LSST-Italy meeting
Jan, 2026

LSST-popstar

ITA-INA S25

Leo Girardi – INAF Padova, Italy

Most slides from Giada Pastorelli

In-kind contribution ITA-INA S25: Popstar-LSST

★ Population models of LSST stellar content

    Popstar-LSST, PI Léo Girardi

★ **Non-directable software contribution**
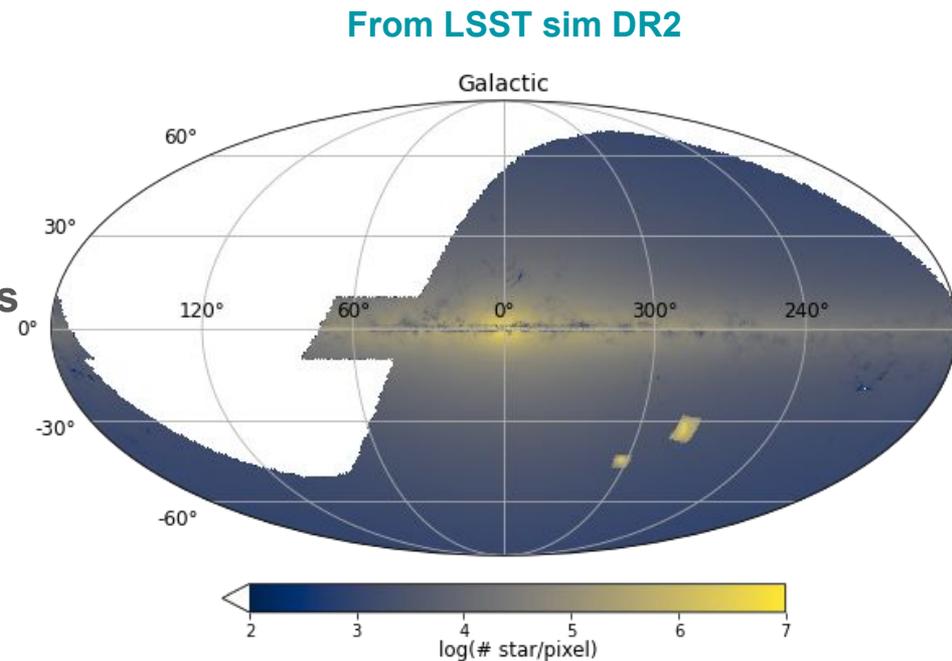
    INAF-Padova (ITA-INA S25)

★ **TRILEGAL-LSST synthetic stellar catalogs**

    ○ Density maps, luminosity functions,

       crowding maps

    ○ Jupyter notebook tutorials

★ Support survey observing strategy

★ SMWLV SC (main recipient)

From LSST sim DR2

Dal Tio, Pastorelli, Girardi + 2022

Popstar-LSST team

PARSEC-COLIBRI stellar models

PI Léo Girardi
INAF-OAPd

Paola Marigo
U. Padova

Sandro Bressan
SISSA Trieste

Guglielmo Costa
U. Lyon

Guglielmo Volpato
U. Padova

Diego Bossini
U. Padova

Chi Thanh Nguyen
INAF-OATs

Kendall Shepherd
SISSA Trieste

Francesco Addari
SISSA Trieste

Stellar Populations

Giada Pastorelli
U. Padova

Michele Trabucchi
U. Padova

Alessandro Mazzi
U. Bologna

Globular clusters & public outreach

Simone Zaggia
INAF-OAPd

Yazan Al Momany
INAF-OAPd

Federico di Giacomo
INAF-OAS Bo

Collaborations: *Željko Ivezić, Mario Jurić*@U. Washington; *Knut Olsen, Alice Jacques*@NOIRLab; *Mauro Barbieri*@ESO-Garching; *Lovro Palaversa* @RBI Zagreb; *Tomislav Jurkić*@ U. Rijeka; *Will Clarkson* @ U. Michigan; **LSST-Brazil team** @ LinEA; **SMWLV** & **TVS**
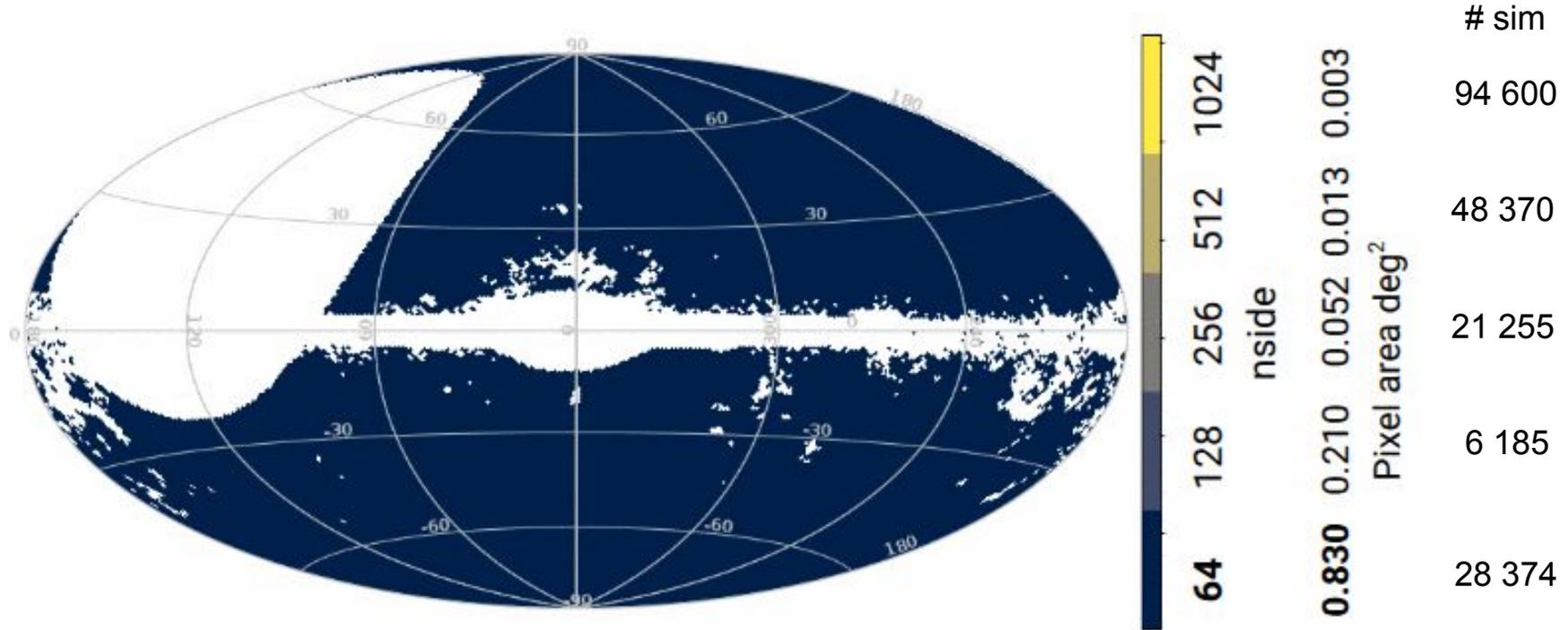**Past Members:** Piero Dal Tio, Thaise Rodrigues, Yang Chen

