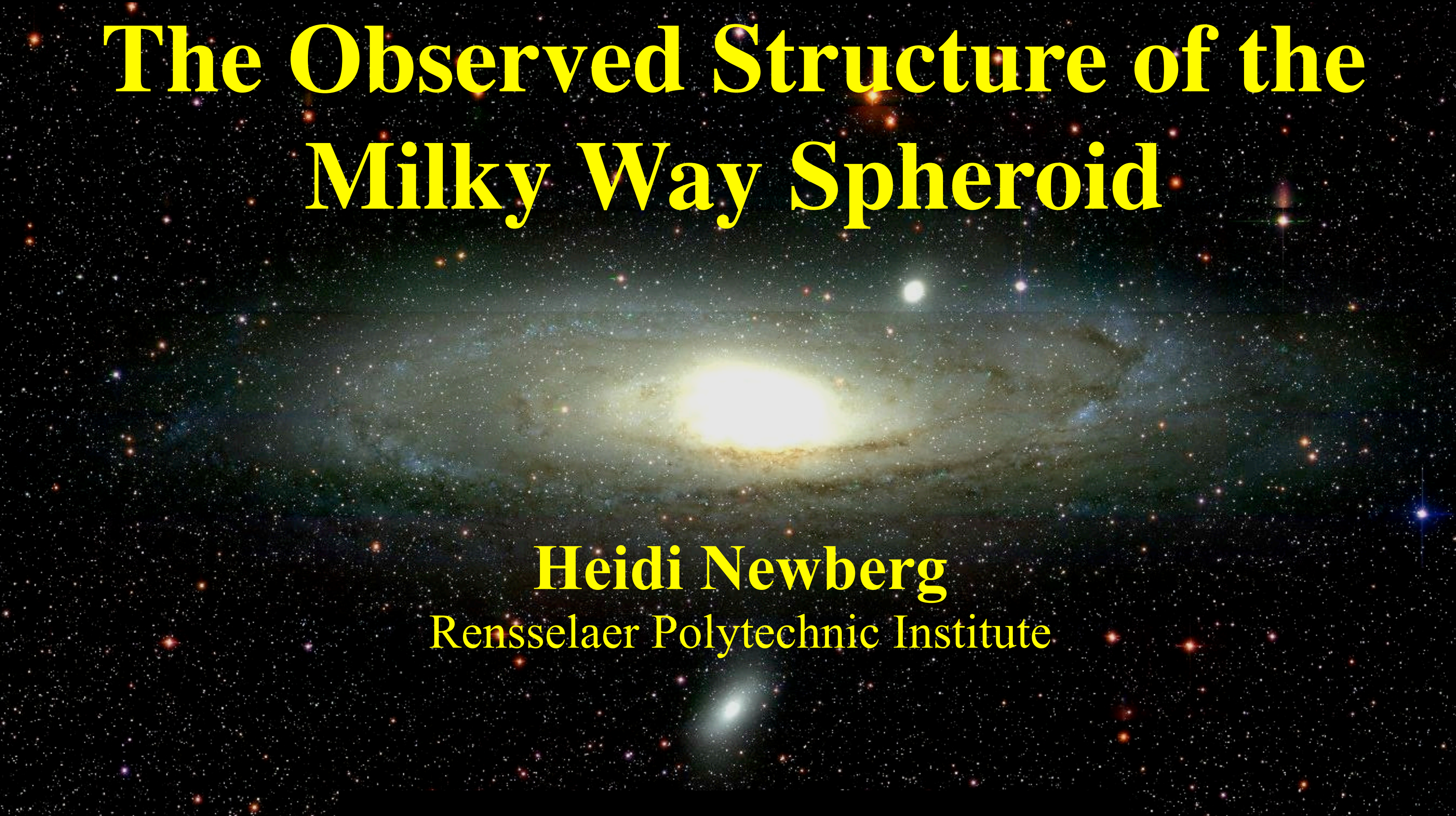
The Observed Structure of the Milky Way Spheroid



Heidi Newberg
Rensselaer Polytechnic Institute

Overview

(1) The Milky Way spheroid is spatially lumpy
  (a) Tidal debris and the Sgr dwarf galaxy
  (b) dwarf galaxies and globular clusters
  (c) oblate, prolate, or spherical?
  (d) asymmetry
  (e) maximum likelihood technique

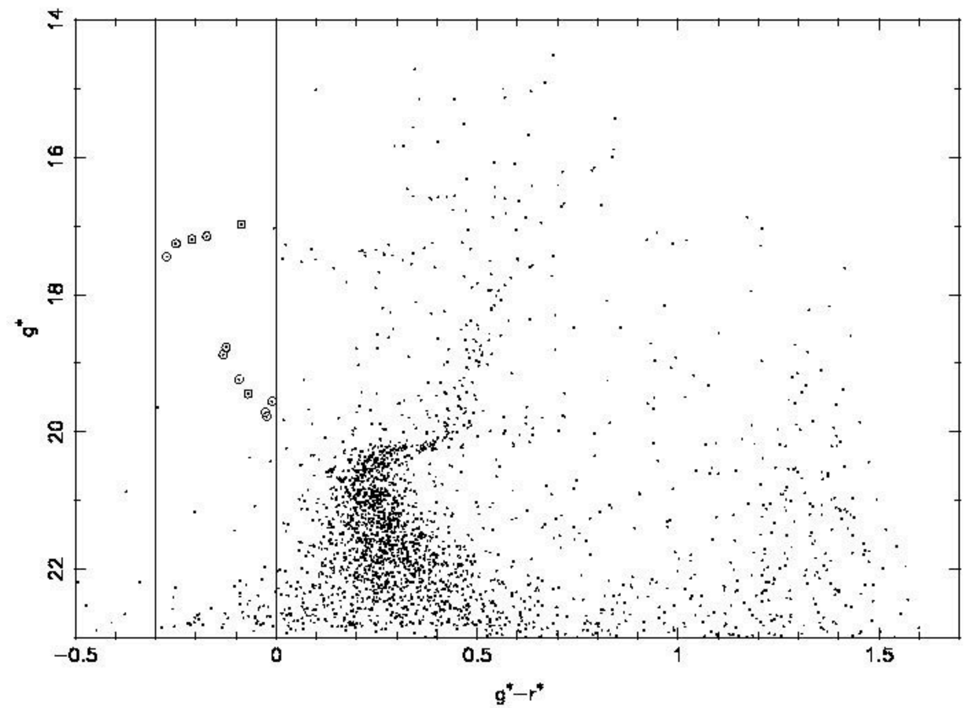
(2) Velocity Substructure
  (a)The Sloan Extension for Galactic Understanding and Exploration (SEGUE)
  (b) The overdensity in Virgo and the triaxial spheroid

(3) The need for a larger spectroscopic survey of Milky Way Stars (RAVE, GAIA, LAMOST?)

Techniques for finding spatial substructures

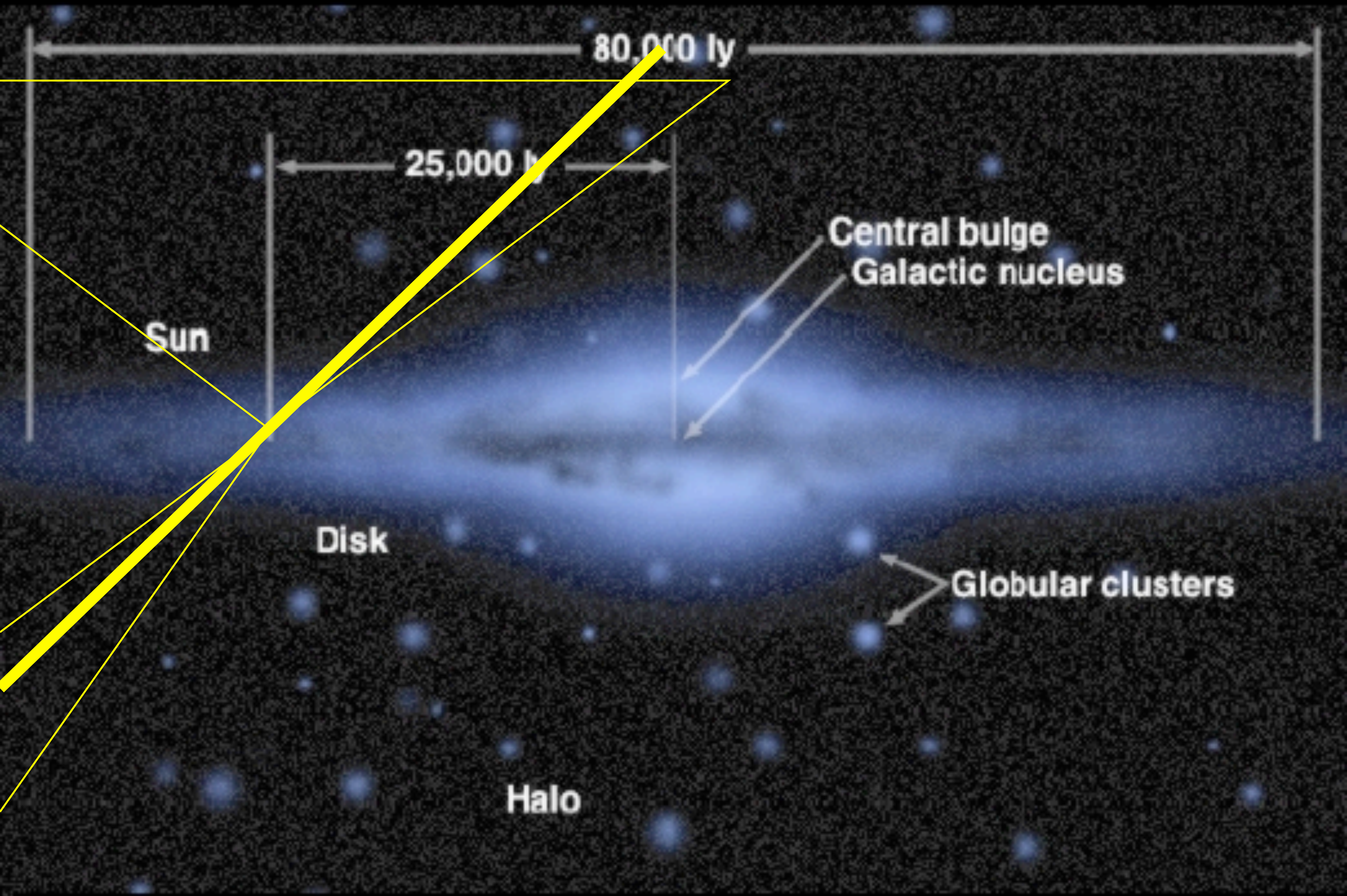
(1) Select a tracer of known luminosity to use as a distance tracer.
(2) Select a tracer that can be used statistically to measure distance to a structure
(3) Convolve with a presumed color-magnitude distribution

