Nearby Halo Streams

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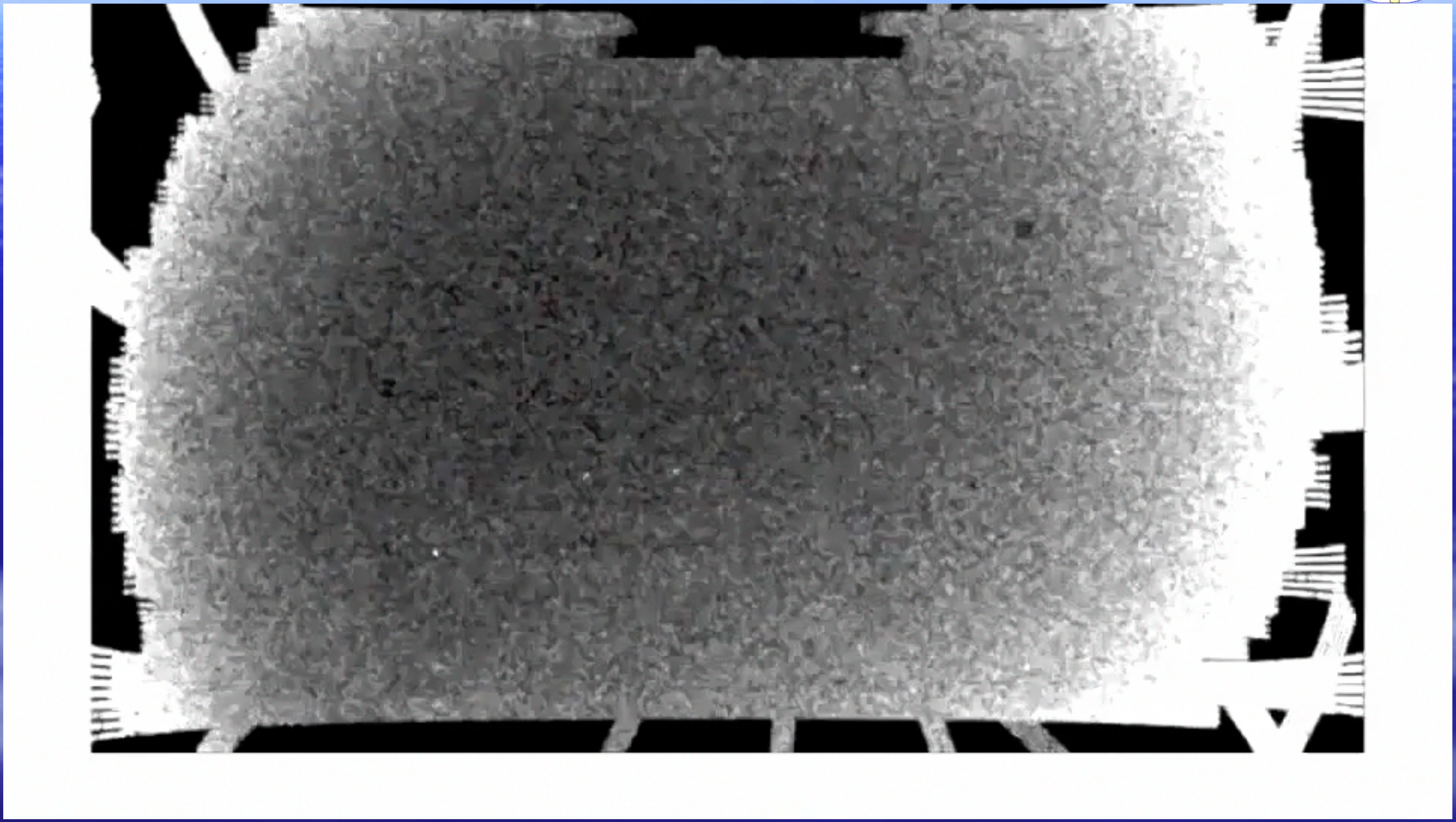
Current Tally: 21 Nearby Halo Streams

