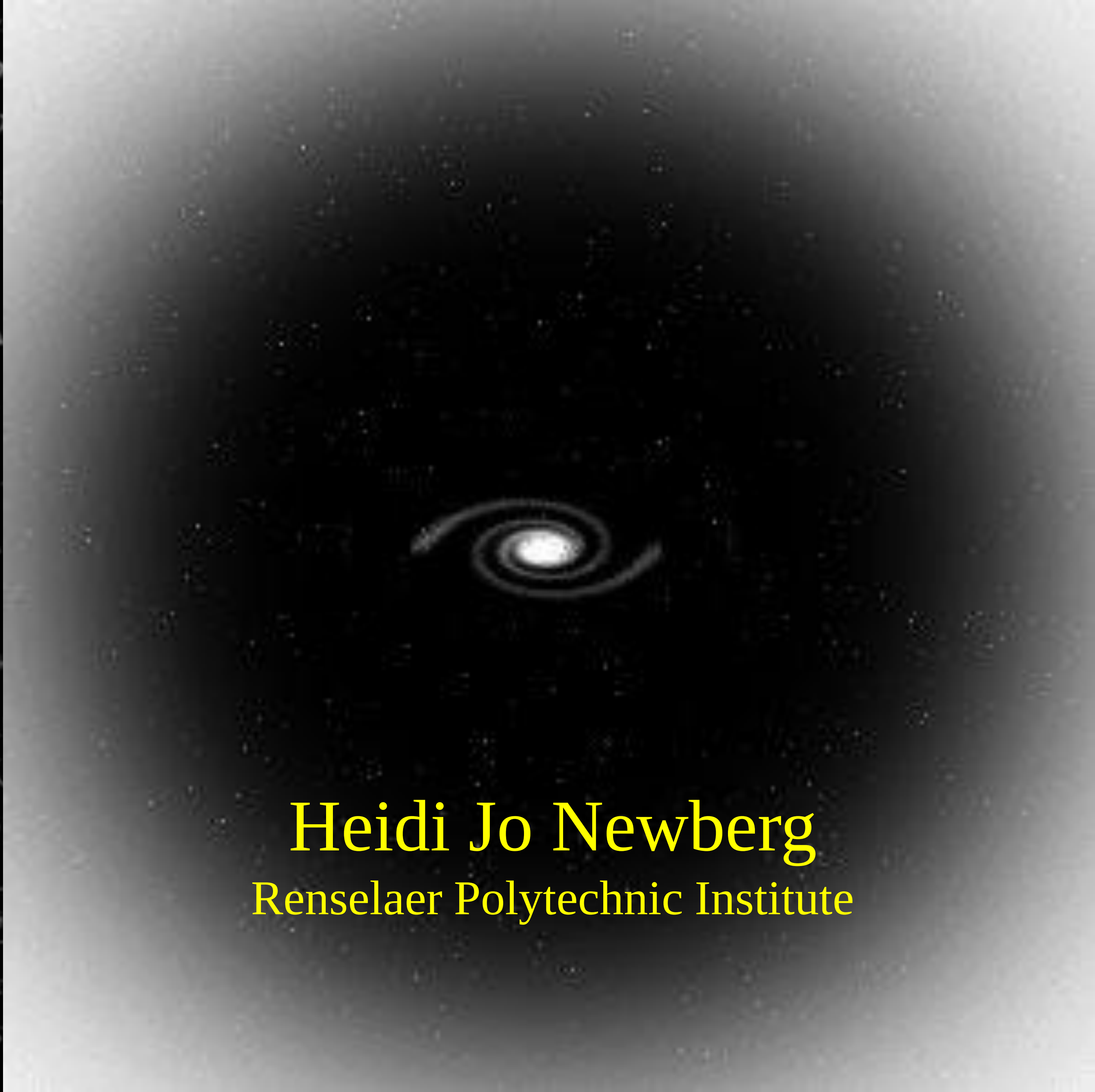
The Milky Way Galaxy
For Dark Matter Hunters



Heidi Jo Newberg

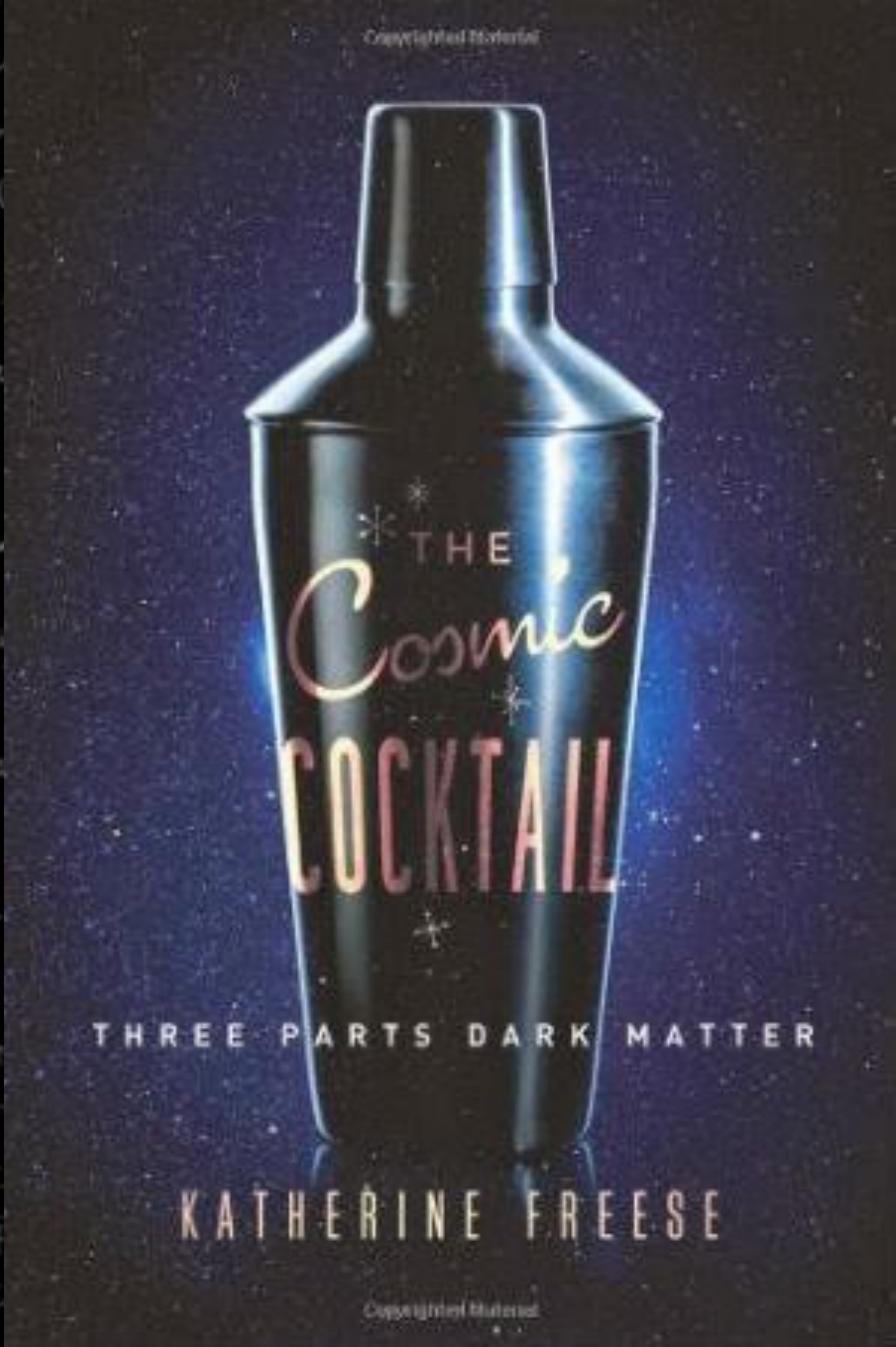
Renselaer Polytechnic Institute

Overview

- Dark matter discovered
- Astrophysics of structure formation
- The Milky Way in motion
- The dark matter (probably) not in equilibrium
- Determining the density distribution of dark matter from stars
- Dark matter (probably) dominates dwarf galaxies

The Cosmic Cocktail Recipe

3 oz. dark matter
7 oz. dark energy
½ oz. hydrogen and helium gas
0.003 oz. other chemical elements
0.005 oz. stars
0.005 oz. neutrinos
0.0005 oz. CMBR light
0.000001 oz. black holes



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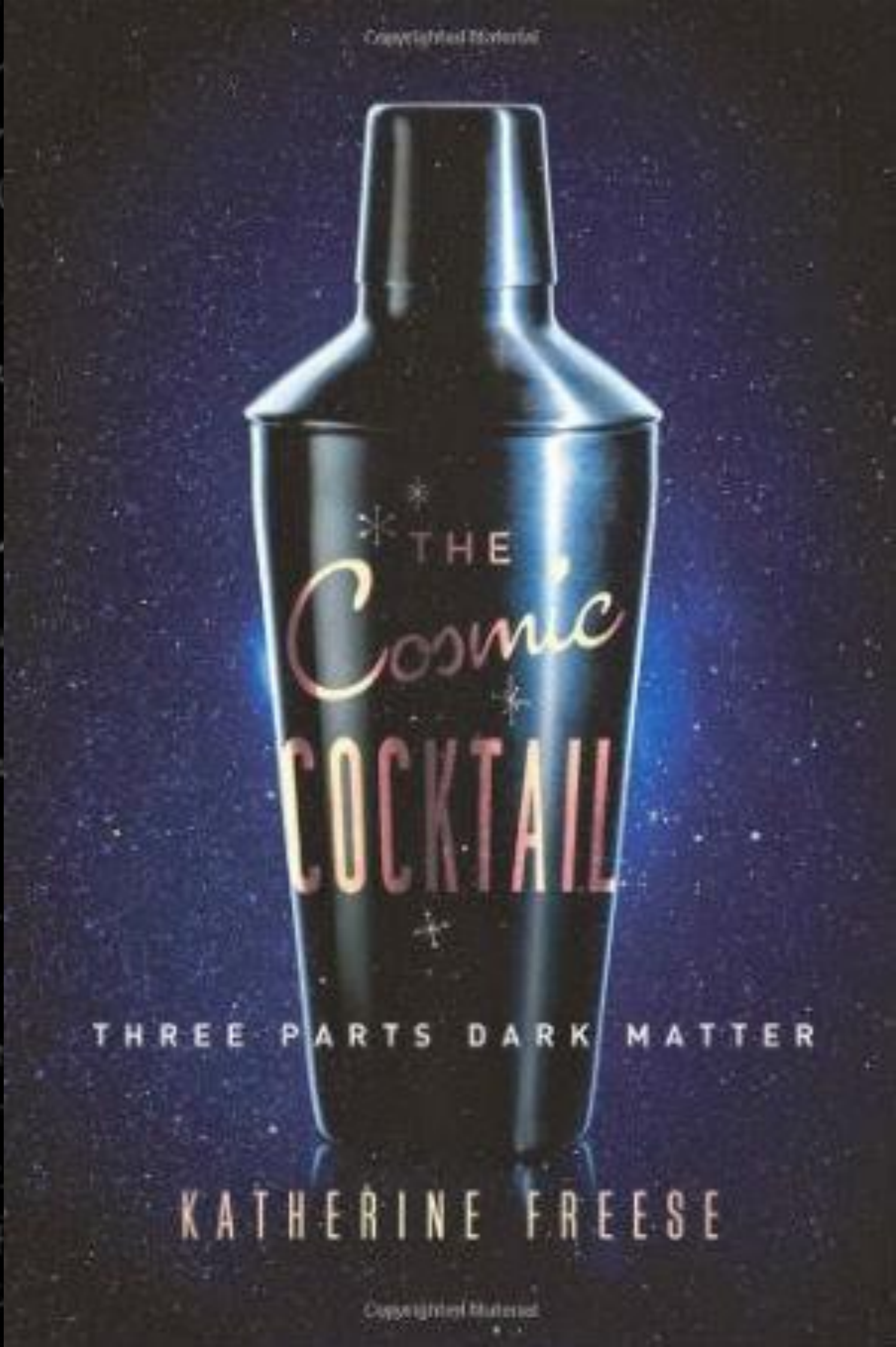
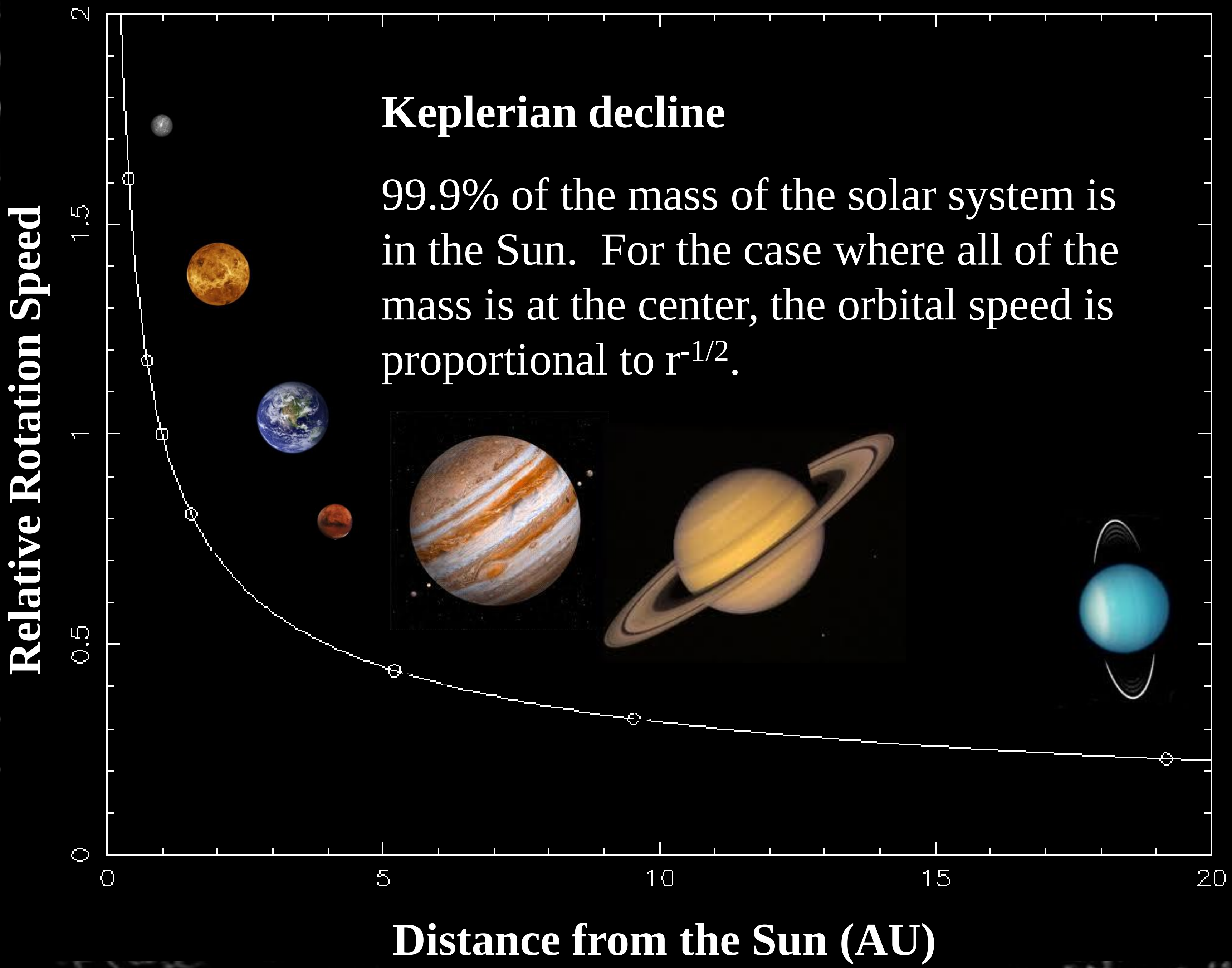
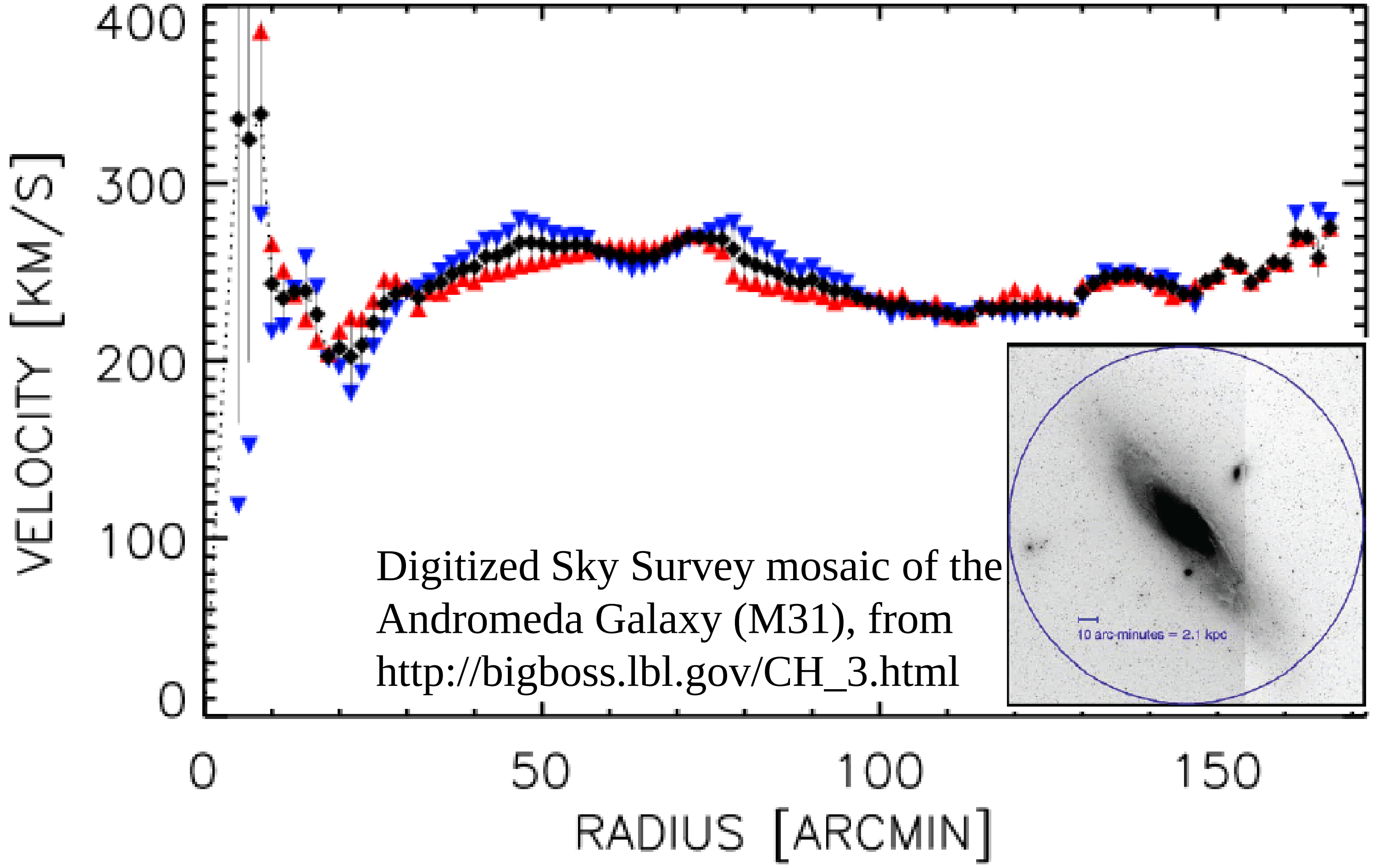


Keplerian decline

99.9% of the mass of the solar system is in the Sun. For the case where all of the mass is at the center, the orbital speed is proportional to $r^{-1/2}$.

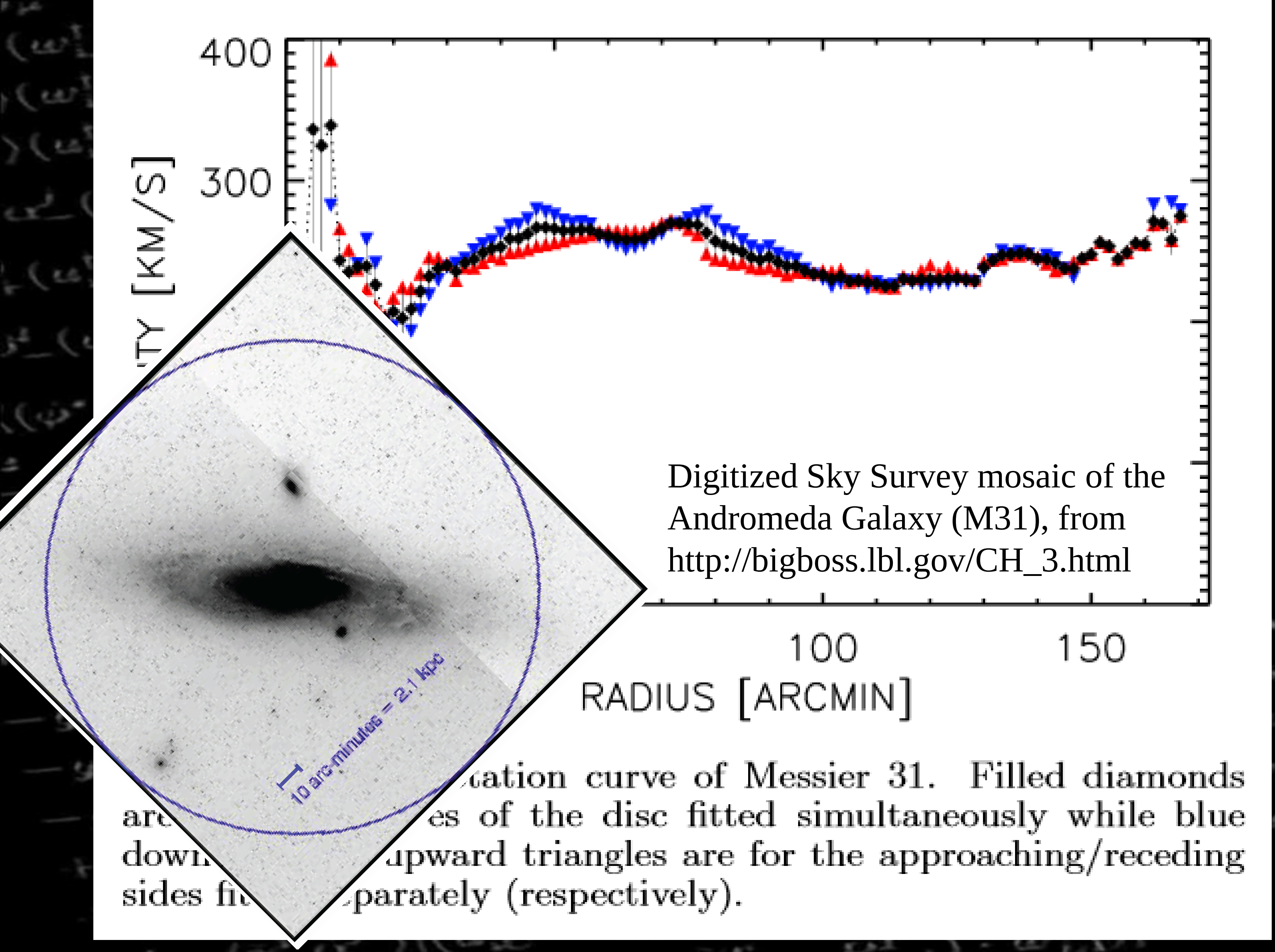




Digitized Sky Survey mosaic of the Andromeda Galaxy (M31), from http://bigboss.lbl.gov/CH_3.html

FIG. 10.— HI rotation curve of Messier 31. Filled diamonds are for both halves of the disc fitted simultaneously while blue downward/red upward triangles are for the approaching/receding sides fitted separately (respectively).

Chemin, Carignan & Foster (2009)



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Digitized Sky Survey mosaic of the Andromeda Galaxy (M31), from http://bigboss.lbl.gov/CH_3.html

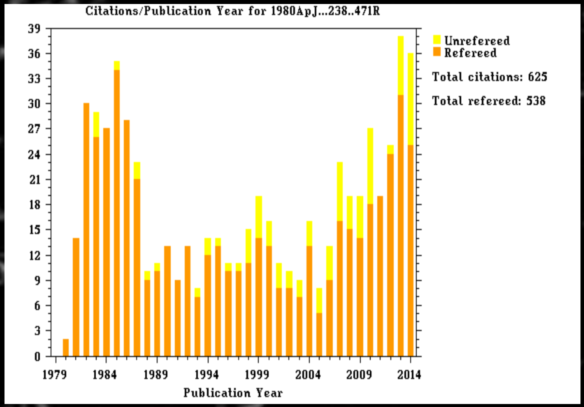
Chemin, Carignan & Foster (2009)

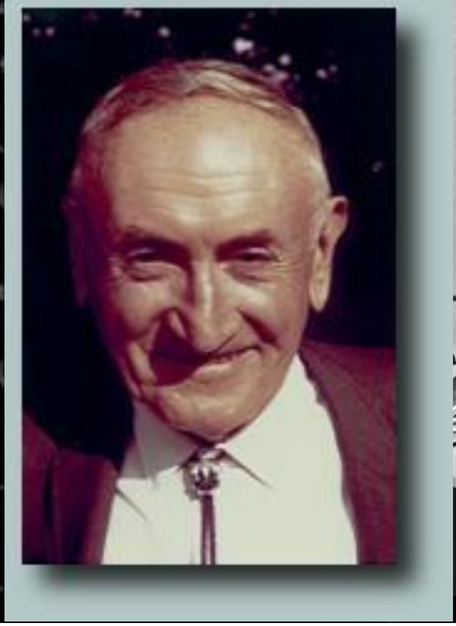
1980: Vera Rubin discovers that galaxy rotation curves indicate too much mass at large radii in galaxies.

