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AIP

The Magellanic Clouds

"Some of the most interesting objects of research can be reached only from the southern hemisphere: the central parts of the galaxy and the nearest extragalactic systems" (A. Blaauw 1991)

ESO@2020

Garching 19-22 Jan. 2015

Foreword

Fernão de Magalhães (1480-1521)

- The Magellanic Clouds are the most luminous and largest dIrr satellite galaxies of the Milky Way.
- They are located at 50-60 kpc above the MW plane.
- They are metal poor ([Fe/H]=-0.3, -0.73).
- They have a mass of 10^{10} and 10^{9} $M_{\odot}$.
- They show clear signs of interactions between themselves and with the Milky Way.

Important facts about the MCs

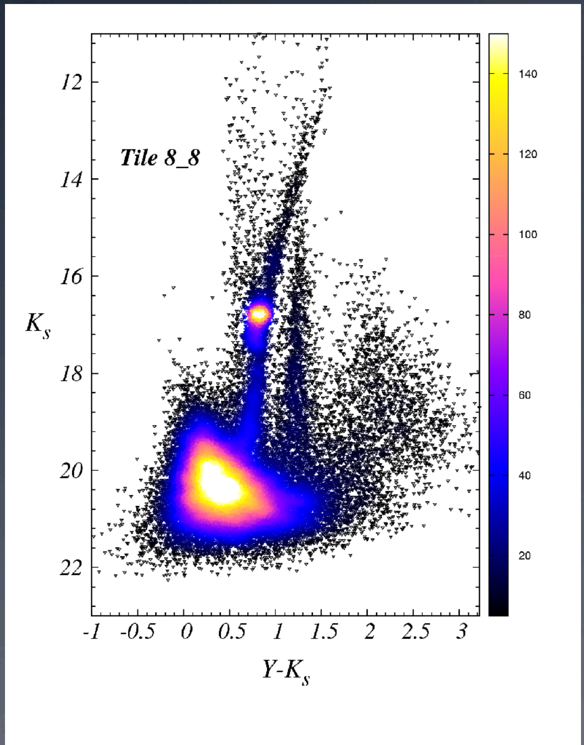
- Contain stars of all ages
- Contain variable stars of all types
- Probe the dwarf-dwarf galaxy interaction
- Probe the interaction with Milky Way type galaxies
- We can study the link between star formation and chemical history, and dynamics
- We can measure their structure and substructures

Tarantula nebula and SN 1987A

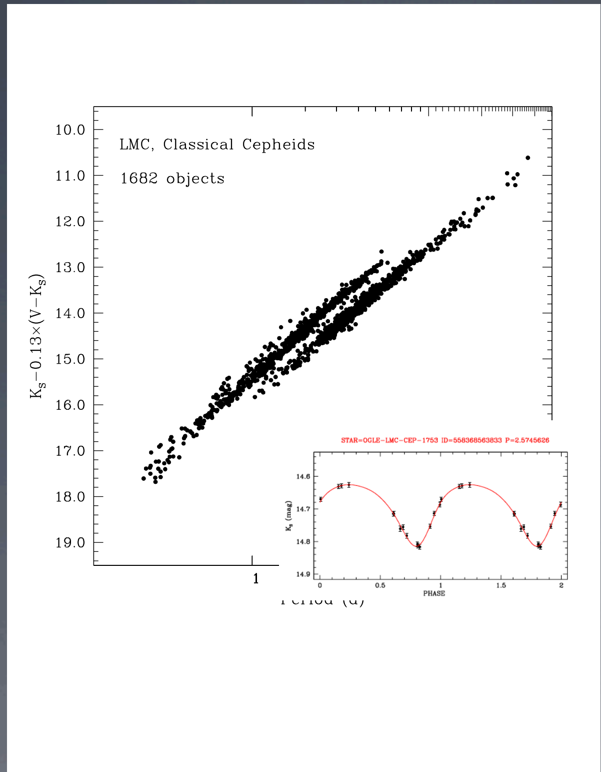
The Magellanic Clouds host many interesting objects, from new born stars to the remnants of stellar explosions.

ESO press release 1033.

Popular stellar population tools



Multi-lambda deep colour-magnitude diagrams for probing e.g. age, metallicity.



Period-luminosity relations, e.g. Cepheids. for e.g probing distance.

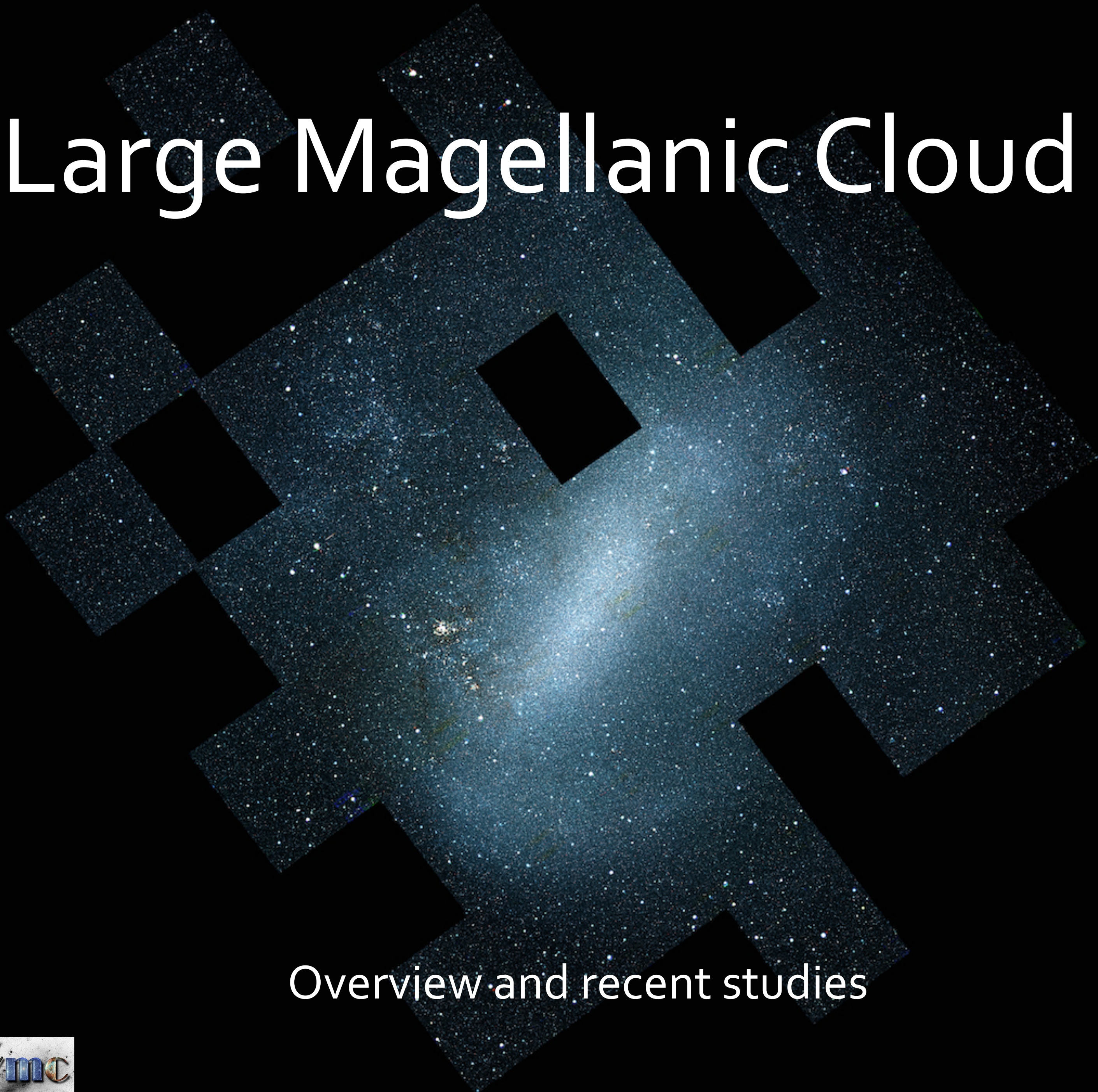
+ Spectra for probing chemistry and radial velocity.

+ Proper Motion for probing tangential velocity.

(Rubele+2012)

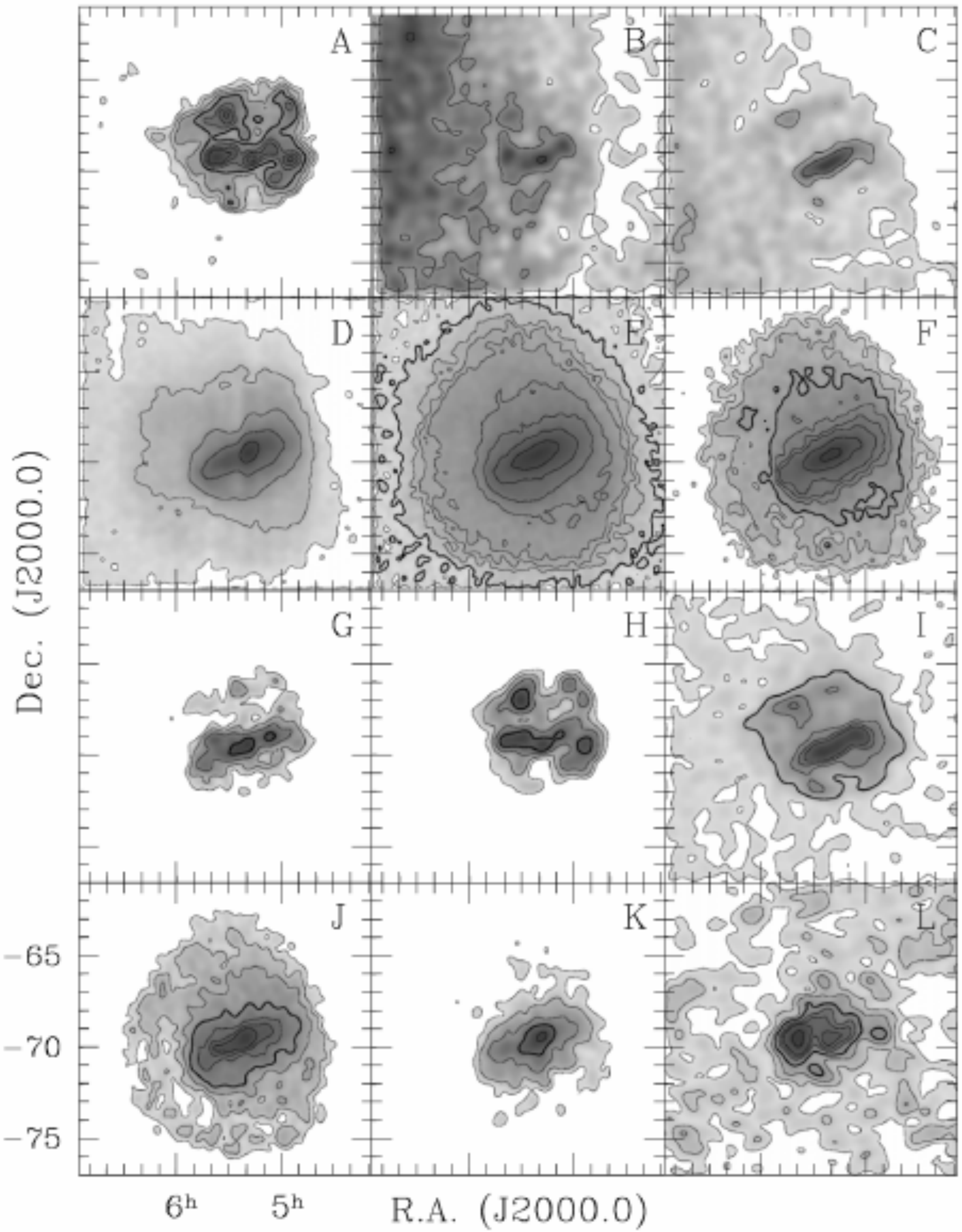
(Ripepi+ in prep.)

