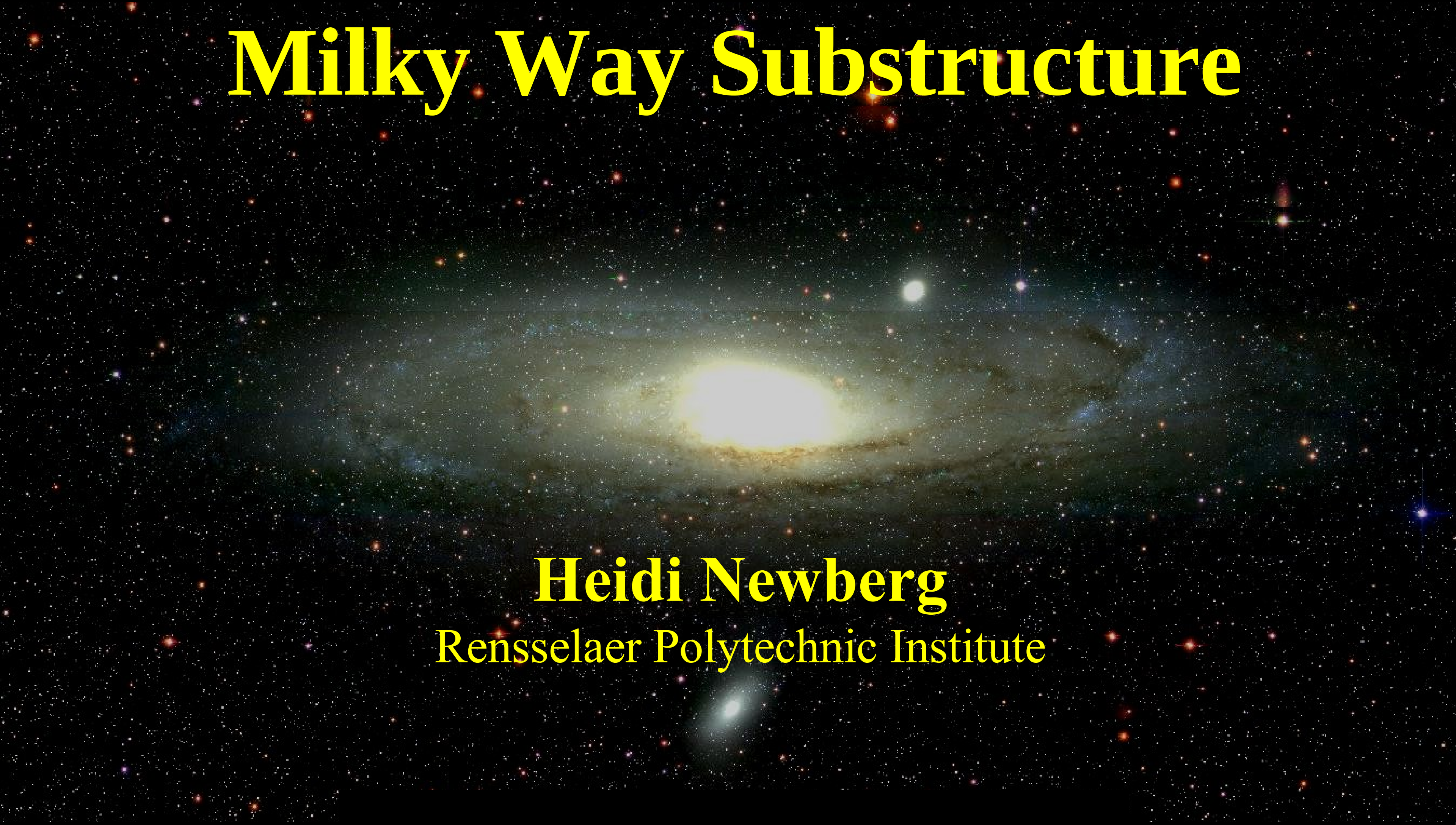
Milky Way Substructure



Heidi Newberg
Rensselaer Polytechnic Institute

Overview

(1) The Milky Way spheroid, pre-SDSS

(2) The Milky Way spheroid, now

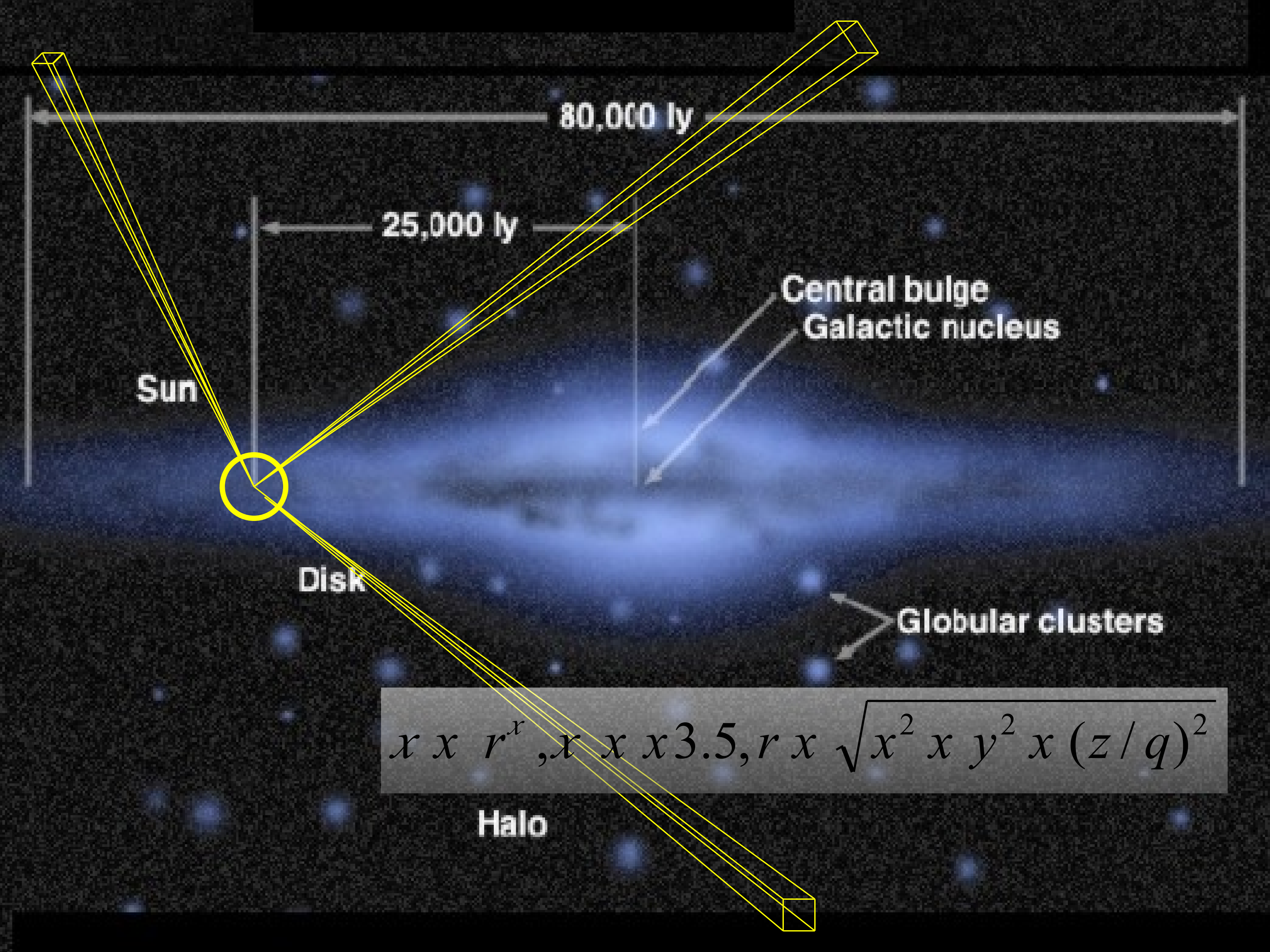
  (a) tidal debris

  (b) dwarf galaxies and globular clusters

  (c) global properties of spheroid stars

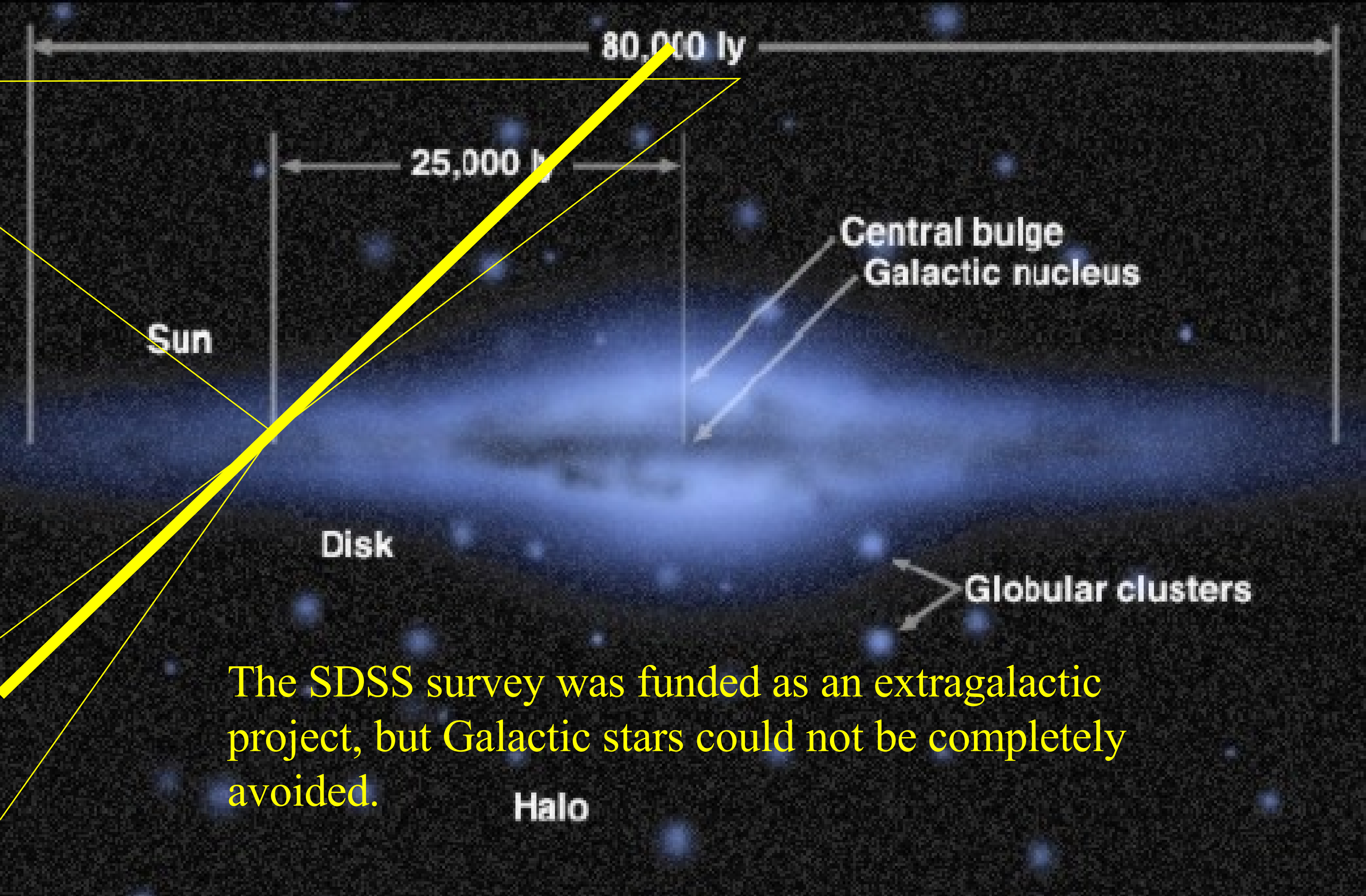
(6) The Virgo Overdensity and the Big Toe of Hercules

(4) Open problems and the need for a larger spectroscopic survey Milky Way stars (RAVE, SEGUE II, LAMOST, WFMOS)


80,000 ly
25,000 ly
Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo
$x\ x\ \ r^{x}\ ,x\ \ x\ x3.5, r\ x\ \sqrt{x^{2}\ x\ y^{2}\ x\ (z/q)^{2}}$

Experts within the Galactic structure field were aware of (among other things):

(3) Moving groups (Majewski, Munn, and Hawley 1994)
(4) High surface brightness A stars in the spheroid (Rodger, Harding, Saddler 1981)
(5) BHBs would be good tracers of the spheroid (Wilhelm, Beers, and Gray 1999); thank you Jeff Pier for making these top priority for SDSS stellar spectra.
(6) Velocities of K giant stars could be used to trace moving groups in the halo to great distances (Morrison et al. 2000, the Spaghetti survey)
(5) Apparent asymmetries in spheroid star counts (Larsen and Humphreys 1996)
(6) Inconsistencies in the halo flattening (Gilmore, Wyse and Kuijken 1989)
(7) The Sagittarius dwarf galaxy should be in the process of disrupting (Ibata and Lewis 1998) – tidal stream found in carbon stars (Ibata et al. 2001)
(8) Extra-tidal wings on globular clusters (Grillmair et al. 1995)
(9) Significant spatial substructure in the spheroid was unlikely, or at least difficult to detect.

