

Experience WorldWide Telescope, free, at worldwidetelescope.org



The Bones of the Milky Way

Alyssa A. Goodman (Harvard-Smithsonian Center for Astrophysics)

with collaborators at (alphabetically by institution):

Boston University: James Jackson

Caltech: Jens Kauffmann

Harvard - Smithsonian: Christopher Beaumont, Michelle A. Borkin, Cara Battersby, Thomas M. Dame

ITA, Heidelberg: Rowan Smith

Max Planck Institute for Astronomy: Thomas Robitaille

U. Munich: Andreas Burkert

U. Virginia: Catherine Zucker

U. Vienna: Joao F. Alves

U. Wisconsin: Robert A. Benjamin

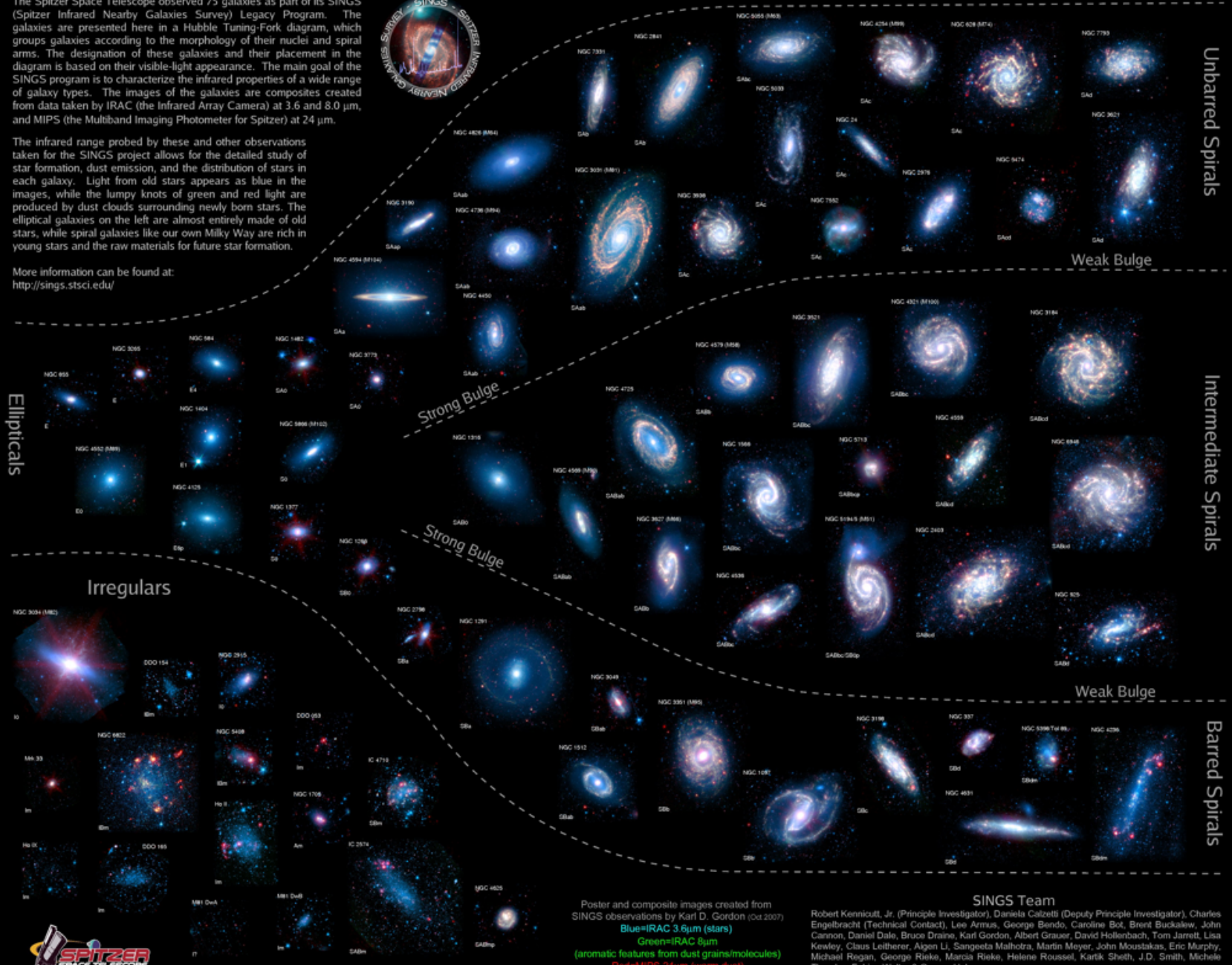
Music: Davis Jerome, Richard Woodhams & The Mozart Orchestra - Oboe Concerto in C Major: II. Adagio, by Sir William Herschel

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork

The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm , and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm .

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.

More information can be found at: <http://sings.stsci.edu>



Ellipticals

Irregulars

Strong Bulge

Strong Bulge

Weak Bulge

Weak Bulge

Unbarred Spirals

Intermediate Spirals

Barred Spirals

Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
 Blue=IRAC 3.6 μm (stars)
 Green=IRAC 8 μm (aromatic features from dust grains/molecules)
 Red=MIPS 24 μm (warm dust)

SINGS Team

Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Algen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou



1936: "The Realm of the Nebulae" by Edwin Hubble

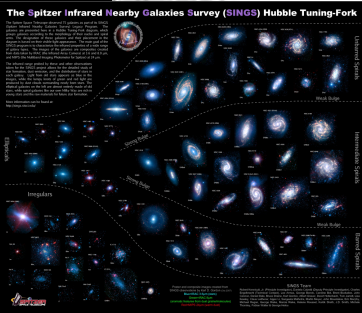
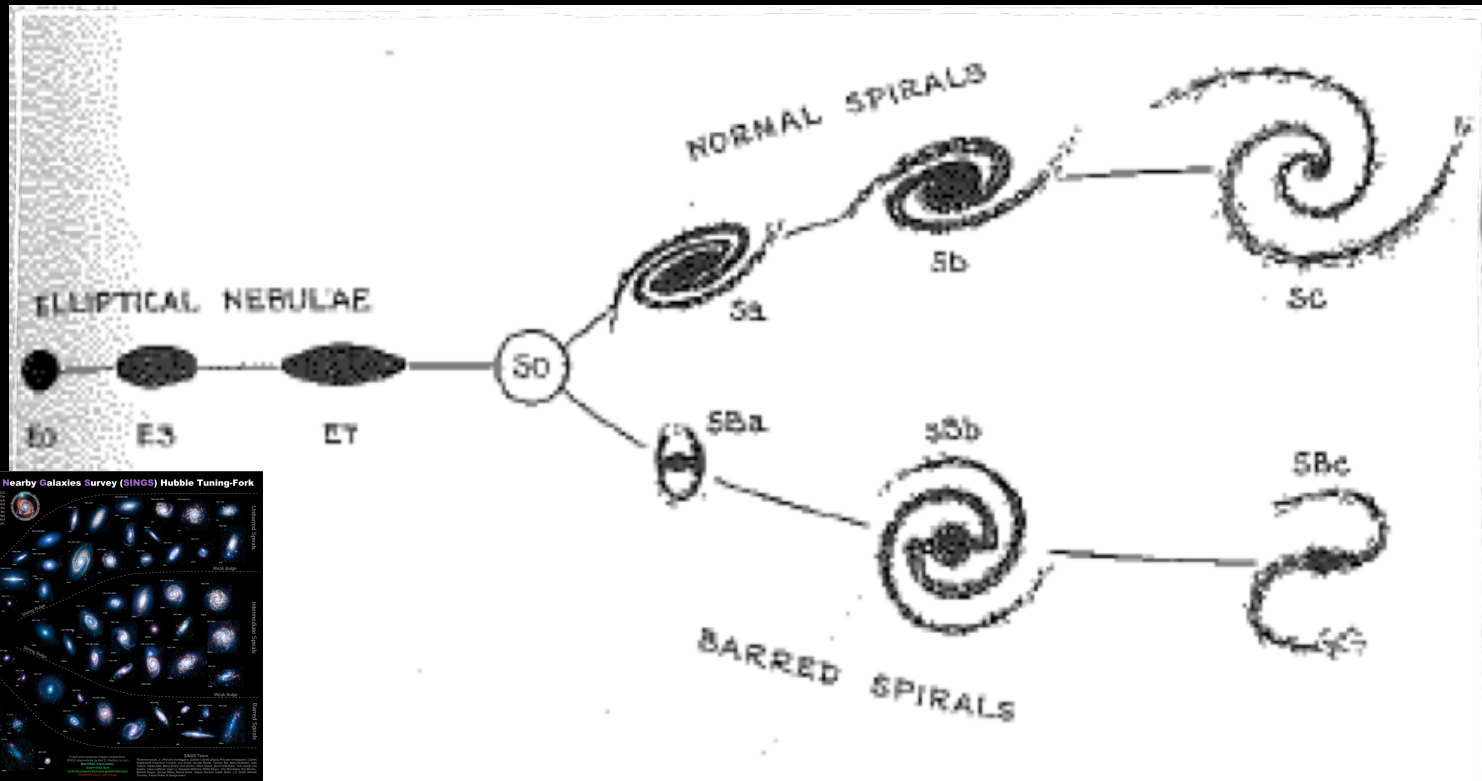


FIG. 1. *The Sequence of Nebular Types.*

The diagram is a schematic representation of the sequences of classification. A few nebulae of mixed types are found between the two sequences of spirals. The transition stage, S0, is more or less hypothetical. The transition between E7 and SB_a is smooth and continuous. Between E7 and S_a, no nebulae are definitely recognized.

“Hubble’s Tuning Fork Diagram”



**The Shapley-Curtis Debate at the
Smithsonian Natural History Museum, 1920**

From National Academy of Sciences,
Smithsonian Institution, Washington, D. C.
(Carl H. Butman, Representative).

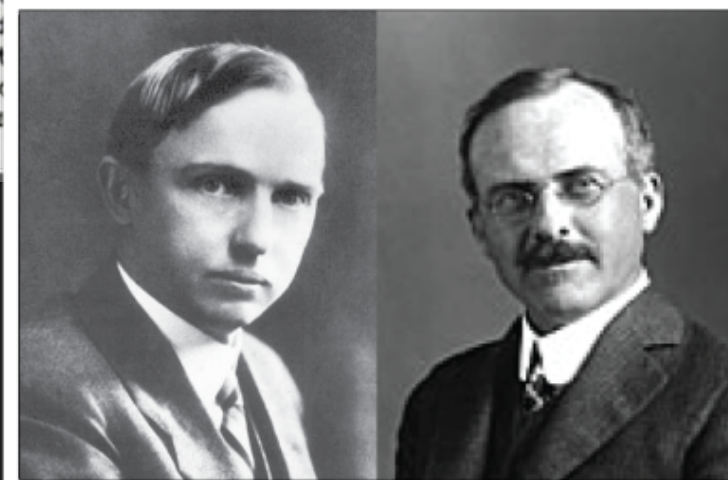
For Release to Afternoon Papers,
Monday, April 26

HOW MANY UNIVERSES ARE THERE?

This evening two California astronomers will discuss the Size of the Universe, and present their views as to whether or not there is only one or several universes, before the National Academy of Sciences, which is now in session in Washington.

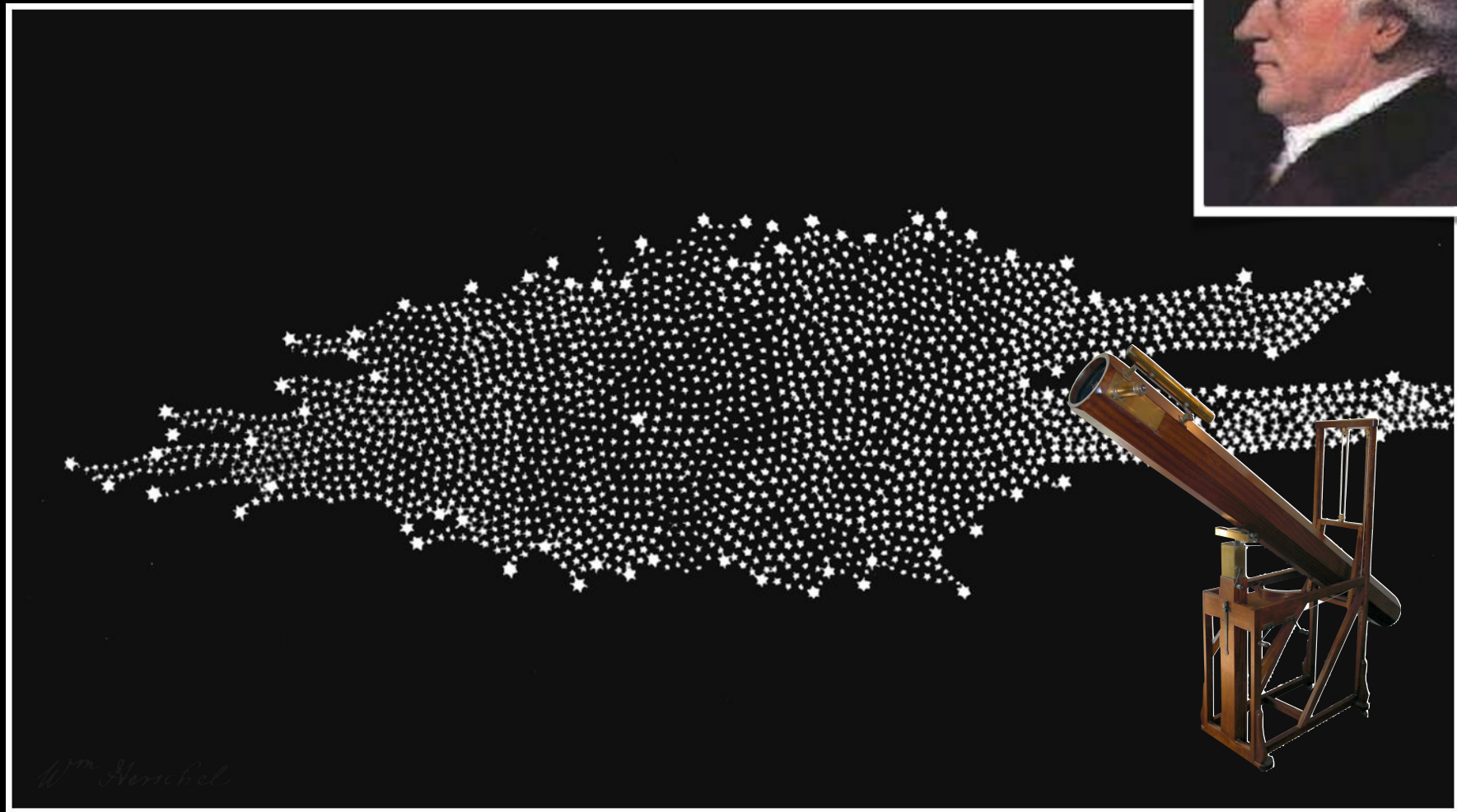
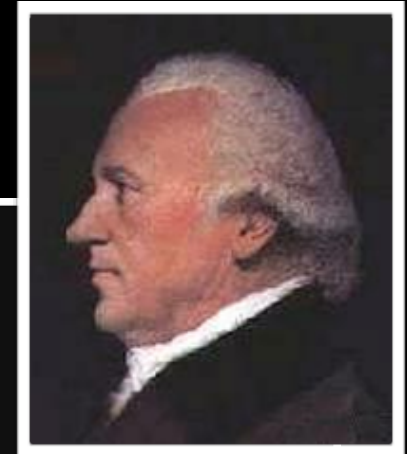
In this public meeting, Dr. Harlow Shapley of the Mt. Wilson Solar Observatory, will discuss recently secured evidence pointing to the dimensions of our galaxy of stars, known popularly as the Milky Way, which he believes to be ten times greater than is held in the older theories concerning the dimensions and compositions of the Milky Way. In other words, he claims that it takes light about three hundred thousands of years to cross from one side to the other of the space occupied by the 3,000,000,000 stars of which our sun is the nearest one. He holds the spiral nebulae, those clam-shell-like cloudy luminous objects seen by great telescopes, to be inside our system.

