# Milky Way Tidal Tails:
## An Historical Perspective

Steven R. Majewski
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Satellites and Streams in Santiago, April 15, 2015

# Milky Way Tidal Tails: Development of a Research Field

Some general phases:
- not strictly serially ordered, but temporally overlapping
- conceptually delineated by salient paradigms

- Anecdotal and Circumstantial Evidence Phase
- Discovery and Verification Phase
- Mapping and Cataloging Phase
- Science Exploitation Phase
- The Future

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# Turbulent Galaxy Growth – an Old Idea

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 114 SEPTEMBER 1951 NUMBER 2

## THE EVOLUTION OF GALAXIES AND STARS

C. F. von Weizsäcker
Max Planck Institut, Göttingen
*Received May 17, 1951*

ABSTRACT

*I. Aims of the theory.*—A hydrodynamical scheme of evolution is proposed, confined to events after the time when the average density in the universe was comparable to the density inside a galaxy at our time.

*II. Hydrodynamical conditions.*—Gas in cosmic space is moving according to hydrodynamics, mostly in a turbulent and compressible manner. Dust is carried with the gas, probably by magnetic coupling. Star systems cannot be described hydrodynamically and hence do not show turbulence and supersonic compressibility.

*III. The spectral law of incompressible turbulence.*—The relative velocity of two points at a distance $l$ is proportional to $l^{1/3}$. This is deduced from the picture of a hierarchy of eddies.

*IV. Compressibility and interstellar clouds.*—A hierarchy of clouds is considered.

*V. General evolutional scheme for a gaseous body.*—A gravitationally stable, turbulent cloud is first flattened into a rotating disk, which then is dissolved into a uniformly rotating central body and a part returning into cosmic space. The time scale of these changes is somewhat larger than the diameter of the cloud divided by the turbulent velocity.

*VI. The origin of galaxies.*—They seem to have been formed by a competition between expansion and turbulence.

*VII. The evolution of galaxies and spiral structure.*—Irregular nebulae must be young, spirals intermediate, elliptical nebulae genetically old. Spiral structure is the distortion of turbulent clouds by nonuniform rotation. A bar is more stable than a disk. A two-armed spiral seems to be a distorted bar.

*VIII. The origin of the stars.*—Three groups of stars are considered instead of Baade's two populations: (*a*) stars belonging to the galactic center dynamically; (*b*) old stars belonging to the disk; (*c*) "young" stars. Stars could be formed as long as there were no stars present, because stellar radiation inhibits the contraction of clouds to form new stars.

*IX. "Young stars."*—They seem to be, more exactly, rejuvenated stars. The mechanism of the accretion of interstellar matter by a star is discussed hydrodynamically.

*X. Rotation, planetary systems, and double stars.*—Stars must be formed rotating because of the

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Secondly, one might ask whether our considerations should not be applied to clusters of galaxies rather than to single galaxies. In a theory starting from the idea of a hierarchy of clouds we should probably not be surprised to find the aggregation of matter taking place in different levels at the same time. The competition between turbulence and expansion may lead to the looser aggregation in clusters for very large clouds and to the denser form which we call "galaxies" for somewhat smaller systems. The precise meanings of the quantities $t_0$, $a$, and $b$ will not be clear without a more detailed theory of these distinctions.

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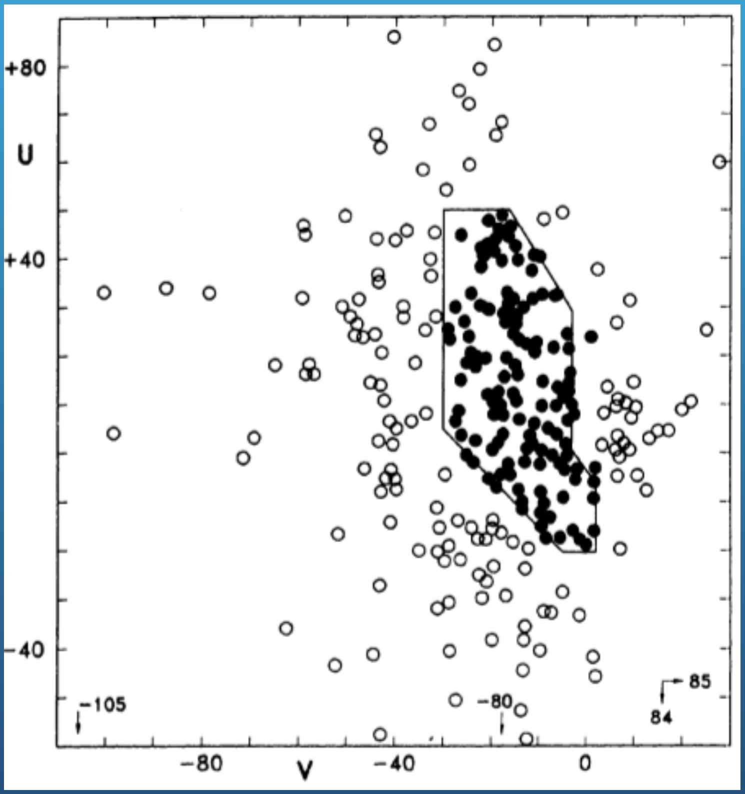
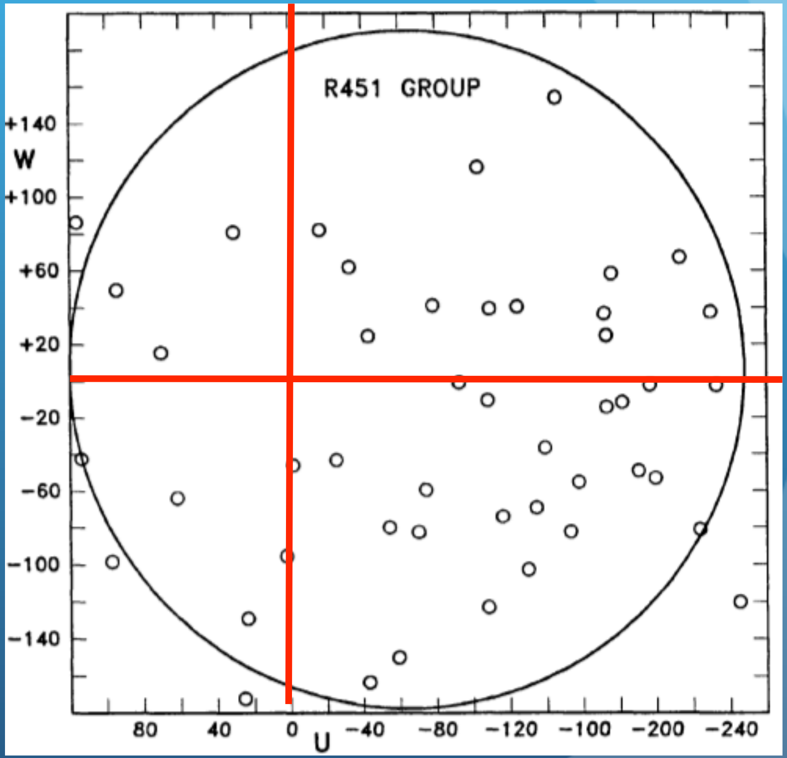
# “Anecdotal Evidence”: Moving Groups

- Over 1957-1998 Olin Eggen labored intensely – but in near isolation – on discovery and definition of “moving groups”.
- Not widely accepted….or understood.




Eggen 1995, 1996

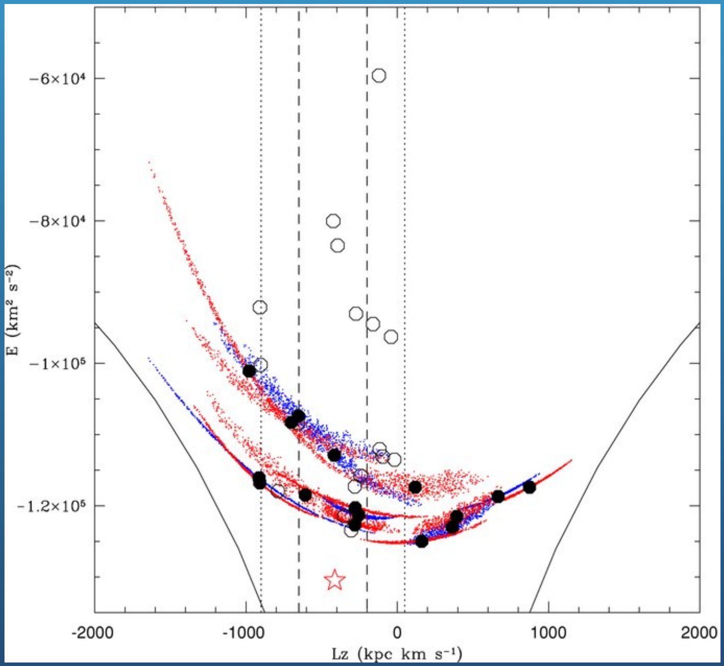
# “Anecdotal Evidence”: Moving Groups

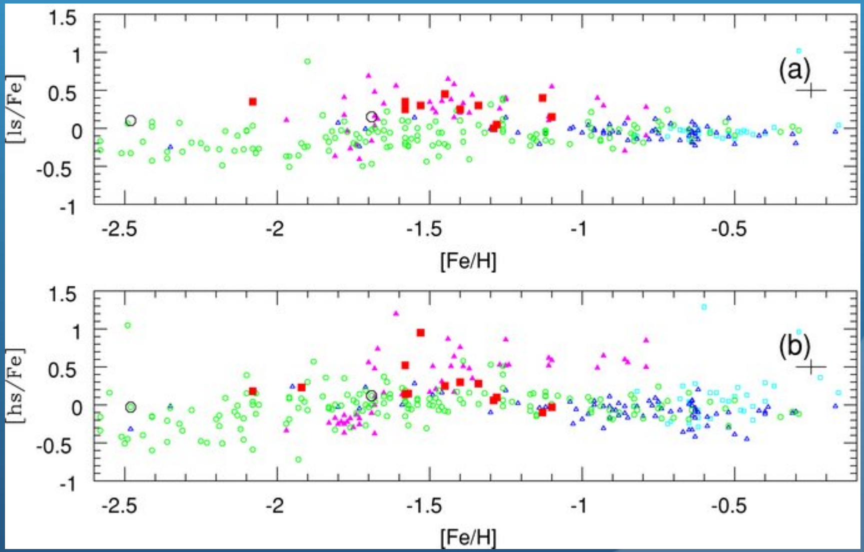
- Over 1957-1998 Olin Eggen labored intensely – but in near isolation – on discovery and definition of “moving groups”.

- But some of those with metal-poor stars may be real – e.g., Kapteyn’s star group, Arcturus Group.

- Indeed, evidence that Kapteyn’s Group contains ω Cen debris

Wylie-de Boer, Freeman & Williams (2010)




*but* cf. Navarette et al. poster.

# Other early suggestions of halo moving groups:

- Sommer-Larsen & Christensen 1987:
  5 BHB in 2deg$^2$ @ 3.6=/-0.3kpc with $\sigma_v$<20 km/s
- Doinidis & Beers 1989: excess of BHB star pairs @ < 10'
- Croswell et al. 1991: 8 NGP dwarfs, [Fe/H]=-1.7, *w*=30 km/s
- Arnold & Gilmore 1992: 4 BHB @30 kpc, *v*=70 km/s, $\sigma_v$<12 km/s
- Poveda et al. 1992: 5 $E$-$L_z$ moving groups in 206 halo stars
- Majewski 1992a,
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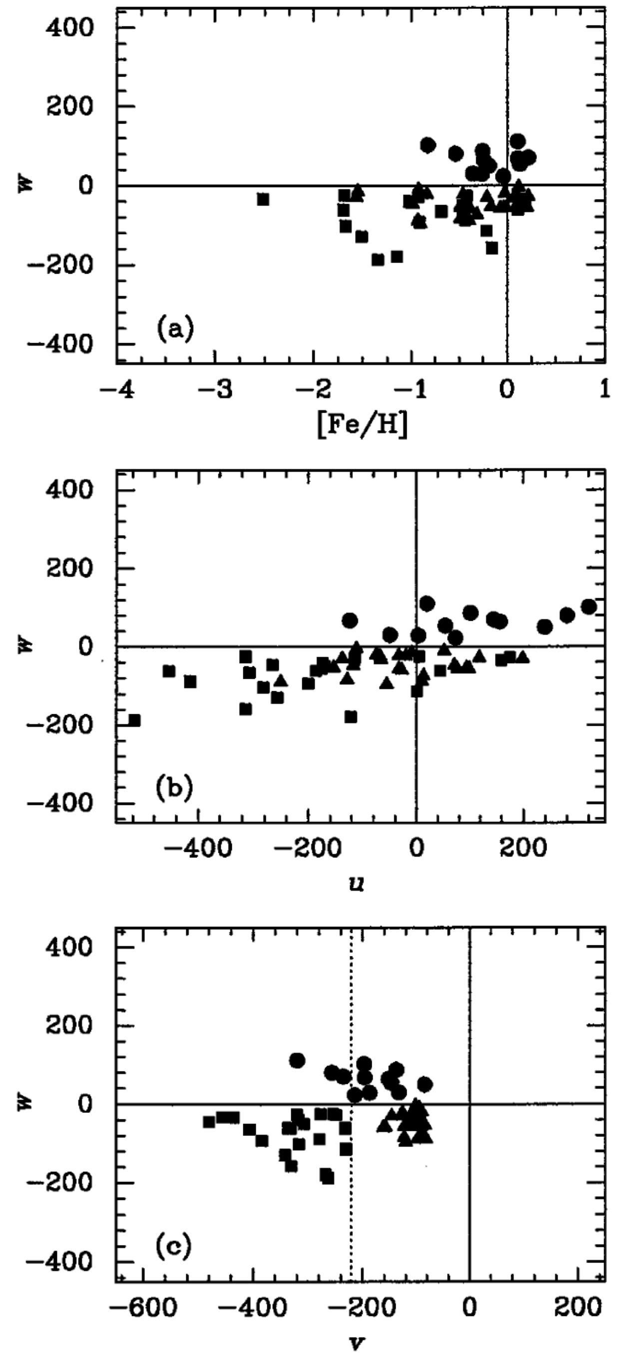

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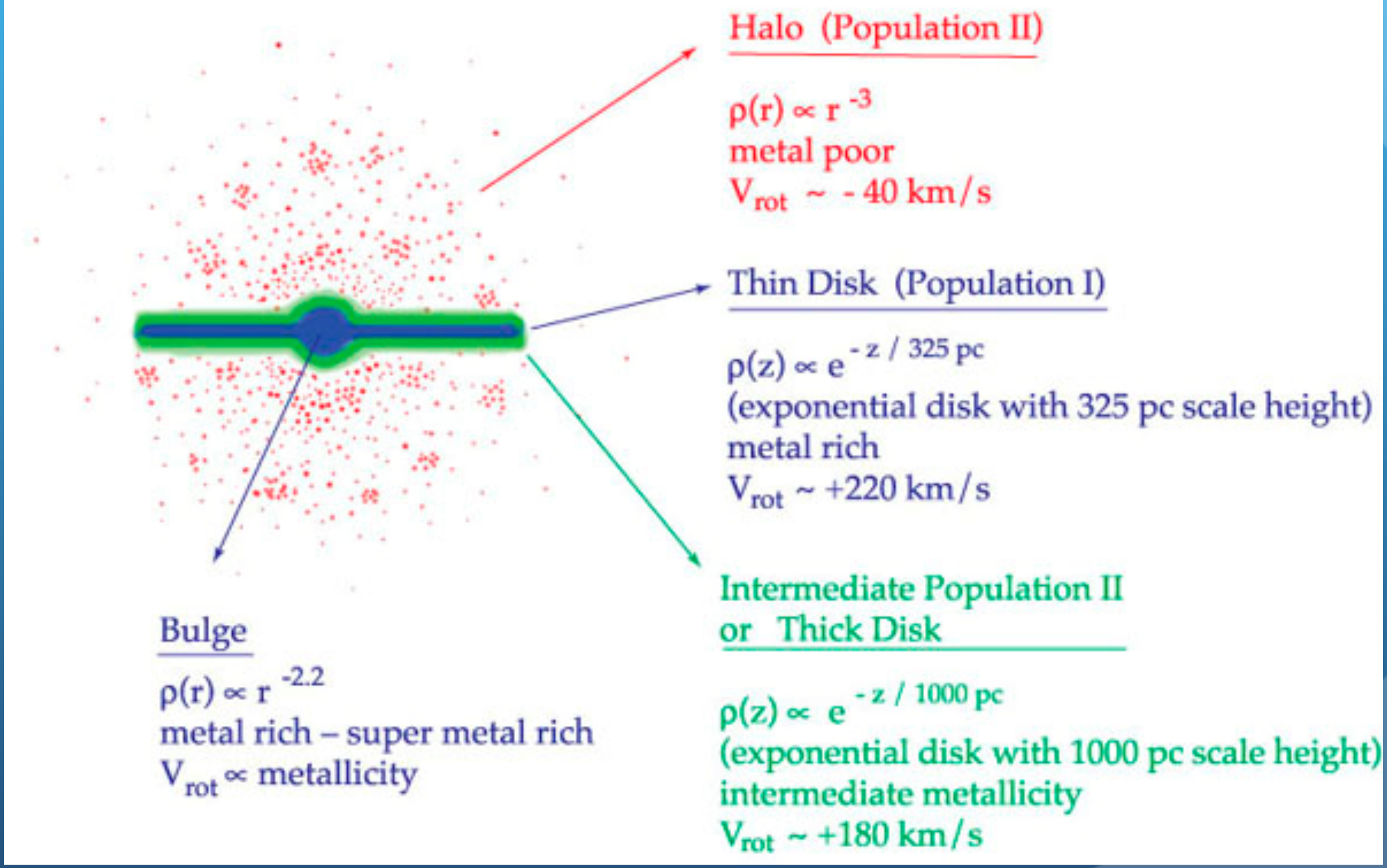
Often regarded with skepticism or indifference.

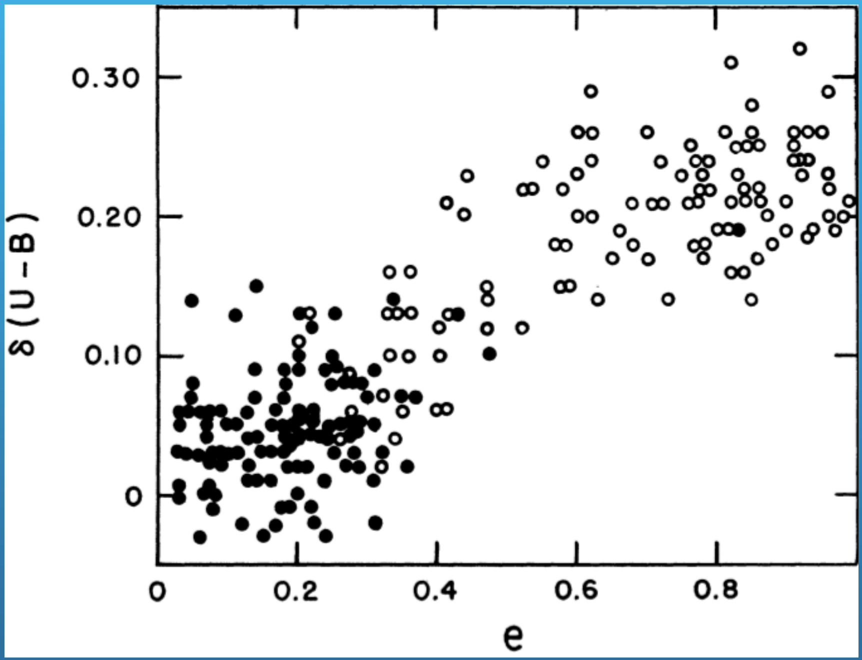
# “Circumstantial”: “ELS vs. SZ”

- Global models to explain
  “conventional picture of Milky Way stellar populations”.



# "ELS"

- Correlations of abundances to  and gradients to kinematics.
- Star formation and enrichment during rapid collapse from larger volume.



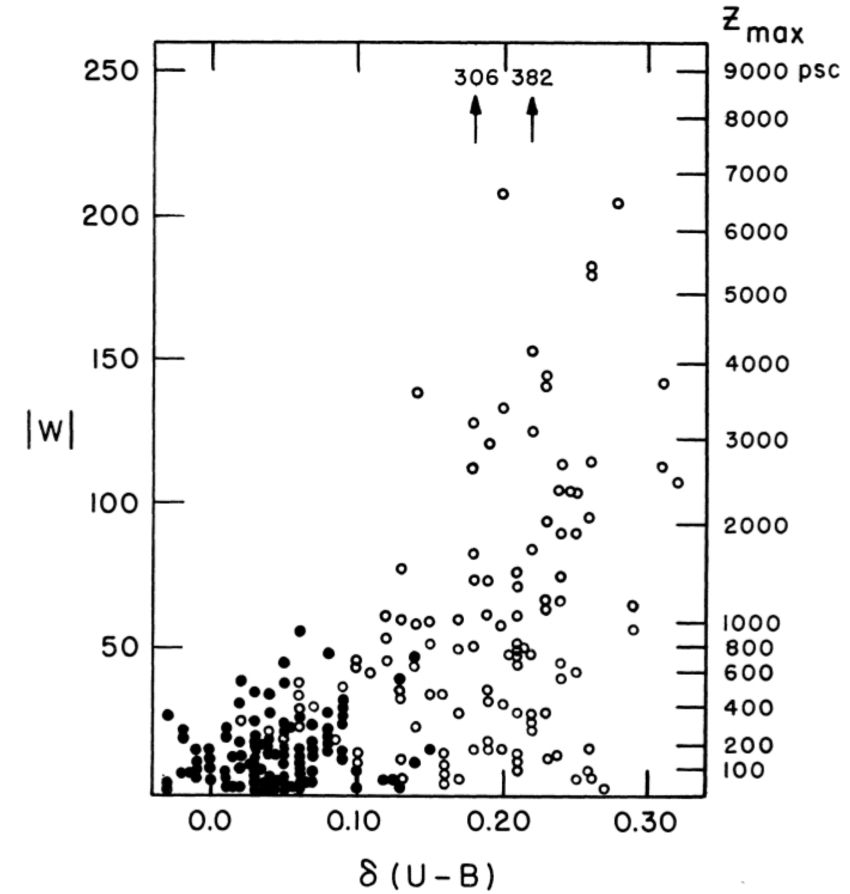




FIG 5 —The correlation between the *W*-velocity, perpendicular to the galactic plane, and the ultraviolet excess for the 221 stars in our sample. The filled and open circles represent the stars in our first and second catalogues, respectively.

Eggen, Lynden-Bell & Sandage (1962)

# "SZ"

- No metallicity gradient in outer ($R_{GC}$ > 8 kpc) cluster system.
  - *Consistent w/ELS rapid collapse, but also any other model where clusters form with kinematics uncorrelated with abundances.*

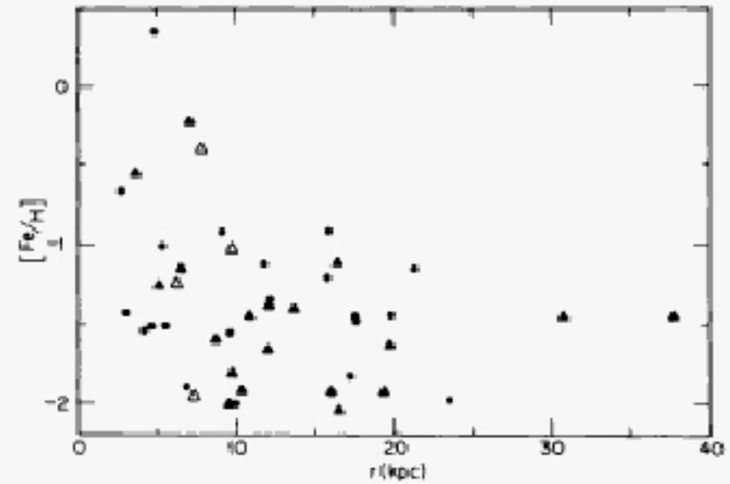



FIG. 9.—Abundances plotted against galactocentric distance for all clusters with tolerable estimates of both quantities. The solid triangles are the clusters studied in this paper. Open triangles are other clusters with first-rate abundance determinations. The circles represent clusters for which the abundance estimates were taken from Kukarkin (1974). Outside $r = 8$ kpc, the distribution over abundance does not change significantly with galactocentric distance.