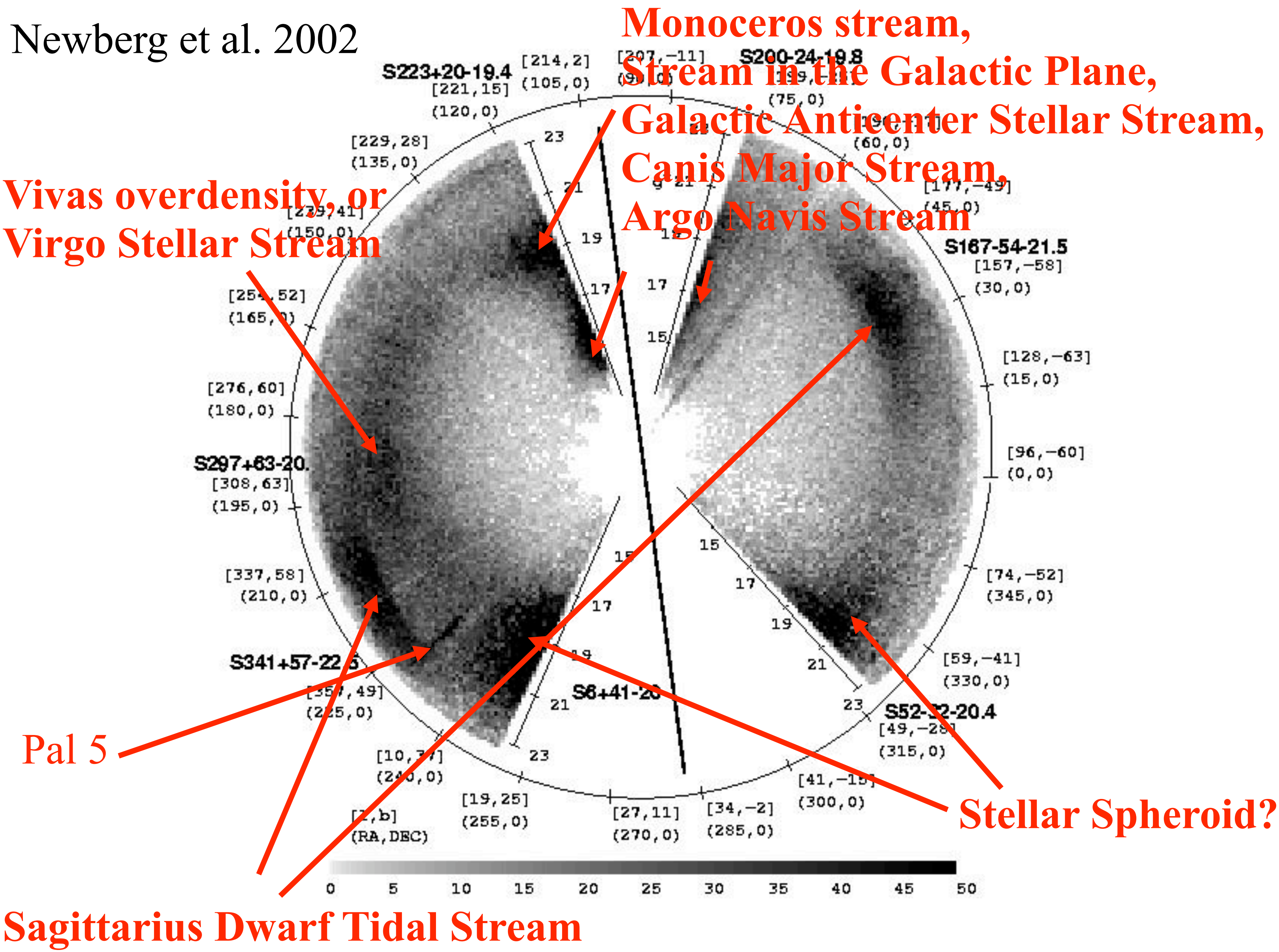
Pal 5 globular cluster

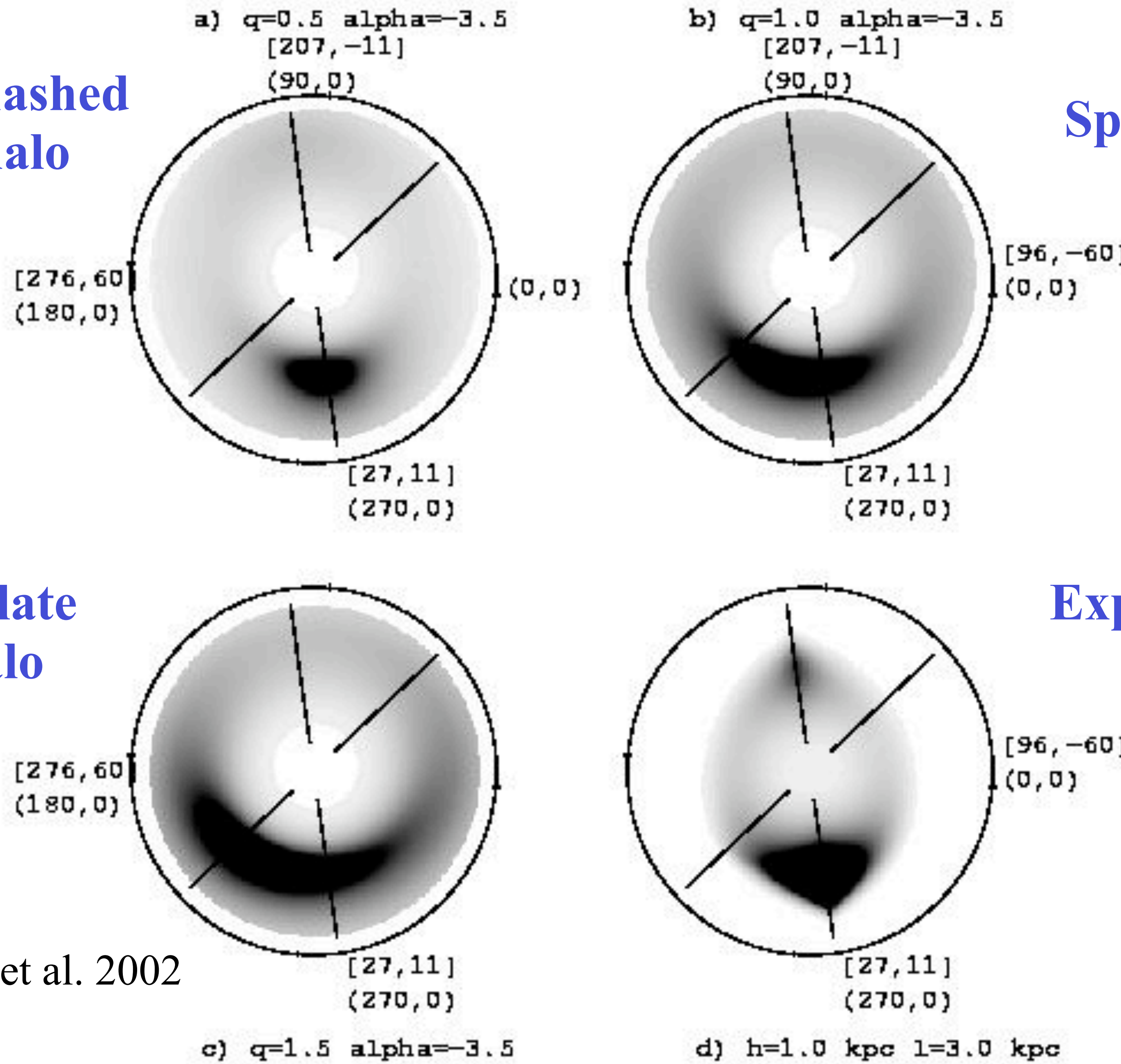


Yanny et al. 2000

SDSS


80,000 ly
25,000 ly
Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo


Newberg et al. 2002
Monoceros stream,
Stream in the Galactic Plane,
Galactic Anticenter Stellar Stream,
Canis Major Stream,
Argo Navis Stream
Vivas overdensity, or
Virgo Stellar Stream
Pal 5
Stellar Spheroid?
Sagittarius Dwarf Tidal Stream
S223+20-19.4
S167-54-21.5
S297+63-20.
S341+57-22.5
S6+41-20
S52-32-20.4
[l,b]
(RA,DEC)
0
5
10
15
20
25
30
35
40
45
50



Squashed halo

Spherical halo

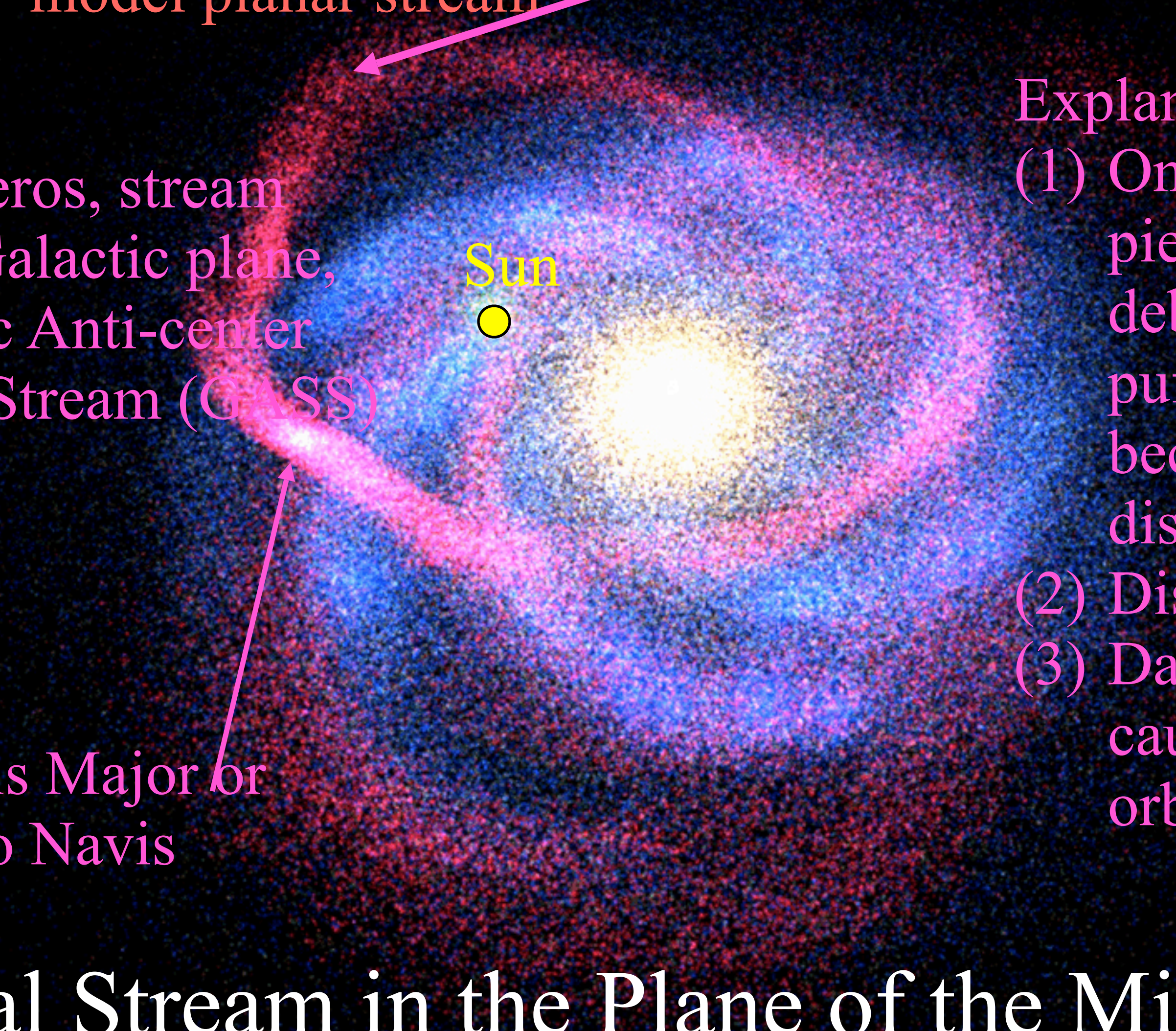
Prolate halo

Exponential disk

Newberg et al. 2002

Kathryn Johnston

Kathryn Johnston



Explanations:

(1) One or more pieces of tidal debris; could have puffed up, or have become the thick disk.
(2) Disk warp or flare
(3) Dark matter caustic deflects orbits into ring

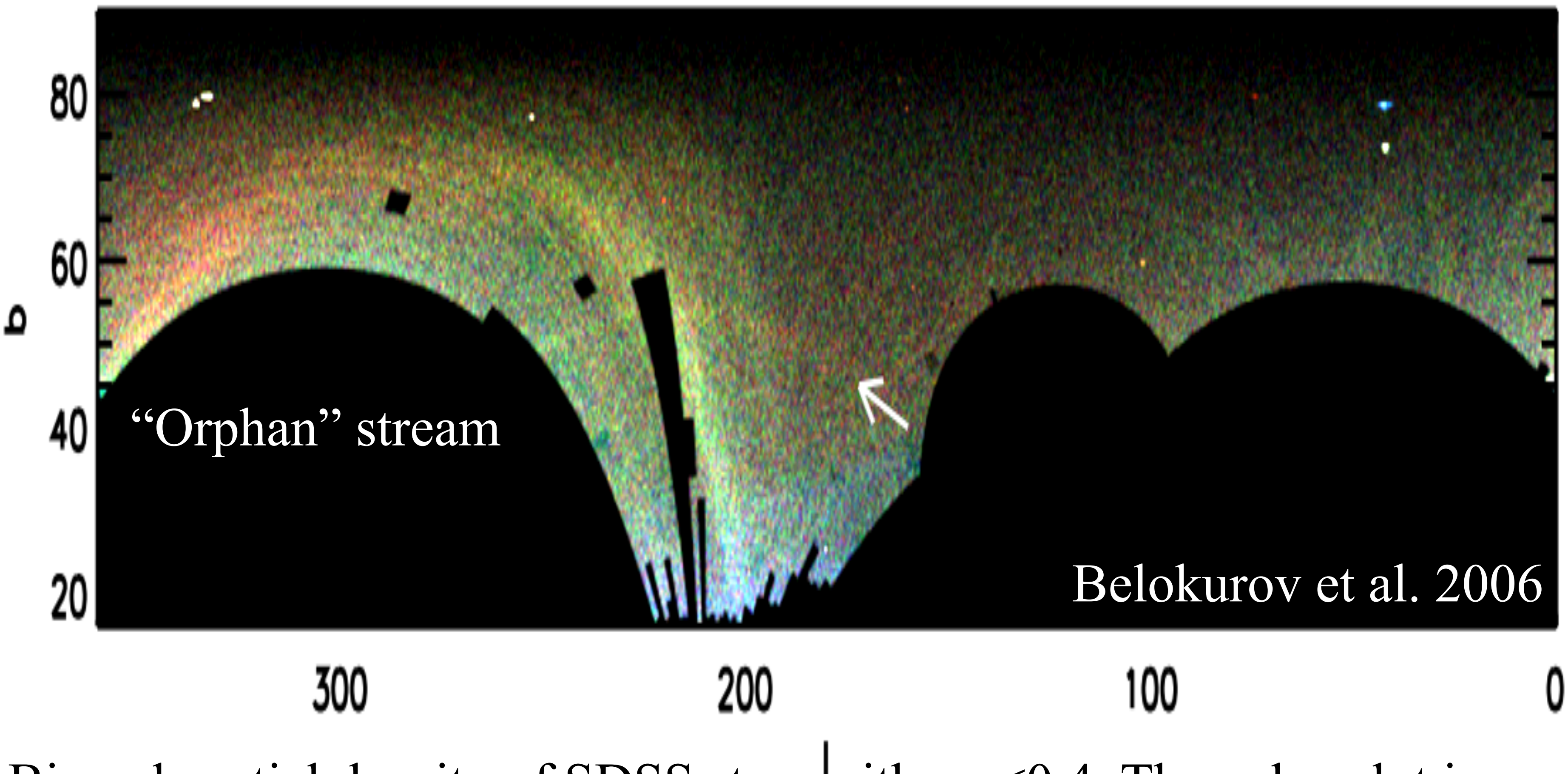
Tidal Stream in the Plane of the Milky Way