Doctor Shapley's views will be followed by the discussion of Doctor Heber D. Curtis of the Lick Observatory, who will defend the older view that our Milky Way is approximately of the dimensions suggested by Newcomb, about 30,000 light-years in diameter, with the spiral nebulae regarded as very probably individual galaxies of "island universes", like ours. Thus there may be a million other universes each having 3,000,000,000 stars. Inhabitants of numerous universes would see our Milky Way as a spiral nebula. The lectures of these two learned astronomers will be followed by a general discussion of the auditors present who are interested in the development of this new field in scientific research.

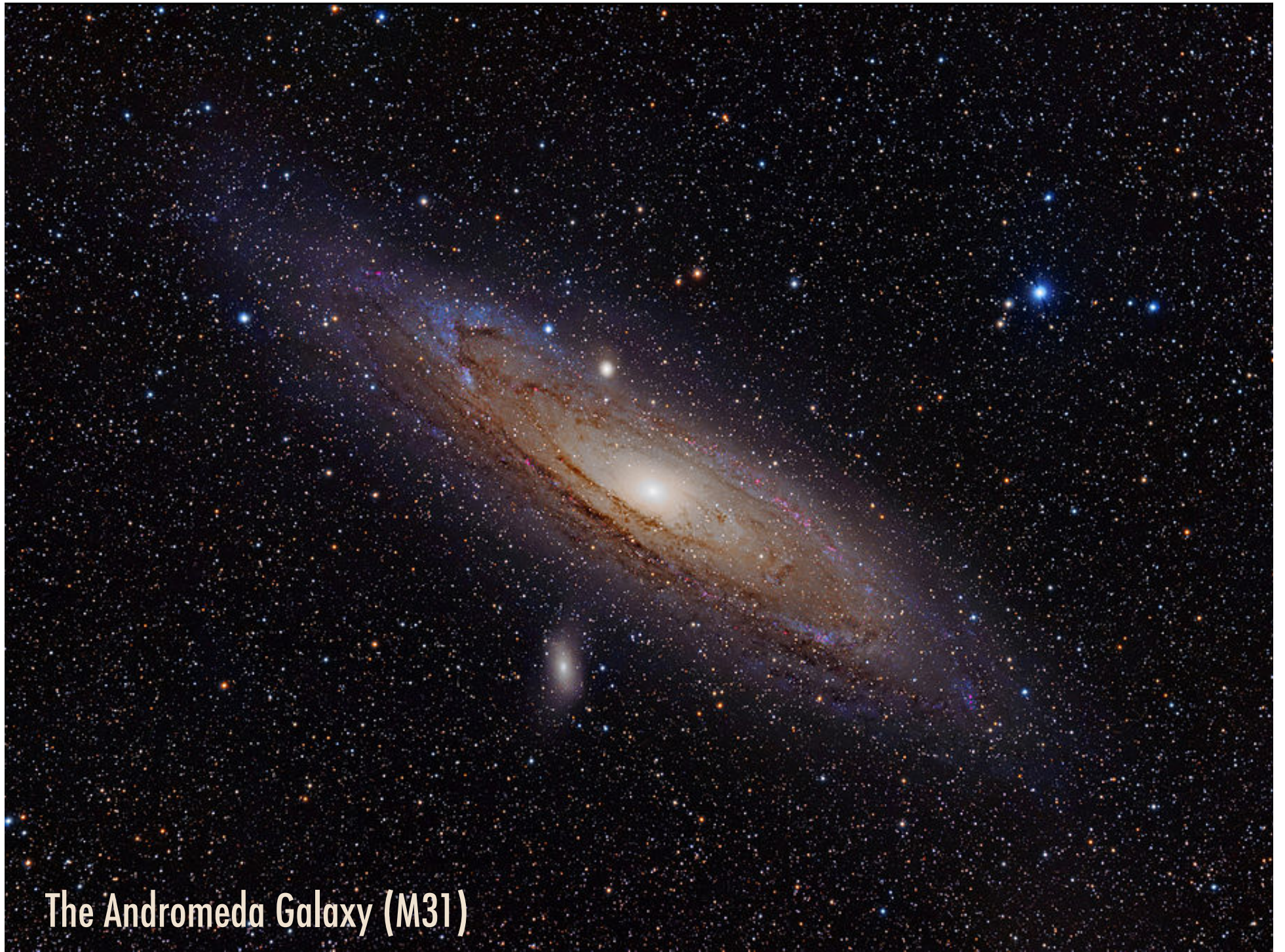


The Shapley-Curtis Debate at the
Smithsonian Natural History Museum, 1920

William Herschel's Milky Way Galaxy in 1781



More info at <http://cosmology.carnegiescience.edu/timeline/1781> (Herschel); <http://cosmology.carnegiescience.edu/timeline/1920> (Shapley-Curtis)



The Andromeda Galaxy (M31)



The Andromeda Galaxy (M31)



The Andromeda Galaxy (M31)

Stars your
Eyes would
See

Optical

Dust +
Dying Stars

"Glowing"
Dust

Infrared

For fun...

Composite

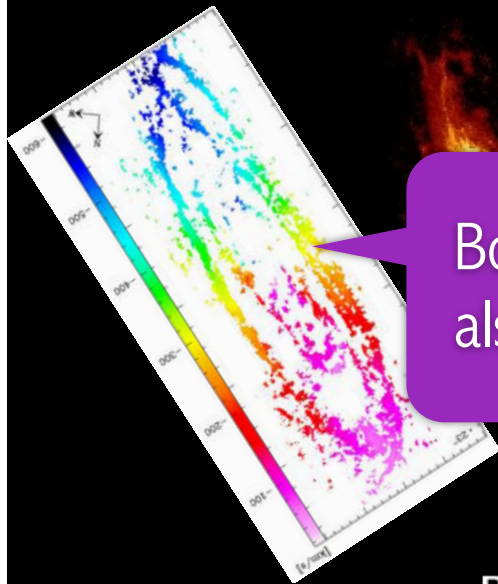
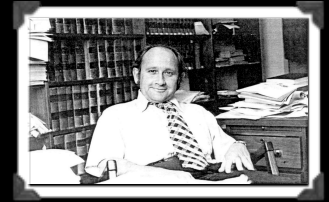
Infrared & X-rays

"Dying"
Stars

X-rays

The Andromeda Galaxy (M31)

Gas, Dust, Stars at Many Wavelengths



Bonus: “spectral line mapping,” especially in the radio, also gives velocity, thanks to the Doppler effect

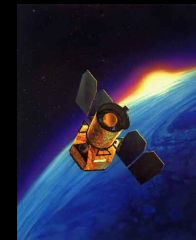
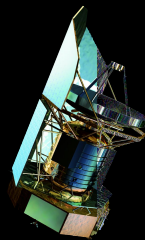
Radio

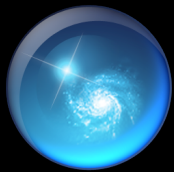
Infrared

Visible

Ultra-violet

X-ray





Microsoft® Research WorldWide Telescope

[demo]

worldwidetelescope.org

The screenshot shows the WorldWide Telescope interface. At the top, there are navigation tabs: 'Explore', 'Guided Tours', 'Search', 'View', and 'Settings'. Below these is a 'Collections' bar with thumbnails for 'All-Sky Surveys', 'Digitized Sky Survey', 'VLSS: VLA Low-frequency Sky Survey', 'WMAP ILC 5-Year Temperature Anisotropy Map', 'SFD Dust Map (Infrared)', 'IRIS: Improved Resolution', '2MASS: Two Micron All Sky Survey', and 'Hydrogen Alpha Filter'. The main view is a 3D sky with a central galaxy. A 'Finder Scope' window is open, displaying details for NGC224, including its classification as a 'Spiral Galaxy in Andromeda' and various astronomical coordinates. At the bottom, there is a 'Look At' dropdown menu set to 'Sky', an 'Imagery' section with a 'Digitized Sky Survey' thumbnail, and a 'Context bar' showing thumbnails for 'NGC221' and 'M31'. A 'Context globe' is also visible, showing the current field of view on a celestial sphere.

Seamlessly explore imagery from the best ground and space-based telescopes in the world

Expert led tours of the Universe

Control time to study how the night sky changes

View and compare images from across the electromagnetic spectrum

Much more than "just" the sky at night! 3D features can take you to other planets, stars & galaxies.

Finder Scope links to Wikipedia, publications, and data, so you can learn more

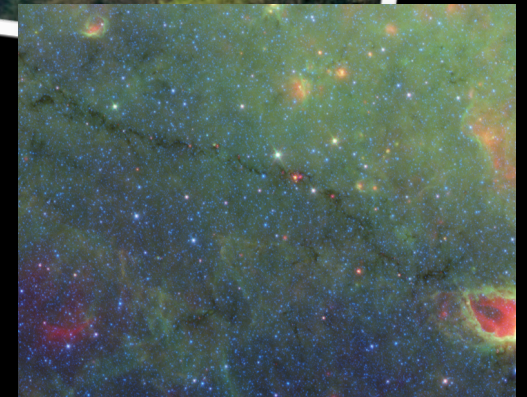
Context bar shows items of interest in current field of view

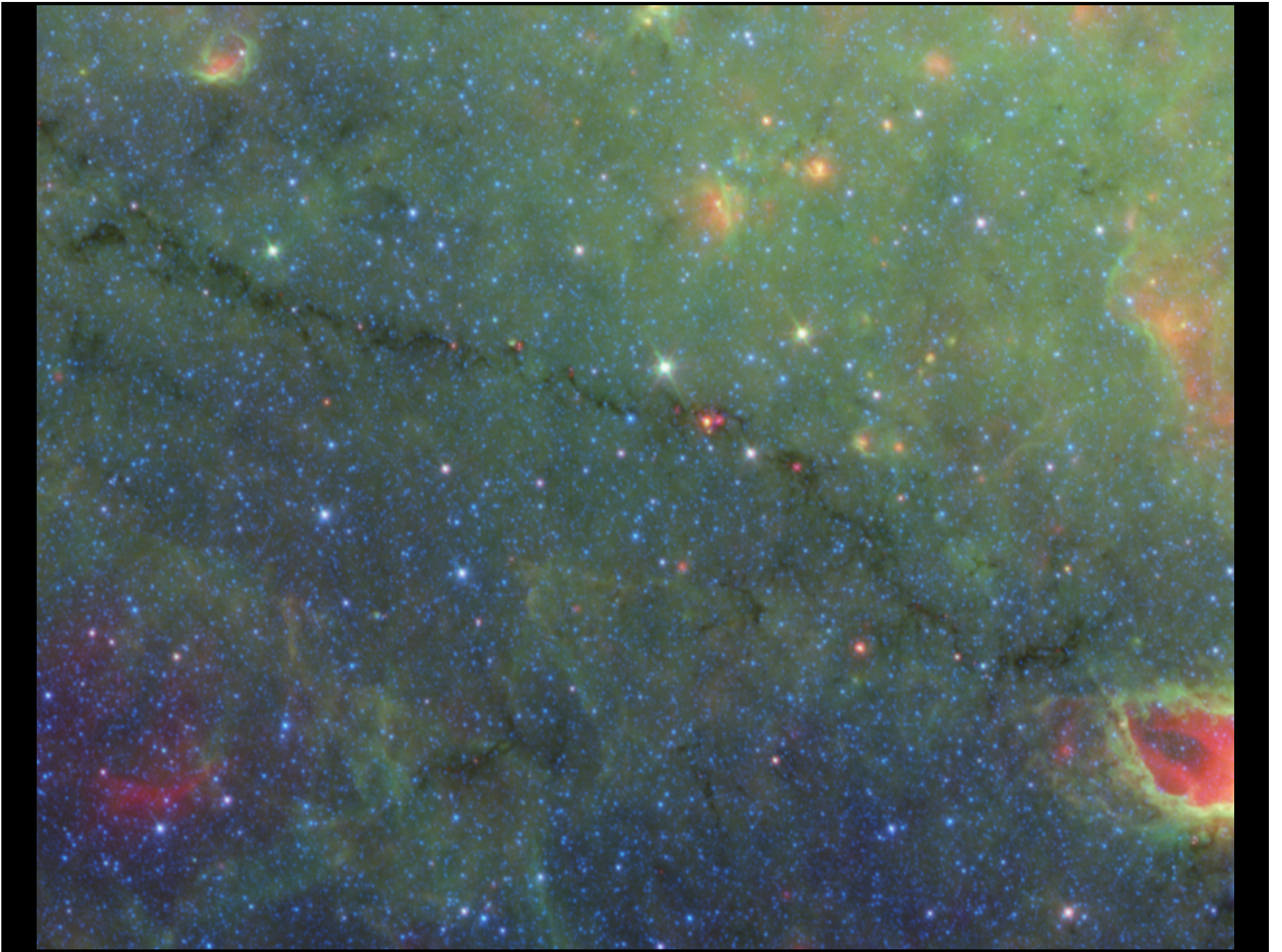
Context globe shows where you're looking.



