MAVIS: A REVOLUTION IN THE STUDY OF RESOLVED STELLAR POPULATIONS

CHARACTERISING STAR CLUSTERS IN THE UNIVERSE

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MAVIS IN A NUTSHELL
(HTTP://MAVIS-AO.ORG/MAVIS/)

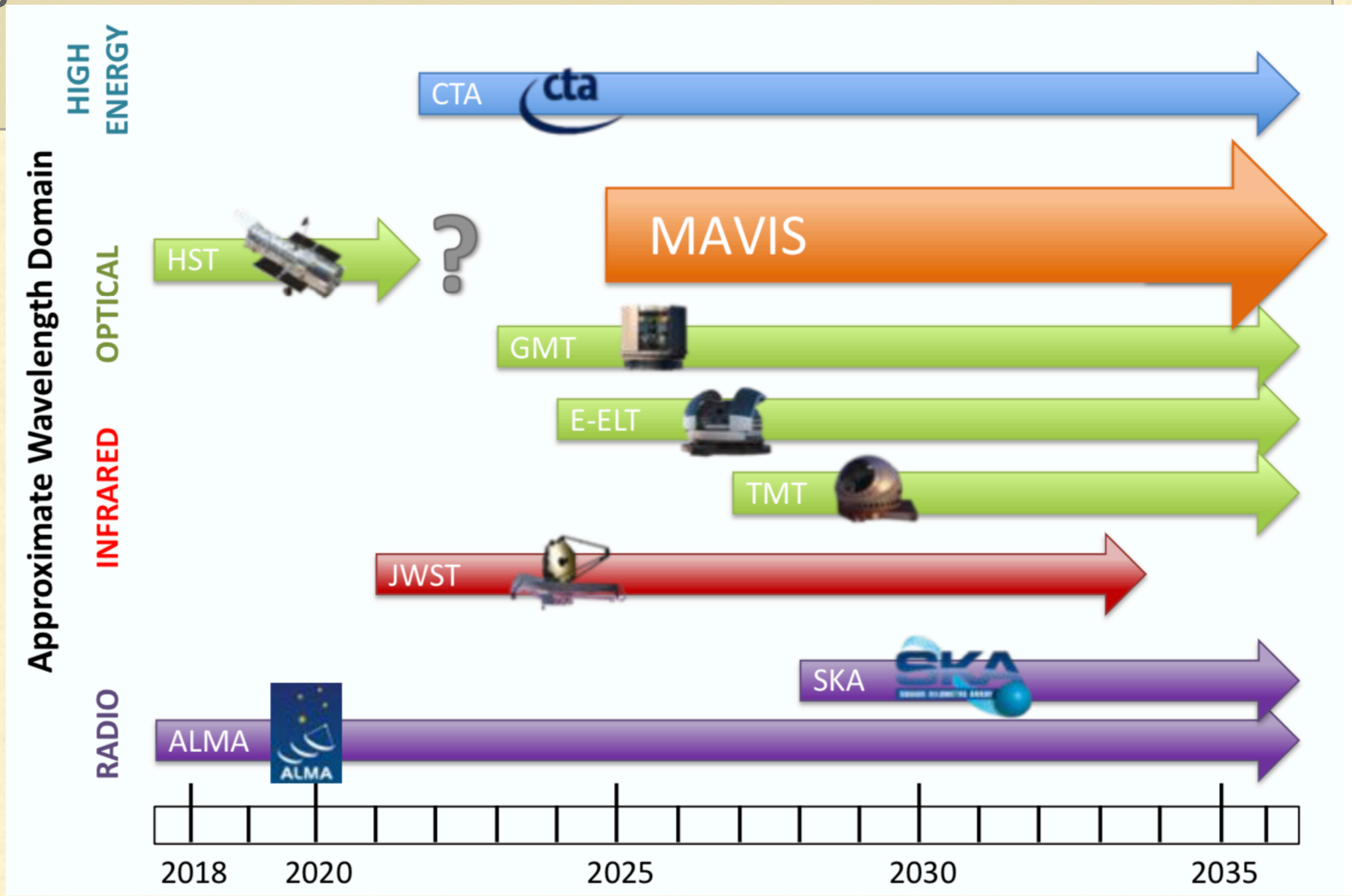
- **MAVIS** is a proposed instrument for the ESO's VLT AOF (Adaptive Optics Facility, UT4 Yepun).
- MAVIS stands for **M**CAO **A**ssisted **V**isible **I**mager and **S**pectrograph.
- It is intended to be installed at the Nasmyth focus of the VLT AOF and is made of two main parts:
  - an **Adaptive Optics** (AO) system that cancels the image blurring induced by atmospheric turbulence and its **post focal instrumentation**, for which the baseline is a 4000x4000 pixel imager
  - a **Spectrograph,** both covering the visible part of the light spectrum (in low -**R=5000** and medium -**R=15000** spectral resolution, **3"x3" IFU**?)

MAVIS IN A NUTSHELL

(HTTP://MAVIS-AO.ORG/MAVIS/)

- **Optical wavelengths are information-rich**, with many well-understood astrophysical diagnostics
- **Sky background is x1,000-10,000 times fainter than IR** - possible to compete with present and forthcoming space facilities

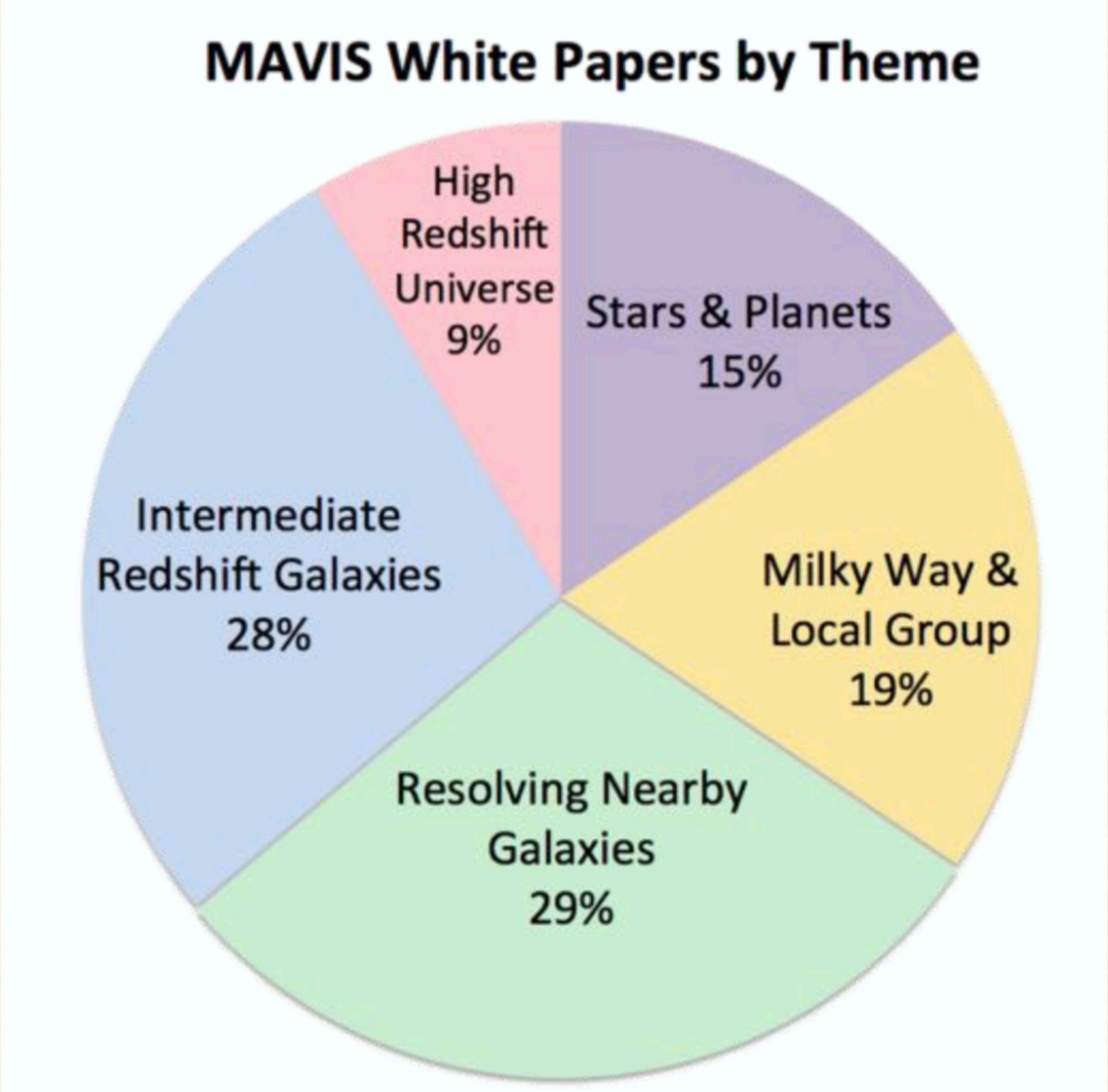
- MAVIS operations overlaps well with ELT era
- Overlaps with JWST core (5yr) and goal (10yr) mission
- Will fill the gap left at optical wavelengths in the post-HST era



Courtesy of R. McDermid

WHICH SCIENCE WITH MAVIS?