Table 1.1 Currently Known Halo Streams

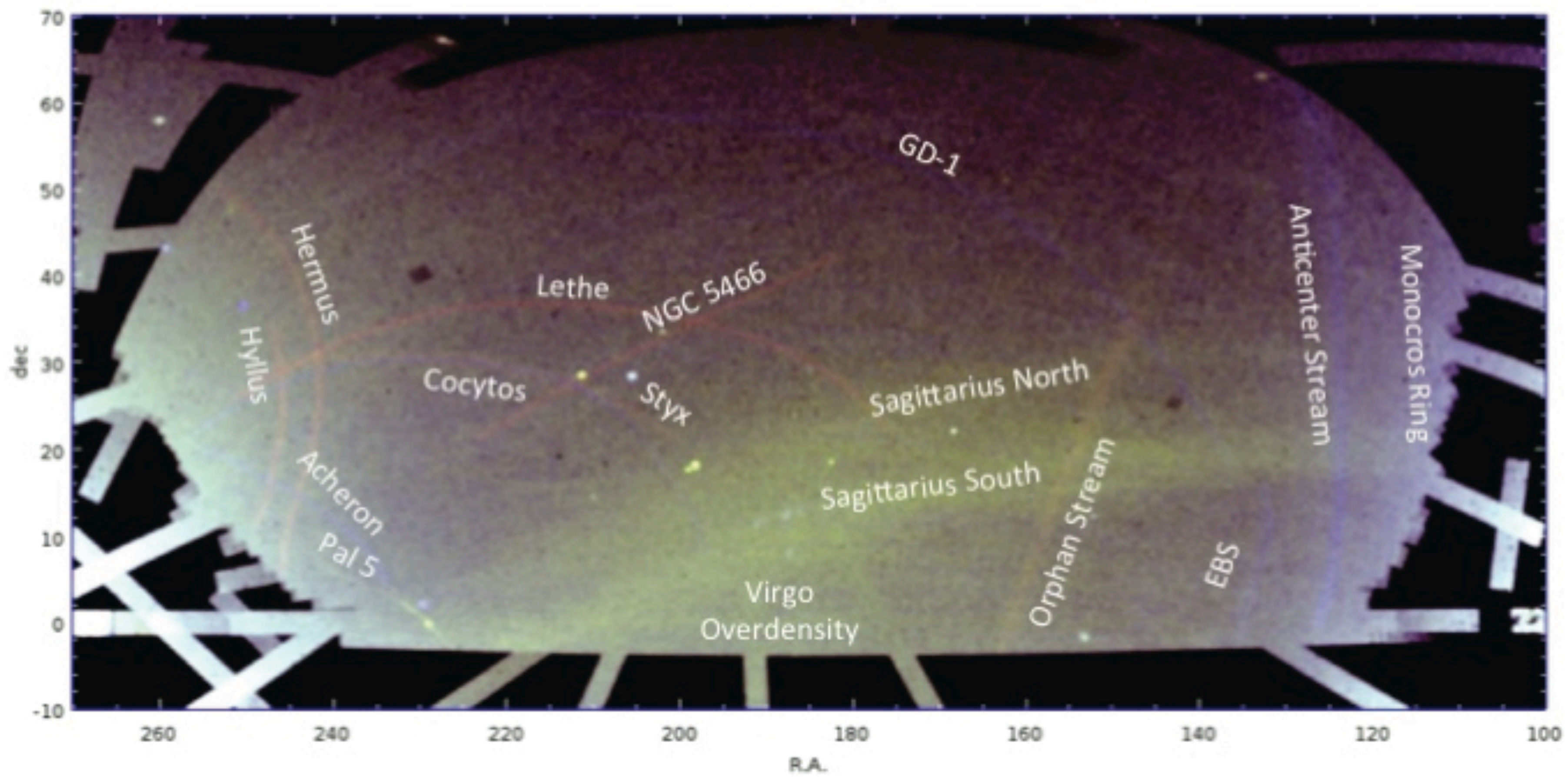
Designation	Progenitor	Known Extent	Distance kpc	V_{hel} km s^{-1}	[Fe/H]	Selected References
Sagittarius Stream	Sagittarius dSph	Circum-sky	7-100	(-200, +200)	(-1.15, -0.4)	Ibata et al. 1994, Mateo et al. 1998, Alard 1996, Toten & Irwin 1998, Ibata et al. 2001a, b, Majewski et al. 2003, Martinez-Delgado et al. 2004, Vivas et al. 2005, Belokurov et al. 2006b, Fellhauer et al. 2006, Bellazzini et al. 2006, Chou et al. 2007, Law et al. 2009, Law & Majewski 2010, Keller et al. 2010 Carlin et al. 2012a, Koposov et al. 2012
Virgo Stellar Stream	NGC 2419?	$180° < R.A. < 195°$ $-4° < \delta < 0°$	19.6	128	-1.78	Vivas et al. 2001, Duffau et al., 2006, Newberg et al. 2007, Duffau et al. 2014
Palomar 5	Palomar 5	$225° < R.A. < 250°$ $-3° < \delta < 8.5°$	23	-55	-1.43	Odenkirchen et al. 2001, 2003, 2009, Rockosi et al. 2002, Grillmair & Dionatos 2006a, Carlberg, Grillmair, & Hetherington 2012
Monoceros Ring	dG?	$108° < R.A. < 125°$ $-3° < \delta < -41°$	≈ 10.5	≈ 100	-0.8	Newberg et al. 2002, Yanny et al. 2003, Ibata et al. 2003, Rocha-Pinto et al. 2003, Penarrubia et al. 2005, Li et al. 2012 Slater et al. 2014
NGC 5466	NGC 5466	$182° < R.A. < 224°$ $21° < \delta < 42°$	17	108	-2.2	Belokurov et al. 2006a, Grillmair & Johnson 2006, Fellhauer et al. 2007b, Lux et al. 2012
Orphan Stream	dG?	$143° < R.A. < 165°$ $-17° < \delta < +48°$	20-55	(95,240)	-2.1	Grillmair 2006a, Belokurov et al. 2007a Fellhauer et al. 2007a, Sales et al. 2008, Newberg et al. 2010, Sesar et al. 2013 Casey et al. 2013
GD-1	GC?	$134° < R.A. < 218°$ $14° < \delta < 58°$	7 - 10	(-200,+100)	-2.1	Grillmair & Dionatos 2006b, Willett et al. 2009, Koposov, Rix, & Hogg 2010, Carlberg & Grillmair 2013
AntiCenter Stream	dG?	$121° < R.A. < 130°$ $-3° < +63°$	≈ 8	(50, 90)	-0.96	Grillmair 2006b, Grillmair, Carlin, & Majewski 2008, Li et al. 2012
EBS	GC?	$132° < R.A. < 137°$ $-3° < \delta < 16°$	10	(71, 85)	-1.8	Grillmair 2006b, Grillmair 2011, Li et al. 2012
Acheron	GC?	$232° < R.A. < 258°$ $3° < \delta < 20°$	3.5 - 3.8		-1.7?	Grillmair 2009
Cocytos	GC?	$197° < R.A. < 257°$ $8° < \delta < 30°$	11		-1.7?	Grillmair 2009
Lethe	GC?	$176° < R.A. < 252°$ $22° < \delta < 37°$	13		-1.7?	Grillmair 2009
Styx	Bootes III?	$201° < R.A. < 250°$, $21° < \delta < 31°$	45		-2.2?	Grillmair 2009
Cetus Polar Stream	NGC 5824?	$19° < R.A. < 37°$ $-11° < \delta < +39°$	24 - 36	(-200, -160)	-2.1	Newberg, Yanny, & Willett 2009, Yam et al. 2013
Pisces/ Triangulum	GC?	$21° < R.A. < 24°$ $23° < \delta < 40°$	35	120	-2.2	Bonaca et al. 2012b, Martin et al. 2013, Martin et al. 2014
Alpheus	NGC 288?	$22° < R.A. < 28°$ $-69° < \delta < 45°$	1.6 - 2.0		-1.0?	Grillmair 2013
ATLAS stream	Pyxis?	$18° < R.A. < 30°$ $-32° < \delta < -25°$	20		-1.4?	Koposov et al. 2014
PAndAS MW Stream	dG?	$0° < R.A. < 22°$ $40° < \delta < 48°$	17	127	-1.5?	Martin et al. 2014
Hermus	GC?	$241° < R.A. < 254°$ $5° < \delta < 50°$	18.5		-2.3?	Grillmair 2014
Hyllus	GC?	$245° < R.A. < 249°$ $11° < \delta < 34°$	20		-2.3?	Grillmair 2014
Ophiuchus stream	GC	$241° < R.A. < 243°$ $-7.2° < \delta < 6.7°$	8 - 9.5	290	-1.95	Bernard et al. 2014, Sesar et al. 2015

