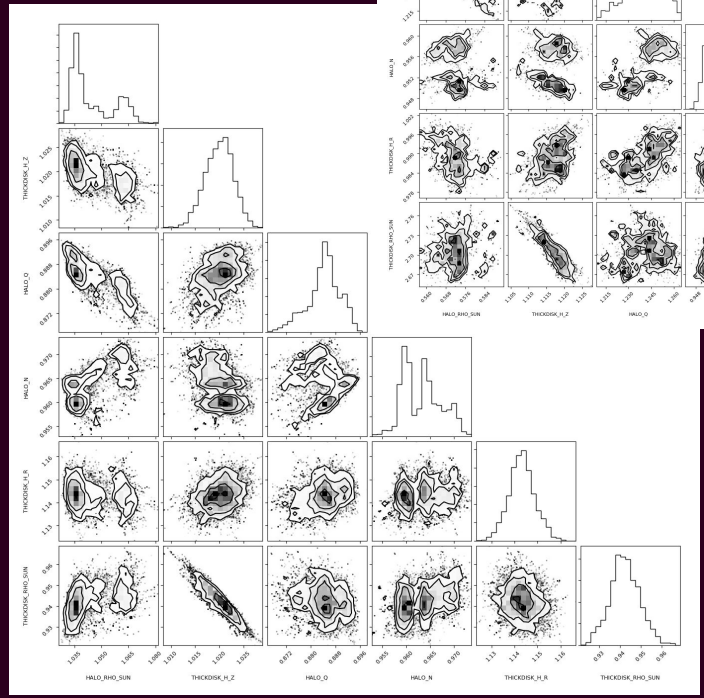
300 walkers, 200 steps (burner=100 steps)
25 DES fields + 25 SDSS fields (OverFactor=32)



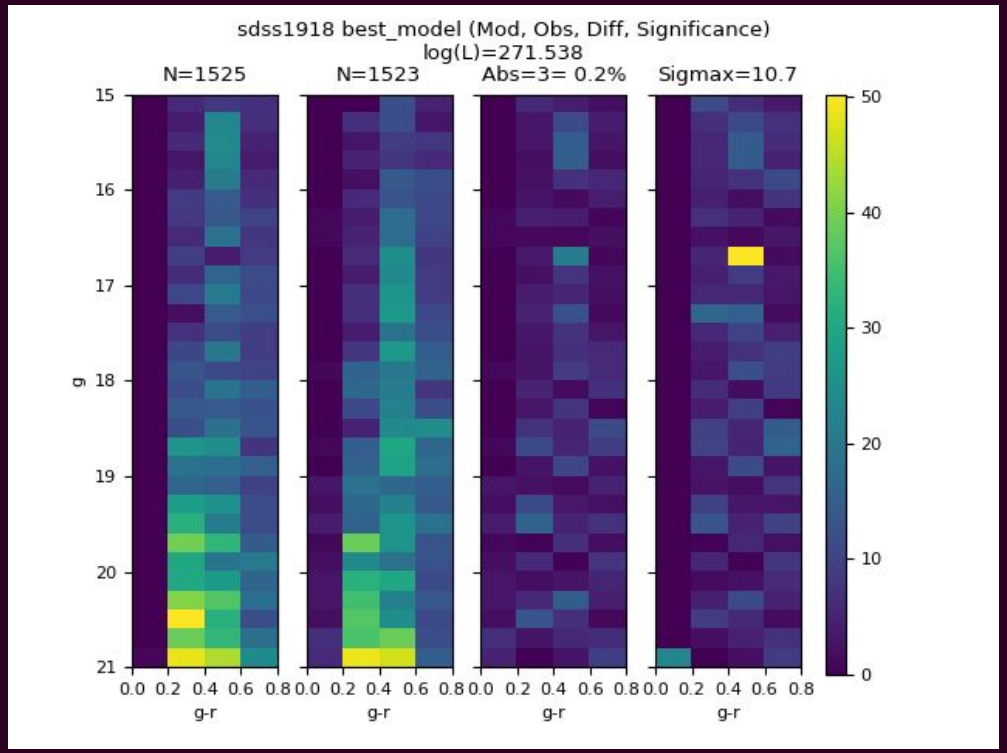
100 walkers, 500 steps (burner=400 steps)
30 (only) SDSS fields (OverFactor=32)