Searle & Zinn 1978

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  - *The inner halo seems to have collapsed faster ("<$10^9$ years") than the outer halo (>$10^9$ years).*

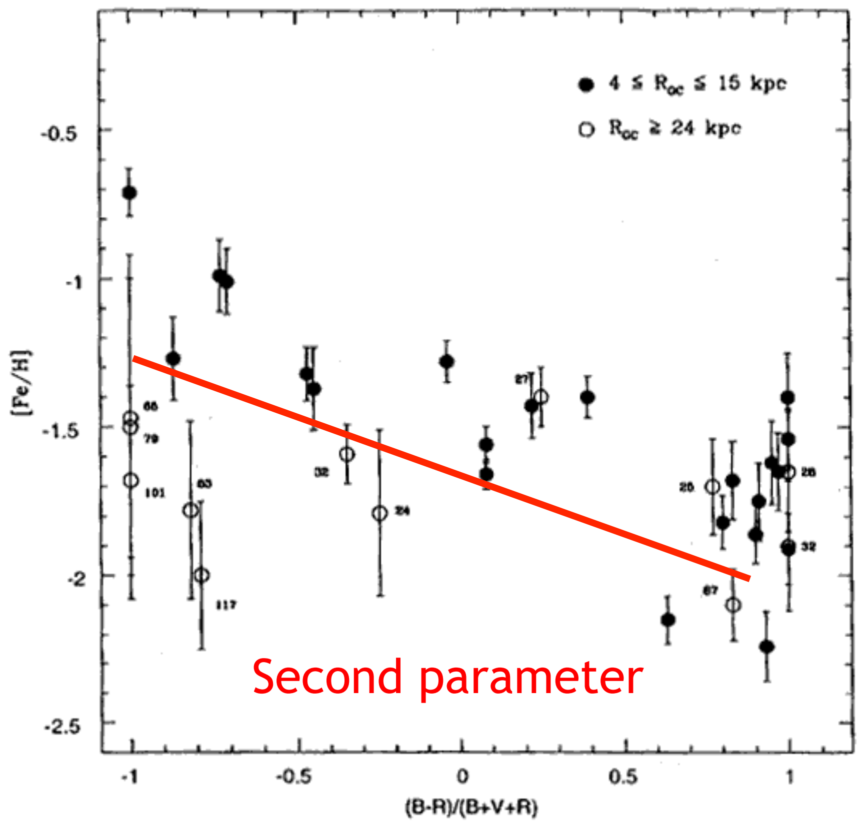


**Fig. 21.** The colors of local and distant globular clusters *vs.* metallicity. The numbers next to the *open circles* are the Galactocentric distances in kpc

Zinn (1985), Carney (2001)

Searle & Zinn 1978

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- MDF not consistent with closed-box, requires leaky box.
  - Evolution in subunits from which gas could be blown out by SNe.

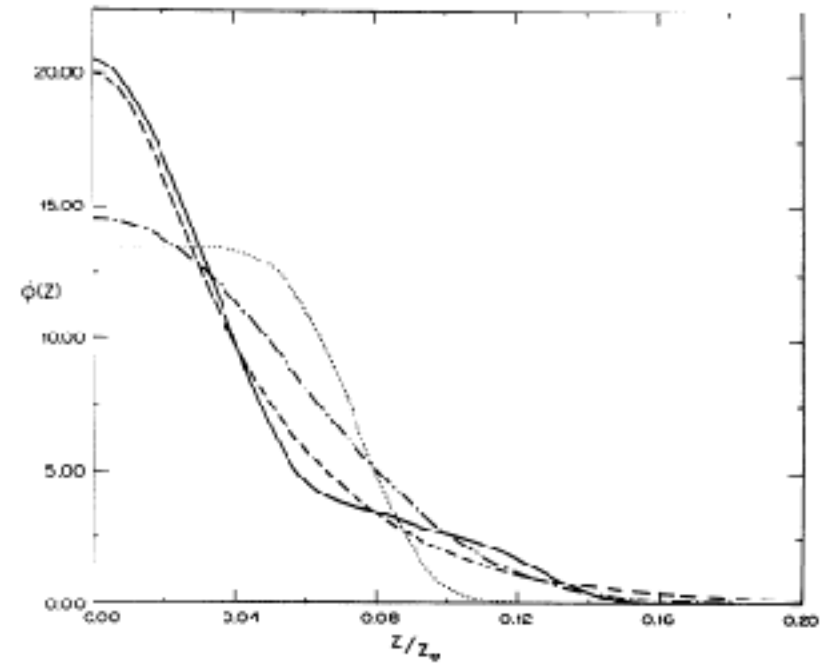


FIG. 12.—Observed and theoretical abundance distributions. The solid line is an empirical probability density function obtained from a sample of halo clusters and subdwarfs. The dash-dot curve is the prediction of the $\mu = 5$ case of Searle's (1977) stochastic model. The dotted curve is the prediction of the simple model of galactic evolution in the limit of negligible gas consumption. The dashed curve, which provides a close fit to the observed one, is the prediction of the simple model in the limit of complete gas consumption. The theoretical distributions have been subjected to the same convolution that was used in estimating the empirical one.

Searle & Zinn 1978

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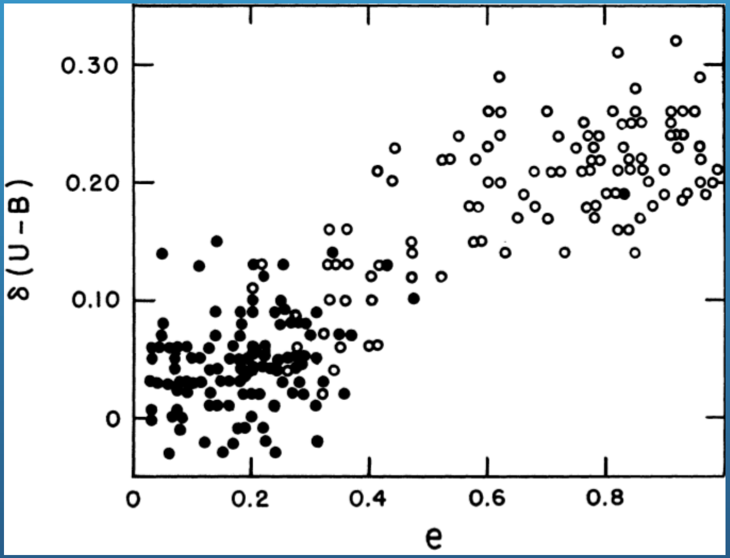
Clusters formed as parts of "transient protogalactic fragments that continued to fall into dynamical equilibrium with the Galaxy for some time after the collapse of its central regions had been completed."

Searle & Zinn 1978

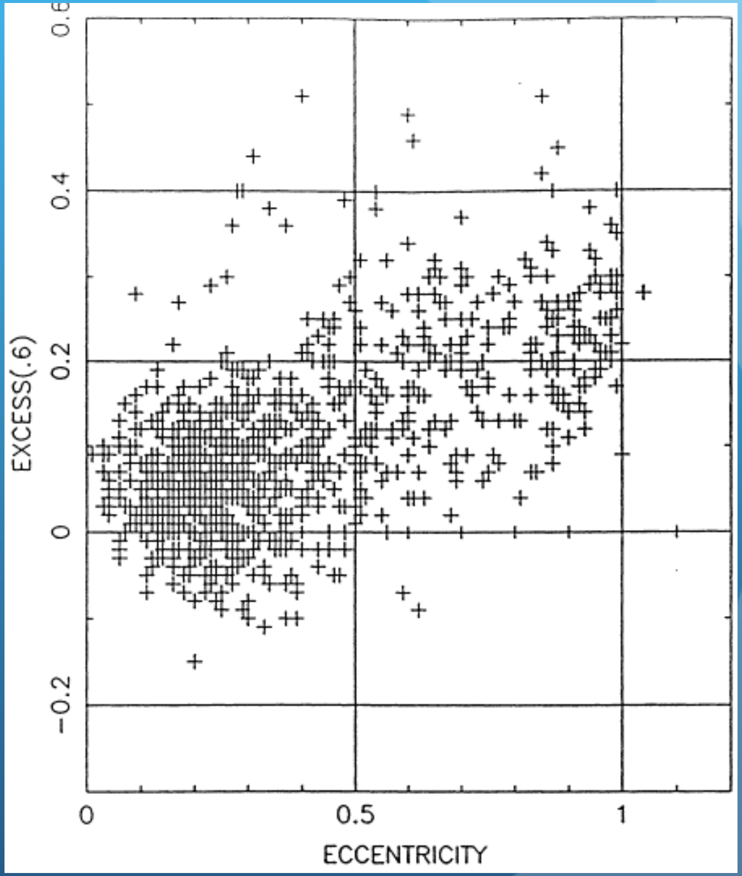
# “ELS vs. SZ”

Irony 1: For quite some time Sandage continued to use evidence of correlations and gradients as signature of collapse model even though NO metallicity gradients expected in halo (timescale for enrichment exceeds collapse timescale).

Thick disk (Yoshii 1982, Gilmore/Reid 1983) helped as intermediate, dissipational stage. (1990: ELS timescale should not have been specified, “SZ =  ELS + noise”.)




Eggen, Lynden-Bell & Sandage (1962)




Sandage & Fouts 1987

# "ELS vs. SZ"

Irony 2: Sandage coauthored one of first discoveries of a halo moving group: Groombridge 1830 group.

Still actively studied as likely halo substructure (e.g., Gozha & Shatsova 2010 using Hipparcos + radial velocities).

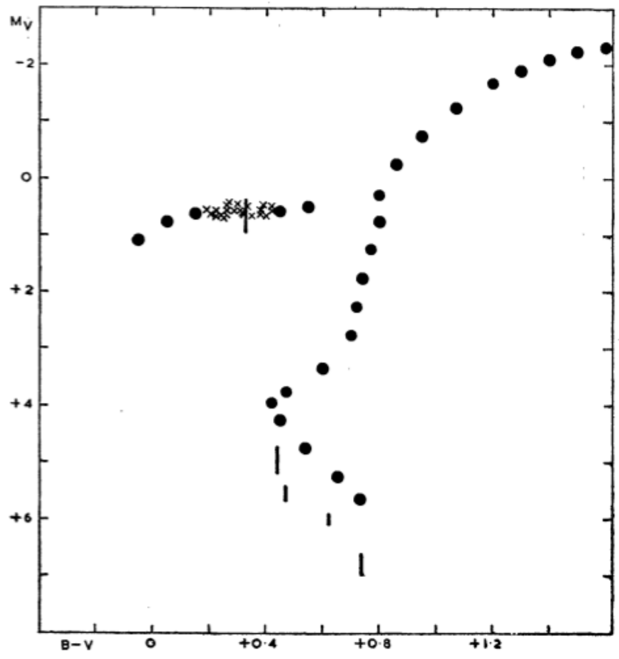



FIG. 8.—($M_V$, $B-V$)-diagram for M3. The modulus of $15^{m}\cdot 0$ was derived from a comparison of the variables with RR Lyrae. The vertical lines represent members of the Groombridge 1830 group. The mean colour and luminosities of representative variables in M3 are plotted as crosses.

Eggen & Sandage 1959

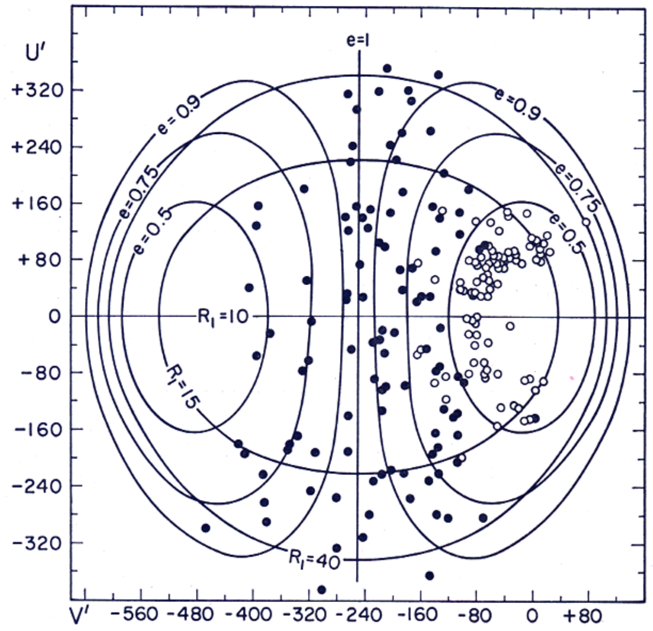



FIG. 7.—Bottlinger diagram for stars with total space velocity over 100 km/sec. The filled circles indicate objects with an ultraviolet excess greater than $+0^{m}15$ and the open circles those with smaller excess. Curves of equal eccentricity, $e$, and apogalactic distance, $R_1$, have been computed from a galactic model by Lynden-Bell.

Eggen 1965

# Anecdotal and/or Circumstantial: Early Clues of Cluster/Satellite Accretion

- 1970s , 1980s, "great streams" of tidal debris were proposed.
  - Magellanic Plane Group: Kunkel (1979), Kunkel & Demers (1976).

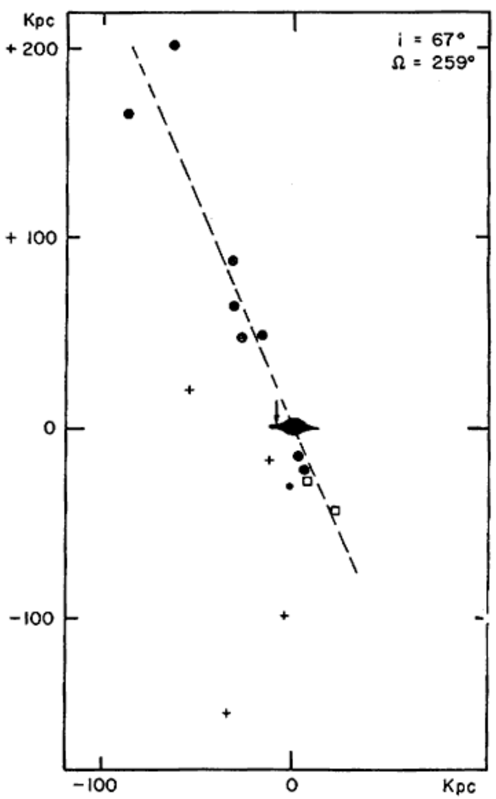



*Fig. 3. Distribution in the Galaxy of galaxies and globular clusters listed in Table 1. The broken line shows the plane (Ω = 259°, i = 67°) through the galactic centre that best describes the ten objects in the Magellanic Plane Group (MPG). See text.*

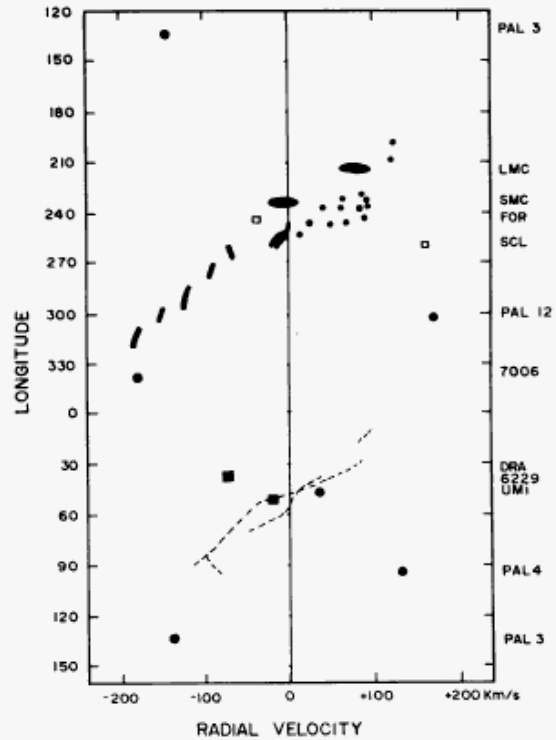



Fig. 4.—Radial velocities of MS and MPG as a function of orbital longitude. Solid ovals represent the Magellanic Clouds. Solid line segments and small dots represent the MS. Large filled circles and squares are MPG clusters and spheroidal galaxies. Open squares are nonmember spheroidal galaxies. The broken line near longitude 180° represents an H I filament in the northern sky apparently not related with the current perigalactic pass of the LMC/SMC (see text).

# Anecdotal and/or Circumstantial: Early Clues of Cluster/Satellite Accretion

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  - The Fornax-Leo-Sculptor Stream by Lynden-Bell (1982).

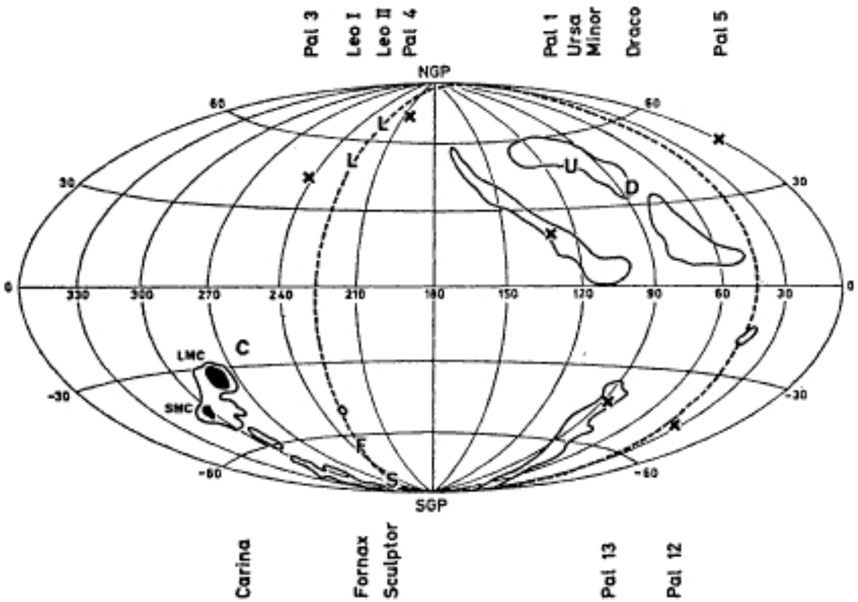



FIG. 1

The Fornax–Leo–Sculptor great circle plotted on a map of high-velocity clouds with the dwarf spheroidal galaxies and diffuse globular clusters. The plot is in Galactic coördinates as observed from the Sun. Correction to the Galactocentric coördinates are minor and are detailed in Table I.

- See also Majewski 1994, Fusi Pecci et al. 1995, Lynden-Bell & Lynden-Bell 1995, Palma et al. 2002

# Continued interest/improved evidence for great planes…

- E.g., Metz et al.2007,2008,2009, Keller et al. 2012, Pawlowski & Kroupa 2014

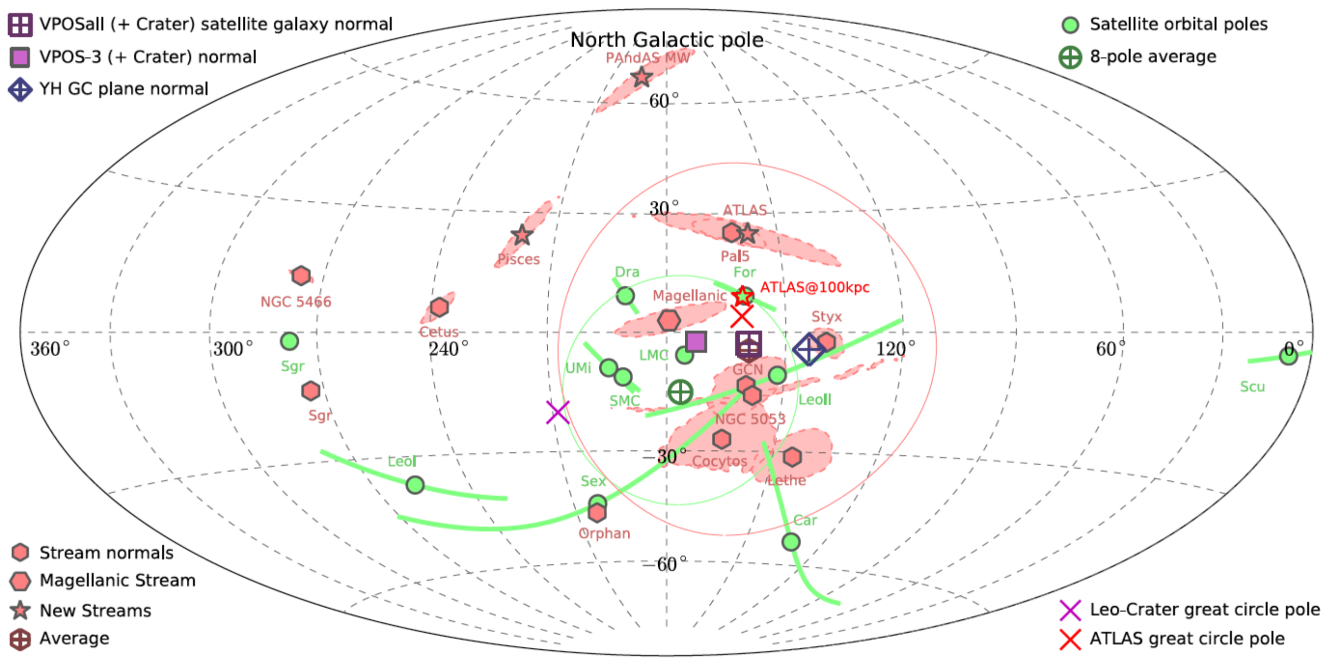



**Figure 3.** All-sky plot showing the orientation of the planes fitted to the positions of the satellite galaxies (squares, magenta in the online journal) and young halo globular clusters (YH GC, diamond, blue in the online journal), the orientation of individual satellite orbital planes (circles, green in the online journal; with uncertainty lines) and of individual streams (hexagons, red in the online journal; with $1\sigma$ uncertainty contours). Note that it is not positions that are shown, but the directions of plane-normal vectors, orbital poles, and stream normals, i.e., vectors perpendicular to these features. Axial directions (all normal vectors, but not the orbital poles which indicate the vectorial angular momentum directions) have only been plotted in the range $120° < l < 300°$, i.e., the mirrored directions were omitted for clarity. See the text for a more detailed description and discussion.

(A color version of this figure is available in the online journal.)

# Anecdotal and/or Circumstantial: Early Clues of Cluster/Satellite Accretion

- Rodgers & Paltoglou (1984): retrograde kinematics among globular clusters with -1.3 > [Fe/H] > -1.7, range with 2nd P effect, which suggests they are slightly younger than typical halo globular clusters.

  Suggest proto-halo consisted of a few "parental galaxies", some with "distinct" (i.e. retrograde) orbits, that may have seeded the halo with families of clusters like the retrograde one they identified.

TABLE 1

ROTATIONAL PROPERTIES OF GLOBULAR CLUSTERS

| Range of [Fe/H] | $V_{rot}$ (km $s^{-1}$) | $\varepsilon$ (km $s^{-1}$) | $\sigma_{LOS}$ (km $s^{-1}$) | No. of Clusters |
|---|---|---|---|---|
| −0.1 to −0.5 .... | 168 | 26 | 80 | 12 |
| −0.5 to −0.9 .... | 51 | 57 | 63 | 9 |
| −0.9 to −1.3 .... | 42 | 37 | 83 | 14 |
| −1.3 to −1.7 .... | −72 | 41 | 116 | 30 |
| −1.7 to −2.1 .... | 95 | 41 | 119 | 27 |
| −2.1 to −2.5 .... | 97 | 83 | 135 | 10 |

- van den Bergh (1993) -- with updated data – confirmed 8/10 clusters with retrograde orbits fall within the above narrow metallicity range.