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

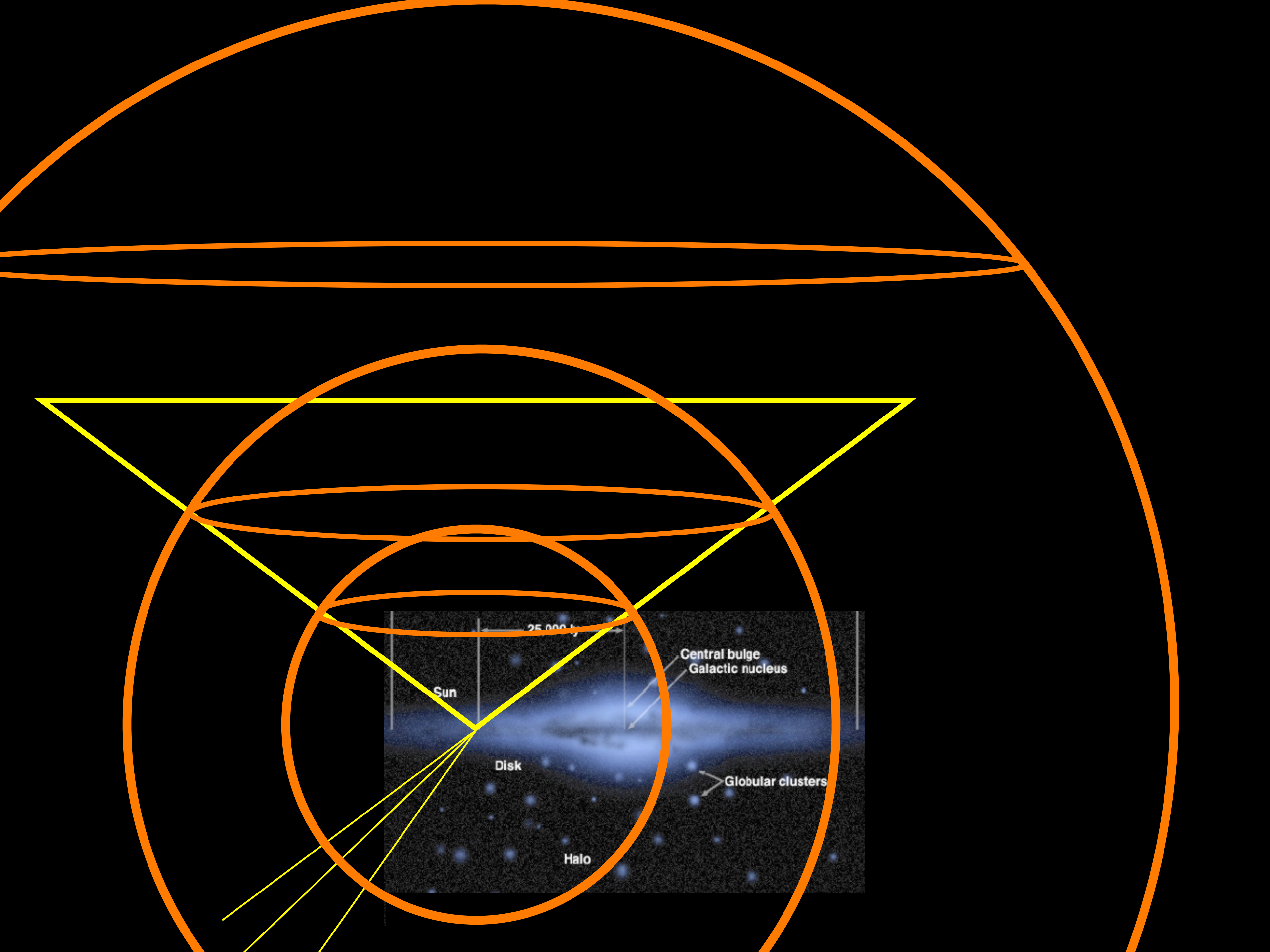
ulp UNIVERSITÉ LOUIS PASTEUR STRASBOURG

Press release, November 4, 2003

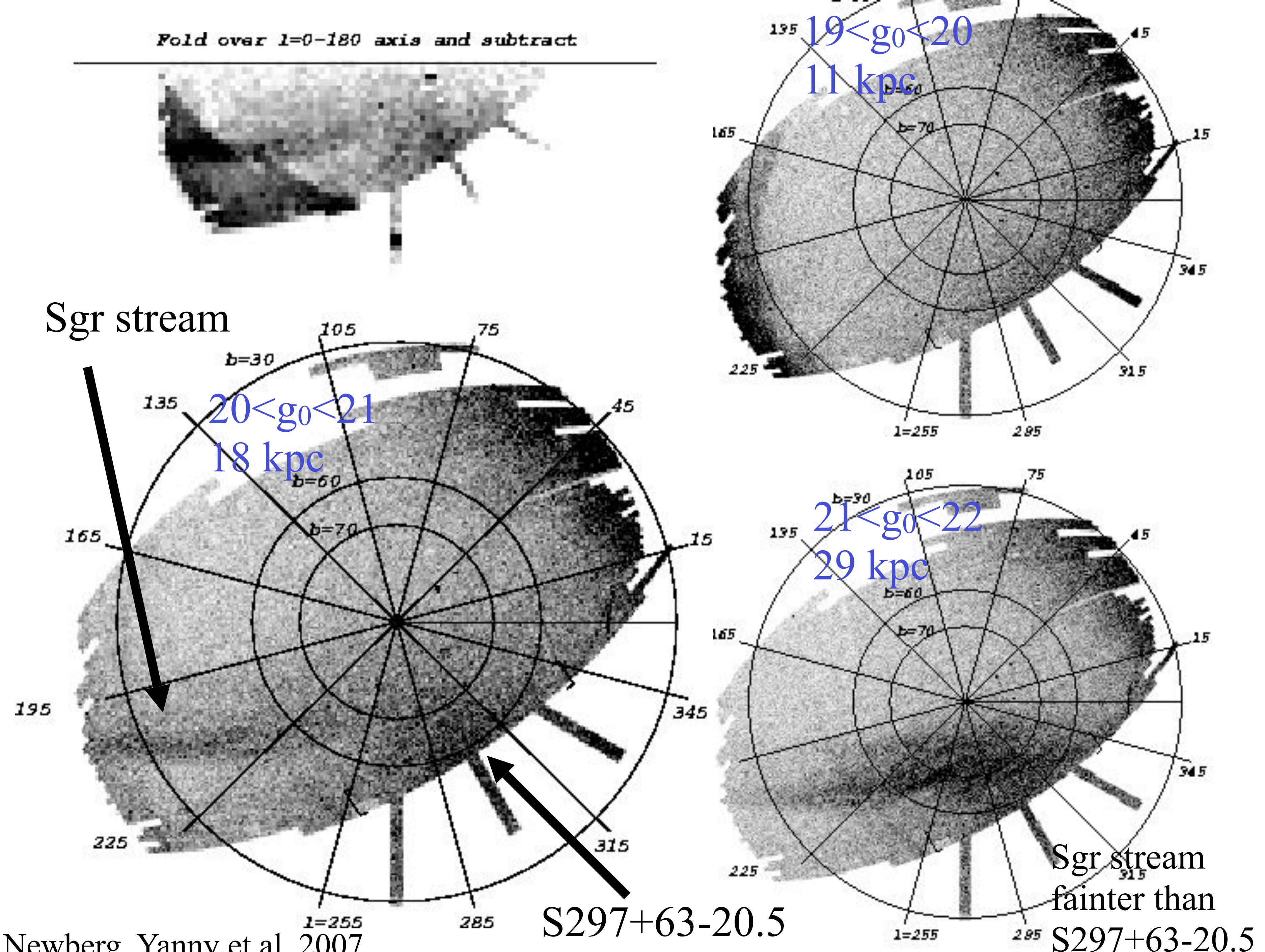
The "Field of Streams"



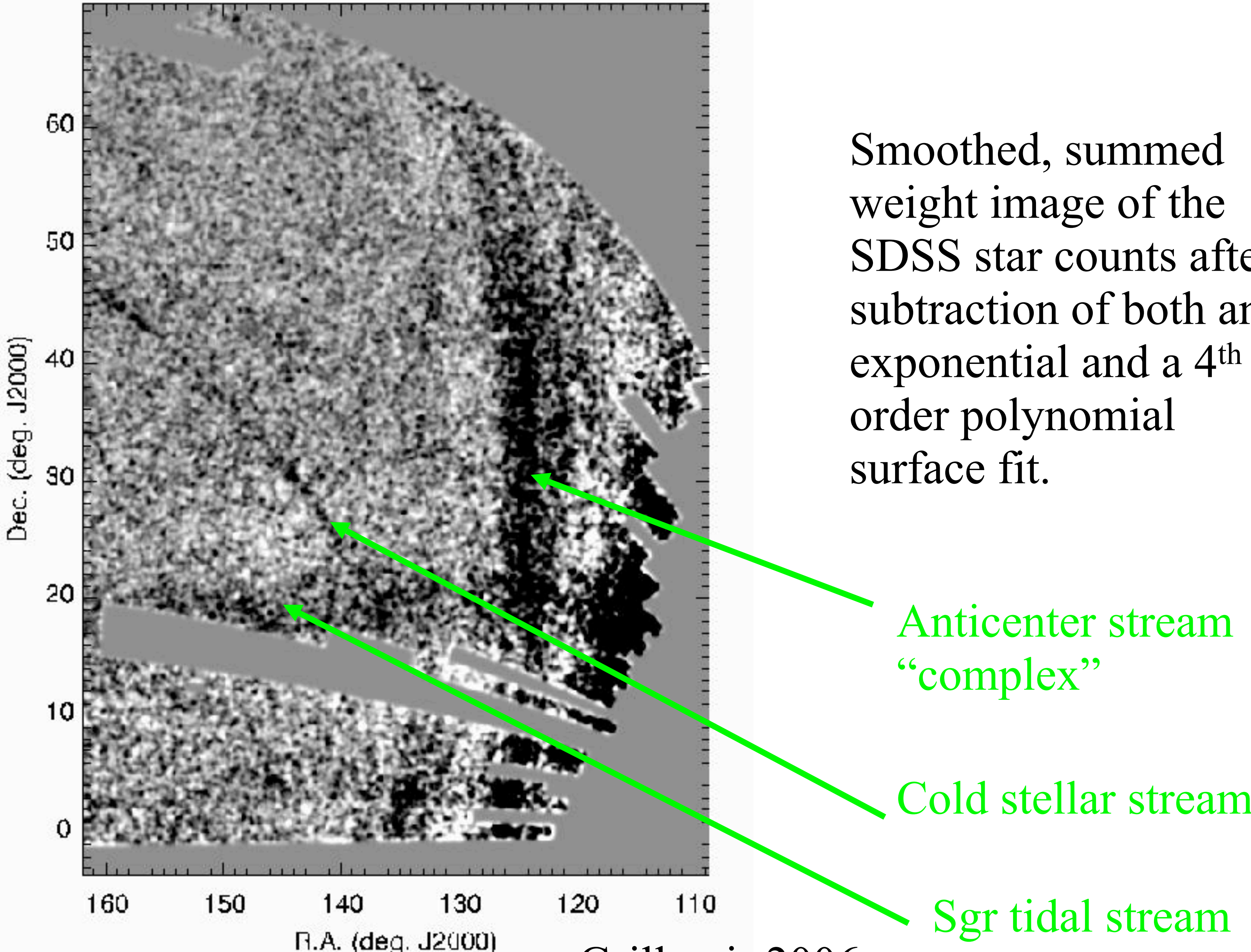
Binned spatial density of SDSS stars with g-r<0.4. The color plot is an RGB composite with blue for the most nearby stars with 20<r<20.66, green for stars with 20.66<r<21.33, and red for the most distant stars with 21.33<r<22.0.



