Dwarf Galaxies and Dark Matter in the Milky Way

Heidi Newberg

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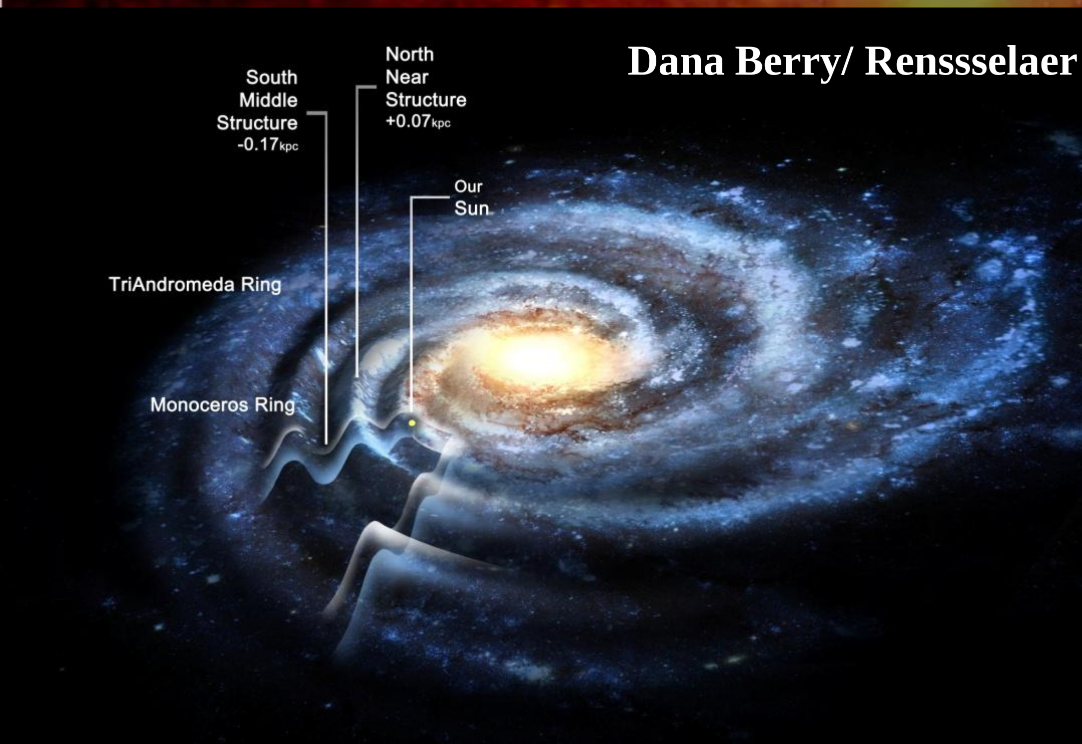
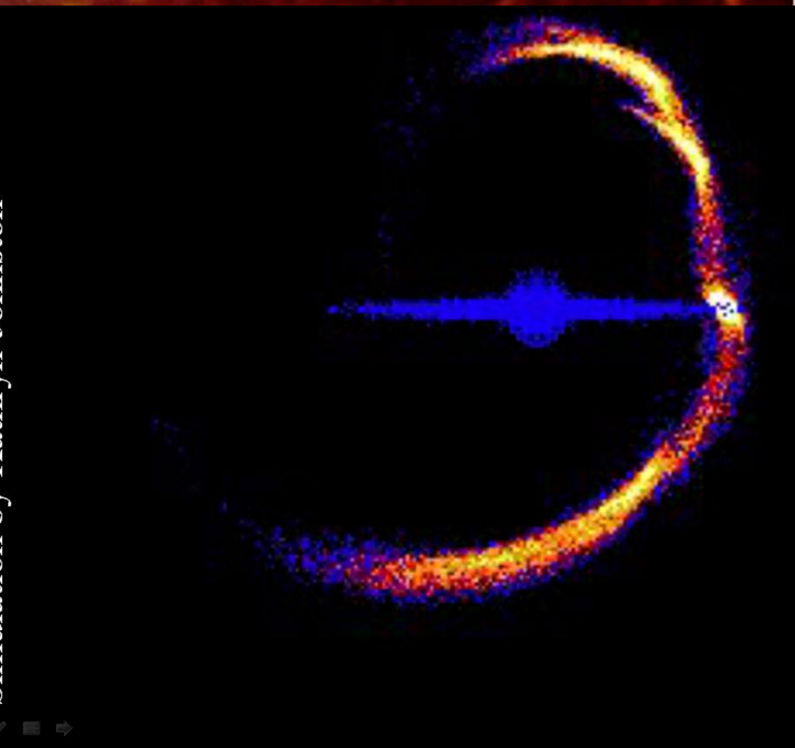


Simulation by Kathryn Johnston



Overview

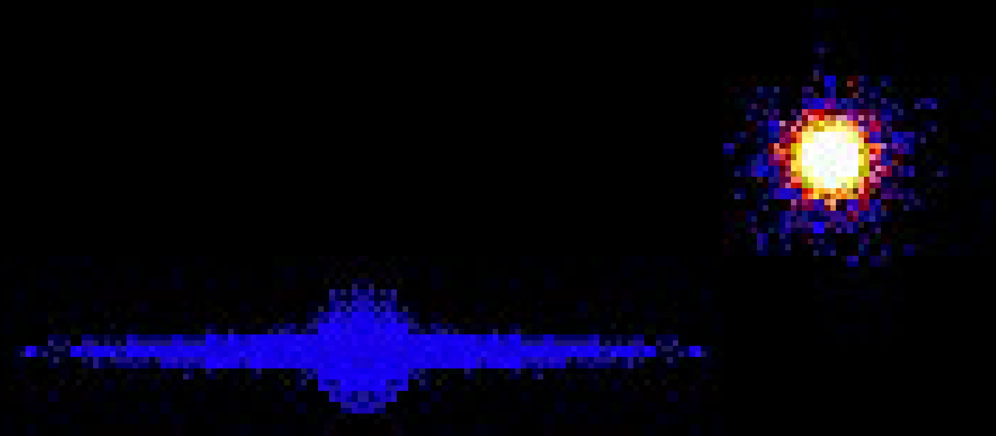
(1) The connection between tidal streams, disk substructure, and dark matter.

(2) The proliferation of known tidal streams.

(3) Methods to constrain the lumpiness of dark matter in the Milky Way, the overall shape of the dark matter halo, and the dark matter content of dwarf galaxies.

(4) MilkyWay@home

(5) Reconstructing the progenitor of the Orphan Stream



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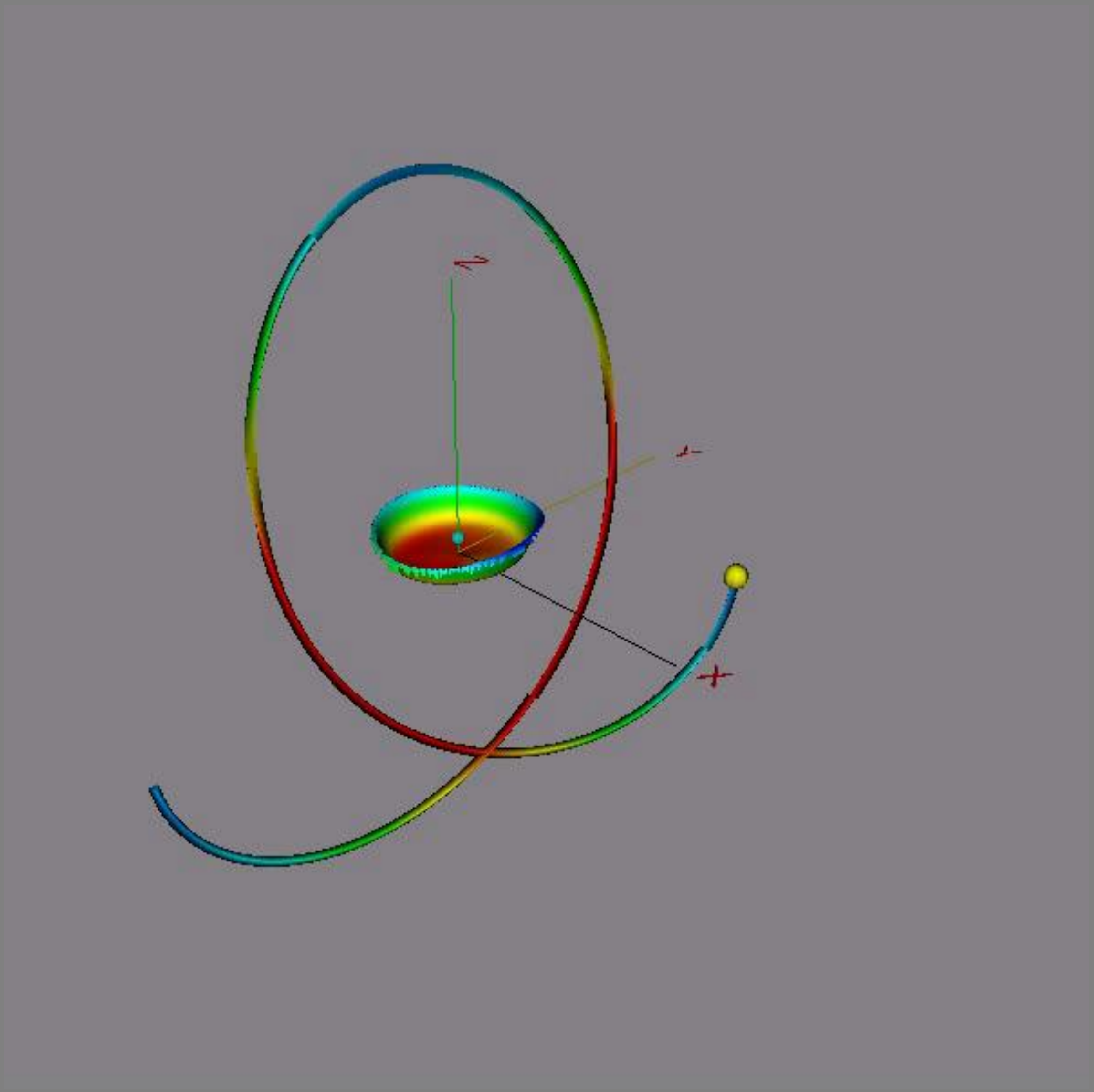
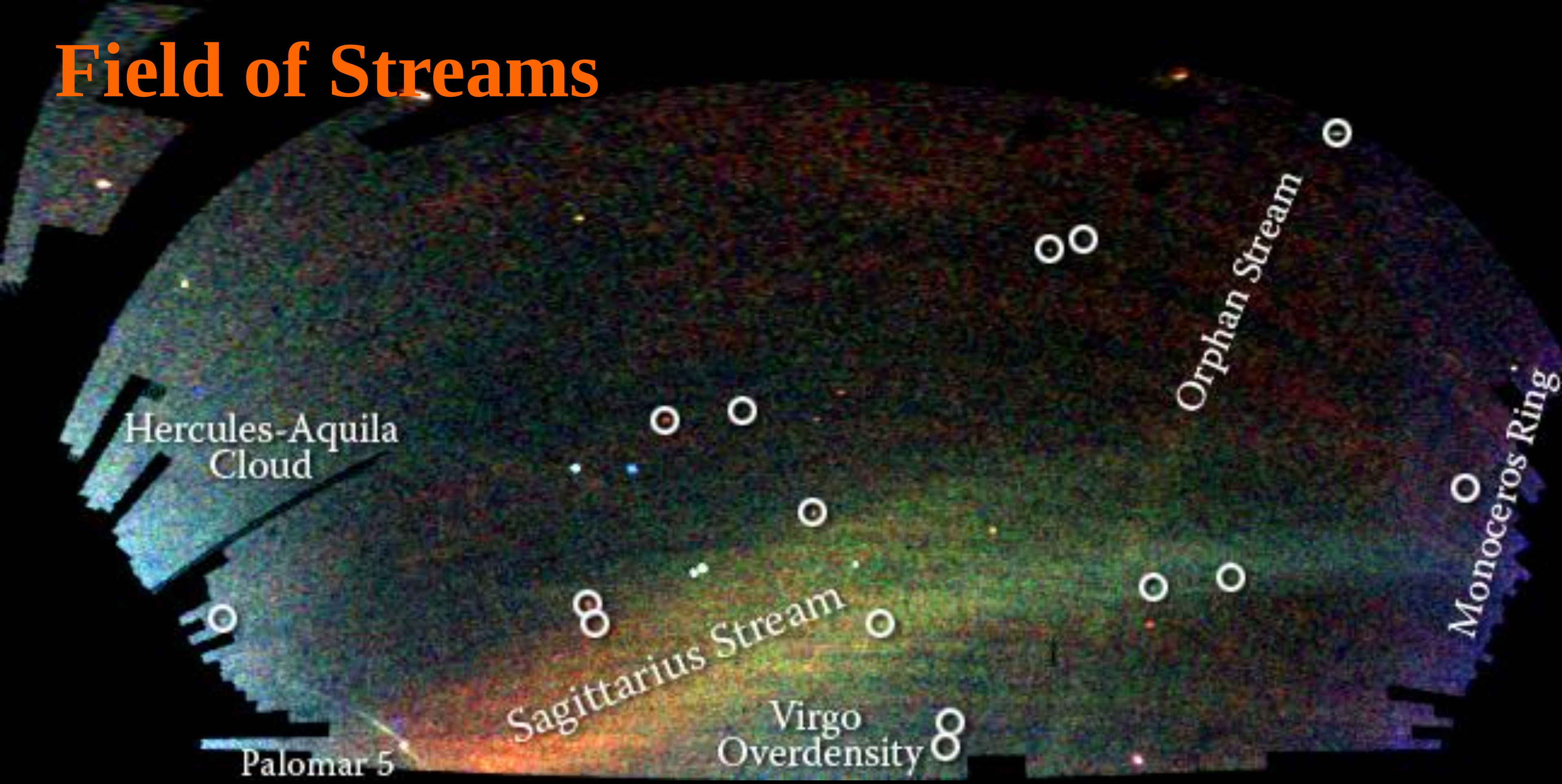


The Magellanic Clouds could be causing the Galactic warp.

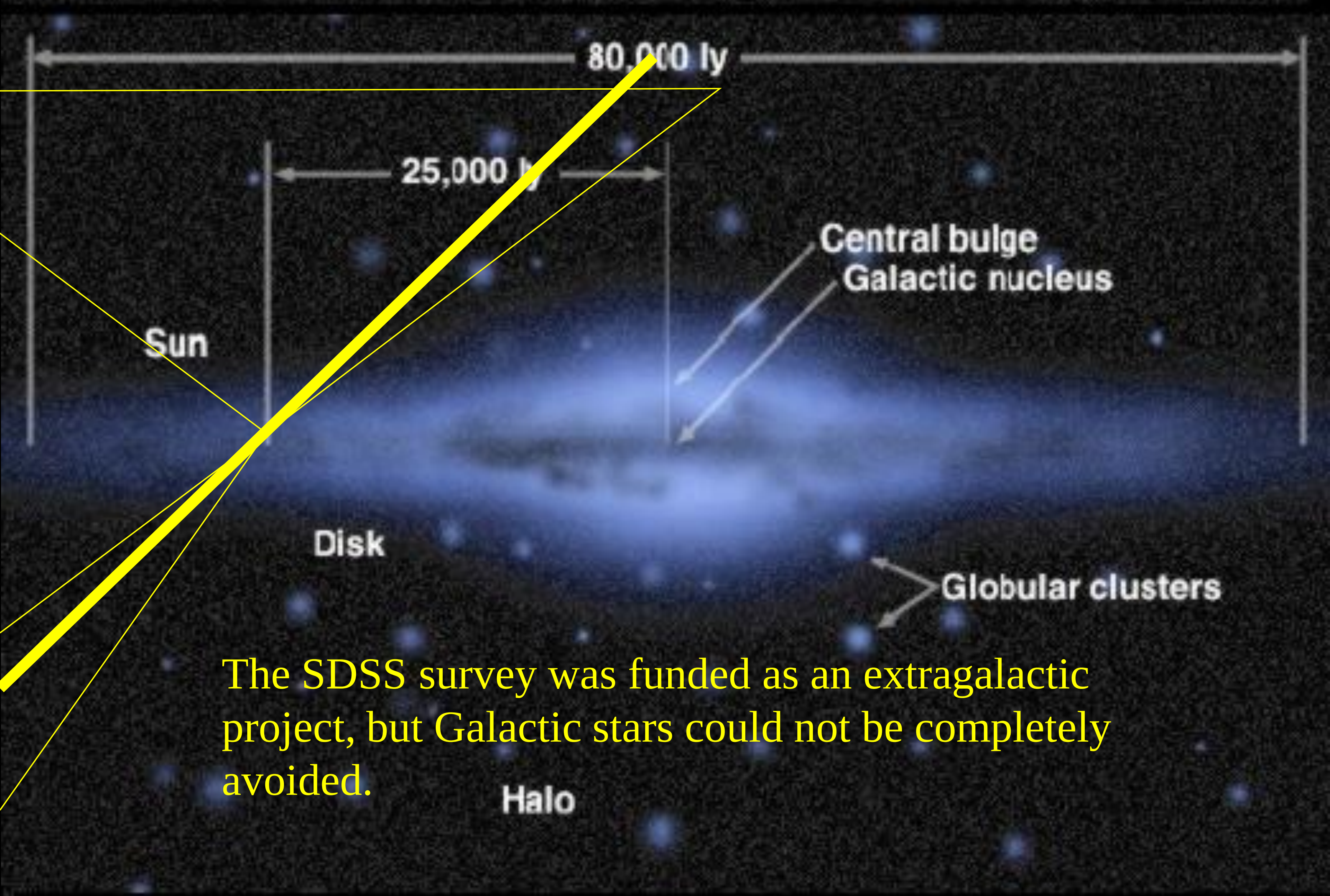
Leo Blitz and Martin Weinberg (2006)

Dierickx, Blecha & Loeb (2014) – Andromeda spiral/rings caused by collision with M32