# Anecdotal & Circumstantial:
# Early Clues of Cluster/Satellite Accretion

- Zinn (1993,1994) commits to "young halo" and "old halo" clusters

- Young
  - retrograde
  - extended dist'n
  - Larger $\sigma_v$

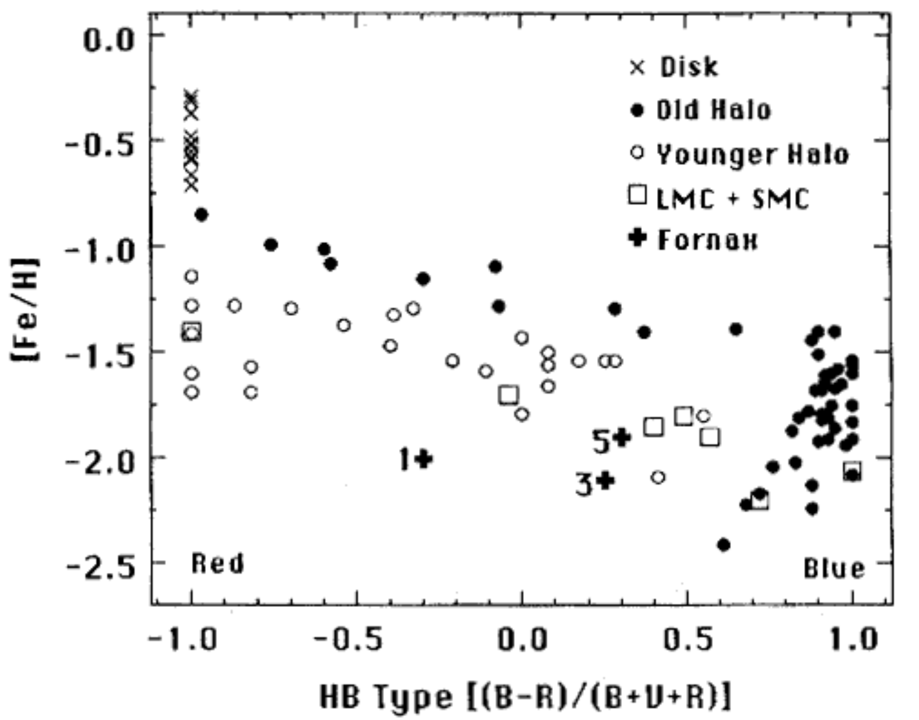
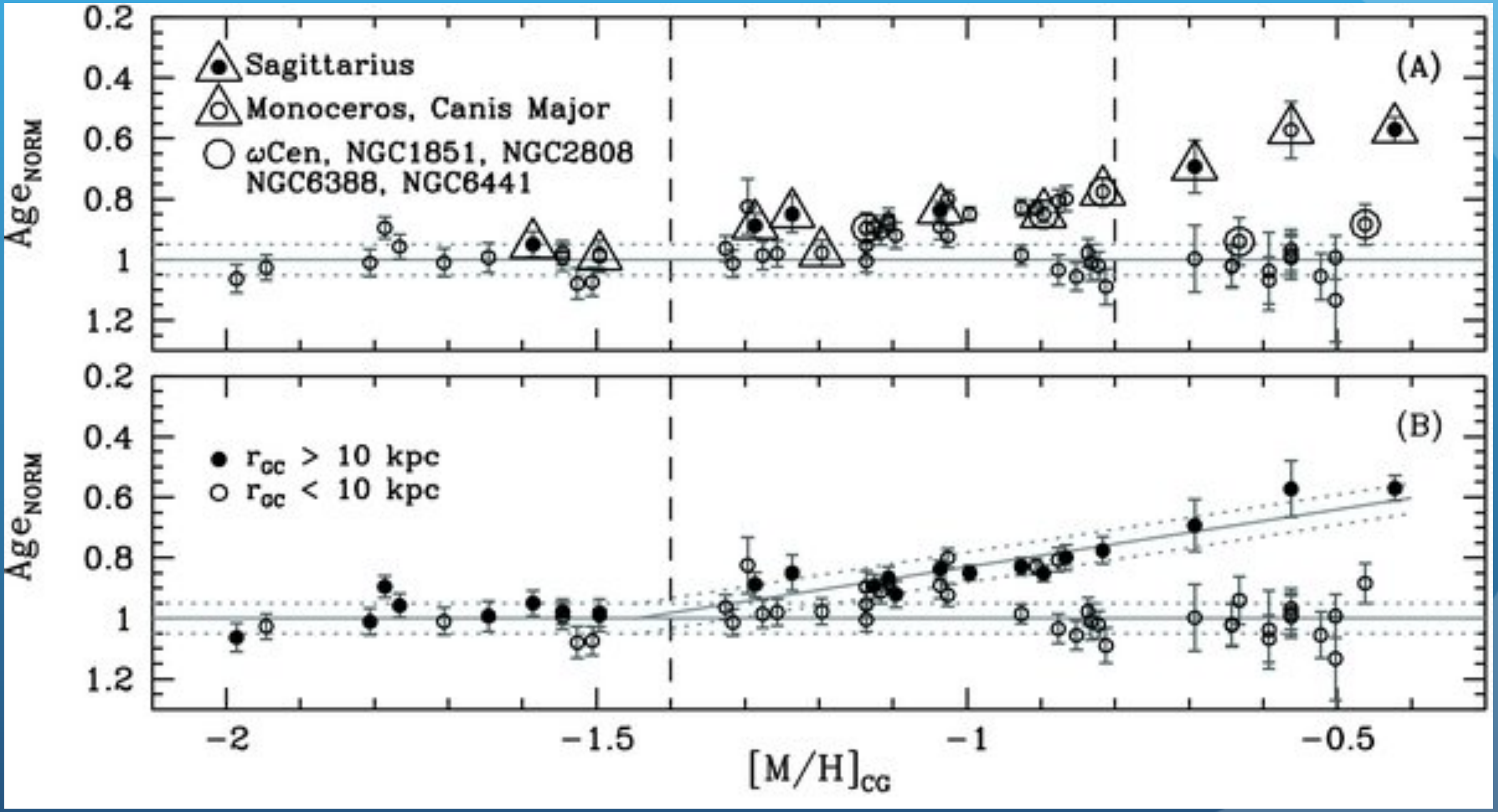



TABLE I Kinematics

| Sample | N | $v_{rot}$ (km s$^{-1}$) | $\sigma_{los}$ (km s$^{-1}$) | $v_{rot}/\sigma_{los}$ |
|---|---|---|---|---|
| All $R_{gc}$ < 40 kpc | 65 | 44±25 | 113±12 | 0.39±0.23 |
| Younger Halo | 19 | -64±74 | 149±24 | -0.43±0.50 |
| Old Halo | 46 | 70±22 | 89±9 | 0.79±0.26 |
| Old Halo $R_{gc}$ < 6 kpc | 22 | 66±26 | 81±12 | 0.81±0.34 |
| Old Halo 6 - 40 kpc | 24 | 75±37 | 99±14 | 0.76±0.39 |

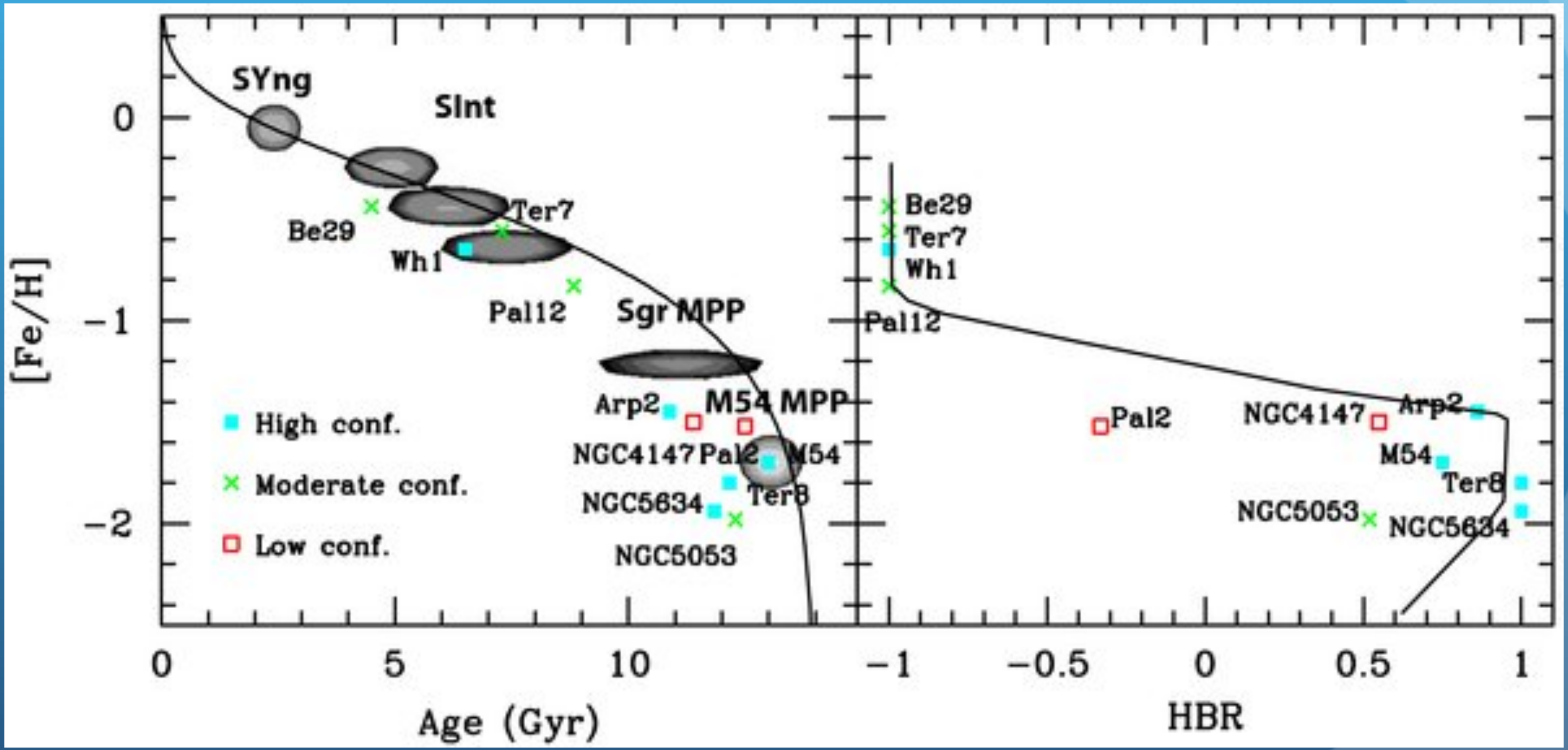
# Age Spread in the Halo Globulars

- Borne out by subsequent work. E.g., HST GC Treasury Survey Marin-Franch et al. 2009 (but cf. Leaman's talk).



# Accretion and the Second Parameter Effect

- Sgr clusters break the paradigm (e.g., Law & Majewski 2010b).
- See also NGC 2419 (Newberg et al. 2003, Belokurov 2014).



# More than Circumstantial?: Magellanic Stream

- Discovery of Stream (Mathewson et al. 1974).
- Ram pressure vs. tidal disruption
  (but no obvious leading arm).

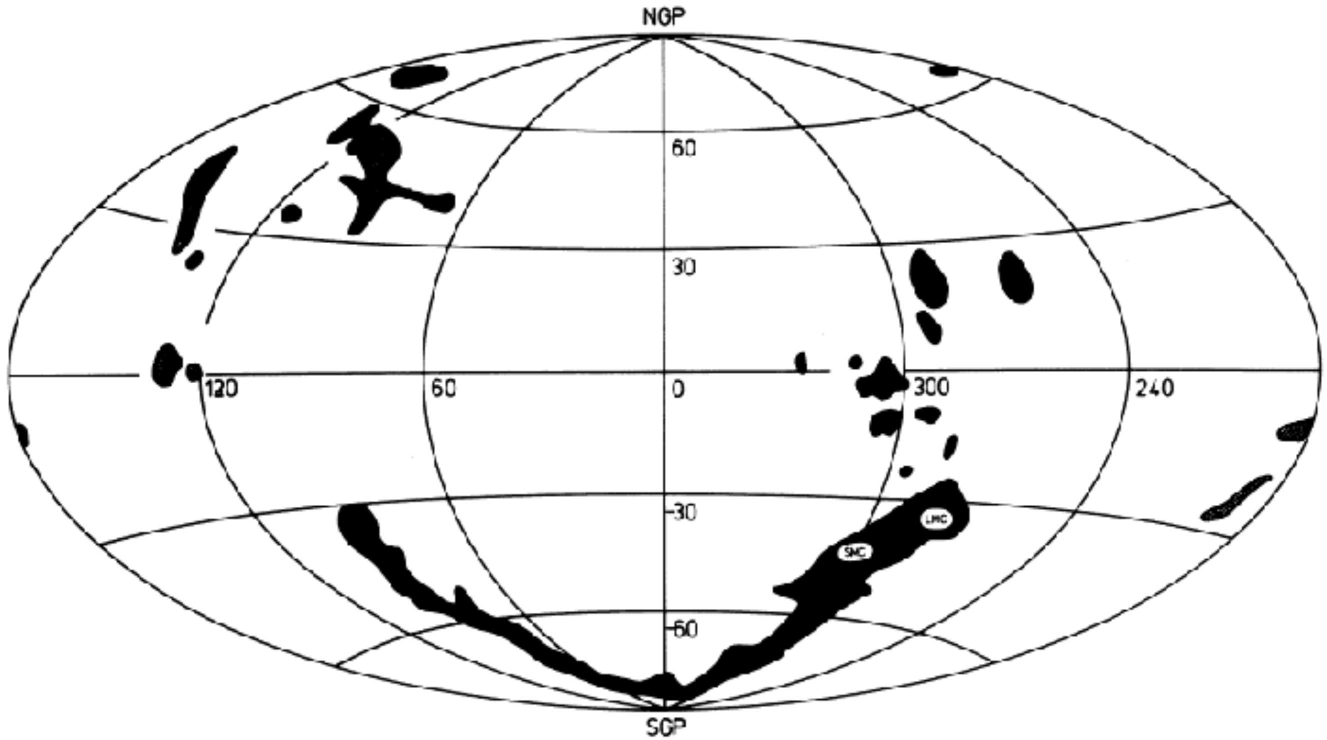



FIG. 3.—The Magellanic Stream is inked in on this Aitoff projection in galactic coordinates. The crosshatched areas are the high-velocity H I clouds discovered much earlier by northern hemisphere observers (cf. Hulsbosch 1972).

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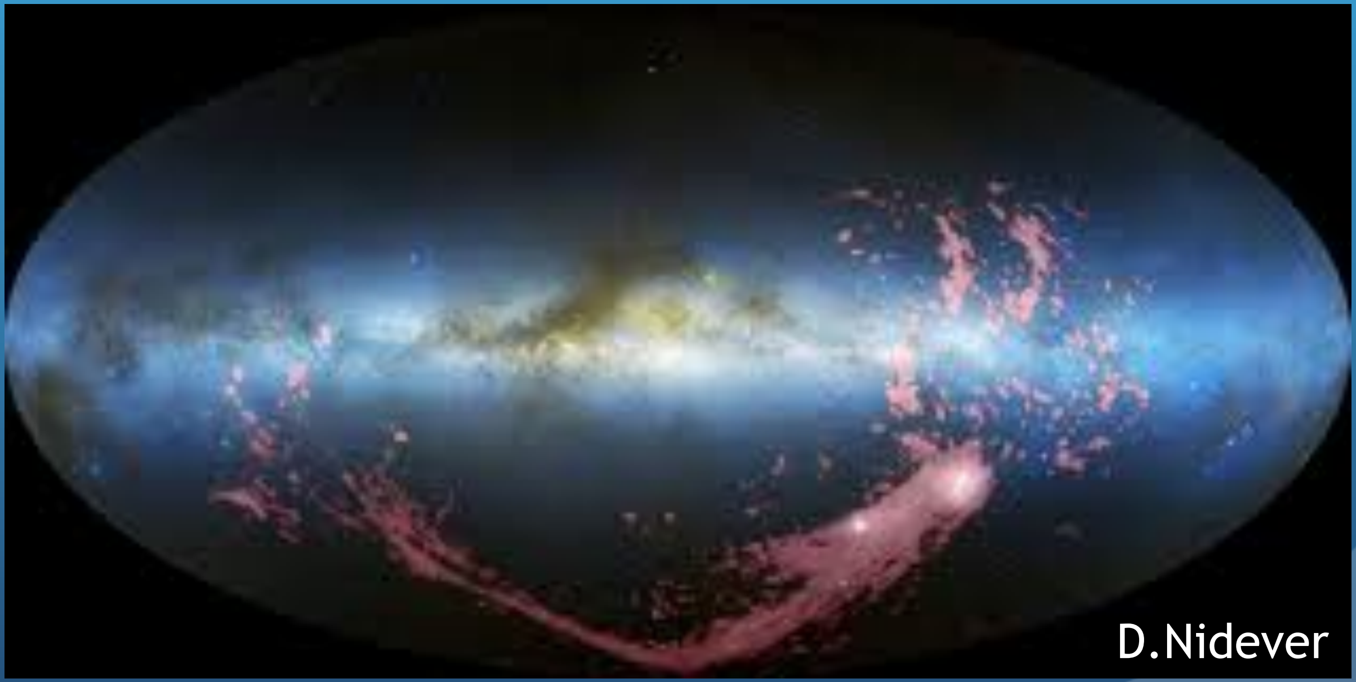

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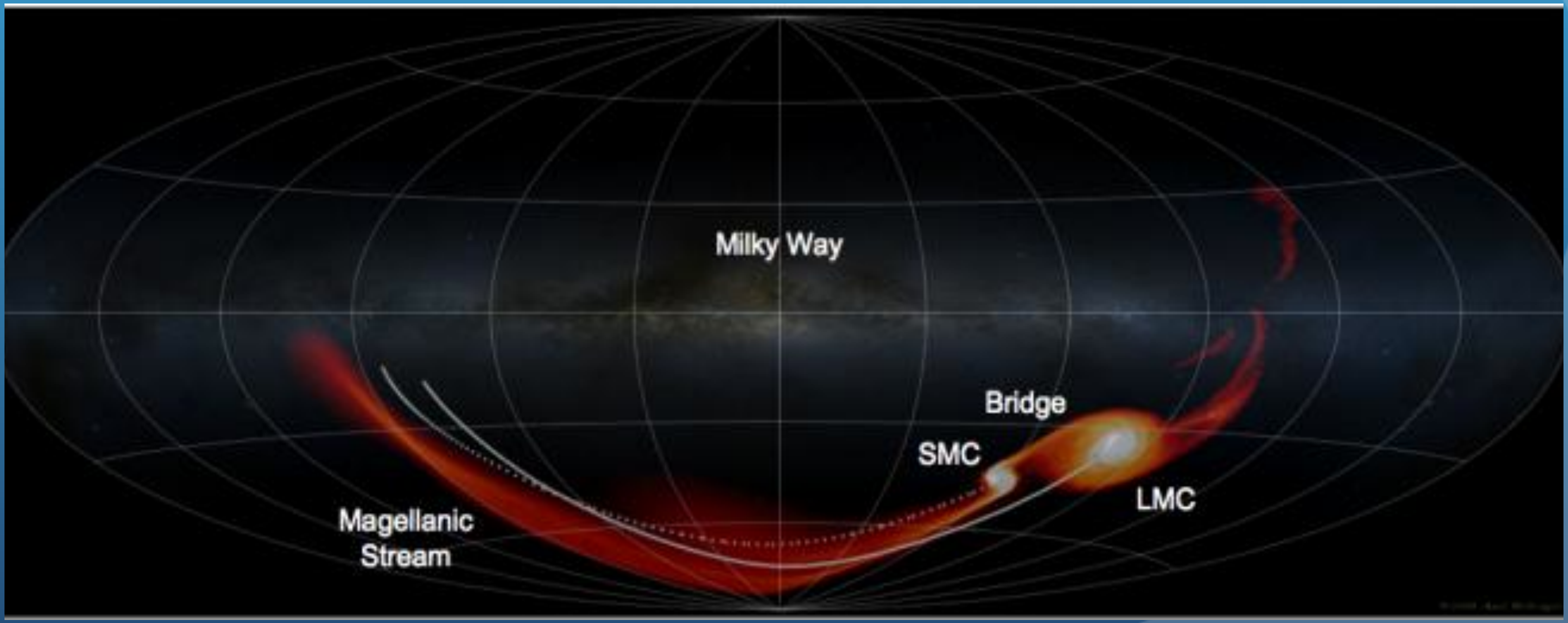

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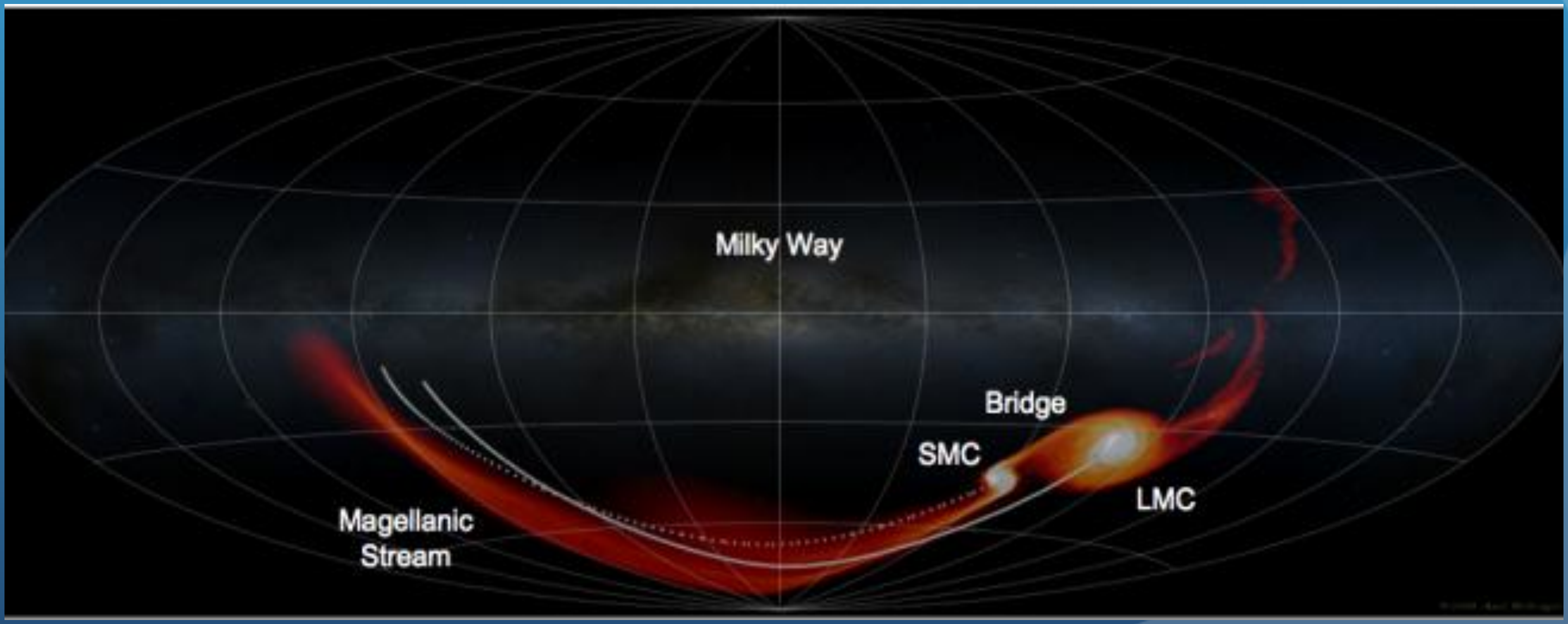
- Still no confirmed stars in the stream.