25,000 ly
Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo



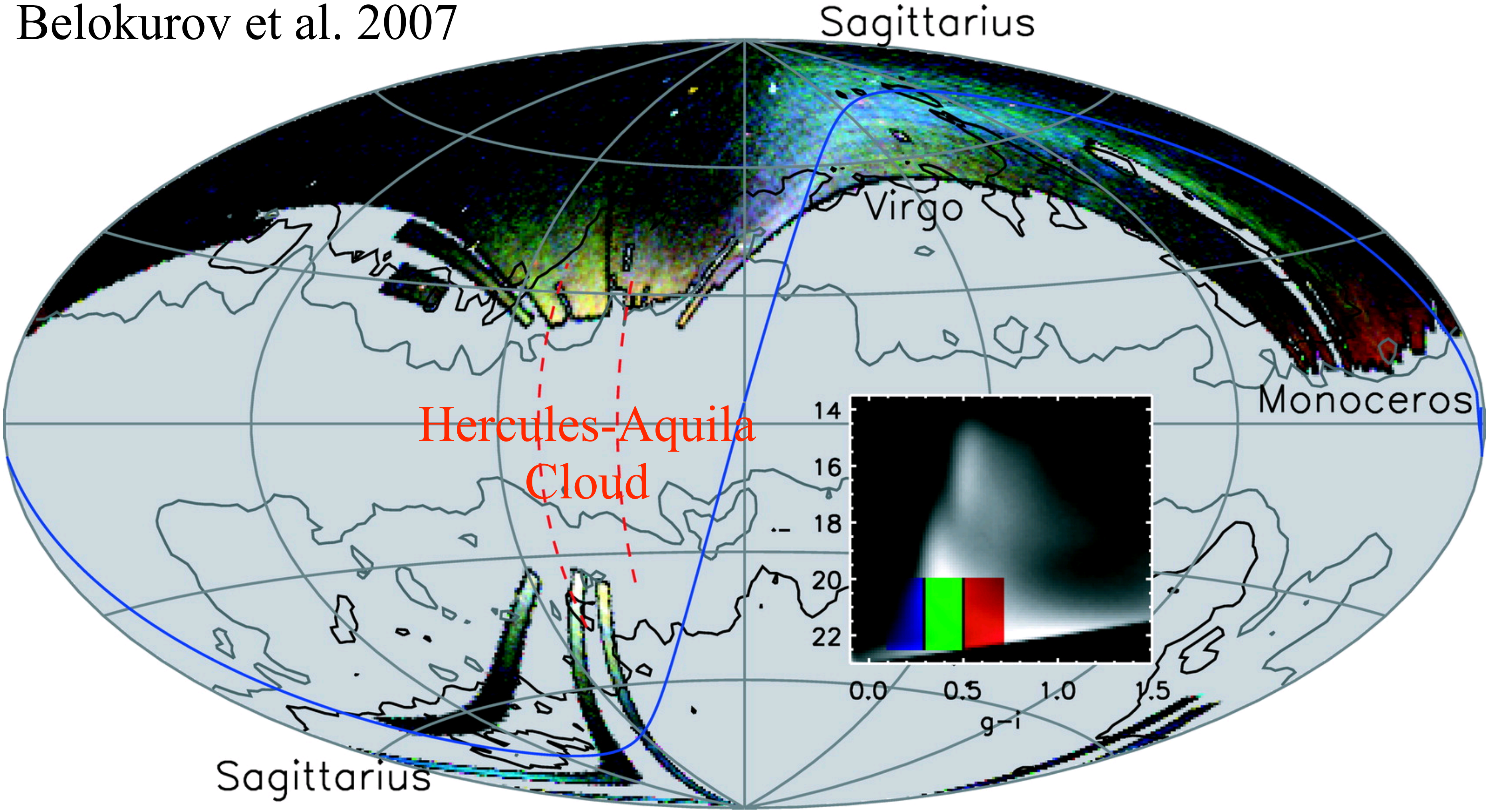
Newberg, Yanny et al. 2007



Grillmair 2006

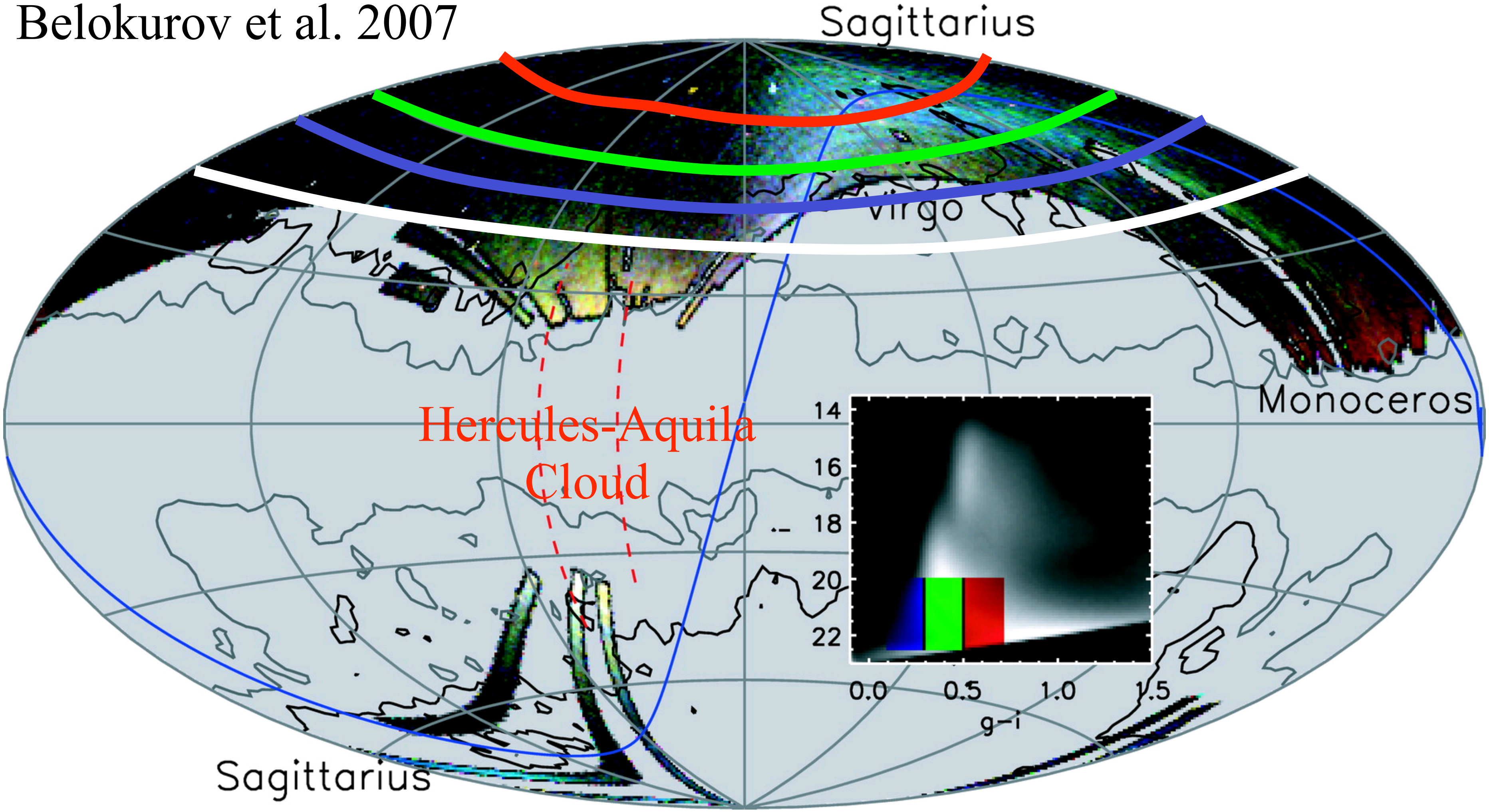
Smoothed, summed weight image of the SDSS star counts after subtraction of both an exponential and a 4th order polynomial surface fit.

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.

Belokurov et al. 2007



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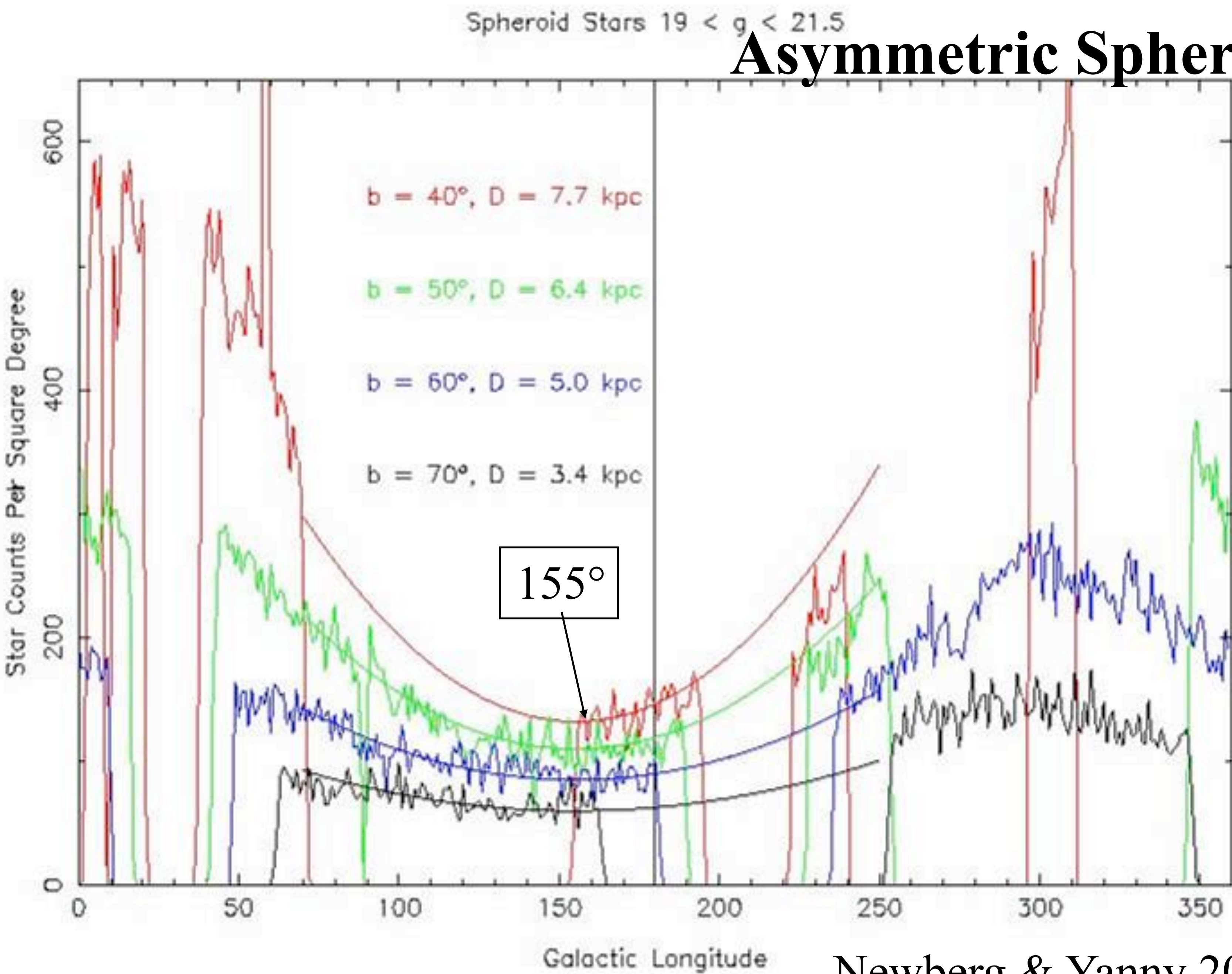
#4

Asymmetric Spheroid



Newberg & Yanny 2005

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

Odenkirchen et al. 2003

(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

Globular cluster streams:

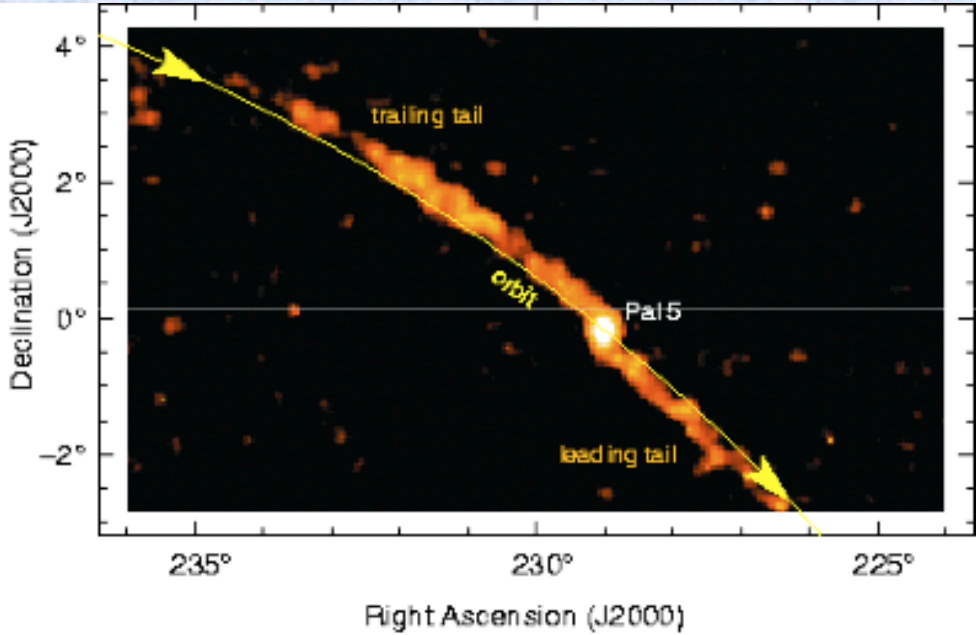
(1) Pal 5: Odenkirchen et al. 2003

(2) ?? Grillmair & Dionatos 2006

(3) NGC 5466: Grillmair & Johnson 2006

Other:

