Dr Maria-Rosa Cioni

The status of the VMC survey and the Proper Motions of the Magellanic Clouds

Bologna, 2nd May 2013

Introduction

- The Magellanic Clouds (MCs) are the largest and most luminous dwarf irregular galaxies of the Milky Way (MW)
- The MCs are the closest (50-60 kpc) example of interacting galaxies contributing to the enrichment of the MW halo
- Open questions:
  - Are the MCs bound to each other and since how long? Are there distinguishable tidal features?
  - Are the MCs truly approaching the MW for the first time?
  - What is the mass of the MCs and their internal kinematics?
  - What is the link between dynamical processes, structure and star forming events?

NGC4449a-b

- A Magellanic type Irr with mass ~ LMC mass) at 3.8 Mpc
- The dwarf companion was discovered in deep images by Rich et al. (Nature 2012)
- The companion is being tidally disrupted.
- The system is engulfed in HI.
- There is also DDO125 at ~40 kpc.

The frequency of MC galaxies around MW type ones is only a few% (e.g. Robotham et al. 2011)

Presentation Layout

- The VISTA survey of the Magellanic Clouds system (VMC) – the most sensitive survey of the Magellanic Clouds in the near-IR and with the best spatial resolution to date
  - Characteristics
  - Status of observations
  - Highlights of first results
- The proper motion of the Magellanic Clouds
  - Previous studies
  - Recent HST results
  - VMC contribution

15 institutes worldwide

VMC team

Core: Cioni (PI), Bekki, Clementini, Emerson, Evans, de Grijs, Gibson, Girardi, Groenewegen, Ivanov, Marconi, Miszalski, Moore, Napiwotzki, Oliveira, Ripepi, van Loon, Wilkinson, Wood

Associates: Haberl, Marquette, Piatti, Rubele, Smart, Zaggia

Postdocs: Anders, Guandalini, For, Subramanian

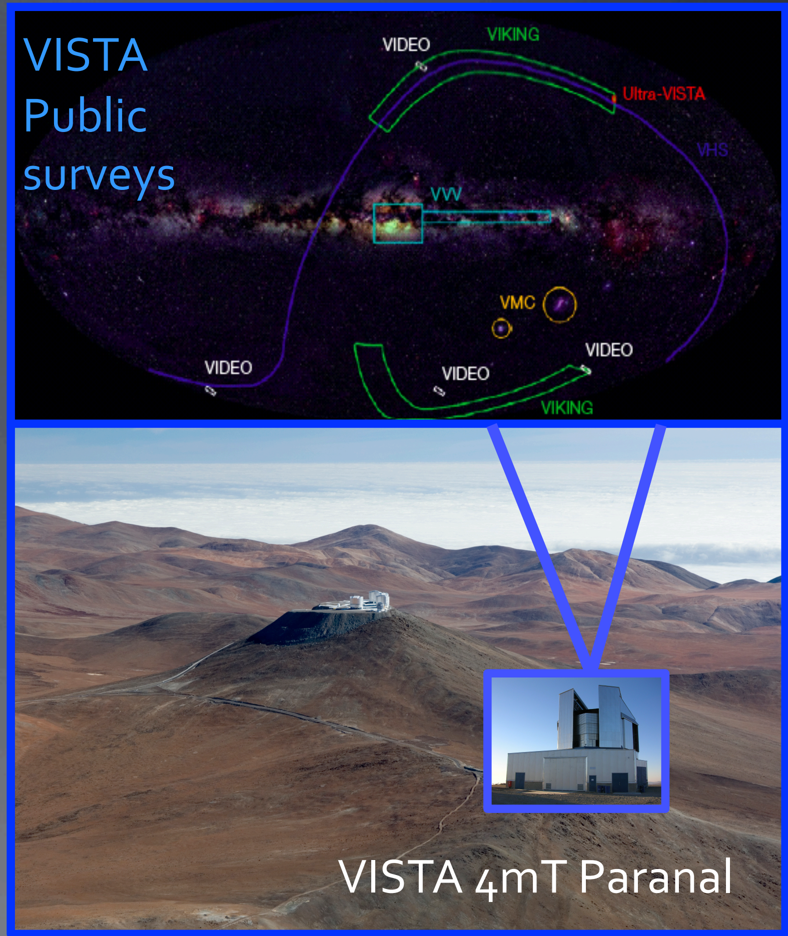
Students: Bagheri, Kasmath, Moretti, Muraveva, Romita, Tatton

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

>36% complete

VMC survey

- Filters: Y, J, K_s
- Camera: 16 Rayethon detectors
- Sampling: 0.34"/pix
- FOV: 1.65 deg^2
- Area: 218 deg^2
- Sensitivity: YJK_s~22 (5σ Vega)
- Saturation: K_s~10
- Epochs: 3 (YJ) + 12 (K_s)
- Time-scale: 2009-2018

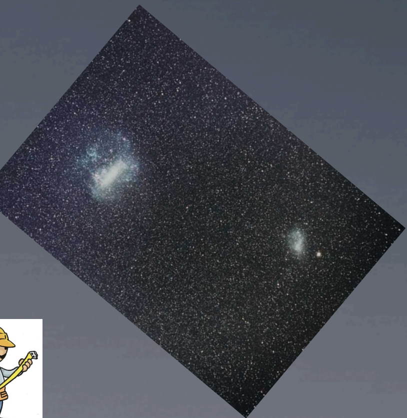


Cioni et al., A&A, 2011, 527, A116

VMC main science

- Spatially resolved star formation history
  - By reaching stars below the old main-sequence turnoff
  - By interpreting colour-magnitude diagrams with models

- 3D geometry
  - Using Cepheids and RR Lyrae stars
  - Using red clump giant stars

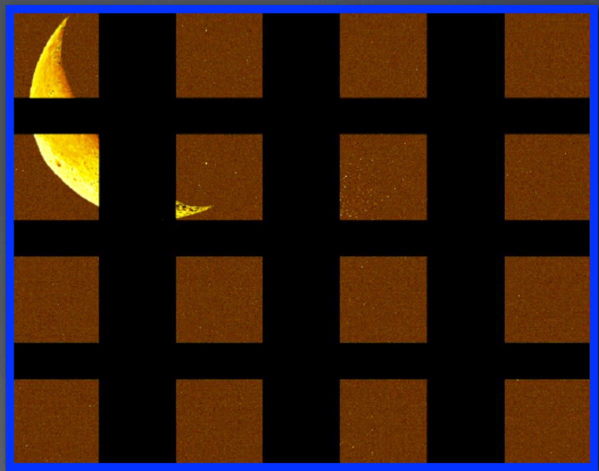


The depth of the LMC is a few kpc (0.2 mag)
and that of the SMC up to 20 kpc (0.7 mag)

VMC legacy science

- Milky Way
- Star formation
- Individual stars
- Stellar clusters
- System dynamics
- Quasars

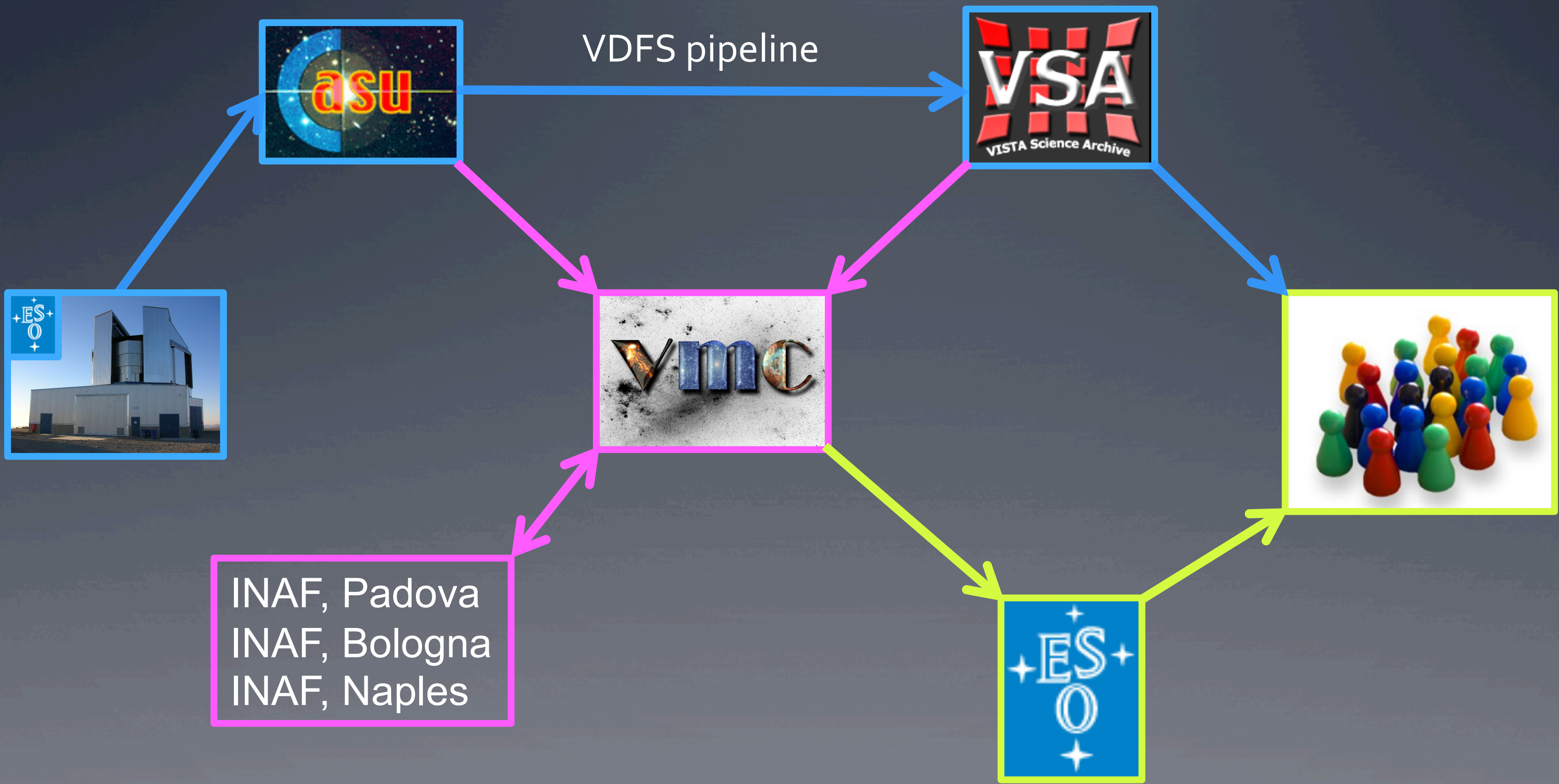
VISTA field of view



Average quality of VMC individual epochs

Filter	FWHM	Ellipticity	Zero-Point	Mag. Limit
Y	0.96 (0.12)	0.06 (0.01)	23.17 (0.22)	19.96 (0.85)
J	0.95 (0.11)	0.06 (0.01)	23.26 (0.33)	19.82 (0.66)
Ks	0.93 (0.10)	0.06 (0.01)	23.04 (0.11)	19.31 (0.26)