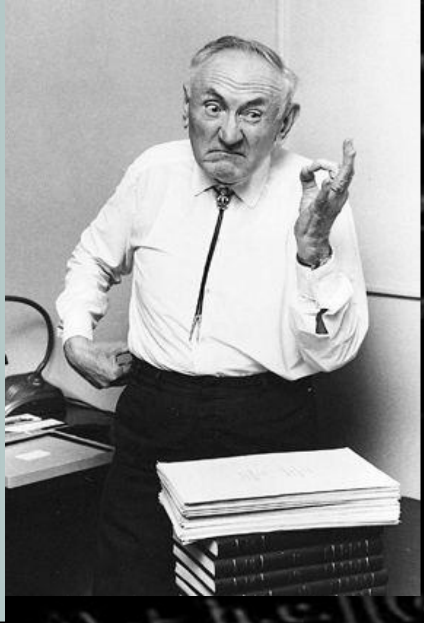
“The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.”

Scanned at the American Institute of Physics

In the late 60’s and the 70’s, astronomers – and most notably Vera Rubin – used newly developed spectrographs to measure the rotation curves of galaxies.

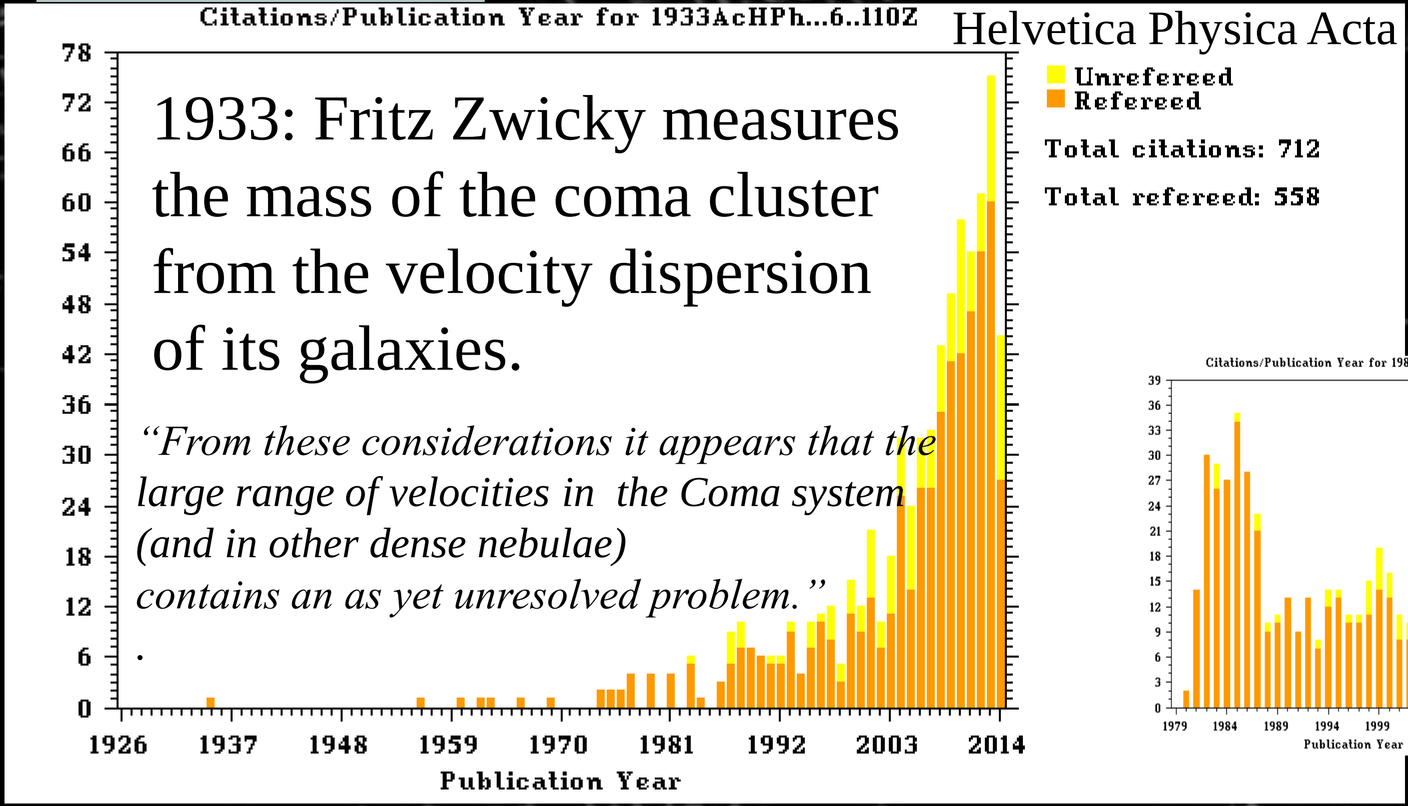






1980: Vera Rubin discovers that galaxy rotation curves indicate too much mass at large radii in galaxies.

"The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy."



Helvetica Physica Acta

1933: Fritz Zwicky measures the mass of the coma cluster from the velocity dispersion of its galaxies.

"From these considerations it appears that the large range of velocities in the Coma system (and in other dense nebulae) contains an as yet unresolved problem."

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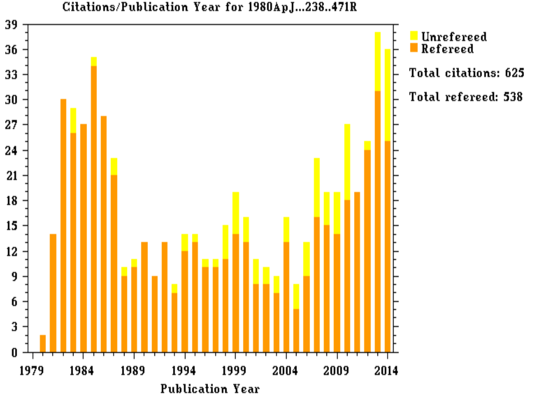


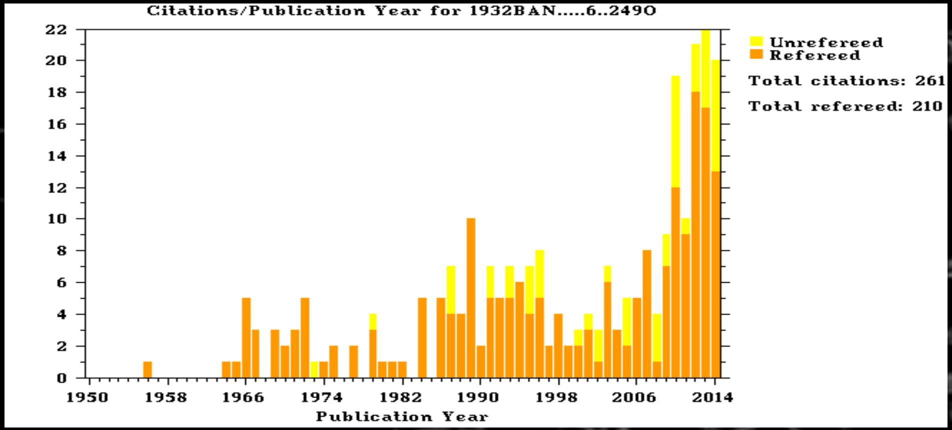
Wikipedia says dark matter was first postulated in 1932 by Jan Oort.

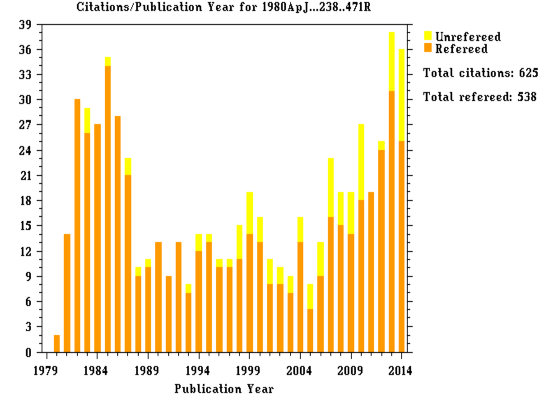
1980: Vera Rubin discovers that galaxy rotation curves indicate too much mass at large radii in galaxies.

"The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy."

1932: Jan Oort measures the mass of the Milky Way's disk from the vertical motions of stars.

"There is an indication that the invisible mass is more strongly concentrated to the galactic plane than that of the visible stars."

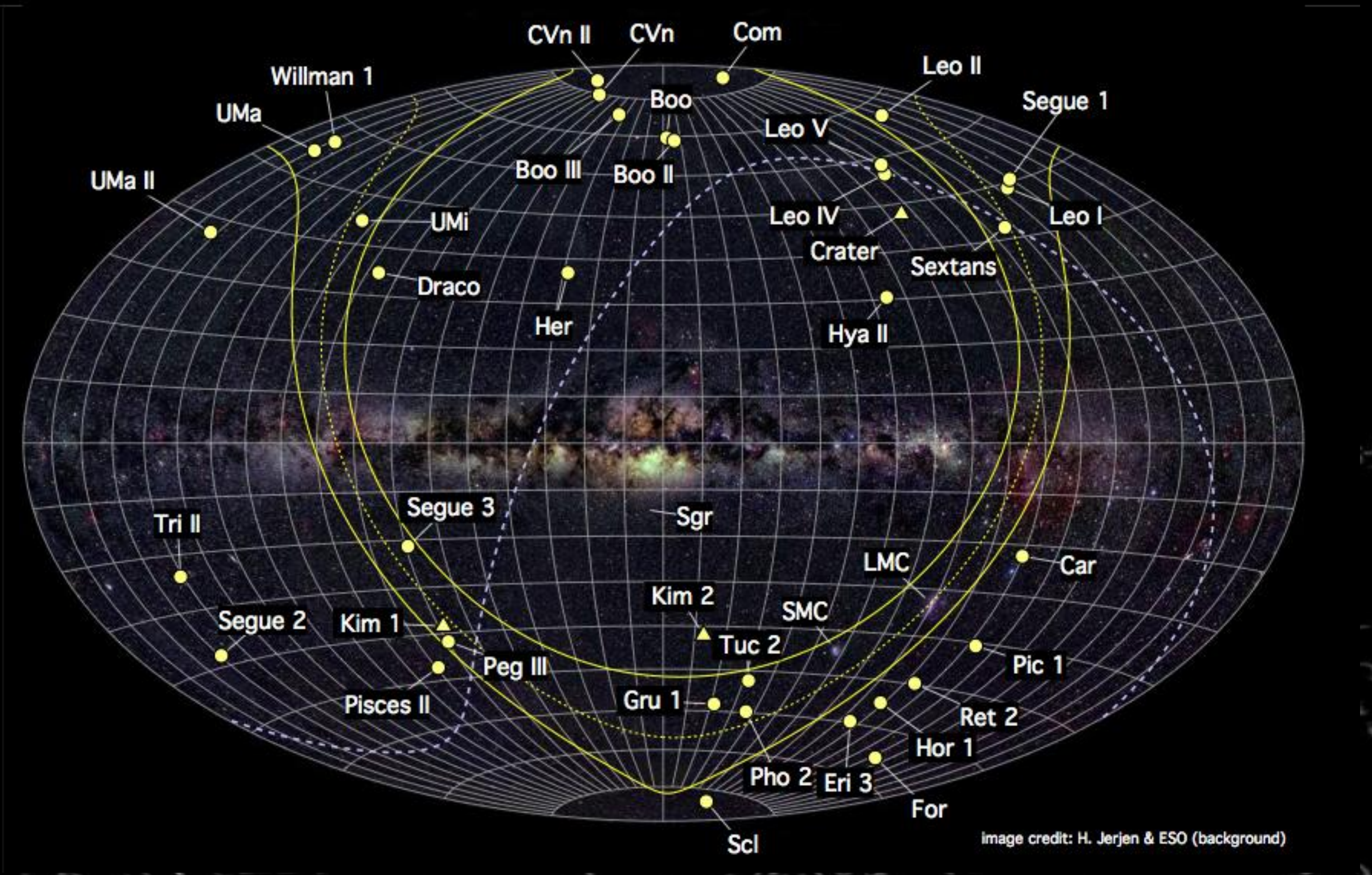




Heidi Jo Newberg, 9/24/2014


R = 6.0 Mpc
z = 10.155
a = 0.090
diemand 2003

Diemand et al. (2006)



Acknowledgment: Jerjen, H., 2010, PASA, 29, 383)

Dozens of known dwarf galaxy satellites, maybe aligned in a plane, and maybe some associated with the Magellaic clouds.

The Physics of Universe Formation

For dark matter: initial conditions, gravity, cosmological model, possibly self-interaction

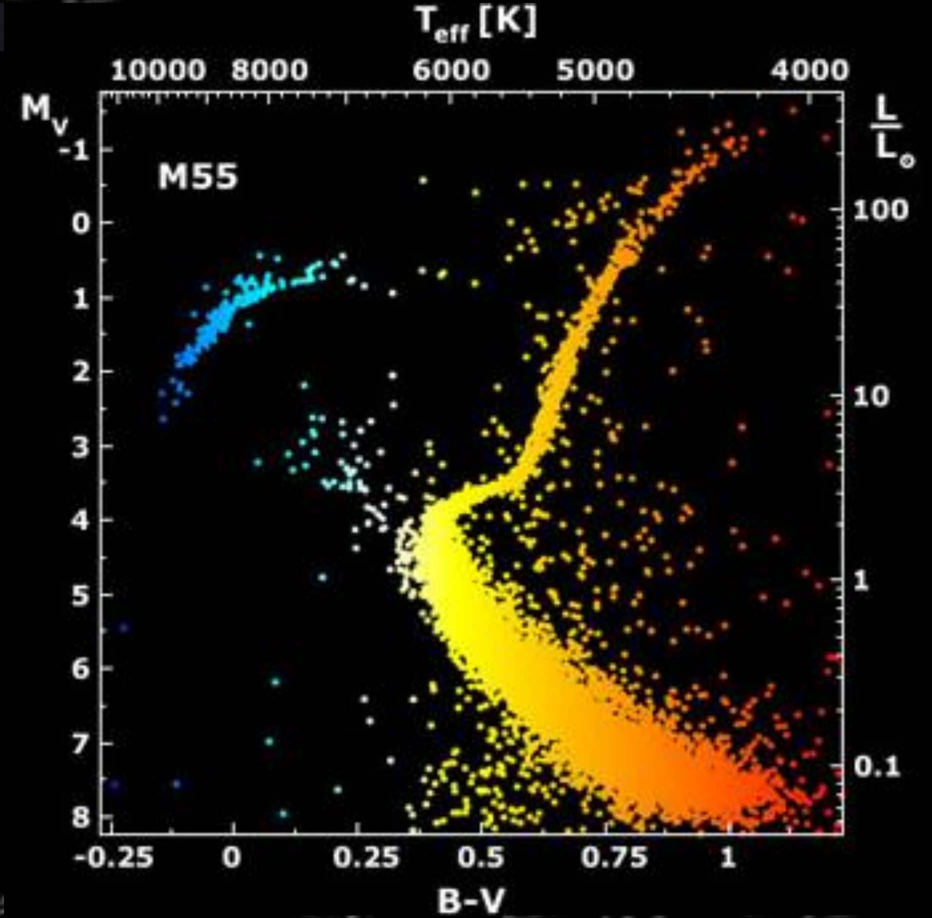
For Baryons: also magnetohydrodynamics, gas cooling and photo-ionization (recombination and reionization, star formation (rate, initial mass function, stellar interiors, stellar atmospheres), stellar evolution, gas radiation, metal line cooling, chemical evolution, supermassive black hole formation /merging/ accretion of gas, quasar formation/feedback, AGB feedback, supernovae Ia and II, stellar feedback-driven galaxy-scale gas outflows, guess we need to add neutron star mergers…..

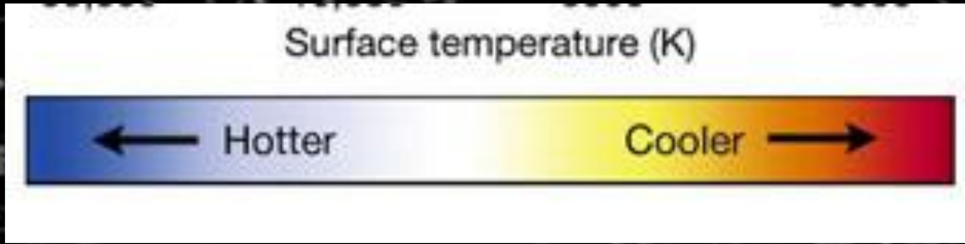
The globular cluster M55

Image credit: Daniel Verschatse, via http://www.astrosurf.com/antilhue/m55.htm.

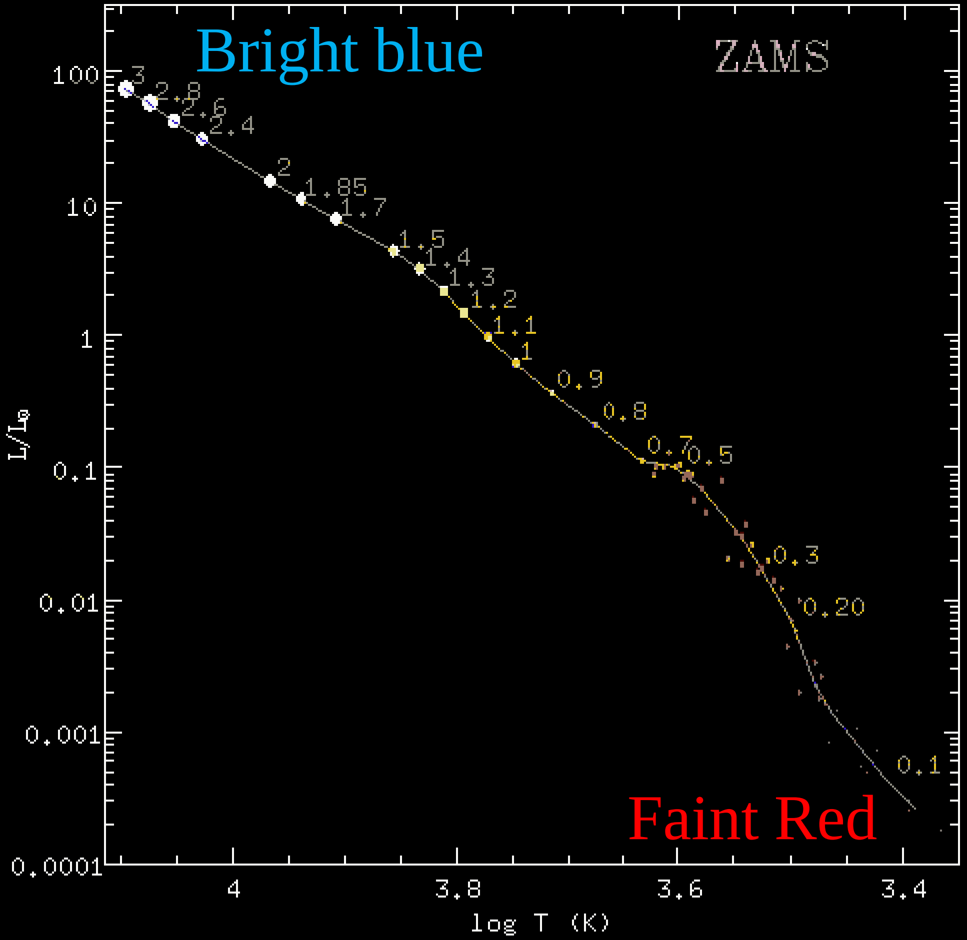
Brighter

Fainter





Stellar Evolution

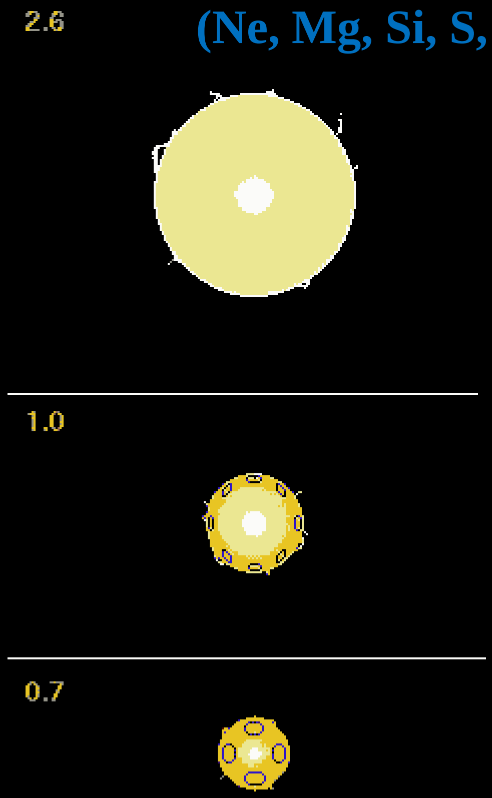


Brightness of star {magnitude}

Temperature (color) of star

Type II Supernova

Alpha elements (Ne, Mg, Si, S, Ar, Ca and Ti)



White Dwarf/ Type Ia SN

Iron peak elements (Ti, V, Cr, Mn, Fe, Co and Ni)

Still Star

Elements locked up

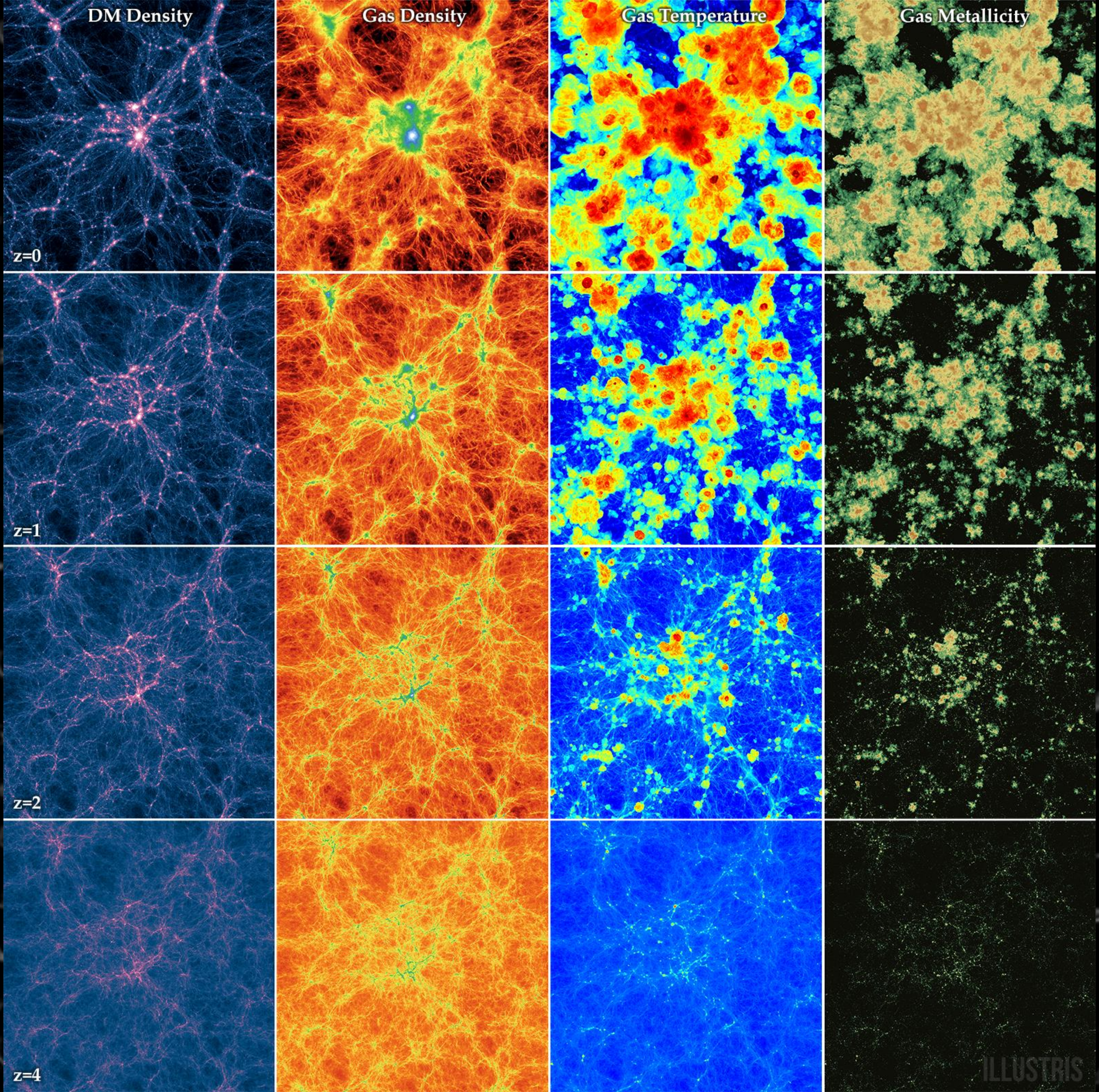
https://www.astro.ufl.edu/~guzman/ast7939/lectures/basics/stellar_evol.html

First Stars?