(1) Hercules-Aquila Cloud



Doubling the known dwarf galaxies

Belokurov et al. 2007

A QUINTET OF NEW MILKY WAY COMPANIONS 7

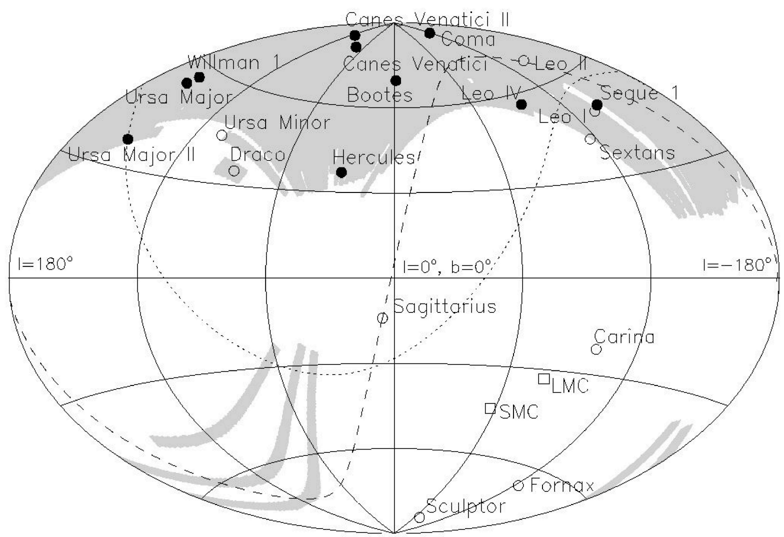


FIG. 7.— The locations of Milky Way satellites in Galactic coordinates. Filled circles are satellites discovered by SDSS, unfilled circles are previously known Milky Way dSphs. The light grey shows the area of sky covered by the Sloan survey and its extensions to date. The dashed and dotted lines show the orbital planes of the Sagittarius and Orphan Streams, respectively, taken from Fellhauer et al. (2006a) and Fellhauer et al. (2006b).

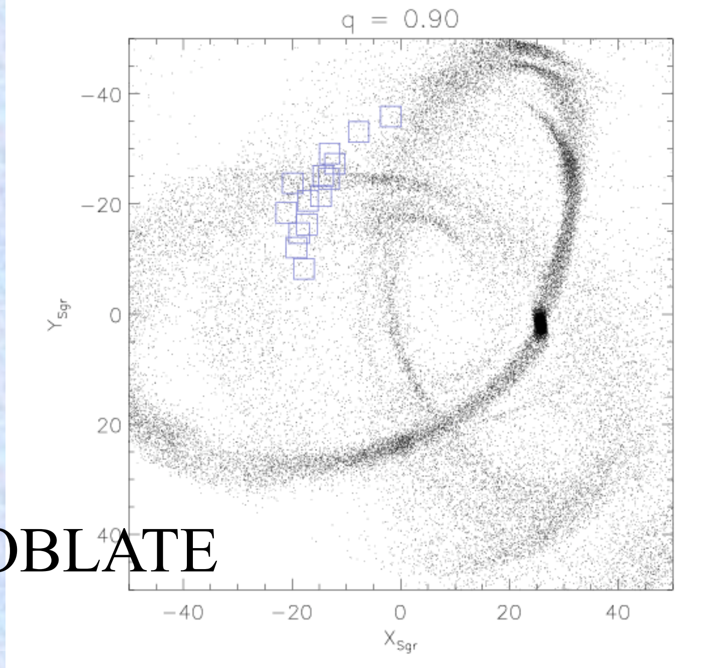
- Canis Major/Argo dwarf galaxy in Galactic plane; Martin et al. 2004, Rocha-Pinto et al. 2006
- Eight new dwarf galaxies in Ursa Major, Canes Venatici, Bootes, Ursa Major II, Coma Berenices, Canes Venatici, Leo, and Hercules; Willman et al. 2005, Zucker et al. 2006a, Belokurov et al. 2006, Zucker et al. 2006b & Grillmair 2006, Belokurov et al. 2007

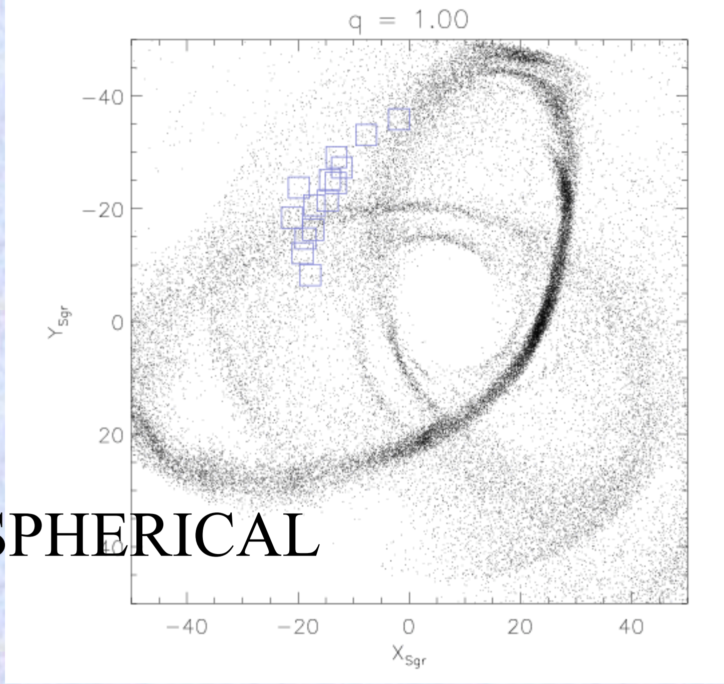
Now that we know the spheroid is lumpy, why do we care?

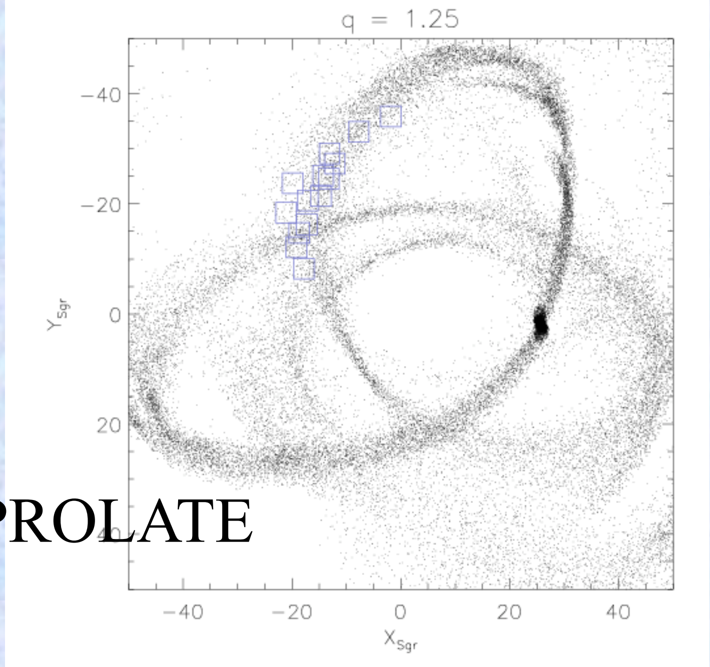
(3) We can wonder whether there is a smooth component to the spheroid, and what it would look like if we could find it. Newberg & Yanny estimated 20% of spheroid stars are in large tidal debris streams. Bell et al. 2007 say σ/total = 40%.

(2) We can match characteristics of the substructure to models of galaxy formation.

- We can measure the dark matter potential and substructure. Although we can in principle measure the 3D positions and space velocities for every star in the Milky Way, stars in tidal streams are the only ones for which we know where they were in the *past*.



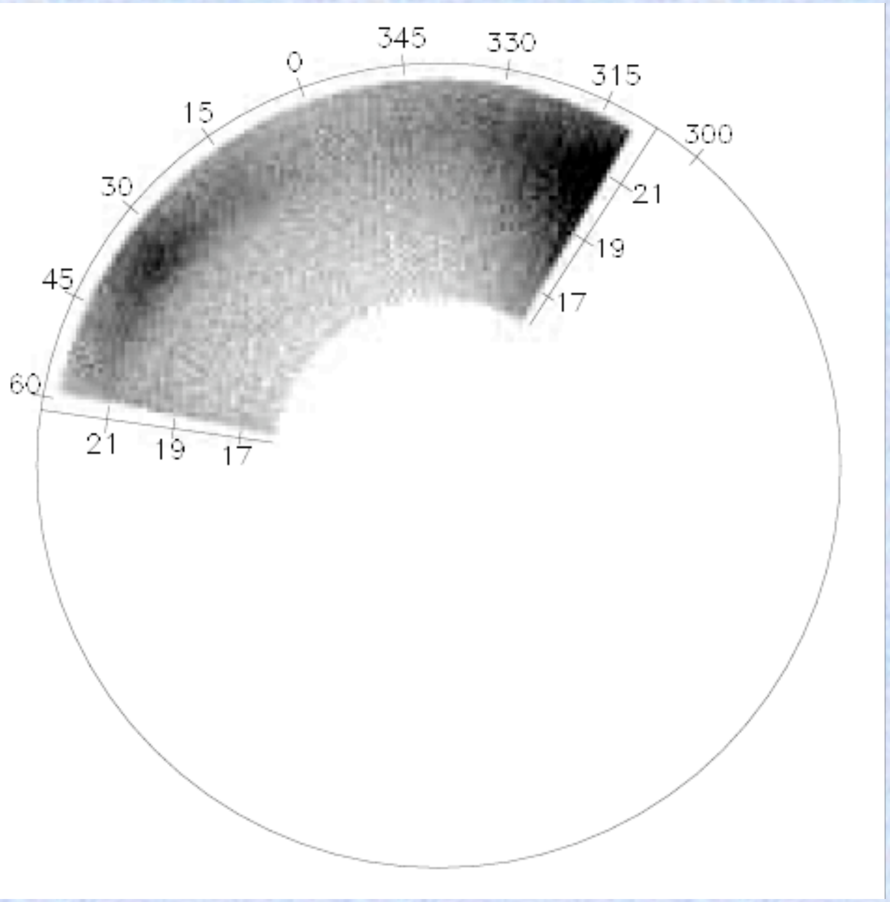




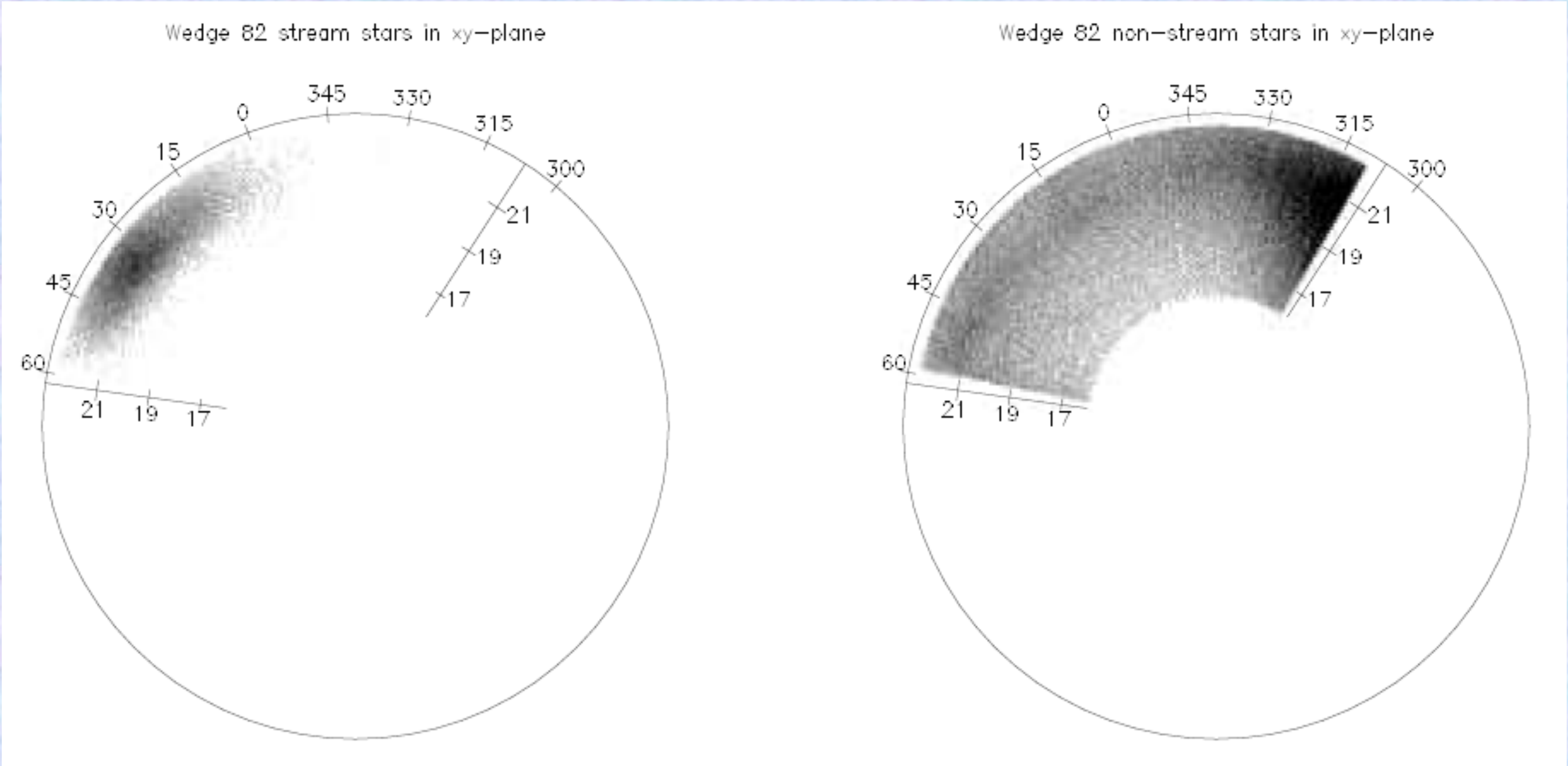
Models of the Sgr dwarf tidal stream compared to new data (Helmi, private communication). The prolate model fits better, but there is an inconistency with the tilt of the tidal tails.