VMC data path



VMC Images


LMC 5_5


SMC 5_4


LMC 4_6


LMC 3_5


LMC 9_7


LMC 6_8


Bridge 3_5


LMC 6_4

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

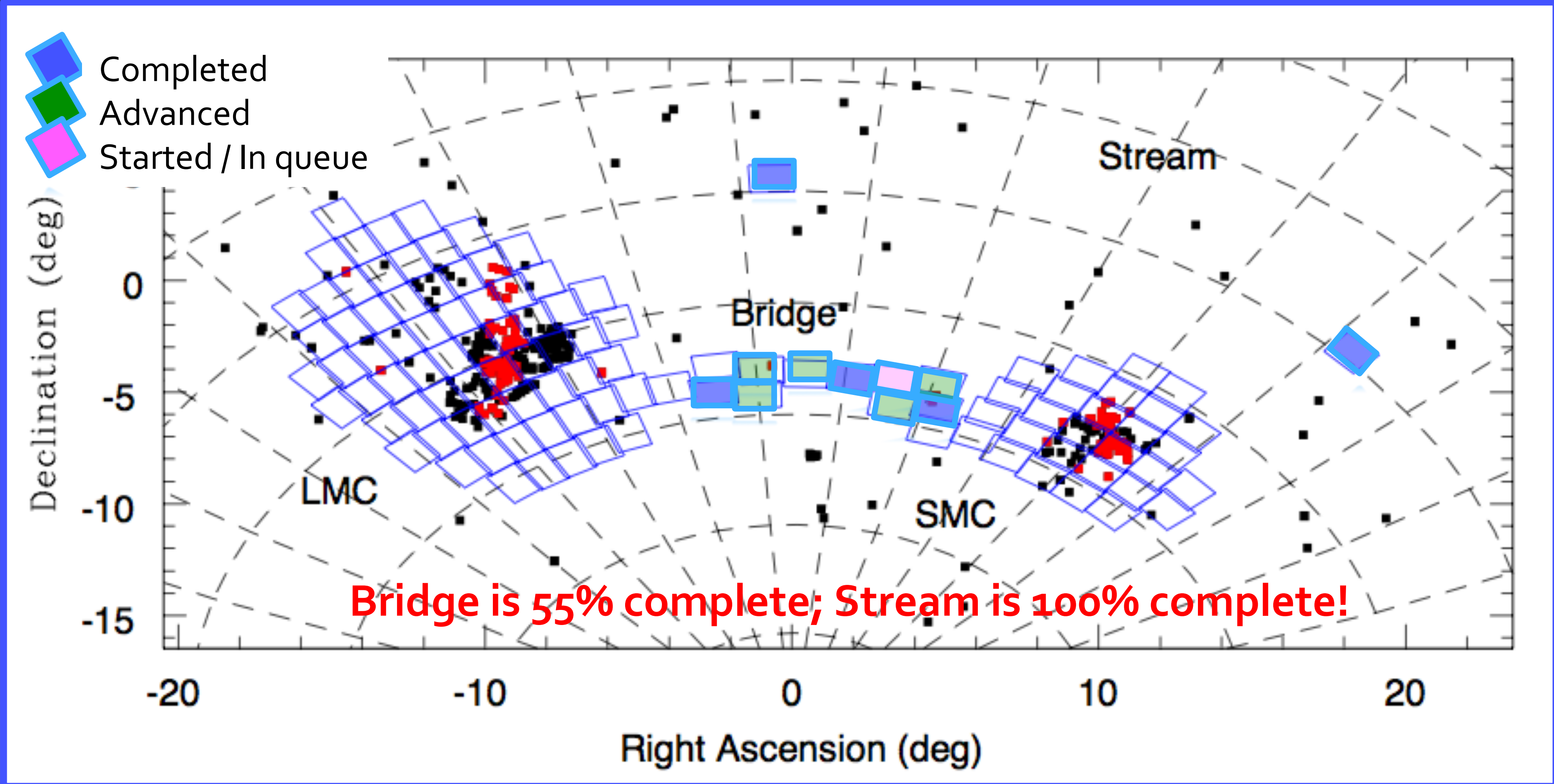
VMC images

In the LMC bar

Spiral galaxy

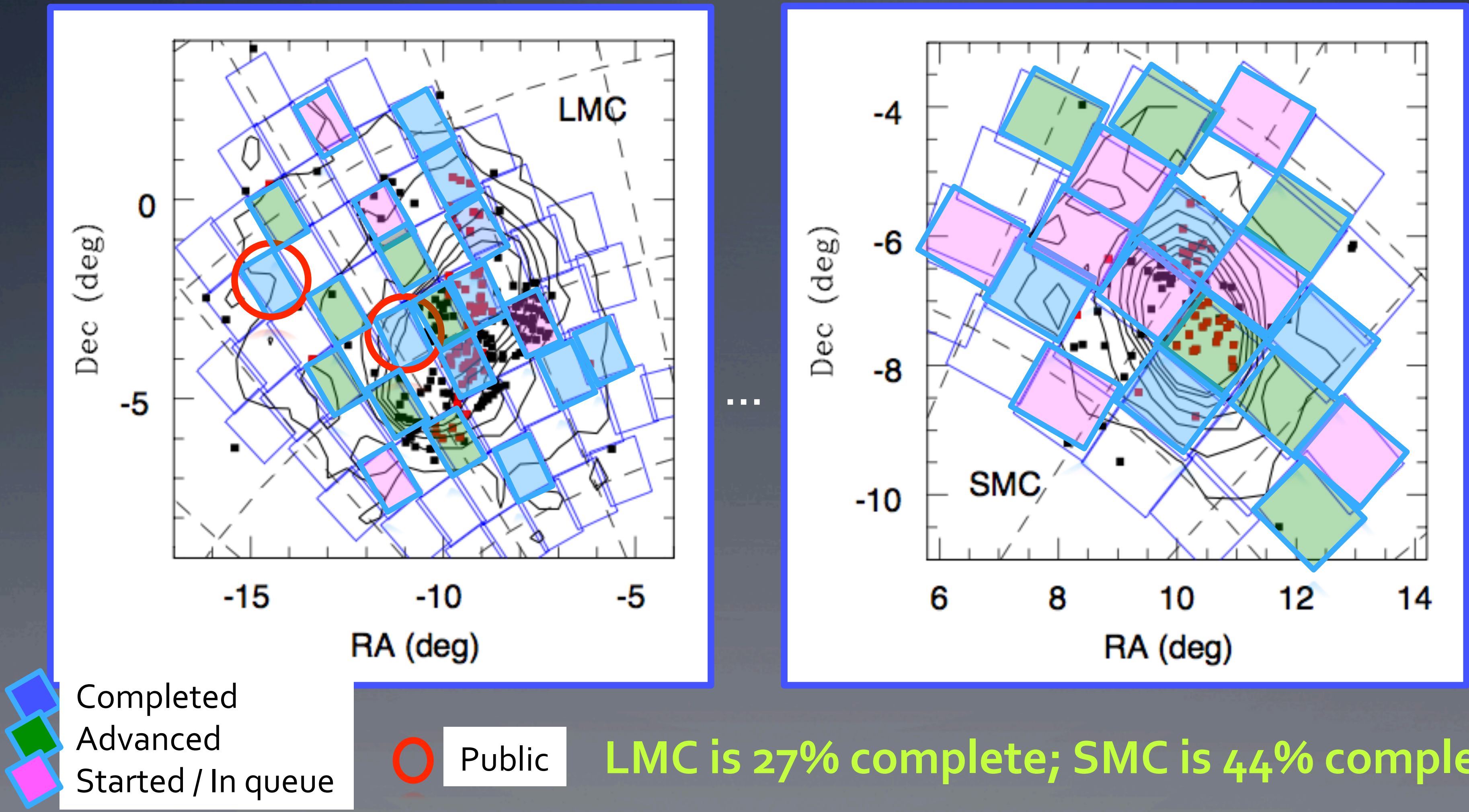
http://star.herts.ac.uk/~mcioni/vmc

VMC survey progress Bridge & Stream



Advanced = all YJ and at least 6 K_s epochs have been observed.

VMC survey progress
LMC & SMC



LMC is 27% complete; SMC is 44% complete!

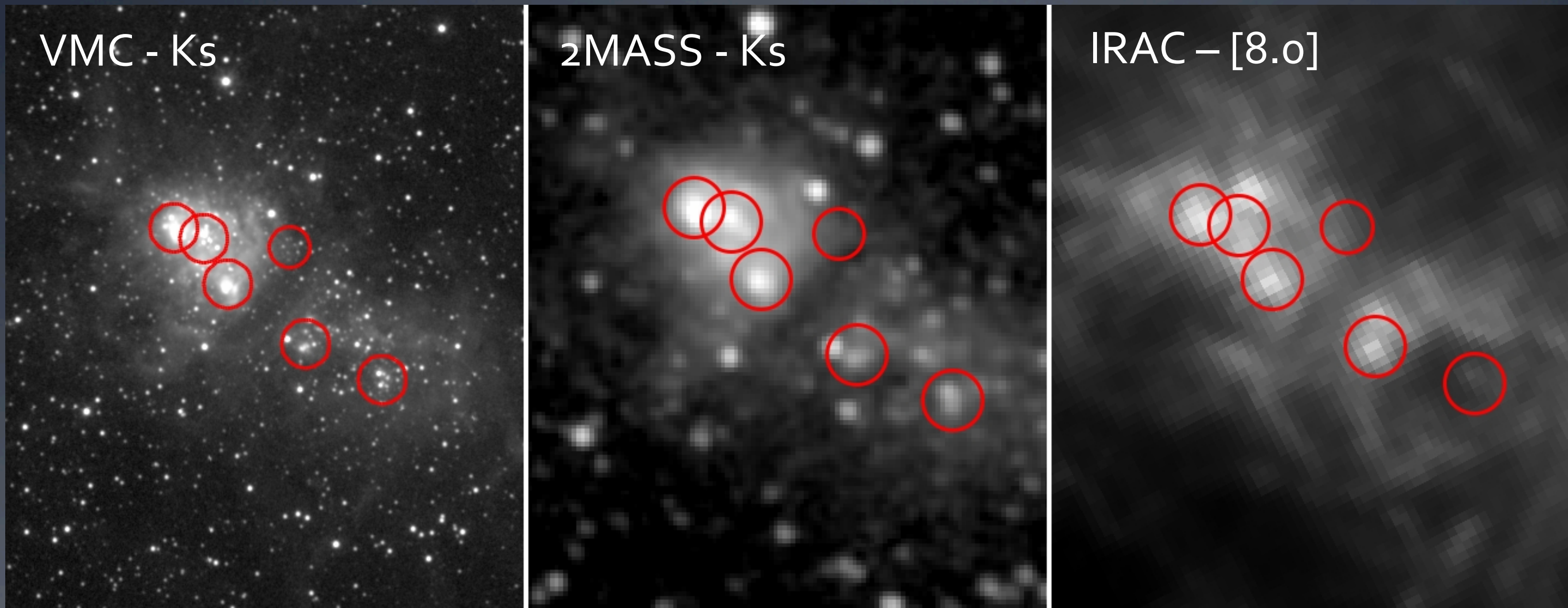
Advanced = all YJ and at least 6 K_s epochs have been observed.

Publications

- The VMC survey - I. Strategy and first data (Cioni et al. 2011)
- The VMC survey – II. Planetary Nebulae (Miszalski et al. 2011)
- The VMC survey – III. The SED of AGB stars (Gullieuszik et al. 2012)
- The VMC survey - IV. The SFH of the GAIA field (Rubele et al. 2012)
- The VMC survey – V. Classical Cepheids (Ripepi et al. 2012)
- The VMC survey – VI. Quasars behind the Magellanic system (Cioni et al. 2013)
- The VMC survey – VII. Reddening in 30 Dor tile (Tatton et al. 2013, accepted)
- The VMC survey – VIII. Anomalous Cepheids (Ripepi et al., submitted)
- The VMC survey – IX. Variable stars (Moretti et al., to be submitted)
- The VMC survey – Messenger, June 2011

VMC: embedded clusters

SPATIAL RESOLUTION



191 clusters identified by eye from VMC 30 Dor image
- 83 clusters with CO counterparts;

44.5% overlap with YSOs from Spitzer
- 69 newly discovered!

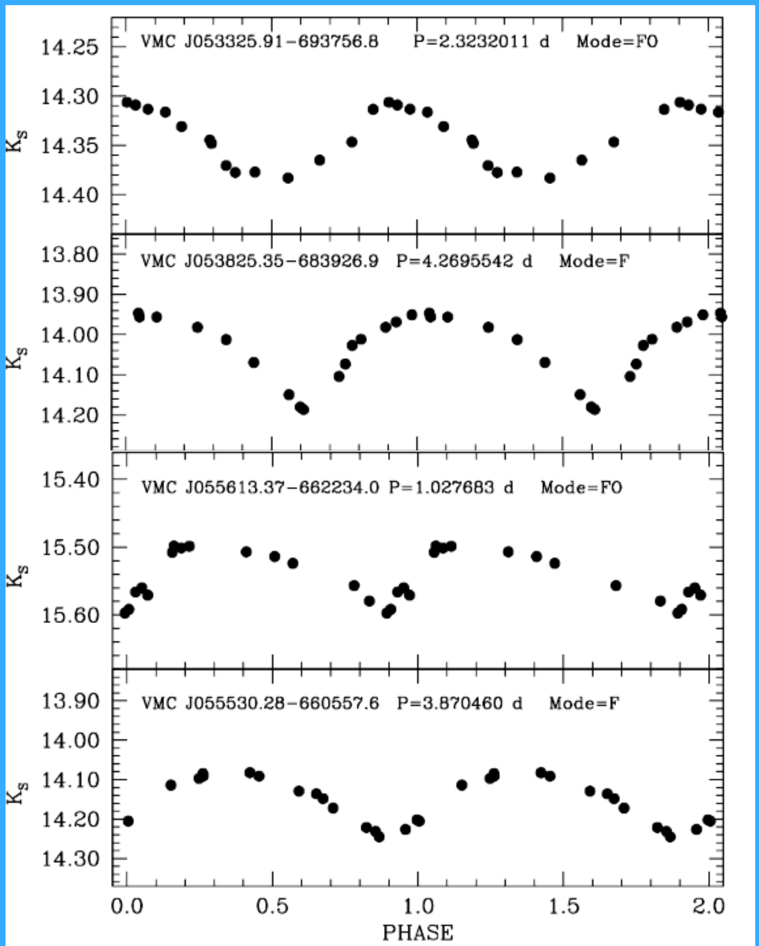
Automatic procedure being developed.