LSST stellar catalogs with TRILEGAL
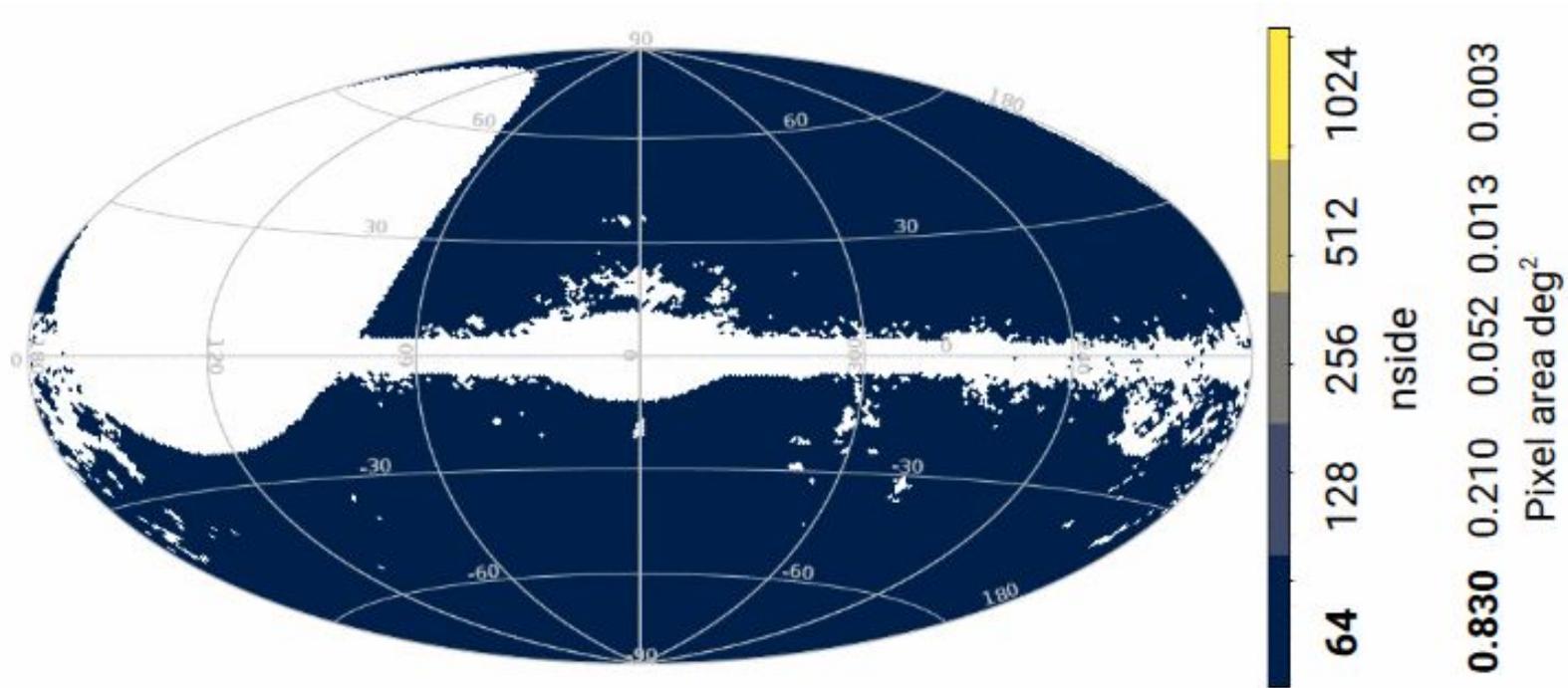
We simulate conic sections of the Milky Way:
- **Galaxy components** →Thin disk + Thick Disk + Bulge + Halo
- **Dust layer** → *Extinction-at-infinity maps* and *exp. dust layer* with fixed scale height
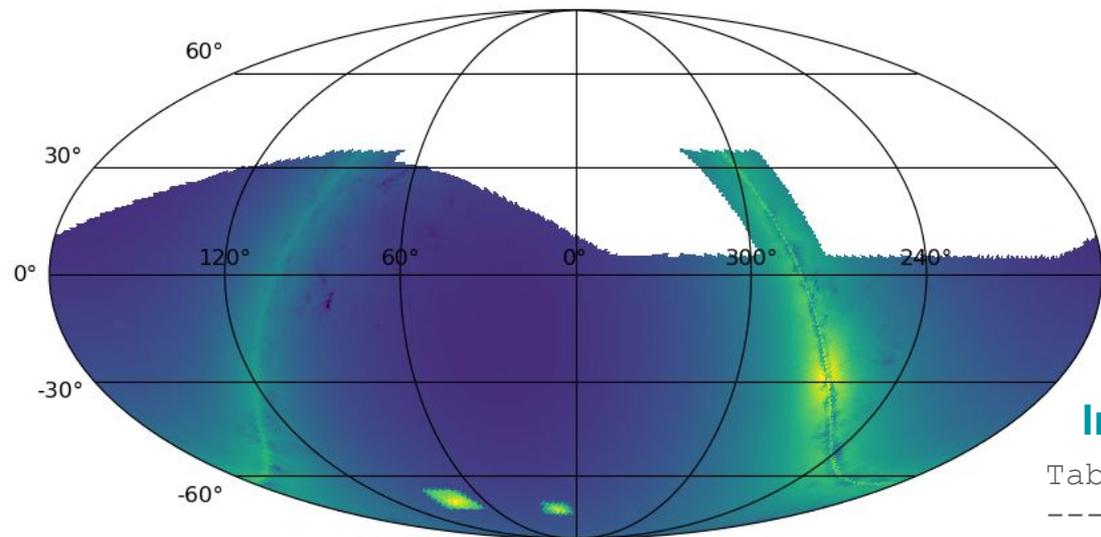 (Girardi+05,+12, Pieres+2020, Mazzi+2021)

LSST stellar catalogs with TRILEGAL

LSST Simulated sky areas defined by HEALPix scheme: variable resolution depending on surface mass density (TRILEGAL) & extinction variations (Planck collaboration +2014)

sim

94 600

48 370

21 255

6 185

28 374

sim tot
198 784

8000 hrs

TRILEGAL stellar catalogs

Single star catalog

```
Table name: simdr2 AKA  single stars
-----------------------------------------
 Nr. of rows:              ~11.4 billions
 Table Size:               ~3122.9 GB
 Nr. of columns:                       55
 Nr. of indexed columns:               24
 Indexes Size:             ~5133.7 GB
 Total Size:               ~8256.6 GB
-----------------------------------------
```

Interacting & detached binary star catalog

```
Table name: simdr2_binary AKA  binary stars
-----------------------------------------
 Nr. of rows:              ~1.2 billions
 Table Size:               ~502.1 GB
 Nr. of columns:                       92
 Nr. of indexed columns:               42
 Indexes Size:             ~933.5 GB
 Total Size:               ~1435.6 GB
-----------------------------------------
```

o Co-added survey depth of **r = 27.5 mag**

TRILEGAL stellar catalogs

○ **Photometry** in **LSST** u, g, r, i, z, y - *Gaia* G, G_{BP}, G_{RP} Vega mags - **Euclid (in next DR3)**

	mbolmag	umag	gmag	rmag	imag	zmag	ymag	gaia_gmag	g_bpmag	g_rpmag
1	17.195	24.005	19.876	18.239	17.493	17.115	16.896	18.065	19.212	17.061
2	2.875	10.965	10.102	8.193	5.73	4.513	3.499	6.3	9.254	4.782
9	8.585	16.06	12.746	11.318	9.477	8.737	8.324	10.21	12.234	8.941

Table Browser for 3: TAP_4_lsst_sim.simdr2

Co-added survey depth of **r = 27.5 mag**

DR3: "mag limits crowding dependent"

○ **Positional and kinematic properties** (distances, proper motions, space velocities)

	ra	dec	gall	galb	gc	mu0	av	velu	velv	velw	vrad	pmracosd	pmdec
1	70.17615	-42.96964	247.63276	-41.4876	3	20.8	0.069	97.75	-250.13	54.17	178.29	0.32	0.01
2	70.26653	-42.92973	247.58032	-41.42109	1	7.5	0.051	21.	-22.38	16.95	21.79	21.08	12.42
9	69.39223	-38.09844	241.08116	-41.88049	2	12.2	0.08	-27.03	-67.49	11.95	38.19	3.39	-3.58

Table Browser for 3: TAP_4_lsst_sim.simdr2

○ **Stellar properties & surface composition**

	m_ini	mratio	mass	logl	logte	logg	label	mcoretp	c_o	mloss	tau1m	x	y	xc	xn	xo	cexcess	z
1	0.86438	0.	0.564	3.35	3.5696	0.07	8	0.534	0.474	-1.00000E-6	0.06	0.7345	0.2627	0.000438	0.000219	0.001233	-1.	0.002797
2	2.22999	0.	2.124	3.758	3.4633	-0.188	8	0.569	0.497	-0.	0.03	0.62	0.3426	0.005573	0.004937	0.01494	-1.	0.03743
9	0.91947	0.	0.71	3.354	3.5206	-0.03	8	0.531	0.482	-0.	0.04	0.7251	0.2693	0.000887	0.000417	0.002454	-1.	0.00553

Table Browser for 3: TAP_4_lsst_sim.simdr2

○ **Pulsation periods**   ○ Other useful information

	period0	period1	period2	period3	period4	pmode	htm9	ring256	nest4096	random_id	elon	elat
1	141.63	64.82	40.87	33.18	26.93	0	2309366	660123	140128003	93.9424	55.45312	-64.05008
2	317.32	144.98	90.83	71.07	58.38	2	2309356	661127	140127677	24.012	55.62496	-64.03245
9	179.05	82.35	51.64	41.71	33.93	0	2308523	635589	141587548	26.89	57.23561	-59.21578