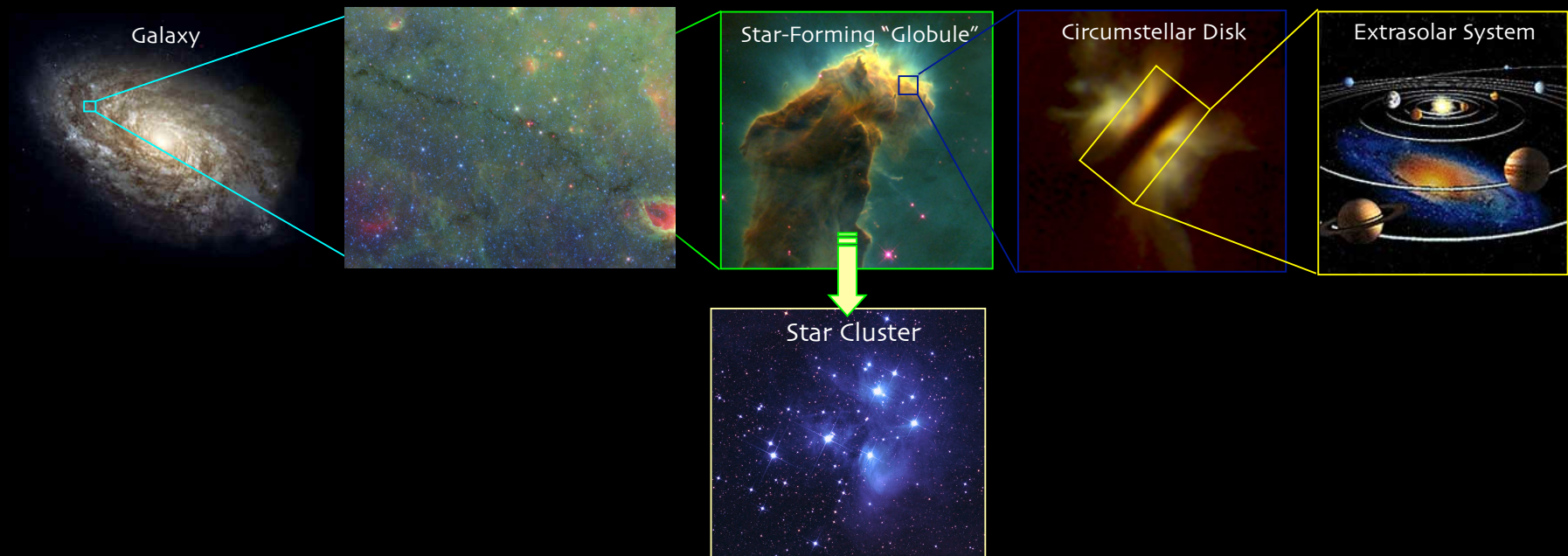
**Once upon a time (2012), in an
enchanted castle (in Bavaria)**

...at a conference about star formation





Star and Planet Formation



**Once upon a time (2012), in an
enchanted castle (in Bavaria)**

...at a conference about star formation

QUESTION *Andi Burkert*: Is Nessie
“parallel to the Galactic Plane”?

ANSWER *no one* immediately knew the
answer!



The Milky Way

“Galactic Plane”



The Milky Way
(Artist's Conception)



"Is Nessie Parallel to the Galactic Plane?"



Yes, but why not at Zero of Latitude ($b=0$)?

The image shows a screenshot of the "GLIMPSE | MIPS GAL VIEWER" interface. At the top, there is a header with the NASA logo and the text "GLIMPSE | MIPS GAL VIEWER". To the right of the header are three buttons: "LINK TO CURRENT VIEW", "TOGGLE PINS", and "QUESTIONS?". The main view is a large, rounded rectangular window displaying a dense field of stars in various colors (red, orange, yellow, blue). A horizontal yellow line is drawn across the upper portion of the star field, labeled "b=0". A horizontal white line is drawn across the lower portion of the star field, labeled "b=-0.5 deg". A green dinosaur illustration is positioned in the lower right quadrant of the star field. At the bottom of the viewer window, there is a control bar with a "? IRAC" button, a "IRAC/MIPS" button, and another "?". To the right of these buttons are navigation controls: a zoom in (+) and zoom out (-) button, four directional arrow buttons (up, down, left, right), and a refresh/clock button. A "COORDINATES" label is visible on the right side of the viewer window. At the bottom of the entire image, there is a copyright notice "©2008 Space Science Institute" and a link "back to: alienearths.org/glimpse".

GLIMPSE | MIPS GAL VIEWER

LINK TO CURRENT VIEW TOGGLE PINS QUESTIONS?

$b=0$

$b=-0.5$ deg

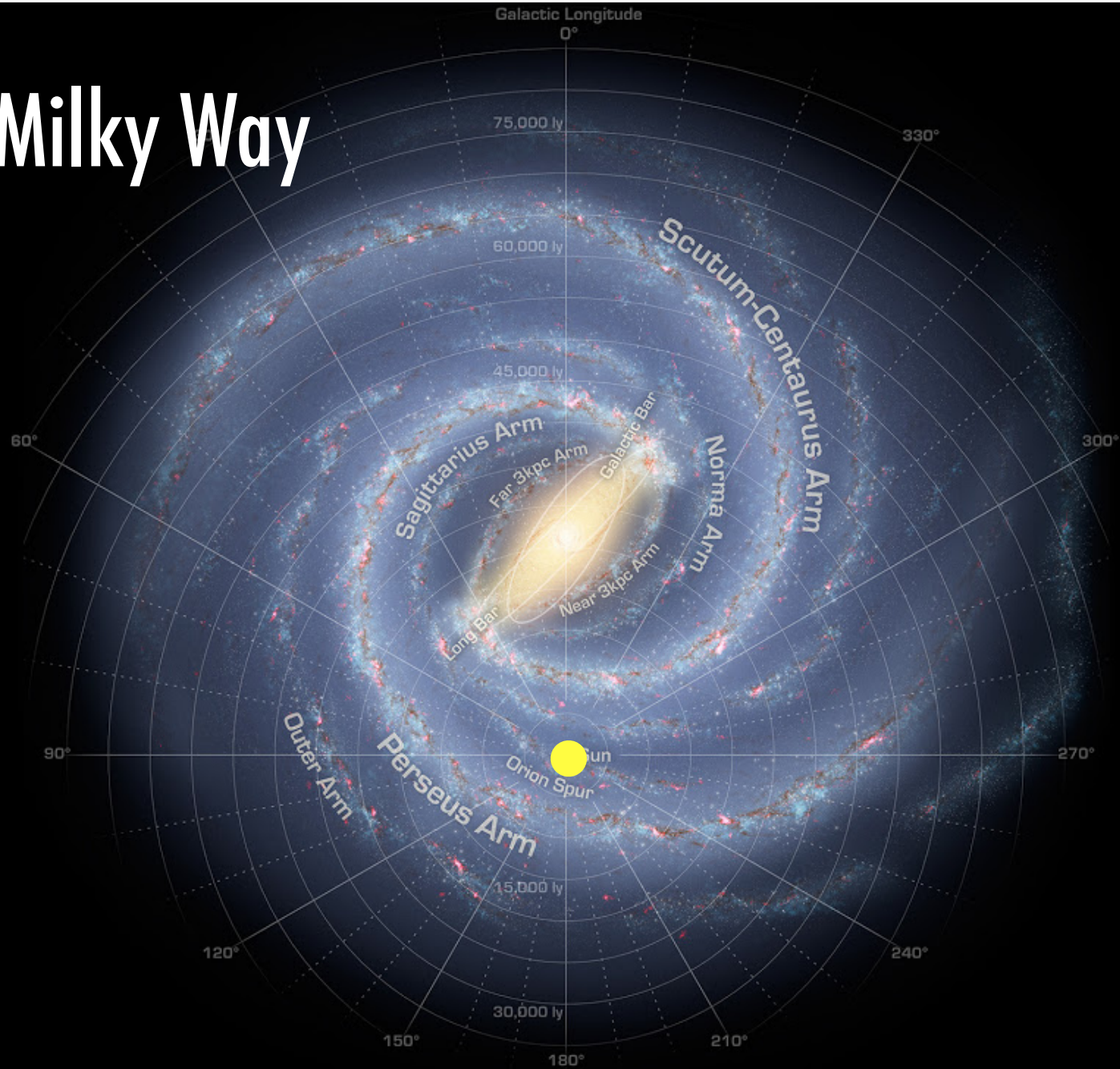
COORDINATES

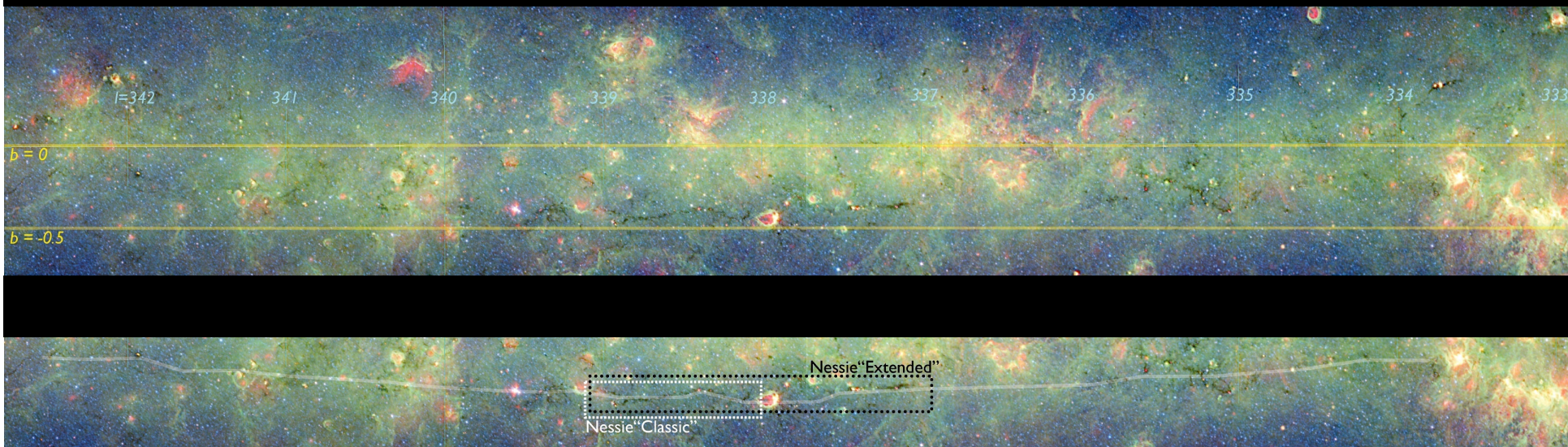
? IRAC IRAC/MIPS ?

©2008 Space Science Institute

back to: alienearths.org/glimpse

The Milky Way





"Nessie Extended"

~500 light years long & 1.5 light years thick

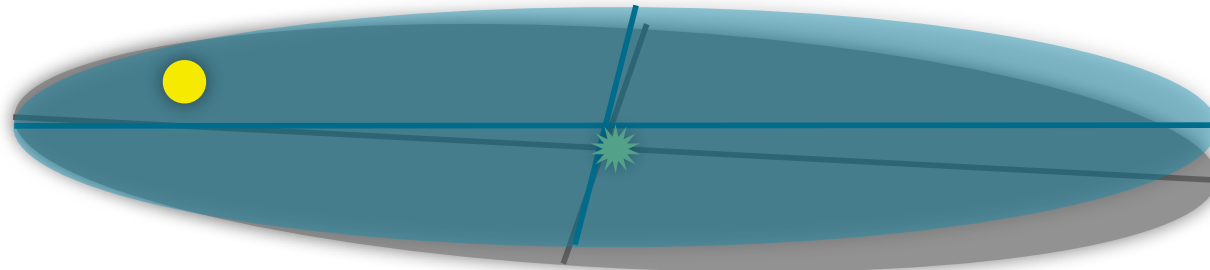
300:1 axial ratio

200,000 solar masses

BUT, why is it near $b=-0.5$, and not $b=0$?

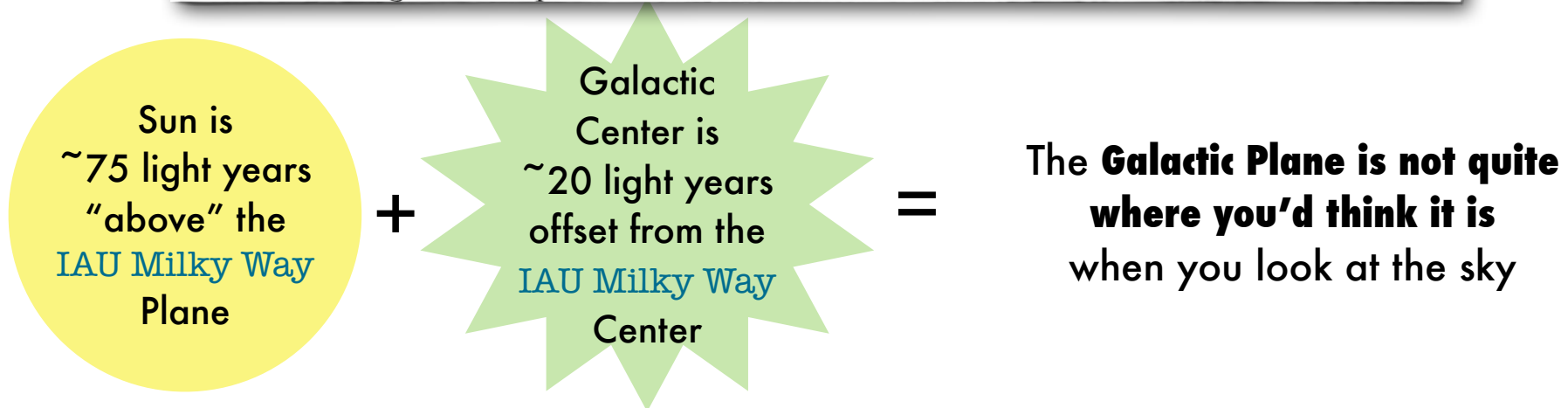
Where are we, really?