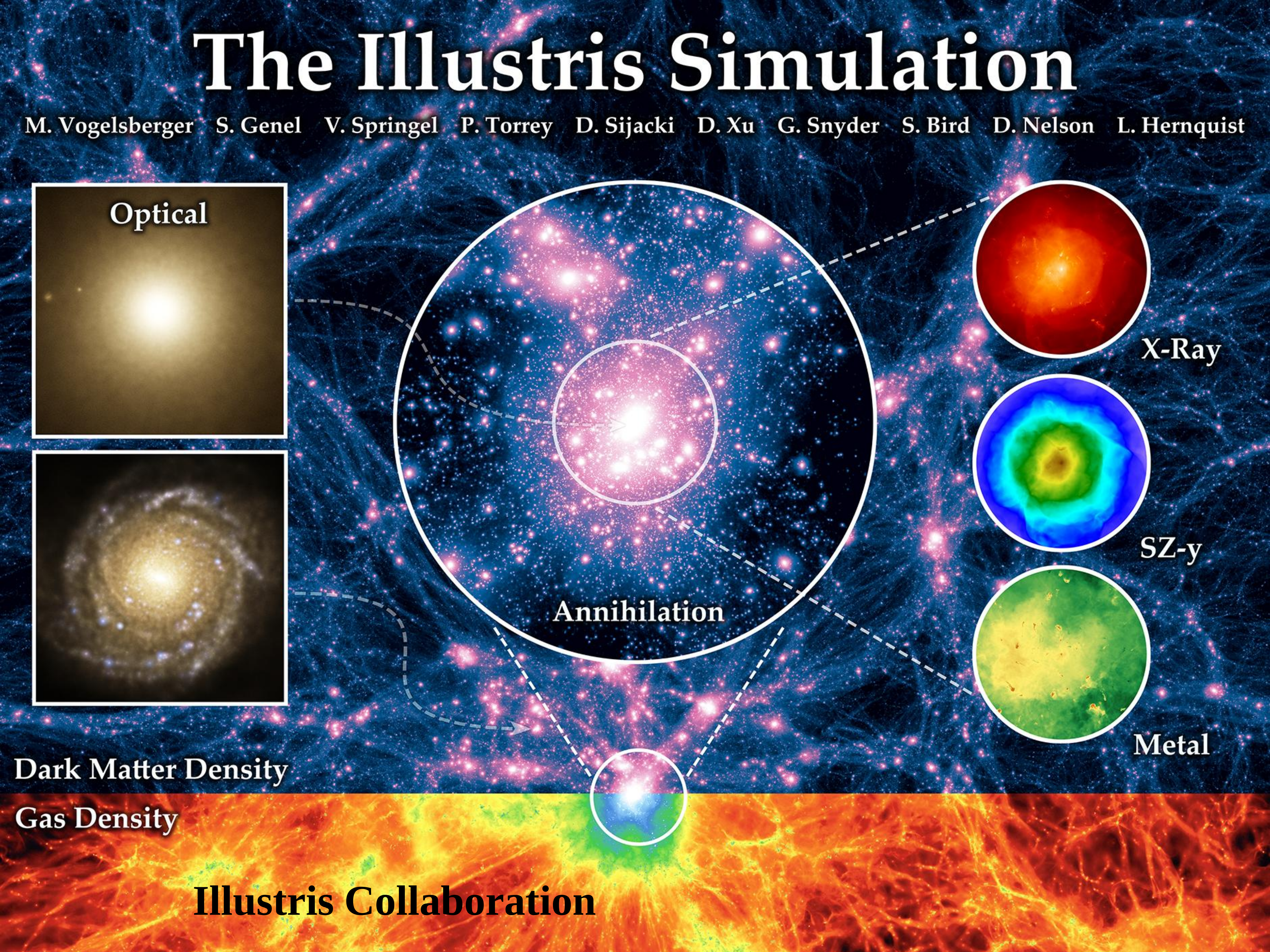
The first stars in the Universe should have the composition of big bang nucleosynthesis, but none have been found (except maybe one, Sobral et al. 2015). This can be explained if they are all high mass and quickly blow up as some kind of supernova (Abel et al. 2002).

The epoch of reionization, which is 056±0.20 Gyr after the Big Bang, at an age of 13.24±0.20 Gyr ago (Planck Collaboration et al. 2016). The first stars (e.g. Sokasian et al. 2004), or the first luminous galaxies (e.g. Haardt & Madau 2012) reionized the Universe. Not sure whether dwarf galaxies (Bouwens et al. 2012, Wise et al. 2014) or bright galaxies (Sharma et al. 2018) produced more ionizing photons.

Ages of the oldest known stars have been falling, from 16 Gyr when I was a graduate student, to about 14 Gyr now (VandenBerg et al. 2014, Ge et al. 2016, Cho et al. 2016, Christleib 2016). These are not "first stars" that have primordial element abundance.



Illustris Collaboration/Illustris Simulation



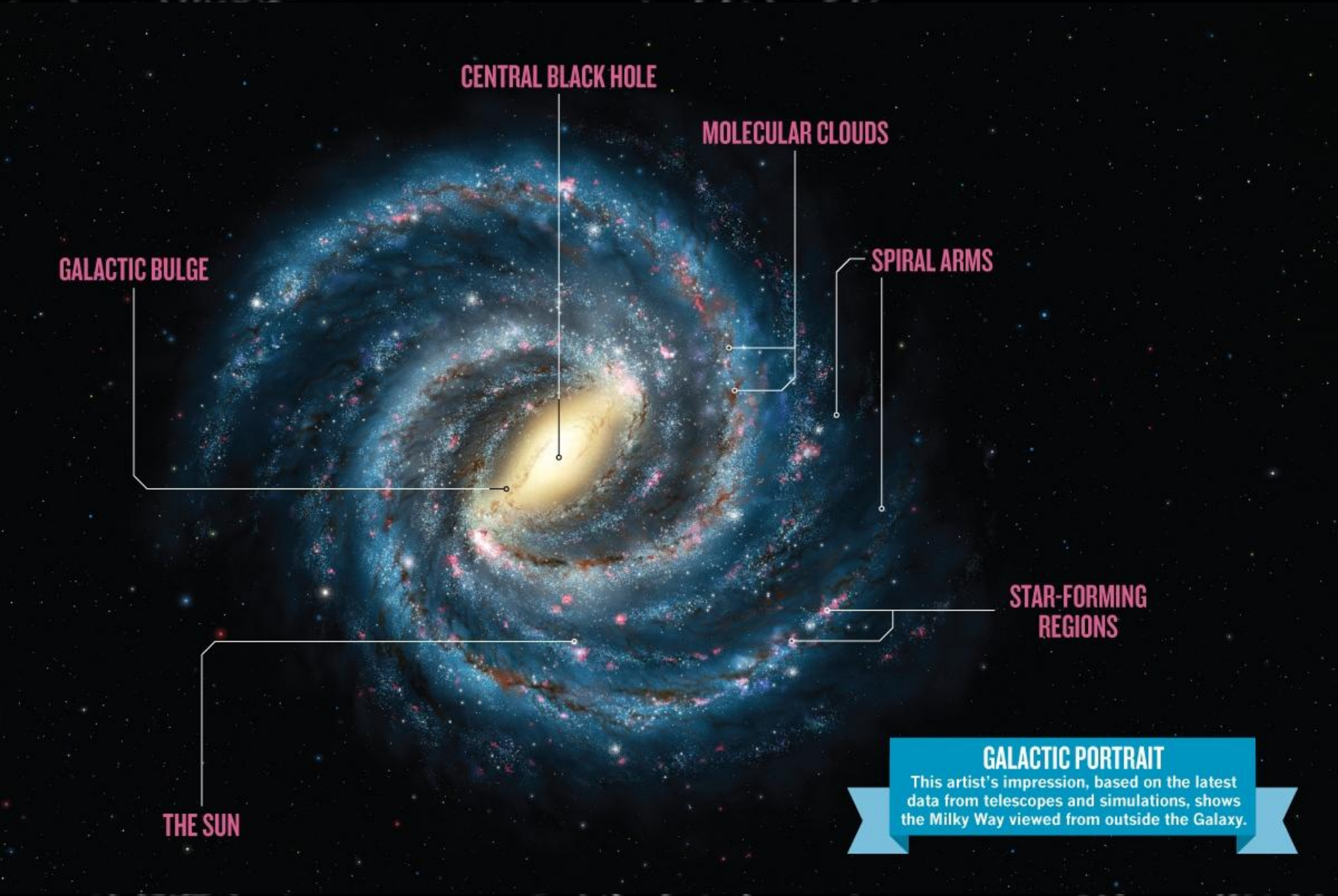
Illustris Collaboration

There are a lot a lot of knobs to turn in these simulations.

As a result, nothing is now a problem for the model.

They can make anything.

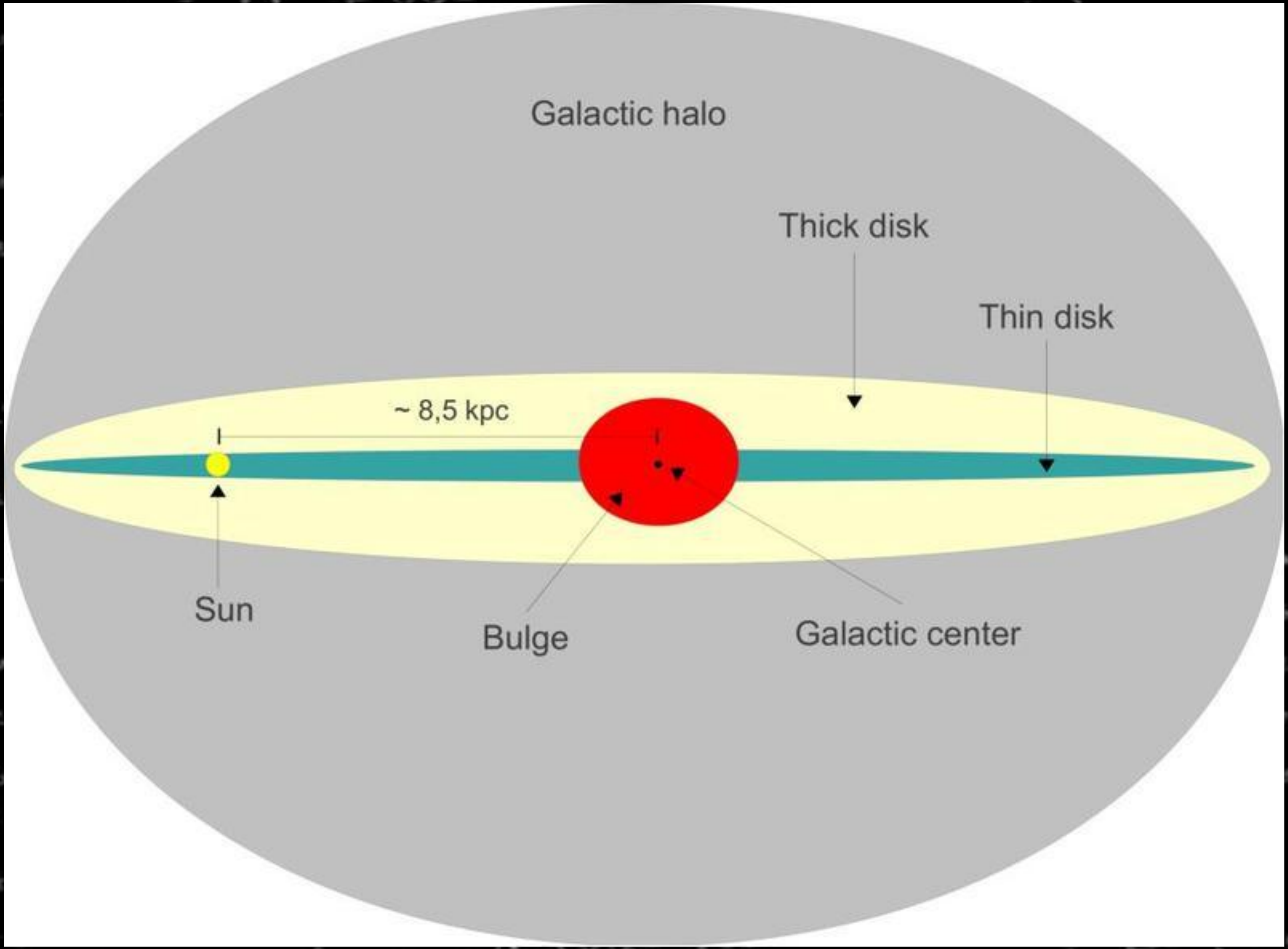
This makes it necessary to supply long lists of observations that must be fit.



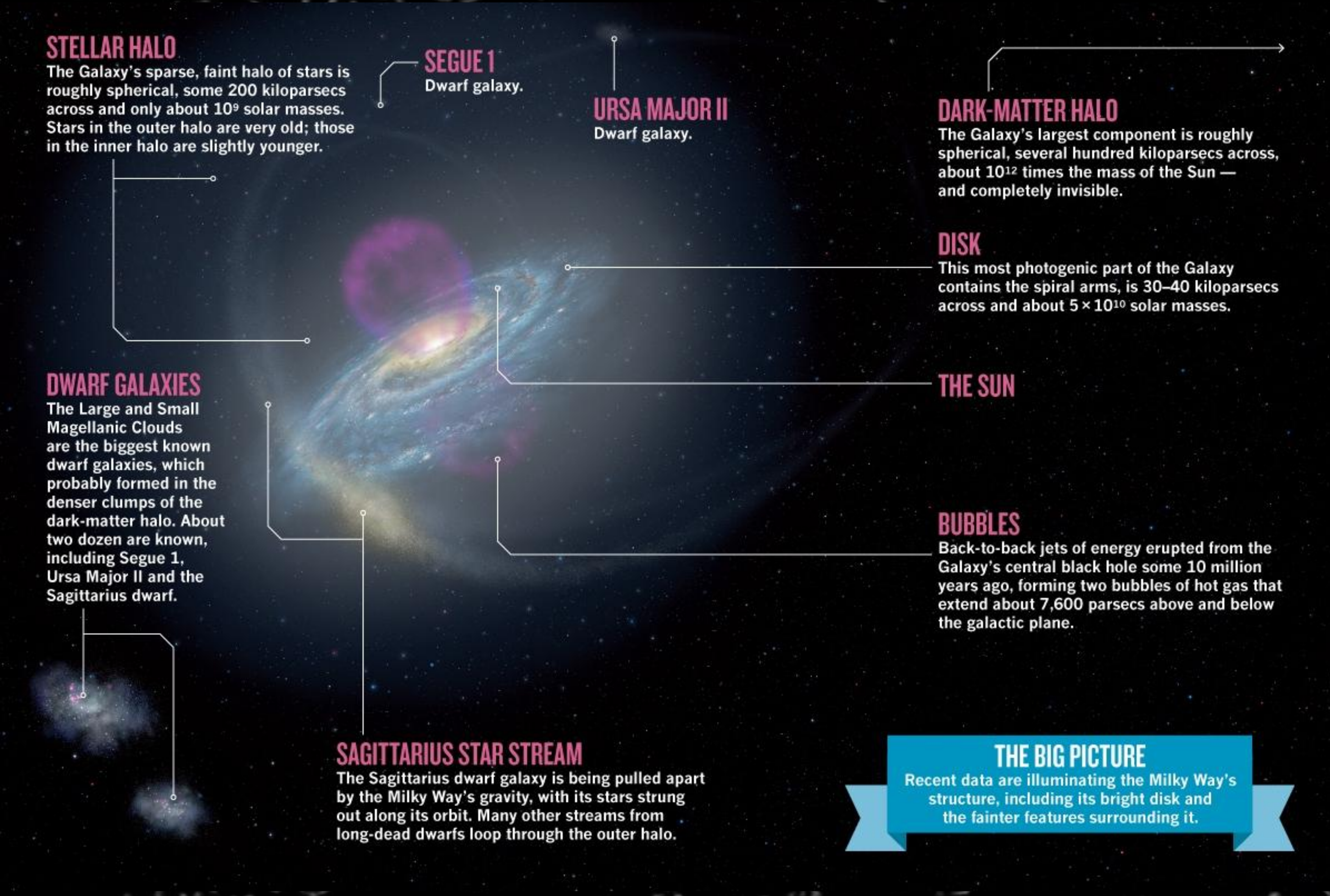
GALACTIC PORTRAIT

This artist's impression, based on the latest data from telescopes and simulations, shows the Milky Way viewed from outside the Galaxy.

The Galaxy when I was a student



Wikipedia image by Gaba p



STELLAR HALO

The Galaxy's sparse, faint halo of stars is roughly spherical, some 200 kiloparsecs across and only about 10^9 solar masses. Stars in the outer halo are very old; those in the inner halo are slightly younger.

SEGUE 1

Dwarf galaxy.

URSA MAJOR II

Dwarf galaxy.

DARK-MATTER HALO

The Galaxy's largest component is roughly spherical, several hundred kiloparsecs across, about 10^{12} times the mass of the Sun — and completely invisible.

DISK

This most photogenic part of the Galaxy contains the spiral arms, is 30–40 kiloparsecs across and about 5×10^{10} solar masses.

THE SUN

DWARF GALAXIES

The Large and Small Magellanic Clouds are the biggest known dwarf galaxies, which probably formed in the denser clumps of the dark-matter halo. About two dozen are known, including Segue 1, Ursa Major II and the Sagittarius dwarf.

BUBBLES

Back-to-back jets of energy erupted from the Galaxy's central black hole some 10 million years ago, forming two bubbles of hot gas that extend about 7,600 parsecs above and below the galactic plane.

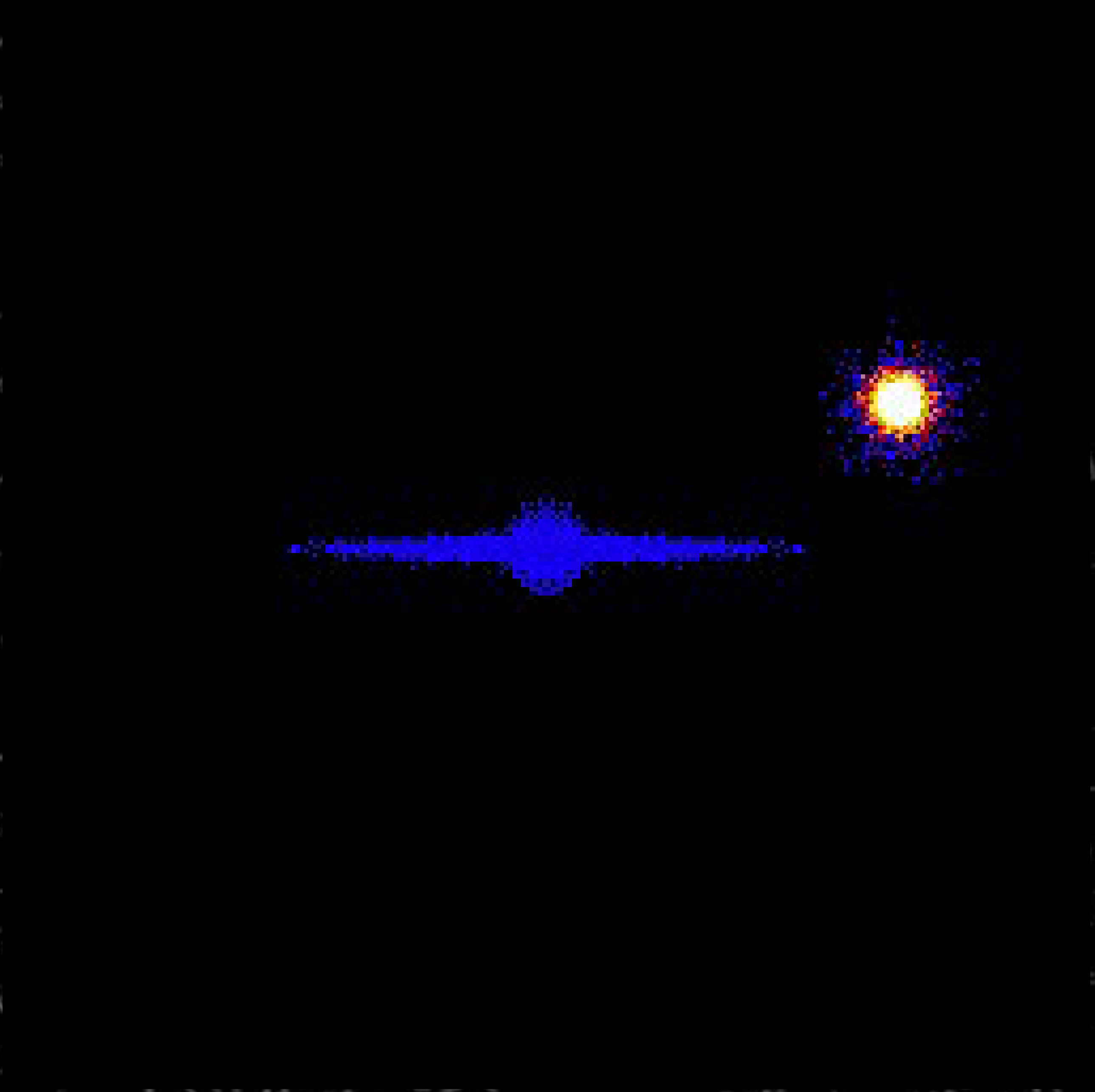
SAGITTARIUS STAR STREAM

The Sagittarius dwarf galaxy is being pulled apart by the Milky Way's gravity, with its stars strung out along its orbit. Many other streams from long-dead dwarfs loop through the outer halo.

THE BIG PICTURE

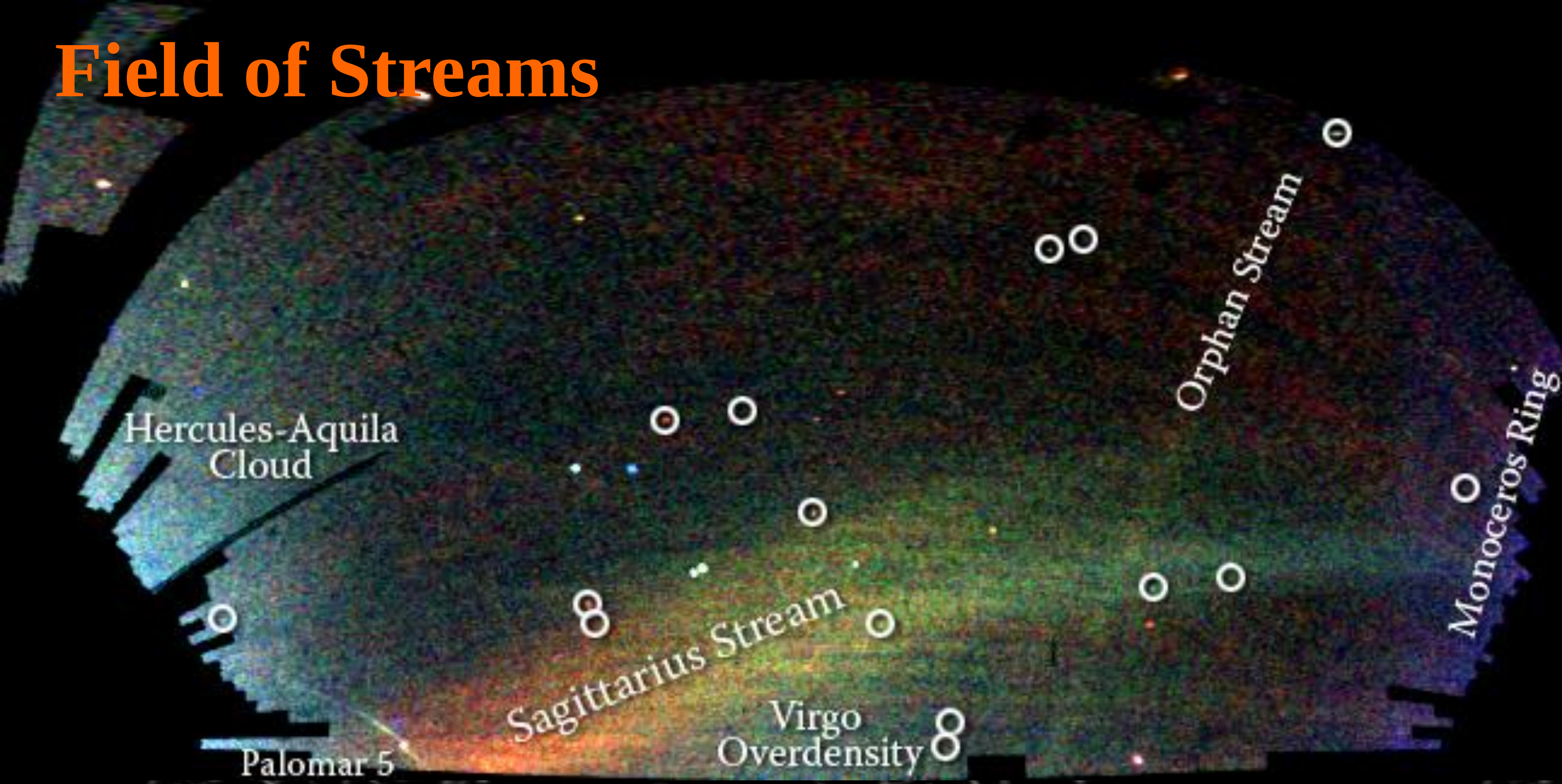
Recent data are illuminating the Milky Way's structure, including its bright disk and the fainter features surrounding it.

LYNETTE COOK



Simulation of a dwarf galaxy in orbit around the Milky Way by Kathryn Johnston.