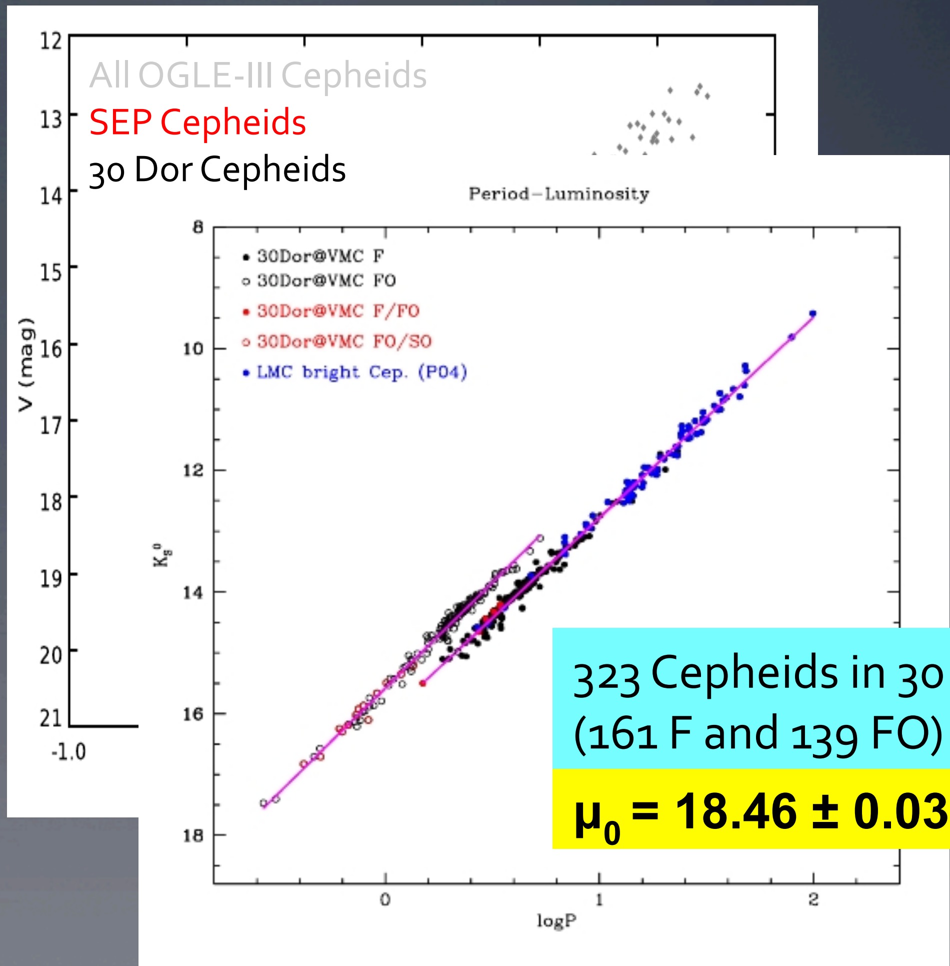
Cluster luminosity is related to cluster mass: LMC clusters are more luminous than MW ones.

Romita et al., in preparation

VMC: Cepheids

PHOTOMETRIC ACCURACY





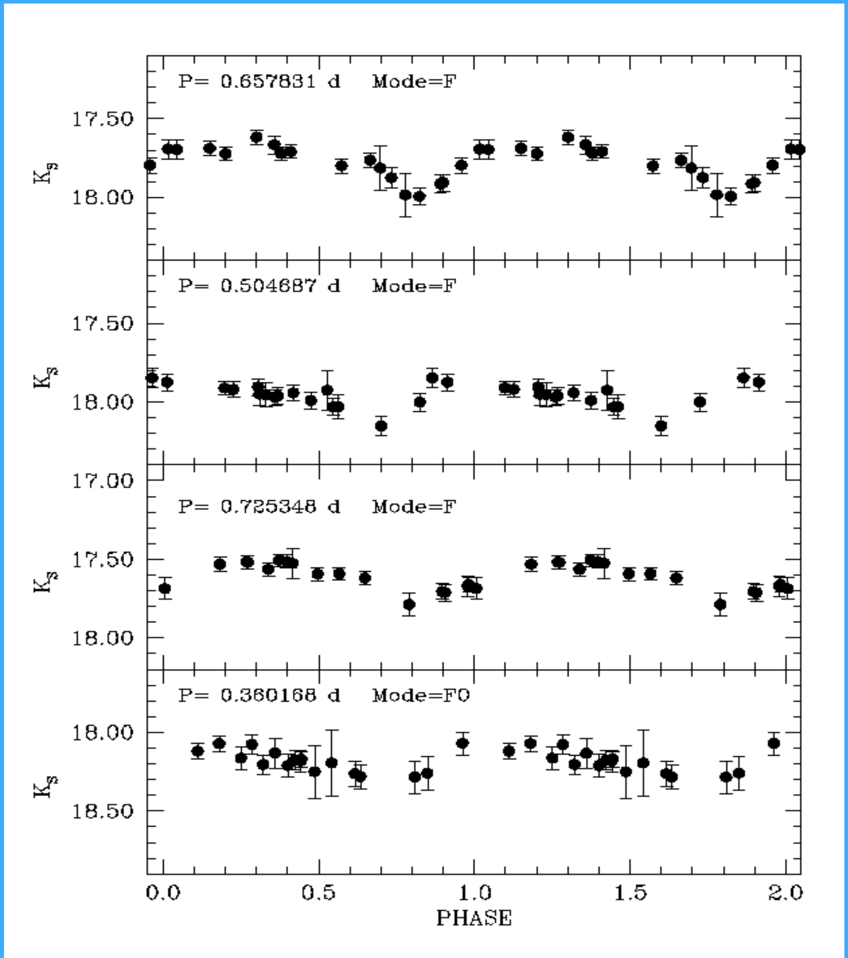
323 Cepheids in 30 Dor (161 F and 139 FO)

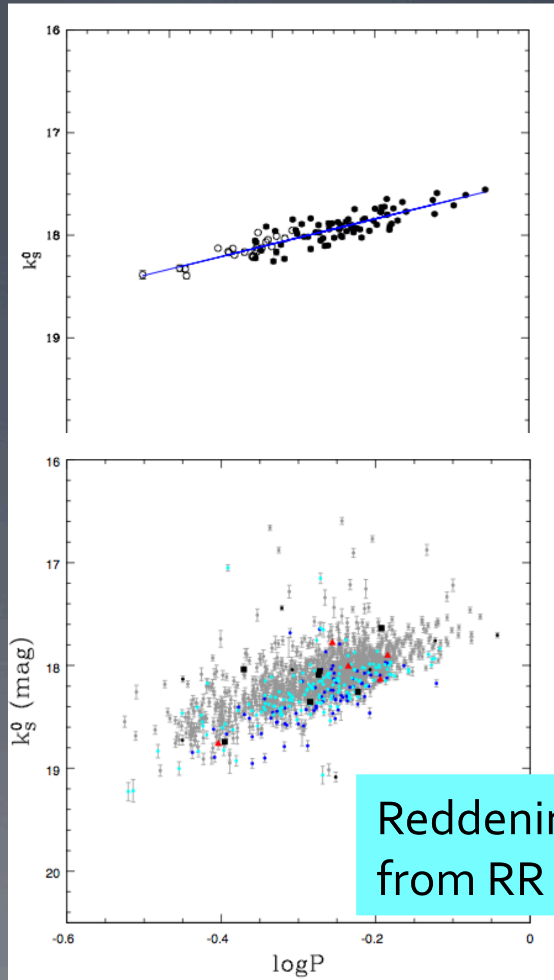
μ_0 = 18.46 ± 0.03 mag

Ripepi et al., MNRAS, 424, 1807, 2012

VMC: RR Lyrae stars

PHOTOMETRIC ACCURACY





PL relation in SEP field.

Updated with OGLE-IV data!

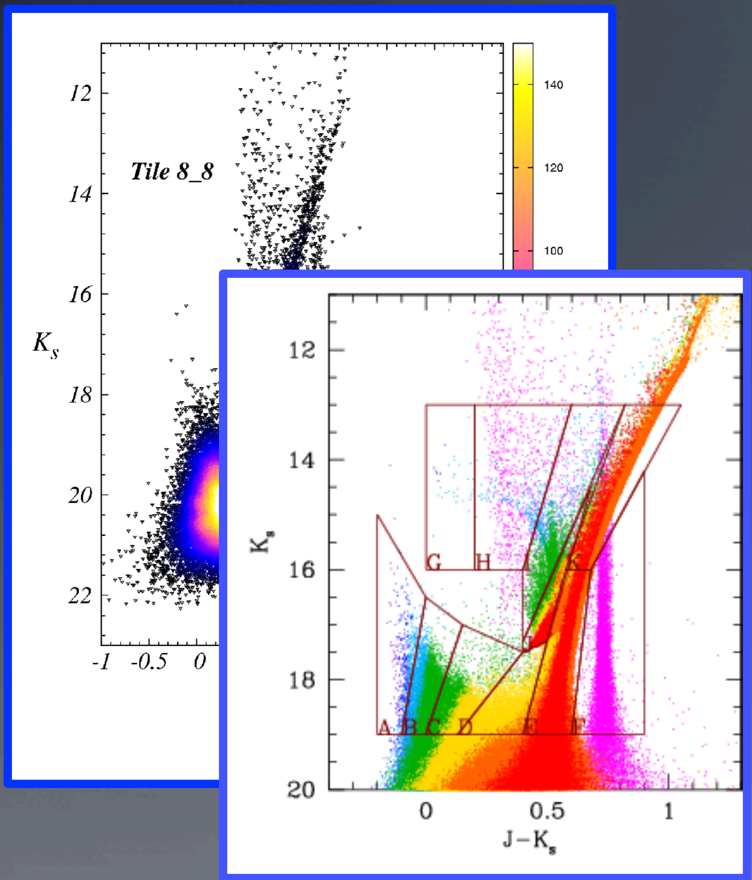
PL relation in 30Dor field.

Reddening can be estimated from RR Lyrae stars.

Moretti et al., in preparation

VMC: SFH

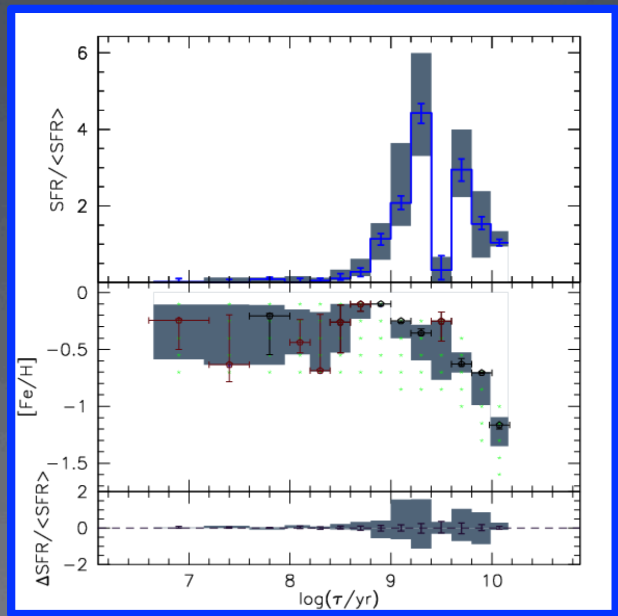
SENSITIVTY



SFH from near-IR data works well!

~30% of the mass formed at 8 Gyr

~20% of the mass formed at 1 Gyr



Reddening and distance modulus are also derived.

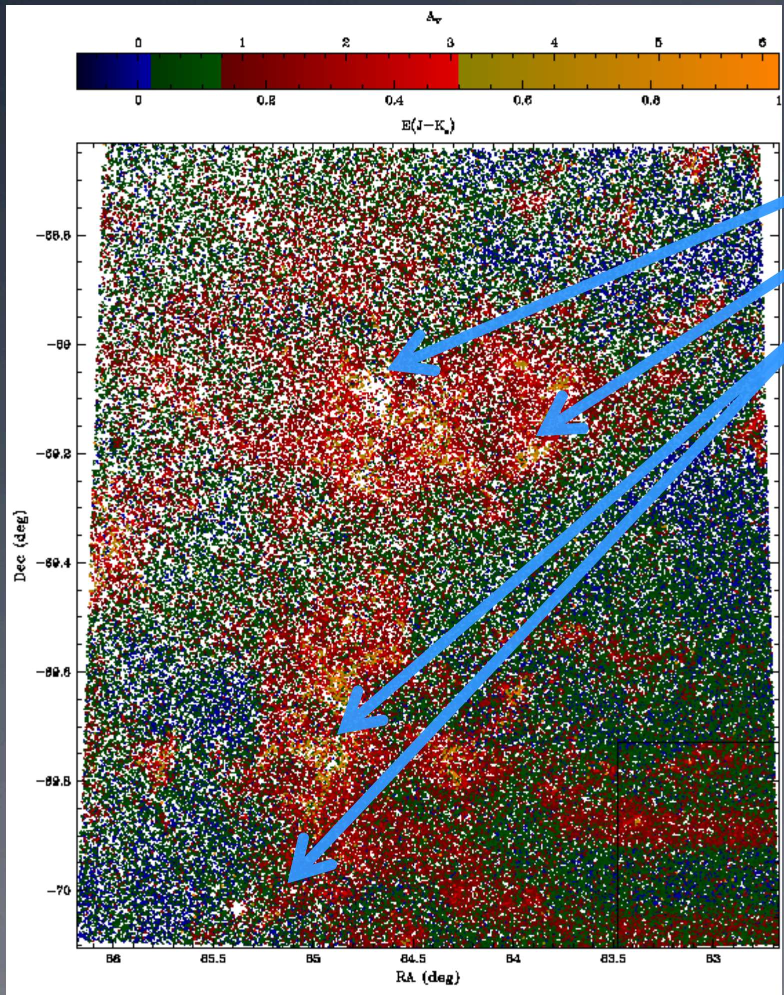
Systematic errors are reduced if geometry of LMC is taken into account.