Newberg & Carlin 2015

The Galactic Web

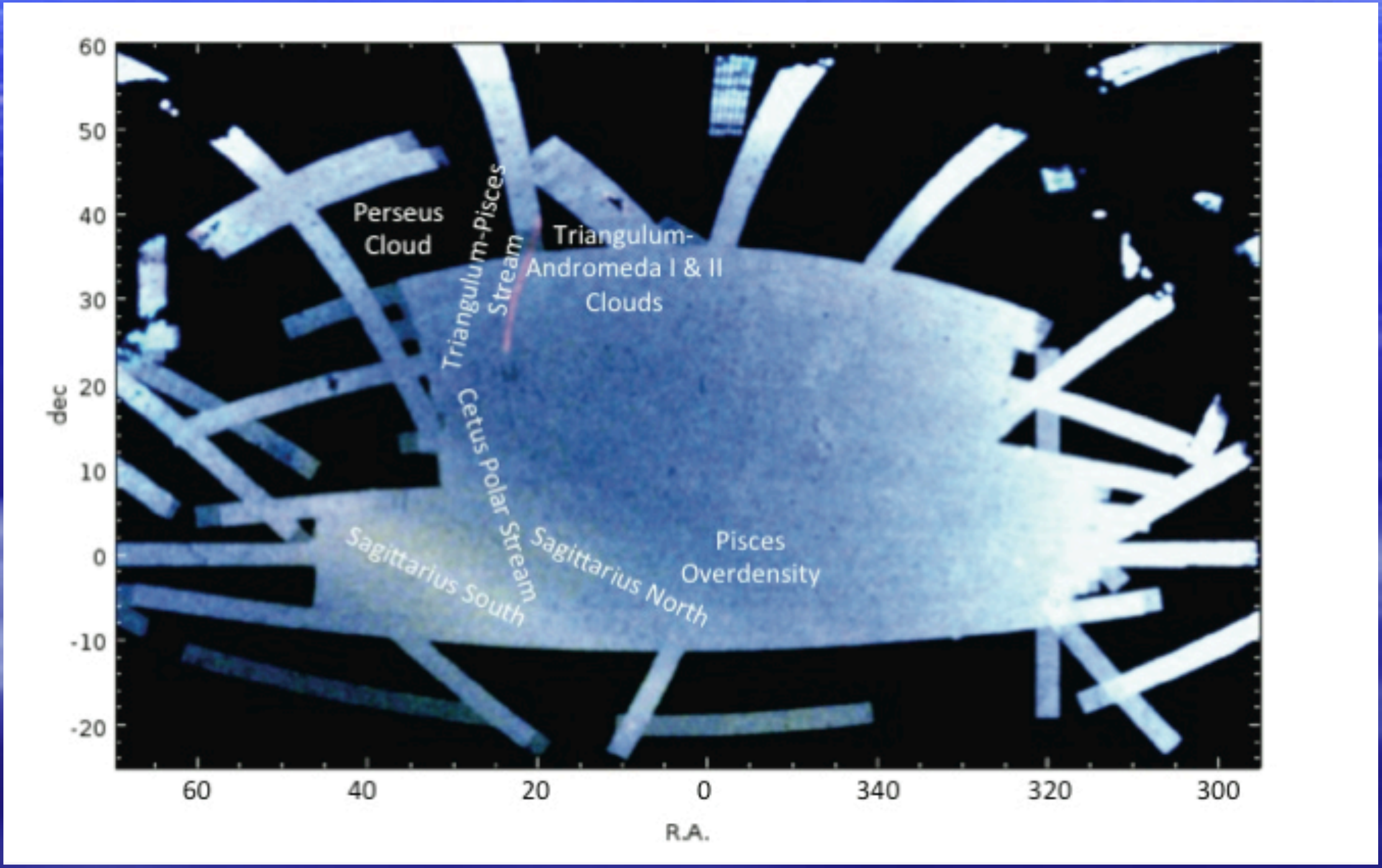


SDSS North

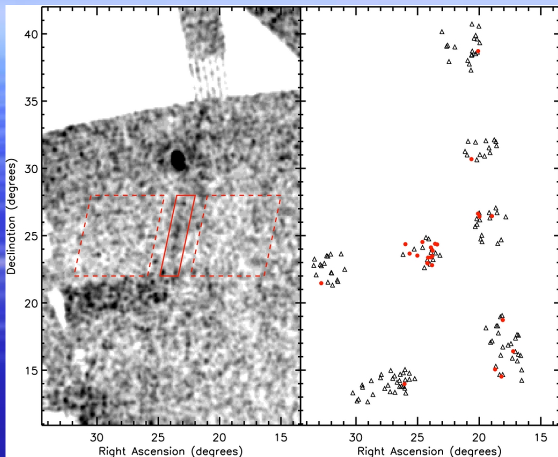


GD-1
Hermus
Lethe
NGC 5466
Hyllus
Cocytos
Styx
Sagittarius North
Anticenter Stream
Monocros Ring
Acheron
Sagittarius South
Pal 5
Orphan Stream
EBS
Virgo
Overdensity
dec
R.A.
70
60
50
40
30
20
10
0
-10
260
240
220
200
180
160
140
120
100

