Pulsating variable stars, powerful tools for galactic structure and evolution

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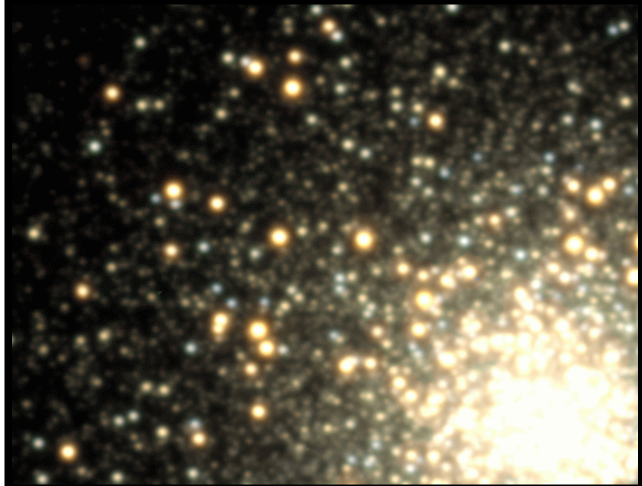
Sevres, 7-11 June 20010

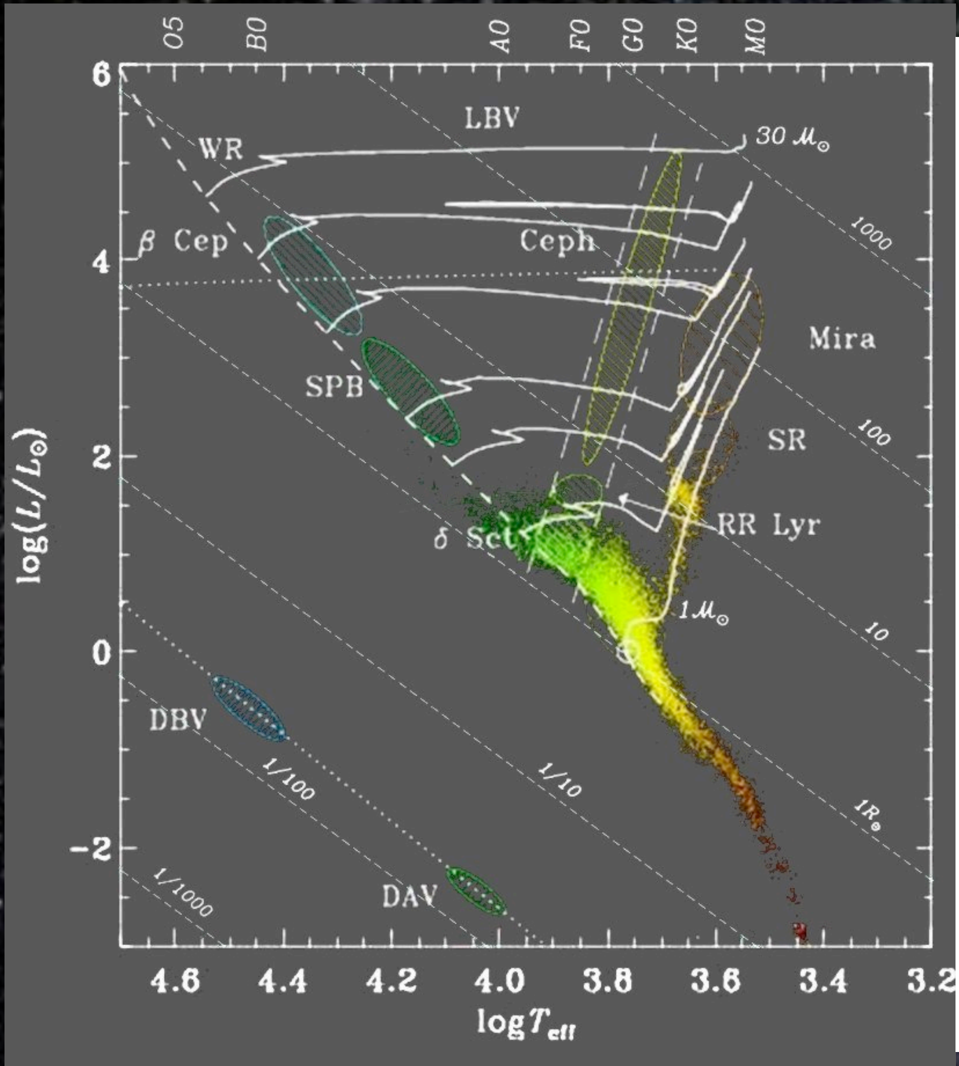
Variable stars: Why?

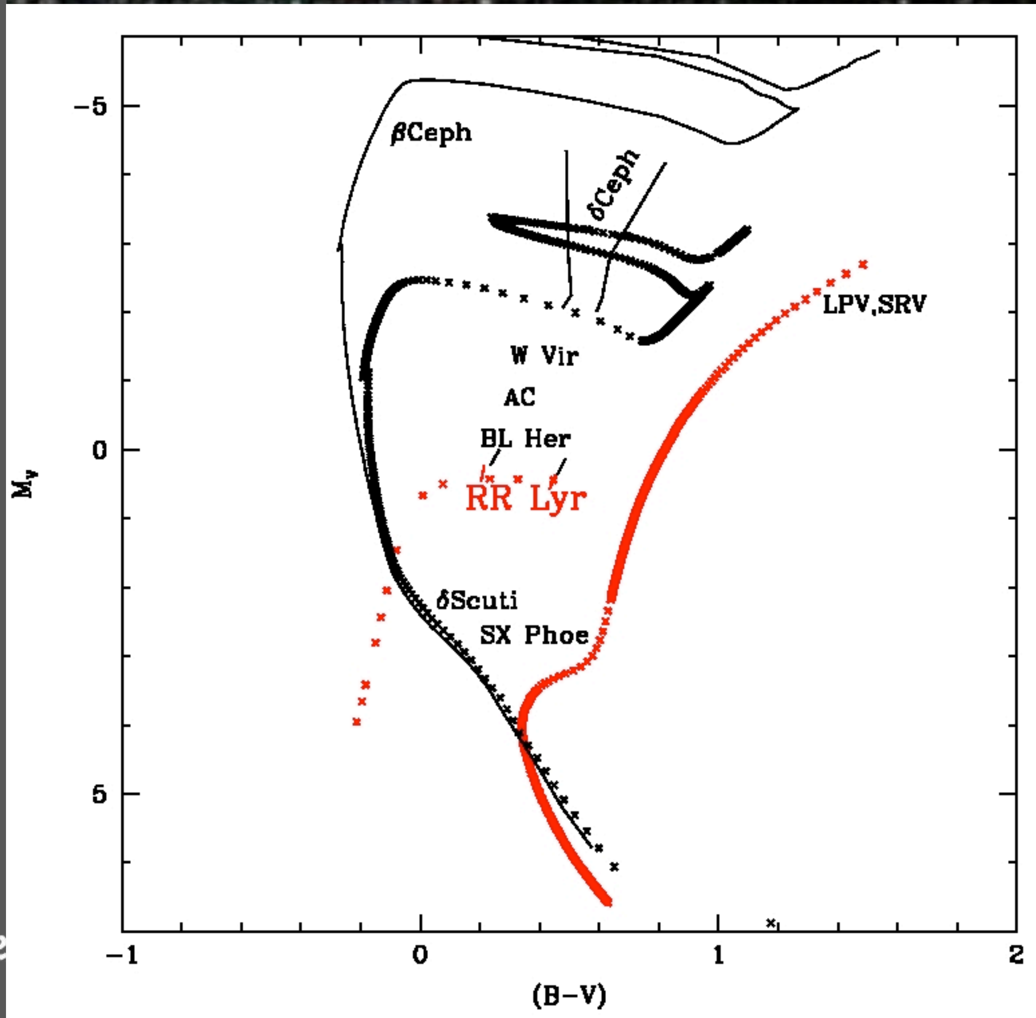
- set the astronomical distance scale
- trace different stellar generations in galaxies
- map 3D structures, radial trends, halos, streams
- provide hints on how galaxies have formed



"easily" recognized thanks to the light variation, periods and amplitudes are unaffected by distance and reddening

Pulsating Variable stars





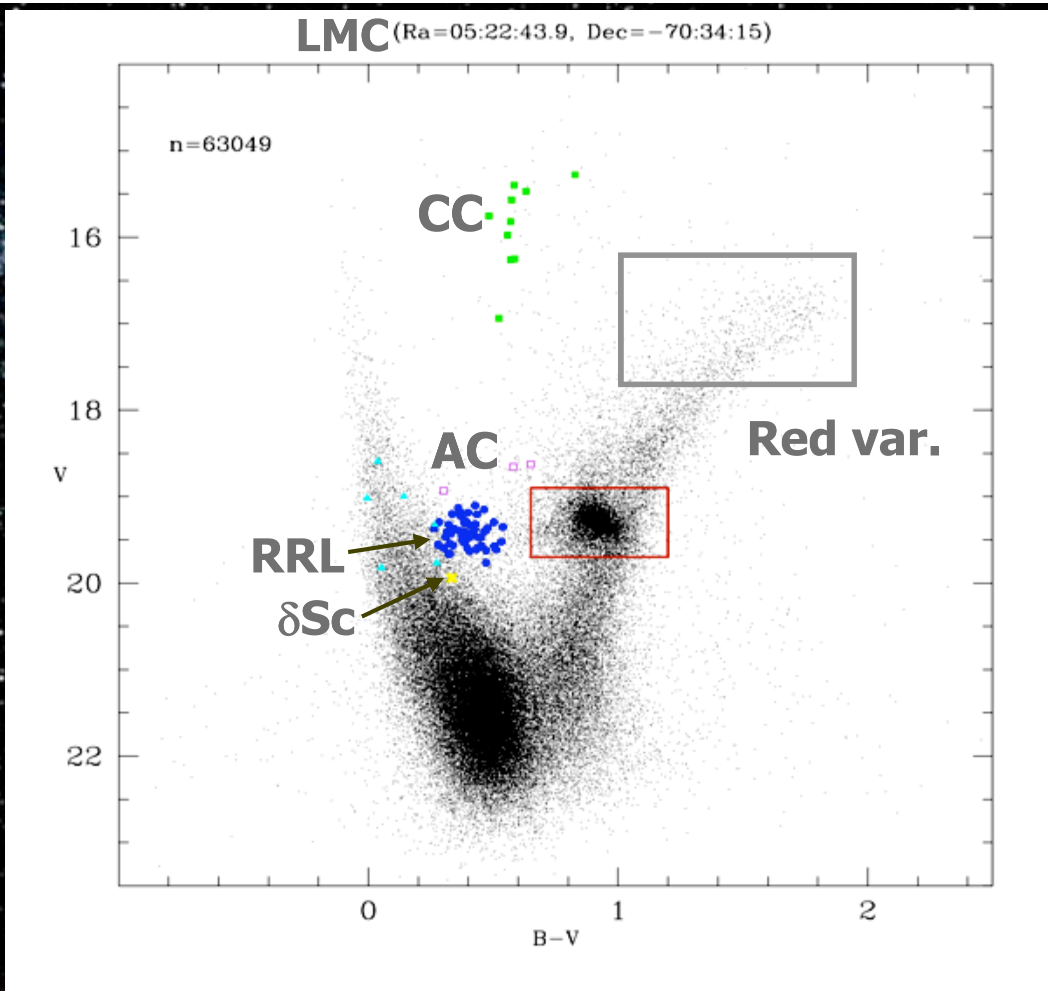
Pulsating Stars

Class	Period (days)	M_V	Pop	Evo. Phase
δ Cephei (CC)	1 - 100(?)	-7(-8) ÷ -2	I	Blue Loop
δ Scuti (δSc)	< 0.5	2 ÷ 3	I	MS-PMS
β Cephei	< 0.3	-4.5 ÷ -3.5	I	MS
RV Tauri	30 - 100	-2 ÷ -1	I, II	post-AGB
Miras	> 100	-2 ÷ 1	I, II	AGB
Semiregulars (SR)	> 50	-3 ÷ 1	I, II	AGB
RR Lyrae (RRL)	0.2 - 1	~0.5 ÷ 0.6	II	HB
W Virginis (Type2C)	10 - 50	-3 ÷ -1	II	post-HB
BL Herculis (Type2C)	< 10	-1 ÷ 0	II	post-HB
SX Phoenicis (SXPhe)	< 0.1	2 ÷ 3	II	MS
ACs	0.3 - 2.5	-2 ÷ 0	?	HB-turnover
SP Cepheids (SPC)	< 2	≤ 0.0	I	Blue Loop
LL Cepheids (LLC)	0.55 - 0.65	≤ 0.4	?	?

