2nd LSST regional workshop
Plitvice, Croatia October 10-13 2022

Simulating the LSST stellar content with TRILEGAL

Giada Pastorelli

on behalf of the Popstar team

In-kind LSST contribution – INAF, Padova, Italy

OSSERVATORIO ASTRONOMICO DI PADOVA

STScI

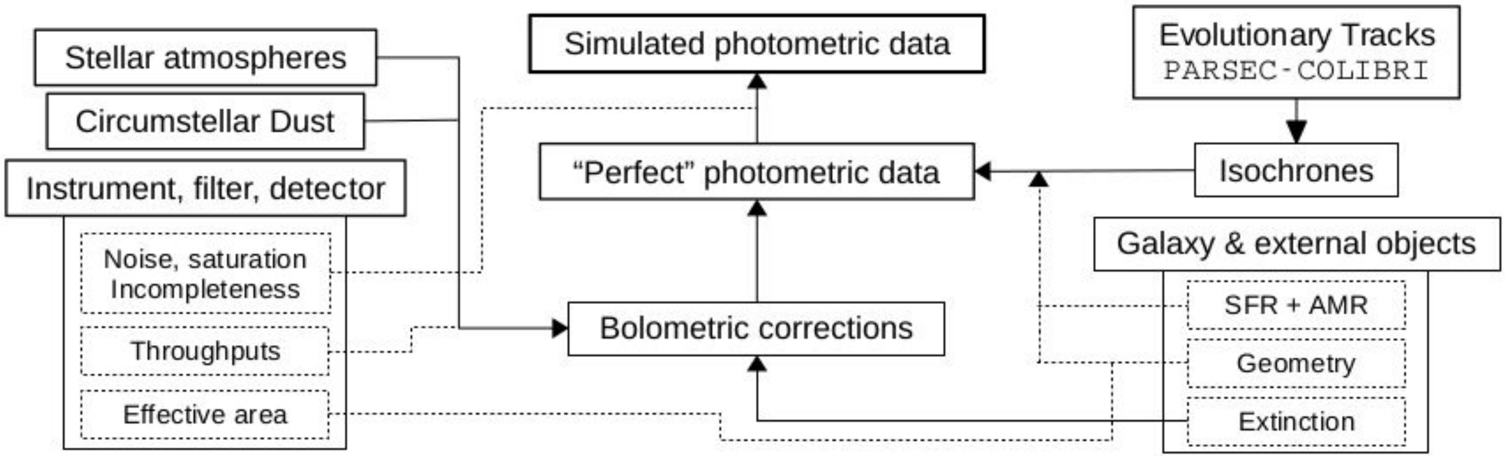
UNIVERSITÀ DEGLI STUDI DI PADOVA

VERA C. RUBIN OBSERVATORY

LSST Legacy Survey of Space and Time

The TRILEGAL code

TRIdimensional modeL of thE GALaxy (*Girardi + 2005, 2012; Marigo + 2017*)



We simulate **conic sections of the MW**:

- central coordinates
- total area
- extinction at infinity and its rms variation across the area

The TRILEGAL code: Milky Way model

Galaxy components:

1) **Thin disk** → *Exp. in radial direction and sech2 in vertical direction*
   Scale height increases with population age
2) **Thick disk** → *Exp. with fixed scale height*
3) **Bulge** → *Triaxial truncated spheroid*
4) **Halo** → *Oblate power-law with*

Dust layer → *Extinction-at-infinity maps* and *exp. dust layer* with fixed scale height

Details in Table 1 of Pieres+2020 and Table 1 of Mazzi+2021

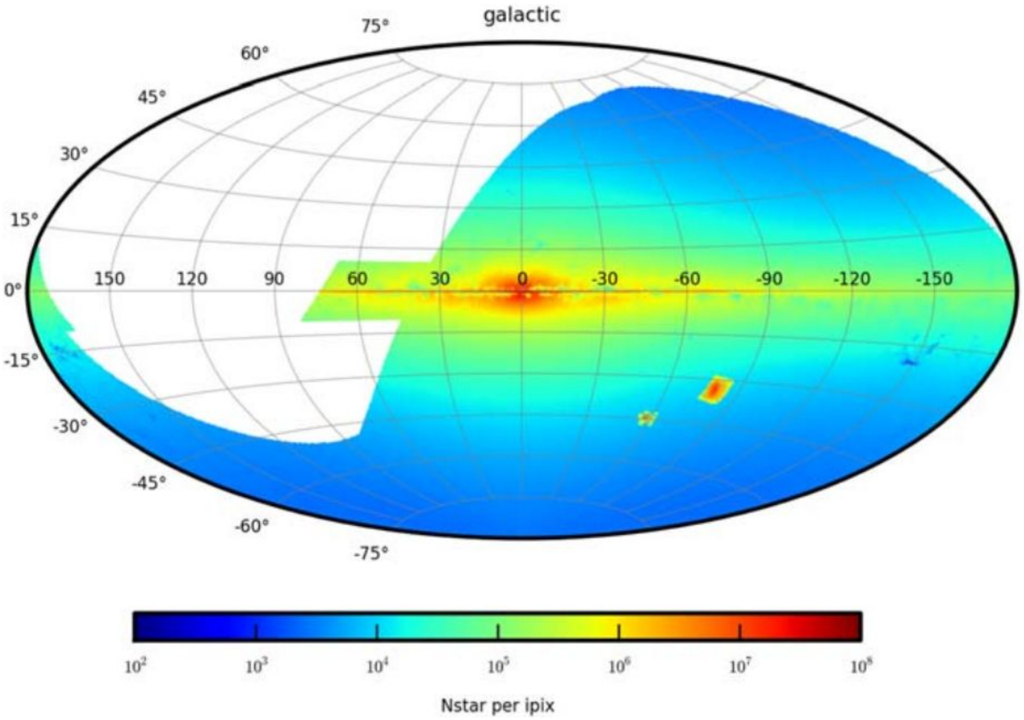
External objects → Magellanic Clouds

The LSST simulations

- Co-added survey depth of r < 27.5 mag

- Current sky footprint:
  - $\delta < 5°$,
  - $\beta < 10°$
  - Within $|b| < 10°$ of Galactic plane and with $\delta < 35°$

- HEALPix scheme with variable resolution based on
  - “surface mass density”: projected mass of the Galaxy components per sq. deg. (Girardi+2012)
  - extinction variations: Planck collaboration + 2014 dust maps



Dal Tio, Pastorelli + 2022

Stellar types

Single stars → Evolutionary tracks (Marigo+2017)

- Pre-main sequence **(PMS)**
- Main sequence **(MS)**
- Hertzsprung gap
- Red giant branch **(RGB)**
- Core helium burning **(CHeB)**
- Early asymptotic giant branch **(EAGB)**

} **PARSEC v1.2S** (Bressan+2012)

- Thermally pulsing AGB **(TP-AGB)**

} **COLIBRI PR16** (Marigo+13, Rosenfield+16)

- Post-AGB

} Miller Bertolami 2016

- CO-WD

} WD cooling tracks (Renedo+2010)

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- Post-AGB } Miller Bertolami 2016
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Binary stars → **BinaPSE@TRILEGAL** (Dal Tio+2021)

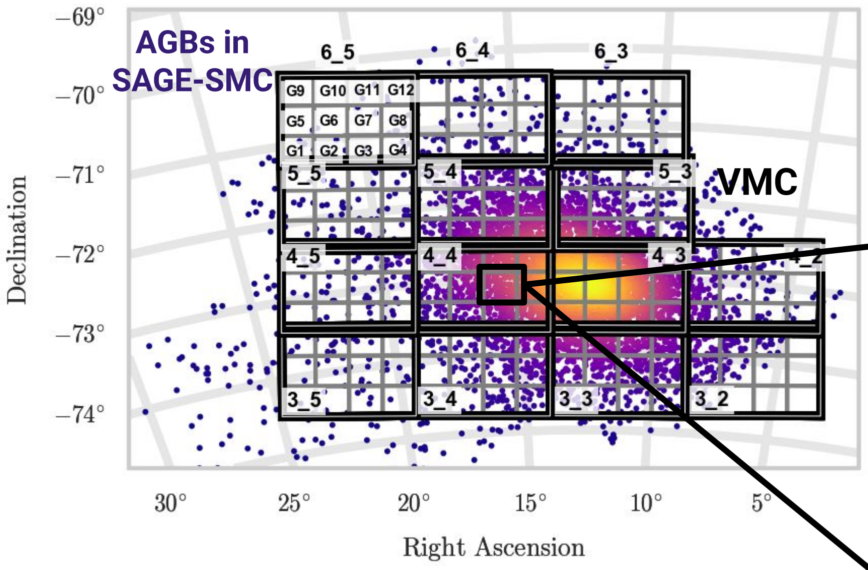
Detached & interacting binaries

Products of binary evolution:

- Helium main sequence
- Helium Hertzsprung gap
- Helium giant branch
- He-WD
- ONe-WD
- Neutron star
- Black hole

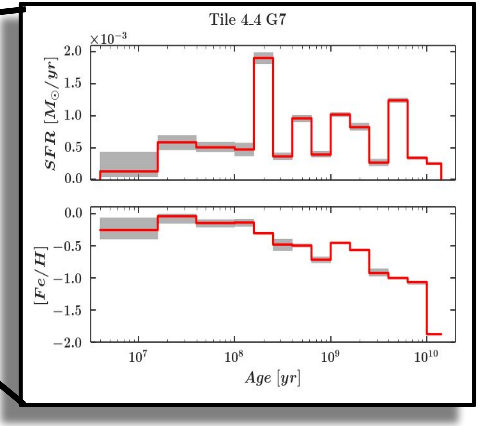
- Binary evolution (BSE code, Hurley+2022)
- Orbital parameters (Eggleton 2006)

Magellanic Clouds simulation - SMC



Spaced-resolved SFH from **NIR data** of the VMC survey *(Rubele+15, Rubele+18)*

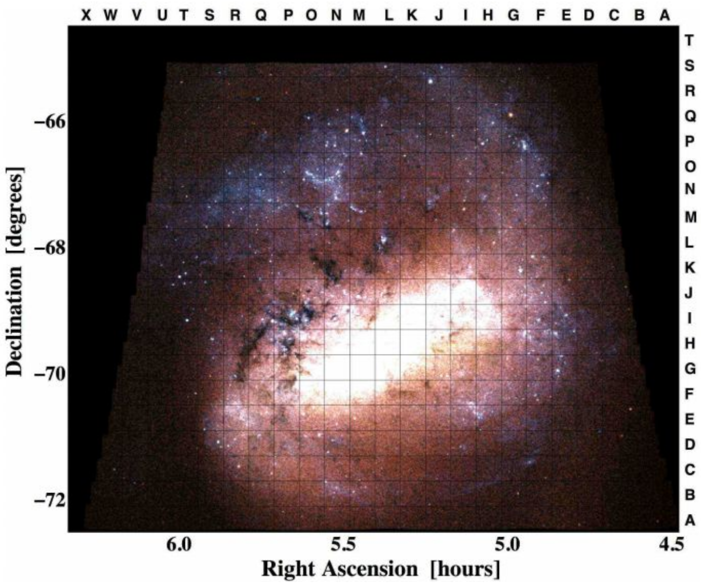
Calibration of AGB models *(Pastorelli + 2019)*



SFR(t), Zi(t), Av, and distance

Total area: **~24 deg^2**

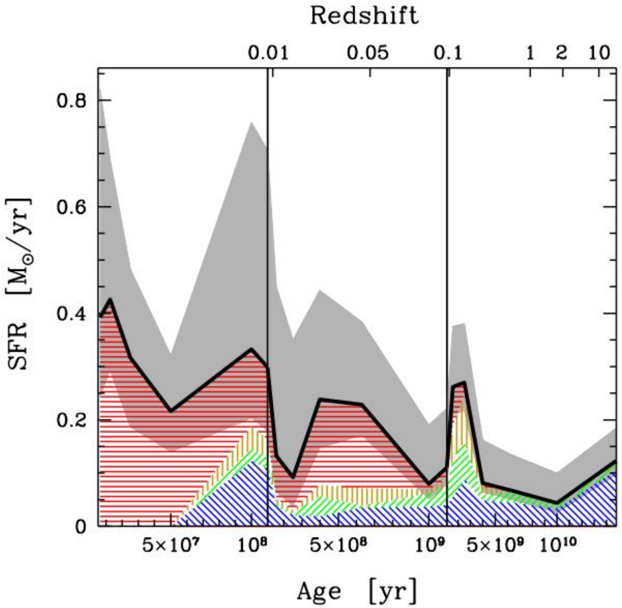
Magellanic Clouds simulation - LMC



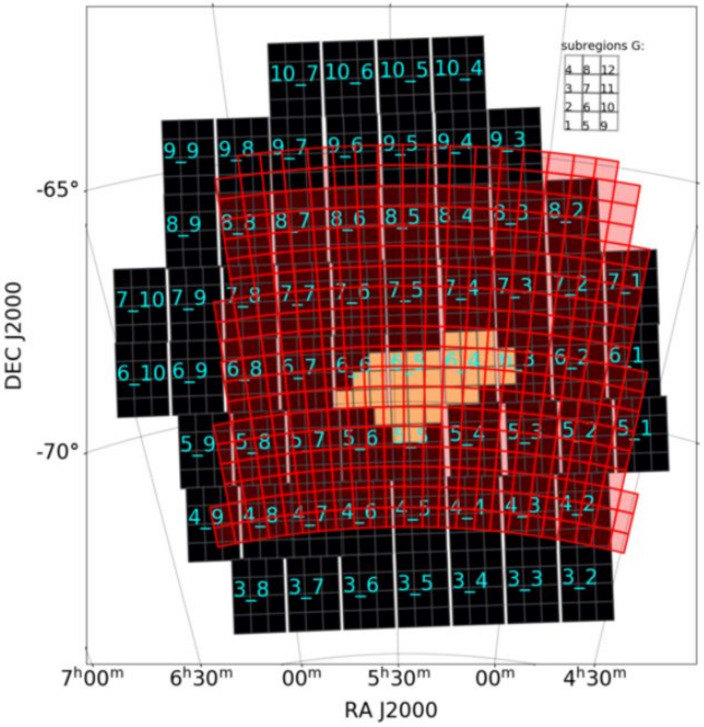
Spaced-resolved SFH from **optical MCPS** data *(Harris & Zaritsky 2009)*