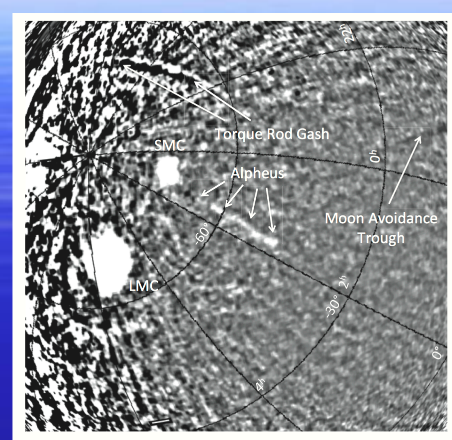
SDSS South


Perseus Cloud
Triangulum-Pisces Stream
Triangulum-Andromeda I & II Clouds
Cetus Polar Stream
Sagittarius South
Sagittarius North
Pisces Overdensity
dec
R.A.
60
50
40
30
20
10
0
-10
-20
60
40
20
0
340
320
300

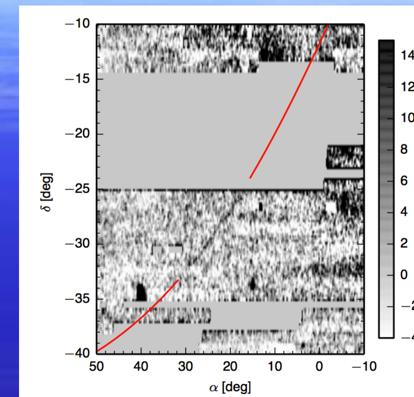
Recently Discovered Streams



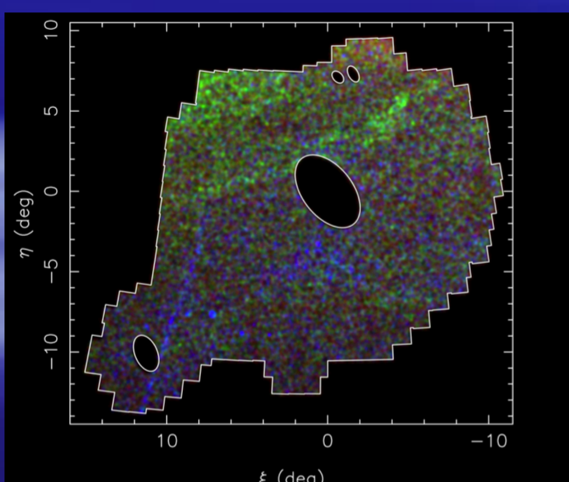
Pisces/Triangulum Stream
Bonaca et al. 2012