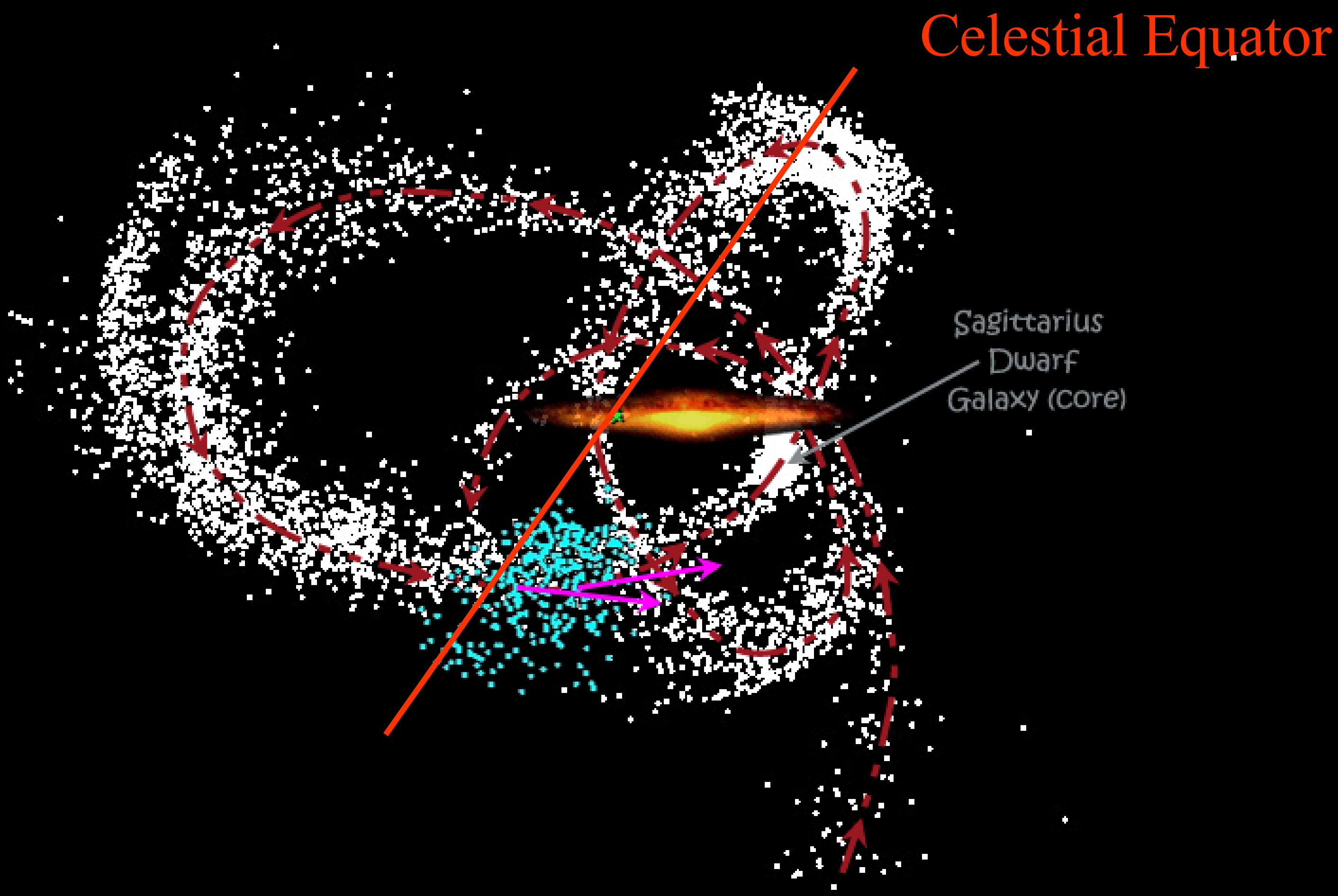


The SDSS survey was funded as an extragalactic project, but Galactic stars could not be completely avoided.

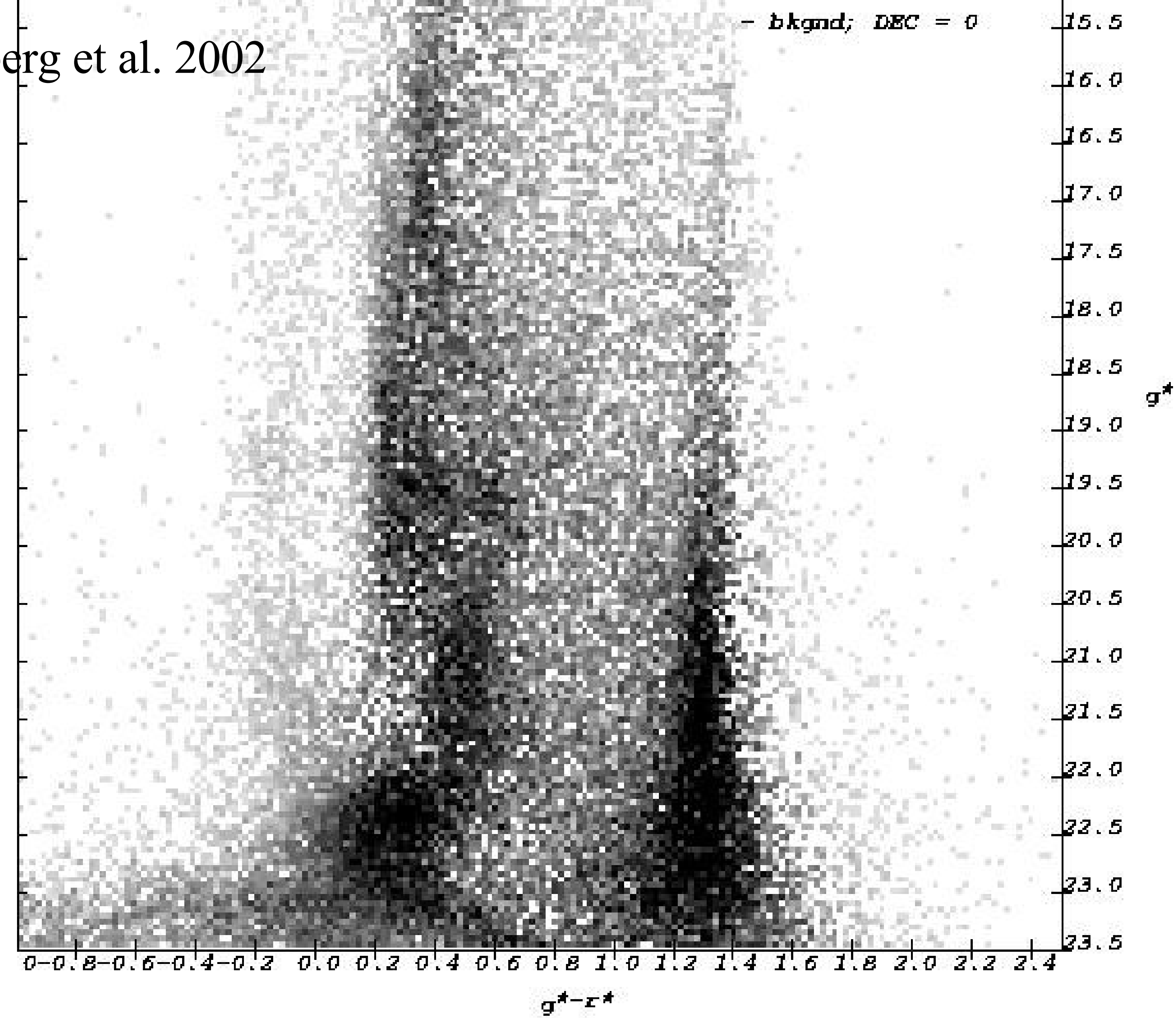
The beginning of SDSS Galactic structure

- Brian Yanny and I tried to fit the star counts on the Celestial Equator to the Bahcall-Soneira model → failed
- We tried to tweak the B-S model to fit the data → failed
- We selected only the bluest stars, expected to be BHB stars only, to trace the flattening of the spheroid population only → spheroid parameters depended on position

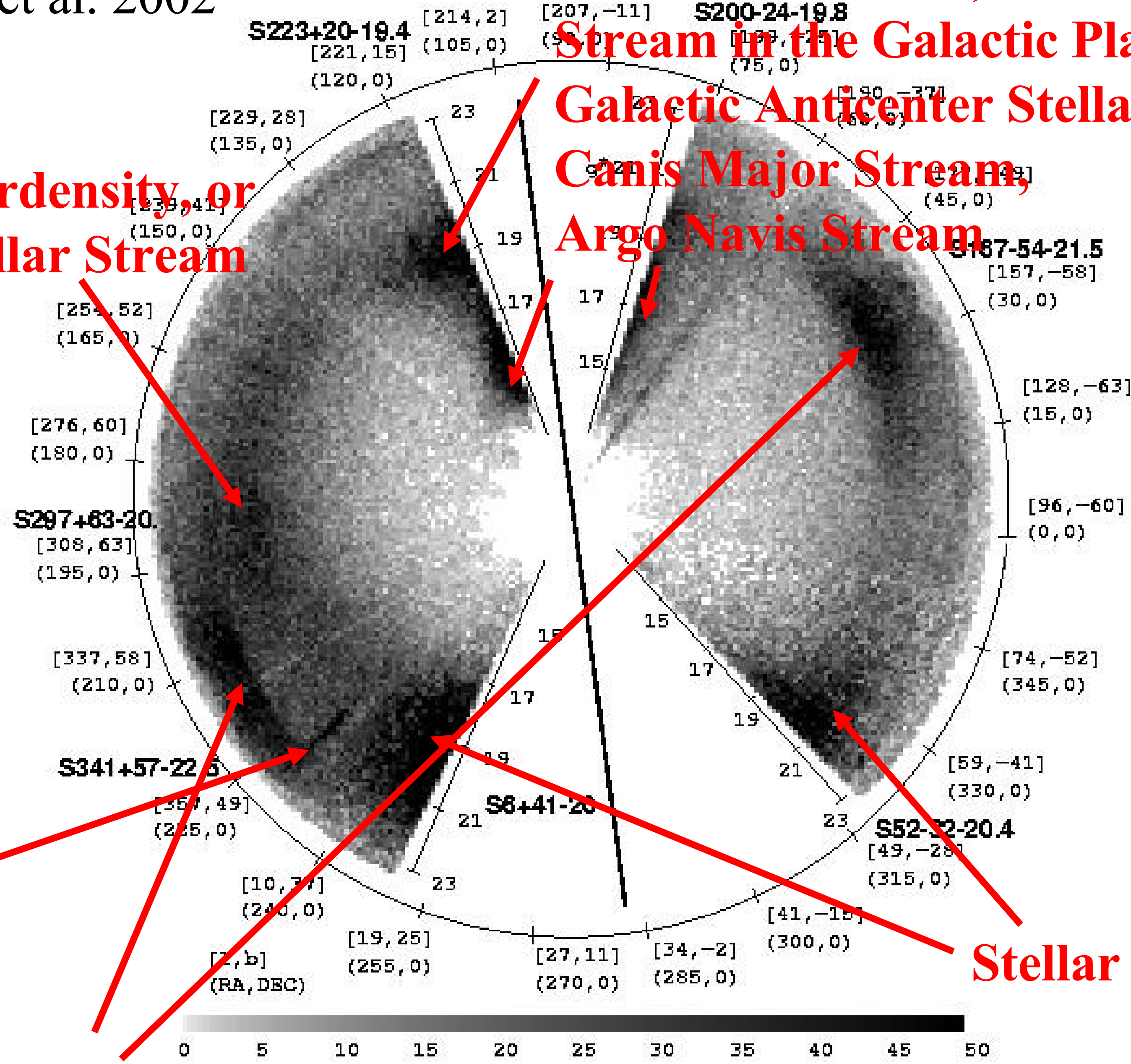
Progress is made by simplifying the problem, and reducing the data set.


Celestial Equator
Sagittarius
Dwarf
Galaxy (core)