SFR(t), Zi(t), Av, and distance

Total area **~ 64 deg^2**



Magellanic Clouds simulation - LMC



Spaced-resolved SFH from **infrared VMC** data *(Mazzi+2021)*

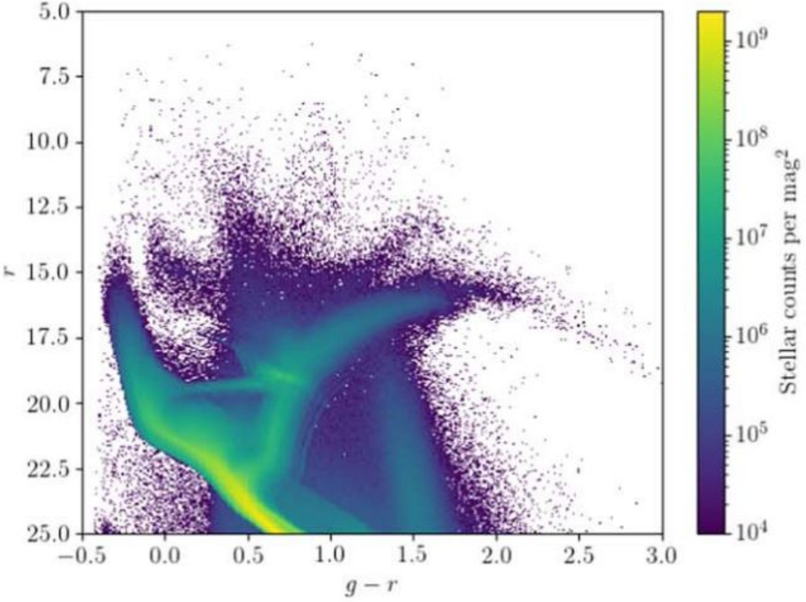
SFR(t), Zi(t), Av, and distance

Total area **~ 96 deg^2**

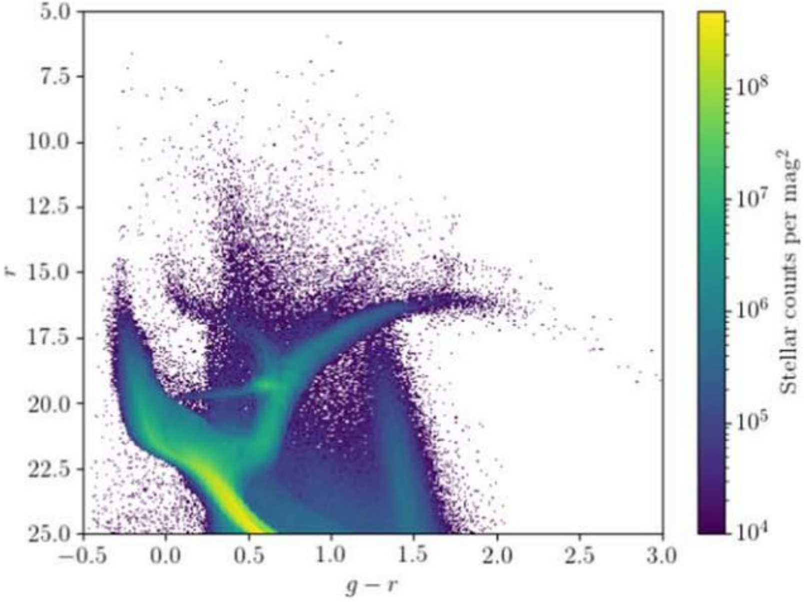
To be included in the next simulation

Magellanic Clouds simulation

LMC + MW foreground



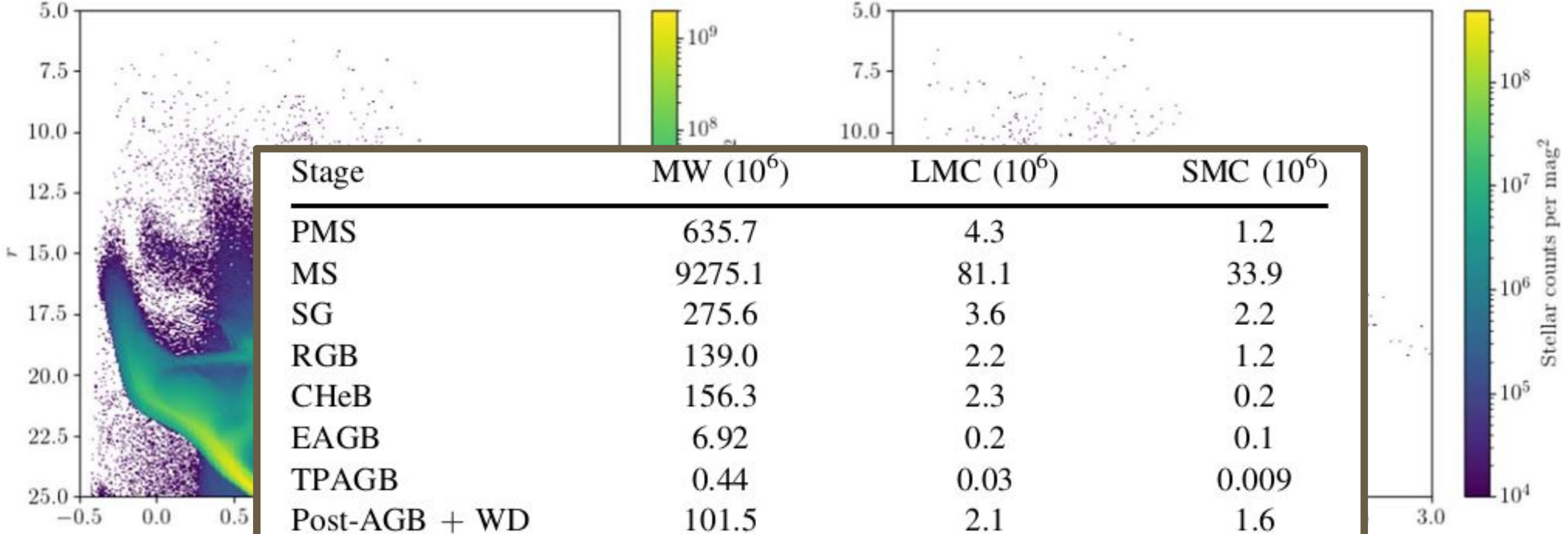
SMC + MW foreground



Magellanic Clouds simulation

LMC + MW foreground

SMC + MW foreground



Stage	MW (10^6)	LMC (10^6)	SMC (10^6)
PMS	635.7	4.3	1.2
MS	9275.1	81.1	33.9
SG	275.6	3.6	2.2
RGB	139.0	2.2	1.2
CHeB	156.3	2.3	0.2
EAGB	6.92	0.2	0.1
TPAGB	0.44	0.03	0.009
Post-AGB + WD	101.5	2.1	1.6
Total	10489.1	95.8	40.4

Full catalogs in Datalab

- **10.6 billion single** stars → datalab.noirlab.edu/query.php?name=lsst_sim.simdr2

- **1.61 billion binary** systems → datalab.noirlab.edu/query.php?name=lsst_sim.simdr2_binary

  (1/10 of the expected numbers)

- **Photometry** in **LSST** u, g, r, i, z, y AB magnitudes & ***Gaia*** G, GBP, GRP Vega magnitudes
- **Stellar properties** (luminosity, temperature, surface composition, gravity, pulsation periods)
- **Positional and kinematic properties** (distances, proper motions, space velocities)
- **Additional quantities for binary systems** include: stellar types, orbital parameters, radial velocity amplitudes, max depth of primary and secondary eclipses

Exploring our LSST simulation

Jupyter notebook tutorials to be included in Datalab (**in progress).**

Planned notebooks:

- CMDs and CCDs of the South Galactic Pole
- Combining single and binary catalogs
- Star counts in Bulge and inner disk fields
- Eclipsing binaries in the MW
- Classical Cepheids in the MW
- Long Period Variables in the MW

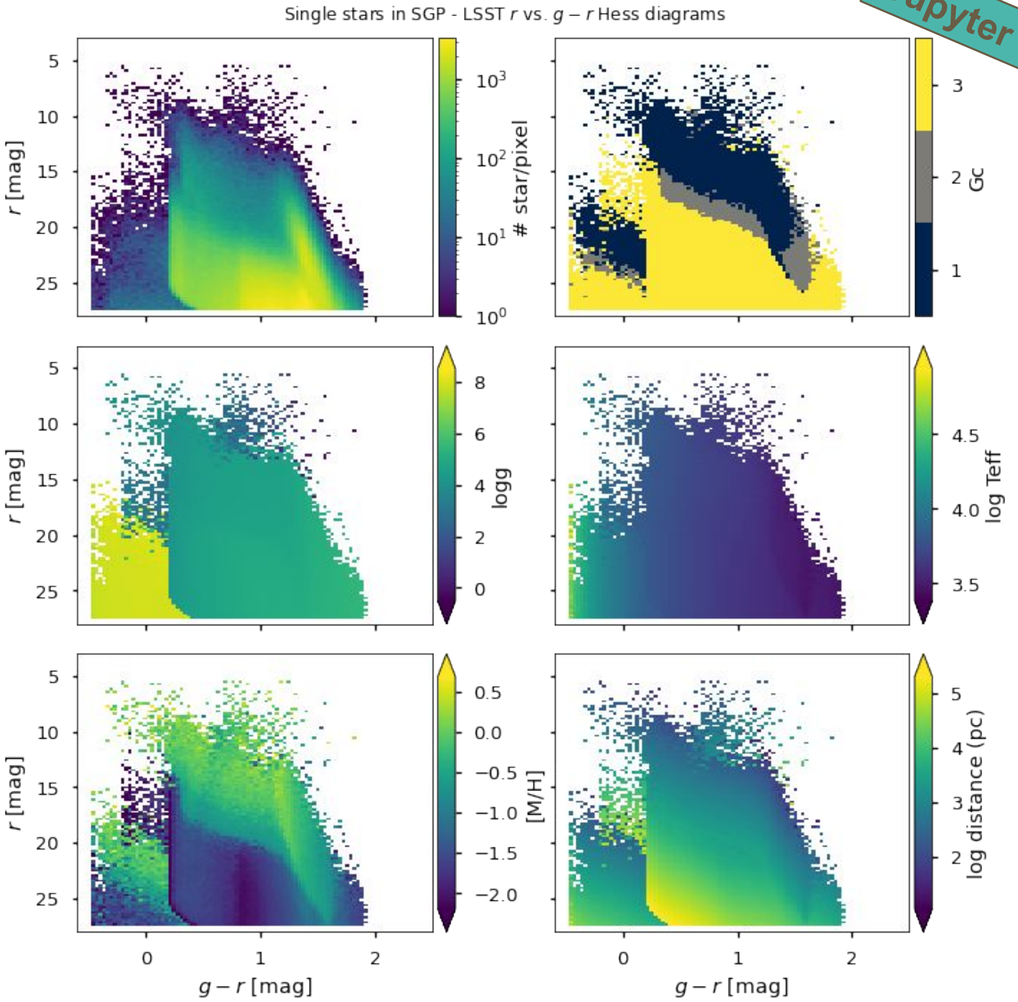
We welcome your feedback and request for additional tutorials