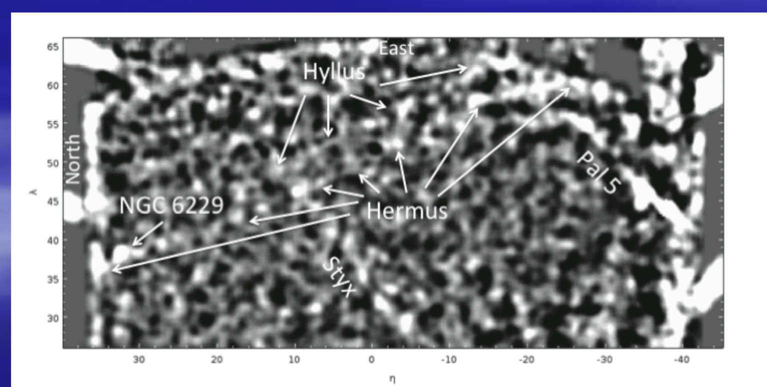
Alpheus
Grillmair et al. 2013



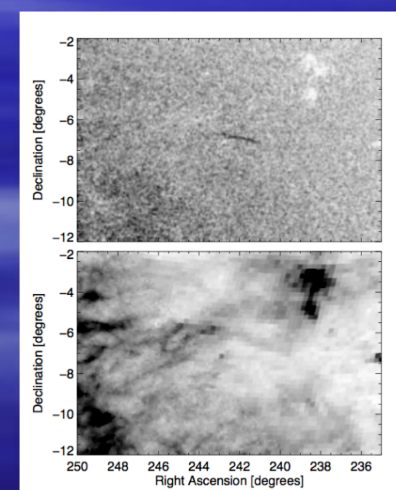
ATLAS Stream
Koposov et al. 2014



PAndAS MW Stream
Martin et al. 2014

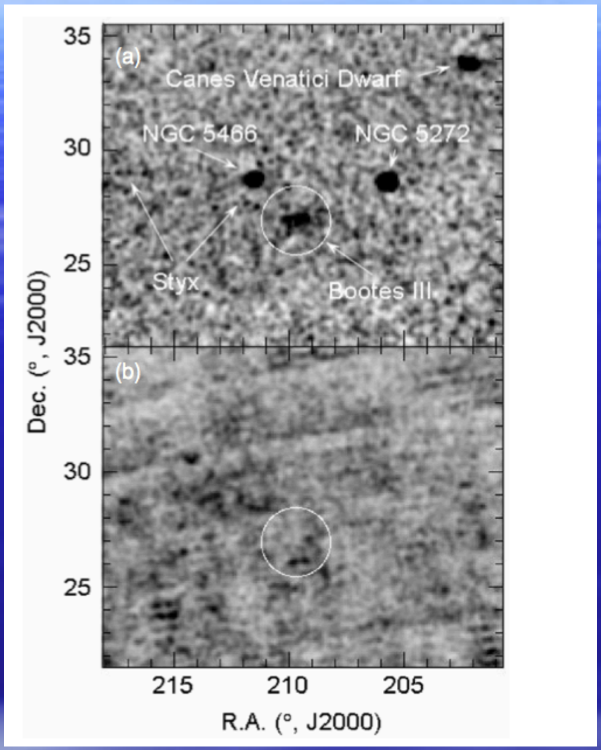


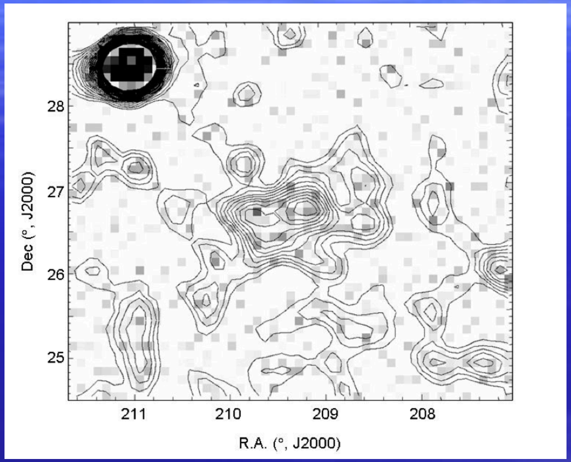
Hermus & Hyllus
Grillmair 2014

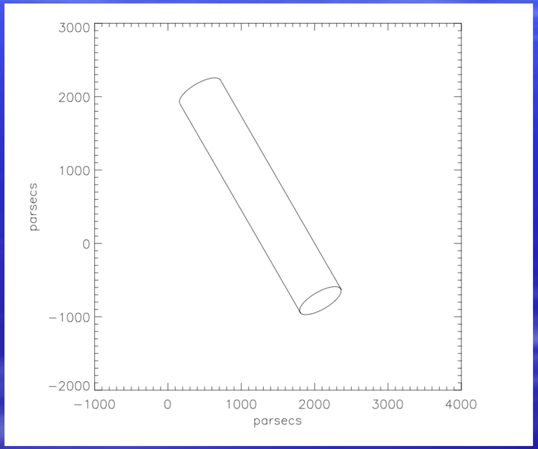


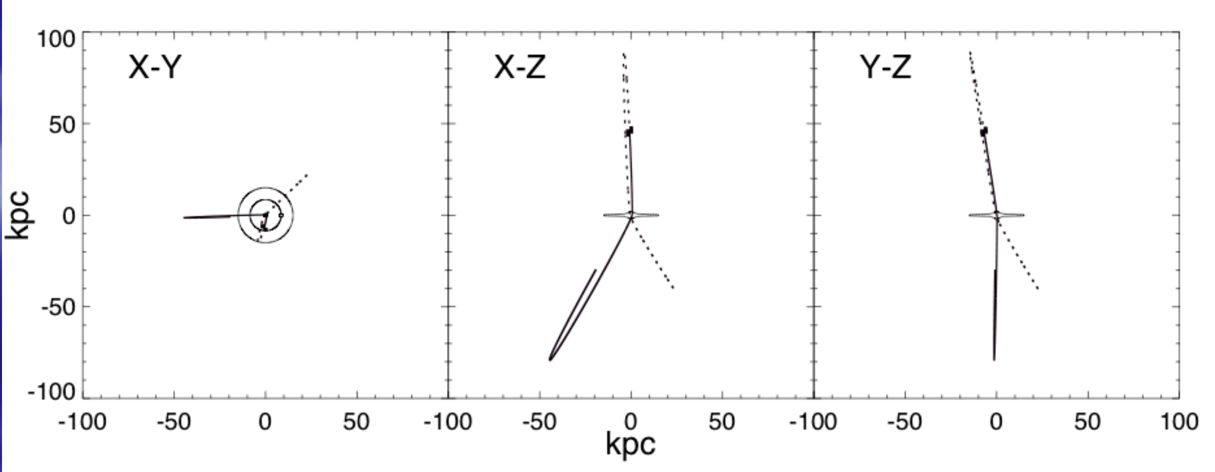
Ophiuchus Stream
Bernard et al. 2014

Bootes III – an End-On, High Velocity Stream?