Rubele et al., A&A, 537, A106, 2012

*not yet with the PARSEC tracks

VMC: reddening map of 30 Dor

DUST



Extinction values for > 150,000 red clump stars. Key regions:

- R136 (Tarantula Nebula)
- SN 1987A
- HII regions (along a molecular ridge)

Highlights:

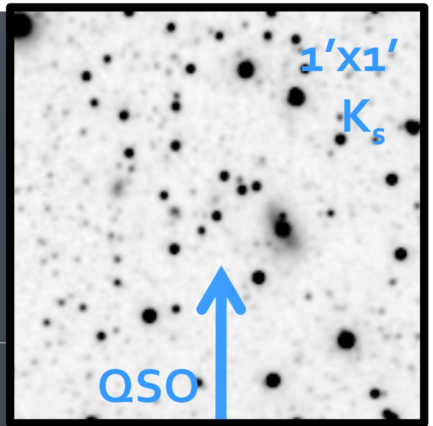
- Probes extinctions to A_V~6
- Shows details more than with OGLE-III
- VMC is the only near-IR survey that resolves stars down to the red clump

De-reddening RC stars is necessary before using them for tracing 3D geometry.

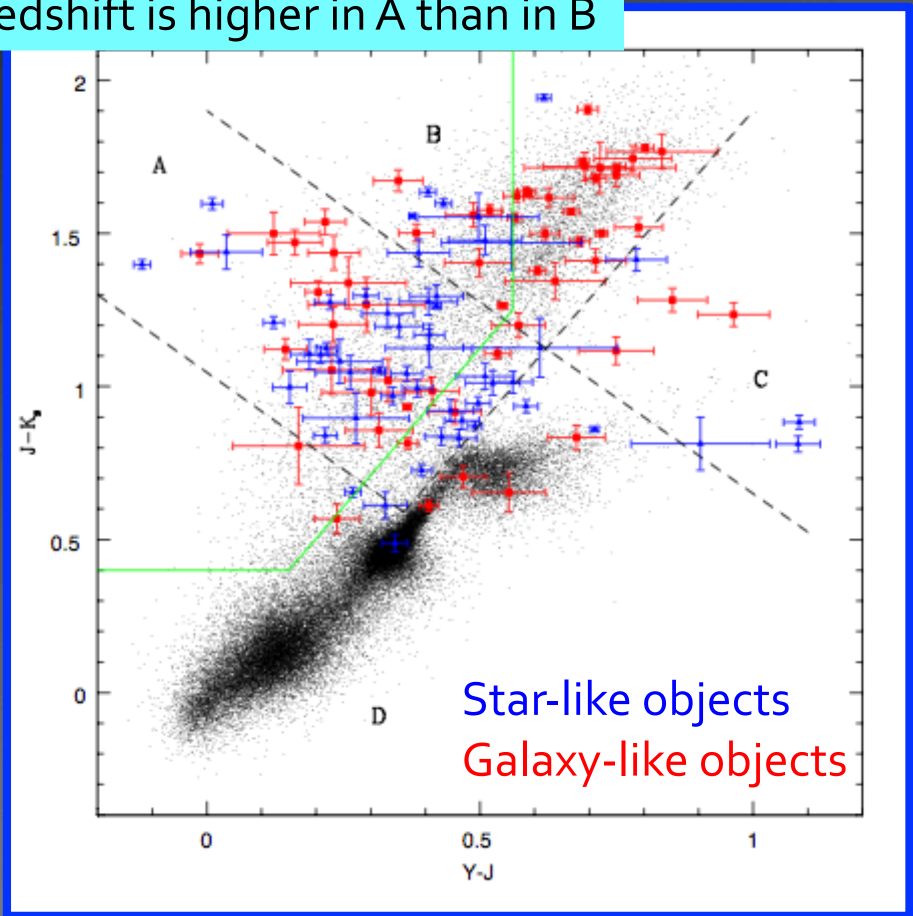
Tatton et al., 2013, accepted, arXiv:1304.1153

DISTANCE

VMC: quasars

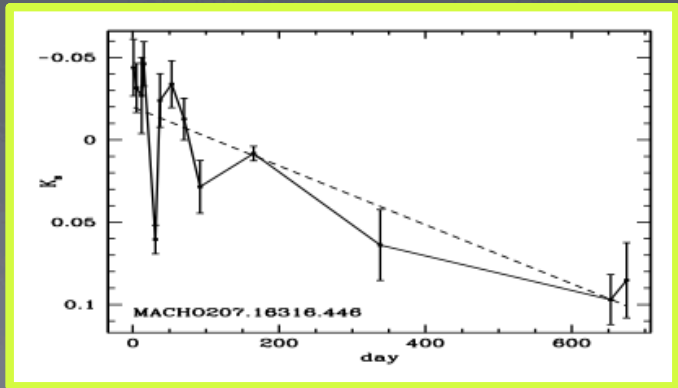


Redshift is higher in A than in B



Quasars are mostly confided in region A and B of the VMC colour space.

Quasars have a K_s light-curve with a slope > 10^{-4} mag/day.

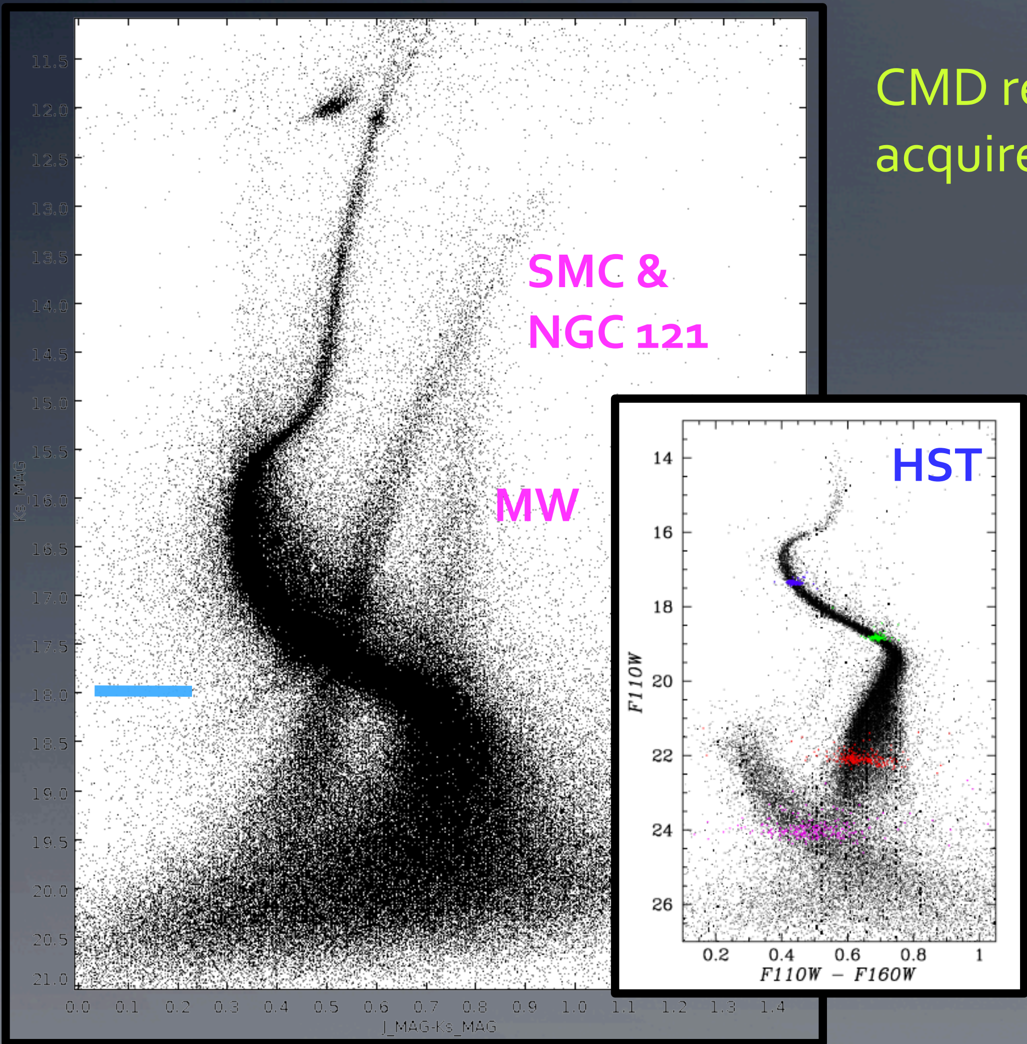


Cioni et al., A&A, 549, A29, 2013

CHALLENGE

VMC: 47 Tuc

Measure tidal radius.
Investigate outer structure.
Trace tidal streams.
Study multi-pops.



CMD refers to 5h in Ks, but 11 have been acquired at present!

Proper motion

Stellar motion

- Stars born out of the same molecular cloud share chemical composition and location at origin.

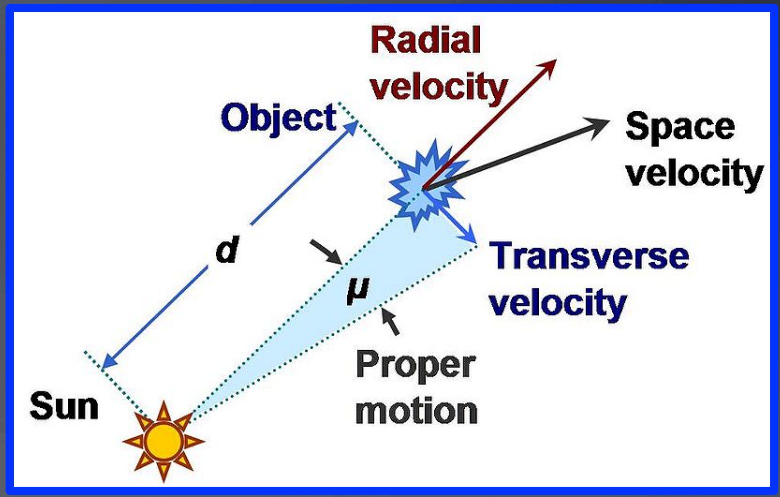


Image credit Wikipedia

- The stellar motion changes with age, as a consequence of interactions and under the influence of the parent galaxy.

- A measure of the motion of stars is a key ingredient for understanding the assembly of the host system and its orbit.

- The proper motion (PM) is the measurement of the change in position in the plane of the sky over time.
- The radial velocity is the motion along the line of sight.

Previous PM studies

- Initial observations were aimed at establishing the orbits of the MCs and explaining the formation of the HI Stream emanating from them as result of their interaction with the MW (Jones et al. 1989; 1990; Tucholke & Hiesgen 1991; Kroupa et al. 1994; Kroupa & Bastian 1997).

- These works were based on a limited number of stars, were restricted to specific regions of the MCs and/or were affected by large uncertainties.