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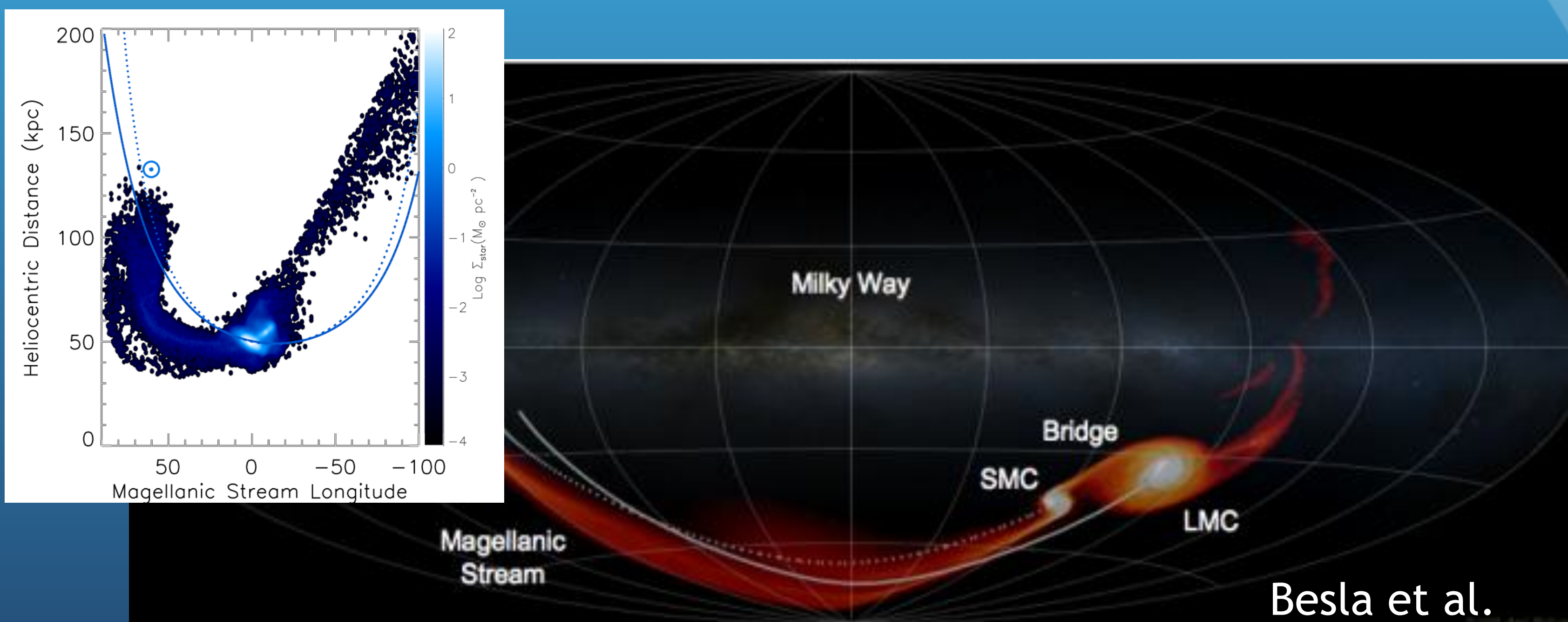
- Stellar material in LA: Martin et al. (2015) Hydra II



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- Mapping and Cataloging Phase
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- The Future

# Discovery of the Sagittarius dSph

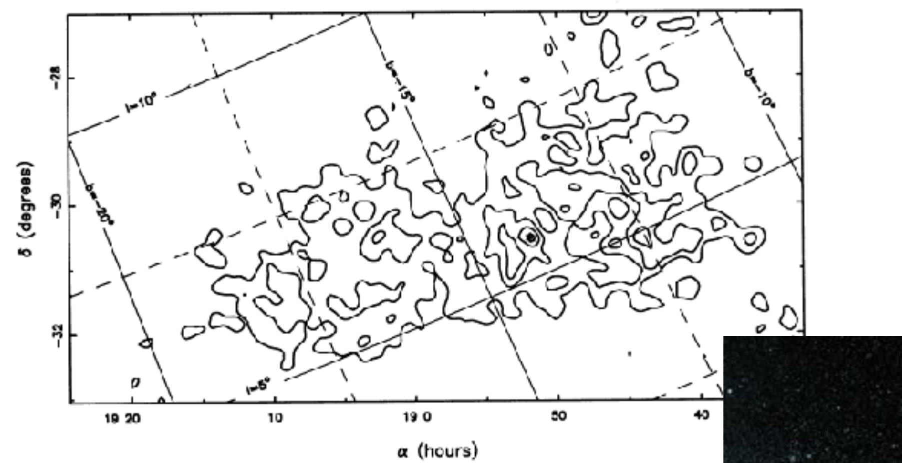



**Figure 11.** Isopleth maps for UKST fields 458 and 459, constructed from the excess of images present at the horiz
The lowest contour is 1/8 image arcmin$^{-2}$. Contours increment by 1/2 image arcmin$^{-2}$. The position of the globular cl
by a 'star' symbol.

- Ibata et al. (1994, 1995)

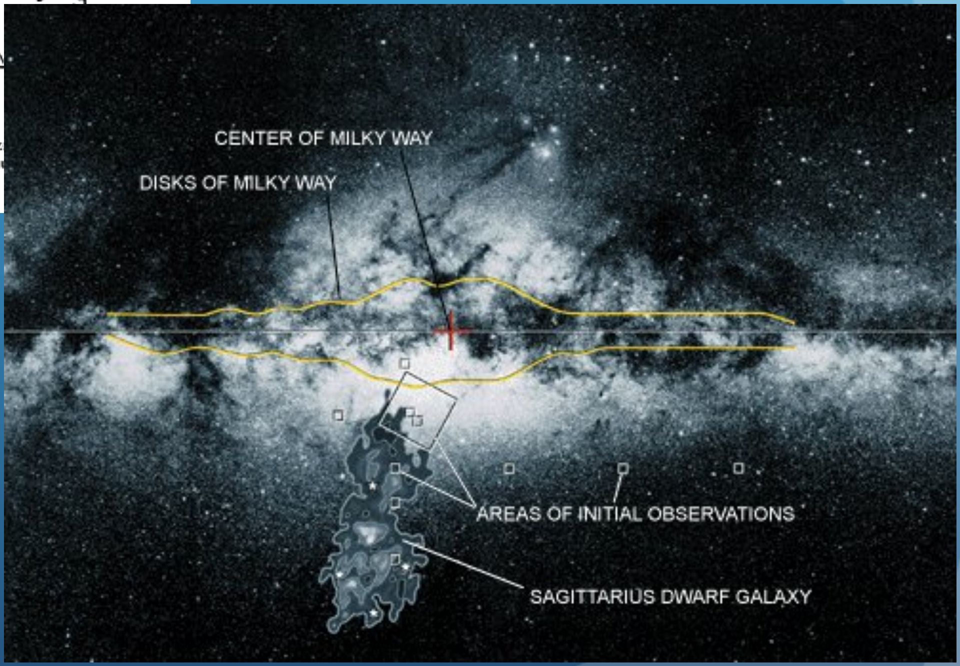
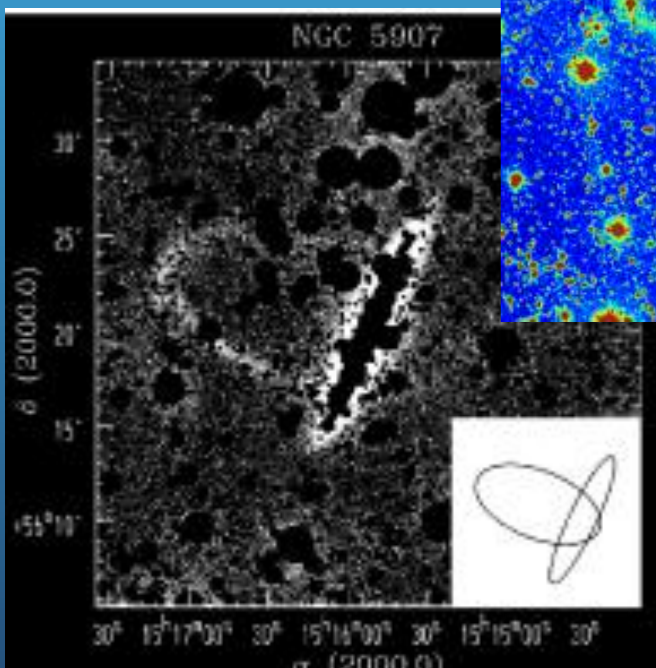
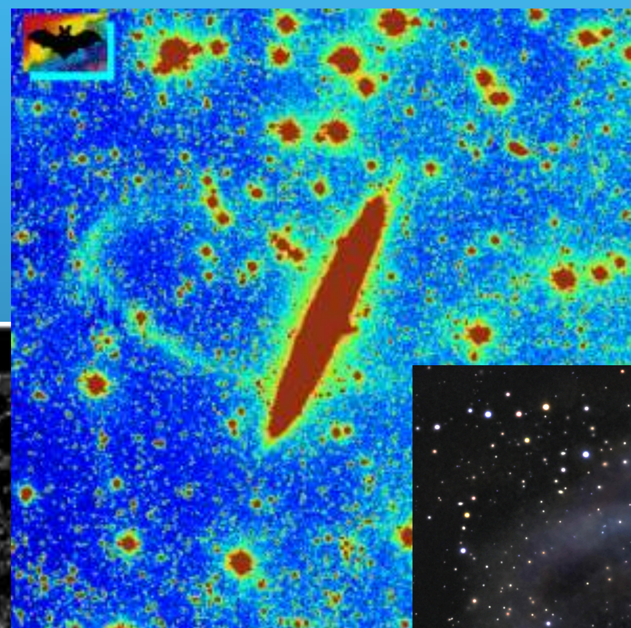


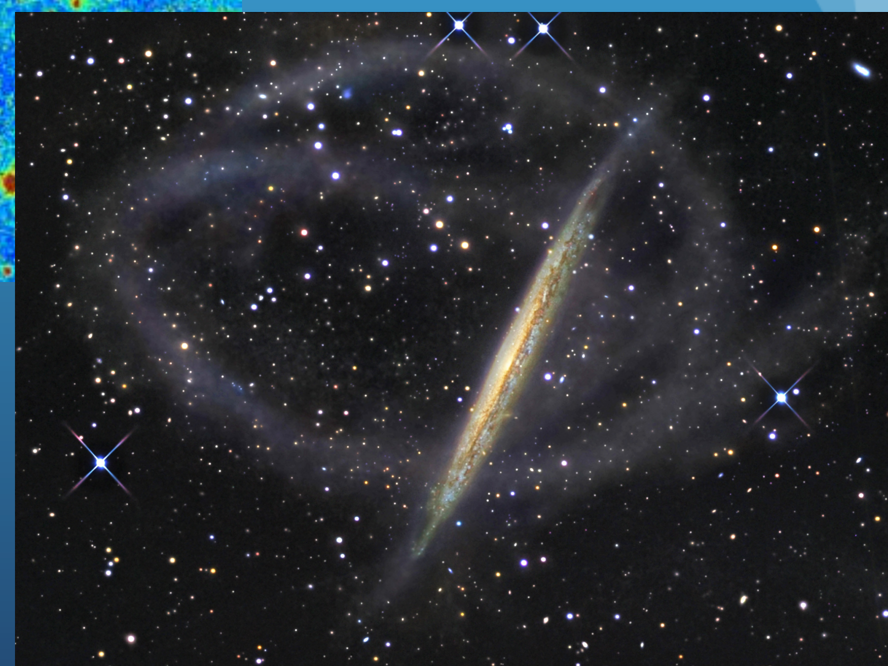

**Figure by R. Wyse (JHU).**

# Extragalactic Satellite Tidal Stream

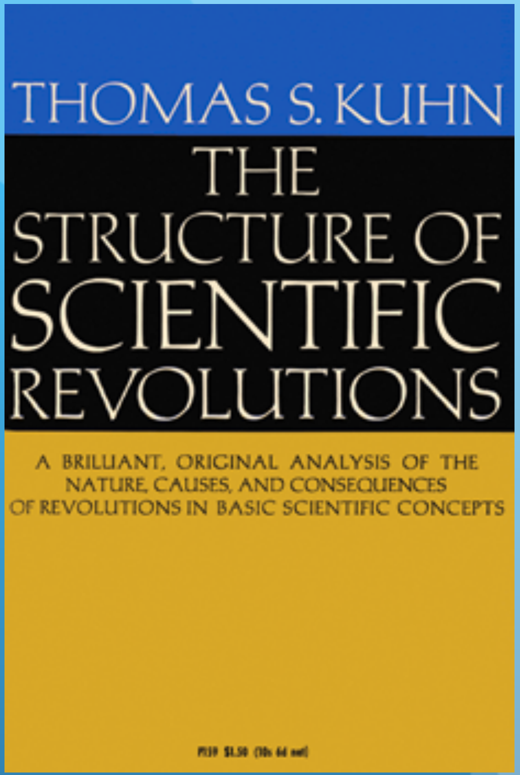
- NGC 5907 (Shang et al. 1998, Zheng et al. 1999, Martinez-Delgado et al. 2008)





# “Paradigm Shift”




Not strictly Kuhn-like, nor as dramatic, but some similarities (thus my shameless appropriation of some of the useful terminology):

- Not motivated by a breakdown of old paradigm and invocation of new theory,
  - but, rather, by striking verification leading to rapid changes in the “sociology, enthusiasm and scientific promise” of the field.

- Patterns of thinking, working, discussing changed.
  - E.g., skepticism about ‘’moving groups’’ quickly disappeared.
  - Replaced by frequent reporting and searching for coherent groups and structures.

- Almost immediate and full acceptance.

- “Once a paradigm shift has taken place, the textbooks are rewritten.”

# "Paradigm Shift"

- Field was already ripe to accept the notion of accretion based on results of comological N-body modeling (w/CDM).
- But Sgr discovery *reinvigorated* Milky Way studies.
- Gained renewed respecta-bility by lending to *direct* tests of cosmology.
- "Galactic Structure" → "Near Field Cosmology" (Freeman & Bland-Hawthorn 2002)

*Simulations of X-ray clusters* 723

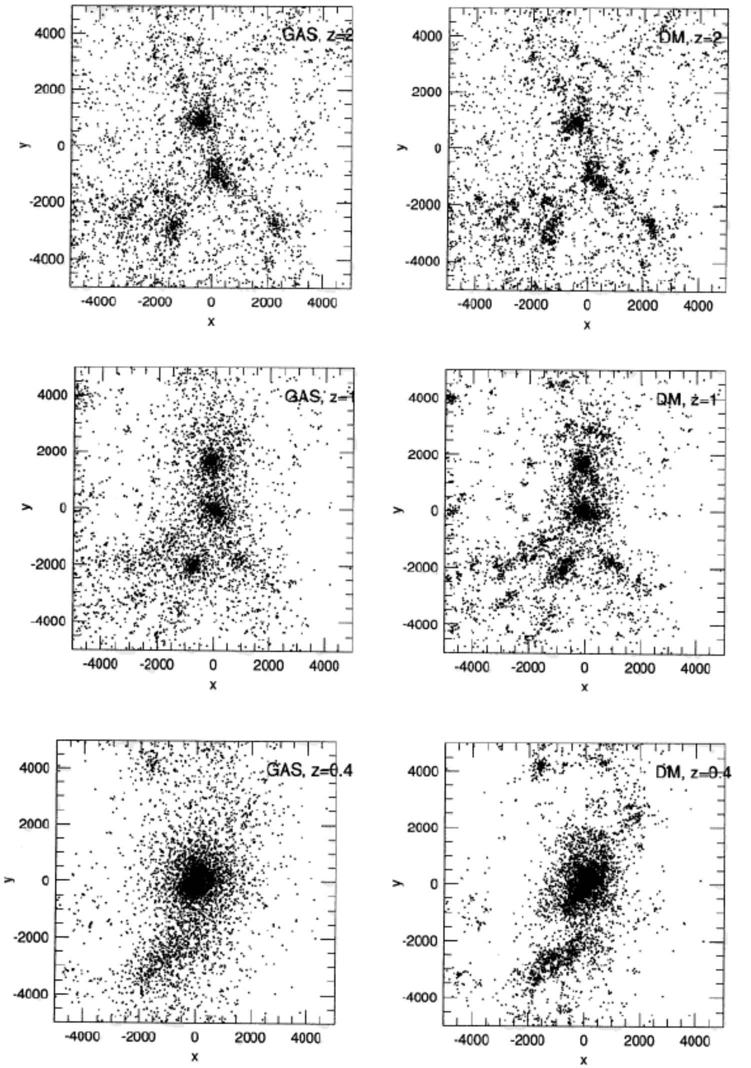
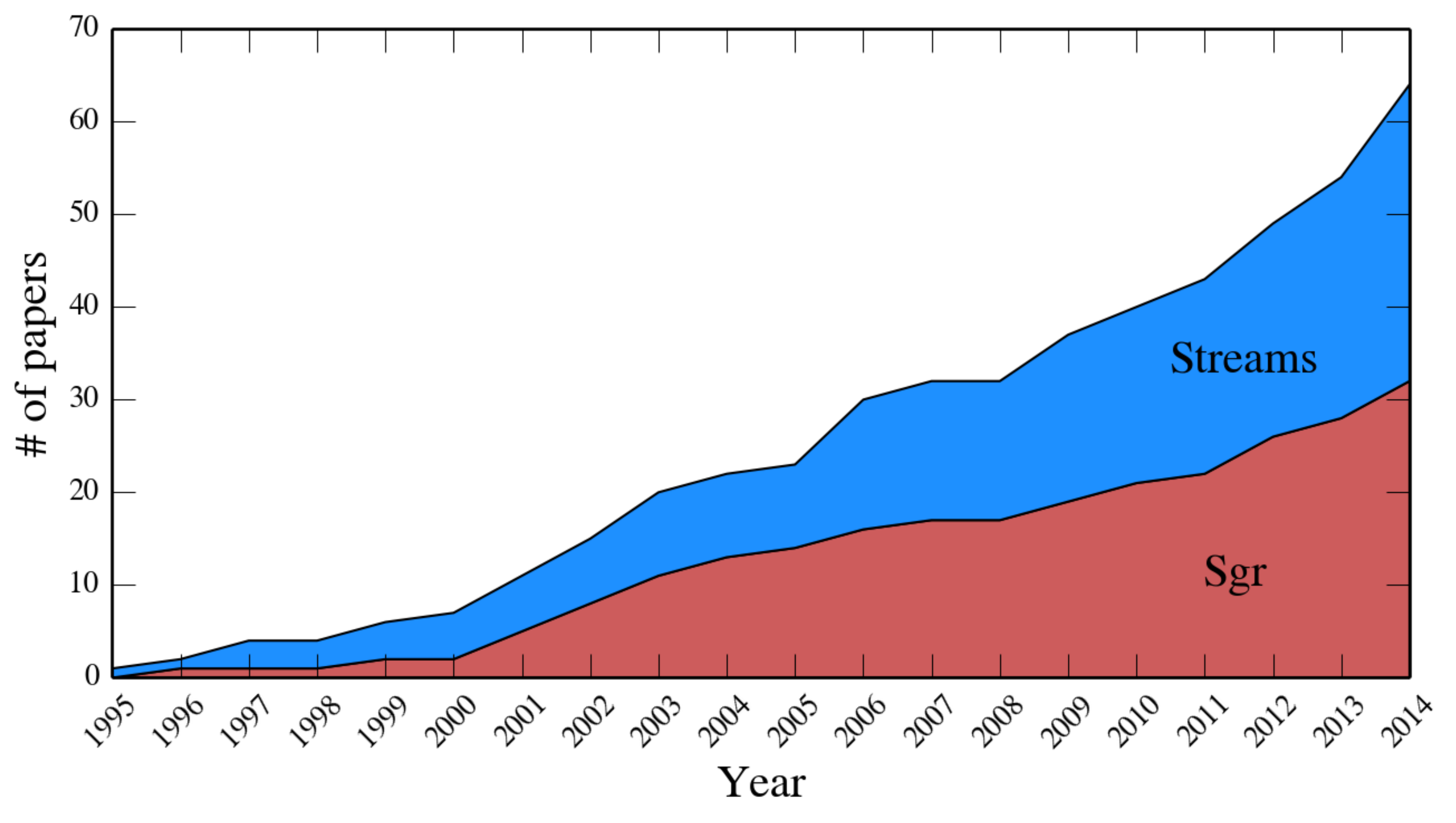



**Figure 1.** Evolution of the distribution of gas (left) and dark matter (right) for cluster CL1. This is the most massive cluster in our ensemble of simulations. The epochs shown correspond to redshifts 2, 1, 0.4 and 0. Units are in *physical* kpc for $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$. Note the resemblance between the distributions of gas and dark matter at all times.

Navarro, Frenk & White 1995

# “Paradigm Shift”

- Commonly accepted birthdate of new field.




from Kupper introductory presentation on Monday

# Milky Way Tidal Tails: Development of a Research Field

Some general phases:
- not strictly serially ordered, but temporally overlapping
- conceptually delineated by salient paradigms

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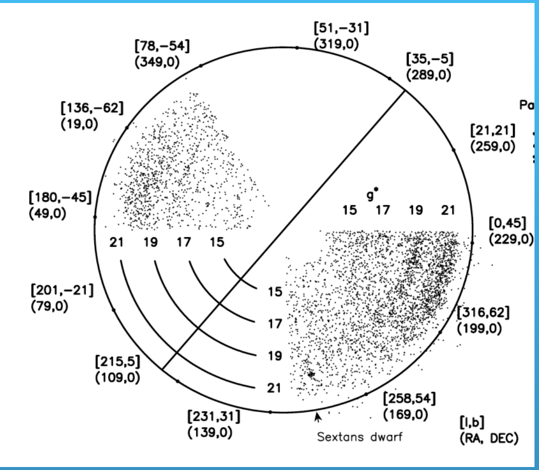
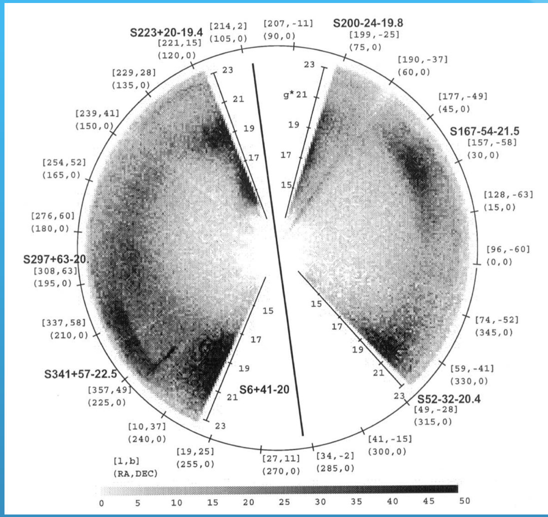
- The Future

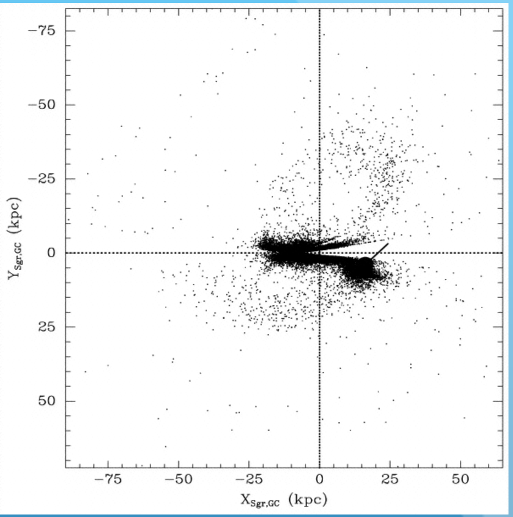
# Mapping the Sgr Stream: 2MASS + SDSS



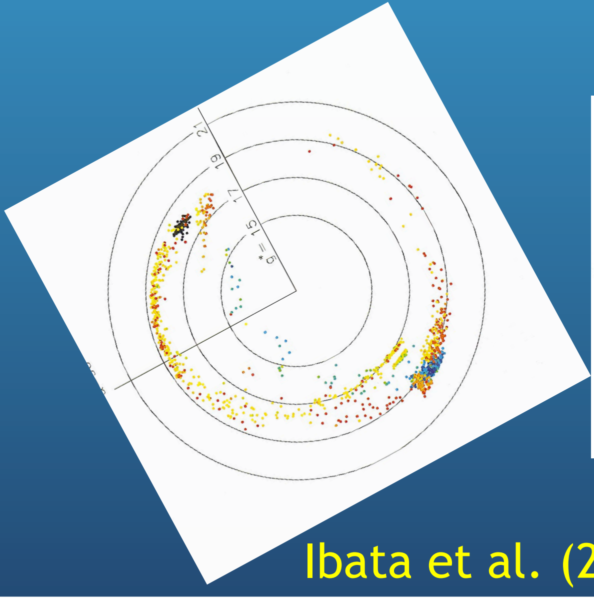

Yanny et al. (2000)