CMDs of single stars

South Galactic Pole

Stellar and population parameters

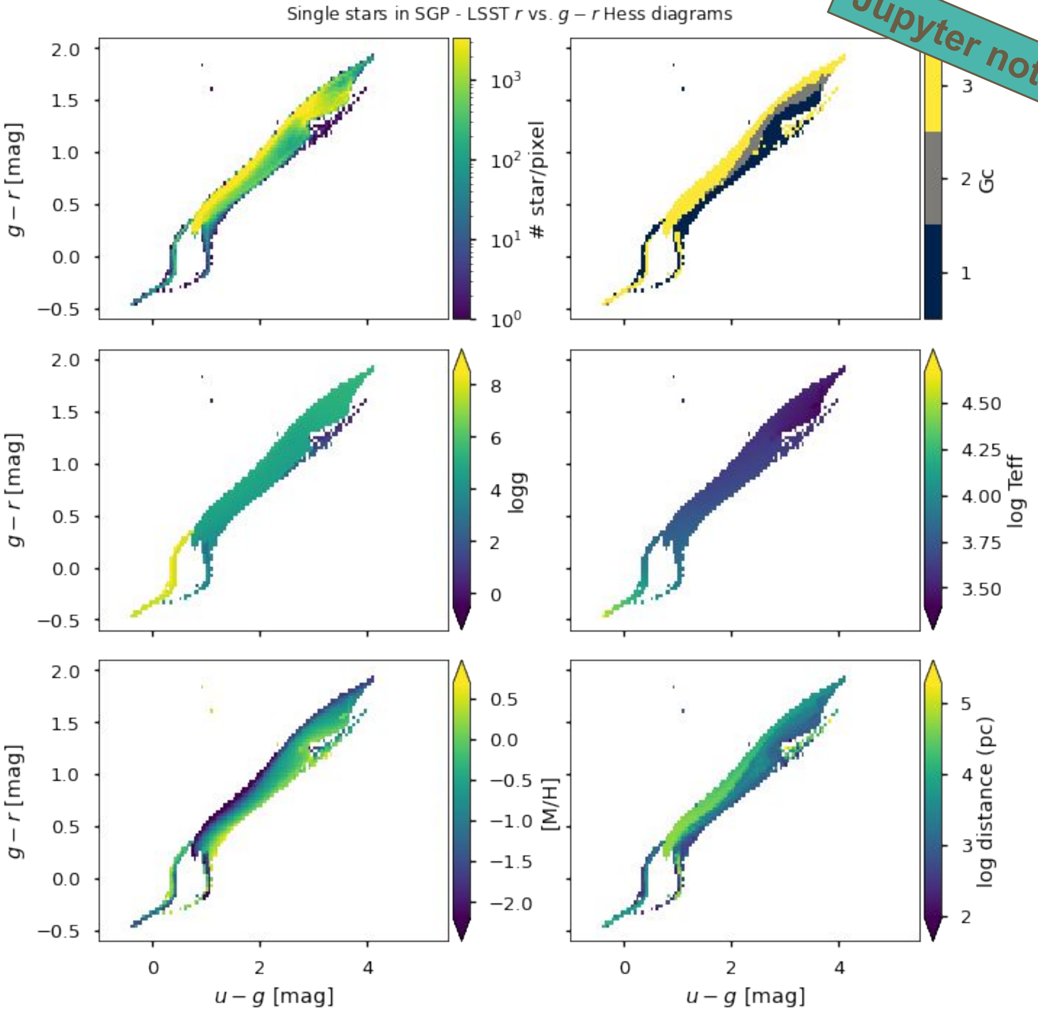
Jupyter notebook



CCDs of single stars

South Galactic Pole

Stellar and population parameters



Jupyter notebook

Jupyter notebook

Combining single and binary models

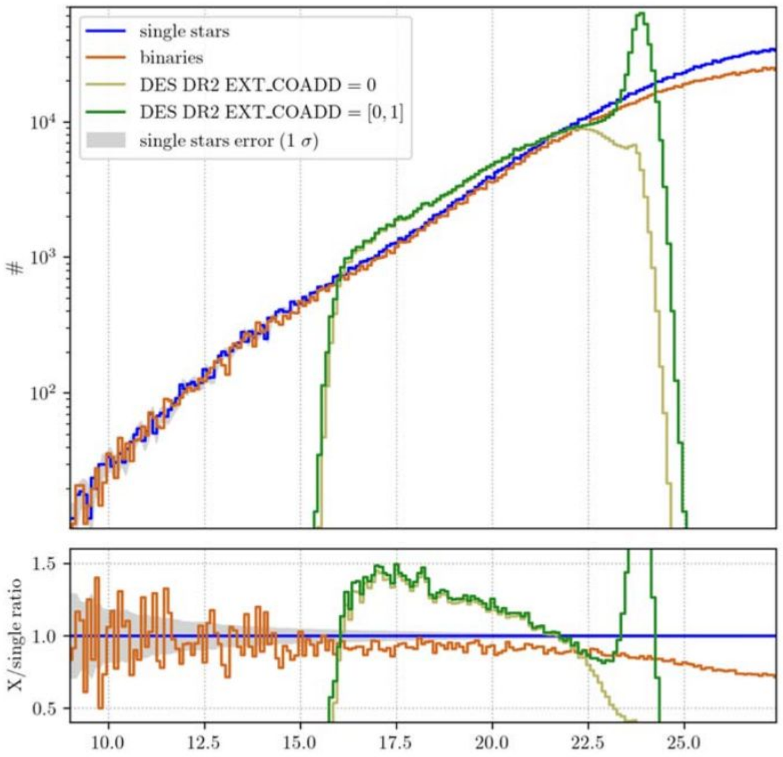
Binary systems simulated with BinaPSE module

Caveats:

- TRILEGAL parameters calibrated using a different approach for non interacting binaries
- Current simulation contains 1/10 of the expected binary systems