Table Browser for 3: TAP_4_lsst_sim.simdr2

TRILEGAL stellar catalogs

o **Additional quantities for binary systems**

Quantity	Description
ID	Identification number of the binary system.
c1_KW, c2_KW	Stellar types (as in Table 2).
P	Current orbital period in days.[a]
a	Current semimajor axis in $R_\odot$.[a]
e	Current eccentricity.[a]
i	Inclination of the orbit in degrees.
K1, K2	Radial velocity amplitudes in $R_\odot$/days.[a]
Delta_r1, Delta_r2	Maximum depth of the primary and secondary eclipses, in magnitudes, in the r band.[b]

Parameters for primary and secondary stars (c1_*** and c2_***)

Photometry for primary, secondary and total binary system (c3_***)

DR2 contains only 10% of expected binaries

We aim to go up to 40% in next simulations

k	Stellar Kind
0	Main sequence (MS) and fully convective
1	MS and not fully convective
2	Hertzsprung gap (HG)
3	Giant branch (GB)
4	Core helium burning (CHeB)
5	Early asymptotic giant branch (EAGB)
6	Thermally pulsing AGB (TP-AGB)
7	Naked helium star MS (HeMS)
8	Naked helium star HG (HeHG)
9	Naked helium star GB (HeGB)
10	Helium white dwarf (He-WD)
11	Carbon–oxygen white dwarf (CO-WD)
12	Oxygen–neon white dwarf (ONe-WD)
13	Neutron star (NS)
14	Black hole (BH)
15	Massless remnant

Project timeline and current status

2020   **2022**   **2024**   **2025**   **2026**

LSST sim DR1   **LSST sim DR2**   **LSST sim DR3**   LSST sim DR4/DR5

○ Single & Binary star catalogs in Astro Datalab
○ Stellar density-luminosity functions for 6 filters used in MAF (maf.CrowdingM5)
○ Dal Tio, Pastorelli et al. (2022)
○ Jupyter notebooks
○ Calculations @ DIRAC institute facilities

○ **Single star catalog completed**
○ Binaries, MCs & GCs in progress
○ Updates:
   - footprint and throughput curves
   - SFH of Galactic disk
   - LMC SFH
   - Kinematic model

○ **Improved models** Wolf-Rayets, AGB, post-AGB, WDs
○ **Periods, amplitudes, light curves** RR Lyr, Cepheids, LPVs
○ **Alpha-enhanced** models
○ Rapidly **rotating stars**
○ **3D extinction maps**

Next TRILEGAL calculations on BURA supercomputer @ University of Rijeka

Jupyter notebook tutorials
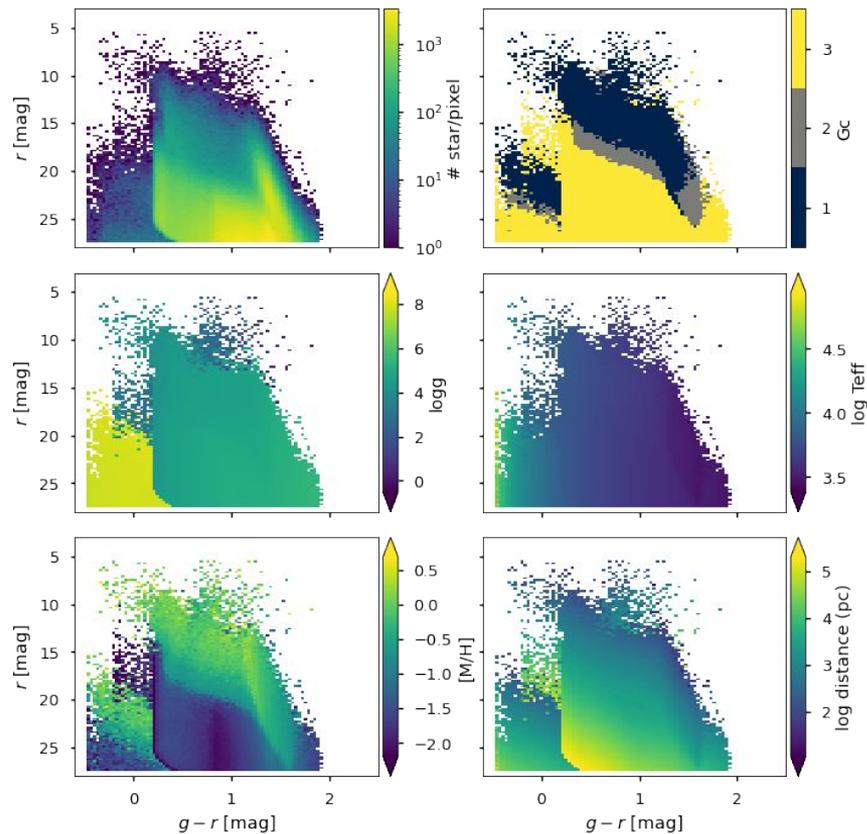
CMDs and CCDs

in all LSST & Gaia

filters

Jupyter notebooks:
05_Contrib/LSST_Sim

Expected counts of LPVs for $i < 24$ mag

3
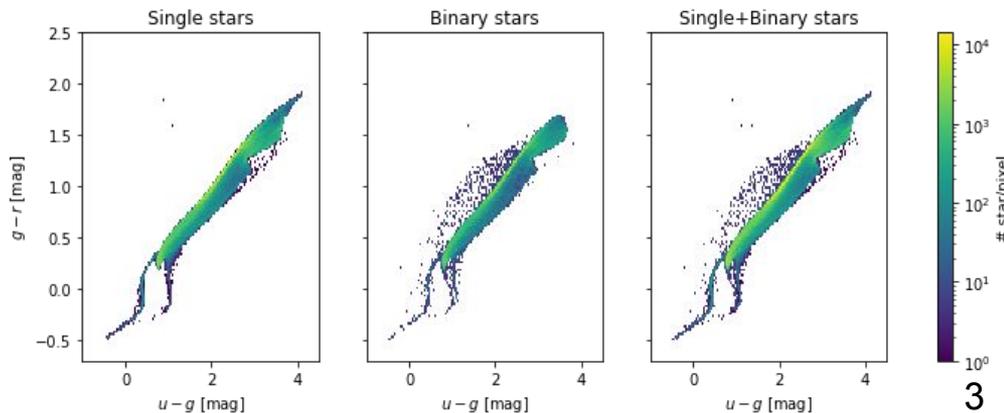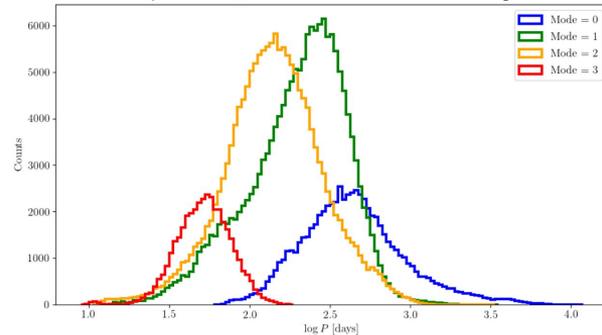
LSST sim DR3 main updates

Priority to LSST footprint, all sky sims will be also available

Updated throughput curves
LSST, *Gaia,* Euclid filters

Kinematic model based on SDSS data
(Bond+2010, validated by Domínguez+2024
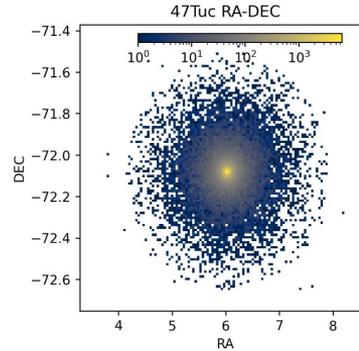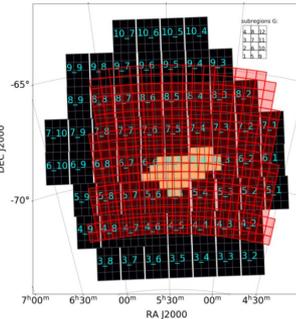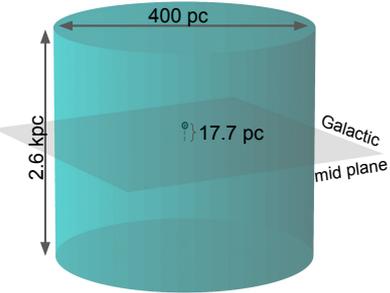
New galactic disk SFH based on Gaia Data and LMC w/ VMC (Mazzi+21,24)