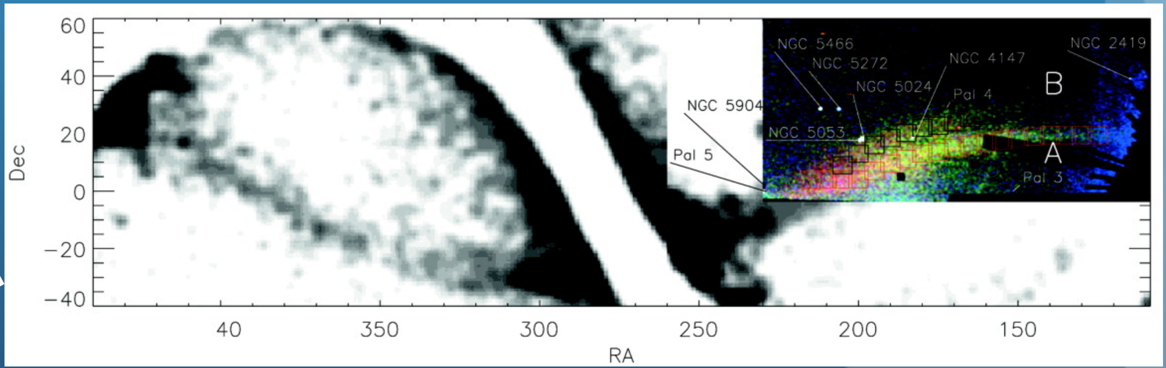

Newberg et al. (2002)




Majewski et al. (2003)



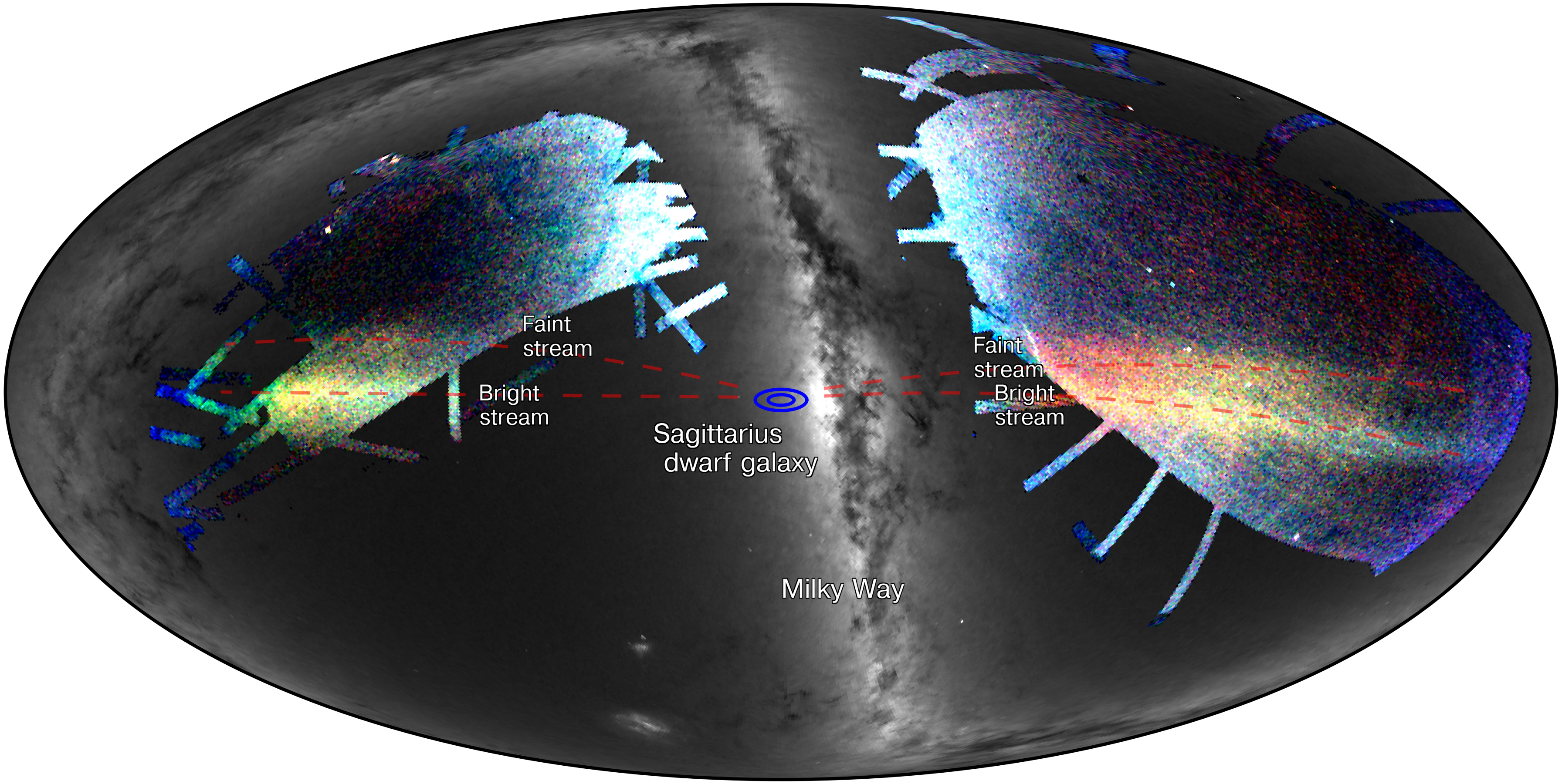
Ibata et al. (2001)




Belokurov et al. (2006)

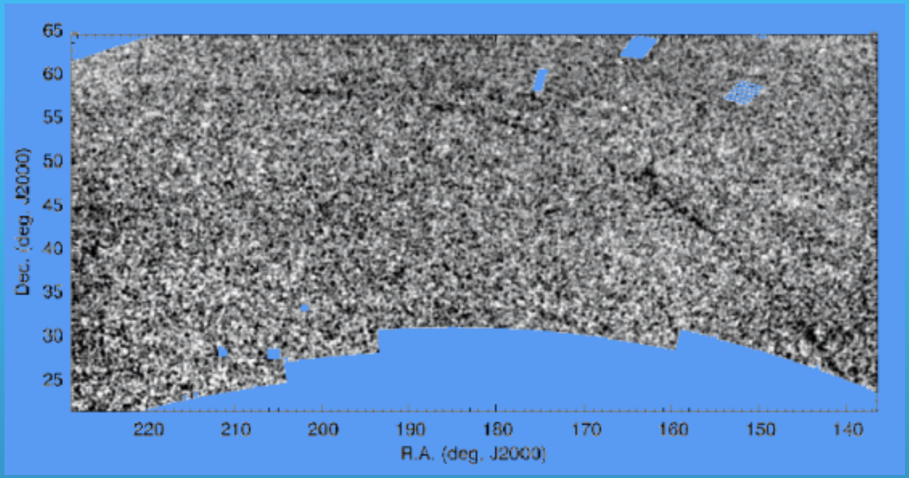
# Mapping the Sgr Stream: SDSS

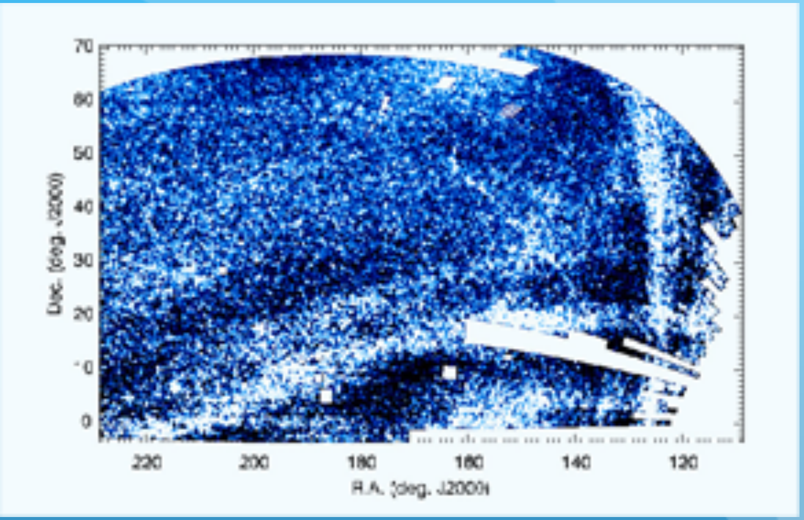
Koposov et al. (2012)




*SDSS observations of Sagittarius stream in both Galactic hemispheres. Bifurcated stream in BOTH hemispheres.*

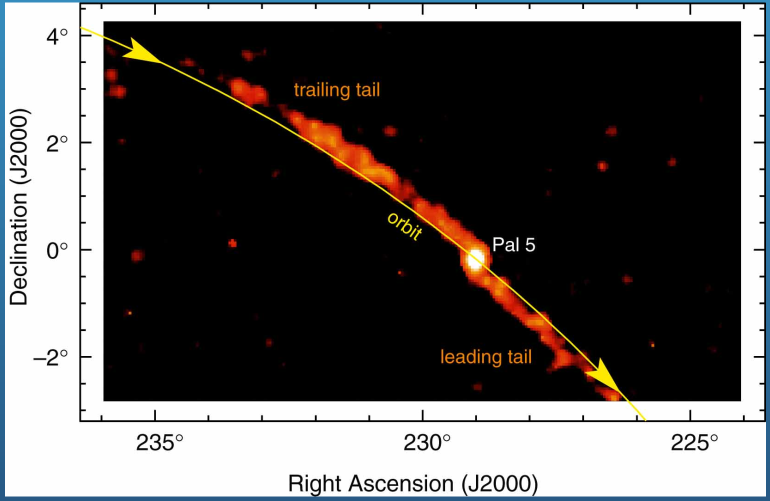
# Mapping Streams: SDSS

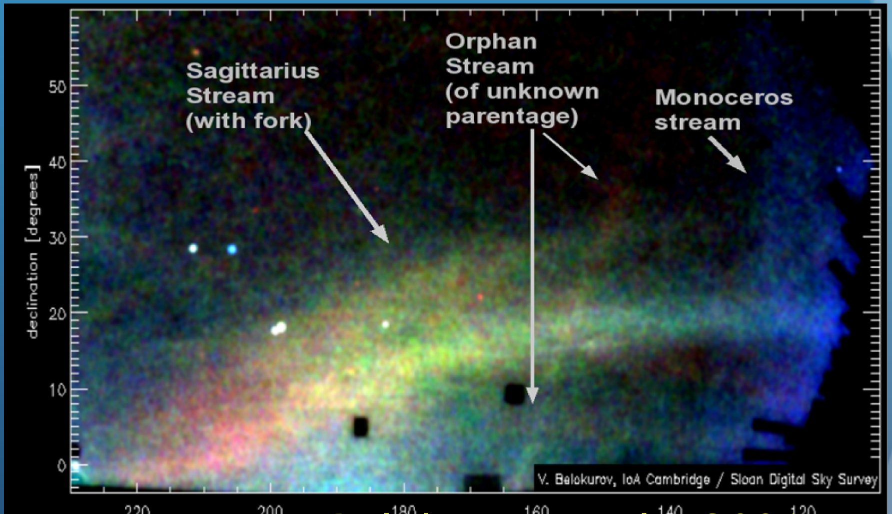



Grillmair & Dionatos 2006

Grillmair (2006)

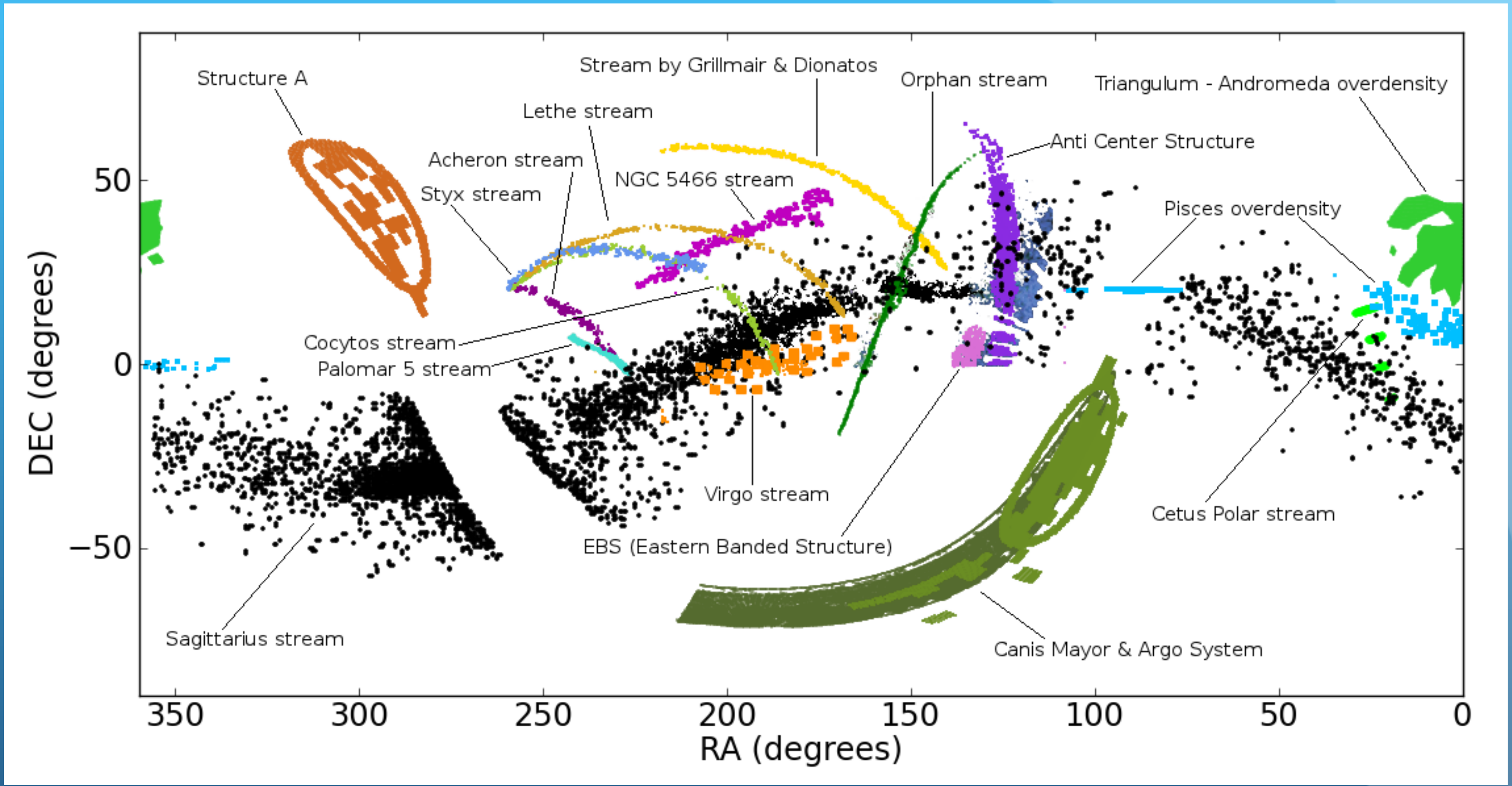



Odenkirchen et al., Rockosi et al.

Belokurov et al. (2006)

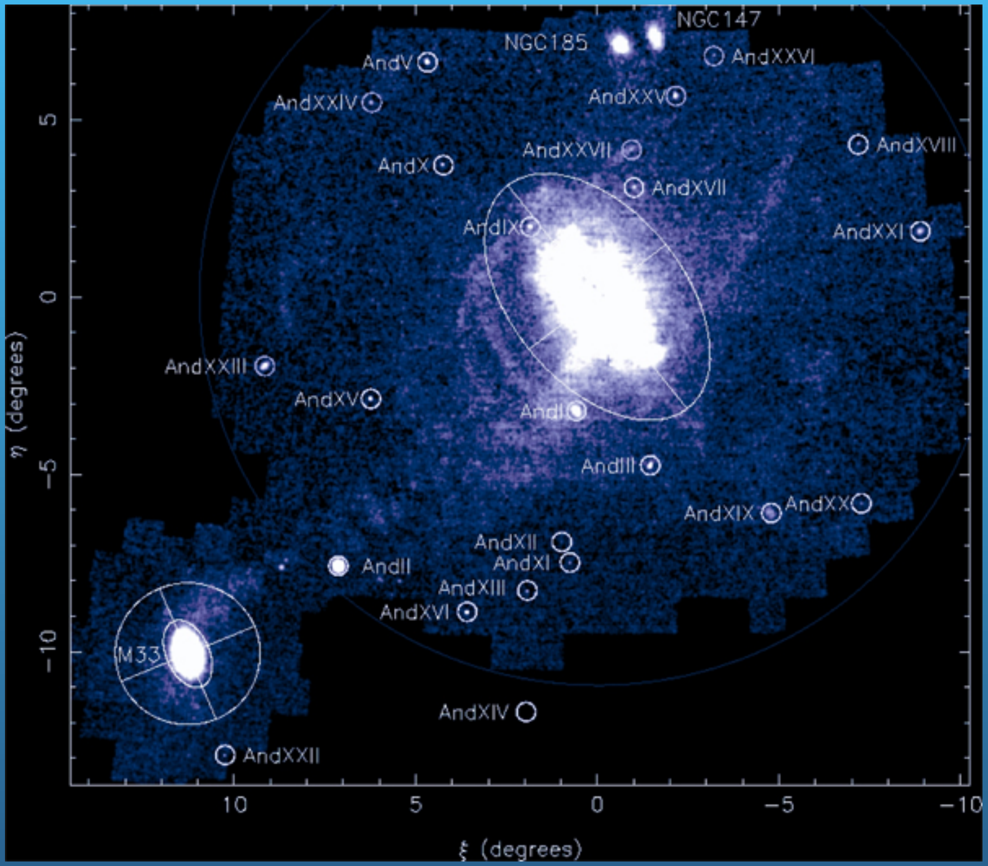
# Cataloging Streams

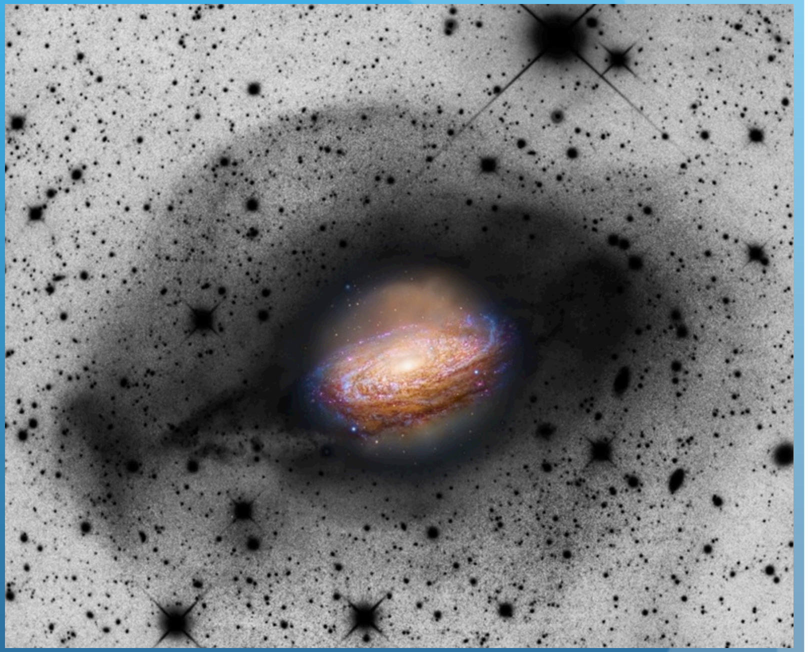



Local Group inventory
*of dwarf galaxies and stellar streams*
*http://lg-inventory.strw.leidenuniv.nl/stellar_streams.html*

Credit: B. Pila Díez.

# Other Galaxies



Martinez-Delgado, Gabany et al.

Geraint Lewis and the PANDAS collaboration.

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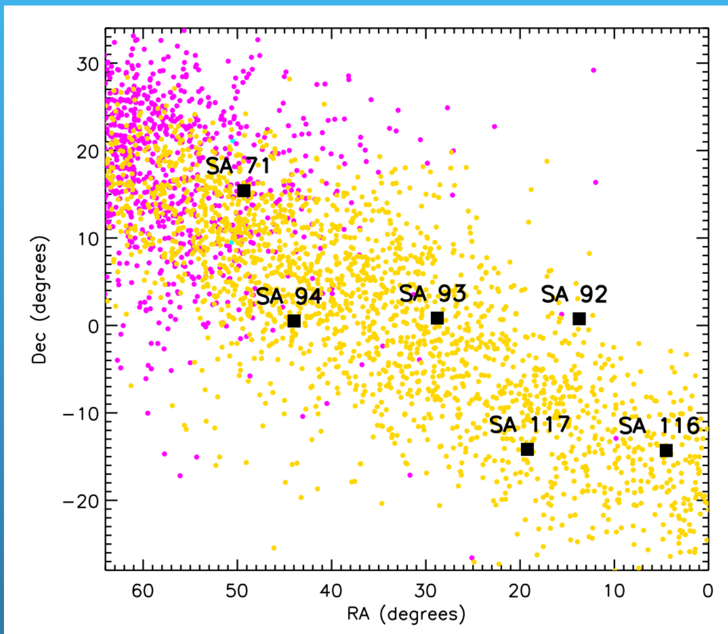
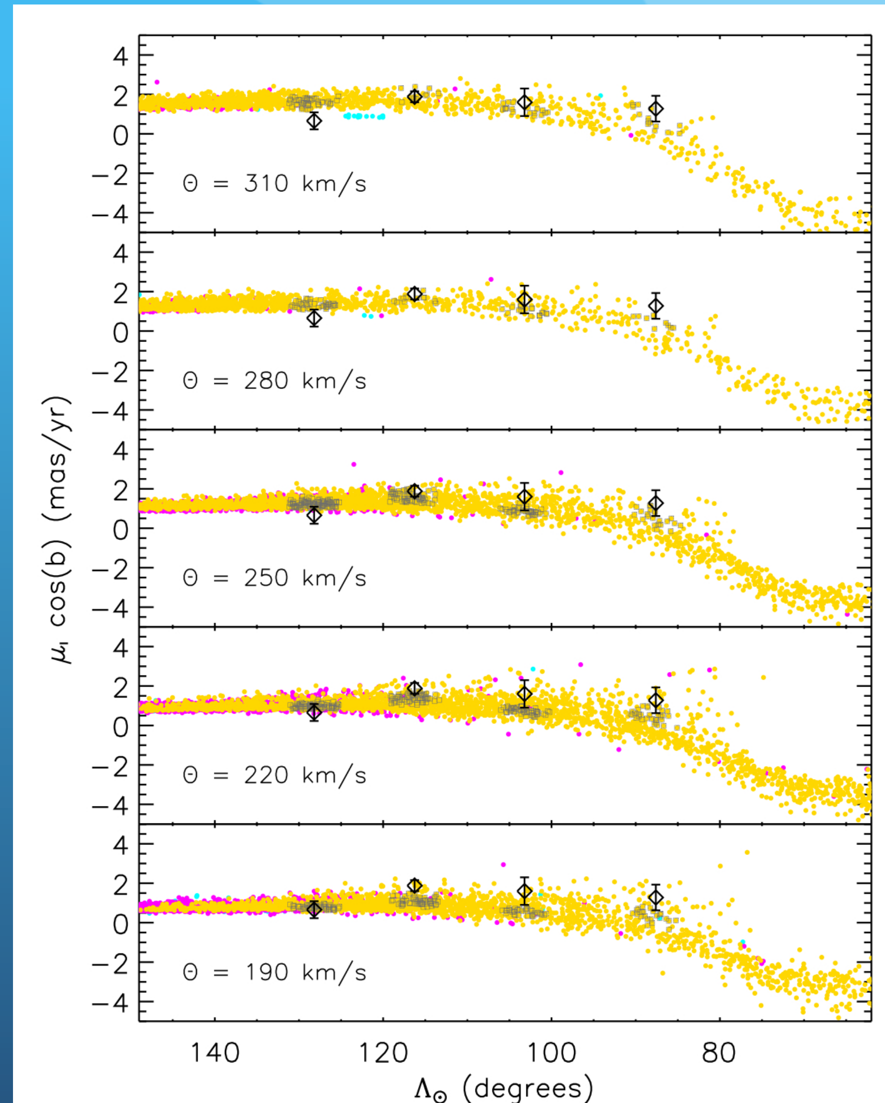
# Measuring the MW LSR velocity