Single and binary catalogs can be combined given a binary fraction f_{bin}

Recommended f_{bin} is 0.4

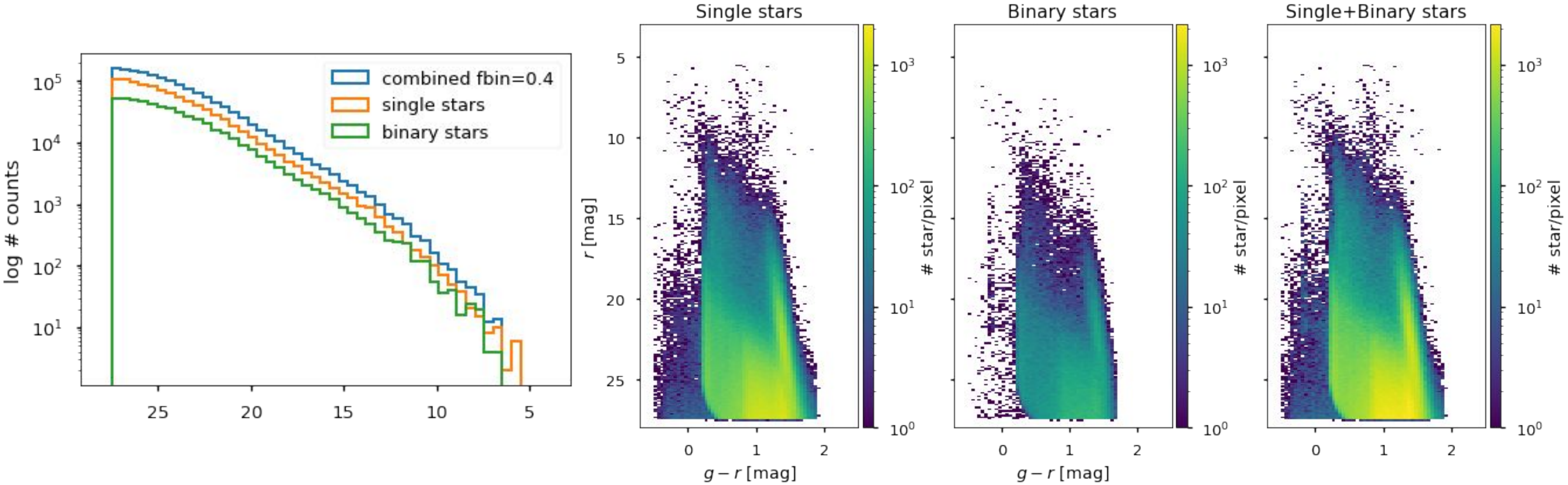


Jupyter notebook

Combining single and binary models

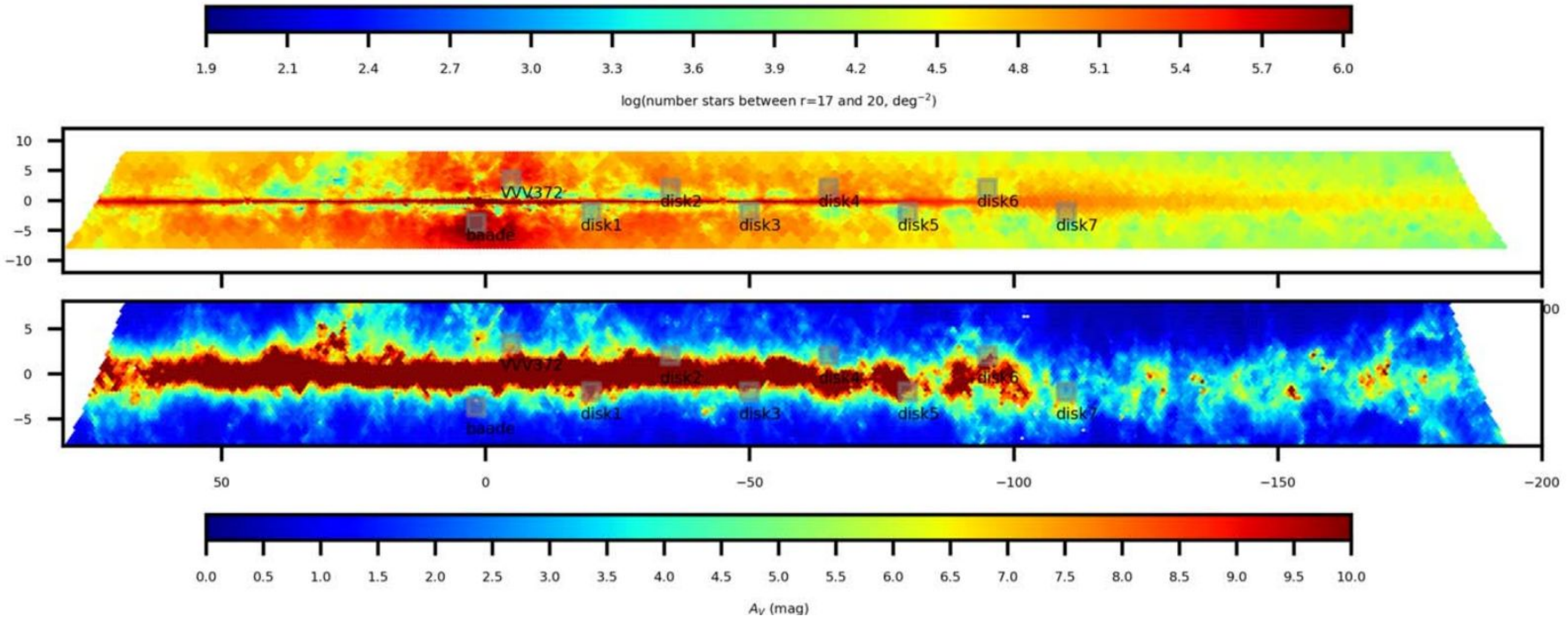
South Galactic Pole

Star counts and CMDs from single and binary catalogs



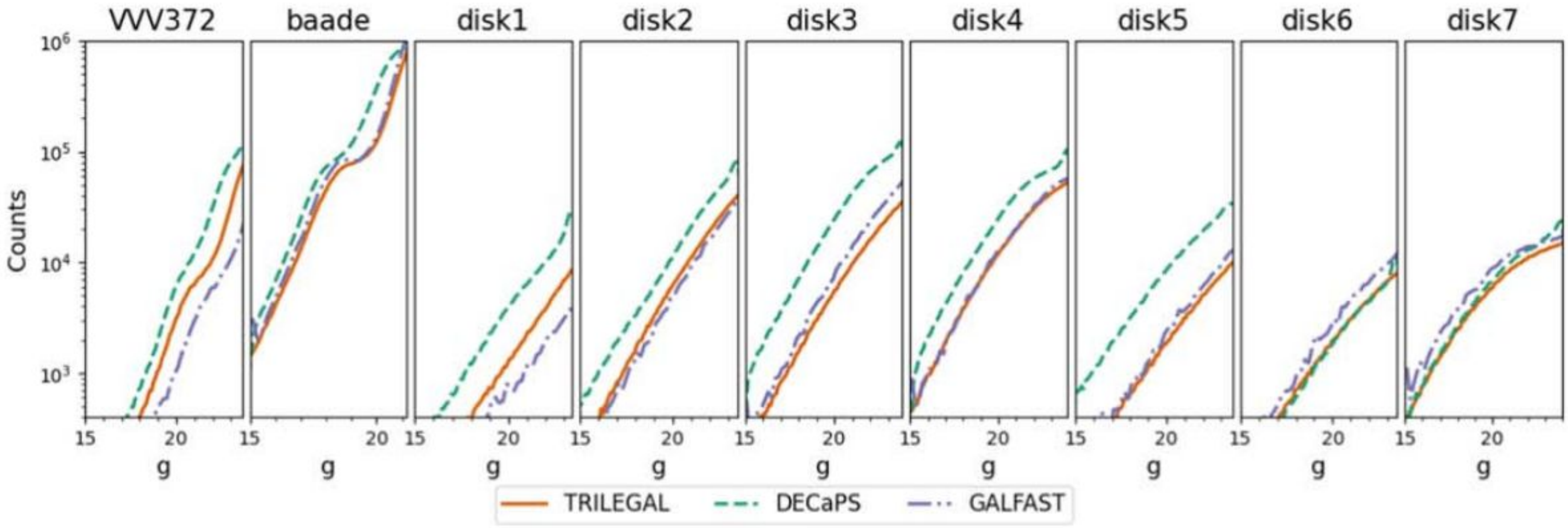
Bulge and inner disk fields

Jupyter notebook
In progress

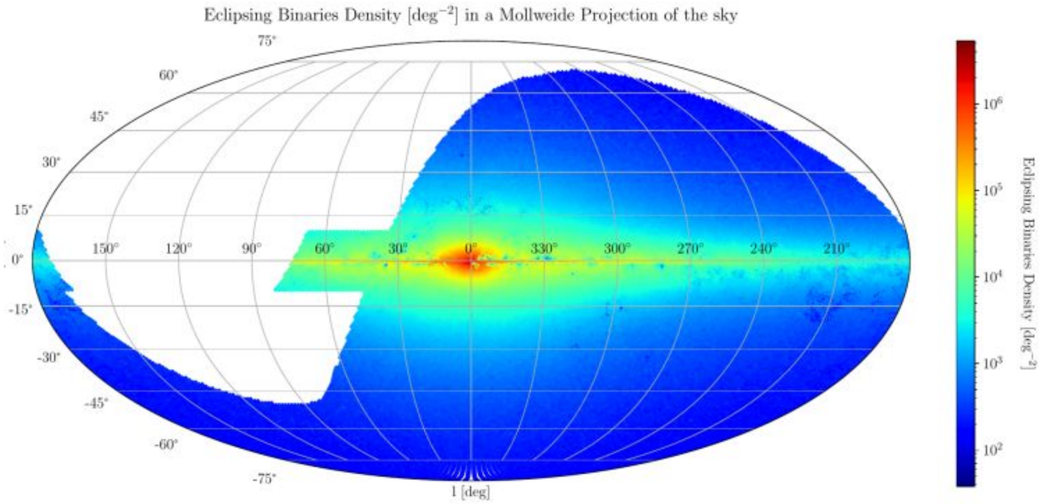


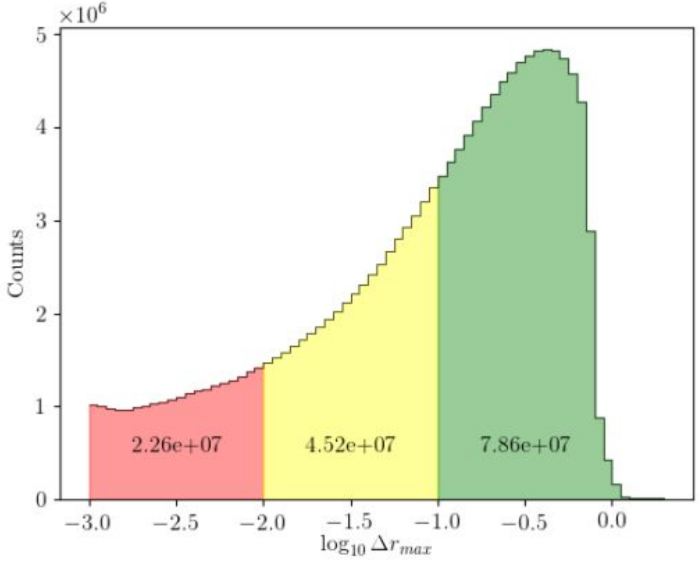
Bulge and inner disk fields

Jupyter notebook
In progress



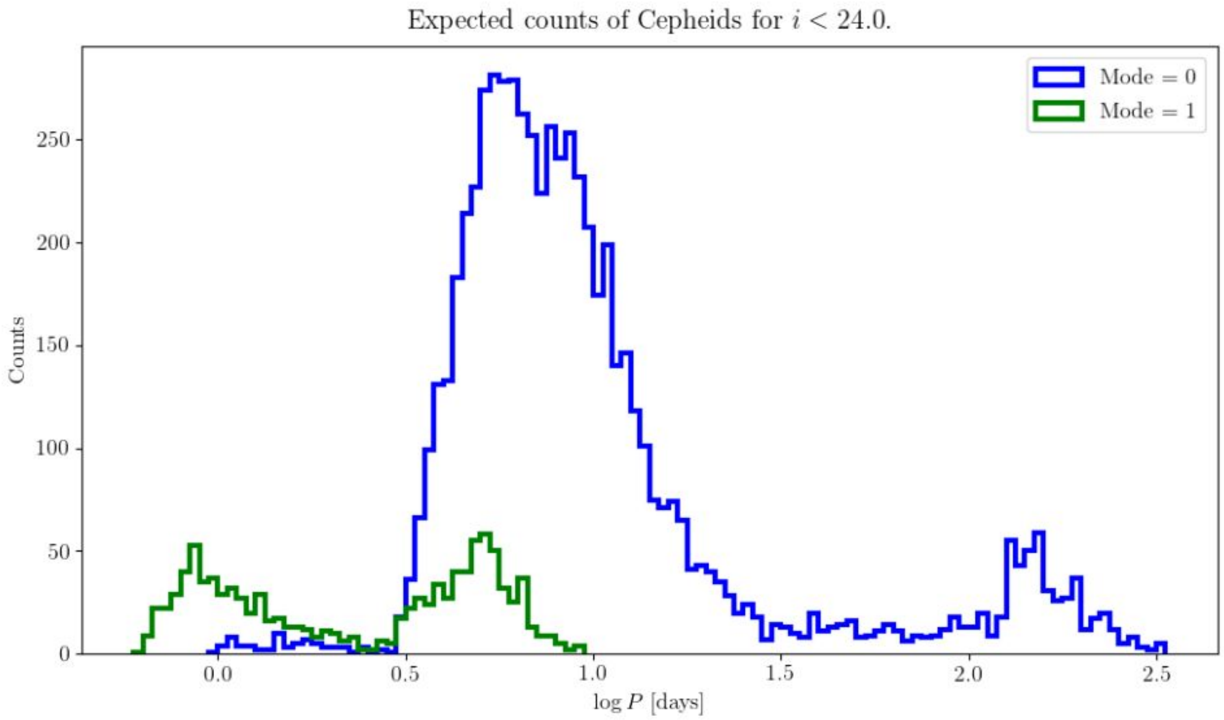
Eclipsing binaries in the MW





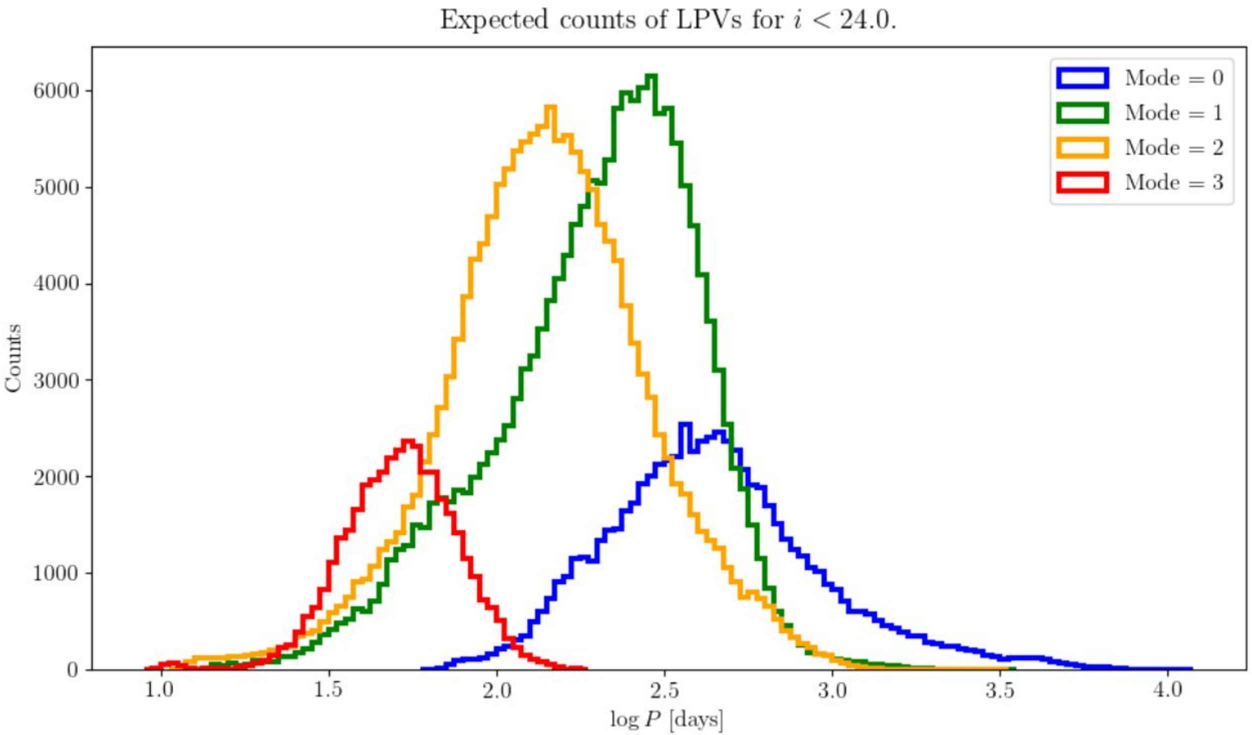
Cepheids in the MW

Jupyter notebook
In progress



LPVs in the MW

Jupyter notebook
In progress



Details in Michele's talk

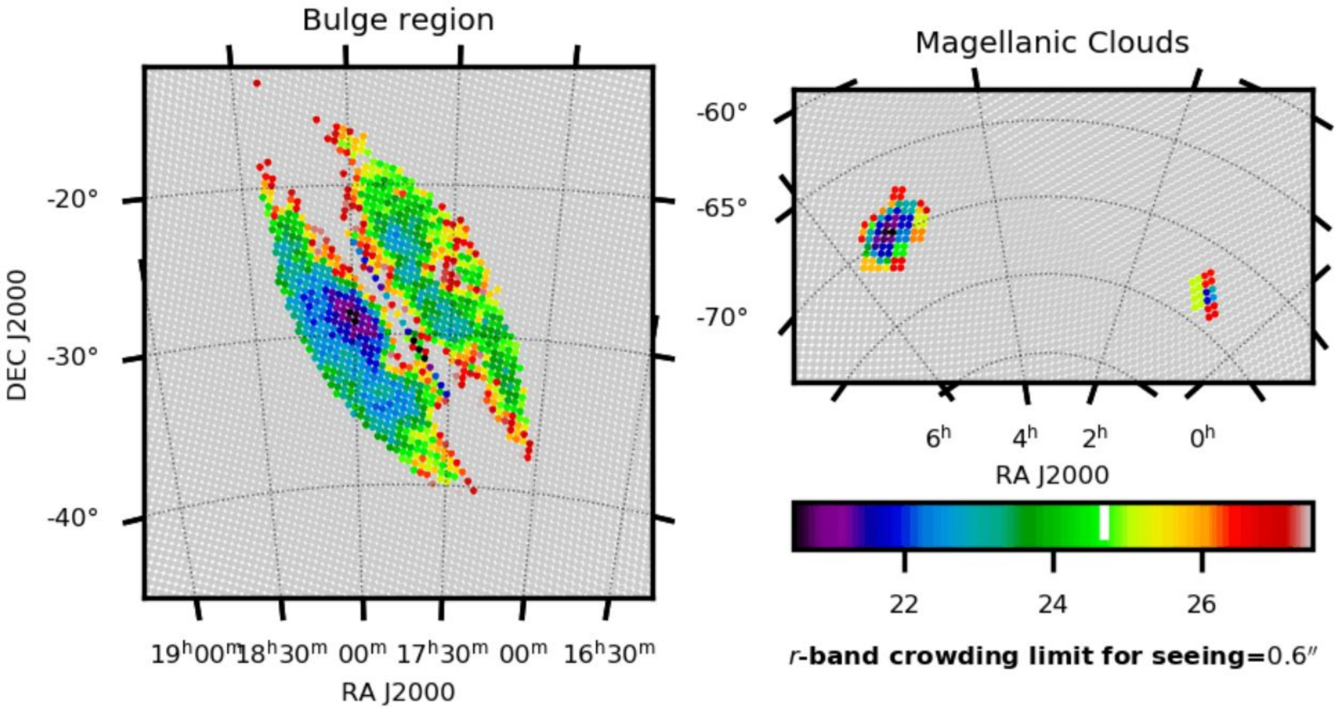
Total of ~ 444k LPVs

Dominant modes of LPVs from fundamental to 3rd overtone (Trabucchi+2019)

Next simulation → Amplitude information and updates to fundamental mode pulsators from non-linear models (Trabucchi+2021, in prep.)

Maps of crowding limit

Jupyter notebook
In progress

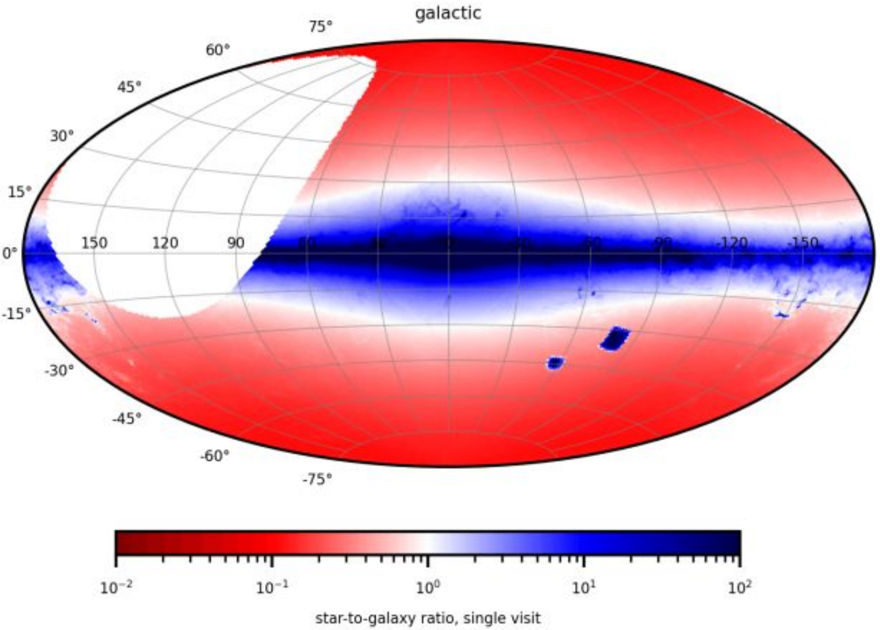


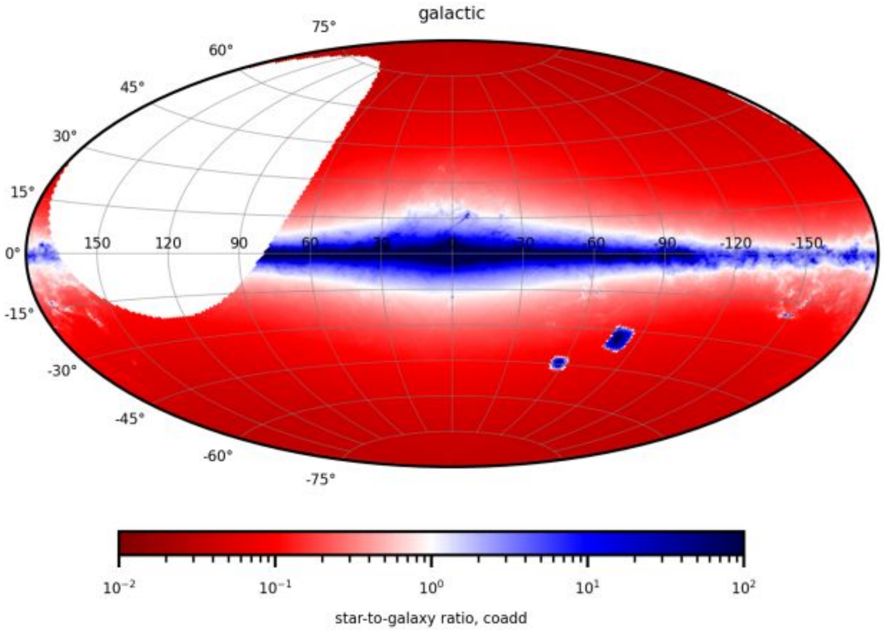
Based on stellar density files in all LSST filters already used in MAF following the formalism developed by Olsen et al. (2003).