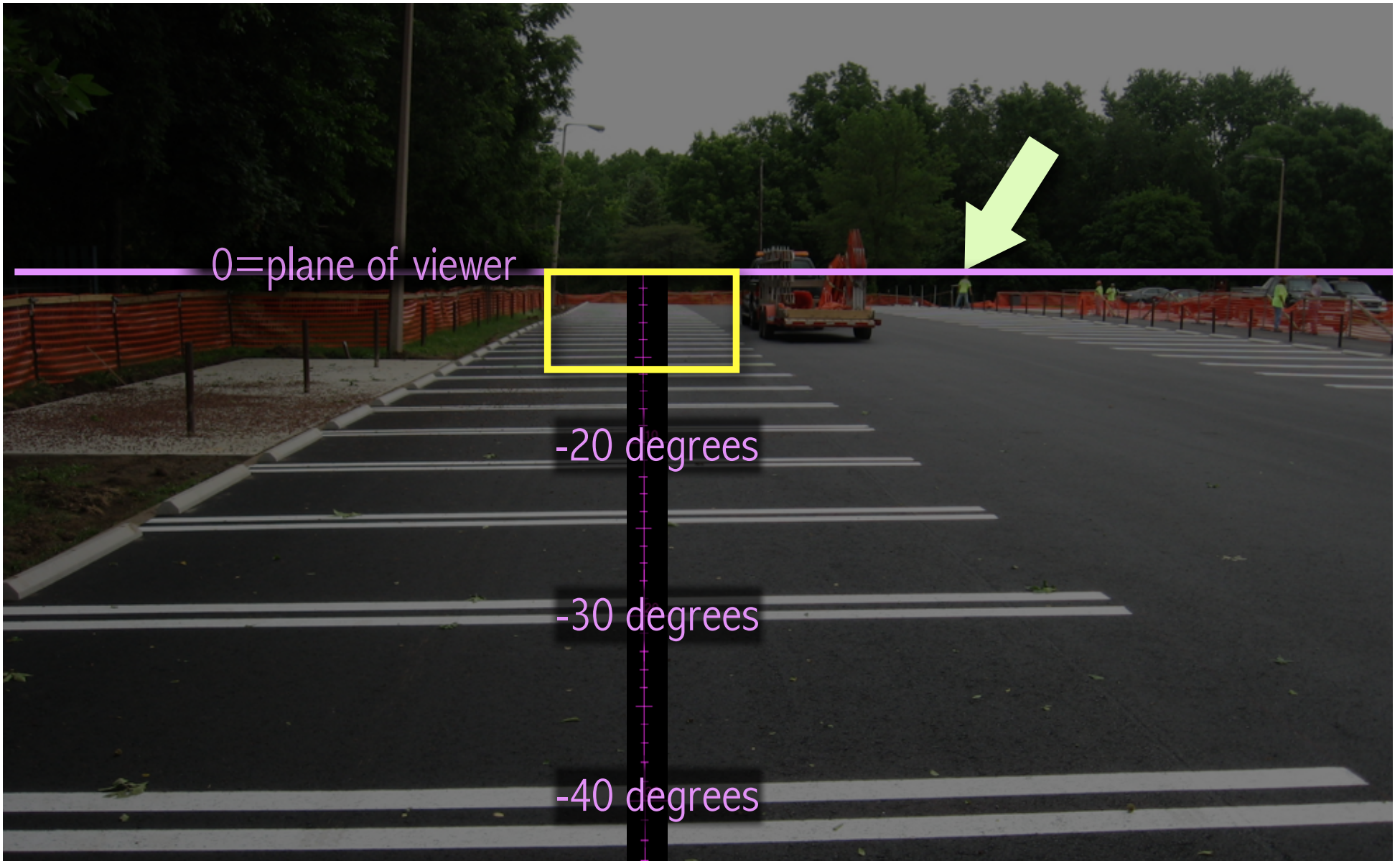
“IAU Milky Way”, est. 1959



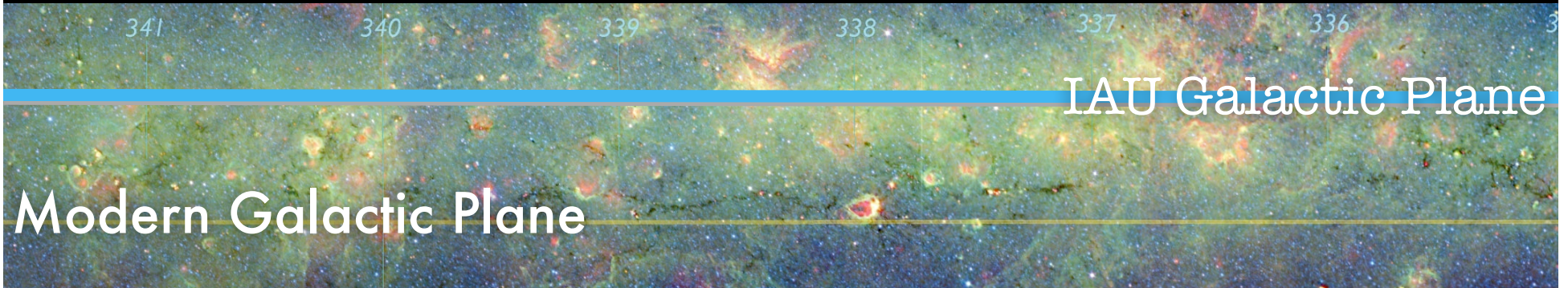
True Milky Way, modern

The equatorial plane of the new co-ordinate system must of necessity pass through the sun. It is a fortunate circumstance that, within the observational uncertainty, both the sun and Sagittarius A lie in the mean plane of the Galaxy as determined from the hydrogen observations. If the sun had not been so placed, points in the mean plane would not lie on the galactic equator. *[Blaauw et al. 1959]*





"Viewed from known elevation, features in a flat plane are found at angular positions given by their distance."



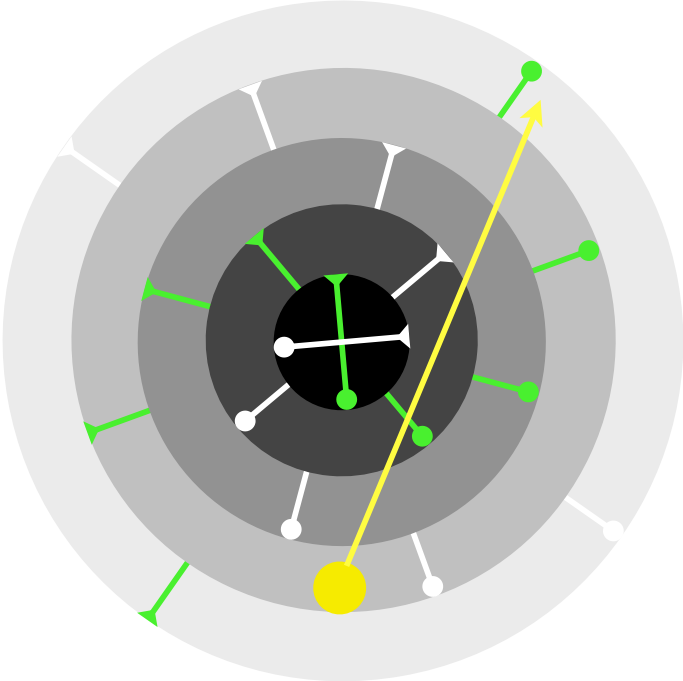
Yes, Nessie is EXACTLY in the Galactic Plane!

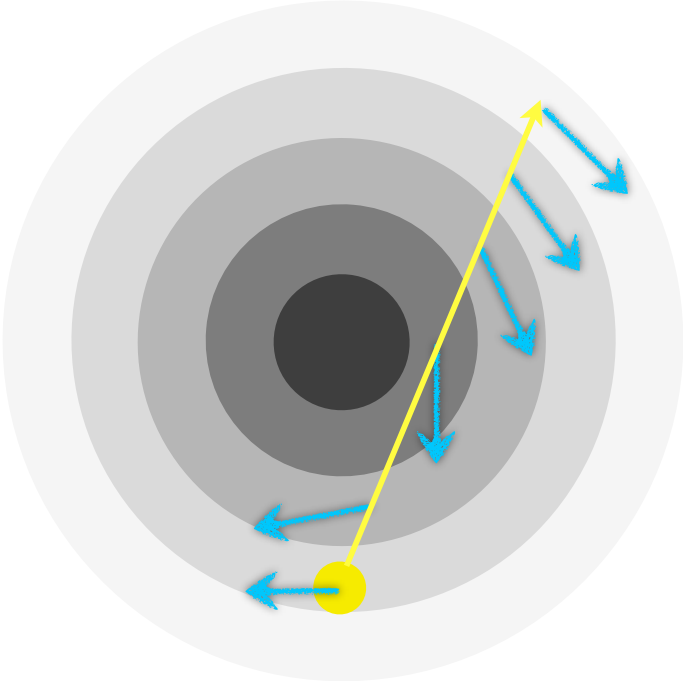
What about its distance?

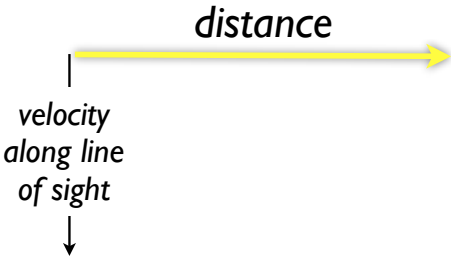
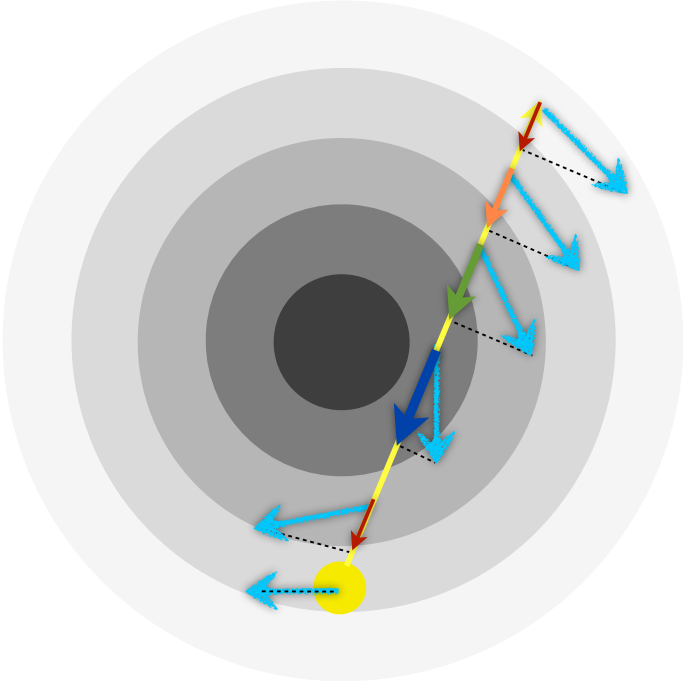
we can use “radial velocities” to estimate distance in a rotating galaxy..

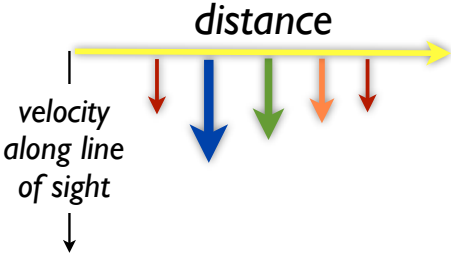
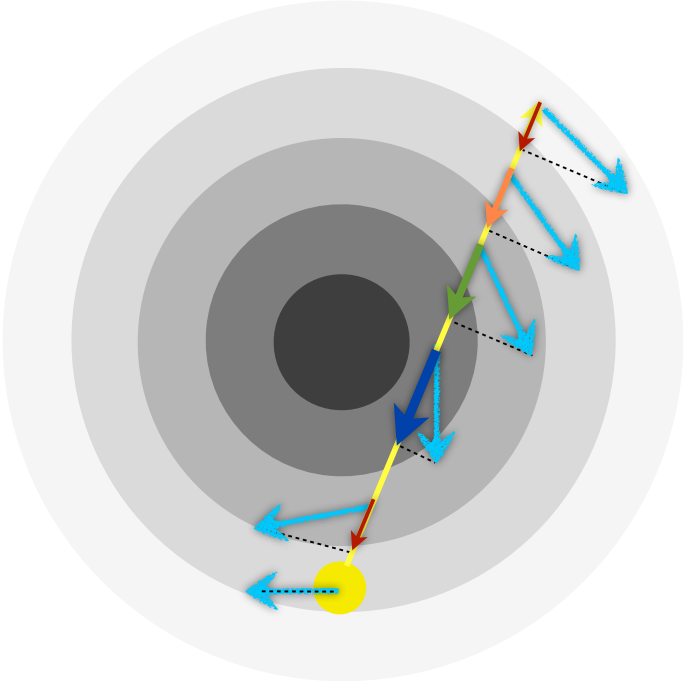
A Rotating (Spiral) Galaxy Observed from its Outskirts...