Field of Streams

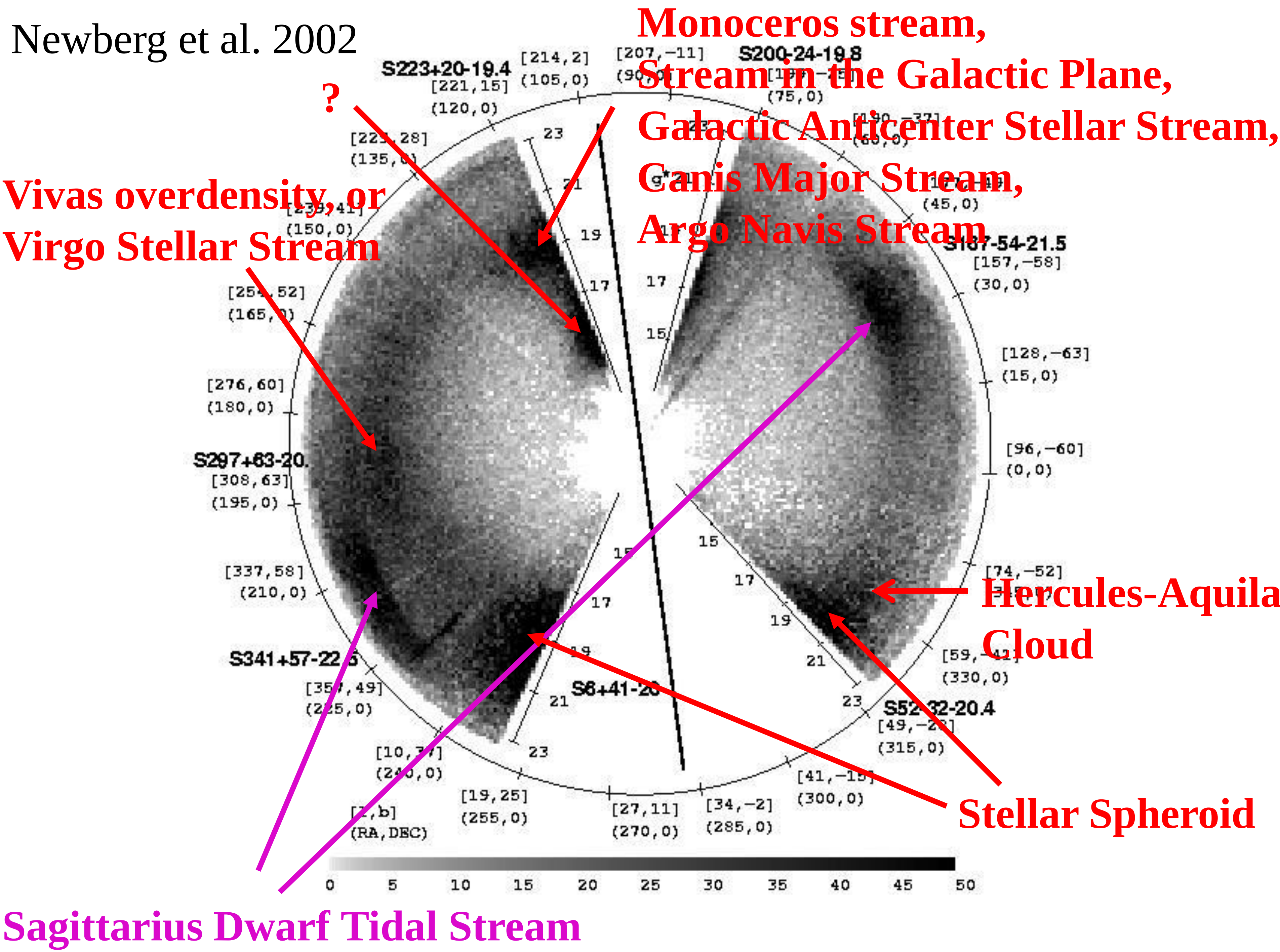


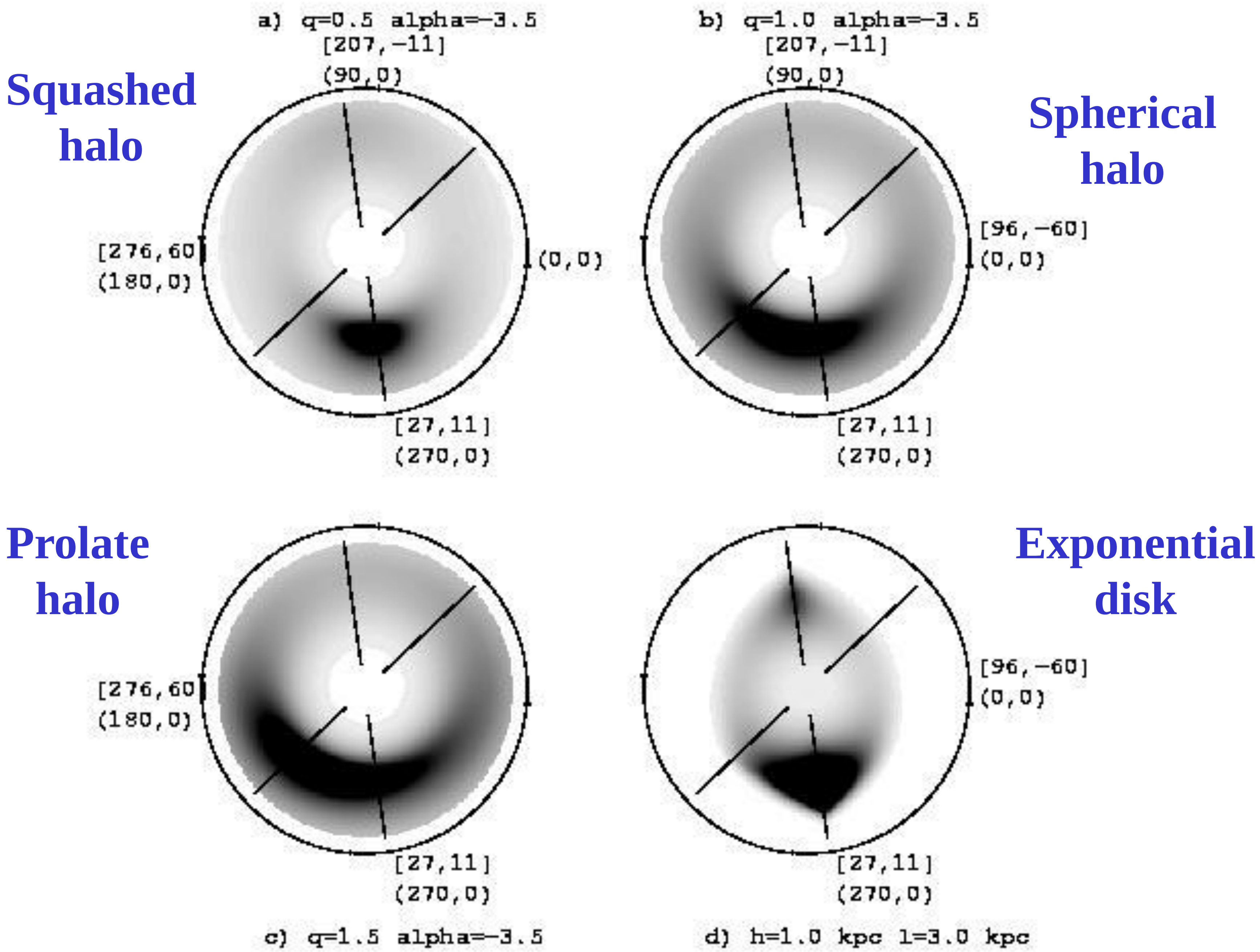
A map of stars in the outer regions of the Milky Way Galaxy, derived from SDSS images. The color indicates the distance of the stars, while the intensity indicates the density of stars on the sky. Circles enclose new Milky Way companions discovered by the SDSS; two of these are faint globular star clusters, while the others are faint dwarf galaxies.
Credit: V. Belokurov and the Sloan Digital Sky Survey.



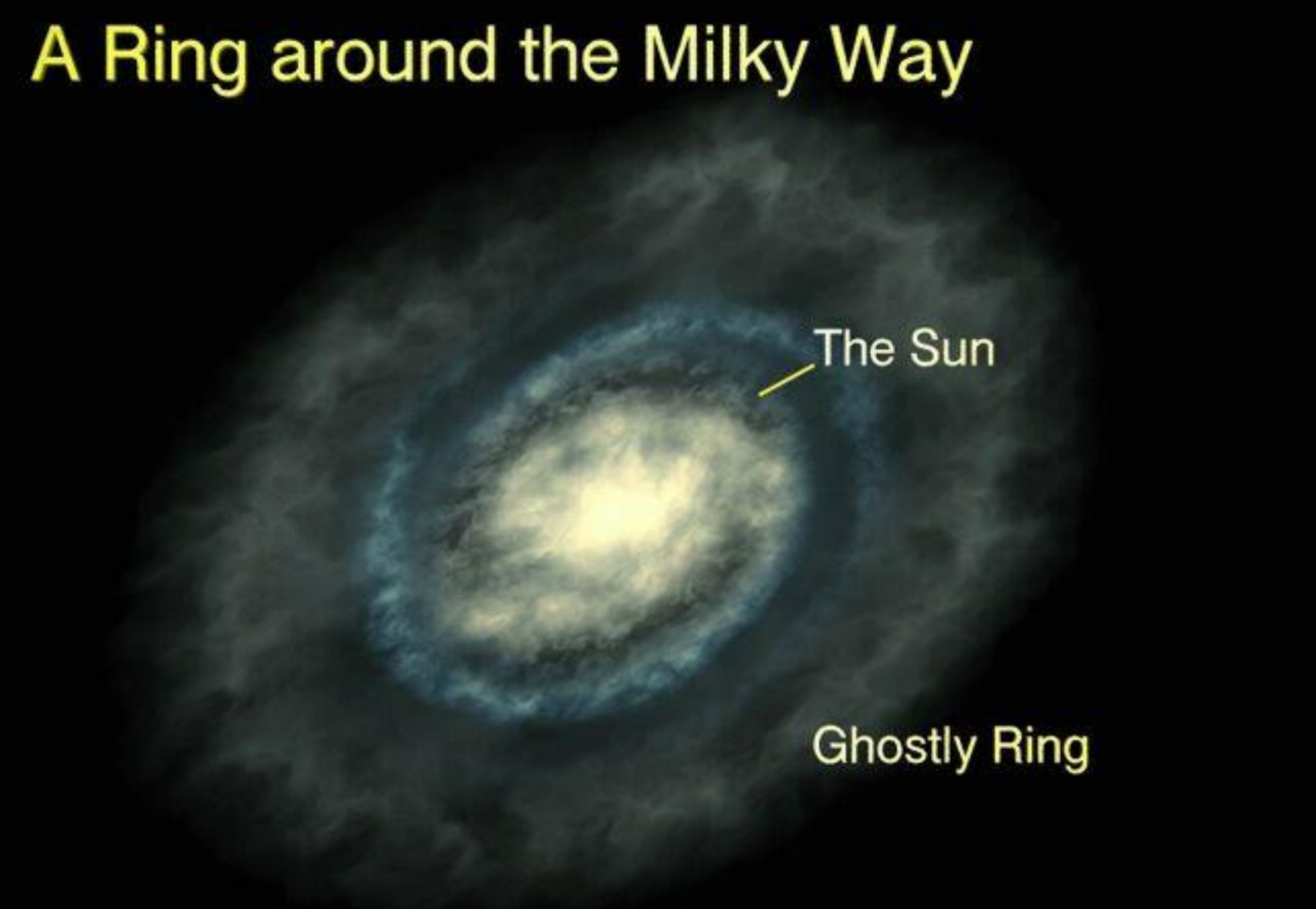
The SDSS survey was funded as an extragalactic project, but Galactic stars could not be completely avoided.

Newberg et al. 2002



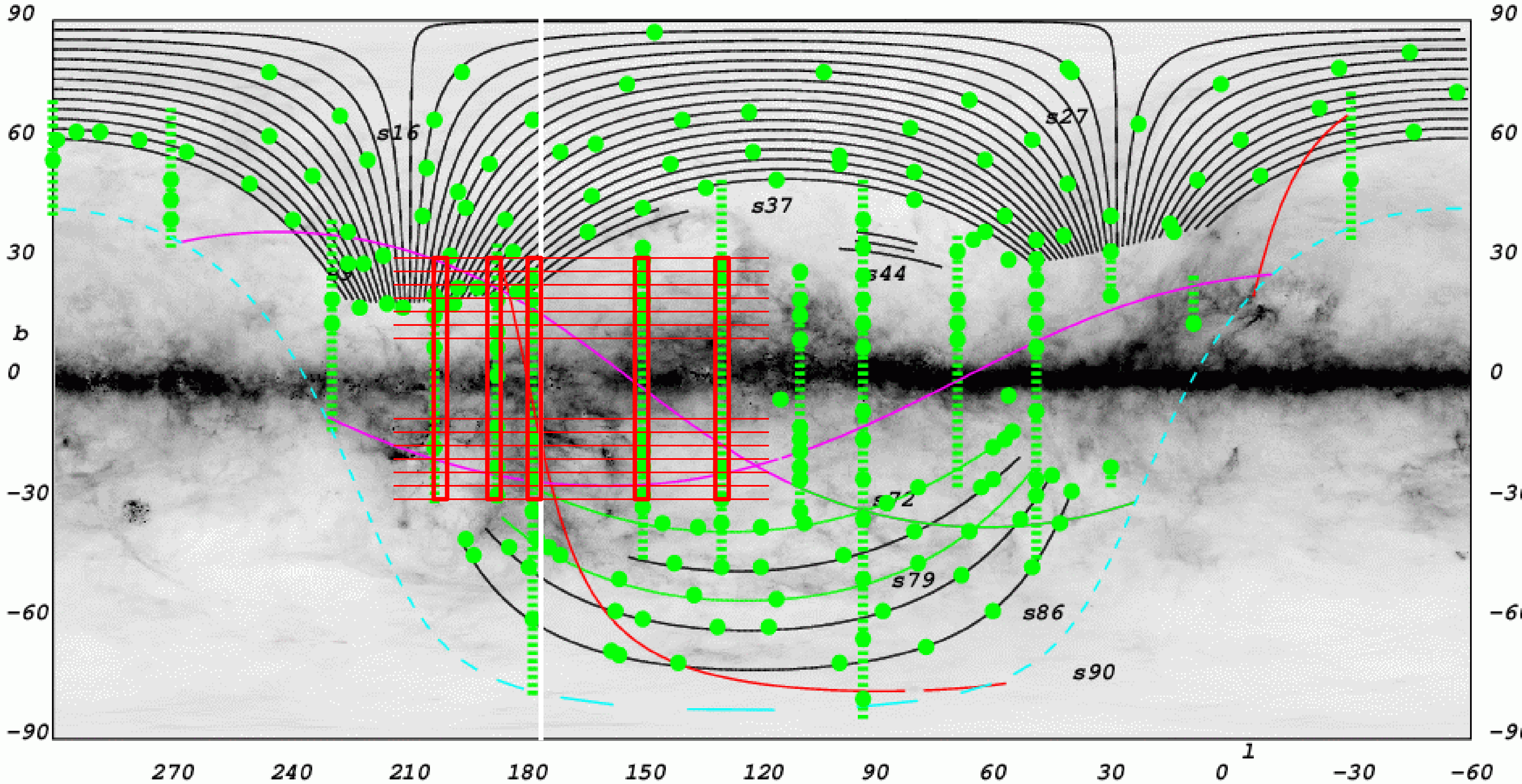


Squashed halo
a) q=0.5 alpha=-3.5
[207,-11]
(90,0)
[276,60]
(180,0)
(0,0)
[27,11]
(270,0)
Spherical halo
b) q=1.0 alpha=-3.5
[207,-11]
(90,0)
[96,-60]
(0,0)
[27,11]
(270,0)
Prolate halo
[276,60]
(180,0)
[27,11]
(270,0)
c) q=1.5 alpha=-3.5
Exponential disk
[96,-60]
(0,0)
[27,11]
(270,0)
d) h=1.0 kpc l=3.0 kpc

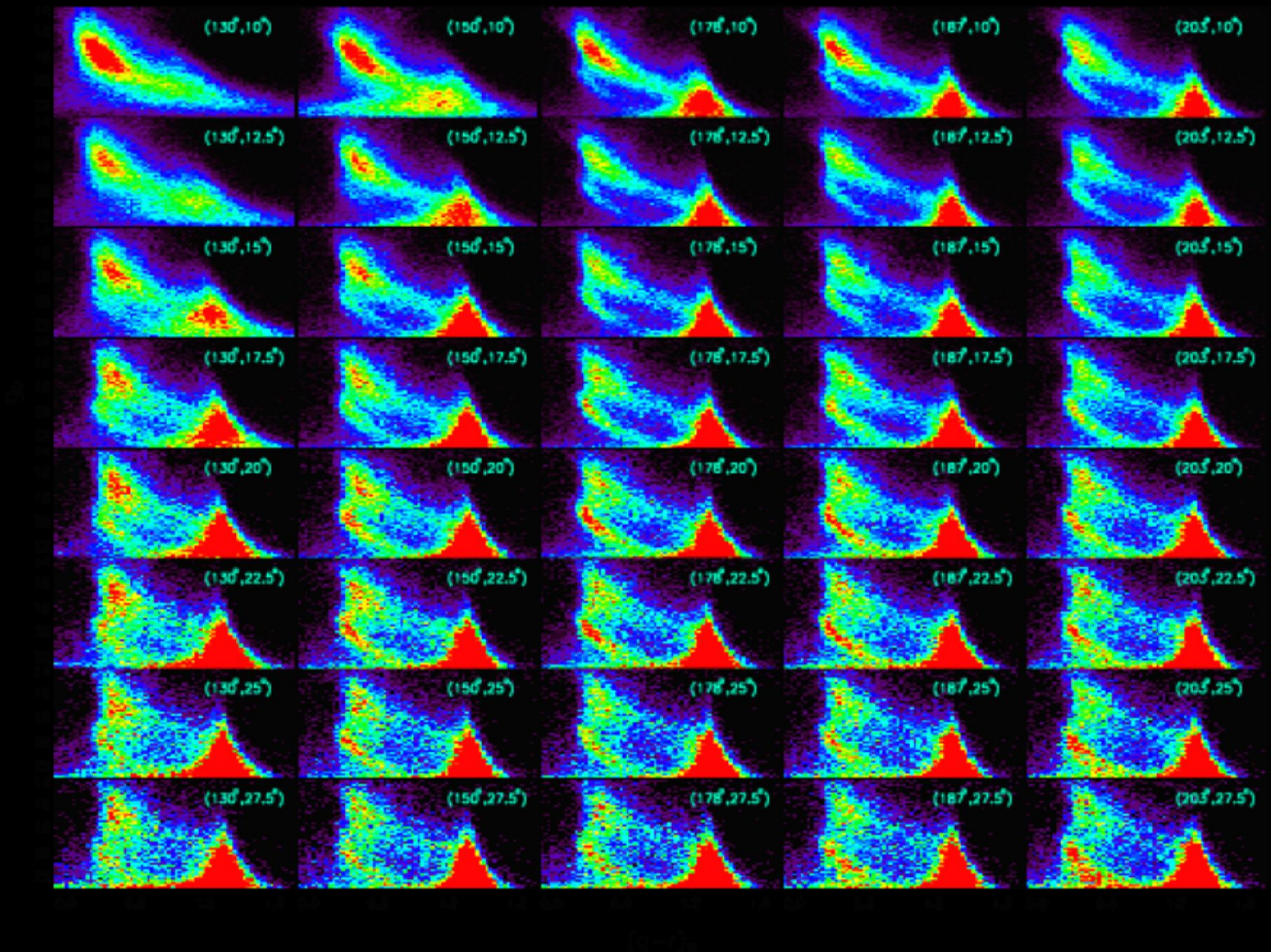


The Monoceros Ring

Science – no image credit



The SDSS also took imaging (and spectroscopic) data along 2.5°-wide stripes at constant Galactic longitude. These stripes cross the Galactic plane.