Maps of star-to-galaxy ratio

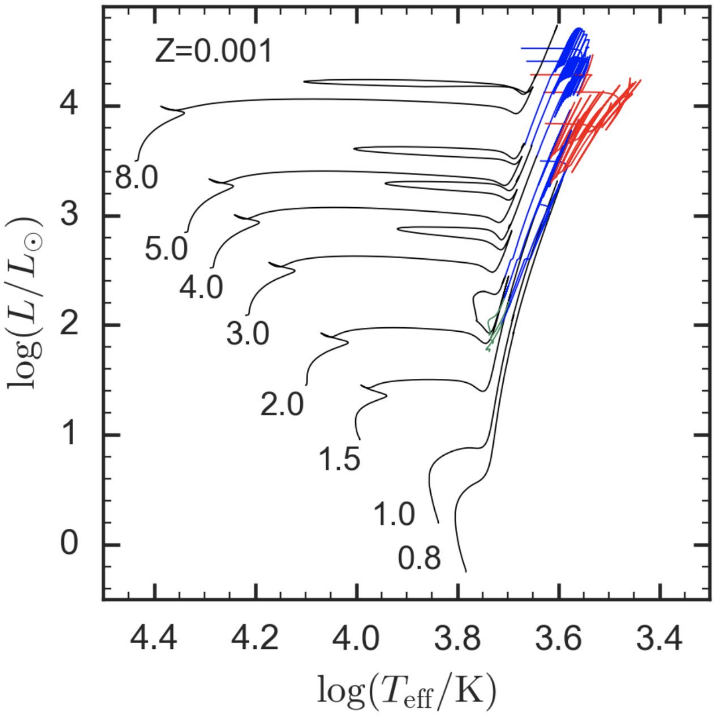
Jupyter notebook
In progress

Star counts from simulated LFs on MAF & galaxy counts from eq. 3.7 of LSST Science Collaboration et al. (2009): $N_{gal} = 46 \times 10^{0.31(imax-25)}$ galaxies arcmin^{-2}

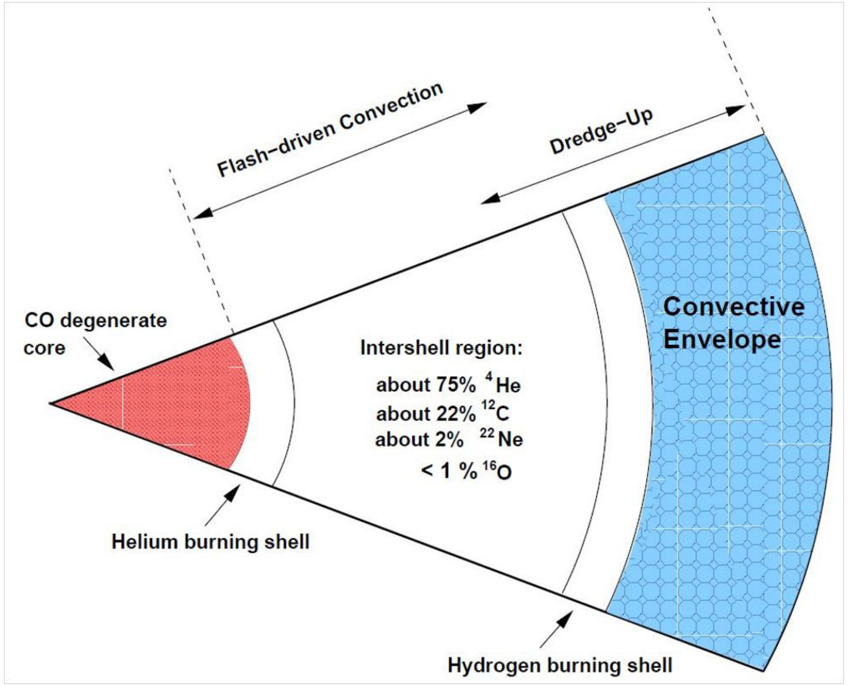




TP-AGB stars

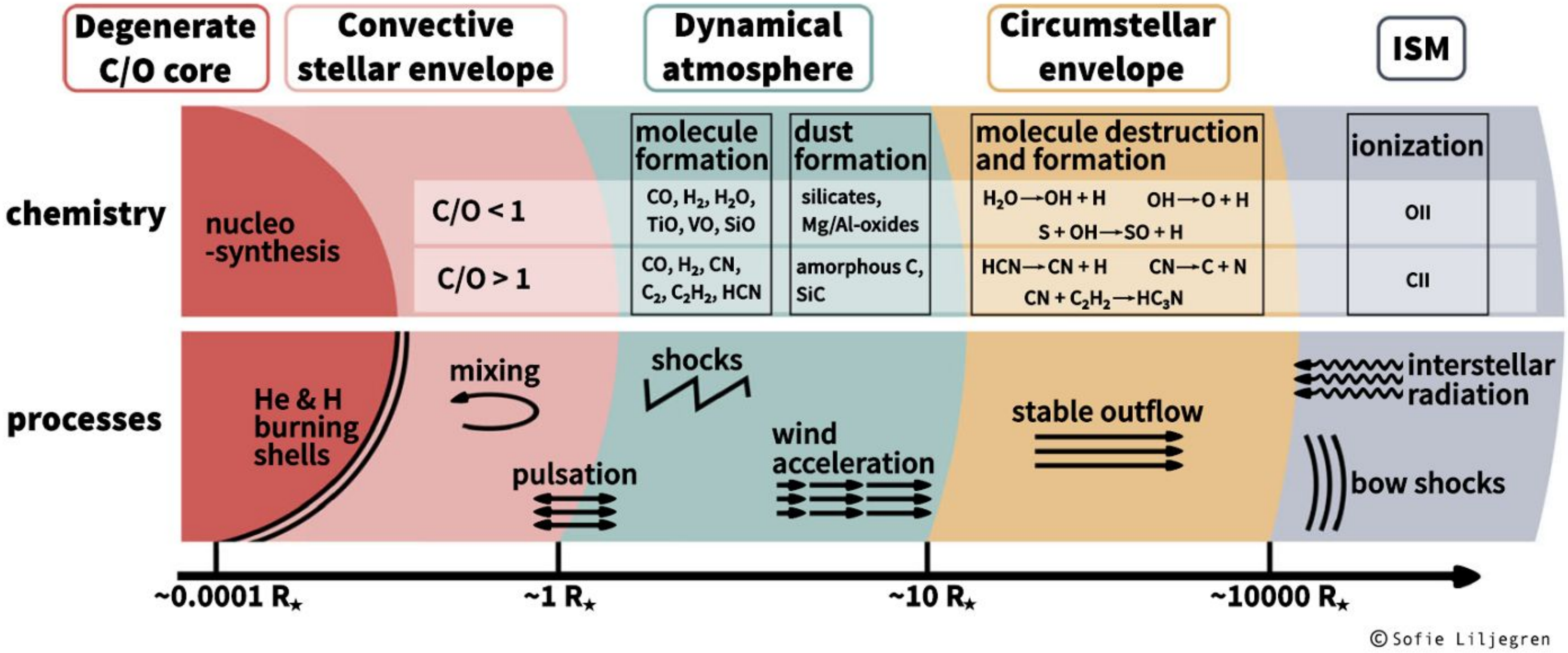


(PARSEC+COLIBRI models, Marigo+17)



(Karakas, Lattanzio & Pols 2002)

TP-AGB stars



Degenerate C/O core
Convective stellar envelope
Dynamical atmosphere
Circumstellar envelope
ISM
chemistry
nucleo -synthesis
C/O < 1
C/O > 1
molecule formation
CO, H2, H2O, TiO, VO, SiO
CO, H2, CN, C2, C2H2, HCN
dust formation
silicates, Mg/Al-oxides
amorphous C, SiC
molecule destruction and formation
H2O → OH + H
OH → O + H
S + OH → SO + H
HCN → CN + H
CN → C + N
CN + C2H2 → HC3N
ionization
OII
CII
processes
He & H burning shells
mixing
pulsation
shocks
wind acceleration
stable outflow
interstellar radiation
bow shocks
~0.0001 R★
~1 R★
~10 R★
~10000 R★
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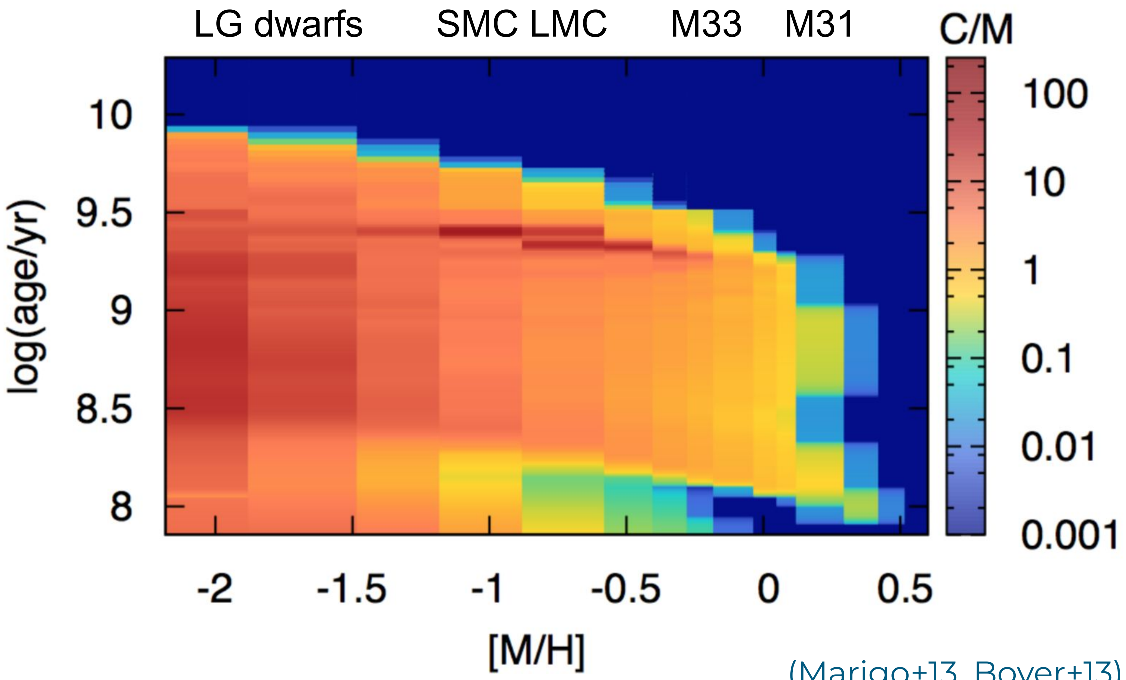
AGB models calibration in nearby galaxies