Large Magellanic Cloud



Overview and recent studies

Morpholoy of the LMC*



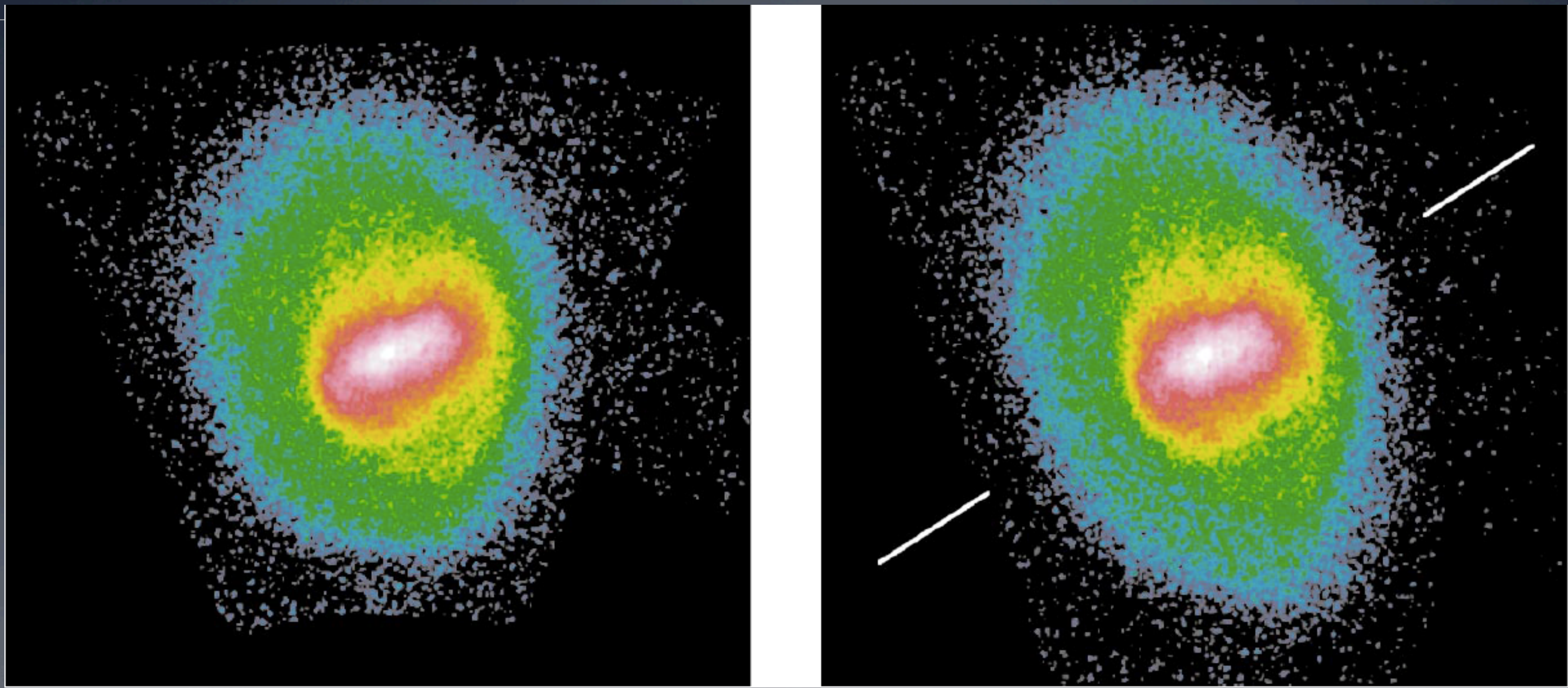
To note:

Bar: thin / thick
Disk
MW contamination
Clumpiness
Smoothness

* Based on 2MASS data

(Nikolaev & Weinberg 2000)

LMC structure from AGB stars*



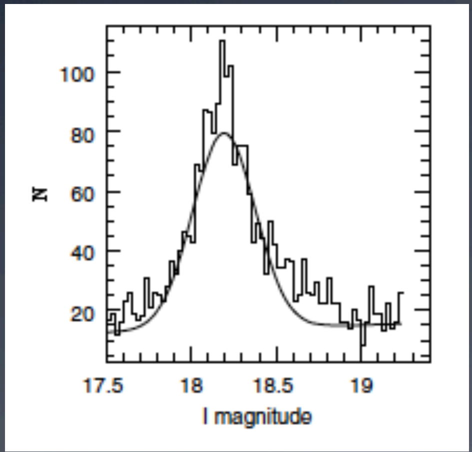
Observed distribution of stars   Projected distribution of stars

The intrinsic shape of the LMC is elliptical.

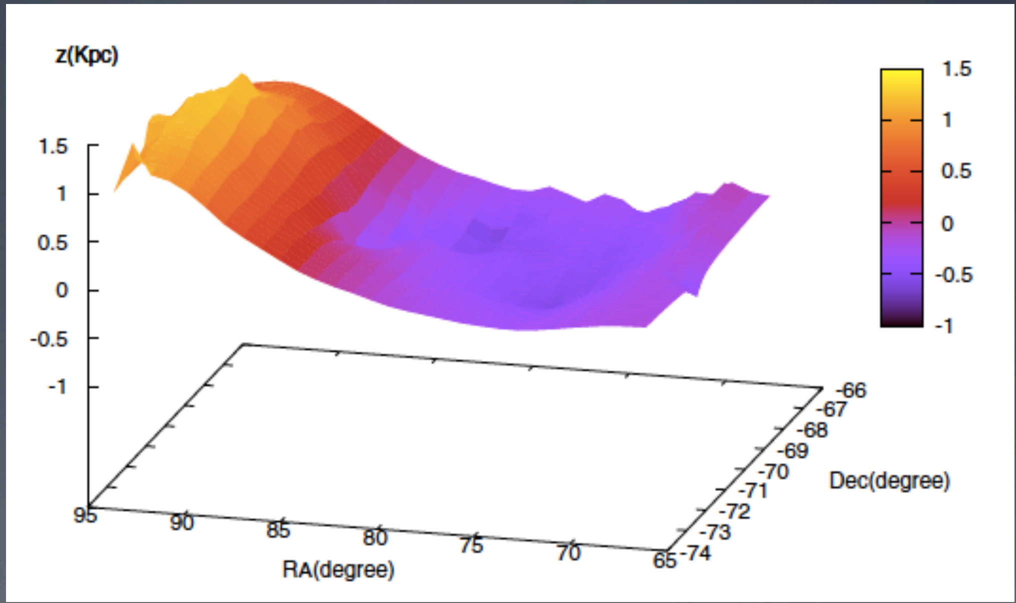
*Based on DENIS and 2MASS data

(van der Marel 2001)

LMC structure from RC stars*



Red clump stars.



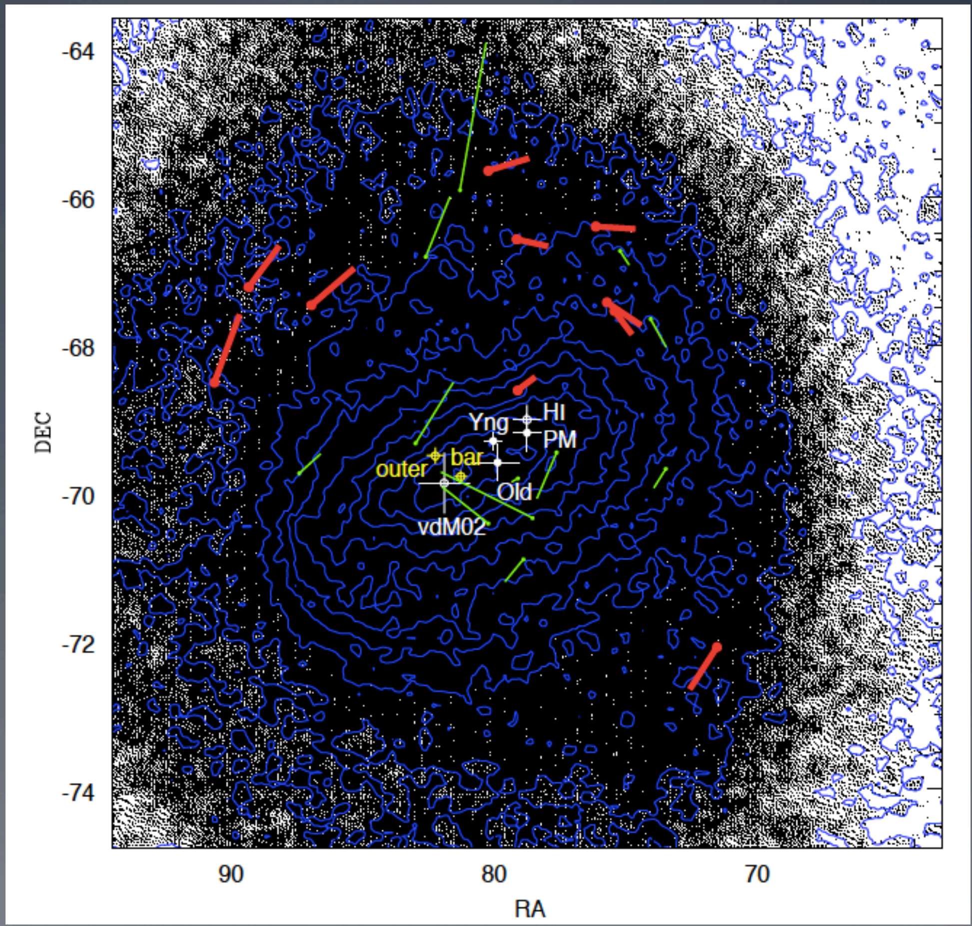
The inner regions have a smaller inclination than the outer regions.
This may be an effect of interaction with the Milky Way.

* Based on OGLE III data (Subramanian & Subramaniam 2010)

Where is the centre of the LMC?

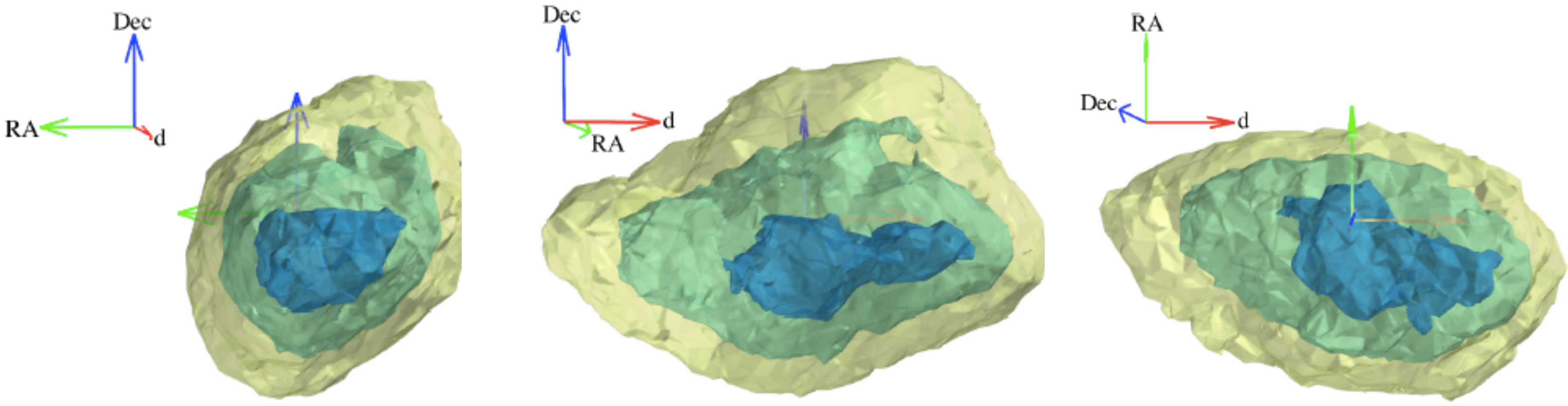
Discrepancies of 0.4-1.8 deg among:

- Bar
- Outer isophotes
- Carbon stars
- Proper motion (mixed population)
- RSG/young stars radial velocity
- AGB+RGB/old stars radial velocity
- HI gas



(van der Marel+2014)

LMC structure from RRL stars*



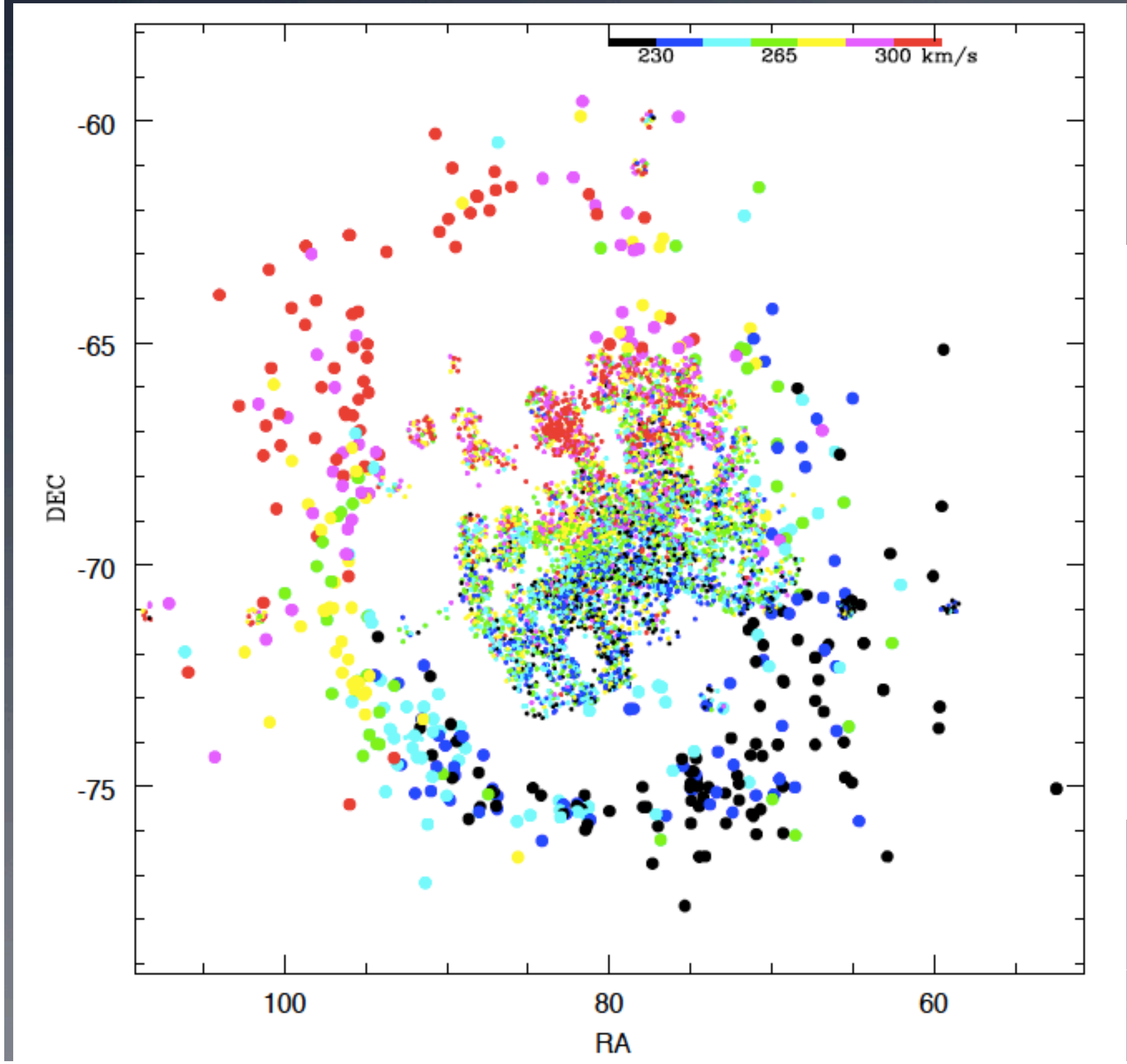
Star density plots where the distance is given from the displacement from the period-luminosity relation.