adapted from Marconi 2001

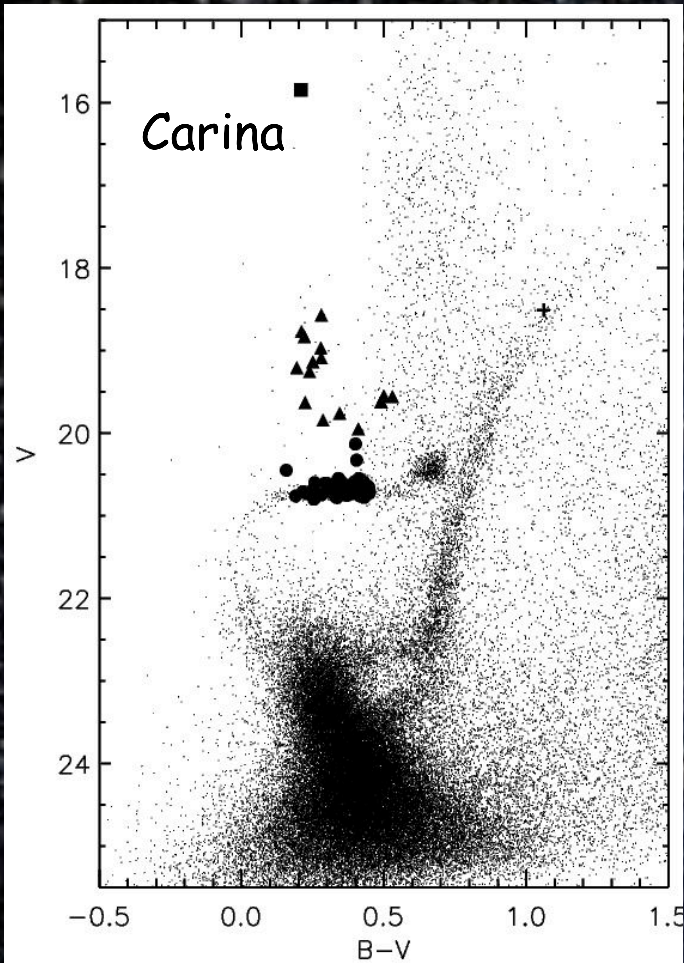
➢ trace different stellar generations in galaxies

- old (t > 10 Gyr) ➡ RR Lyrae, Pop II Cepheids, (SX Phoenicis)
- intermediate age ➡ Anomalous Cepheids, LL Cepheids (?)
- young (t < 100 Myr) ➡ Classical Cepheids, (δ Scuti stars)