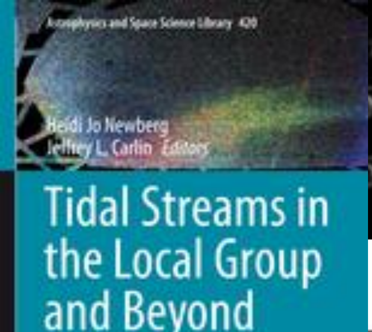
Field of Streams



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 Spaghetti Halo



Astrophysics and Space Science Library 420

Heidi Jo Newberg
Jeffrey L. Carlin *Editors*

Tidal Streams in the Local Group and Beyond

Observations and Implications

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

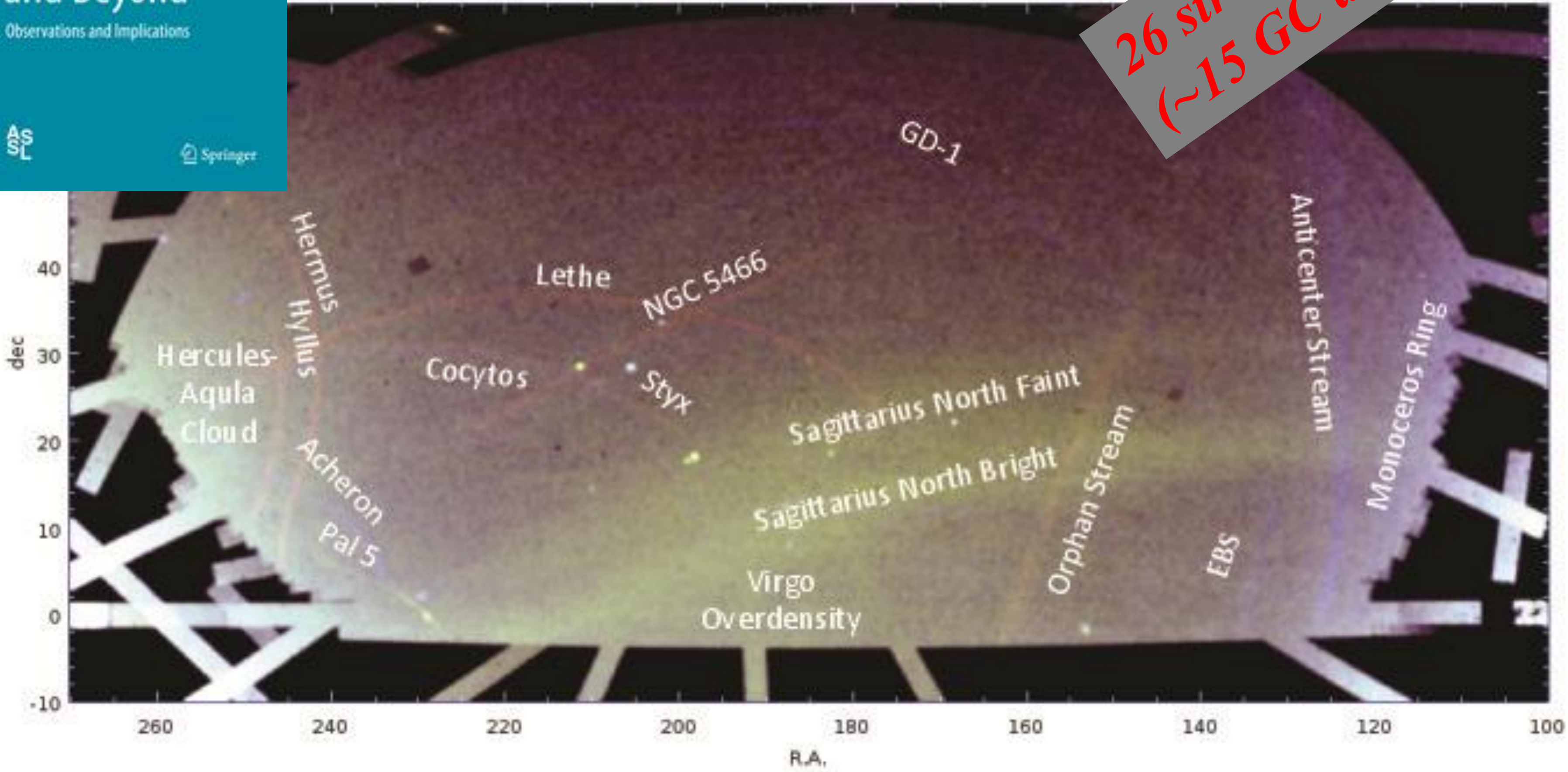
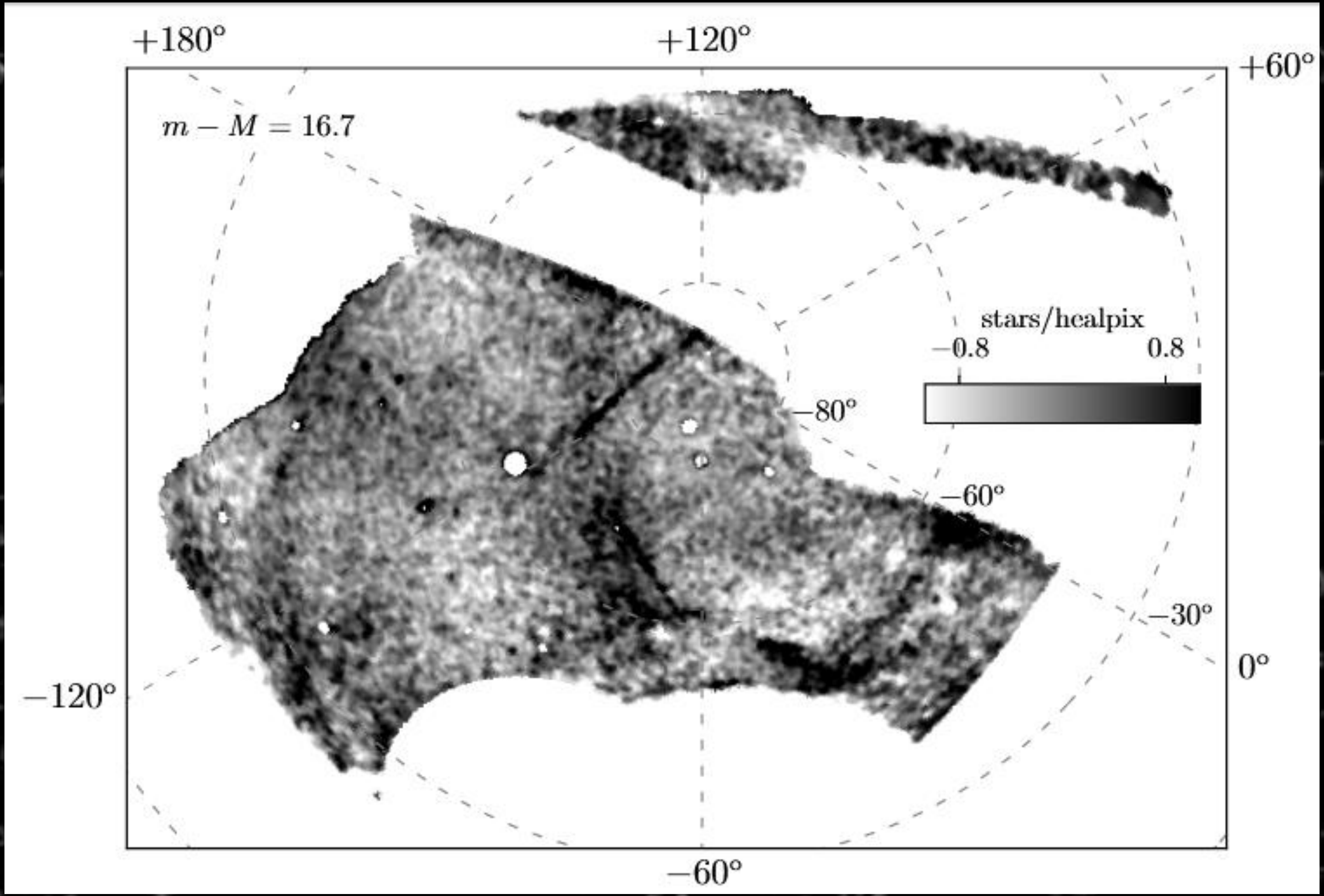


Image credit: Carl Grillmair, in Springer book: *Tidal Streams in the Local Group and Beyond*, Eds. Newberg & Carlin (2015)

~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
MilkyWay@home: Weiss et al. (2018) – 1 stream

(Not counting velocity substructure found in Gaia)



Shipp et al. (2018)

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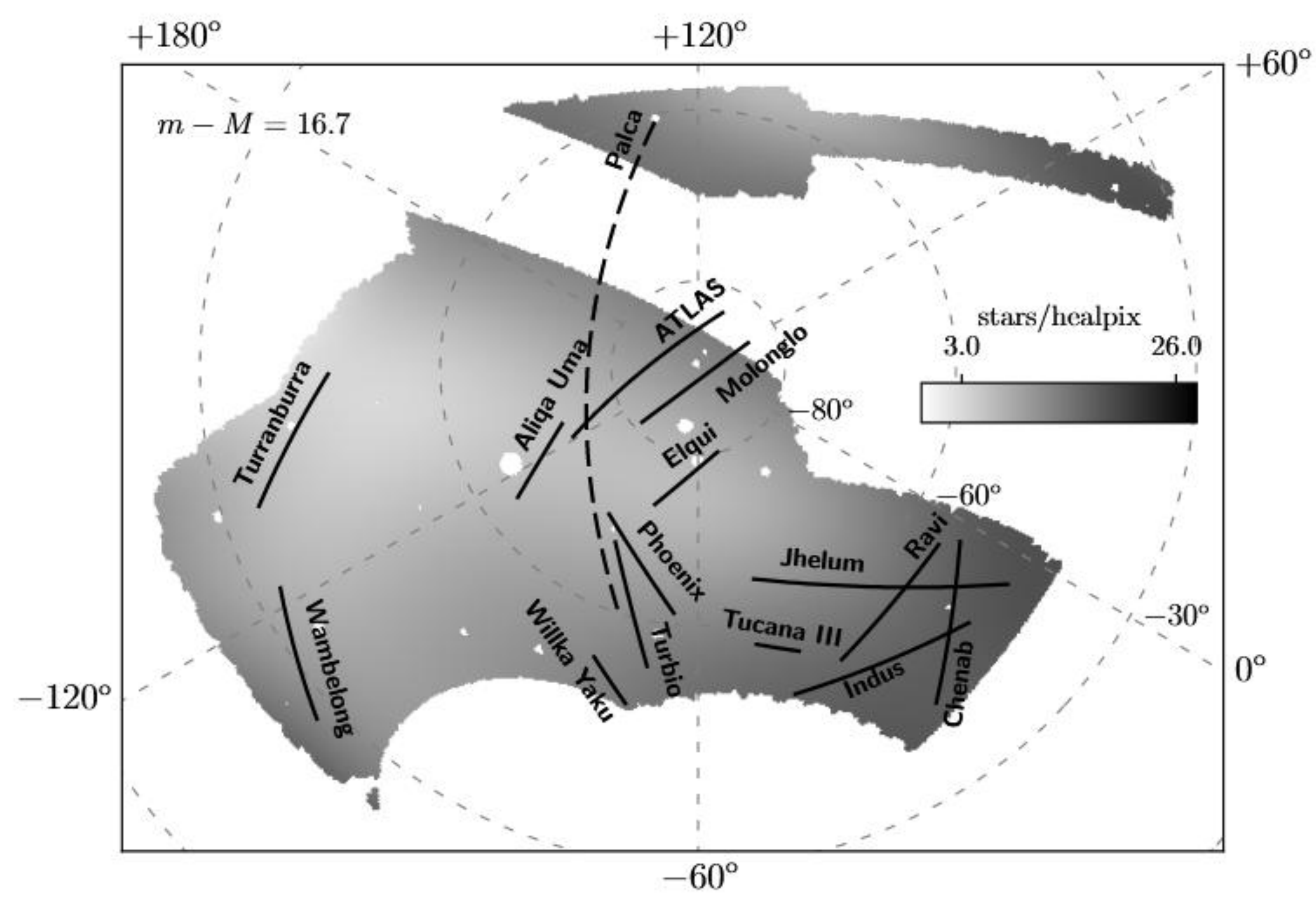
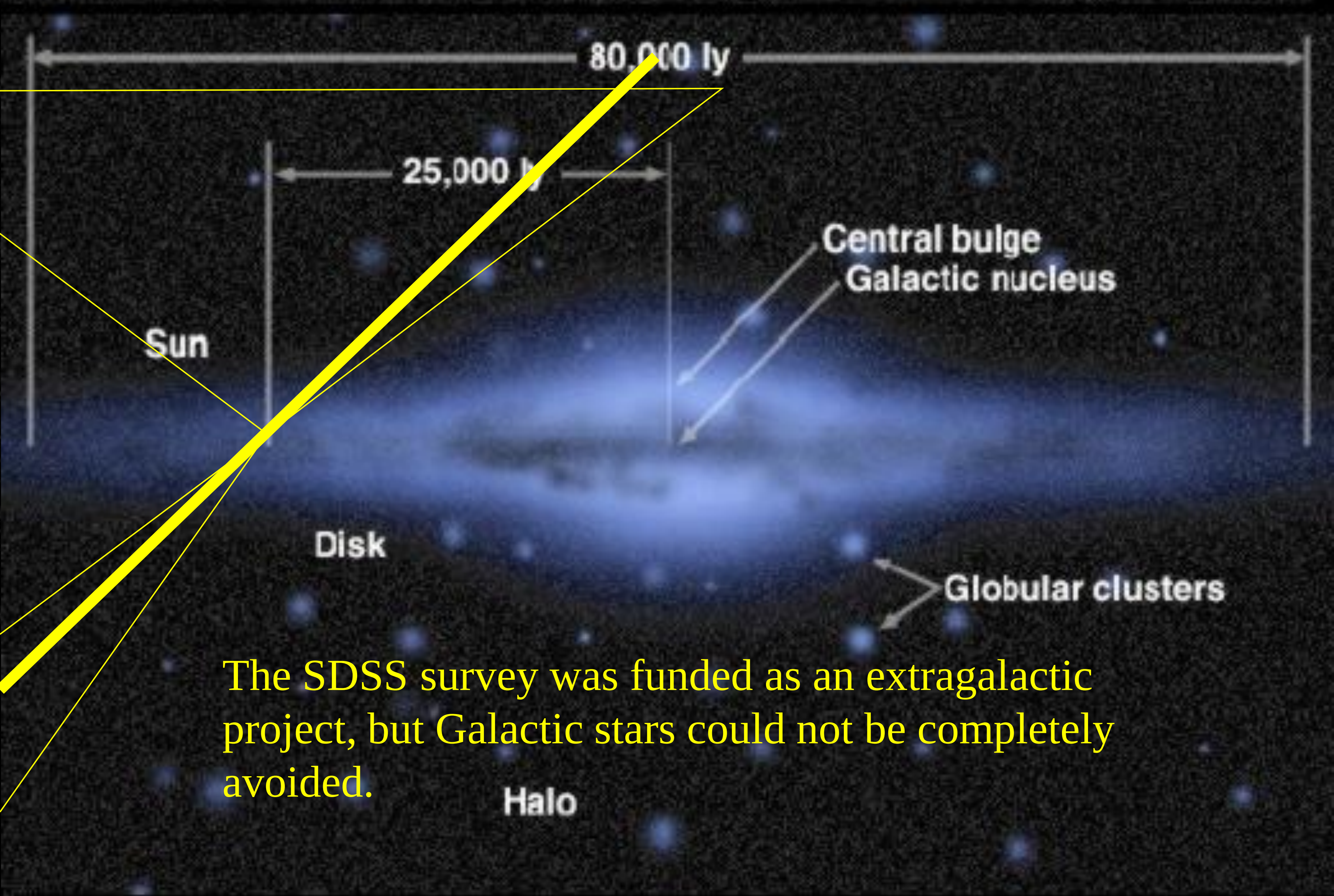
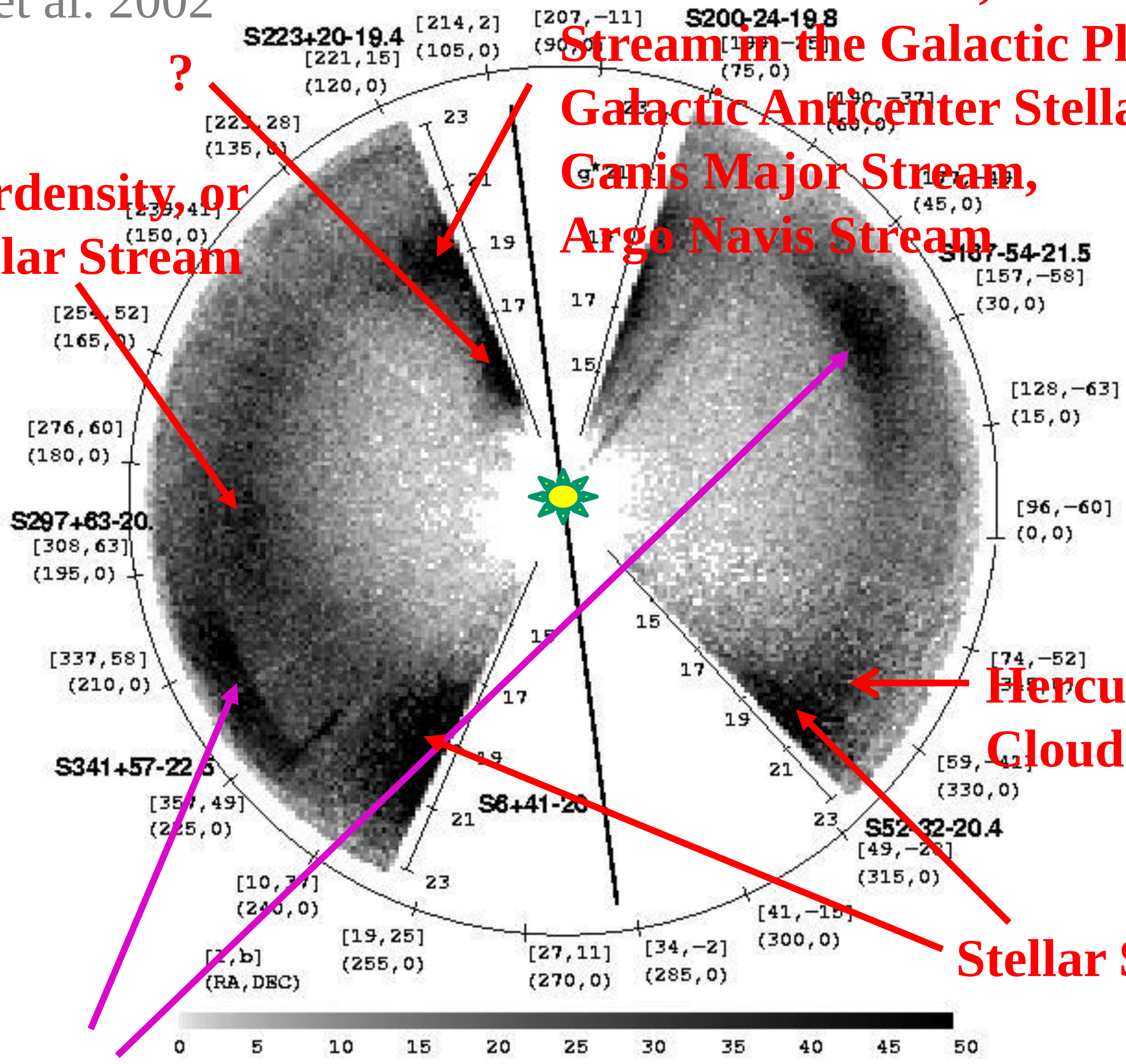


Shipp et al. (2018)



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

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

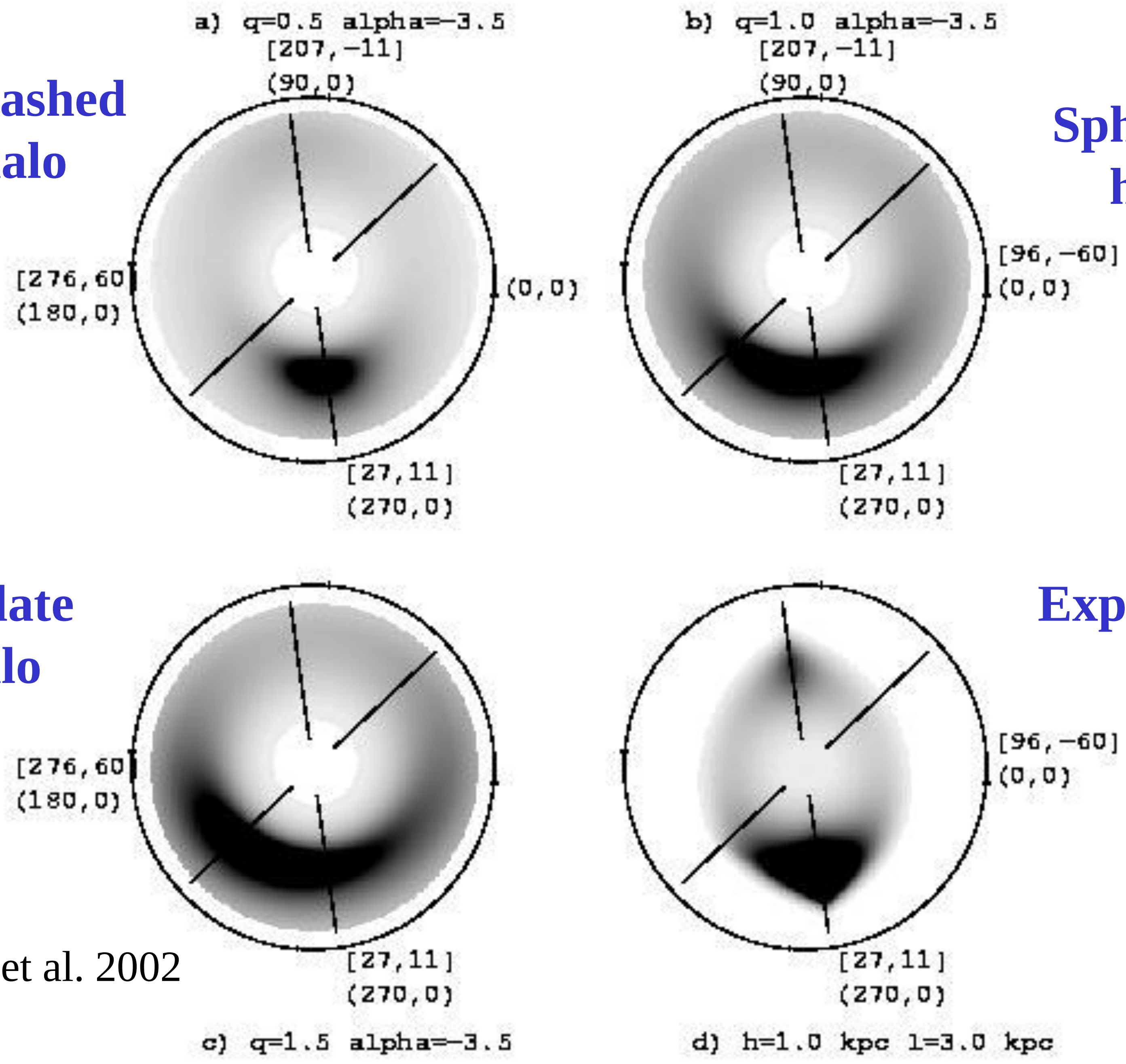
Hercules-Aquila Cloud

Stellar Spheroid

Sagittarius Dwarf Tidal Stream

Squashed halo

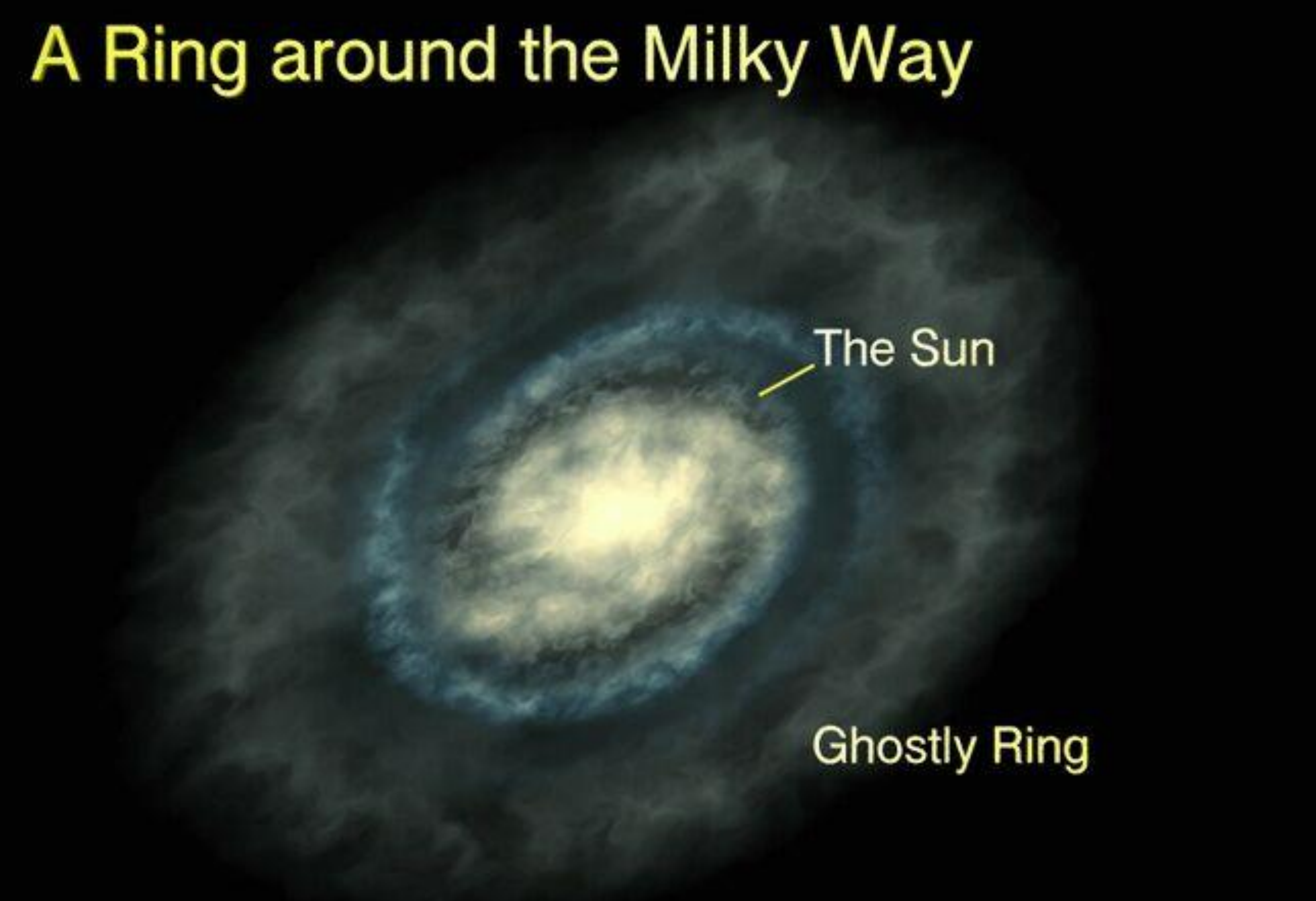
Spherical halo



Prolate halo

Exponential disk

Newberg et al. 2002



The Monoceros Ring

The disk of the Milky Way exhibits wavelike bulk motions.