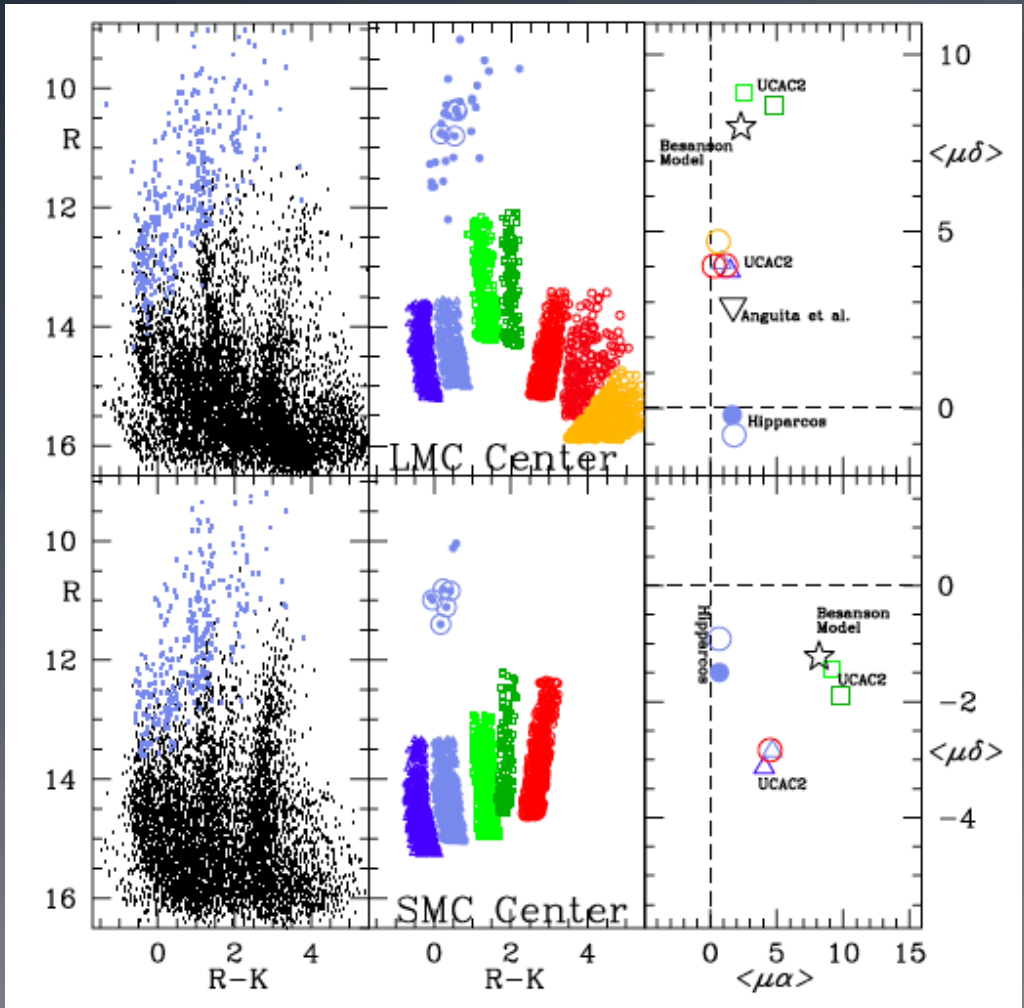
- The use of Quasars as reference objects for PM of the MCs began later (Anguita et al. 2000); Pedreros et al. 2002; 2006). Previous works used background galaxies.

- A large scale study including many stars used MACHO data (Drake et al. 2002) but uncertainties did not improve.

Previous PM studies (cont.)

- Momany & Zaggia (2005) measured a consistent motion from different stellar populations using UCAC2+2MASS and a large velocity inconsistent with current MC-MW understanding.
- The MCs have always been considered as MW satellites.
- This scenario was challenged by Kallivayalil et al. (2006) with HST measurements of the PM suggesting that the MCs move faster than expected and may not be bound to the MW.
- Subsequent ground-based studies by Costa et al. (2009), Vieira et al. (2010) and Pedreros et al. (2011) have reduced the PM values in favour of a recent bound state of the MCs to the MW and a tidal origin for the Stream.

Stellar populations

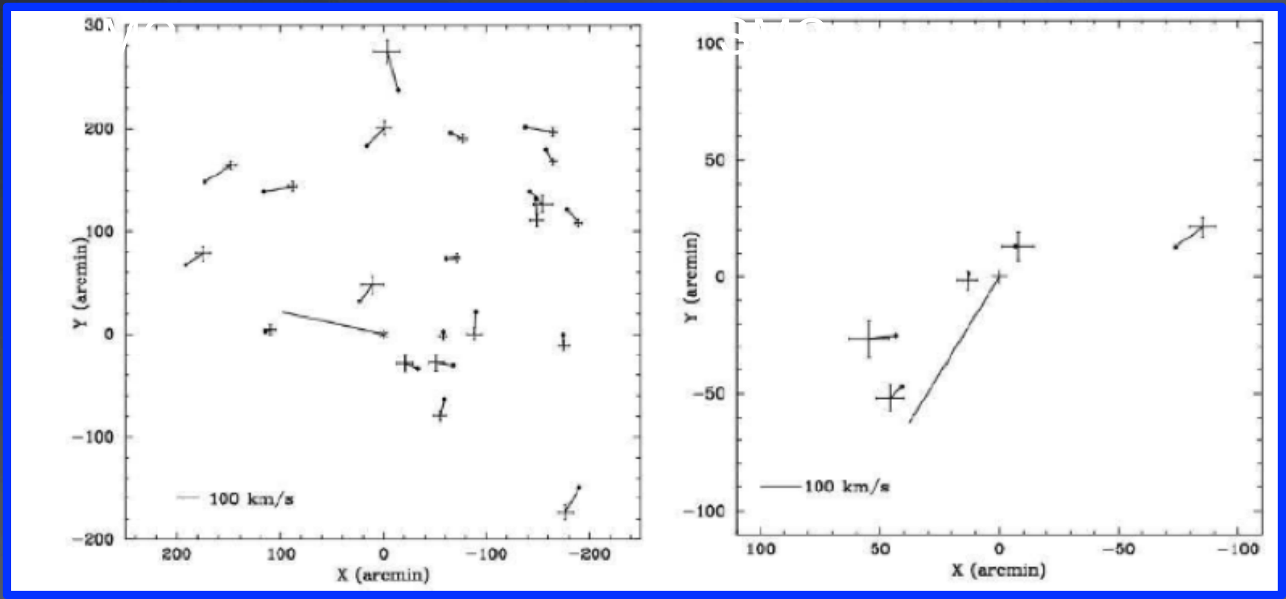


UCAC2 – 2MASS proper motion (all sky) (Momany & Zaggia 2005)

Young, red supergiants and AGB stars + MW foreground

Results suggest a high velocity (1000 km/s!), hence an un-bound MCs with respect to the MW unless the MW mass is high (>$3*10^{12}$ M_{sun}).

Rotation and streaming



Re-analysis of HST results show rotation in the LMC and suggests streaming in the SMC (Piatek et al. 2008)

The tangential velocity is 300-350 km/s.

Internal structure and sub-structures:

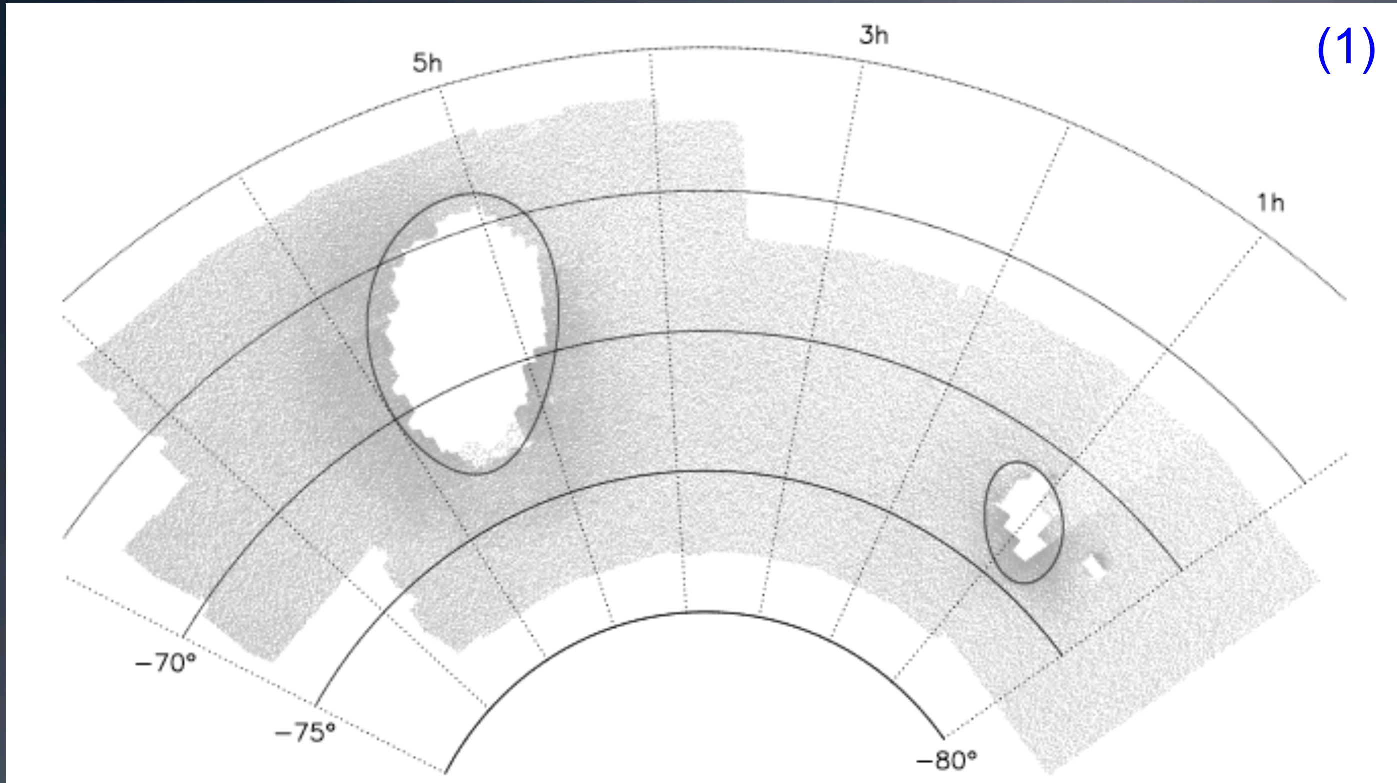
- OB type candidates distribution (LMC-SMC collision ~150 Myr ago) ; Casetti-Dinescu et al. 2012

- SMC stars accreted by the LMC (radial velocity & chemistry difference); Olsen et al. 2011

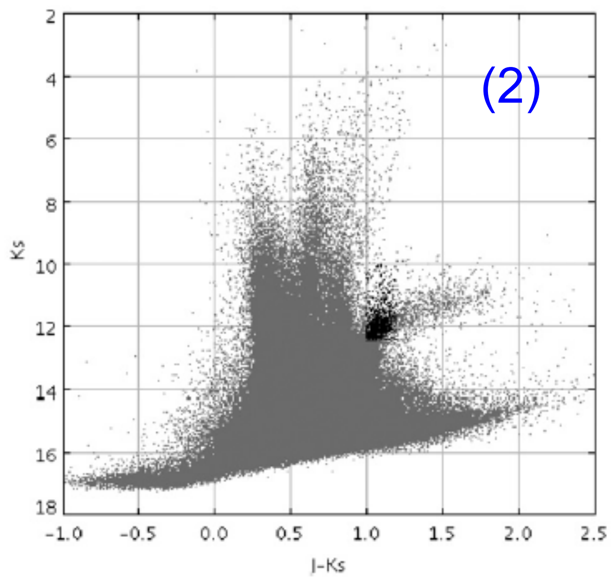
Recent Ground-Based studies

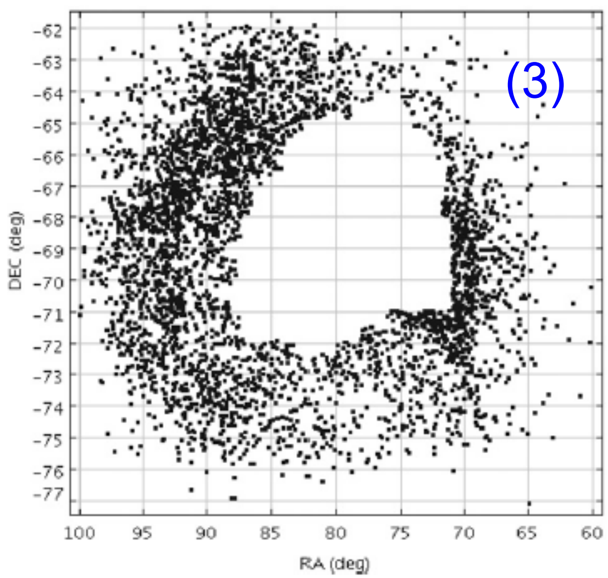
- 40-yr baseline SPM data (Vieira et al. 2010):
  - The relative PM between the Clouds is well constrained
  - The Clouds are on elongated orbits around the MW
  - The Clouds may be marginally bound to the MW

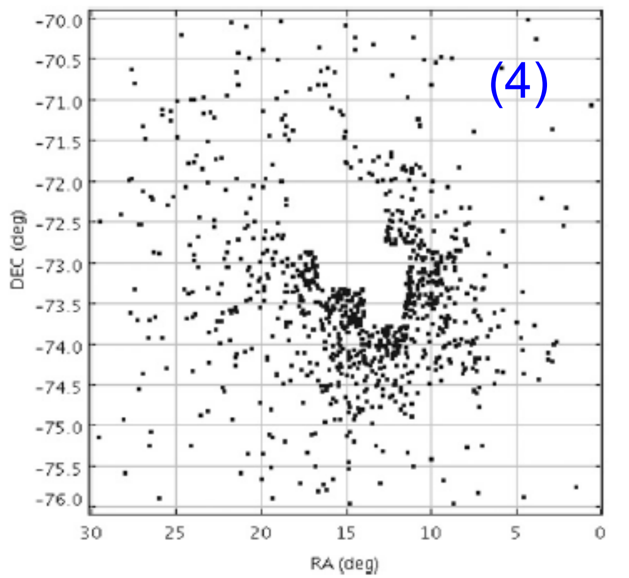
  - Limitations:
    - Proper motion uncertainties are large, 0.3-0.4 mas yr^{-1}
    - Proper motions are limited to the outskirts of the MCs
    - Results are based on 4000/1000 O-rich AGB stars in the LMC/SMC