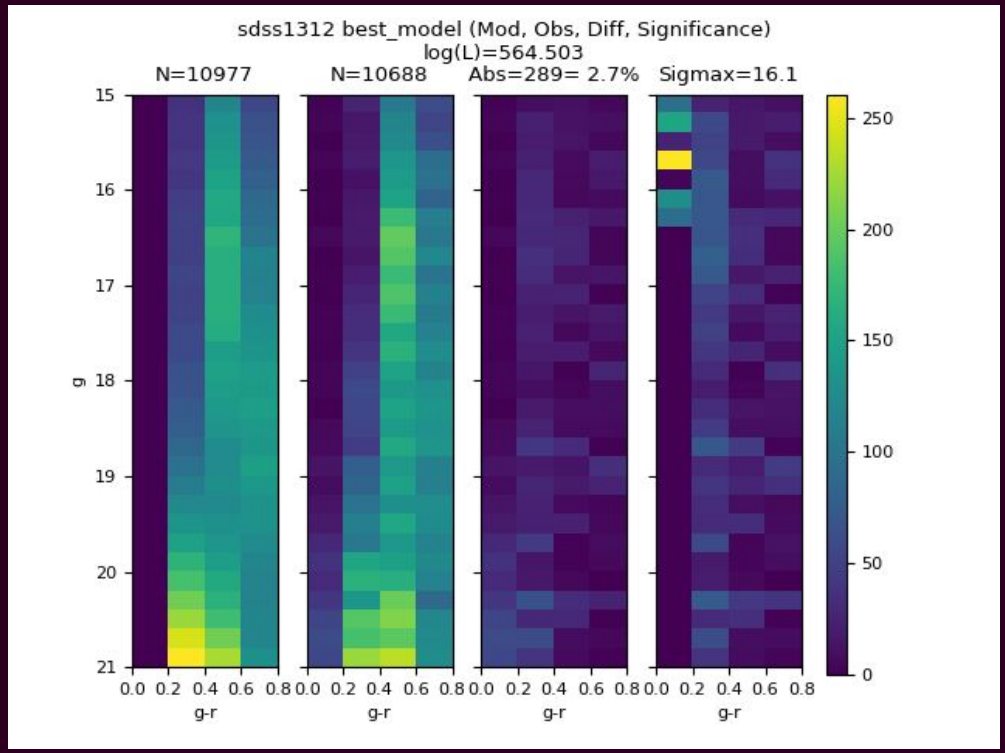


300 walkers, 300 steps
(burner=200 steps)
40 (only) SDSS fields
(OverFactor=32)