Newberg et al. 2002



Newberg et al. 2002

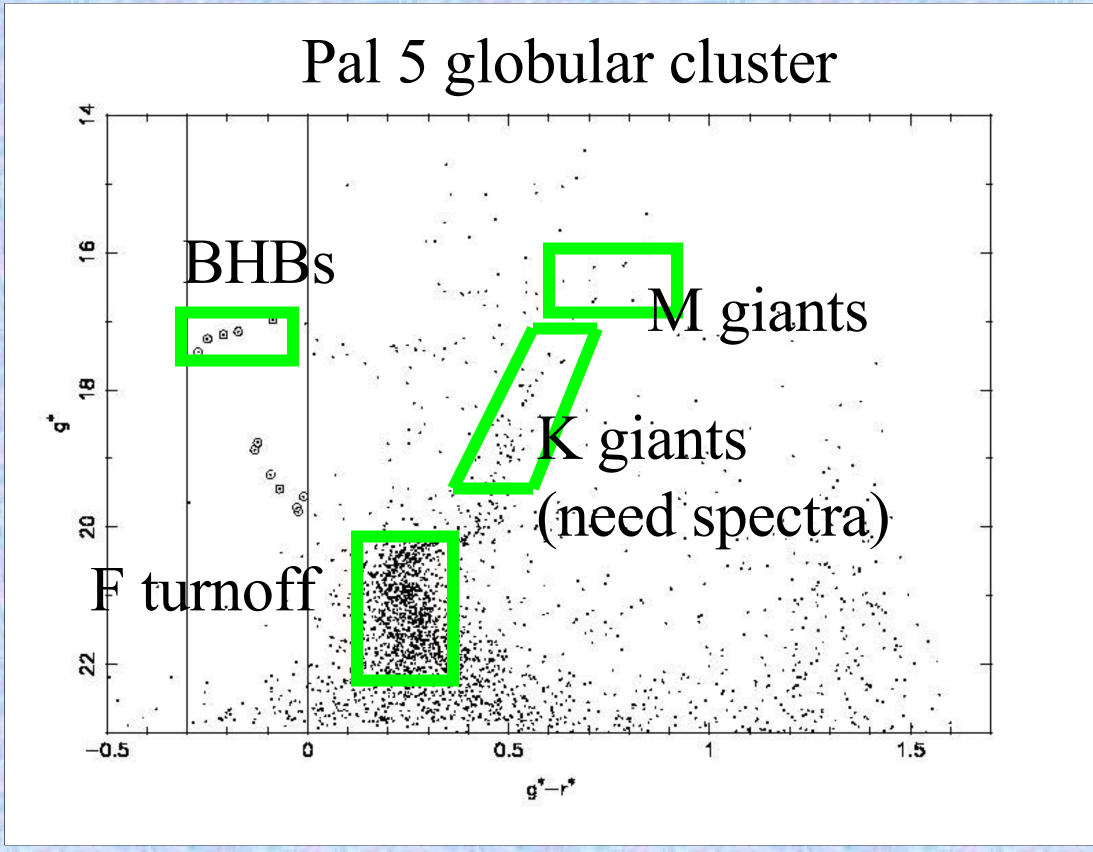


Spheroid Substructure ~~Today~~

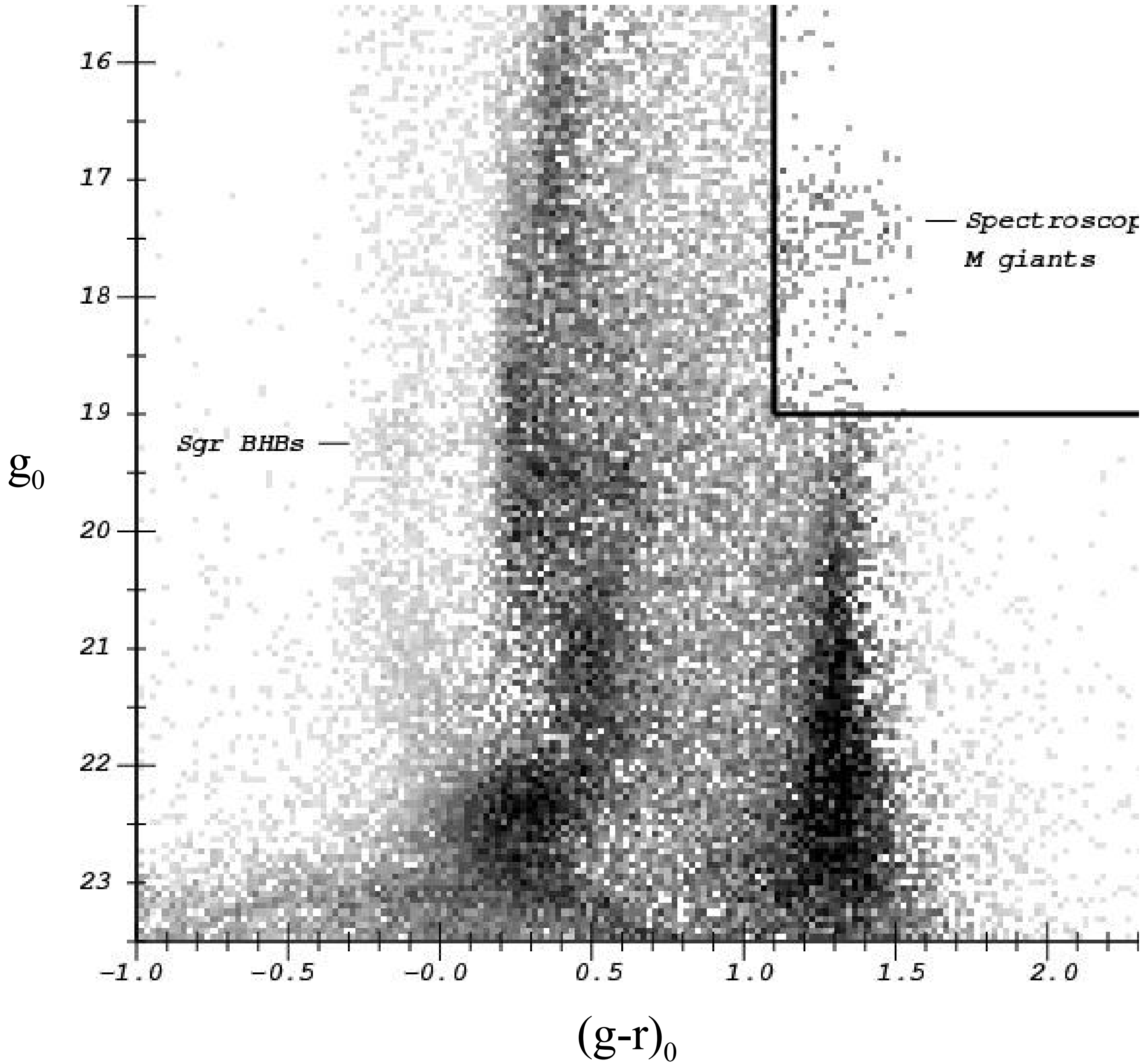
Yesterday

Techniques for finding spatial substructures

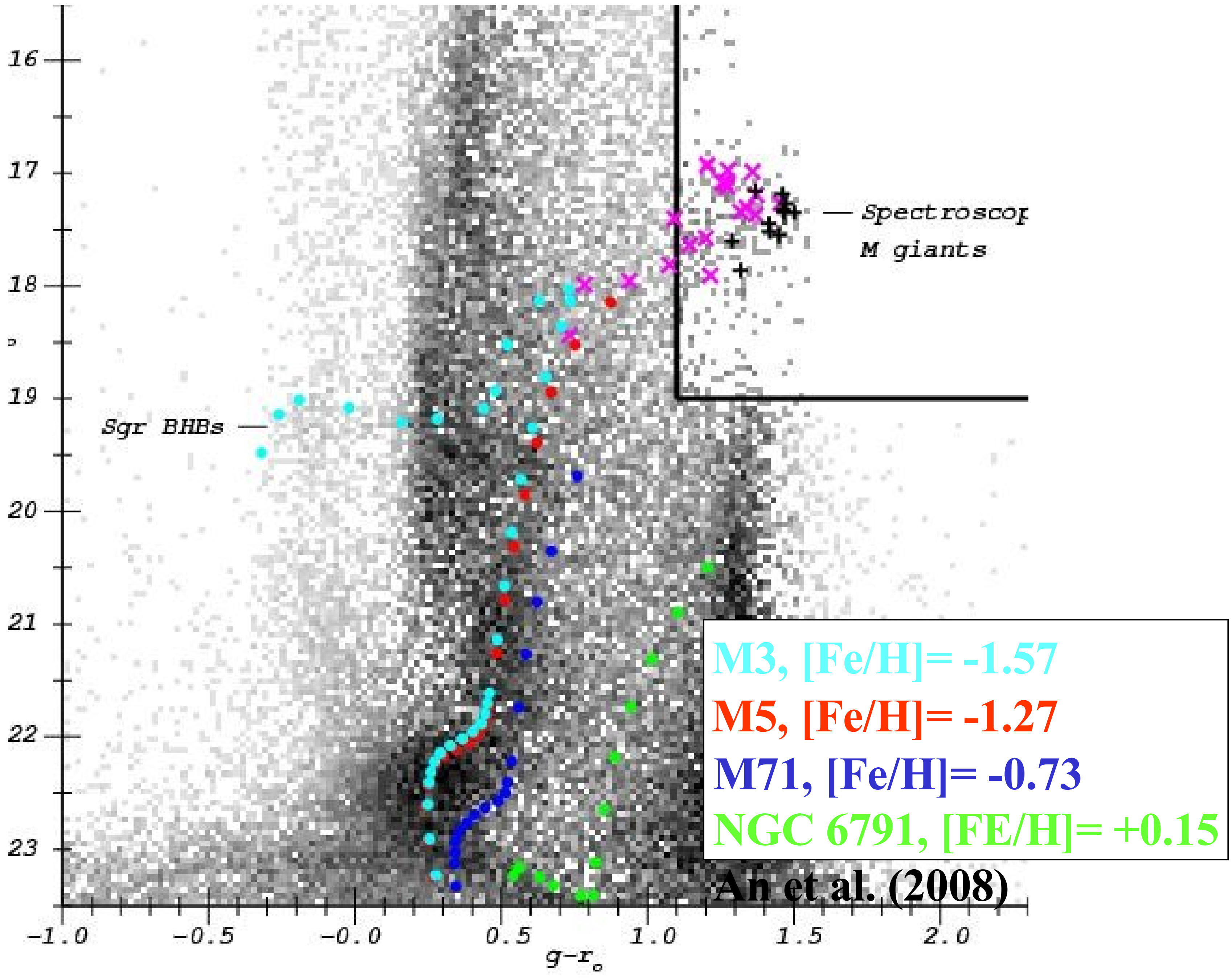
(1) Select a tracer of known luminosity to use as a distance indicator.
(2) Select a tracer that can be used statistically to measure distance to a structure
(3) Convolve with a presumed color-magnitude distribution



Yanny et al. 2000



16
17
18
19
20
21
22
23
g_0
Spectroscop
M giants
Sgr BHBs
−1.0
−0.5
−0.0
0.5
1.0
1.5
2.0
$(g\text{-}r)_0$


16
17
18
19
20
21
22
23
Spectroscop
M giants
Sgr BHBs
M3, [Fe/H]= -1.57
M5, [Fe/H]= -1.27
M71, [Fe/H]= -0.73
NGC 6791, [FE/H]= +0.15
An et al. (2008)
-1.0
-0.5
-0.0
0.5
1.0
1.5
2.0
g-r₀

Summary of Spheroid Substructure

Dwarf galaxy streams:

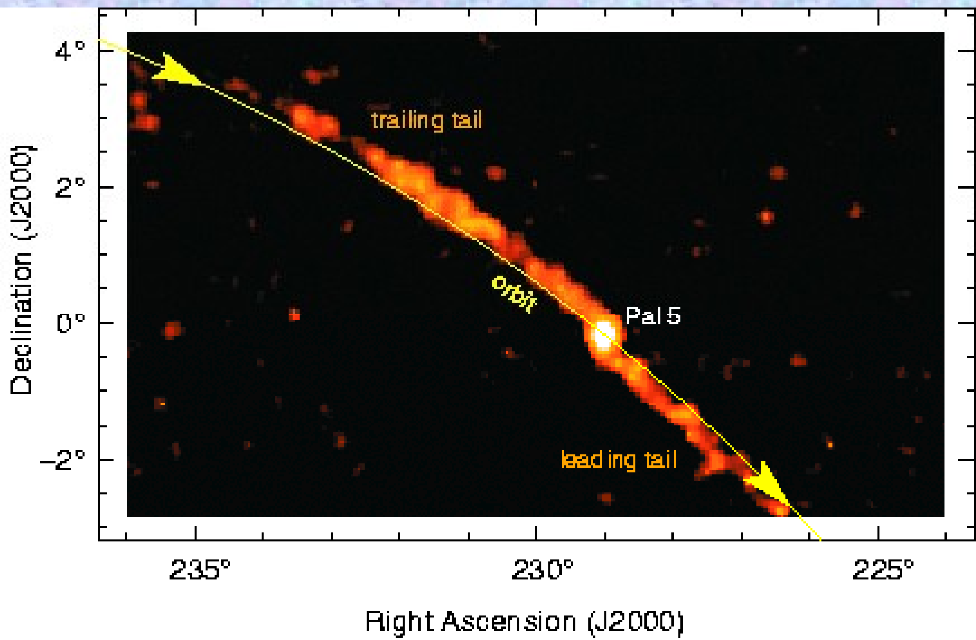
(1) Sagittarius: Ibata et al. 2001a, Ibata et al. 2001b, Yanny et al. 2000

(2) Canis Major/Argo Navis? →Monoceros (Newberg et al. 2002, Yanny et al. 2003), GASS (Frinchaboy et al. 2004), TriAnd (Majewski et al. 2004), TriAnd2 (Martin, Ibata & Irwin 2007), tributaries (Grillmair 2006)

(3) ?? Orphan stream, Grillmair 2006, Belokurov et al. 2006

(4) ?? Virgo Stellar Stream, Vivas et al. 2001, Newberg et al. 2002, Zinn et al. 2004, Juric et al. 2005, Duffau et al. 2006, Newberg et al. 2007

Odenkirchen et al. 2003



Globular cluster streams:

- Pal 5: Odenkirchen et al. 2003

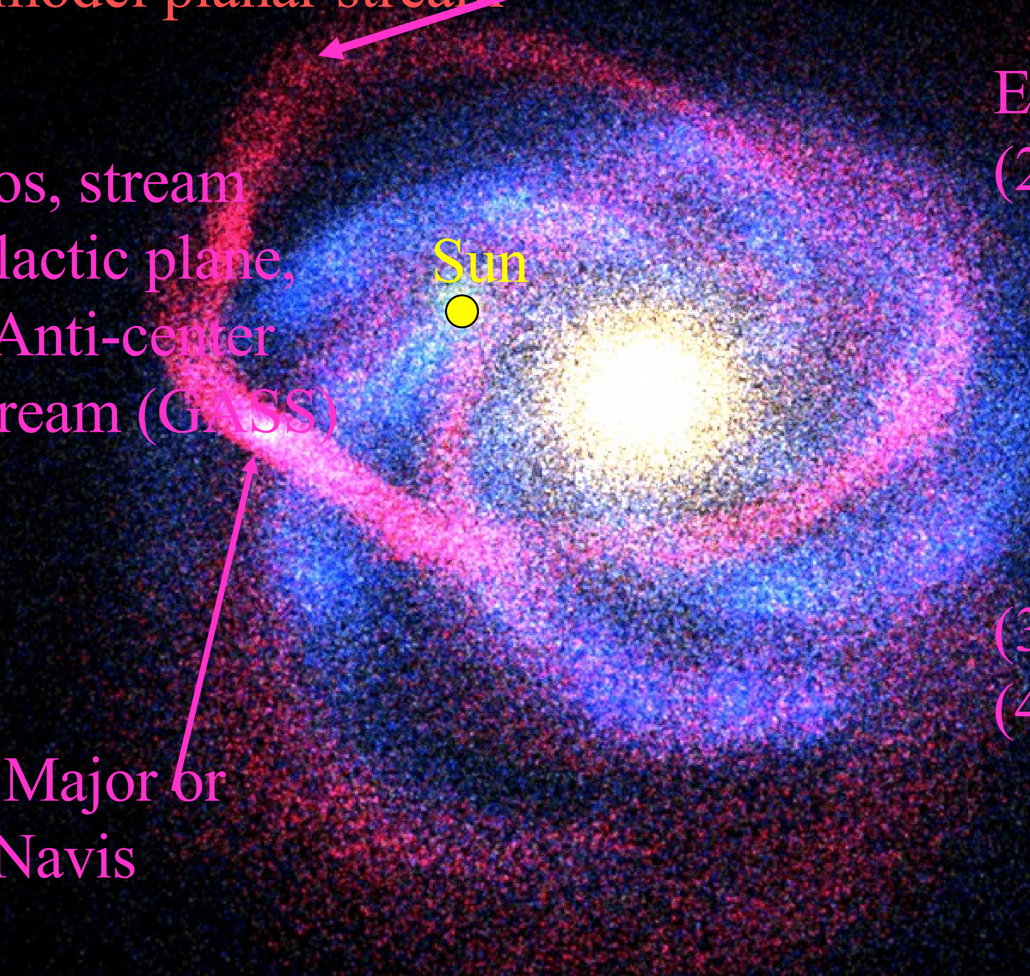
(2) ?? Grillmair & Dionatos 2006

(3) NGC 5466: Grillmair & Johnson 2006

Other:

(1) Hercules-Aquila Cloud

Tidal Stream in the Plane of the Milky Way



Explanations:

(2) One or more pieces of tidal debris; could have puffed up, or have become the thick disk.

