A provisional discussion of halo kinematics in the Anticenter direction using BHB and RR Lyrae stars

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Nearby globular clusters with age and kinematic data

Relative ages & [Fe/H]: 64 GCs (HST-ACS Treasury program - *Marin-Franch et al. 2009)*
UVW space motions, orbital characteristics, HB morphology: 44 GCs
(Dinescu et al. 1999; Casetti-Dinescu et al. 2007)

	Young clusters (15) mean value (range)	Old clusters (21) mean value (range)
<V> (km/s)	-226 ± 40 (-23 to -530)	-135 ± 22 (+38 to -300)
<Zmax> (kpc)	8.5 ± 1.9 (1.0 to 21.2)	5.4 ± 1.8 (0.7 to 34.1)
Mean eccentricity	0.61 ± 0.06 (0.08 to 0.87)	0.51 ± 0.06 (0.17 to 0.86)
Mean orbit apocentric distance (kpc)	19 ± 3 (5 to 37)	12 ± 3 (3 to 57)
Mean $[Fe/H]_{CG}$	-1.03 ± 0.03 (-0.81 to -1.28)	-1.33 ± 0.10 (-0.64 to -1.98)
N. of clusters with RHB	8	0

Coarse age classification ➔ only large differences between groups are significant

If **young** = **recently accreted** ➔ only slightly different orbital characteristics **except V**
➔ R_{gal} not an effective discriminant (although accreted clusters may predominate at large R_{gal})
See D'Orazi poster for a different classification of GCs based on positions & kinematics only

Duality in the field star halo – I

► **Abundant evidence of substructures in the halo: accretion plays a large role**

► **Increasing evidence for duality: at least two distinct accretion/formation processes**

see several talks (Zolotov, Helmi, Carollo, etc.) and posters at this conference

Miceli et al. (2008): LONEOS-I survey on 1430 deg^2, **834 RRab from 3 to 30 kpc,** photometric survey, P-A relation to separate Oosterhoff types

❑ no evidence for overdensities

❑ **different spatial density profiles** :
RRL of Oosterhoff **type I** (~ 74%) have a **more extended** and **flatter galactocentric distribution** than the (older) RRL of **type II** (~ 26%)

► *Watkins et al (2009) & this conference* [using ~ 400 RR Lyrae stars in SDSS Stripe 82]
confirm density law up to 25 kpc
find steeper law & lot of structure beyond

Duality in the field star halo – II

Carollo et al. (2007) & this conference: ~ **17,000** local SDSS calibration stars
► evidence for inner and outer field star halo (mostly based on RV)

- peak metallicity of **outer** halo is 1/3 that of the inner halo (-2.2 vs -1.6)

- **inner halo**:
  non-spherical distribution
  small net **prograde** rotation (0-50 km/s)
  dominates up to 10 − 15 kpc

- **outer** halo:
  spherical distribution
  net **retrograde** rotation (-40 to -70 km/s)
  dominates beyond 15 − 20 kpc

Roederer (2009), Zhang et al. (2009): ~ 700 stars, based on high resolution data (mostly from previous studies)

- inner halo chemically homogeneous
- larger **spread of metallicity** in **outer** halo

Prograde or Retrograde?

Kinematics (mostly V) is very important to identify substructures/components

Space motion V is determined

- ❑ by **proper motions** if the star is on the **galactic meridian** i.e. plane through the Sun, Galactic center and NGP

- ❑ by **radial velocity** if the star is at **b = 0º** and **l = 90º and 270º**

Halo stars are best studied at high galactic latitudes

➔ proper motions are very important for reliable determinations of V

Proper motions for halo field stars

Hipparcos: currently best pm, magnitude limit V ~ 12 (complete to V ~ 9)
➔ brightest halo stars within **1-2 kpc**
Helmi et al.(1999); Kepley et al. (2007); Morrison et al. (2009):
➔ ~ 10% of the metal-poor stars in the local halo are in small groups with common motions

NOMAD Catalog *(Zacharias et al. 2004):*
Kinman et al. (2009) ➔ separate halo from thick disk stars at distances **up to 3 kpc**

combined **USNO-B & SDSS** positions ➔ pm (σ ~ 4 mas/yr)
Koposov et al. (2009) ➔ trace GD-1 stream of stars **out to 10 kpc** from Sun

Three-epoch (~ 90 yr baseline) **plates** (Mt. Wilson, POSS-I, du Pont)
➔ pm (σ ~ 0.85 mas/yr) in a 40'x40' field
Casetti-Dinescu et al. (2009) ➔ identify part of Virgo stellar stream at a distance of **17 kpc**