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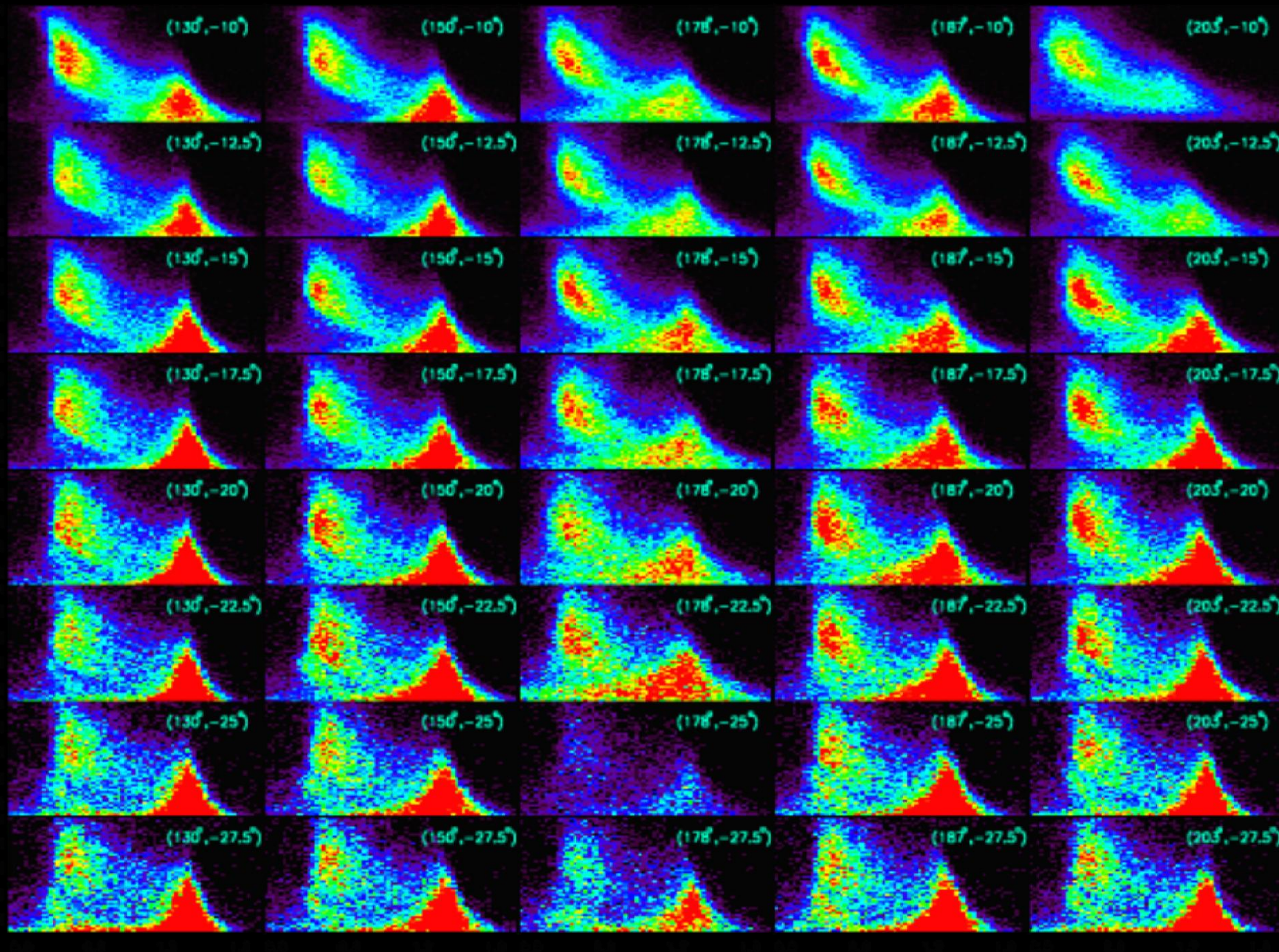
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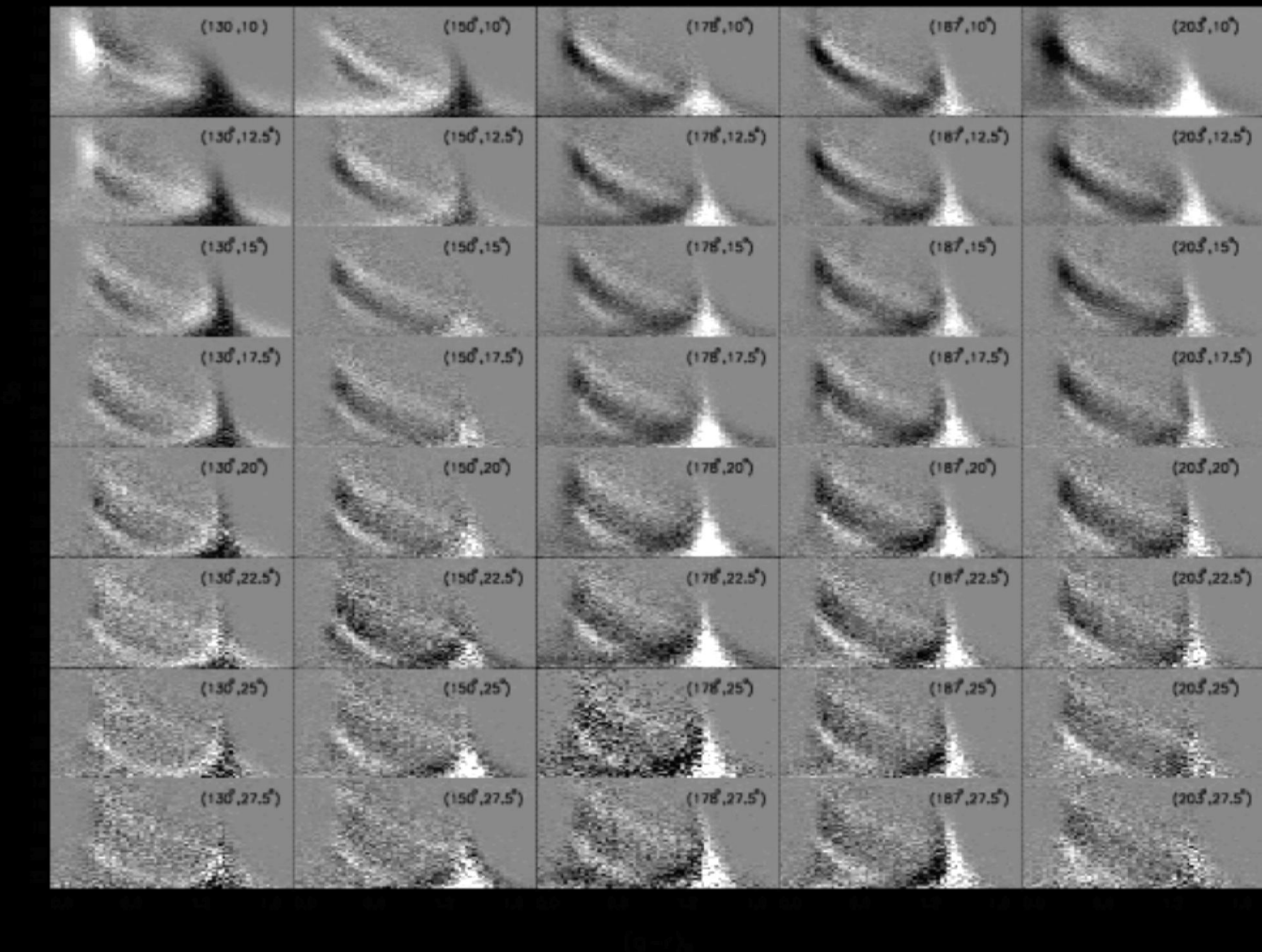
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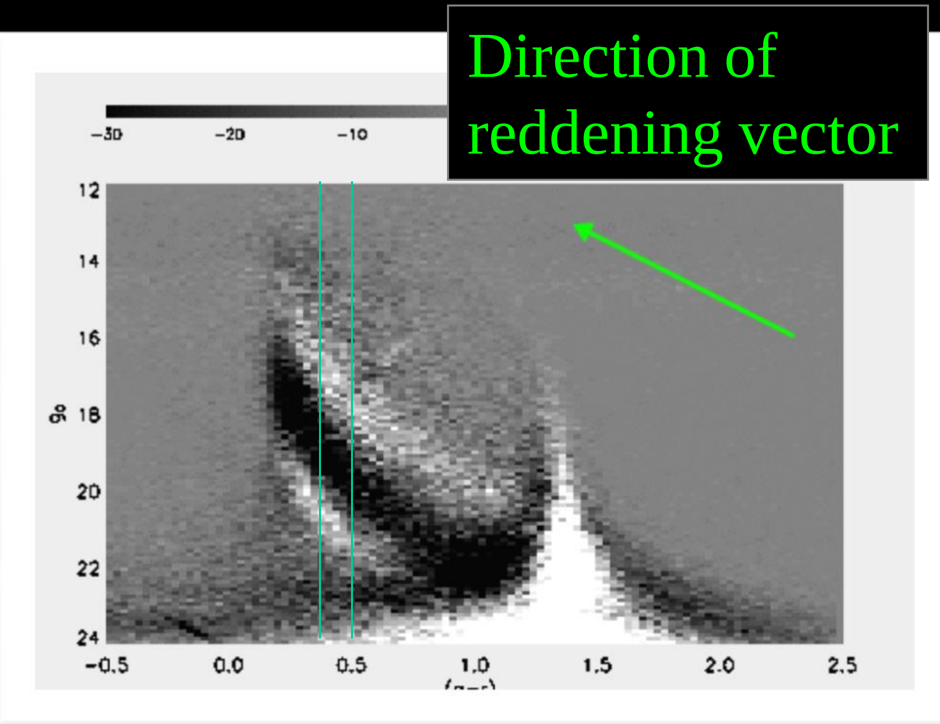
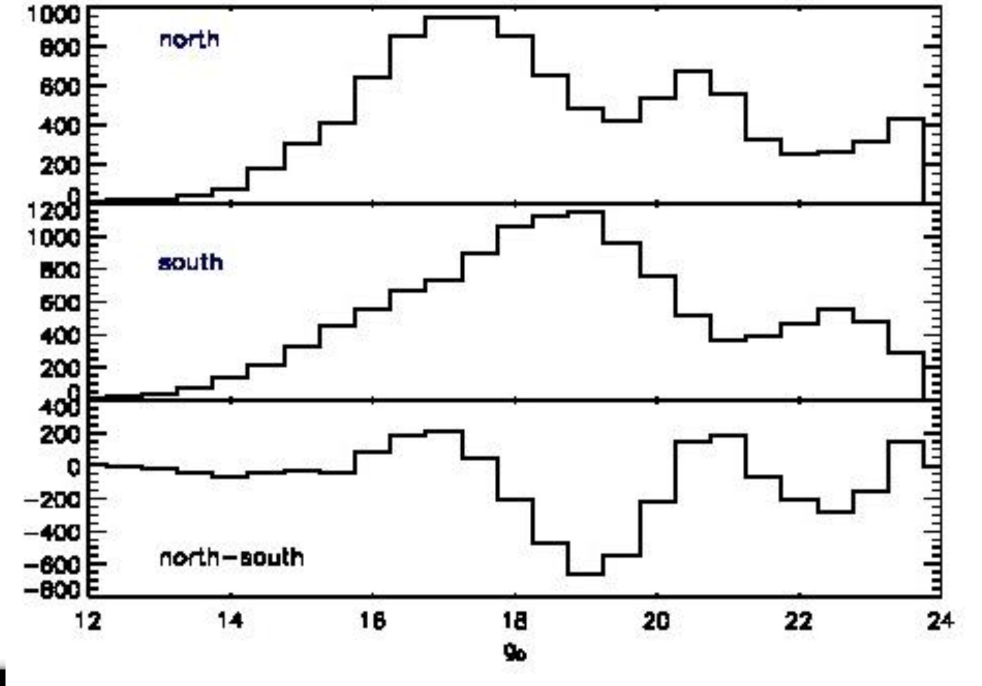
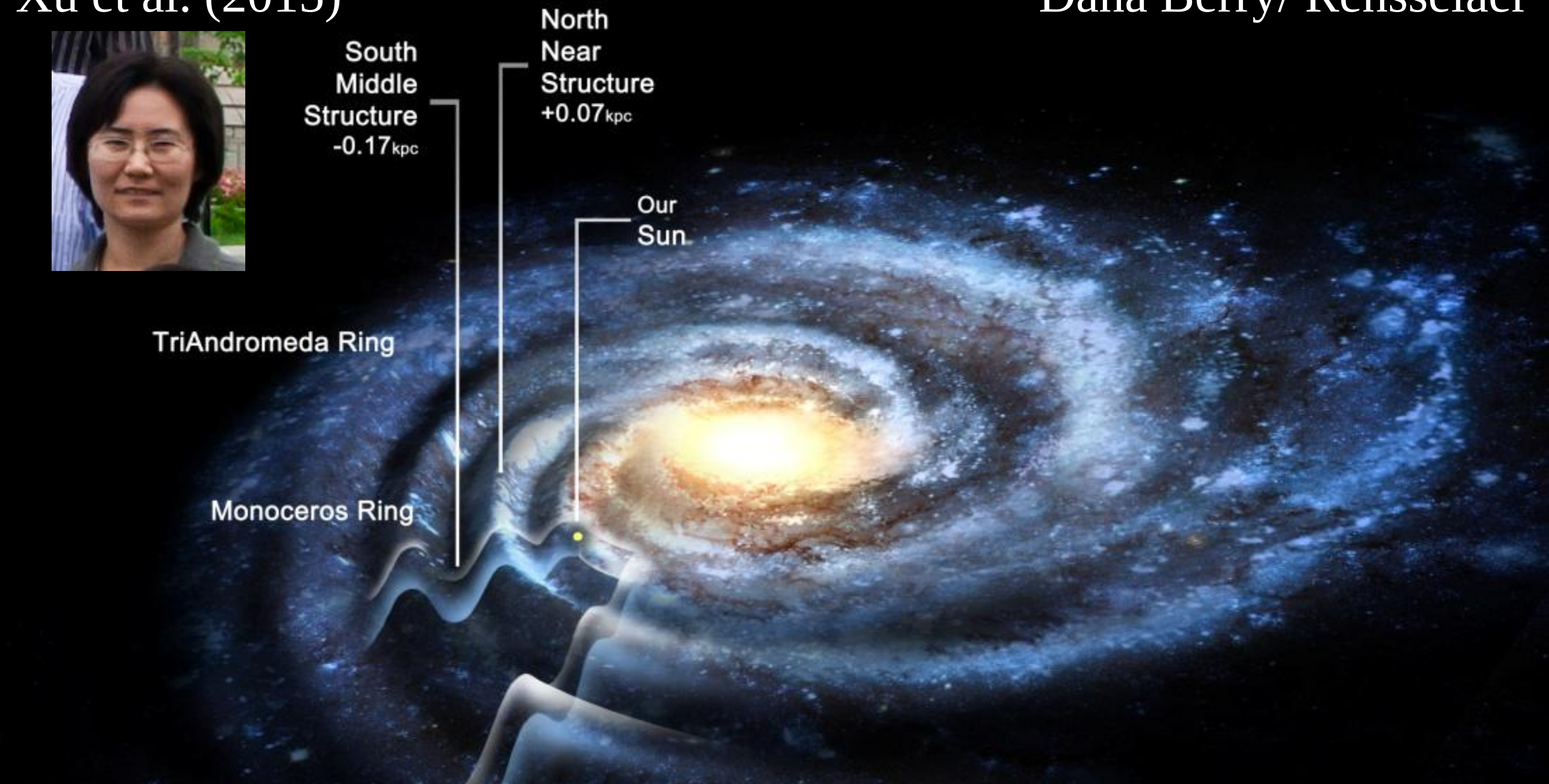




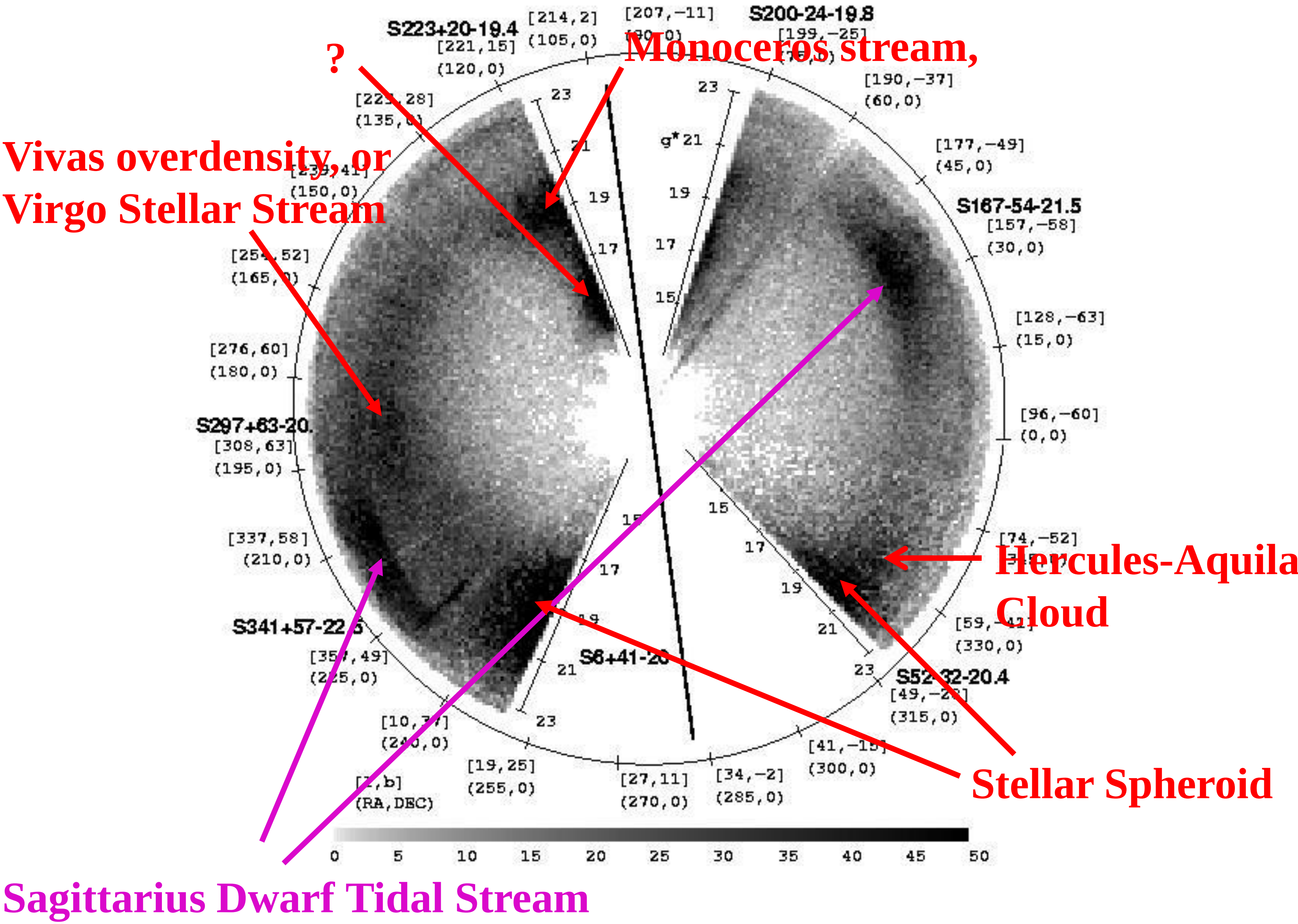
Getting the reddening wrong does not change the result.
The difference in counts is huge – like a factor of two.