Simulated Globular Clusters
Database Baumgardt+2020: ~168 GCs w/ sky coordinates, stellar parameters & kinematics
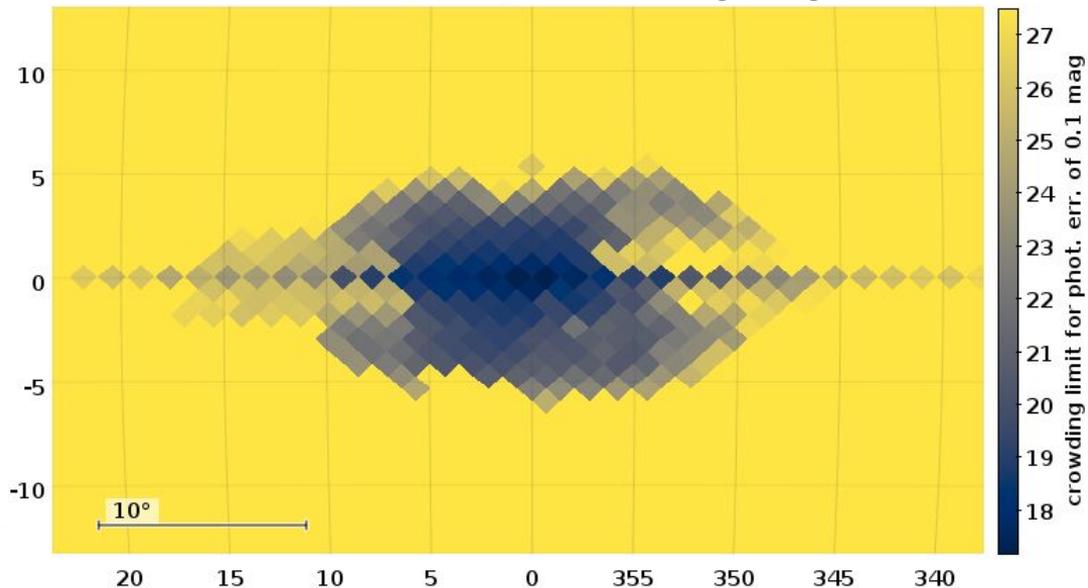
LSST sim DR3: from crowding maps to magnitude limit maps

Example of r-band LF and crowding error
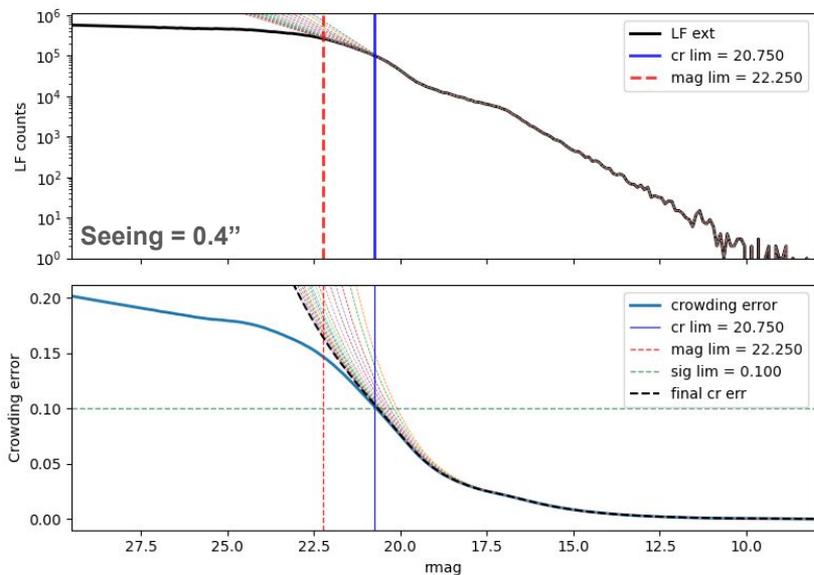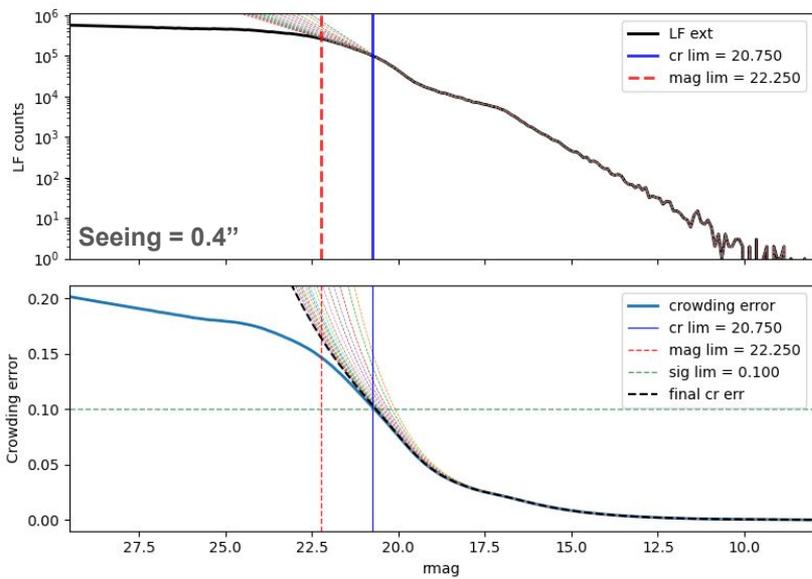
Zoom in of the results in the Bulge region
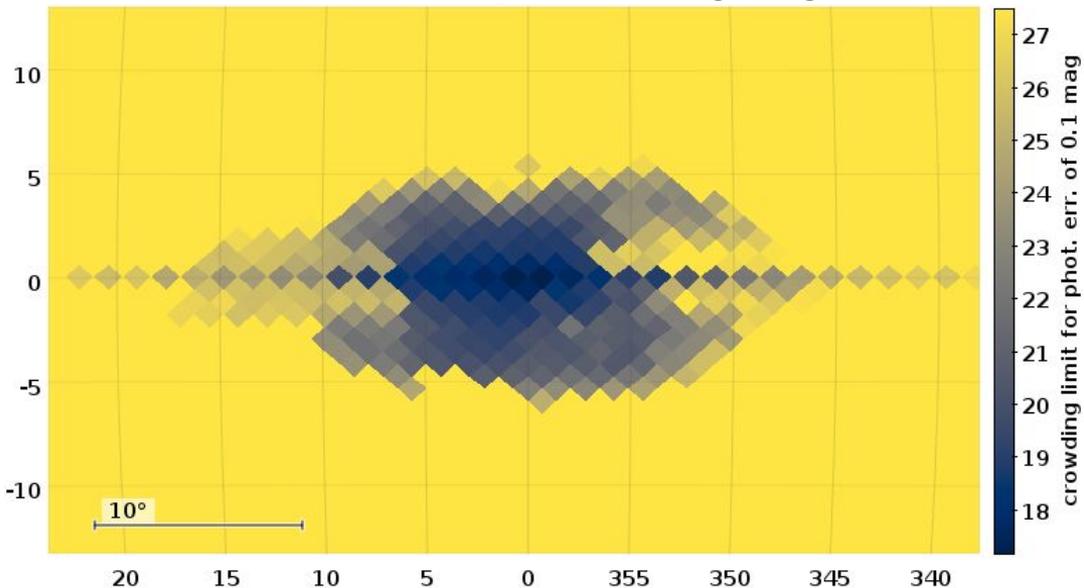
Given a seeing value, what is the magnitude at which photometric uncertainty due to crowding σ$_{crowd}$ is dominant?

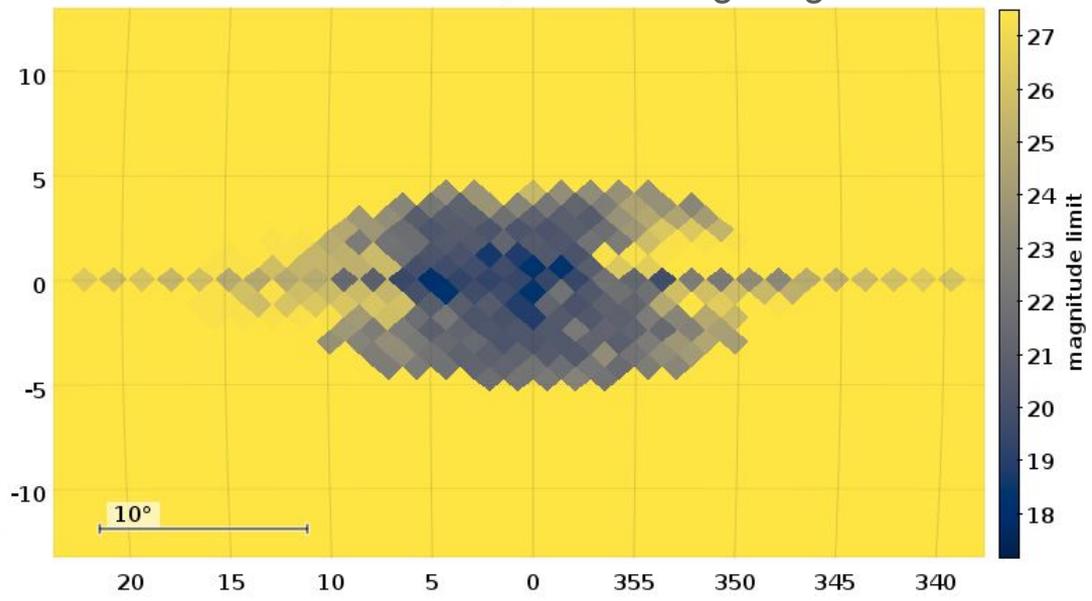*Analytical model from Olsen+2003* | When σ$_{crowd}$ = 0.1–0.25 completeness drops sharply | Prisinzano+23, Usher+23