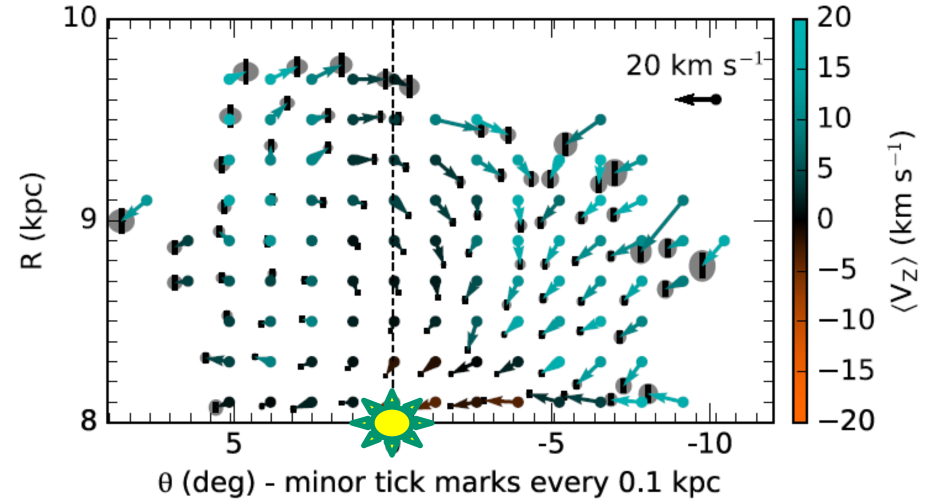
Williams et al. (2013) find velocity substructure in RAVE data

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

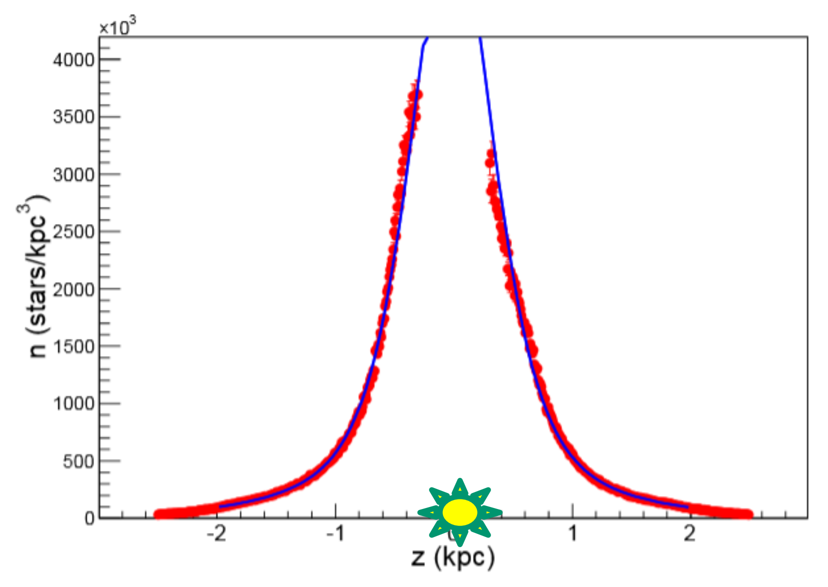
Carlin et al. (2013) find velocity substructure in LAMOST data

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

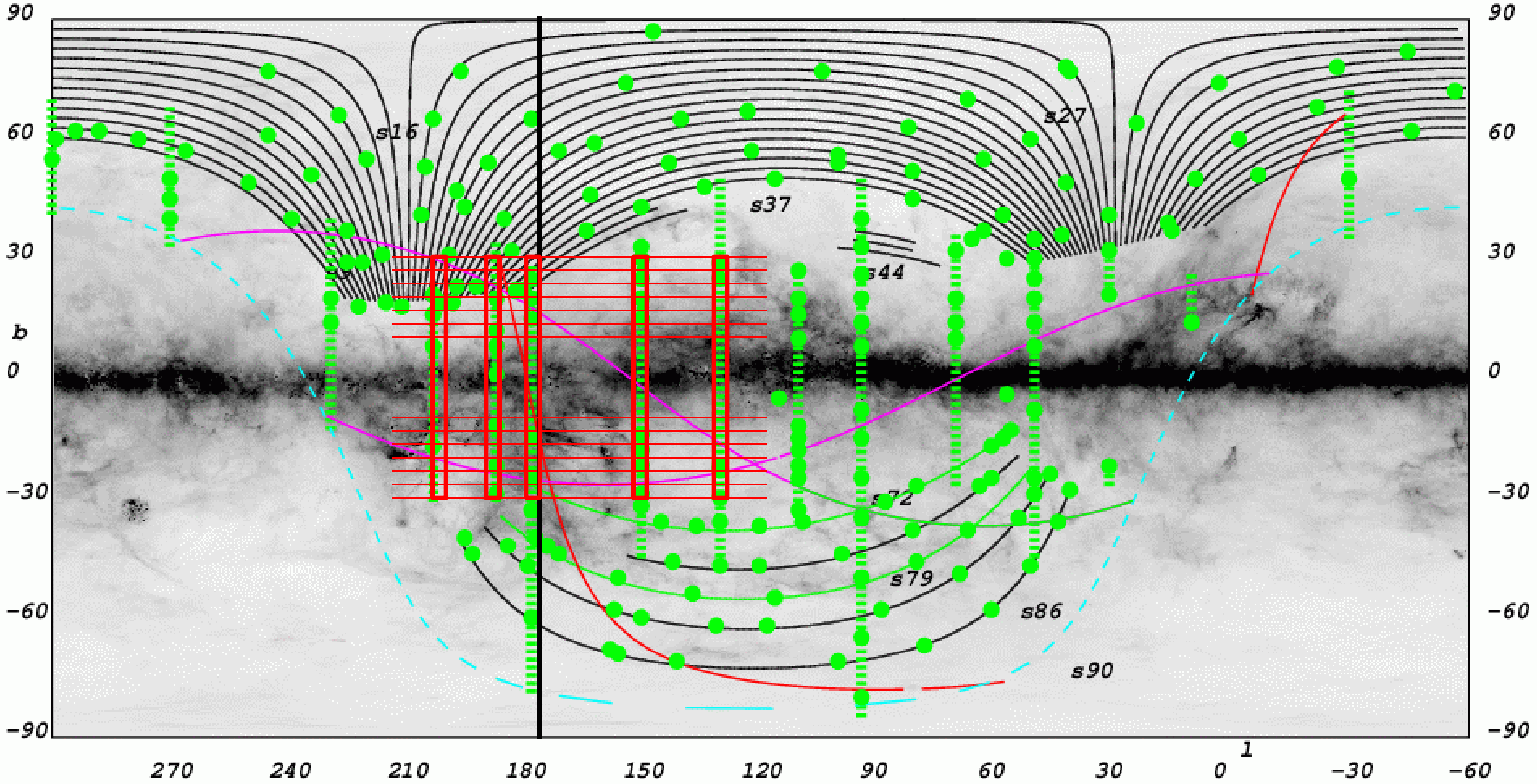
Pearl et al. (2017) find velocity substructure, with errors, using LAMOST and PPMXL



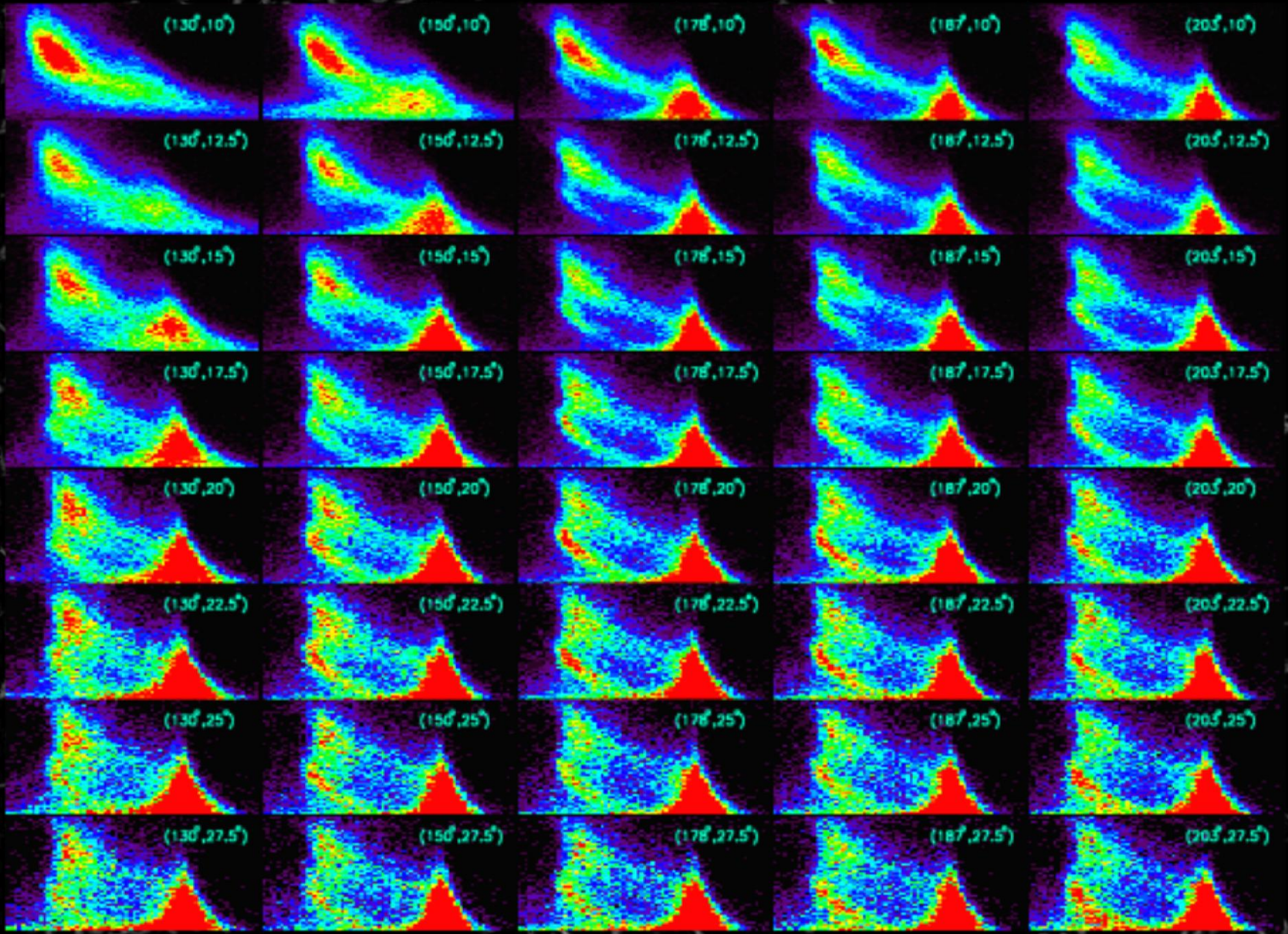
Pearl et al. (2017)



Yanny & Gardner (2013)



The 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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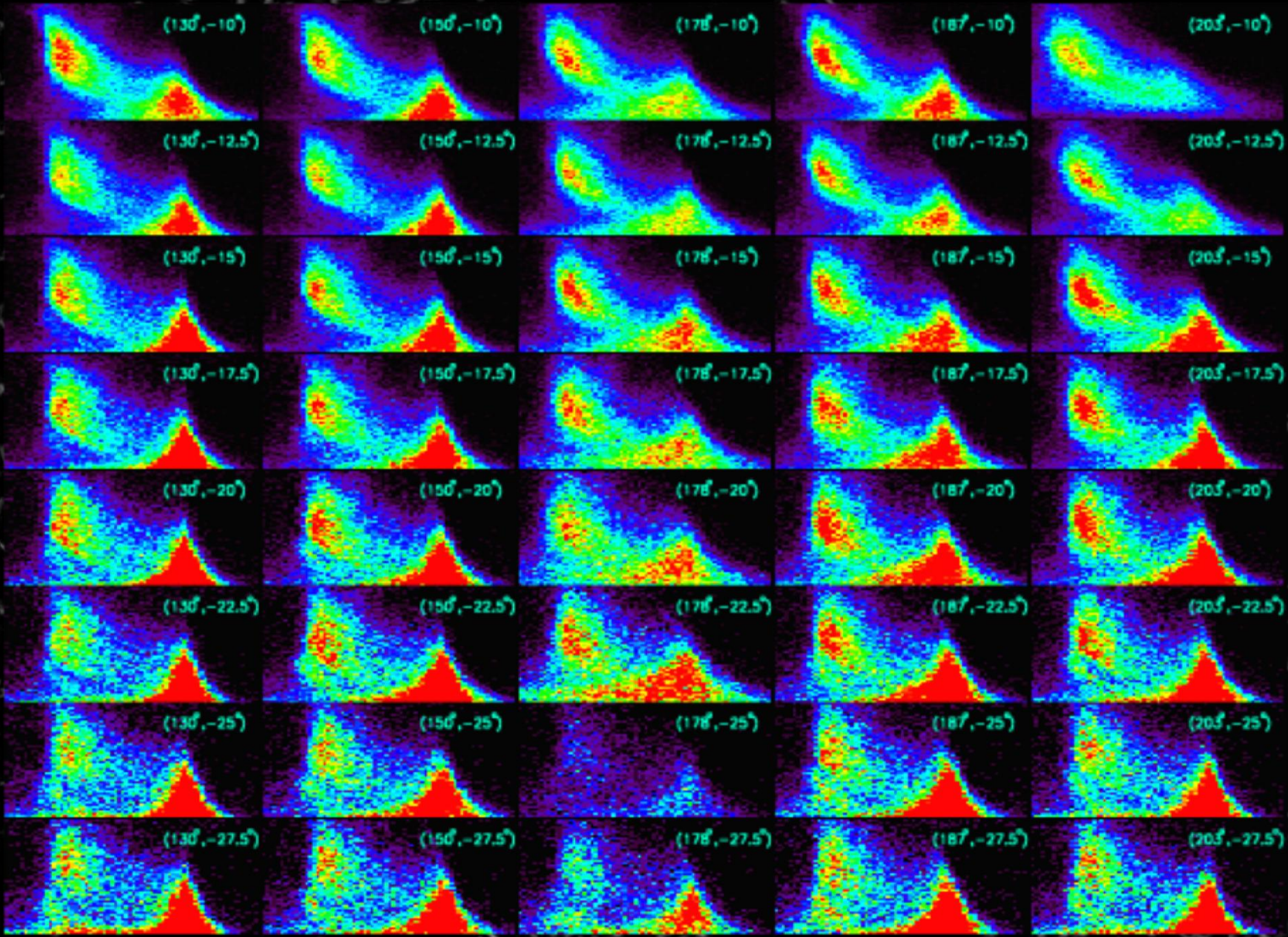
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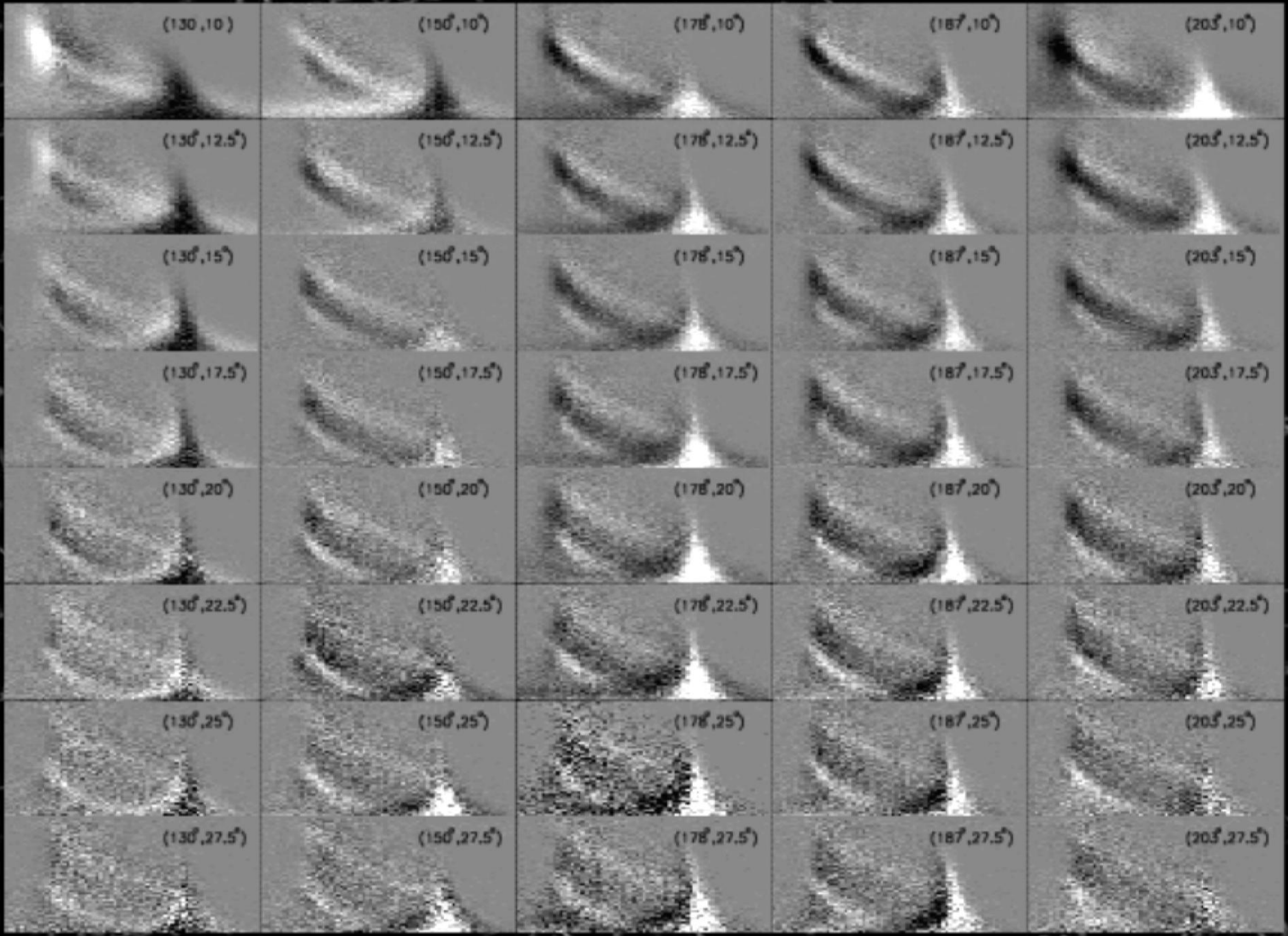
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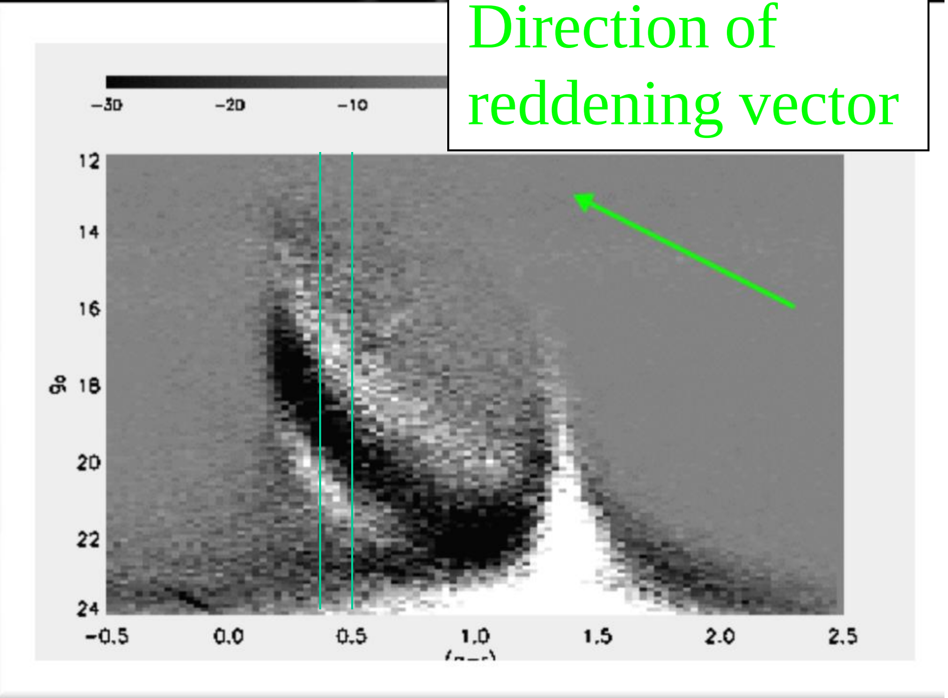
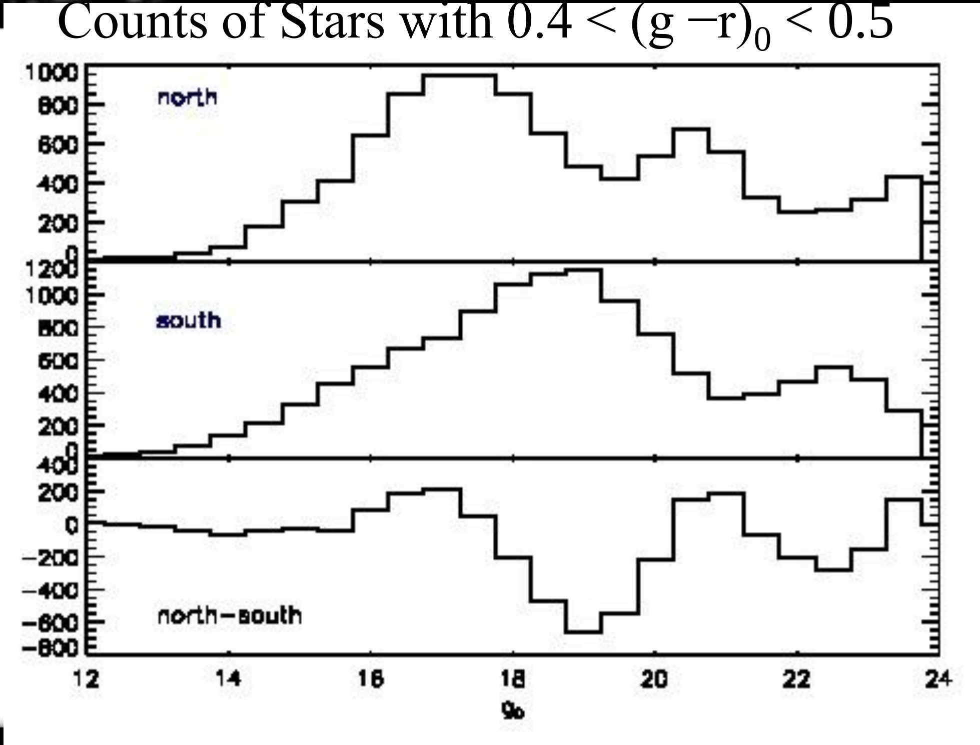
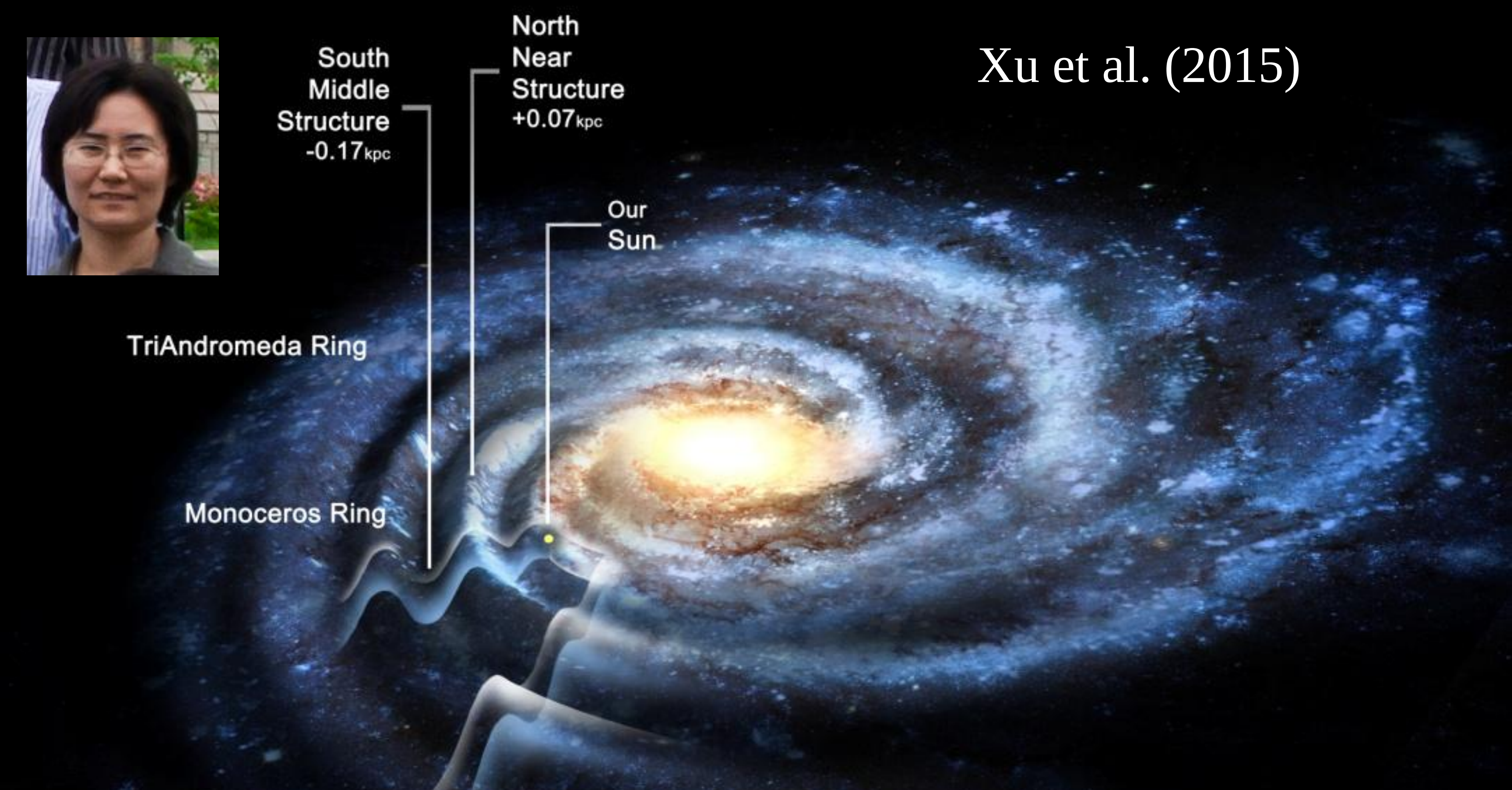