Xu et al. (2015)

Dana Berry/ Rensselaer



The “Near North” structure is 10.5 kpc from the Galactic center, and is perturbed approximately 70 pc above the plane. The “South Middle” structure is 14 kpc from the Galactic center and 170 pc below the plane. The next oscillations coincide with the Monoceros and TriAnd “Rings.”



?
Monoceros stream,
Vivas overdensity, or
Virgo Stellar Stream
Hercules-Aquila
Cloud
Stellar Spheroid
Sagittarius Dwarf Tidal Stream
S223+20-19.4
S200-24-19.8
S167-54-21.5
S297+63-20.
S341+57-22.5
S6+41-20
S52-32-20.4
[214,2]
(105,0)
[207,-11]
[221,15]
(120,0)
[190,-37]
(60,0)
[177,-49]
(45,0)
[157,-58]
(30,0)
[128,-63]
(15,0)
[96,-60]
(0,0)
[74,-52]
[59,-41]
(330,0)
[49,-26]
(315,0)
[41,-15]
(300,0)
[34,-2]
(285,0)
[27,11]
(270,0)
[19,25]
(255,0)
(240,0)
(225,0)
[337,58]
(210,0)
[308,63]
(195,0)
[276,60]
(180,0)
(165,0)
(150,0)
(135,0)
(RA,DEC)
g*21
0
5
10
15
20
25
30
35
40
45
50

The disk of the Milky Way exhibits wavelike bulk motions.

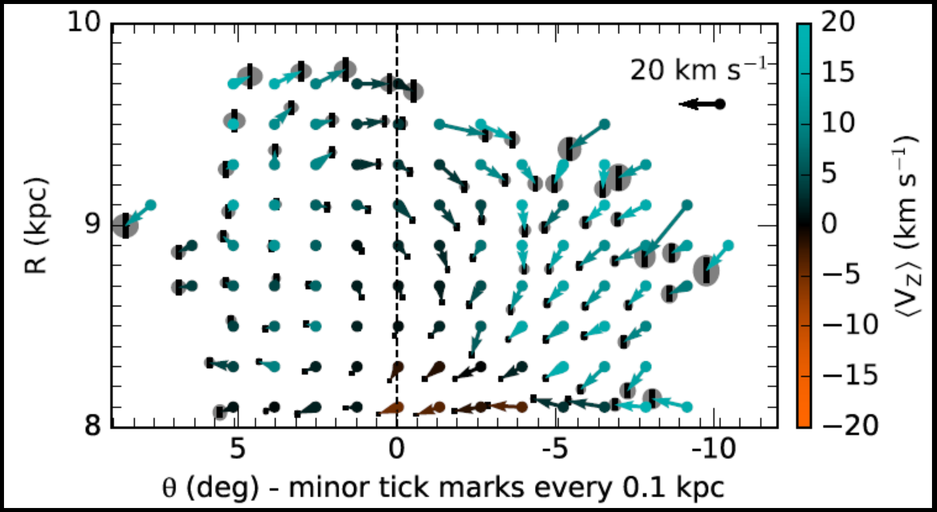
Williams et al. (2013) find velocity substructure in RAVE data

Widrow et al. (2012) find velocity substructure in SDSS data

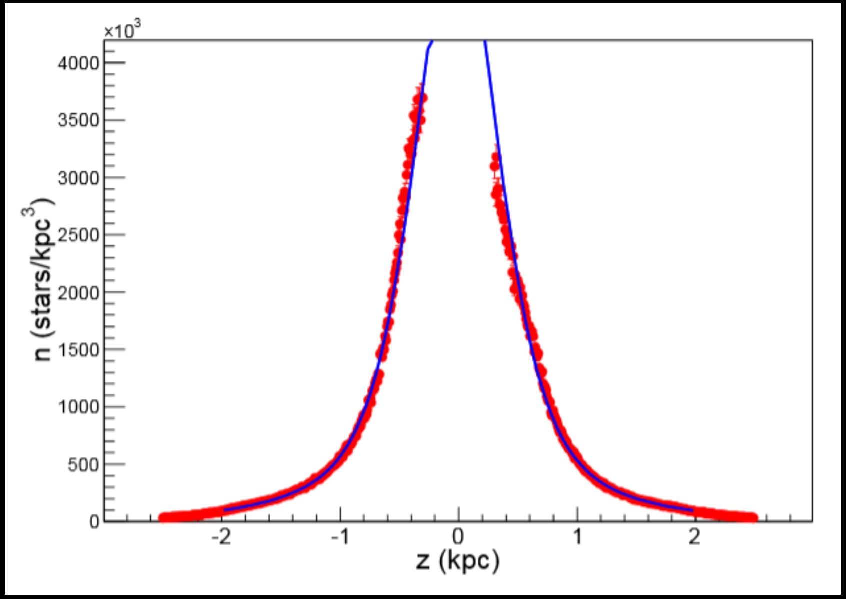
Carlin et al. (2013) find velocity substructure in LAMOST data

Yanny & Gardner (2013) find density oscillations in SDSS data.

Pearl et al. (2017) find velocity substructure, with errors, using LAMOST and PPMXL

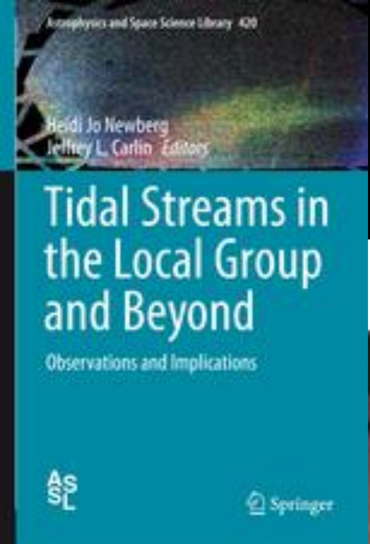


Pearl et al. (2017)



Yanny & Gardner (2013)

The Spaghetti Halo



26 streams & clouds
(~15 GC and 11 dG?

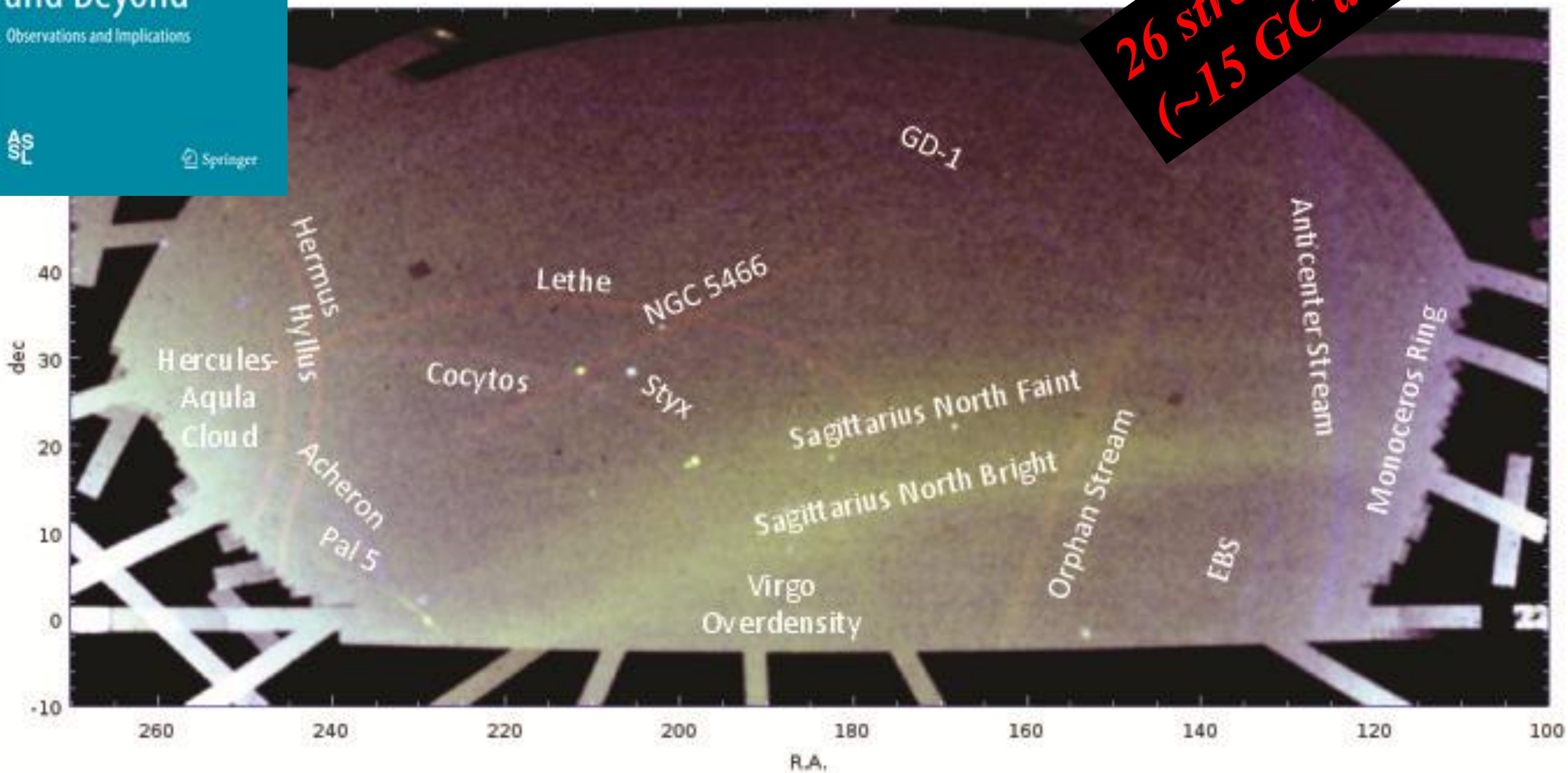
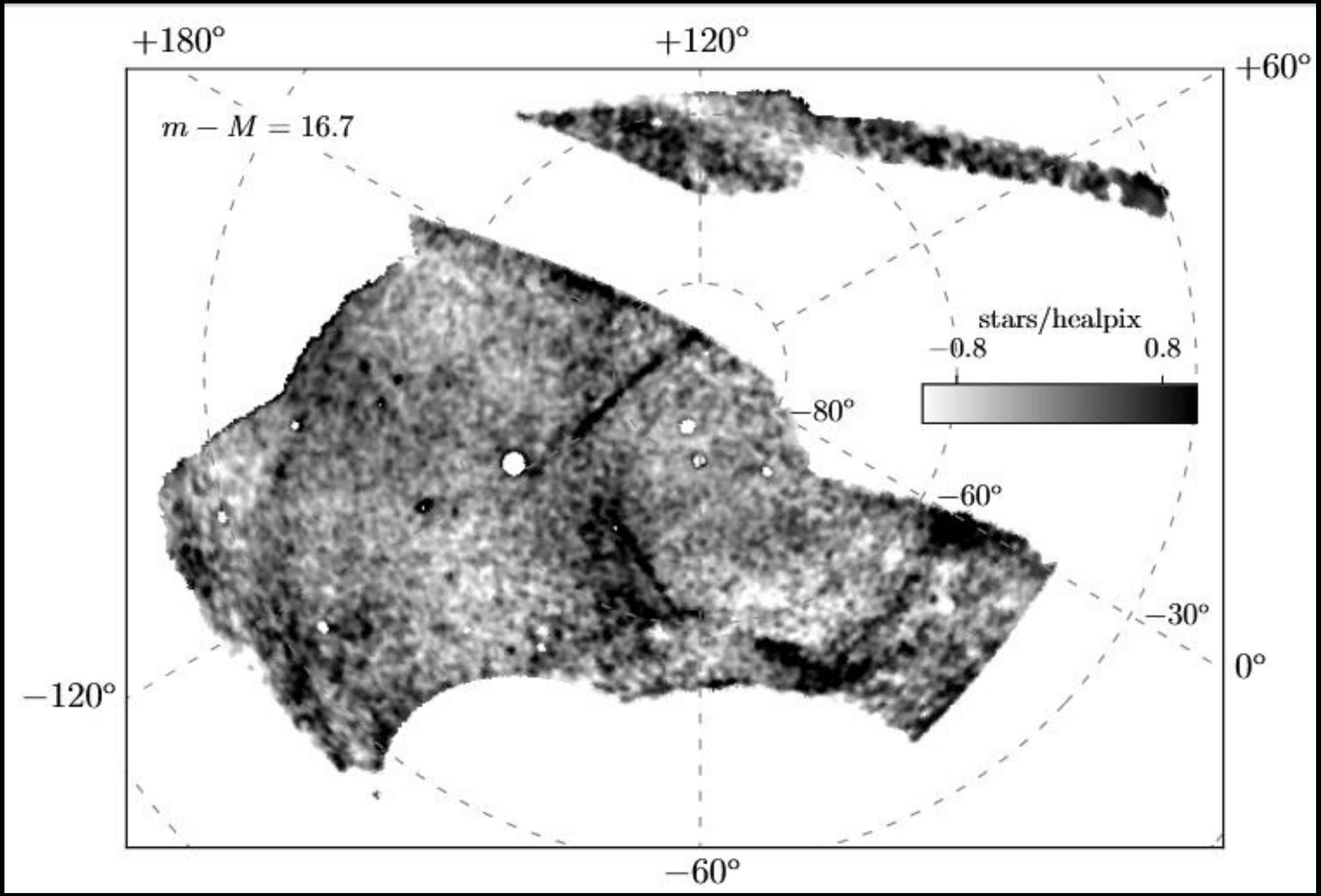


Image credit: Carl Grillmair, in Springer book: *Tidal Streams in the Local Group and Beyond*, Eds. Newberg & Carlin (2015)

~20 new tidal streams (or tidal stream candidates):

DES: Li et al. (2016), Shipp et al. (2018) – 12 streams
HST: Sohn et al. (2016) – 1 stream
PanSTARRs: Grillmair (2017a) – 4 streams
SDSS: Grillmair (2017b) 0-4 streams
SLAMS survey: Jethwa et al. (2017) – 1 stream

Shipp et al. (2018)



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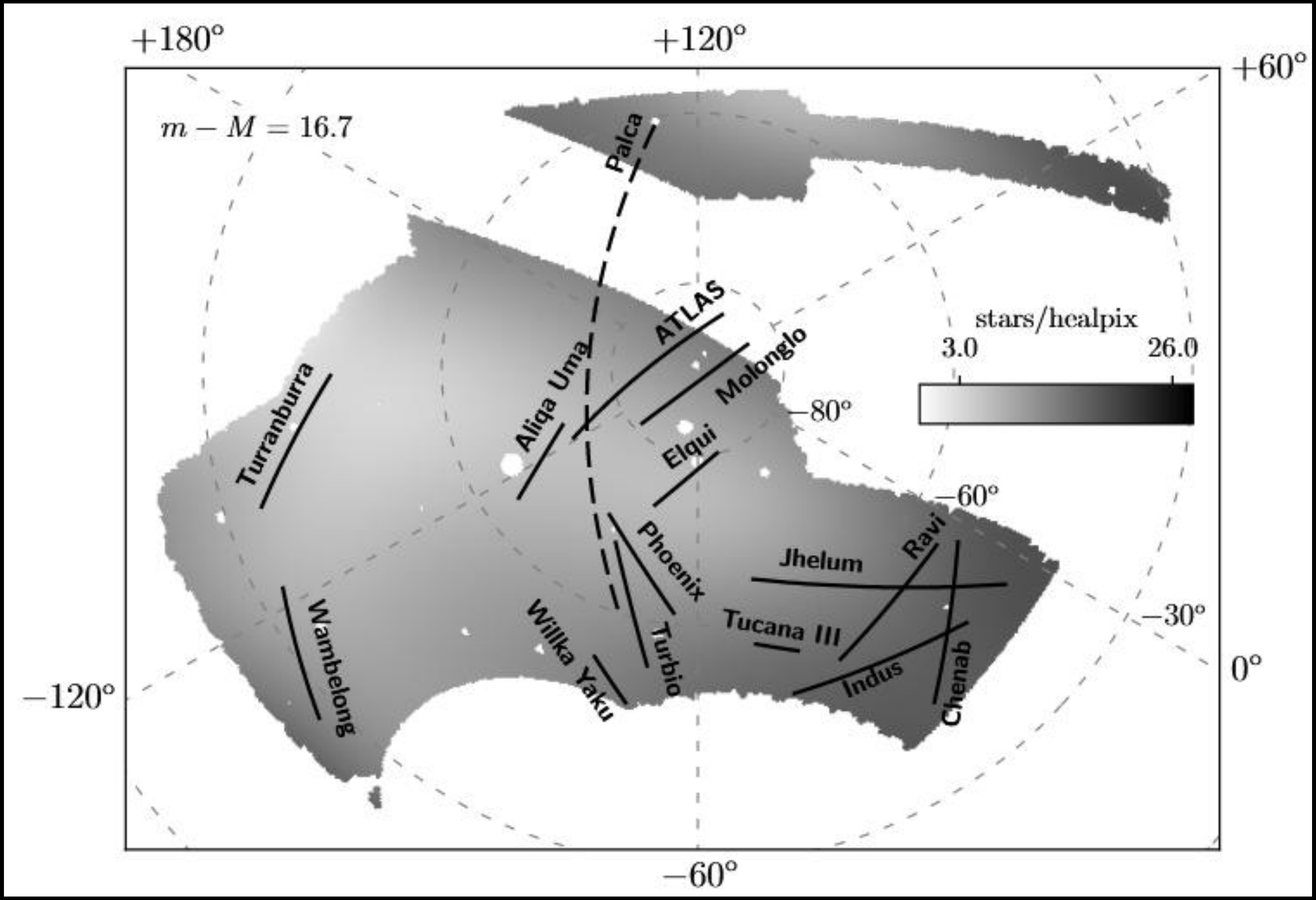
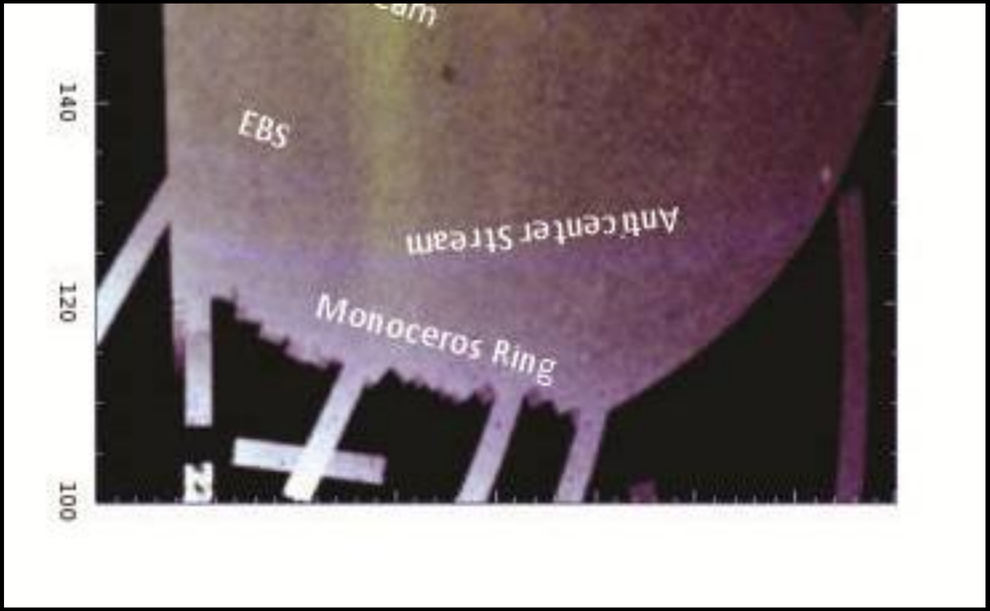
SLAMS survey: Jethwa et al. (2017) – 1 stream

