Population II pulsating stars as tracers of the Milky Way and Local Group evolution. II

Matteo Monelli

INAF - Rome Observatory

IAC - ULL

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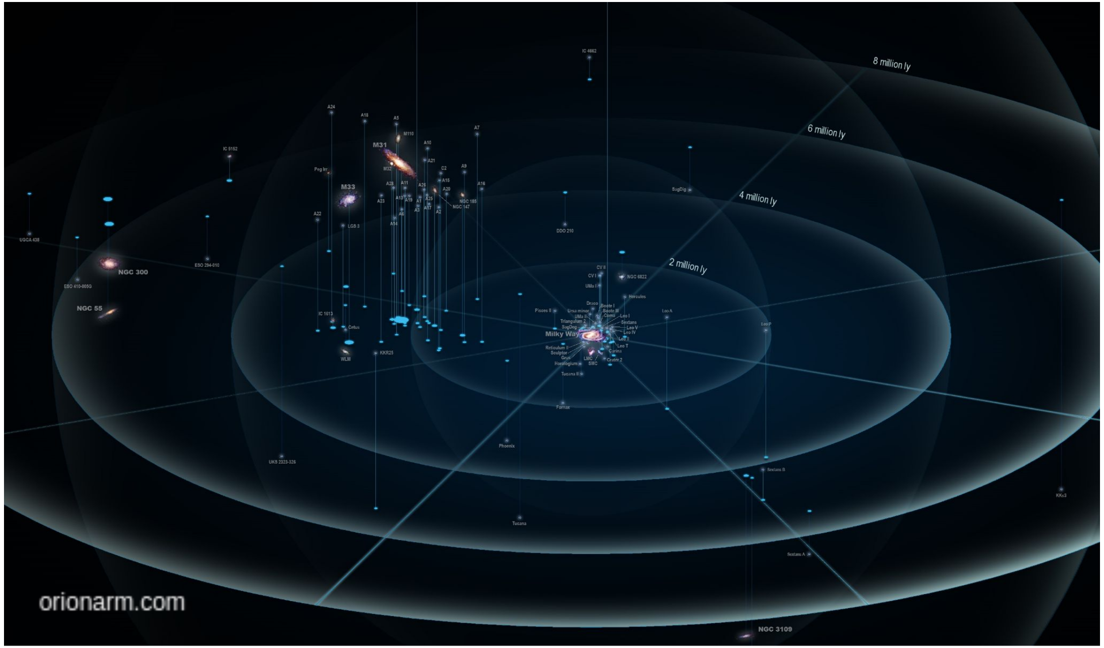
matteo.monelli@inaf.it

The Local Group



The Local Group in a nutshell

- mass-dominated by two spirals
- few “massive dwarfs” (M33, MCs)
- variety of morphological types (dSph, dIrr, dTr, dE)
- morphology-density relation
- variety of star formation history (SFH)

Variable stars in Local Group galaxies

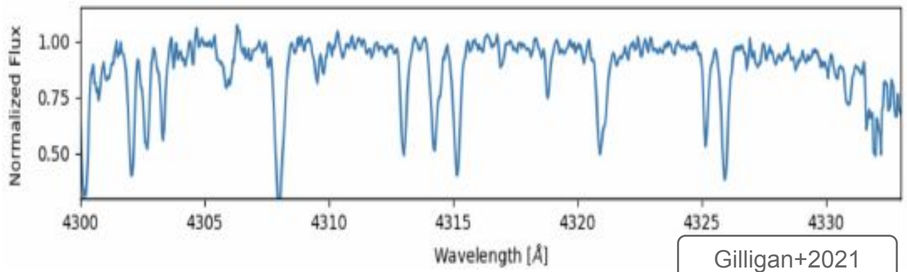
Galaxy	R.A.	Dec.	Group	N_{RRab}	N_{RRcd}	N_{AC}	N_{CC}	N_{TIIC}	Photometry	Reference
ESO410-G005	00:15:31.6	−32:10:48.0	Scl	225	44	9 **	13 **	0 **	VI*	Yang et al. [31]
And XIX	00:19:32.1	+35:02:37.0	M31	31	8	8	0	0	BV	Cusano et al. [32]
Cetus	00:26:11.0	−11:02:40.0	isol	506	124	8	0	0	BVI, F475W, F814W	Bernard et al. [33], Monelli et al. [34]
ESO294-G010	00:26:33.4	−41:51:19.0	Scl	219	13	3 **	16 **	0 **	VI*	Yang et al. [31]
And XXV	00:30:08.9	+46:51:07.0	M31	46	11	3	0	0	BV	Cusano et al. [35]
NGC 147	00:33:12.1	+48:30:32.0	M31	118	58	2	0	0	F606W, F555W	Monelli et al. [36]
And III	00:35:33.8	+36:29:52.0	M31	84	15	4	0	0	F475W, F814W	Martínez-Vázquez et al. [37]
And XXVII	00:37:27.1	+45:23:13.0	M31	58	31	1	0	0	BV	Cusano et al. [38]
NGC 185	00:38:58.0	+48:20:15.0	M31	544	272	3	0	0	F606W, F555W	Monelli et al. [36]
NGC 205	00:40:22.1	+41:41:07.0	M31	30	0	7	0	0	g	Saha et al. [39]
M 32	00:42:41.8	+40:51:55.0	M31	375	134	4	0	0	VI*	Fiorentino et al. [40], Sarajedini et al. [41]
And I	00:45:39.8	+38:02:28.0	M31	229	48	0	0	0	F475W, F814W	Martínez-Vázquez et al. [37]
And XI	00:46:20.0	+33:48:05.0	M31	12	5	0	0	0	VI*	Yang and Sarajedini [42]
And XIII	00:51:51.0	+33:00:16.0	M31	8	1	0	0	0	VI*	Yang and Sarajedini [42]
SMC	00:52:44.8	−72:49:43.0	MW	4961	1407	4915	109	53	VI	Soszyński et al. [43–45]
And XVI	00:59:29.8	+32:22:36.0	M31	3	5	0	0	0	F475W, F814W	Martínez-Vázquez et al. [37], Monelli et al. [46]
Sculptor	01:00:09.4	−33:42:33.0	MW	289	247	4	0	0	BVI	Martínez-Vázquez et al. [47]
IC 1613	01:04:47.8	+02:07:04.0	isol	61	29	0	160	0	F475W, F814W	Bernard et al. [33], Tammann et al. [48]
And XV	01:14:18.7	+38:07:03.0	M31	80	24	4	0	0	F475W, F814W	Martínez-Vázquez et al. [37]
And II	01:16:29.8	+33:25:09.0	M31	187	48	4	0	0	F475W, F814W	Martínez-Vázquez et al. [37]
Triangulum	01:33:50.9	+30:39:37.0	M31	85	14	0	?	0	VI*	Tanakul et al. [49]
Phoenix	01:51:06.3	−44:26:41.0	isol	54	24	19 **	0	0	VI*	Gallart et al. [50], Ordoñez et al. [51]
Segue 2	02:19:16.0	+20:10:31.0	MW	1	0	0	0	0	BV	Boettcher et al. [52]
Eridanus 3	02:22:45.5	−52:17:01.0	MW	0	1	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Fornax	02:39:59.3	−34:26:57.0	MW	1493	493	0	5	2	BVI	Braga et al. in prep.
Eridanus 2	03:44:21.1	−43:32:00.0	MW	44	23	2	0	0	gri, F475W, F814W	Martínez-Vázquez et al. [54]
Reticulum 3	03:45:26.4	−60:27:00.0	MW	1	0	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
LMC	05:23:34.5	−69:45:22.0	MW	27620	11461	4628	141	285	VI	Soszyński et al. [43,44,45]
Carina	06:41:36.7	−50:57:58.0	MW	71	21	20	0	0	UBVI	Coppola et al. [55]
Carina 2	07:36:25.6	−57:59:57.0	MW	1	1	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Ursa Major 2	08:51:30.0	+63:07:48.0	MW	2	2	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Hydra 1	08:55:36.0	+03:36:00.0	MW	4	0	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
UGC4879-VV124	09:16:02.2	+52:50:24.0	isol	532	146	10	78	1	F475W, F814W	Neeley et al. [56]
Leo T	09:34:53.4	+17:03:05.0	MW	4	1	17	0	0	F475W, F606W, F814W	Surot et al. in prep.
Antlia 2	09:35:32.8	−36:46:02.3	MW	193	104	8	0	0	r, i	Vivas et al. [57]
Leo A	09:59:26.5	+30:44:47.0	isol	7	3	0 **	156 **	0	F475W, F814W	Bernard et al. [58]
Segue 1	10:07:04.0	+16:04:55.0	MW	1	0	0	0	0	gi	Simon et al. [59]
Leo 1	10:08:28.1	+12:18:23.0	MW	136	38	55 **	0 **	0	UBVRI	Stetson et al. [60]
Sextans	10:13:03.0	−01:36:53.0	MW	26	10	9	0	0	BV, BVI, gr	Mateo et al. [61], Amigo et al. [62], Vivas et al. [63]
Leo P	10:21:45.1	+18:05:17.0	isol	9	1	0	0	0	F475W, F814W	McQuinn et al. [64]
Ursa Major 1	10:34:52.8	+51:55:12.0	MW	6	0	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Leo 2	11:13:28.8	+22:09:06.0	MW	106	34	4	0	0	BV	Siegel and Majewski [65]
Leo 5	11:31:09.6	+02:13:12.0	MW	3	0	0	0	0	gr	Medina et al. [66]
Leo 4	11:32:57.0	−00:32:00.0	MW	3	0	0	0	0	BV	Moretti et al. [67]
Crater 2	11:49:14.4	−18:24:47.0	MW	84	15	7	0	0	BV, BVI, gri	Joo et al. [68], Monelli et al. [69], Vivas et al. [70]
Hydra 2	12:21:42.1	−31:59:07.0	MW	1	0	0	0	0	gri	Vivas et al. [71]
Coma Berenices	12:26:59.0	+23:54:15.0	MW	2	0	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Centaurus 1	12:38:20.4	−40:54:07.2	MW	1	2	0	0	0	gi	Martínez-Vázquez et al. [72]
Canes Venatici 1	13:28:03.5	+33:33:21.0	MW	18	5	3	0	0	BV	Kuehn et al. [73]
Bootes 3	13:57:12.0	+26:48:00.0	MW	4	3	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Bootes 2	13:58:00.0	+12:51:00.0	MW	1	0	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Bootes 1	14:00:06.0	+14:30:00.0	MW	1	2	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Ursa Minor	15:09:08.5	+67:13:21.0	MW	47	35	7	0	0	BV	Nemec et al. [74]
KKR 25	16:13:48.0	+54:22:16.0	isol	39	7	25	0	0	F475W, F814W	Neeley et al. [56]
Hercules	16:31:02.0	+12:47:30.0	MW	6	3	1	0	0	B	Musella et al. [75]
Draco	17:20:12.4	+57:54:55.0	MW	211	56	9	0	0	VI	Kinemuchi et al. [76]
Sagittarius dSph	18:55:19.5	−30:32:43.0	MW	1636	409	0	0	174	VI	Soszyński et al. [77], Hamanowicz et al. [78]
NGC 6822	19:44:56.6	−14:47:21.0	isol	24	2	15	30	0	BV	Baldacci et al. [79]
Sagittarius 2	19:52:40.5	−22:04:05.0	MW	2	3	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Grus 2	22:04:04.8	−46:26:24.0	MW	0	1	0	0	0	gri	Martínez-Vázquez et al. [80]
Pegasus 3	22:24:22.6	+05:25:12.0	MW	1 *	0	1 *	0	0	BV	Garofalo et al. [81]
And XXVIII	22:32:41.2	+31:12:58.0	M31	35	34	3	0	0	F475W, F814W	Martínez-Vázquez et al. [37]
Tucana	22:41:49.6	−64:25:10.0	isol	216	142	7	0	0	F475W, F814W	Bernard et al. [82]
Tucana 2	22:51:55.1	−58:34:08.0	MW	1	2	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
Grus 1	22:56:42.4	−50:09:48.0	MW	2	0	0	0	0	gri	Martínez-Vázquez et al. [80]
Pisces 2	22:58:31.0	+05:57:09.0	MW	1 *	0	1 *	0	0	BV	Garofalo et al. [81]
And VII	23:26:31.7	+50:40:33.0	M31	336	187	7	0	0	F435W, F555W	Monelli et al. [36]
Phoenix 2	23:39:59.4	−54:24:22.0	MW	1	0	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]
And VI	23:51:46.3	+24:34:57.0	M31	91	20	6	0	0	BV*	Pritzl et al. [83]
And XXI	23:54:47.7	+42:28:15.0	M31	37	4	9	0	0	BV	Cusano et al. [84]
Tucana 3	23:56:36.0	−59:36:00.0	MW	5	1	0	0	0	G, G_{BP}, G_{RP}	Vivas et al. [53]

Monelli & Fiorentino+2022

RR Lyrae stars as chemical evolution tracers

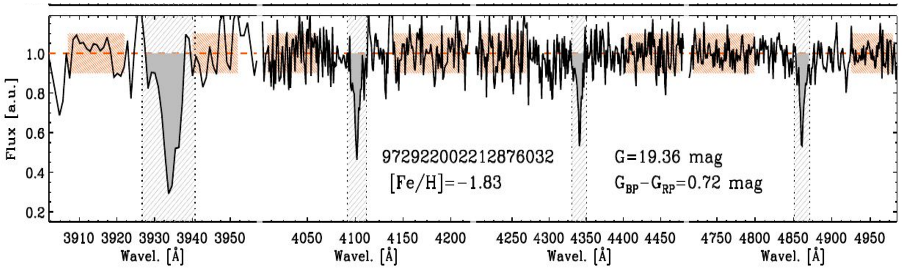
RR Lyrae stars as chemical evolution tracers

High Resolution



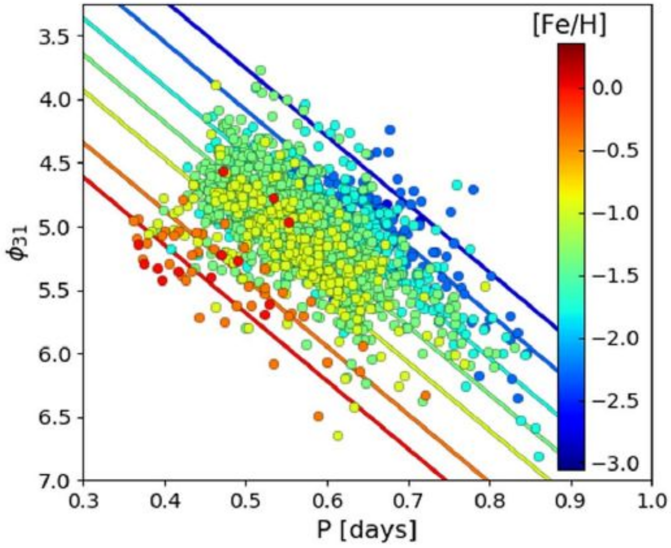
Gilligan+2021

Low Resolution



Fabrizio+2019

Fourier coefficients



Mullen+2021,2022

RR Lyrae stars as chemical evolution tracers

Period-Luminosity relation

$$[\mathrm{Fe/H}] = \frac{M_I - b\log P - a}{c}$$

Inverse of the PL(I)

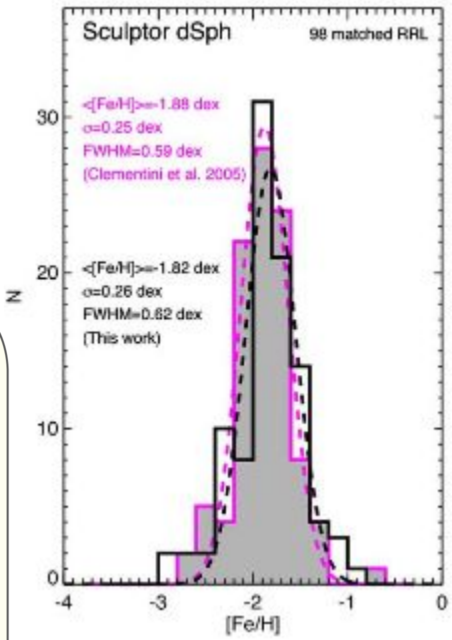
★ works for individual stars

★ relies on solid observables

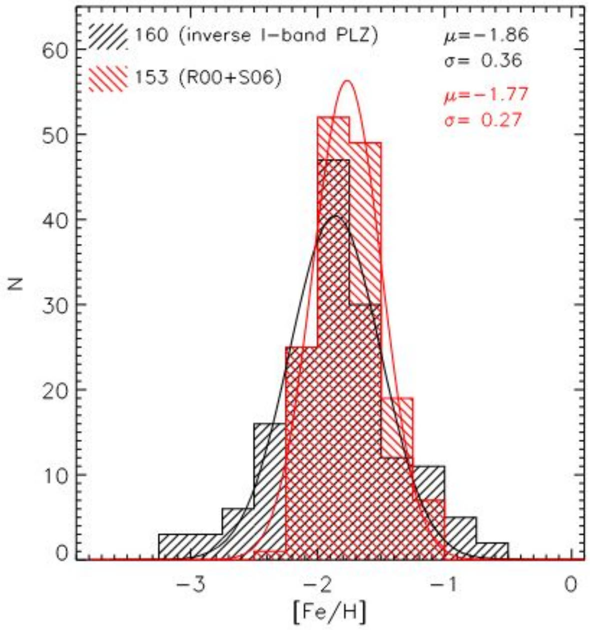
★ needs an independent distance

★ dispersion is a solid estimate

★ resolution of ~0.25 dex



Martínez-Vázquez+2016



Braga+2016

RR Lyrae stars as chemical evolution tracers

Period-Luminosity relation

$$[\mathrm{Fe/H}] = \frac{M_I - b\log P - a}{c}$$

Inverse of the PL(I)

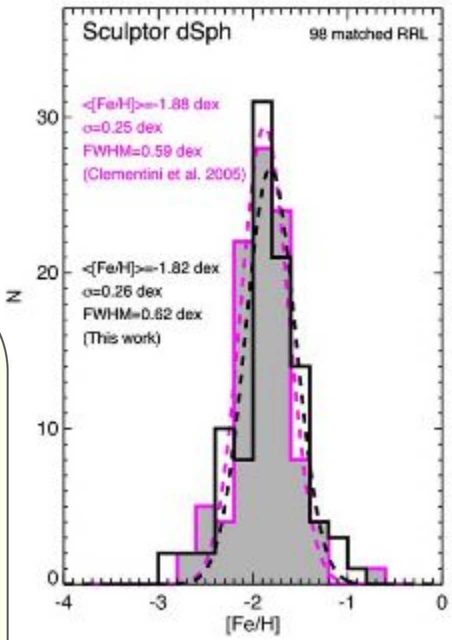
★ works for individual stars

★ relies on solid observables

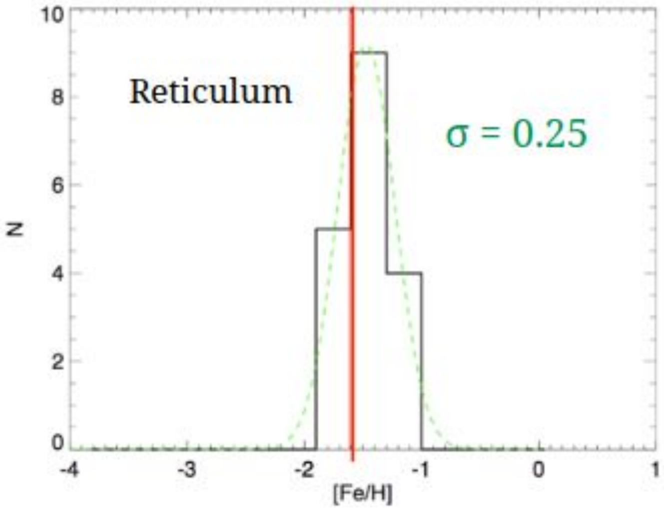
★ needs an independent distance

★ dispersion is a solid estimate

★ resolution of ~0.25 dex

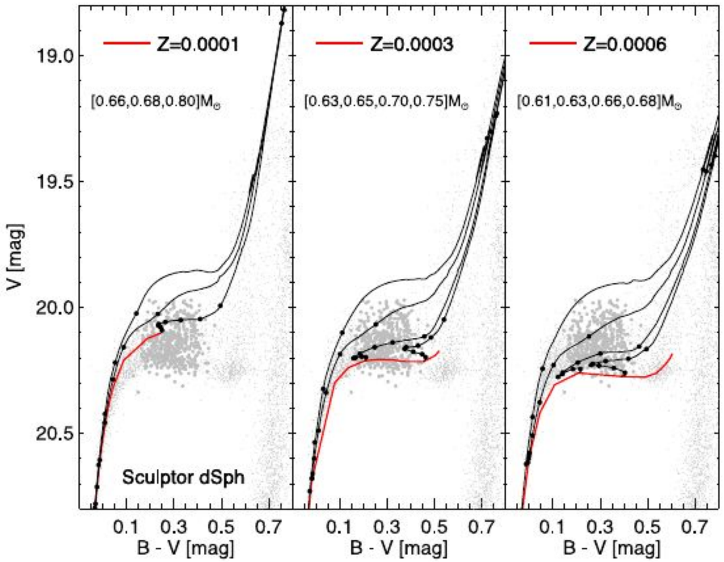


Martínez-Vázquez+2016



RR Lyrae stars as chemical evolution tracers

Martínez-Vázquez+2015,2016ab

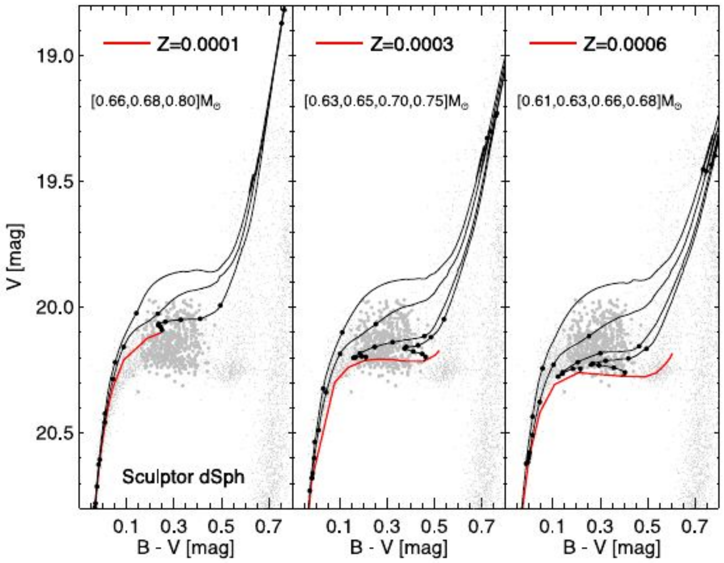


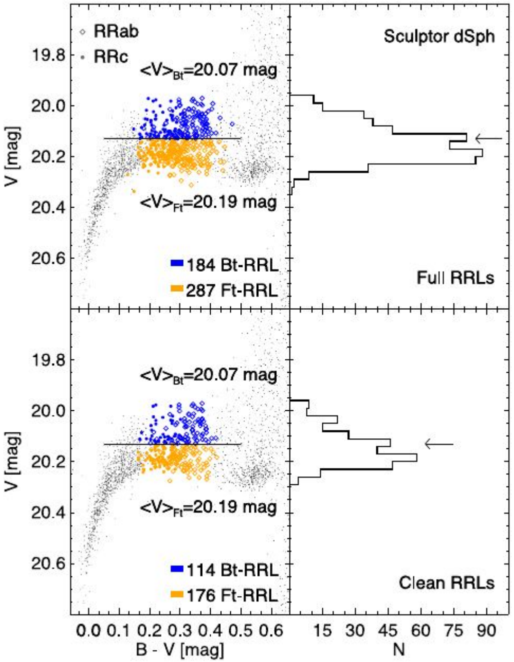
Sculptor dSph

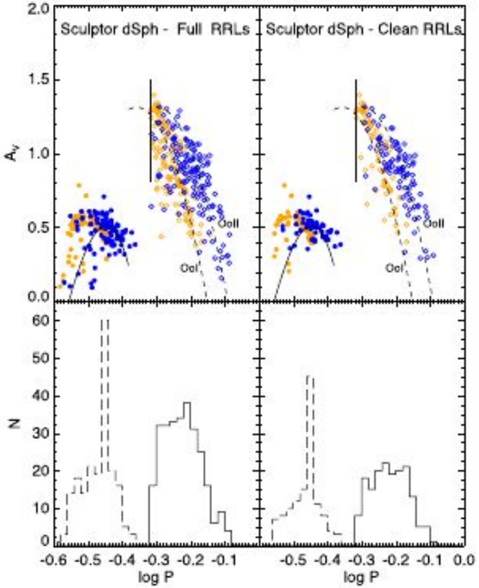
RR Lyrae stars as chemical evolution tracers