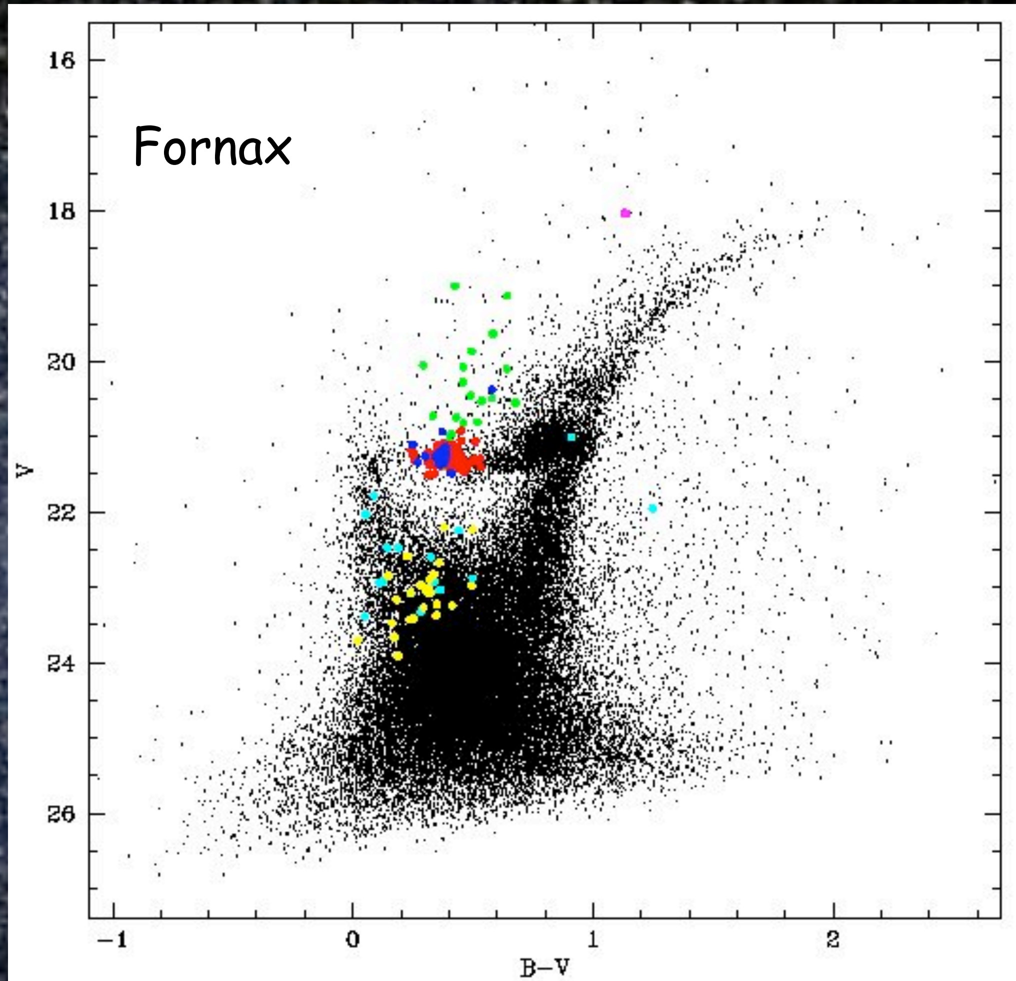


adapted from Clementini et al. 2003

➢ trace the different stellar generations in galaxies



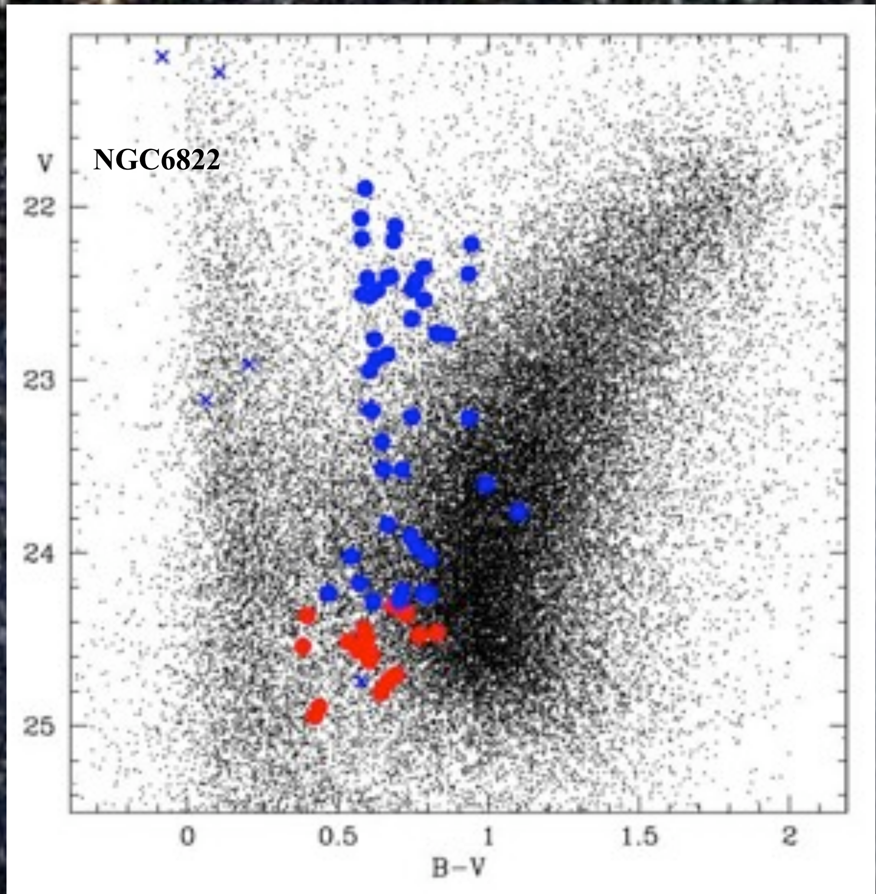
Fornax



Dall’Ora et al. 2003

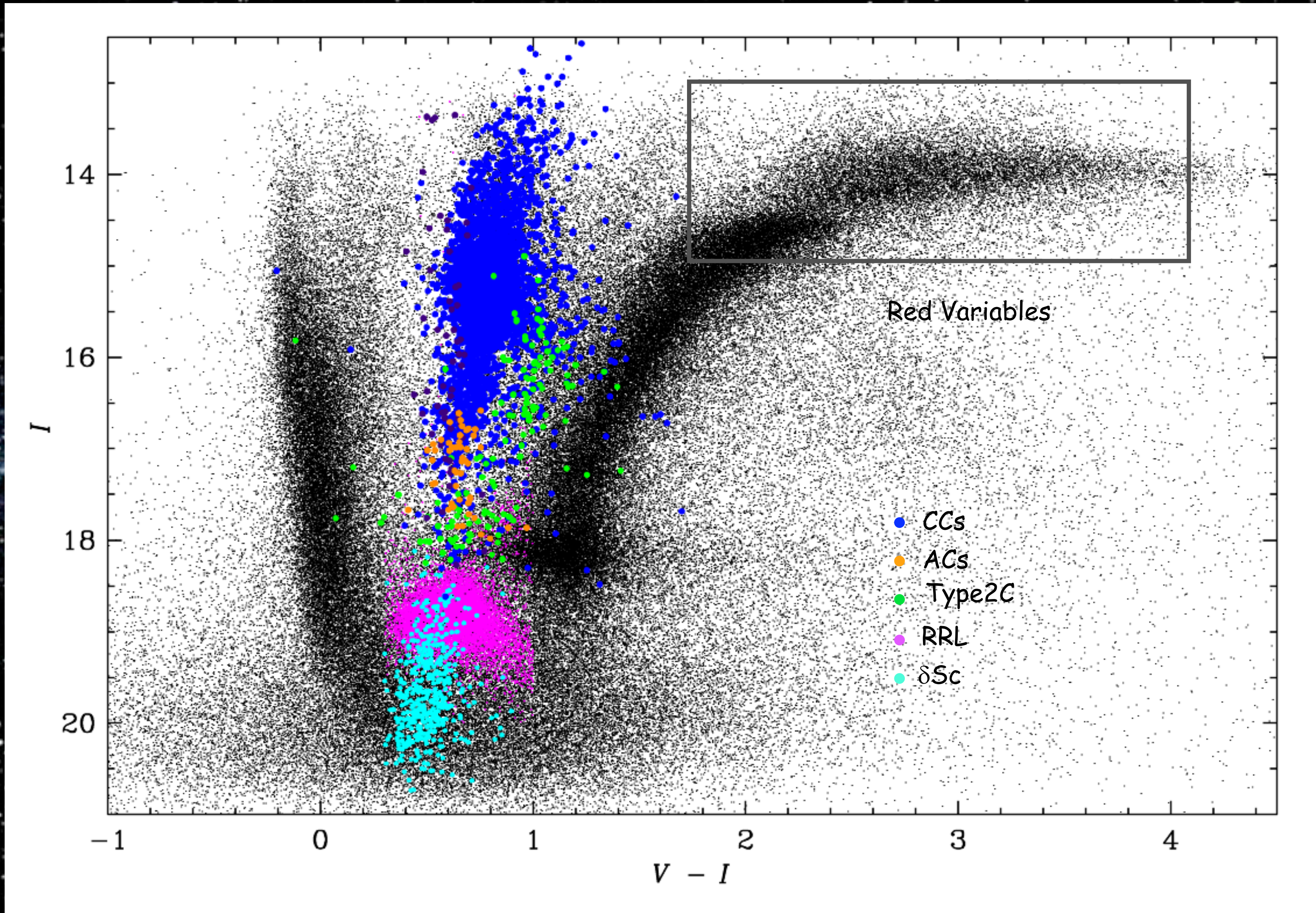
Greco et al. 2007

➢ trace the different stellar generations in galaxies



Clementini et al. 2003

LMC variables from OGLE III



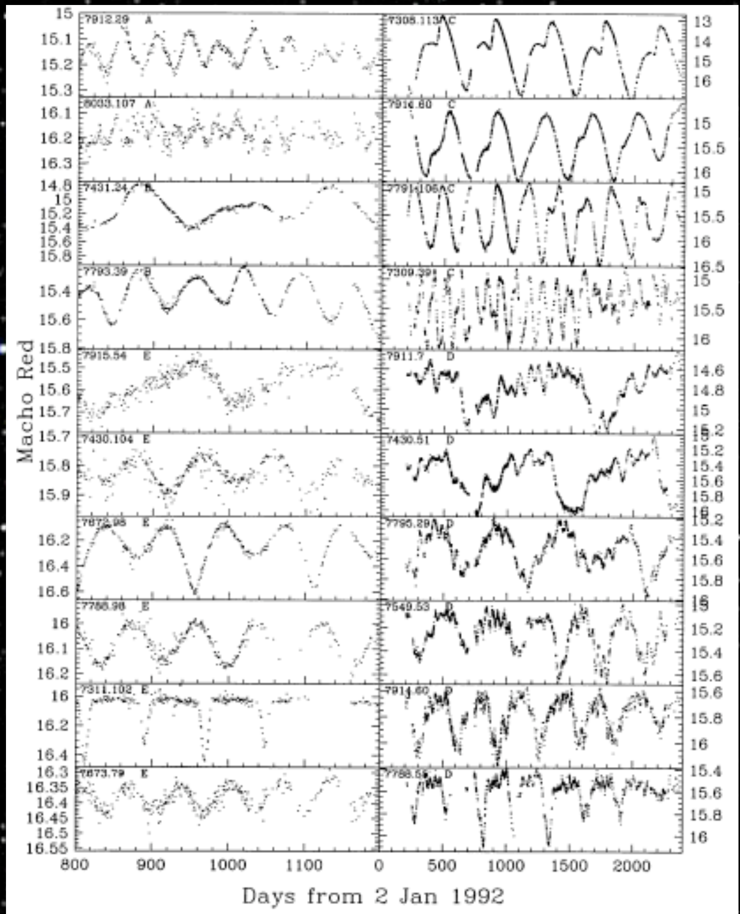
Soszynski et al. 2009

Red Variables

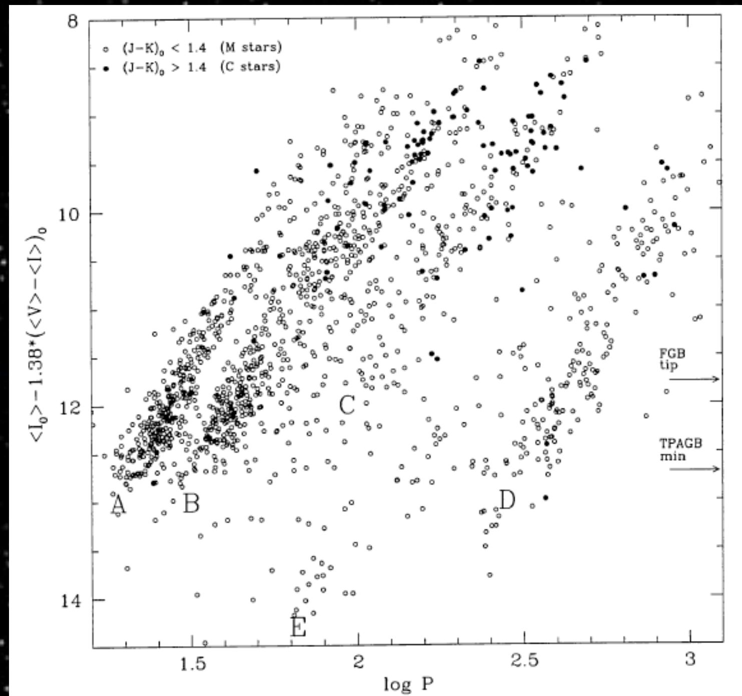
MIRAs – SRs – SARVs/OSARGs – LSPs –Elipsoidal Variables

Light curves often semi-regular and multiperiodic

Mass-loss - Stellar winds - Dust emission



Wood et al. 1999, Wood 2000



A Small amplitude red variables (SARVs)

B Semi Regular variables (SR)

C Miras

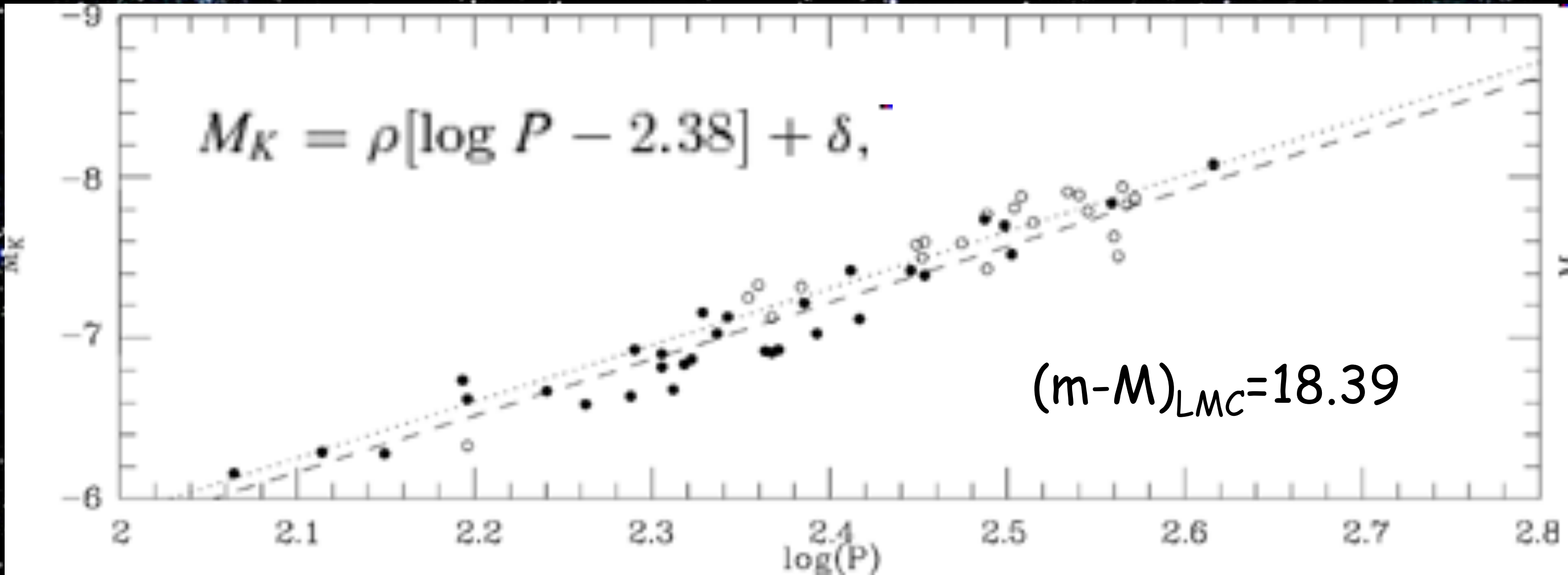
D Long Secondary Period variables (LSPs)

E Binaries

➢ set the astronomical distance scale

Miras	100 ≤ P≤ 1000 days	Pop. I-II	AGB	fundamental-mode	P/L
SRs	P > 50 days	Pop. I-II	AGB		P/L

distance indicators for old and intermediate age populations

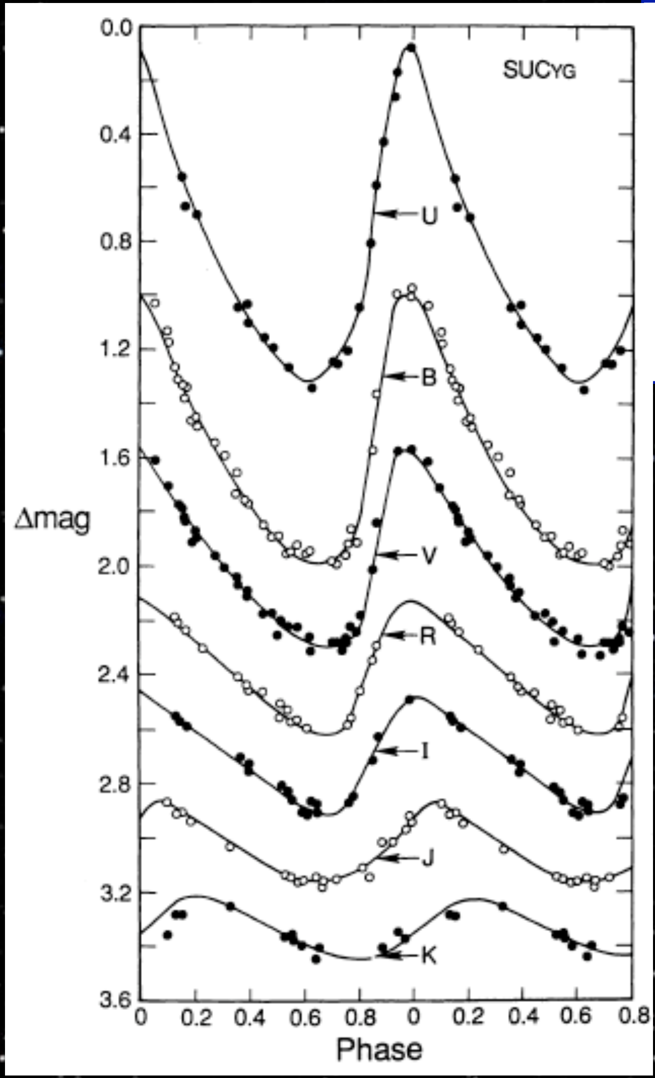


PL(K) relations for O-rich (solid circles) and C-rich (open circles) Miras in the LMC

Whitelock, Feast & van Leeuwen 2008

Classical Cepheids

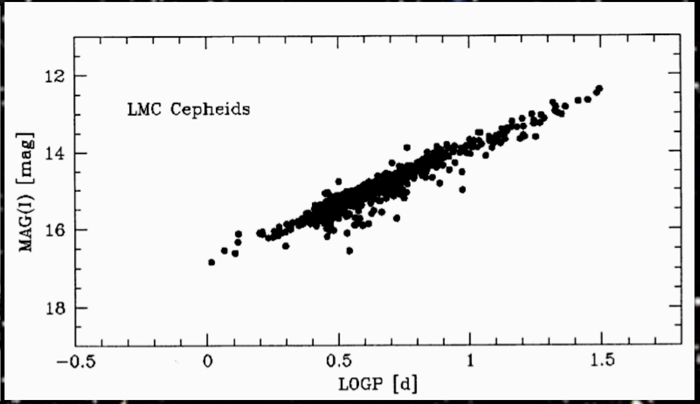
Characteristics



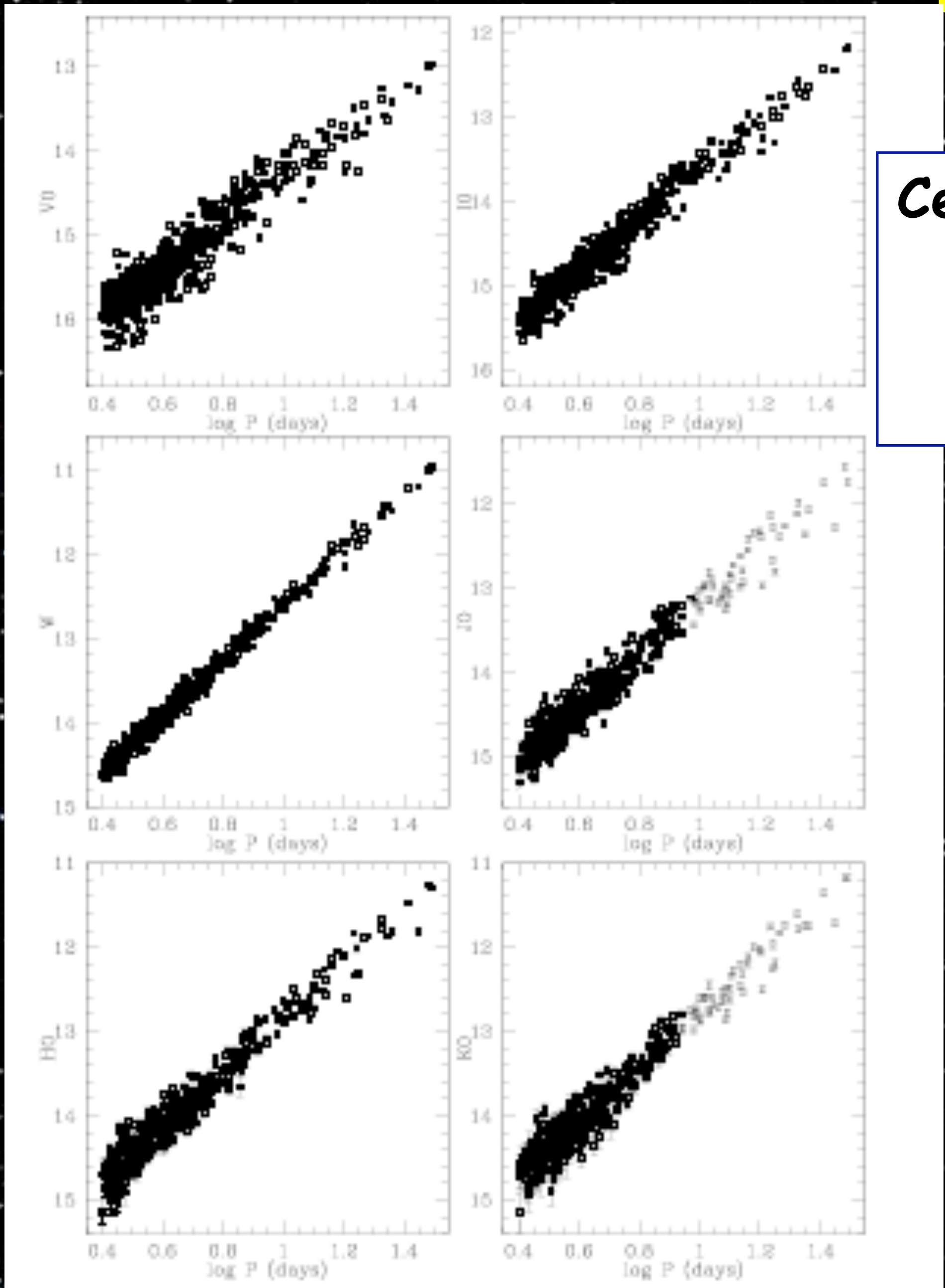
P = 1 – 100(?) days
$A_V \leq 1.5$ mag
S_p Type: F6 – K2
Pop I
Evo. Phase: Blue Loop
Young stars, tracing star forming regions, spiral arms