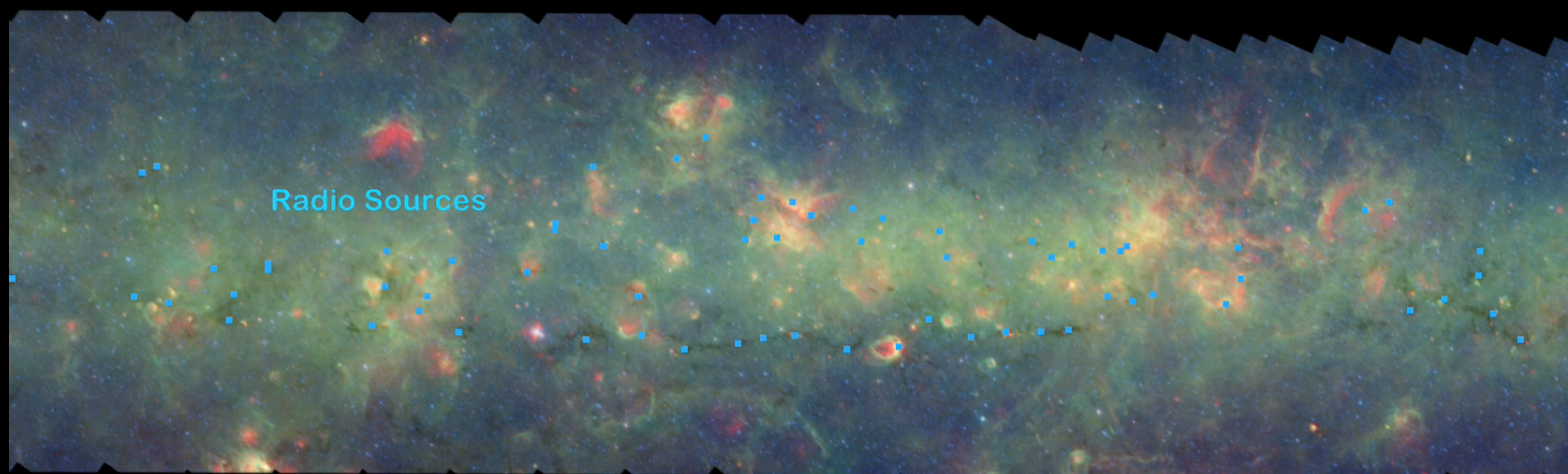




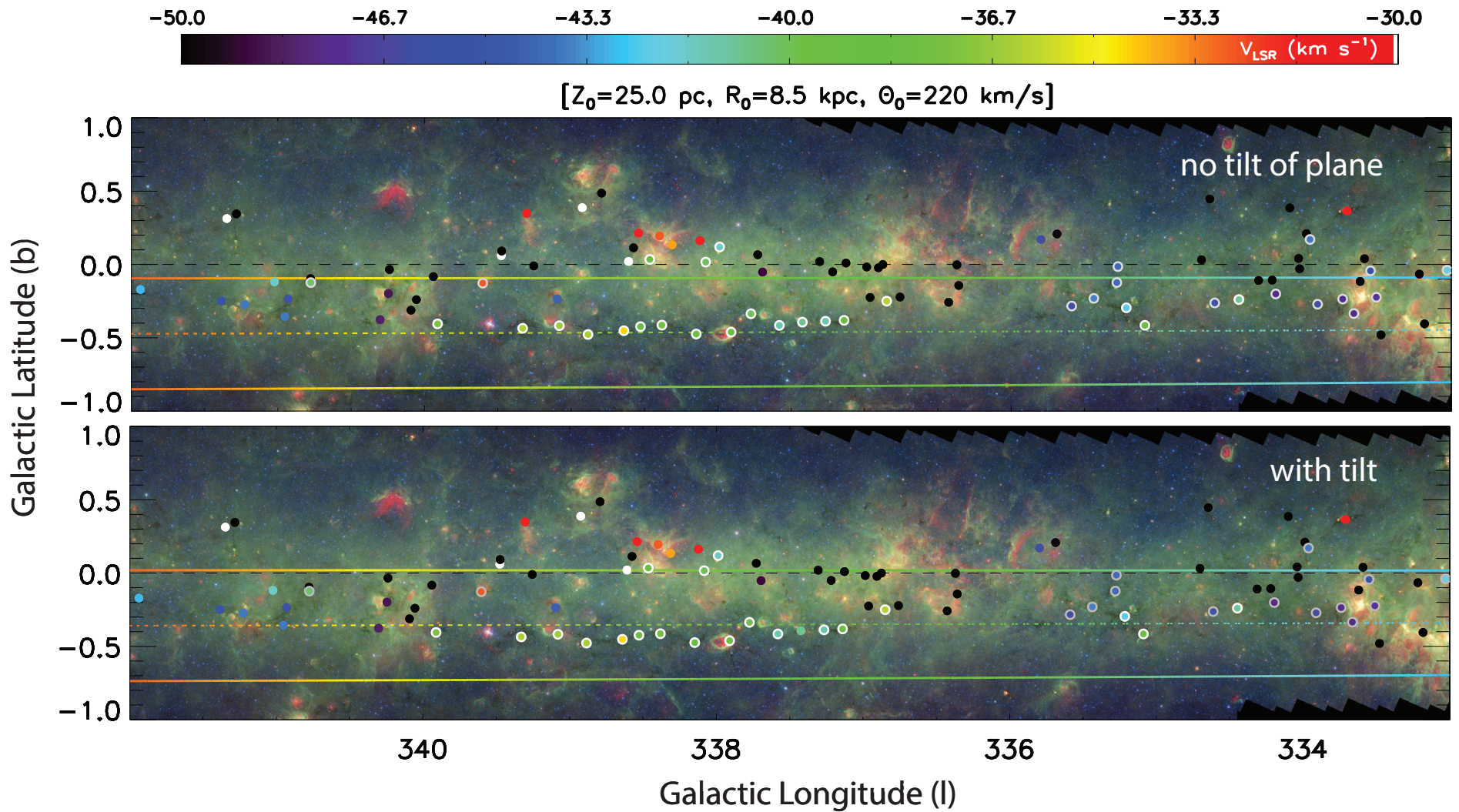


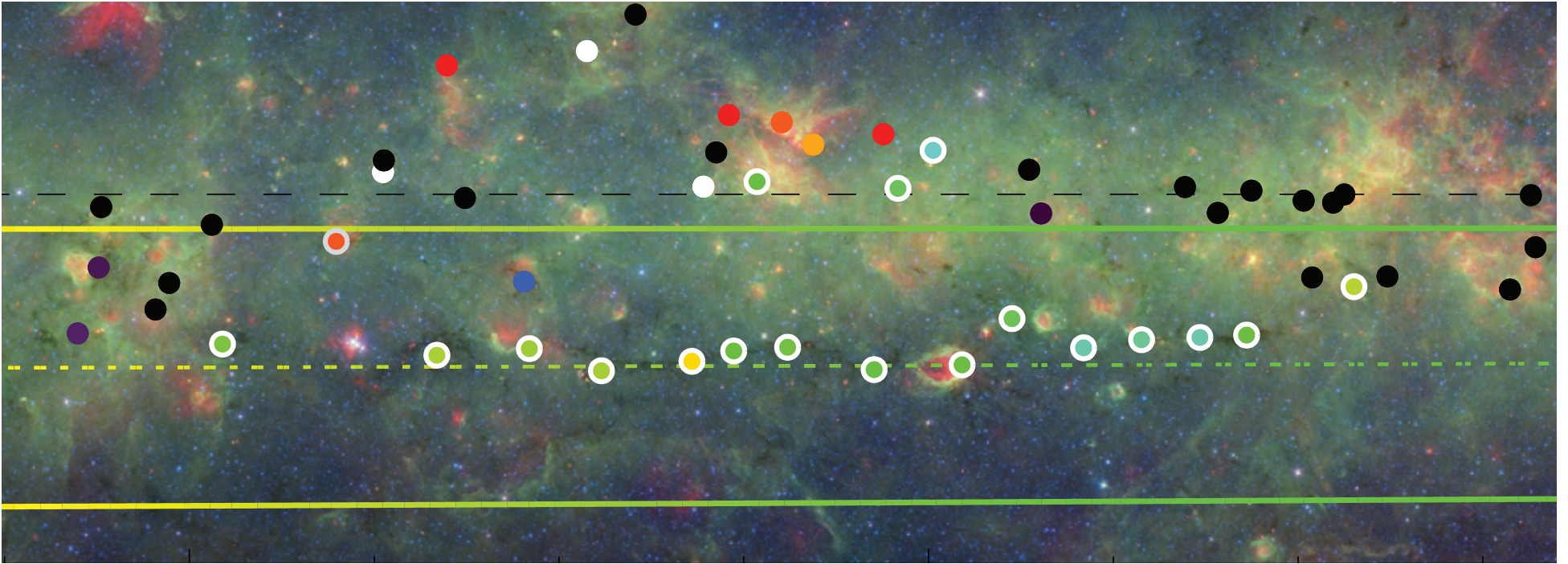


Velocity to Distance



In the plane and at the distance of spiral arm!



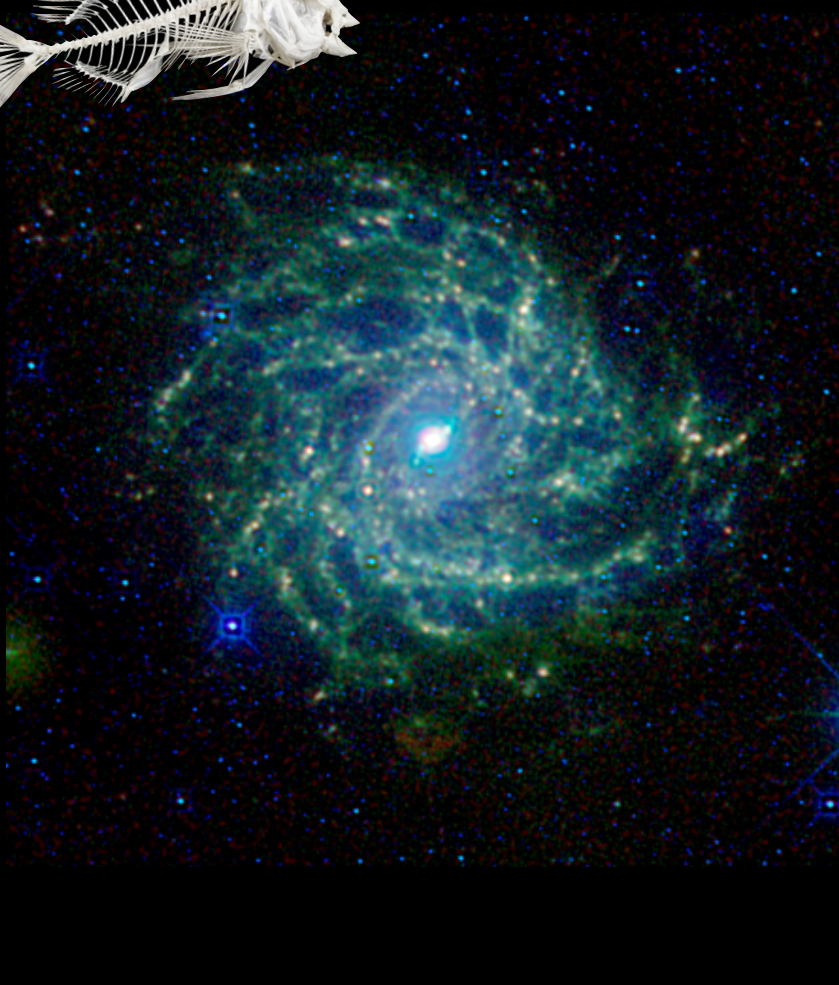
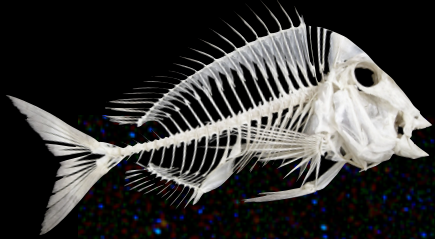


...eerily precisely...

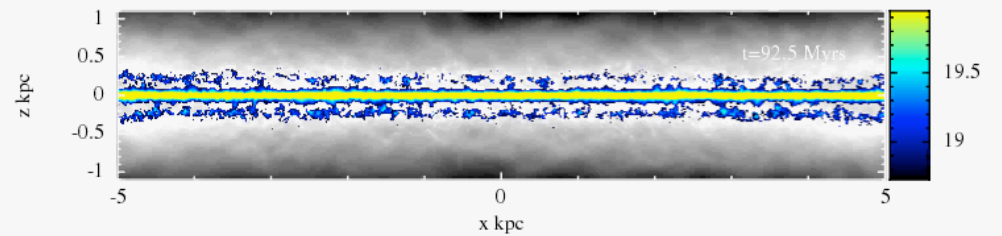
Monster to Bone

There could be 1000s more of these to find...a full skeleton perhaps?

A full 3D skeleton?