Maximum Likelihood fit to the Celestial Equator

- F-turnoff stars
  - $0.1 < (g-r)_0 < .3$
  - $16 < g_0 < 22.5$
  - $(u-g)_0 > 0.4$
  - $310^o < ra < 59^o$
  - 115,907 stars
- Gaussian magnitude distribution with std. deviation of 0.6 and median 4.2



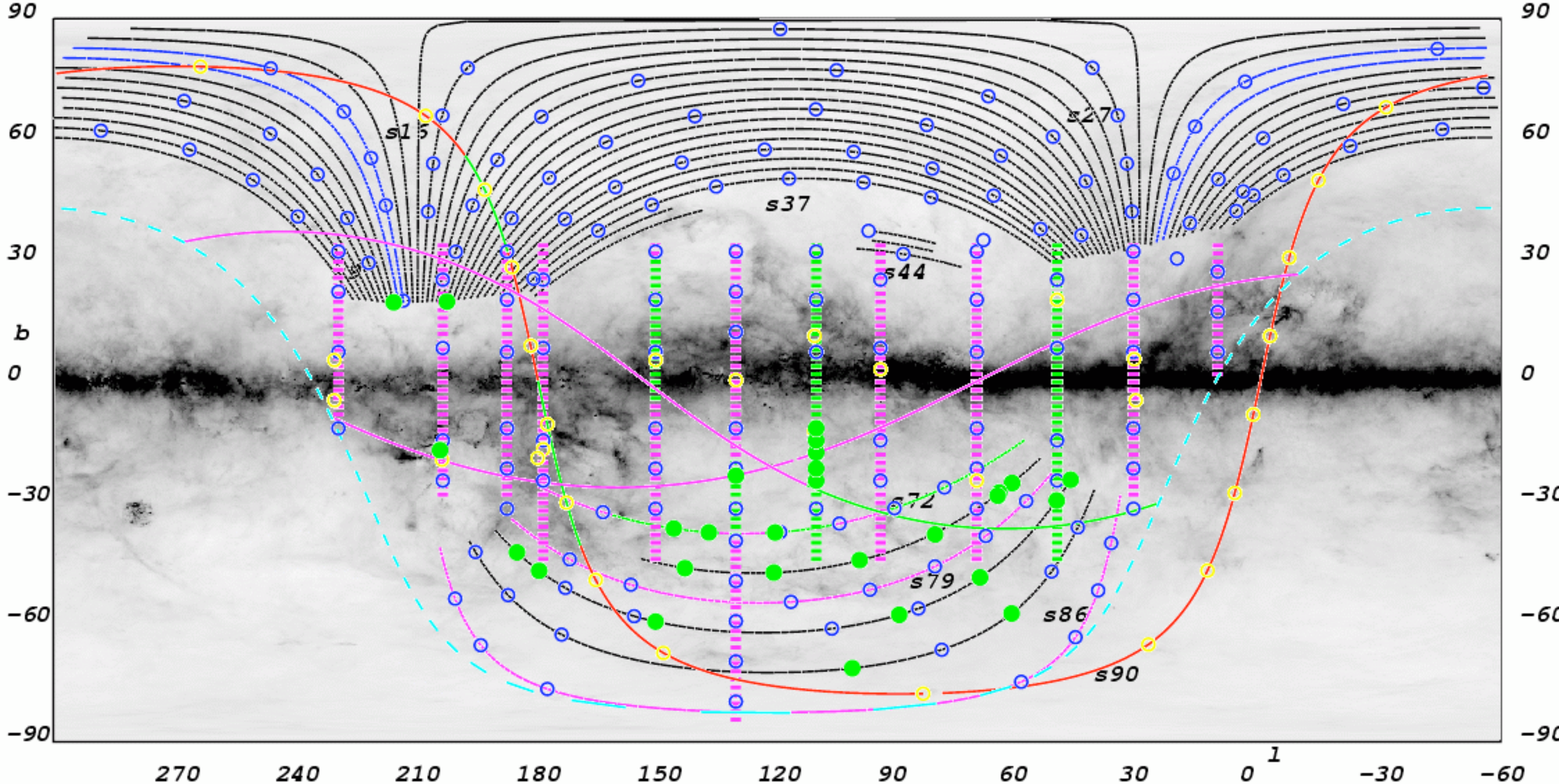
Stripe 82 Separation



ging Galactic structure into the infor

SEGUE

Sloan Extension for Galactic Understanding and Exploration



March 24-28, 2006 Santa Fe, New Mexico

SEGUE Collaboration

China

LAMOST

Germany

Astrophysical Institute Potsdam

Max-Planck Heidelberg

Max-Planck Garching

Japan

Japan Participation Group

Korea

Korean Scientist Group

UK

Cambridge University

United States

American Museum of Natural History

University of Chicago

Fermilab

Johns Hopkins University

JINA/Michigan State/Notre Dam/Chicago

Los Alamos National Laboratory

New Mexico State University

Ohio State University

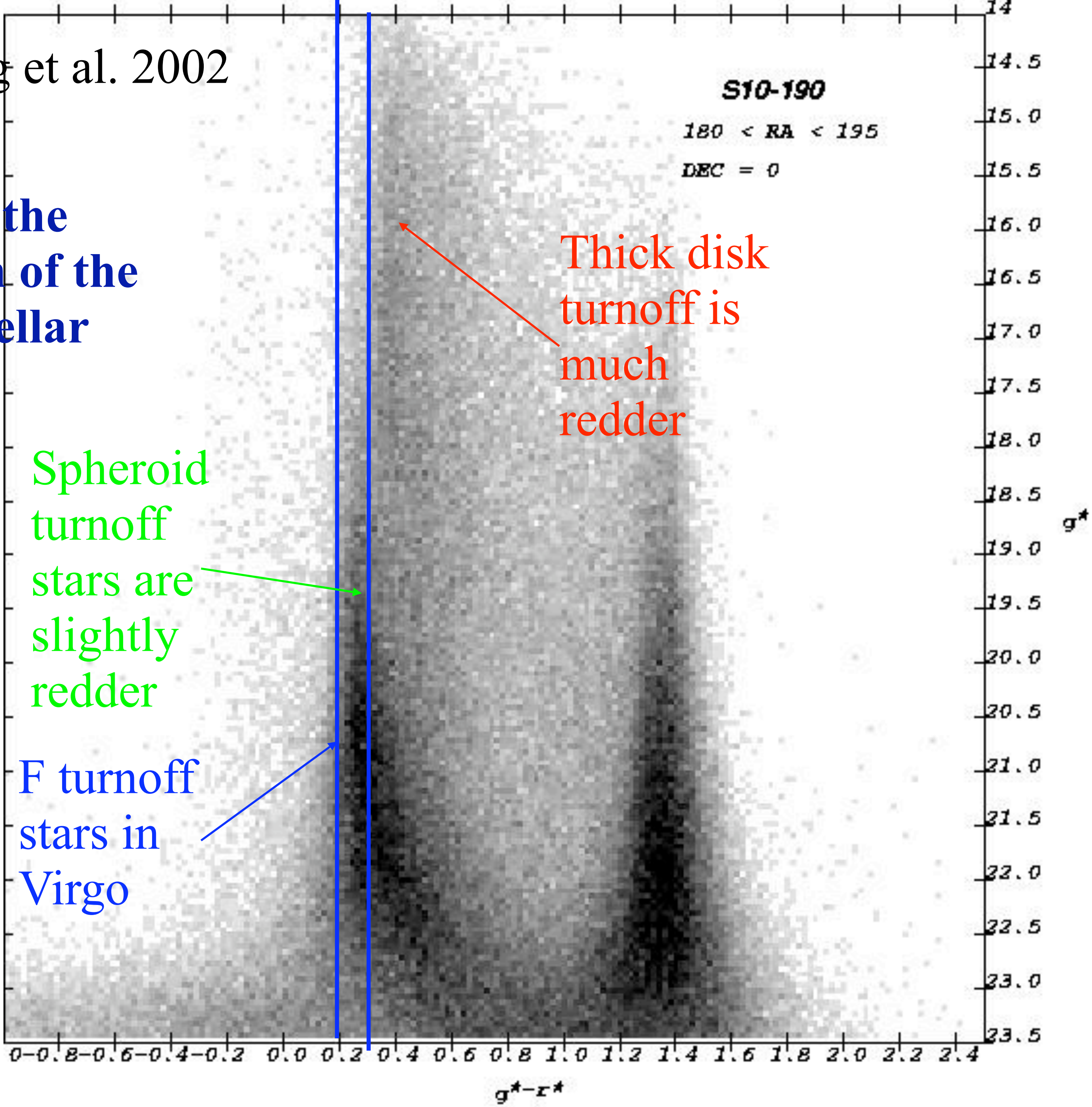
Princeton University

US Naval Observatory

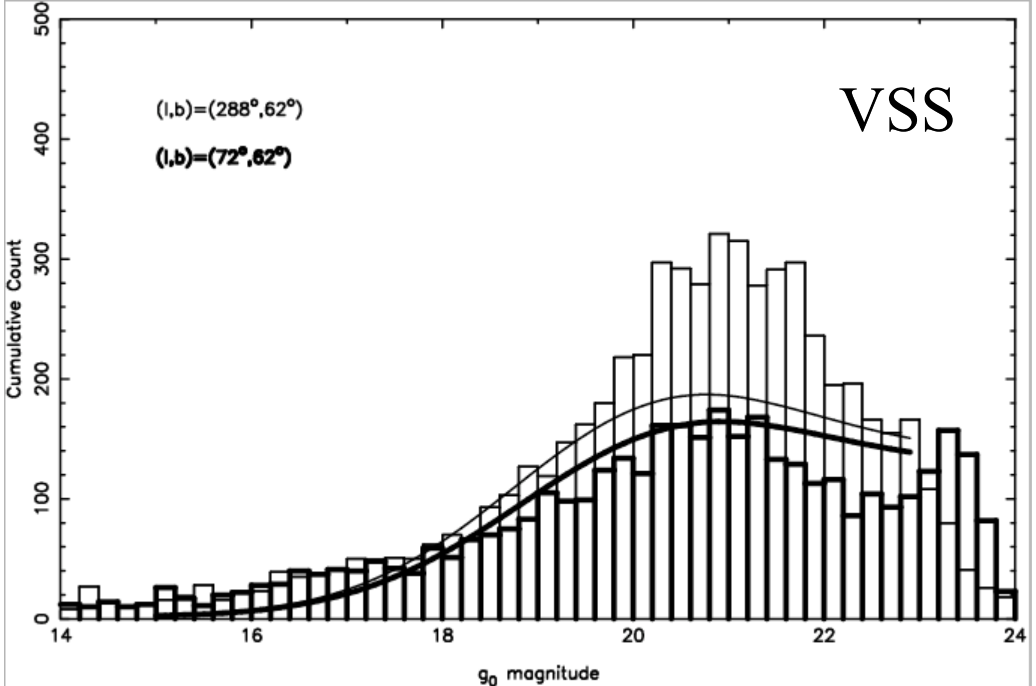
University of Washington