(HTTP://MAVIS-AO.ORG/MAVIS/)

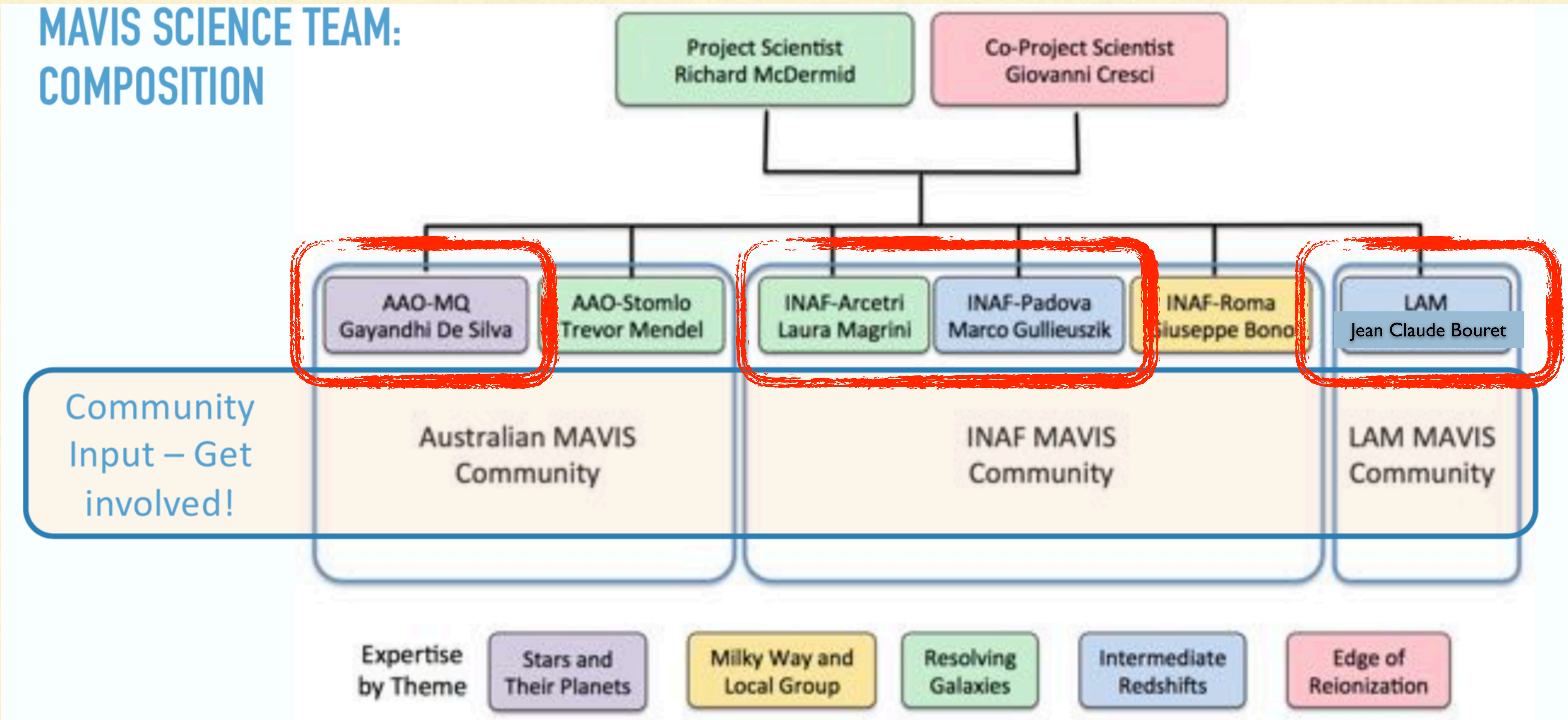


Courtesy of R. McDermid

- About half of the science cases are related to resolved stellar populations
- Form the Milky Way component to stellar population in nearby and high-redshift galaxies
- Among them, **star clusters play a linking role between Galactic and extragalactic science cases**

TOWARDS THE MAVIS SCIENCE DESCRIPTION DOCUMENT

(MARCH 2020)

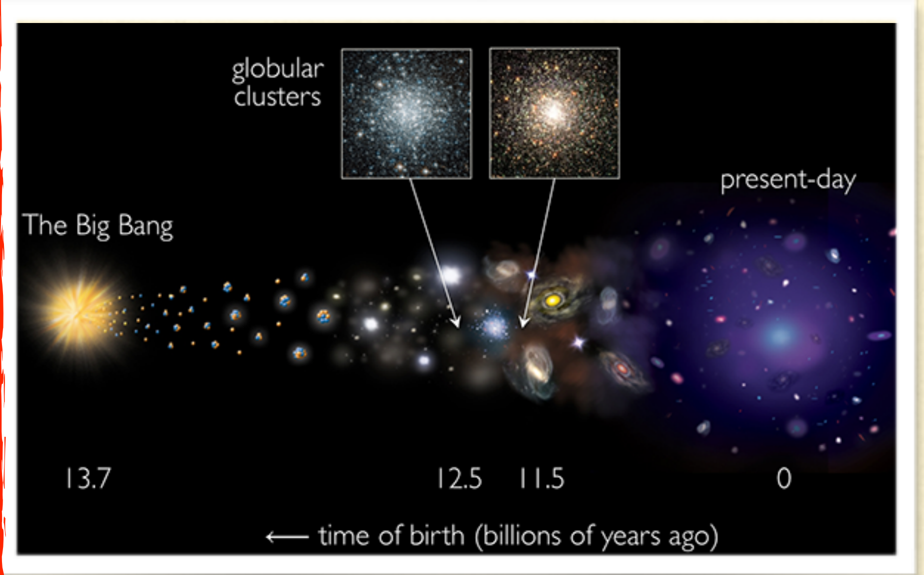


A collaborative chapter: from the MW to high-z galaxies, to understand the clusters' phenomenon

STAR CLUSTERS ACROSS COSMIC TIME

- Key constituents of many fields of astrophysics: from **star formation** to **stellar** and **galactic evolution,** finally to the **formation of structures** and **to cosmology** (see Krumholz et al. 2019 for a review)

- **Ubiquitous**: observed from the very nearby Universe to the high-redshift galaxies
- No longer stand-alone studies, but **corner-stone objects** to improve our knowledge of the Universe across cosmic time



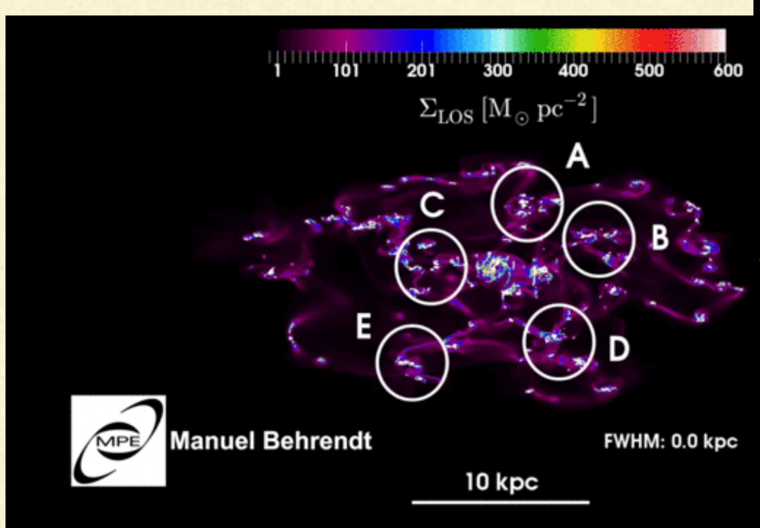
THE COMBINATION OF MAVIS CAPABILITIES ALLOWS TO STUDY:
STAR CLUSTERS ACROSS COSMIC TIME

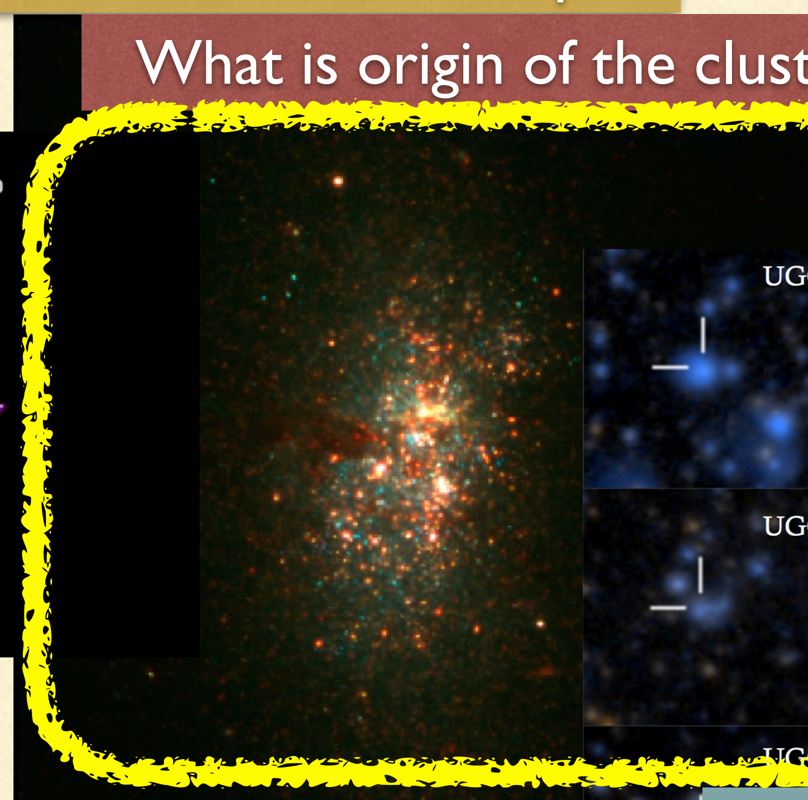
Connecting the dominant mode of star formation in the past epochs to the present time clusters and cluster relics, to disentangling the nature Galactic disc open clusters and old globular clusters.