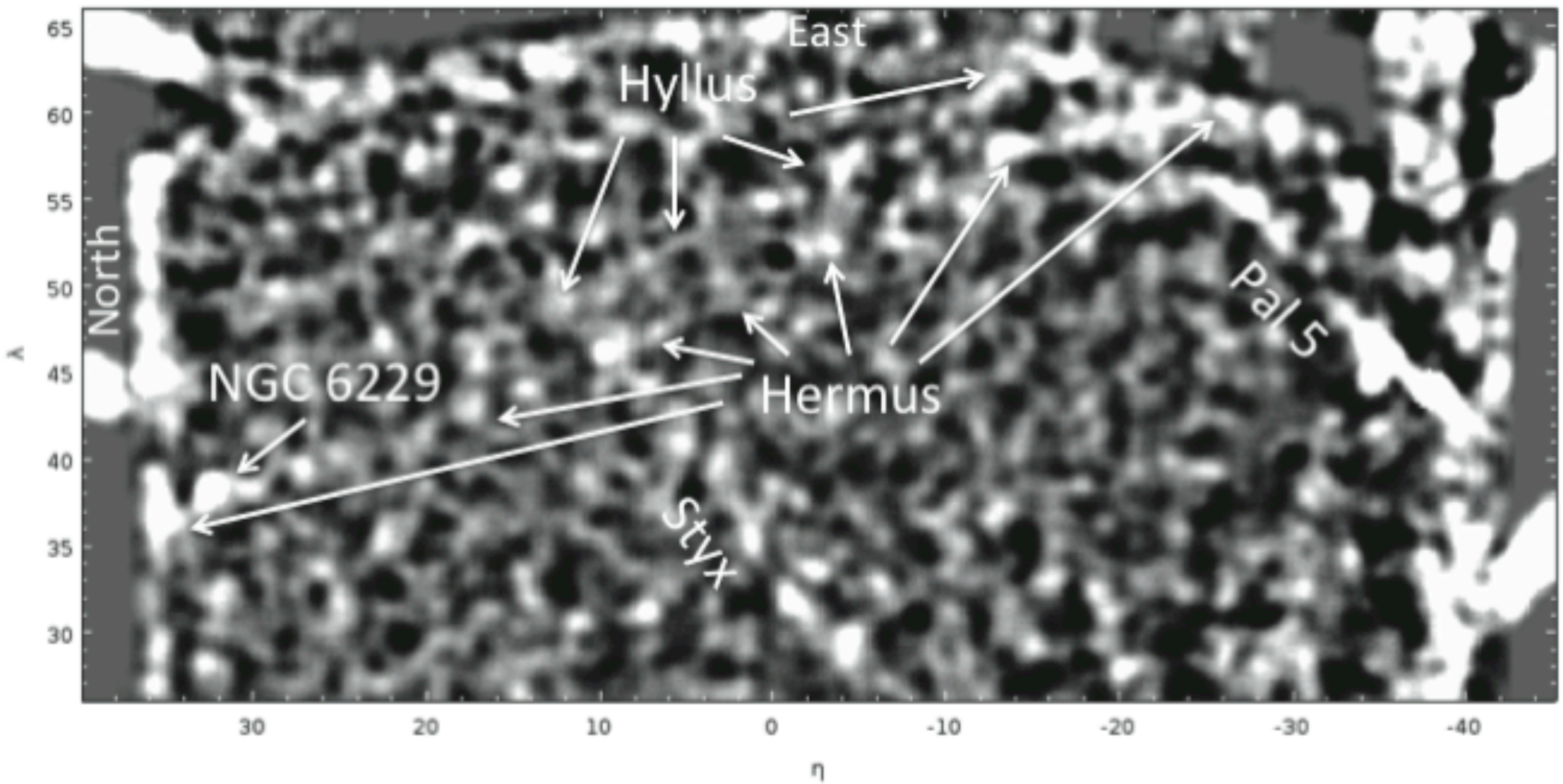
R_a = 91 ± 2 kpc

R_p = 0.5 ± 0.1 kpc

V @ 0.5 kpc = 655 km/sec!

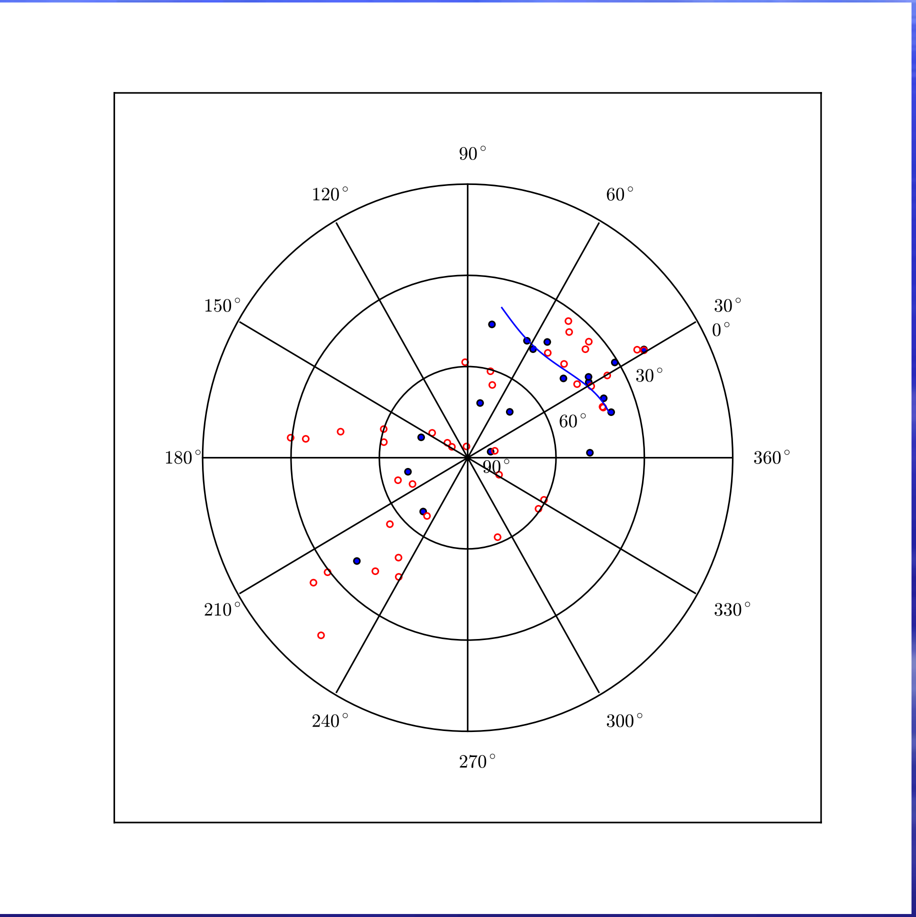
Orbital eccentricity = 0.989 ± 0.001 !!!!