LSST sim DR3: from crowding maps to magnitude limit maps

To **speed up** computation and **save storage** space we use **crowding maps** from LSST DR2 simulation to assign **magnitude limits** for each sky area instead of simulating down to r = 27.5 mag
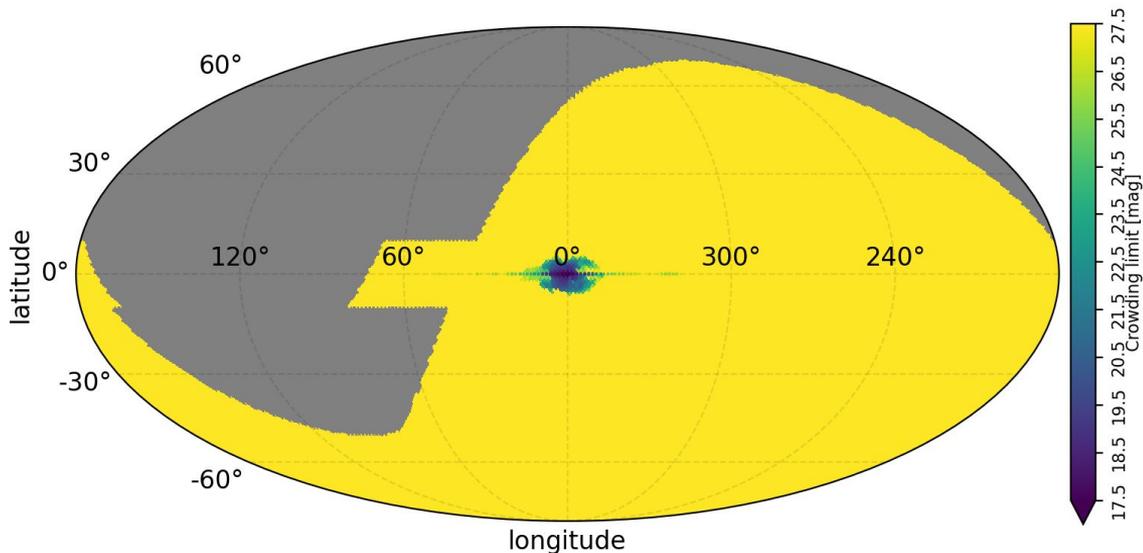
LSST sim DR3: from crowding maps to magnitude limit maps

Example of r-band LF and crowding error
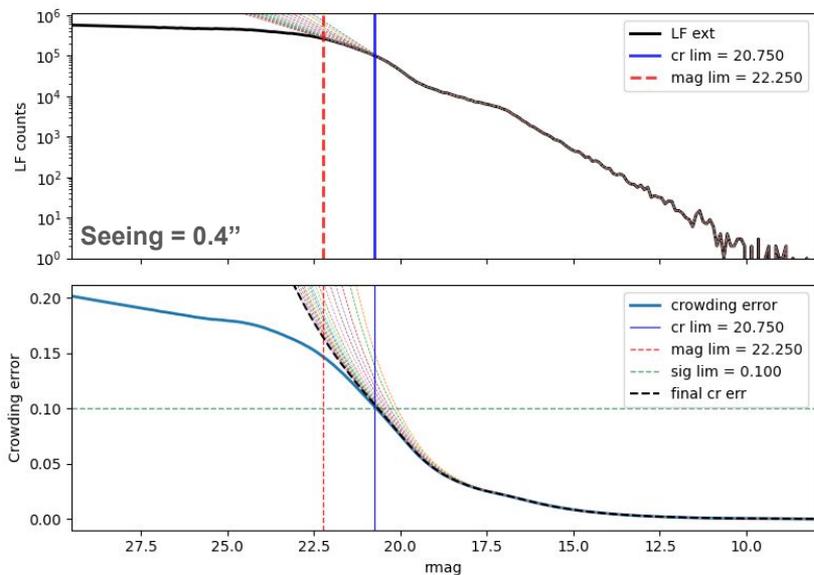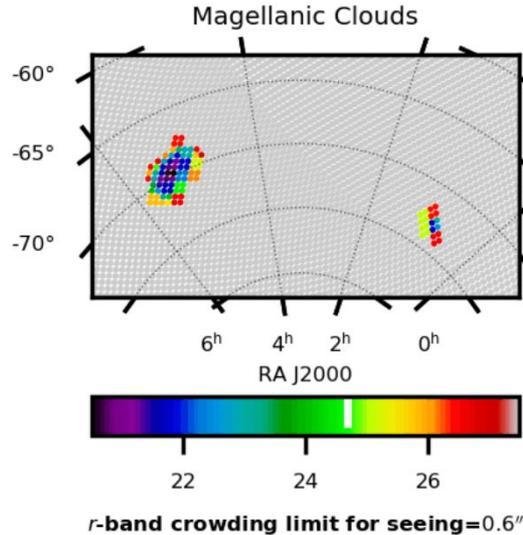
Zoom in of the results in the Bulge region

Given a seeing value, what is the magnitude at which photometric uncertainty due to crowding σ_crowd is dominant?

Analytical model from Olsen+2003 | When σ_{crowd} = 0.1–0.25 completeness drops sharply | Prisinzano+23, Usher+23

TRILEGAL LFs & maf.CrowdingM5Metric

LSST sim DR3: from crowding maps to magnitude limit maps

Example of r-band LF and crowding error

Zoom in of the results in the Bulge region

Given a seeing value, what is the magnitude at which photometric uncertainty due to crowding σ$_{crowd}$ is dominant?

Analytical model from Olsen+2003 | When σ$_{crowd}$ = 0.1–0.25 completeness drops sharply | Prisinzano+23, Usher+23

TRILEGAL LFs & maf.CrowdingM5Metric

Some Applications

TRILEGAL stellar density maps in MAF: photometric errors due to **stellar crowding** for each LSST filter as a function of seeing (formalism by Olsen+2003)

AGILE: Simulation pipeline for realistic LSST catalog-level data including AGN, galaxies and stars. In-kind ITA-INA S2. *A. Bongiorno, A. Viitanen*

Magellanic Clouds

-60°
-65°
-70°

6ʰ   4ʰ   2ʰ   0ʰ
RA J2000

22   24   26

r-band crowding limit for seeing=0.6″

Priors & training set for estimating **photometric distances** and stellar parameters from LSST data *(L. Palaversa+25, K. Mrakovčić+25)*

Light curve's recovery with Rubin-LSST: importance of crowding *(M. Di Criscienzo+24)*

Symbiotic binaries classification *(T. Jurkic)*

TRILEGAL catalogs now included in ImSim/skyCatalogs framework *(DESC, in prep.)*

In-kind contribution ITA-INA S25: Popstar-LSST

ITA-INA-S25 is also a history of <u>missed opportunities</u>:

★ We **initially asked for 5 years of assegno di ricerca, got only 2** from INAF.