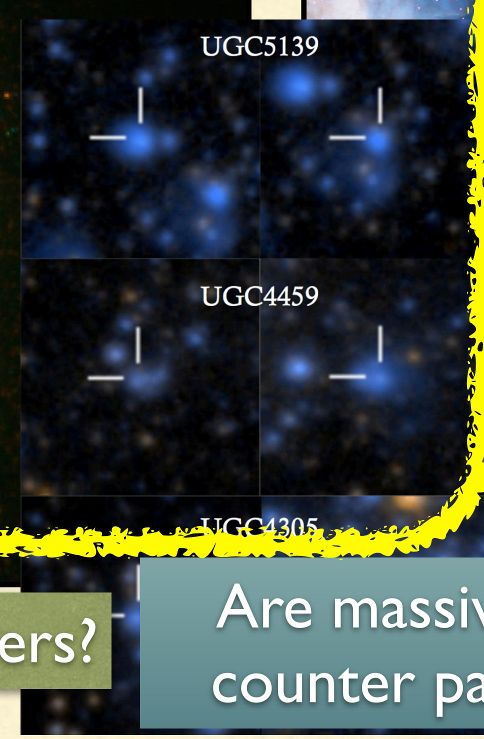
Do massive clusters contain intermediate mass black holes?

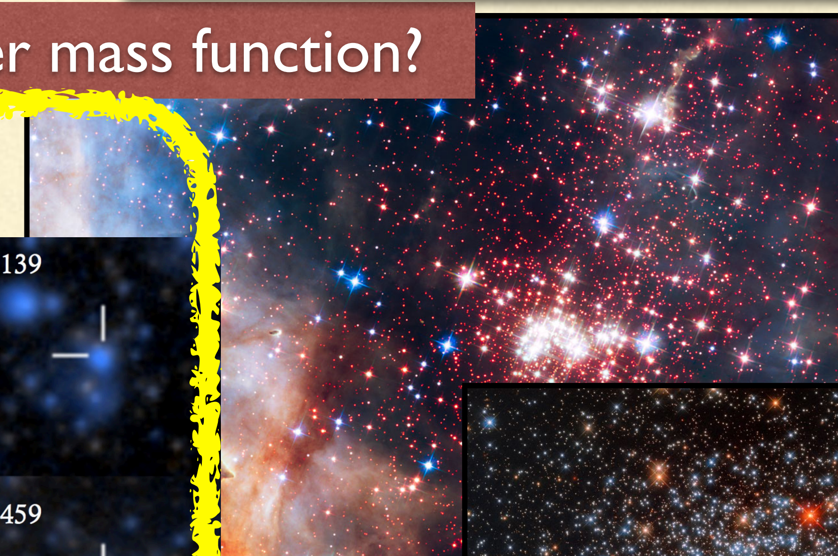
What is the fate of the high-redshift stellar clumps?

What is origin of the cluster mass function?









Are high-z clumps the progenitors of globular clusters?

Are massive clusters in the MC the young counter parts of the old globular clusters?

KEY-QUESTIONS AND MAVIS

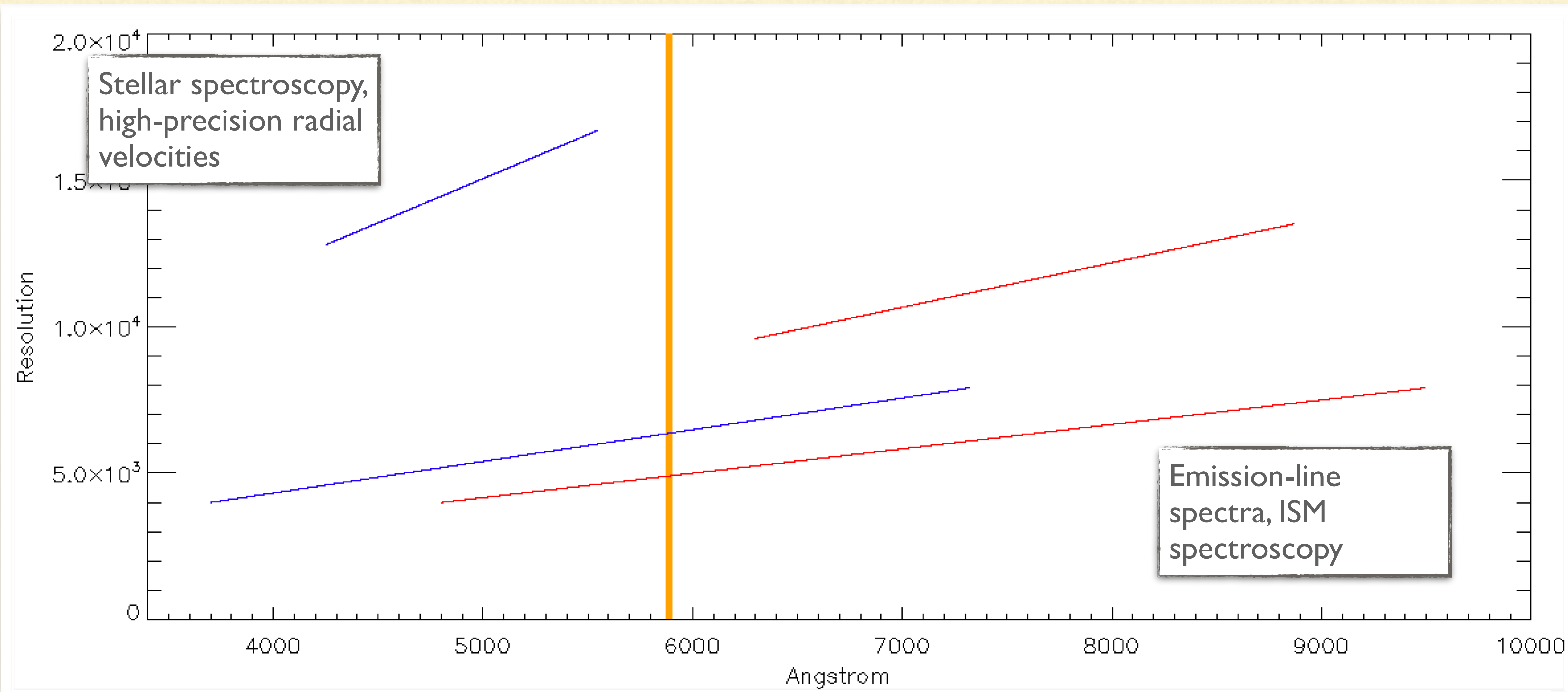
- Is there a Universal Cluster mass function?
- Does the Initial Mass function depend on the environment and on the metallicity?
- Is the separation between open and globular clusters still valid outside the Galaxy?
- Is there an age-metallicity relationship in star cluster populations? How does their spatial metallicity distribution vary with time?

Searching for answers with MAVIS:

- Imaging in different bands —> **AO-assisted spatial resolution** to resolve stellar populations in crowded/distant fields
- **Low- and high-resolution spectroscopy** (from blue to red) with a wide spectral coverage
- **MAVIS** will allow to explore new parameter space, offering exciting opportunities to study star clusters, linking across Galactic and extra-galactic astronomy