Martínez-Vázquez+2015,2016ab

Sculptor dSph

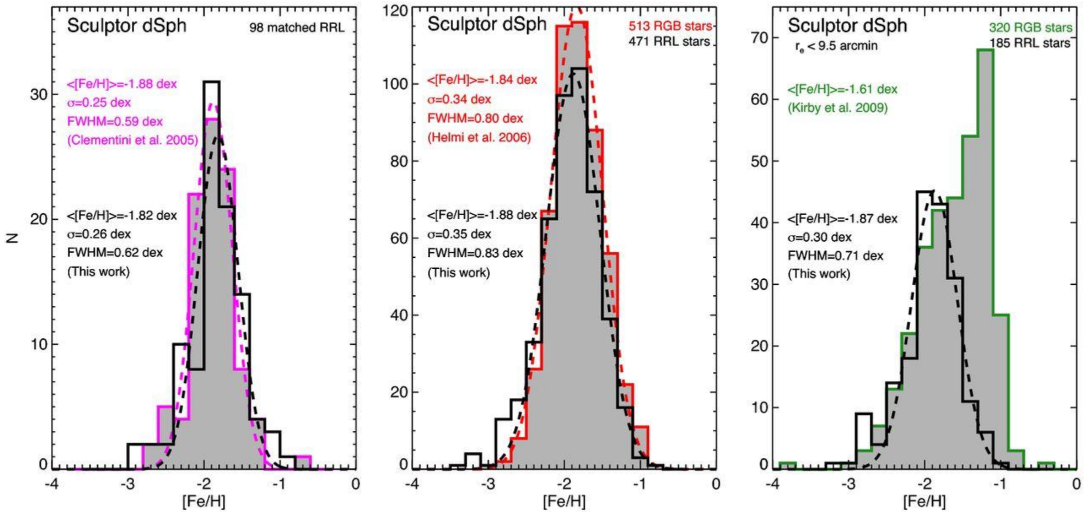






RR Lyrae stars as chemical evolution tracers

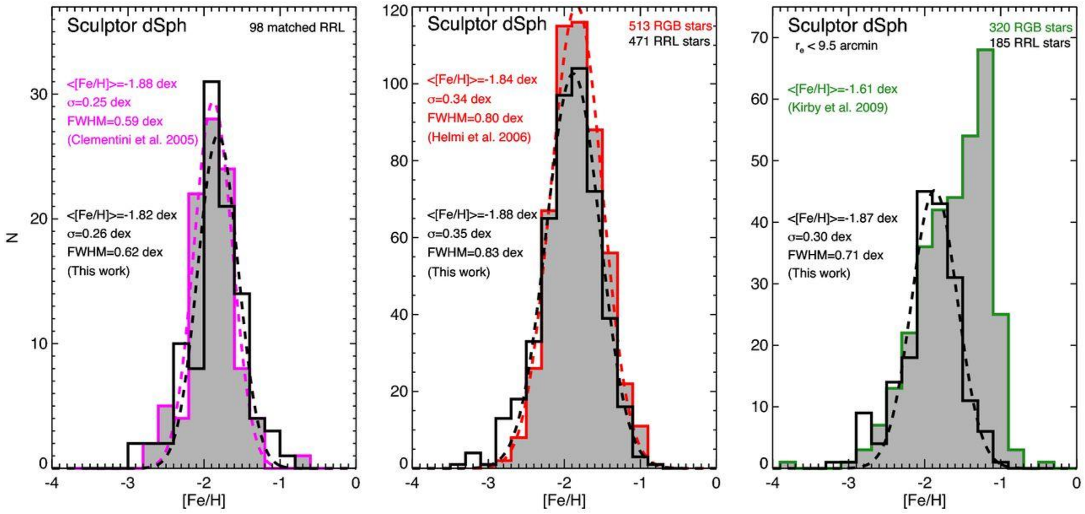
Martínez-Vázquez+2015,2016ab



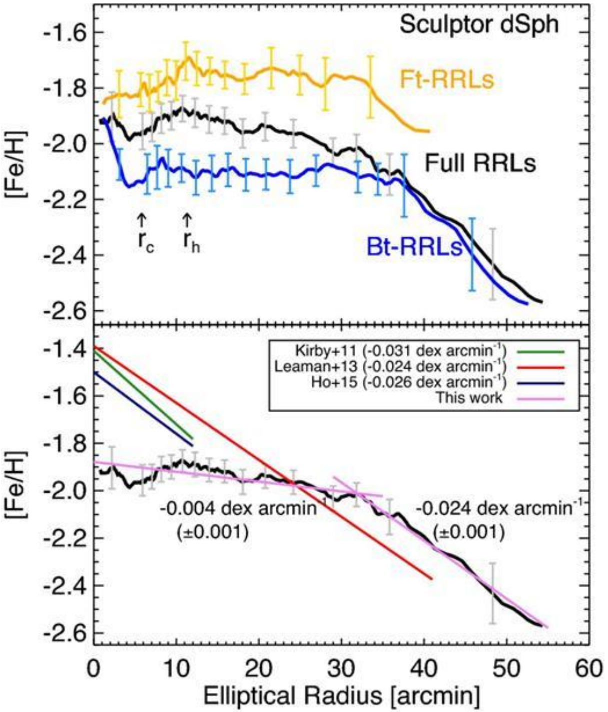
Sculptor dSph

RR Lyrae stars as chemical evolution tracers

Martínez-Vázquez+2015,2016ab



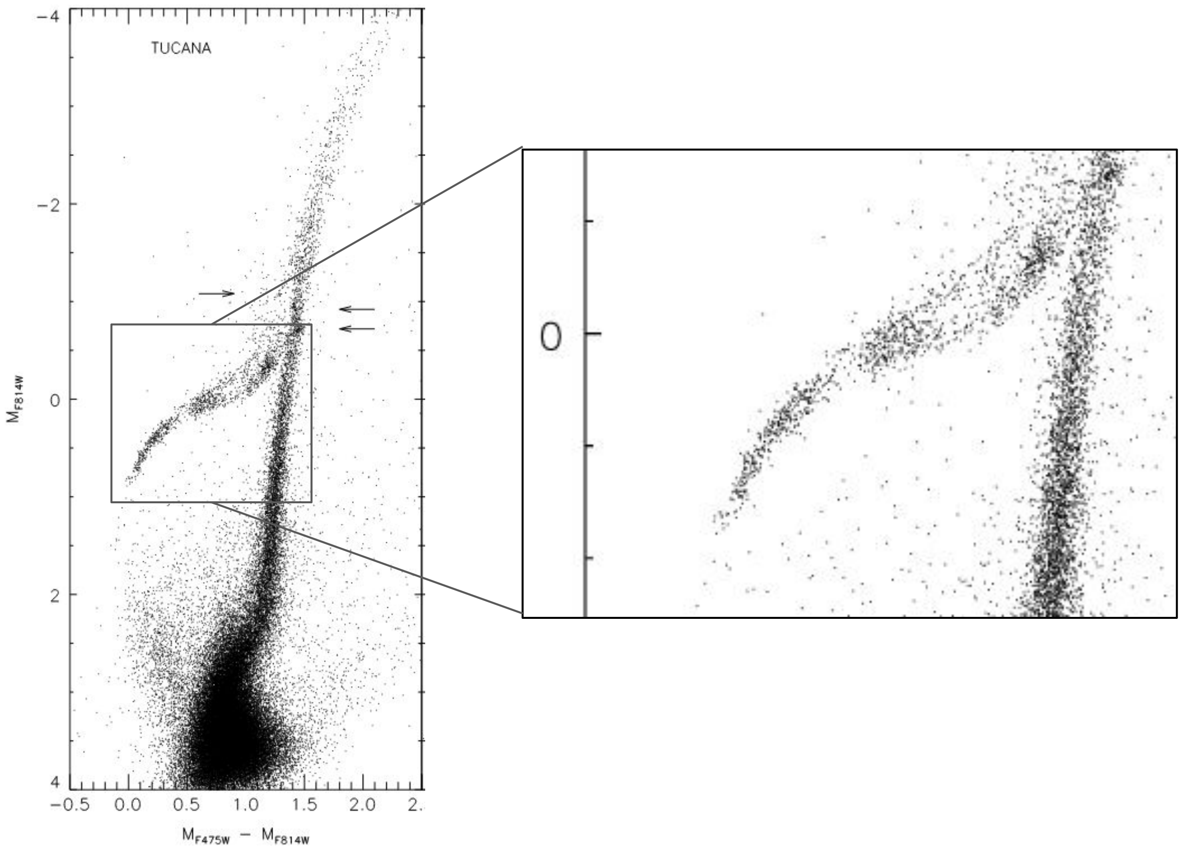
Sculptor dSph



RR Lyrae stars as chemical evolution tracers

Bernard+2008, Monelli+2010

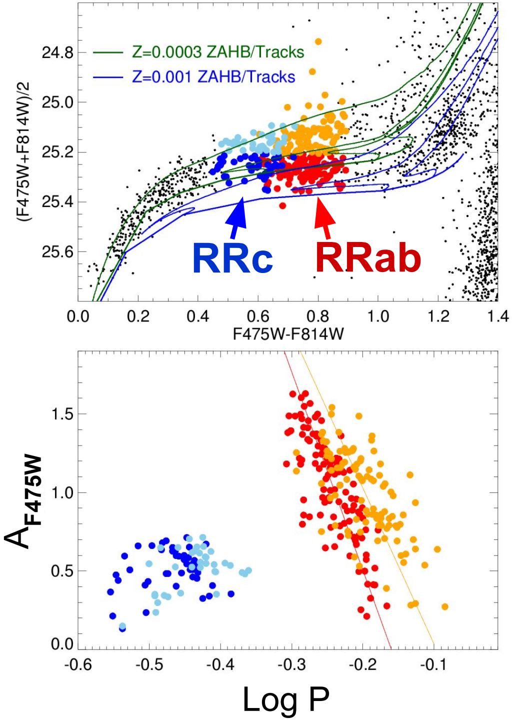
Tucana dSph

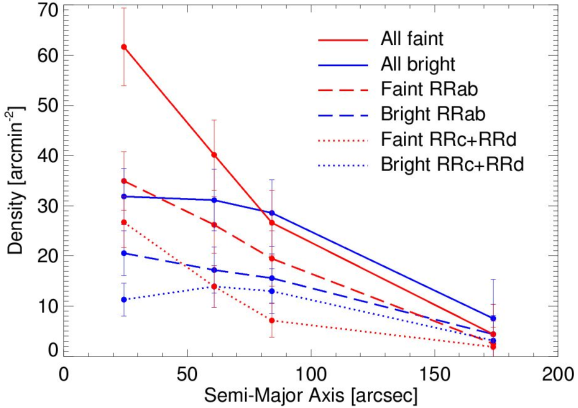


RR Lyrae stars as chemical evolution tracers

Bernard+2008, Monelli+2010

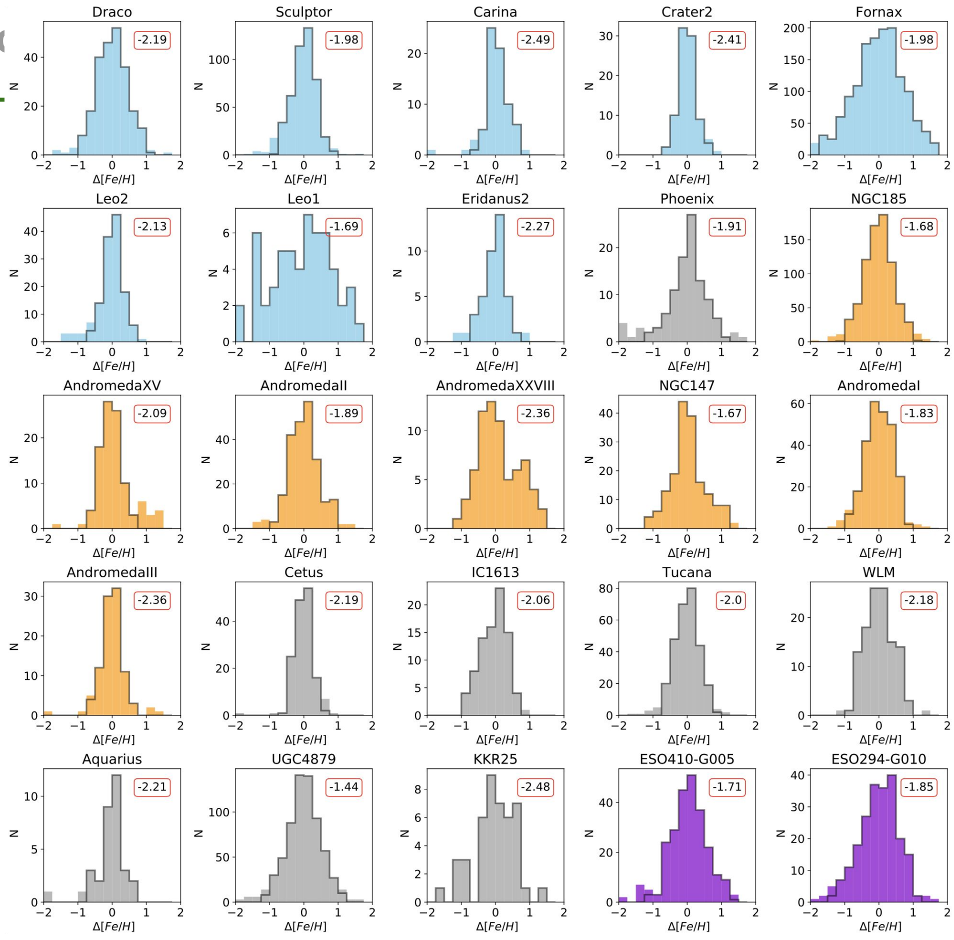
Tucana dSph





RR Lyrae stars as chemical evolution trac

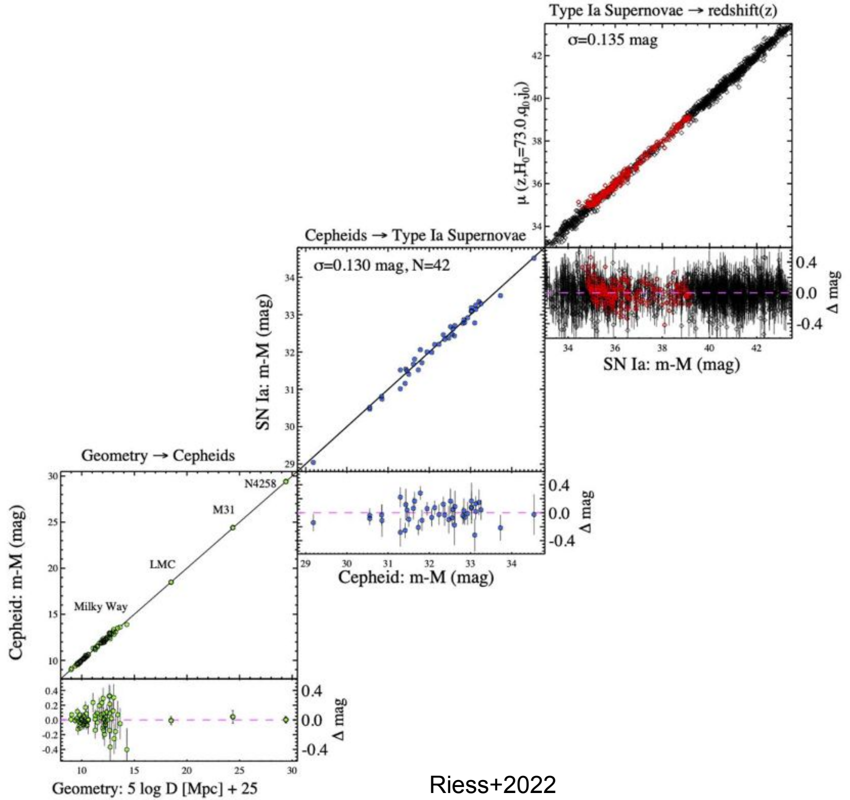
Towards a global vision of the early chemical evolution in the whole Local Group



Martínez-Vazquez+ in prep.

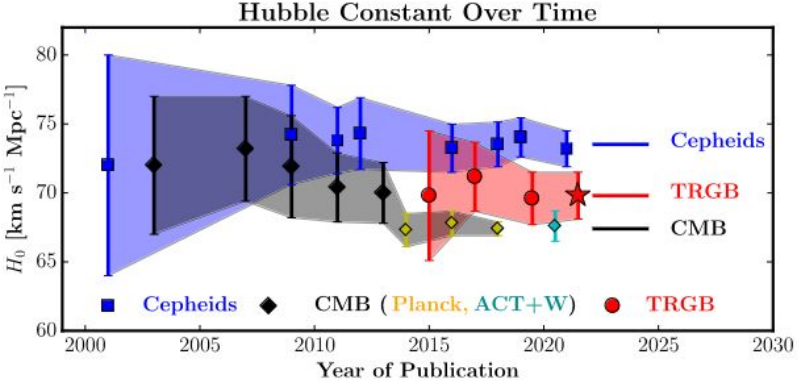
RR Lyrae stars as distance tracers

RR Lyrae stars as distances indicators



Riess+2022

Hubble tension



RR Lyrae stars as distances indicators

Class	Band	α	β	γ	Sample	Reference
RRLab	V	19.385 ± 0.017	-	0.214 ± 0.047	LMC	Gratton et al. (2004)
RRLab	M_V	0.93 ± 0.12	-	0.23 ± 0.04	GCC	Chaboyer et al. (1999)
RRLab	M_V	0.82 ± 0.04	-	(0.214)	GAL	Gaia Collaboration et al. (2017)
RRLab	W(V,I)	17.172 ± 0.003	-2.933 ± 0.009	-	LMC	Jacyszyn-Dobrzeniecka et al. (2017)
RRLab	W(V,I)	17.492 ± 0.007	-3.001 ± 0.028	-	SMC	Jacyszyn-Dobrzeniecka et al. (2017)
RRLab	K	17.43 ± 0.01	-2.73 ± 0.25	0.03 ± 0.07	LMC	Murareva et al. (2015)
RRLab	K	13.28 ± 0.02	-2.33 ± 0.08	-	M5	Coppola et al. (2011)
RRLab	K	10.420 ± 0.024	-2.33 ± 0.07	-	M4	Braga et al. (2015)
RRLab	K	12.752 ± 0.054	-2.232 ± 0.044	0.141 ± 0.020	ω Cen	Navarrete et al. (2017)
RRLab	M_K	-1.16 ± 0.27	(-2.33)	-	GAL	Groenewegen & Salaris (1999)
RRLab	M_K	-1.05 ± 0.13	-2.38 ± 0.04	0.08 ± 0.11	GCC	Sollima et al. (2006)
RRLab	M_K	-0.95 ± 0.14	-2.53 ± 0.36	0.07 ± 0.04	GAL	Murareva et al. (2015)
RRLab	M_K	-1.17 ± 0.10	(-2.73)	0.07 ± 0.07	GAL	Gaia Collaboration et al. (2017)
RRLab	[3.6]	10.229 ± 0.010	-2.332 ± 0.106	-	M4	Neeley et al. (2015)
RRLab	[4.5]	10.192 ± 0.010	-2.336 ± 0.105	-	M4	Neeley et al. (2015)
RRLab	W1	-1.113 ± 0.013	-2.38 ± 0.20	-	GAL	Klein et al. (2014)
RRLab	W2	-1.111 ± 0.013	-2.39 ± 0.20	-	GAL	Klein et al. (2014)
T2C	G	18.640 ± 0.085	-1.650 ± 0.109	-	LMC	Clementini et al. (2016)
T2C	W(V,I)	17.365 ± 0.015	-2.521 ± 0.022	-	LMC	Matsunaga et al. (2009)
T2C	W(V,I)	17.554 ± 0.083	-2.304 ± 0.107	-	SMC	Matsunaga et al. (2011)
T2C	K	13.27 ± 0.10	-2.24 ± 0.14	-	GB	Groenewegen et al. (2008)
T2C	K	17.412 ± 0.029	-2.278 ± 0.047	-	LMC	Matsunaga et al. (2009)
T2C	K	17.600 ± 0.082	-2.113 ± 0.105	-	SMC	Matsunaga et al. (2011)
T2C	K	17.47 ± 0.02	-2.385 ± 0.030	-	LMC	Ripepi et al. (2015)
T2C	K	17.405 ± 0.038	-2.483 ± 0.089	-	LMC	Bhardwaj et al. (2017)
T2C	M_K	-1.58 ± 0.17	(-2.385)	-	GAL	Gaia Collaboration et al. (2017)
T2C	W(V,K)	17.33 ± 0.02	-2.49 ± 0.03	-	LMC	Ripepi et al. (2015)
T2C	W(V,K)	17.415 ± 0.012	-2.456 ± 0.025	-	LMC	Bhardwaj et al. (2017)
AC FU	G	18.00 ± 0.04	-2.95 ± 0.27	-	LMC	Clementini et al. (2016)
AC FU	K	16.74 ± 0.02	-3.54 ± 0.15	-	LMC	Ripepi et al. (2014)
AC FU	W(V,K)	16.58 ± 0.02	-3.58 ± 0.15	-	LMC	Ripepi et al. (2014)
CEP FU	G	17.361 ± 0.020	-2.818 ± 0.032	-	LMC	Clementini et al. (2016)
CEP FU	M_V	-1.43 ± 0.10	(-2.81)	-	GAL	Feast & Catchpole (1997)
CEP FU	M_V	-1.275 ± 0.023	-2.678 ± 0.076	-	GAL	Fouqué et al (2007)
CEP FU	M_V	-1.54 ± 0.10	(-2.678)	-	GAL	Gaia Collaboration et al. (2017)
CEP FU	W(V,I)	16.375 ± 0.014	-3.314 ± 0.020	-	SMC	Ngeow et al. (2015a)
CEP FU	W(V,I)	15.897 ± 0.001	-3.327 ± 0.001	-	LMC	Inno et al. (2016)
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CEP FU	$M_{W(V,I)}$	-2.60 ± 0.03	-3.32 ± 0.08	(0.0)	MC+G	Storm et al. (2011b)
CEP FU	$M_{W(V,I)}$	-2.414 ± 0.022	-3.477 ± 0.074	-	GAL	Fouqué et al. (2017)
CEP FU	$M_{W(V,I)}$	-2.82 ± 0.11	(-3.477)	-	GAL	Gaia Collaboration et al. (2017)
CEP FU	K	16.494 ± 0.026	-3.212 ± 0.033	-	SMC	Groenewegen (2000)
CEP FU	K	16.514 ± 0.025	-3.213 ± 0.032	-	SMC	Ngeow et al. (2015a)
CEP FO	K	15.941 ± 0.032	-3.132 ± 0.083	-	SMC	Bhardwaj et al. (2016b)
CEP FU	K	16.051 ± 0.050	-3.281 ± 0.040	-	LMC	Persson et al. (2004)
CEP FU	K	16.070 ± 0.017	-3.295 ± 0.018	-	LMC	Ripepi et al. (2012)
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CEP FU	M_K	-2.282 ± 0.019	-3.365 ± 0.063	-	GAL	Fouqué et al. (2007)
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CEP FU	M_K	-2.33 ± 0.03	-3.30 ± 0.06	(0.0)	MC+G	Storm et al. (2011b)
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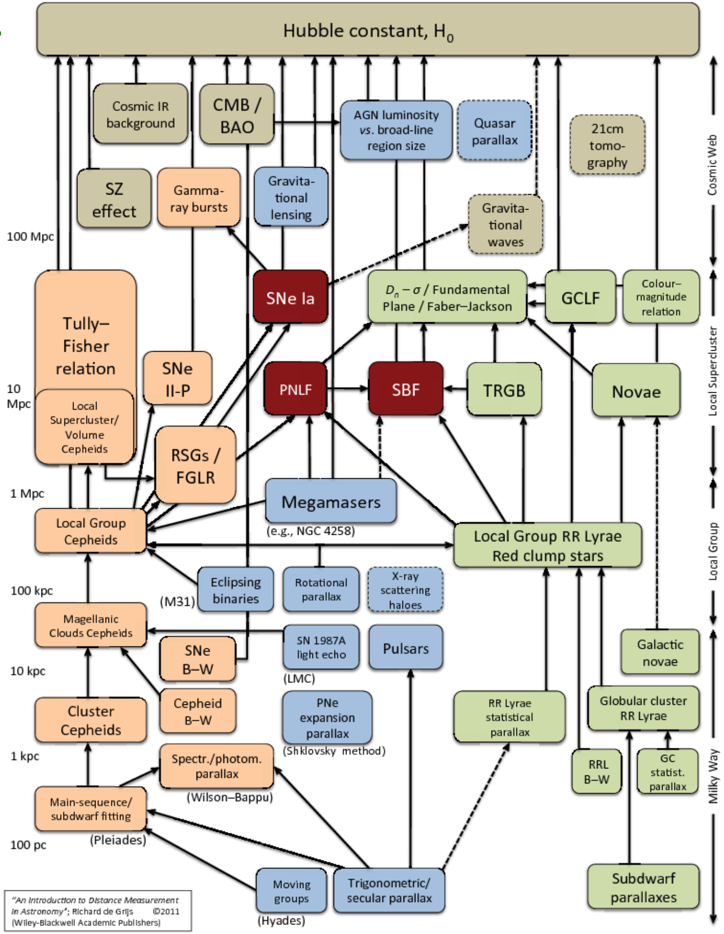
CEP FU	W(V,K)	15.894 ± 0.002	-3.314 ± 0.002	-	LMC	Inno et al. (2016)
CEP FU	W(V,K)	15.837 ± 0.049	-3.287 ± 0.010	-	LMC	Bhardwaj et al. (2016a)
CEP FU	$M_{W(V,K)}$	-2.87 ± 0.10	(-3.32)	-	GAL	Gaia Collaboration et al. (2017)
CEP FU	$M_{W(V,K}$	-2.69 ± 0.08	-3.11 ± 0.07	$+0.04 \pm 0.10$	MC+G	Groenewegen (2013)
CEP FU	[3.6]	16.01 ± 0.02	-3.31 ± 0.05	-	LMC	Monson et al. (2012)
CEP FU	[4.5]	15.90 ± 0.02	-3.21 ± 0.06	-	LMC	Monson et al. (2012)
CEP FU	$M_{[24]}$	-2.46 ± 0.10	-3.18 ± 0.10	-	GAL	Ngeow et al. (2015b)

Groenewegen 2017

RR Lyrae stars as distances indicators

De Grijis 2011



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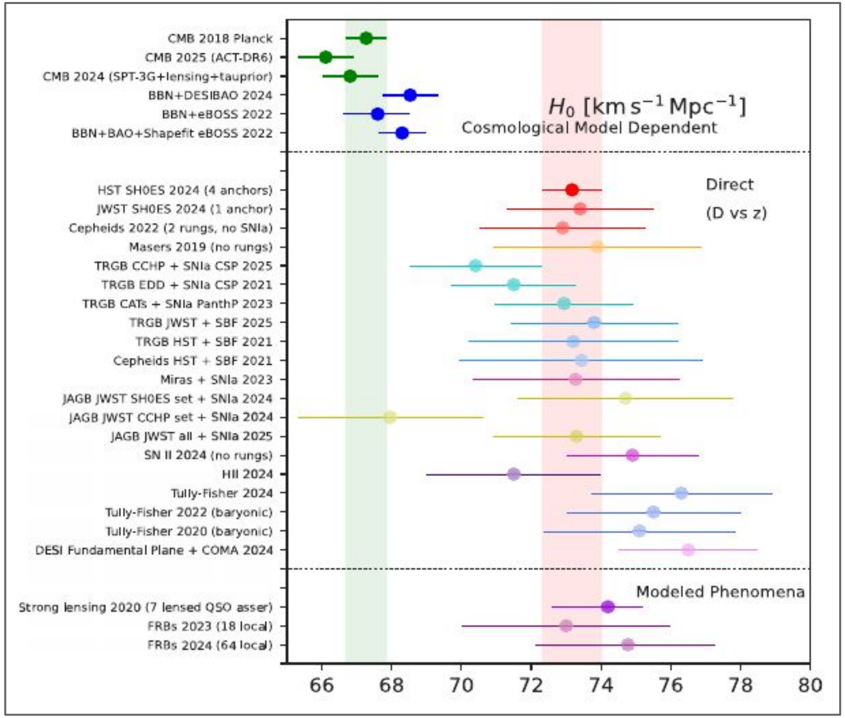

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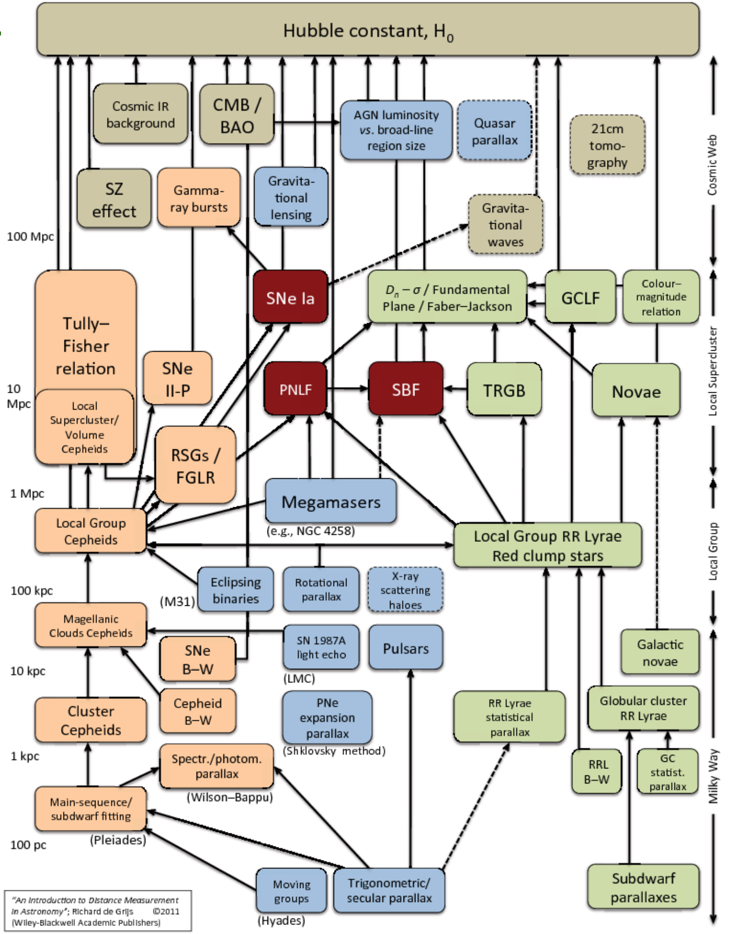
Verde+2024, ARA&A



RR Lyrae stars as distances indicators

Class	Band	α	β	γ	Sample	Reference
RRLab	V	19.385 ± 0.017	-	0.214 ± 0.047	LMC	Gratton et al. (2004)
RRLab	M_V	0.93 ± 0.12	-	0.23 ± 0.04	GCC	Chaboyer et al. (1999)
RRLab	M_V	0.82 ± 0.04	-	(0.214)	GAL	Gaia Collaboration et al. (2017)
RRLab	W(V,I)	17.172 ± 0.003	-2.933 ± 0.009	-	LMC	Jacyszyn-Dobrzeniecka et al. (2017)
RRLab	W(V,I)	17.492 ± 0.007	-3.001 ± 0.028	-	SMC	Jacyszyn-Dobrzeniecka et al. (2017)
RRLab	K	17.43 ± 0.01	-2.73 ± 0.25	0.03 ± 0.07	LMC	Murareva et al. (2015)
RRLab	K	13.28 ± 0.02	-2.33 ± 0.08	-	M5	Coppola et al. (2011)
RRLab	K	10.420 ± 0.024	-2.33 ± 0.07	-	M4	Braga et al. (2015)
RRLab	K	12.752 ± 0.054	-2.232 ± 0.044	0.141 ± 0.020	ω Cen	Navarrete et al. (2017)
RRLab	M_K	-1.16 ± 0.27	(-2.33)	-	GAL	Groenewegen & Salaris (1999)
RRLab	M_K	-1.05 ± 0.13	-2.38 ± 0.04	0.08 ± 0.11	GCC	Sollima et al. (2006)
RRLab	M_K	-0.95 ± 0.14	-2.53 ± 0.36	0.07 ± 0.04	GAL	Murareva et al. (2015)
RRLab	M_K	-1.17 ± 0.10	(-2.73)	0.07 ± 0.07	GAL	Gaia Collaboration et al. (2017)
RRLab	[3.6]	10.229 ± 0.010	-2.332 ± 0.106	-	M4	Neeley et al. (2015)
RRLab	[4.5]	10.192 ± 0.010	-2.336 ± 0.105	-	M4	Neeley et al. (2015)
RRLab	W1	-1.113 ± 0.013	-2.38 ± 0.20	-	GAL	Klein et al. (2014)
RRLab	W2	-1.111 ± 0.013	-2.39 ± 0.20	-	GAL	Klein et al. (2014)
T2C	G	18.640 ± 0.085	-1.650 ± 0.109	-	LMC	Clementini et al. (2016)
T2C	W(V,I)	17.365 ± 0.015	-2.521 ± 0.022	-	LMC	Matsunaga et al. (2009)
T2C	W(V,I)	17.554 ± 0.083	-2.304 ± 0.107	-	SMC	Matsunaga et al. (2011)
T2C	K	13.27 ± 0.10	-2.24 ± 0.14	-	GB	Groenewegen et al. (2008)
T2C	K	17.412 ± 0.029	-2.278 ± 0.047	-	LMC	Matsunaga et al. (2009)
T2C	K	17.600 ± 0.082	-2.113 ± 0.105	-	SMC	Matsunaga et al. (2011)
T2C	K	17.47 ± 0.02	-2.385 ± 0.030	-	LMC	Ripepi et al. (2015)
T2C	K	17.405 ± 0.038	-2.483 ± 0.089	-	LMC	Bhardwaj et al. (2017)
T2C	M_K	-1.58 ± 0.17	(-2.385)	-	GAL	Gaia Collaboration et al. (2017)
T2C	W(V,K)	17.33 ± 0.02	-2.49 ± 0.03	-	LMC	Ripepi et al. (2015)
T2C	W(V,K)	17.415 ± 0.012	-2.456 ± 0.025	-	LMC	Bhardwaj et al. (2017)
AC FU	G	18.00 ± 0.04	-2.95 ± 0.27	-	LMC	Clementini et al. (2016)
AC FU	K	16.74 ± 0.02	-3.54 ± 0.15	-	LMC	Ripepi et al. (2014)
AC FU	W(V,K)	16.58 ± 0.02	-3.58 ± 0.15	-	LMC	Ripepi et al. (2014)
CEP FU	G	17.361 ± 0.020	-2.818 ± 0.032	-	LMC	Clementini et al. (2016)
CEP FU	M_V	-1.43 ± 0.10	(-2.81)	-	GAL	Feast & Catchpole (1997)
CEP FU	M_V	-1.275 ± 0.023	-2.678 ± 0.076	-	GAL	Fouqué et al (2007)
CEP FU	M_V	-1.54 ± 0.10	(-2.678)	-	GAL	Gaia Collaboration et al. (2017)
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Groenewegen 2017

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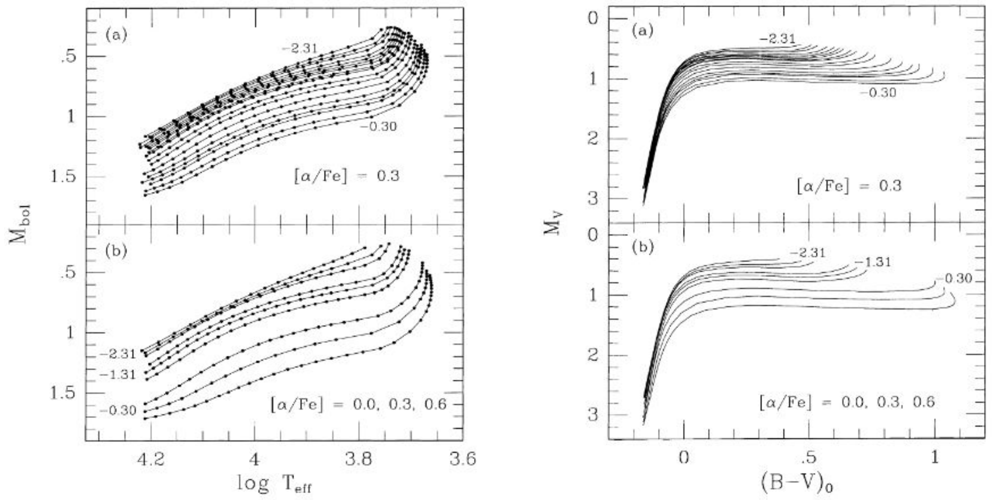
Groenewegen 2017

Game changer: Gaia!