Contours indentify densities of 200, 250, and 300 stars per kpc^{-3}.
The length of each vector is 1 kpc.
The depth of the core is larger than its extent.

* Based on OGLE III data

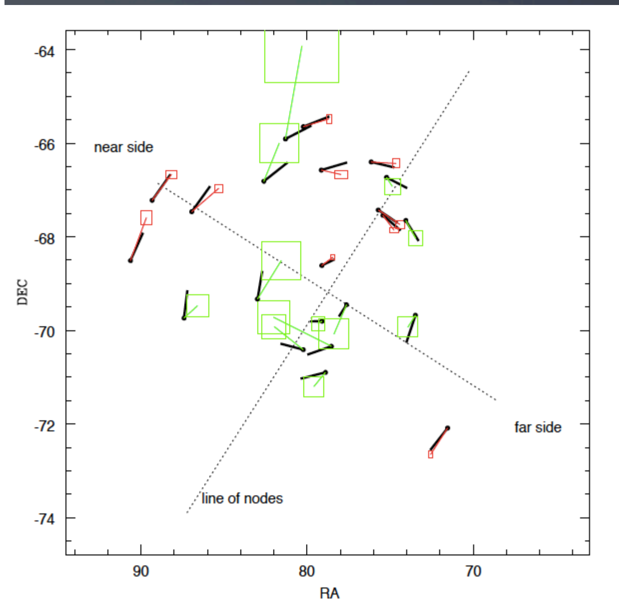
(Klein+ 2014)

Radial velocity* & Proper Motion**



* Based on spectroscopic data

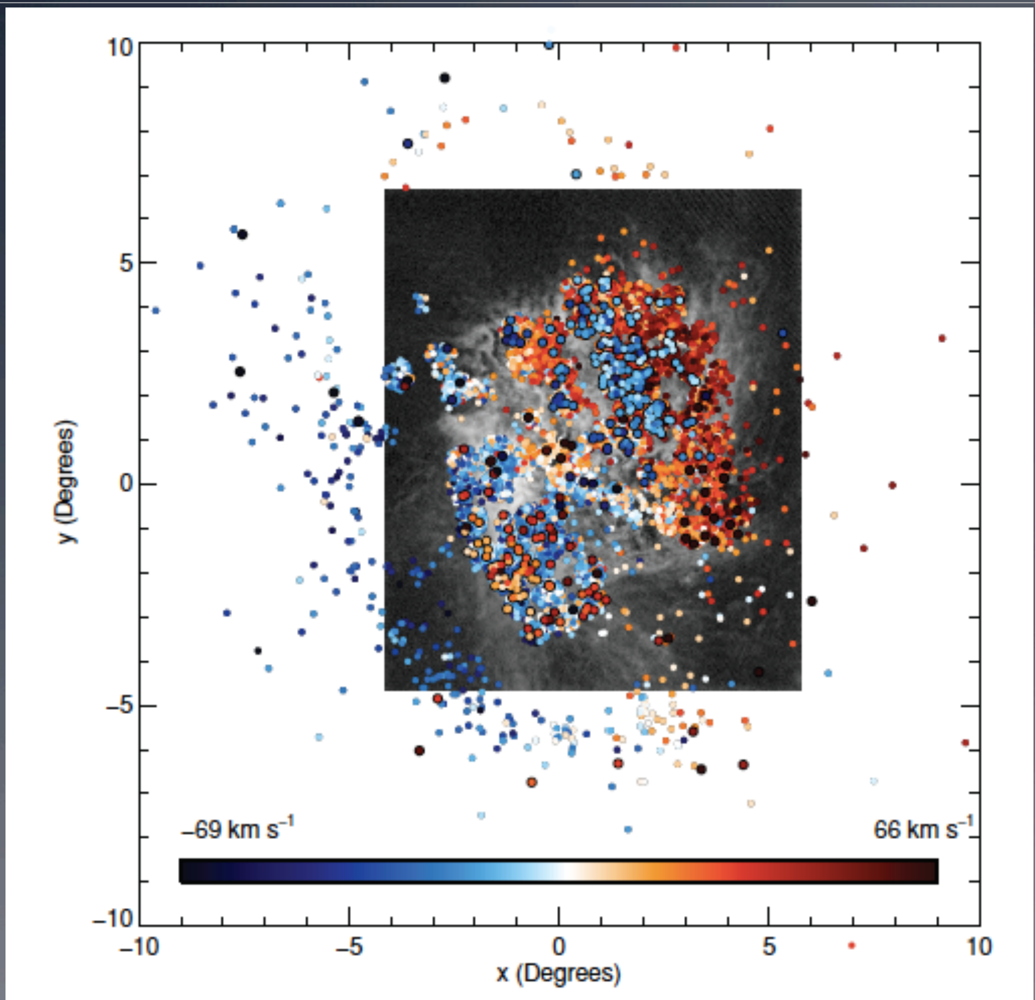
** Based on HST data



2-3 epochs, 3-7 years, 30 stars per field

(van der Marel+2014)

LMC radial velocity



6000 stars:
red super giant stars, carbon-rich and M-type AGB stars.

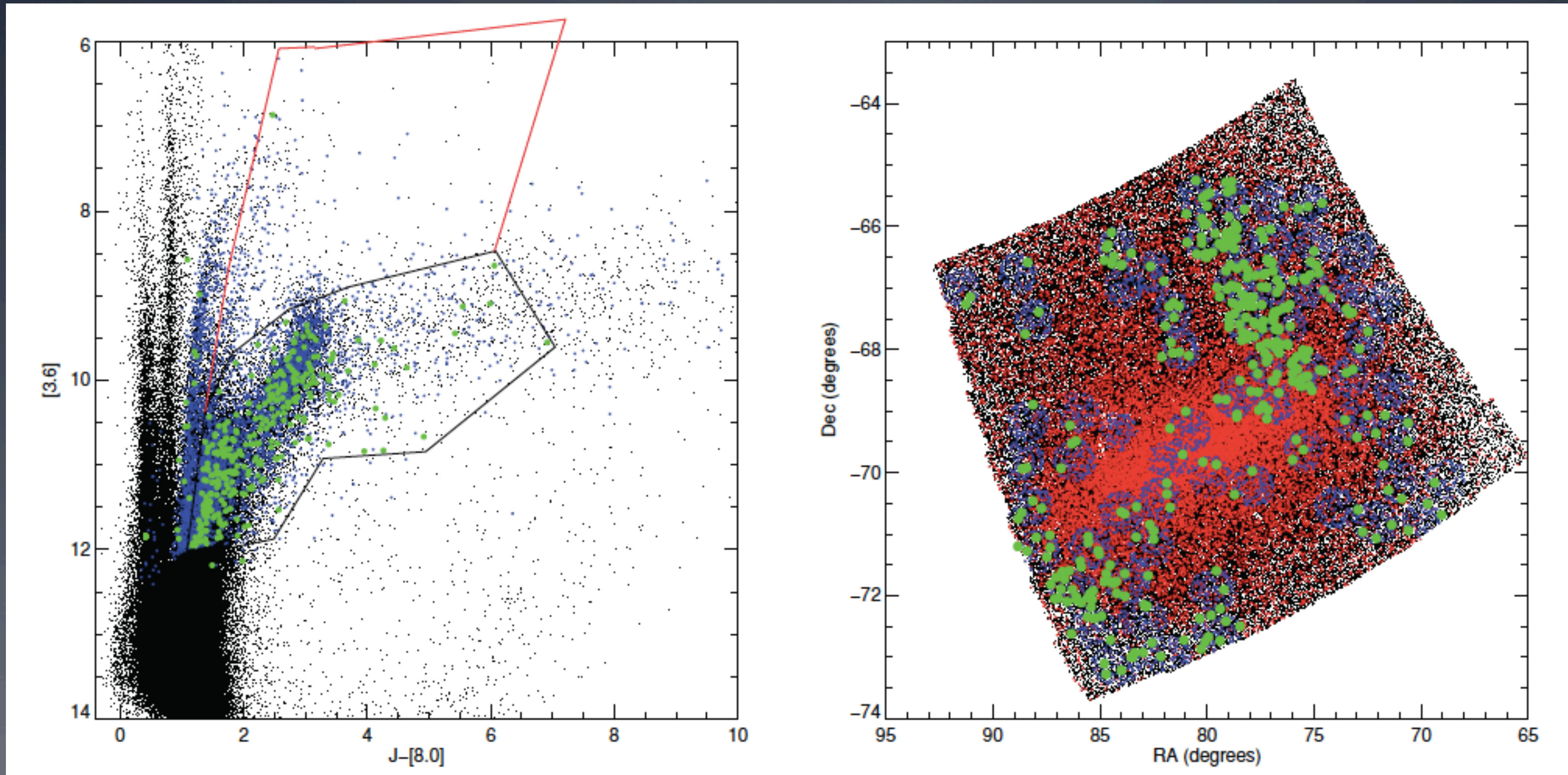
Galaxy rotation.

Outliers (black) indicate stars that either counter-rotates or rotates in an inclined plane compared to the main plane.

The metallicity of these outliers suggests they are coming in from the SMC.

(Olsen+2011)

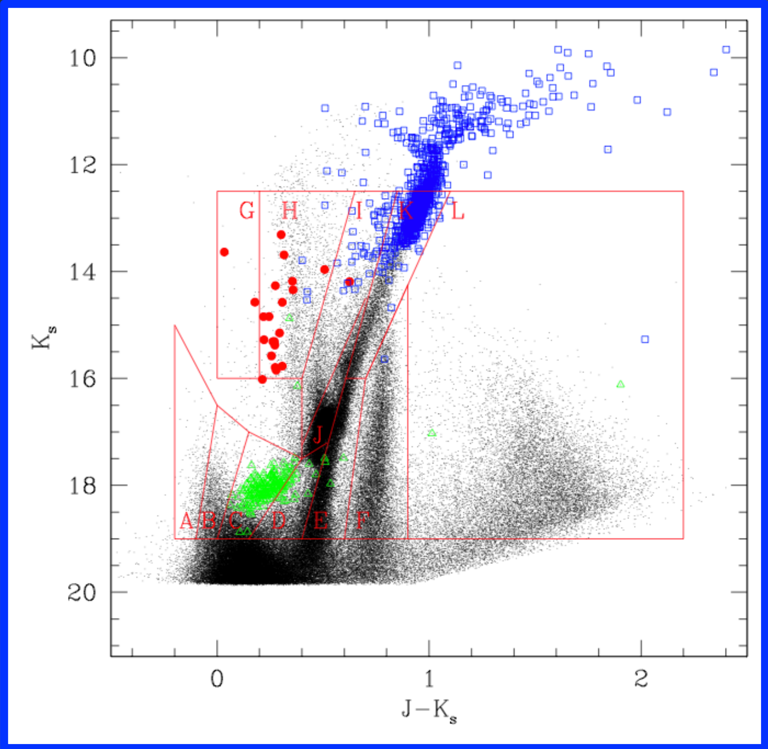
LMC velocity outliers

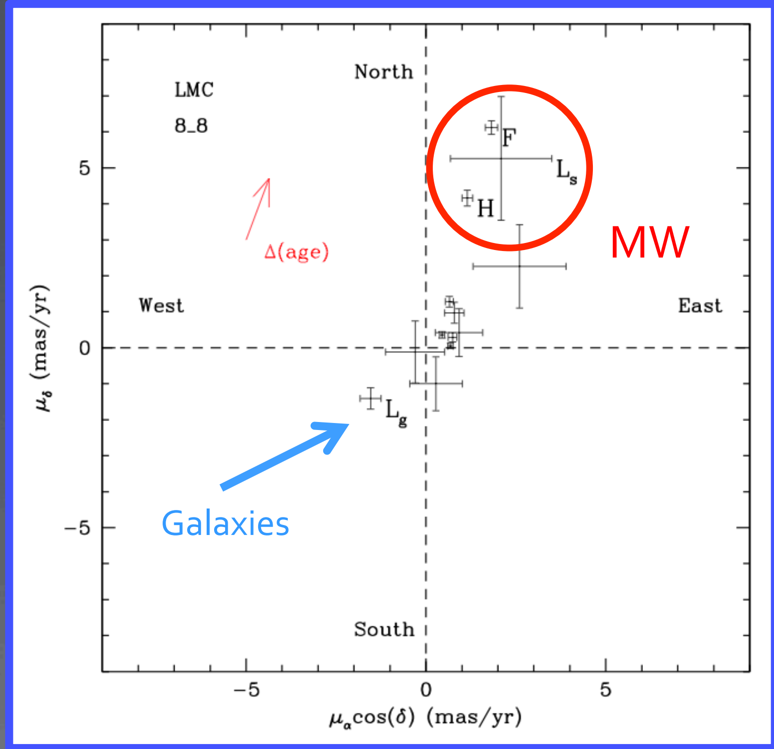


Velocity outliers are consistent with being AGB stars and are preferentially located in arms that coincide with HI-gas arms.