PL relation, H. Leavitt (1900s)
$L = \alpha \text{Log } P + \beta$
LG ⇒ 100 Mpc ⇒ H_0
HST Key Project and SNIa Project


Scanned at the American Institute of Physics



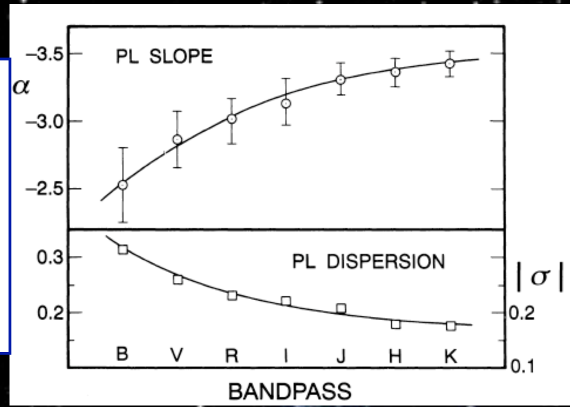
Classical Cepheid P/L relation



MCs Cepheid VIW(Ogle2)JHK P/L relations
Fouque et al . 2003

Cepheid PL relation

$$L = \alpha \text{Log } P + \beta$$



Cepheids in the LMC → α

Trig. Parall. of MW Cepheids → β

B-W of MW Cepheids → β

universal ? — if yes

metallicity dependent ? — if yes

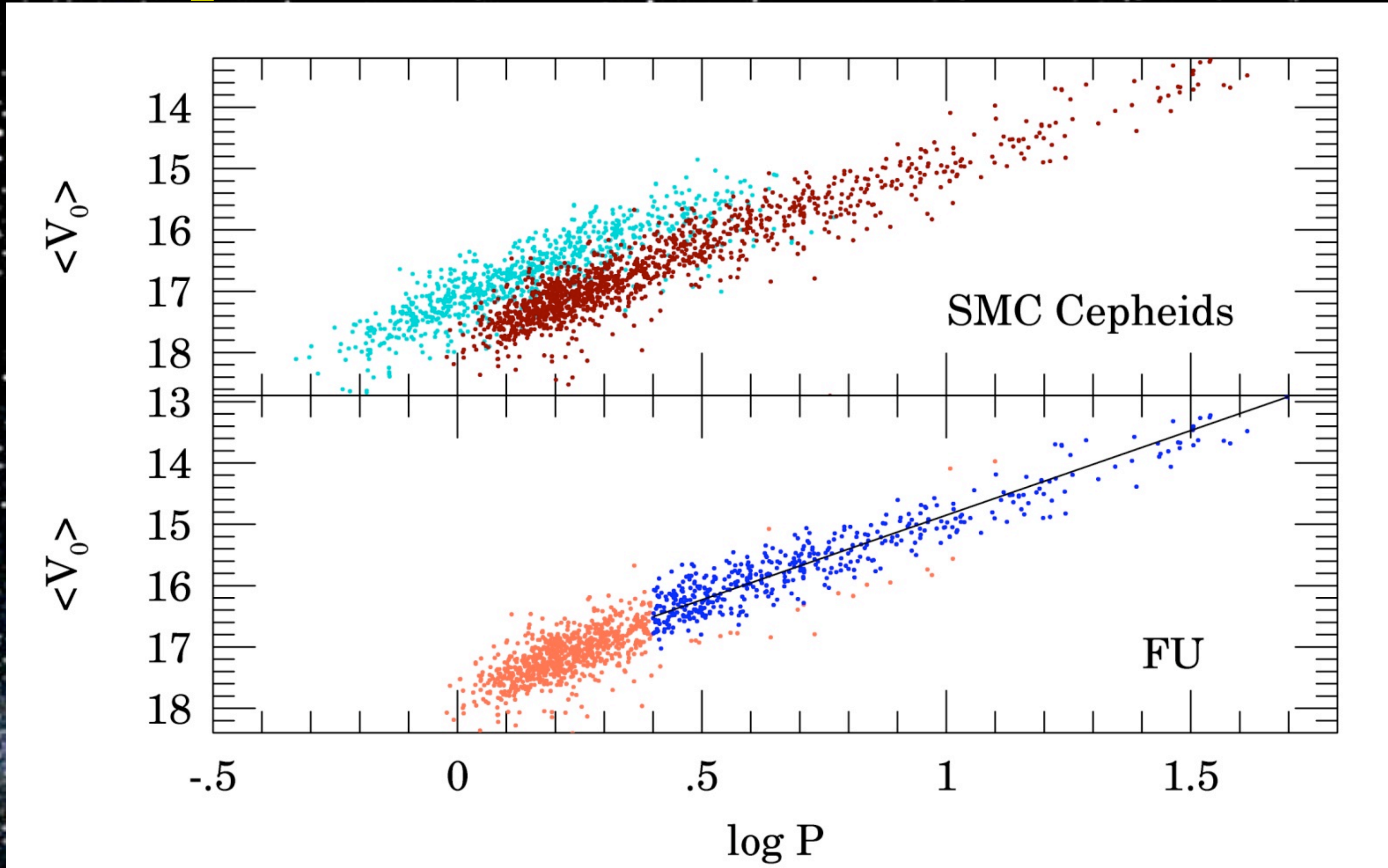
HST Key Project
31 galaxies
700 Kpc < d < 20 Mpc

-0.2 ± 0.2 mag/dex
in V, I

$H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$

Freedman et al. 2001

Cepheid P/L relations in the MCs

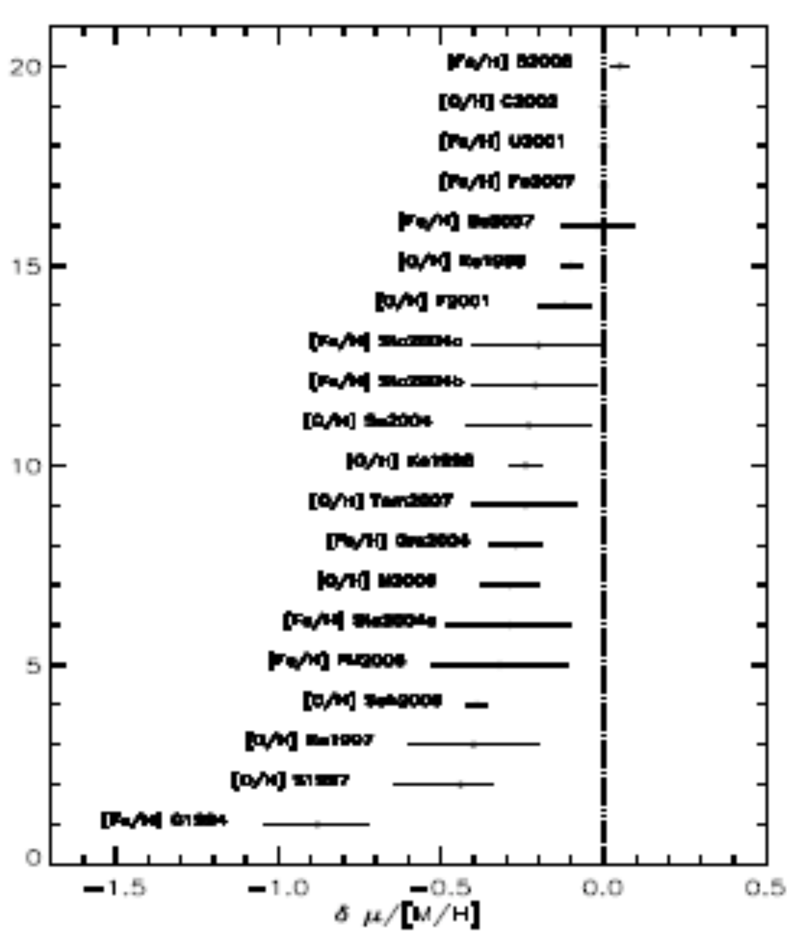


$V_0(LMC)$=-2.760 logP-17.042 σ=0.159 mag (649 FU CCs)

$V_0(SMC)$=-2.760 logP-17.611 σ=0.258 mag (466 FU CCs)

Udalski et al. 1999

- Is the Cepheid P/L relation metallicity dependent?