Match star counts and LFs of resolved stellar populations

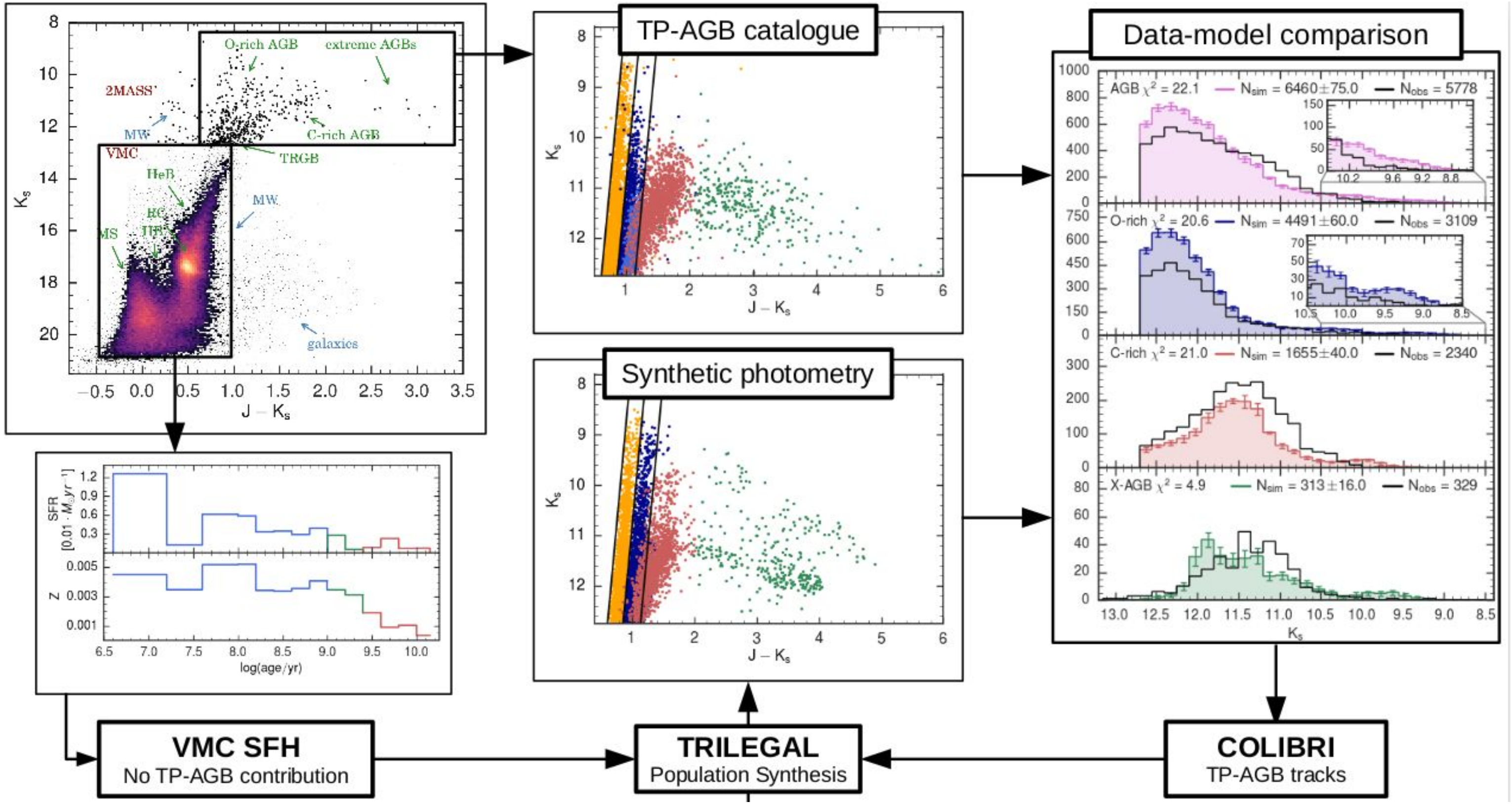
Calibration of 3DU parameters and mass-loss prescriptions and efficiency

- Robust SFHs
- TP-AGB evolutionary tracks
- TRILEGAL for population synthesis
- Observed AGB catalogs



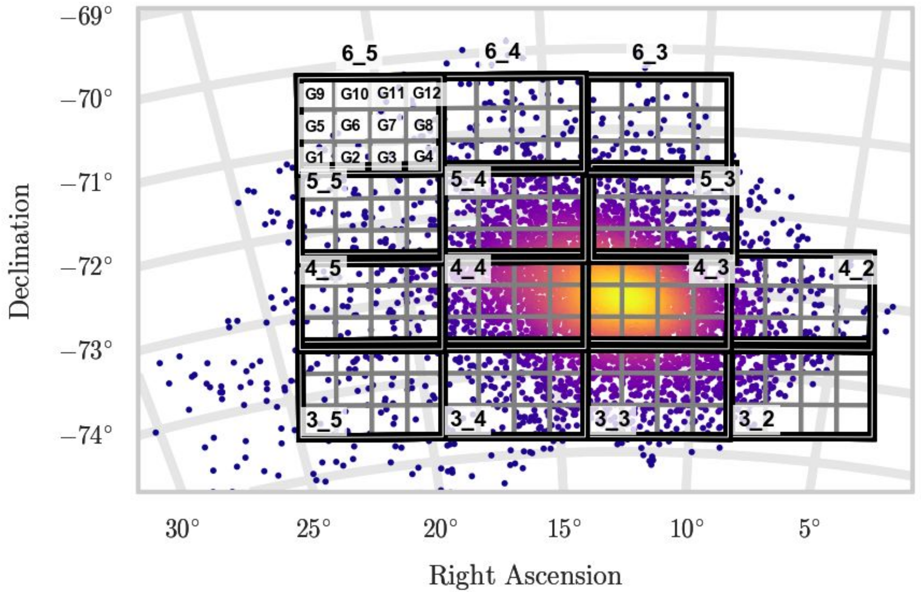
(Marigo+13, Boyer+13)

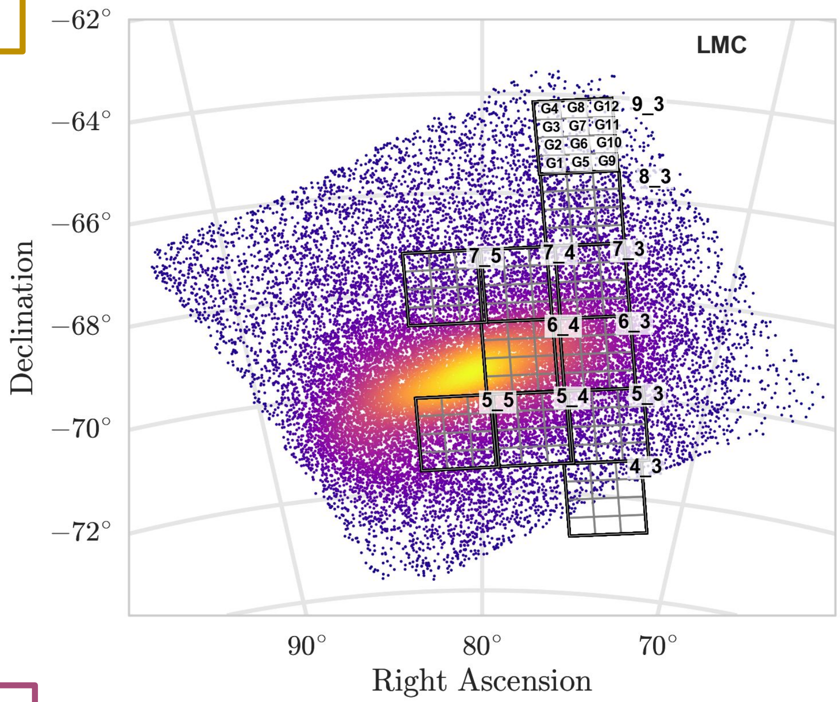
AGB models calibration in nearby galaxies



AGBs in the Magellanic Clouds

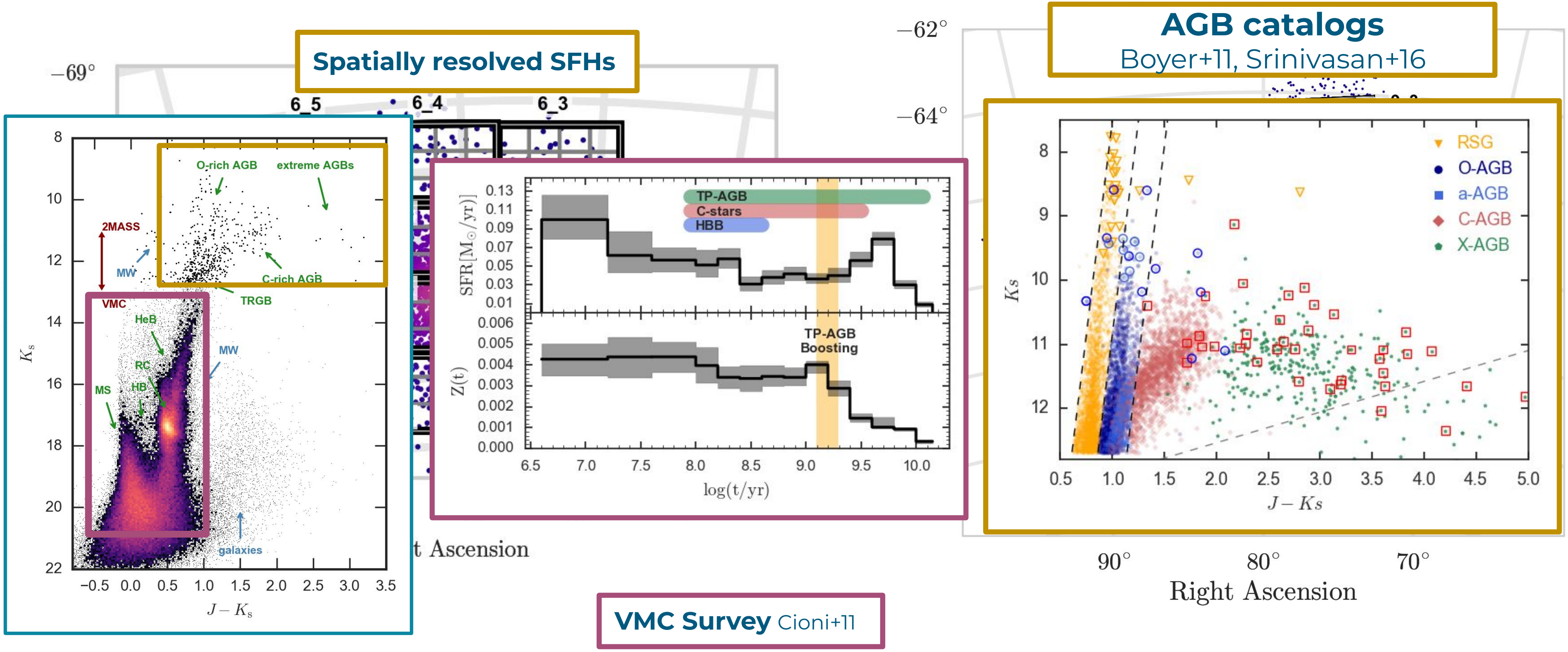
SAGE-SMC & SAGE-LMC Surveys Gordon+11





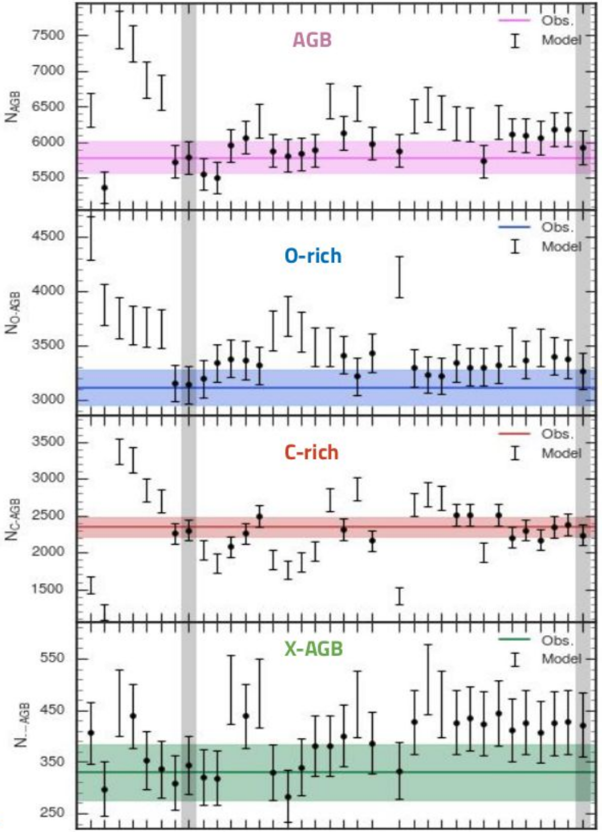
VMC Survey Cioni+11

AGBs in the Magellanic Clouds



Models calibration: mass-loss & 3DU

	Mass Loss							Third Dredge-Up			
	Pre-Dust		Dust - driven					Activation	Efficiency		
			M-stars		C-stars						
SET	Id	η	Id	η	Id	η	Sel[1]	$\log(T_b^{dred}/[K])$[2]	λ		
S_00	SC05	–	BE88	–	BE88	–	(a)	6.40	K02		
S_01	CS11	2	BL95	0.05	BL95	0.05	(a)	6.40	K02		
S_02	CS11	2	BL95	0.02	CDYN	1	(a)	6.40	K02		
S_03	CS11	2	BL95	0.03	CDYN	1	(a)	6.40	K02		
S_04	CS11	2	BL95	0.05	CDYN	1	(a)	6.40	K02		
S_05	CS11	2	BL95	0.06	CDYN	1	(a)	6.40	K02		
S_06	CS11	3	BL95	0.06	CDYN	1	(a)	6.40	K02		
S_07	CS11	3	BL95	0.06	CDYN	1	(a)	$f_1(Z_i)$	K02		
S_08	CS11	3	BL95	0.06	CDYN	1	(a)	$f_1(Z_i)$	λ_{max}= 0.5		
S_09	CS11	3	BL95	0.02	BL95	0.02	(a)	$f_1(Z_i)$	λ_{max}= 0.5		
S_10	CS11	3	BL95	0.01	BL95	0.01	(a)	$f_1(Z_i)$	λ_{max}= 0.5		
S_11	CS11	3	BL95	0.01	CDYN	1	(a)	$f_1(Z_i)$	λ_{max}= 0.5		
S_12	CS11	3	BL95	0.01	CDYN	1	(a)	$f_1(Z_i)$	K02		
S_19	CS11	3	VW93		CDYN	1	(a)	$f_1(Z_i)$	K02		
									$\tilde{\lambda}_{max}$	$\tilde{M}_c[M_\odot]$	$M_{c,\lambda=0}[M_\odot]$
S_13	CS11	3	BL95	0.01	CDYN	1	(a)	$f_1(Z_i)$	0.5	0.65	0.95
S_14	CS11	3	BL95	0.01	CDYN	1	(a)	$f_1(Z_i)$	0.5	0.65	0.85
S_15	CS11	3	BL95	0.01	CDYN	1	(a)	$f_1(Z_i)$	0.6	0.60	0.85
S_16	CS11	3	BL95	0.01	CDYN	1	(a)	$f_2(Z_i)$	0.6	0.60	0.85
S_17	CS11	3	BL95	0.01	CDYN	1	(b)	$f_2(Z_i)$	0.6	0.60	0.85
S_18	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.6	0.60	0.85
S_20	CS11	3	BL95	0.02	CDYN	1	(a)	$f_2(Z_i)$	0.6	0.60	0.85
S_22	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.7	0.70	0.85
S_23	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.8	0.60	0.85
S_24	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.8	0.60	1.30
S_25	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.8	0.60	1.00
S_26	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.7	0.60	0.85
S_27	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.7	0.60	1.00
S_28	CS11	3	BL95	0.02	CDYN	1	(a)	$f_2(Z_i)$	0.7	0.60	1.00
S_29	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.7	0.625	1.00
S_30	CS11	3	BL95	0.02	CDYN	1	(b)	$f_2(Z_i)$	0.5	0.6	1.00
S_31	CS11	3	BL95	0.01	CDYN	1	(a)	$f_1(Z_i)$	K02, $\lambda_{max} = 0.4$ if $M_c < 0.75$		
S_32	CS11	3	BL95	0.02	CDYN	1	(a)	$f_2(Z_i)$	0.5	0.5	1.00
S_33	CS11	3	BL95	0.02	CDYN	1	(a)	$f_2(Z_i)$[3]	0.5	0.5	1.00
S_34	CS11	3	BL95	0.02	CDYN	1	(a)	$f_2(Z_i)$	0.6	0.6	1.00
S_35	CS11	3	BL95	0.03	CDYN	1	(b)	$f_2(Z_i)$	0.7	0.60	1.00