(Olsen+2011)

Proper Motion in SEP region*





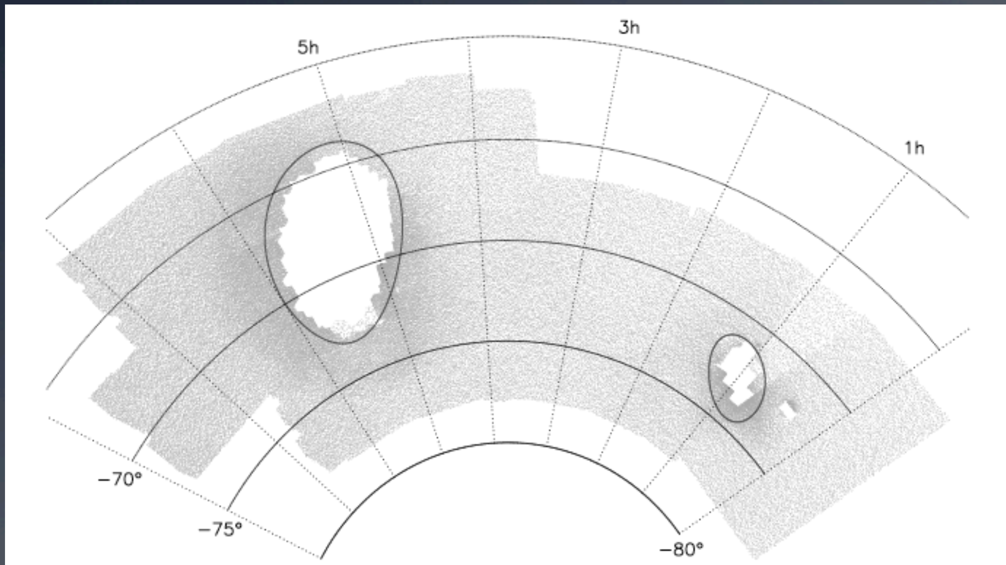
LMC (~40000 sources): $\mu_\alpha \cos(\delta)=+2.20$ (0.06, 0.29), $\mu_\delta=+1.70$ (0.06, 0.30)

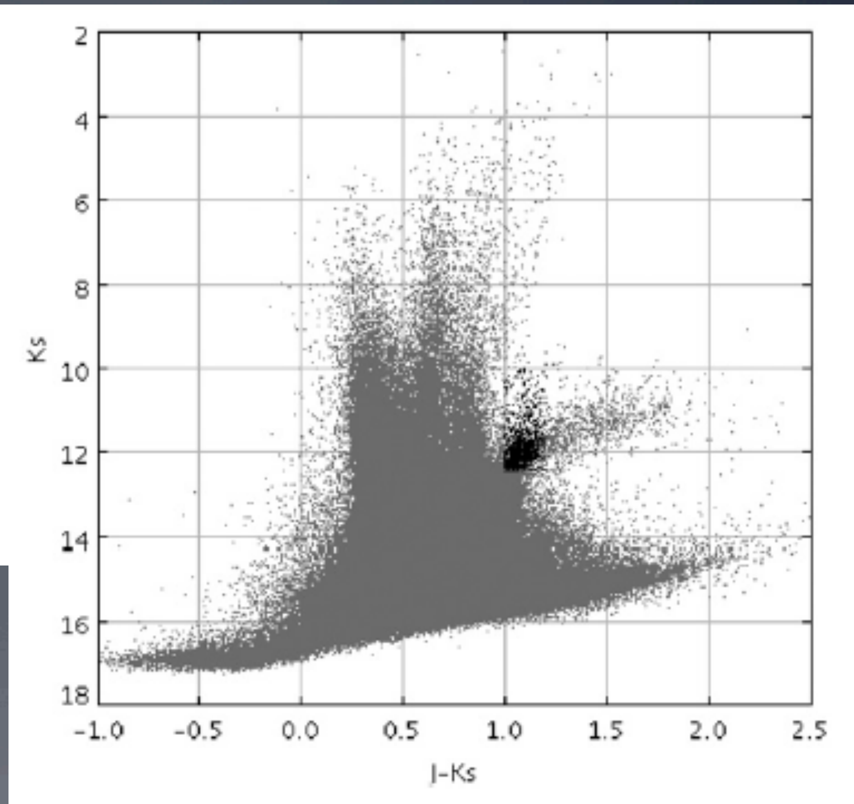
Calibrated on ~8000 background galaxies. Time baseline = 1 yr.

* Based on VISTA data

(Cioni+2014)

Proper motion in the outer MC*





Time baseline = 40 years
Epochs = 2
Type of stars = O-rich AGB stars
Number of stars = 4000/1000 in LMC/SMC
Uncertainties = 0.3-0.4 mas yr^{-1}

* Based on SPM data

(Vieira+2010)

Star formation history*

The most recent study of the SFH in the LMC from small-scale fields.

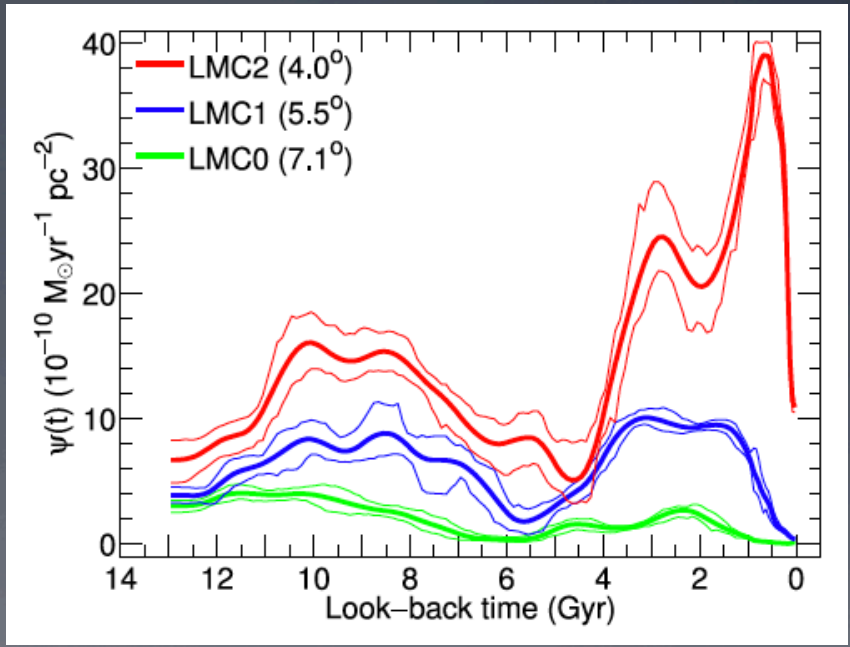
Stellar population gradient.

Two main star forming episodes.

SF going on in the innermost field.

Outside-in quenching.

Effects of MW interaction.



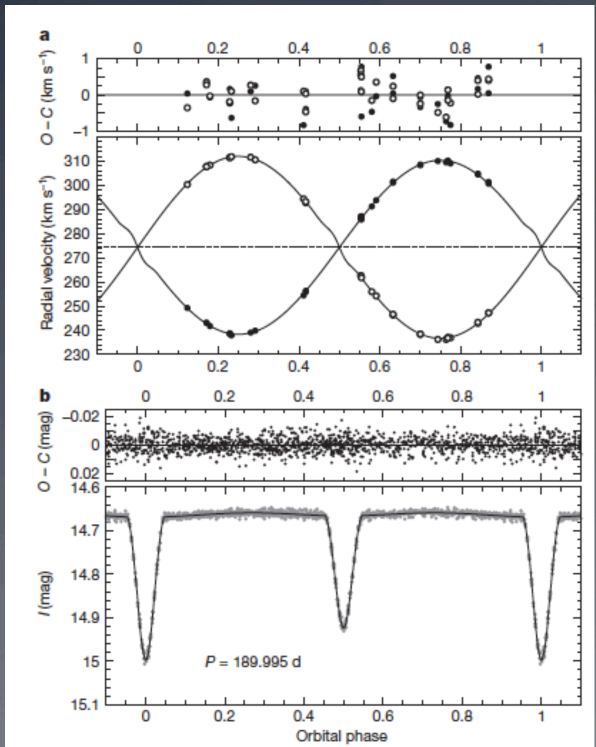
A comprehensive spatial and temporal investigation of the LMC SFH is lacking.

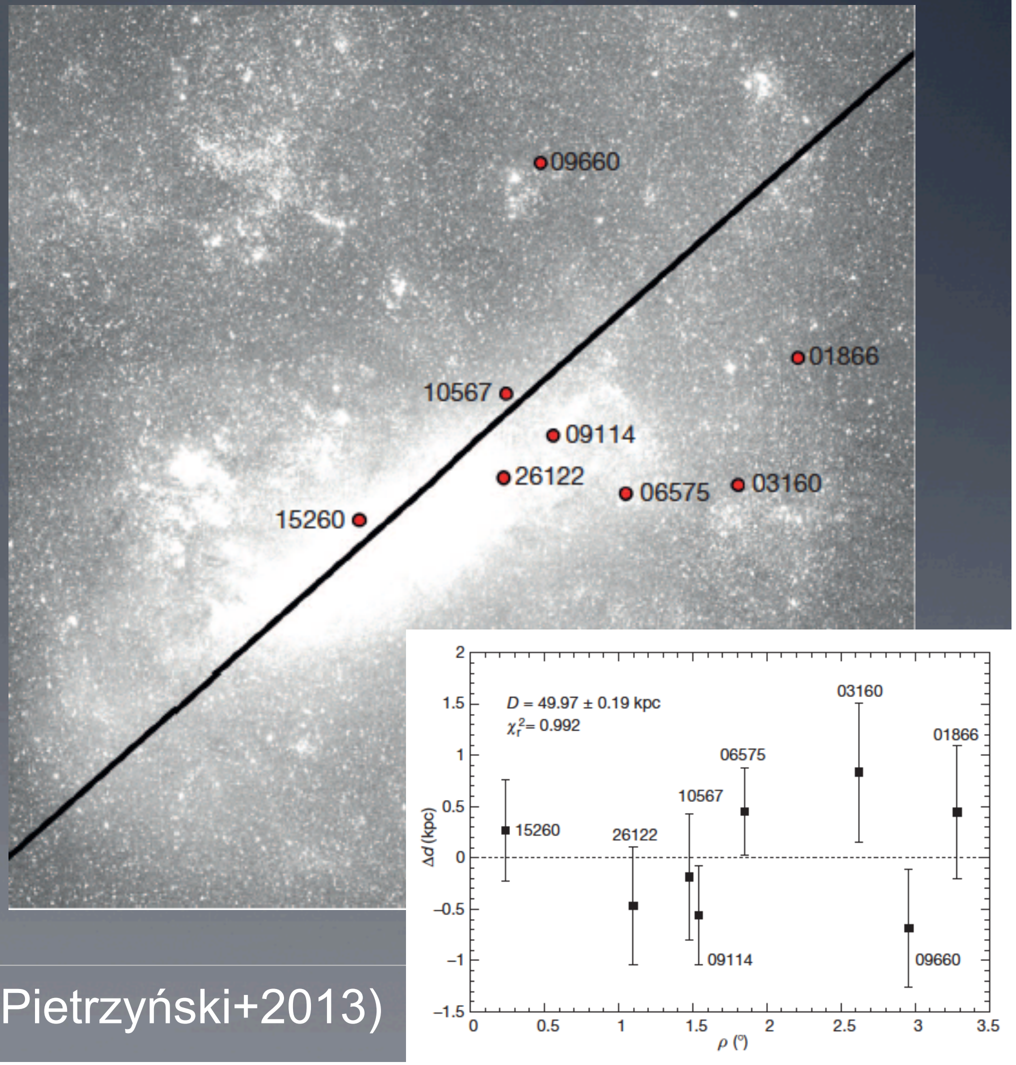
*Based on CTIO data

(Meschin+2014)

Distance to the LMC*

Eclipsing binary systems.
Cool giants.

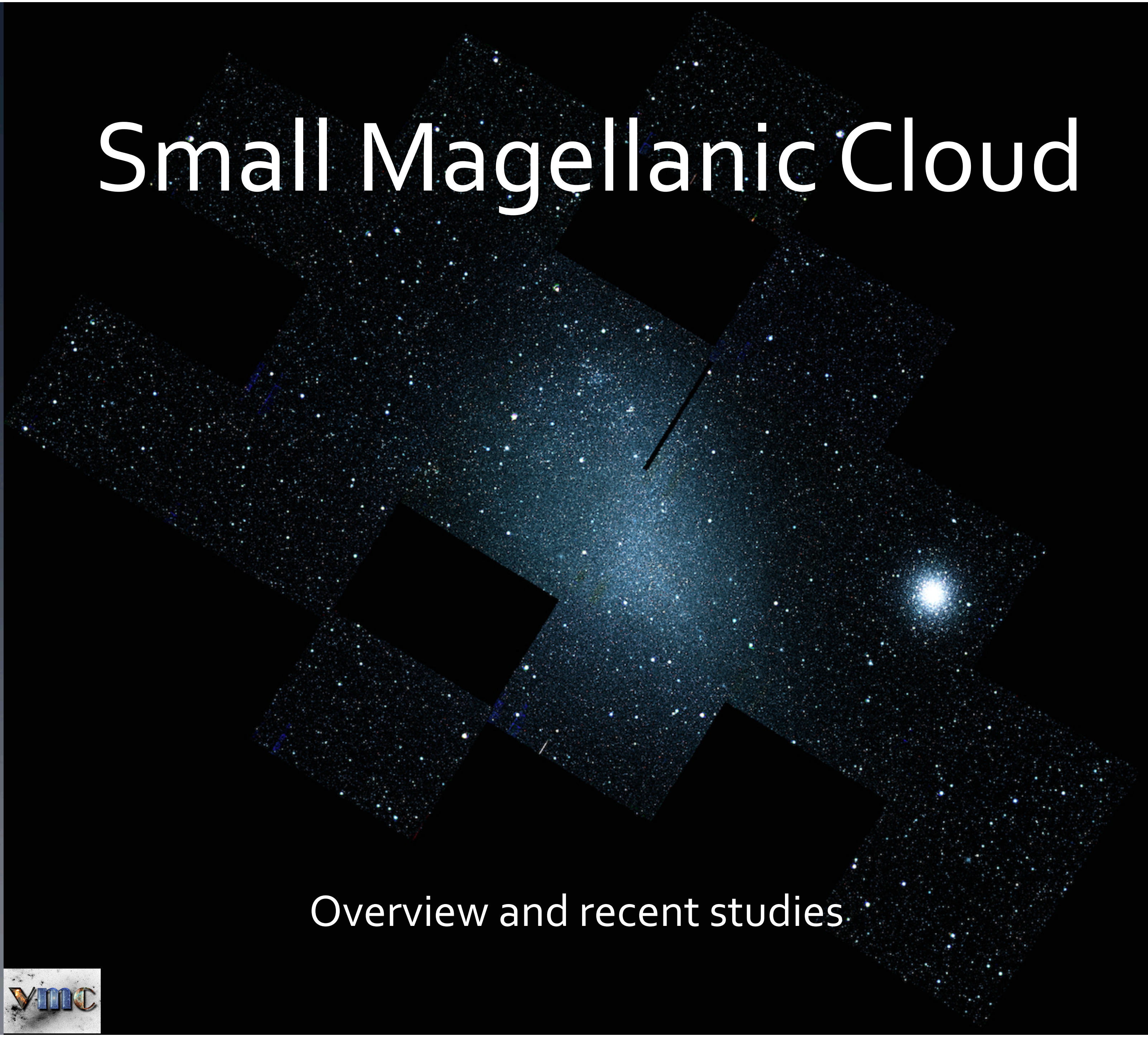




* Based also on HARPS data

(Pietrzyński+2013)