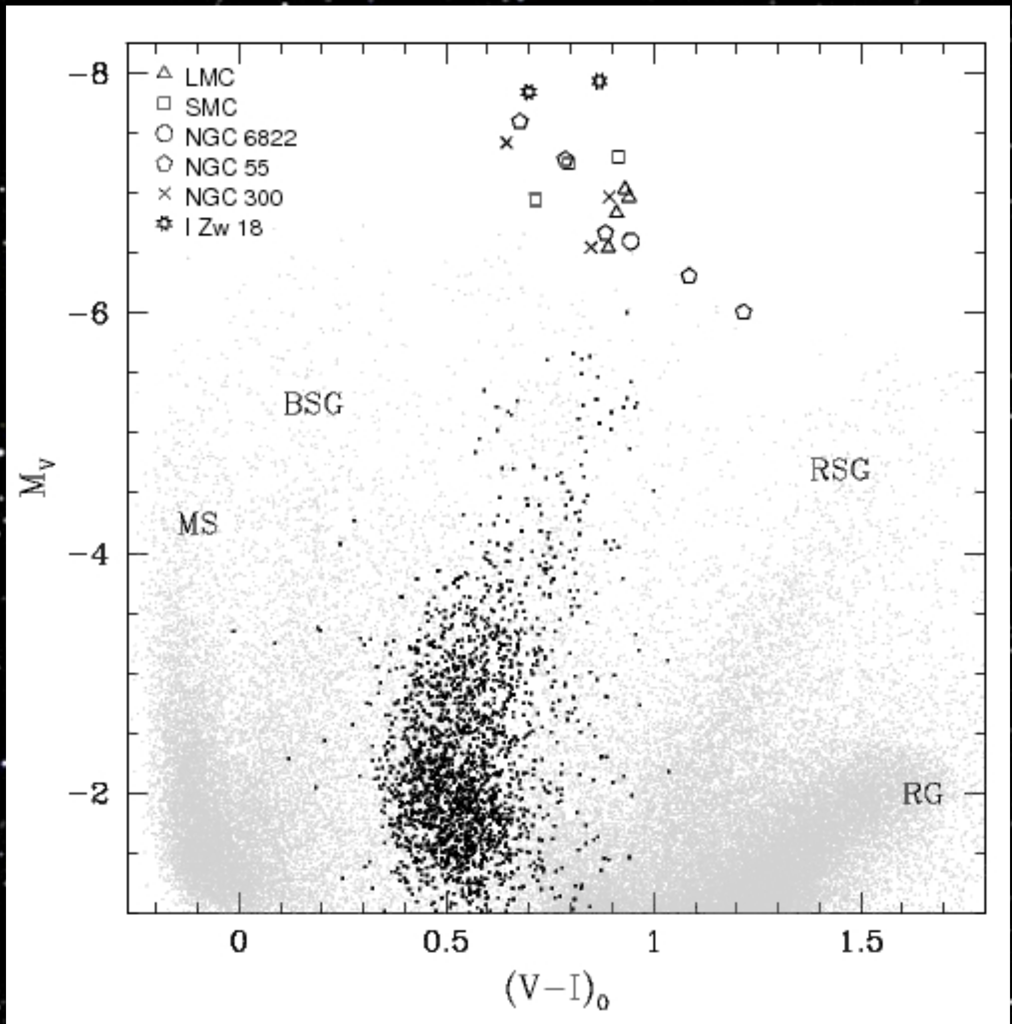


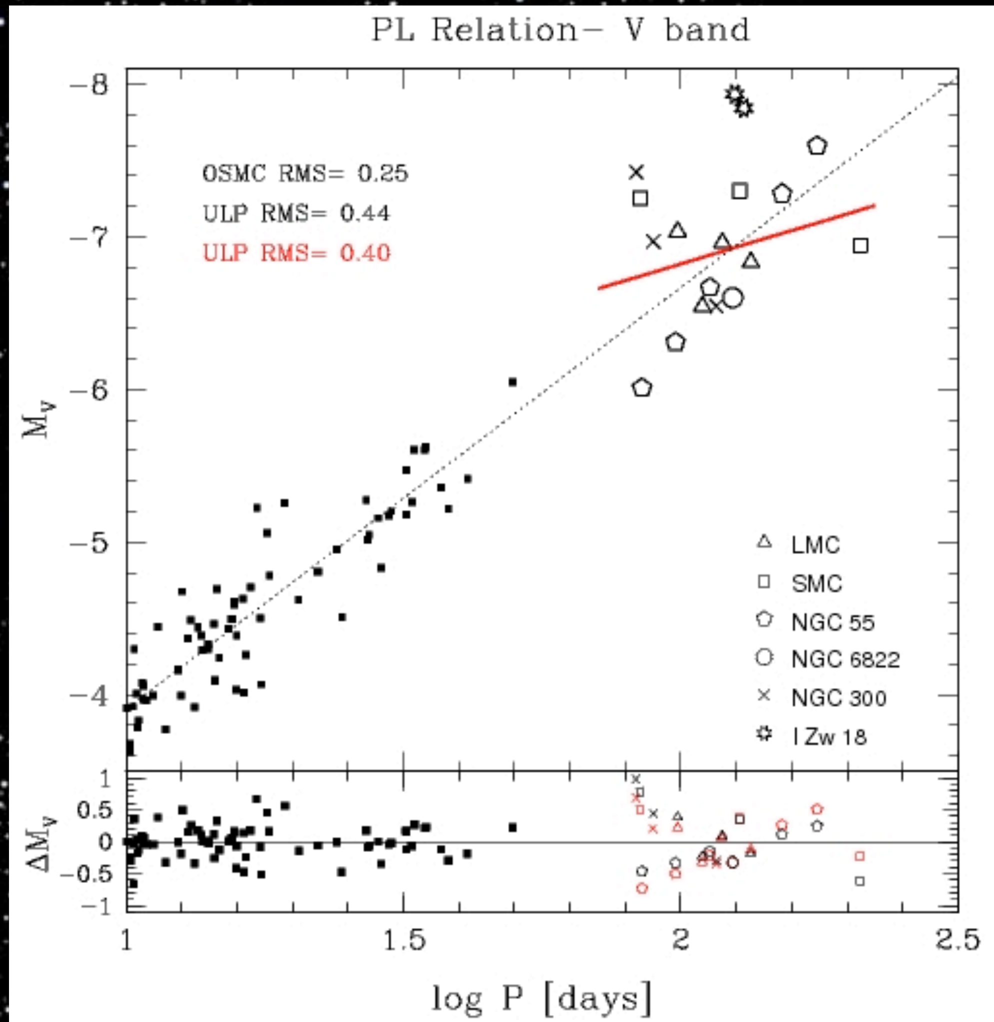
$\delta\mu/\delta[M/H]$ (mag/dex)		Method	Reference
-0.32 ± 0.21	[Fe/H]	Analysis of Cepheids in 3 fields of M31 (*BVRI* bands)	Freedman & Madore (1990)
-0.88 ± 0.16	[Fe/H]	Comparison of Cepheids from 3 fields of M31 and LMC (*BVRI* bands)	Gould (1994)
-0.40 ± 0.20	[O/H]	Simultaneous solution for distances to 17 galaxies (*UBVRIJHK* bands)	Kochanek (1997)
$-0.44^{+0.10}_{-0.20}$	[O/H]	Comparison of EROS observations of SMC and LMC Cepheids (*VR* bands)	Sasselov et al. (1997)
-0.24 ± 0.16	[O/H]	Comparison of HST observations of inner and outer fields of M101	Kennicutt et al. (1998)
-0.12 ± 0.08	[O/H]	Comparison of 10 Cepheid galaxies with Tip of the Red Giant Branch distances	Kennicutt et al. (1998)
-0.20 ± 0.20	[O/H]	Value adopted for the HST Key Project final result	Freedman et al. (2001)
0	[Fe/H]	OGLE result comparing Cepheids in IC1613 and MC (*VI* bands)	Udalski et al. (2001)
0	[O/H]	Comparison of Planetary Nebula luminosity function distance scale and Surface Brightness fluctuation distance scale	Ciardullo et al. (2002)
-0.24 ± 0.05	[O/H]	Comparison of 17 Cepheid galaxies with Tip of the Red Giant Branch distances	Sakai et al. (2004)
-0.21 ± 0.19	[Fe/H]	Baade-Wesselink analysis of Galactic and SMC Cepheids (*VK* bands)	Storm et al. (2004)
-0.23 ± 0.19	[Fe/H]	Baade-Wesselink analysis of Galactic and SMC Cepheids (*I* band)	Storm et al. (2004)
-0.29 ± 0.19	[Fe/H]	Baade-Wesselink analysis of Galactic and SMC Cepheids (*W* index)	Storm et al. (2004)
-0.27 ± 0.08	[Fe/H]	Compilation from the literature of distances and metallicities of 53 Galactic and MC Cepheids (*VIWK* bands)	Groenewegen et al. (2004)
-0.39 ± 0.03	[Fe/H]	Cepheid distances to SNe Ia host galaxies	Saha et al. (2006)
-0.29 ± 0.09	[O/H]	Cepheids in NGC 4258 and [O/H] gradient from Zaritsky et al. (1994)	Macri et al. (2006)
-0.10 ± 0.03	[Fe/H]	Weighted mean of Kennicutt, Macri and Groenewegen estimates	Benedict et al. (2007)
-0.017 ± 0.113	[O/H]	Comparison between Cepheid and TRGB distances for 18 galaxies	Tammann et al. (2007)
0	[Fe/H]	Comparison between the slopes of Galactic and LMC Cepheids	Fouqué et al. (2007)
+0.05 ± 0.03	[Fe/H]	Predicted Period-Wesenheit (*V, I*) relation	Bono et al. (2008)

Romaniello et al. 2008

- Non-linear LMC P/L relations: the 10 days break?

Ultra Long Period Cepheids



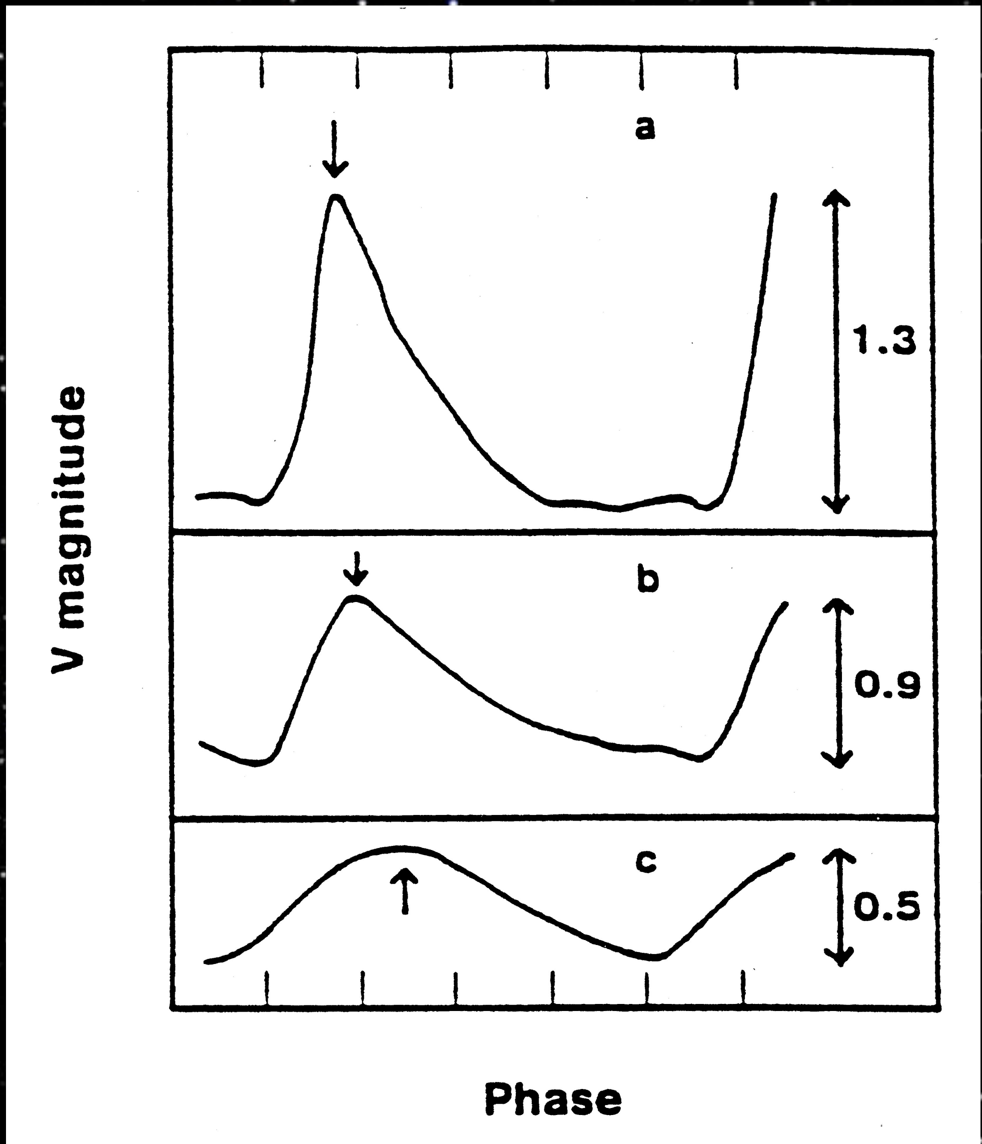


Bird et al. 2009

ELSA 2010

RR Lyrae stars

Characteristics



Smith 1995

Properties of RR Lyrae stars

Period	0.2–1.1 days
$\langle M_v \rangle$	+0.6 ± 0.2 (metal-poor stars)
$\langle T_e \rangle$	7400 K–6100 K
$\langle \log g \rangle$	2.5–3.0
[Fe/H]	0.0– –2.5
Mass	$\approx 0.7\ M_\odot$
Radius	≈ 4–$6\ R_\odot$

Pop II
Evo. Phase: HB (He-core burning)
t > 10 Gyr

M_v (RR) = α[Fe/H] +β

PLZ in the K band

MW ⇒ M31

- RR Lyraes trace the oldest stellar population

RR Lyrae are low mass ($M < 1\ M_{\odot}$) old ($t \geq 10$ Gyr) stars

⇒ their detection in a galaxy demostrates that the galaxy started forming stars at an early epoch

RR Lyrae stars have been found in "all" Local Group galaxies where they have been searched for.

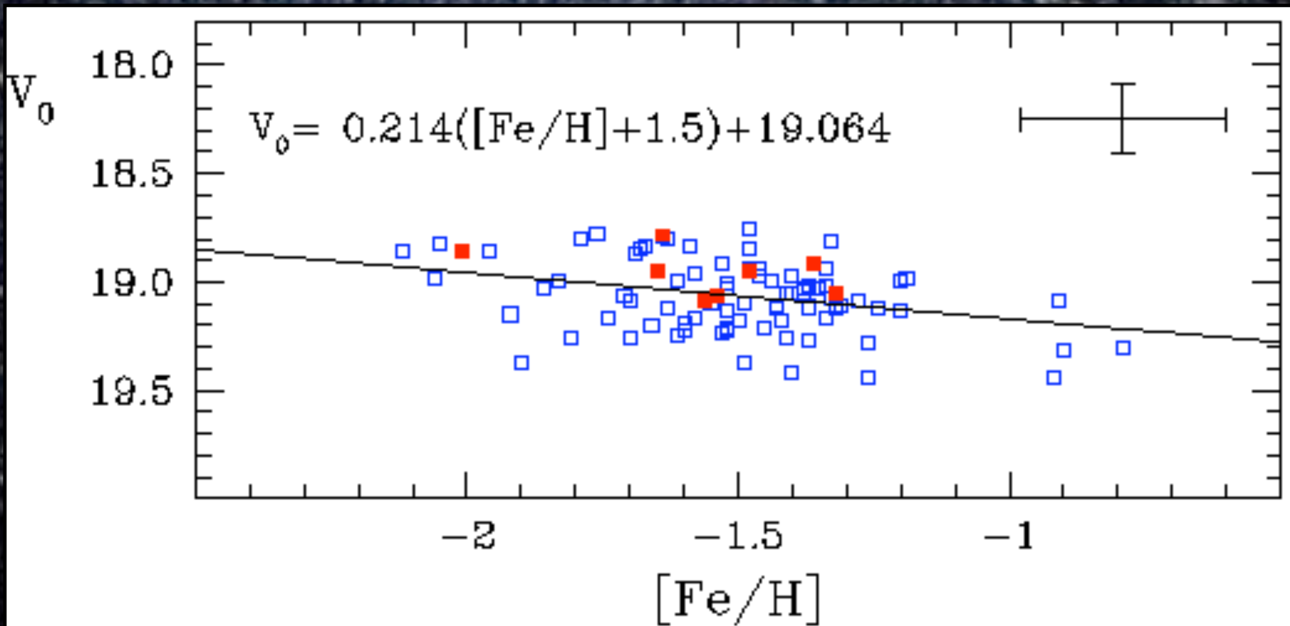
⇒ "All Local Group galaxies contain a very old population component, i.e. all nearby galaxies started to form stars just after they were formed".