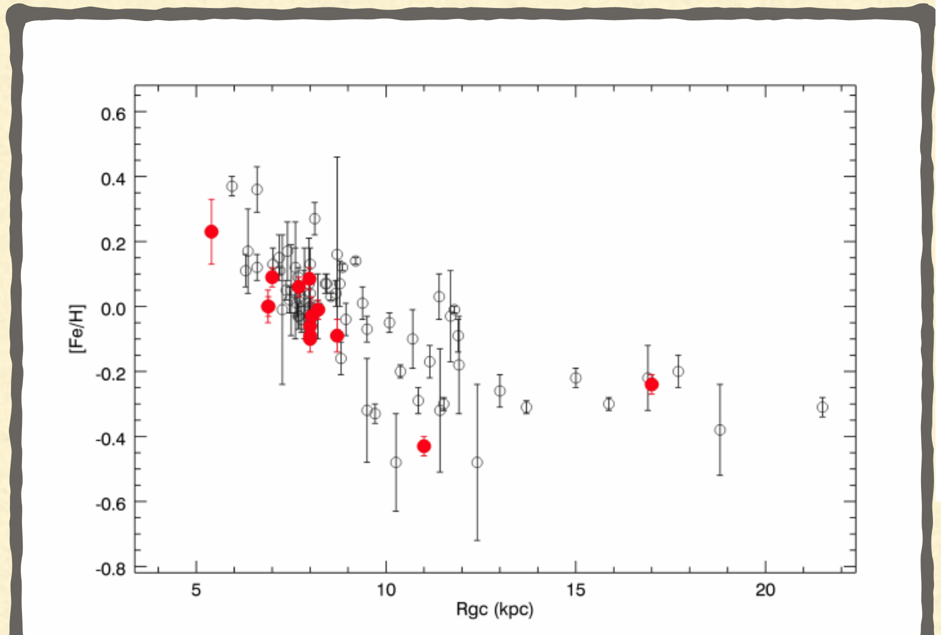
SPECTROSCOPIC FACILITY

- Spectral resolutions and wavelength rages

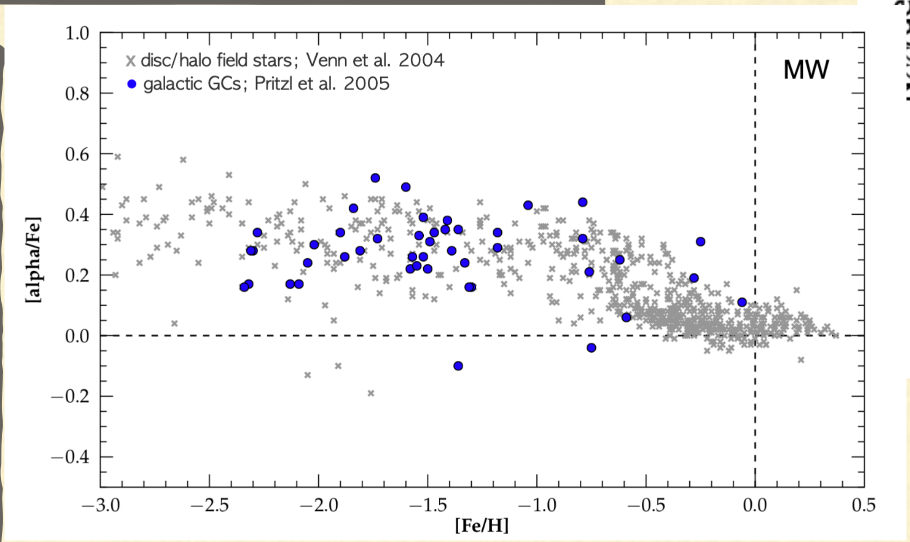


STAR CLUSTERS IN THE GALAXY

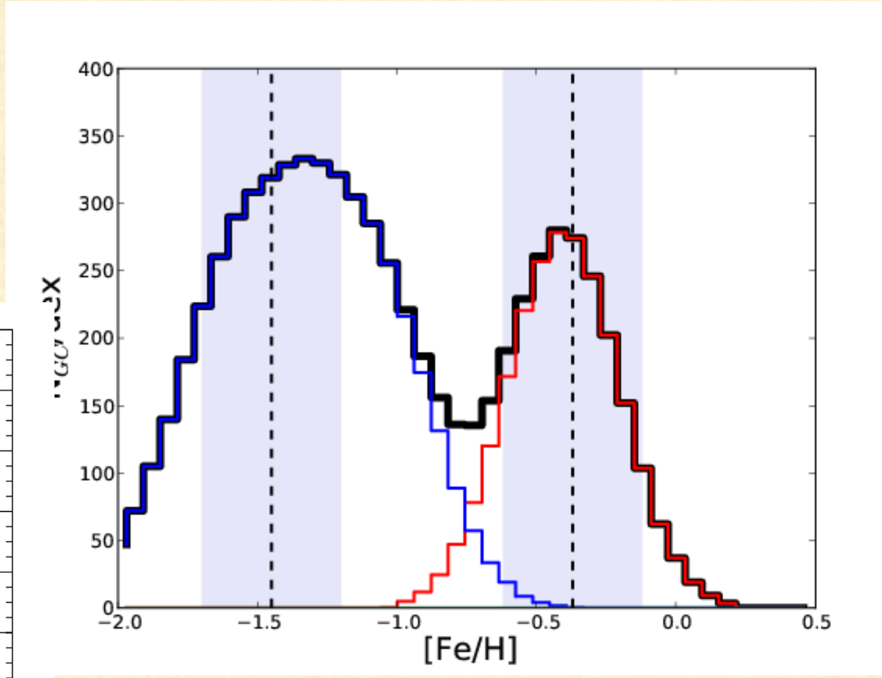
- Complex populations
- Young/intermediate open star clusters in the disc
- Old, more massive globular clusters in the halo



Radial metallicity gradient from Gaia-ESO



High- alpha/fe: formed with rapid chemical enrichment



Bimodal metallicity distribution of Galactic Globular Clusters

…moving outside the Galaxy is a step forwards to a complete understanding of star clusters

STAR CLUSTERS IN NEARBY GALAXIES

- Test particles for which we can measure **ages, distances, metallicity, abundances**
- Constraints for chemical and dynamical evolution of galaxies
- Testbed for stellar evolution (especially at low metallicity)

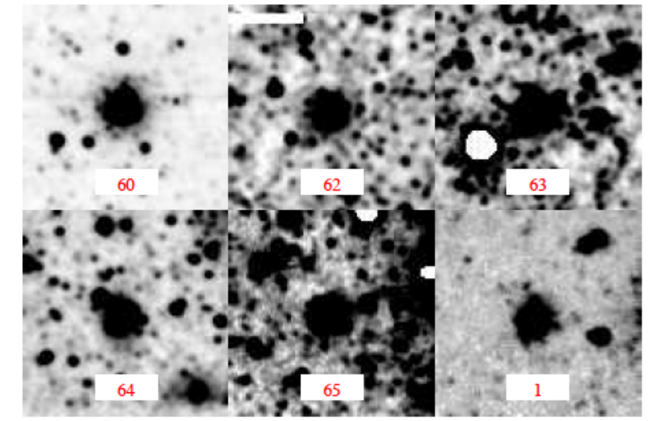


FIG. 2.— Gray scale maps of thumbnail R band Suprime-cam images of five newly found star clusters in IC 10, and one known star cluster (ID 1). Field of view of each image is 10″by 10″. North is up and east to the left.

Form Grebel et al. 2003

Table 1. Star Clusters in the Local Group

Galaxy	Type	D_{Sp} [kpc]	M_V [mag]	N_{GC}	S_N	[Fe/H] [dex]	N_{OC}
M31	Sb I-II	0	−21.2	~600	2:	−2.5, 0.4	many
Galaxy	S(B)bc I-II	0	−20.9	~160	0.7	−2.5, 0.4	>1000
M33	Sc II-III	220	−18.9	$\gtrsim$54	1.5:	−3.0, −0.8	> 600
LMC	Ir III-IV	50	−18.5	~13	0.5	−2.3, −1.2	$\gtrsim$4000
SMC	Ir IV/IV-V	63	−17.1	1	0.1	−1.4	$\gtrsim$2000
NGC 6822	Ir IV-V	500	−16.0	1	0.4	−2.0	~20
WLM	Ir IV-V	840	−14.4	1	1.7	−1.5	≥1
IC 10	Ir IV:	250:	−16.3	0	0	—	$\gtrsim$13
IC 1613	Ir V	500	−15.3	0	0	—	$\gtrsim$5
Phe	dIrr/dSph	405	−12.3	[4:]	[48:]	—	?
PegDIG	Ir V	410	−11.5	0	0	—	$\lesssim$3
LGS 3	dIrr/dSph	280	−10.5	0	0	—	$\lesssim$13
NGC 205	Sph	60	−16.4	$\gtrsim$8	$\gtrsim$2.2	−1.9, −1.3	≥2
NGC 185	Sph	170	−15.6	$\gtrsim$6	$\gtrsim$3.4	−2.5, −1.2	some
NGC 147	Sph	100	−15.1	≥4	$\gtrsim$3.6	−2.5, −1.9	?
Sgr	dSph(t)	28	−15.0:	≥4	≥4:	−2.0, −0.4	0
For	dSph	138	−13.1	5	22.8	−2.2, −1.8	0

- Diversity in the cluster populations in the Local Group galaxies
- No clear dichotomy between old (globular) and young (open) clusters
- Clusters in the stellar halo of M31 have a mean metallicity that is nearly an order of magnitude higher than the stellar halo of the MW -> different accretion history? (see D'Souza et al. 2018)
- Massive and young clusters in interacting galaxies (see, i.e., clusters in the LMC and SMC) with typical tidal radii < 70 pc with typical lifetimes of at least 1 Gyr).