(1) Total area covered by the SPM project.
(2) CMD with selected SMC stars (black)
(3) LMC AGB stars
(4) SMC AGB stars



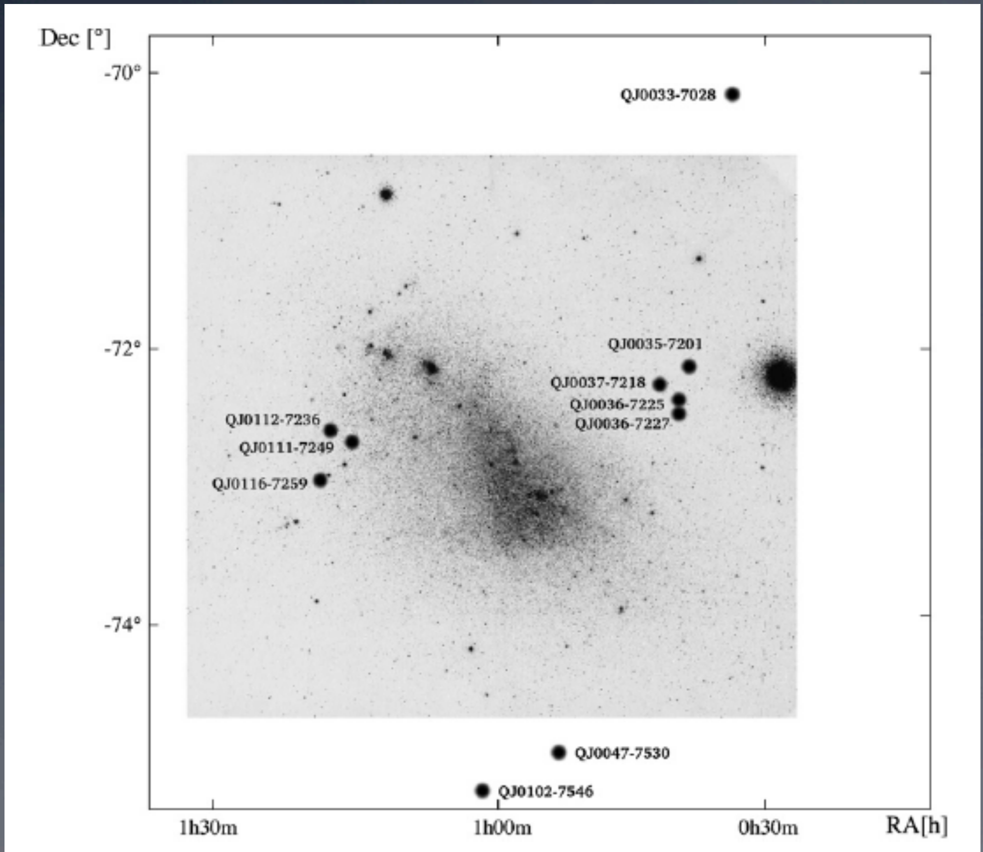


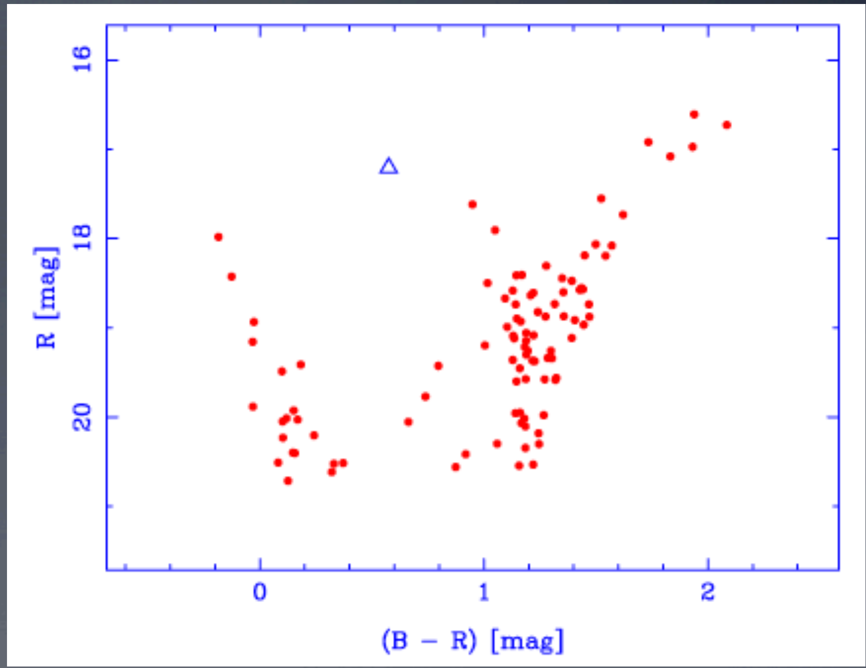


Recent Ground-Based studies (cont.)

- Las Campanas Observatory PM program (Costa et al. 2009, 2011); 5-7 yr baseline; 7-8 epochs
  - Two fields may indicate streaming motion in the SMC
  - The other fields indicate the SMC bulk transverse motion and agree with other results in the literature
  - Results support a scenario were the MCs are bound to the MW

  - Limitations:
    - PM uncertainties are ~0.13 mas yr^{-1}
    - The size of the fields is small (9'x9')
    - The number of fields is limited (10 SMC, 1 LMC)
    - The stellar population is mixed





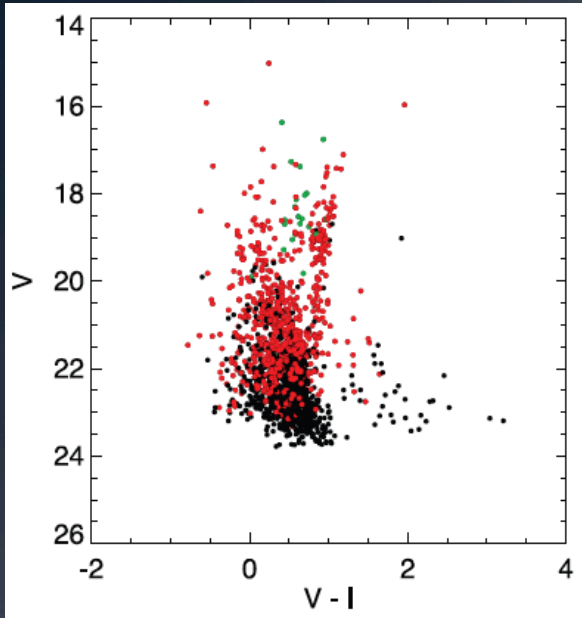
An average CMD per SMC field with ~270 stars.

Distribution of fields in the SMC.

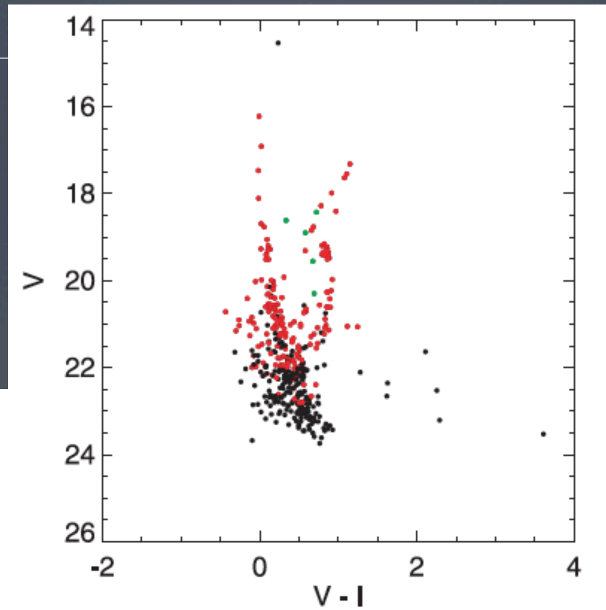
Recent HST results

- Third epoch HST data (Kallivayalil et al. 2013) imply*:
  - Proper motions with small error bars (0.03 mas yr^{-1})
  - The Clouds are on a first infall scenario on to the MW
  - The Clouds are bound to each other – <u>assumed</u>
  - The SMC is on an elliptical orbit around the LMC
  - The LMC mass is high (> 10^{11} M_{Sun})
  - The MW mass is low (< 1.5 10^{12} M_{Sun})
- Limitations of HST data:
  - Mixed stellar populations
  - Limited number of fields (~12) and stars per field (~30)
  - The number of epochs is limited (3)
  - Uncertainties on internal kinematics and structure of the Clouds dominate PM uncertainties.
  - Influence of random motion (Bekki 2011 suggests using >1000 fields!)

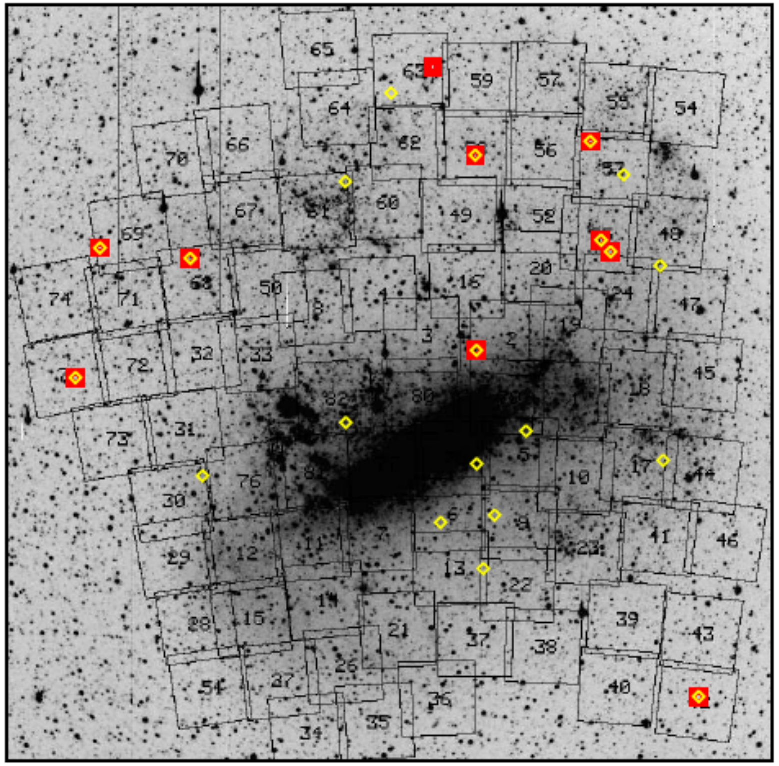
* Details of the Stream are not yet explained in this scenario.

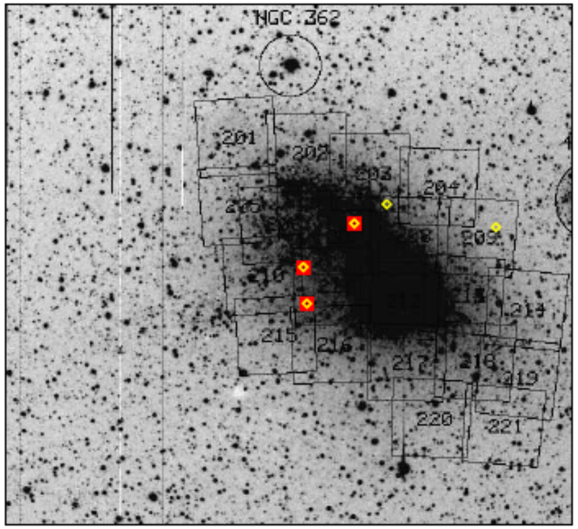


Stars in all HST fields used for PM (red)



The CMD shows a mixed stellar population of: RGB stars, red clump stars and main sequence stars.

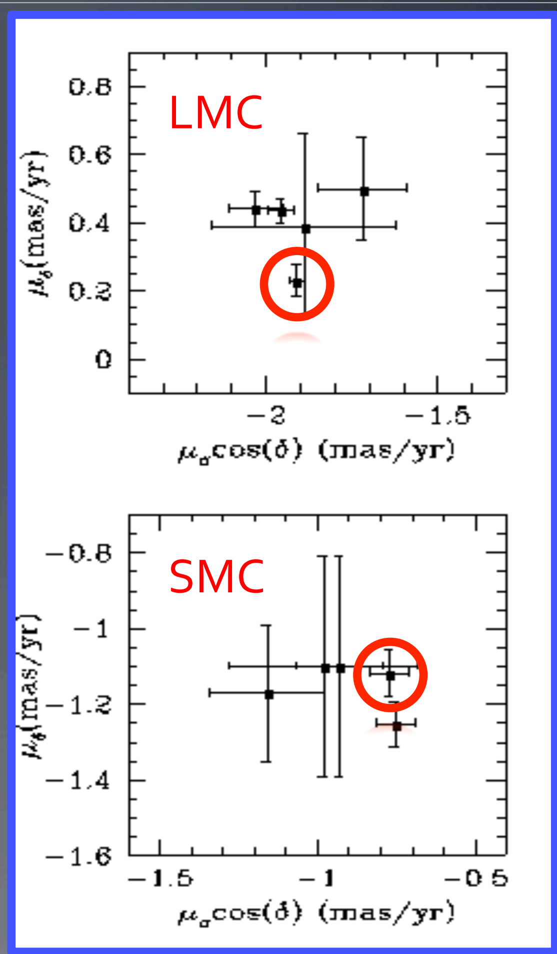




Red fields have 3 HST epochs while yellow fields have only 2 HST epochs.