In other words there are **no truly young** galaxies in the Local Group.

-RR Lyraes set the astronomical distance scale

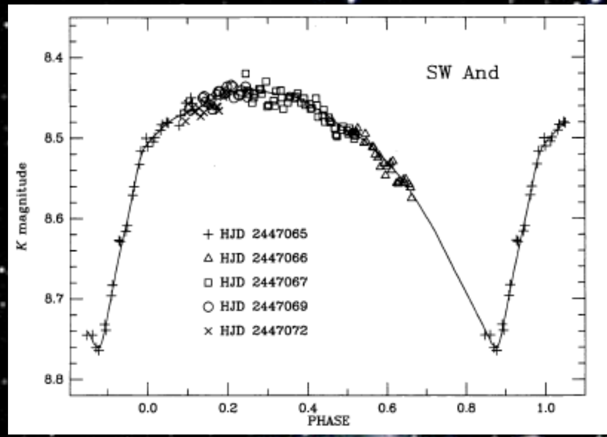
RR Lyrae are primary distance indicators for Population II systems through the Mv(RR) - [Fe/H] relation in the visual band and the Period-Luminosity-Metallicity (PLZ) relation in the K band

RR Lyrae luminosity-metallicity relation



Gratton et al. 2004

RR Lyrae stars in the near-IR



Smaller amplitudes (A_K~ 0.2-0.3 mag)

Tight PLZ_K relation (σ~0.05 mag)

M_K=-2.101 logP+0.231[Fe/H] – 0.77 (Bono et al. 2003)

M_K=-2.353 logP+0.175logZ – 0.597 (Catelan et al. 2004)

M_K=-2.38 logP+0.08[Fe/H] – 1.07 (Sollima et al. 2008)

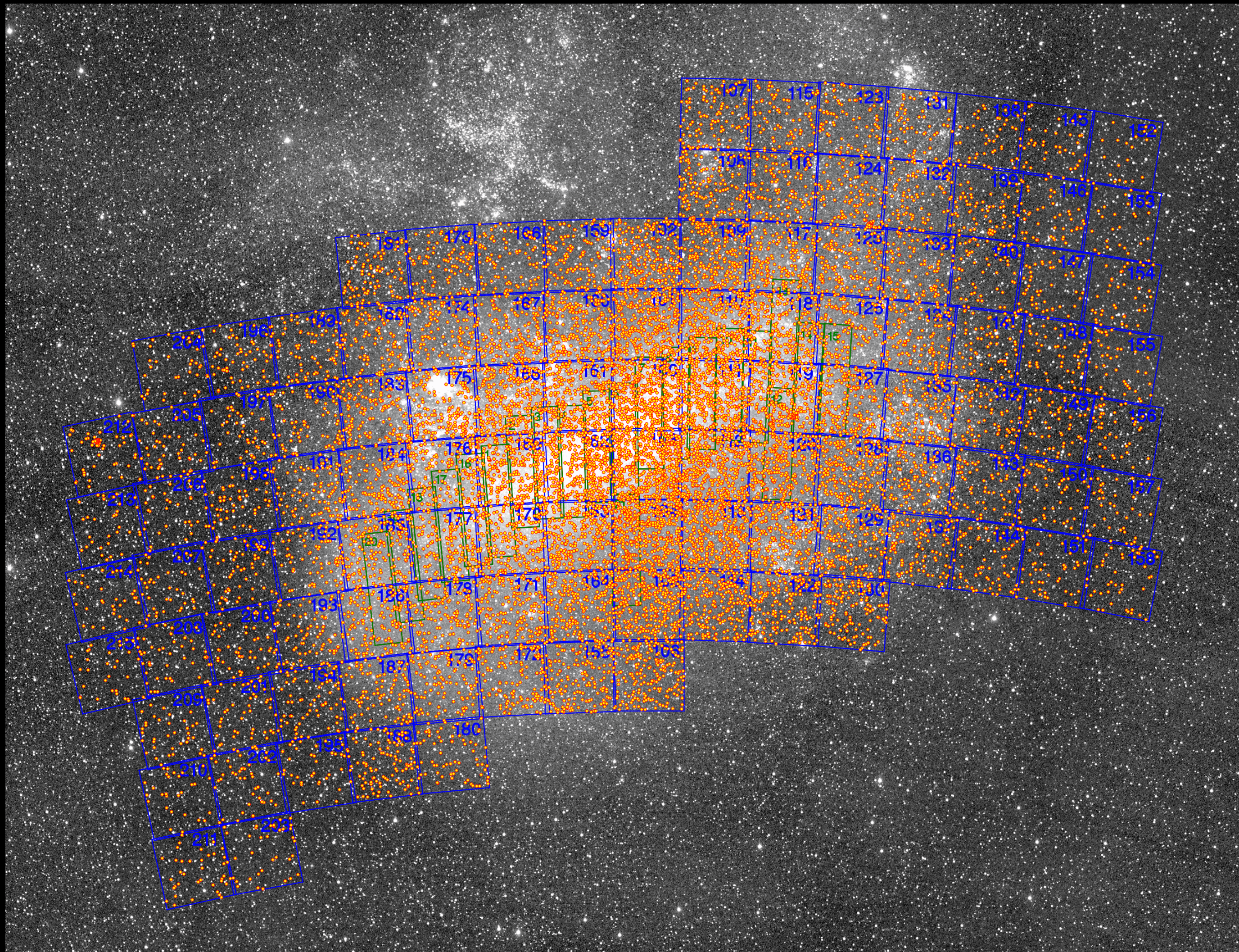
- **map 3D structures, radial trends, halos, streams**

A local overdensity of RR Lyrae stars in the Galactic halo is the northen tidal stream left over by the Sagittarius dwarf spheroidal galaxy

RR Lyrae stars trace galactic halos, Cepheids trace star forming regions and spiral arms

Results from the OGLE surveys of the LMC

RR Lyrae stars



Soszynski et al. 2009

EROS II survey of the LMC: RR Lyrae stars

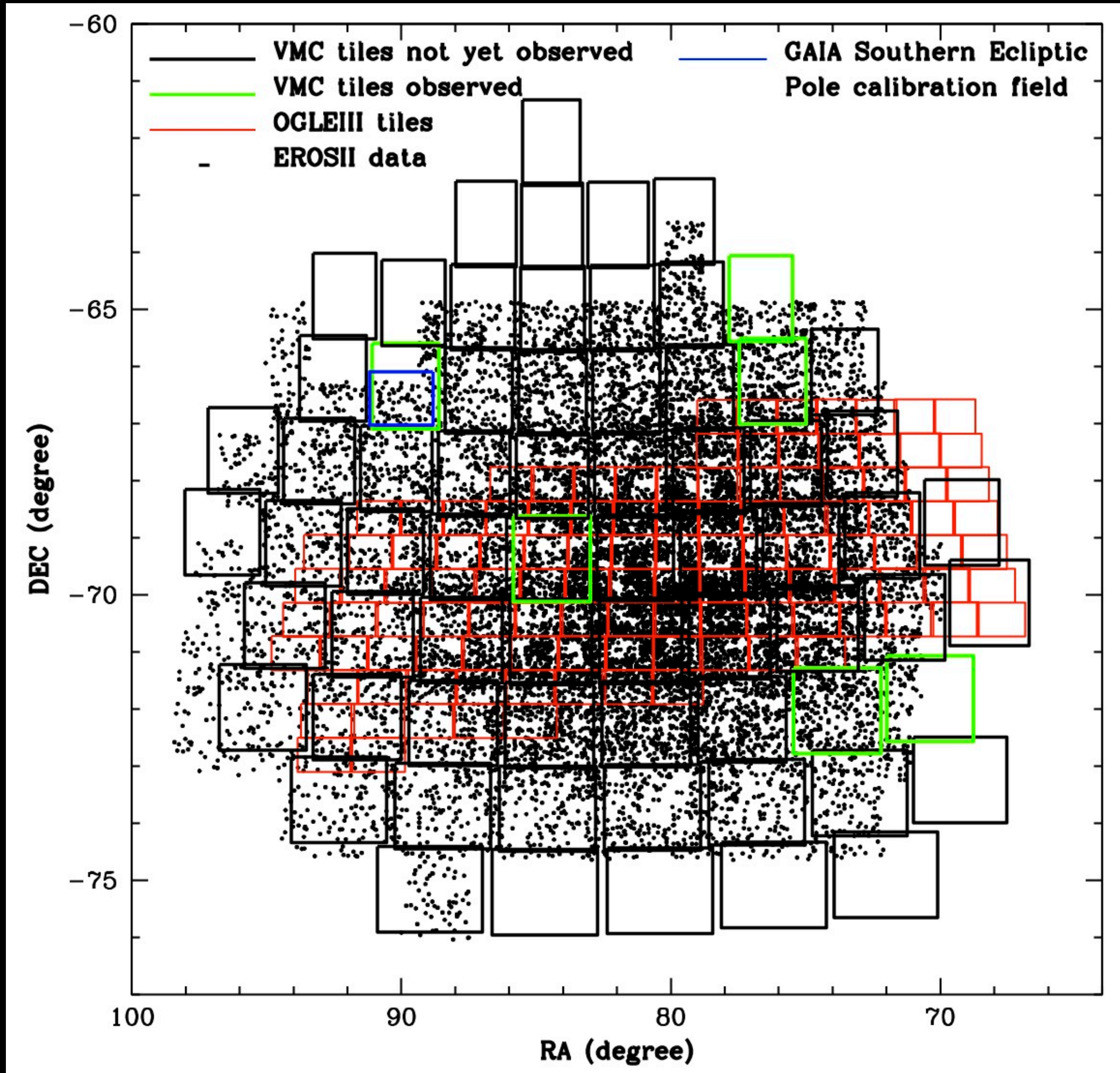
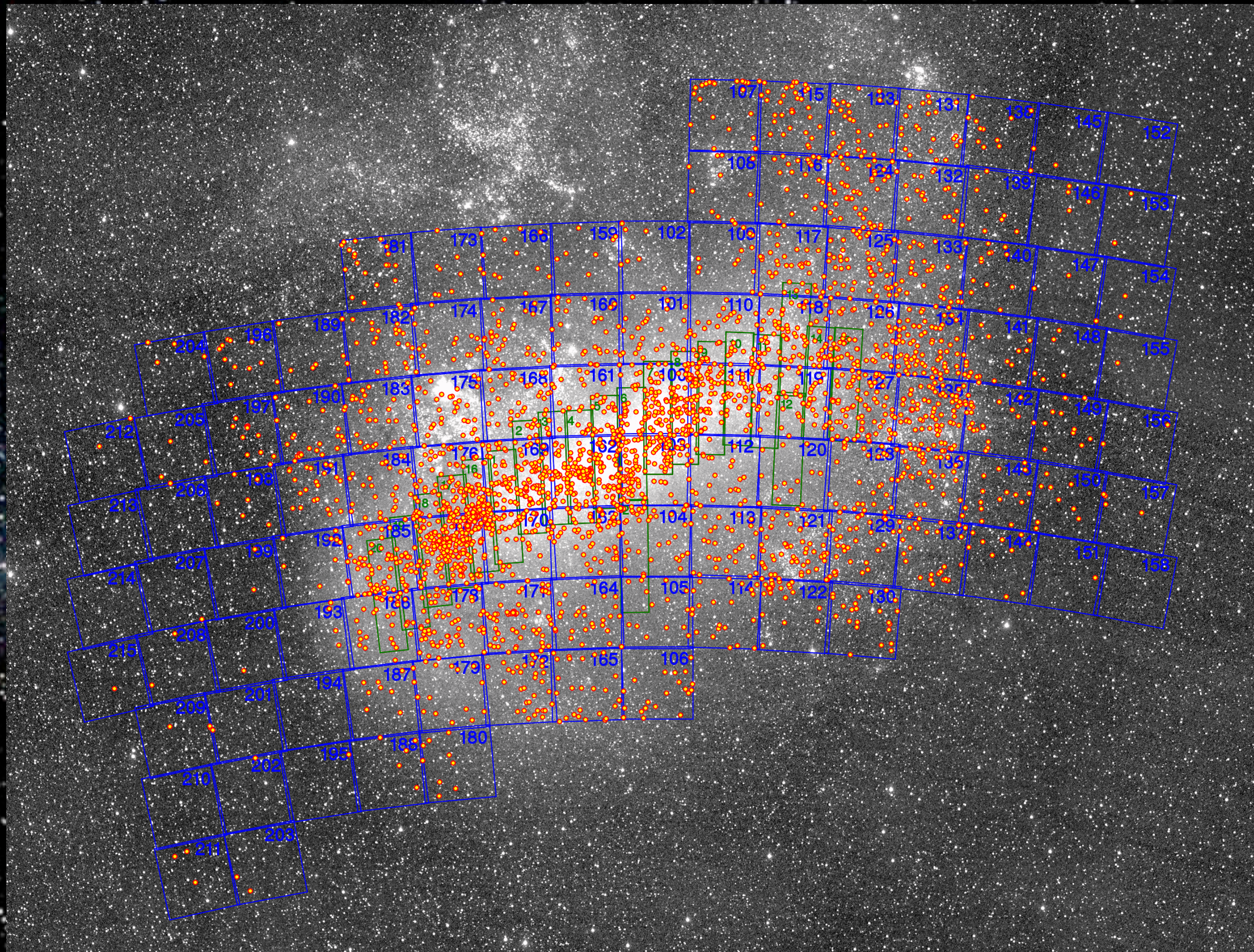