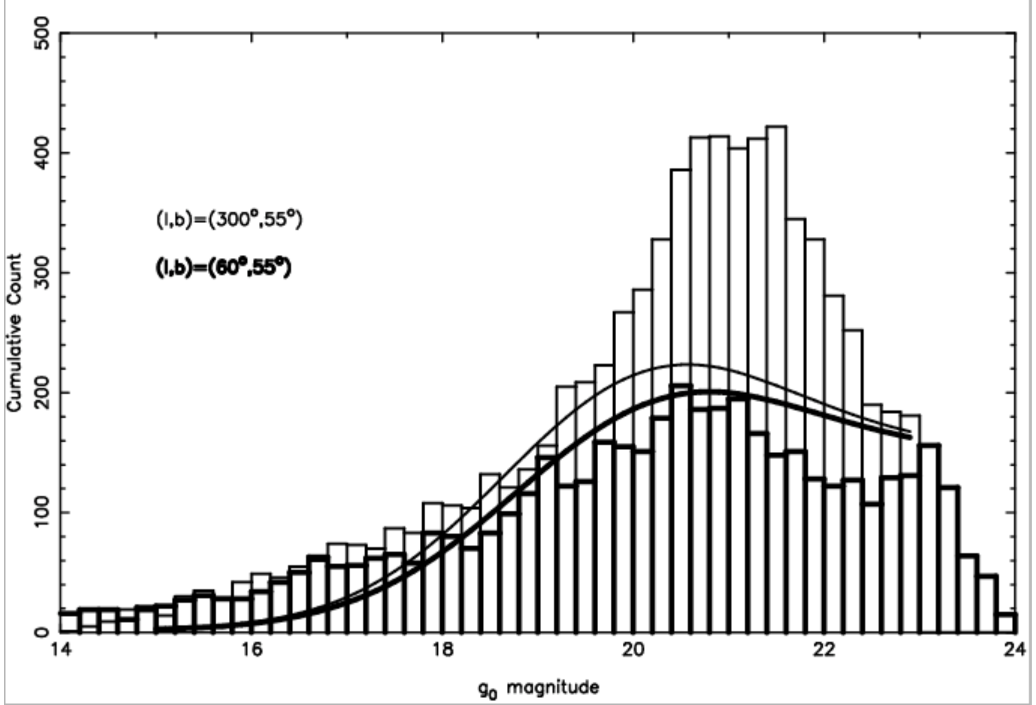
Newberg et al. 2002

CMD in the direction of the Virgo Stellar Stream



Newberg, Yanny et al., submitted





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

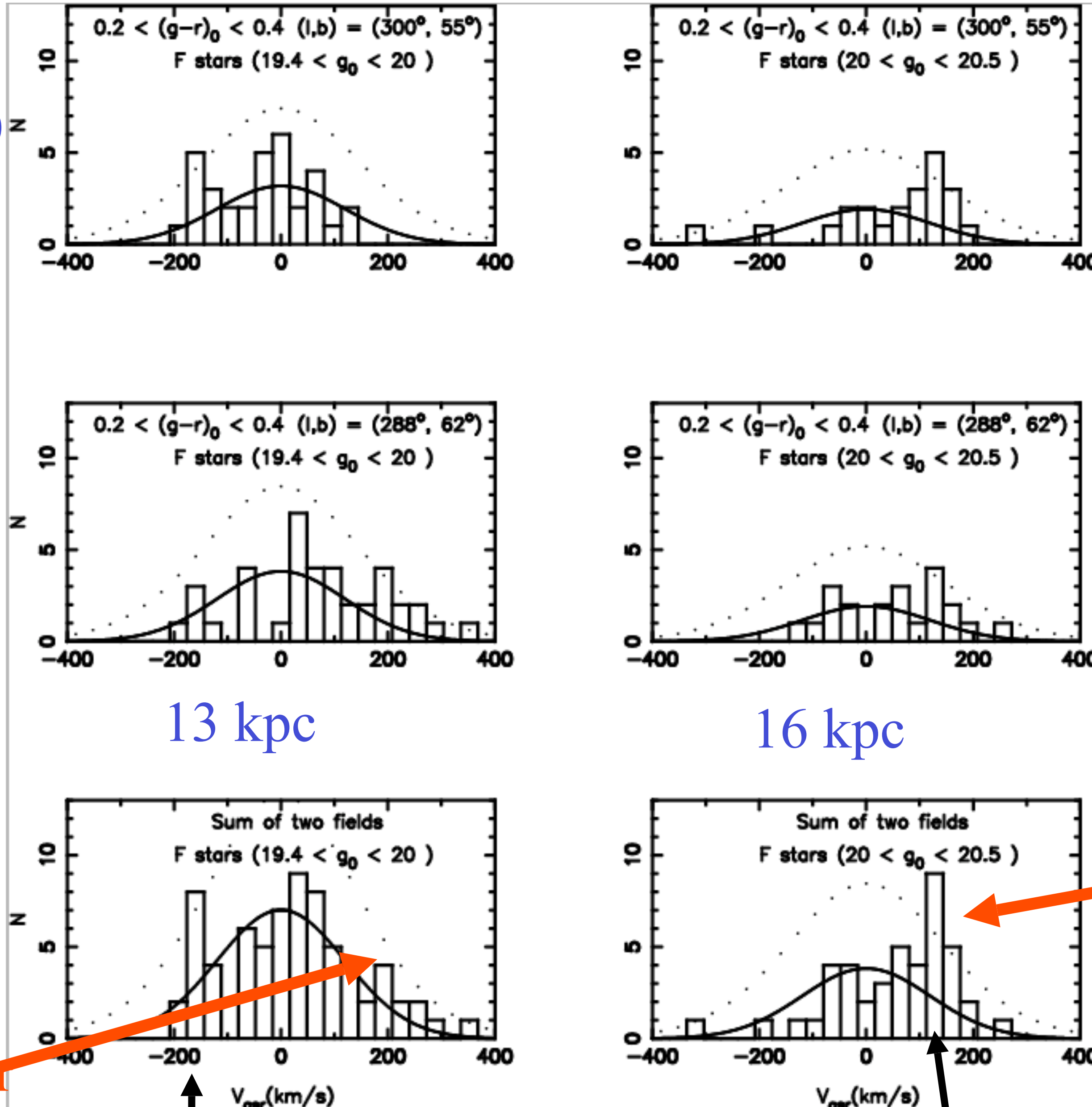
We compare one sight line in Virgo with the symmetric point with respect to the Galactic center. In a symmetric spheroid, the star counts in the two directions should be the same.

Models are Galactocentric triaxial Hernquist profiles.

(300°,55°)

VSS field

Sum of the two



40±11% of the stars are in the peak.

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

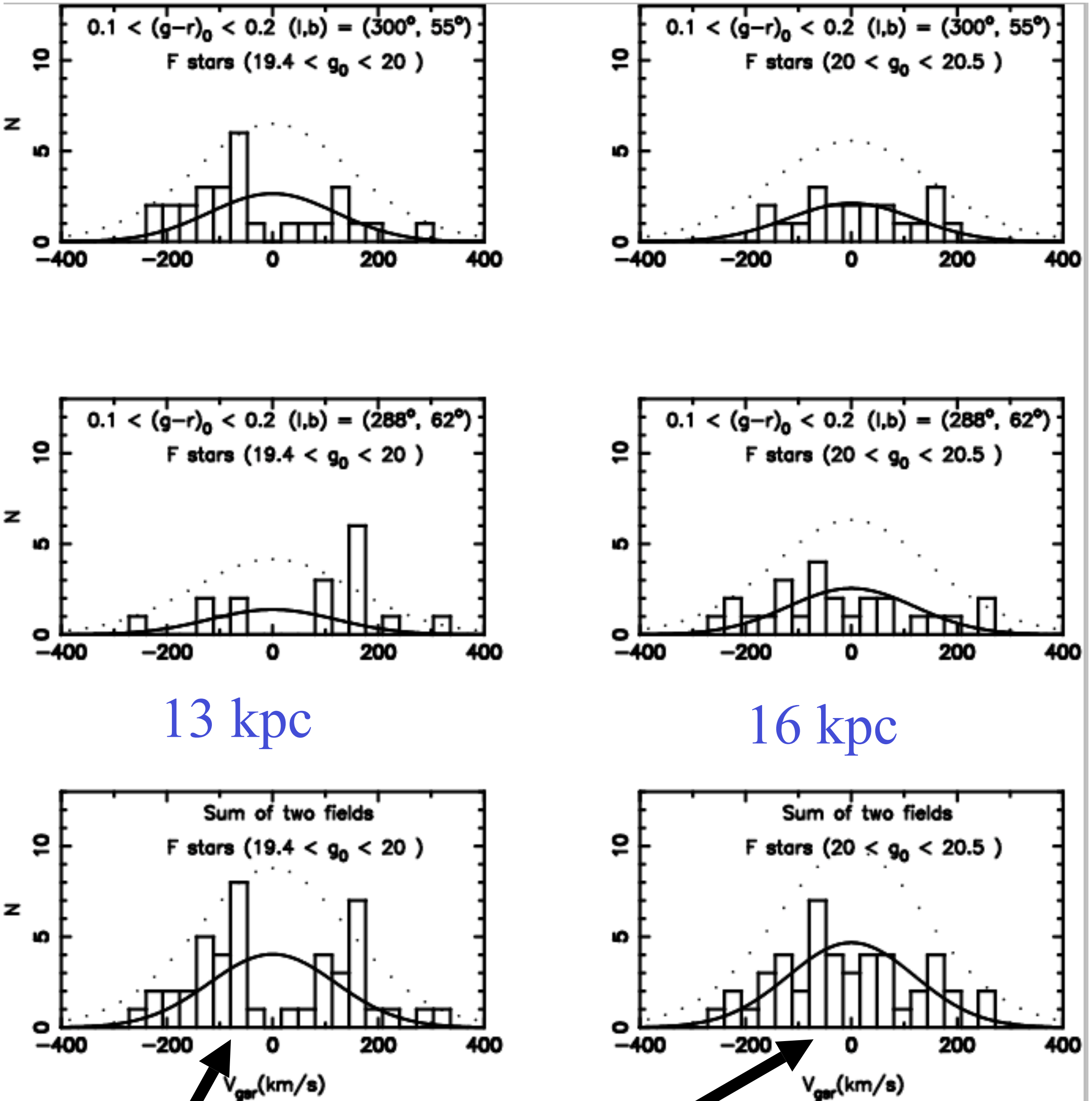
Vgsr=-168±10 km/s

S297+63-20.5
Vgsr=130±10 km/s

(300°,55°)

VSS field

Sum of the two



13 kpc

16 kpc

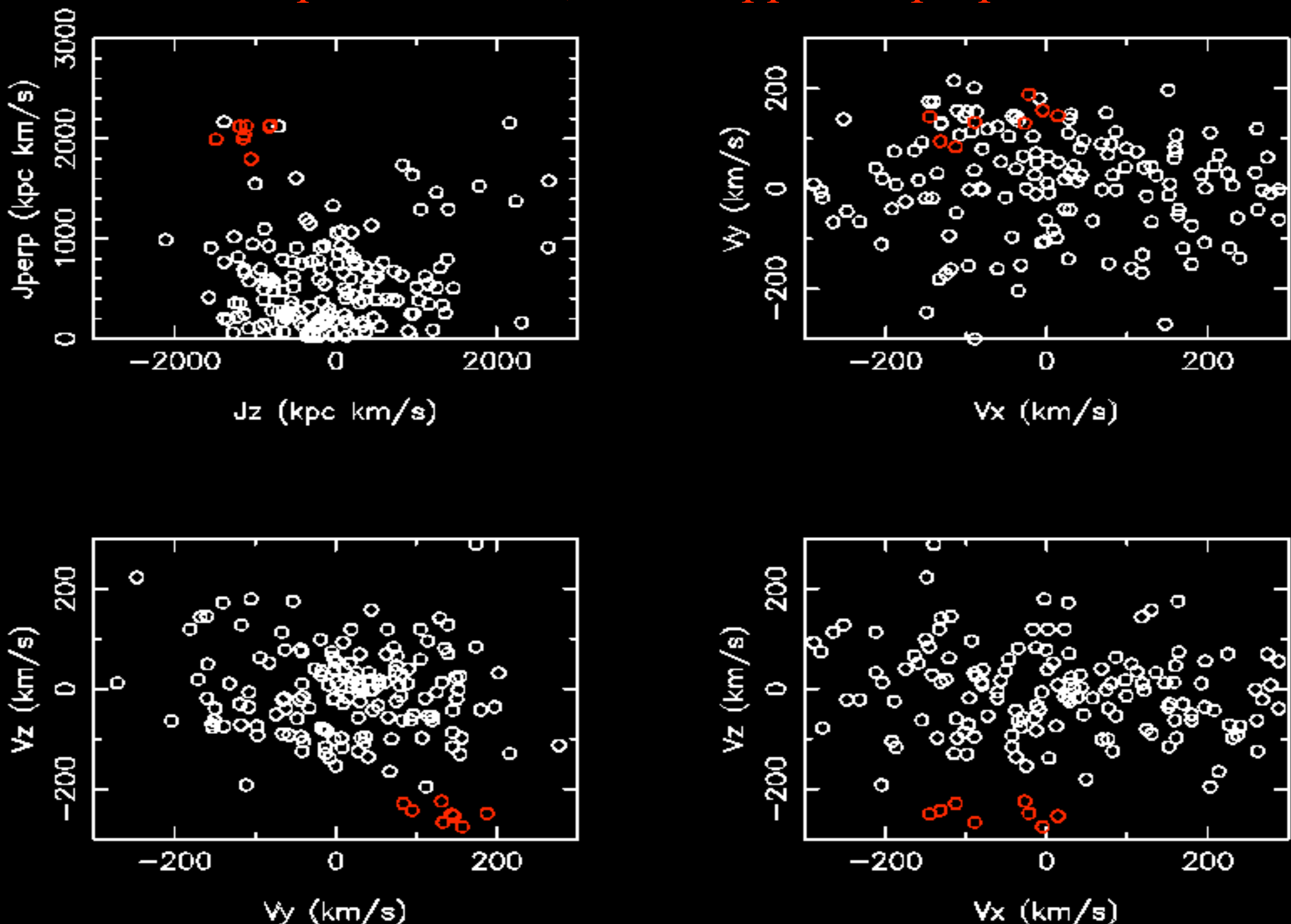
Vgsr=-76±10 km/s

Other SEGUE Plates

With only the small amount of analysis we have done with SEGUE spectra, we have found at least one moving group on *every* SEGUE plate. The statistics are not consistent with Gaussian in any selection of stars limited in stellar population and volume.