GSC-II proper motions for halo field stars

At the NGP:

GSC-II multi- epoch positions (POSS-I, Quick-V and POSS-II surveys)
➔ proper motions (rms ≤ 3 *mas/yr*) *(Spagna et al. 1996)*

pm zero-points: from 122 QSO & galaxies in the field
zp(RA) = -0.25 ± 0.28 mas/yr σ = 3.1 mas/yr
zp(DEC) = -0.07 ± 0.31 mas/yr σ = 3.4 mas/yr

At the Anticenter:

Combined **GSC-II & SDSS** multi- epoch positions (see talk by Spagna et al.)
➔ proper motions (rms ~ 2-3 *mas/yr*)

pm zero-points: from 235 QSOs in the field
zp(RA) = 0.13 ± 0.20 mas/yr σ = 3.0 mas/yr
zp(DEC) = 0.10 ± 0.18 mas/yr σ = 2.7 mas/yr

↓ ↓

at 10 kpc: **5 km/s** **140 km/s**

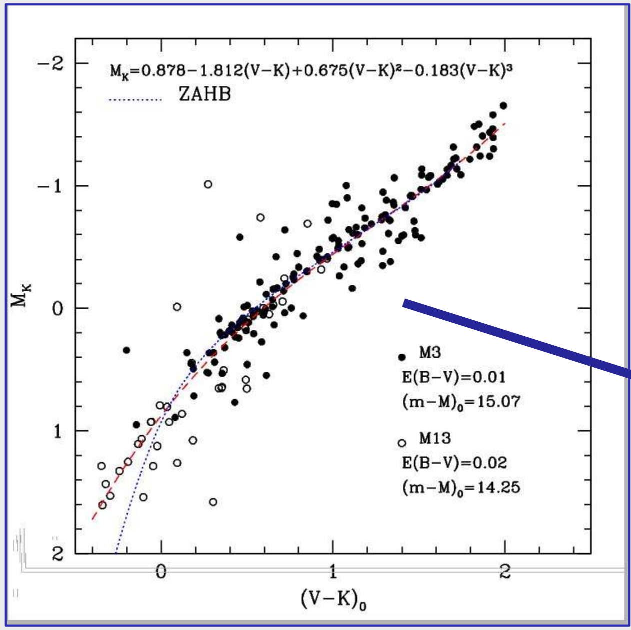
Sub-structures in the Galactic halo @ NGP - I

Kinman, Cacciari, Bragaglia, Buzzoni & Spagna (2007)

- Survey in a ~200 deg^2 area around the NGP: 26 **RRL** & 52 **BHB** stars with **Z < 8 kpc**
- Data: GSC-II pm, RV, BVK photometry, [Fe/H], RRL periods ➔ distances
- ➔ UVW space velocities (right-handed system → positive towards Galactic centre, Galactic rotation, NGP)

Distances

normalised at μ_{LMC}= 18.52



RRL

M_V= 0.21 [Fe/H] +0.86 *(Clementini et al. 2003)*

M_k = -2.40 logP + 0.06 [Fe/H] -1.06 *(Nemec et al. 1994)*

BHB

M_v = 1.00 - 4.423(B-V) + 17.74$(B-V)^2$ - 35.73$(B-V)^3$
(Preston et al. 1991)

M_k = -0.878 – 1.912(V-K) + 0.675$(V-K)^2$ – 0.183$(V-K)^3$
(Kinman et al. 2007)