STAR CLUSTERS IN NEARBY GALAXIES

Photometry and high-resolution spectroscopy of resolved stellar population in stars clusters

	Nearby Galaxies	distance (kpc)	distance modulus	G5III-K0III (clump old clusters)	O5V (MS young clusters)	B0V (MS young clusters)	B5V (MS young clusters)	angular size"	S/N~10, Exposure 1hr
LG	Sagittarius	30	17.39	17.89	11.59	13.29	16.29	68.76	
LG	LMC	50	18.49	18.99	12.69	14.39	17.39	41.25	Photometry with MAVIS
LG	SMC	60	18.89	19.39	13.09	14.79	17.79	34.38	HRb 3x3 3600 S/N=10
LG	Sculptor	90	19.77	20.27	13.97	15.67	18.67	22.92	HRr3x3 3600 S/N=10
LG	Sextans	90	19.77	20.27	13.97	15.67	18.67	22.92	LRb 3x3 3600 S/N=10
LG	Carina	100	20.00	20.50	14.20	15.90	18.90	20.63	HRr 3x3 3600 S/N=10
LG	Fornax	140	20.73	21.23	14.93	16.63	19.63	14.73	
LG	Phoenix	400	23.01	23.51	17.21	18.91	21.91	5.16	
LG	NGC6822	500	23.49	23.99	17.69	19.39	22.39	4.13	
LG	IC1613	720	24.29	24.79	18.49	20.19	23.19	2.86	
LG	Tucana	870	24.70	25.20	18.90	20.60	23.60	2.37	
LG	WLM	930	24.84	25.34	19.04	20.74	23.74	2.22	
LG	Aquarius	1020	25.04	25.54	19.24	20.94	23.94	2.02	
Sextans group	Sextans A	1500	25.88	26.38	20.08	21.78	24.78	1.38	
Sextans group	Sextans B	1500	25.88	26.38	20.08	21.78	24.78	1.38	
Sextans group	NGC3109	1500	25.88	26.38	20.08	21.78	24.78	1.38	
Local Uni	NGC5253	3150	27.49	27.99	21.69	23.39	26.39	0.65	
Local Uni	NGC7793	3440	27.68	28.18	21.88	23.58	26.58	0.60	
Local Uni	NGC1313	4390	28.21	28.71	22.41	24.11	27.11	0.47	
Local Uni	NGC1705	5100	28.54	29.04	22.74	24.44	27.44	0.40	
Local Uni	IC4247	5110	28.54	29.04	22.74	24.44	27.44	0.40	
Local Uni	NGC1433	8300	29.60	30.10	23.80	25.50	28.50	0.25	
Local Uni	NGC1291	10400	30.09	30.59	24.29	25.99	28.99	0.20	

Within 100 kpc

- Star clusters of **all ages**, complete chemical characterisation of the host galaxy (age-metallicity relationship, radial metallicity gradients, etc.)
- Chemical characterisation of star clusters, seeking homogeneity (or inhomogeneity) and abundance anti correlation in young analogues of Galactic globular clusters

Within 1.5 Mpc

- Young massive star clusters (low and high-resolution spectroscopy and photometry) to:
  - Constrain the IMF in dense, starburst regions, metal-poor environments
  - Mass loss in massive stars, origin of fast-rotating massive stars, binarity fraction, consequence on surface abundances

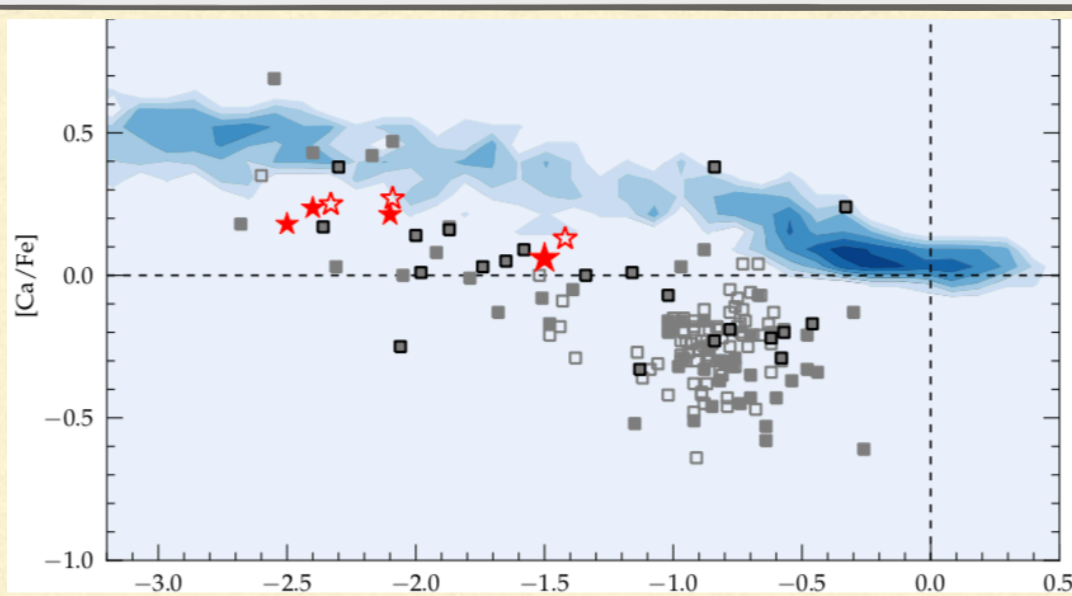
STAR CLUSTERS IN NEARBY GALAXIES

Do clusters show the same chemical composition of the field stars?

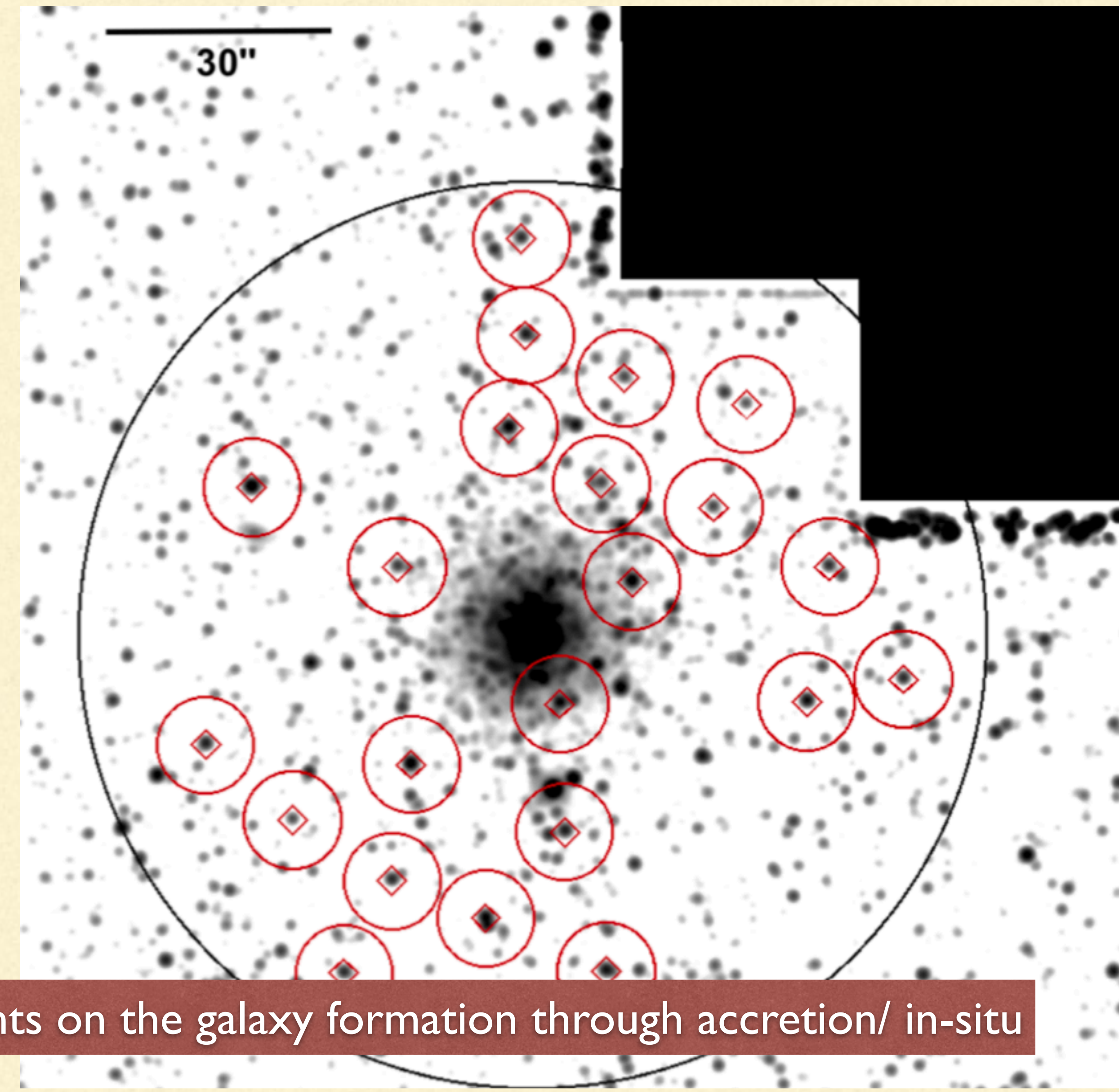
<u>Photometry and high-resolution spectroscopy of resolved stellar population in stars clusters</u>

Within ~100 kpc

- Resolving the CMD of each cluster
- Individual spectroscopy of brightest stars
- Abundances of many nucleosynthesis channels: constraints on time scales of galaxy evolution