Figure courtesy JB Marquette & MI Moretti

Results from the OGLE surveys of the MCs

Cepheids



Soszynski et al. 2009

EROS II survey of the LMC: Cepheids

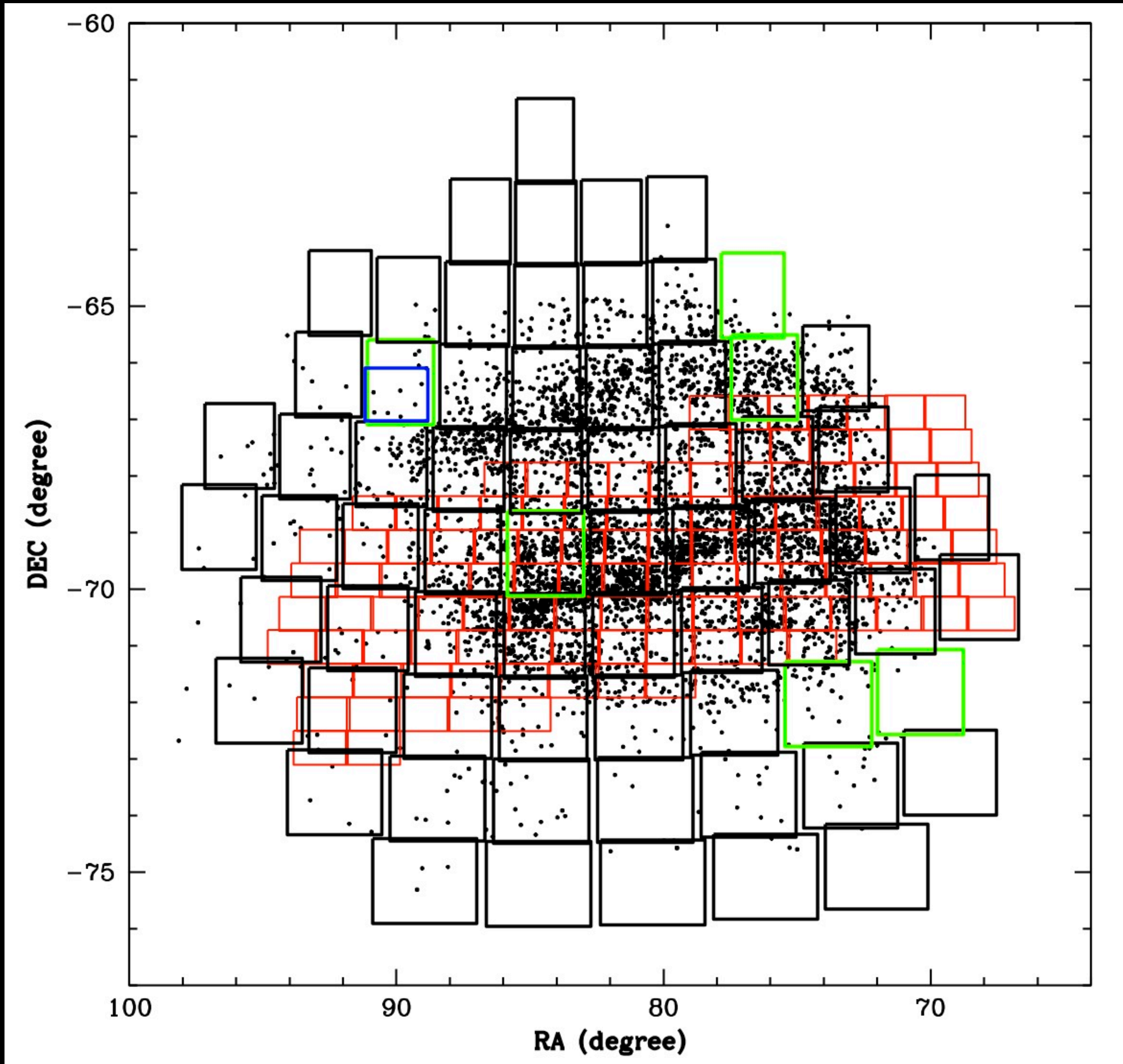


Figure courtesy JB Marquette & MI Moretti

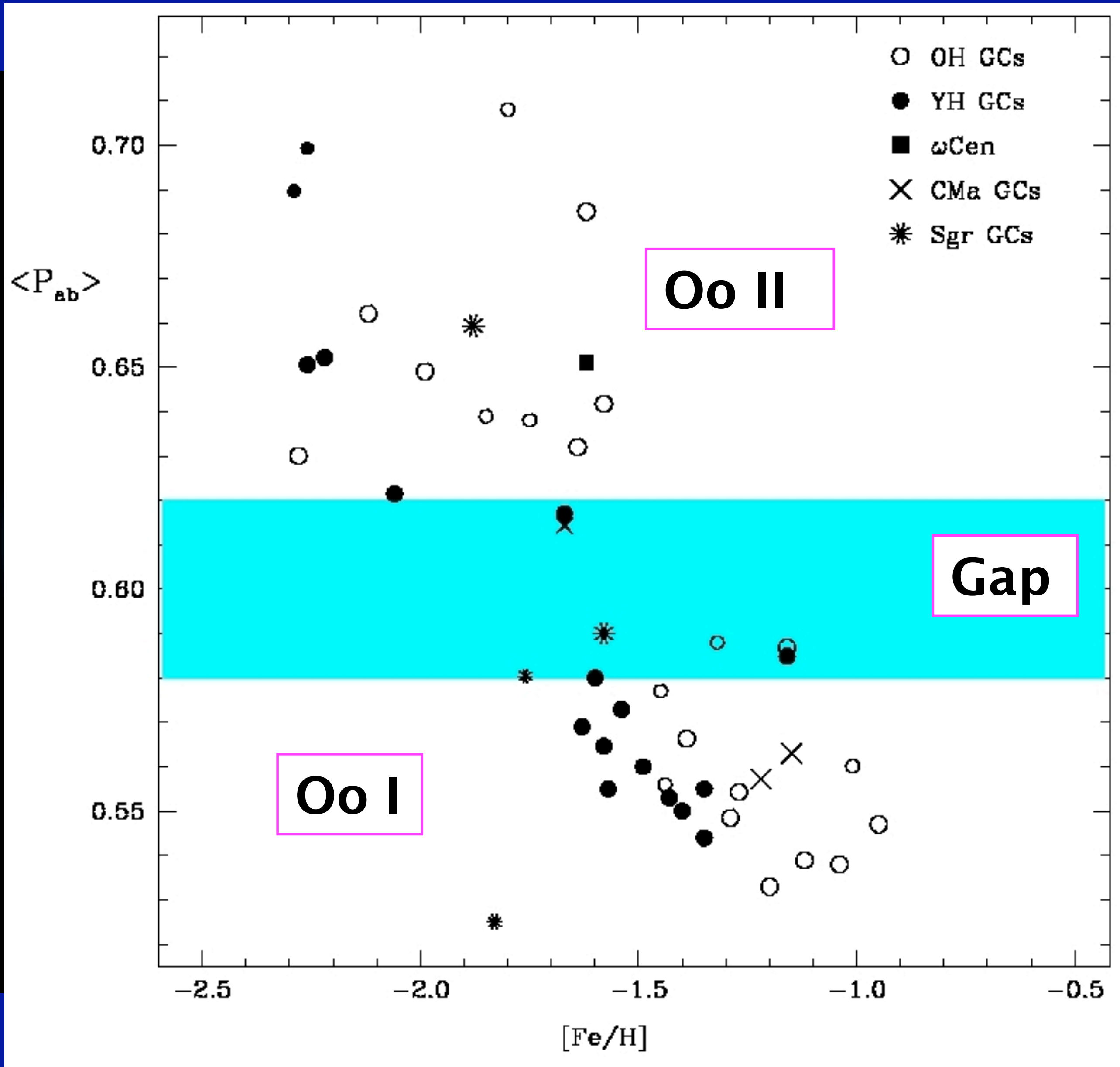
➢ provide hints on how galaxies have formed

The "Oosterhoff dichotomy" of the Milky Way RR Lyrae stars (GCs and field)

In the MW, most of the GCs with an RR Lyrae population sharply divide into two distinct groups, based on the mean period of the fundamental mode RR Lyrae stars, <Pab> (Oosterhoff 1939). Field RR Lyrae stars in the MW halo belong predominantly to Oo I, but with a significant Oo II component.

Type	<Pab>	<Pc>	N_c/N_{total}	[Fe/H]
Oo I	0.55 d	0.32 d	0.17	~ -1.4
Oo II	0.64 d	0.37 d	0.44	~ - 2.0

The Oosterhoff dichotomy: MW GCs



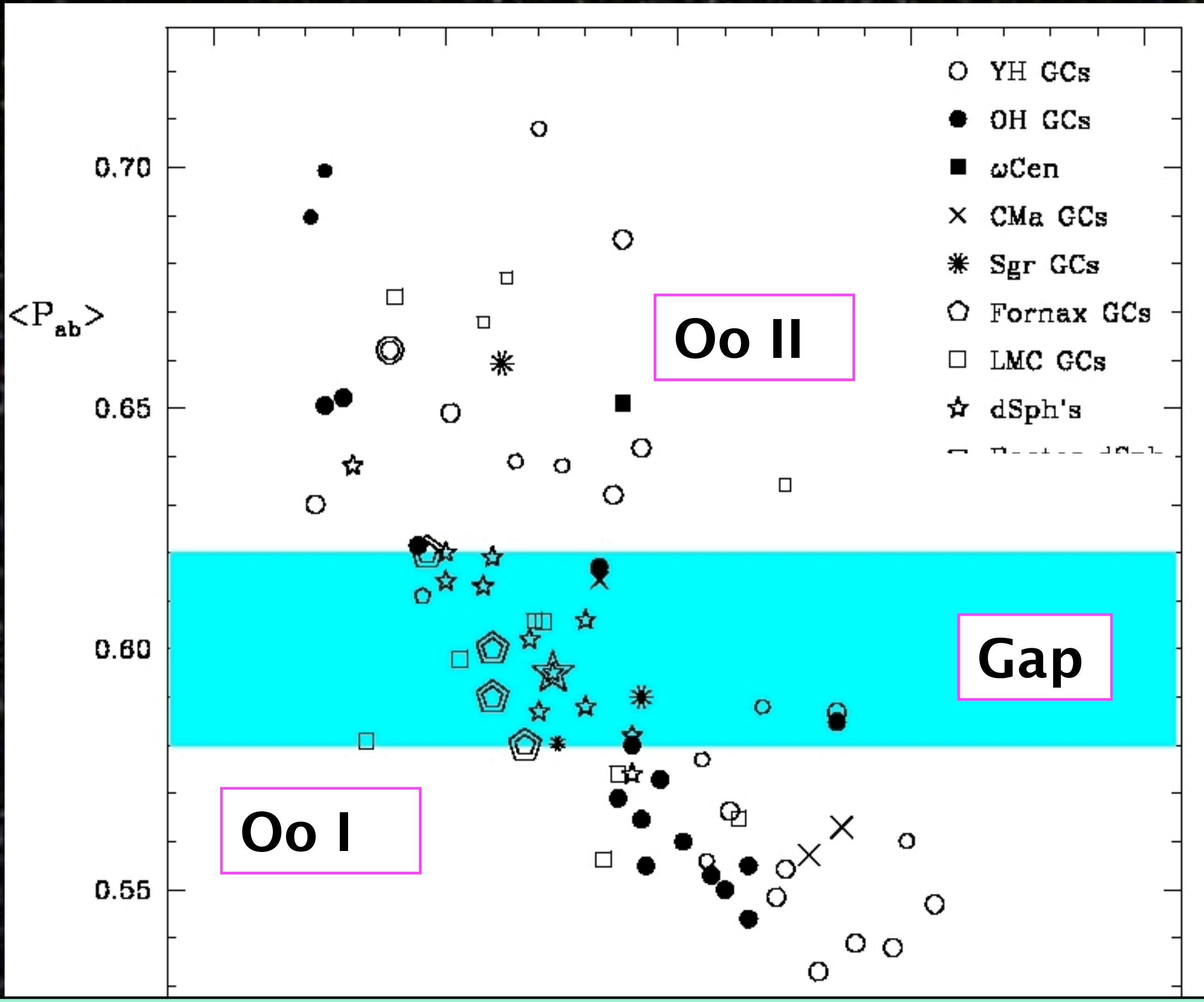
Oo I <Pab> = 0.55 d
OoII <Pab> = 0.64 d

KMM test: <u>Galactic</u> distribution is bimodal with p > 99.99%

*If the MW has formed early on by accretion of protogalactic fragments resembling __the early counterparts__ of its present-day **satellite galaxies**, the RR Lyrae stars in these galaxies should conform to the Oosterhoff dichotomy observed in the MW*

Is there an Oosterhoff dichotomy among the Milky Way satellites?