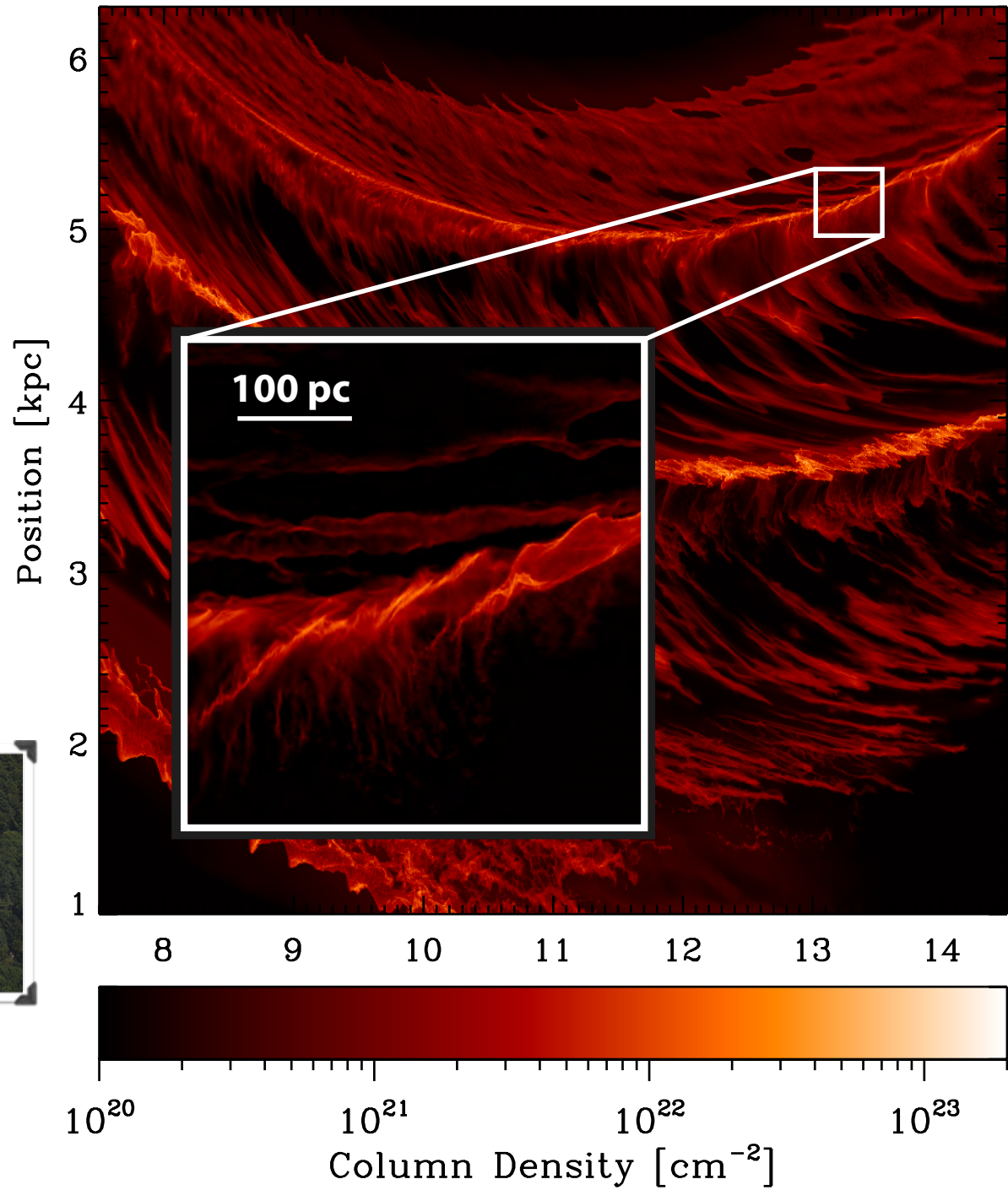


(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas



simulations courtesy Clare Dobbs

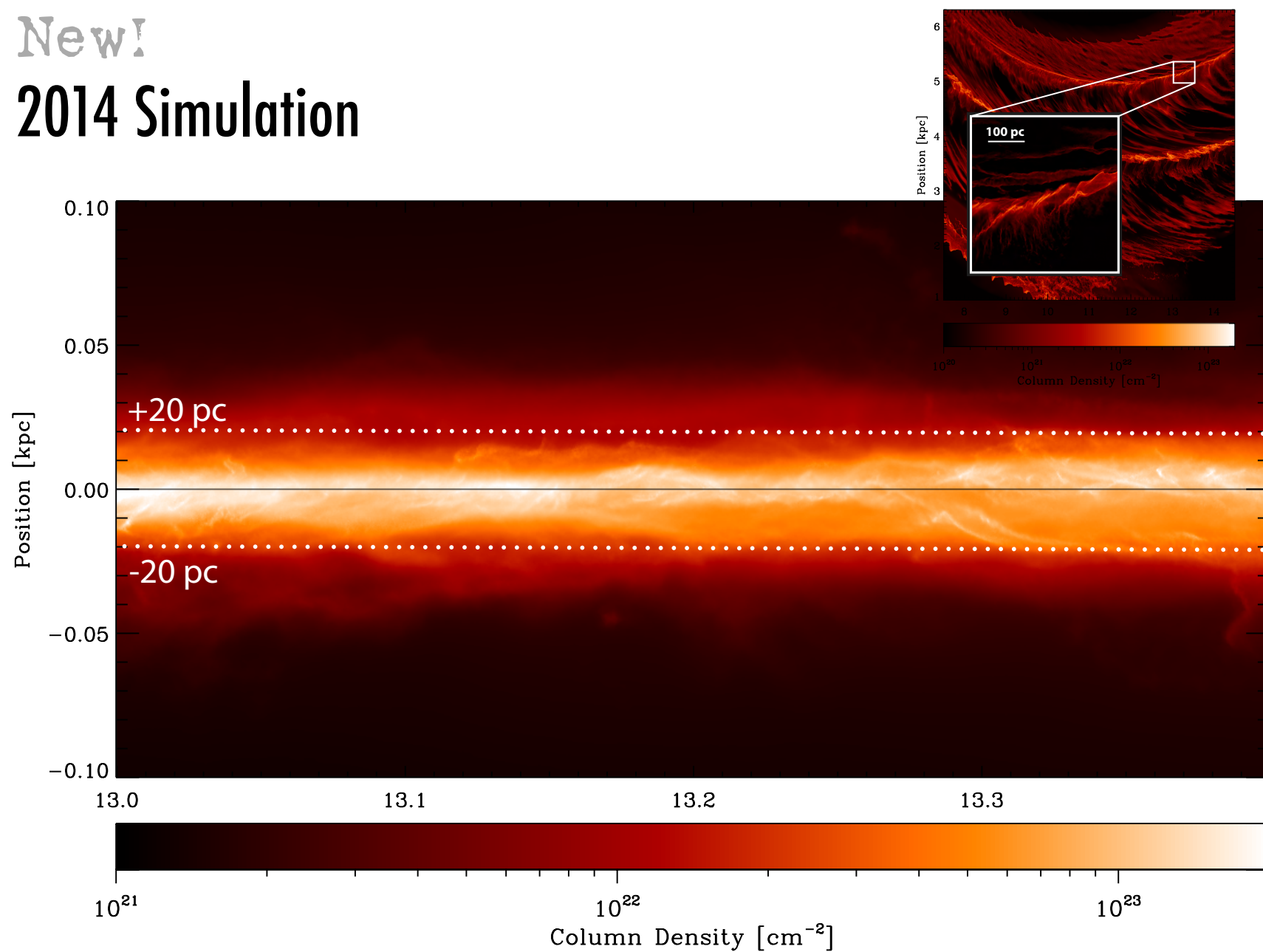
New! 2014 Simulation



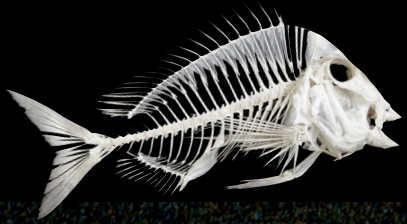
Smith et al. 2014, using AREPO

New!

2014 Simulation



Smith et al. 2014, using AREPO

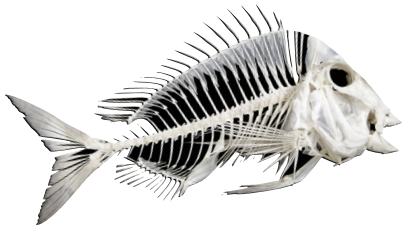


Can we find more bones?

A Tour of Possible Milky Way Bones
(images show Spitzer MIPS GAL overlain on optical image;
dotted lines show projected sky position of Milky Way spiral arms)
Alyssa Goodman
January 2014

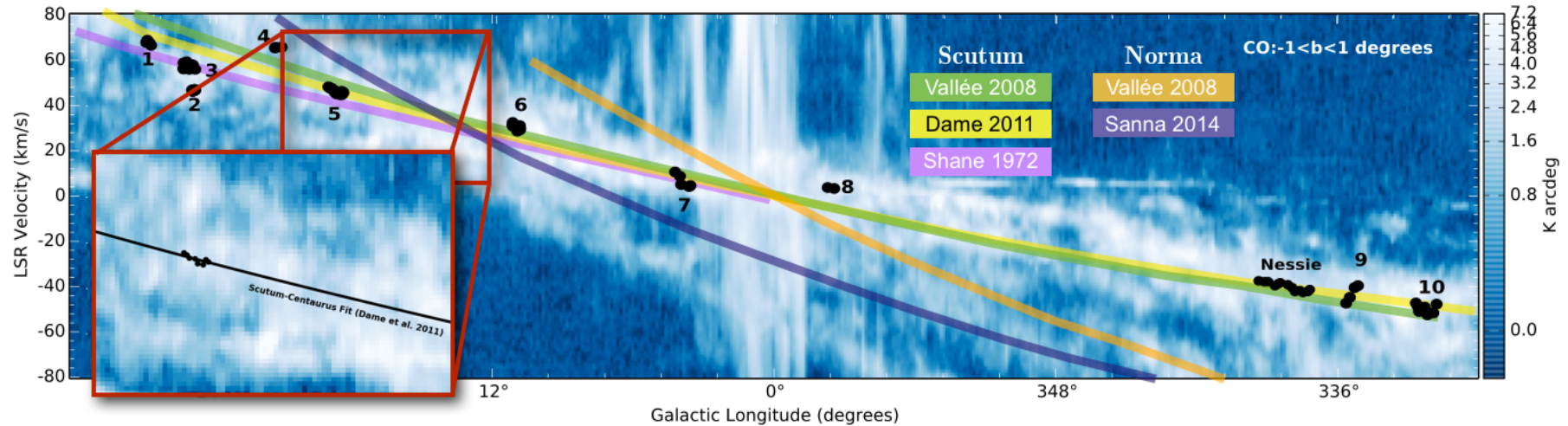
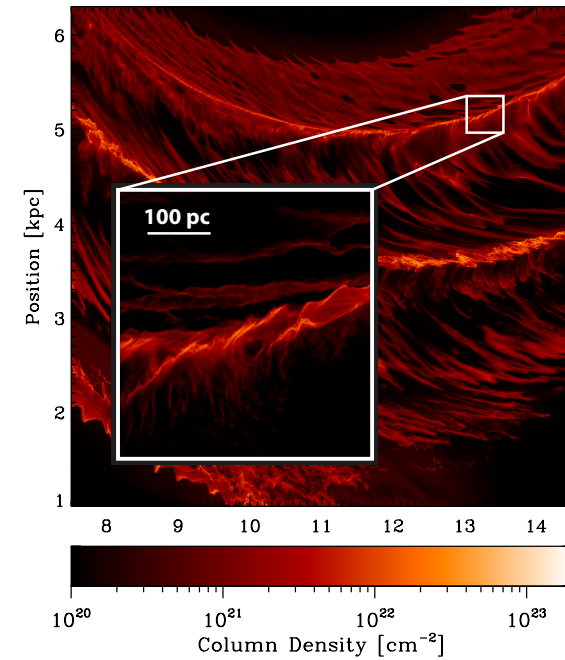


[demo]



Short Answer: Yes

Both on the sky, and along the line of sight (so in “3D”), we find “bones” in the right places to give a detailed skeleton.





Longer Answer: (Also Yes).

Au|thorea

FEATURED ARTICLES ABOUT PLANS BLOG

PUBLIC ROUGH DRAFT Index Settings Fork Quickedit Word Count

The Milky Way Skeleton

Catherine Zucker, Cara Battersby, Alyssa Goodman

1 Abstract

Recently, Goodman et al. (2014) argued that a very long, very thin infrared dark cloud "Nessie" lies directly in the Galactic mid-plane and runs along the Scutum-Centaurus arm in position-position-velocity space as traced by low density CO and high density NH₃ gas. Nessie was presented as the first "bone" of the Milky Way, an extraordinary long, thin, high contrast filament that can be used to map our galaxy's "skeletal" structure. The existence of additional "bones" in the Milky Way galaxy, and the possibility of future discovery of many filaments that could potentially trace the full list of fan bone candidates are all long, filamentary, mid-plane excitation features which lie parallel to, and no more than twenty parsecs from, the physical Galactic mid-plane. We use CO, NH₃, and NHI radial velocity data to establish the location of the candidates in position-velocity space. Of the few filament candidates that have a projected aspect ratio greater than 10, the Scutum-Centaurus arm in position-velocity space has three candidates: Nessie-like filaments, interarm clouds associated with the Milky Way's galactic structure. As molecular spectral-line and extinction maps of the sky at increasing resolution and sensitivity, we hope to see these filaments in future studies, to ultimately create a global-fit to the galaxy's spiral arms by piecing together individual skeletal features. This work is supported in part by the NSF REU and DOD ASSURE programs under NSF grant no. 1262851 and by the Smithsonian Institution.

2 Introduction

Over the past several decades, astronomers have begun to define the structure and kinematic properties of the Milky Way. Yet, despite a large conglomeration of literature on the subject, many key questions remain. For instance, how many spiral arms does the Milky Way have, cf. (Vallée 2008)? What is the location of these arms? And how would these arms appear to an observer viewing the Milky Way from the outside? An understanding of the Milky Way's three dimensional structure has eluded us, largely due to the fact that we are embedded in the galaxy we are attempting to delineate.

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT SOLICITATION NO. CLOSING DATE (if not in response to a program announcement solicitation enter NSF 14-1)

NSF 12-589 11/17/14 FOR NSF USE ONLY

FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.)

AST - ASTRONOMY & ASTROPHYSICS RES GRANTS NSF PROPOSAL NUMBER

DATE RECEIVED	NUMBER OF COPIES	DIVISION ASSIGNED	FUND CODE	DUNSN# (Data Universal Numbering System)	FILE LOCATION
				062359691	

EMPLOYER IDENTIFICATION NUMBER (EIN) OR TAXPAYER IDENTIFICATION NUMBER (TIN) 042183580

SHOW PREVIOUS AWARD NO. IF THIS IS A RENEWAL OR AN ACCOMPLISHMENT-BASED RENEWAL

IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES NO IF YES, LIST AGENCY(IES)

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE: Harvard University

ADDRESS OF AWARDING ORGANIZATION, INCLUDING 9 DIGIT ZIP CODE: Harvard University, 1350 Massachusetts Avenue, Cambridge, MA, 02138346

AWARDEE ORGANIZATION CODE (if known): 002150000

NAME OF PRIMARY PLACE OF PERF: Harvard University

ADDRESS OF PRIMARY PLACE OF PERF, INCLUDING 9 DIGIT ZIP CODE: Harvard University

IS AWARDING ORGANIZATION (Check All That Apply) SMALL BUSINESS HUBZONE VETERAN-OWNED DISADVANTAGED HAWAIIAN OTHER (Specify) IS A PRELIMINARY PROPOSAL (See SPIR I.C.2.6) YES NO

TITLE OF PROPOSED PROJECT: The Skeleton of the Milky Way

REQUESTED AMOUNT \$ 700,851

PROPOSED DURATION (Months) 36

REQUESTED STARTING DATE 07/01/15

IS THIS PROPOSAL RELATED TO A PREVIOUS PROPOSAL? YES NO

THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW:

BEGINNING INVESTIGATOR (IG I.C.2)

DISCLOSURE OF LOBBYING ACTIVITIES (IG I.C.1.e)

PROPRIETARY & PRIVILEGED INFORMATION (IG I.D.1, I.C.2)

HISTORIC PLACES (IG I.C.2.b)

VETERINARIAN ANIMALS (IG I.D.1) (ACU App. Date:)

PIF Animal Welfare Assurance Number:

IS FUNDING MECHANISM Research - other than RAPID or EAGER Other (Specify) proposal

PIPO DEPARTMENT: Harvard College Observatory

PIPO POSTAL ADDRESS: Harvard University, 60 Garden Street, Cambridge, MA 02138, United States

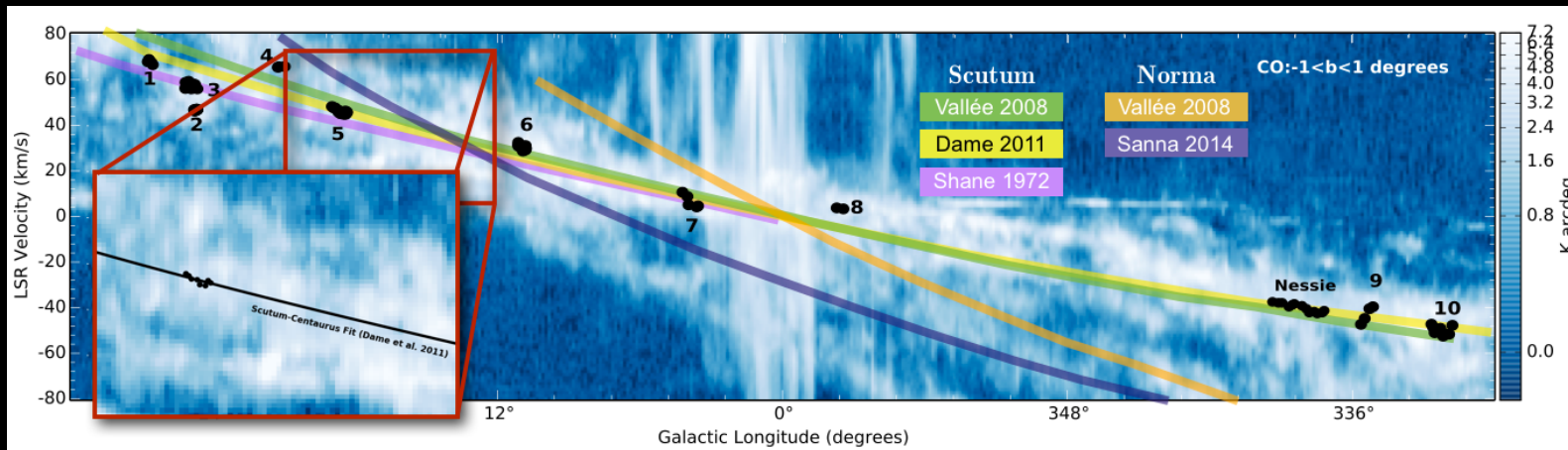
PIPO FAX NUMBER: 617-495-7345

NAME (TYPIED)	Hght Degree	Yr of Degree	Telephone Number	Email Address
Alyssa A Goodman	PhD	1989	617-495-9278	agoodman@cfa.harvard.edu

Page 1 of 3

Open Preprint 2014

Funding Proposal 2014



Open Preprint 2013

The Bones of the Milky Way
 Alyssa Goodman, Alberto Pepe, Tom Dame, James Jackson, Jens Kauffmann, Thomas Robitaille, Chris Beaumont, Michelle Borkin, Andreas Burkert, Robert A. Benjamin, Jolito Alves

This is a preprint. The published article is available at the Astrophysical Journal (ApJ) 767:121 (2013). This online version, published in December 2012, is available as an online "Author's" preprint, and you can use the article's URL to cite it.