Total budget for ITA-INA S25 = about 90 keuro (2.5 % of LSST-Italy)

Data rights generated by ITA-INA S25: = 4 PIs + 16 JAs (4.2 % of LSST-Italy)

★ We continued with a **"best effort"** approach – with very limited support to definition of survey strategy + science

In-kind contribution ITA-INA S25: Popstar-LSST

ITA-INA-S25 is also a history of <u>missed opportunities</u>:

★ Early on:
- ○ Losing dedicated students (P. Dal Tio, A. Mazzi) because there was no decent fellowship
- ○ Timid participation in survey definition (rubin_sim, and MAF) despite requests by P. Yoachim, W. Clarkson, R. Street

★ Now:
- ○ No dedicated young researcher
- ○ Timid collaborations with the DESC ImSim initiative (C. Walter et al.), ITA-INA S2 (re: variables), ITA INA S27 (massive stars) and with TVS-microlensing subgroup
- ○ A Large Grant INAF – "Adding crowding errors and completeness to LSST DRs" – is bringing us back to the science

Simulated Globular Clusters with TRILEGAL

Cluster parameters from Baumgardt+2020 Database:
- Central coordinates
- Core radius, half-light radius, half-mass radius, tidal radius
- V-band magnitude
- Distance
- Av
- Metallicity

~150 clusters
in LSST footprint
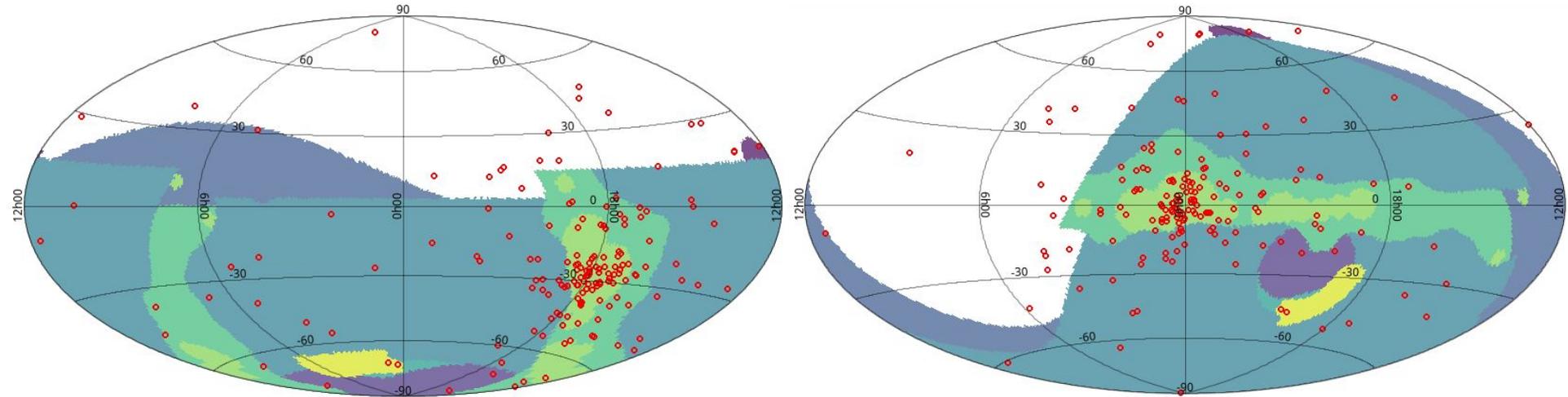
Simulated Globular Clusters with TRILEGAL

1) Simple Stellar Population given age & metallicity: cluster total mass normalized to V-band magnitude

2) Actual stellar cluster simulation

3) Sky coordinates assigned to each star based on a King profile

4) *Kinematic properties (work in progress)*
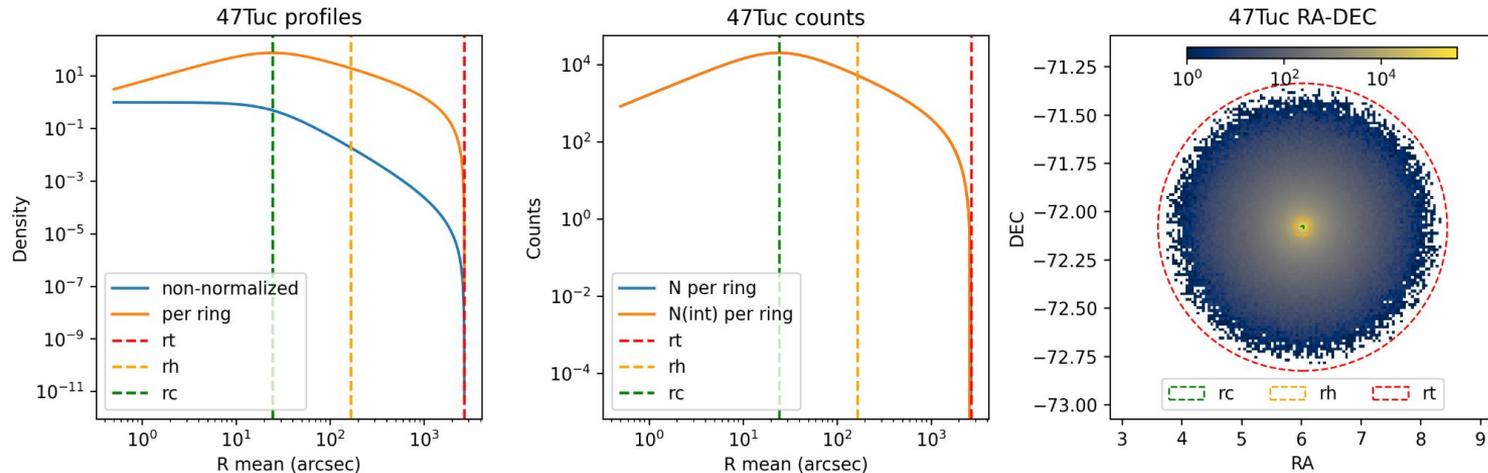
Simulated Globular Clusters with TRILEGAL

1) Simple Stellar Population given age & metallicity: cluster total mass normalized to V-band magnitude
2) Actual stellar cluster simulation
3) Sky coordinates assigned to each star based on a King profile
4) *Kinematic properties (work in progress)*