Shipp et al. (2018)

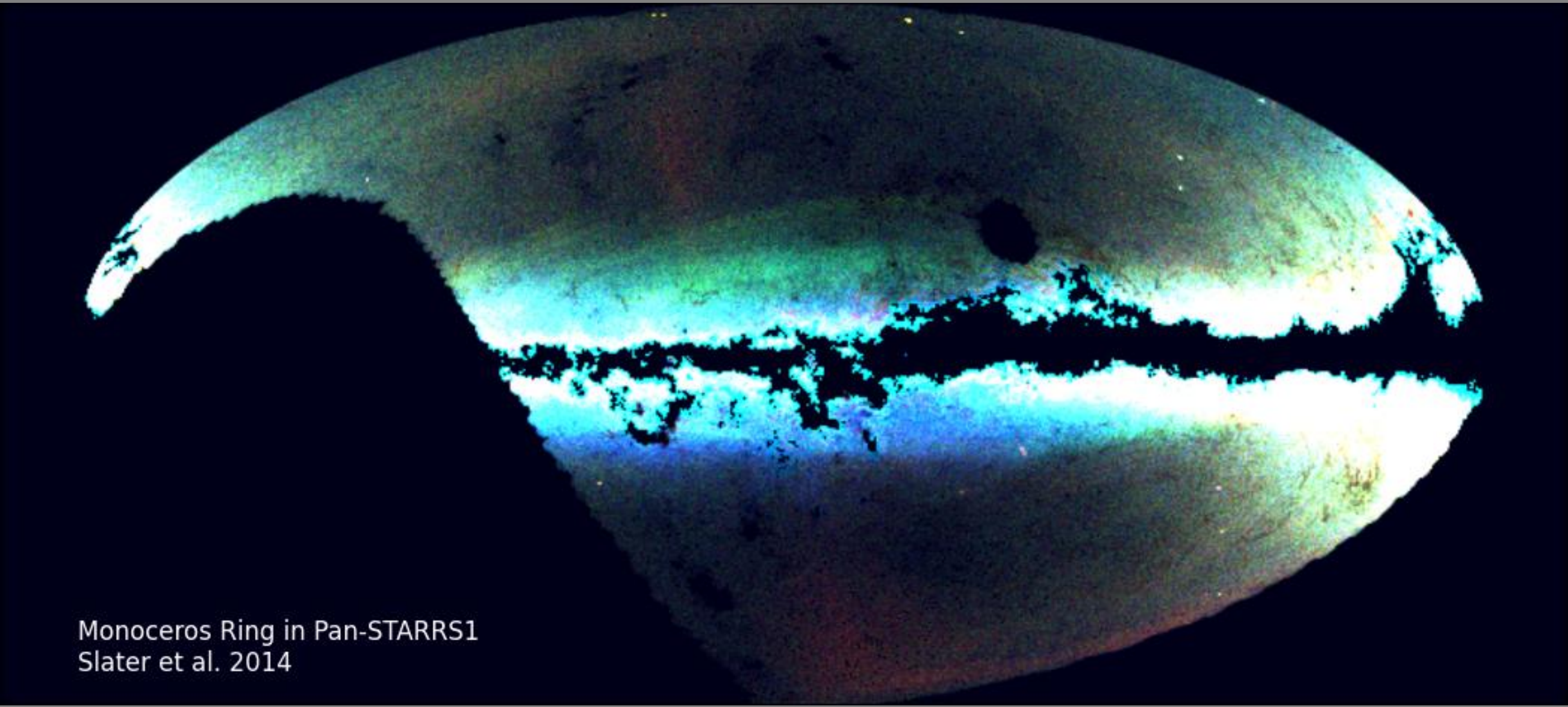


The streams/clouds at low latitude



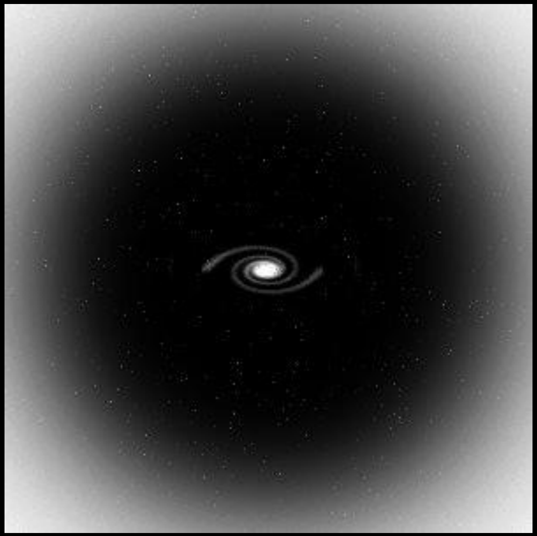
Monoceros Ring
Anticenter Stream
Eastern Banded Structure

Triangulum-Andromeda Stream
Canis Major Dwarf Galaxy
TriAnd2
PAndAS MW Stream
PAndAS NE blob

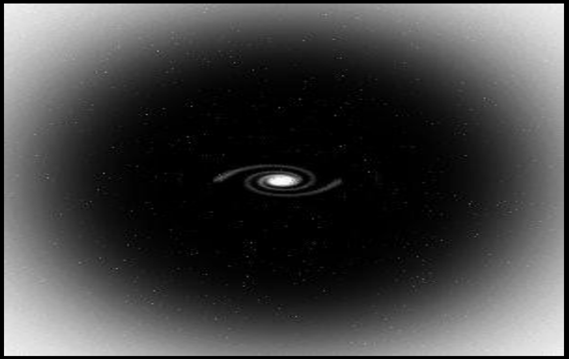


Turnoff stars with 0.2<g-r<0.3; blue is closer than green. This shows a tremendous amount of substructure in the plane, at all (l,b) where |b|<30°.

Possible Dark Matter Halo Shapes

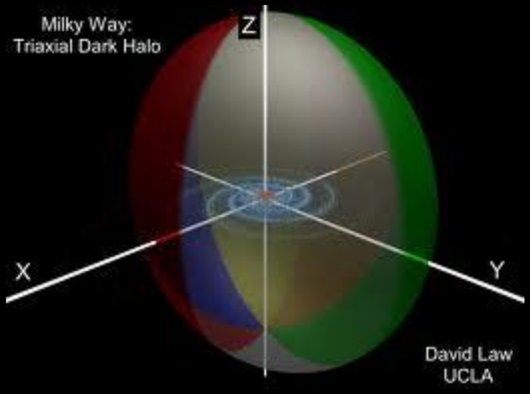


spherical

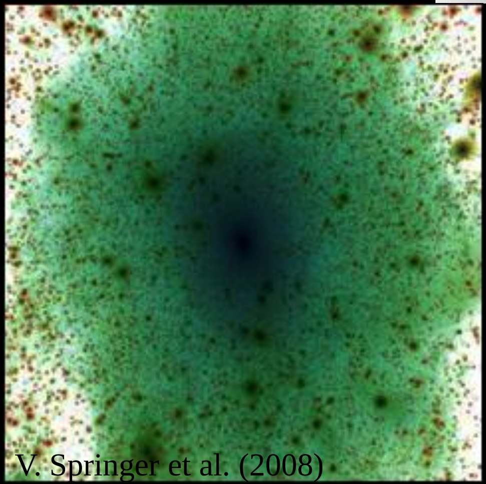


oblate

prolate



triaxial



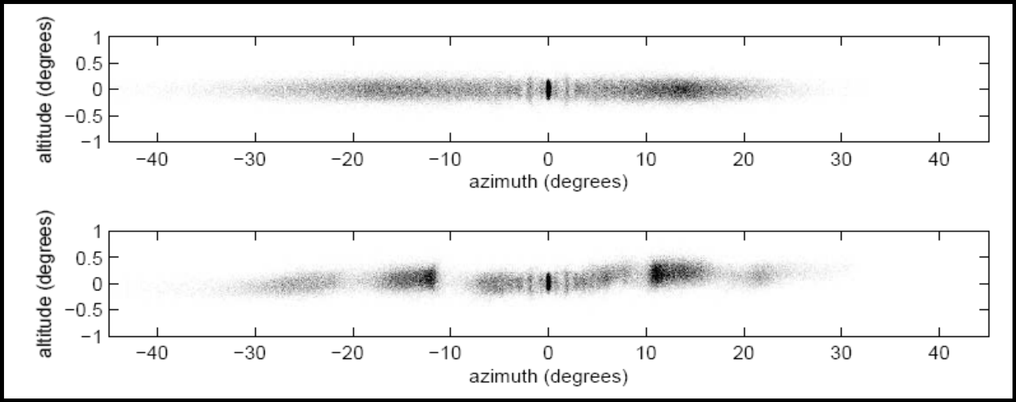
lumpy

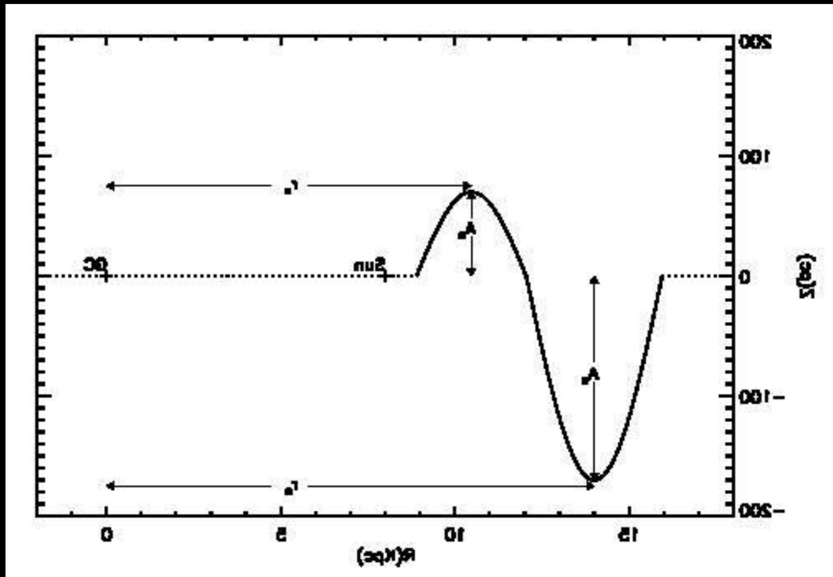
Also, the shape could change with time and radius…

The only things we know for sure about the dark matter is from the motions of matter that we can see.

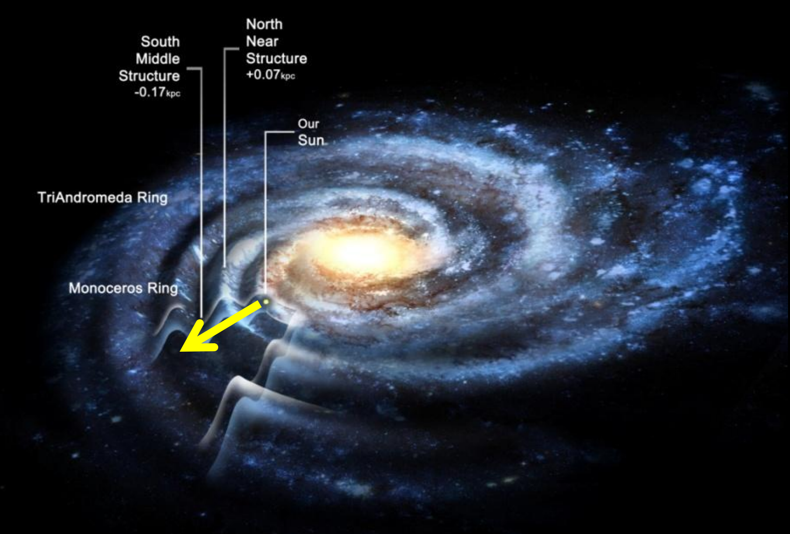
We can measure the lumpiness of the dark matter distribution by:

- Looking for gaps in streams
- Broadening of streams with time
- Stars that have been thrown out of streams
- Galactoseismology





Vertical displacement of the Milky Way disk from Xu et al. (2015)



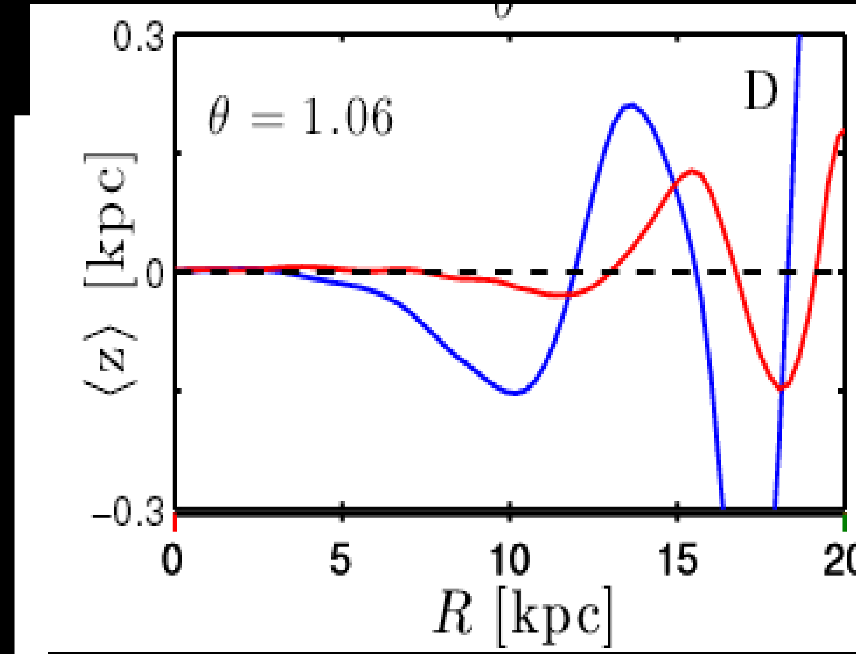
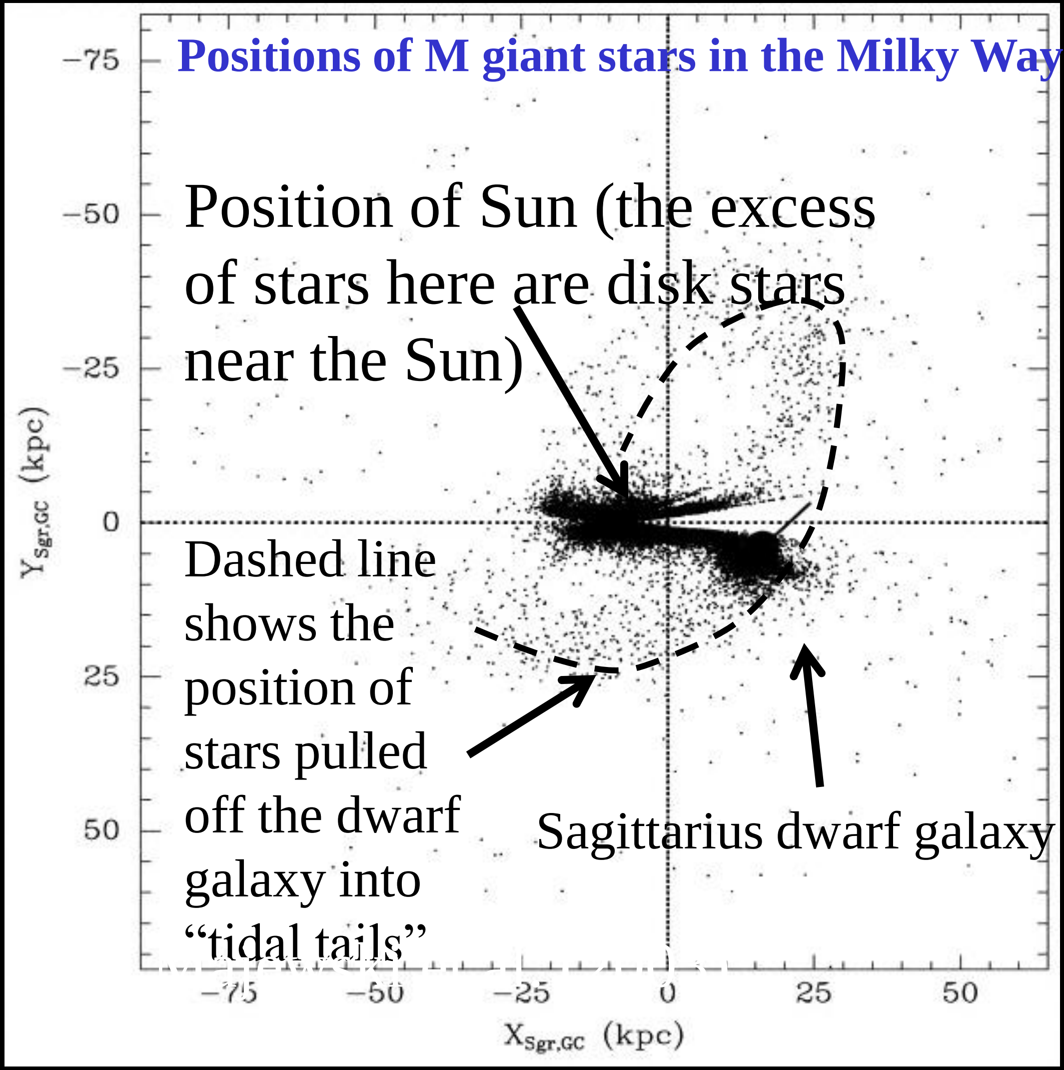


Figure 6. Panel d: Comparison of the mean vertical displacement of the disk from a light ($10^{10.5}\,M_\odot$, red) and heavy ($10^{11}\,M_\odot$, blue) Sagittarius dwarf galaxy, as a function of galactocentric radius.