Abstract: The very long and thin filament "Nessie" has been long known to lie directly in the Milky Way's mid-plane, tracing out a highly elongated bone-like feature within the prominent Scutum-Centaurus spiral arm. Re-analysis of mid-infrared images from the Spitzer Space Telescope shows that the IRDCs at least 2, and possibly as many as 10 times longer than previously claimed by Nesbitt et al. (2010). Its aspect ratio is therefore at least 10:1 for both the Sun's offset from the Galactic plane and the Sun's offset from the Scutum-Centaurus Arm in position-position-velocity space. As a result, Nesse lies in a position-position-velocity space well removed from the Galactic plane and the Scutum-Centaurus Arm in position-position-velocity space, well removed from the Galactic plane and the Scutum-Centaurus Arm in position-position-velocity space, well removed from the Galactic plane and the Scutum-Centaurus Arm in position-position-velocity space.

1 Introduction
 Determining the structure of the Milky Way, from our vantage point within it, is a perpetual challenge for astronomers. We know the Galaxy has spiral arms, but it remains unclear exactly how many of them there are (Vallee 2007). Recent observations of major proper motions give unprecedented accuracy in determining the three-dimensional position of the Galaxy's center and rotation speed (Reid et al. 2009, Brunttner et al. 2011). But, to date, we still do not have a definitive picture of the Milky Way's three dimensional structure.

Refereed Article 2014

THE BONES OF THE MILKY WAY
 ALYSSA A. GOODMAN¹, JOLO ALVES², CHRISTOPHER N. BEAUMONT³, ROBERT A. BENJAMIN⁴, MICHELLE A. BORKIN⁵, ANDRIAS BURKERT⁶, THOMAS M. DAME⁷, JAMES JACKSON⁸, JENS KAUFFMANN⁹, THOMAS ROBITAILLE¹⁰, AND ROBERT A. SMITH¹¹

ABSTRACT
 The very long and thin filament "Nessie" has been long known to lie directly in the Milky Way's mid-plane, tracing out a highly elongated bone-like feature within the prominent Scutum-Centaurus spiral arm. Re-analysis of mid-infrared images from the Spitzer Space Telescope shows that the IRDCs at least 2, and possibly as many as 10 times longer than previously claimed by Nesbitt et al. (2010). Its aspect ratio is therefore at least 10:1 for both the Sun's offset from the Galactic plane and the Sun's offset from the Scutum-Centaurus Arm in position-position-velocity space. As a result, Nesse lies in a position-position-velocity space well removed from the Galactic plane and the Scutum-Centaurus Arm in position-position-velocity space, well removed from the Galactic plane and the Scutum-Centaurus Arm in position-position-velocity space.

1 INTRODUCTION
 Determining the structure of the Milky Way from our vantage point within it is a perpetual challenge for astronomers. We know the Galaxy has spiral arms, but it remains unclear exactly how many there are (see Vallee 2007). Recent observations of major proper motions give unprecedented accuracy in determining the three-dimensional (3D) position of the Galaxy's center and rotation speed (Reid et al. 2009; Brunttner et al. 2011). But, to date, we still do not have a definitive picture of the Milky Way's 3D structure.



WorldWide Telescope



Open Preprint 2014

The Milky Way Skeleton
 Catherine Zucker, Cara Battersby, Alyssa Goodman

1 Abstract
 Recently, Goodman et al. (2014) argued that a very long, very thin infrared dark cloud "Nessie" lies directly in the Galactic mid-plane and runs along the Scutum-Centaurus arm in position-position-velocity space as traced by low density CO and high density NH₃ gas. Nessie was presented as the first "bone" of the Milky Way, an extraordinary, very thin, high contrast filament that can be used to map our galaxy's "skeleton" and to determine the existence of additional "bones" in the Milky Way galaxy. However, while Nessie is highly elongated, it is not as thin as one of many filaments that could potentially be used to map the Milky Way's skeleton. A list of ten bone candidates are all long, filamentary, and lie in the Galactic mid-plane, parallel to, and no more than twenty parsecs from, the physical Galactic mid-plane. We use CO, NH₃, and 224 μm radial velocity data to establish the location of the candidates in position-position-velocity space. Of the ten filaments, six have a projected aspect ratio of at least 10:1, and three have three candidates are Nessie-like in position-position-velocity space. Other candidates could be spurs, feathers, or interarm clouds associated with the Milky Way's galactic structure. As molecular spectral-line and extinction tracers, these filaments could be used to create a global-fit to the galaxy's spiral arms by piecing together individual skeletal features. This work is supported in part by the NSF nEU and DOD ASSURE programs under NSF grant no. 1262951 and by the Smithsonian Institution.

2 Introduction
 Over the past several decades, astronomers have begun to define the structure and kinematic properties of the Milky Way. Yet, despite a large conglomeration of literature on the subject, many key questions remain. For instance, how many spiral arms does the Milky Way have, of (Vallee 2007)? What is the location of these arms? And how would these arms appear to an observer viewing the Milky Way from the outside? An understanding of the Milky Way's three dimensional structure has eluded us, largely due to the fact that we are embedded in the galaxy we are attempting to delineate.



Funding Proposal 2014

COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT SOLICITATION NO. CLOSERING DATE: 11/17/14
 FOR NSF USE ONLY
 NSF PROPOSAL NUMBER: 08135961

NSF 12-889 11/17/14
 FOR COUNCIL ON ENVIRONMENTAL SCIENCES (CEE) SOLICITATION NO. (program, division, etc.)

AST - ASTRENDA & ASTROPHYSICS RESEARCH GRANTS
 08135961

DATE RECEIVED: / / NUMBER OF COPIES: DIVISION ASSIGNED: FUND CODE: DUNSIF (Use Internal Tracking System): FILE LOCATION:

PROPOSAL IDENTIFICATION NUMBER (200 CHARACTERS): 04210550
 HAS THIS PROPOSAL PREVIOUSLY AWARDED? IF YES: YES () NO ()
 IS THIS PROPOSAL BEING SUBMITTED TO ANOTHER FEDERAL AGENCY? YES () NO ()
 IS AN ACCUMULATED FUNDING REQUEST?

NAME OF ORGANIZATION TO WHICH AWARD SHOULD BE MADE: Harvard University
 ADDRESS OF AWARDING ORGANIZATION, INCLUDING ITS OFFICE CODE: 1350 Massachusetts Avenue, Cambridge, MA, 02138

AWARDEE ORGANIZATION CODE (if known): 002150000
 ADDRESS OF PRIMARY PLACE OF RESEARCH: Harvard University

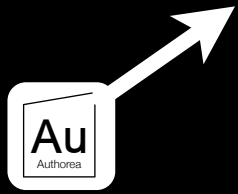
IS AWARDING ORGANIZATION (NAME AS APPEARS ON COVER SHEET) THE SAME AS THE AWARDING ORGANIZATION? YES () NO ()
 TITLE OF PROPOSED PROJECT: The Skeleton of the Milky Way

REQUESTED AMOUNT: \$ 200,000
 THIS PROPOSAL INCLUDES ANY OF THE ITEMS: YES () NO ()
 DISCLOSURE OF LOBBYING ACTIVITIES (SPS) YES () NO ()
 DISCLOSURE OF PRIVILEGED INFORMATION YES () NO ()
 HISTORIC PLACES (SPS) (S) YES () NO ()
 HISTORIC STRUCTURES (SPS) (S) YES () NO ()
 PREVIOUS AWARDS (SPS) (S) YES () NO ()
 IS THIS PROPOSAL A RESEARCH PROPOSAL? YES () NO ()
 IS THIS PROPOSAL A RESEARCH PROPOSAL? YES () NO ()
 IS THIS PROPOSAL A RESEARCH PROPOSAL? YES () NO ()

PERFORMING INSTITUTION: Harvard College Observatory
 PERFORMING INSTITUTION ADDRESS: 60 Garden Street, Cambridge, MA 02138, United States

PURPOSE NUMBER: 617-495-7482
 NAME (TITLE): Alyssa A Goodman
 POSITION: PI
 PHONE: 617-495-9218
 EMAIL: agoodman@cfa.harvard.edu







**SEAMLESS
ASTRONOMY**
Linking scientific data, publications, and communities



Universe Information System

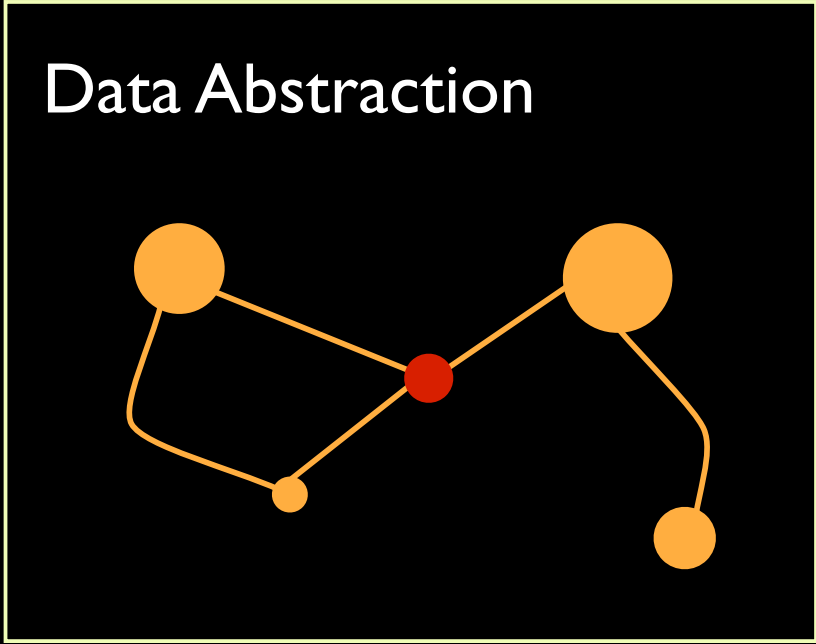
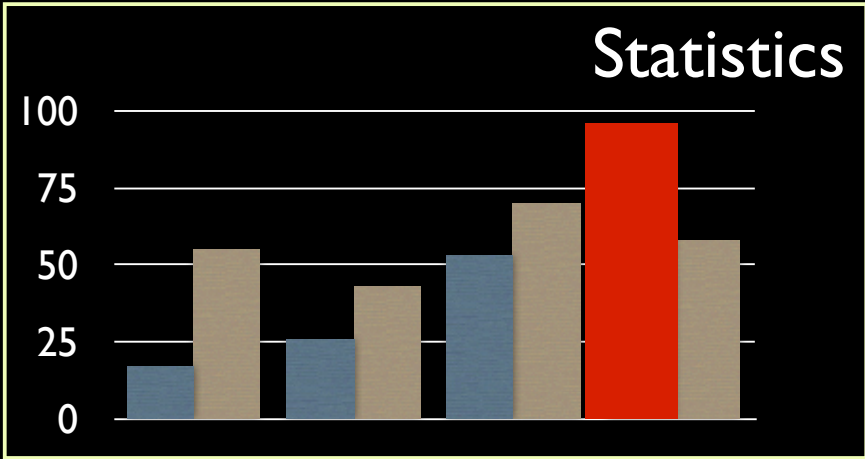
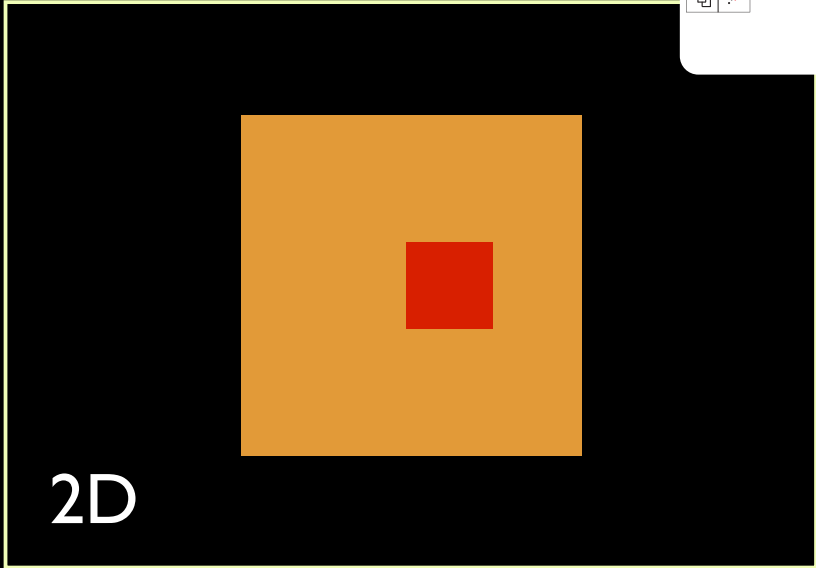
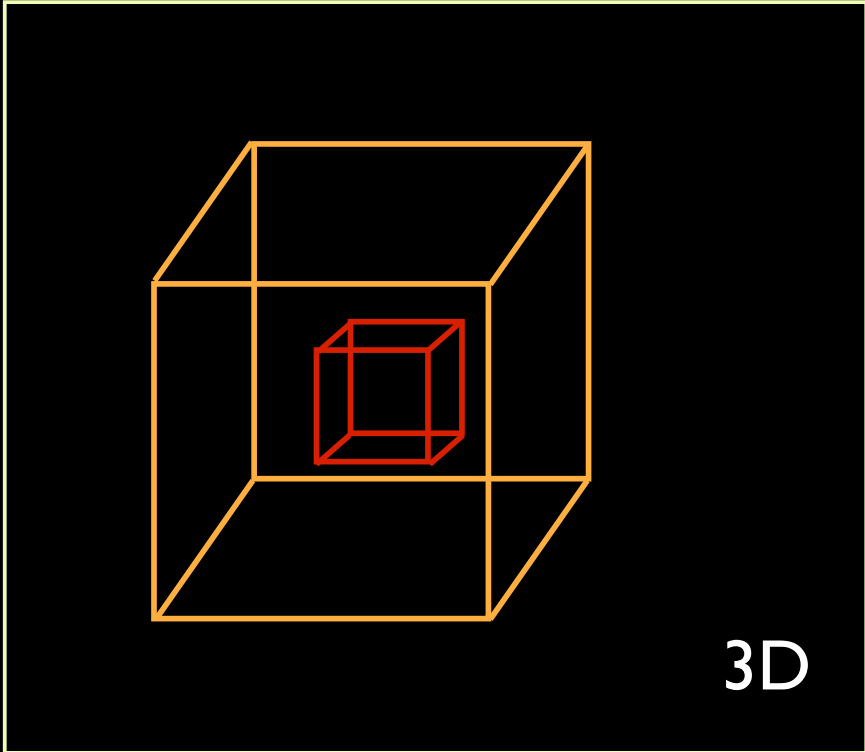