(3) Disk warp or flare

(4) Dark matter caustic deflects orbits into ring

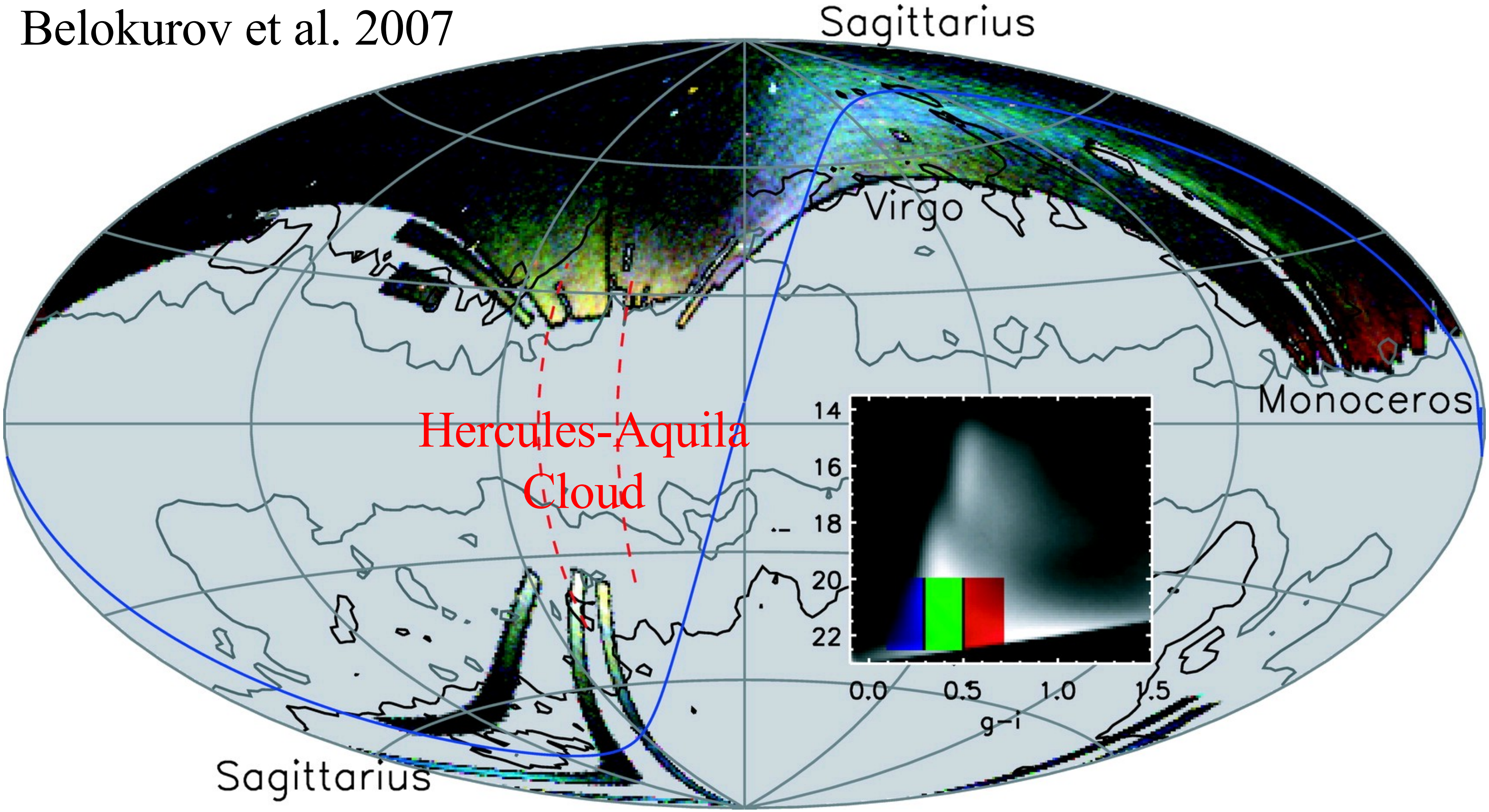
If it's within 30° of the Galactic plane, it is tentatively assigned to this structure

Press release, November 4, 2003

Global properties of the spheroid

- Juric et al. (2008) – Distance estimates to 48 million stars, fit smooth components and identify large lumps
- Bell et al. (2008) – Smooth power law is a very poor fit to the spheroid density, 4 million F turnoff stars
- Xue et al. (2008) – 2401 BHB stars fit rotation curve of Galaxy to find dark matter halo mass of 1×10^{12} solar masses
- Carollo et al. (2008) – Two component spheroid model, kinematics of 10,123 F subdwarfs within 4 kpc of the Sun

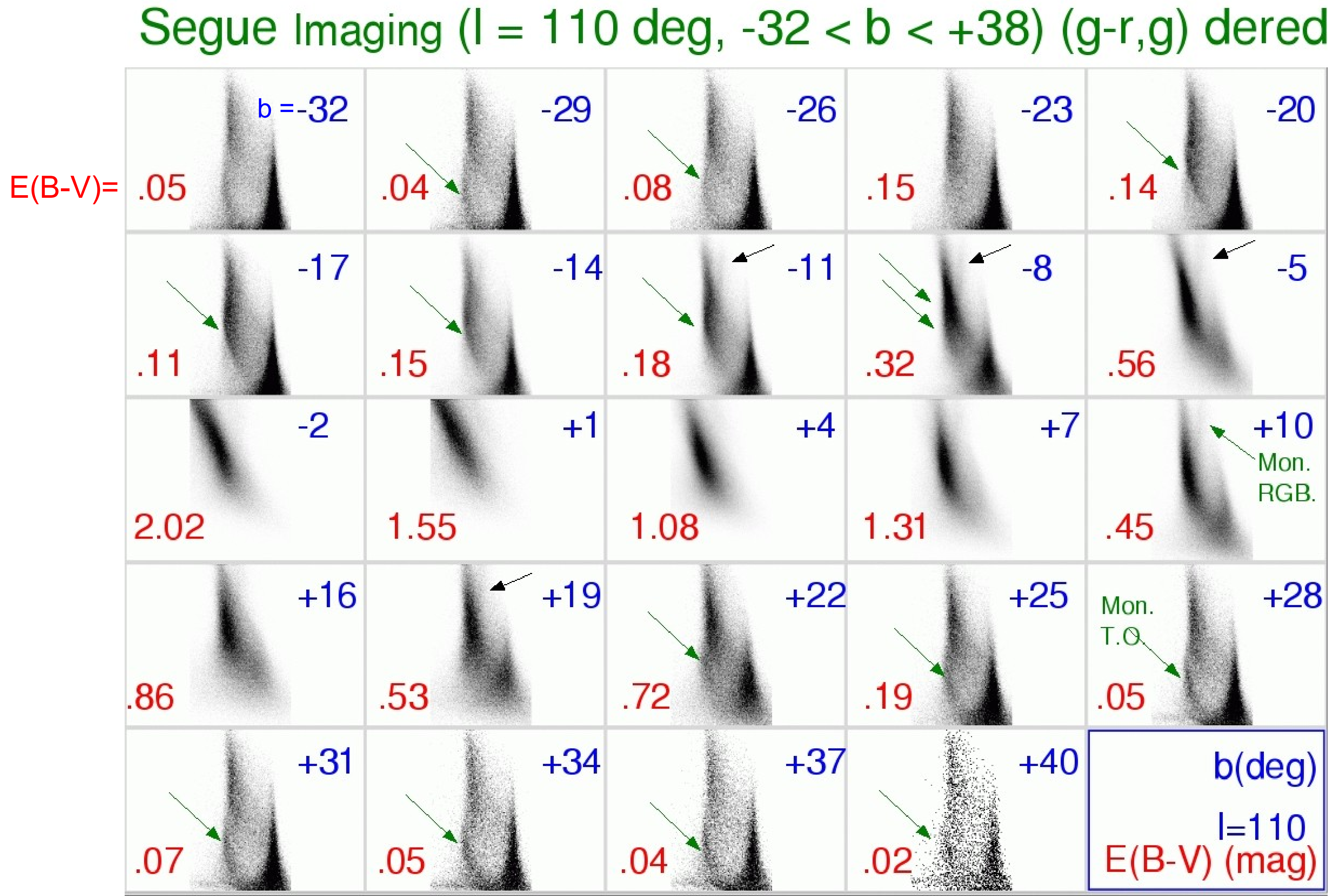
Belokurov et al. 2007



Areal density of SDSS stars with 0.1<g-i<0.7 and 20<i<22.5 in Galactic coordinates. The color plot is an RGB composite with colors representing regions of the CMD as shown in the inset. The estimated distance to the cloud is 10-20 kpc.

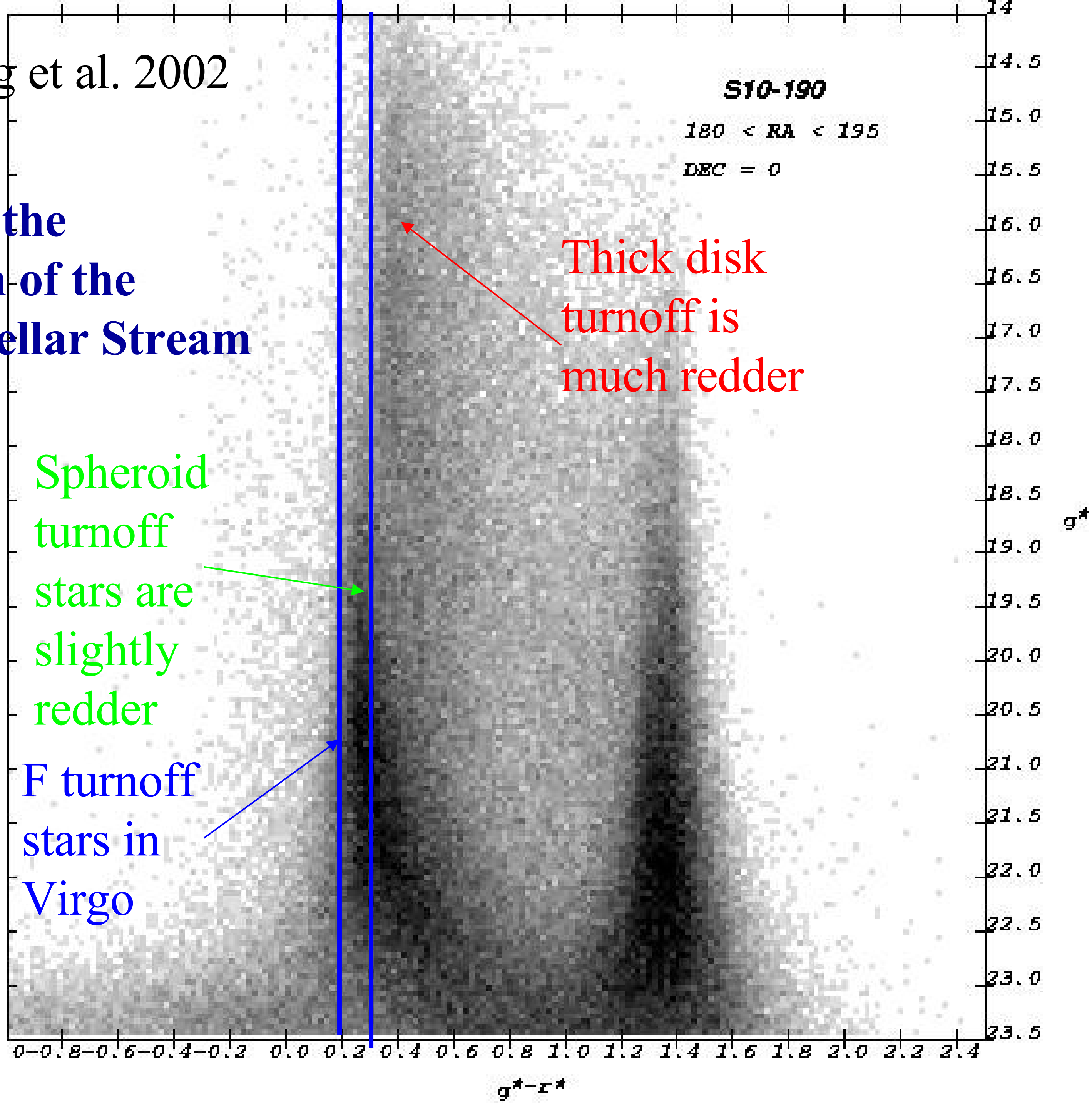
Turnoffs and Giant Branches visible, even at low latitudes