→ Synthetic stellar catalogs in LSST, Gaia, Euclid filters
→ Ongoing analysis of crowding effect
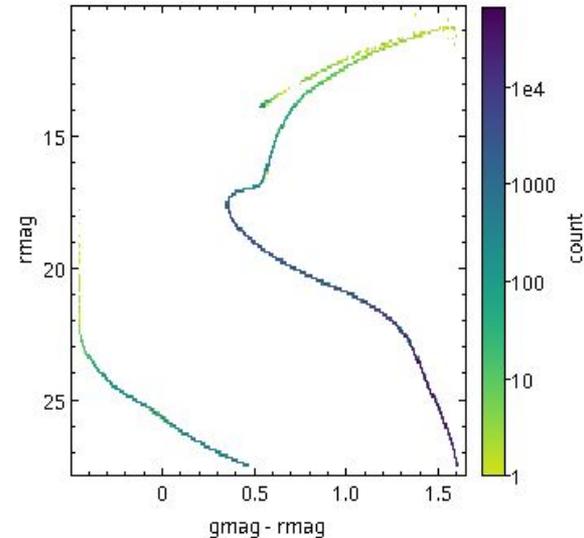
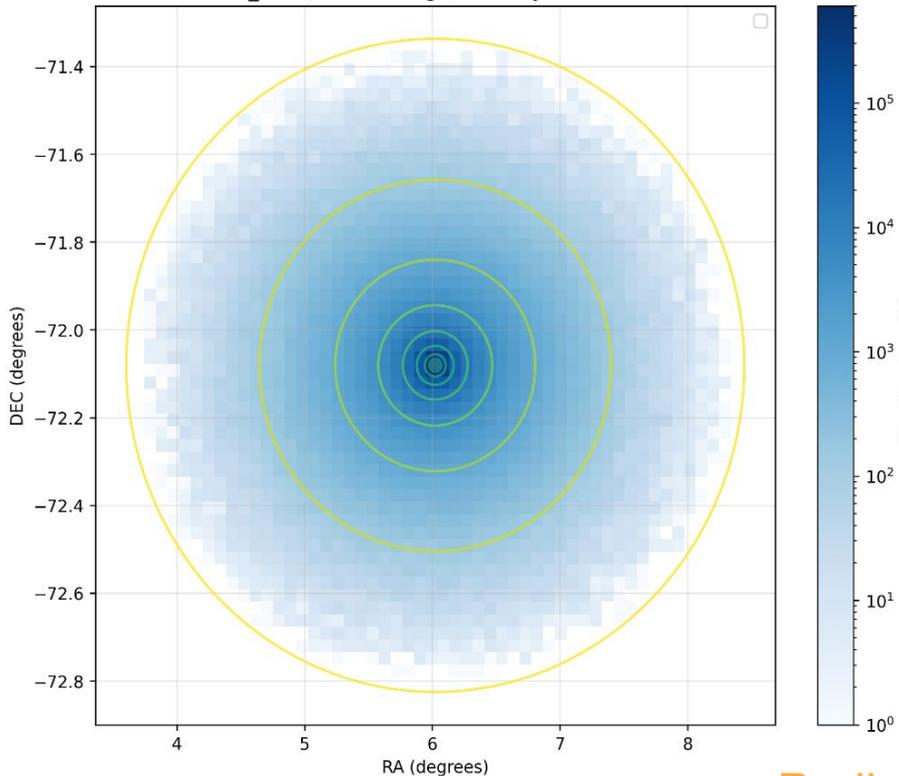# Simulated LSST CMD - 47 Tuc, SMC, MW
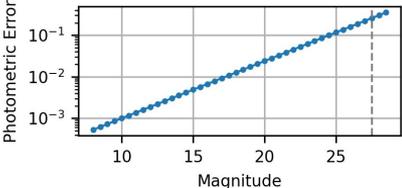
NGC_104: Perfect Photometry
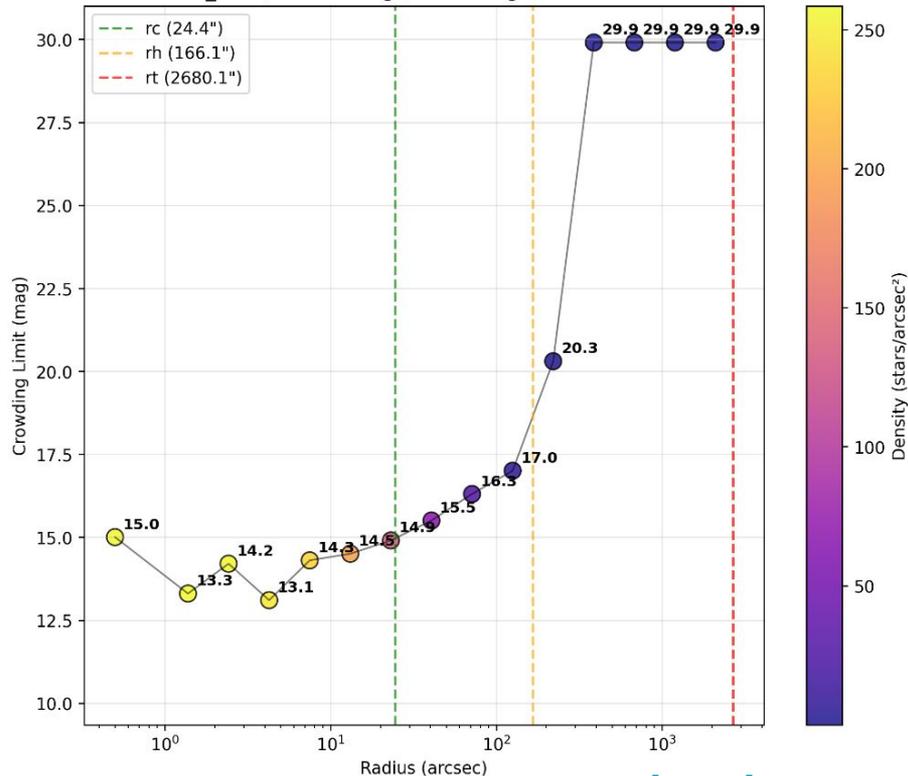N = 6,621,277 stars
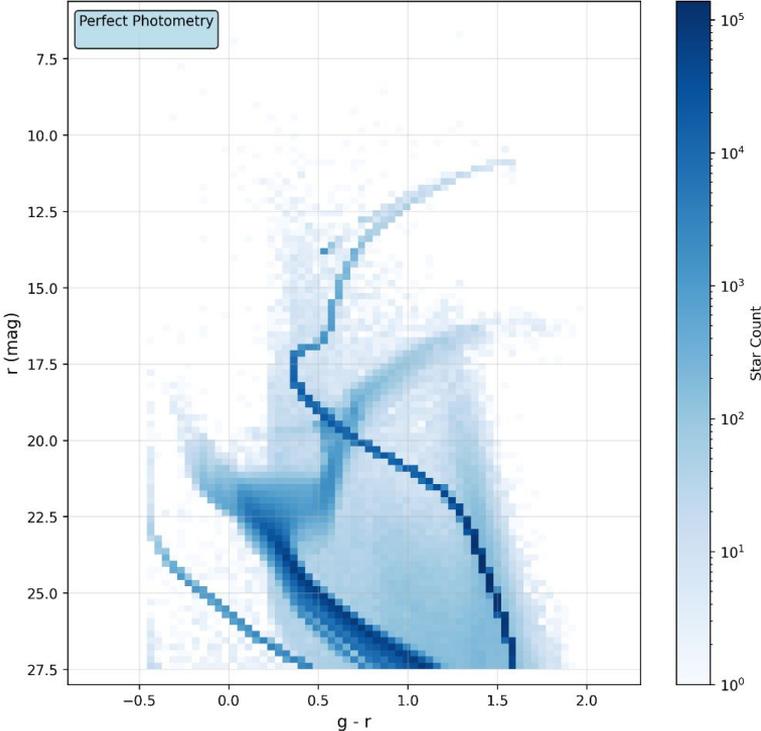
NGC_104: With Photometric Errors
f(mag)
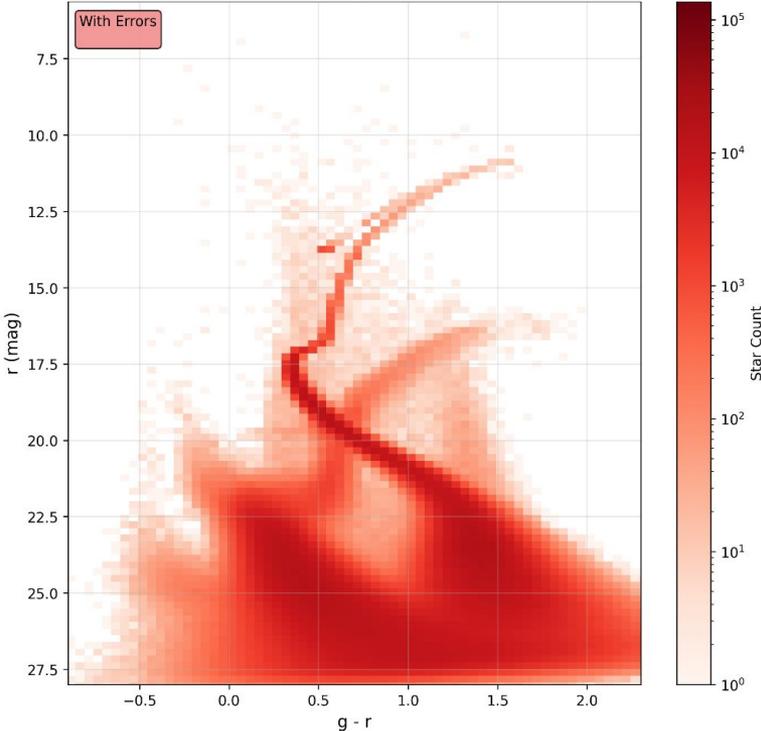
Crowding estimates - 47 Tuc - seeing = 0.4" sigma_lim = 0.1