accuracy to ~ 5 – 10 %

Sub-structures in the Galactic halo @ NGP - II

This halo sample is not homogeneous

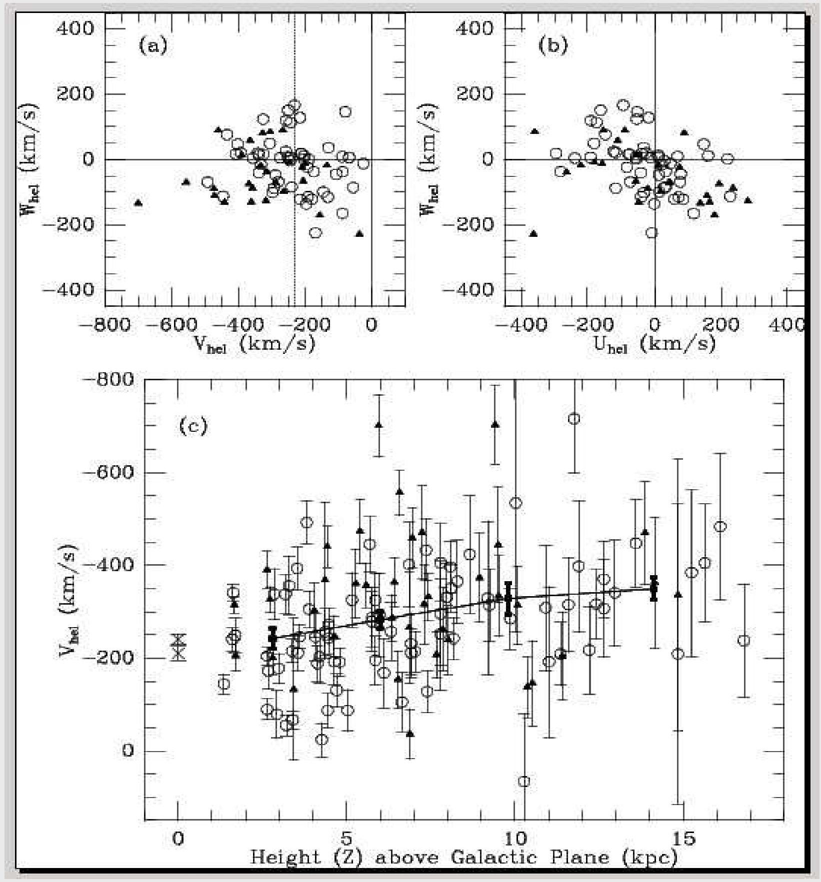
- **BHB & RRL**: retrograde galactic rotation -268 km/s ➔ ~ same as by Majewski (1992) in SA57 @ NGP
- **BHBs: zero galactic rotation** (<V> ~ -239 km/s)
- **RRLs: retrograde rotation** (<V> ~ -328 km/s)
- **Velocity dispersion of RRL** is much larger for those with W<0 (*streaming down*)
- **Ratio RRL/BHB** is larger for W<0 sample

Table 1. Mean heliocentric space-velocities <U> & <V> for our BHB & RRL stars for different ranges of the space-velocity W.

Star Type	Range in W	Number	<U>	<V>	σV
RRL	W< 0	20	+12±41	−321±36	156
BHB	W< 0	24	+11±20	−216±24	116
All	W< 0	44	+12±21	−264±22	145
RRL	W> 0	6	−112±41	−351±31	69
BHB	W> 0	28	−64±20	−258±19	98
All	W> 0	34	−72±21	−275±17	99
RRL	All W	26	−17±35	−328±28	143
BHB	All W	52	−29±16	−239±15	108
All	All W	78	−25±16	−268±14	124

Sub-structures in the Galactic halo @ NGP - III

V retrograde rotation increases with Z →



▲ = RRL ○ = BHB

Sub-structures in the Galactic halo @ NGP - IV

This halo sample occupies ~ 10 kpc^3 at <Z> (i.e. $<R_{hel}>$) ~ 5 kpc

⬇

one component

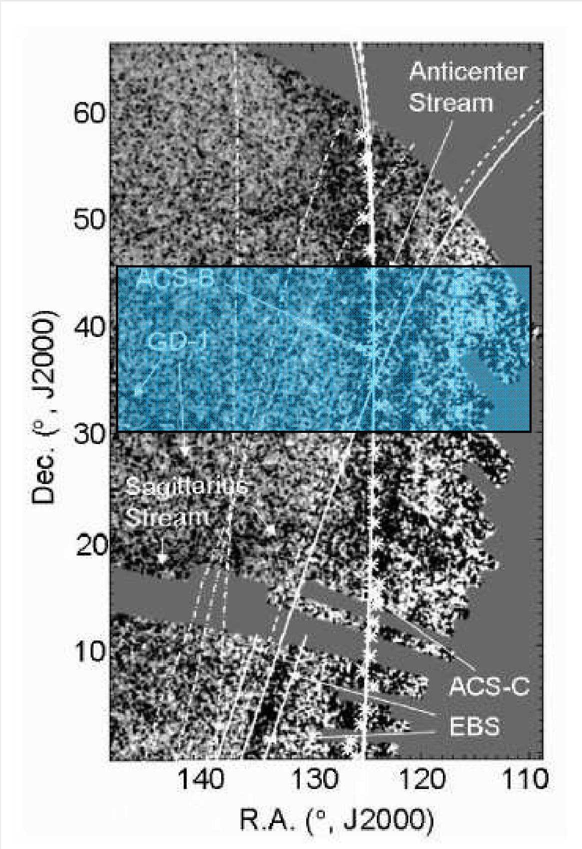
- rich in RRL
- retrograde rotation
- streaming motion
  → accretion process
- HB morphology
  → young halo GCs