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation



Vandenberg 2000

$M_V = a \cdot [Fe/H] + b$

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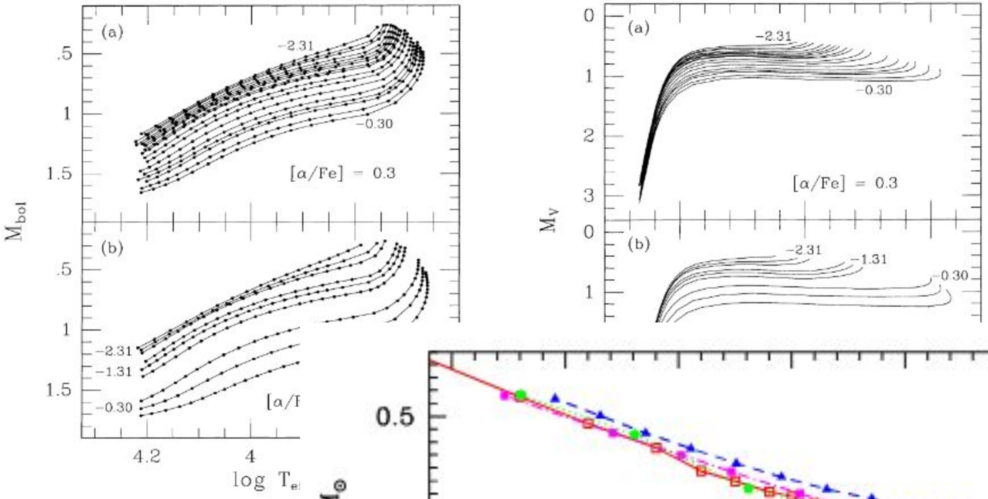

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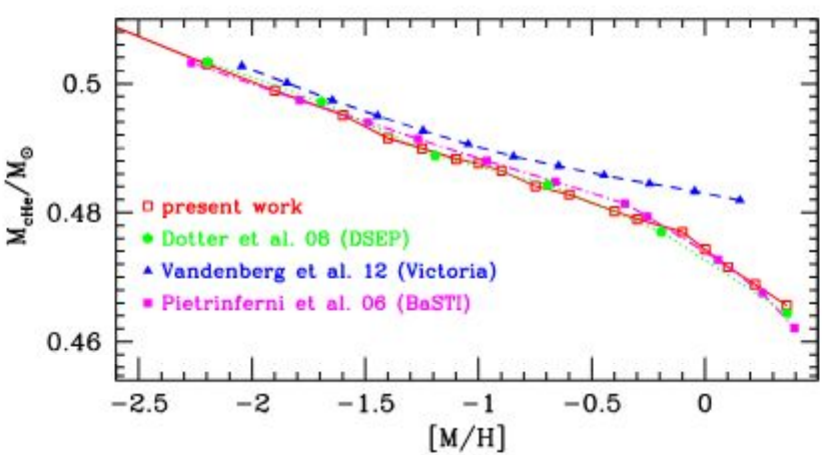

Pietrinferni+2021

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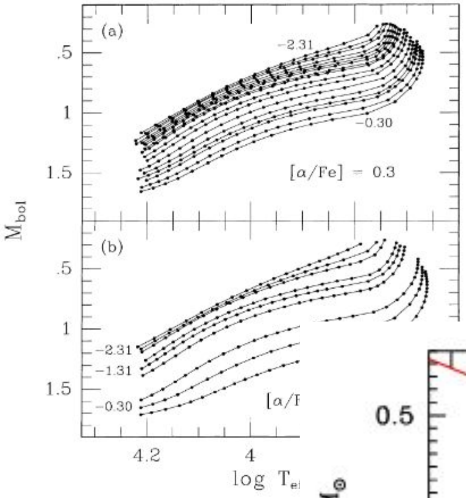

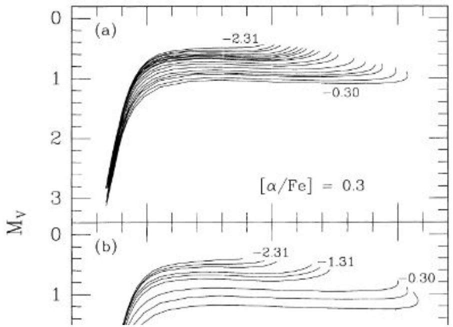

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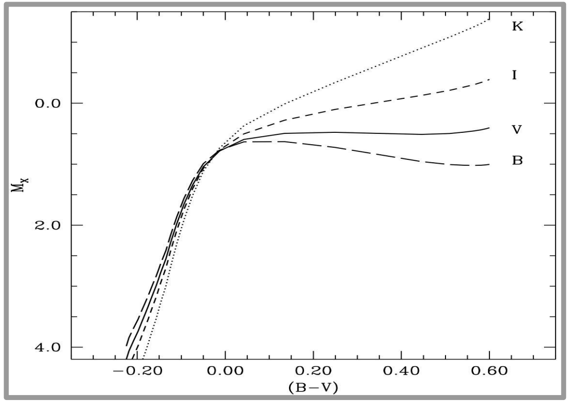
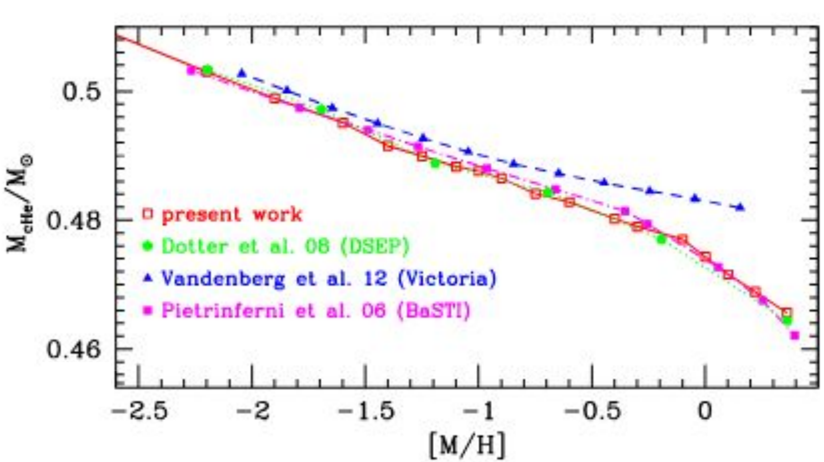


Cassisi & Salaris 2014



Pietrinferni+2021

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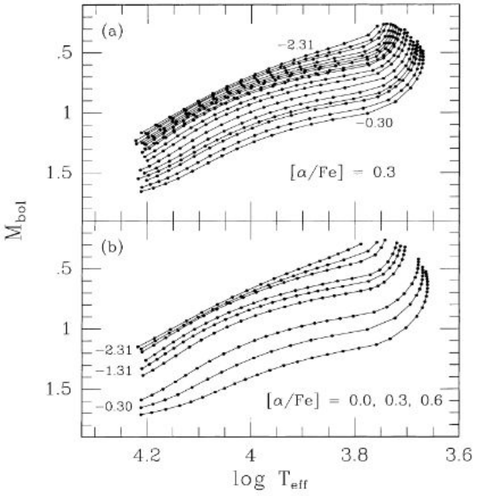

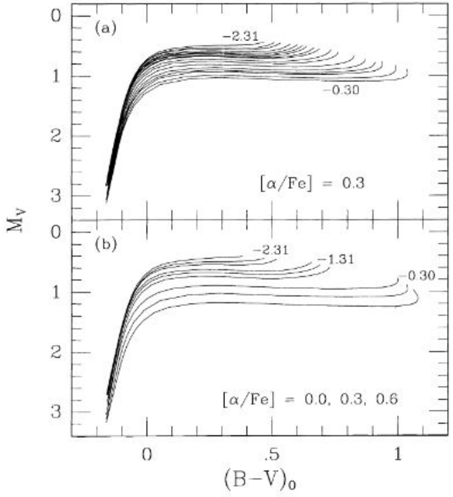

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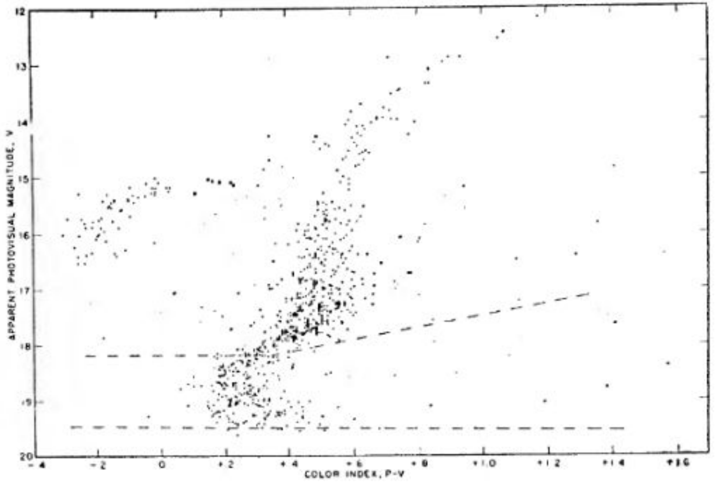


Fig. 1. Color-magnitude array for the globular cluster M92.

Arp, Baum & Sandage 1952

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

$$M_V = a \cdot [Fe/H] + b$$

Why?

Basically EVERY LG galaxy with known RRL stars have a distance calculated with this method

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

$M_V = a \cdot [Fe/H] + b$

Why?

Basically EVERY LG galaxy with known RRL stars have a distance calculated with this method

1) easy

2) linear

3) two observables (apparent mean magnitude, metallicity)

→ powerful and widely used

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

$M_V = a \cdot [Fe/H] + b$

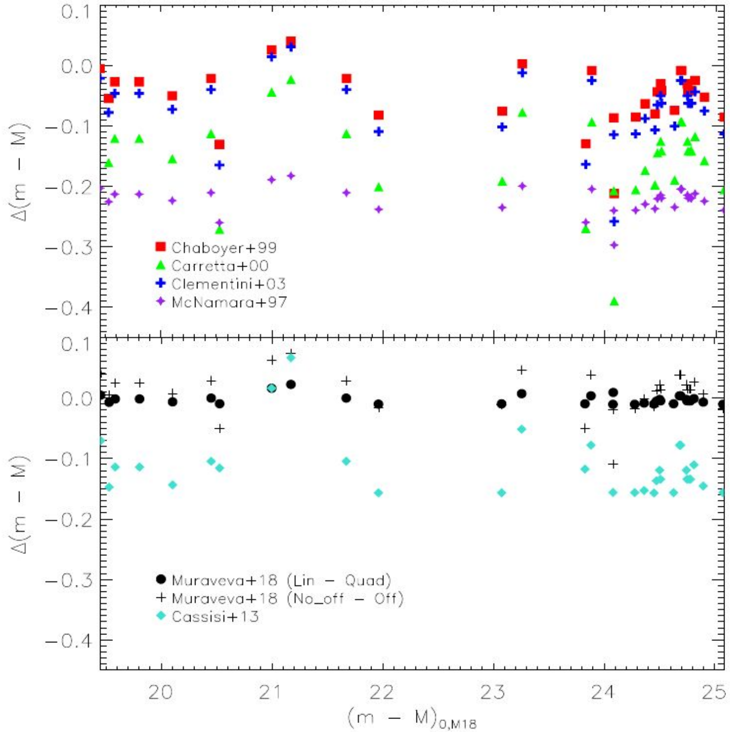
Caveats

i. calibration: a = ? b = ?

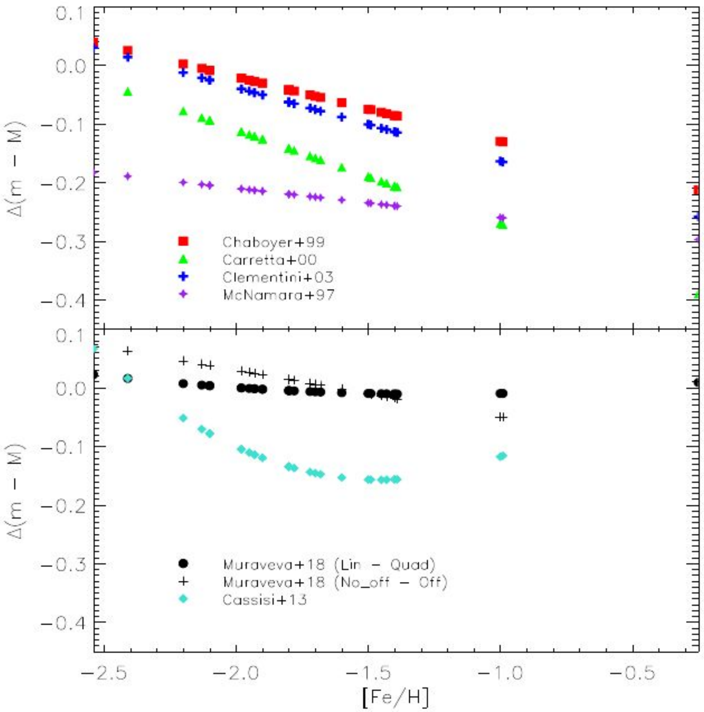
many different calibrations: $\langle M_V \rangle = 0.18[Fe/H]+0.74$ (Carretta+00)
$\langle M_V \rangle = 0.214[Fe/H]+0.88$ (Clementini+03)
$\langle M_V \rangle = 0.29[Fe/H]+0.96$ (McNamara+97)

➜ Difference of the order of 0.2 mag

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation



18[Fe/H
214[Fe
29[Fe/H



Monelli & Fiorentino 2022

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

$M_V = a \cdot [Fe/H] + b$

Caveats

ii. Reddening: an uncertainty of 0.01 mag on the E(B-V) translates into a 0.03 mag error on the distance

Differential reddening ???

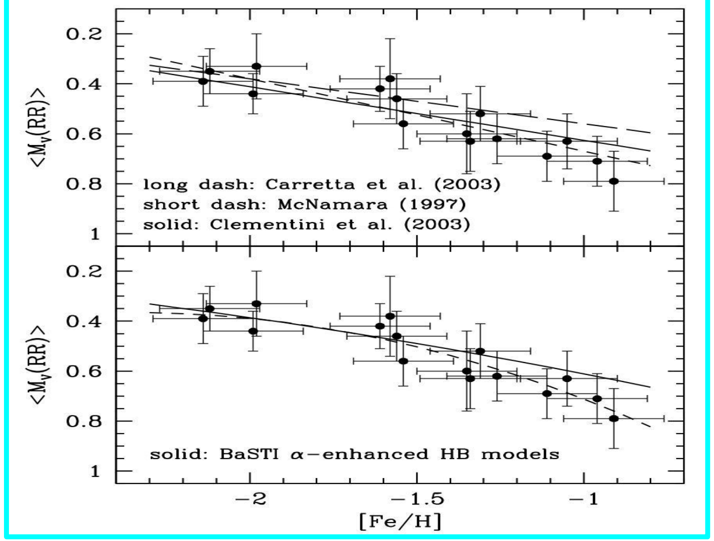
RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

Caveats

iii. Linearity: evidence supports that the relation is NOT linear, but it is steeper in the more metal-rich regime (Caputo+00)

M_V= a·[Fe/H] + b

$<M_V>$= 0.177[Fe/H]+0.718 if [Fe/H] < -1.6
= 0.359[Fe/H]+1.038 if [Fe/H] > -1.6 (Bono+03)



$<M_V>$ = 1.415 +0.893[Fe/H] +0.190[Fe/H]^2

Cassisi & Salaris 2014

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

$M_V = a \cdot [Fe/H] + b$

Caveats

iv. Metallicity: [Fe/H] = ?

a) lack of high-resolution spectroscopy of RR Lyrae stars in dwarf

b) dependence on the metallicity scale

c) observation provide Fe (or a proxy, such as Ca), but the models assume the global metallicity [M/H] → knowledge α-enhancement is crucial

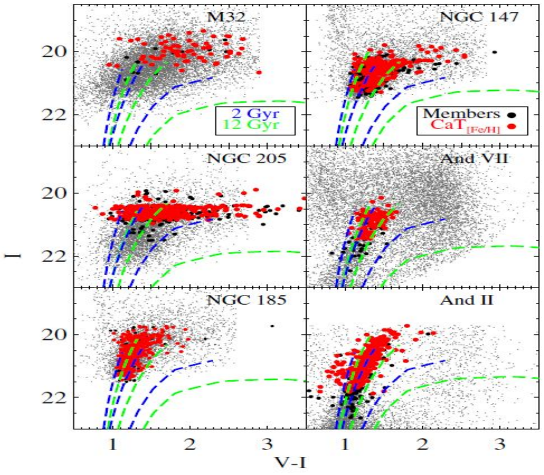
d) M_V depends on the He abundance as well

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

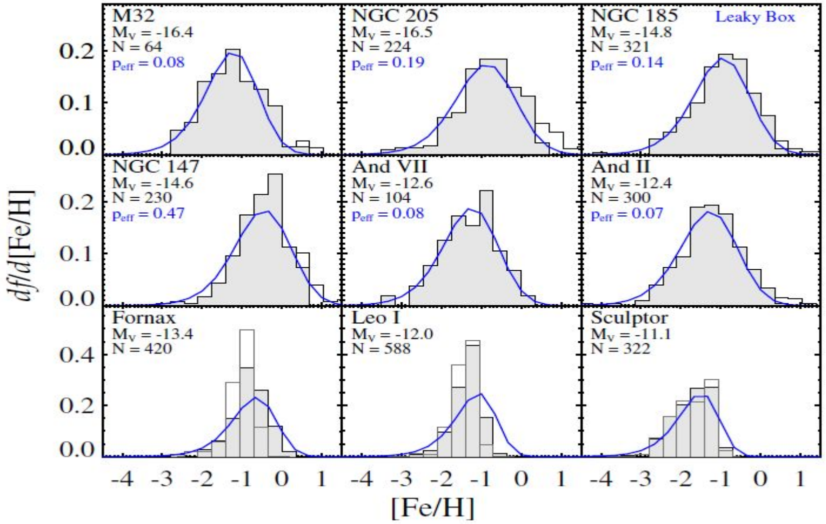
Caveats

v. metallicity

$M_V = a \cdot [Fe/H] + b$



Ho+2015



Metallicities based **RGB** stars+ CaT may not be representative of old RR Lyrae stars

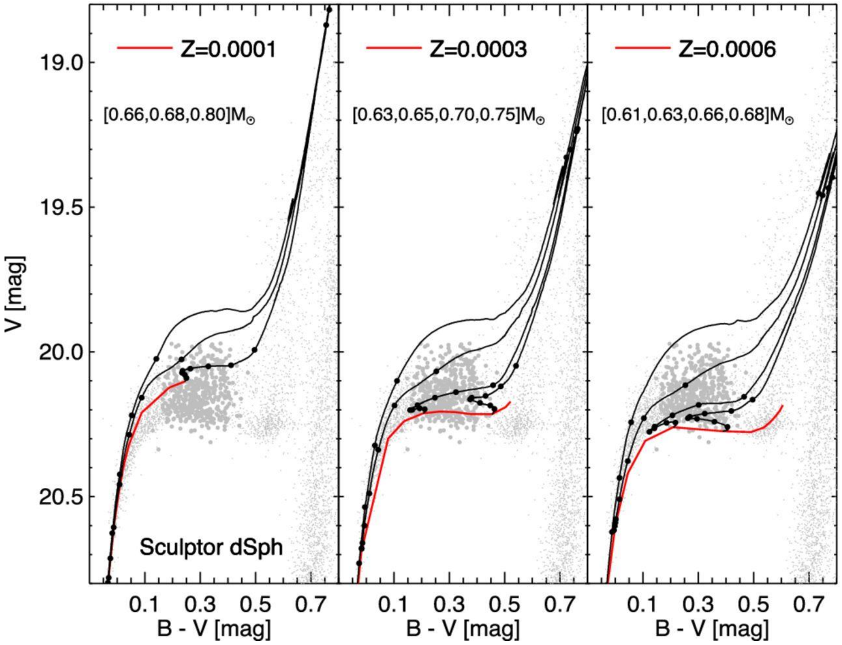
RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

$M_V = a \cdot [Fe/H] + b$

Caveats

iv. Metallicity: [Fe/H] = ?

The populations of RR Lyrae stars in galaxies are **often complex** and present an **intrinsic spread in metallicity**. A large spread in metallicity in the RR Lyrae population cause an intrinsic spread in luminosity



RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

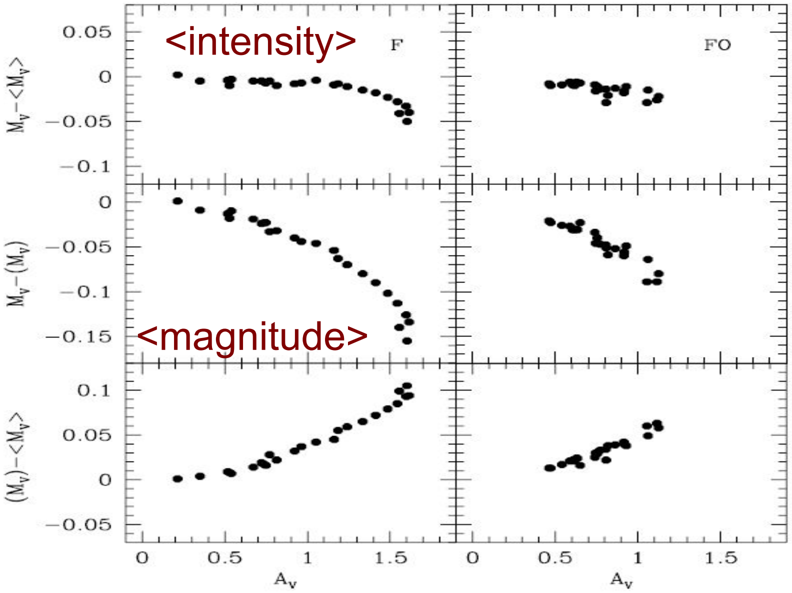
$$M_V = a \cdot [Fe/H] + b$$

Caveats

v. Apparent magnitude

How to calculate the mean magnitude of a star?
The mean magnitude of a static star is different from the intensity averaged mean magnitude of a RRL, by few hundredths

How to calculate the mean magnitude of the population of RRL stars?



Marconi 2003

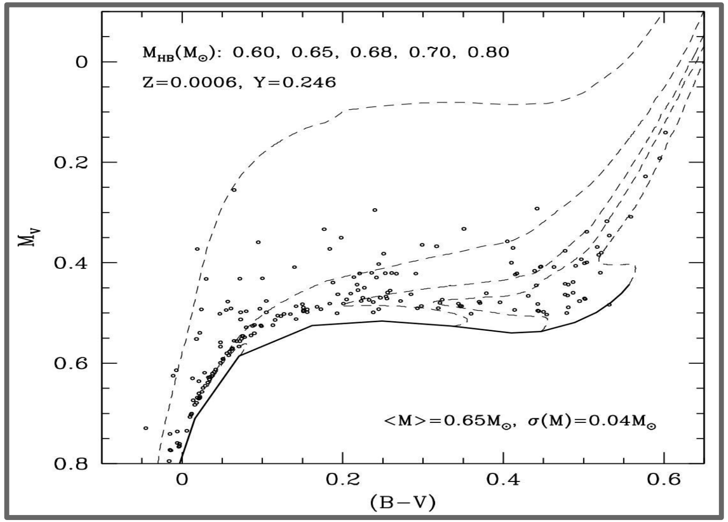
RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

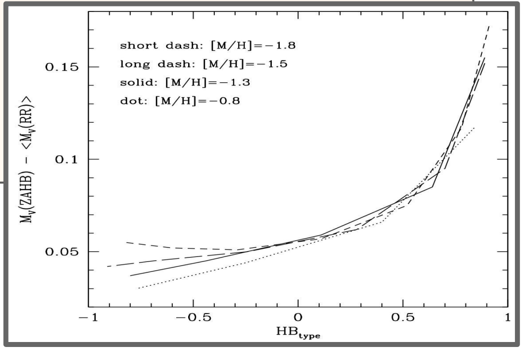
Caveats

v. Apparent magnitude: **Evolutionary effects** are completely neglected: HB stars spend most of their life at a magnitude level ~0.1 mag brighter than the ZAHB, with strong dependence on the HB morphology.

Dependency on the HB morphology…

$$M_V = a\cdot[Fe/H] + b$$

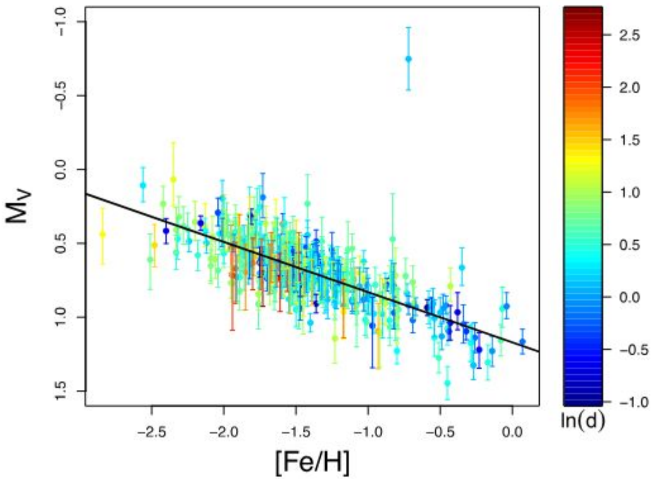




Cassisi & Salaris 2014

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

Muraveva+2018
Gaia DR2 + GC, calibrated using using a sample of ~400 stars, but only 23 with HR metallicity.

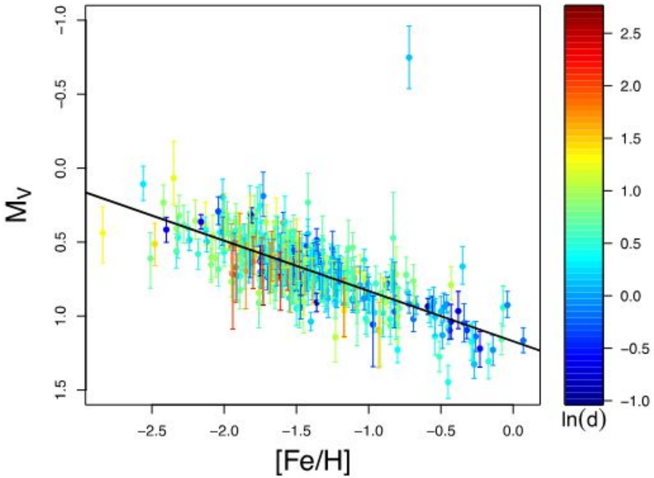


Lin. M_V–[Fe/H]	381	$M_V = \left(0.34^{+0.03}_{-0.03}\right)[\mathrm{Fe/H}] + \left(1.17^{+0.04}_{-0.04}\right)$

RR Lyrae stars as distances indicators: the Luminosity-Metallicity relation

Muraveva+2018
Gaia DR2 + GC, calibrated using using a sample of ~400 stars, but only 23 with HR metallicity.

Garofalo+2022
Gaia DR3 + GC



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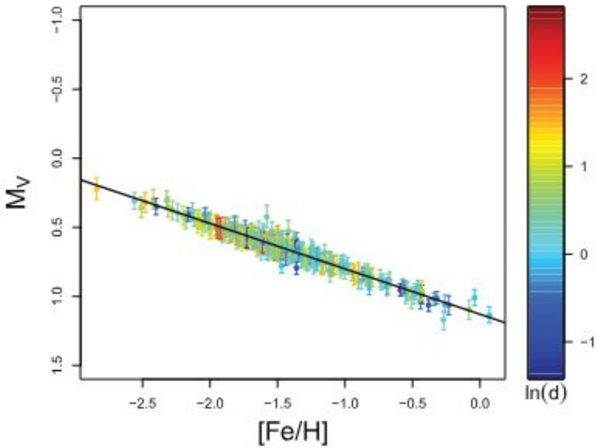
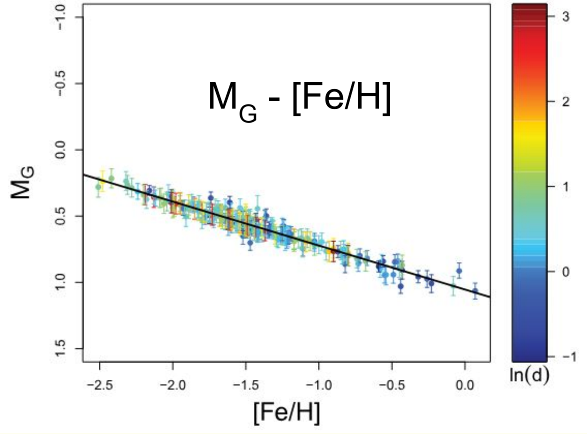
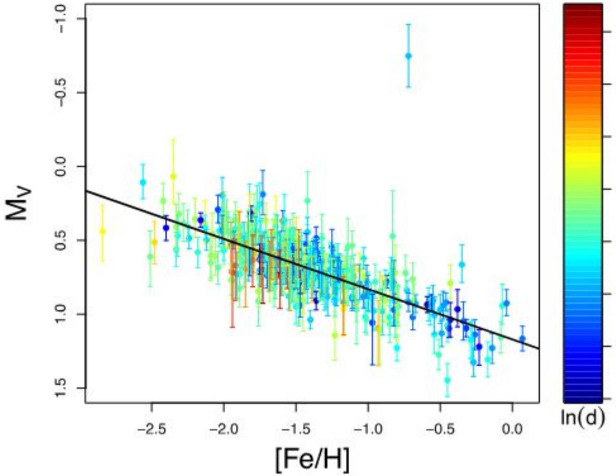


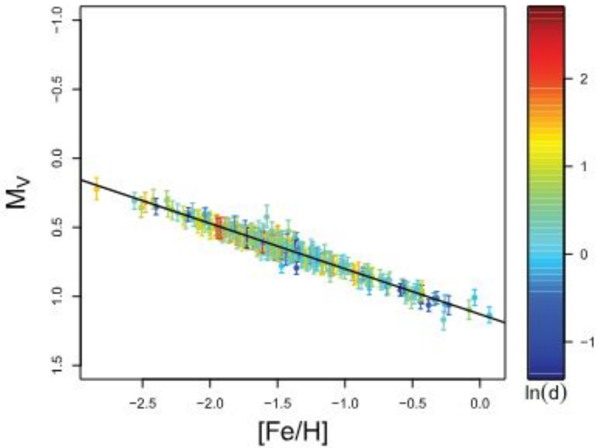
$$M_V = \left(0.29^{+0.35}_{-0.29}\right) [\mathrm{Fe/H}] + \left(1.05^{+0.43}_{-0.46}\right).$$

indicators: the Luminosity-Metallicity relation



using a sample of ~400
ty.