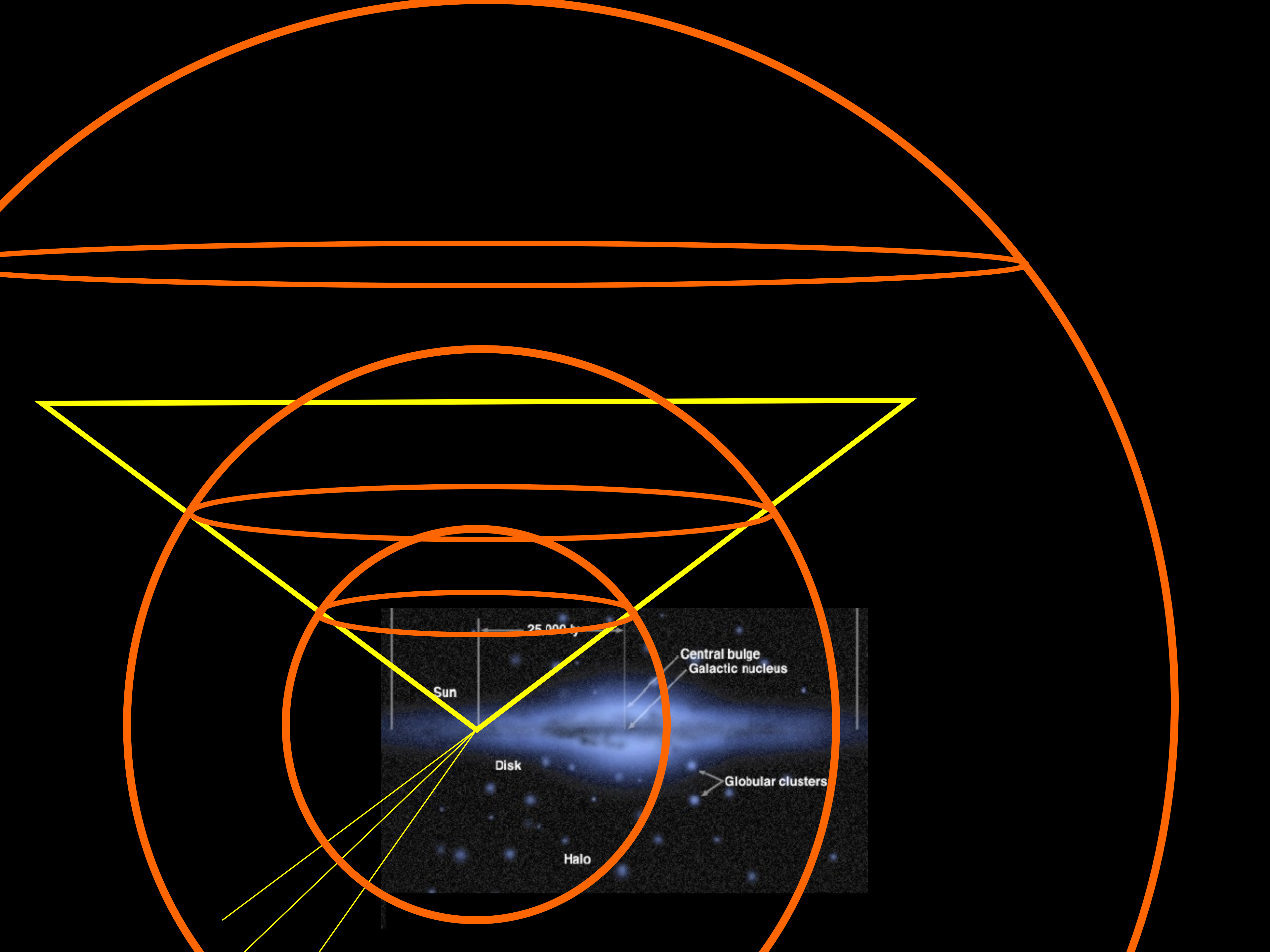
Brian Yanny, private communication



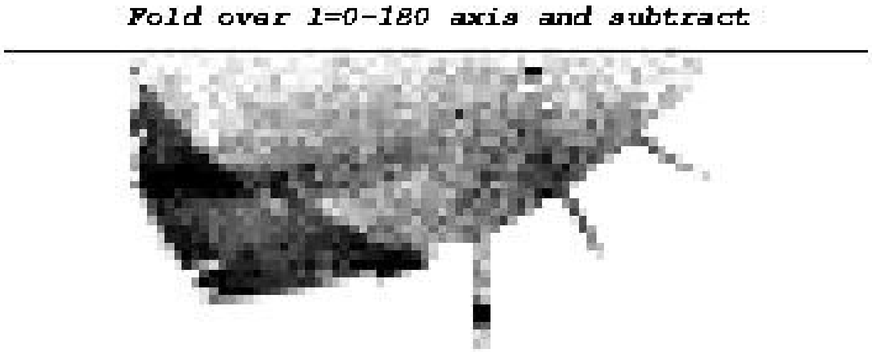
Newberg et al. 2002

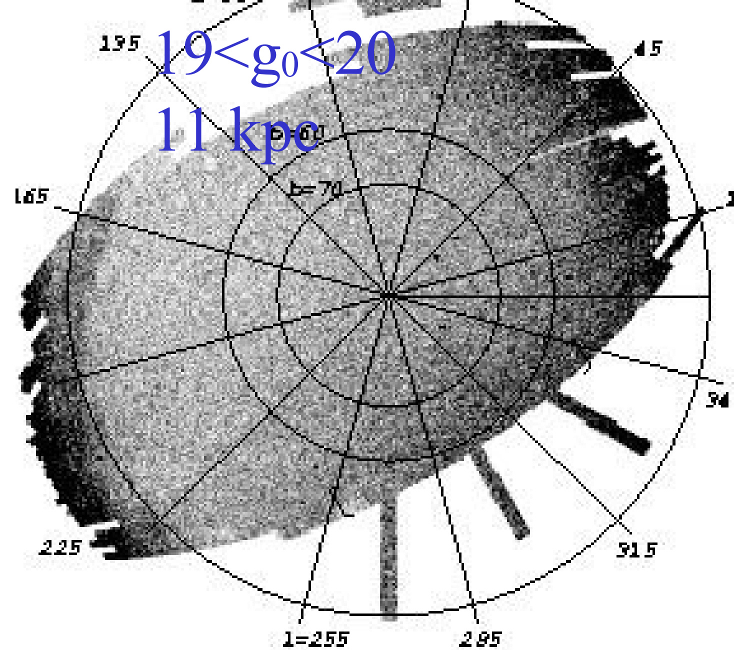
CMD in the direction of the Virgo Stellar Stream



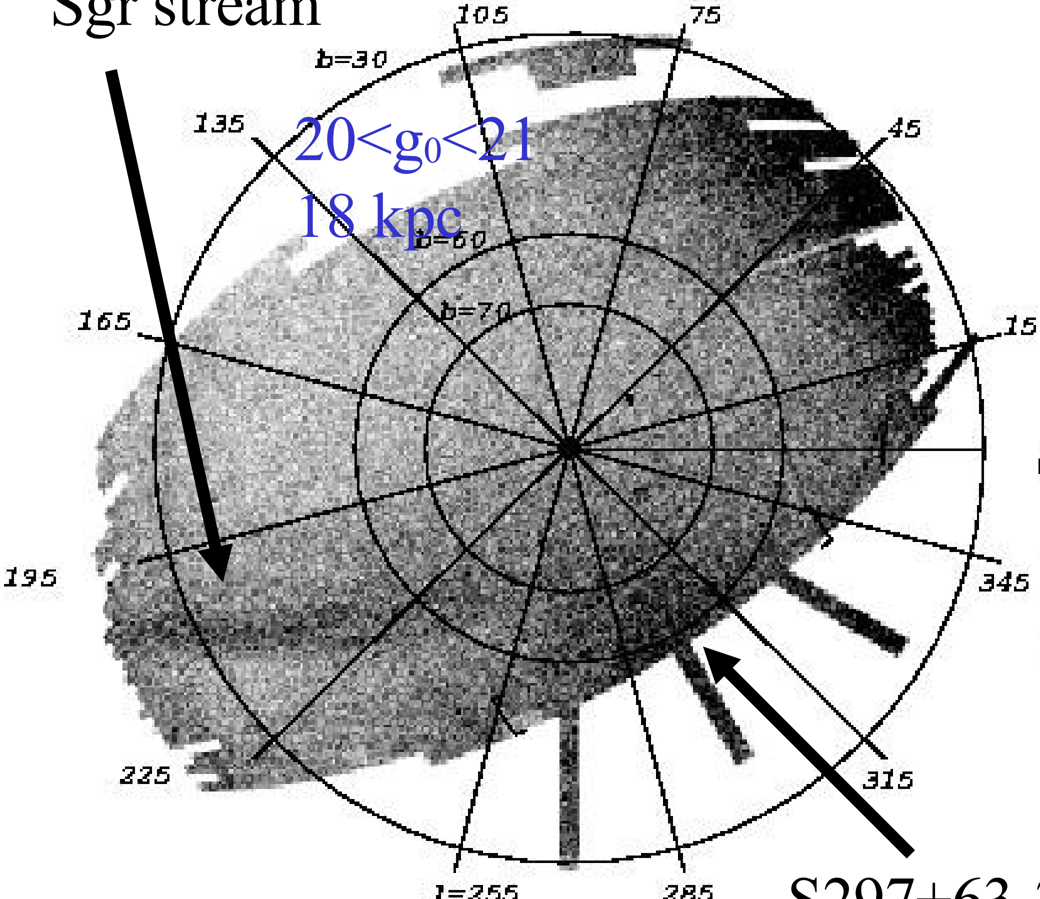


Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo

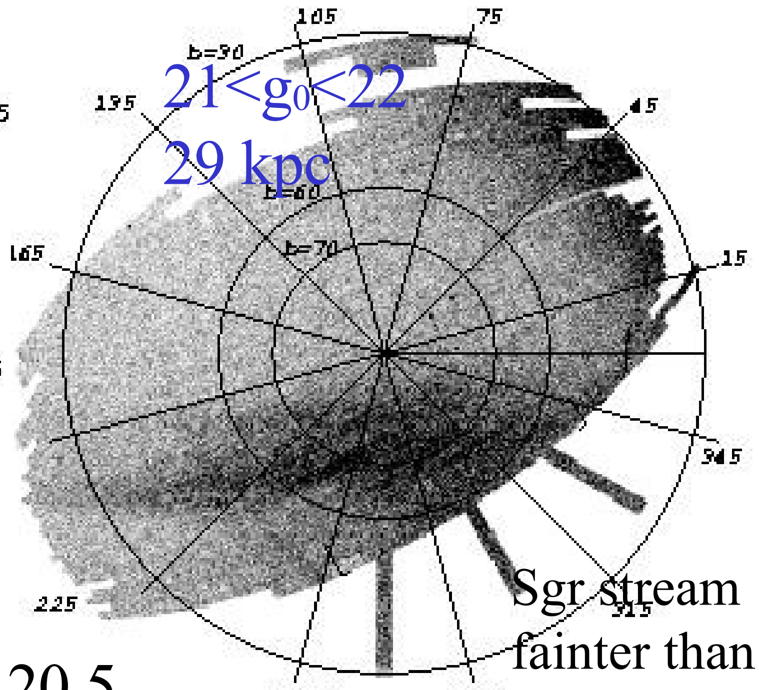




Sgr stream



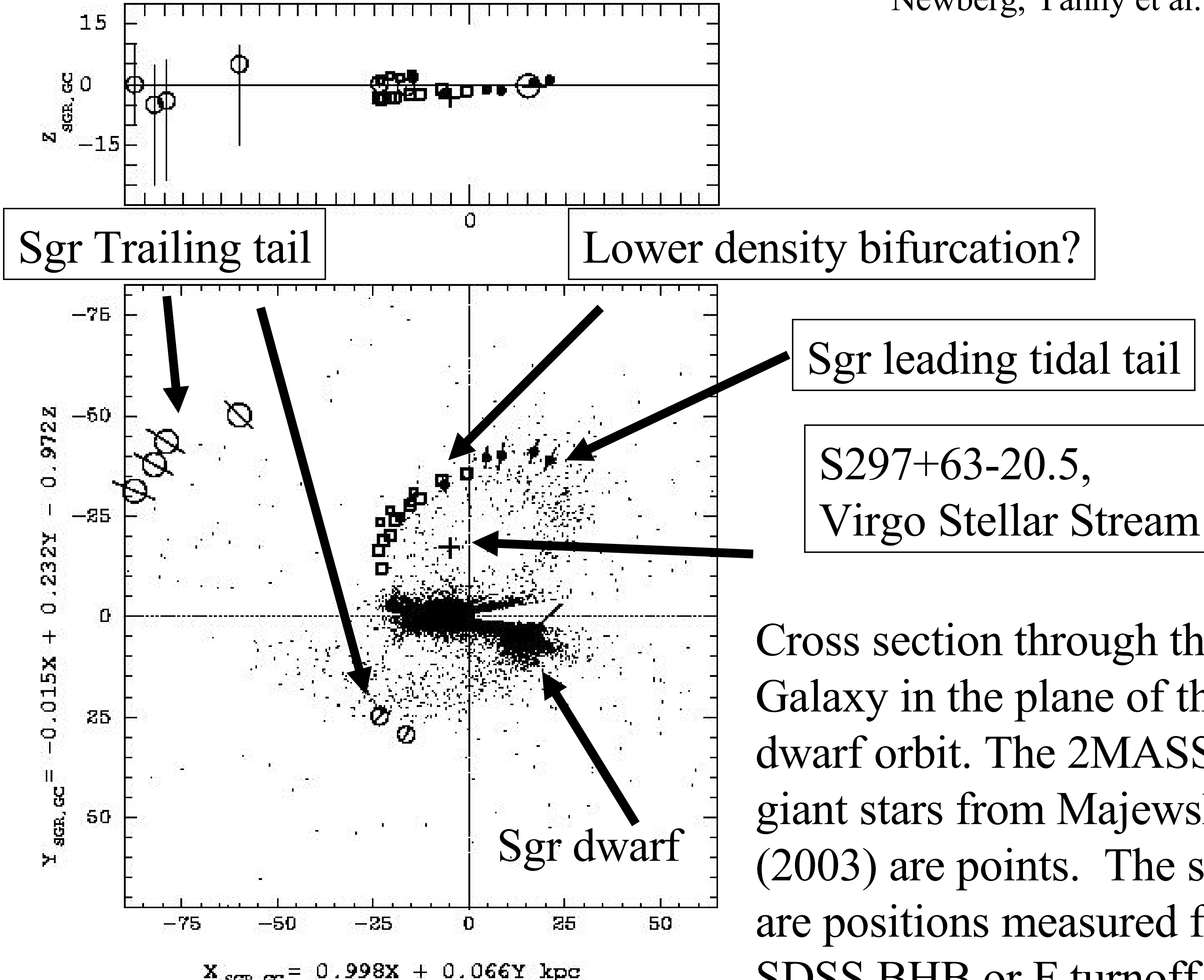
S297+63-20.5



Sgr stream fainter than S297+63-20.5

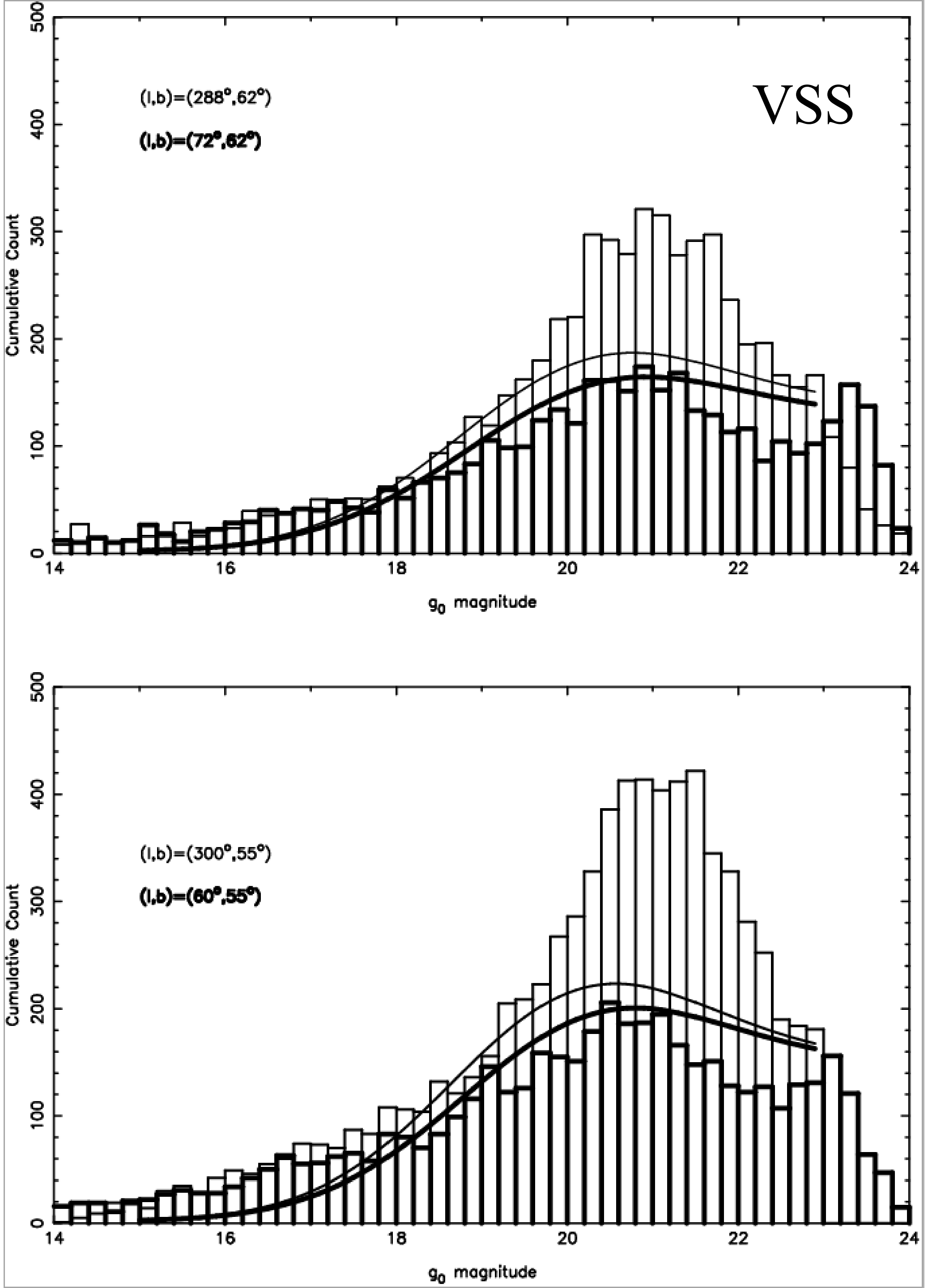
Newberg, Yanny et al. 2007

Newberg, Yanny et al. 2007



Cross section through the Galaxy in the plane of the Sgr dwarf orbit. The 2MASS M giant stars from Majewski et al. (2003) are points. The symbols are positions measured from SDSS BHB or F turnoff stars.