Hermus & Hyllus



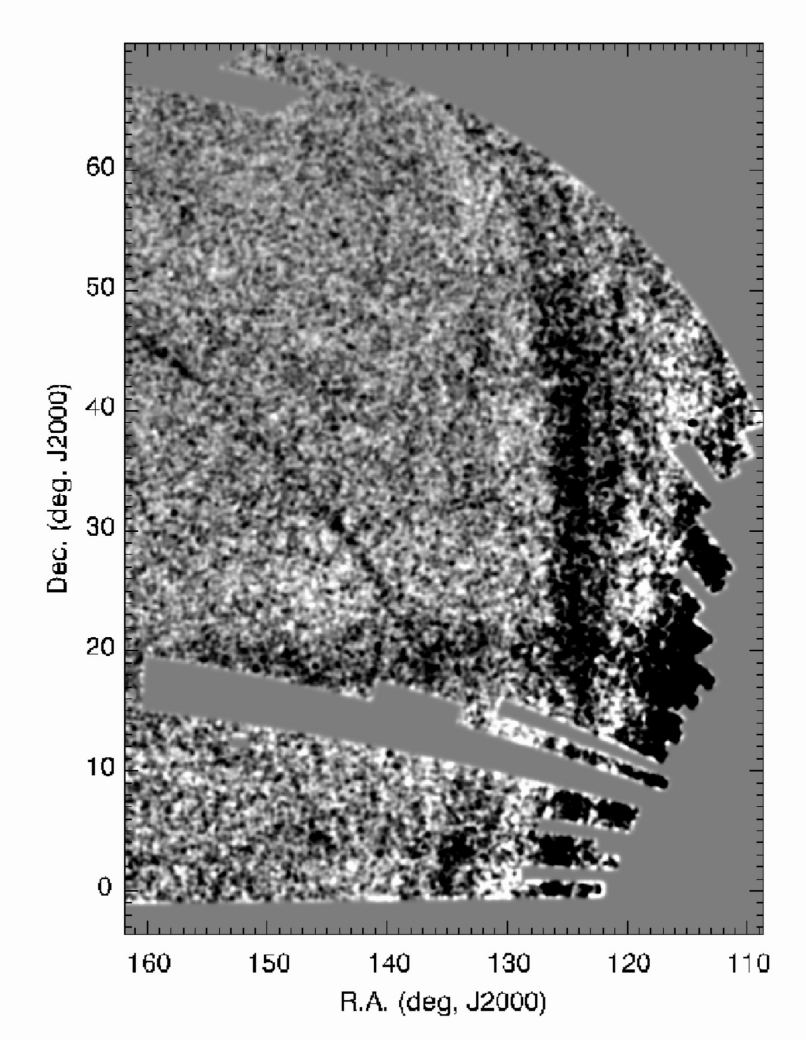
Hermus in Blue Horizontal Branch Stars

$-2.2 < [Fe/H] < -1.6$
$0 < \log g < 3.5$
$-0.23 < (g-r)_0 < -0.1$
$b > 0$
$15.5 < \text{dist} < 21$ kpc
$80 < v_{gsr} < 130$ km/s

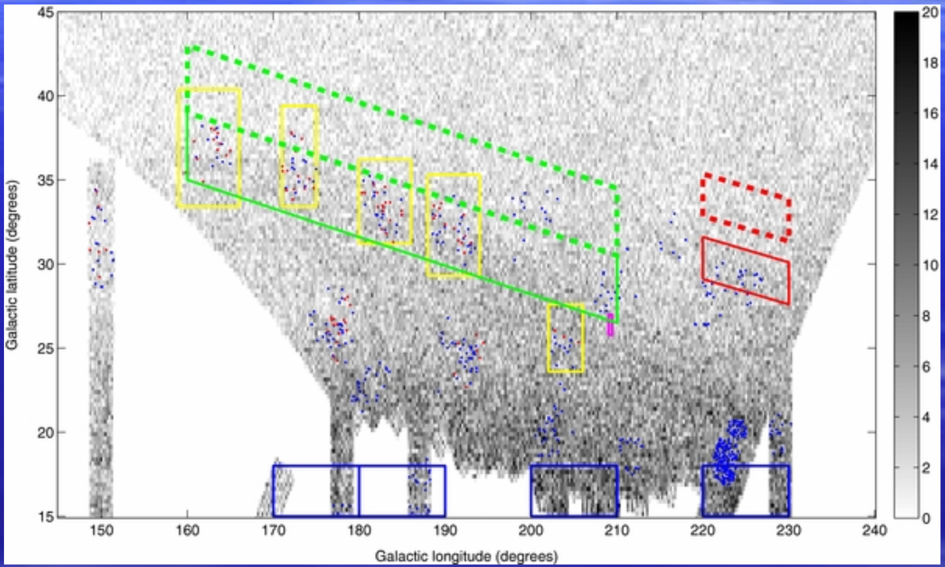


Martin, C. et al, 2015, in prep.

The Anticenter Region



Grillmair 2006



Li et al. 2012

The Anticenter region is much more complex than generally assumed.

The Galaxy's Initial Globular Cluster Population

- 13 globular cluster streams known:
  - Bound/semi-bound clusters still exist for Pal 5, NGC 5466, NGC 288.
  - Progenitors of GD-1, Acheron, Cocytos, Lethe, EBS, Pices, PAndAS MW stream, ATLAS stream, Hermus, & Hyllus apparently do not.

If:

  - globular cluster orbits are oriented isotropically,
  - we are currently sensitive only to those streams oriented between 80° and 90° to our line of sight,
  - we have sampled ~one third of the sky to 50 kpc,
  - detected streams are 90° long or less, and
  - streams are visible over the lifetime of the Galaxy,