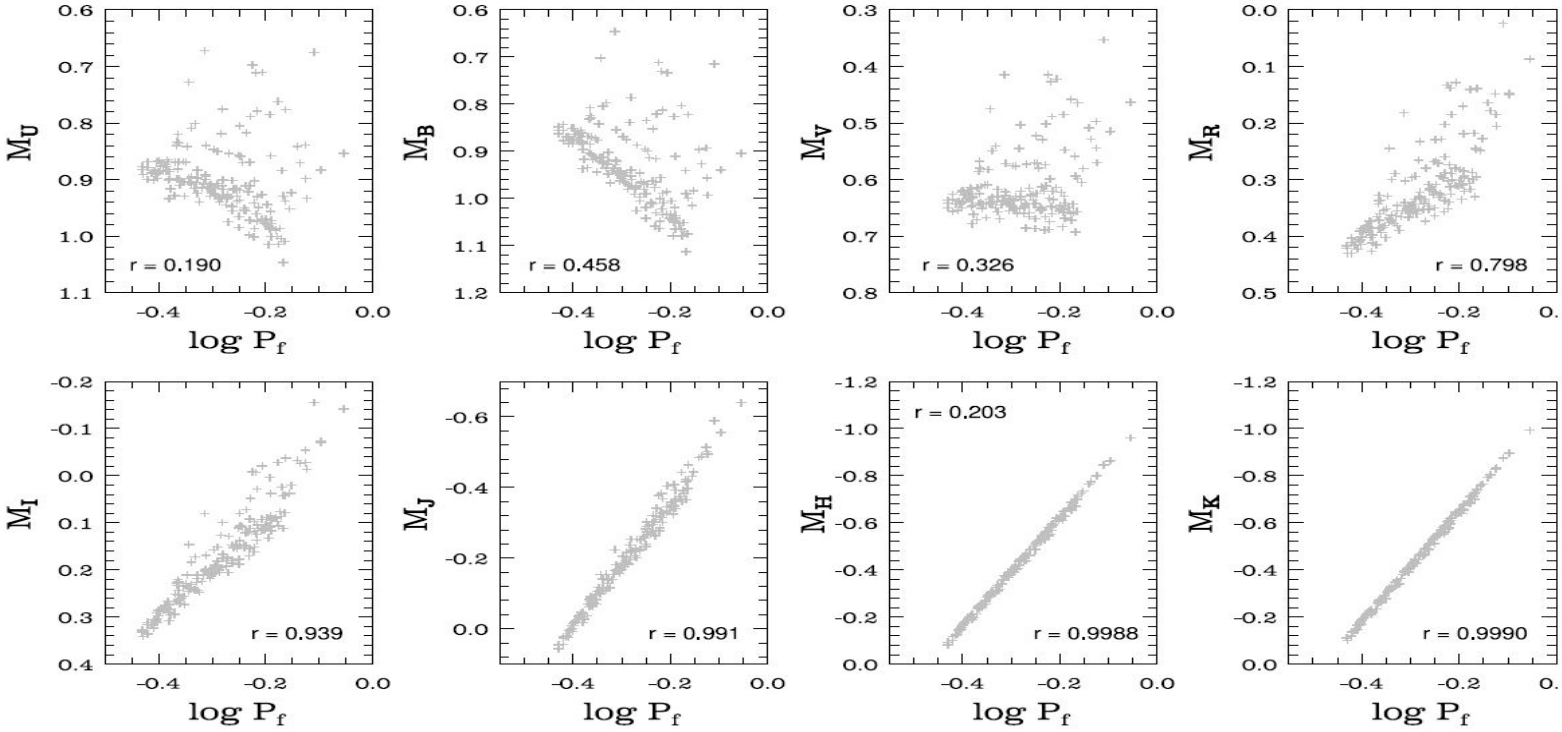


Lin. M_V–[Fe/H] 381 $M_V = \left(0.34^{+0.03}_{-0.03}\right)\,[\mathrm{Fe/H}] + \left(1.17^{+0.04}_{-0.04}\right)$

$$M_V = \left(0.29^{+0.35}_{-0.29}\right)\,[\mathrm{Fe/H}] + \left(1.05^{+0.43}_{-0.46}\right).$$

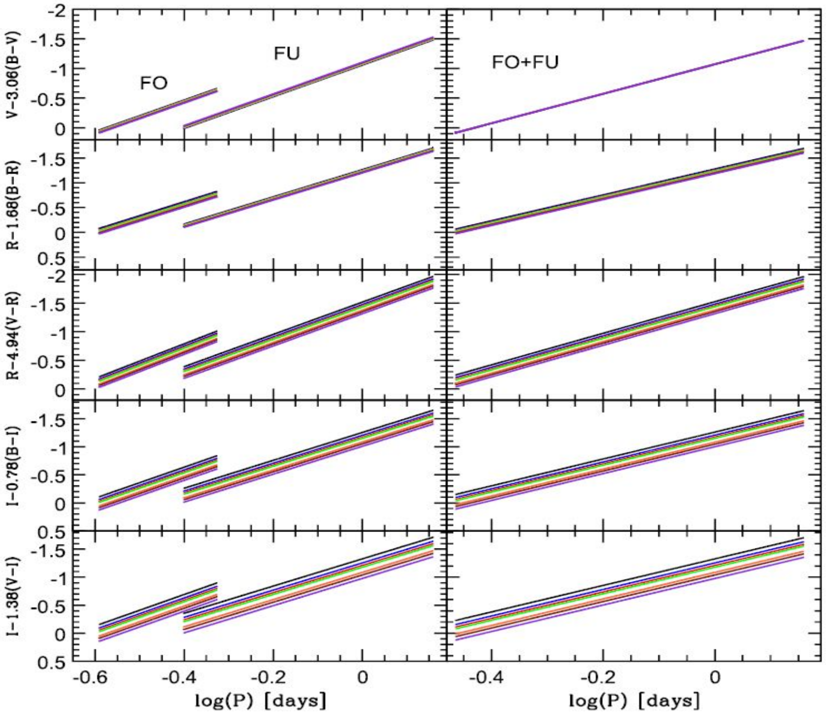
Period-luminosity relation

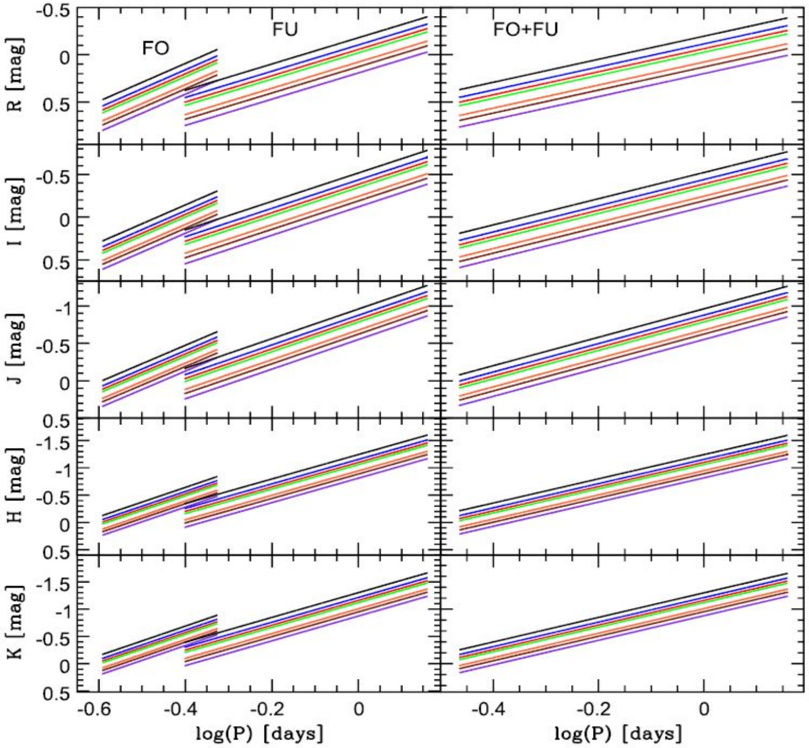
$$M_V = a + b*\log P + c\cdot[Fe/H]$$



Catelan+04

RR Lyrae stars as distances indicators: Period-luminosity relations

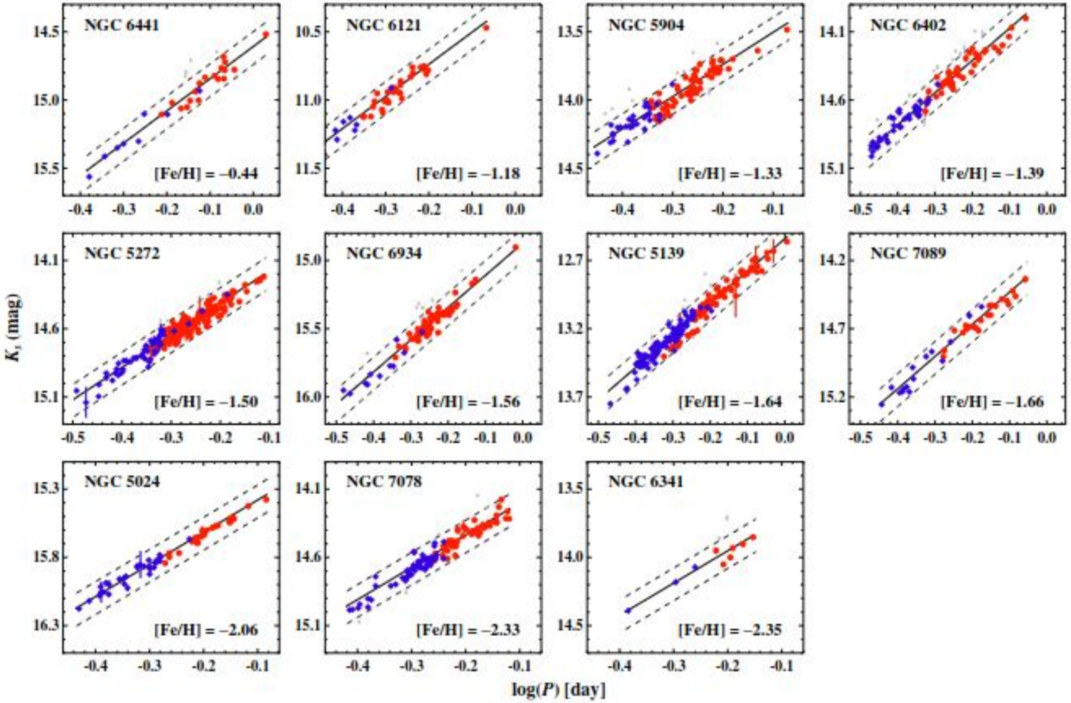


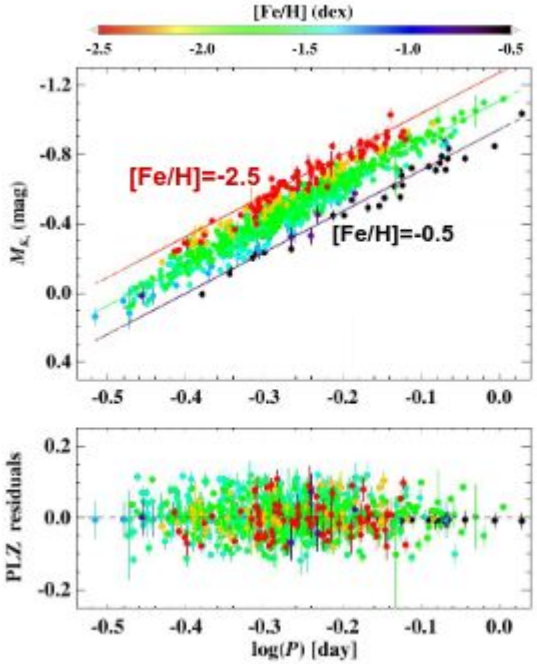


BV ➜ distance + PL(I) ➜ metallicity

Marconi+2015,2018,2022

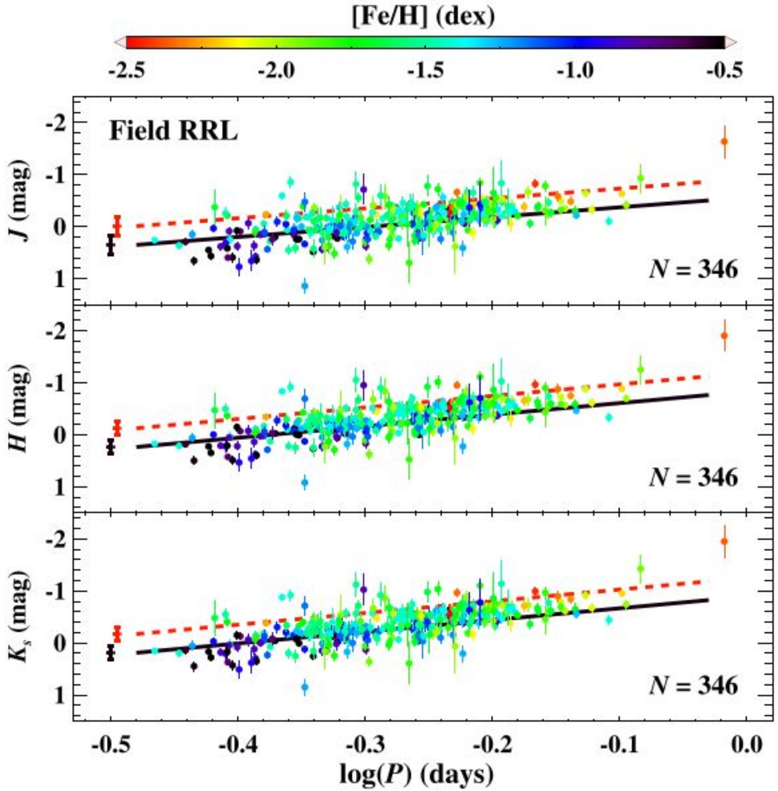
RR Lyrae stars as distances indicators





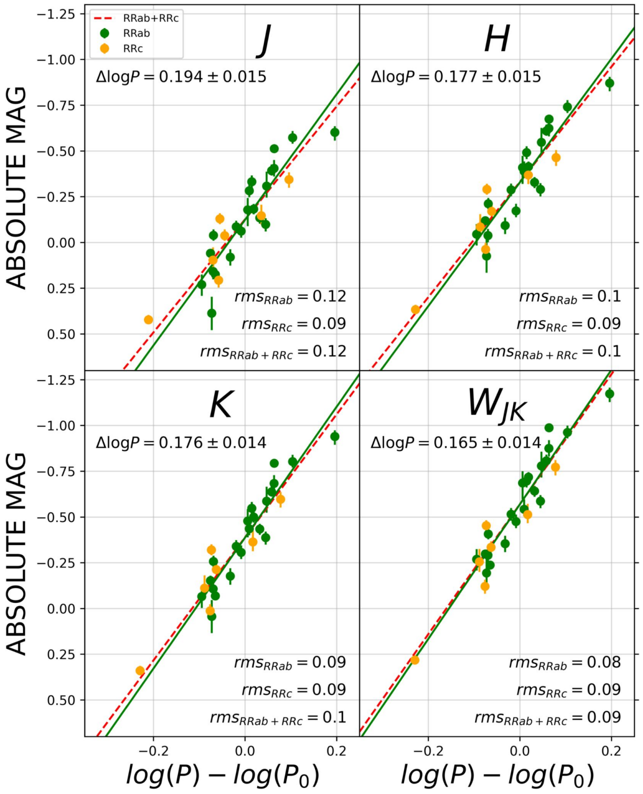
Bhardwaj 2022

RR Lyrae stars as distances indicators



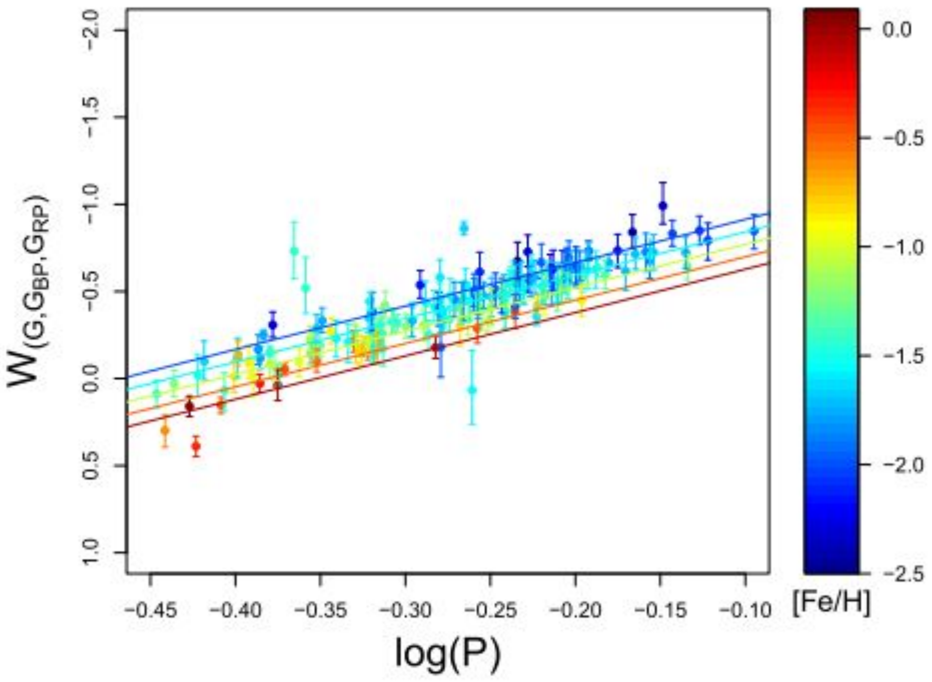
Bhardwaj+2023: calibration of the metallicity dependence of the Period-Luminosity relation using NIR photometry of RRL stars in Globular Clusters

RR Lyrae stars as distances indicators



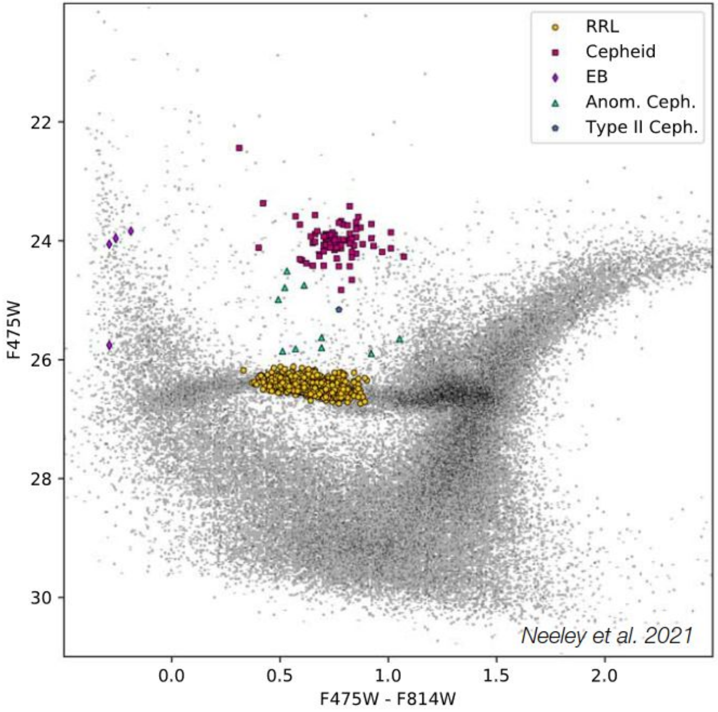
Zgirski+2023: calibration of the Period-Luminosity relation using NIR photometry of 27 field RRL stars, anchored to Gaia distances

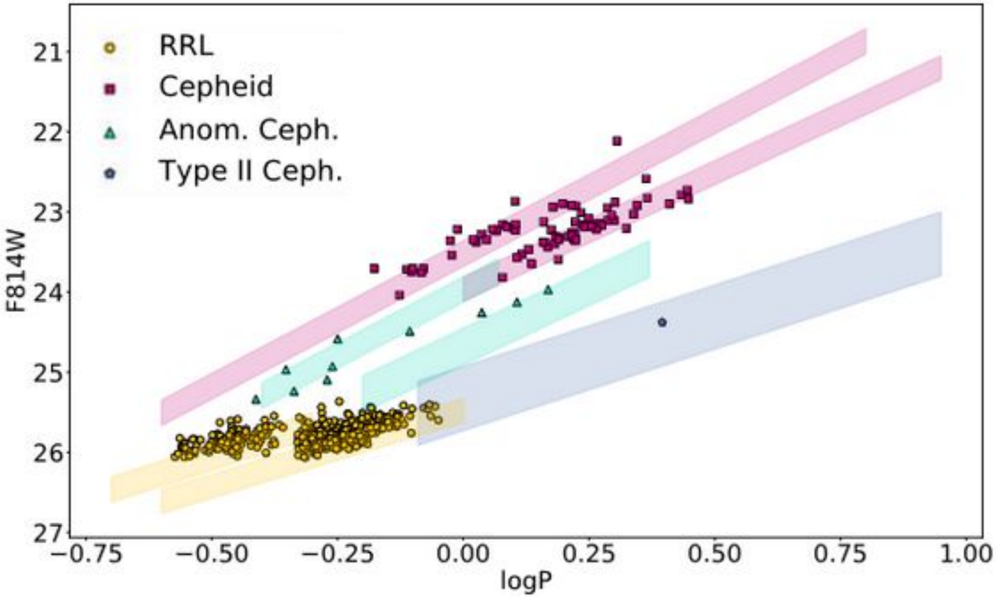
RR Lyrae stars as distances indicators



Garofalo+2023: calibration of the Period-Wesenheit relation in the Gaia bands using Gaia distances + spectroscopic measurements

RR Lyrae stars as distances indicators

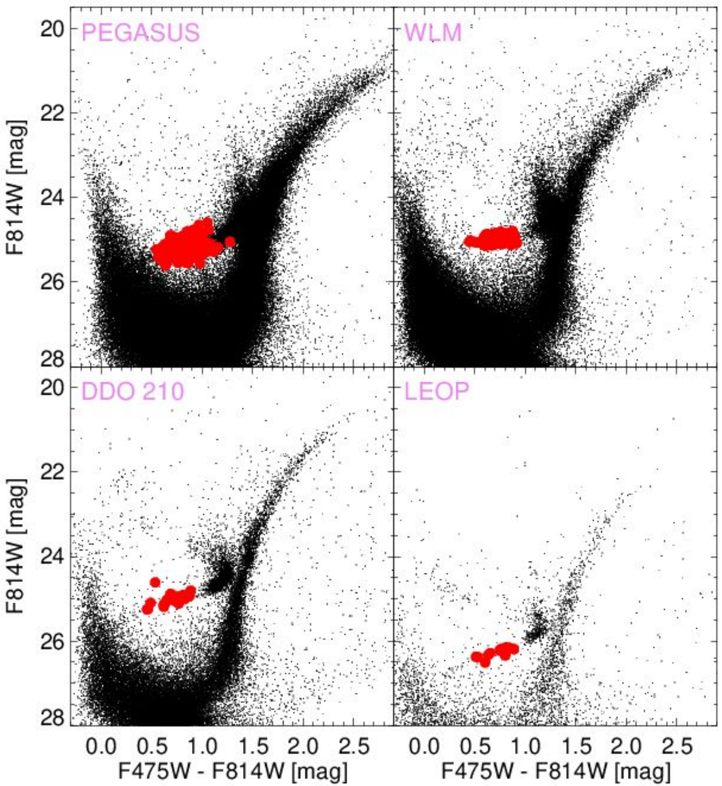




RR Lyrae stars as distances indicators

Pegasus
M_V ~ -14.2 mag
[Fe/H] ~ -1.4
D~920 Kpc
N_{RRL} = 867

DDO210
M_V~ -10.6 mag
[Fe/H] ~ -1.3
D~1072 Kpc
N_{RRL} = 36



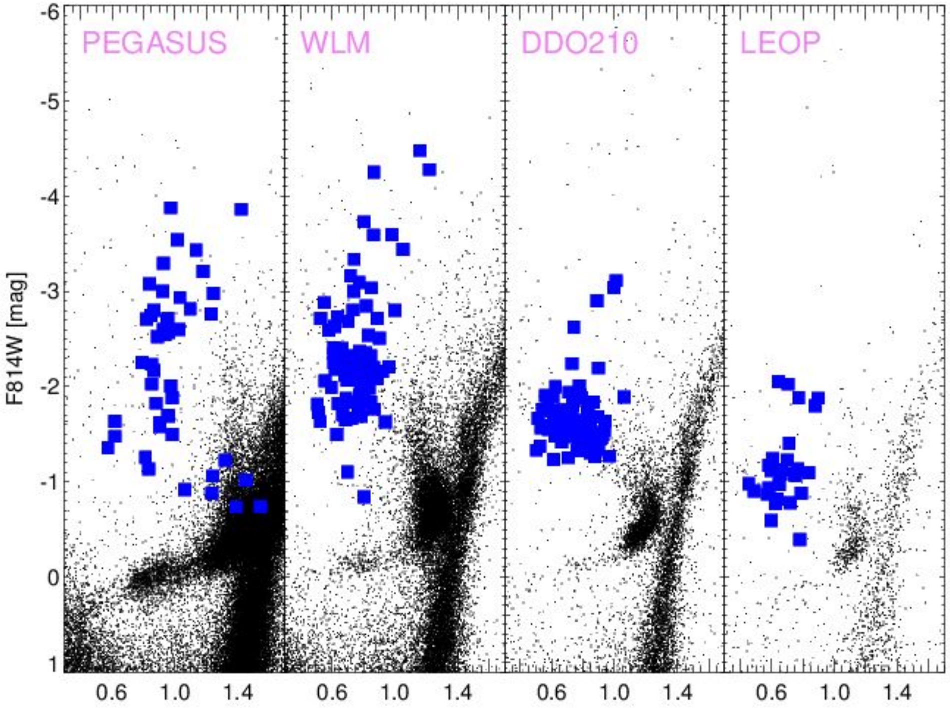
WLM
M_V ~ -12.2 mag
[Fe/H] ~ -1.3
D~933 Kpc
N_{RRL} = 154

Leo P
M_V ~ -9.4 mag
[Fe/H] ~ -1.7
D~1700 Kpc
N_{RRL} = 13

RR Lyrae stars as distances indicators

Pegasus
M_V ~ -14.2 mag
[Fe/H] ~ -1.4
D~920 Kpc
N_{RRL} = 867
N_C = 46

DDO210
M_V~ -10.6 mag
[Fe/H] ~ -1.3
D~1072 Kpc
N_{RRL} = 36
N_C = 81



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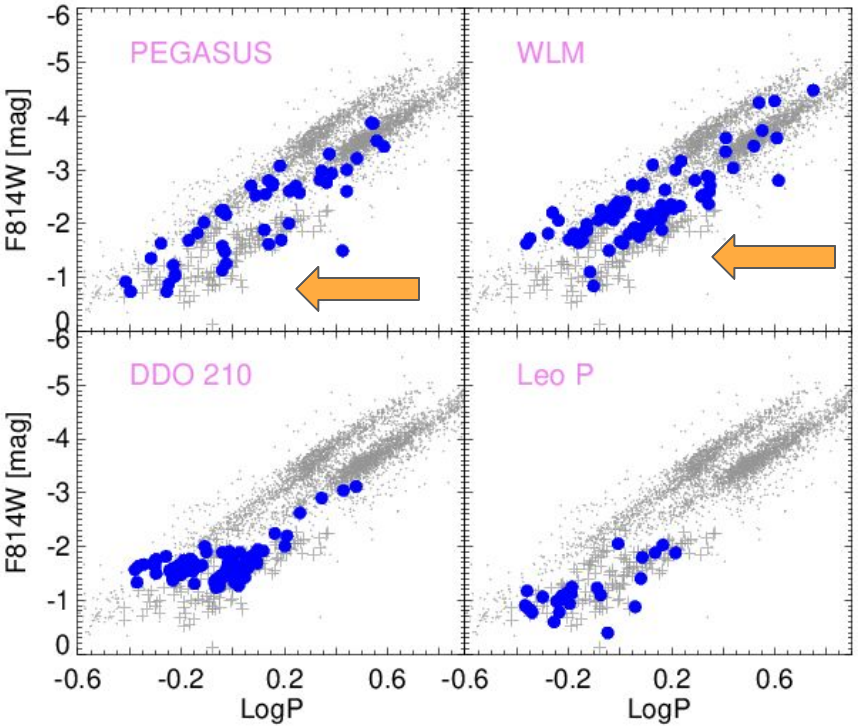
N_{RRL} = 154
N_C = 81

Leo P
M_V ~ -9.4 mag
[Fe/H] ~ -1.7
D~1700 Kpc
N_{RRL} = 13
N_C = 27

Fiorentino, MM et al. (in prep)