Newberg, Yanny et al. (2007)

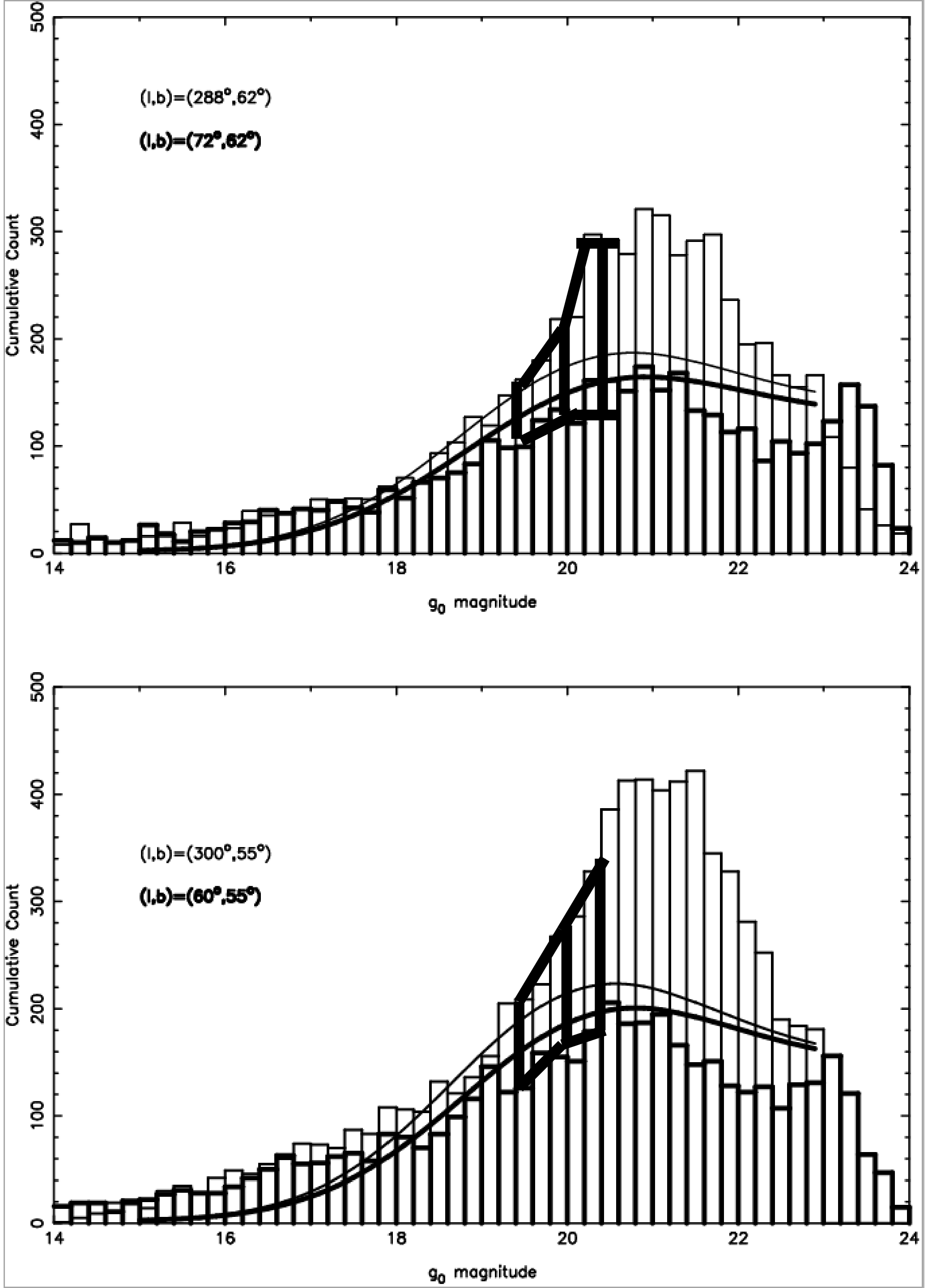


Counts of F turnoff stars with $0.2<(g-r)_0<0.4$.

We compare one sight line in Virgo with the symmetric point with respect to the Galactic center. In a symmetric spheroid, the star counts in the two directions should be the same.

Models are Galactocentric triaxial Hernquist profiles.

Newberg, Yanny et al. (2007)

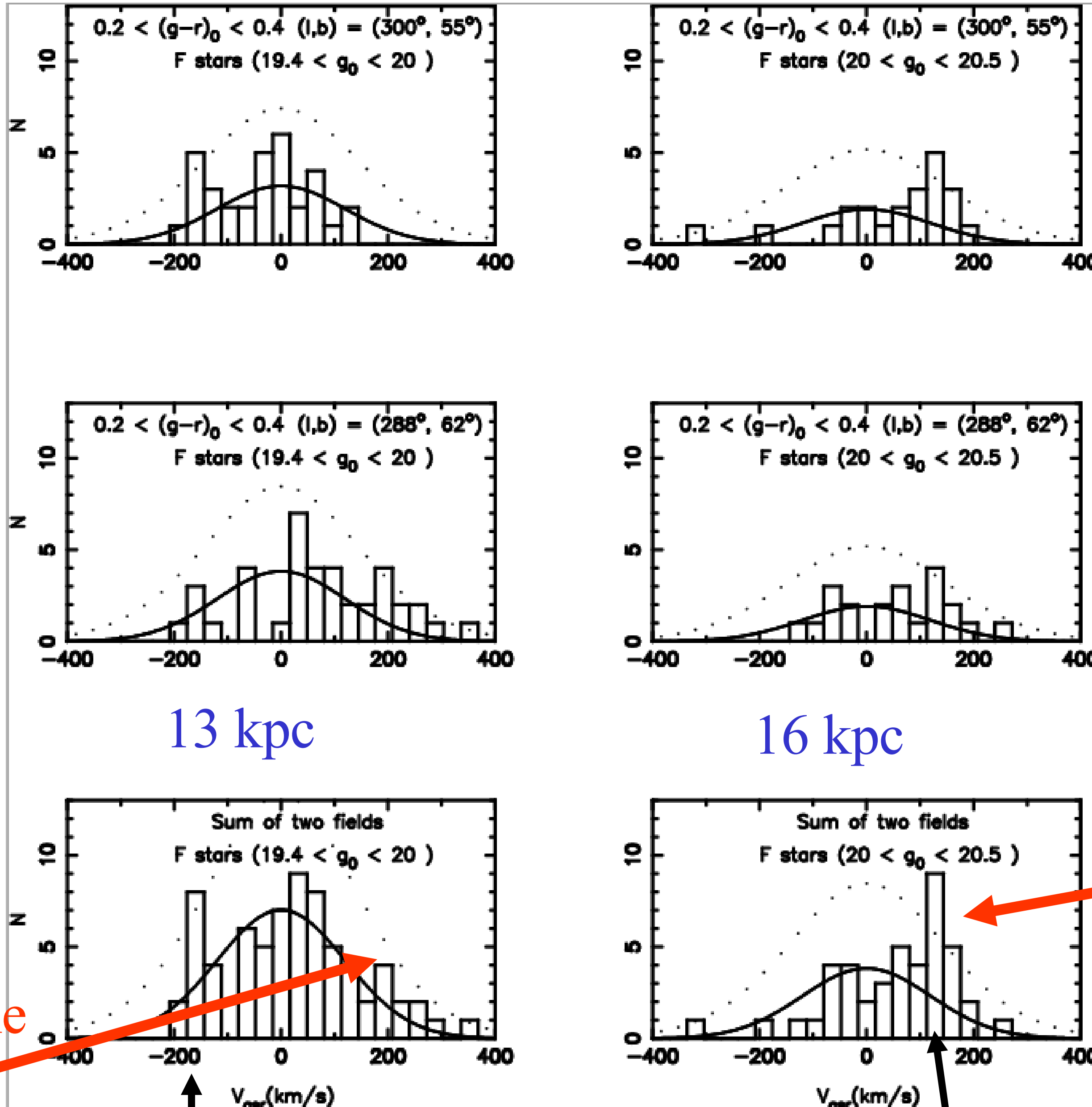


In a symmetric spheroid, we expect **37±4%** of the stars with $19.4<g_0<20.0$ to have coherent velocities, an **46±5%** of the stars with $20.0<g_0<20.3$ to have coherent velocities.

(300°,55°)

VSS field

Sum of the two



13 kpc

16 kpc

40±11% of the stars are in the peak.

<10% of the brighter stars are in the peak.

Vgsr=-168±10 km/s

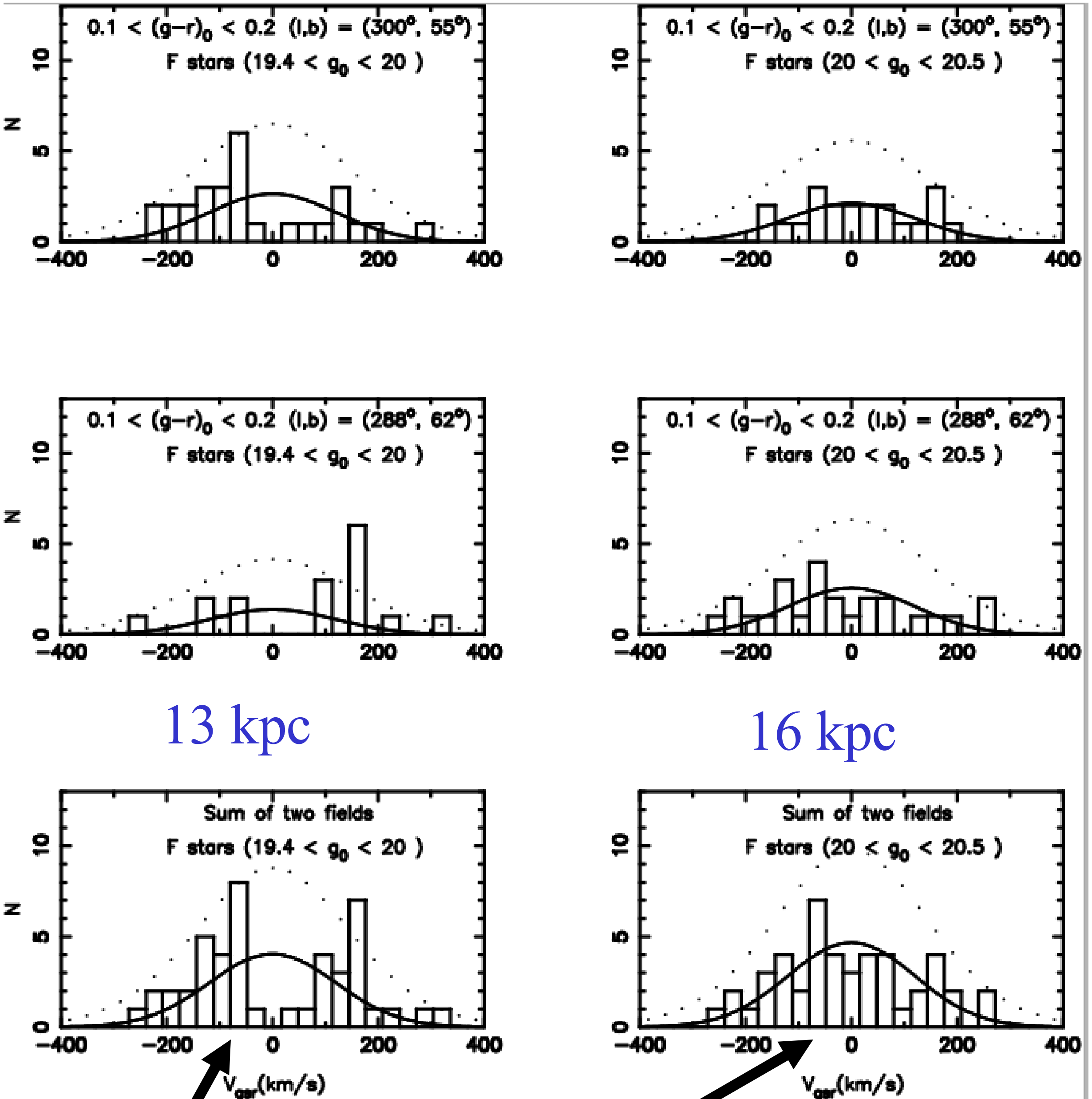
S297+63-20.5

Vgsr=130±10 km/s

(300°,55°)