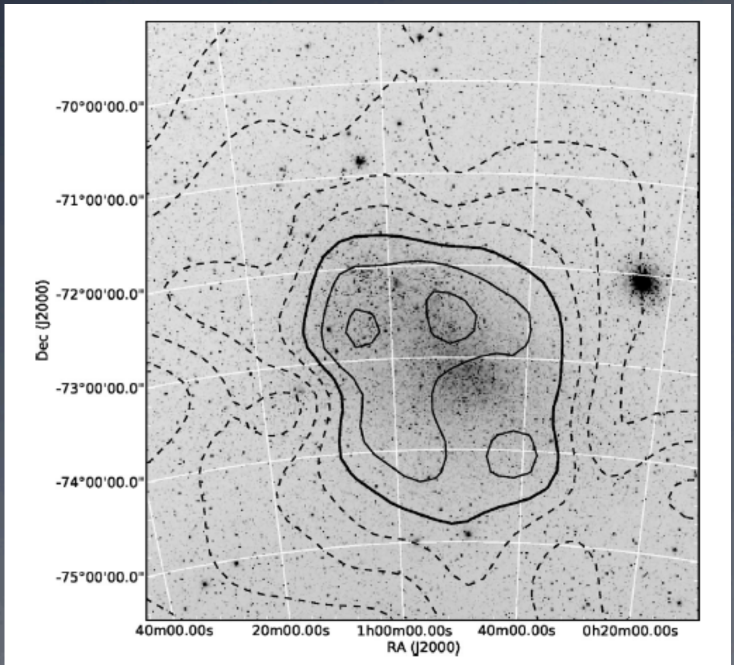
Small Magellanic Cloud

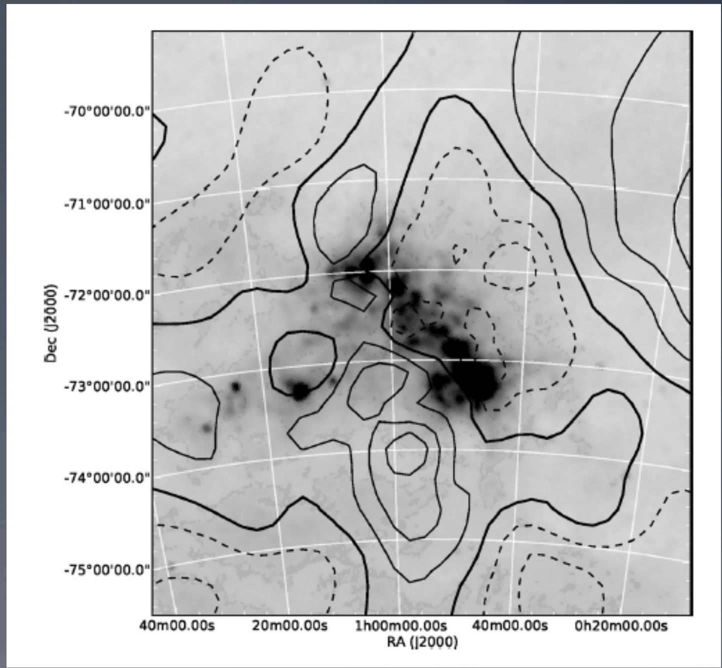


Overview and recent studies

SMC RGB metallicity & velocity*

3000 upper RGB stars with Ca II triplet observation





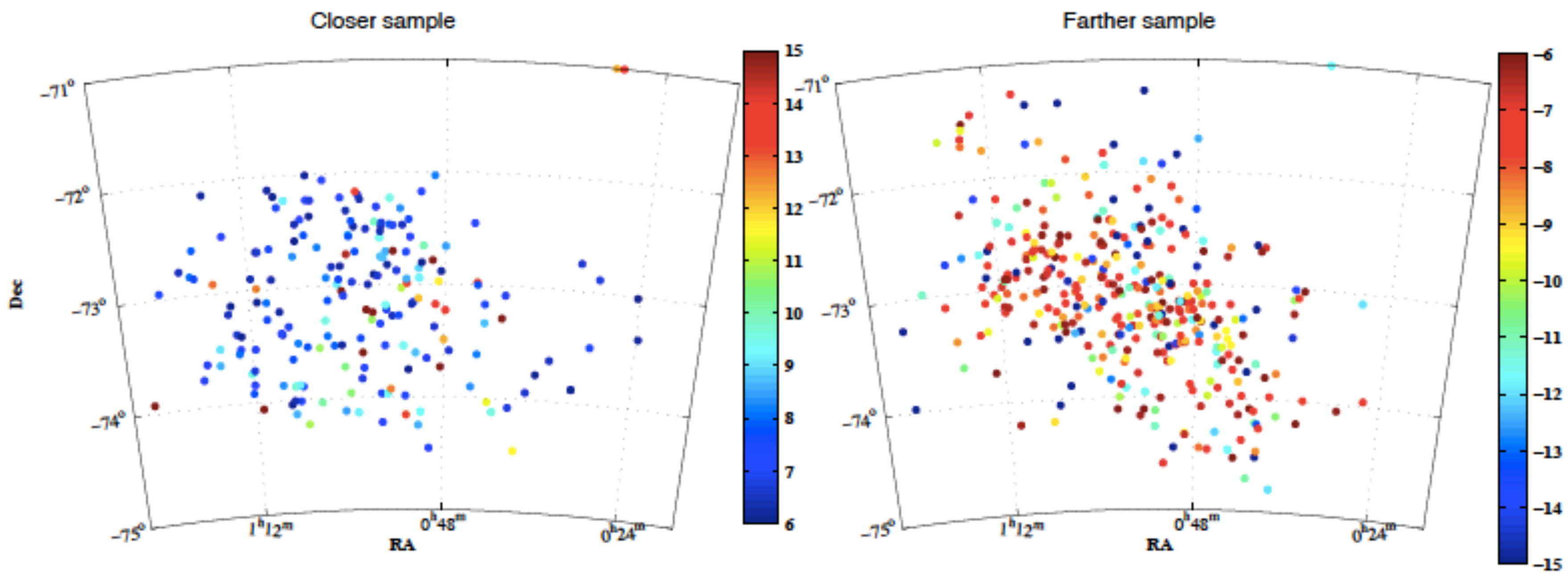
Metallicity gradient.
Metal rich stars are < 6 Gyr old.
LMC interaction 5-6 Gyr.

Velocity gradient at 120 deg PA.
Inconsistent with HI at 60 deg PA.
Outer tidal structures.

*Based on AAT data

(Dobbie+2014, I & II)

Depth of the SMC from Cepheids*

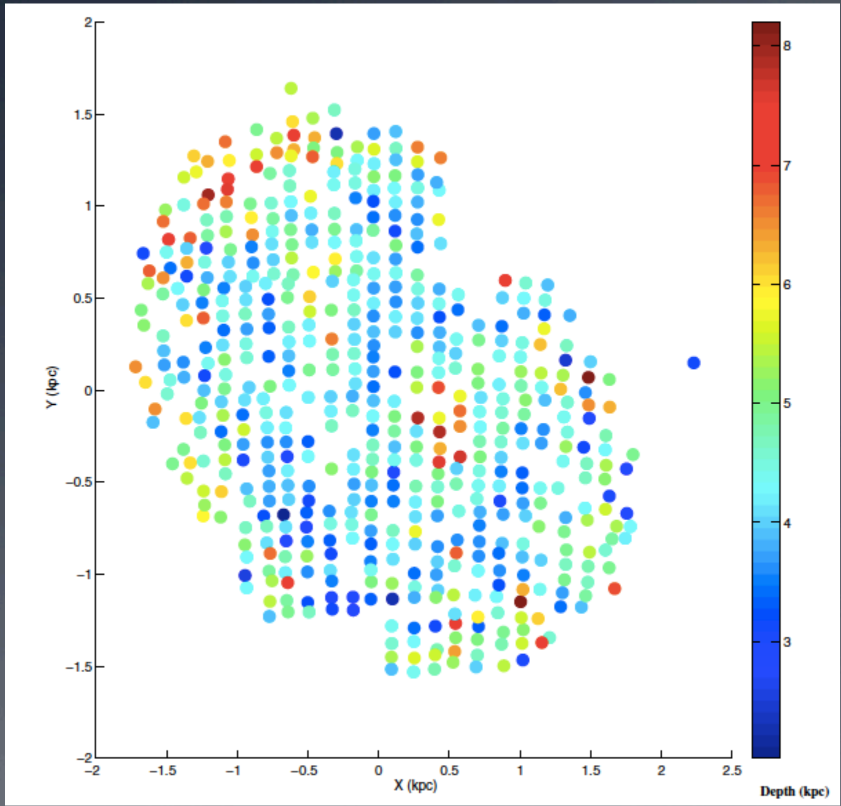


Some closer-by Cepheids may result from the stripping of the gas into the Bridge following an interaction with the LMC that occurred about 200 Myr ago. Cepheids behind the SMC may belong to the counter-Bridge sub-structure.

* Based on OGLE III data

(Subramanian & Subramaniam 2014)

SMC structure from RC stars*



Red clump stars (a few Gyr old).

Map of depth along the line-of-sight.

Spheroidal distribution.

Only a few deg of inclination.

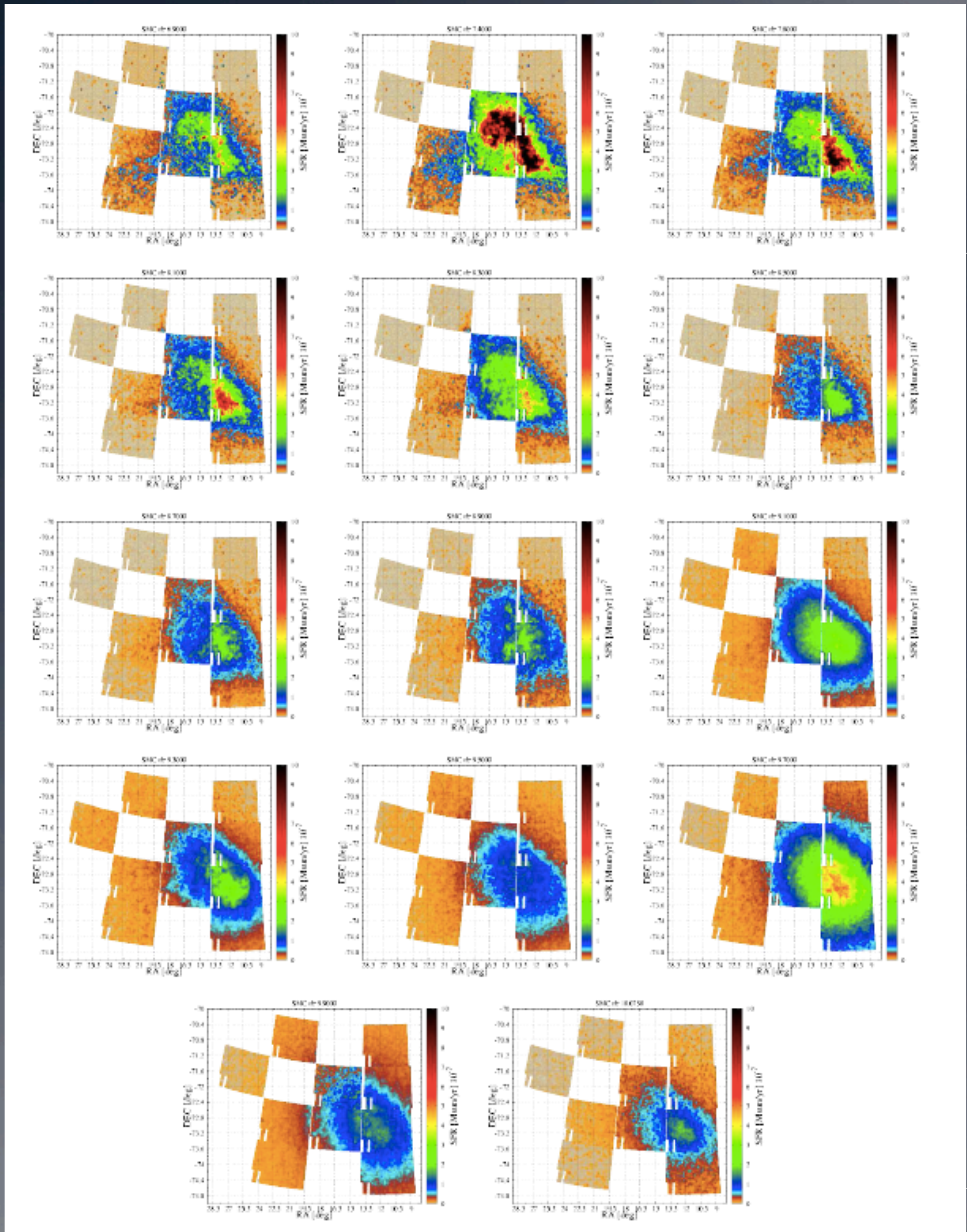
Position angle of 70 deg.

Parameters depend on area covered.