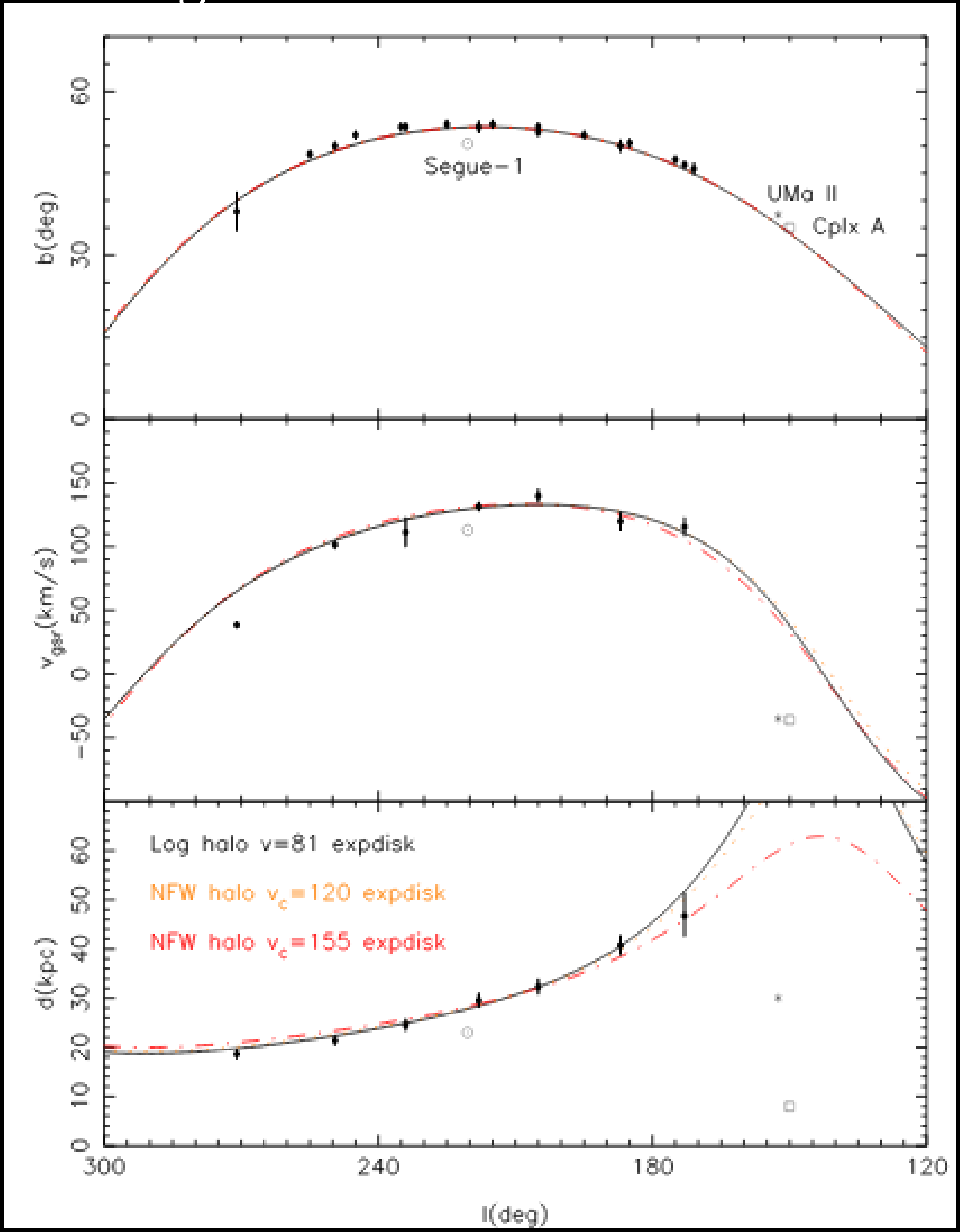
Gomez et al. (2013)

Determining the distribution of dark matter from tidal streams

We can in principle measure the positions and velocities of every star in the Milky Way. But the stars in tidal streams are the only ones for which we know where they were in the past (in the dwarf galaxy). This gives us information about the gravitational potential through which the stars have moved.

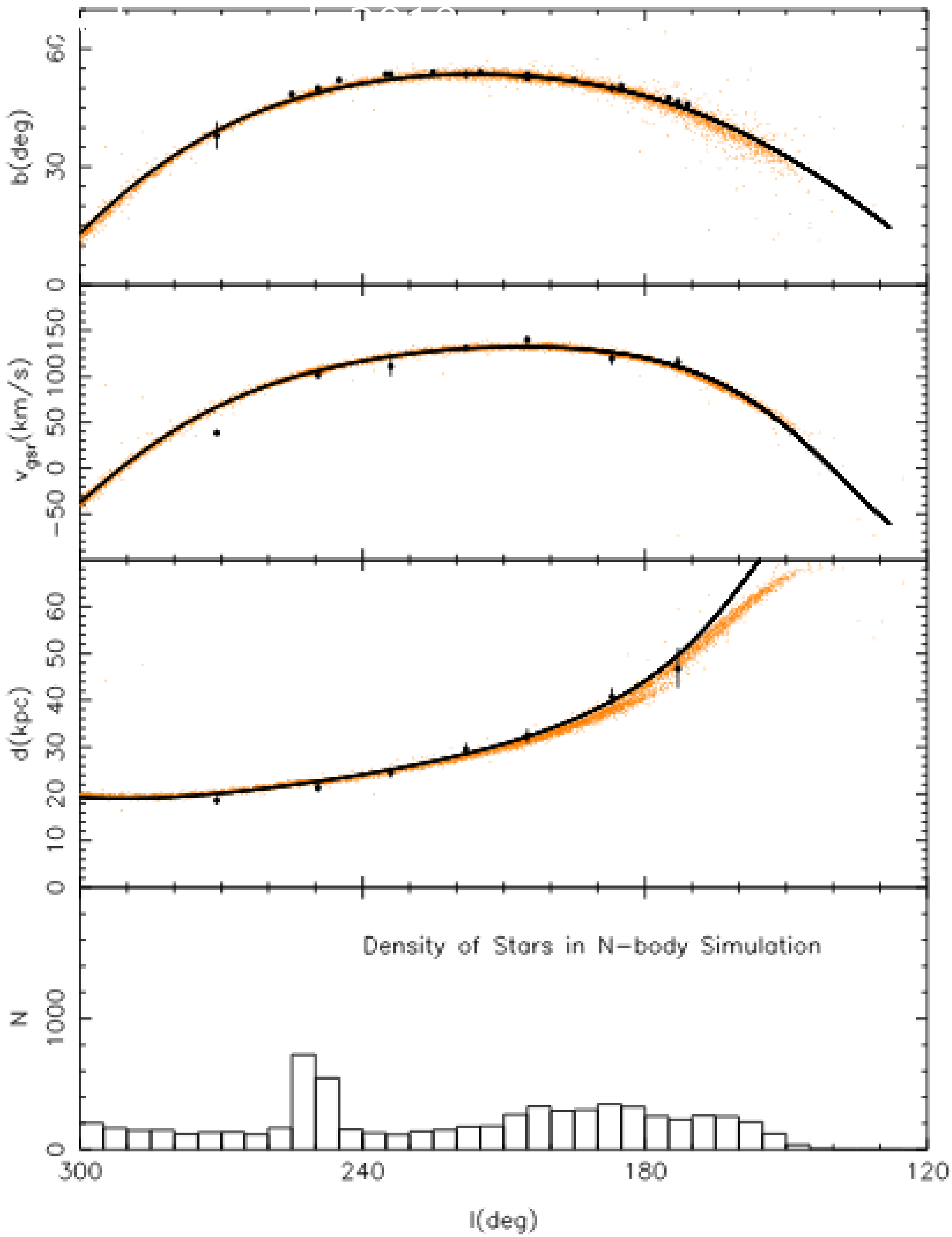


Newberg et al. 2010



An Orbit Fit to the Orphan Stream

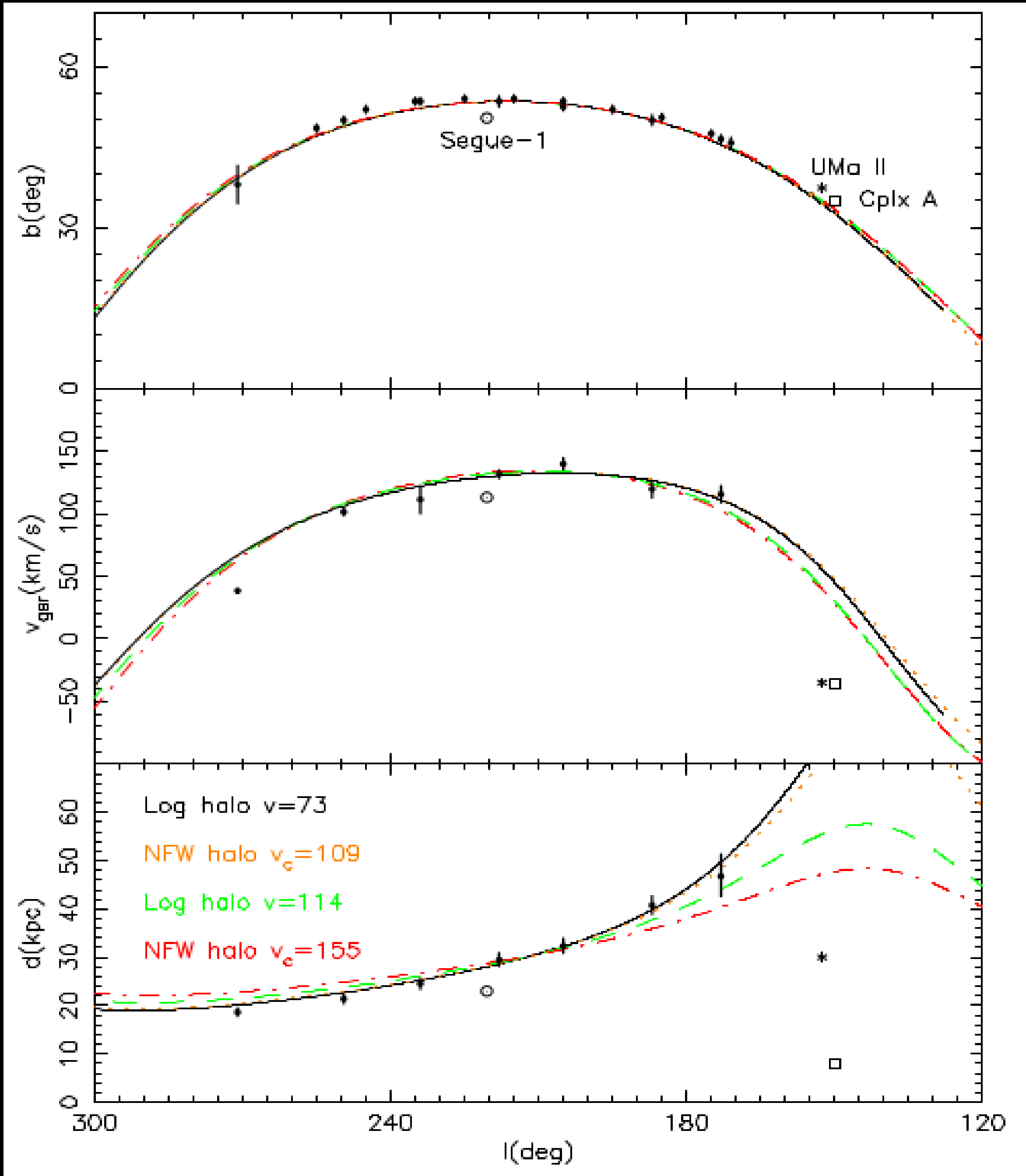
The dwarf galaxy orbit can be fit to the angular *position of the stream in the sky* and the average *velocity of the stream stars*, as a function of angle along the stream.



An N-body simulation of a dwarf galaxy integrated on the orbit fit. The properties of the progenitor dwarf galaxy and the integration time determine the *width of the tidal stream* and the *distribution of stars along the stream*.

The **orbit** of the Orphan Stream can be fit by choosing a reasonable Milky Way potential, and fitting the **position of the stream center on the sky, average line-of-sight velocity, and distance from the Sun as a function of position along the stream**.

We can estimate the **shape and mass of the Milky Way potential using multiple streams** that probe different directions and radii in the halo, and the **rotation curve**.



Newberg et al.. (2010).

Determining the distribution of dark matter from tidal streams

(1) Measure spatial density and velocity information for a dozen known tidal streams (and find more).

(2) Define parameters for orbits and internal properties of dwarf galaxies (10 parameters for each tidal stream), and parameters for the spatial distribution of dark matter (any number of parameters)

(3) Run N-body simulations of the tidal disruption of the dwarf galaxies, and optimize parameters so that the results of the simulation match the measurements of actual tidal streams (30 minutes for 1 dwarf, 1 CPU).

Wow – that's a lot of parameters!

MilkyWay@home

BOINC volunteer computing platform
Began: November 9, 2007

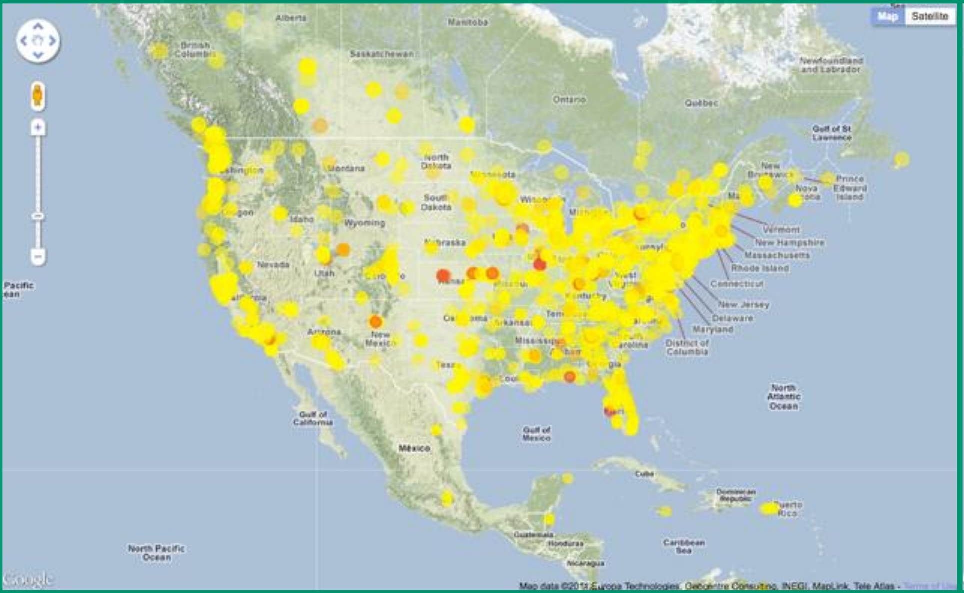
Given a set of data, a parameterized model, and a function that determines how well a given set of parameters fits the data, MilkyWay@home can find the optimal parameters.

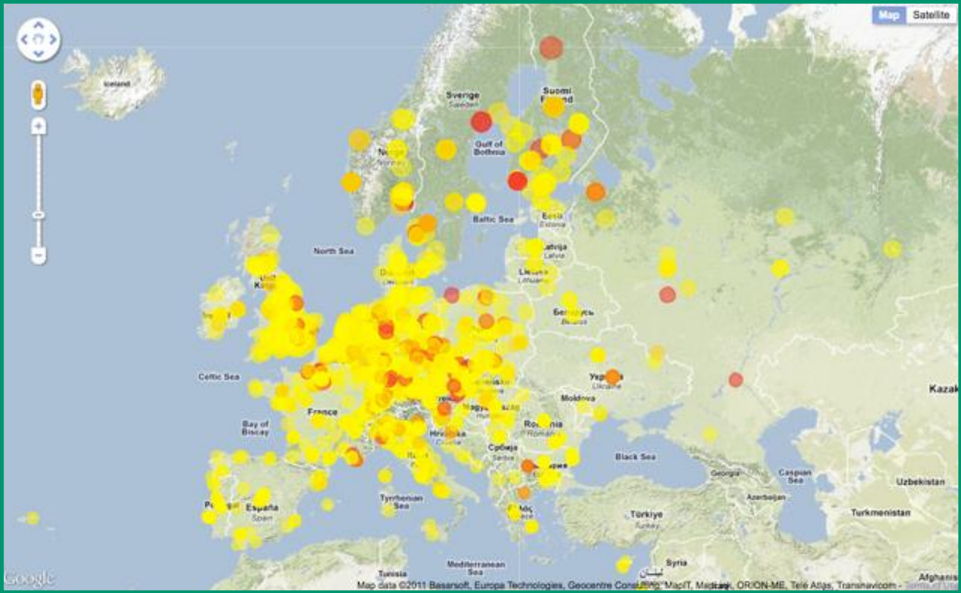
Originally designed to measure the density substructure of the Galactic stellar halo (mostly Sagittarius dwarf tidal stream, bifurcated stream, and Virgo Overdensity/Virgo Stellar Stream

1 PetaFLOPS (10^3 GFLOPS) from 25K users all over the world

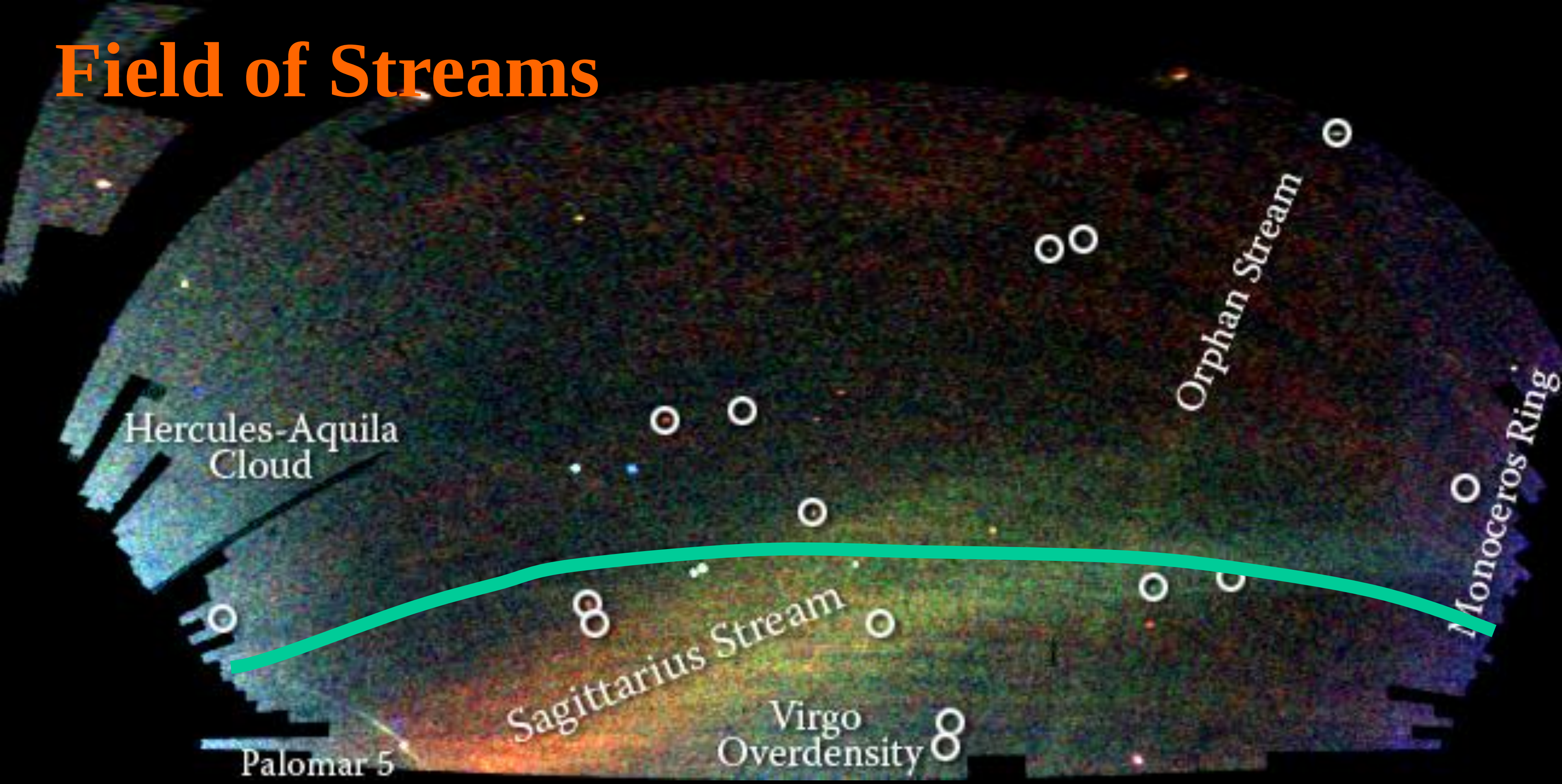
Distribution of Milkyway@home processors