The Oosterhoff dichotomy outside the MW:



the "bright" MW satellites

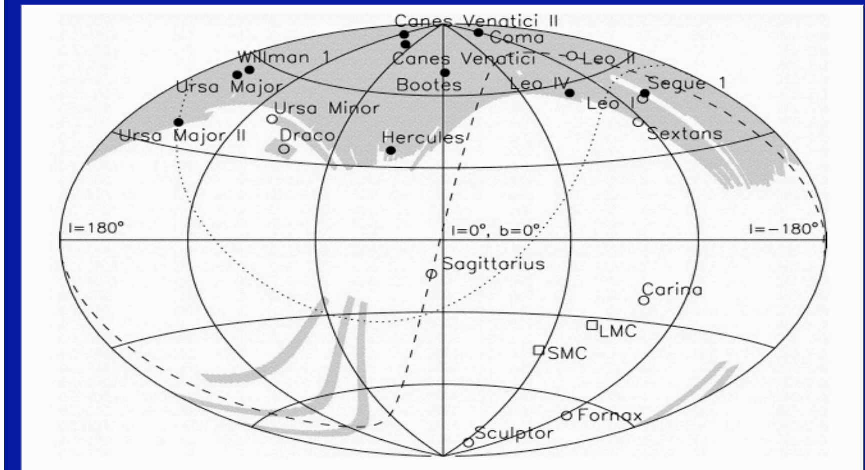
KMM test: __single-peaked__ distribution, with __peak in the middle of the Oosterhoff gap!__

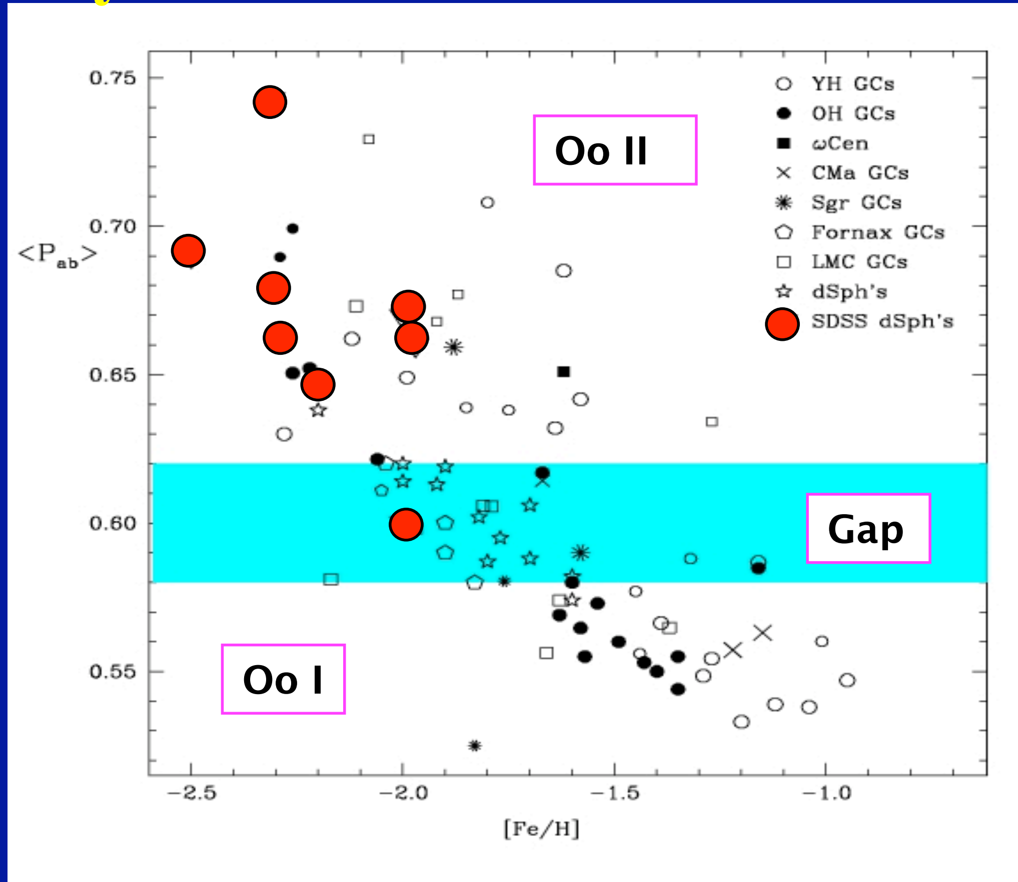
The Galaxy is unlikely to have formed early on by accretion of protogalactic fragments resembling __the early counterparts__ of its present-day "bright" satellite galaxies.

The Oosterhoff dichotomy outside the MW:

the "ultra faint" SDSS dSphs

17 new MW satellites discovered in the last few years, mainly by the SDSS





The Galaxy may have formed early on by accretion of protogalactic fragments resembling <u>the early counterparts</u> of its present-day "ultra-faint" dwarf satellite galaxies.

Variable stars and Gaia

Increased statistics

According to preliminary estimates, from 2000 to 8000 Classical Cepheids and about 70000 RR Lyrae stars will be observed by Gaia. Also, about 2000 Population II Cepheids are likely to be observed by the satellite.

Complete census of the MW Classical Cepheids.

~2000/1000 Classical Cepheids are know in the Magellanic Clouds and observable by Gaia

Variable stars and Gaia

The distance scale: RR Lyrae stars

Presently, 126 RR Lyraes with < V > = 10 to 12.5 (750 - 2500 pc)
$\sigma_\pi/\pi \geq 30$ % (Hipparcos) (Fernley et al. 1998)

RR Lyr (<V>=7.8): only RRL stars with *good* parallax estimate

$\pi = 3.46 \pm 0.64$ mas → mod = 7.30 mag (new Hipparcos, van Leeuwen 2007)
$\pi = 3.82 \pm 0.20$ mas → mod = 7.09 mag (HST, Benedict et al. 2002)
➔ ΔMv ~ 0.2 mag ➔ distance to 10% !

Gaia: within 1.5 kpc to $\sigma\pi/\pi < 1\%$ ($\leq$ 2.5% within 3 kpc, 25-30% at 10 kpc)
RR Lyraes in globular clusters with mean $\sigma\pi/\pi < 1\%$

Variable stars and Gaia

The distance scale: MW Cepheids

Only ~ 800 Galactic Cepheids are known – most are located in the Solar neighbourhood

400 Galactic Cepheids from David Dunlap DB
distance and magnitude ➔ Gaia predicted accuracy for parallax
15 d < 0.5 kpc
65 D < 1 kpc
165 d < 2 kpc

Presently, ~ 250 Cepheids with parallax & photometry
(10 with HST parallax)
only ~ 100 with $\sigma_\pi \leq 1$ mas
(Hipparcos)

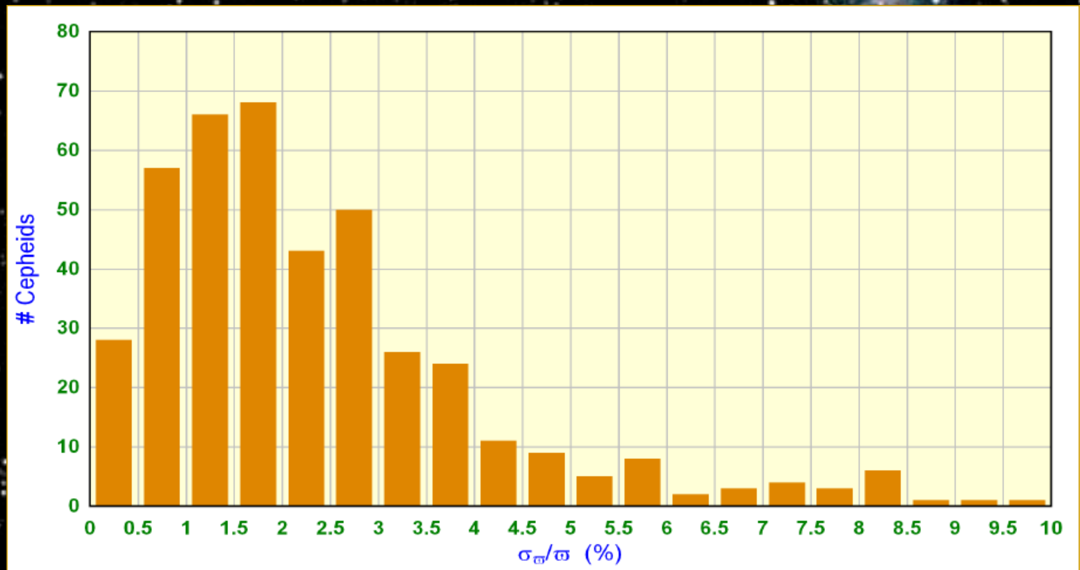


Figure courtesy A. Brown

Variable stars and Gaia

The distance scale: MC Cepheids

600 Cepheids in the LMC (OGLE, Udalski et al. 1999)

The bulk of the distribution for fundamental LMC pulsators lies at Period = 3 – 5 days

Mv ~ -3 ➔ V ~ 15.8 – 16

➔ individual distances to ~ 150%

➔ mean of 400 to ~ 7-8 %

Cepheids with P ≥ 10 d

Mv ≤ ~ - 4.2 ➔ V ~ 14.5

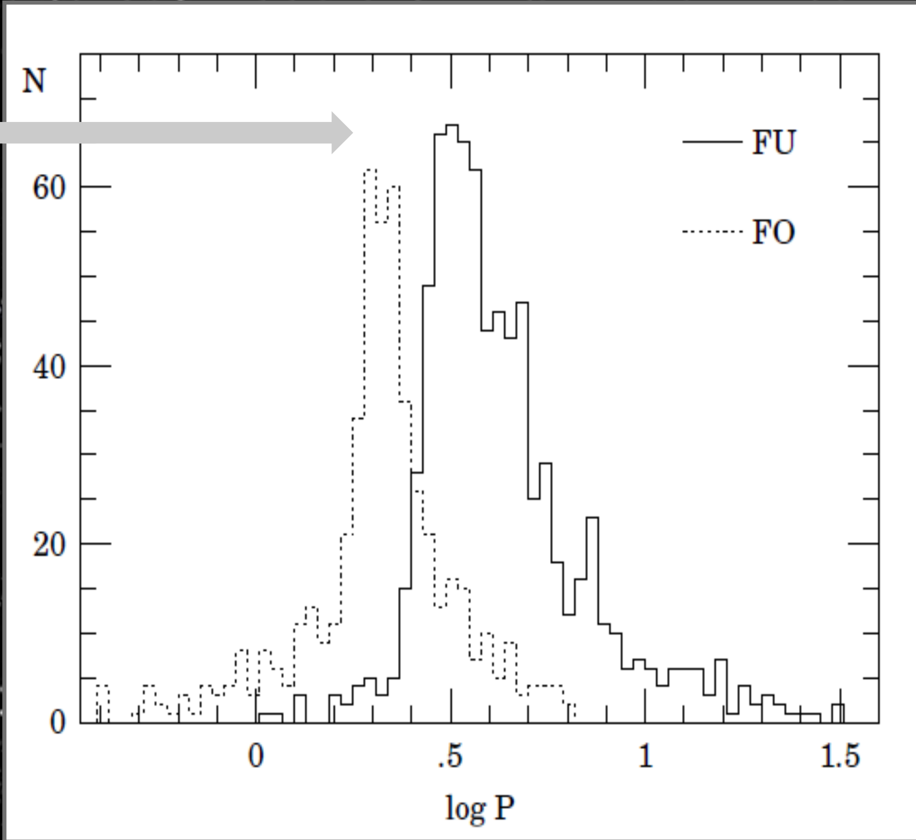
individual distances to ~ 80%

Ultra-long period (> 100 d) Cepheids

Mv ≤ ~ - 7 ➔ V ~ 12

4 in LMC, 3 in SMC (Bird et al. 2009)

individual distances to ~ 45% (LMC) - 55% (SMC)



➔ direct (trigonometric) calibration of the cosmological distance scale


Thank you