other component

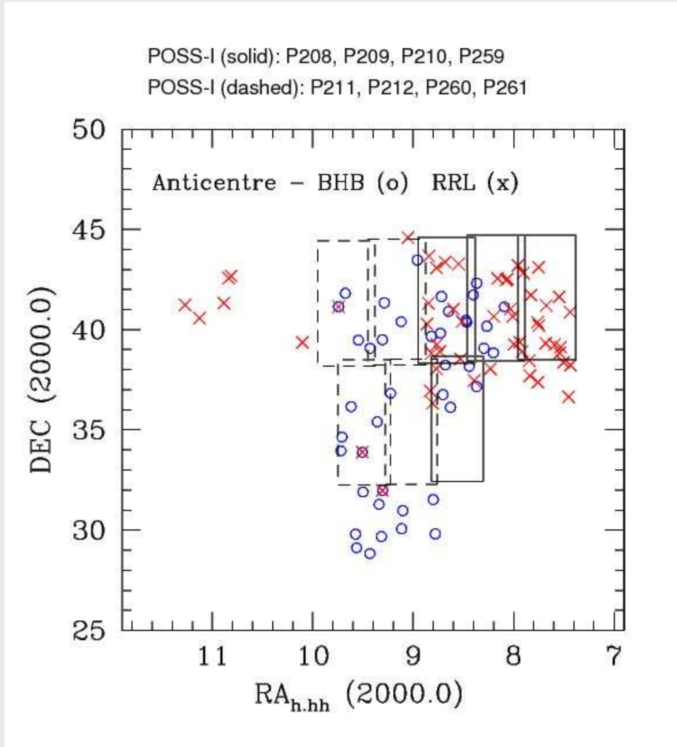
- traced by BHB
- no evidence of rotation
- less evidence of streaming
- HB morphology
  → old halo GCs

The Galactic halo @ Anticenter: our survey - I

- Survey in a **~250 deg²** area around the **Anticenter: 175º < ℓ < 200º & 24º < b < 50º**
- **17 RRL** & **35 BHB** stars with **2.2 < R_{hel} < 10 kpc (<R_{hel}> ~ 6 kpc) <Z> ~ 3.7 kpc**
  this halo sample occupies ~ 20 kpc³ at <Z> ~ 3.7 kpc



Grillmair, Carlin & Majewski (2008)