206 countries (of which 193 are United Nations members)

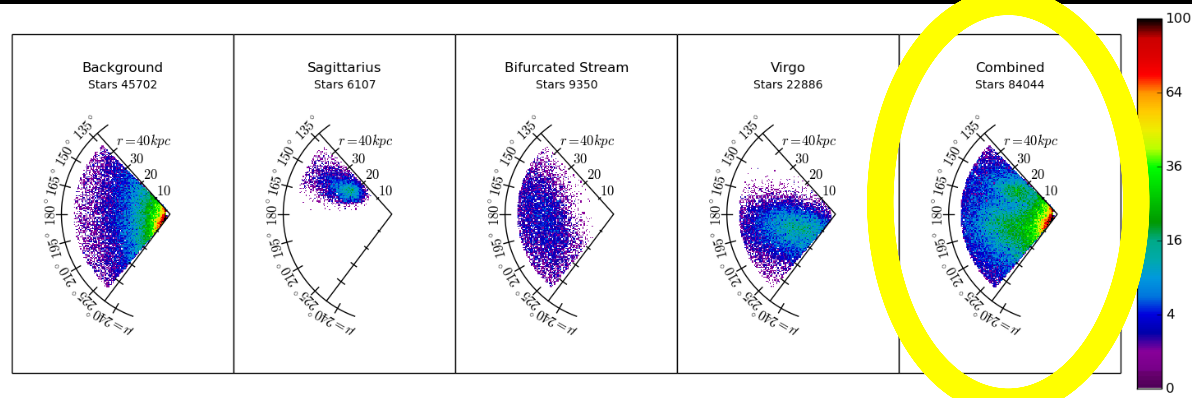




Field of Streams

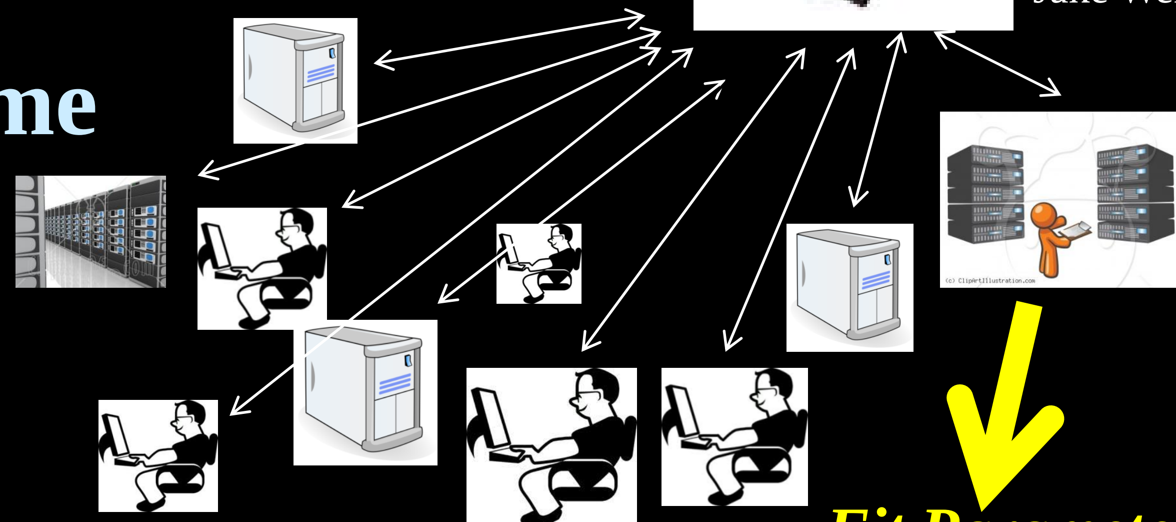


Analyze density of the stars in one SDSS stripe at a time.
Credit: V. Belokurov and the Sloan Digital Sky Survey.



Simulated data

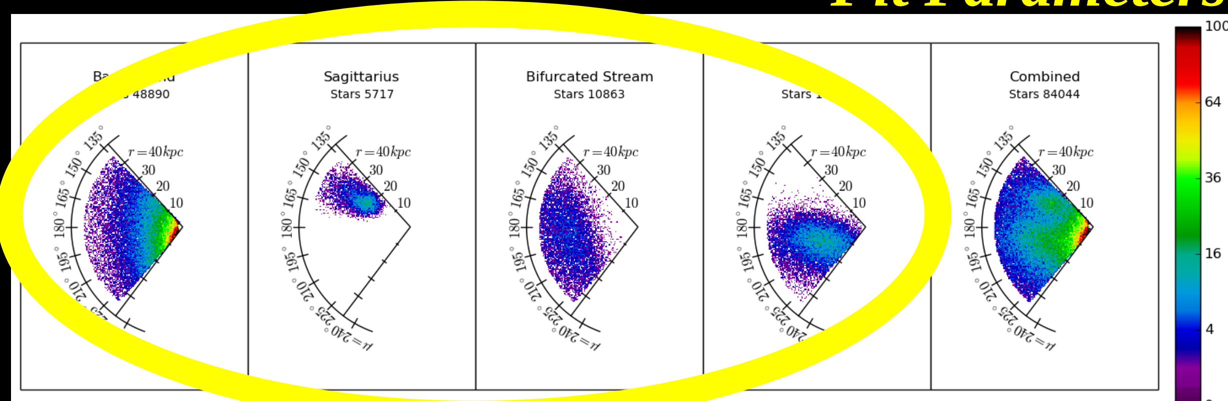
Jake Weiss

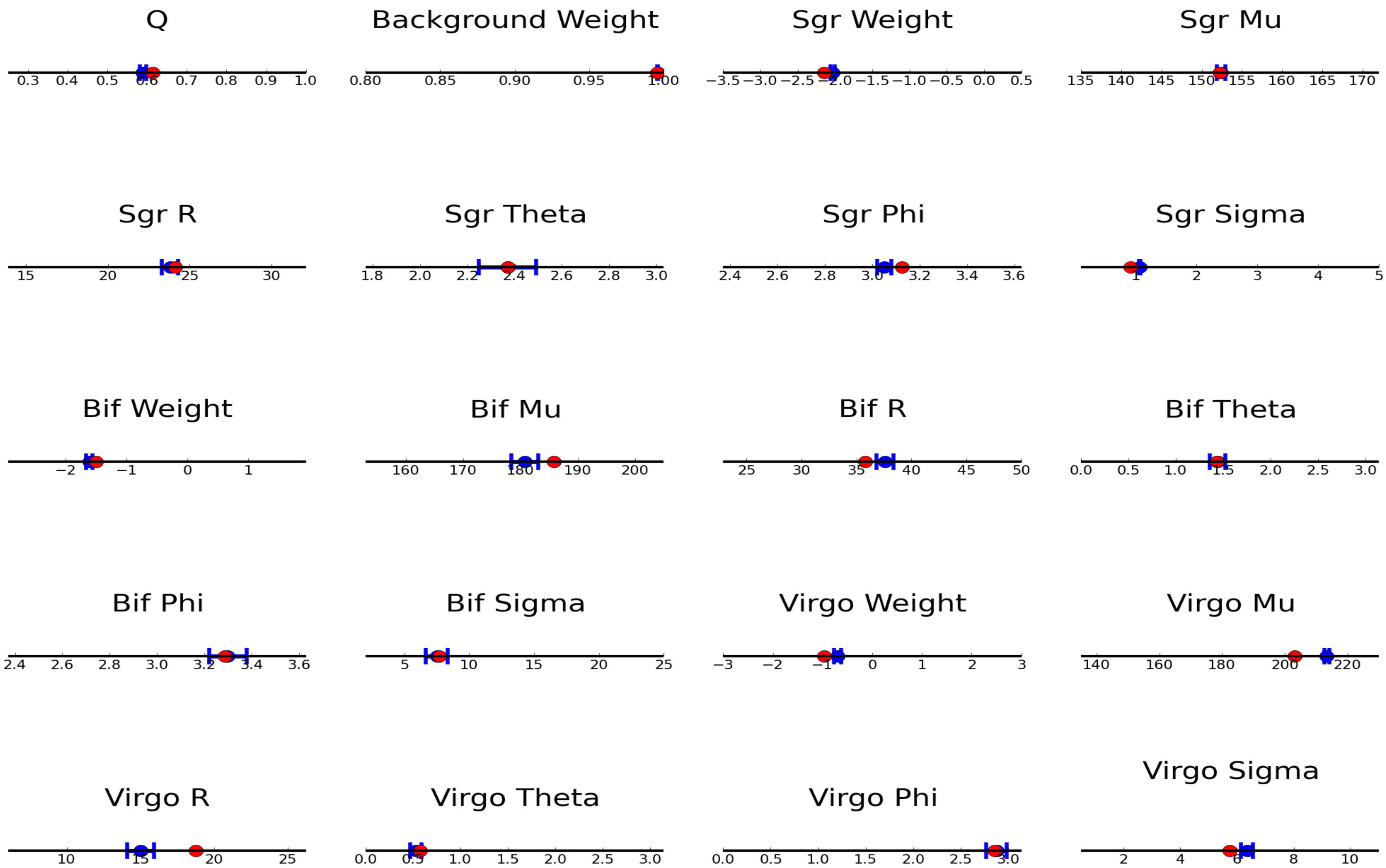


MilkyWay@home

uses the power of volunteer computing to successfully fit ***20 parameters*** *(6 x 3 streams plus two background) in the spatial density of tidal streams in the Milky Way halo.*

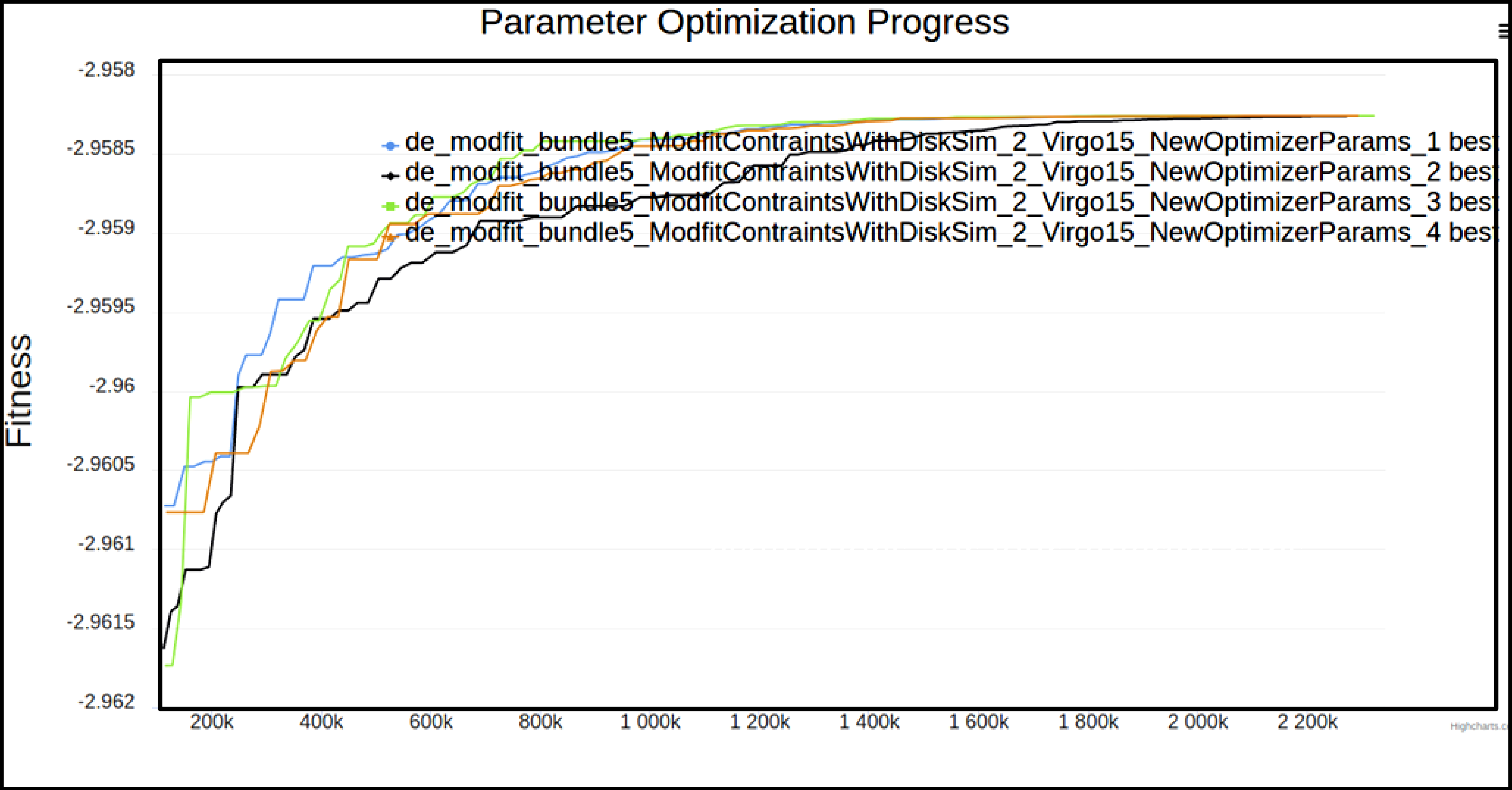
Fit Parameters





Red: simulated parameter value   Blue: parameter value found by MilkyWay@home

Length of bar shows the range of parameters searched.



The parameter space is searched using a differential evolution method with a population of 200 trial parameter sets maintained at any given time. About 2M likelihood evaluations for the algorithm to converge; this takes about a week or two, and ~six optimizations can be run simultaneously with little change in the time to convergence.

How much dark matter is there in ultrafaint dwarf galaxies?

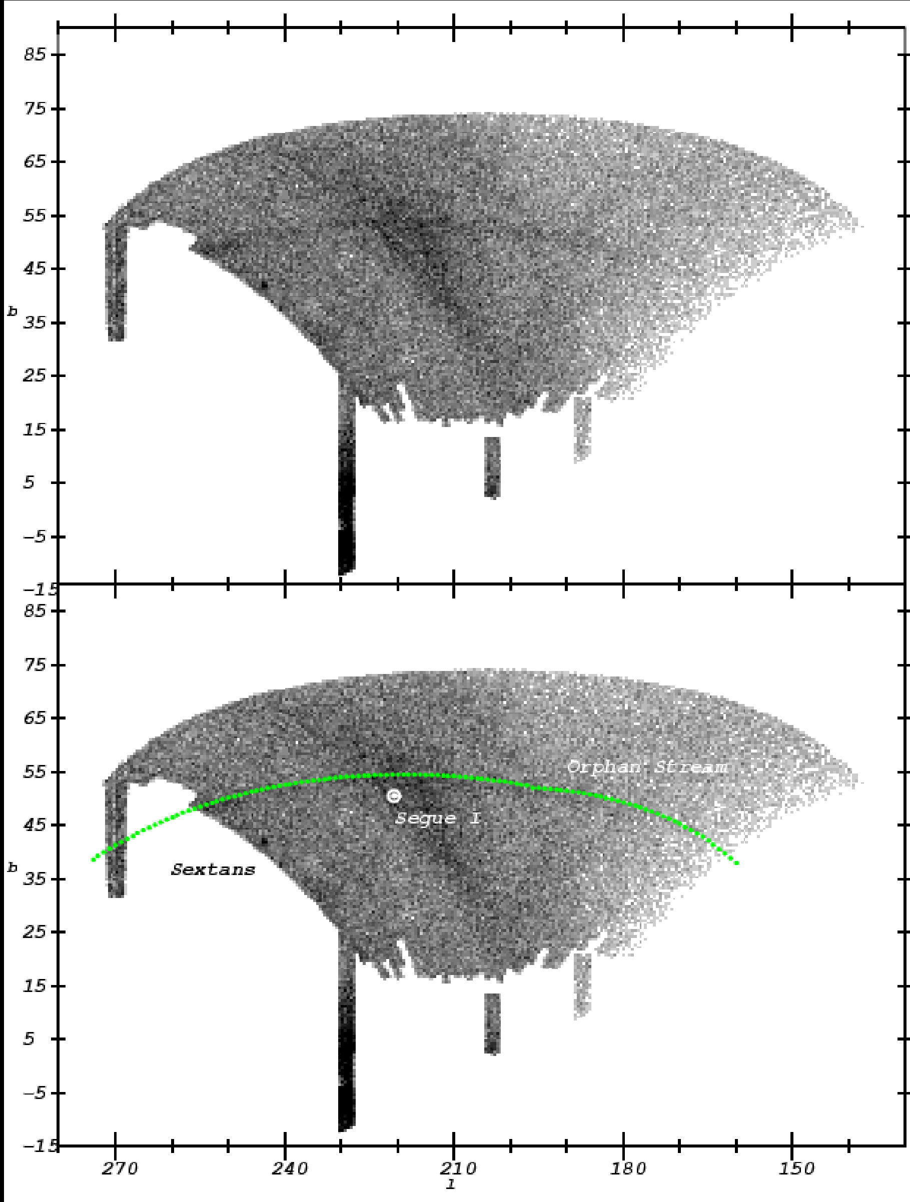
- All dwarf spheroidal galaxies, including ultrafaint dwarf galaxies, have ~10^7 M_{Sun} of mass enclosed within the central 300 pc, independent of the dwarf galaxy's luminosity (Mateo et al. 1993, Gilmore et al. 2007, Strigari et al. 2008).
- The dark matter density profile is the same for all dwarf galaxies (Walker et al. (2009).
- Equilibrium is a reasonable assumption for dwarf spheroidal galaxies (Battaglia, Helmi, & Breddels 2013)

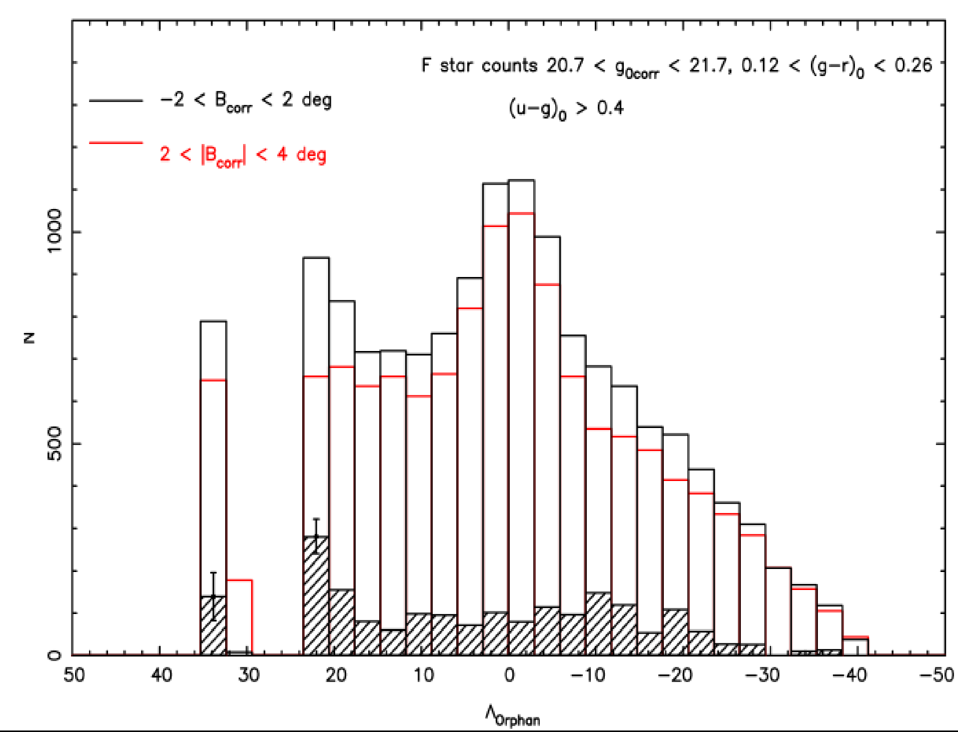
Four "small scale" ΛCDM problems are related to dwarf galaxies: missing satellites problem, Too big to fail problem, Core/Cusp problem, and the Satellite Planes problem.