Pilot study

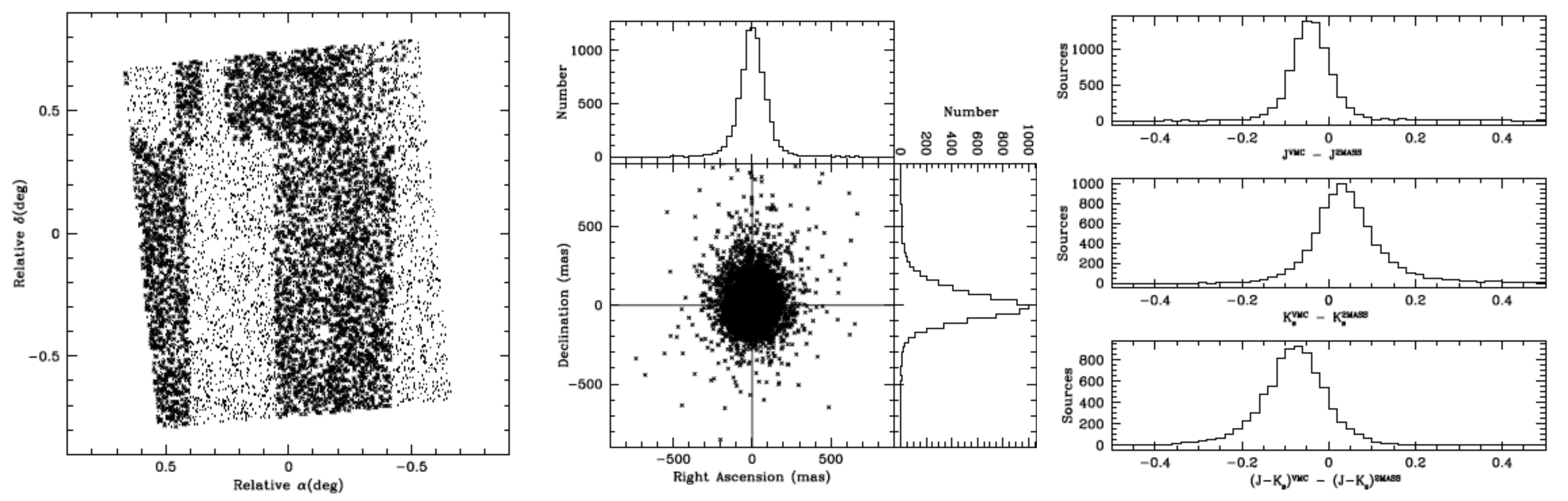
- VMC tile LMC 8_8 (SEP); $(m\text{-}M)_0$=18.39 and A_V=0.2
- VMC – 2MASS proper motion
  (~10 yr baseline, Ks~14.3-15.3; upper RGB, AGB, young and MW stars)
- VMC – VMC proper motion
  (~1 yr baseline; + entire RGB, red clump, sub-giants, main-sequence stars, Cepheids, RR Lyrae stars, binaries)



Current CoM PM

Cioni et al. in preparation

Sample selection

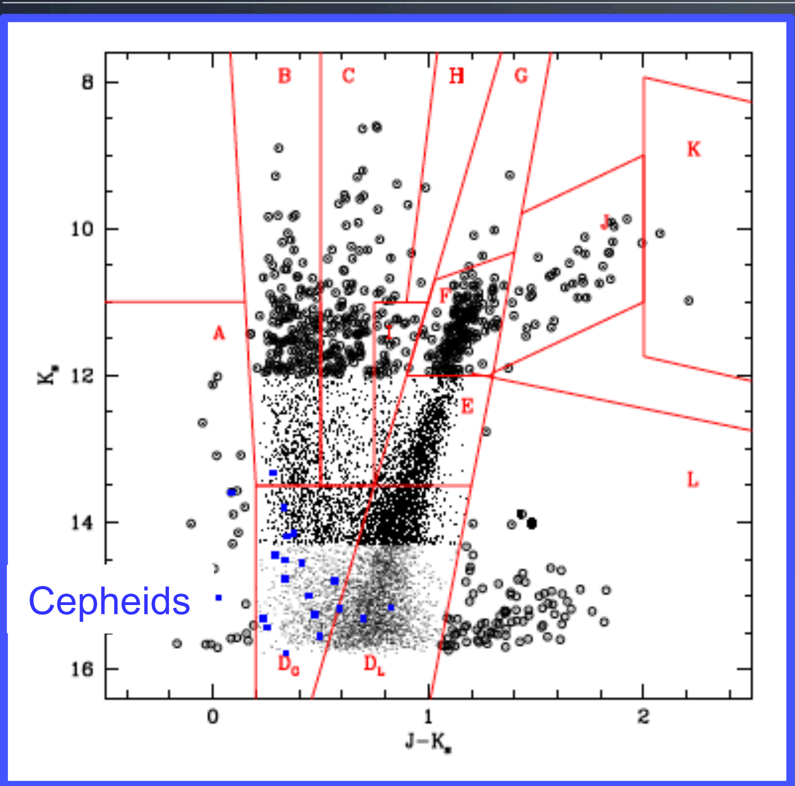


Surface distribution of stars in 2MASS all sky (points) and in 6x 2MASS (crosses).

Coordinate difference between matched VMC and 2MASS sources. Bins are 30 mas.

Number distribution of matched VMC and 2MASS sources. Bins are 0.2 mag.
$\Delta J = -0.05$, $\Delta K_s = +0.03$
$\Delta(J-K_s) = +0.07$

Sample division



A = LMC supergiants and O dwarfs
B = MW F-K dwarfs (80%), LMC supergiants
C = MW K dwarfs (80%), LMC supergiants
D_L = LMC RGB, Early-AGB stars
D_G = MW G-M dwarfs
E = LMC O-rich AGB stars
F = LMC massive AGB stars
G = LMC K-M supergiants
H = MW M dwarfs and K-M giants
I = LMC supergiants, MW K-M dwarfs (55%)
J = LMC C stars
K = LMC dusty AGB stars
L = LMC red RGB, MW M and L dwarfs, galaxies

Best quality 2MASS sources detected in all three VMC magnitudes with differences in magnitudes and colours < 0.5 mag (some sources with K_s<11 and/or ($J-K_s$) >1.2 are excluded) = 7675 sources.

Boxes are like in Nikolaev & Weinberg 2000 but for the extension to 6x 2MASS magnitudes.

PM calculation

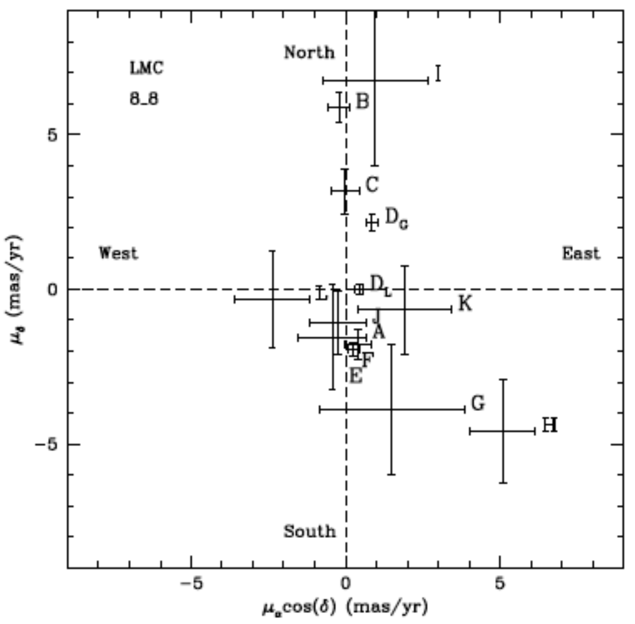
- For each star:
  - Method (1): VMC-2MASS data
    - Calculate positional difference between VMC and 2MASS from individual VMC epochs (up to 11*) and K_s coordinates.
    - Average the independent combinations and derive PM.
  - Method (2): VMC data only for stars in 2MASS
    - Calculate PM from line fitting through VMC data points.
- For each CMD region:
  - Derive average PM by applying iterative 3σ clipping with up to 10 iterations to reject outliers.
  - Derive average PM for types of stars (i.e. combine some CMD regions) using the same rejection technique.

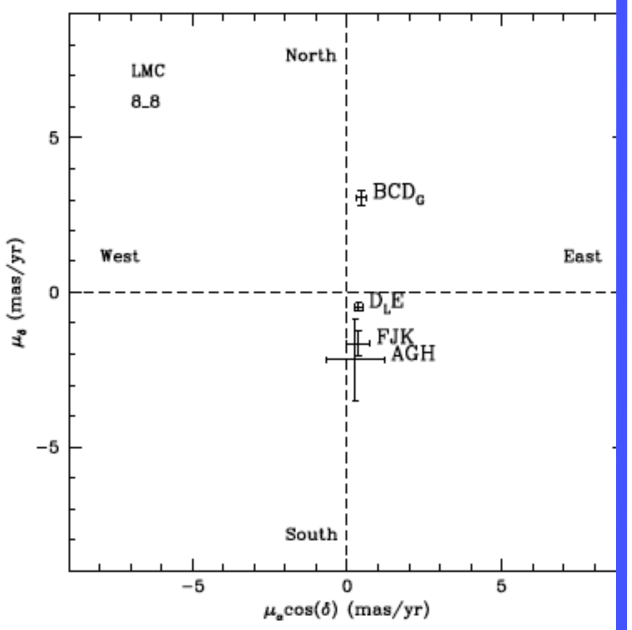
* November 2009 VMC data (4 epochs) excluded.

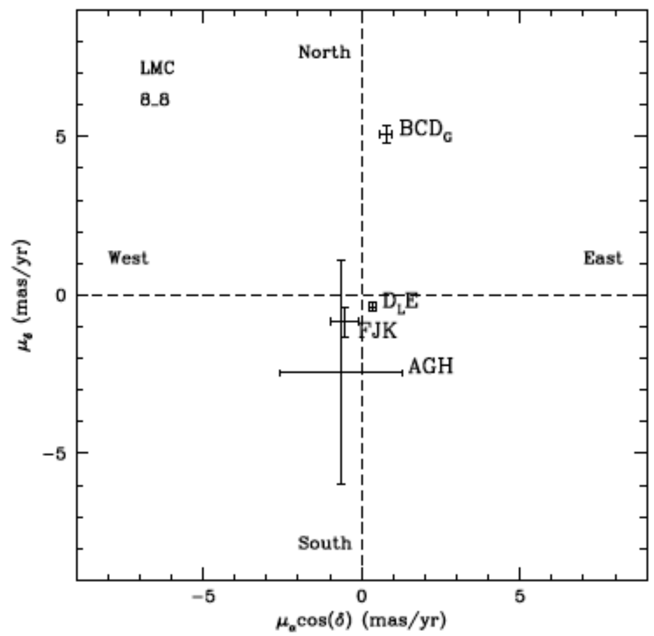
PM results

VMC-2MASS method (1)

VMC-VMC method (2)







2MASS All-sky + 6x 2MASS

2MASS All-sky only

Region D_G still contains LMC stars in the 6x 2MASS selection.

VMC-VMC uncertainties are comparable to VMC-2MASS ones if > 200 stars are present.