Hendricks et al. 2016



Constraints on the galaxy formation through accretion/ in-situ

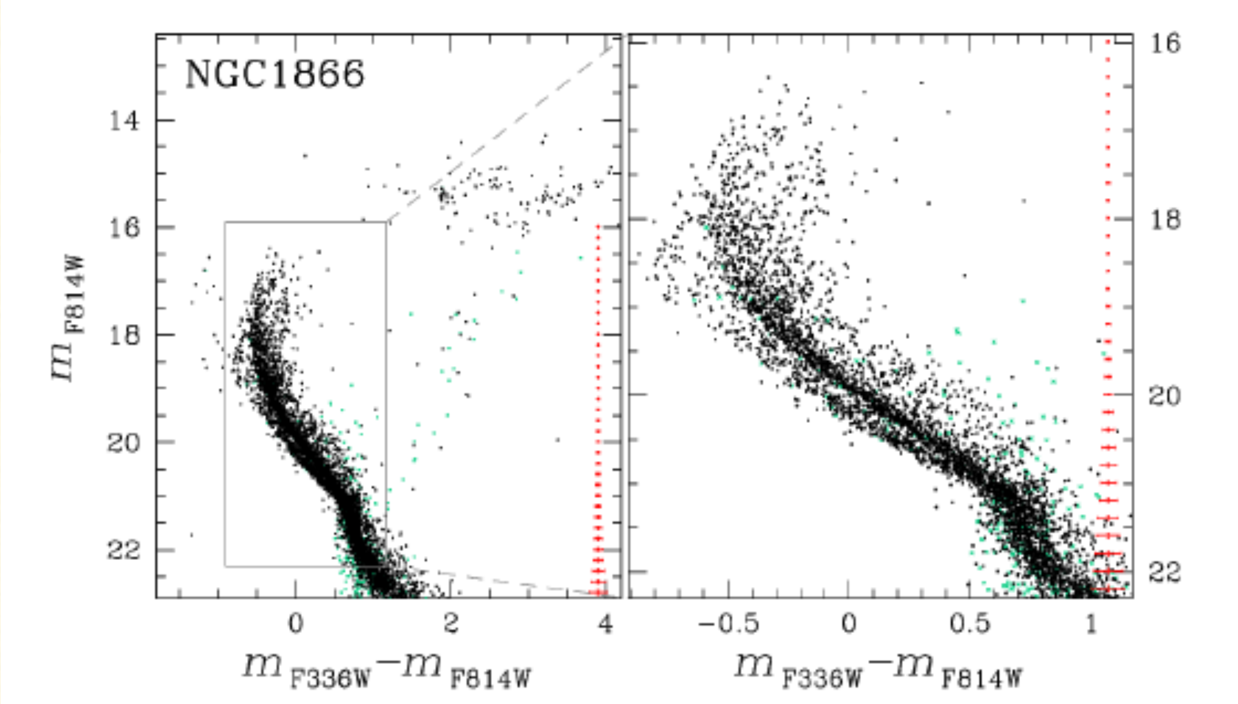
Star cluster population in Fornax (from Hendricks et al. 2016)

WHAT WE CAN LEARN FROM STAR CLUSTERS: MASSIVE CLUSTERS IN THE MAGELLANIC CLOUDS

- High-resolution spectroscopy of individual stars in massive clusters in the MCs to shed light on the debated origin of the multiple populations in Galactic globular clusters (see, e.g., Milone et al. 2018),

- With MAVIS we can reach in **1 hr exposure time a SNR~10 in the MS (m~20), and a SNR > 100 at the MS turn-off and in the clump.**

- The expected SNR for the high-resolution spectra will allow to detect chemical peculiarities and anti-correlations in the multiple populations of MC massive star clusters —> **from the Main Sequence to evolved giant stars**



Multiple populations in NGC1866, from Milone et al. 2018

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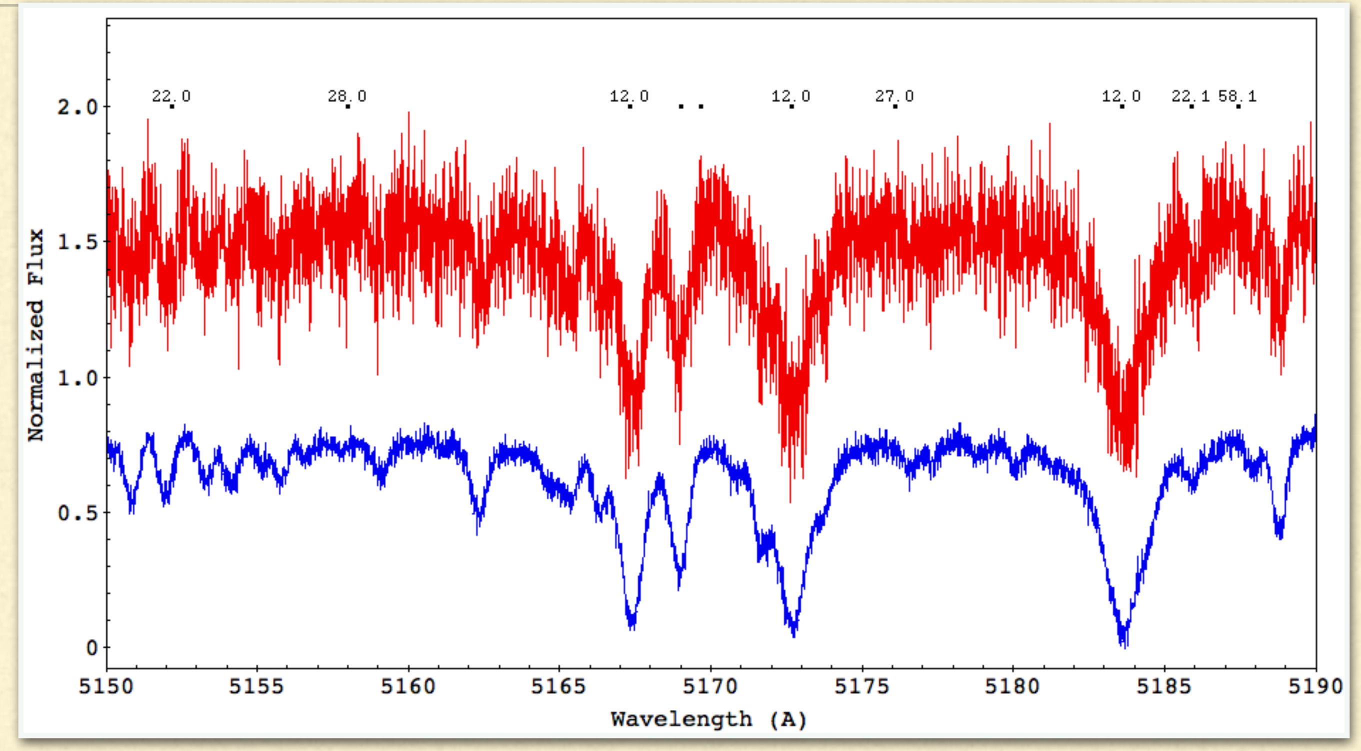

Simulated spectra at R=15000 of a G-type star at SNR~10 (red spectrum) and SNR~35 (blue spectrum). Some absorption lines are marked and labelled with the atomic number of the corresponding element.

SNR~40	*Fe*	*Mg*	*Ca*	*Co*	*Cr*	*Cu*	*Na*	*Ni*	*Sc*	*Si*	*Ti*	*V*	*Y*	*Zn*	*Zr*
15000	9	1	1	4	8	2	1	3	4	3	8	5	4	1	1

STAR CLUSTERS IN NEARBY GALAXIES

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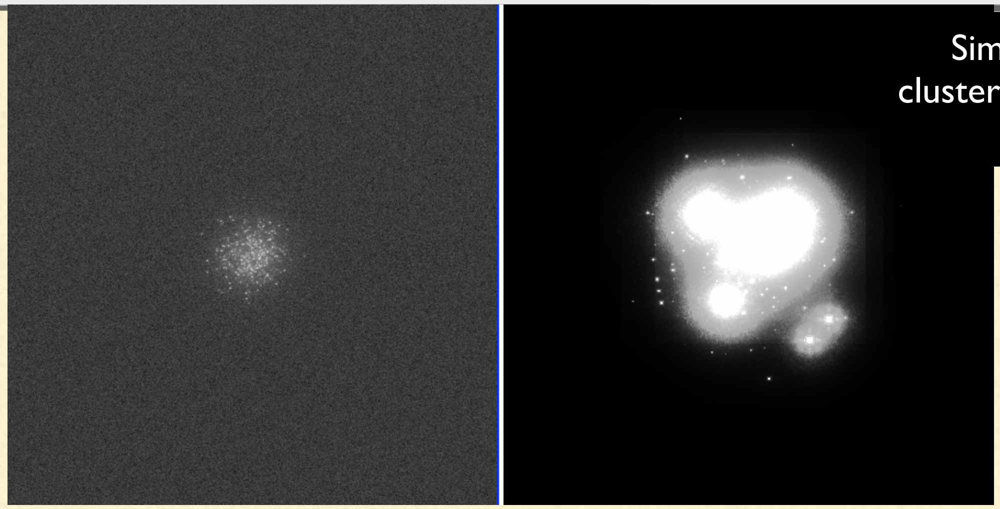
S/N~10, Exposure 1hr
Photometry with MAVIS
HRb 3x3 3600 S/N=10
HRr3x3 3600 S/N=10
LRb 3x3 3600 S/N=10
HRr 3x3 3600 S/N=10

Within d < 10 Mpc

- Photometry of resolved stellar populations in stars clusters
- Cluster mass function
- Colour-magnitude diagrams to estimate age and cluster properties
- Integrated spectra to derive global metallicity and sensitive abundance ratio, as [alpha/Fe]



Simulated old and young clusters@3Mpc, the images are both 6"×6".