VSS field

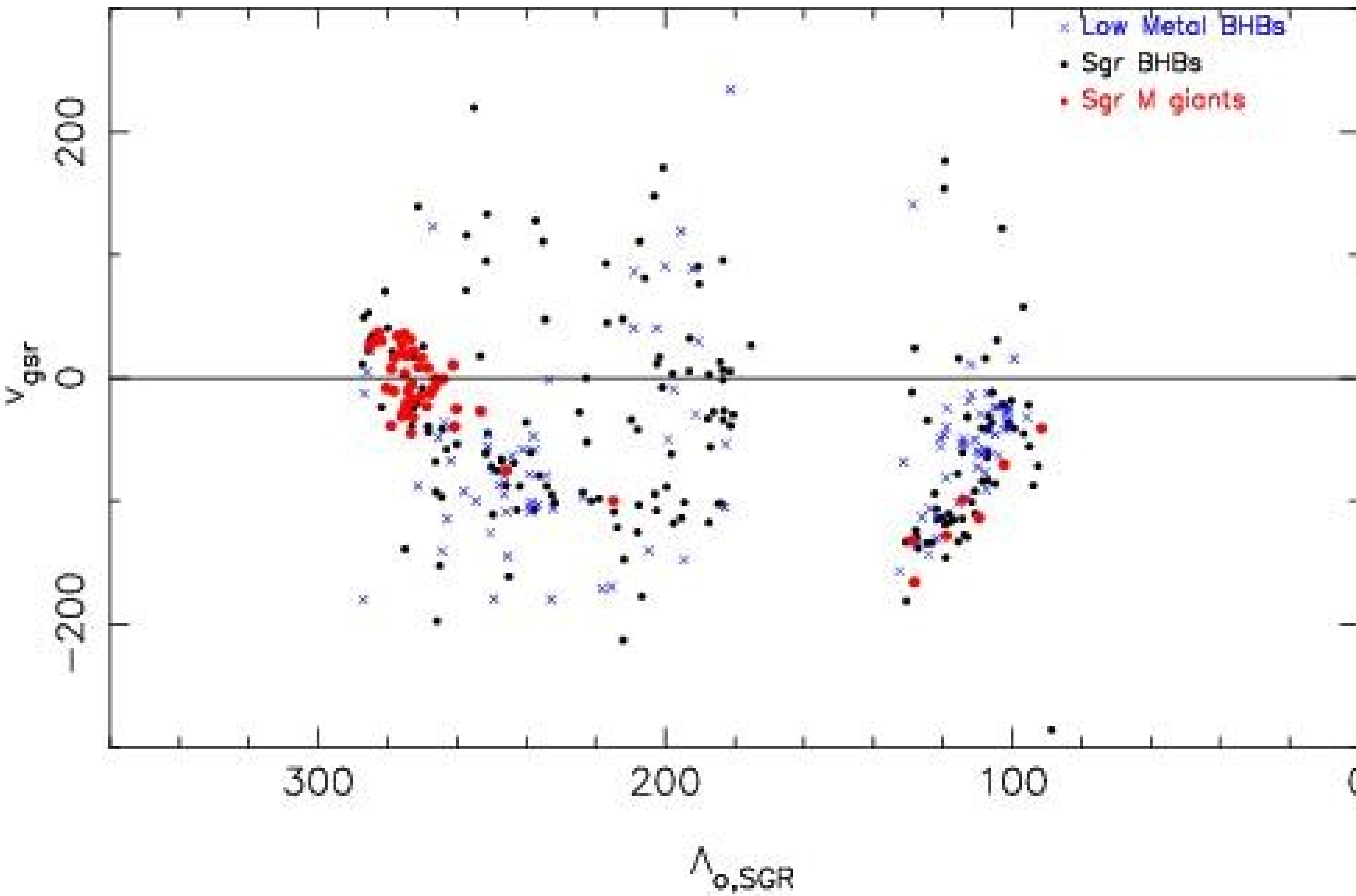
Sum of the two



Vgsr=-76±10 km/s

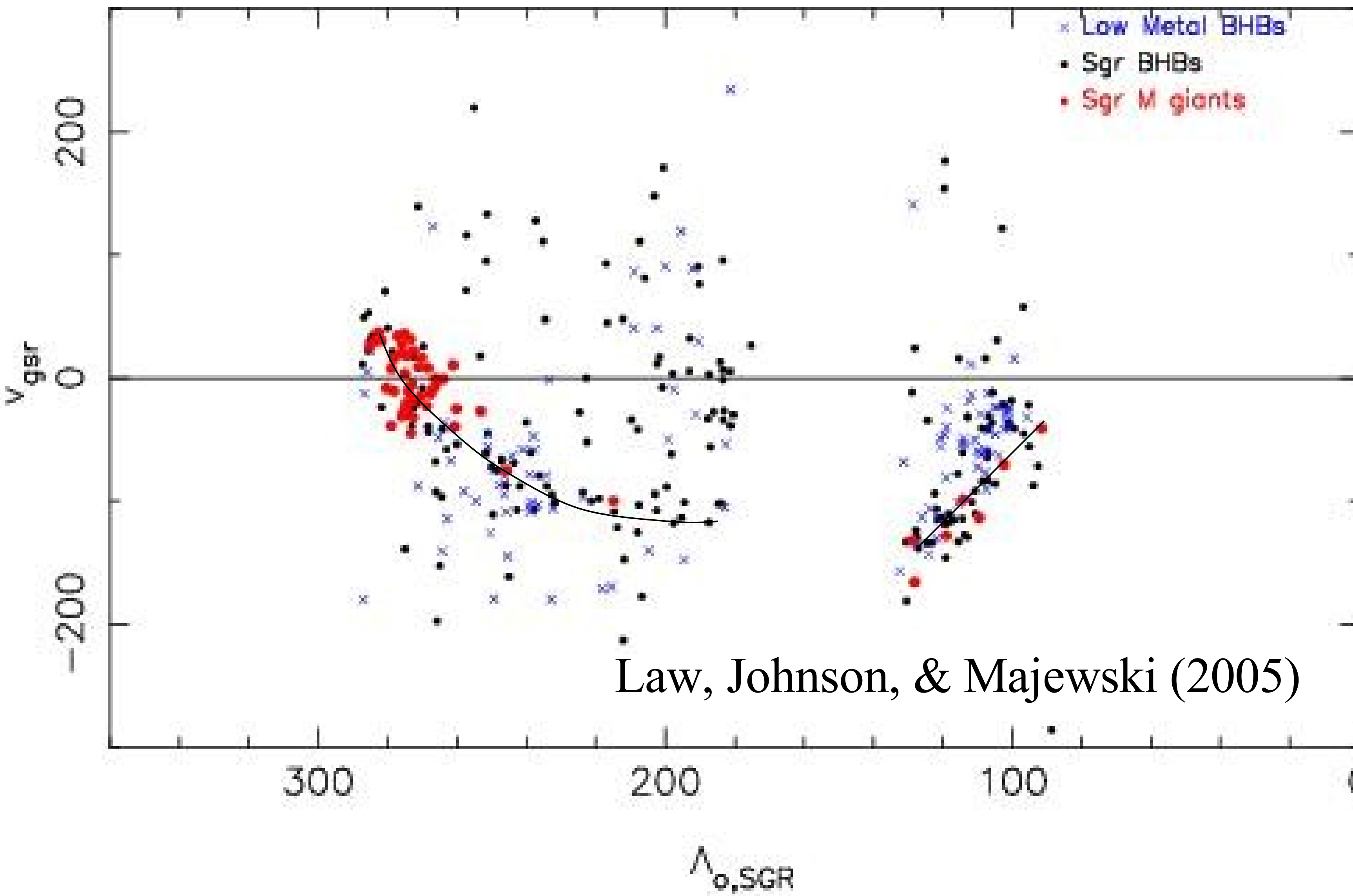
Velocity trend in Sgr tidal stream

Yanny et al., in preparation



SDSS spectroscopy of stars that are spatially in the Sgr tidal stream.

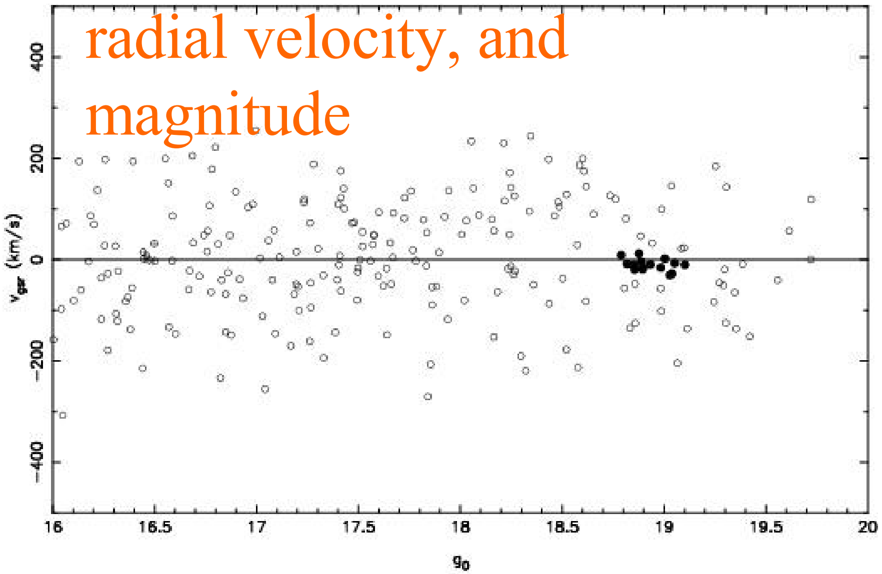
Yanny et al., in preparation



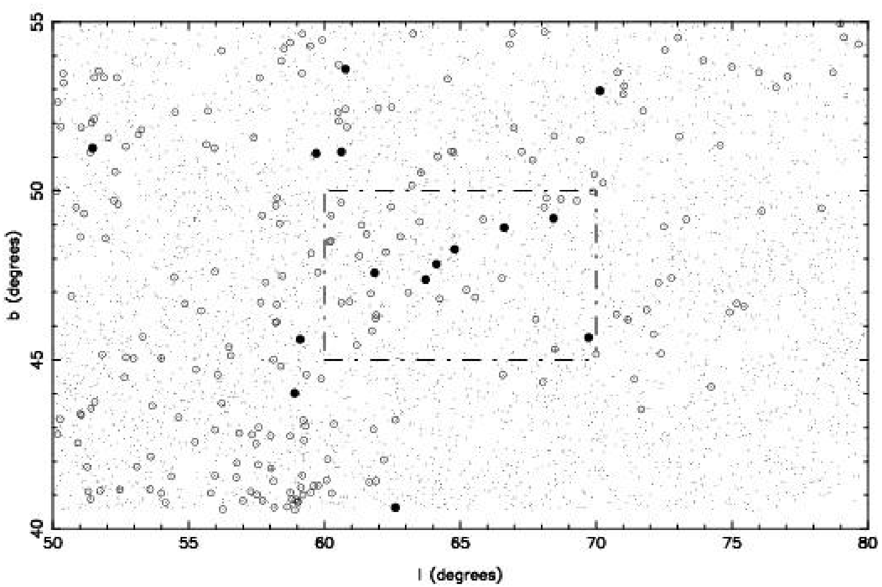
SDSS spectroscopy of stars that are spatially in the Sgr tidal stream.

The Big Toe of Hercules

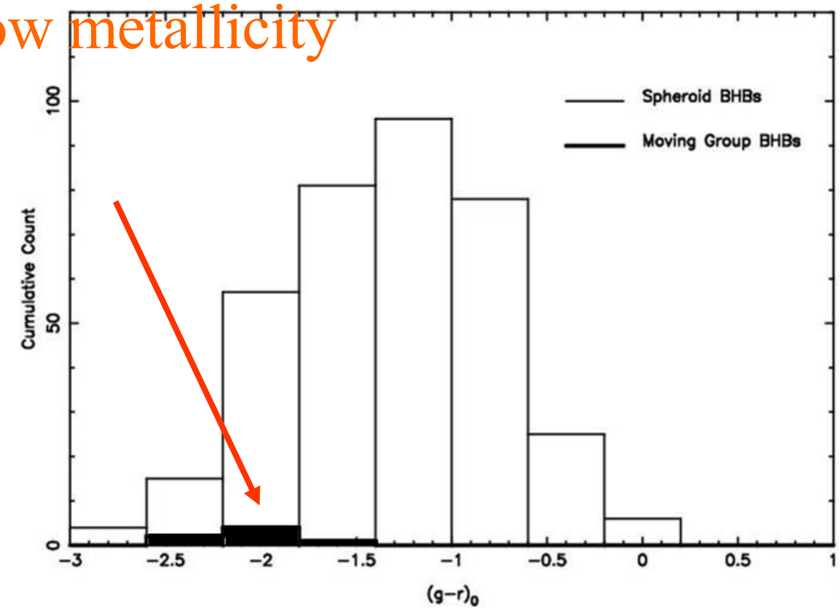
Clumped in position, radial velocity, and magnitude



Undergraduate Matt Harrigan used SDSS/SEGUE spectroscopy of BHB stars to find a moving group of half a dozen stars in the constellation Hercules



Significantly low metallicity



Outstanding Problems

- The data is more complex than the models, both for the structure and dynamics of spheroid substructure. How do we compare them?
- What does the dark matter potential of the Milky way look like? We have yet to successfully extract information about the Galactic potential from tidal streams.
- How many stellar components are there in the Milky Way, and how do we describe them?
- What is the detailed structure of the Milky Way's disk? How is it related to Monoceros/ Canis Major?
- How many small galaxies merged to create the Milky Way, and when?
- Describe the chemical evolution of the Galactic disk(s).
- So far, advances have primarily come from reducing the data size to analyze very clean samples. How do we utilize all of the partial chemical, kinematic, and spatial information at the same time?

The Future of Galactic structure

Yesterday we heard the wonderful progress being made in understanding galaxy evolution by statistical studies of external galaxies.

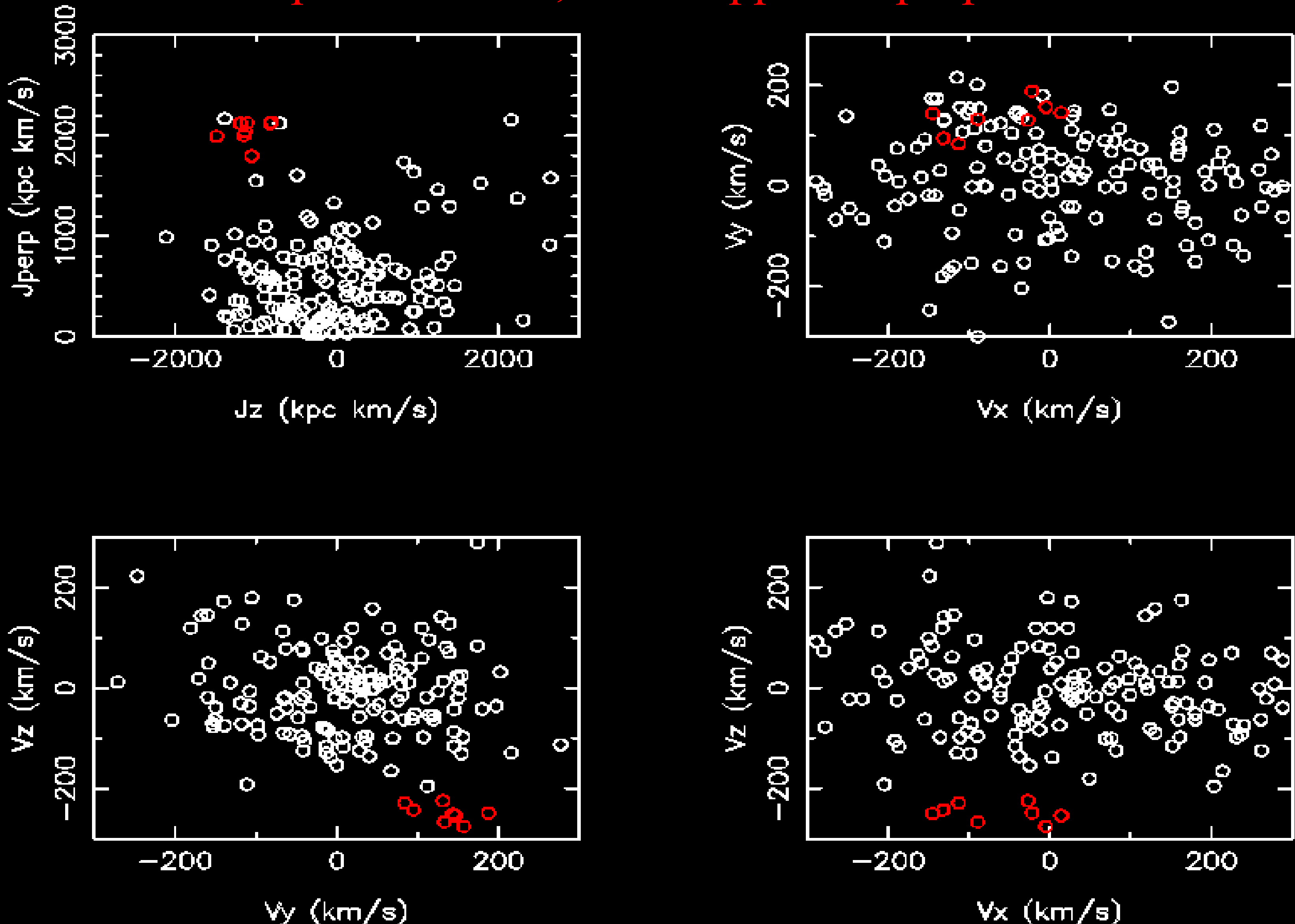
In the Milky Way, we have the opportunity to learn the whole history of one galaxy instead of comparing snapshots of many. It is only now that we have large surveys of the whole sky that we are able to comprehend the Milky Way as a whole. Unlike external galaxies, the picture we are building is in three dimensions of position and velocity.