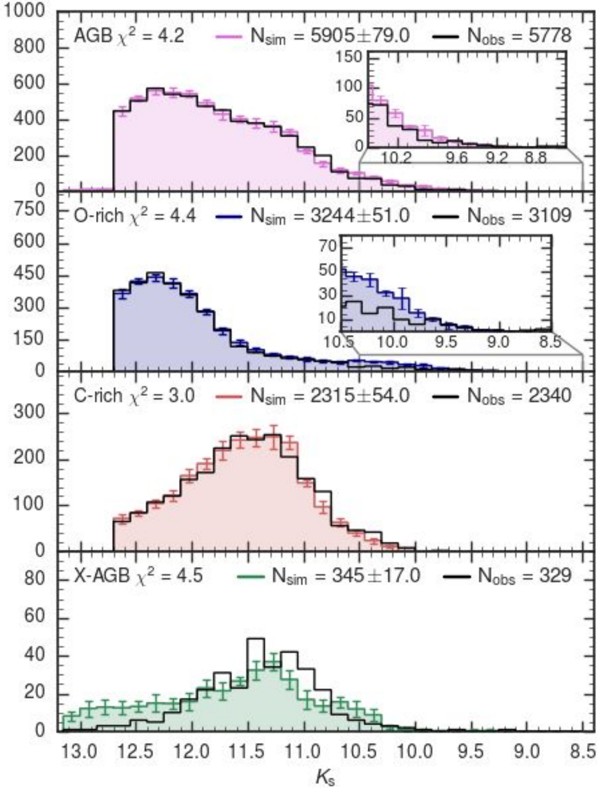


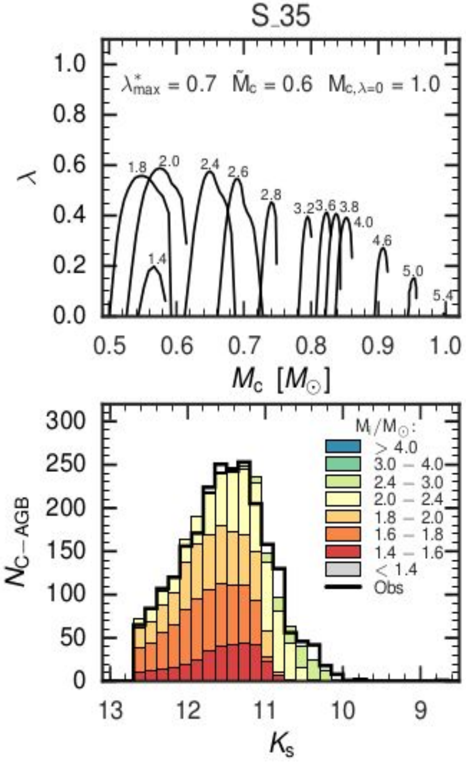
Models calibration: mass-loss & 3DU

- Varying **mass-loss** prescriptions & efficiency
- Varying **3DU** occurrence and efficiency
- Ks-band LFs in the SMC and LMC

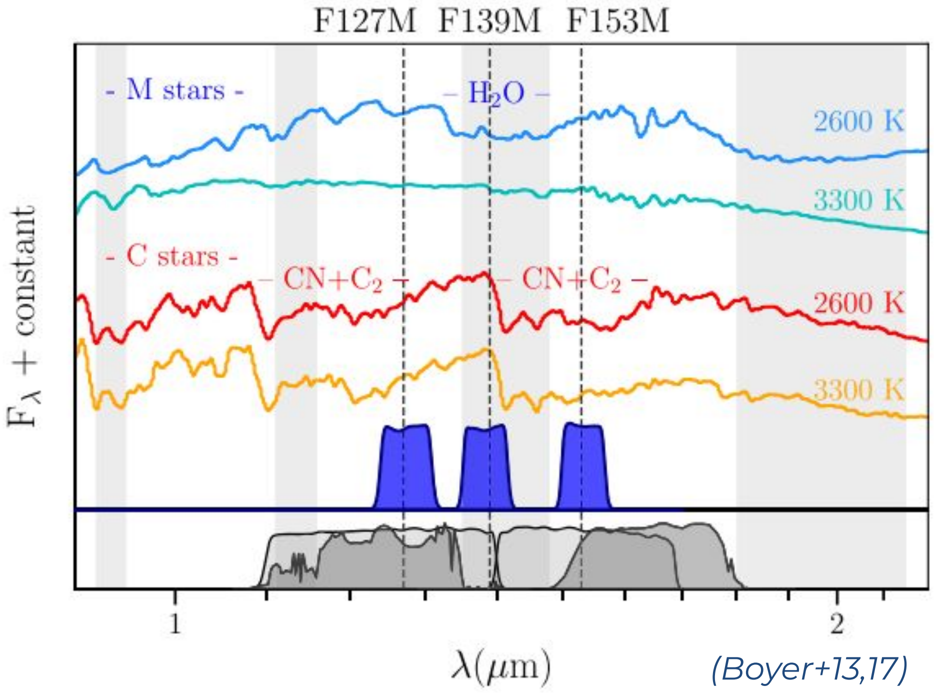
Pastorelli+19,+20

SMC

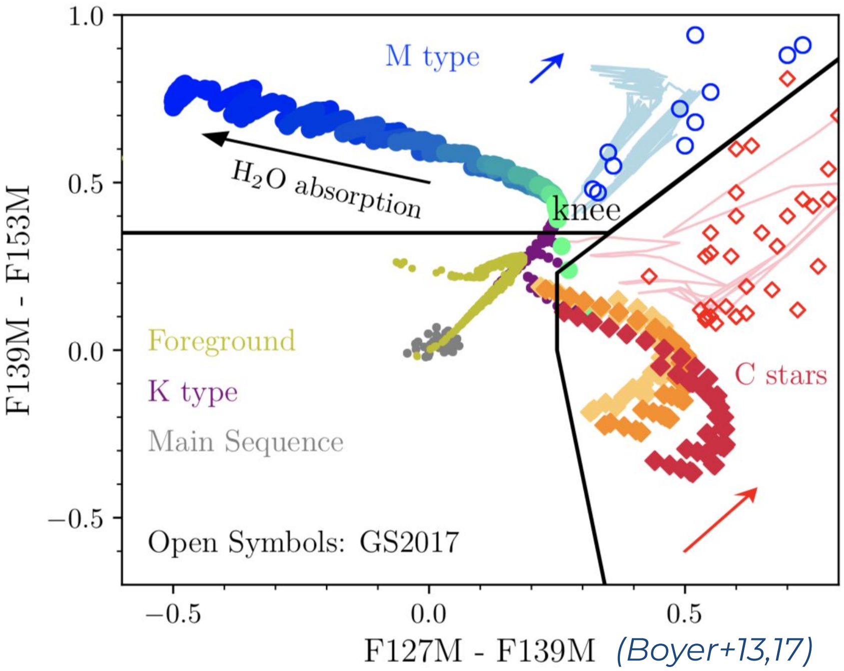




HST medium-band filters: C-, O-rich identification



(Boyer+13,17)



(Boyer+13,17)

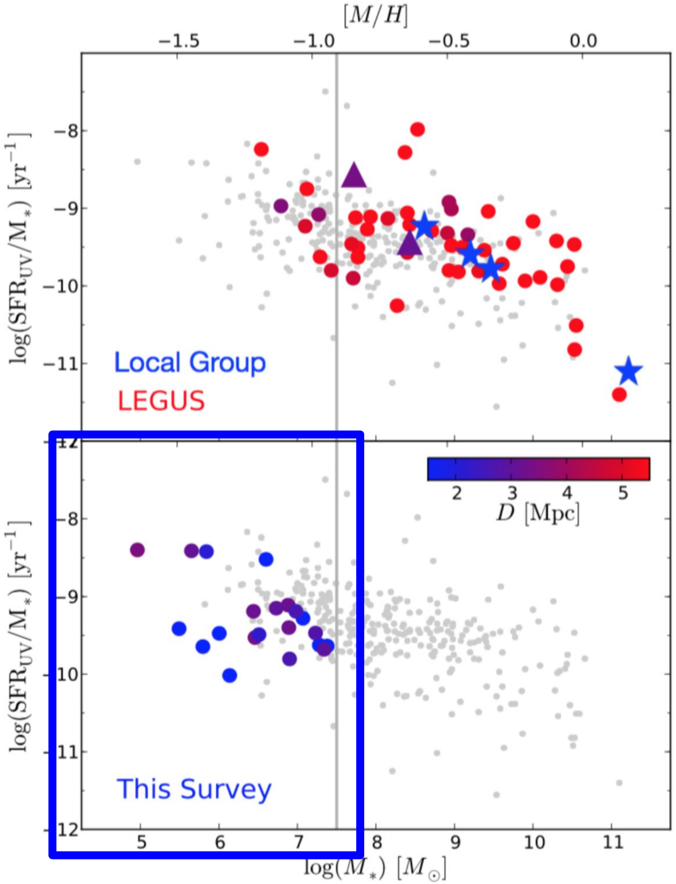
LUVIT project

HST GO-16162 (PI Boyer)

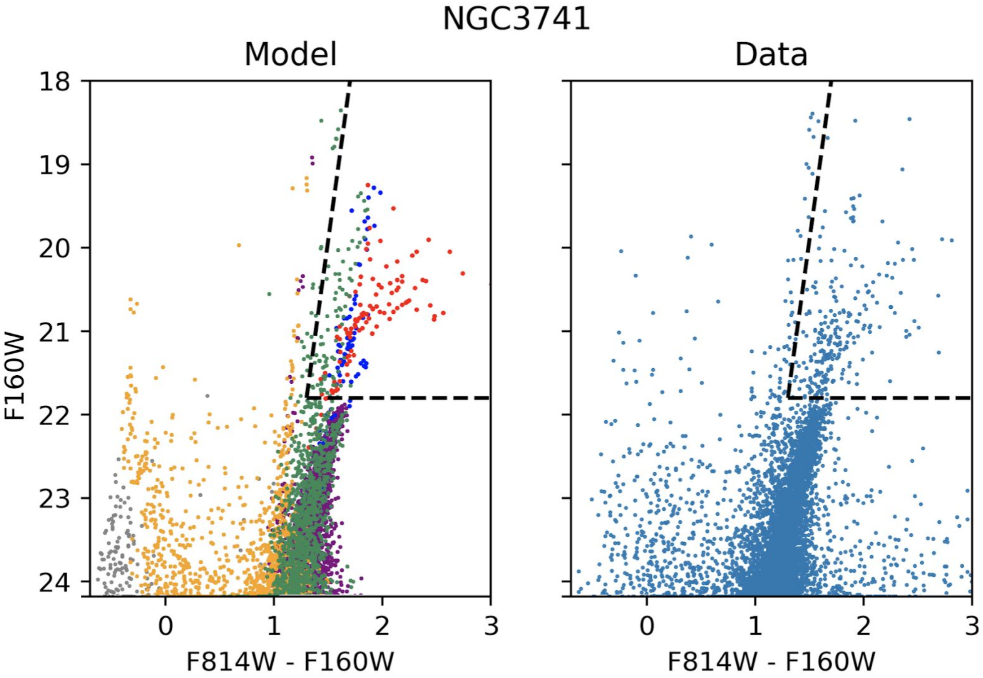
19 metal-poor dwarf galaxies observed with **HST medium-band** filters

- HST photometry from UV to IR
- Homogenous data reduction
- Simultaneous multi-band photometry
- Robust Star Formation History