How much dark matter is in SEGUE 1?

1	(it's a GC) Belokurov et al. (2007)
>1000	Geha et al. (2009)
1?	Niederste-Ostholt et al. (2009)
?	Norris et al. (2010) – either a star cluster or a dark dwarf galaxy
3400	Simon et al. (2011) – velocity dispersion is a good measure
>150?	Martinez et al. (2011) – unlikely but possible it is a star cluster
	Frebel et al. (2014) – least chemically evolved galaxy known
1?	Dominguez et al. (2016) – could be a destroyed star cluster at apogalacticon
dG	Fritz et al. (2017) – not a satellite of Sgr (so maybe not tidally disturbed?), and not at apogalacticon

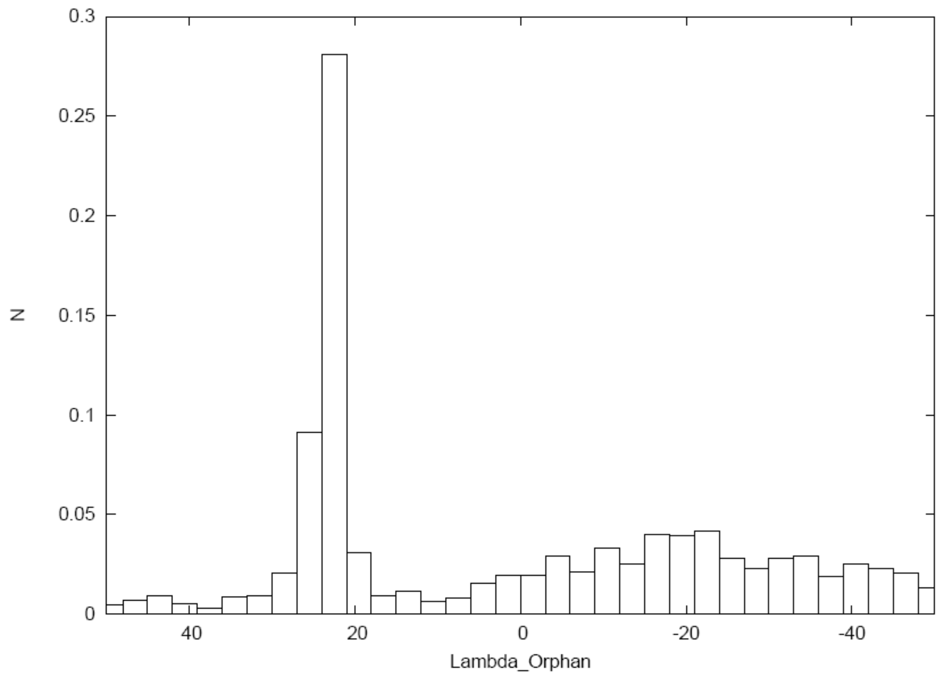
Newberg et al. (2

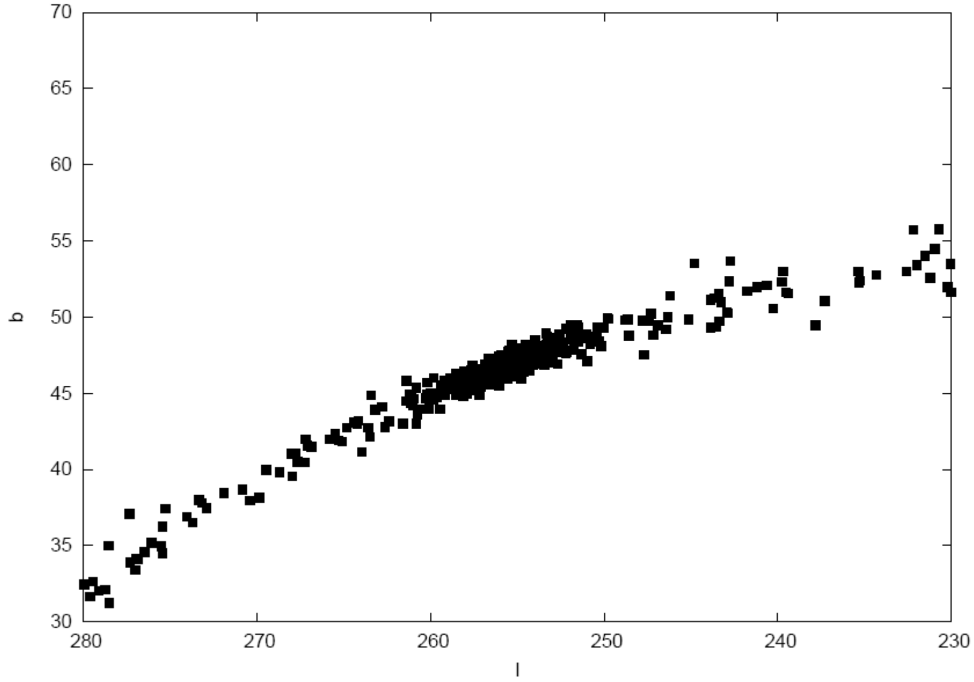




Density of F turnoff stars at the correct distance to be members of the Orphan Stream (left). Density of F turnoff stars within two degrees of the position of the Orphan Stream (above).

Using the **number of stars as a function of position along the stream, and the stream width** (velocity dispersion or angular width) to measure the **mass and scale length of the dwarf galaxy** (stars we can see and dark matter we cannot).

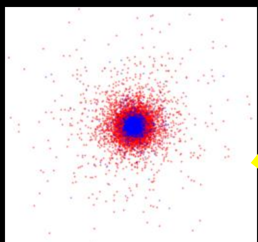


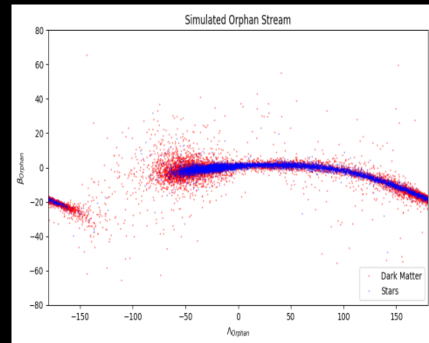


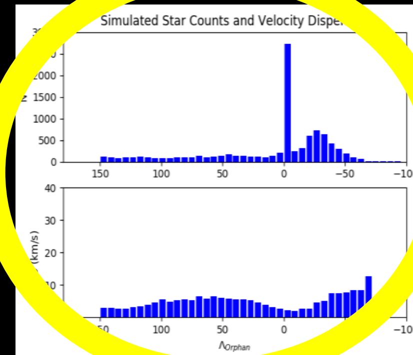
Sample 20,000 particle (sub-sampled above) semi-analytic N-body simulations of the tidal disruption of the Orphan Stream. We fit only the evolution time and the two-component Plummer sphere parameters for the dwarf galaxy, by comparing a histogram of the stellar density along the stream in the “data” and the model.

Sidd Shelton

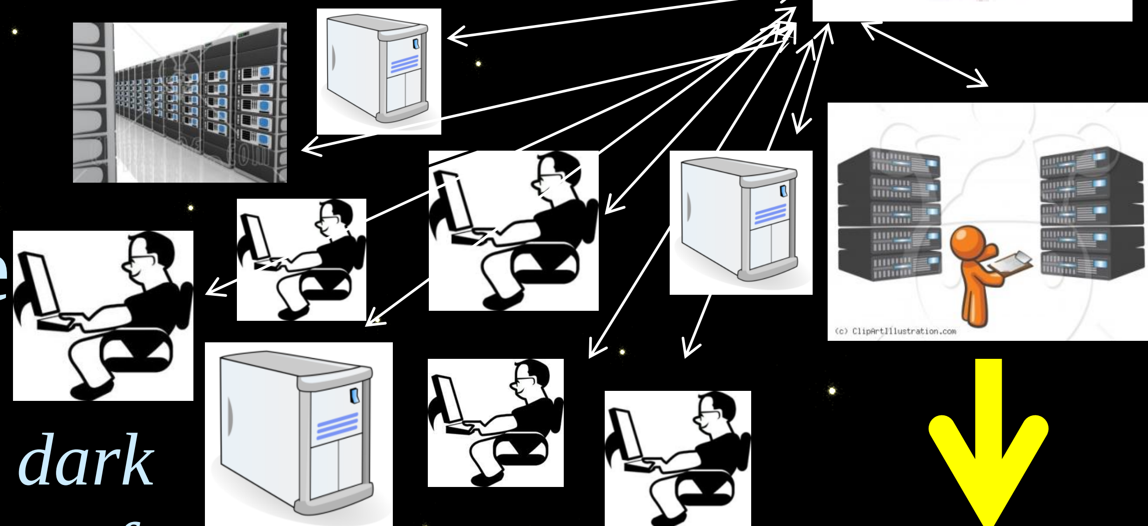
3.95 Gyr







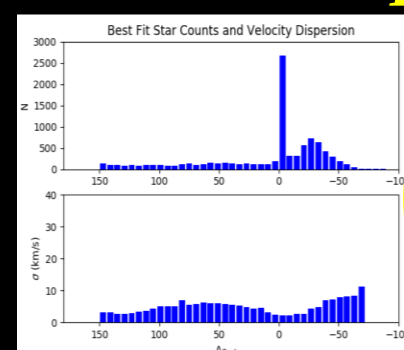
Simulated data

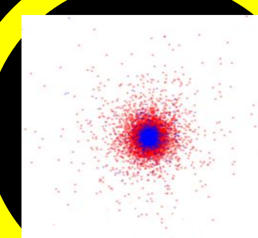


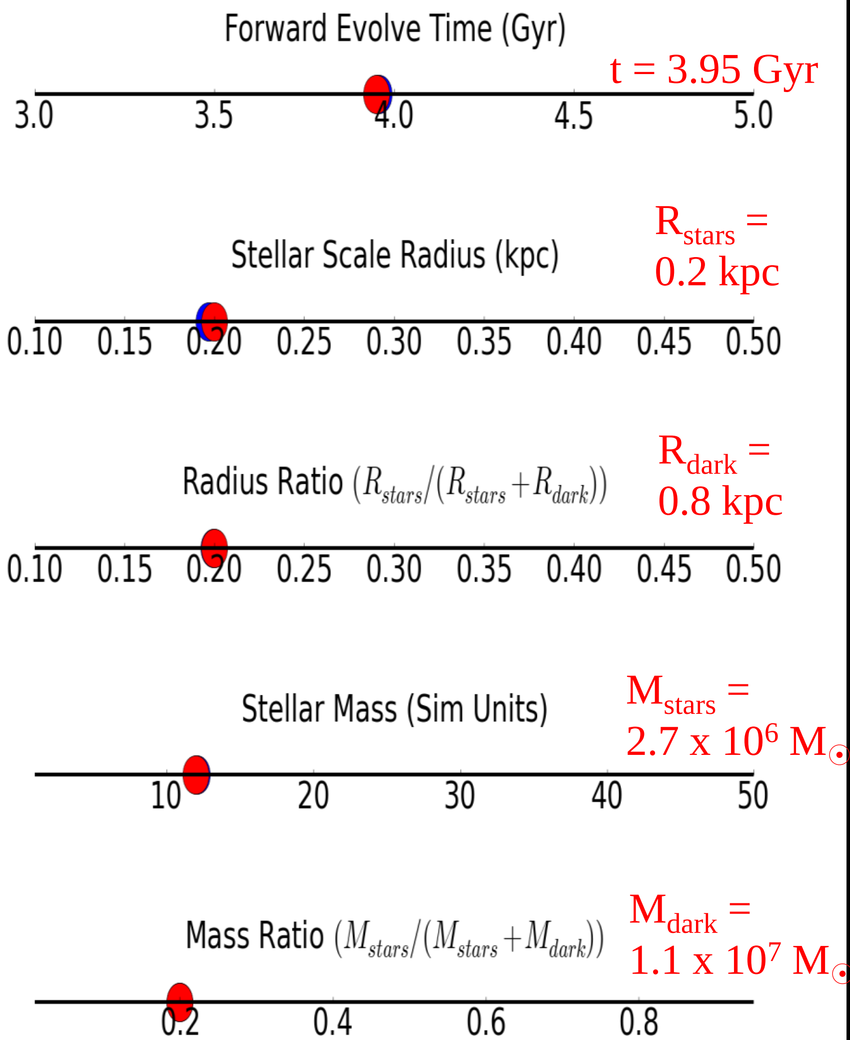
MilkyWay@home

also fits the mass and radial profile of both the dark matter and stars in the dwarf galaxy progenitor of a tidal stream (four parmeters plus time), given the density and angular width or velocity dispersion along the stream.

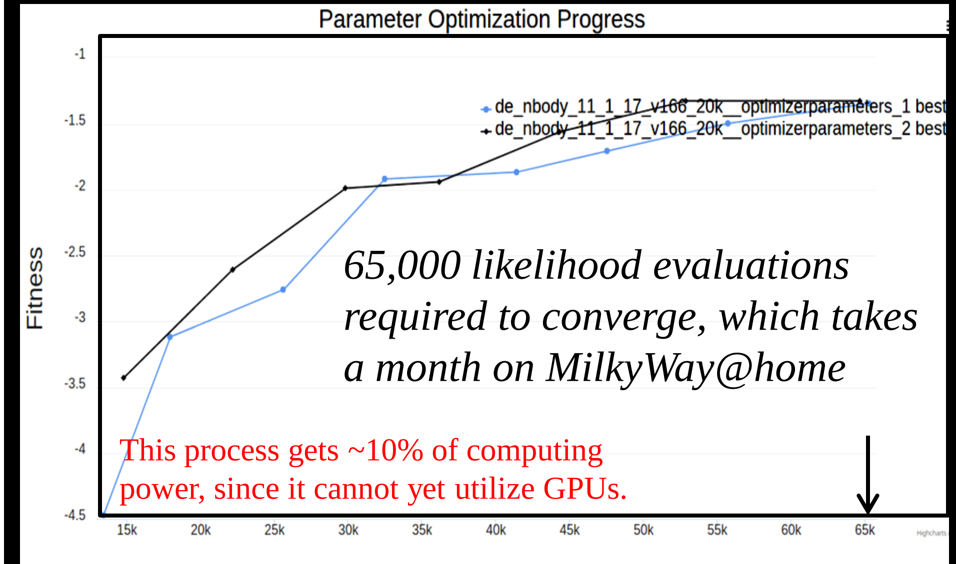
Fit Parameters







Using velocity dispersion



Number of likelihood evaluations

Premise: We know the underlying density model for the dwarf galaxy progenitor, the Milky Way potential, and the dwarf galaxy orbit. We know the density and velocity dispersion of stars along the stream.

Result: We can fit the mass and radial profile of the dwarf galaxy progenitor, and the length of time it has been disrupting, exactly. This includes the dark matter mass and radial distribution!

Parameters	Time (Gyr)	R_B (kpc)	R Ratio	M_B (sim units)	M Ratio
Correct	3.95	0.2	0.2	12.0	0.2
Search Range	[3.0 - 6.0]	[0.1 - 0.5]	[0.1 - 0.5]	[1.0 - 100.0]	[0.01 - 0.95]
Simulation 1	3.9424	0.20458	0.17901	12.03186	0.14057
Simulation 1	3.9495	0.20466	0.18065	12.08123	0.14559
Simulation 1	3.9544	0.20042	0.17640	12.22005	0.13109
Simulation 2	3.9635	0.19505	0.19222	12.14958	0.15653
Simulation 2	3.9409	0.20140	0.18708	11.98203	0.18006
Simulation 2	3.9531	0.19531	0.19402	12.05011	0.15318

Progenitor results for simulated tidal stream ***(using angular dispersion)***

Input dwarf galaxy

baryons: 0.2 kpc, $2.7 \times 10^6\ M_\odot$; dark matter: 0.8 kpc, $1.1 \times 10^7\ M_\odot$

Output dwarf galaxy

baryons: 0.2 kpc, $2.7 \times 10^6\ M_\odot$; dark matter: 0.9 kpc, $1.5 \times 10^7\ M_\odot$

Future Work:

- Exhaustive exploration of sources of error
- Effect of not knowing the exact model
- Different density profiles/properties of the dwarf galaxy progenitors
- Simultaneous fitting of orbit, and progenitor properties
- Simultaneously fit multiple streams to constrain the Milky Way potential (could vary radially, be triaxial or lumpy, and change with time)

This is in principle tractable because there are very many parameters that could be constrained by an enormous number of stream stars from multiple streams.