*Carlin et al. (2012)*

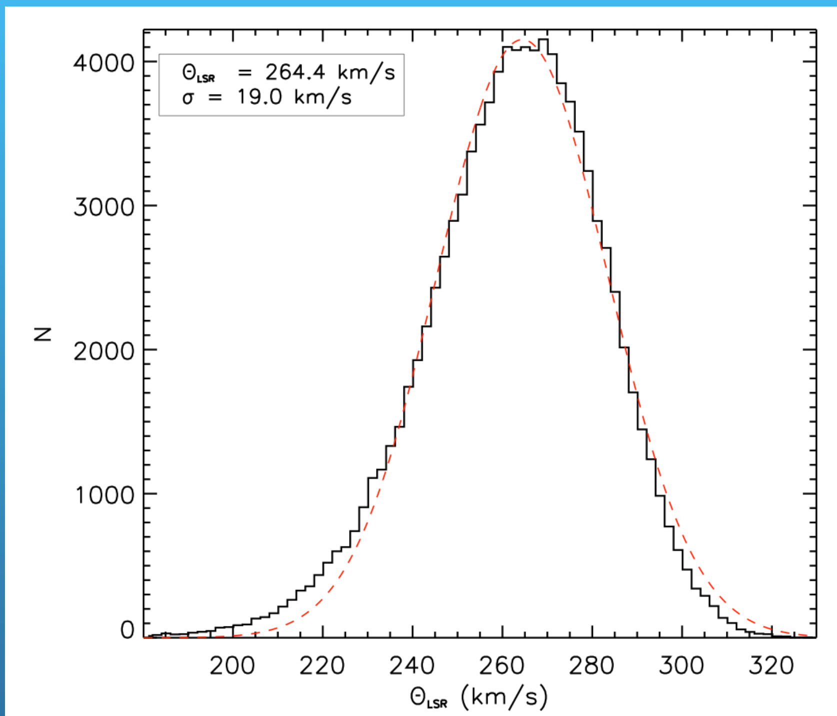


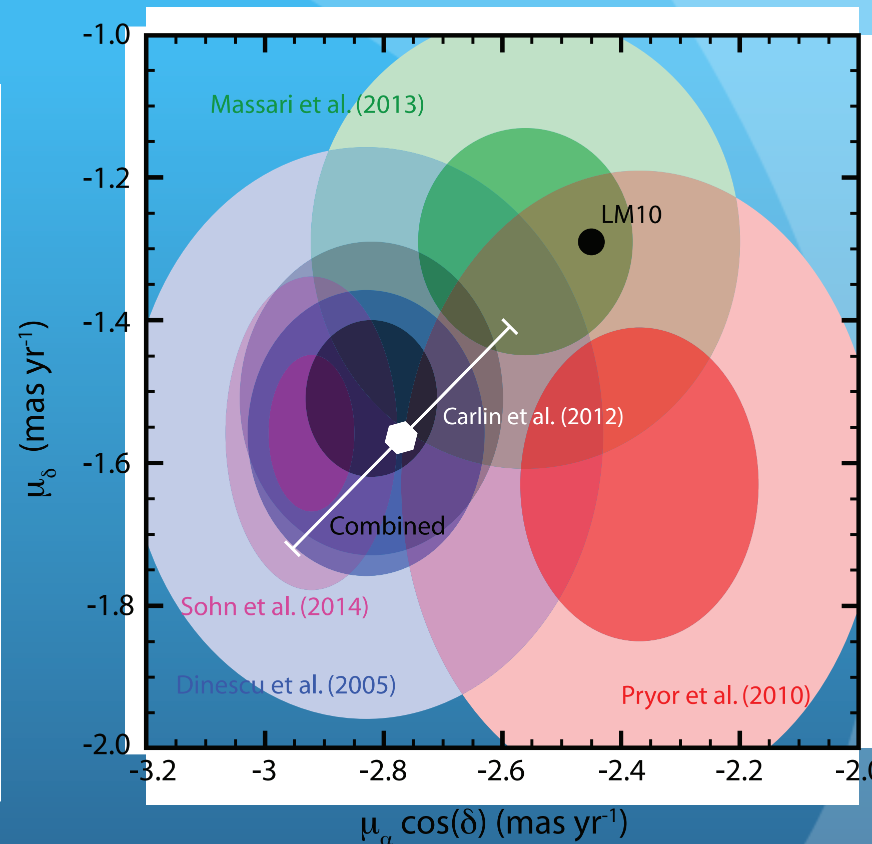




- Sgr trailing tail arcs through South Galactic Pole.
- Space velocity predominantly in X-Z plane.
- Y-direction (i.e., V motion) dominated by solar reflex.

# Measuring the MW LSR velocity

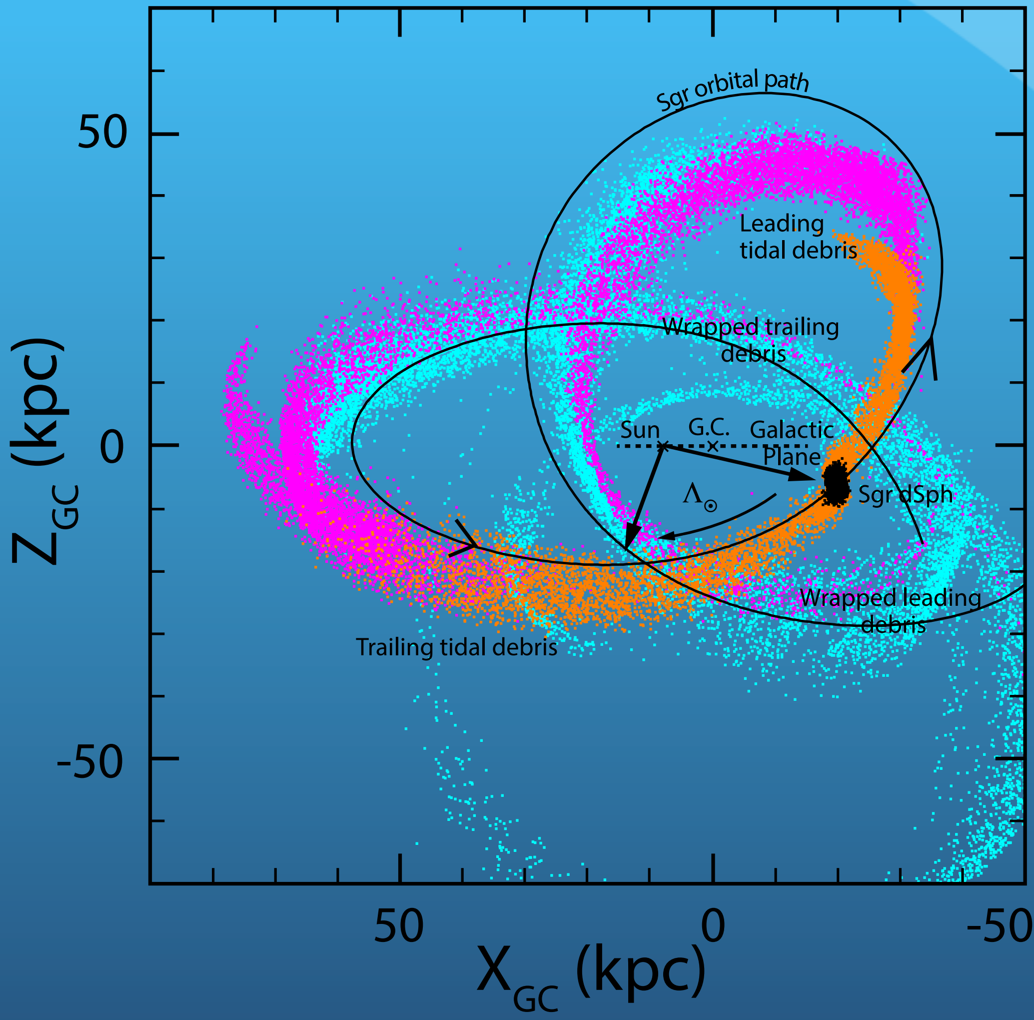
*Carlin et al. (2012)*



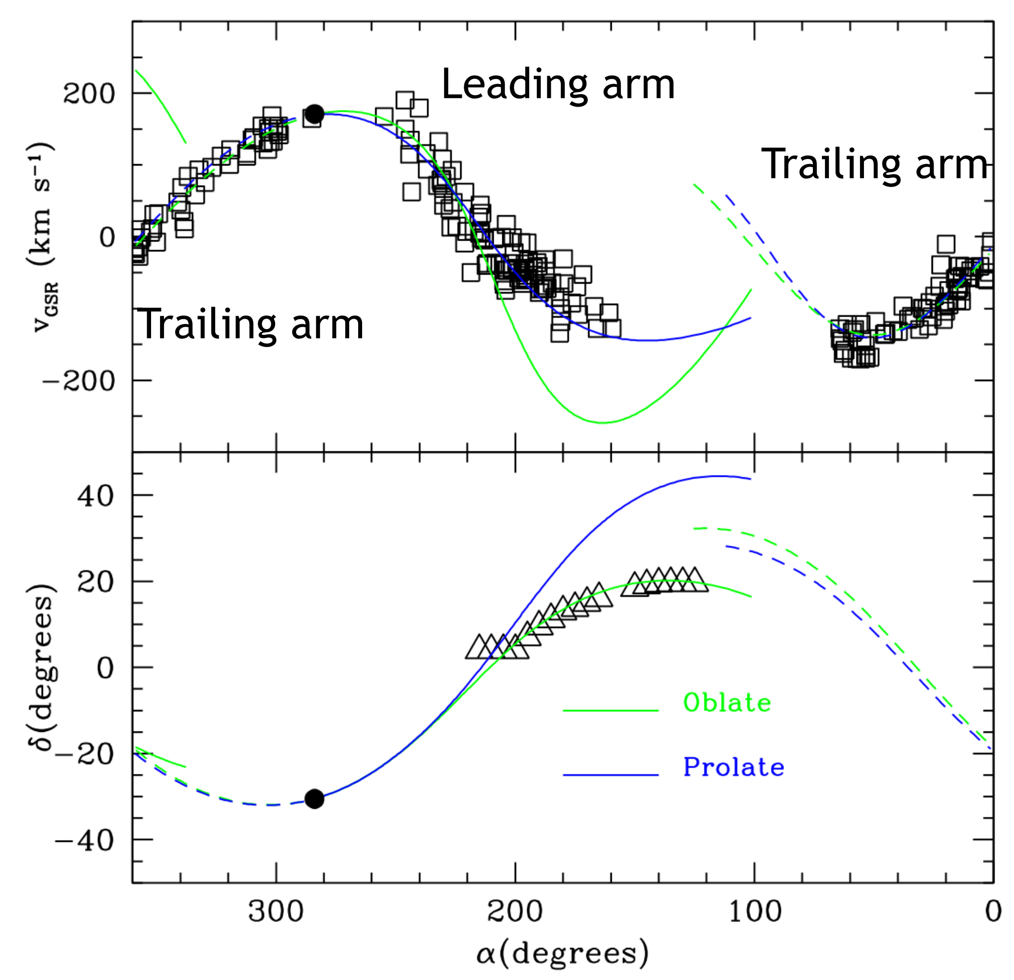




- $Chi^2$ minimization with bootstrap resampling implies best-fit for $\Theta_{LSR}$=264 ± 23 km/s. Consistent with Reid et al. (2009) 250 km/s and <u>independent of $R_\odot$</u>.
- New implied proper motion for Sgr core more consistent with existing observations (e.g., Sohn et al. 2014) than $\Theta_{LSR}$=220 km/s model.

# Modeling the Galactic Potential



# Modeling the Galactic Potential




*Angular position and radial velocity for leading (solid lines) and trailing (dashed lines) arms versus right ascension.*

Early models couldn't match angular position & velocity trends of leading arm simultaneously.

**<u>Oblate/Spherical halo</u>**

Position ✓, Velocity X

*Ibata et al. (2001)*

*Johnston/Law et al. (2005)*

*Fellhauer et al. (2006)*

*Martinez-Delgado et al. (2007)*

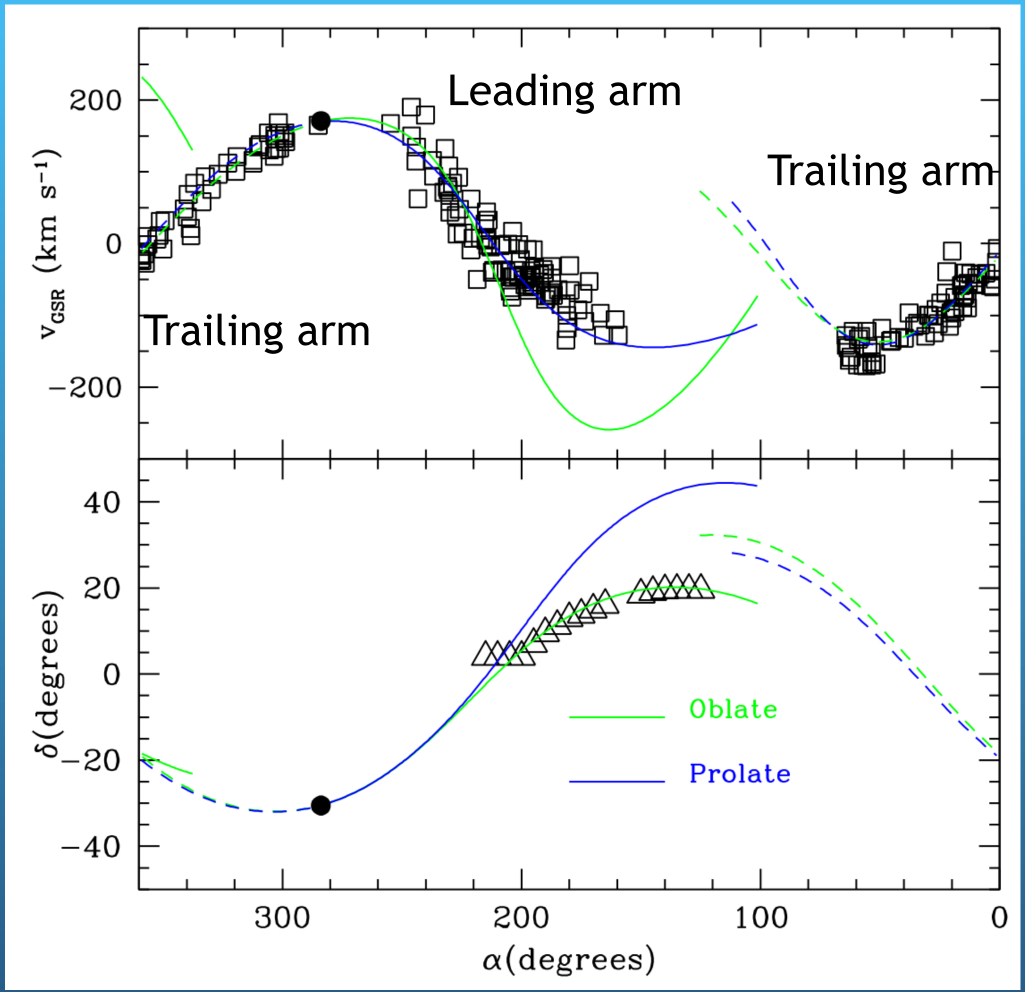
**<u>Prolate halo</u>**

Position X, Velocity ✓

*Helmi et al. (2005)*

*Law et al. (2005)*

# Modeling the Galactic Potential

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*Martinez-Delgado et al. (2007)*

**Prolate halo**

Position X, Velocity ✓

*Helmi et al. (2005)*

*Law et al. (2005)*

**Triaxial halo**

Position ✓, Velocity ✓

*Law et al. (2009)*

*Law & Majewski (2010)*

# Triaxial Galactic Mass Distribution Model

*Law & Majewski (2010)*

- Best fit ($\chi$ = 3.41):

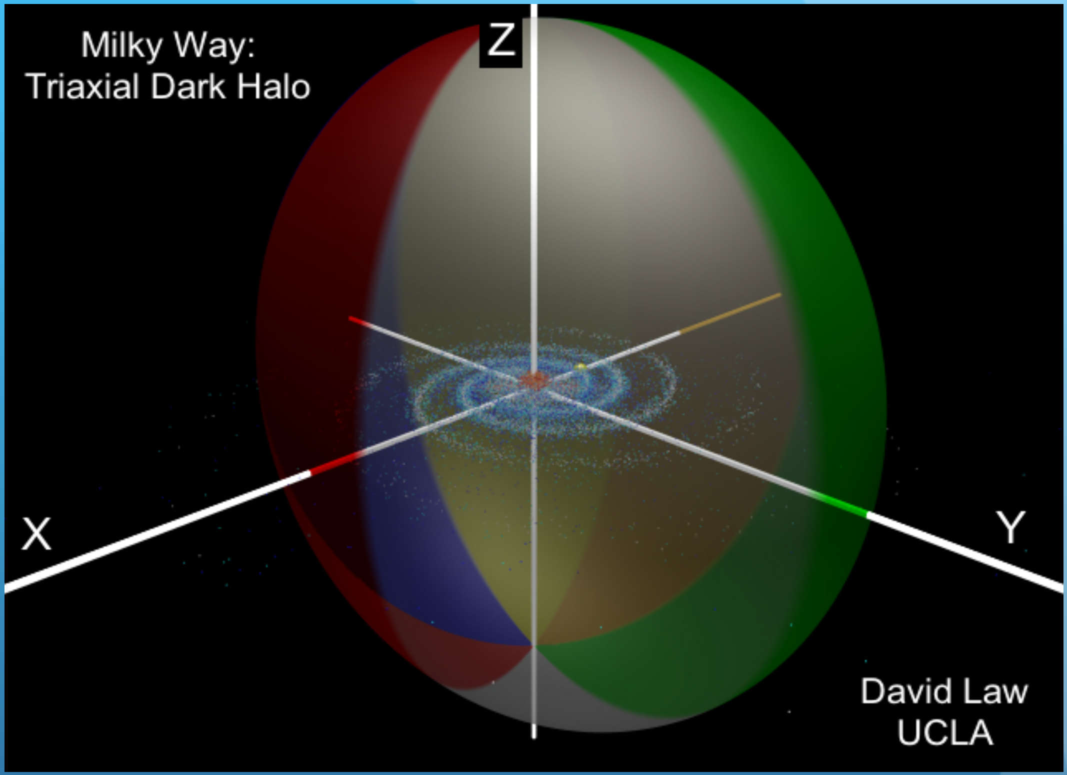
  for 20 < r < 60 kpc

  $(c/a)_\phi$ = 0.72,
  $(b/a)_\phi$ = 0.99

  *i.e., strongly oblate, but minor axis nearly on X-axis.*

- Difficult to reconcile with disk dynamics/stability and CDM models generally.

See also *Deg & Widrow (2013)*.




*Above: 3-d visualization of the flattened dark matter spheroid surrounding the Milky Way.*

- Halo is nearly oblate (uncommon in CDM), short axis towards (l,b) = (7°,0°)
- Highly unexpected orientation, strongly non-axisymmetric in disk plane.
  - Typically (Debattista et al. 2008) expect disk/halo minor axes aligned.
- *Even if triaxial halo is numerical crutch, model unique in fitting all Sgr observations.*

# Triaxial Halo Shape: Alternative Explanations

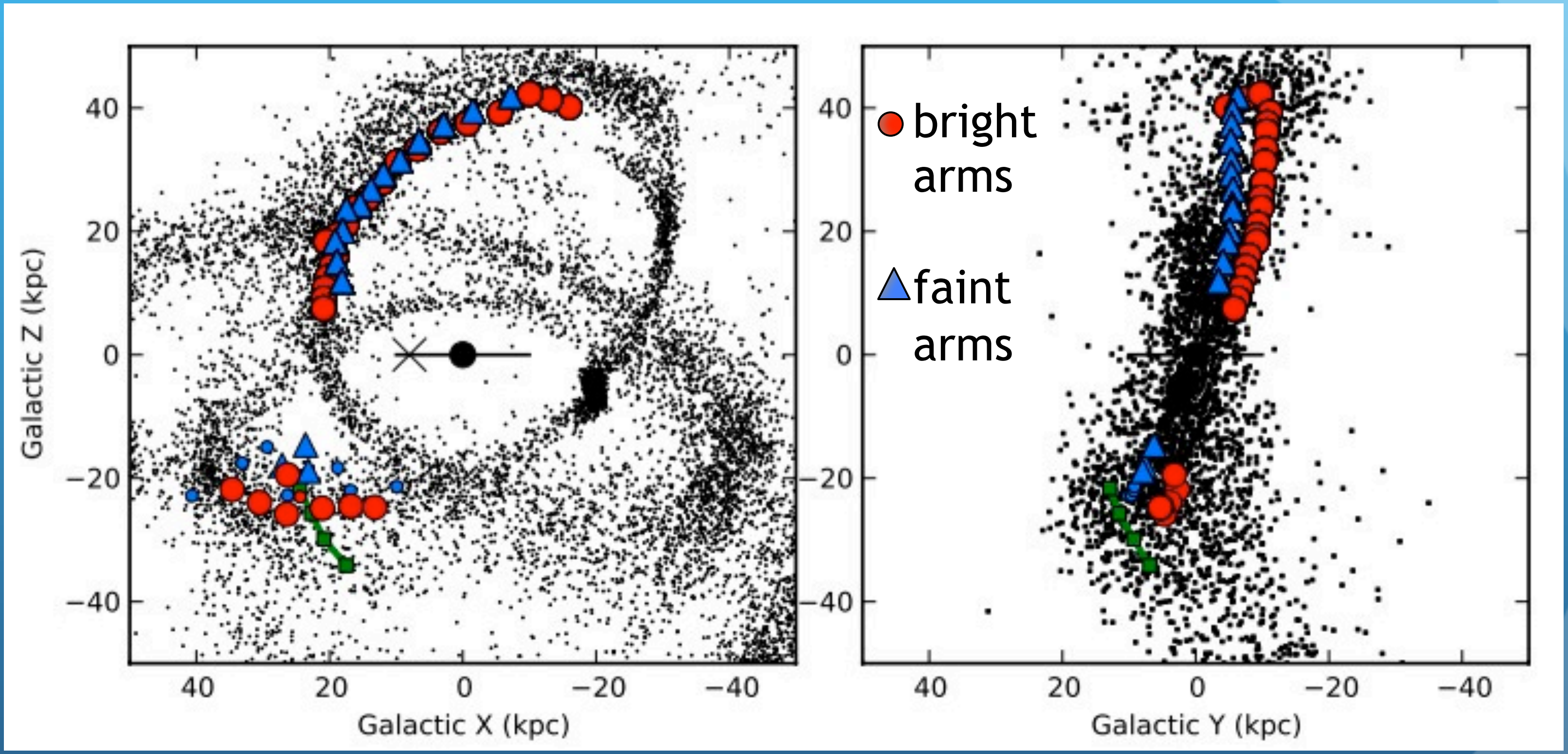
Law & Majewski (2010) looking for alternative explanations?

- Modifications to the properties of Sgr (velocity, orbital pole, etc.) X
- Different halo formalism (e.g., NFW density profile) X
- Different disk/bulge normalization X
  - Galactic bar major axis within ~15°-20° of X axis (i.e. short axis of halo).
  - Stellar halo major axis within ~ 20°-40° of Y axis, but minor axis along Z.
- Orbital evolution (e.g. dynamical friction) ?
  - Possible, requires 2-component models.
- MOND ?
  - Hard to generate non-axisymmetric potential.
- Rotation within the Sgr progenitor? X
  - Not observed in current dSph (Frinchaboy et al. 2012).