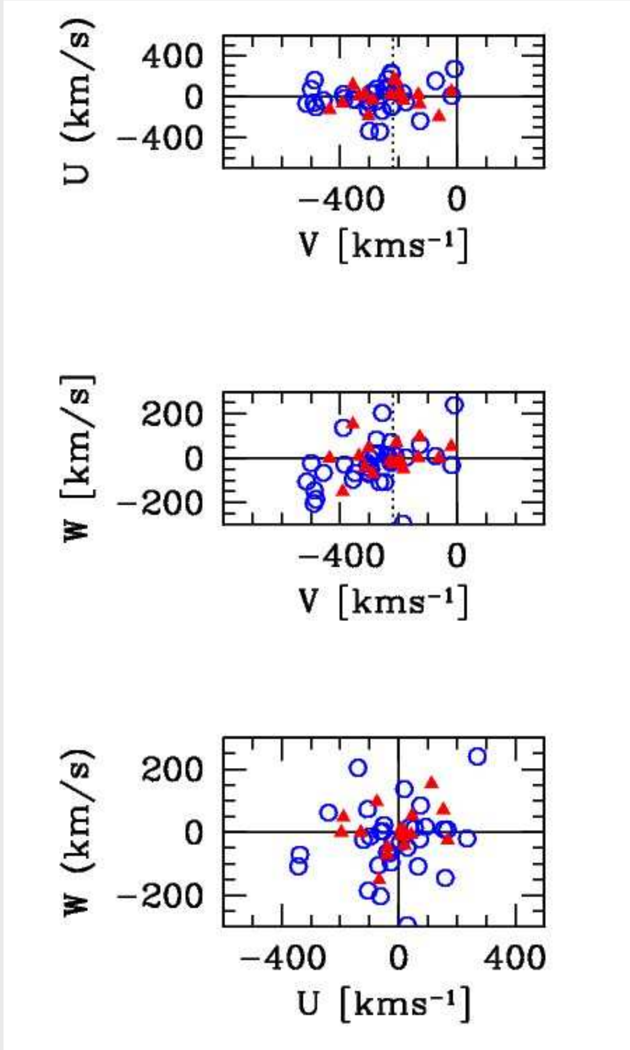


The Galactic halo @ Anticenter: our survey - II

- **Data:**
  - ➔ proper motions from **GSC-II & SDSS** positions (rms ~ 2-3 *mas/yr*)
  - ➔ **RV** (to ± 5-20 km/s) for 34 BHB and 6 RRL
    assumed RV = 0.0 ± 150 km/s when missing
  - ➔ **BV & K(2MASS**) photometry for all
  - ➔ **[Fe/H]** for most RRL, assumed [Fe/H] = -1.6
    when missing (most BHB, a few RRL)
  - ➔ **periods** for a few (6) RRL

- **Derived:**
  - ➔ **distances**, same procedure as for the NGP sample
    accuracy to ~ 5 -10%

    ➔ **UVW** space velocities



BHB & **RRL**

The Galactic halo @ Anticenter: our survey - III

StarType	Z range kpc	N	<V> km/s	σV km/s
RRL	Z < 4	10	-211 ± 29	91
BHB	Z < 4	18	-271 ± 23	98
All	Z < 4	28	-250 ± 19	98
RRL	Z > 4	7	-269 ± 54	142
BHB	Z > 4	17	-296 ± 38	155
All	Z > 4	24	-288 ± 30	149

RRL & BHB: <V> getting more negative with increasing Z ➔ same as at the NGP

	Anticenter	NGP
RRL Z < 4	no rotation	sl. retrograde
BHB Z < 4	sl. retrograde	no rotation
RRL Z > 4	no rotation	retrograde
BHB Z > 4	retrograde	no rotation

The Galactic halo @ Anticenter: our survey - IV

StarType	W range km/s	N	<V> km/s	σV km/s
RRL	W < 0	1	-217 ± ?	---
BHB	W < 0	20	-331 ± 29	131
All	W < 0	21	-325 ± 28	130
RRL	W > 0	5	-227 ± 66	147
BHB	W > 0	15	-220 ± 24	94
All	W > 0	20	-222 ± 24	105

Dispersion of ***streaming down*** **BHBs (W < 0)** is **slightly larger** than dispersion of **BHBs with W > 0**

same **–** but weaker – effect as for the RRL @ NGP

The Galactic halo @ Anticenter: comparison I

Schlaufman et al. (2009):

- ■ SDSS & SEGUE imaging (colour) data to isolate MPMSTO stars in 137 lines of sight
- ■ distances taken from K-band parallaxes
- ■ analyse SEGUE spatial and radial velocity distributions
- ► identify 10 elements of cold halo substructure in inner halo by peak in RV distribution

Overlap: area PC1-7 RA=124º.5 Dec=+38º l=183º.4 b=32º.6 d = 8.7 (+1.1 to -0.7) kpc
radial velocity peak at **+29** km/s
only 16 MPMSTO stars with RV within 1 sigma of peak velocity
only 83 MPMSTO stars in the whole line of sight

In this direction and distance we have:

6 RRL stars, 4 with RV measures → <RV> ~ +137 km/s
2 BHB stars, 1 with RV measure → RV = + 69 km/s

- ➢ MPMSTO stars are thousand times more frequent than HB stars: is MPMSTO overdensity too small to contain enough HB stars?
- ➢ MPMSTO stars are colour-selected → age and metallicity of sample not well defined see Ruhland poster (comparison of BHB and MSTO stars)

- ➢ we have no information on tangential velocity: dispersion of ~ 140 km/s at 10 kpc
- ➢ we are not looking for clusters but for shifts of average motions: rms ~ 5 km/s at 10 kpc

The Galactic halo @ Anticenter: comparison II

Grillmair, Carlin & Majewski (2008):

- Anticenter Stream area B:
  RA = 124º Dec = 37º.5
  distance of 8.9 ± 0.2 kpc

- stars selected by colour-magnitude density (Hess) diagram + M13 search filter

- SDSS/USNO-B proper motions, individual measurement uncertainty of ~ 4 mas/yr

- radial velocity distributions: in ACS-B RV distribution peaks at **+53** ± 8 km/s