STAR CLUSTERS IN NEARBY GALAXIES

2”x2” MAVIS simulated image

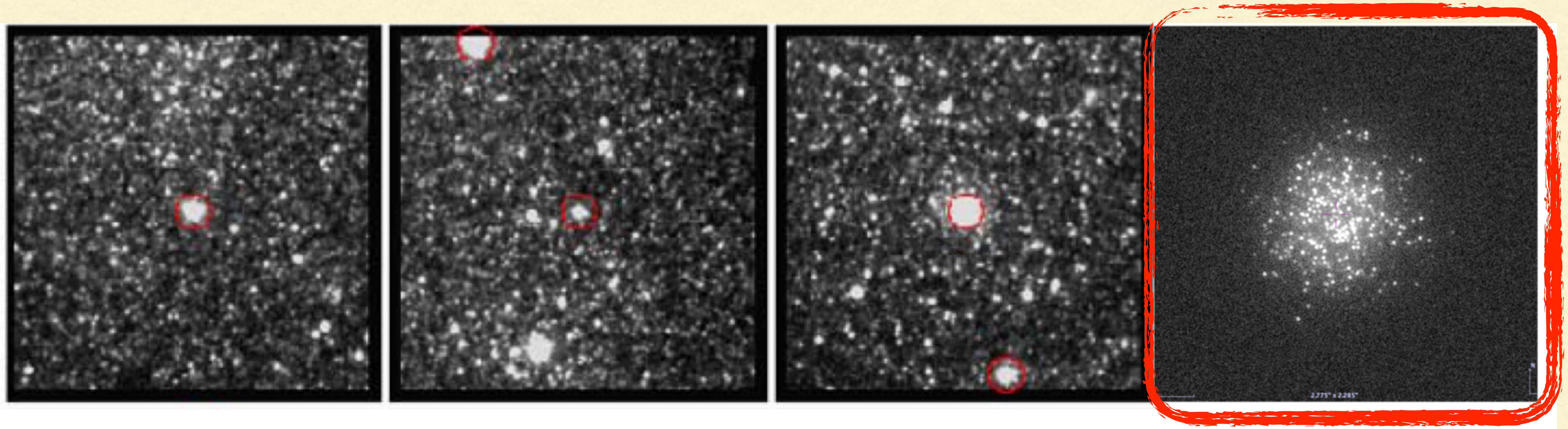
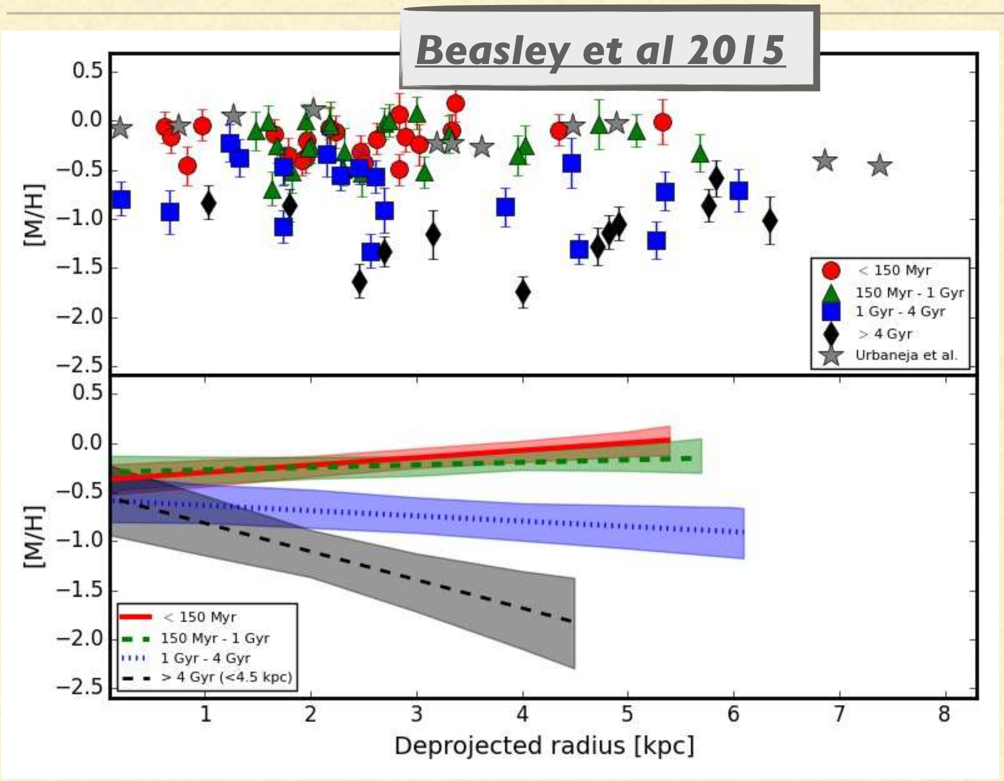


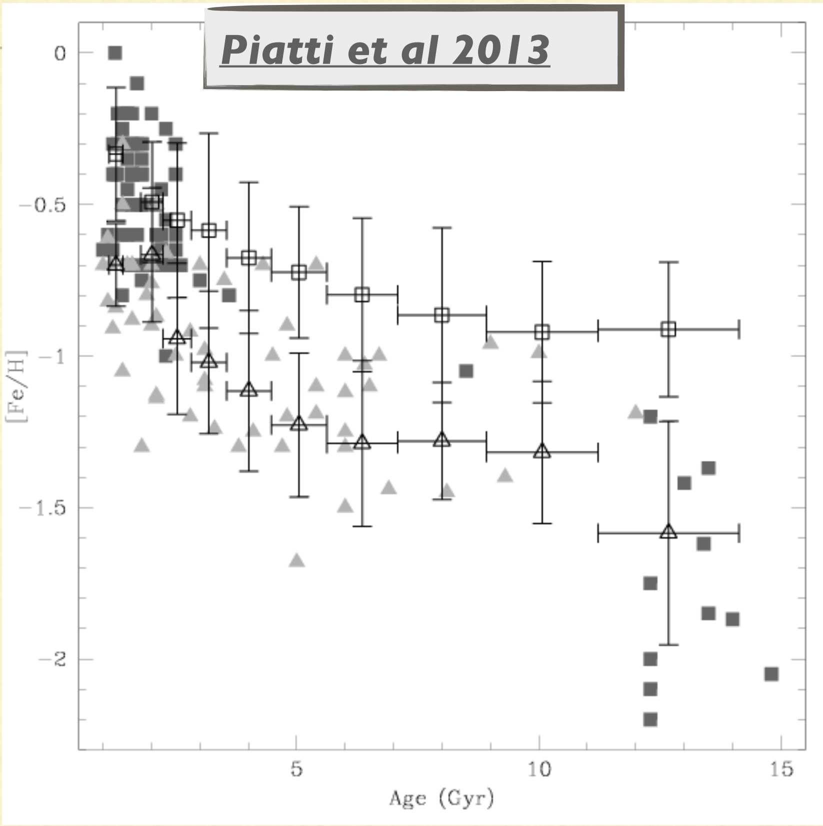
Figure 2: *Left 3 panels:* Stars clusters in NGC 7793 observed with HST from [11]. The images have sizes of 100×100 pixels (~5”x5”). *Right*: Simulated V-band image of an old stars cluster (1,000 $M_\odot$, half-light radius of 5 pc, t_{exp}=1 hr) at the distance of NGC 7793. The angular size of this image is ~2”x2”.