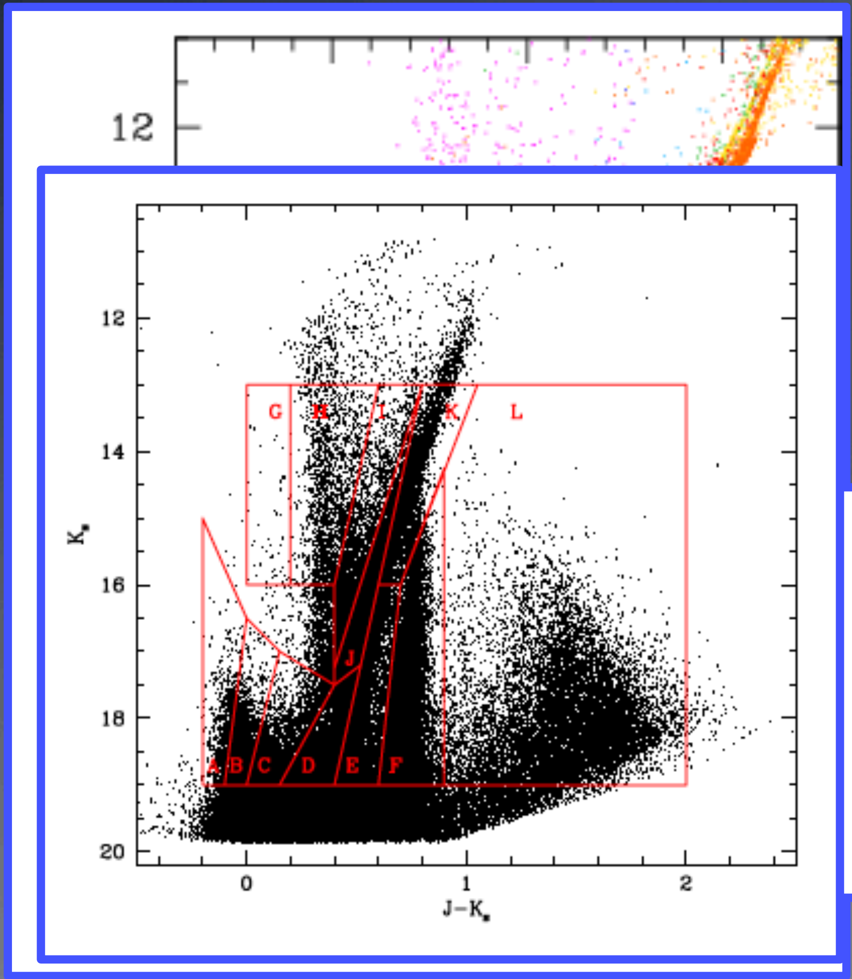
The difference in the AGB (FJK) results is due to carbon stars (J).

Then …

- Finalize the investigation of trends (position, colour, magnitude)
- Derive the PM of 2MASS sources from VMC paw-prints rather than from VMC tiles
- Derive the PM for sources with Ks > 14.3 mag (VMC only)
  - Define a division of the CMD region
  - Calculate the PM in each region
  - Calculate the PM of RR Lyrae stars, binaries and Cepheids

There are ~40 times more sources below the 2MASS limit that can be used for deriving the PM and this implies uncertainties directly comparable with those from HST (0.03 mas yr^{-1}).

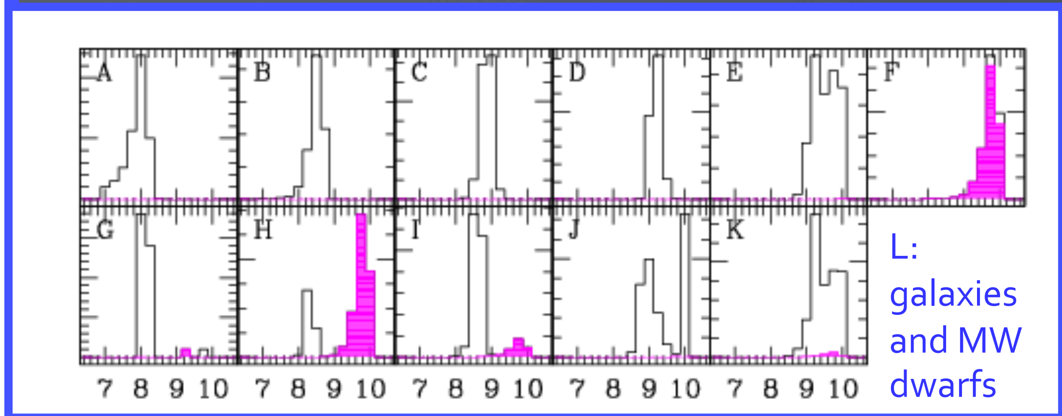
VMC sources



Division of VMC stars by age in tile LMC 8_8.

Regions driven by evolutionary models.

Faint limit corresponds roughly to individual tile sensitivity.

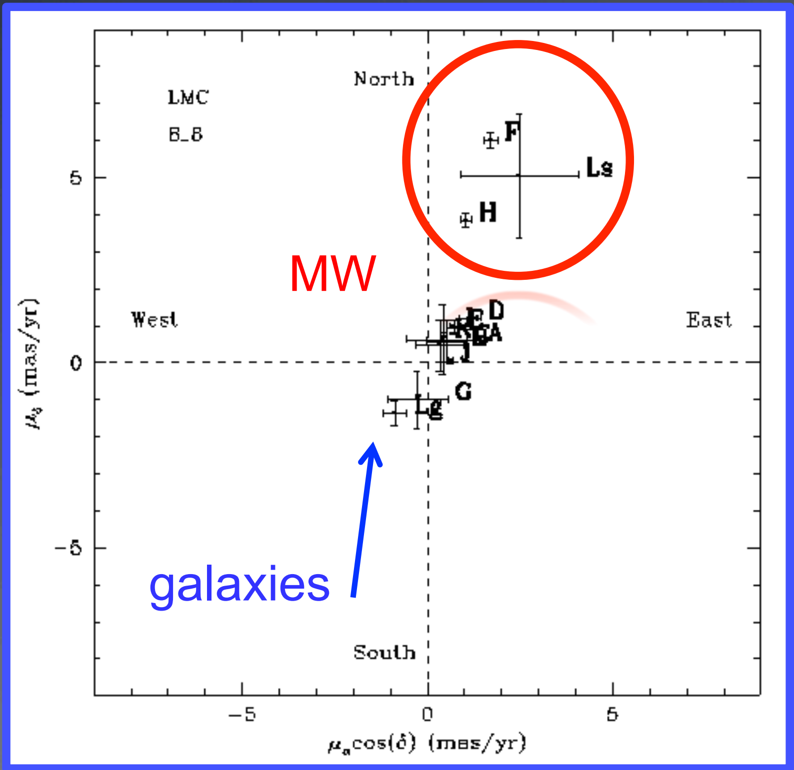


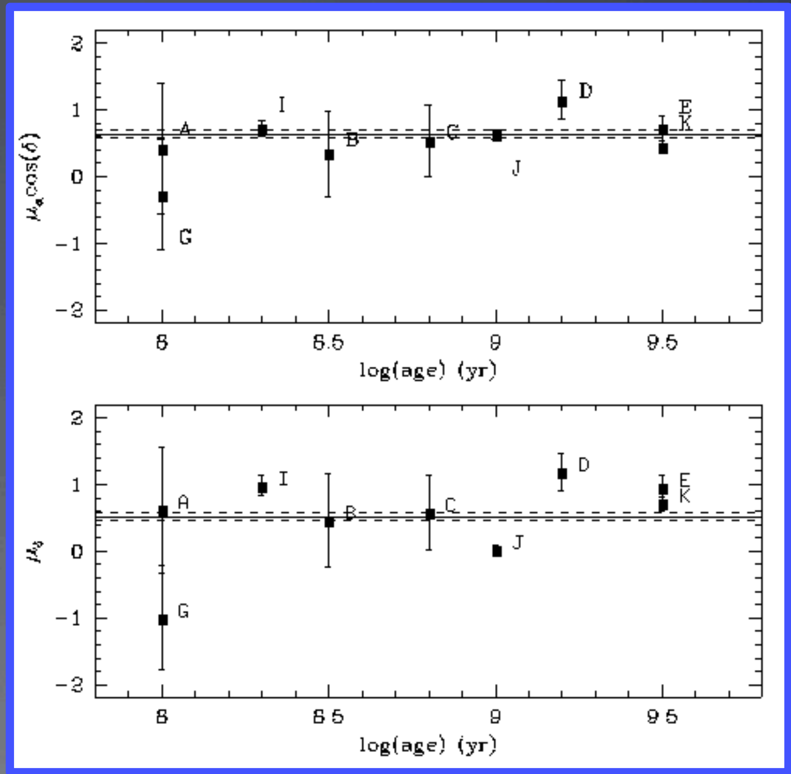
log(age) (yr)

VMC-VMC PM

Proper motion per CMD region.
MW stars are well separated.

LMC proper motion vs mean age.
No clear trend present.

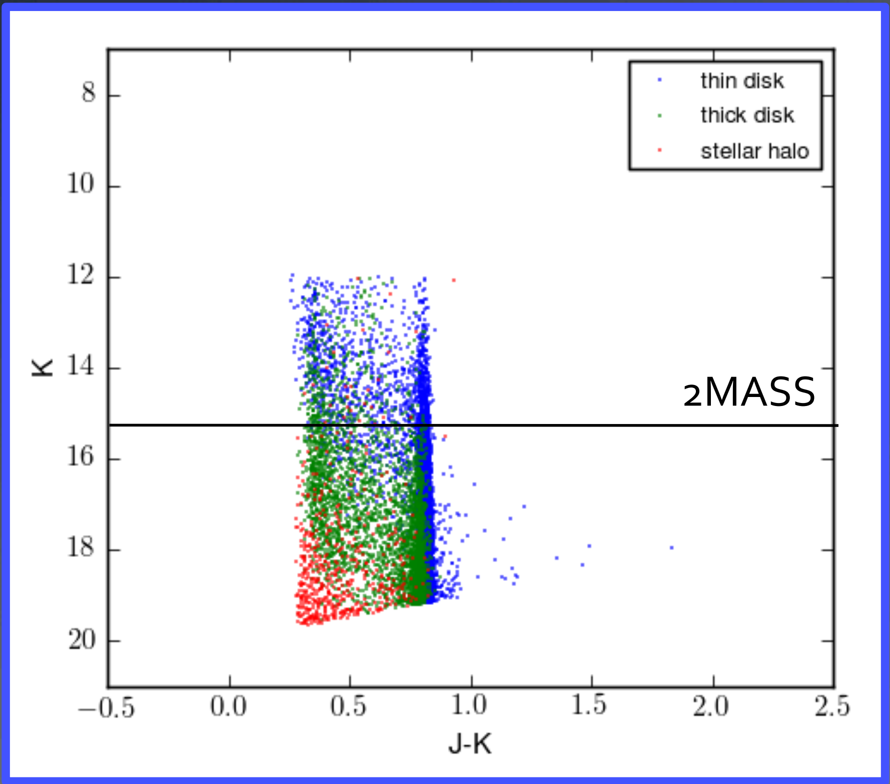


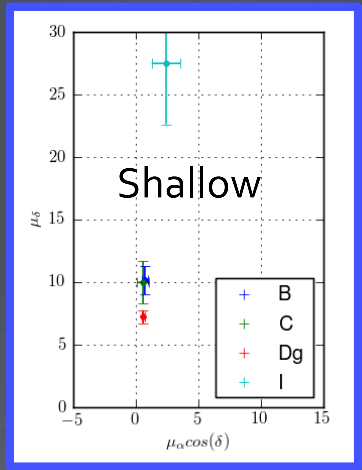


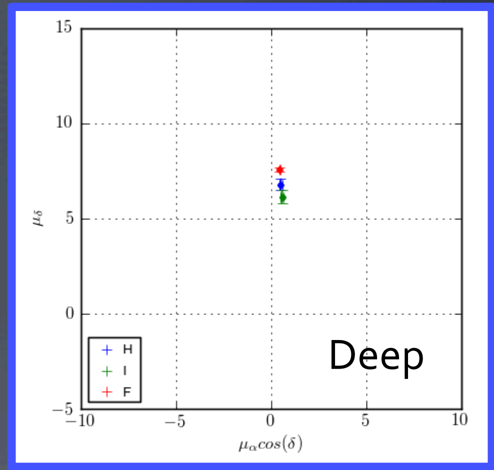
LMC (53391 sources): $\mu_\alpha \cos(\delta)$=+0.62 (0.06), μ_δ=+0.50 (0.06)

Compared to VMC-2MASS results uncertainties are smaller and MW contamination is lower.

MW PM – model comparison







Distribution of MW stars and their PM from the Besançon models in the direction of tile LMC 8_8.

MW stars are within 5 kpc.

MW values are well recovered in region F (VMC-VMC; mostly MW) and the influence of LMC stars explains the reduced motion in the other regions.

Next PM studies

- Explore the PM across the LMC and SMC using presently available tiles and produce dynamical models
  - Up to 2MASS sensitivities (1 VMC tile in K_s): 14 – LMC; 12 – SMC; 7 – Bridge; 2 – Stream
  - Full depth (11 VMC tiles in K_s) : 5 – LMC; 2 – SMC; 1 – Bridge
- Explore the PM in the Bridge region
  - Look for signatures of LMC and SMC objects
  - Look for intrinsic Bridge stars PM
- Explore the PM in the Stream tiles
  - Is there a stellar counterpart?

Conclusions

- The VMC survey with its high spatial resolution and near-IR sensitivity has opened up studies of the Magellanic Clouds stars, structure and dynamics
- The proper motion derived from VMC-2MASS and VMC-VMC relies on a large statistics and wide area. The structure of the MCs is derived also from VMC data.

THANK YOU!

Your time today!
VMC team, CASU, WFAU
Humboldt Foundation
UH, USM, AIP

VMC

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