RR Lyrae stars as distances indicators

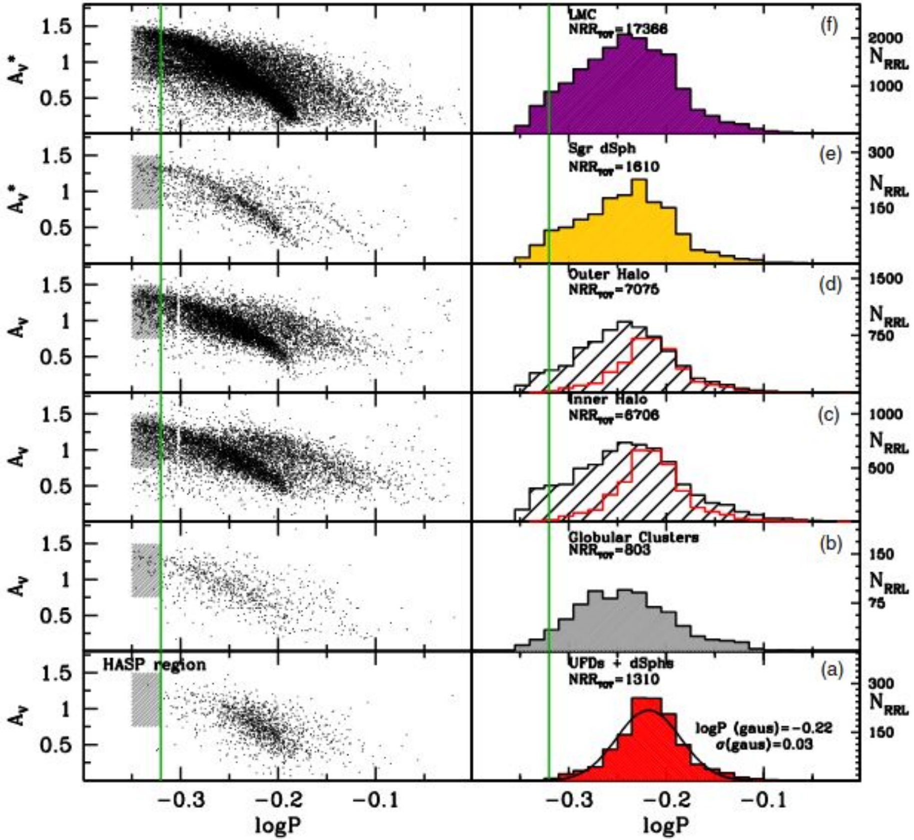


Low metallicity regime: plenty of ACs, but mix with ACs

RR Lyrae stars
and the Milky Way formation

RR Lyrae as tracers of the MW assembly history

Fiorentino+2015



LMC: 17,400 stars
Sagittarius: 1600 stars from OGLE

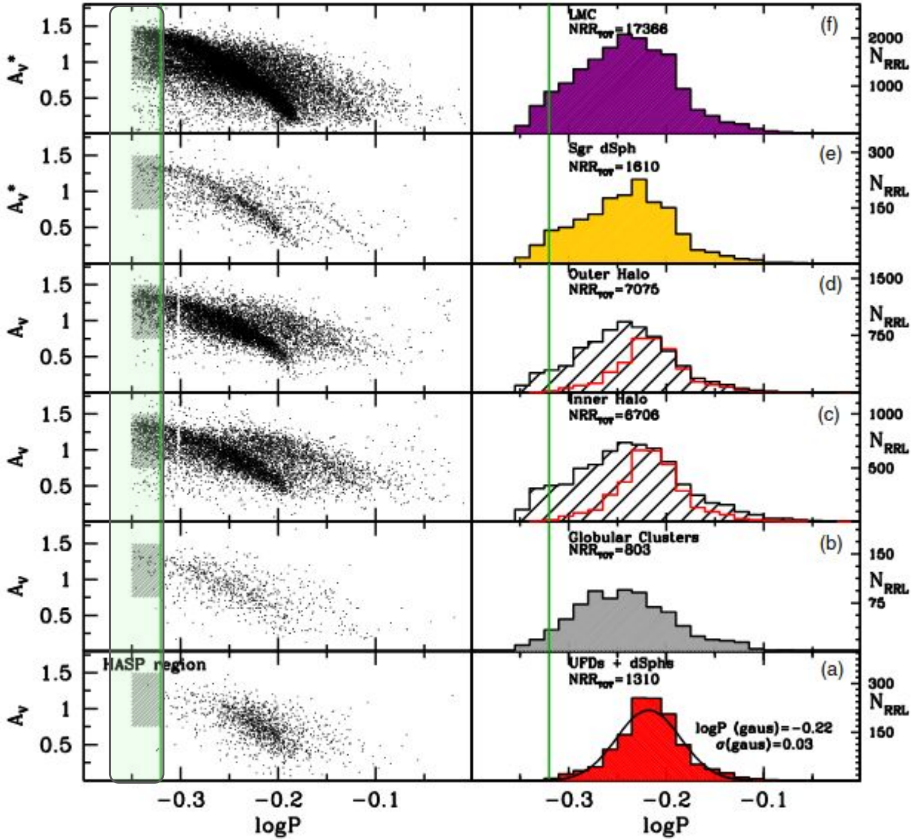
Milky Way halo: 13,700 stars from Catalina, ASAS, QUEST

Collection of **globular clusters**: 1300 stars and **dwarf galaxies**: 800 stars

RR Lyrae as tracers of the MW assembly history

Fiorentino+2015

HASP RRL stars:
High **A**mplitude
Short **P**eriod
P < 0.48 d
A > 0.75 mag



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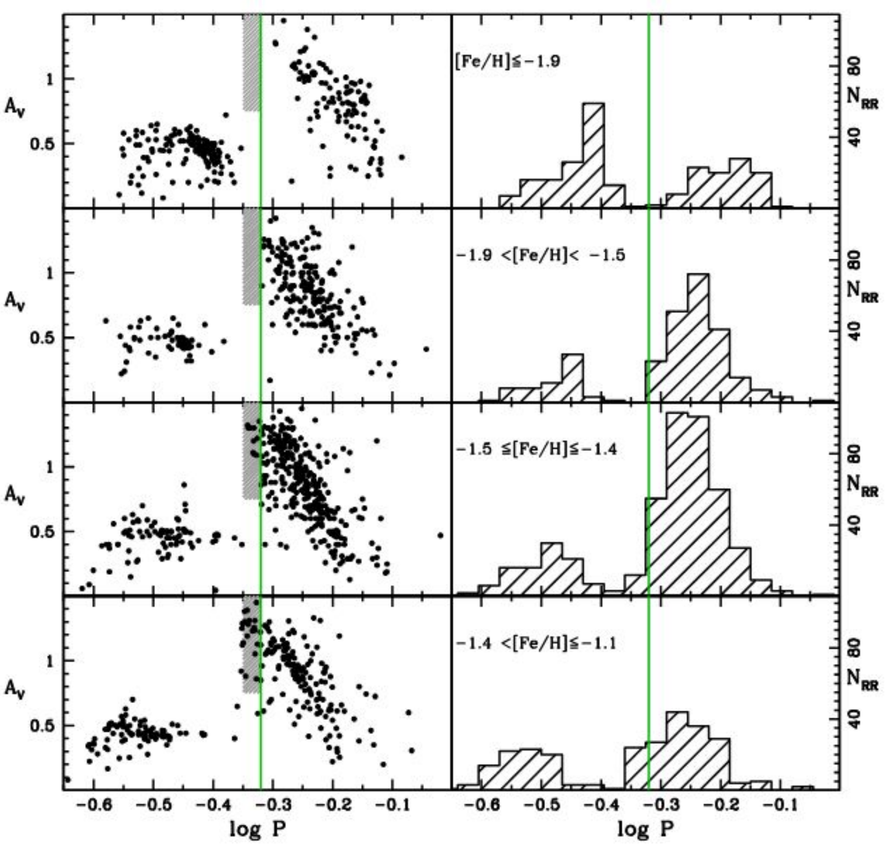


[Fe/H] ≤ -1.9

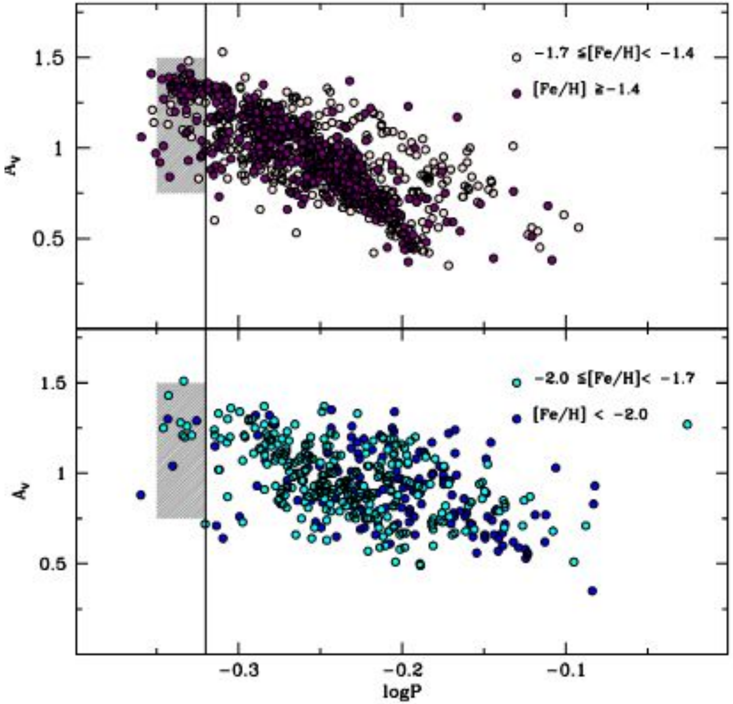
-1.9 < [Fe/H] < -1.5

-1.5 ≤ [Fe/H] ≤ -1.4

-1.4 < [Fe/H] ≤ -1.1

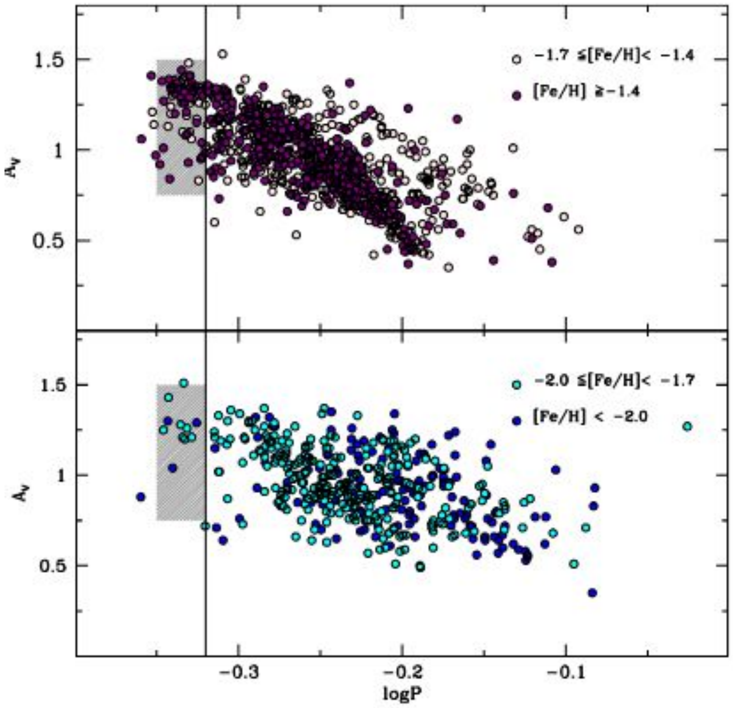
RR Lyrae as tracers of the MW assembly history

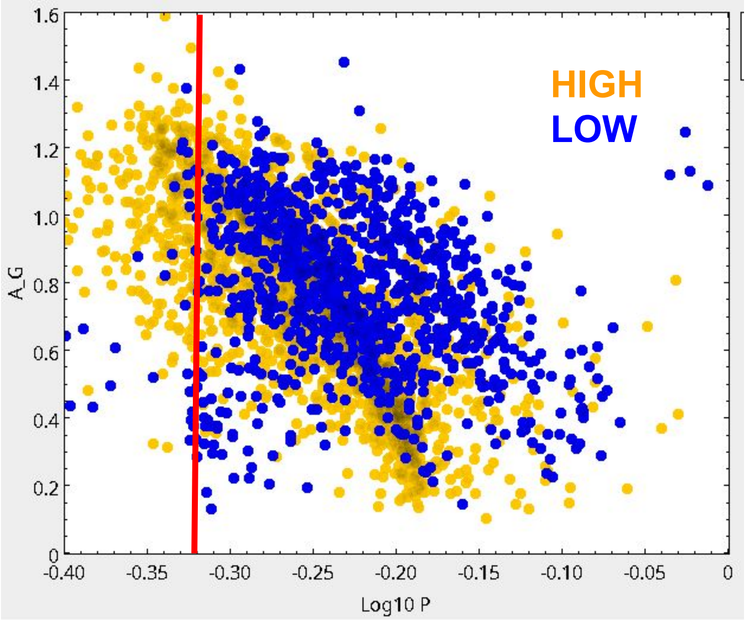
Fiorentino+2015



RR Lyrae as tracers of the MW assembly history

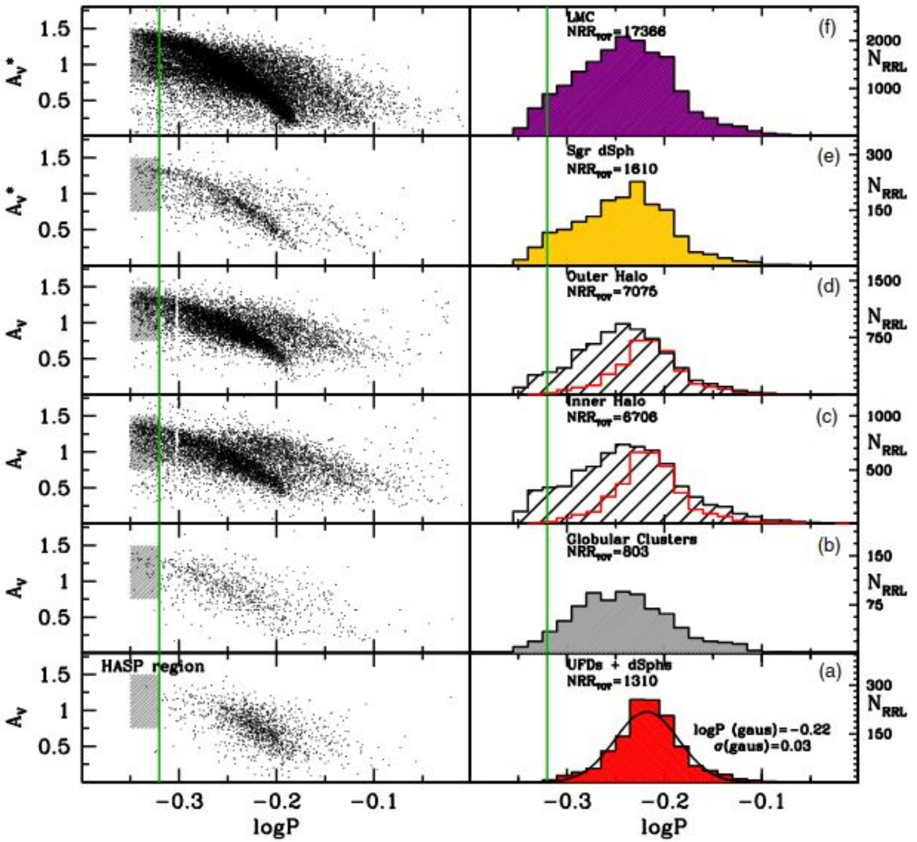
Fiorentino+2015





RR Lyrae as tracers of the MW assembly history

Fiorentino+2015



Massive dwarf galaxies have a (relatively) "metal-rich" old component

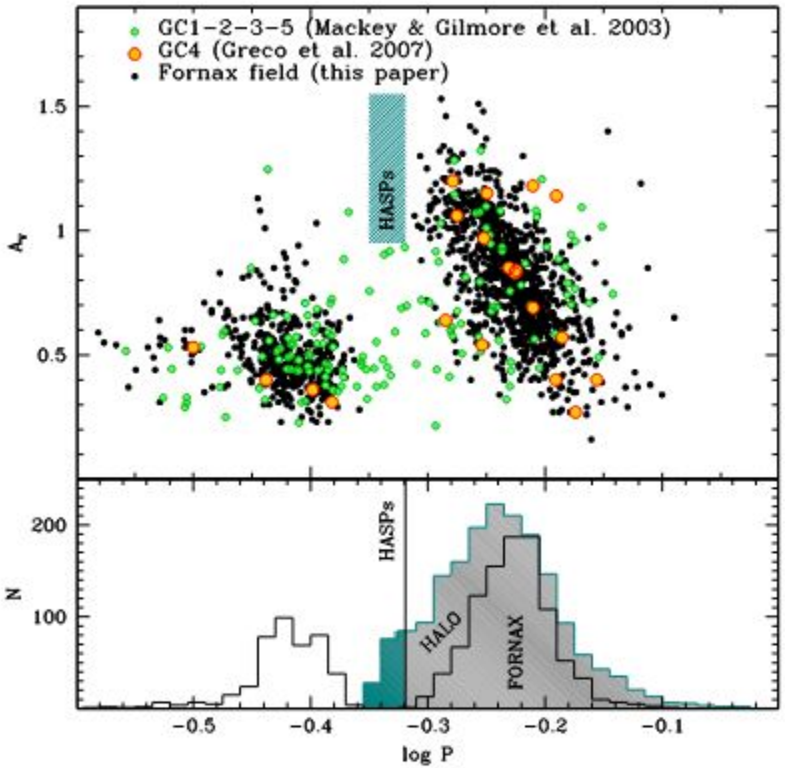
The halo has a (relatively) "metal-rich" old component

(relatively) metal-rich globular clusters hosting RRL stars do exist

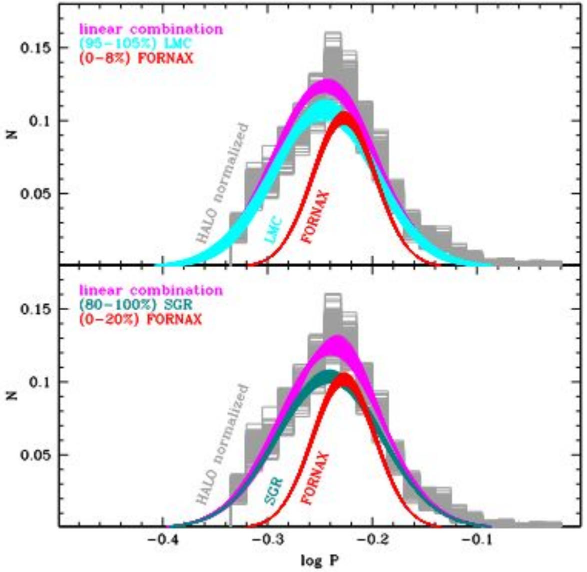
Low-mass dwarf galaxies do **NOT** have a (relatively) "metal-rich" old component

RR Lyrae as tracers of the MW assembly history

Fiorentino+2017

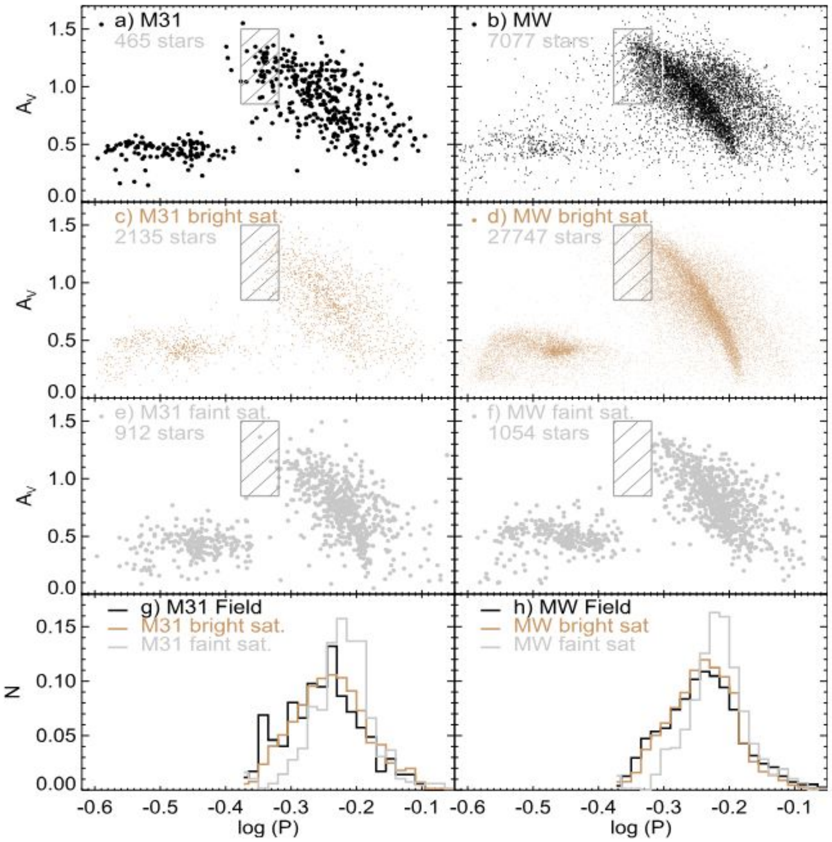


★ **Fornax**: ~2000 RRL stars
★ most massive of the low mass dSph
★ still a marginal contribution to the halo



RR Lyrae as tracers of the MW assembly history

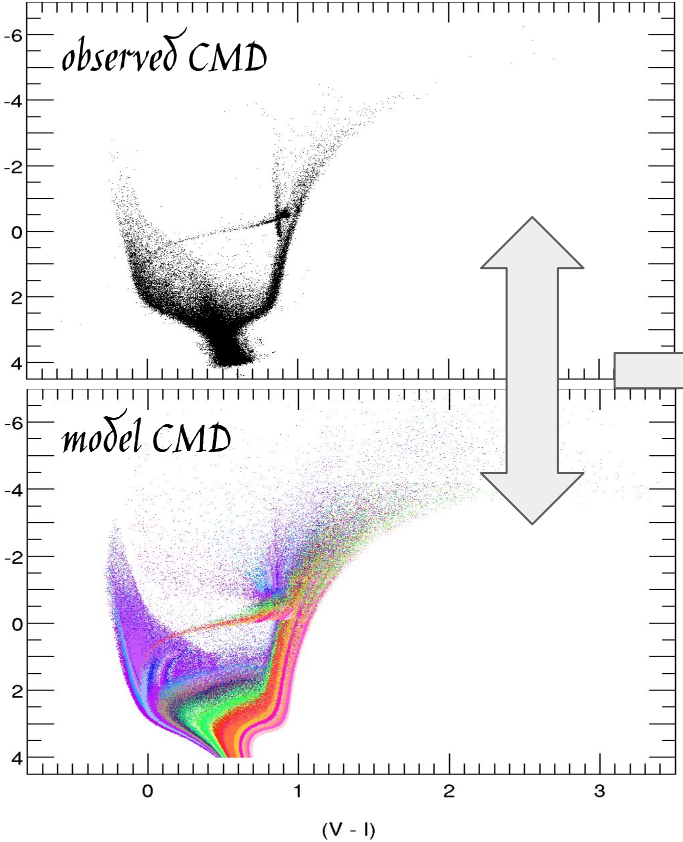
Monelli+2017



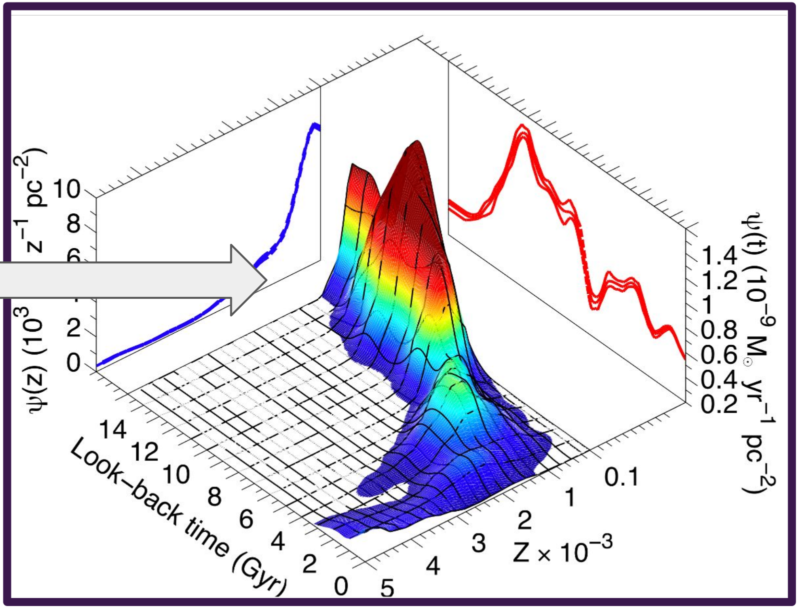
The same occurs in M31!

RR Lyrae stars as star formation history tracers: dwarf galaxies

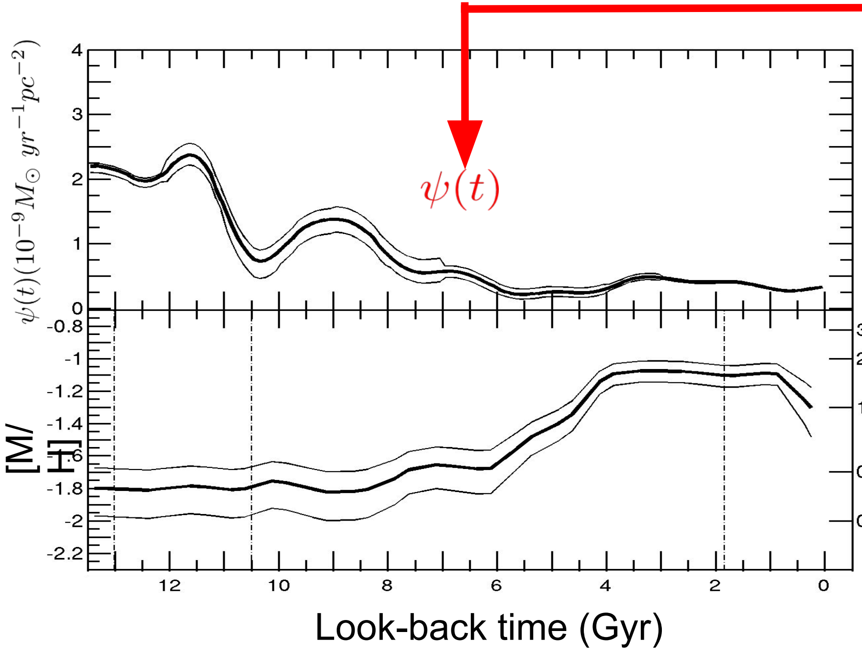
The SFH of resolved stellar systems

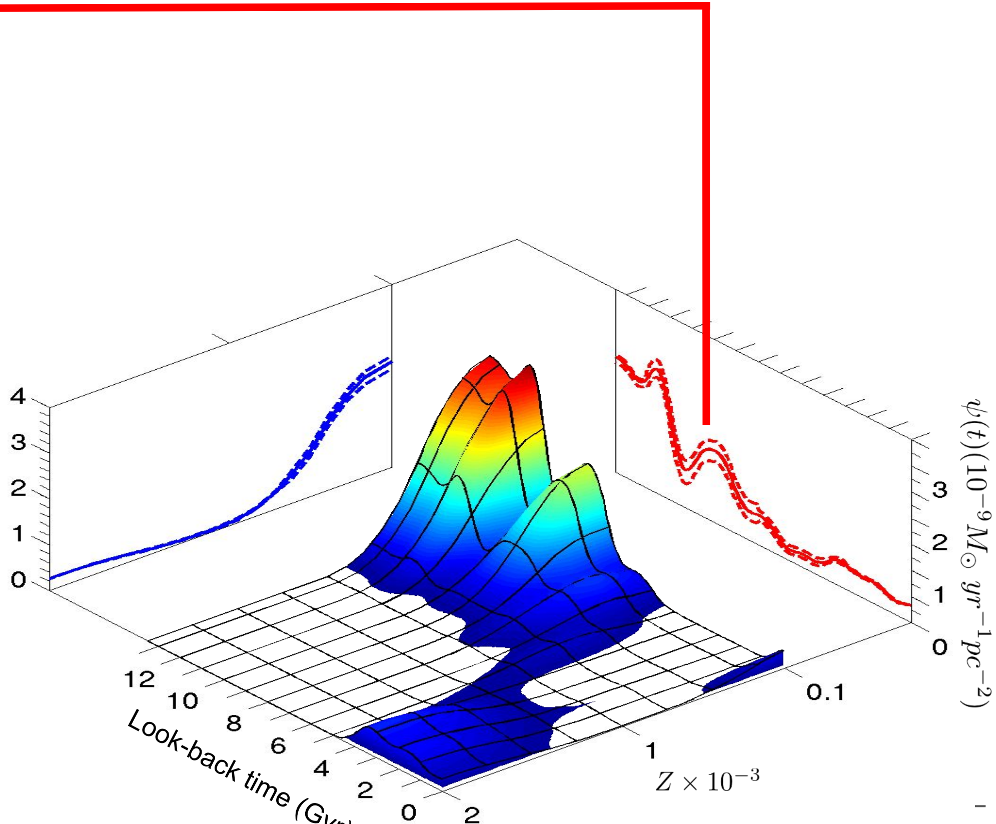


The **distribution of stars** in an observed CMD is compared with that of model CMD.