Metallicity range -1.7 < [Fe/H] < -0.9



LUVIT project

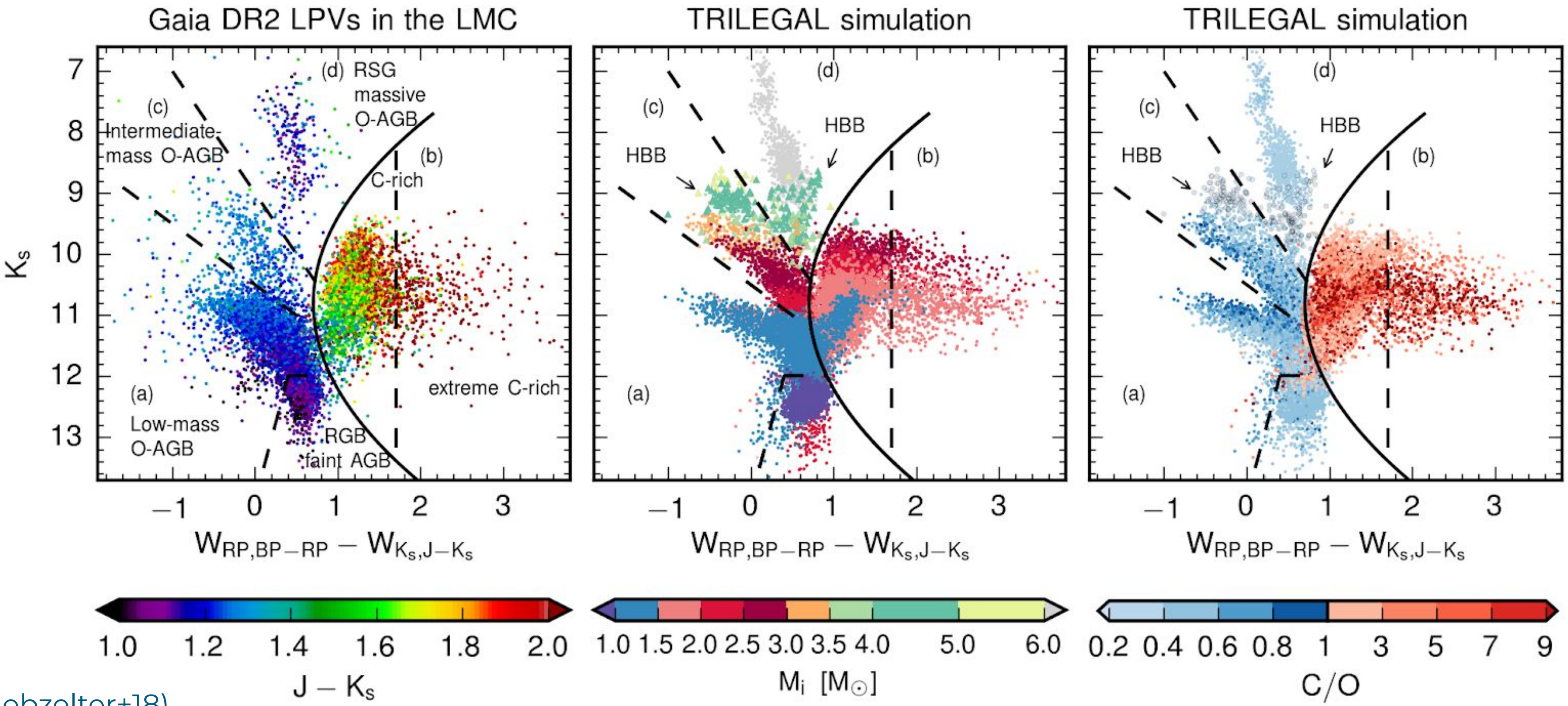


(Pastorelli in prep.)

Work in progress to:

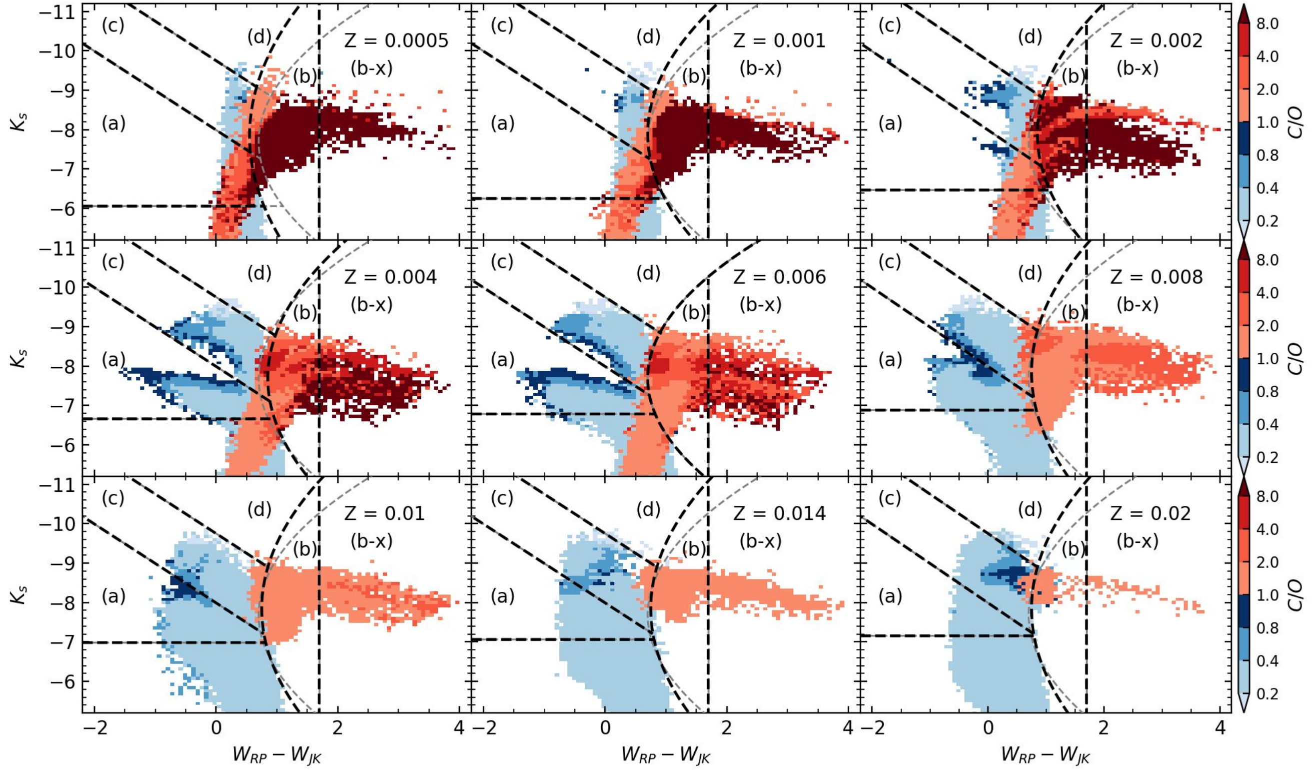
1. Derive SFHs
2. Data-model comparisons
3. Calibration of AGB models at low metallicity

Gaia-2MASS diagram - AGB star identification

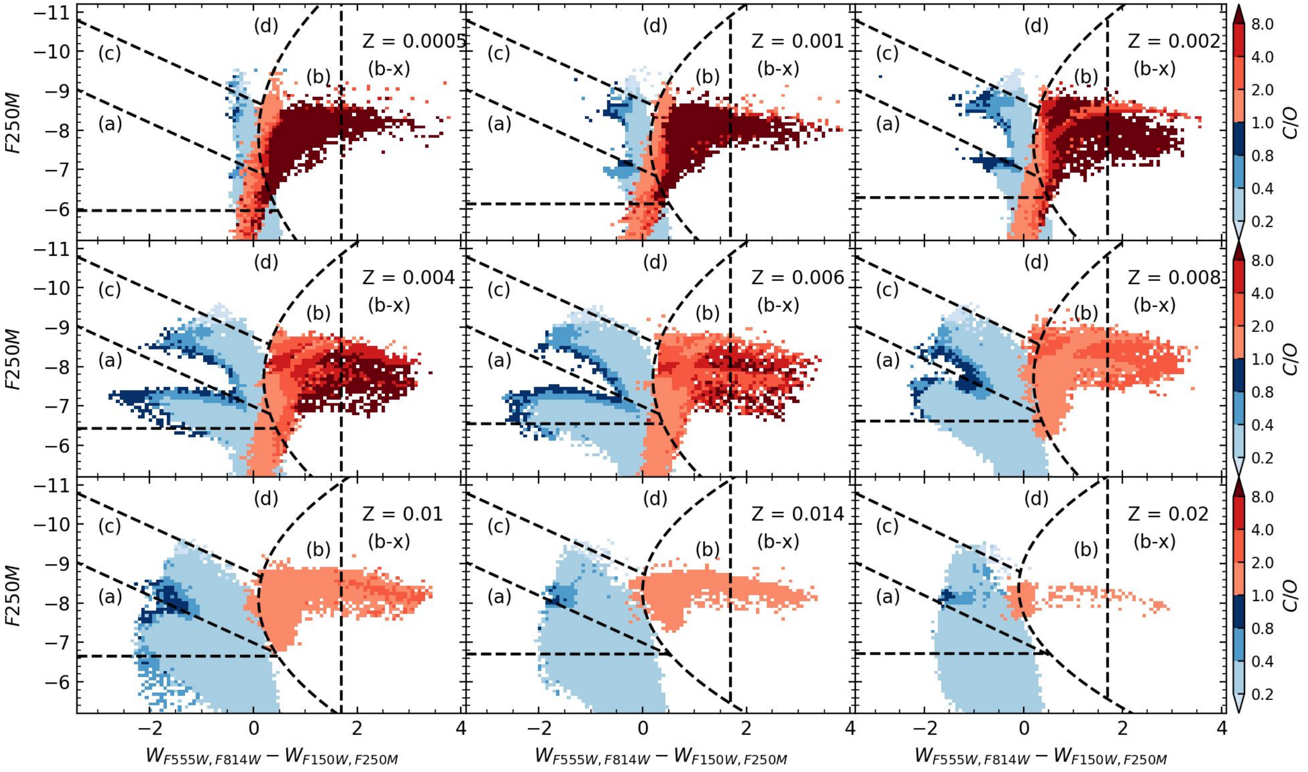


(Lebzelter+18)

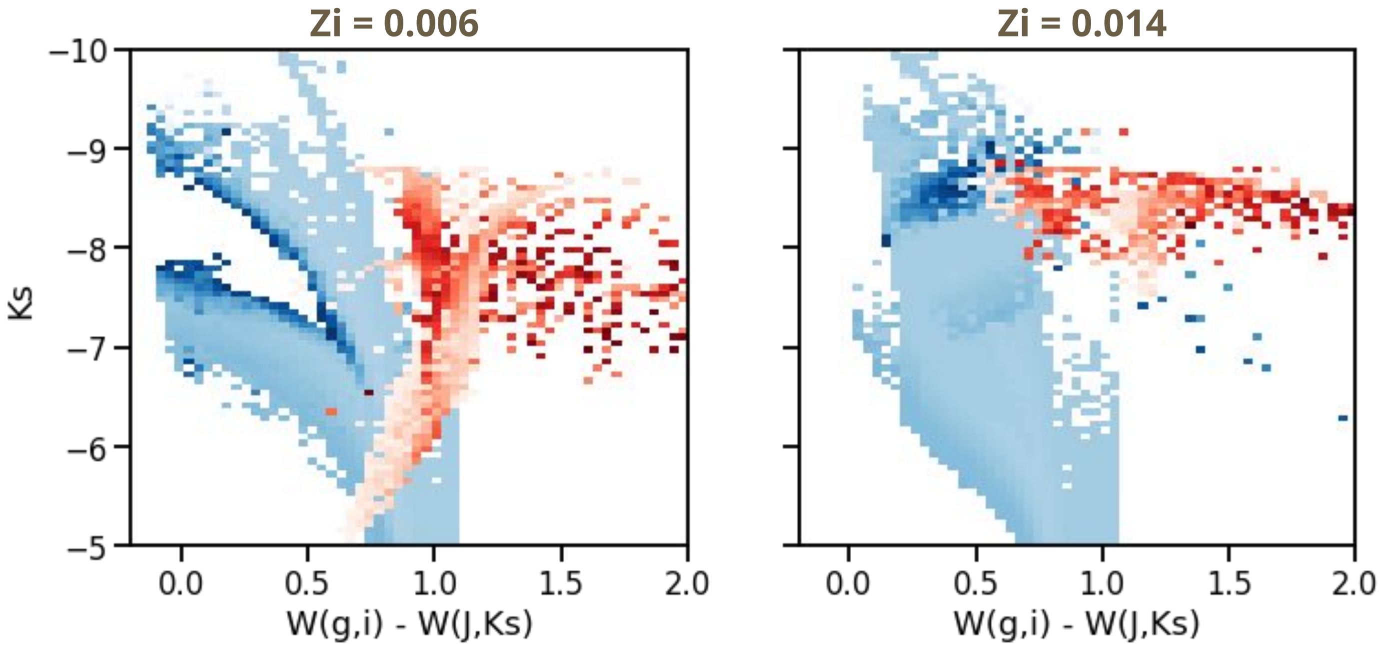
Gaia-2MASS diagram - AGB stars identification



HST-JWST diagram - AGB stars identification



Investigating LSST filters (in progress)



Summary

- Provide **Jupyter notebooks** to explore and use our LSST simulation
- Improve and maintain codes to perform LSST simulations
- Implement **improved models for AGB** stars from Pastorelli+19,+20,in prep.
- Investigate the use of LSST filters in combination with other surveys to **identify and classify AGB stars**

LSST simulations with TRILEGAL

Single stars

→ datalab.noirlab.edu/query.php?name=lsst_sim.simdr2

Binary stars

→ datalab.noirlab.edu/query.php?name=lsst_sim.simdr2_binary

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