RR Lyrae stars show a similar result.

* Based on OGLE III data

(Subramanian & Subramaniam 2012)



SMC SFH*

The most detailed SFR map to date (area and resolution)!

SFR has been modest at ages < 5 Gyr (0.15 $M_{\odot}$ yr^{-1}).

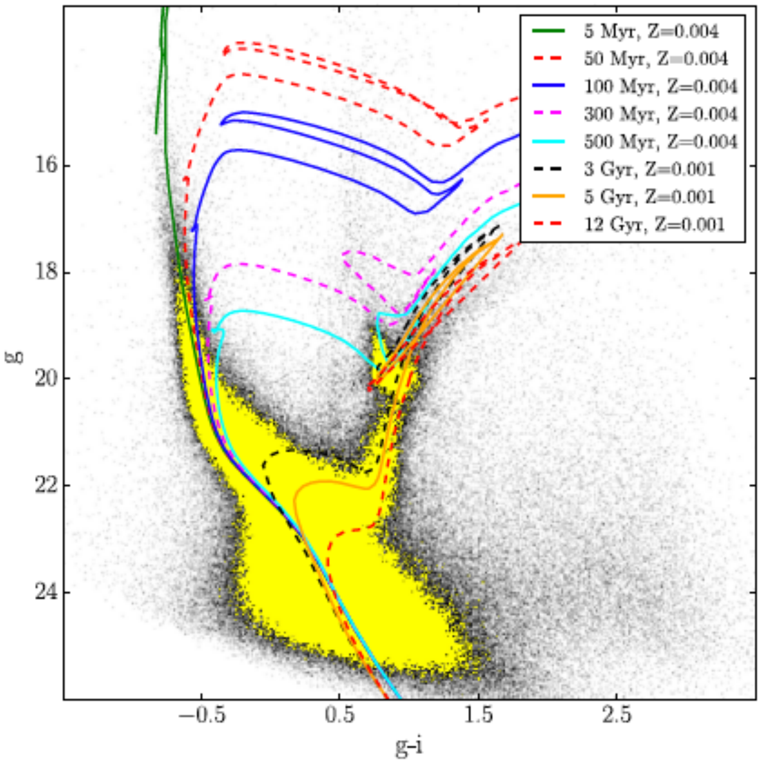
Another peak at 1.5 Gyr agrees with a peak in star cluster and LMC history.

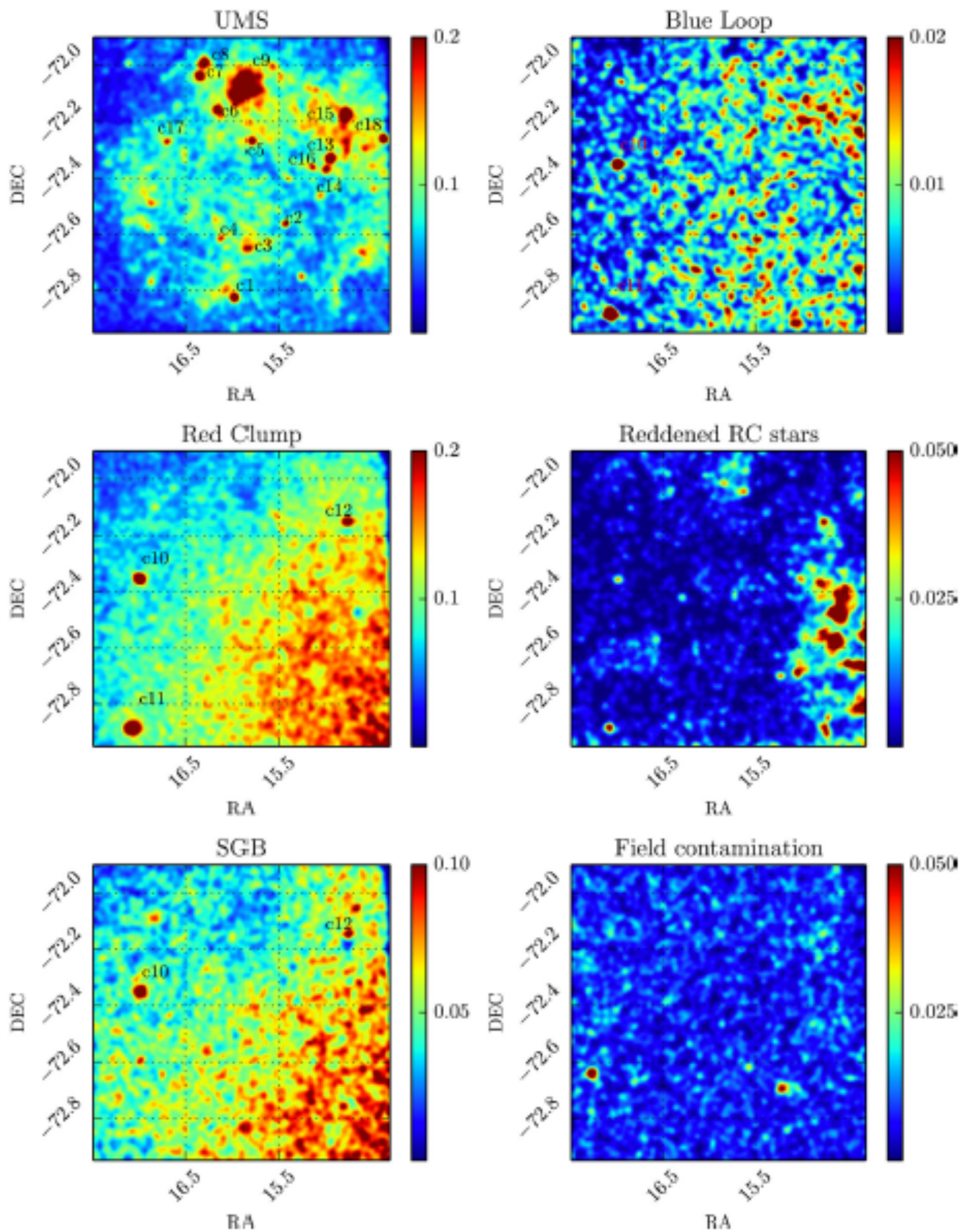
Younger SF is happening in the centre and to the East.

* Based on VISTA data

(Rubele+2014, sub.)

SMC SFH*





* Based on VST data

(Ripepi+2014)

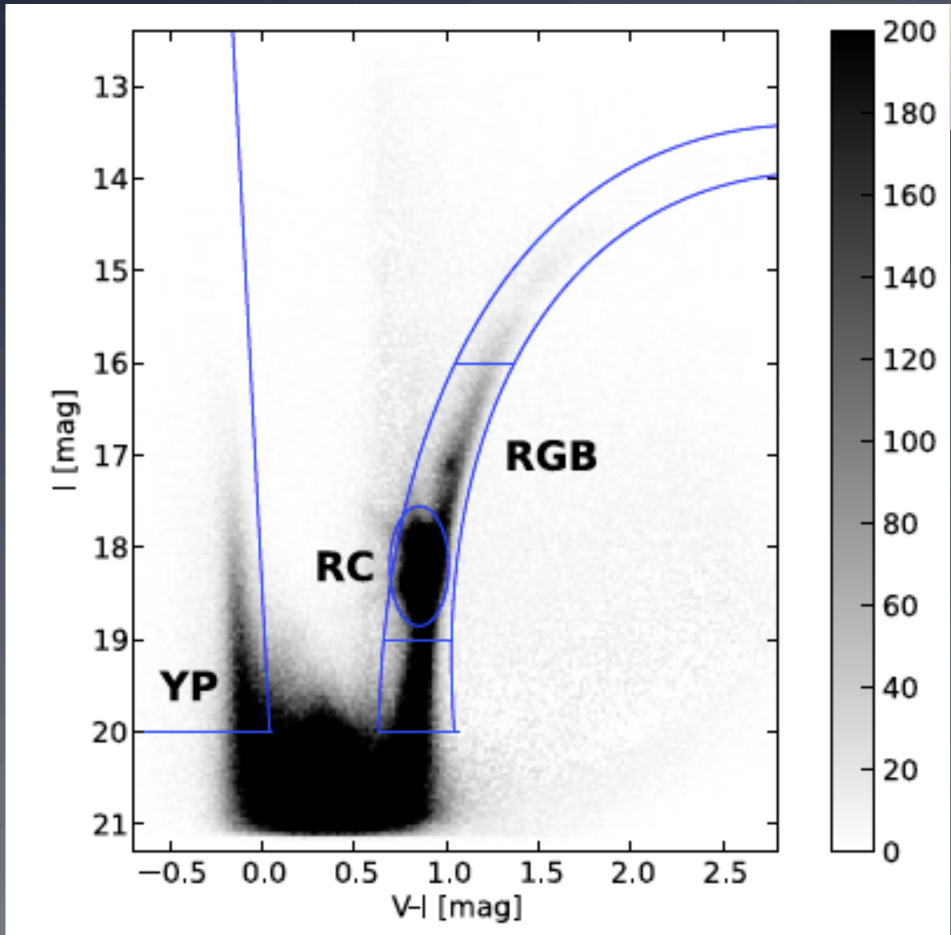
The Magellanic Bridge

Overview and recent studies

Bridge overview

- The Magellanic Bridge is about 200 Myr old. Supported by LMC/SMC orbit, and simulations (Besla+2012; Diaz & Bekki 2012).
- It probably resulted from the collision of the LMC with the SMC.
- It is mostly formed by SMC material.
- It contains HI gas and some young stars (e.g. Mathewson & Ford 1984, Irwin+1985).
- There may be older stars (Bagheri+2013; Nöel+2013) probably stripped from the Clouds.
- Next to the SMC the distribution of red clump stars bifurcates. The closest component is the stellar counterpart of the Bridge (Nidever+2013).

Bridge stellar population



OGLE

Part IV

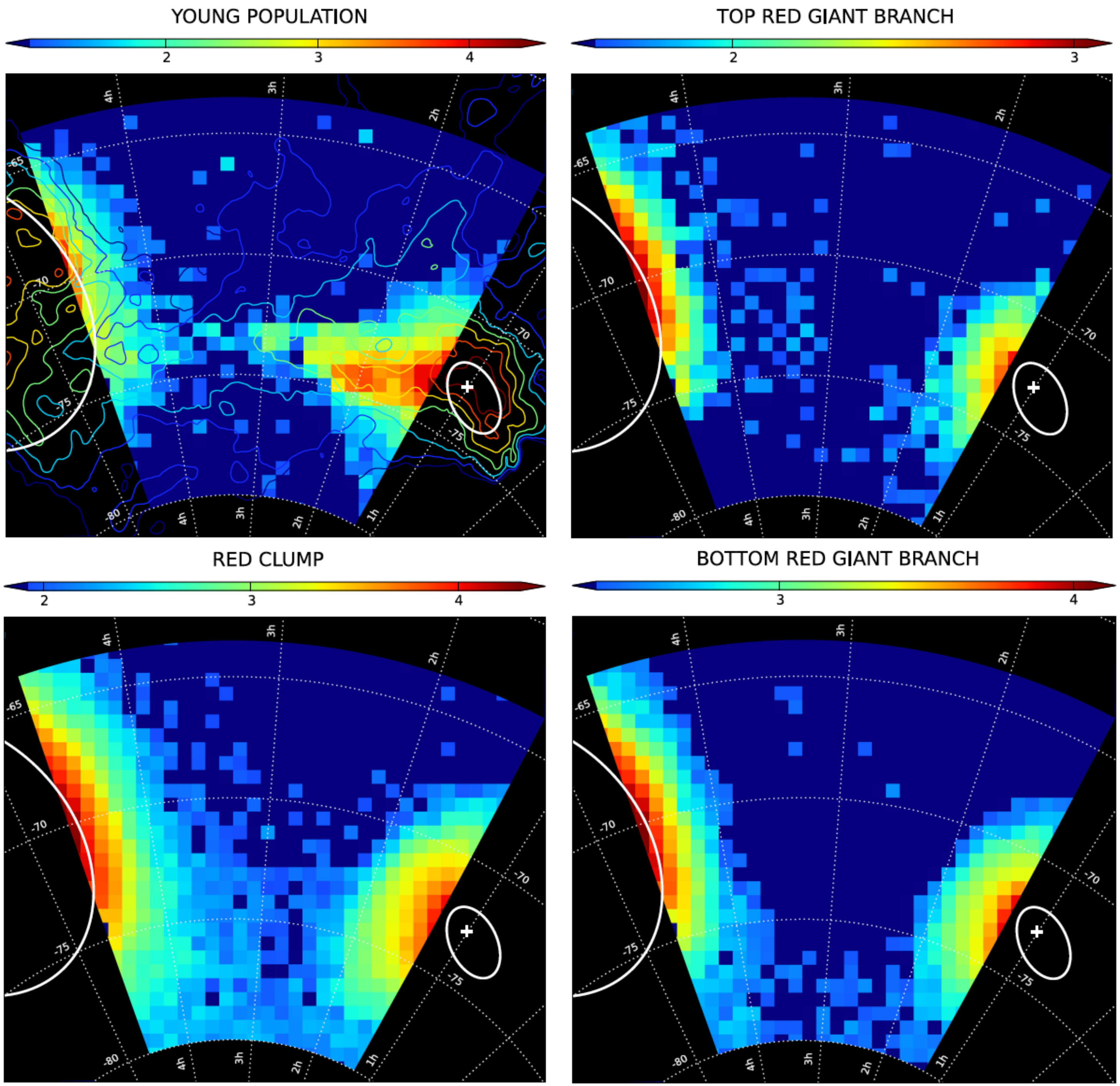
A vertically elongated red clump indicates a large line-of-sight depth.

Age effects are not supported by corresponding main sequence stars.