For Mavis White Papers

Star clusters at the distance of NGC7793, i.e., d=3.9 ± 0.4 Mpc

AGE-METALLICITY RELATION AND RADIAL METALLICITY GRADIENTS

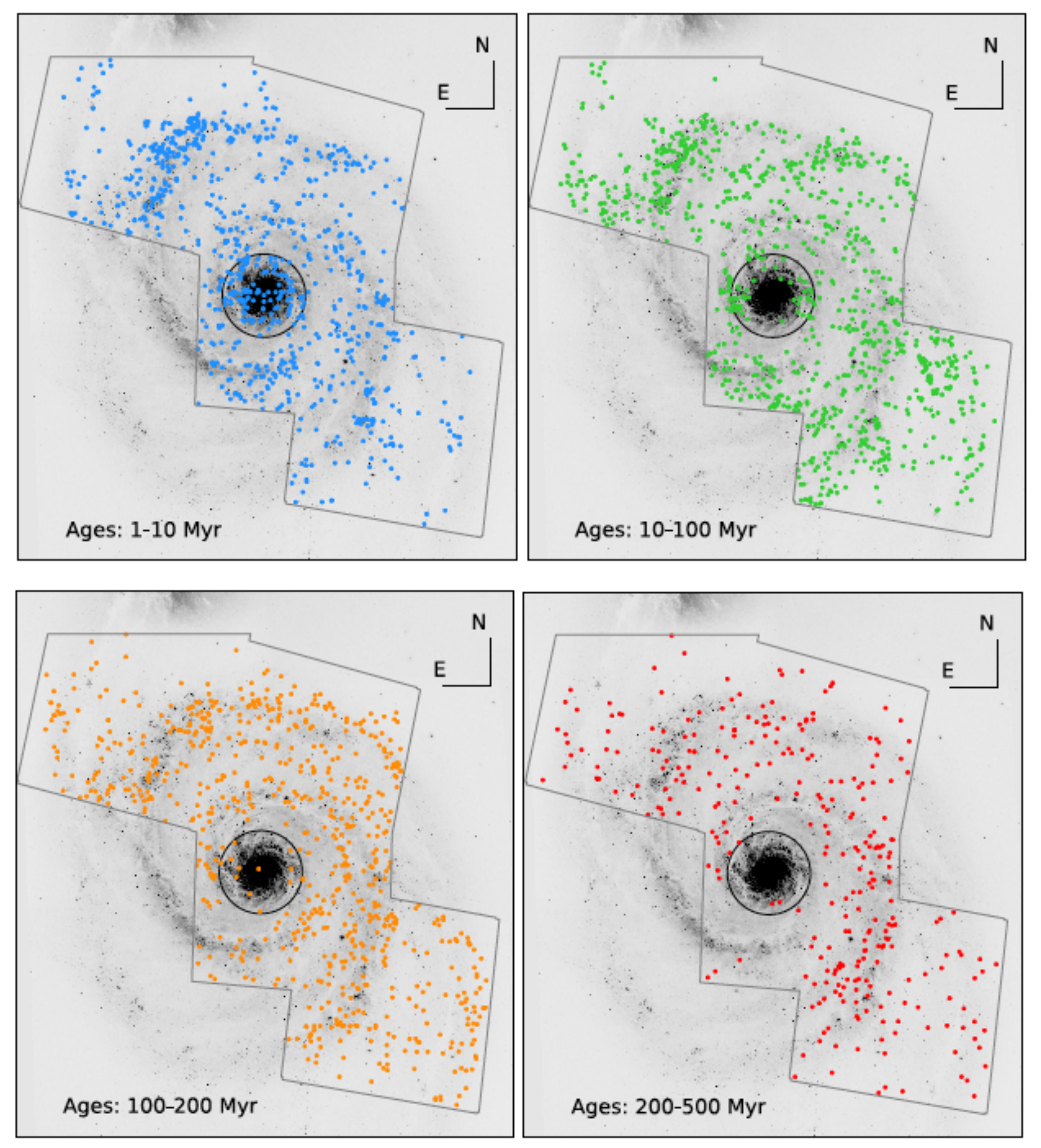




Constraints to the formation and evolution of galaxies:

- Time-evolution of the spatial distribution of abundances: how does the radial metallicity gradient evolve with time?
- How does the age-metallicity relationship tell us about the galaxy evolution? Are they evolving as closed-box or bursting system?
- **MAVIS will allow: age determination (resolved CMD), measurements of different elements with different time-scales**

STAR CLUSTERS IN NEARBY GALAXIES



Cluster populations in M51 (from LEGUS Survey, Messa et al. 2018)

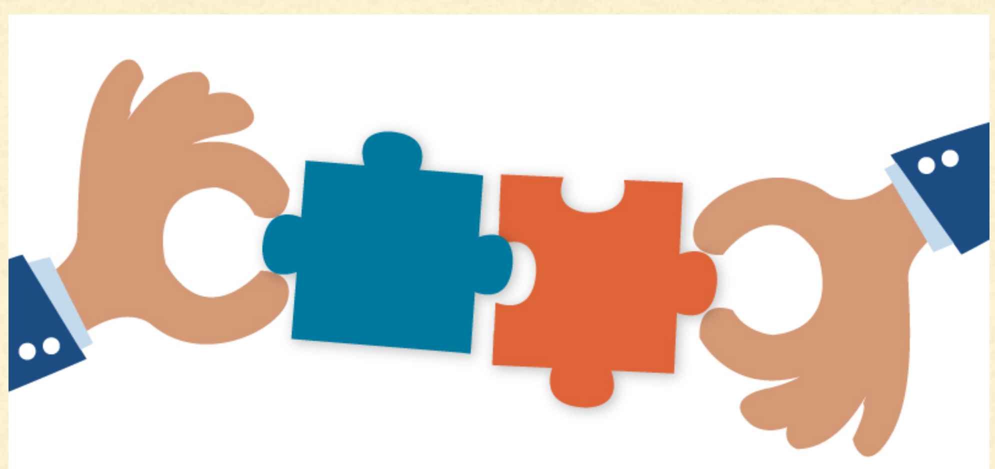
Photometry and low- and high-resolution spectroscopy of integrated light of stars clusters

D > 10 Mpc

- Complementary to the LEGUS (Legacy ExtraGalactic UV Survey) with HST, extending to farther galaxies
- Resolving star cluster populations in galaxies of different morphology, environment, metallicity, etc. to investigate:
-
    - Evolution of clustering star formation
    - Cluster evolution (dissolution, survival time, etc.)
    - Effect of environment

MAVIS PHOTOMETRY AND SPECTROSCOPY:
AN UNPRECEDENTED TOOL FOR EXTRAGALACTIC STELLAR POPULATIONS

- The joint **photometric and spectroscopic capabilities of MAVIS** can move outside our Galaxy the detailed study of stars clusters, allowing to investigate several scientific topics, so far limited to our Galaxy:
  - The chemical evolution of galaxies of different morphological types
  - The nature of cluster populations in different galaxies, and their relationship with the field populations, of morphology, environment, metallicity, etc.
  - The age-metallicity relationships, and spatial distribution of abundances (also as a function of time)



High-z Universe

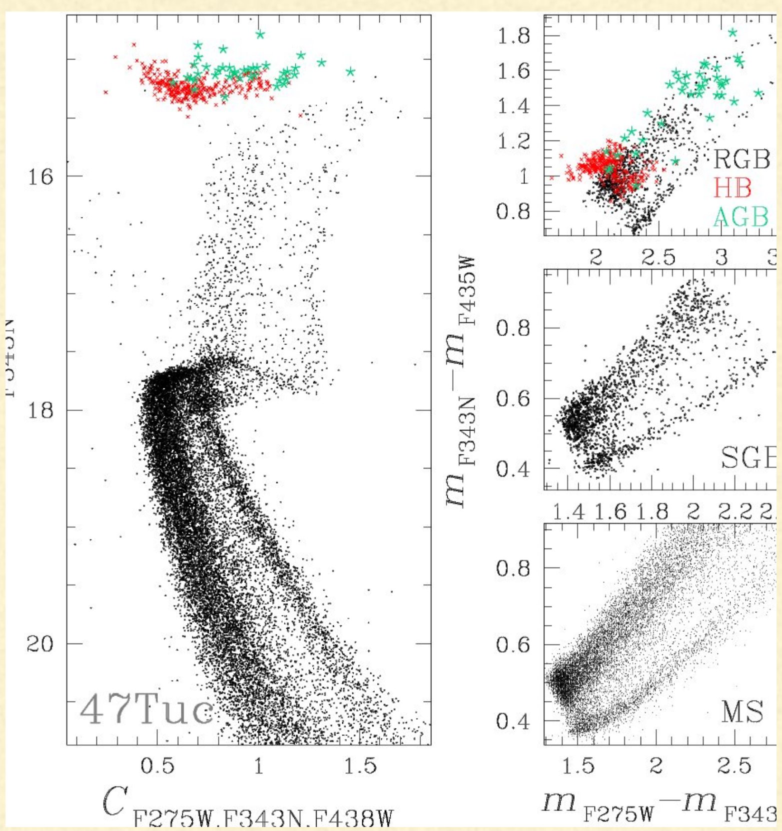
Our Galaxy

FACING THE SAME PROBLEM FROM INSIDE THE MW: THE CORES OF GALACTIC GLOBULAR CLUSTERS

Most of the Galactic Globular clusters show chemical peculiarities, as anti-correlation between Na and O. Usually only the less crowded regions of the clusters are observed.

The cores of GGCs have never been explored.

- Limited to red giant branch —> need MS, unevolved
- No info on the radial distribution of GGC stars —> need central regions to disentangle formation scenarios (e.g. Bastian et al. 2015).



Milone et al. (2013)

- 50 GGCs with HST photometry suitable for spectroscopy and photometry with MAVIS
- MAVIS High-Res spectroscopy at R=15,000 allows precise measurements of abundances in three key nucleosynthetic families; light elements such as C, N and O, alpha elements such as Na, Mg and Al, and neutron capture elements such as Ba, La, Eu.
- SNR~30 allows ~0.1 dex on abundances —> ~1 hr at magB=18

Seeing-limited spectrographs limit the study to the outer cluster region