- Gravitational influence of the LMC ?
  - LMC orbital pole aligned with 'short axis' of halo to within 1° in longitude.
  - Noticeable effect over 8 Gyr, orbital history of LMC major unknown.
  - But first pass problem.

# Triaxial Galactic Mass Distribution Model

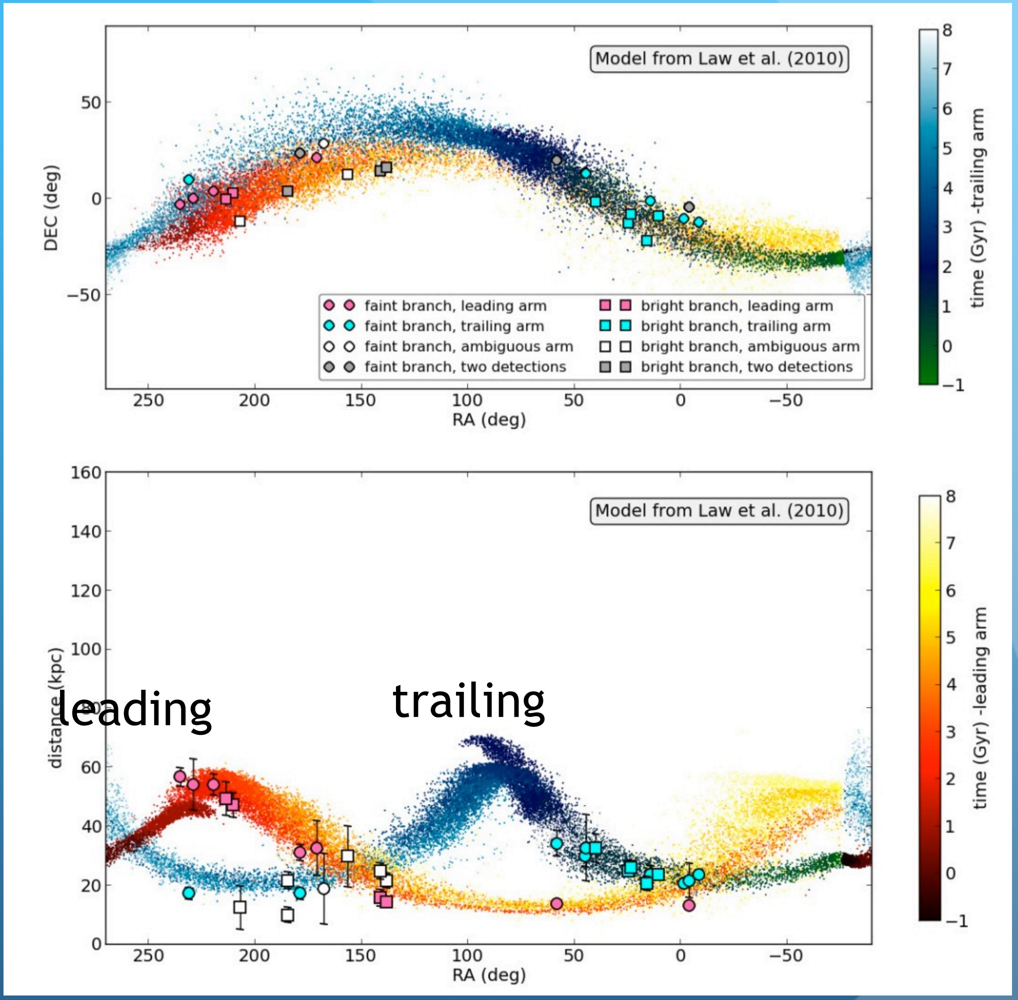
*Slater et al. (2013): Pan-STARRS (red clump & MSTO) and SDSS detections.*
*(NB: Slater et al. comment that Northern SDSS distance scale is too short, and correction would give better match - see Koposov et al. 2013 erratum.)*




- LM10 model remarkably successful in matching even more recent Sgr data.

# Triaxial Galactic Mass Distribution Model

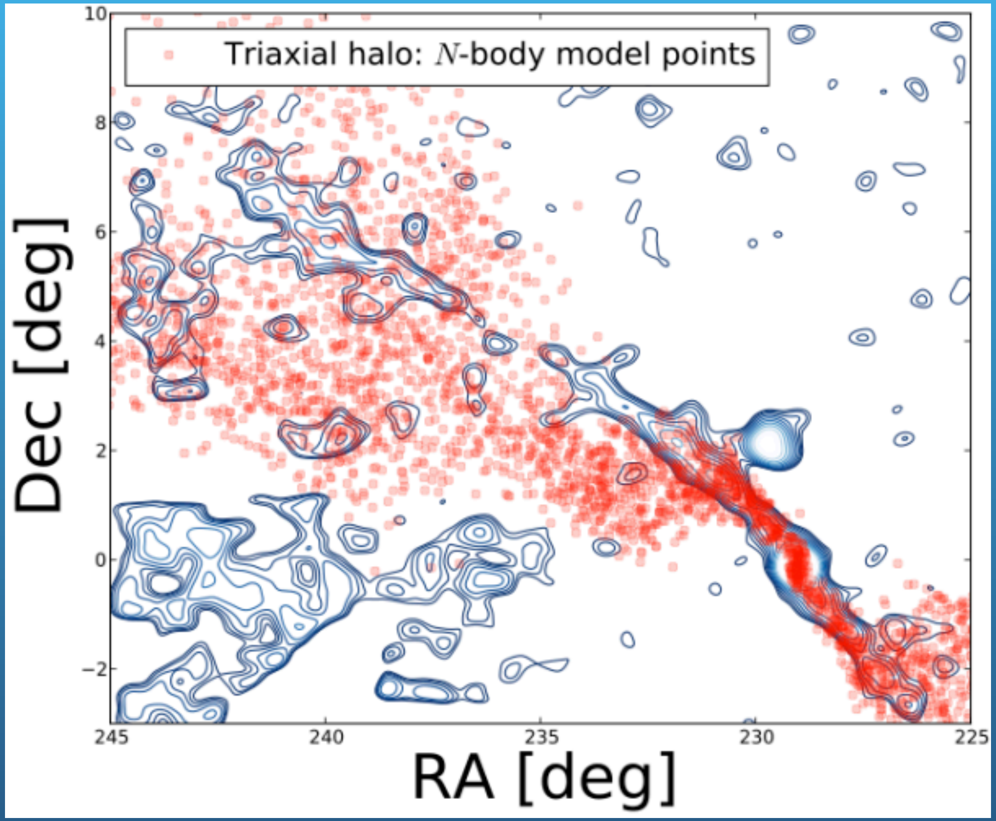
*Pila-Diez et al. (2013): CFHT+MegaCam pencil beams*




- LM10 model remarkably successful in matching even more recent Sgr data.

# Triaxial Galactic Mass Distribution Model

But LM10 model has other problems:
e.g., Pal 5 tidal tails in LM10 potential




Pearson et al. 2015

# Improved, More Sophisticated Mass Model

*Vera-Ciro & Helmi (2014)*

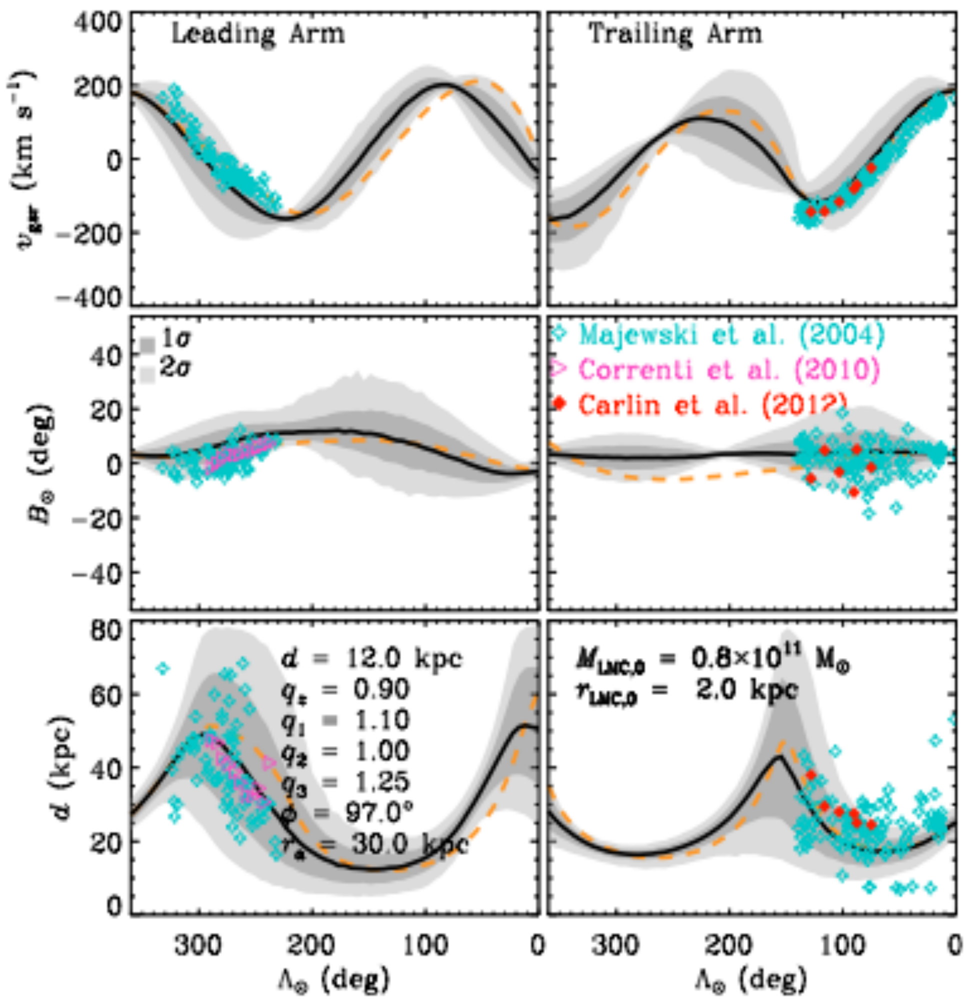
Adopt variable shape with radius: from axisymmetric at small r to LM10 triaxial at large r.

Can get as good fits to data, although still stuck with weird LM10 shape.

More careful accounting of LMC perturbations allows a "more LCDM-palatable" composite potential:

- axisymmetric halo [$q_z = 0.9$], flattened to disk plane (r < 10 kpc)
- outer "triaxial" (not oblate) part to $(c/a)_\phi = 0.8$, $(b/a)_\phi = 0.9$

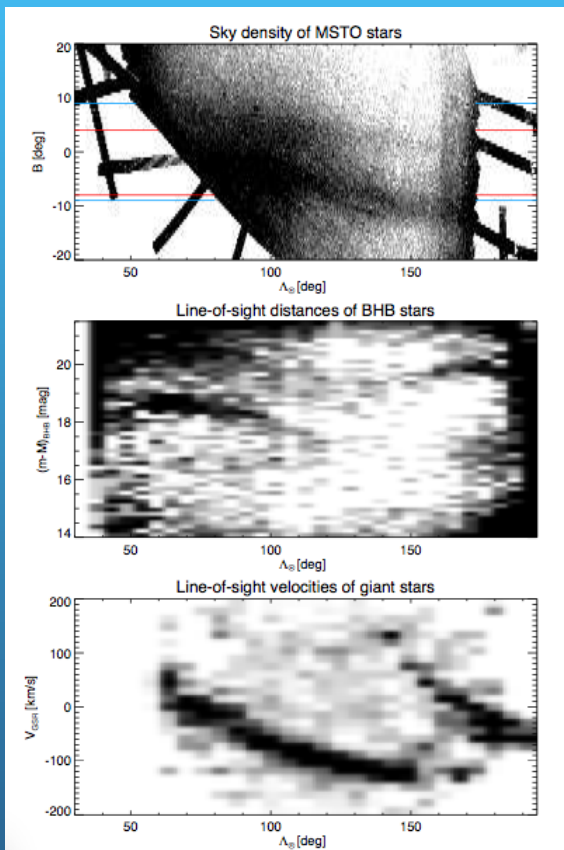
But see Gomez et al. (2015)!!

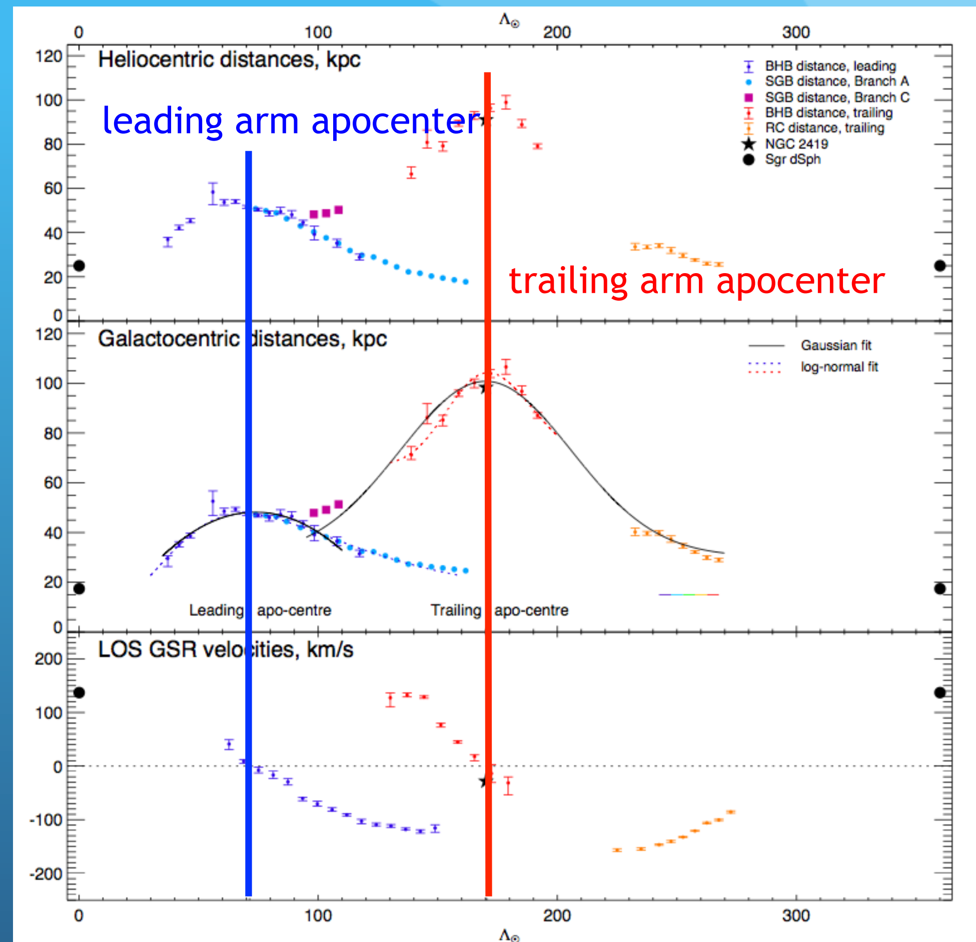



*Orange line = LM10; black line = "composite" potential.*

# Refining the Mapping of the Sgr Stream

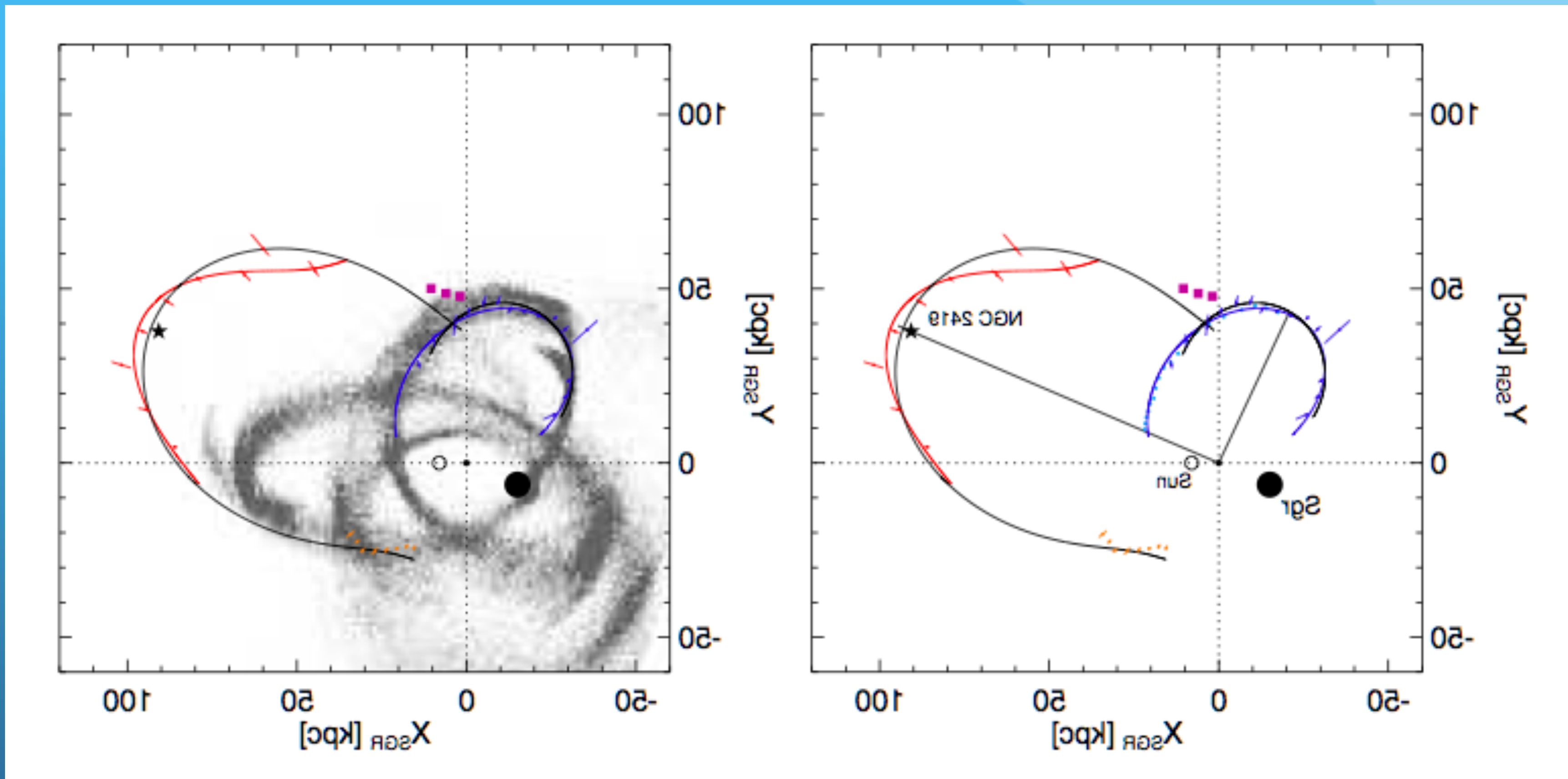
*Belokurov et al. (2014)*




- 93 deg difference between apocenters implies DM density falls off faster than predicted for isothermal haloes (e.g., Law & Majewski 2010 logarithmic halo gives 120 deg).

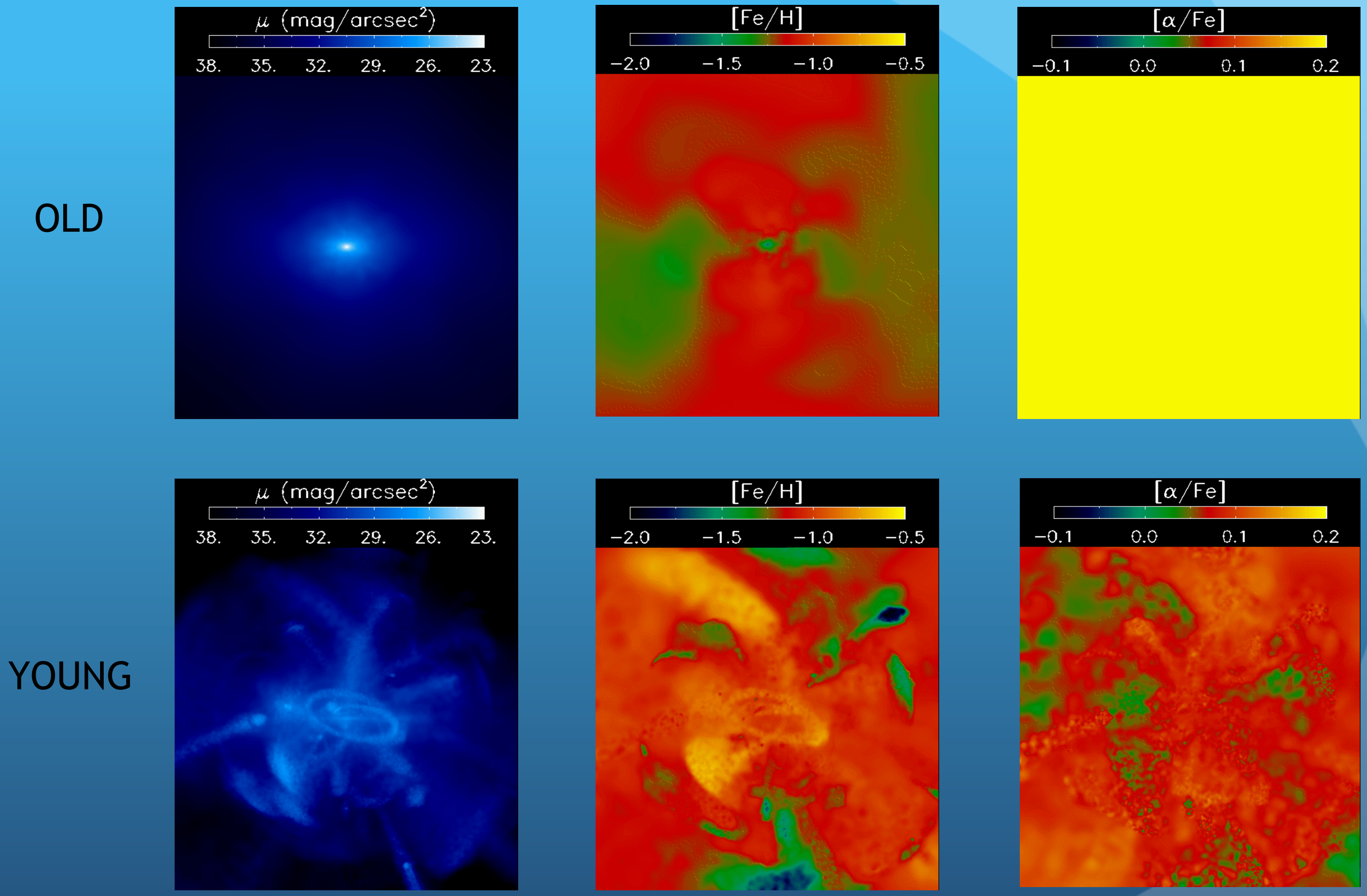
# Refining the Mapping of the Sgr Stream




*Belokurov et al. (2014)*

- New results from Belokurov et al. (2014) and Damke et al. (2015) show that now *trailing arm* needs refinement in the models.
- Globular cluster NGC 2419 looks to be a promising Sgr stream member (Newberg et al. 2003).