(Skowron+2014)

OGLE

Part IV



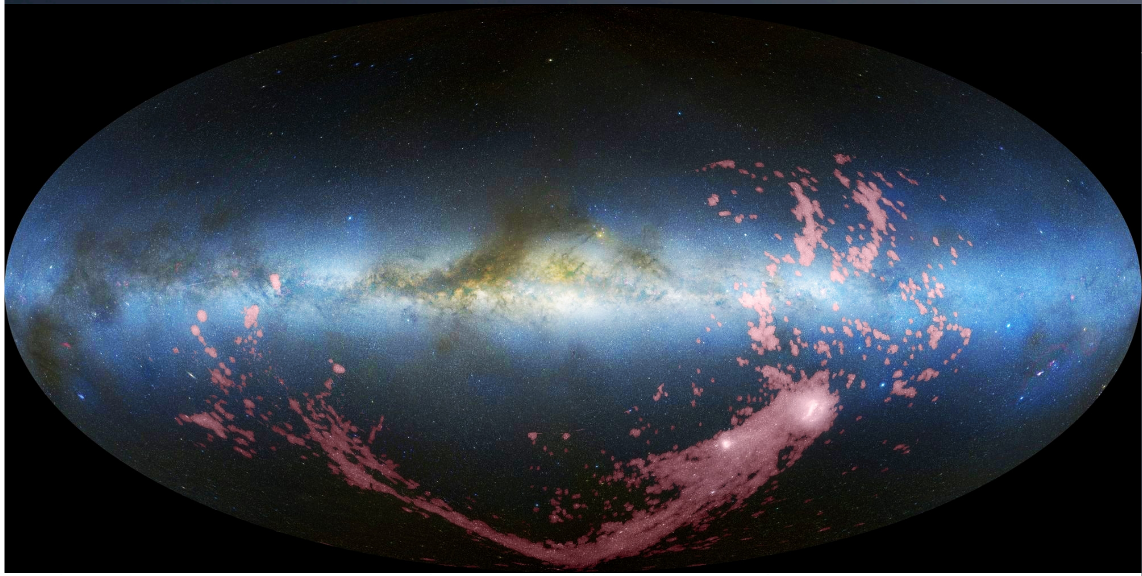
Bridge stellar distribution

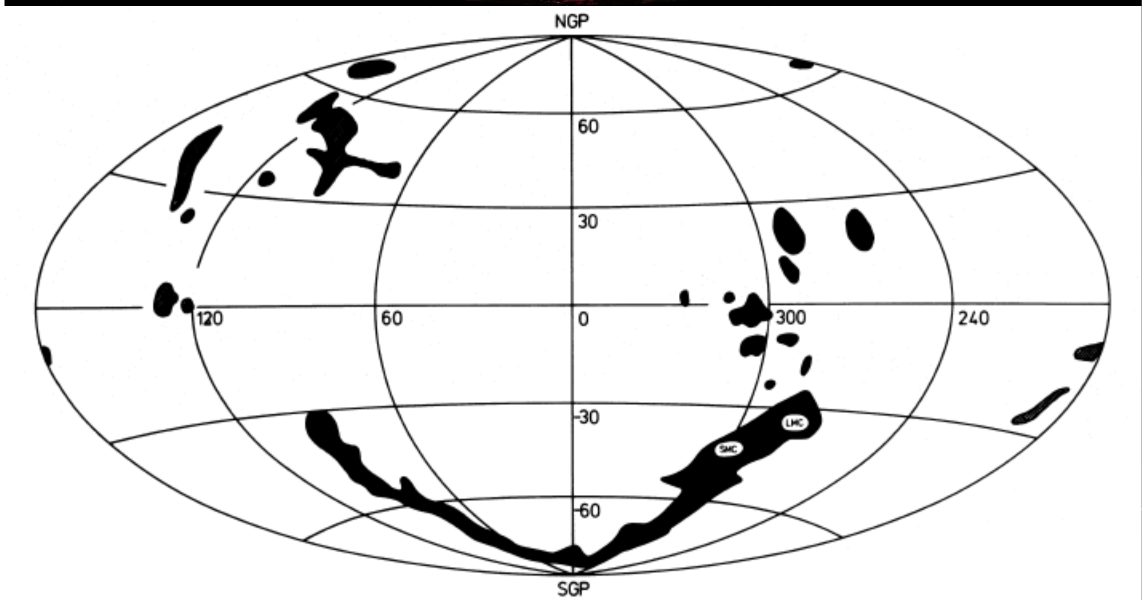
(Skowron+2014)

The Magellanic Stream

Overview and recent studies

The Magellanic Stream





(Nidever+2010)

The Stream was discovered as a 100 deg long structure.

Today, including the leading arm, it covers ~200 deg and reaches the Milky Way plane twice.

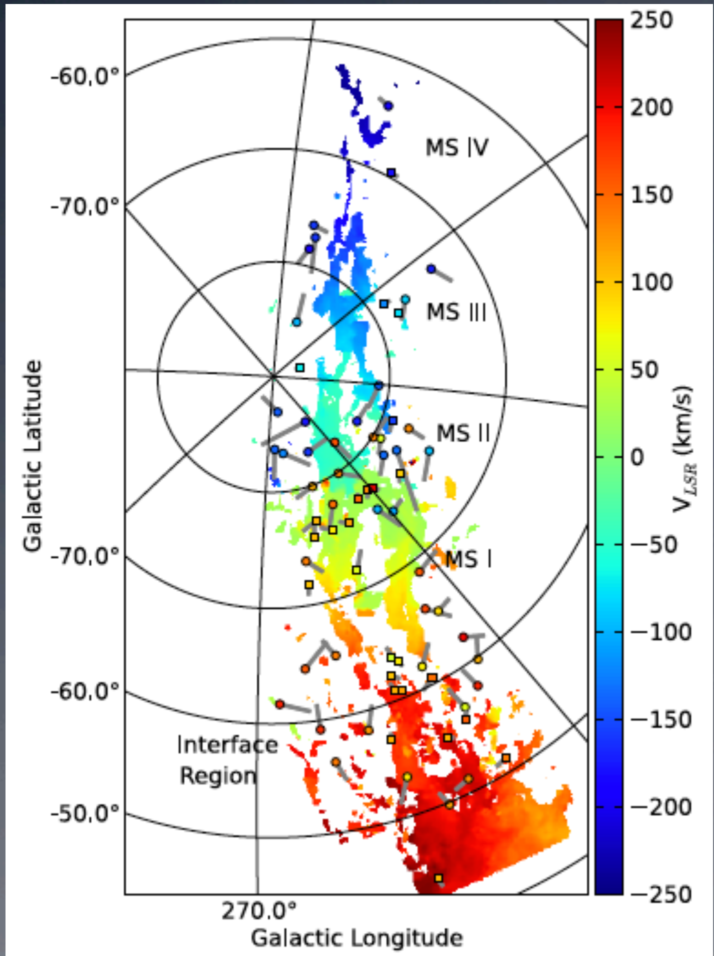
Most of the Stream formed from the SMC as supported by metallicity measurements.

(Mathewson+1974)

Open questions

- What is the origin of the Magellanic Stream?
  - Ram pressure stripping (e.g. Murai & Fujimoto 1980): bifurcation, HI fragmentation.
  - Tidal interaction (e.g. Besla+2012): large extent, leading arm.
  - Both (e.g. Mastropietro+2005): but MW+LMC only.
  - High-redshift tidal interaction (Peebles & Tully 2013): MW+LMC
- Are there stars associated to the Magellanic Stream?
  - Star formation in the Leading Arm (Casetti-Dinescu+2014)

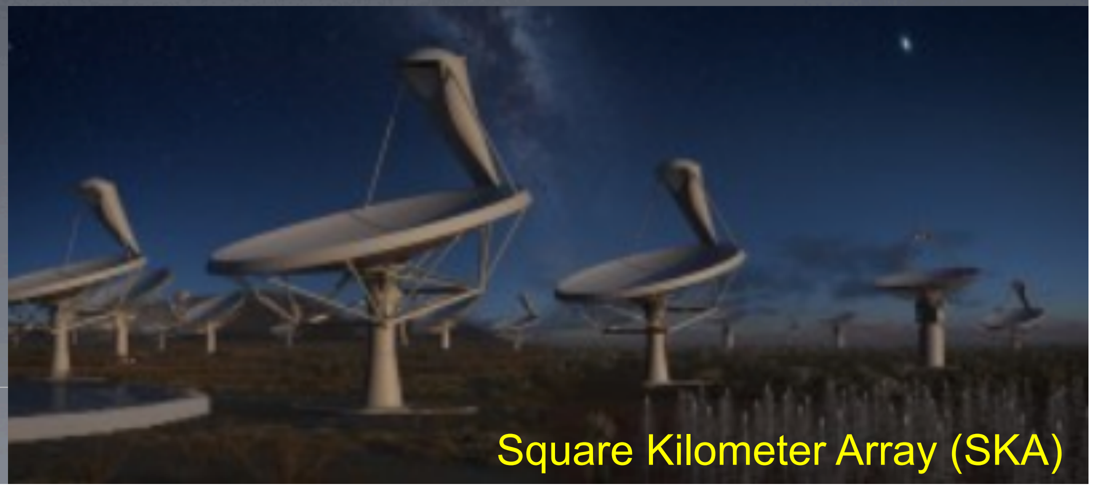
Recent and future observations



(For+2014)

The Stream has a complex filamentary structure. Head-tail clouds suggest turbulence (GASS +ATCA surveys – 15-30 arcmin spatial resolution).

SKA (operational in 2020) will provide an unprecedented view of the MC and of the Stream at arcsec resolutions.



Observations:

On-going & future surveys

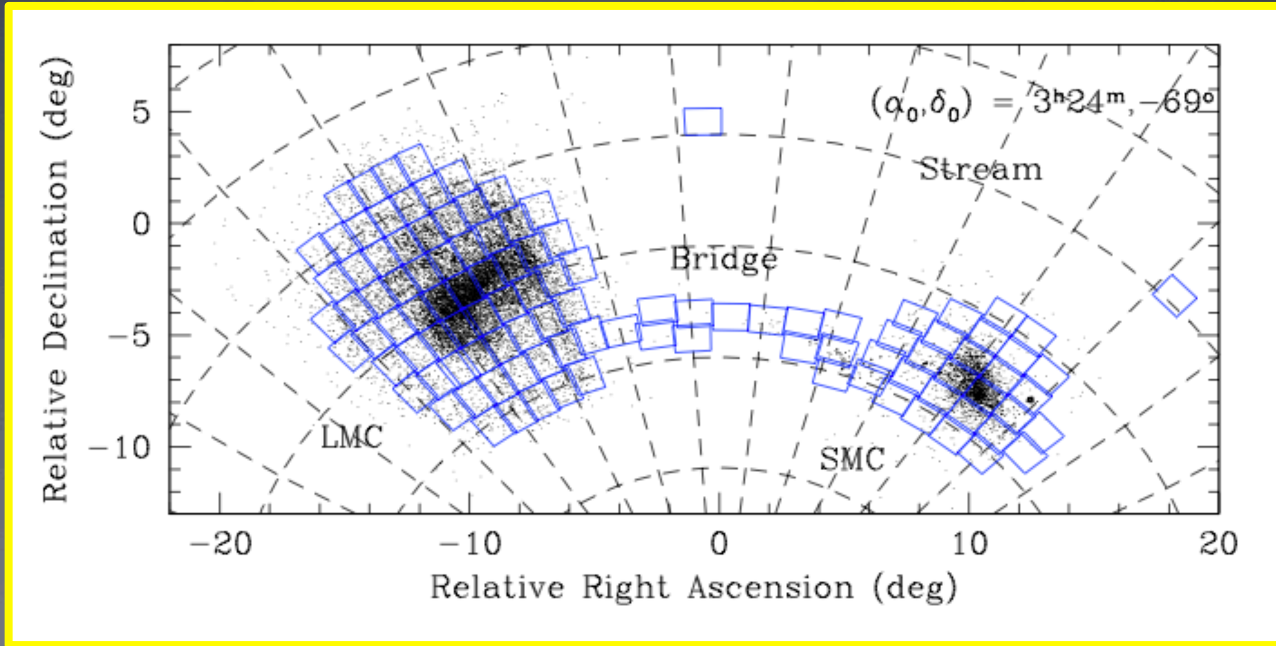
The VMC survey

PI Cioni

- 170 deg²
- 1900ʰ
- YJKs ~ 22 mag
- 12 Ks epochs
- 2009-2018
- >60% complete

13 refereed papers published, 2 submitted; 150 citations

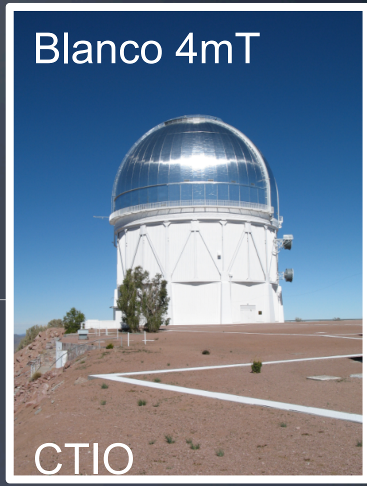
The VISTA survey of the Magellanic Clouds system



http://star.herts.ac.uk/~mcioni/vmc/

(Cioni+2011)