► the AC Stream is on a nearly circular ***prograde*** orbit around the Galaxy

➔ **different techniques & tracers may bring out different results**
➔ **Important to consider them all for a global and comprehensive view**

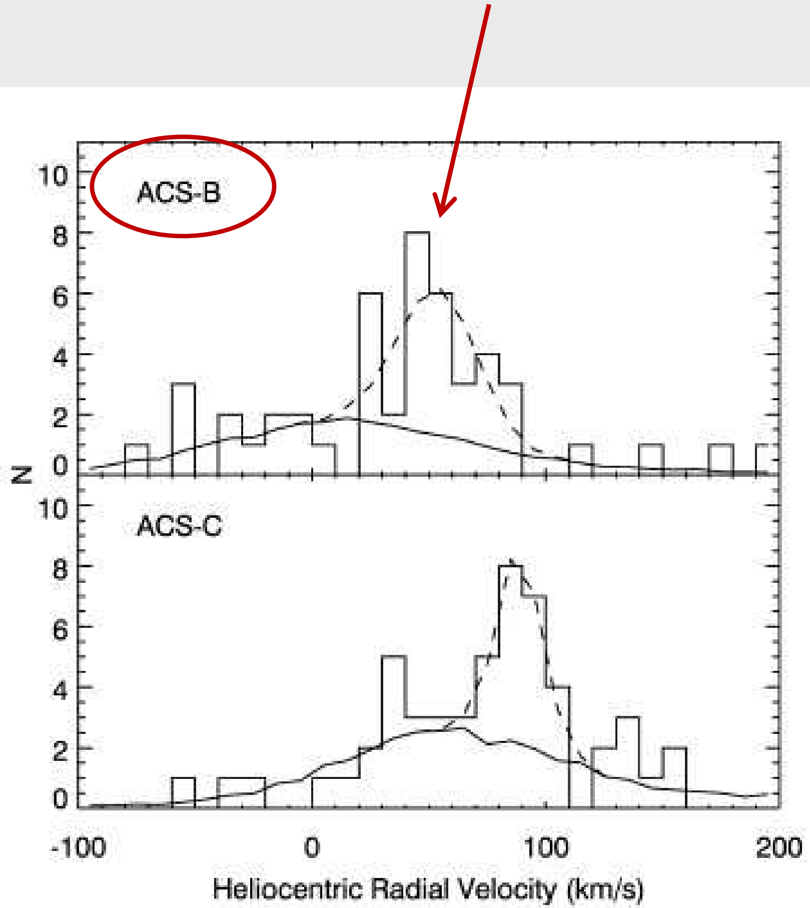


FIG. 1.—Histograms of radial velocities measured in our two fields. The smooth curves show the scaled distributions of foreground stars as predicted by the Besançon model of the Galaxy. The dashed curves show the Gaussian distributions that best fit the stream peaks. The histograms are shown using 10 km s^{-1} wide velocity bins, although our analysis makes use of a variety of bin widths.

The Galactic halo @ Anticenter: preliminary concluding remarks

- In the surveyed area there is BHB some evidence of sub-structure, retrograde rotation and down-streaming motion by stars (typical of old halo population)

  The RRL sample is too small and no definitive conclusions can be reached for them

- This is opposite to the NGP where Oo-I RRL stars (typical of younger halo population) are streaming down in retrograde rotation ➔ accretion event

- This result is consistent with Kinman & Saha (2004): ``*… the halo component of the CMa ring has an HB morphology that does not favor RR Lyrae stars …''*
  and with Mateu et al. (2009) : ``*No excess of RR Lyrae stars in the CMa overdensity ''*

Future work at the Anticenter

Next steps:

- Check for systematics on proper motions, especially for the BHB stars
- Improve the sample of RRL and BHB stars, adding more stars if possible
- Improve the data, e.g. especially radial velocities and periods for the RRL

More distant future ➔ Gaia:

- ❑ Parallaxes: rms 12-25 µas @ V ~ 15
  ➔ RRL & BHB distances to < 10% as far as ~ 10 kpc
- ❑ Proper motions: rms 10-20 µas/yr (0.5 – 1.0 km/s) @ V ~ 15
  ➔ **hundred times better than most present data**
- ❑ radial velocities - from Gaia (to a few km/s) or ground-based surveys
- ❑ astrophysical parameters - from Gaia or ground-based surveys

- **definitive answer to these questions, at least as far as 10 kpc**
- **perform the same type of analysis to larger distances**
- **<u>perform the same type of analysis over the entire sky</u>**

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