Direction of reddening vector


Counts of Stars with $0.4 < (g - r)_0 < 0.5$

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

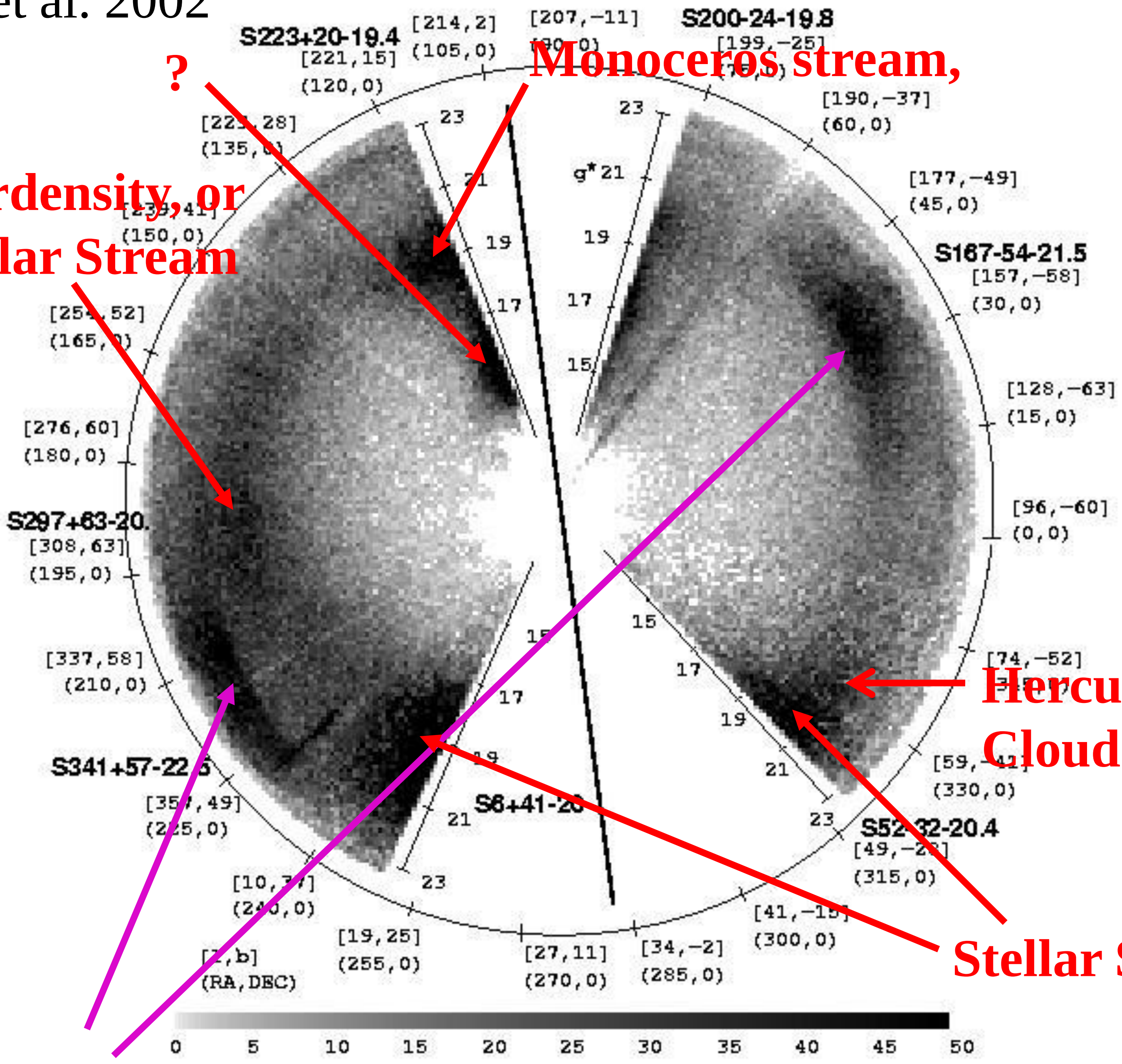
Xu et al. (2015)



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.”

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

Newberg et al. 2002



?

Monoceros stream,

Vivas overdensity, or Virgo Stellar Stream

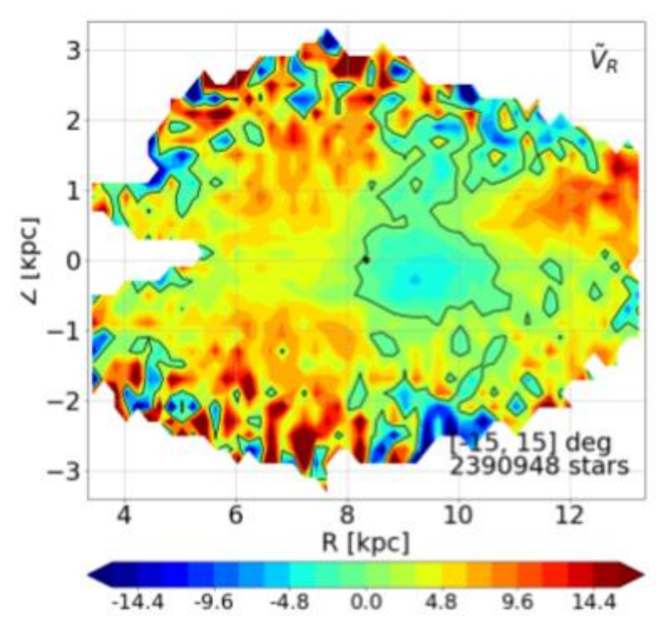
Hercules-Aquila Cloud

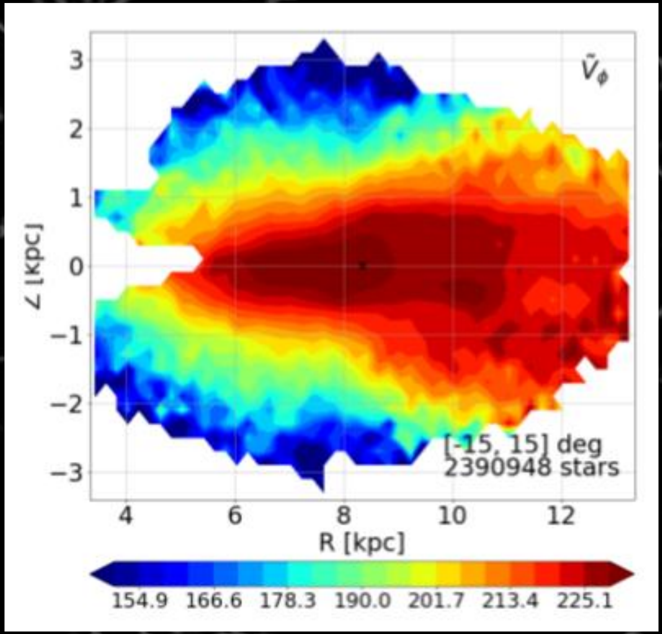
Stellar Spheroid

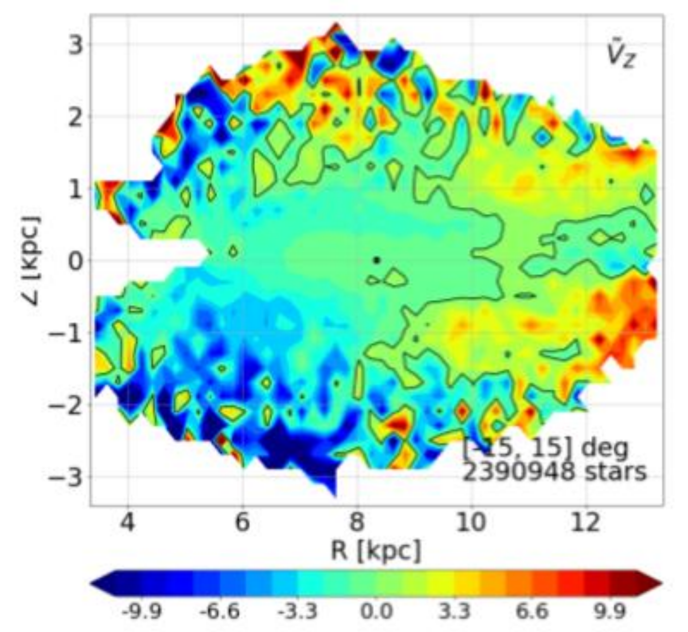
Sagittarius Dwarf Tidal Stream

Gaia Collaboration et al. (2018)

Velocity substructure in the region of the disk near the Sun. Is this wavelike or the result of perturbations from passing halo substructures?







Besla et al. (2007) – The Milky Way is on its first infall (proper motion)
Besla et al. (2012) – The Magellanic streams are LMC/SMC interaction
Kallivayalil et al. (2013) - Mass of LMC must be ~10^{11} for the LMC/SMC pair to remain bound
Gomez et al. (2015) – The Milky Way moves in response to the LMC

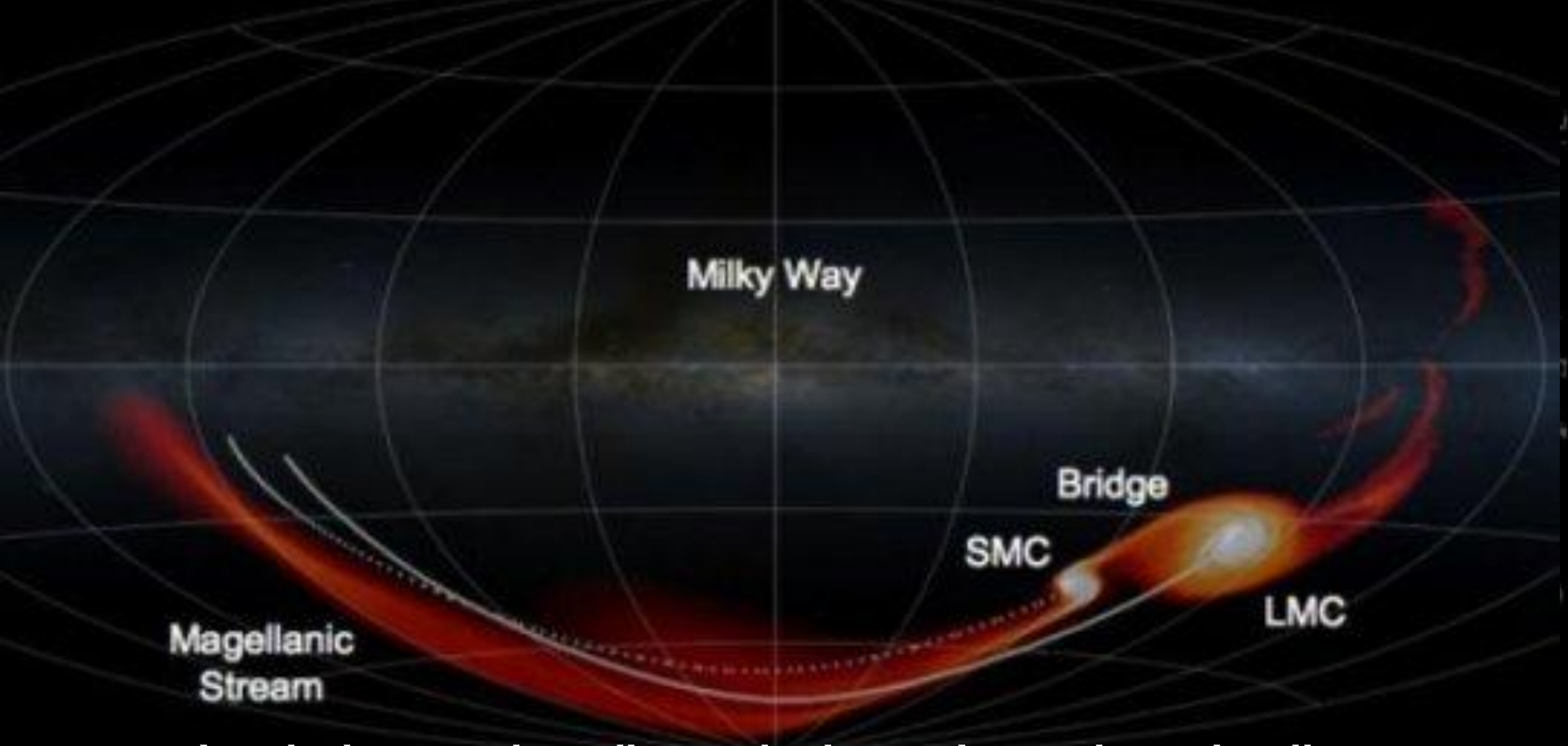
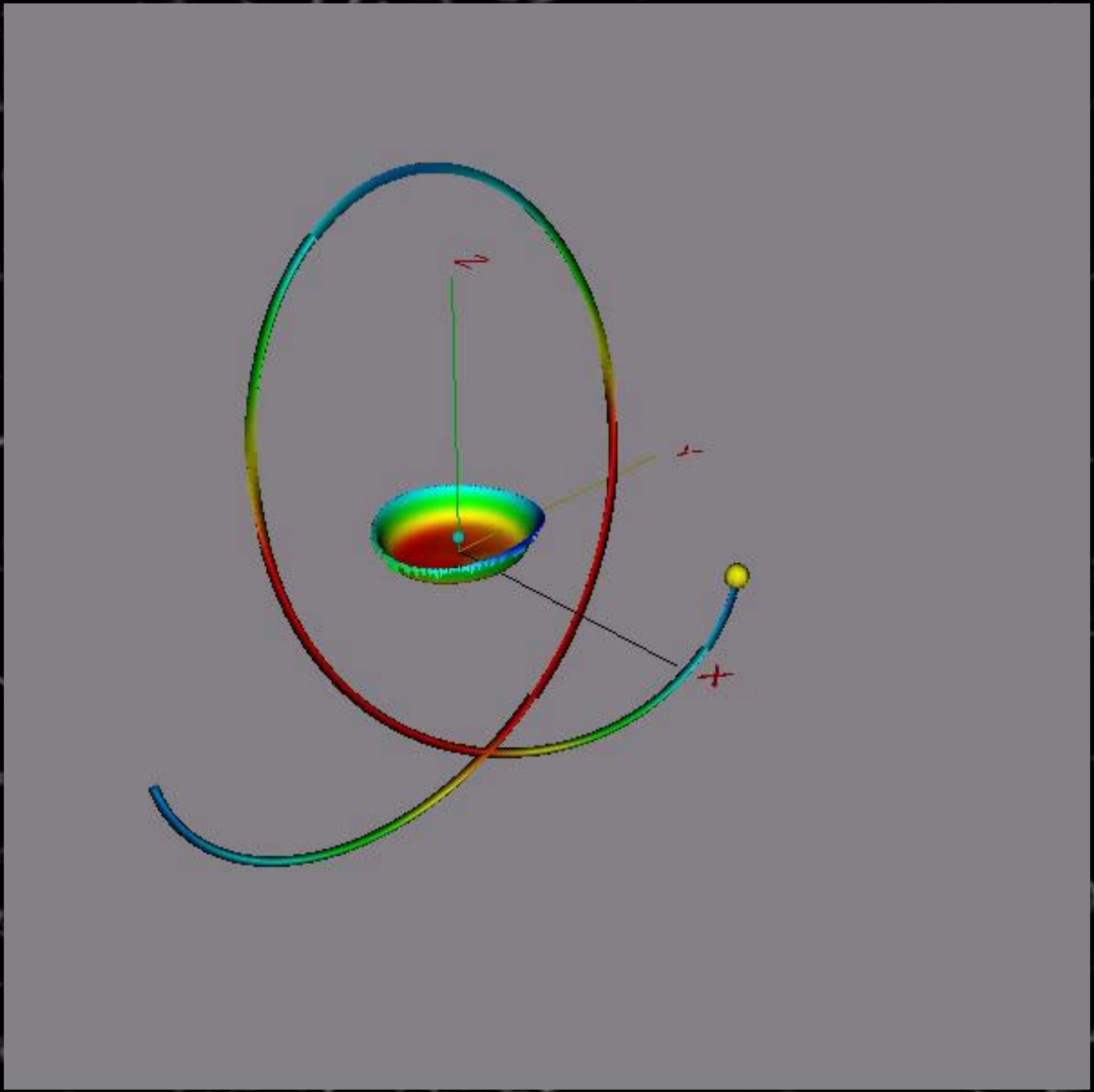


Image credit: *Plot by G. Besla, Milky Way background image by Axel Mellinger*



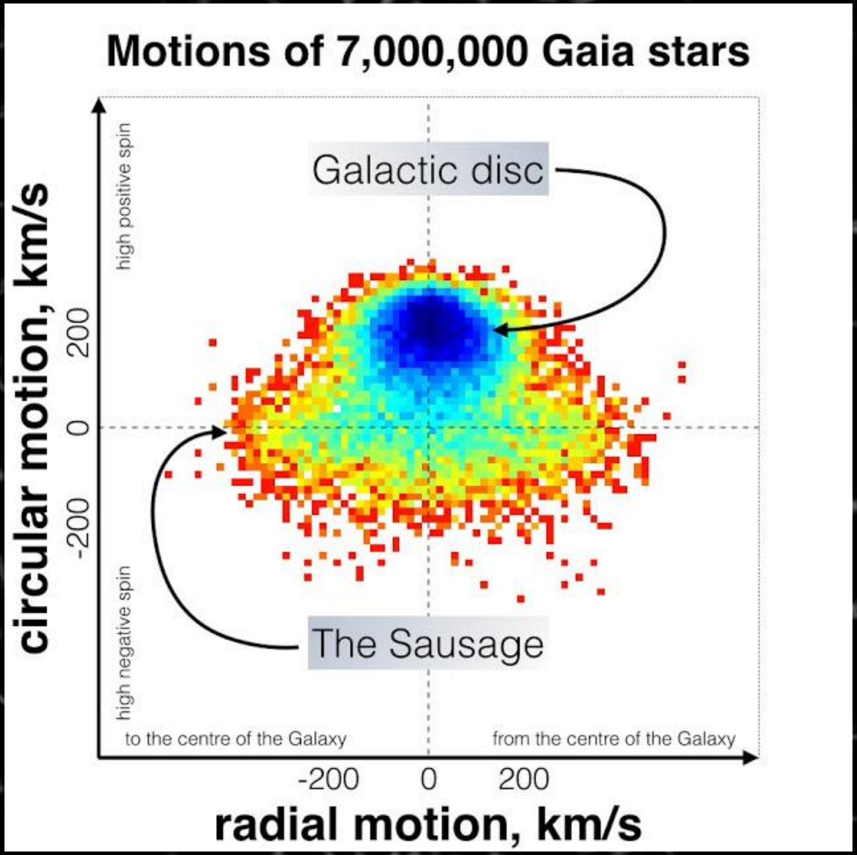
Martin Weinberg & Leo Blitz (2006)

The Magellanic Clouds could be causing the Galactic warp.

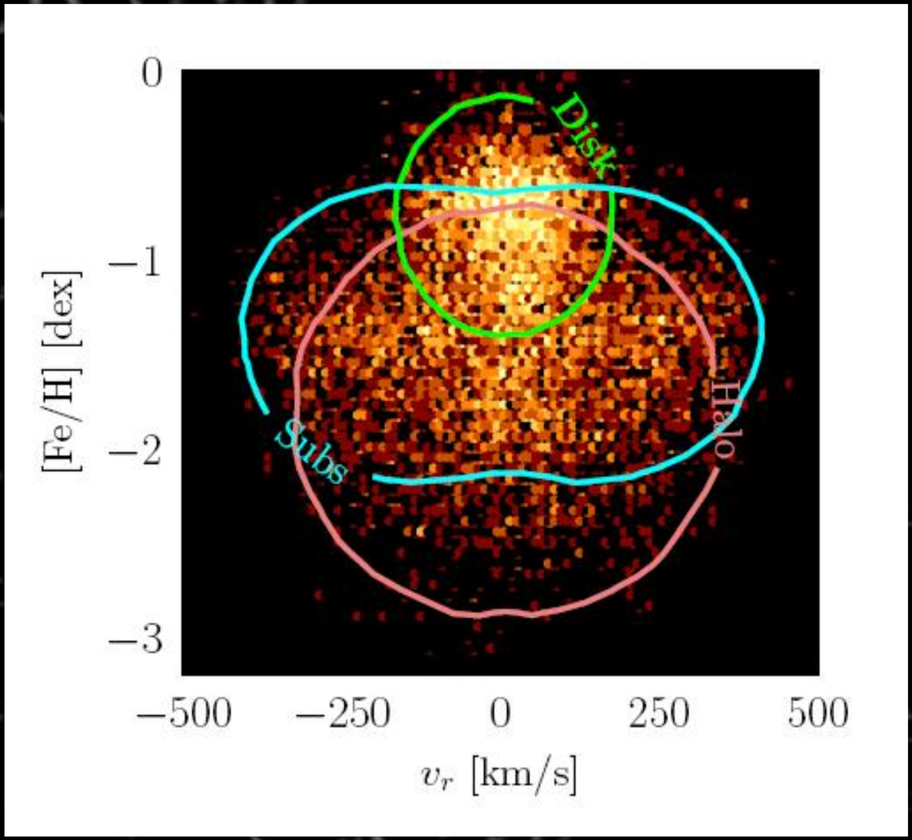
Note this is from 2006 when the mass of the LMC was $2x10^{10}$ $M_{\odot}$ (ten times smaller)

Credit: V. Belokurov (Cambridge, UK); Based on image by ESO/Juan Carlos Munoz

The stellar halo could be a combination of old accretion, plus one 10^{10} $M_\odot$ merger 10 Gyrs ago on a highly radial orbit, that puffed up the thick disk and became the inner halo (Gilmore, Wyse & Norris 2002, Fiorentino 2015, Belokurov et al. 2018a, 2018b, Deason et al. 2018, Myeong et al. 2018, Helmi et al. 2018, Lancaster et al. 2018). Gaia Sausage/Gaia-Enceladus



Credit: V. Belokurov (Cambridge, UK) and Gaia/ESA

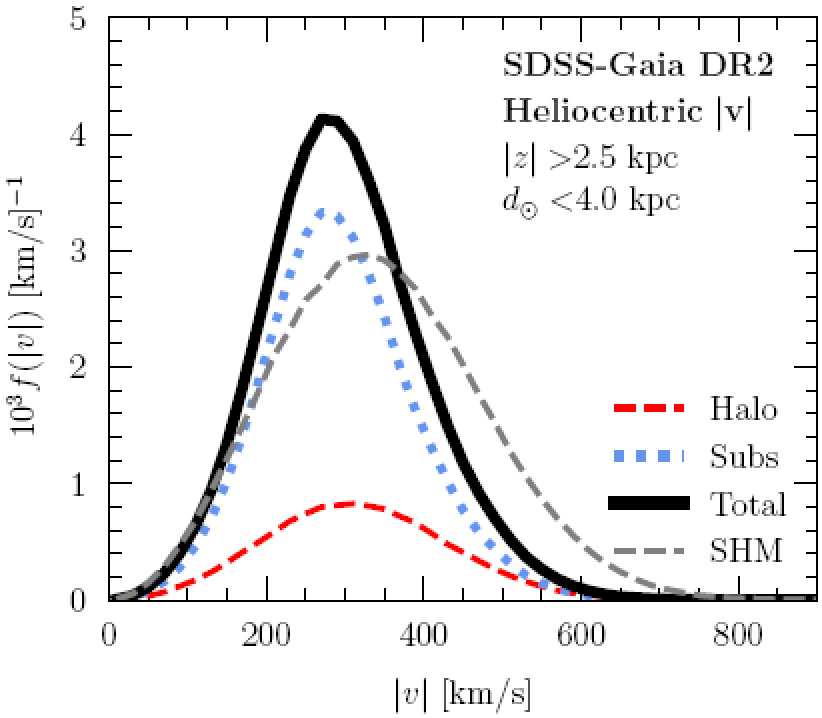


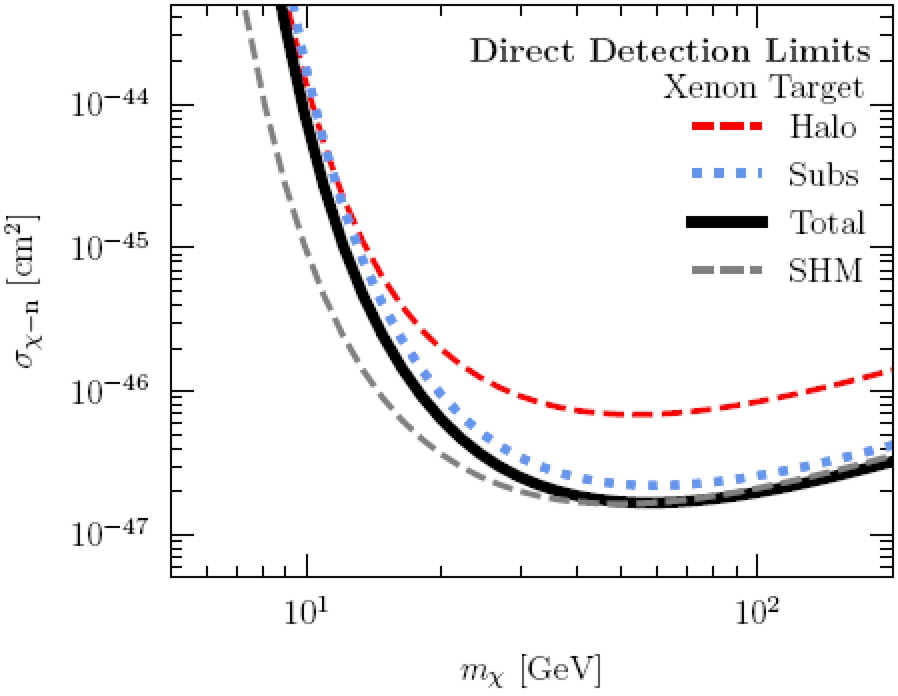
Necib, Lisanti & Belokurov 2018

The Standard Halo Model: Dark matter is virialized with an isotropic and isothermal distribution. The velocities follow a Maxwell-Boltzmann distribution.