# Reconstructing Hierarchical Galaxy Formation




Bullock & Johnston 2005, Johnston et al. 2008

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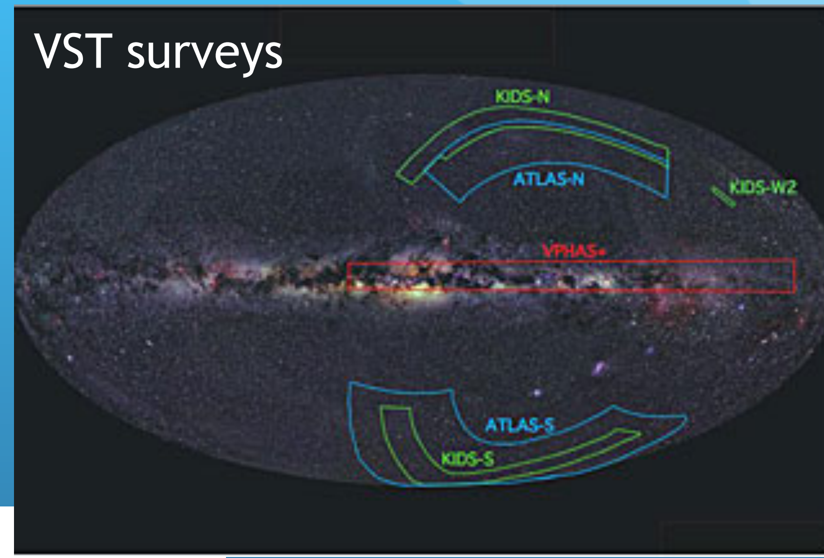
# More and Deeper Imaging Surveys

Including time series – RR Lyrae, standard candles

SkyMapper

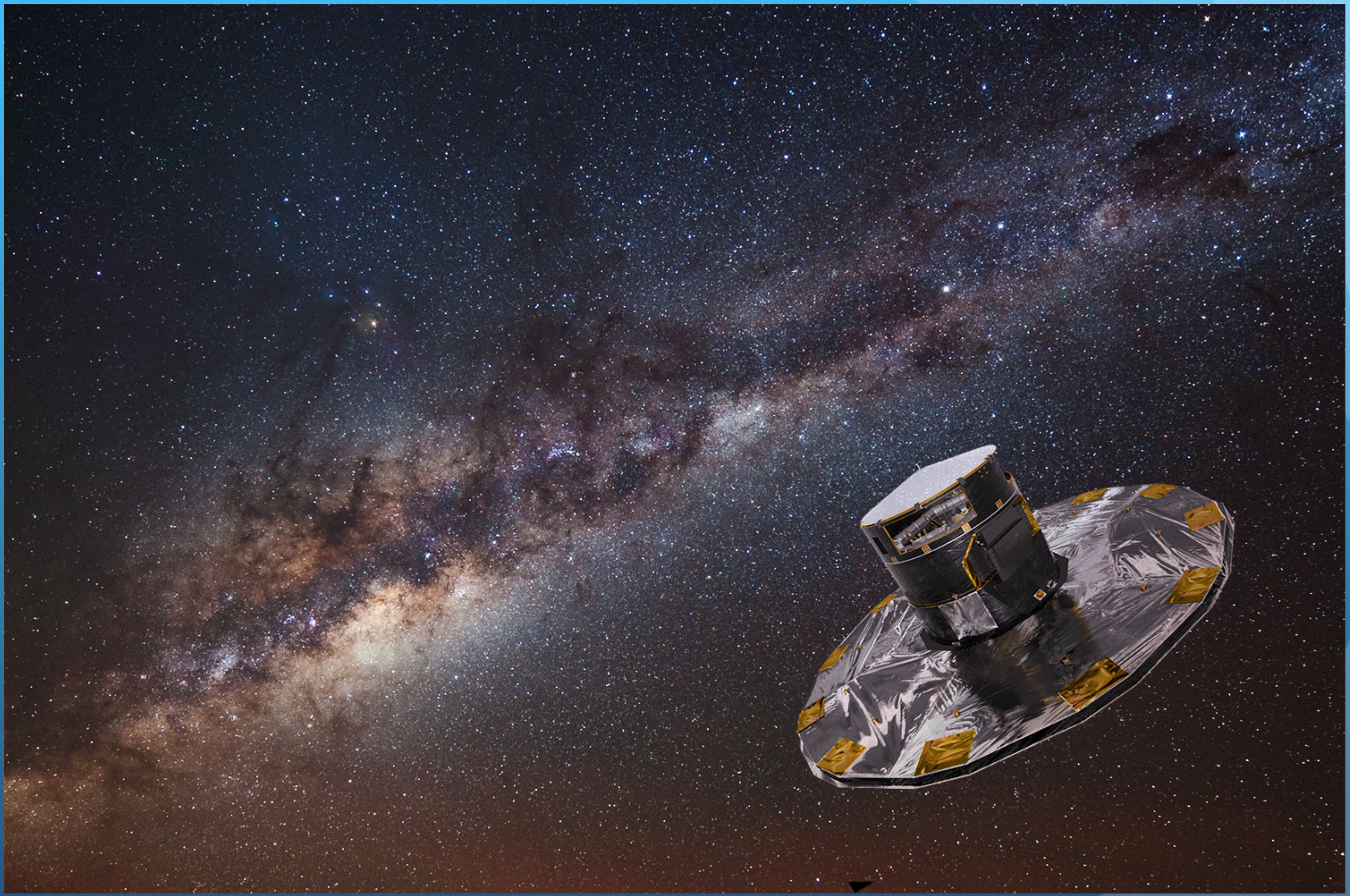



THE DARK ENERGY SURVEY

LSST
Large Synoptic Survey Telescope

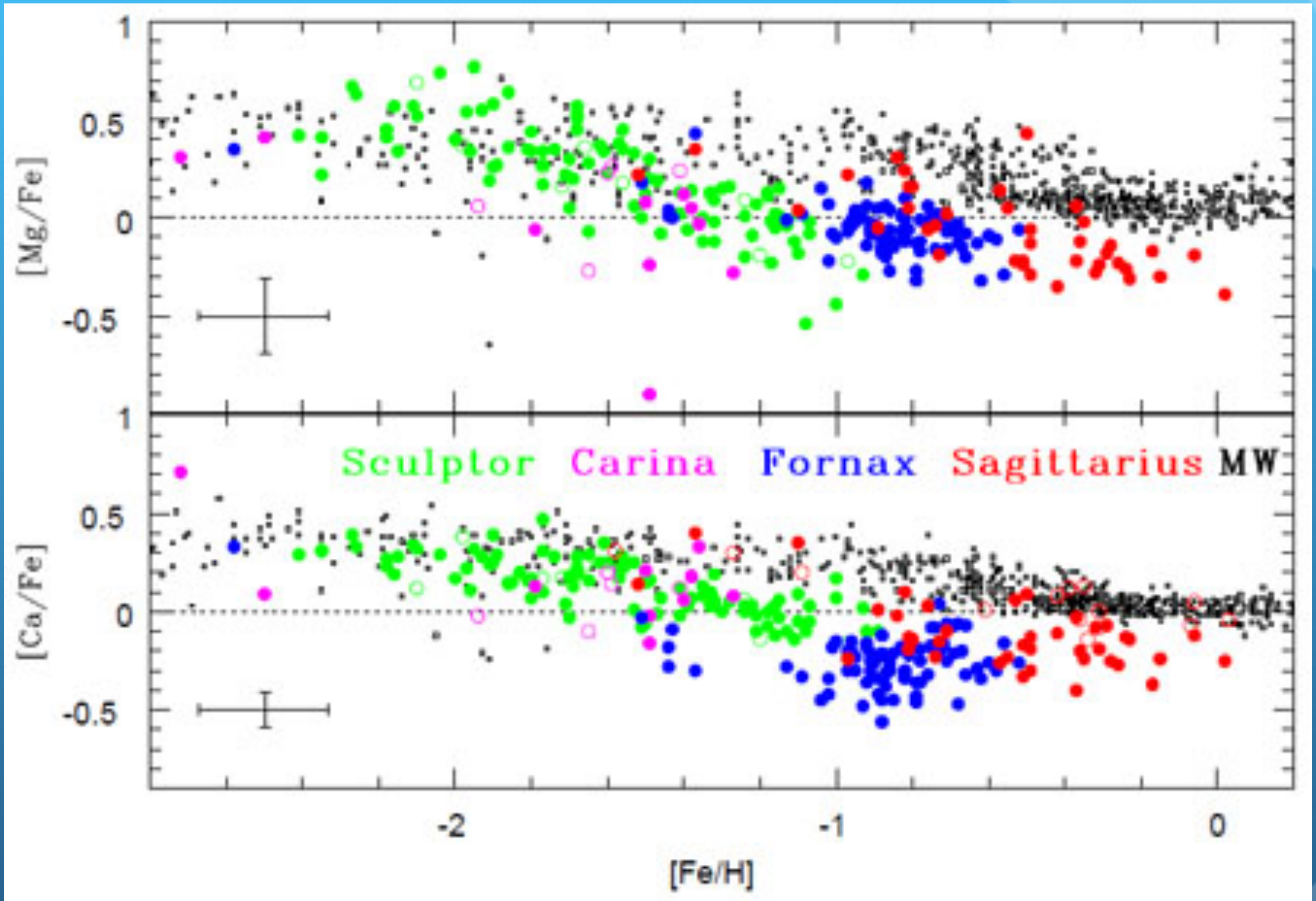
Pan-STARRS

# Gaia, Gaia, Gaia....Astrometry!



# Exploiting Unique Satellite Chemistries

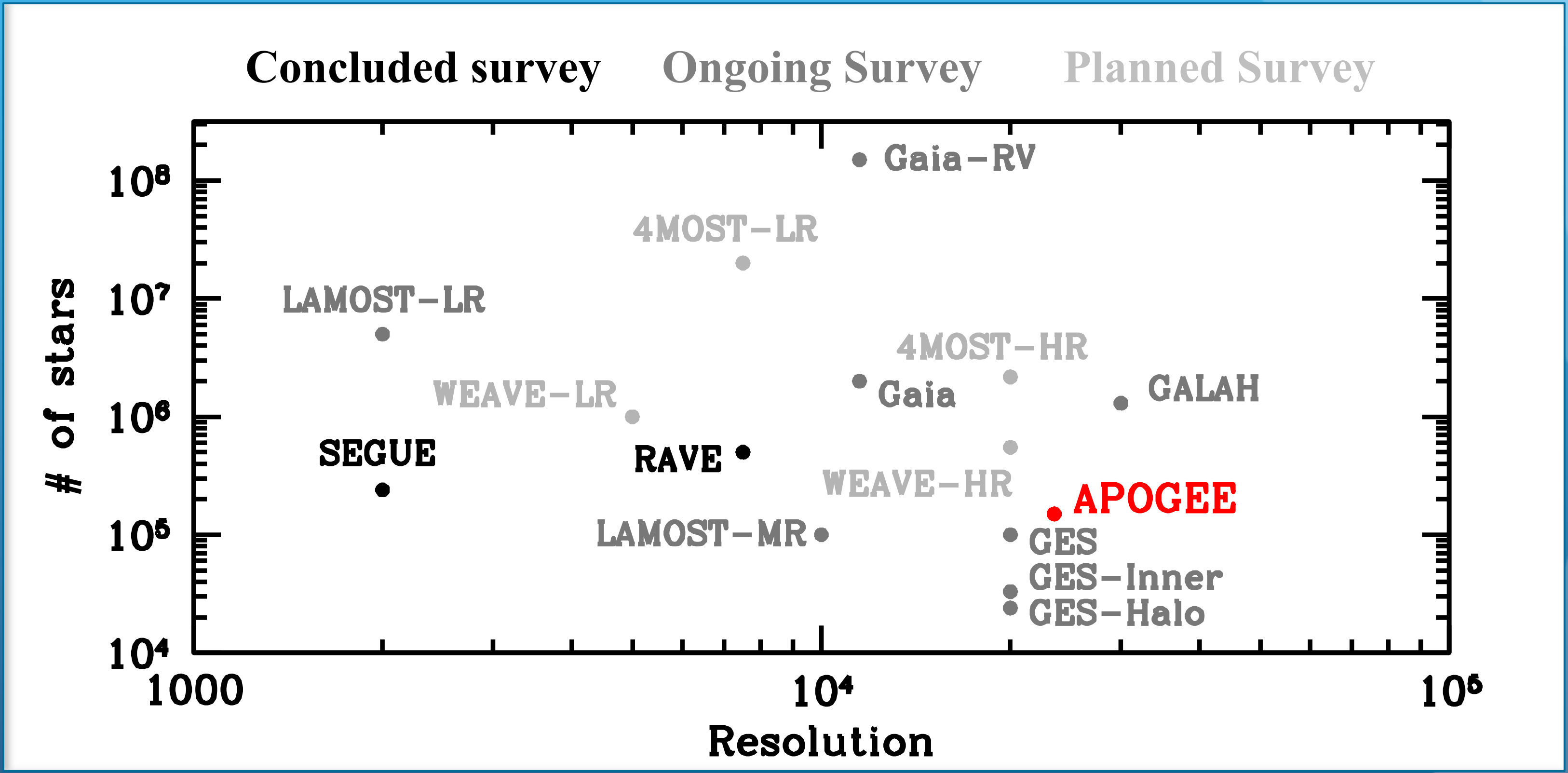
Chemical "Fingerprinting"




Tolstoy, Hill & Tosi (2009)

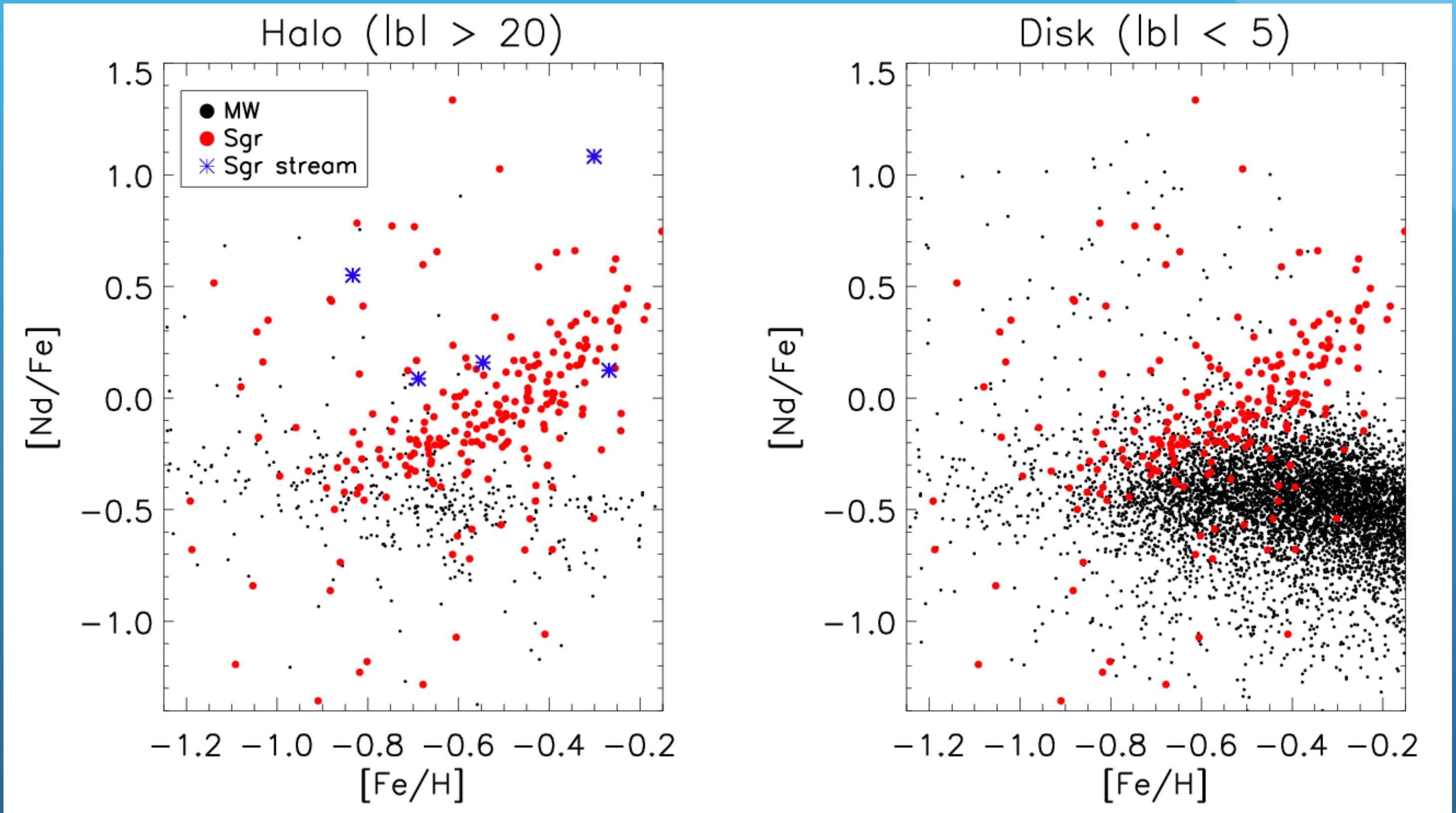
# Exploiting Unique Satellite Chemistries

Era of large area, low and (esp'ly) high resolution spectroscopic surveys.



# Exploiting Unique Satellite Chemistries

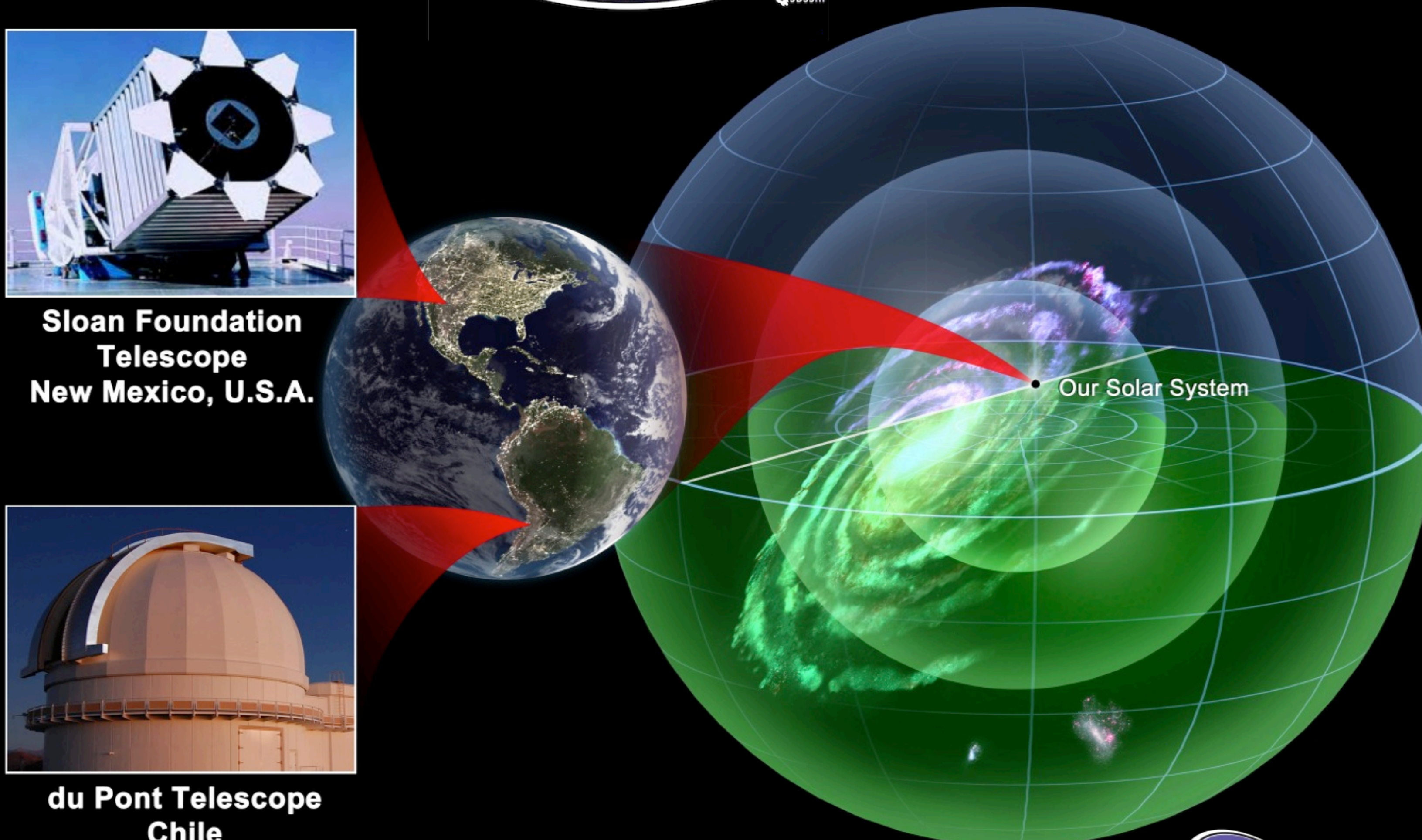
APOGEE Observations of the Sgr core and stream fields.




Hasselquist et al. (2015)

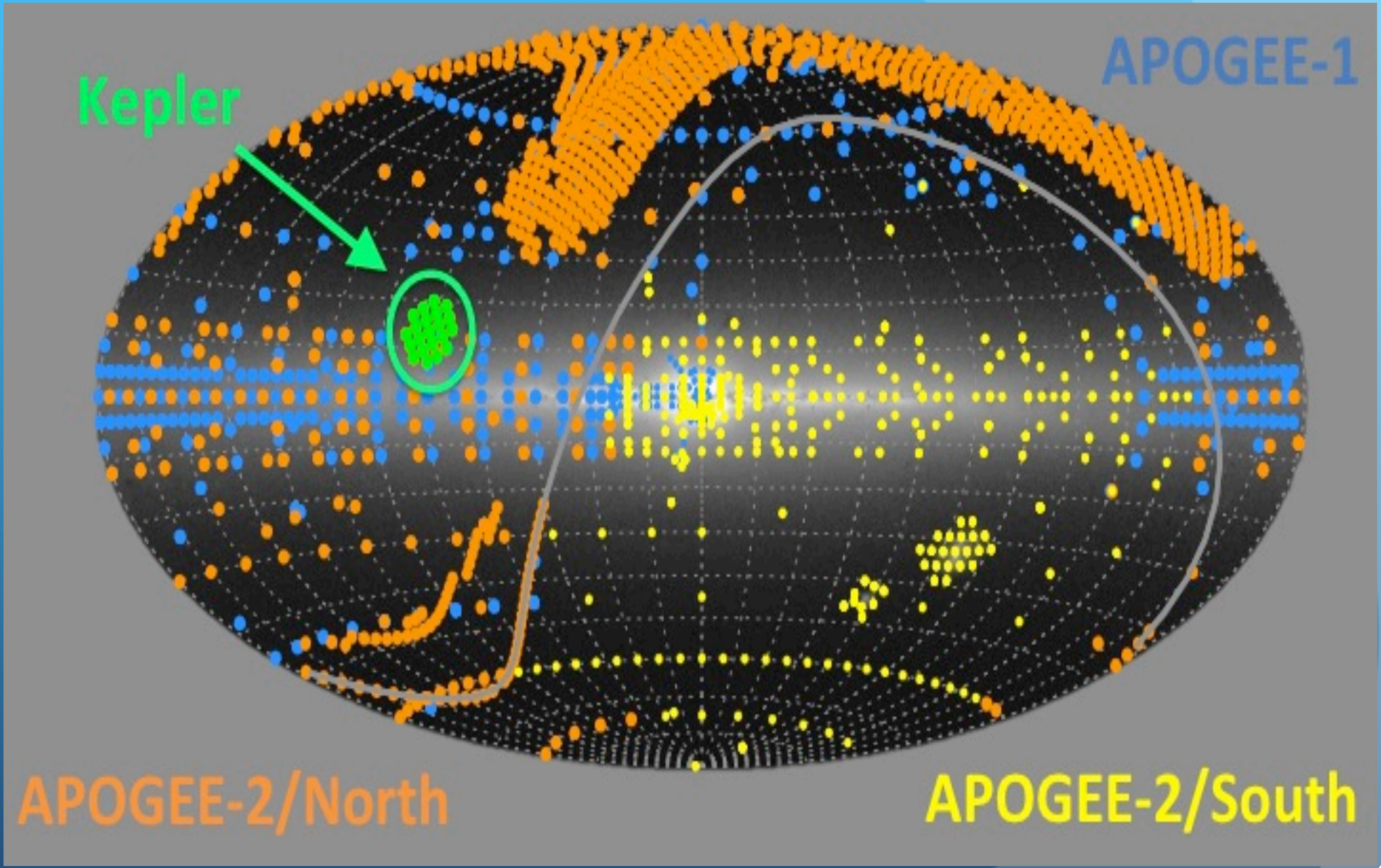
# APOGEE

SDSSIII




SDSS

# APOGEE-1 + -2 Targeting



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# FIN