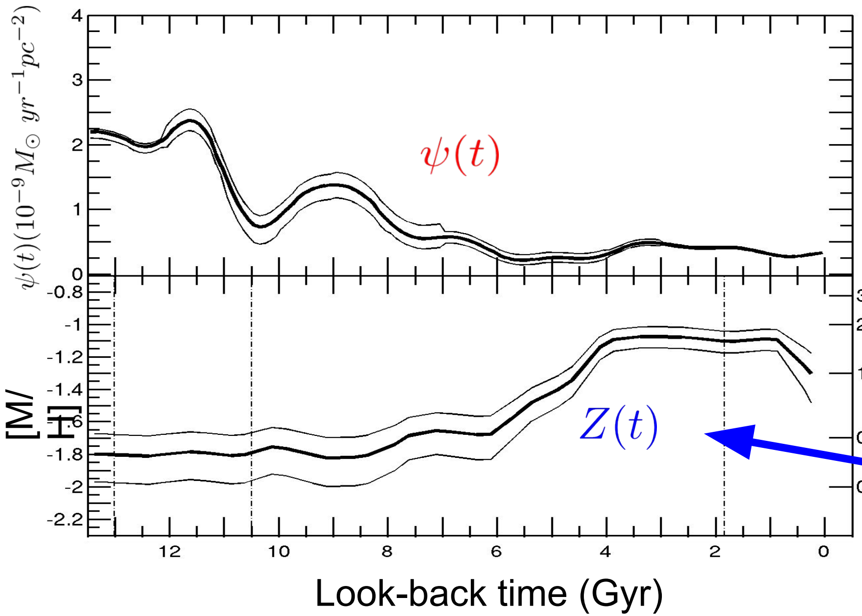


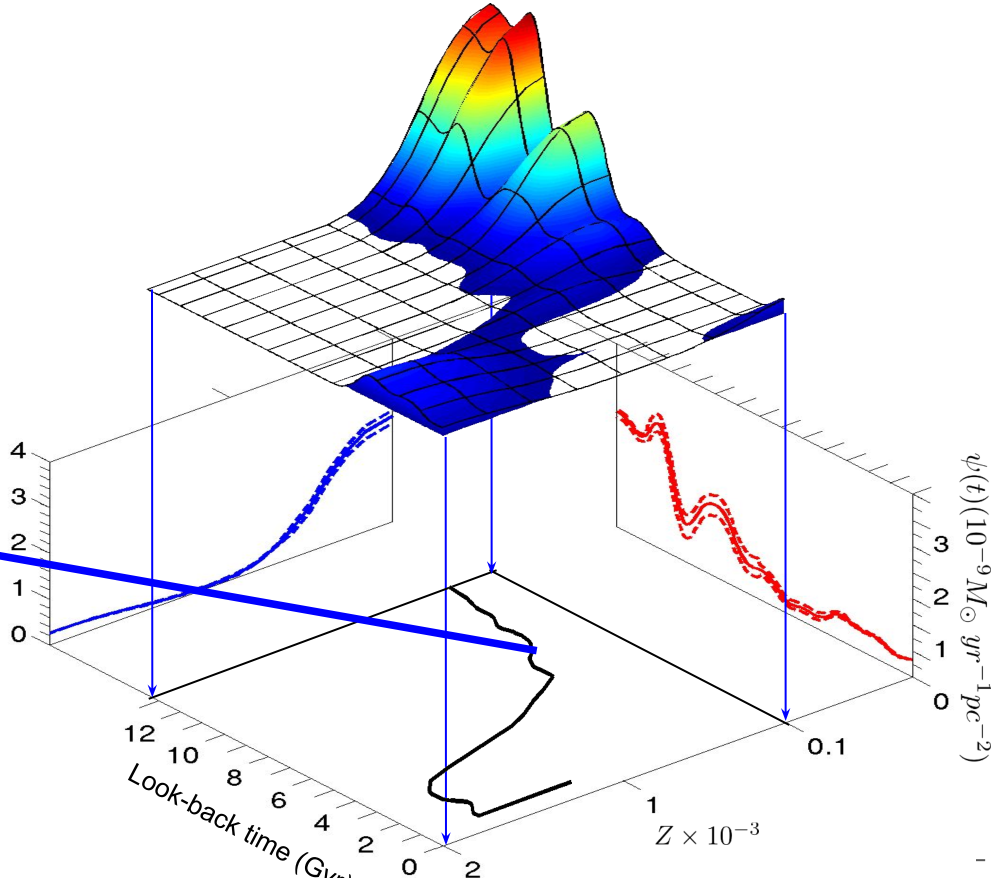
Any SFH can be represented as a function of two independent variables: AGE and METALLICITY


$\psi(t)$
$\psi(t)(10^{-9}M_\odot\ yr^{-1}pc^{-2})$
[M/H]
Look-back time (Gyr)


Look-back time (Gyr)
$Z \times 10^{-3}$
$\psi(t)(10^{-9}M_\odot\ yr^{-1}pc^{-2})$

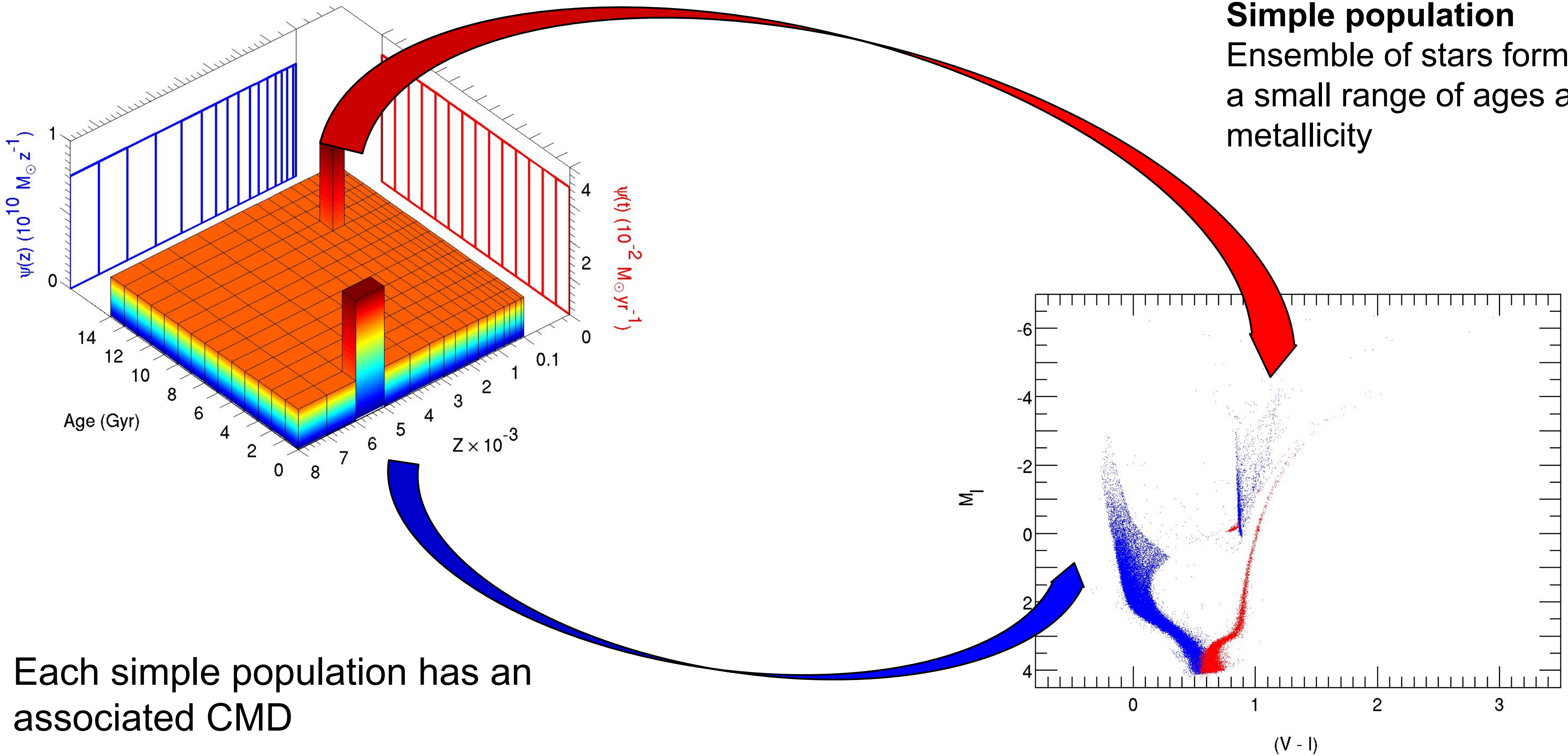
The SFH of resolved stellar systems





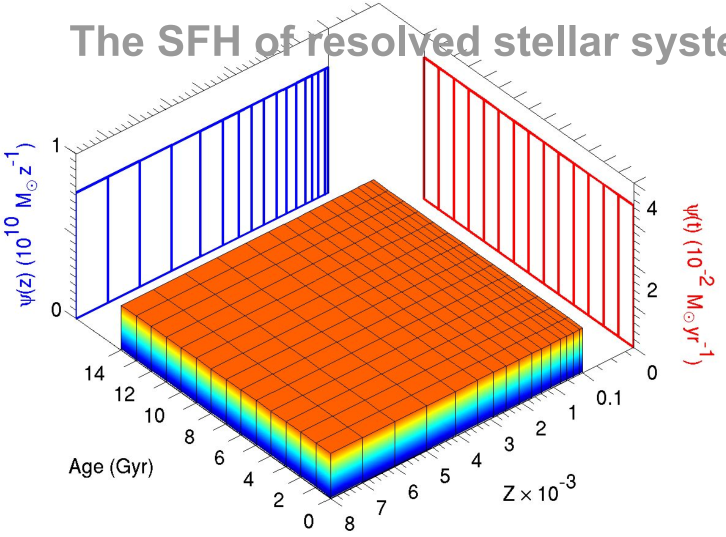
The SFH of resolved stellar systems

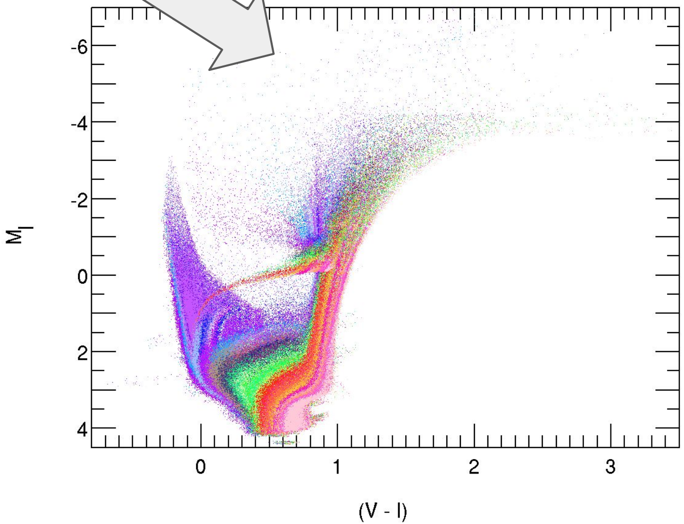
Simple population
Ensemble of stars formed in a small range of ages and metallicity



Each simple population has an associated CMD

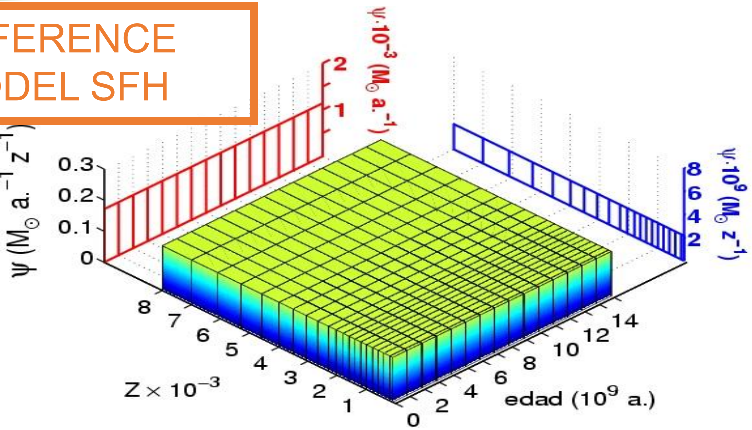
The SFH of resolved stellar systems



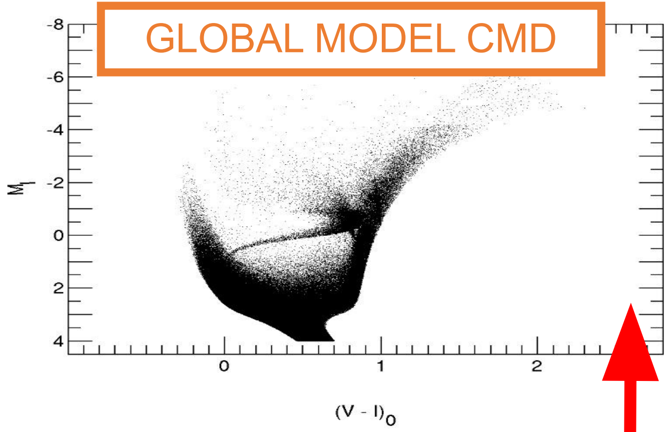


The SFH of resolved stellar systems

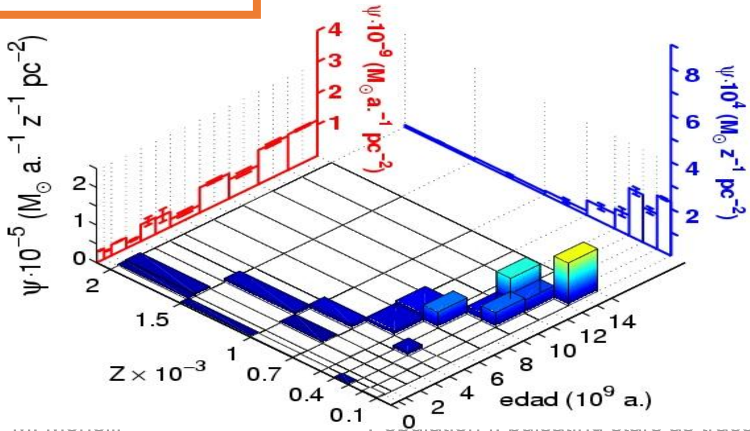
REFERENCE MODEL SFH



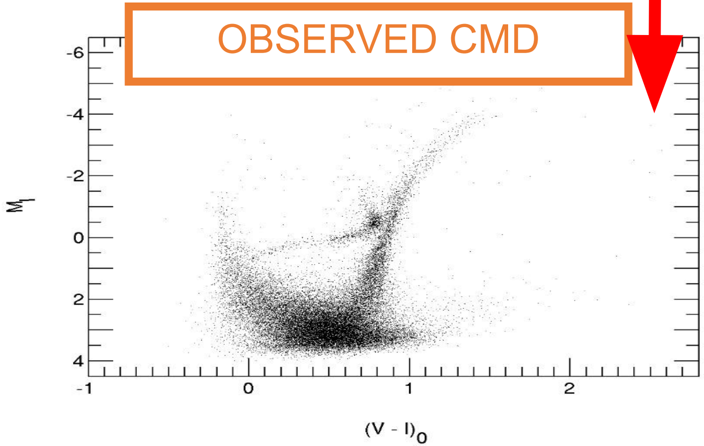
GLOBAL MODEL CMD



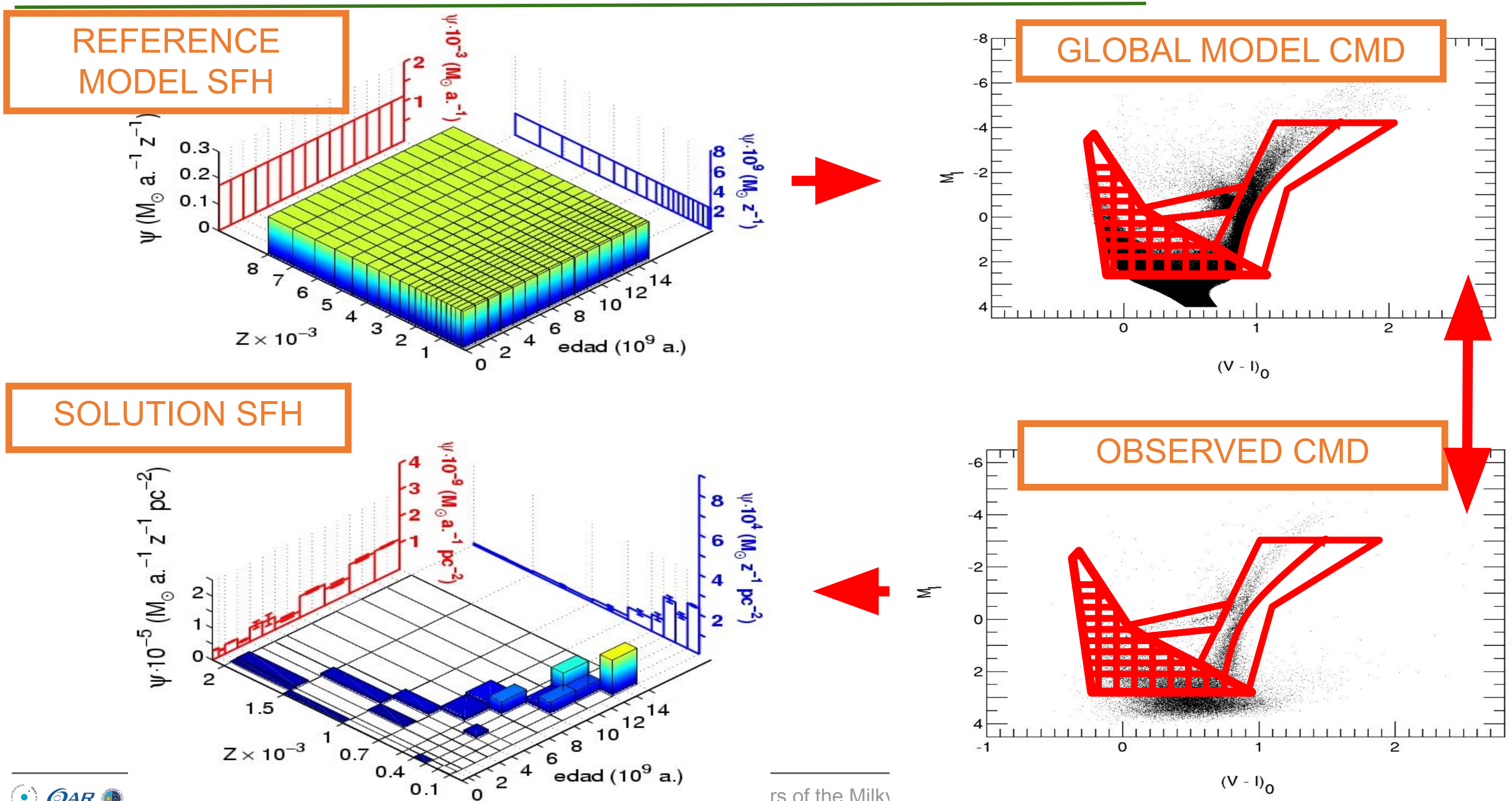
SOLUTION SFH



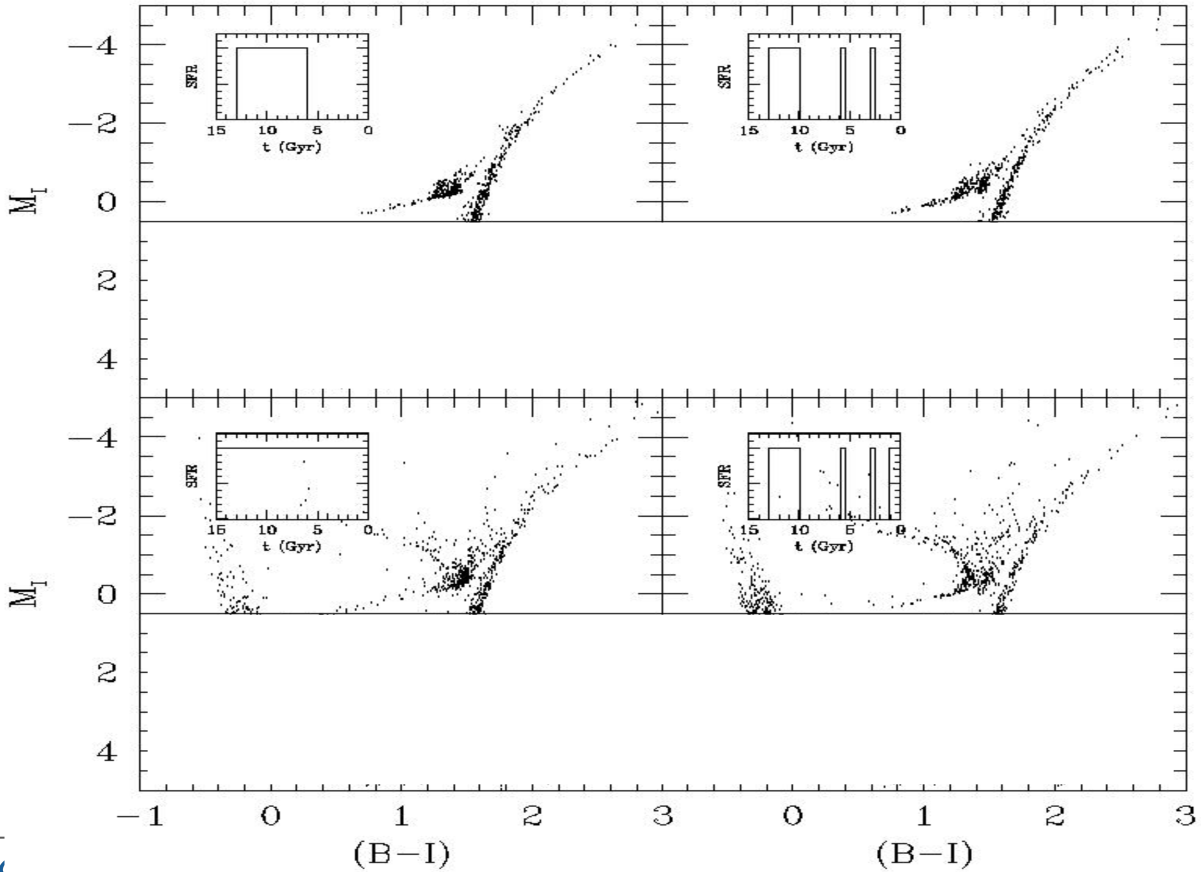
OBSERVED CMD



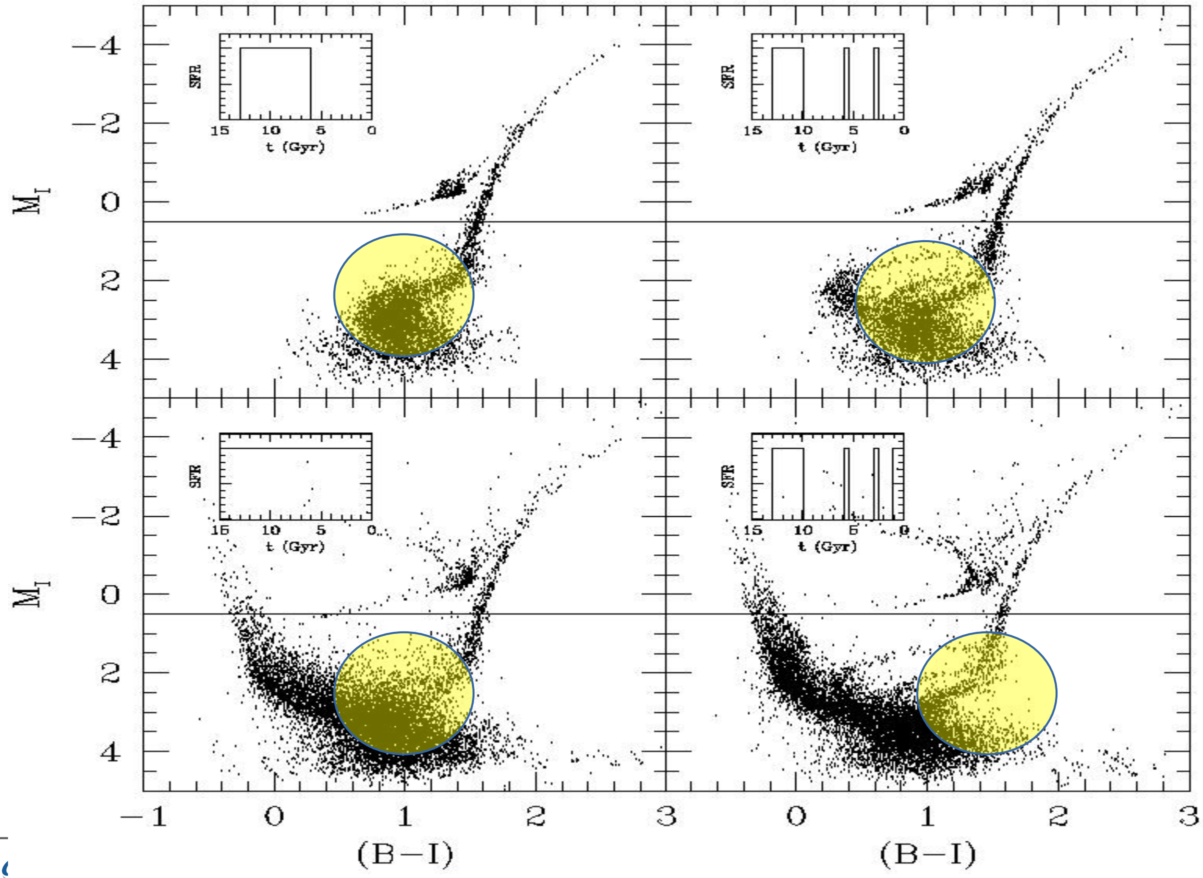
The SFH of resolved stellar systems



The SFH of resolved stellar systems



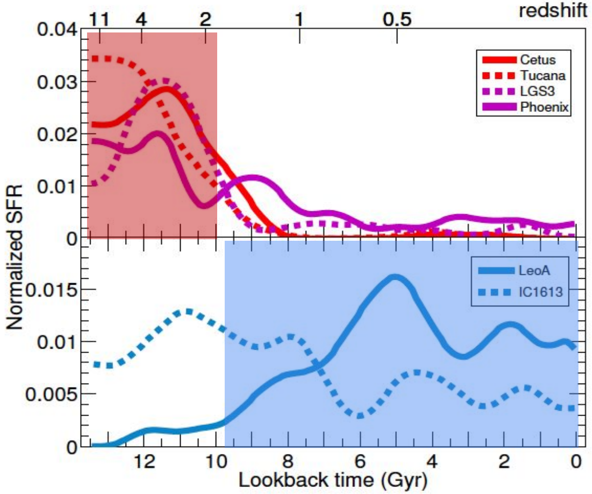
The SFH of resolved stellar systems

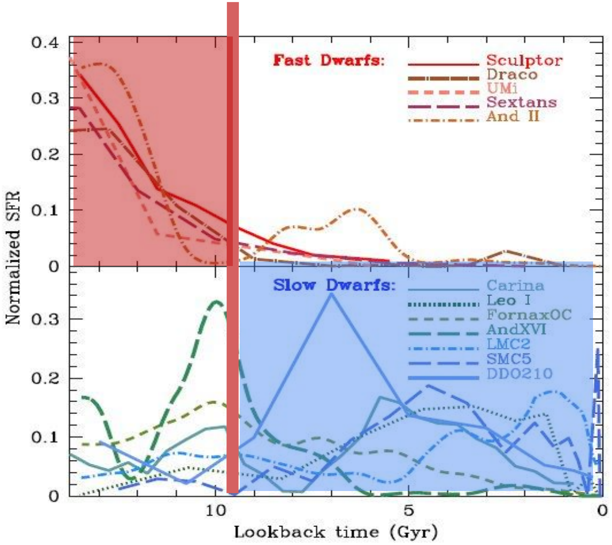


Well measured Turn-Off stars are crucial to have 1 Gyr resolution at old ages

The SFH of resolved stellar systems

FAST dwarf galaxies

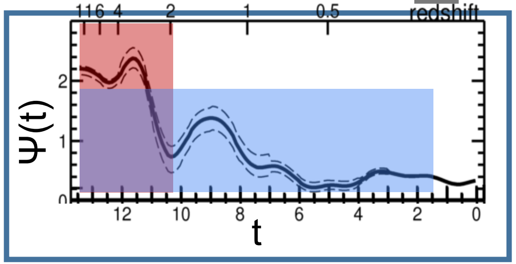




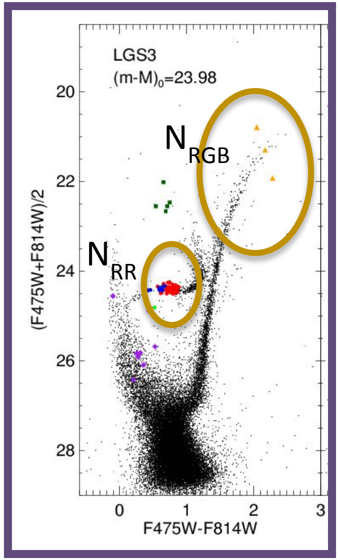
SLOW dwarf galaxies

Gallart+2015

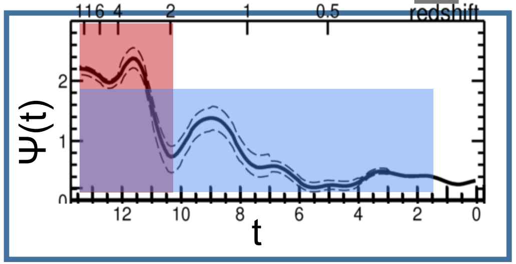
RR Lyrae stars and SFH

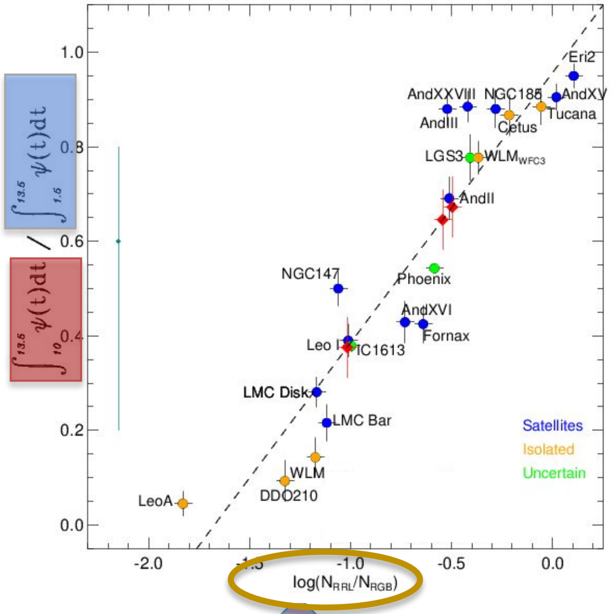


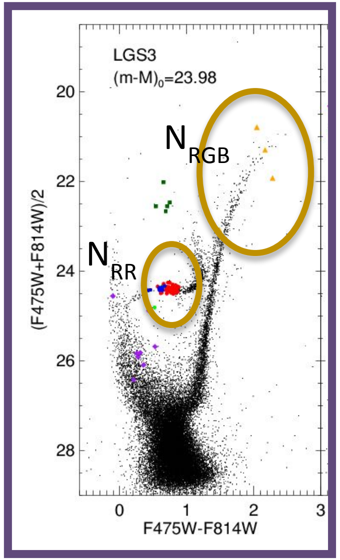
Monelli+(in prep.)



RR Lyrae stars and SFH



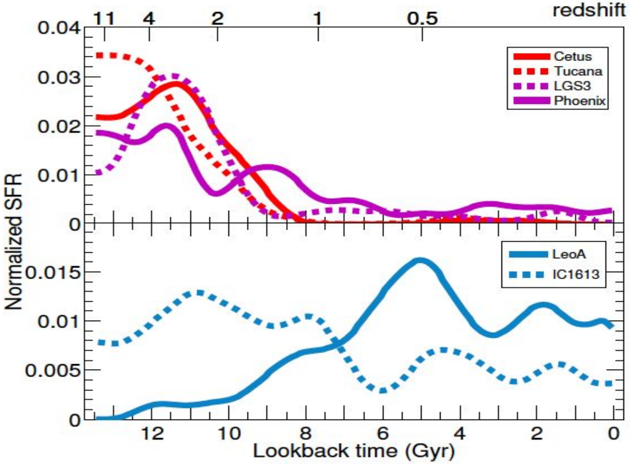




Monelli+(in prep.)

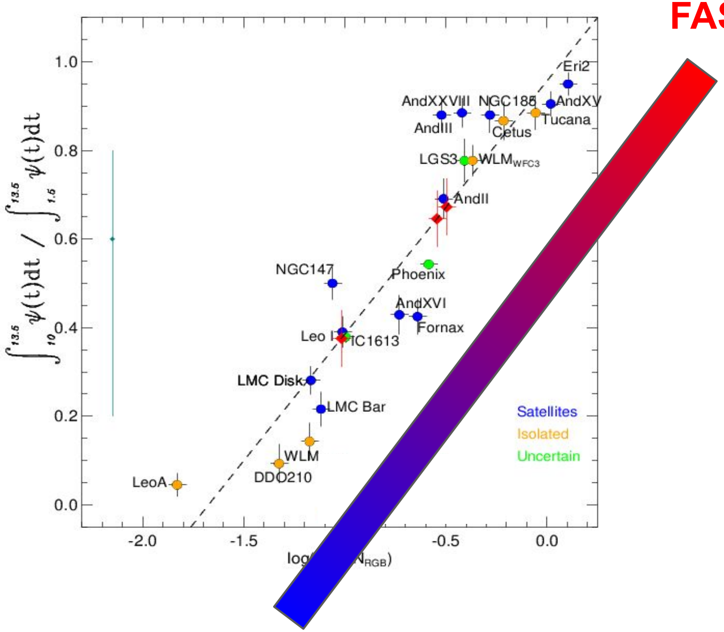
RR Lyrae stars and SFH

FAST



SLOW

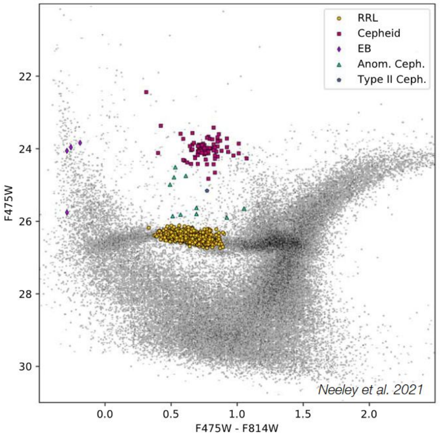
FAST

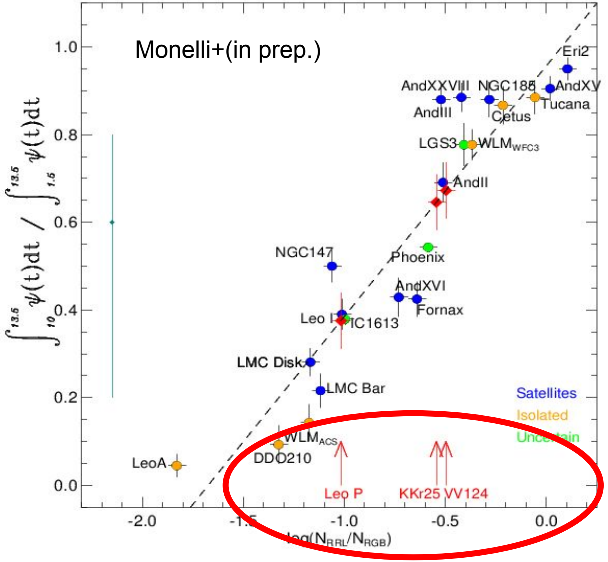


SLOW

Monelli+(in prep.)