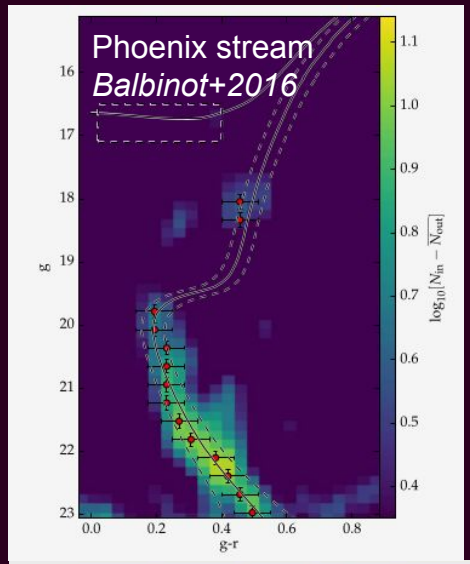


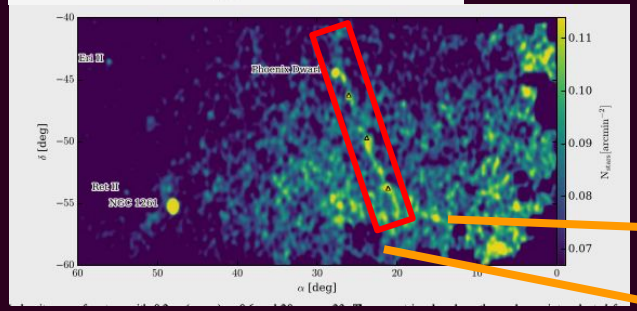
Striking similarities Data-Model

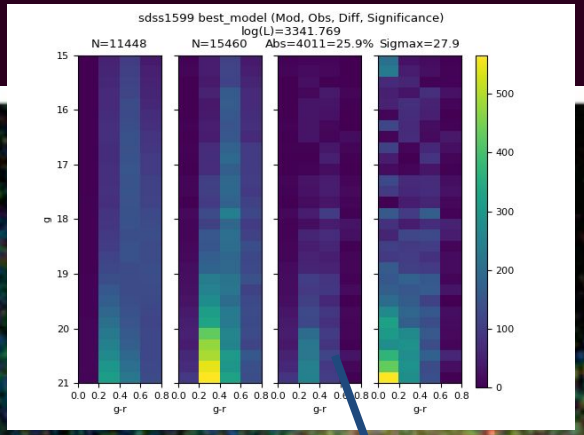


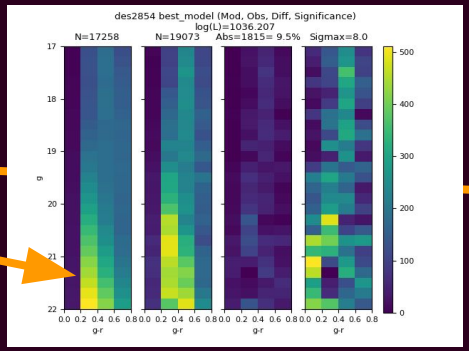


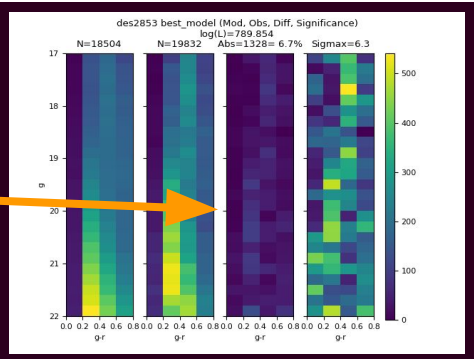
Differences Data-Model are probably over-densities and/or streams