Lisanti et al. (2015), Herzog-Arbeitman et al. (2017) – Mergers that have lost spatial coherence trace the dark matter velocity distribution.

Necib, Lisanti & Belokurov (2018) – The “Gaia Sausage” is dominates the halo, effecting xenon dark matter direct detection limits (below). The annual modulation signature could also be affected.





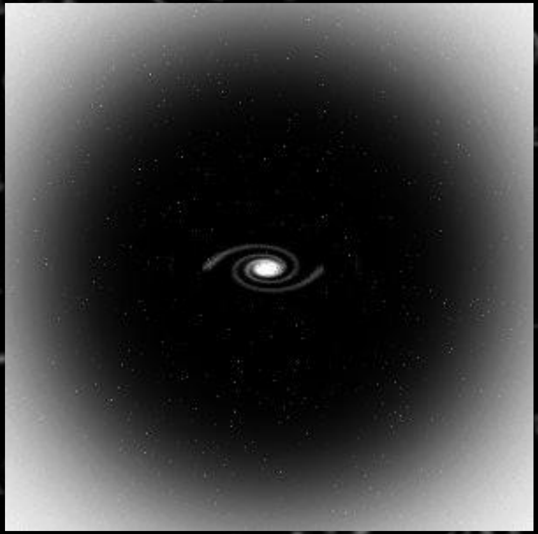
My thoughts on the Standard Halo Model

The identification of the inner halo as originating from a single merger remnant is new but extremely popular.

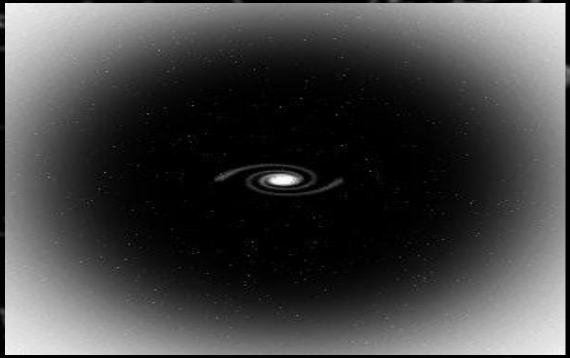
The assumption that the velocity distribution of the stars follows that of the dark matter is dicey, and it is particularly uncertain that the ratio of stars to dark matter is the same in the older mergers as it is in the newer merger.

*However, in a galaxy in which the stars are *this much* out of equilibrium, it seems unavoidable that the dark matter will also be out of equilibrium.*

Possible Dark Matter Halo Shapes

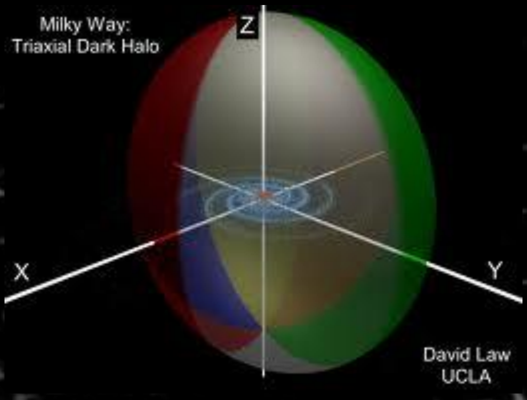


spherical

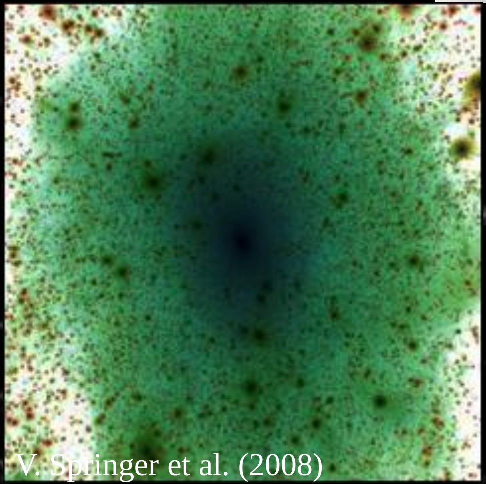


oblate

prolate



triaxial



V. Springer et al. (2008)

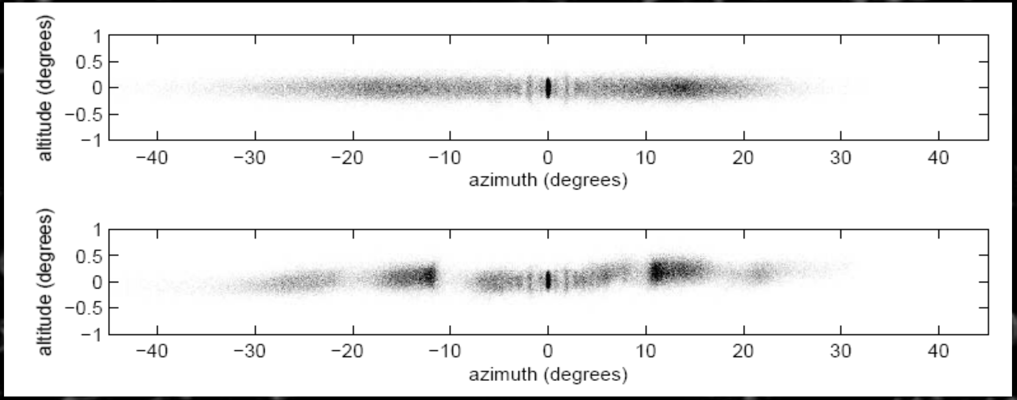
lumpy

Also, the shape could change with time and radius…

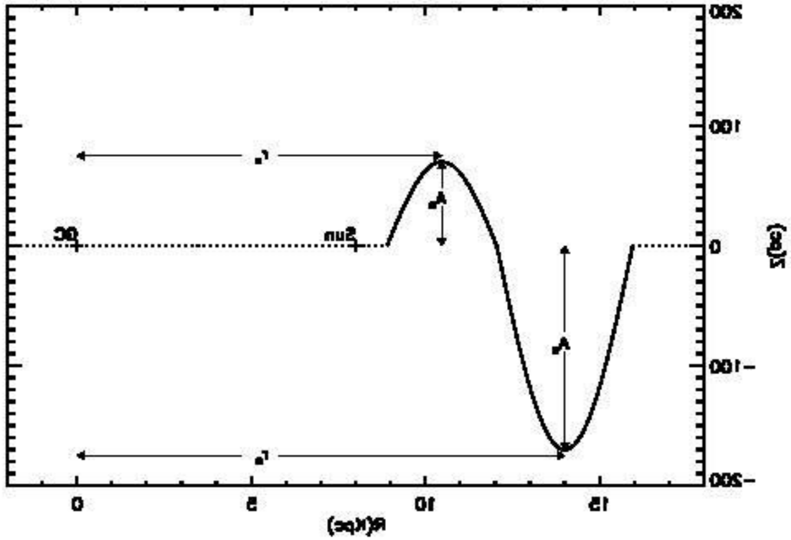
The only things we know for sure about the dark matter is from the motions of matter that we can see.

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

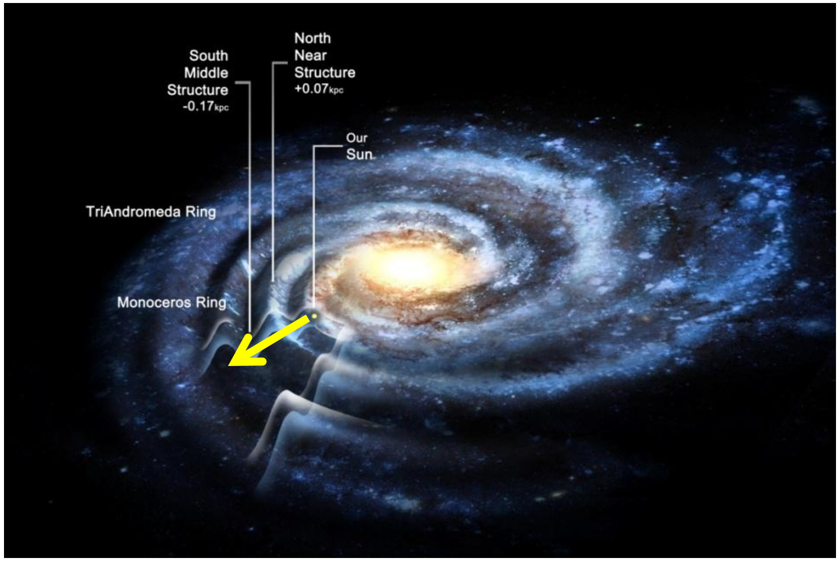
- Looking for gaps in streams
- Broadening of streams with time
- Stars that have been thrown out of streams
- Galactoseismology



Johnston & Carlberg (2016)



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



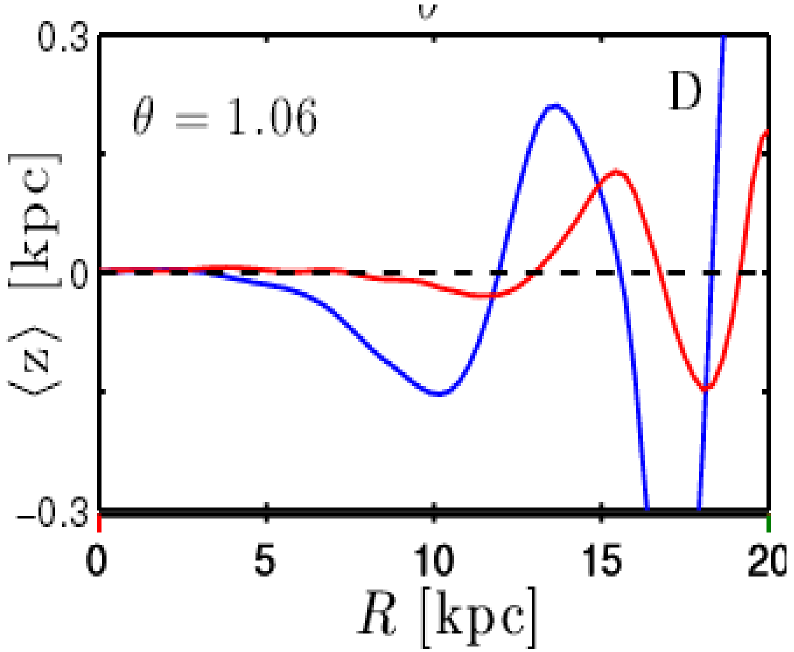
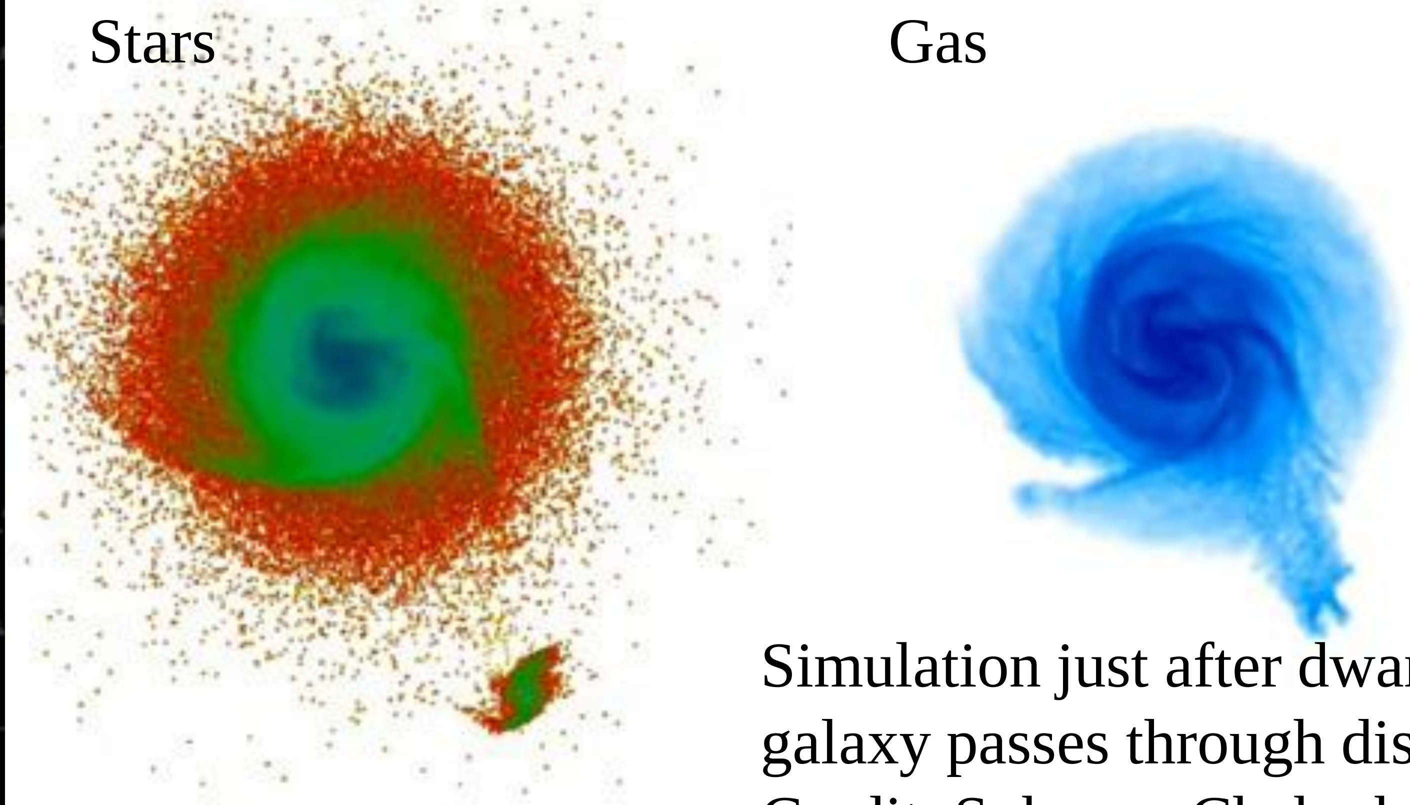


Figure 6. Panel d: Comparison of the mean vertical displacement of the disk from a light ($10^{10.5}$ $M_\odot$, red) and heavy (10^{11} $M_\odot$, blue) Sagittarius dwarf galaxy, as a function of galactocentric radius.

Gomez et al. (2013)

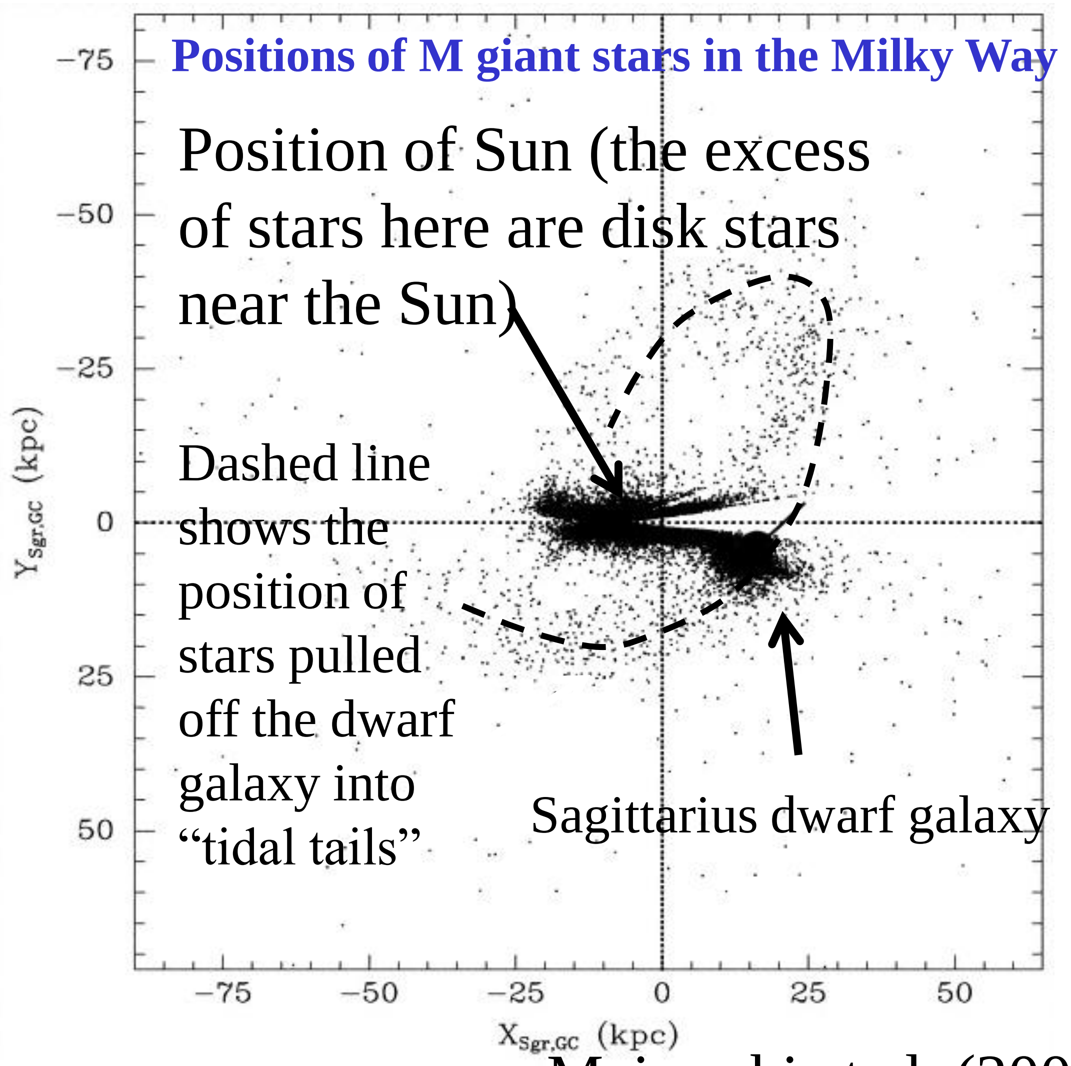


Simulation just after dwarf galaxy passes through disk
Credit: Sukanya Chakrabarti

One *possible* dwarf galaxy was identified from the ripples that are observed in the Milky Way disk gas (Chakrabarti & Blitz 2009; Chang & Chakrabarti 2011; Chakrabarti et al. 2011, 2015, 2017; Chakrabarti 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.



Positions of M giant stars in the Milky Way

Position of Sun (the excess of stars here are disk stars near the Sun)

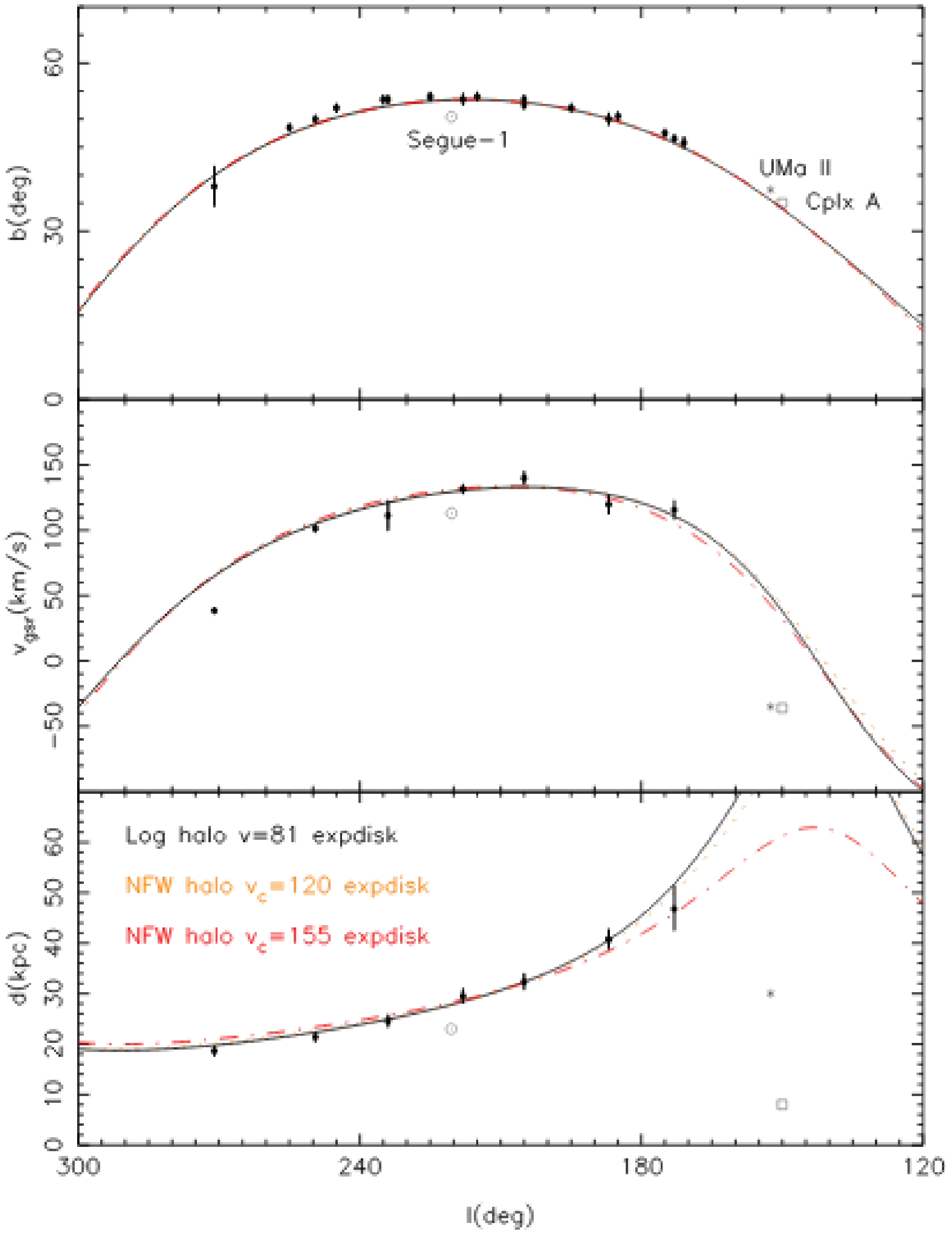
Dashed line shows the position of stars pulled off the dwarf galaxy into "tidal tails"

Sagittarius dwarf galaxy

Majewski et al. (2003)

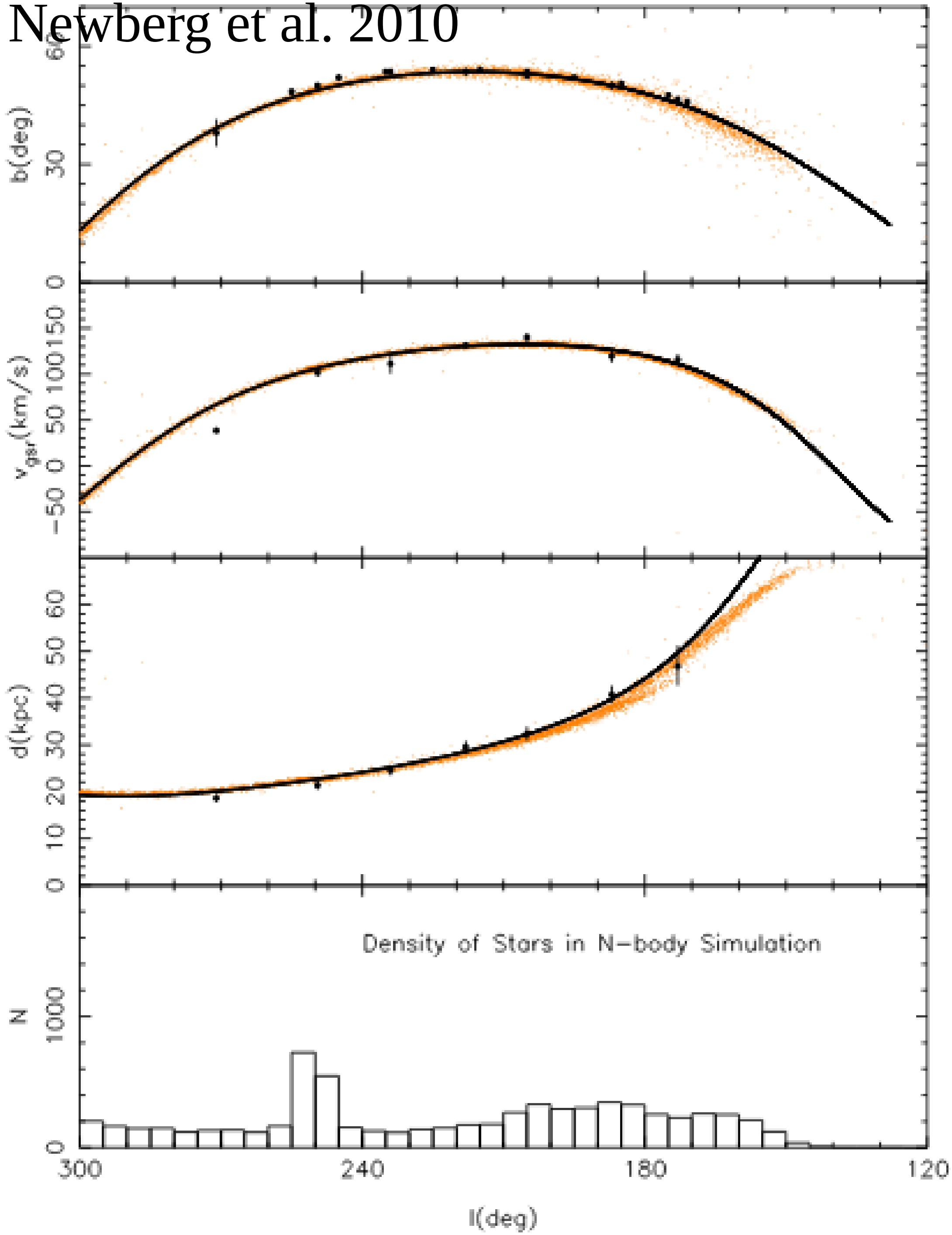
Newberg et al. 2010

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.