RR Lyrae stars and SFH



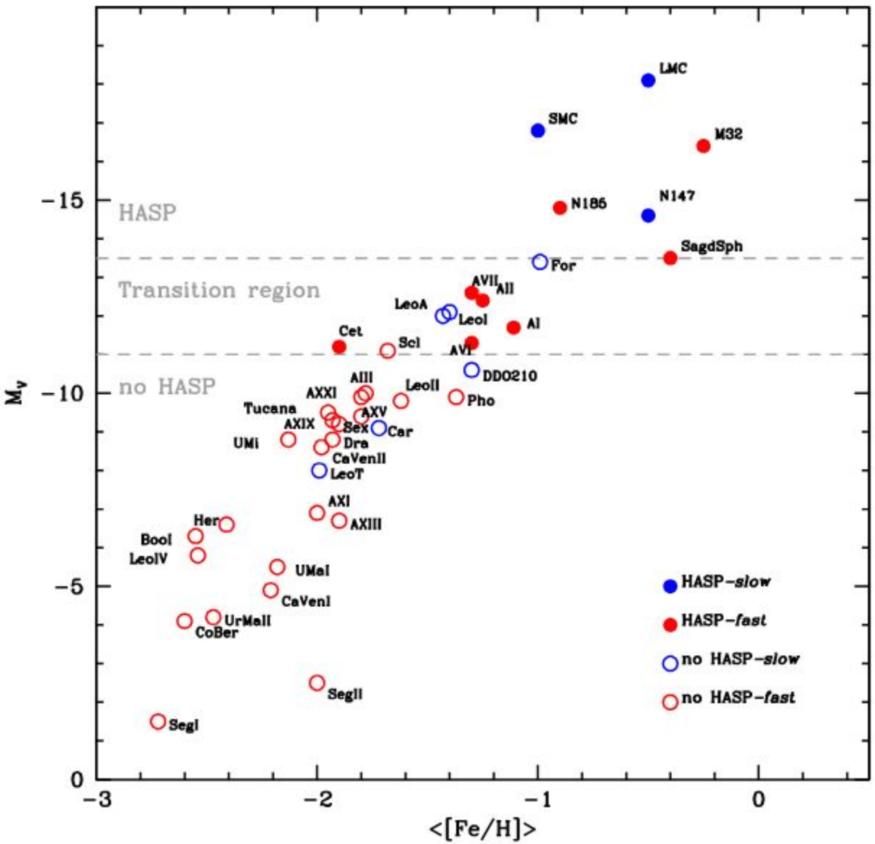


Predict the fraction of old population using RR Lyrae out to 6 Mpc

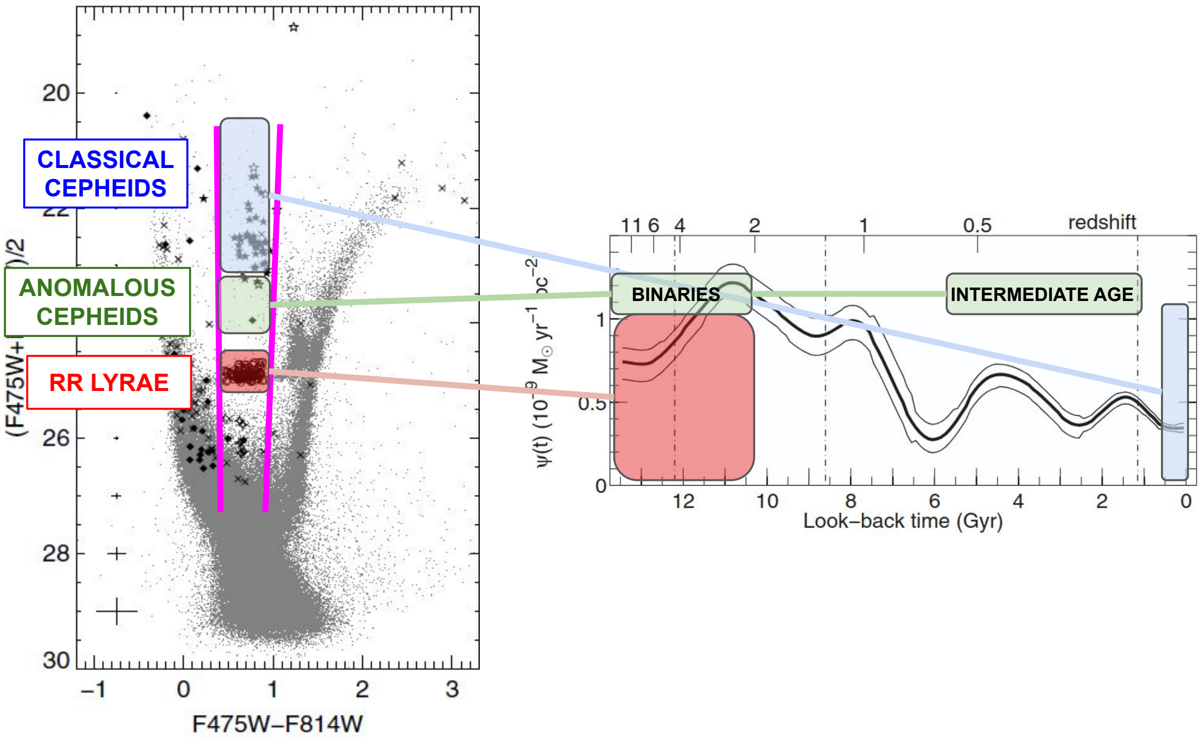
Monelli+(in prep.)

RR Lyrae stars and SFH

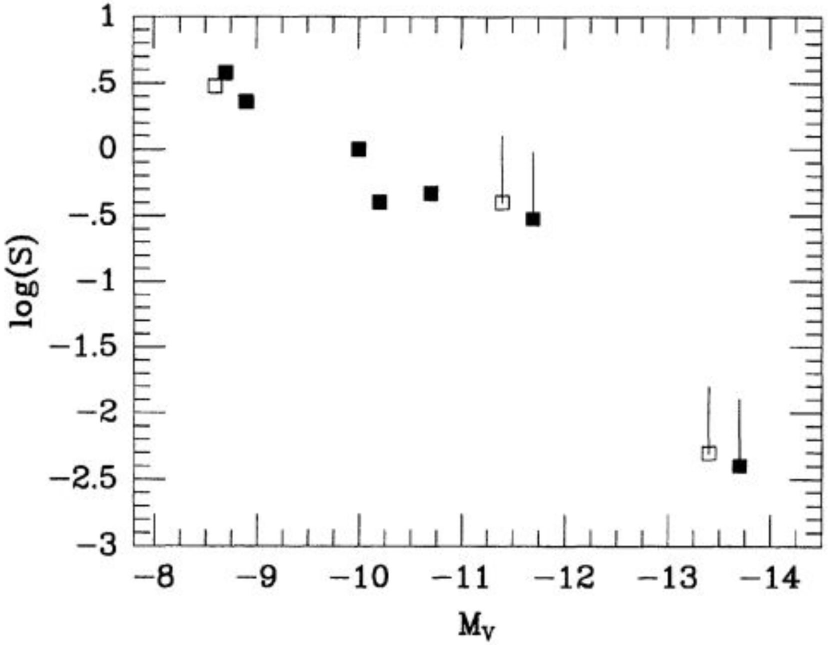
Fiorentino+2017



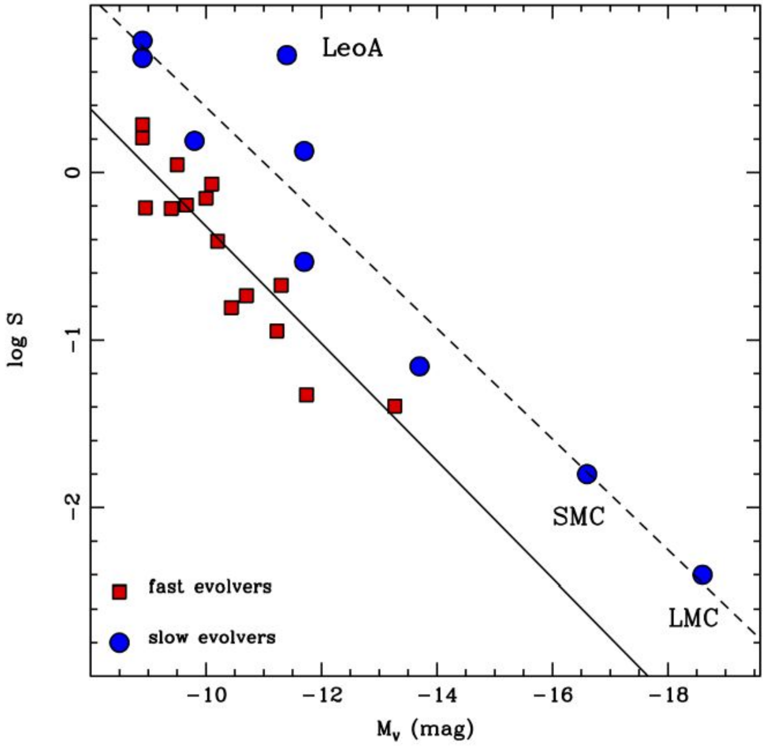
RR Lyrae stars and SFH



Anomalous Cepheids and SFH

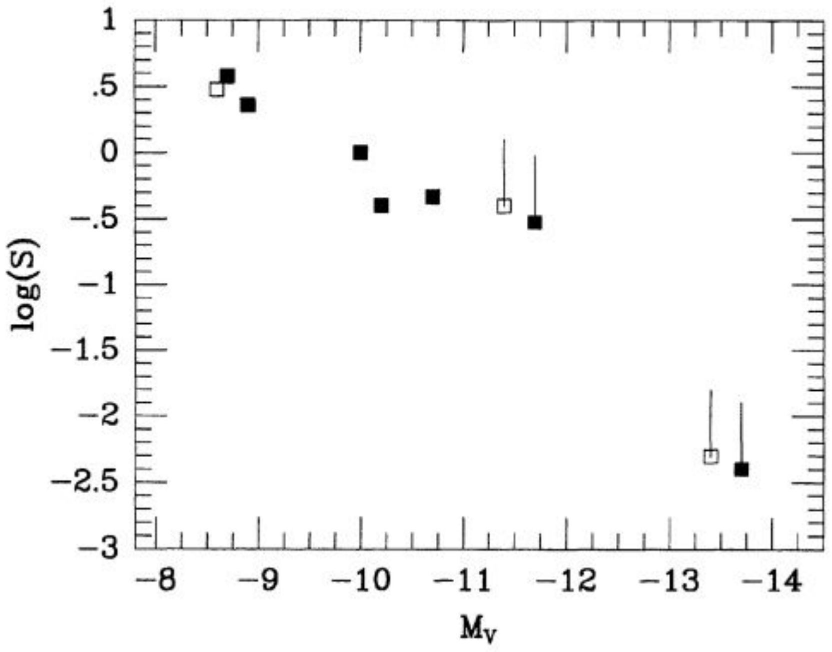


Mateo 1995

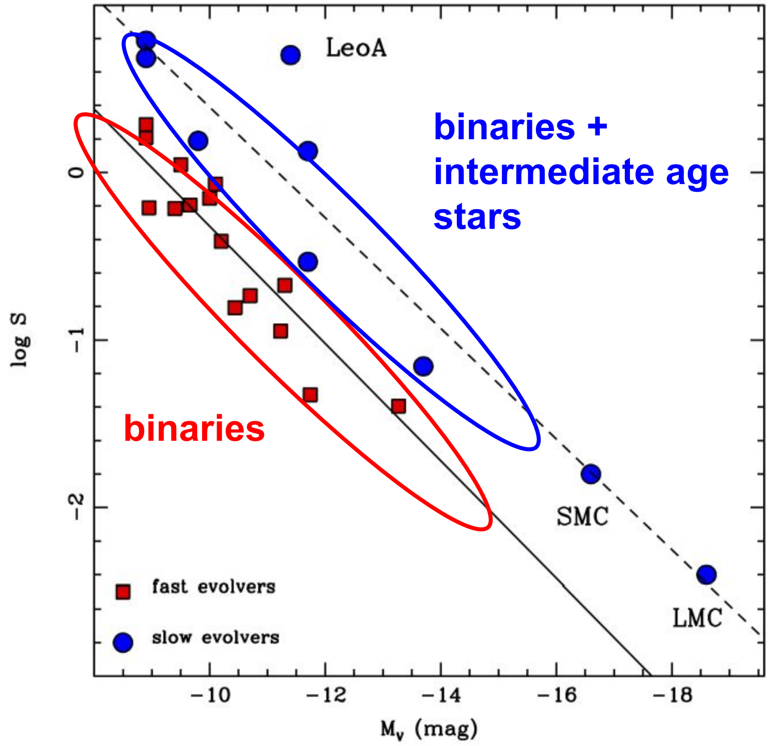


Monelli & Fiorentino 2022

RR Lyrae and SFH



Mateo 1995



Monelli & Fiorentino 2022

On the Local Group

The Local Group: an accelerating revolution

- missing satellite problem
- LG dwarf galaxies as survivors of the accretion process that formed the MW and M31

1.2 Discovery of the Local Group

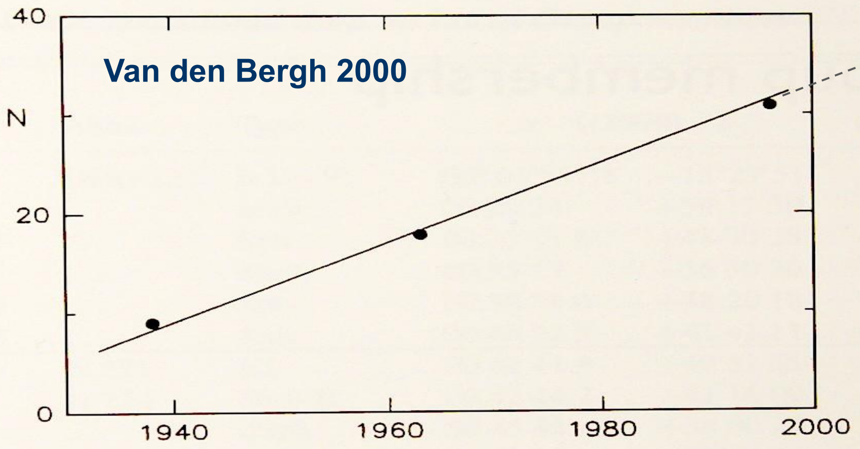


Fig. 1.1. Number of known Local Group members as a function

The Local Group: an accelerating revolution

~ 120 dwarf galaxies in the LG

1.2 Discovery of the Local Group

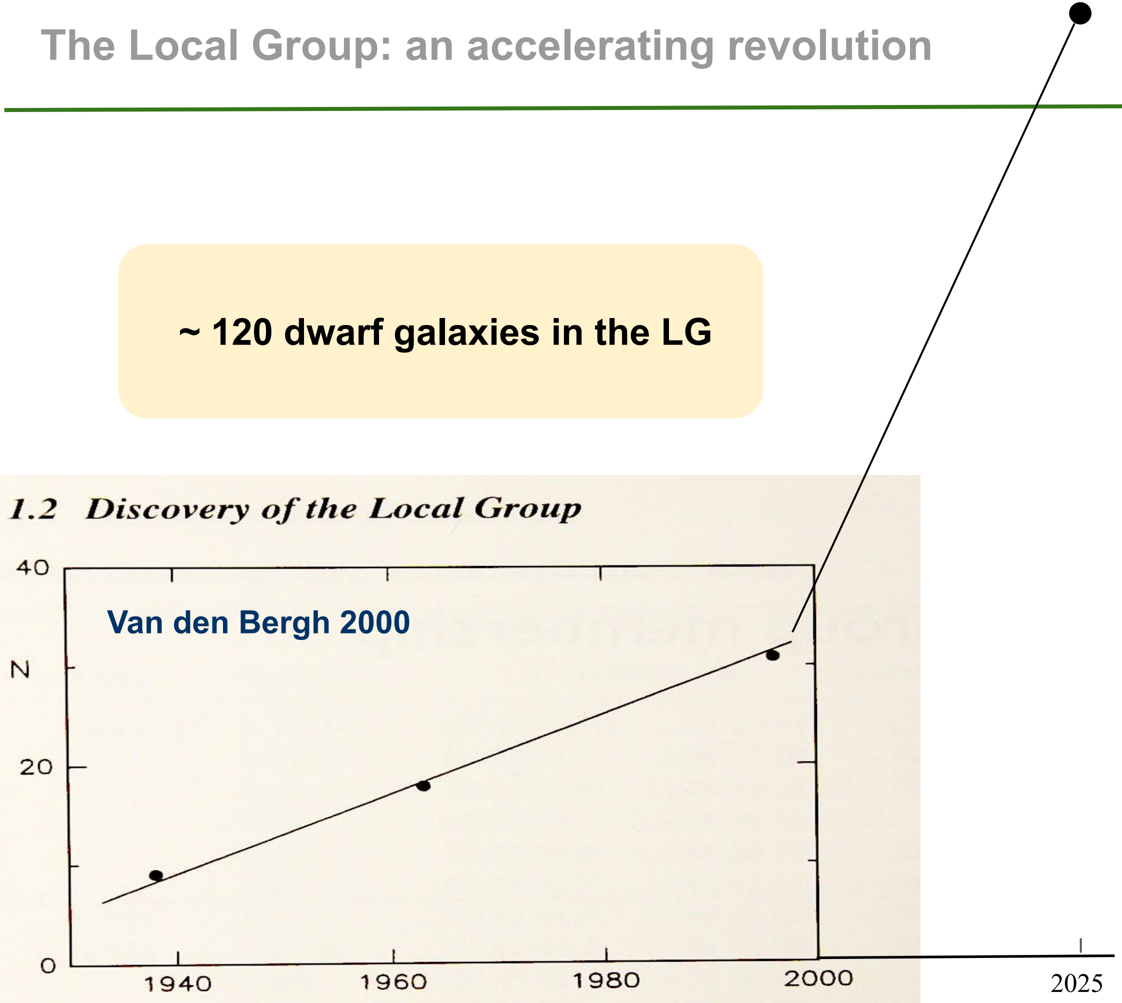


Fig. 1.1. Number of known Local Group members as a function

The Local Group: an accelerating revolution

~ 120 dwarf galaxies in the LG

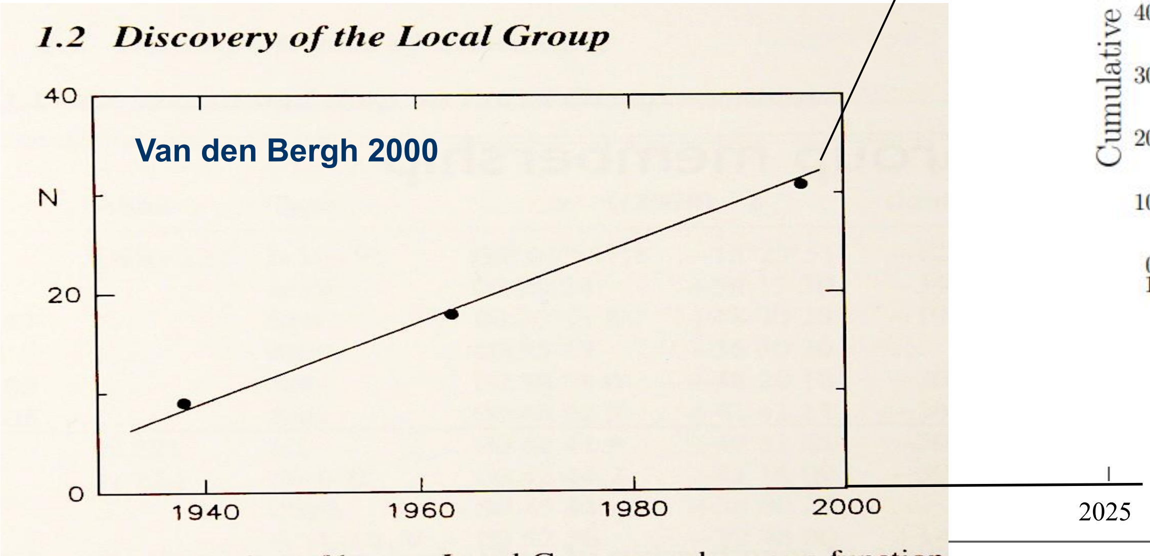
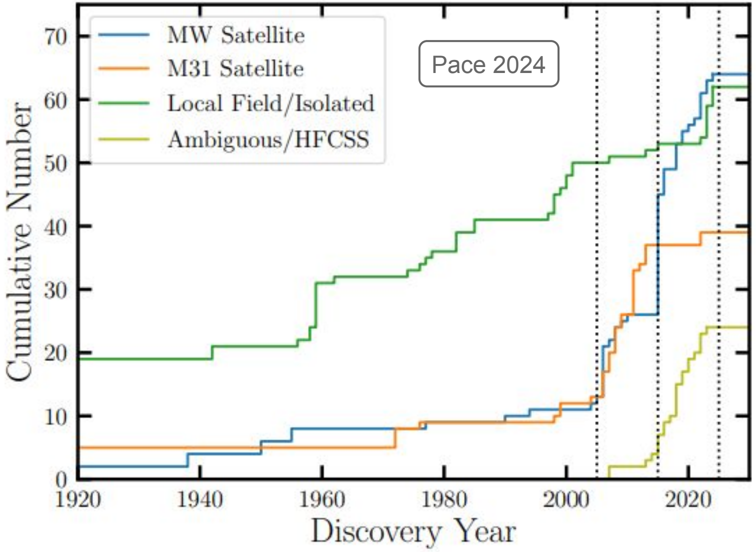
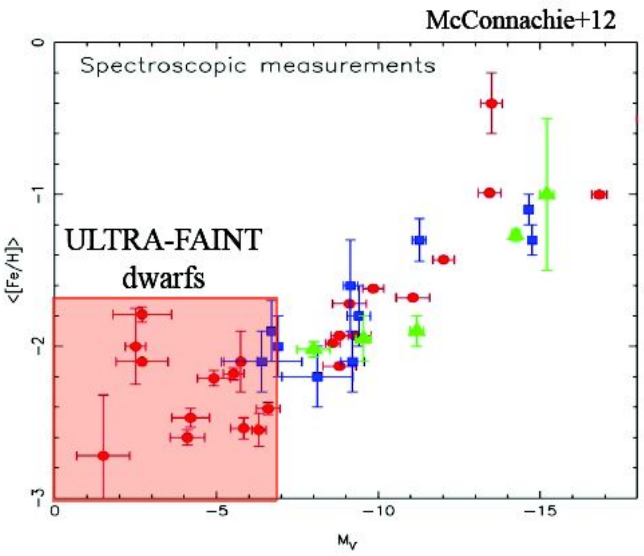
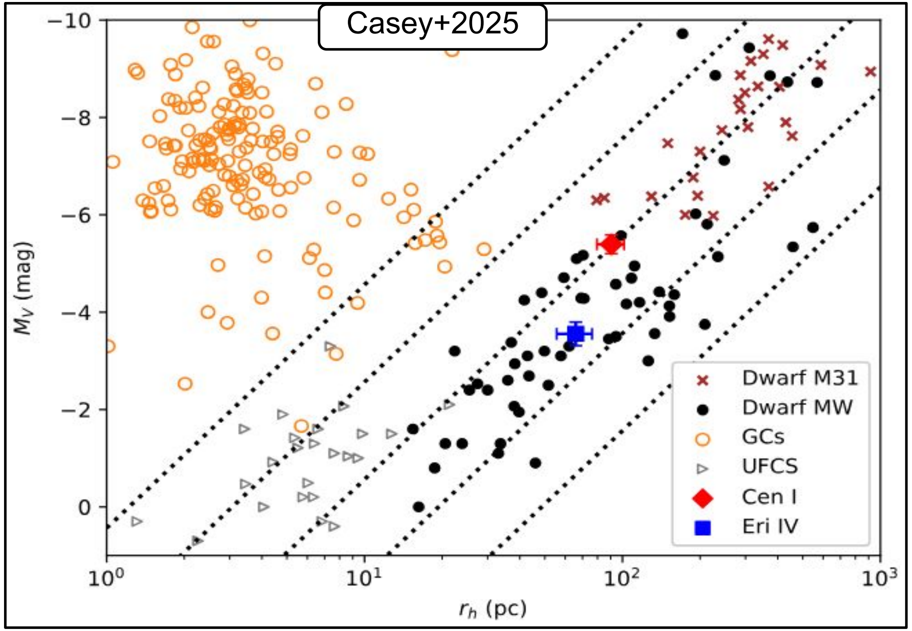


Fig. 1.1. Number of known Local Group members as a function



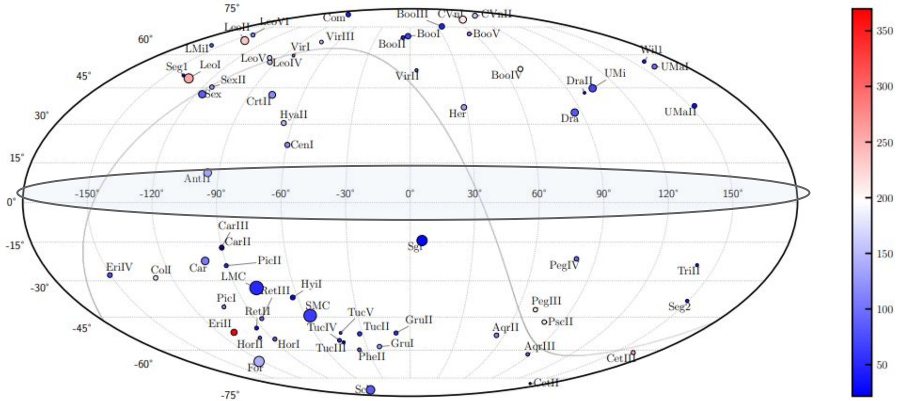
The Local Group: an accelerating revolution

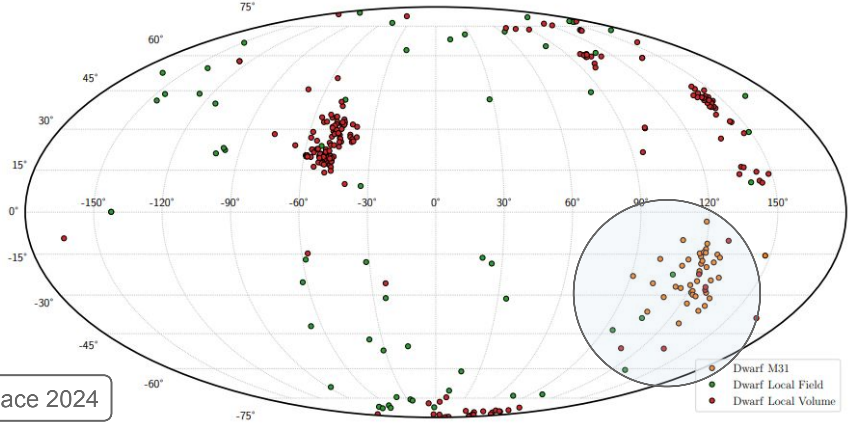




Belokurov+2006; Willman+2005; Slater+2011; Martin+2013; Koposov+2015; Torrealba+2019; Collins+2022, …

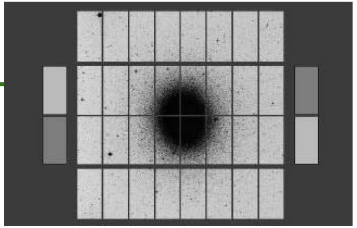
The Local Group: an accelerating revolution

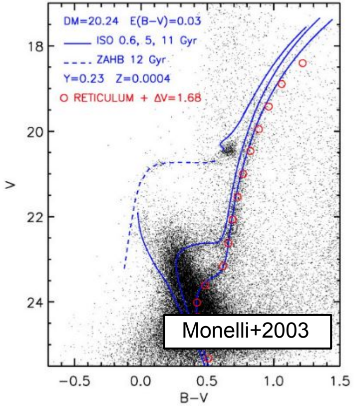




Pace 2024

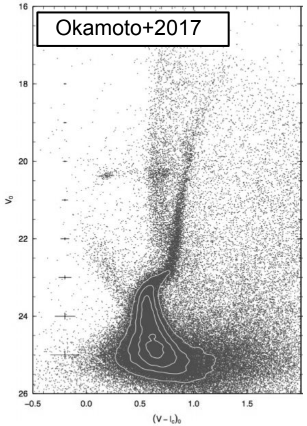
The Local Group: an accelerating revolution

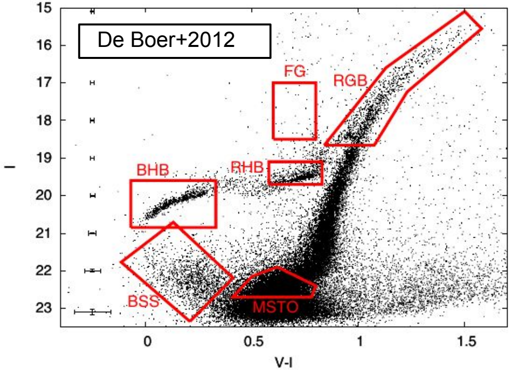




Photometry

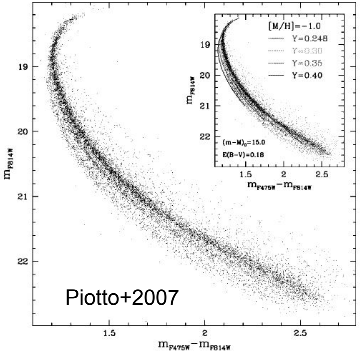
➔ **Wide-field imagers (WFI@2.2m, WFC@INT, MOSAICII@Blanco, CFH12K@CFHT, SuprimeCam@Subaru)**