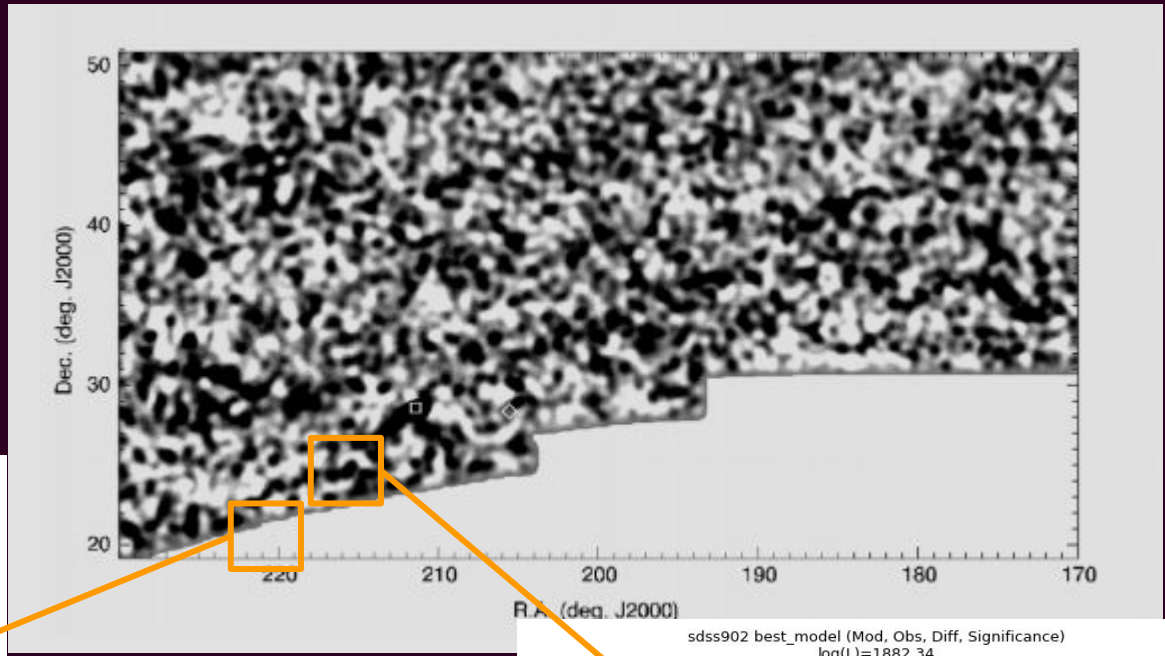


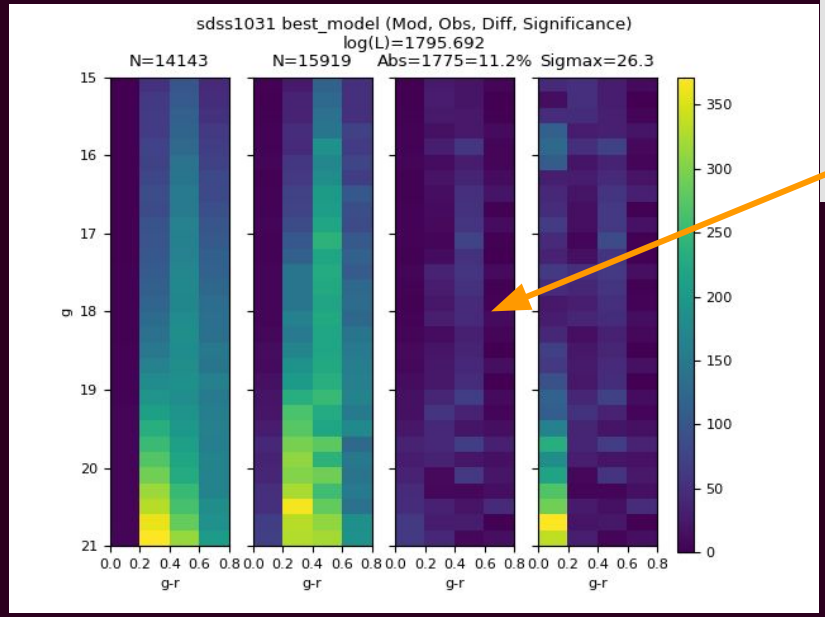


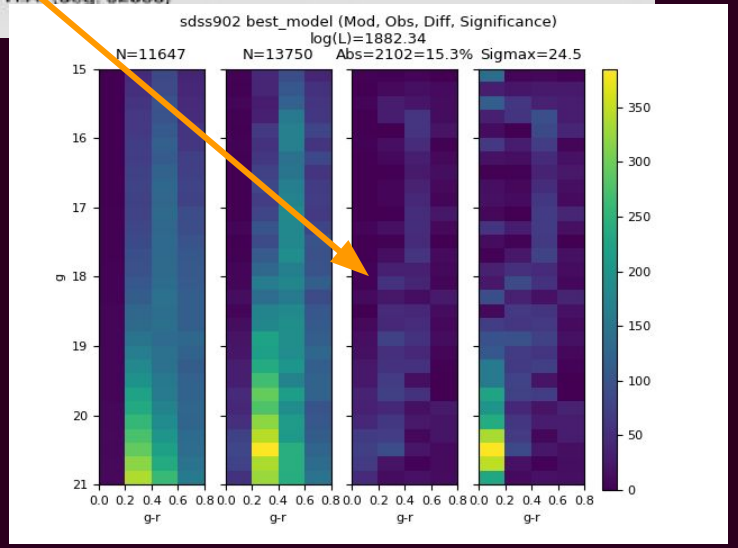


Differences Data-Model are probably over-densities and/or streams

Grillmair+2006
Stream in GC NGC 5466



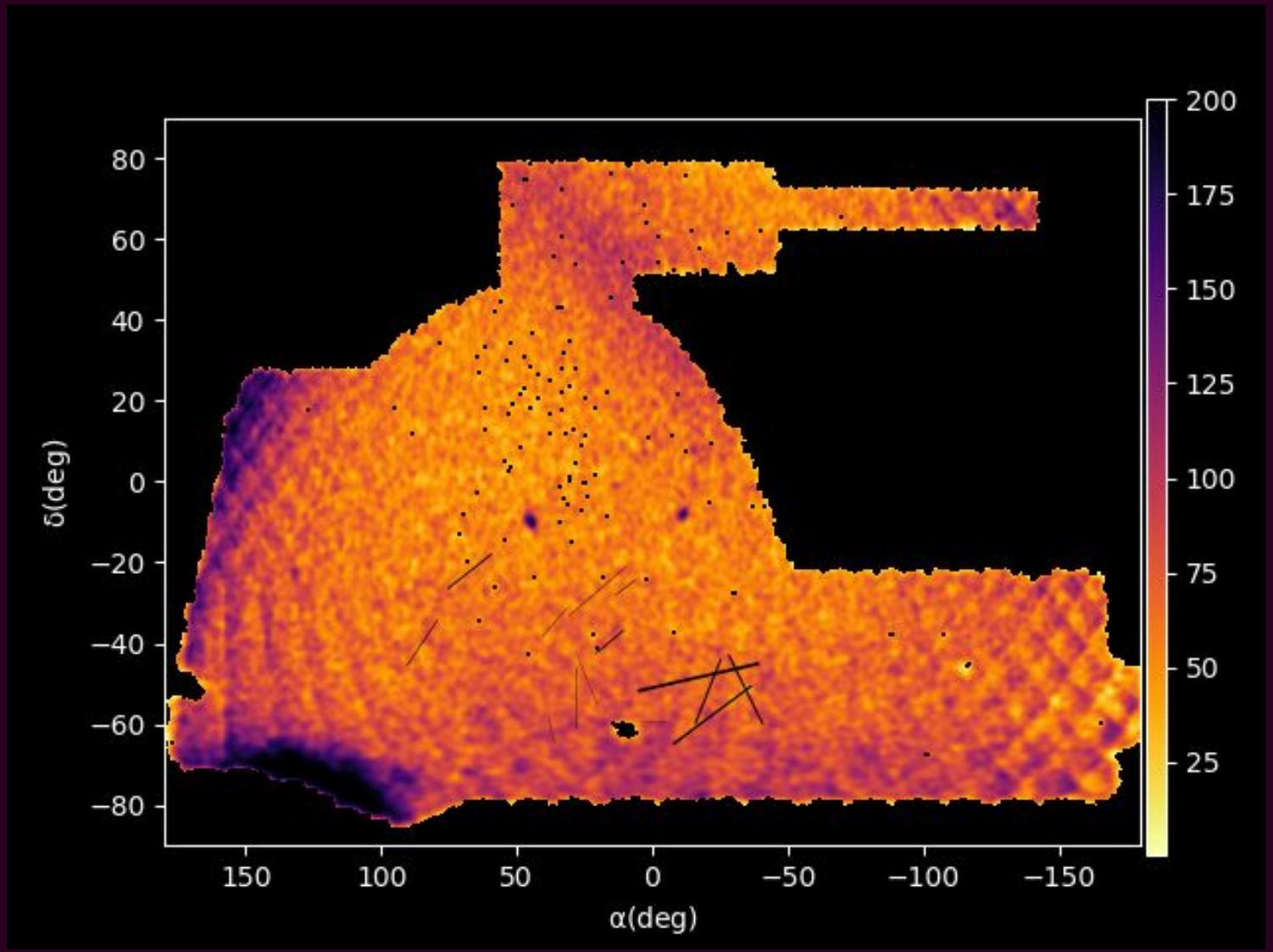




Discussion/Questions:

- Weird behavior for halo components related to broken power-law?
- Dealing with magnitudes where the survey is not 100% complete;
- Fitting halo+thick_disk using simulations to ensure the method is reliable;
- SDSS + DES data (Galactic North + South), triaxial halo;
- SDSS + DES + 2MASS to thin+thick+halo;
- Incorporate PanStaRRs survey;
- Fitting more parameters for MW, running TRILEGAL directly from Hds instead using partial Hds;

EXTRA SLIDES



- g<21 (in this process that simulates catalogs);
- Saturated in 200 stars/sq degree;
- Diffraction effect in the borders (not-desirable);
- Some OD are galaxy clusters;