- Then:
  - $N_{glob,0}$ = 164 + 10x9x3= 434 ± 100

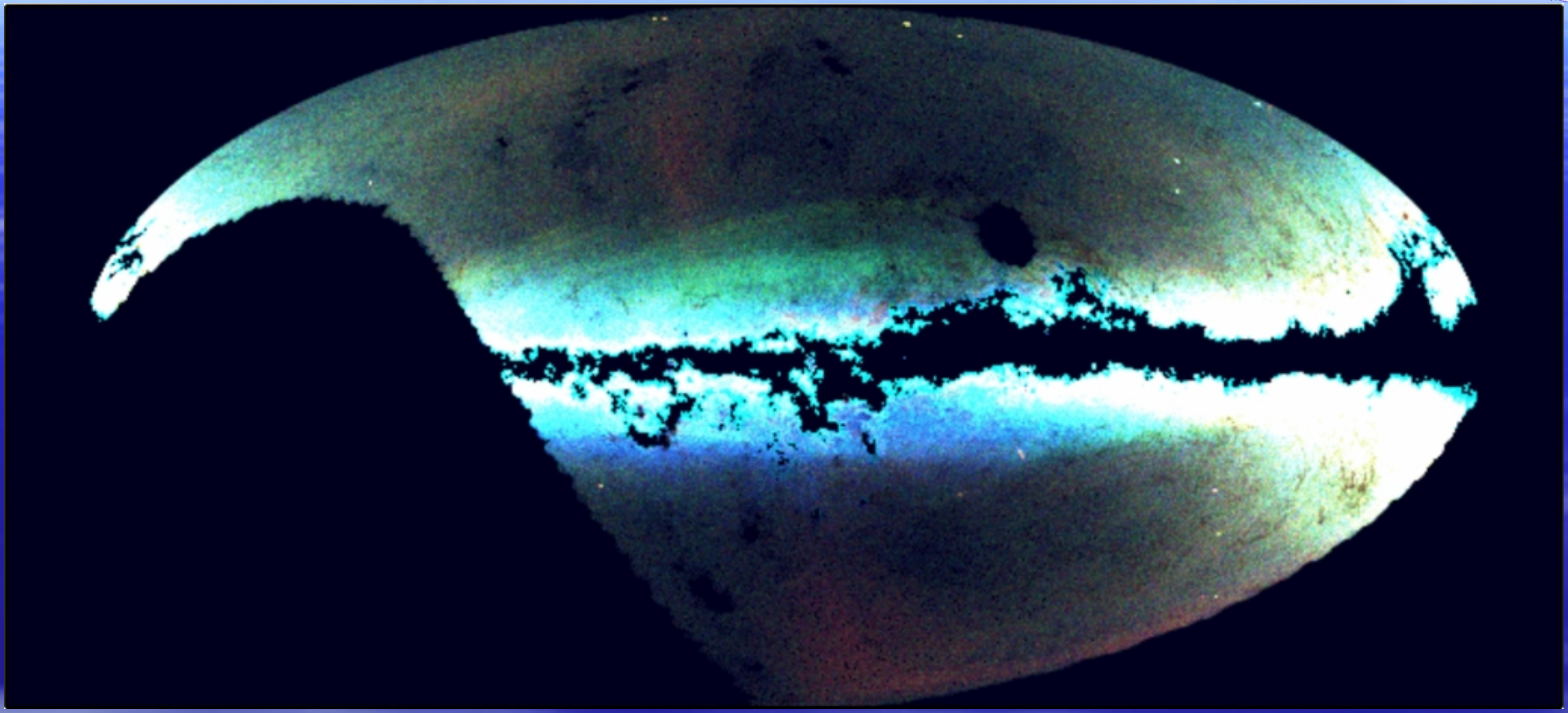
The Galaxy's Initial Globular Cluster Population cont'd

- On the other hand, despite deliberate and focused searches, only two globular clusters are known to have lengthy tidal tails.
  - (despite the fact that most globular clusters have power-law, extra-tidal extensions).
- Current crop of cold streams do not appear to be on highly eccentric orbits, so progenitors were not subject to extraordinary perigalatic shocking.
- Are the extended tidal tails of known globular clusters in some other quadrant of the sky? (e.g. near apogalacticon)
- Due to incomplete information and inaccurate Galactic potentials, have we been unable to match the cold streams to existing globular cluster progenitors?
- Were the progenitors of cold streams more loosely bound than present-day, surviving globular clusters?

Tip of the Iceberg

- Stars do not form alone.
- Groups, associations, clusters, and dwarf galaxies will all eventually be torn apart by Galactic tidal forces.
- It follows that stars not in clusters or dwarf galaxies must be in streams.
- Exceptions would include high velocity stars, pulsars, or any other objects that suffer very large ΔE, ΔL.
- ➔Expect a powerlaw stream distribution function similar to IMF of stellar clusters.

Pan-STARRS

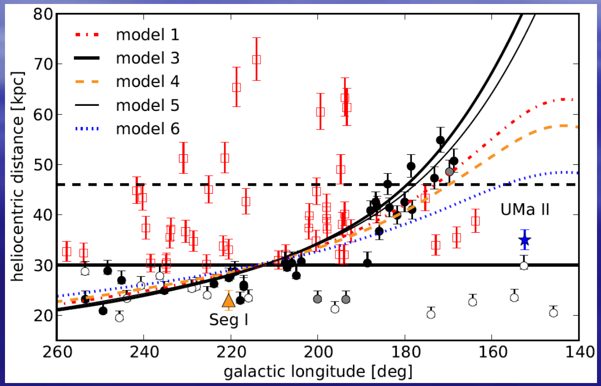


- The release of PS-1 should see a rapid and substantial increase in the number of known streams.
- PS-1 will also enable us to significantly lengthen known SDSS streams.
- Finally, as a completely independent data set, PS-1 will enable us to push much deeper in the regions of overlap between the SDSS and 3π surveys.

Distances to Streams

- Distance estimates to streams remain the Achilles Heel for measurements of the Galactic potential.
- Eyre & Binney have demonstrated technique of measuring "Galactic Parallax", which should greatly improve distance estimates when used with Gaia proper motions.
- Various transient surveys (LINEAR, PTF, Catalina) have now detected many thousands of RR Lyrae. These are now being used to get ~2% distances to the Sagittarius and Orphan streams with Spitzer (SMHASH).

Sesar et al. 2013



Conclusions

- New stream discoveries are now routine.
- We expect to find dozens of new streams in the next couple of years, and probably hundreds by the time the Gaia mission ends.
- Considerable efforts are now being devoted to more fully characterizing streams.
- We are slowly learning how to best use streams for probing both the halo and its constituents.