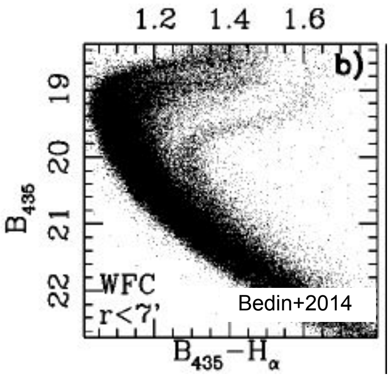




- Deep sub-TO photometry of a large fraction of the MW satellites
- Population gradients (Monelli+03, Okamoto+12)
- Age gradients (Battaglia+12)
- Large **diversity** of SFH (Tolstoy+09)

The Local Group: an accelerating revolution

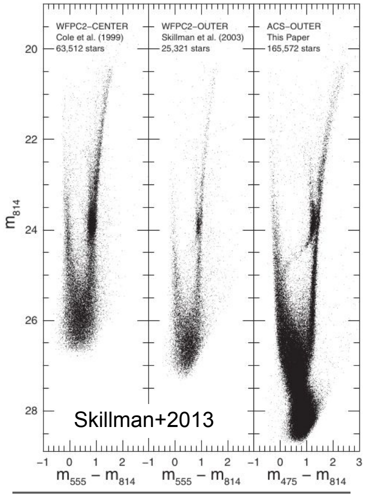


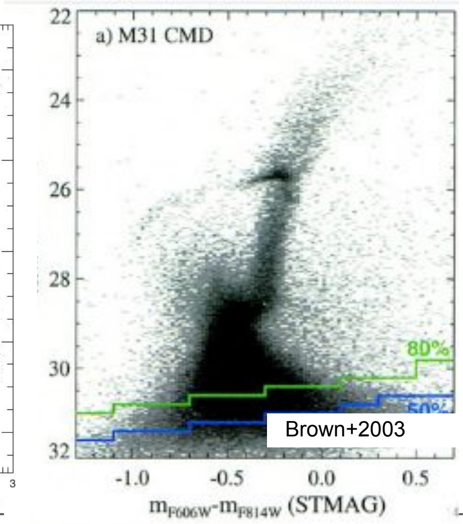


Multi-populations in CGs (e.g. Piotto+15)

Photometry

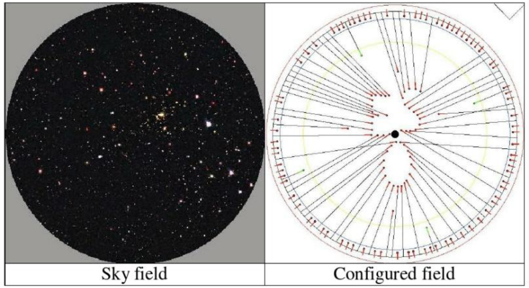
➔ **Wide-field imagers**
➔ **high spatial resolution of the HST**



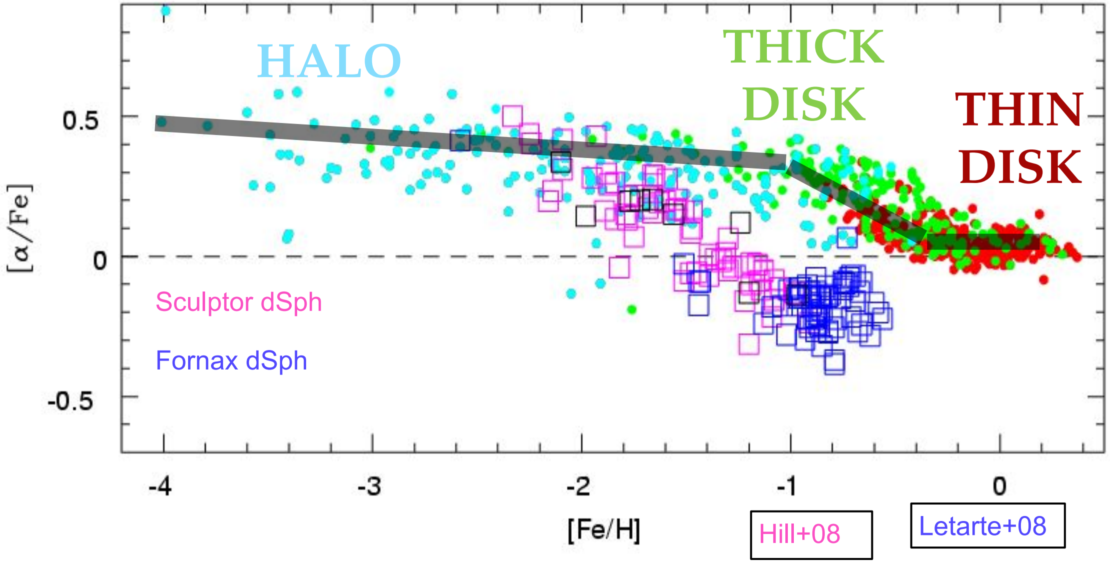


CMD reaching the oldest TO in the whole LC
SFH with age resolution of 1 Gyr at >10 Gyr (Monelli+2010c)
Population gradients (outside-in scenario, Hidalgo+13)
Environmental effect (Gallart+15; Martin+17)
Interactions (Ruiz-Lara+2021)
Reionization (Brown+14; Weisz+14; Monelli+20b; Simon+21)
Feedback (Gallart+21)

The Local Group: an accelerating revolution



Popovic+ 2004



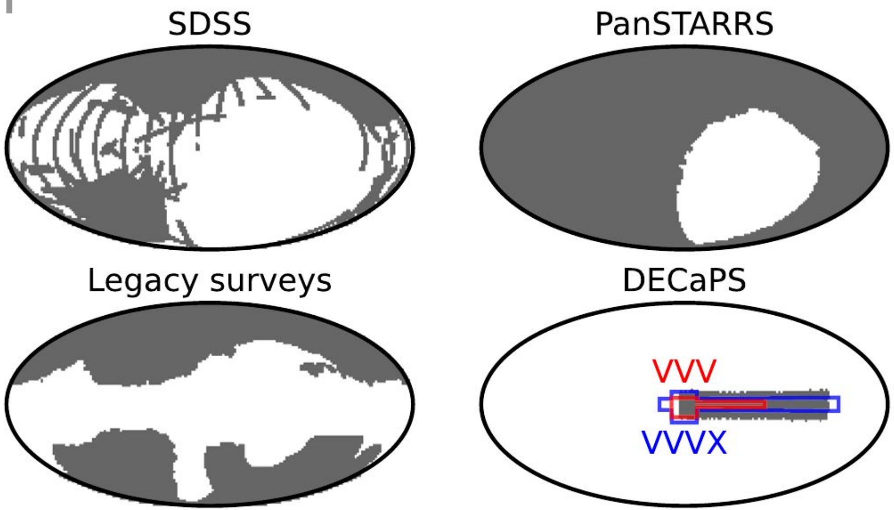
Spectroscopy

- **Multiobjetc Spectroscopy**

The properties of current MW satellite do not match those of the building-blocks that accreted during the early MW evolution

The Local Group: an accelerating revolution

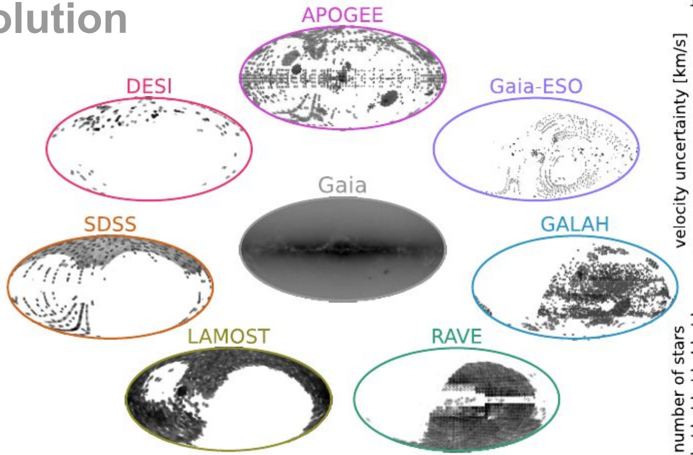
Hunt & Vasiliev 2025

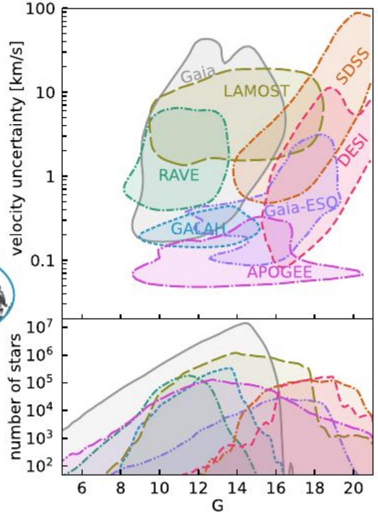


Survey	Date	Telescope	Bands	Wavelength	Depth	Coverage	Num.stars ($\times10^9$)
Gaia	2014–now	space (L2) 1.2 m	G, G_{BP}, G_{RP}	330–1050	$G < 21$	all sky	1.8
SDSS	2000–2009	Sloan (USA) 2.5 m	u, g, r, i, z	320–1000	$g < 22.2$	1/3 sky	0.47
PanSTARRS	2010–2014	PS1 (Hawaii) 1.8 m	g, r, i, z, y	400–1030	$g < 23.3$	3/4 sky	3
Legacy	2013–2019	Blanco (Chile) 4 m	g, r, z	400–1000	$g < 24.0$	1/3 sky	2
DECaPS	2016–2019	Blanco (Chile) 4 m	g, r, i, z, Y	400–1030	$g < 23.7$	2700 deg^2	3.3
2MASS	1997–2001	Whipple (USA), CTIO (Chile) 1.3 m	J, H, K_s	1100–2300	$K_s < 15.3$	all sky	0.47
VVV(X)	2010–2023	VISTA (Chile) 4 m	J, H, K_s	1100–2300	$K_s < 17.5$	1700 deg^2	1.5
WISE	2010–2018	space (LEO) 0.4 m	W_1, W_2	2800–5200	$W_1 < 18$	all sky	2

The Local Group: an accelerating revolution

Hunt & Vasiliev 2025

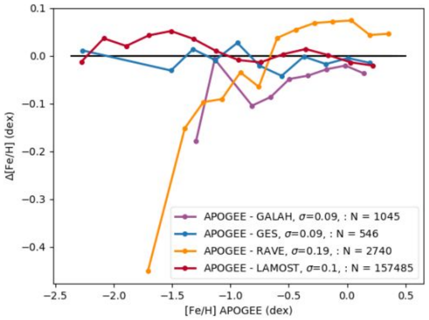




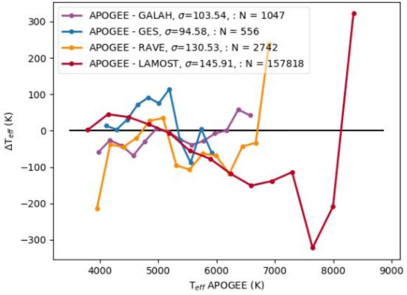
Survey	Date	Telescope	Wavelength	Spec.res.	Fibres	Num.stars
Gaia RVS	2014–now	space (L2) 1.2 m	845–872	11 500	–	33 800 000
RAVE	2003–2013	UKST (Australia) 1.2 m	841–879	7 500	120	518 000
ARGOS	2008–2011	AAT (Australia) 4 m	840–885	11 000	350	(28 000)
SDSS/SEGUE	2005–2009	Sloan (USA) 2.5 m	380–920	1 800	640	510 000
APOGEE	2008–2021	Sloan (USA), du Pont (Chile)	1500–1700	22 500	300	657 000
Gaia–ESO	2011–2018	VLT (Chile) 8.2 m	400–900	18 000+	150	114 000
GALAH	2014–now	AAT (Australia) 4 m	472–789	28 000	390	918 000
LEGUE	2012–now 2017–now	LAMOST (China) 4 m	380–900 495–680	1 500 7 500	4000	4 840 000 840 000
H3	2017–now	MMT (USA) 6.5 m	515–530	23 000	240	(300 000)
S^5	2018–now	AAT (Australia) 4 m	842–882	10 000	350	(100 000)
DESI	2021–now	Mayall (USA) 4 m	360–982	2 500	5000	(7 200 000)
SDSS-V MWM	since 2022	Sloan + du Pont 2.5 m	1500–1700	22 500	300	~5 000 000
WEAVE	since 2023	WHT (Spain) 4 m	366–959 404–685	5 000 20 000	1000	~3 000 000 ~2 000 000
4MOST	after 2025	VISTA (Chile) 4 m	370–950 393–679	6 500 20 000	1600 800	~15 000 000 ~5 000 000
MOONS	after 2025	VLT (Chile) 8.2 m	645–1800	5 000+	1000	~500 000

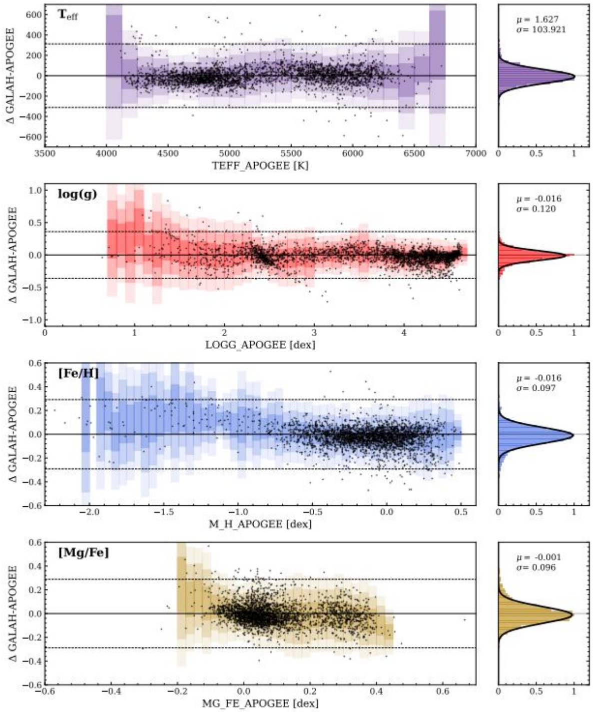
The Local Group: an accelerating revolution

Careful to subtle systematic differences!!!



Tsantaki+2022





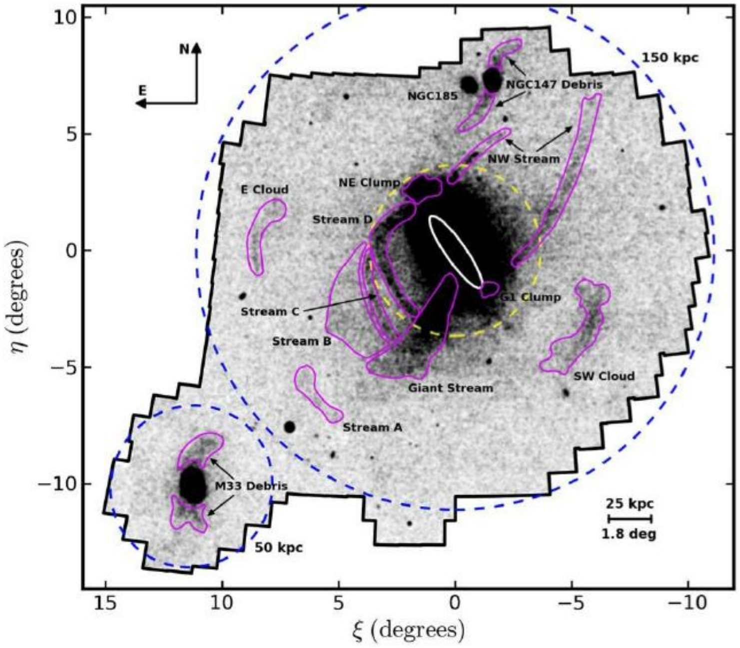
Thomas+2024

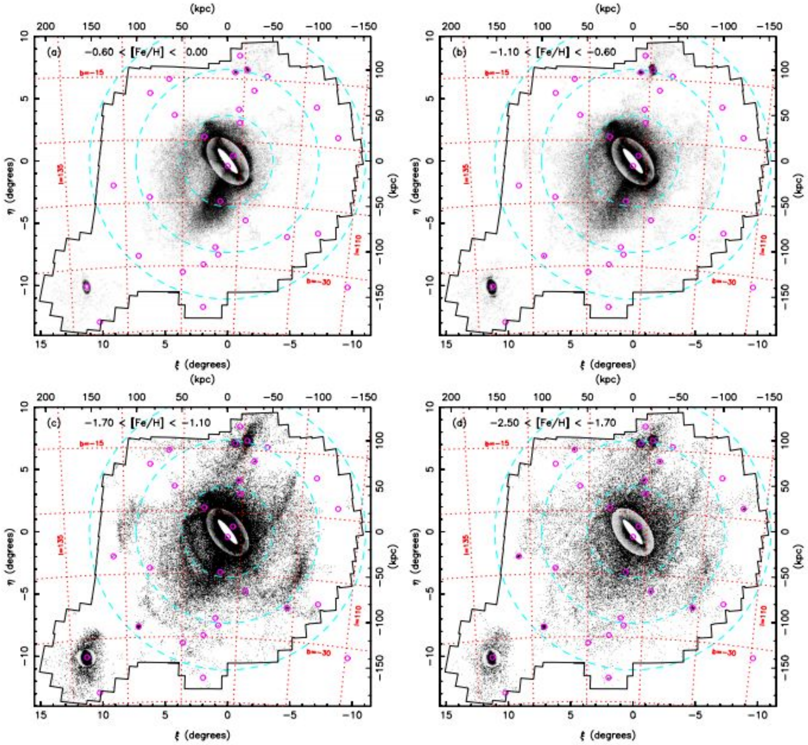
Survey of Surveys:
Tsantaki+2022 (11 M*)
Turchi+2025 (23 M*)

Spectrotranslator:
Thomas+2024

The Local Group: an accelerating revolution

PAndAS project

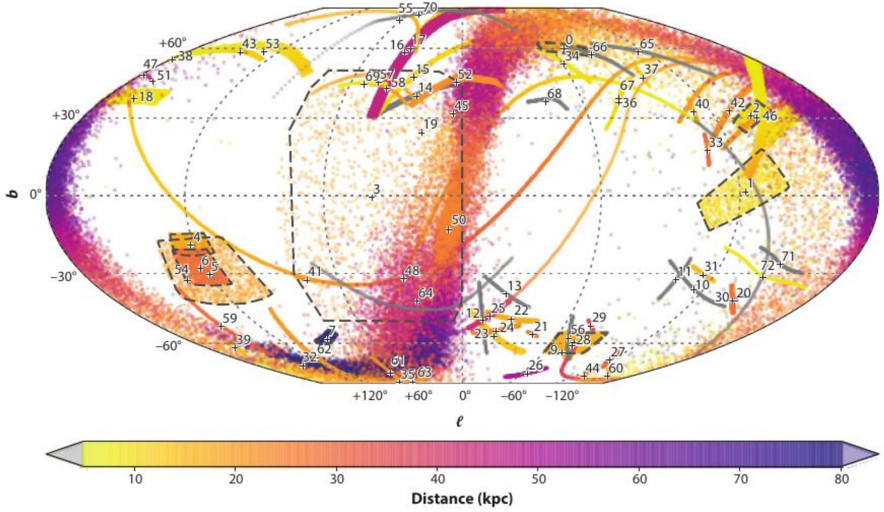




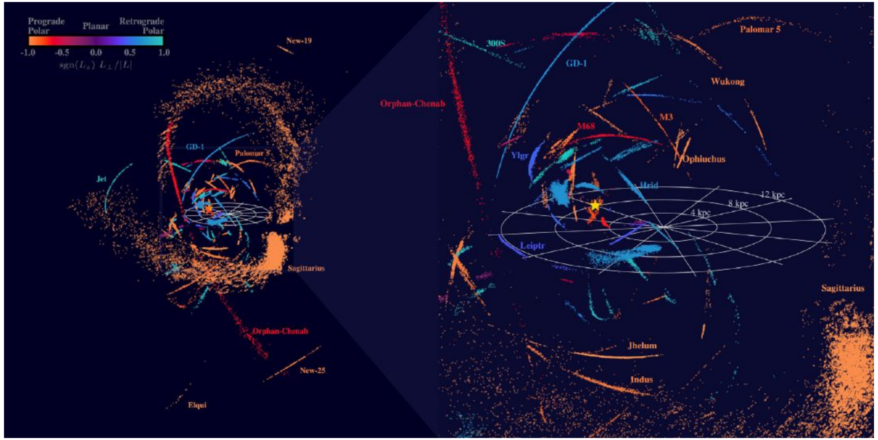
Substructures around M31

Ibata+2014, Ferguson+2016

The Local Group: an accelerating revolution



Helmi 2019



Bonaca & Price-Whelan 2025

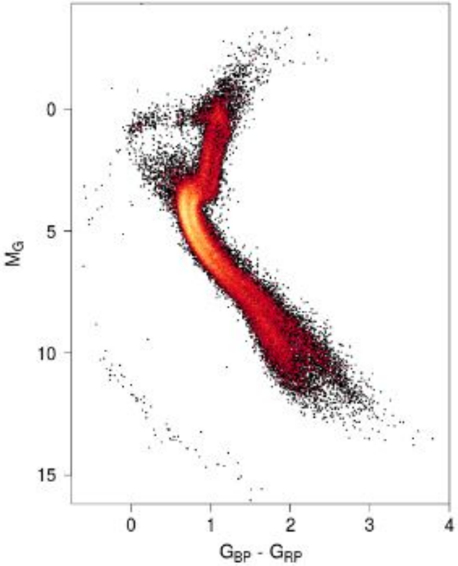
Substructures around the MW

Malhan+2018
Ibata+2024

The Local Group: an accelerating revolution

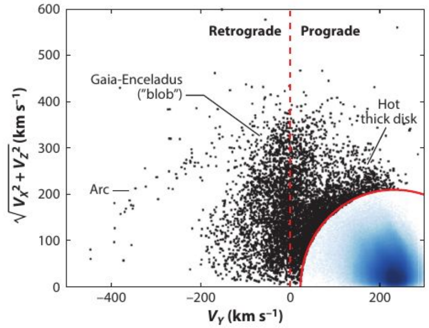
SYNERGY!!!

The discovery of Gaia-Enceladus

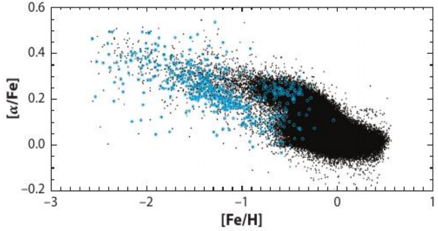


Gaia Photometry
Gaia DR2+2018

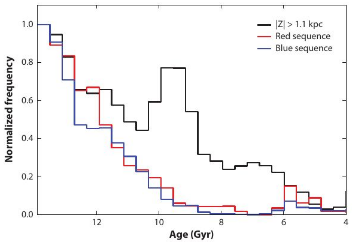
+ radial velocities
Koppelman+2018

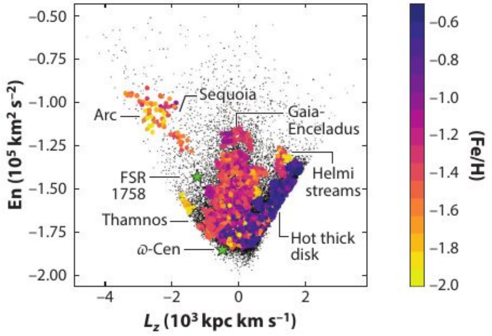


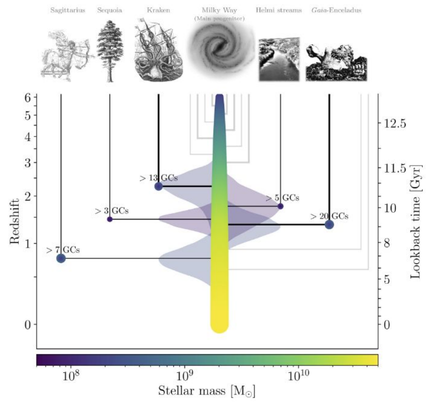
+ abundances from surveys
Helmi+2018



+ ages
Gallart+2019

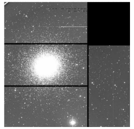




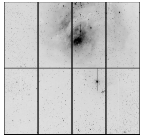


Kruijssen+2020

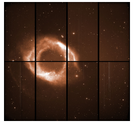
The Local Group: an accelerating revolution



Wide Field Camera, 2.5m Isaac Newton Telescope 1998-2024

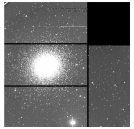


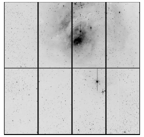
Mosaic-II, Blanco 4m telescope 1998-2012

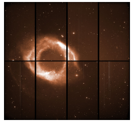


Wide Field Imager, 2.2m ESO/MPI Telescope 1998-2024

The Local Gr







Rubin/LSST

LSSTCAM:
- → 189 CCDs
- → 3.2 Gpx
- → 9.8 deg^2

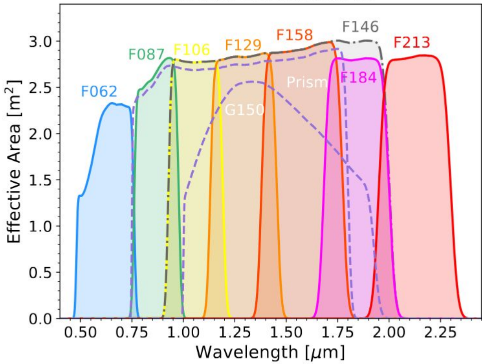
- → 20 Tb/night
- → 15 Pb end of survey

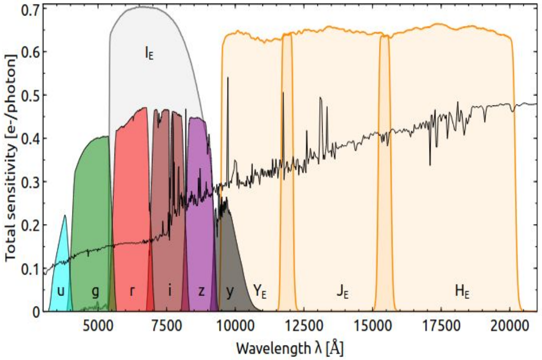
- → 20 B galaxies
- → 17 B stars

The Local Group: an accelerating revolution

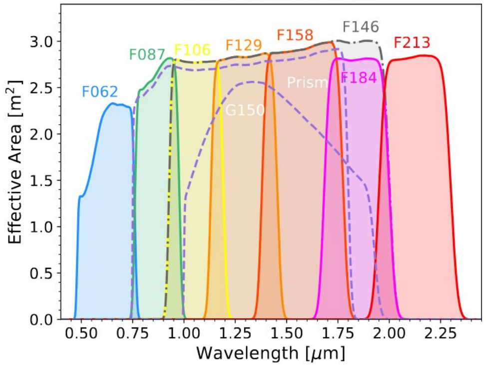
Feature	PLATO *(ESA, 2026)*	Nancy Grace Roman *(NASA, 2026)*	Euclid *(ESA, 2023)*
Primary science goal	Exoplanet detection and characterization; asteroseismology	Dark energy / cosmology (weak lensing & BAO), exoplanets time-domain	Dark energy / cosmology through weak lensing and BAO
Telescope aperture	12 cm × 24	2.4 m	1.2 m
Field of View (FoV)	2232 deg^2 total	~0.28 deg^2 per pointing	~0.54 deg^2
Wavelength coverage	500–1050 nm (optical)	0.48–2.3 μm (optical + near-IR)	0.55–2.0 μm (VIS + NIR)
Photometry	High-precision optical photometry (ppm level)	High-quality optical/NIR photometry	Deep VIS + NIR photometry
Spectroscopy	none	Low-resolution slitless spectroscopy (grism / prism)	NIR slitless spectroscopy
Angular resolution	~15 "/px	~0.11 "/px VIS	VIS: ~0.1 ″/px; 0.3 "/px NIR

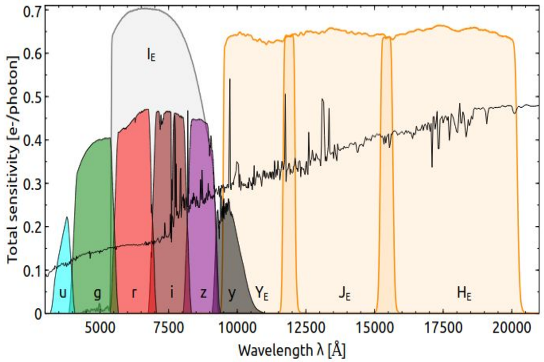
The Local Group: an accelerating revolution

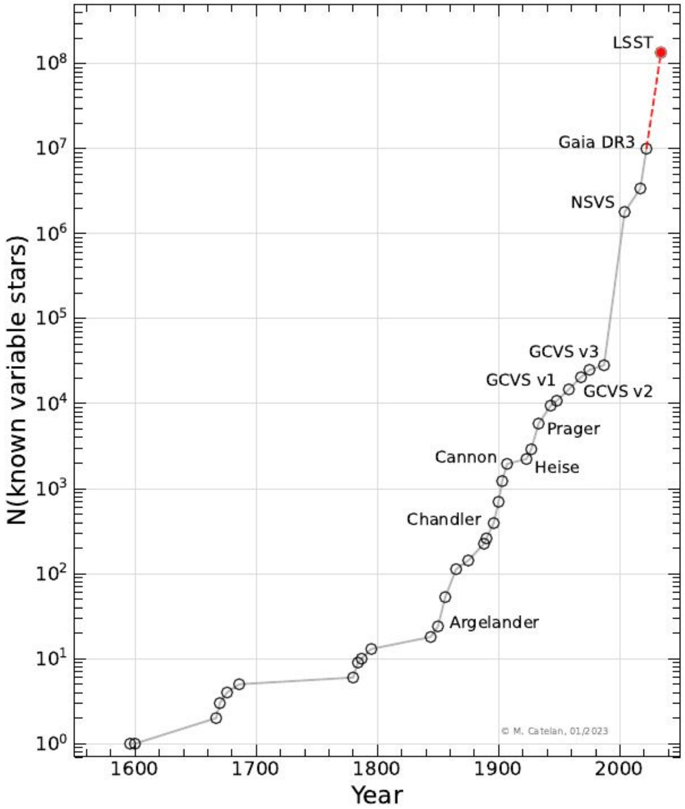




The Local Group: an accelerating revolution







Catelan 2023

Thanks!

SYNERGIES!

★ use complementary approaches
★ use complementary observables
★ use complementary surveys
★ use (develop) unforeseen techniques (IA)

matteo.monelli@inaf.it