We find more substructure on every scale we look for it. Clearly, we need *at least an order of magnitude more spectroscopic data*, and it would be advantageous to have higher resolution.

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.

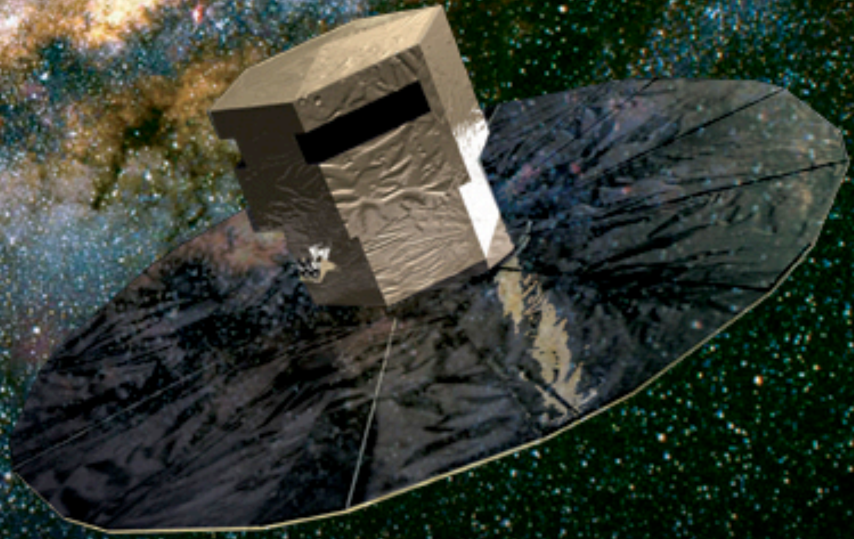
A larger spectroscopic survey of the Milky Way

Now I want to identify all of the individual substructures from which the spheroid formed. We can do that if we group stars by angular momentum. For angular momentum we need distances, tangential velocities, and radial velocities for each star.

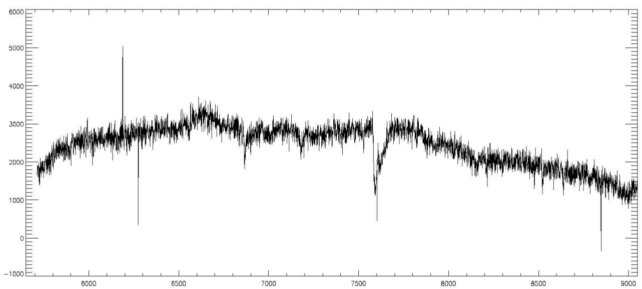
GAIA Astrometric Satellite

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

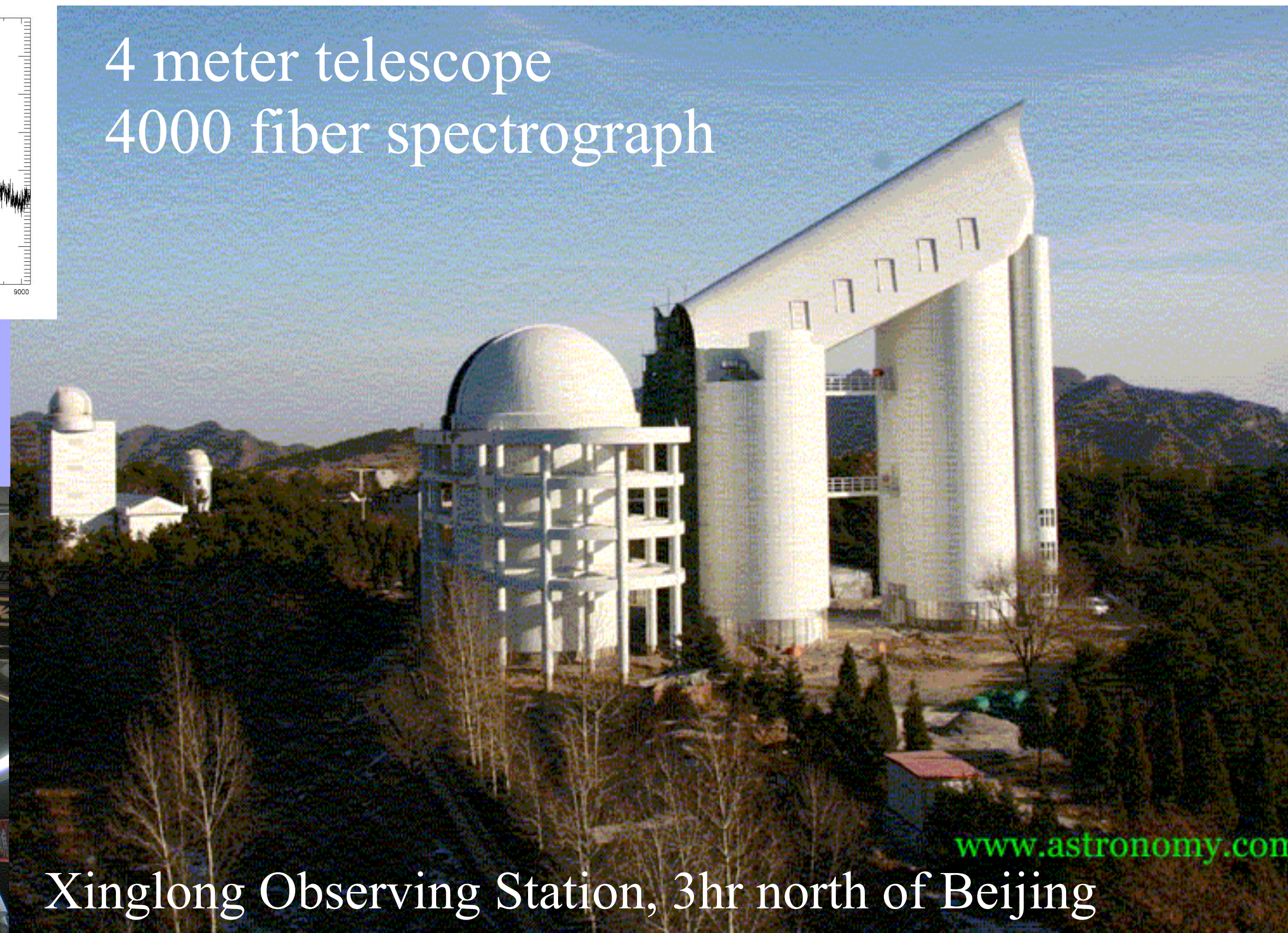
Currently de-scoped, so they will only get radial velocities for stars fainter than 17th magnitude!

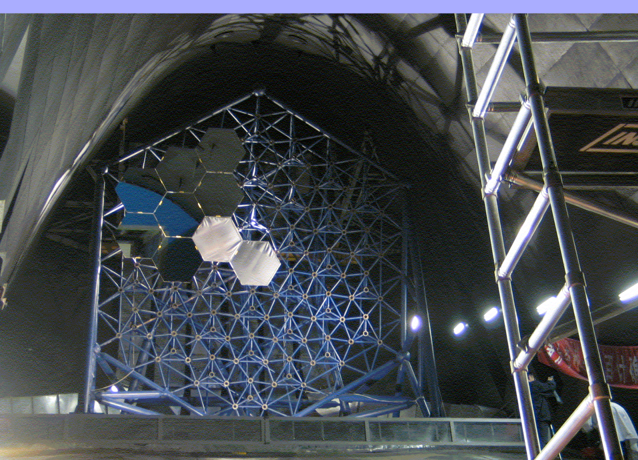


With LAMOST, radial velocities can be obtained for the most interesting magnitude range of 17<V<20, maybe just for blue stars.



First light May 2007,
operations in 2009



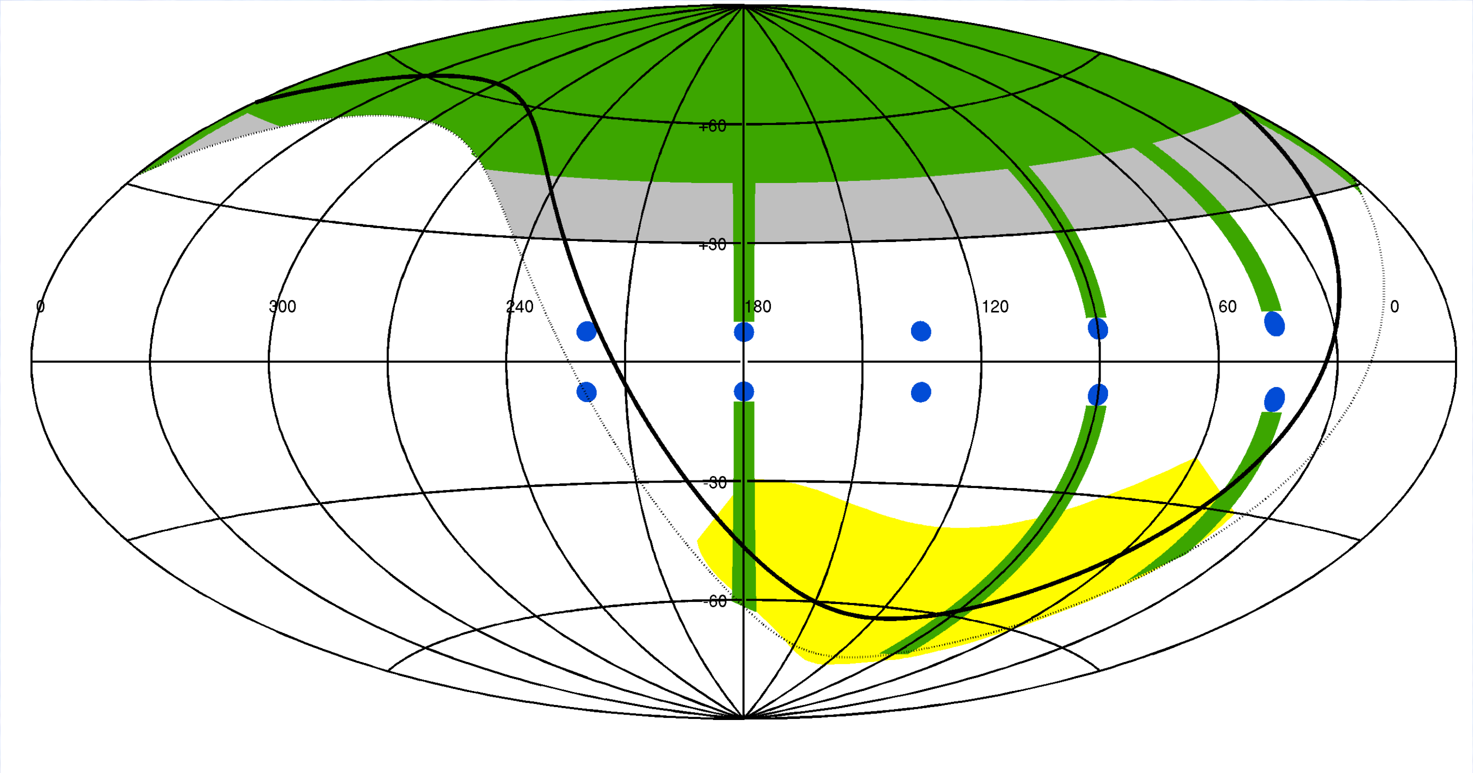


Participants in LAMOST, US (PLUS)

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), Beth Willman (CfA), 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).

A 3-5 year survey of 3-5 million Galactic stars



Sample survey footprint, shown as an Aitoff projection in Galactic coordinates. The green area probes the spheroid and thick disk in the NGC, with targets selected from existing SDSS imaging data. The yellow area probes the spheroid and thick disk in the SGC, and depends on imaging in the first year of SDSS III. The blue areas probe the thin disk.

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