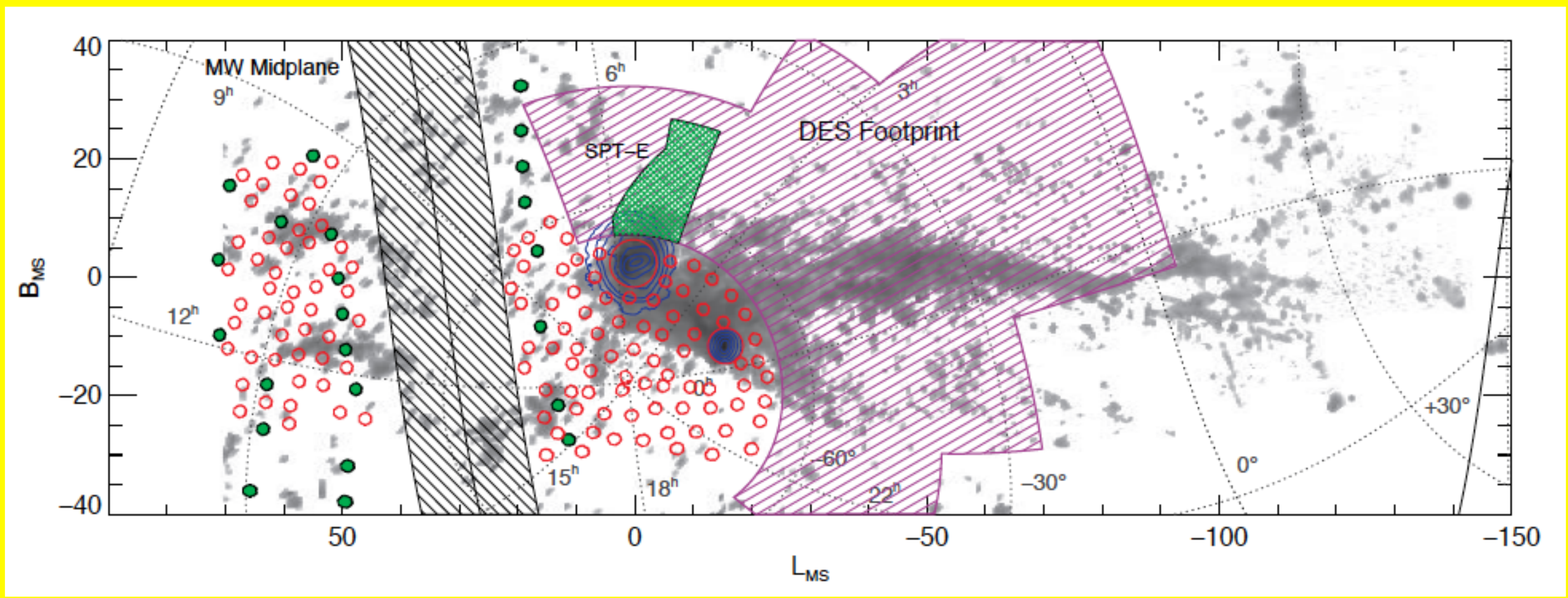
The SMASH survey



- 480 deg²
- 1900ʰ
- uz+gri ~ 24 mag
- 2013-2016

The MCs are larger than expected and have rich field of debris left from their formation and interaction.

PI Nidever

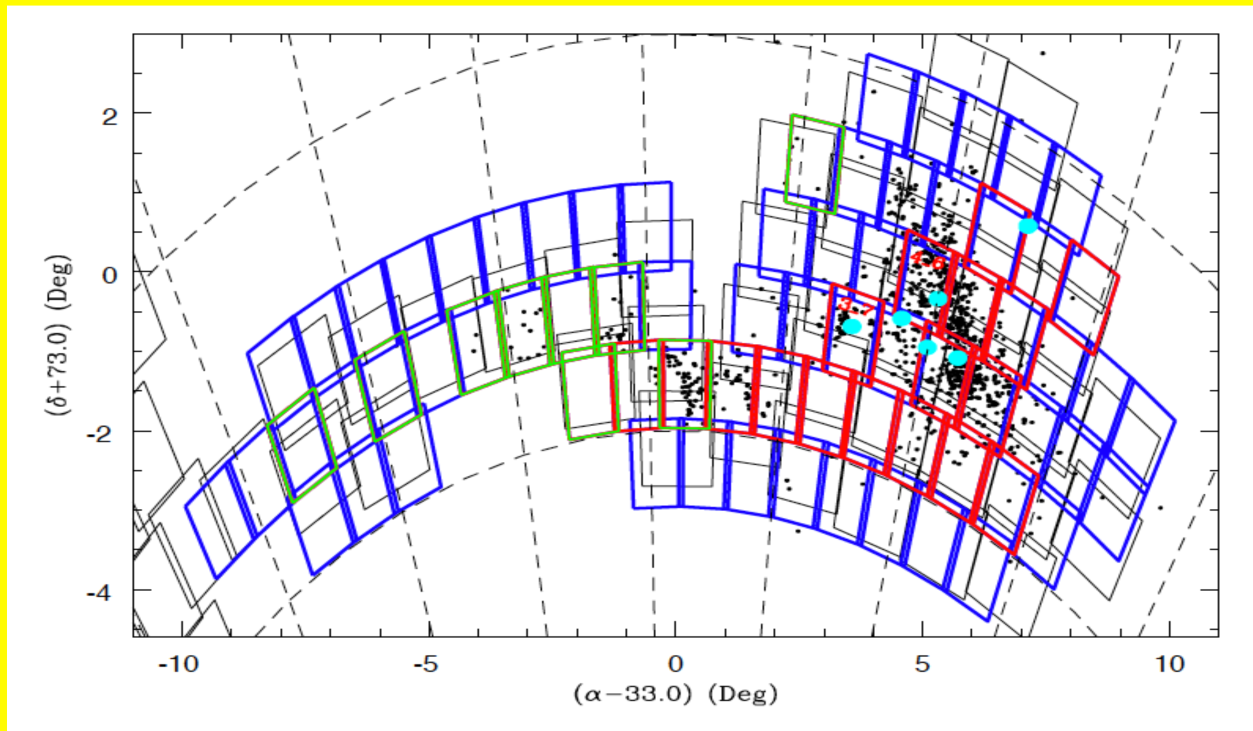


NOAO press release No. 1501

The STEP survey

- 35 deg^2
- gri+Hα ~ 23.5 mag
- 2010+

PI Ripepi



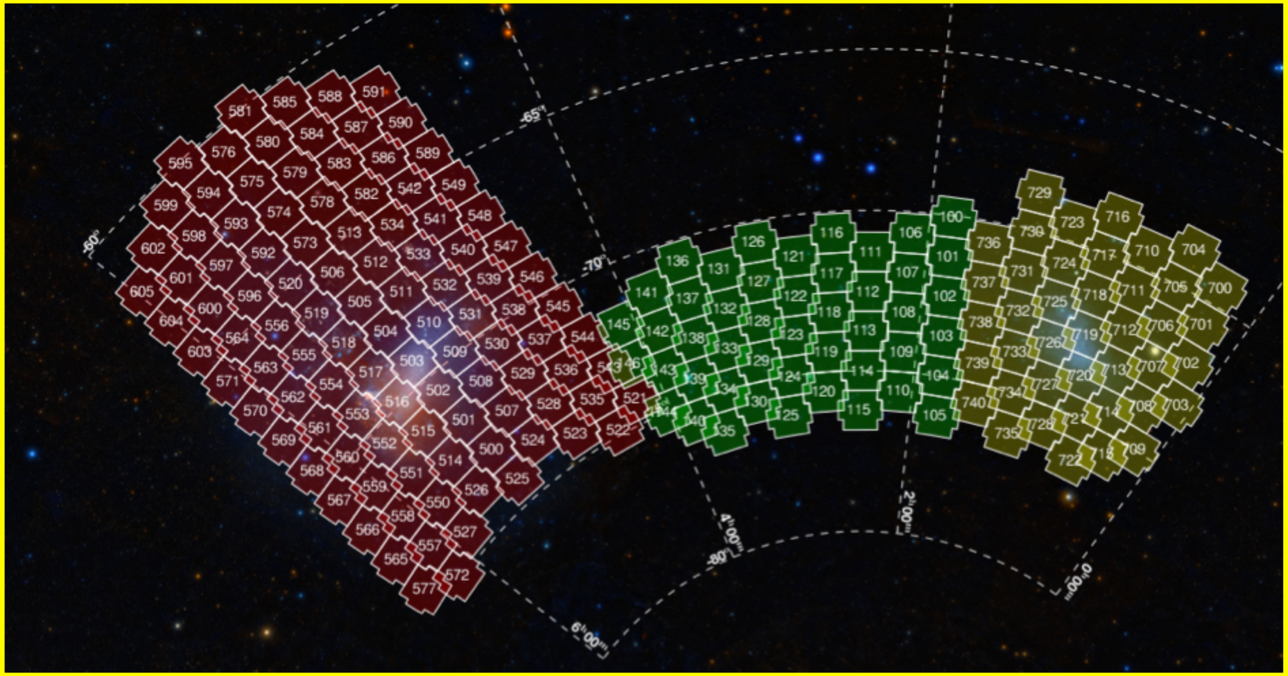
(Ripepi+2014)

The OGLE-IV survey

PI Udalski

OGLE

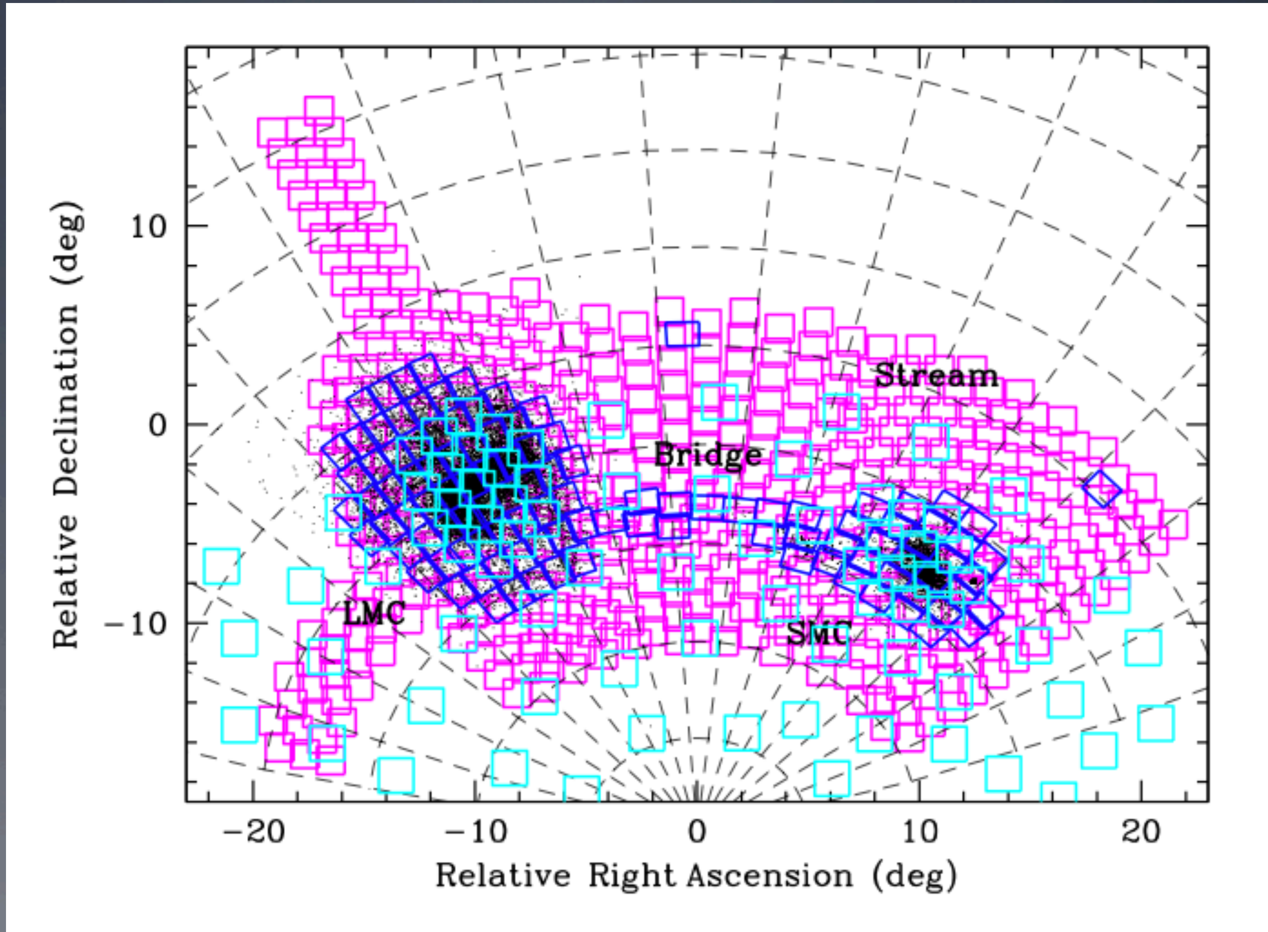
A long-term variability study focused on dense stellar regions.



- 540 deg²
- VI ~ 21/20 mag
- 400 I epochs
- 2010-2014
- completed

Common area coverage: photometry

- OGLE-IV
- SMASH
- VMC
- SMC & Bridge also covered by STEP as VMC



Present and future surveys

Survey	Time scale	Area (deg²)	Repeats	Scale ("/pix)	FWHM (")	Filters	Sensitivity (AB)	S/N
STEP	2011+	35	30 (i)	0.21	0.8-1.0	gi	23.5	7
OGLE-IV	2010-2014	540	~400 (I)	0.26	1.0	VI	21, 20 (Vega)	10
SMASH	2013-2016	480	1	0.27	1.0	uz + gri	24	10, 20
Skymapper	2010+	All	6	0.34	1.5	uvgriz	22-20	5
VMC	2009-2018	160	12 (K_s)	0.34	0.9	YJK_s	22.5-23.4	5
LSST	2021-2031	δ<+34	56-184	0.2	0.8	ugrizy	22-27.5	5
Gaia	2013-2018	All	70	<<0.2	-	G band	20 (Vega)	>10
Euclid	2020-2026	|b|<30*	1	0.1, 0.3	-	Vis, YJH	24	5

All of these surveys provide targets for spectroscopic follow-up studies.

Spectroscopy

- The number of stars with moderate resolution spectra observed is about 3000 (SMC) and 6000 (LMC).
- These cover only a limited number of stellar types and area. Provide only radial velocity and indirect [Fe/H].
- Other chemical elements are measure on considerably smaller samples.

- The 2020s envisage a spectroscopic revolution for investigations of the Magellanic system with multiplex facilities 4MOST (at VISTA) and MOONs (at VLT).