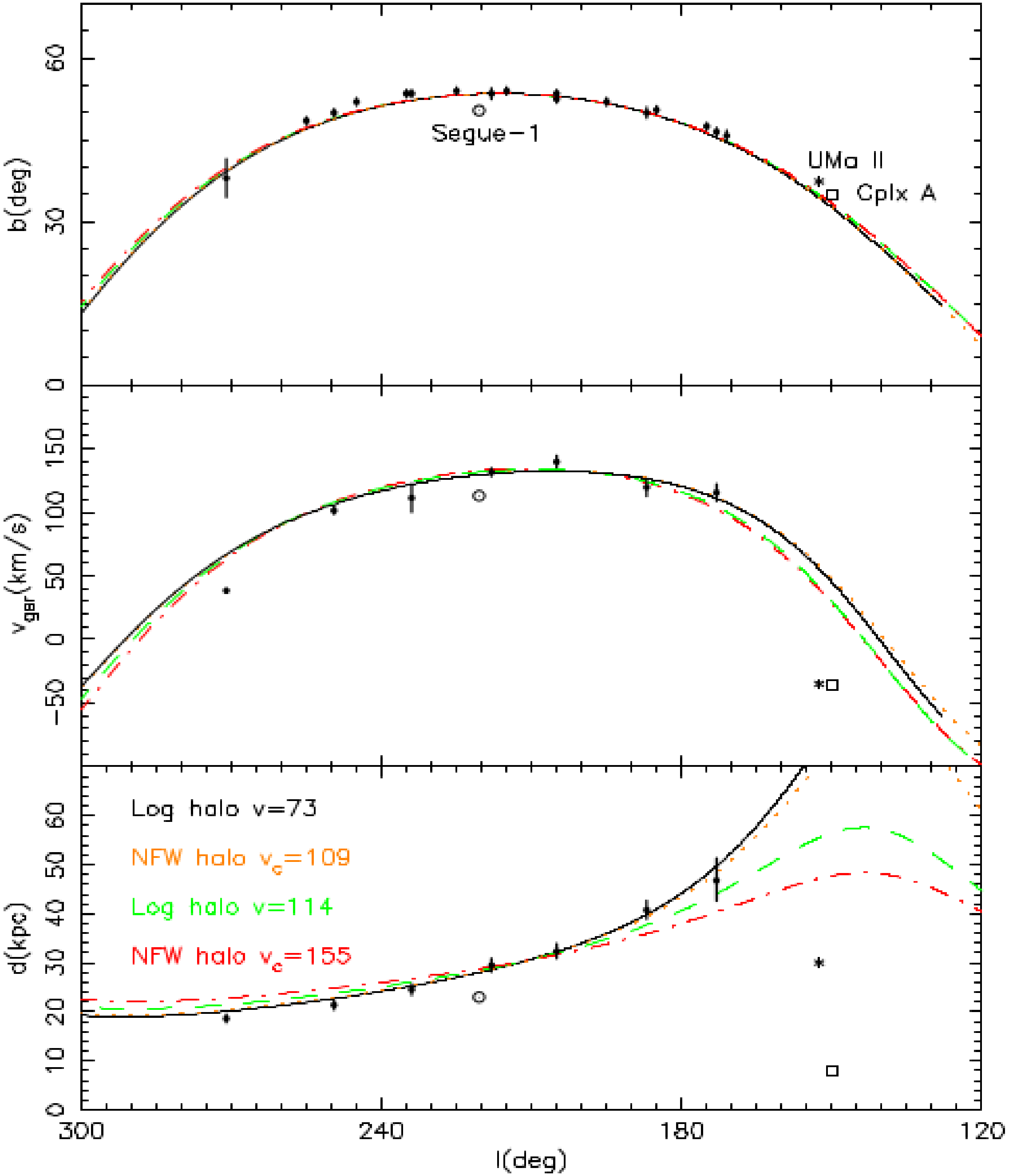
Newberg et al. 2010



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!

How much dark matter is there in ultrafaint dwarf galaxies?

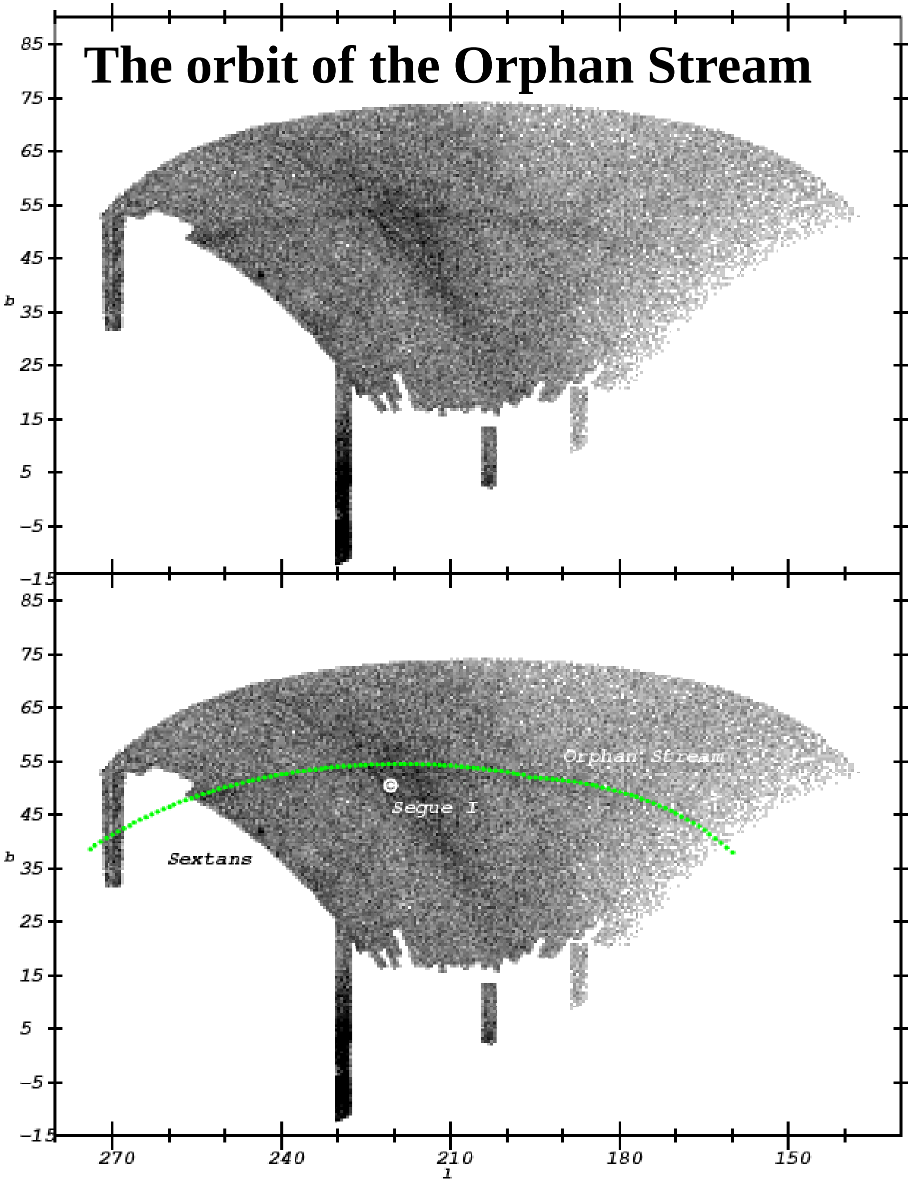
- All dwarf spheroidal galaxies, including ultrafaint dwarf galaxies, have ~10^7 M_{Sun} of mass enclosed within the central 300 pc, independent of the dwarf galaxy's luminosity (Mateo et al. 1993, Gilmore et al. 2007, Strigari et al. 2008).
- The dark matter density profile is the same for all dwarf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

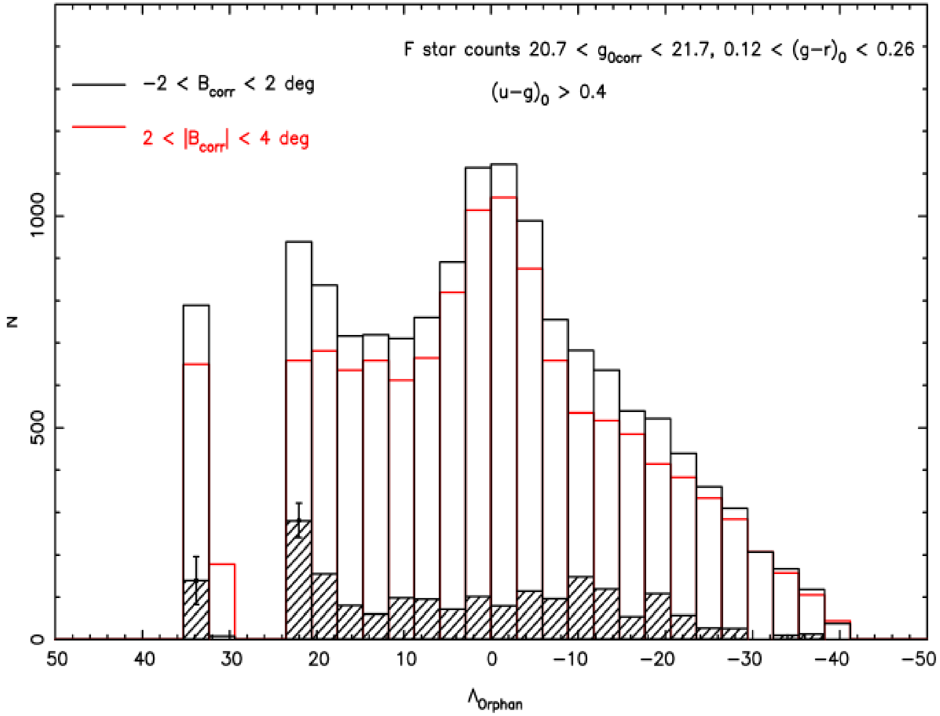
How much dark matter is in SEGUE 1?

M/L Ratio	
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

The orbit of the Orphan Stream

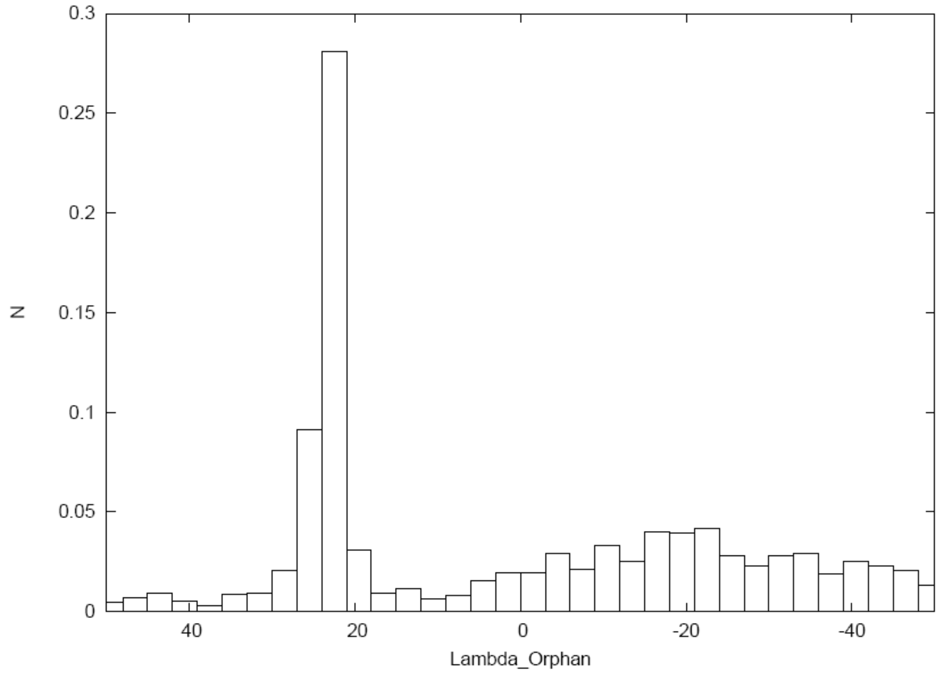


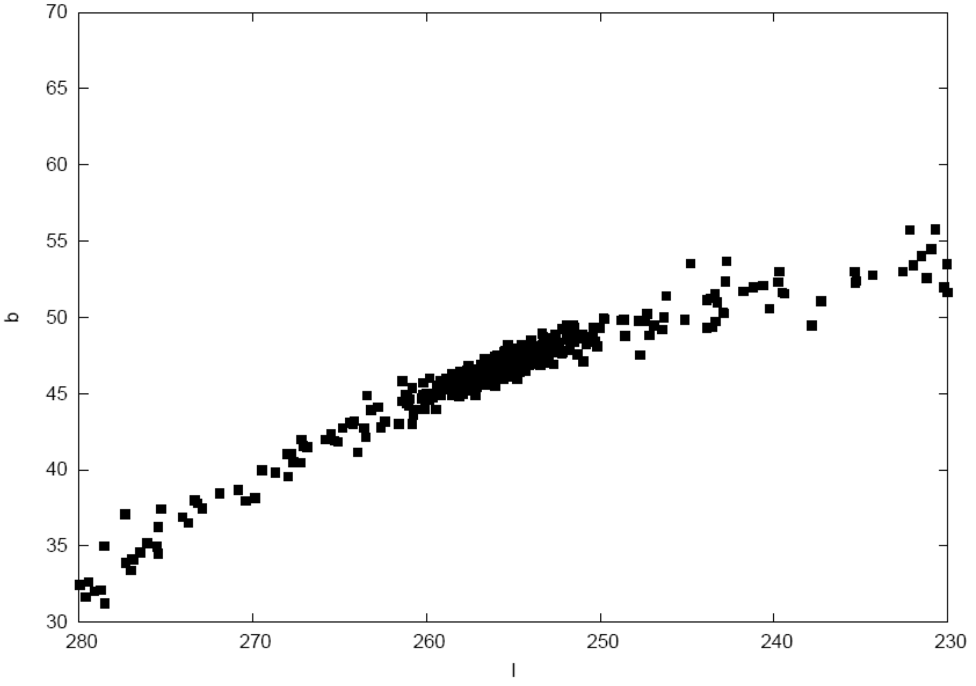
Newberg et al. (2

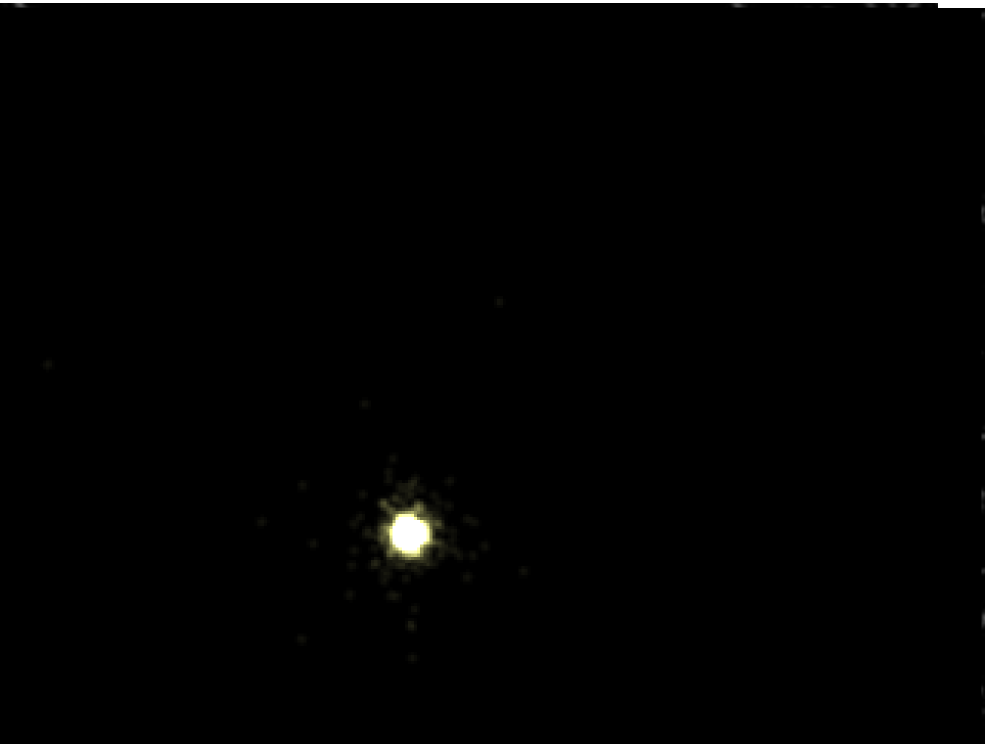


Density of F turnoff stars at the correct distance to be members of the Orphan Stream (left). Density of F turnoff stars within two degrees of the position of the Orphan Stream (above).

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).

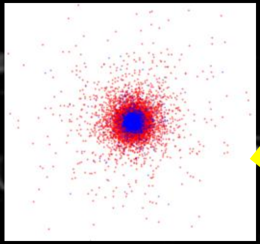




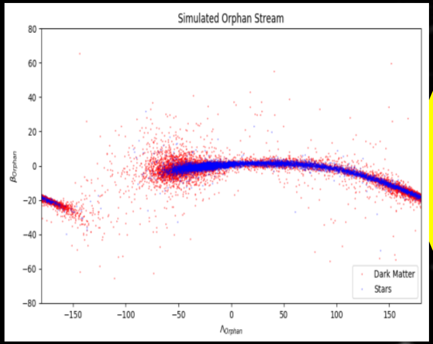


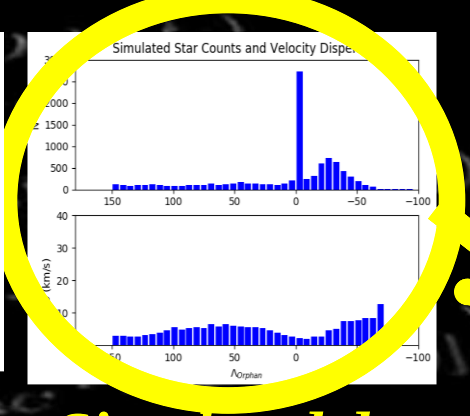
Sample 20,000 particle (sub-sampled above) N-body simulations of the tidal disruption of the Orphan Stream. In an analytic potential of the Milky Way We fit only the evolution time and the two-component Plummer sphere parameters for the dwarf galaxy, by comparing a histogram of the stellar density along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

Sidd Shelton

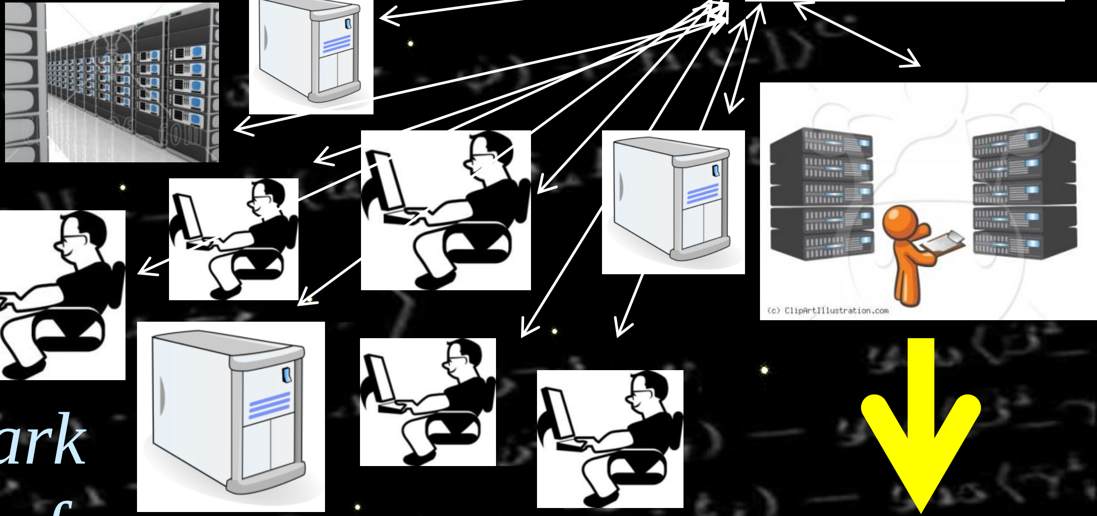


3.95 Gyr





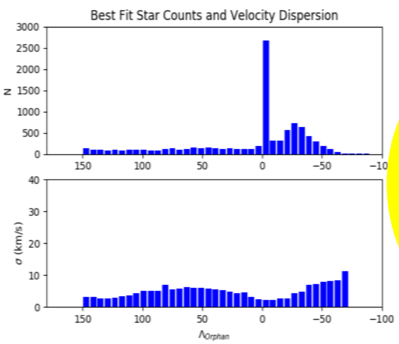
Simulated data

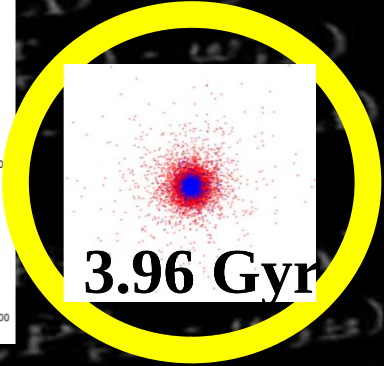


MilkyWay@home

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





3.96 Gyr

The progenitor has four parameters: the scale radius and mass of the baryons, and the scale length and radius of the dark matter.

Progenitor results for simulated tidal stream:

Input dwarf galaxy

- baryons: 0.2 kpc, $2.7x10^{6}\ M_{\odot}$
- dark matter: 0.8 kpc, $1.1x10^{7}\ M_{\odot}$

Output dwarf galaxy

- baryons: 0.2 kpc, $2.7x10^{6}\ M_{\odot}$
- dark matter: 0.9 kpc, $1.5x10^{7}\ M_{\odot}$

Very preliminary results for real data:

- baryons: 0.10 kpc, $2.9x10^{5}\ M_{\odot}$
- dark matter: 0.11 kpc, $2.9x10^{7}\ M_{\odot}$

The mass everyone expected, plus mass follows light..

Future Work:

- Exhaustive exploration of sources of error
- Effect of not knowing the exact MW density model
- Effect of LMC-MW merger
- 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.

What I hope you have learned from this lecture

- Reference Vera Rubin for the discovery of flat rotation curves in galaxies, and touched off the search for dark matter.
- There is a lot of astronomical information still needed to constrain structure formation.
- The Milky Way is a dynamic galaxy with a large amount of gravitational interaction going on. The dark matter (probably) not in equilibrium.
- Efforts to measure the density distribution of dark matter in the Milky Way and in dwarf galaxies is possible, but very difficult and we are working on it.
- Dark matter (probably) dominates dwarf galaxies.