Many surveys currently in progress will provide multi-color imaging of the sky. However, there is a great need for spectroscopic surveys of millions of stars.

Twenty years ago, when the idea for the SDSS was born, large scale structures of galaxies had just been discovered. But there was structure on all scales of the largest surveys of the day. There was a pressing need for a larger spectroscopic survey.

We are at the same place now in the study of the Milky Way. Spatial substructure and moving groups are found in every spectroscopic sample of spheroid stars that is well constrained in position and stellar type. It is guaranteed that a larger survey will reveal more substructure.

Stars within 1 kpc of the Sun, with Hipparcos proper motions



Following Helmi et al. 1999

Tidal streams separate in angular momentum
– need 3D position and velocity through space.

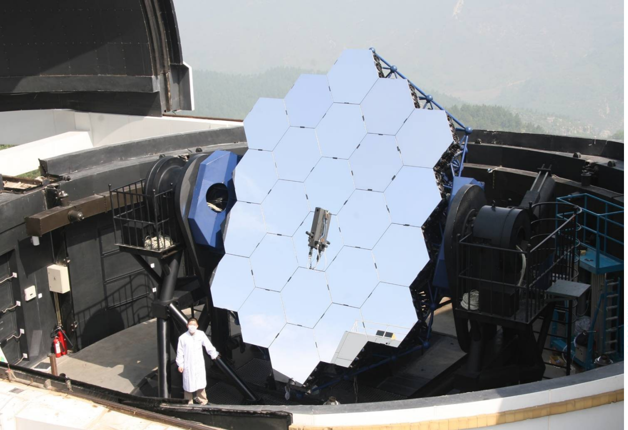
GAIA Astrometric Satellite

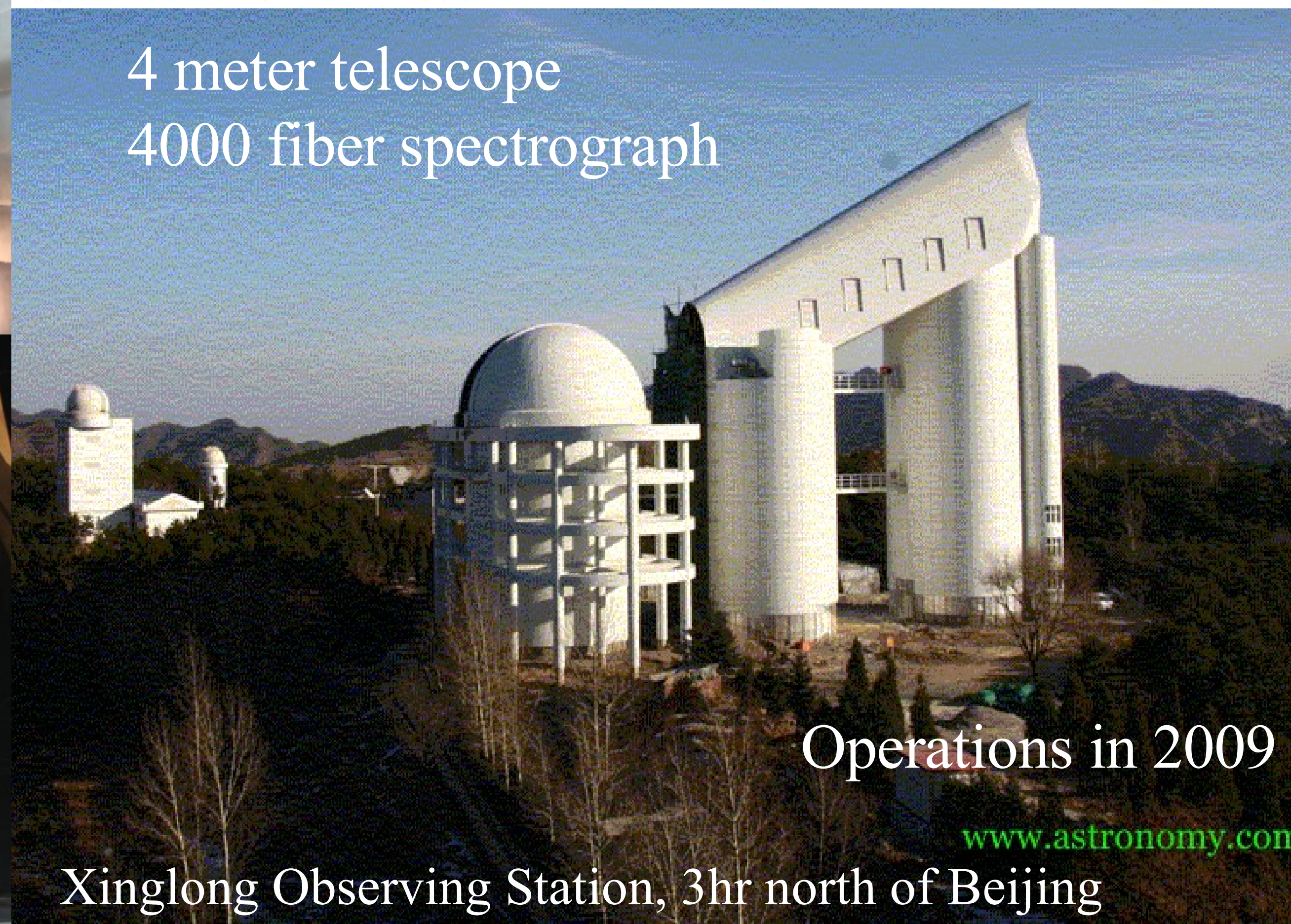
Magnitude limit: 20
1 billion Galactic stars
Astrometry and radial velocities
2011-2020

Will only get radial velocities for stars brighter than 17^{th} magnitude!

With LAMOST, radial velocities can be obtained for the most interesting magnitude range of $17<V<20$

Other large spectroscopic surveys of stars include RAVE (brighter), SDSS III/ SEGUE II (250,000 stars), and WFMOS (in planning stages).





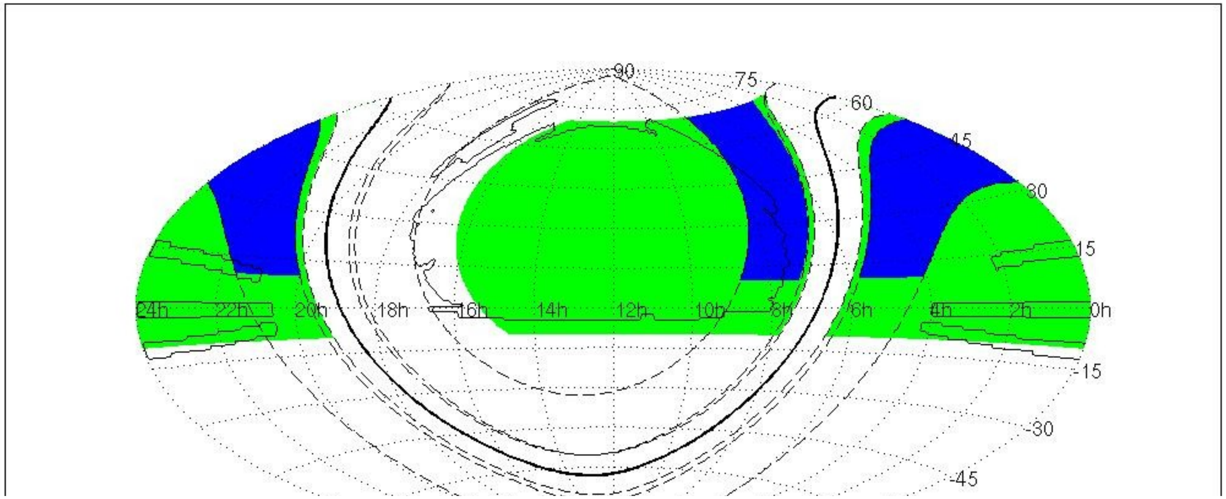
4 meter telescope
4000 fiber spectrograph
Operations in 2009
Xinglong Observing Station, 3hr north of Beijing

The Promise of LAMOST

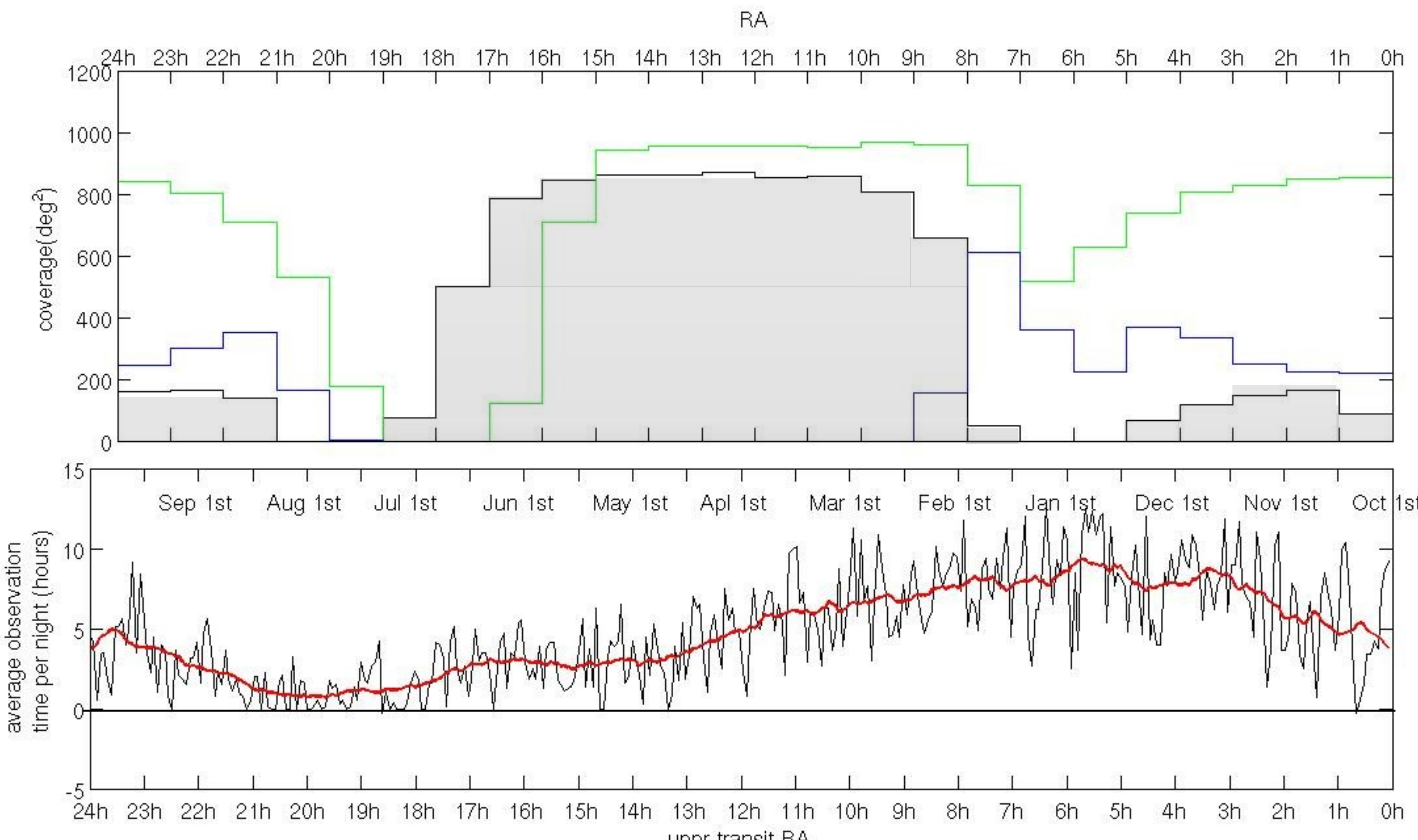
4000 fibers, 4 meter telescope, first light expected December 8, 2008. R=1000/2000, maybe 5000/10,000 gratings in the future.

Two million spectra per year.

Because I believe that LAMOST has the best potential for unraveling the formation history and dark matter potential of the Milky Way galaxy, I will travel 12 time zones 8 times in two years, have committed my sabbatical this year to LAMOST survey planning and design, and started learning Chinese.



The Challenge of LAMOST



LAMOST has strong constraints in declination, angle from the meridian, spacing of the fibers, and weather.

Participants in LAMOST, US (PLUS)

Heidi Newberg (Rensselaer), Timothy Beers (Michigan State), Xiaohui Fan (Arizona), Carl Grillmair (IPAC), Raja Guhathakurta (Santa Cruz), Jim Gunn (Princeton), Zeljko Ivezic (U. Washington), Sebastien Lepine (AMNH), Jordan Raddick (education, Johns Hopkins), Alex Szalay (JHU), Jason Tumlinson (StSci), Beth Willman (CfA), Rosie Wyse (JHU), Brian Yanny (FNAL), and Zheng Zheng (IAS).

The collaborating group of Chinese astronomers, under the leadership of **Licai Deng**(NAOC), includes: Yuqin Chen, Jingyao Hu, Huoming Shi, Yan Xu, Haotong Zhang, Gang Zhao, Xu Zhou (NAOC); Zhanwen Han, Shengbang Qian (Yunnan, NAOC); Yaoquan Chu (USTC); Li Chen, Jinliang Hou (SHAO); Xiaowei Liu, Huawei Zhang (PKU); and Biwei Jiang (BNU).

I currently have an NSF planning grant to develop a partnership with the LAMOST project. We are developing an NSF Science and Technology Center proposal that would fund the collaboration with LAMOST and synergistically create cutting edge tools for eScience that have application across science and engineering disciplines.

If you are interested in getting involved, let me know. We will have a workshop in Beijing in October, and I have travel funds for US participants.

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(2) The Milky Way spheroid, now

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(c) global properties of spheroid stars

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