NGC_104 (Custom Rings): Density Distribution
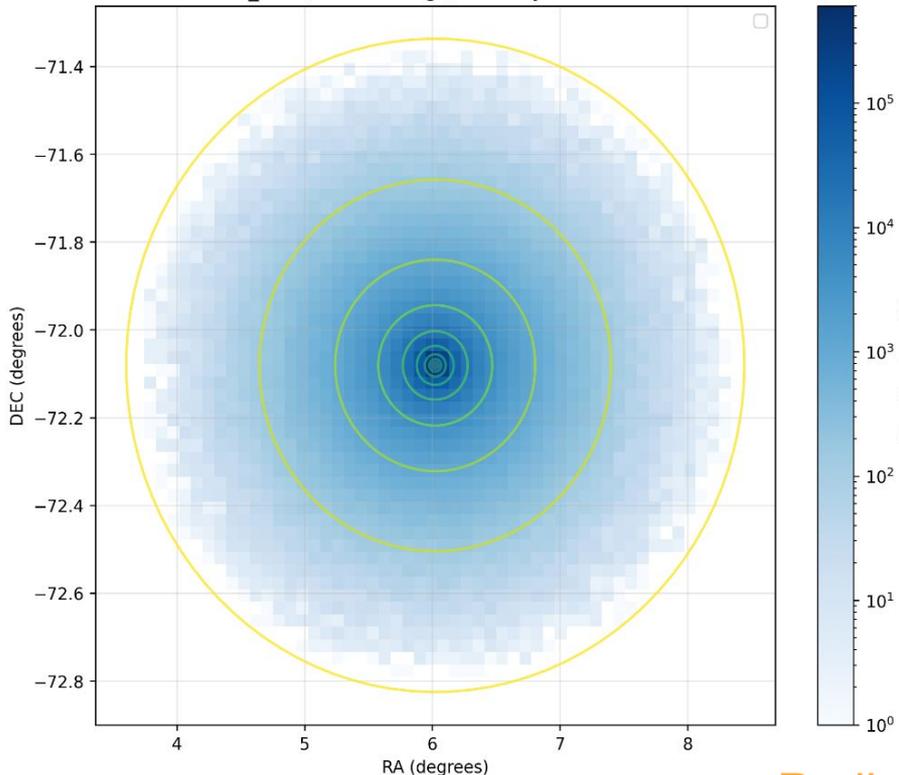
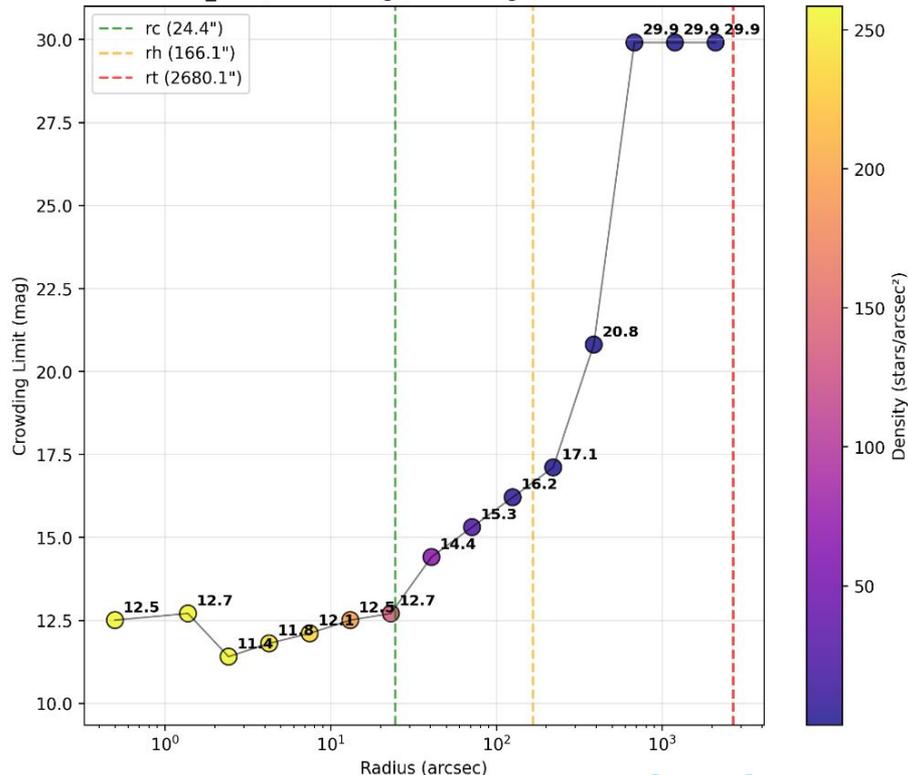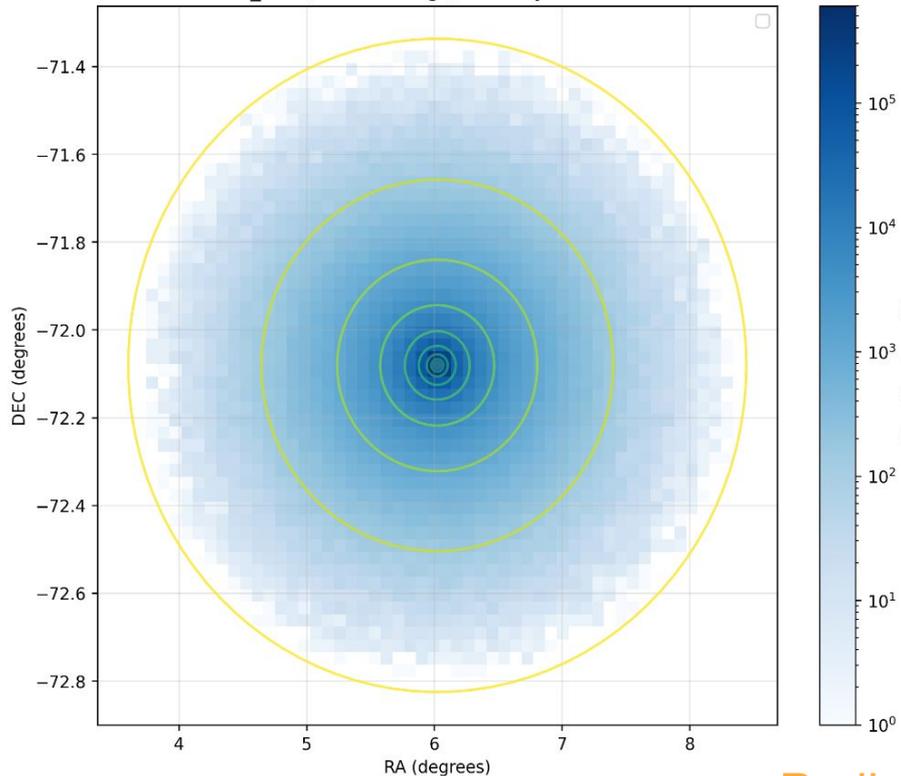NGC_104 (Custom Rings): Crowding Limits vs Radius
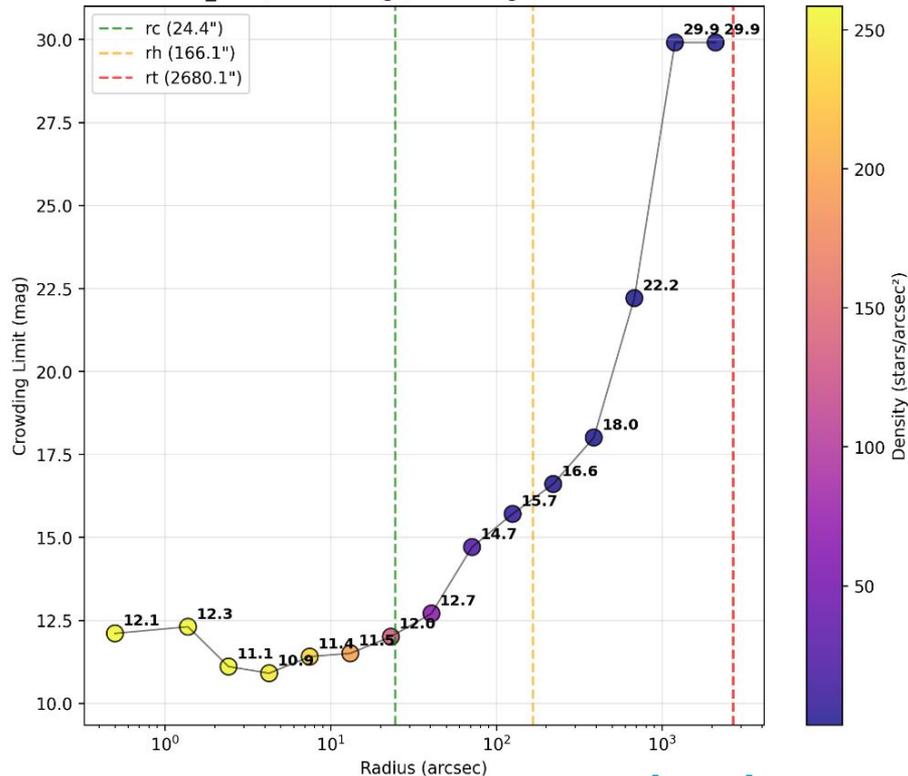
Preliminary

r-band

Crowding estimates - 47 Tuc - seeing = 0.7" sigma_lim = 0.1

Preliminary

r-band

Crowding estimates - 47 Tuc - seeing = 1.0" sigma_lim = 0.1

Preliminary

r-band

SPICE4LSST project and team

Stellar **P**hotometric **I**ncompleteness and **C**rowding **E**rrors **for LSST** Data Releases

INAF Large Grant ~ 200 K @ Astronomical Observatory of Padova - PI L.Girardi

Extensive measurements of incompleteness and photometric errors caused by stellar crowding for each LSST Data Release – **Started October 2025**

INAF: L. **Girardi** (PI), G. **Pastorelli,** M. **Dall'Ora**, M. **Di Criscienzo**, S. **Zaggia**, Y. **Momany**

INAF members & associates: M. **Trabucchi** (Uni. Padova), D. **Bossini** (Uni. Padova), G. **Costa** (Uni Padova), G. **Volpato** (Uni Bruxelles), A. **Bressan**, K. **Shepherd** (SISSA), C. T. **Nguyen** (OA Trieste), F. **Di Giacomo** (OA Padova), A. **Mazzi** (Uni. Bologna), V. **Braga** (OA Roma), S. **Leccia** (OACN),
External Collaborators: Z. **Ivezic**, M. **Juric** (Uni of Washington and DIRAC Institute), K. **Olsen** (NOIRLab), W. **Clarkson** (Univ. Michigan-Dearborn), L. **Palaversa** (Ruder Boskovic Institute)