Linked-View Visualization



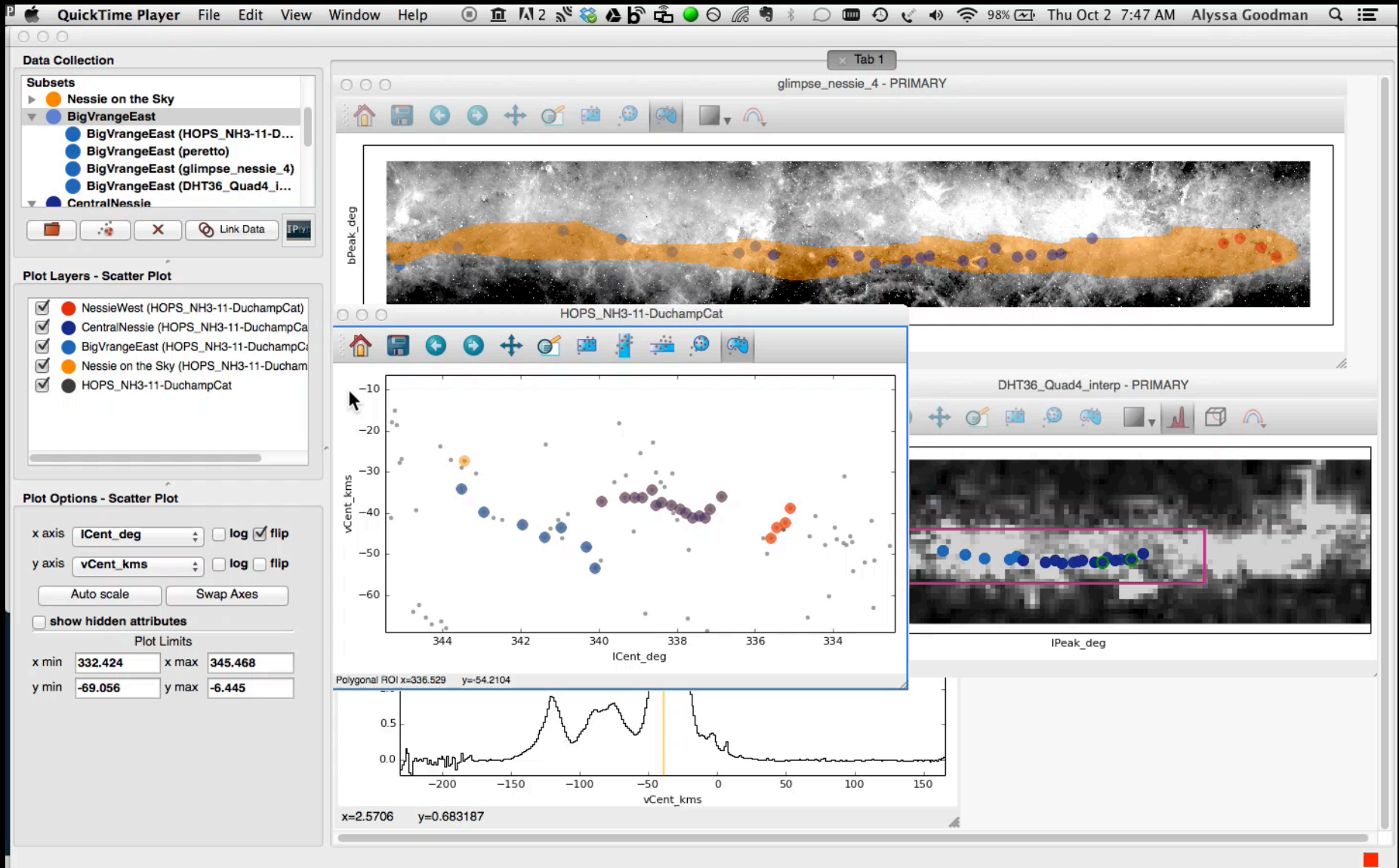
Open Collaborative Publishing

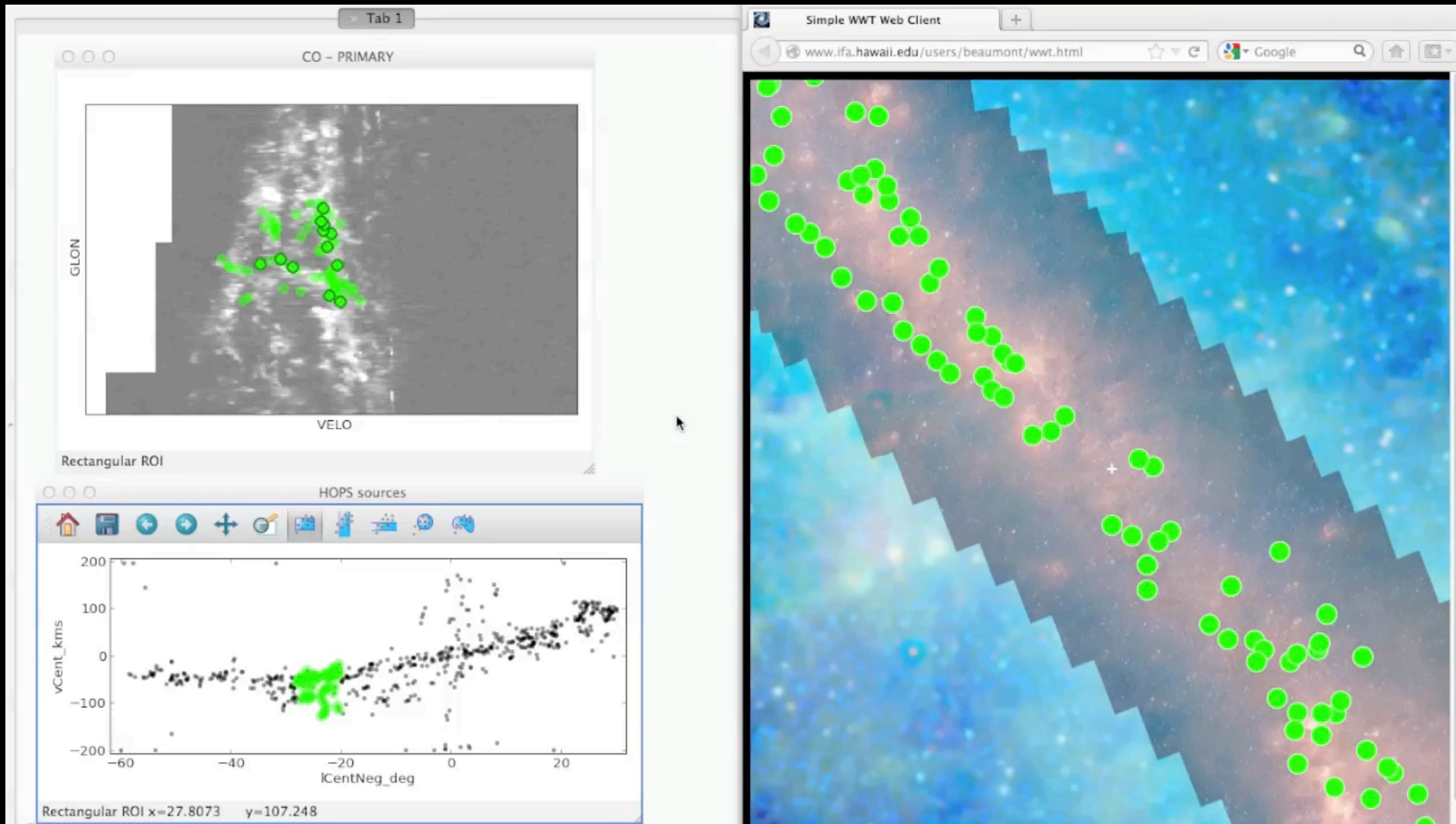
LINKED VIEWS OF HIGH-DIMENSIONAL DATA



figure, by M. Borkin, reproduced from [Goodman 2012](#), "Principles of High-Dimensional Data Visualization in Astronomy"

NESSIE IN GLUE





Video courtesy of Chris Beaumont, Lead Glue Architect

The "Paper" of the Future

2

[Alyssa Goodman](#), [Josh Peek](#), [Alberto Accomazzi](#), [Chris Beaumont](#), [Christine L. Borgman](#), [How-Huan Hope Chen](#), [Merce Crosas](#), [Christopher Erdmann](#), [August Muench](#), [Alberto Pepe](#), [Curtis Wong](#) [+ Add author](#) [Re-arrange authors](#)

A 5-minute video demonstration of this paper is available at [this YouTube link](#).

2

1 Preamble

A variety of research on human cognition demonstrates that humans learn and communicate best when more than one processing system (e.g. visual, auditory, touch) is used. And, related research also shows that, no matter how technical the material, most humans also retain and process information best when they can put a narrative "story" to it. So, when considering the future of scholarly communication, we should be careful not to do blithely away with the linear narrative format that articles and books have followed for centuries: instead, we should enrich it.

Much more than text is used to communicate in Science. Figures, which include images, diagrams, graphs, charts, and more, have enriched scholarly articles since the time of Galileo, and ever-growing volumes of data underpin most scientific papers. When scientists communicate face-to-face, as in talks or small discussions, these figures are often the focus of the conversation. In the best discussions, scientists have the ability to manipulate the figures, and to access underlying data, in real-time, so as to test out various what-if scenarios, and to explain findings more clearly. **This short article explains—and shows with demonstrations—how scholarly "papers" can morph into long-lasting rich records of scientific discourse**, enriched with deep data and code linkages, interactive figures, audio, video, and commenting.

Index

- Preamble
- Pof1
- Collaborative authoring
- Comparison table
- Linking data
- Question
- Dvn
- Zenodo
- Linking and executing ...
- Rho oph
- Better storytelling
- Audio
- Video
- Enhanced figures
- Interactivity
- Index
- 3d in 2d
- Nature screen shot
- Images in context
- Barnardsample
- Deeper easier citations



The Bones of the Milky Way: Credits

Seamless Astronomy-style tools used in this project



authorea.com (open publishing)

theastrodata.org (open data)

glueviz.org (open source tools)

universe3d.org (collaborative data)

worldwidetelescope.org (universe information system)

[virtual observatory standards](#) (international online information-sharing systems)

Supported by



Alyssa Goodman milkywaybones.org



The Bones of the Milky Way

Alyssa A. Goodman (Harvard-Smithsonian Center for Astrophysics)

with collaborators at (alphabetically by institution):

Boston University: James Jackson

Caltech: Jens Kauffmann

Harvard - Smithsonian: Christopher Beaumont, Michelle A. Borkin, Cara Battersby, Thomas M. Dame

ITA, Heidelberg: Rowan Smith

Max Planck Institute for Astronomy: Thomas Robitaille

U. Munich: Andreas Burkert

U. Virginia: Catherine Zucker

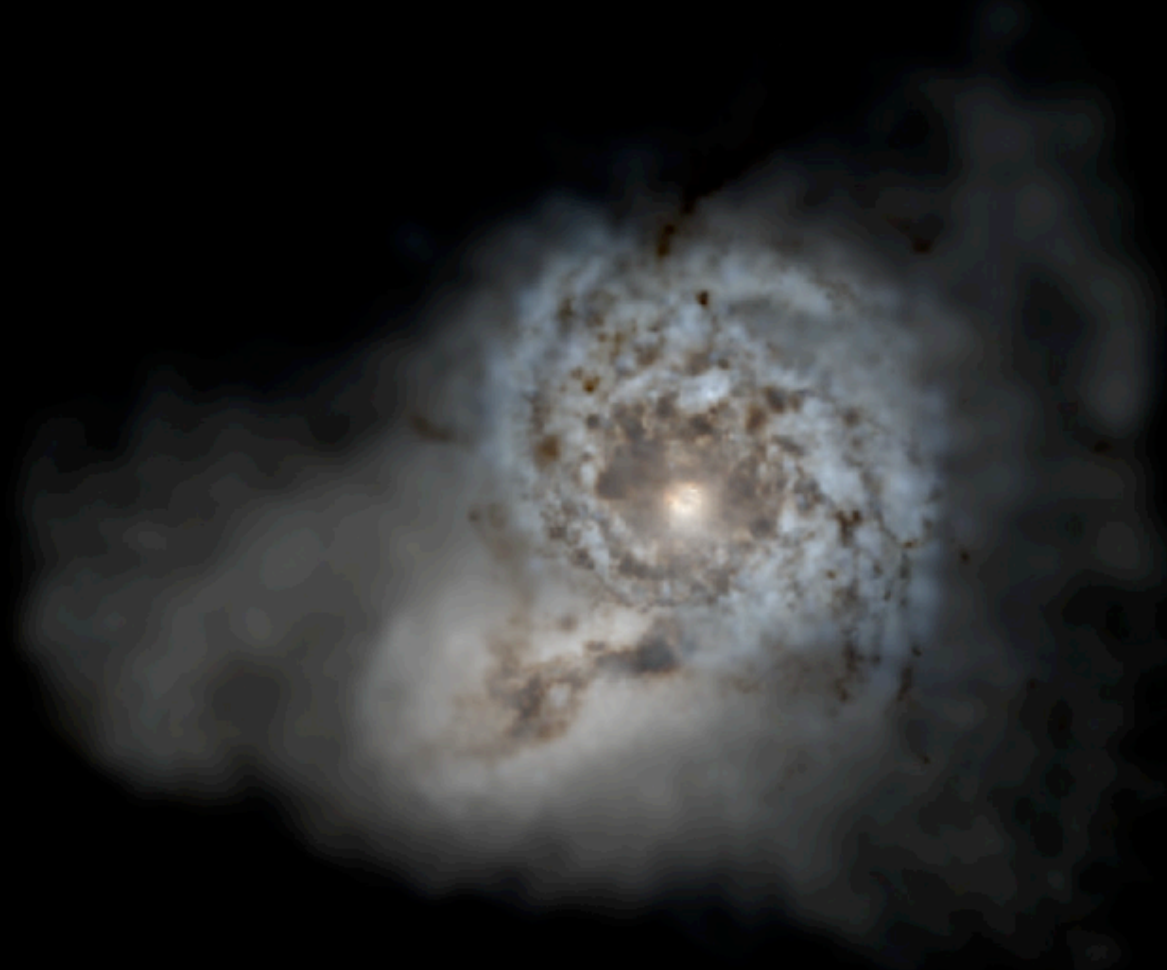
U. Vienna: Joao F. Alves

U. Wisconsin: Robert A. Benjamin

extra slides

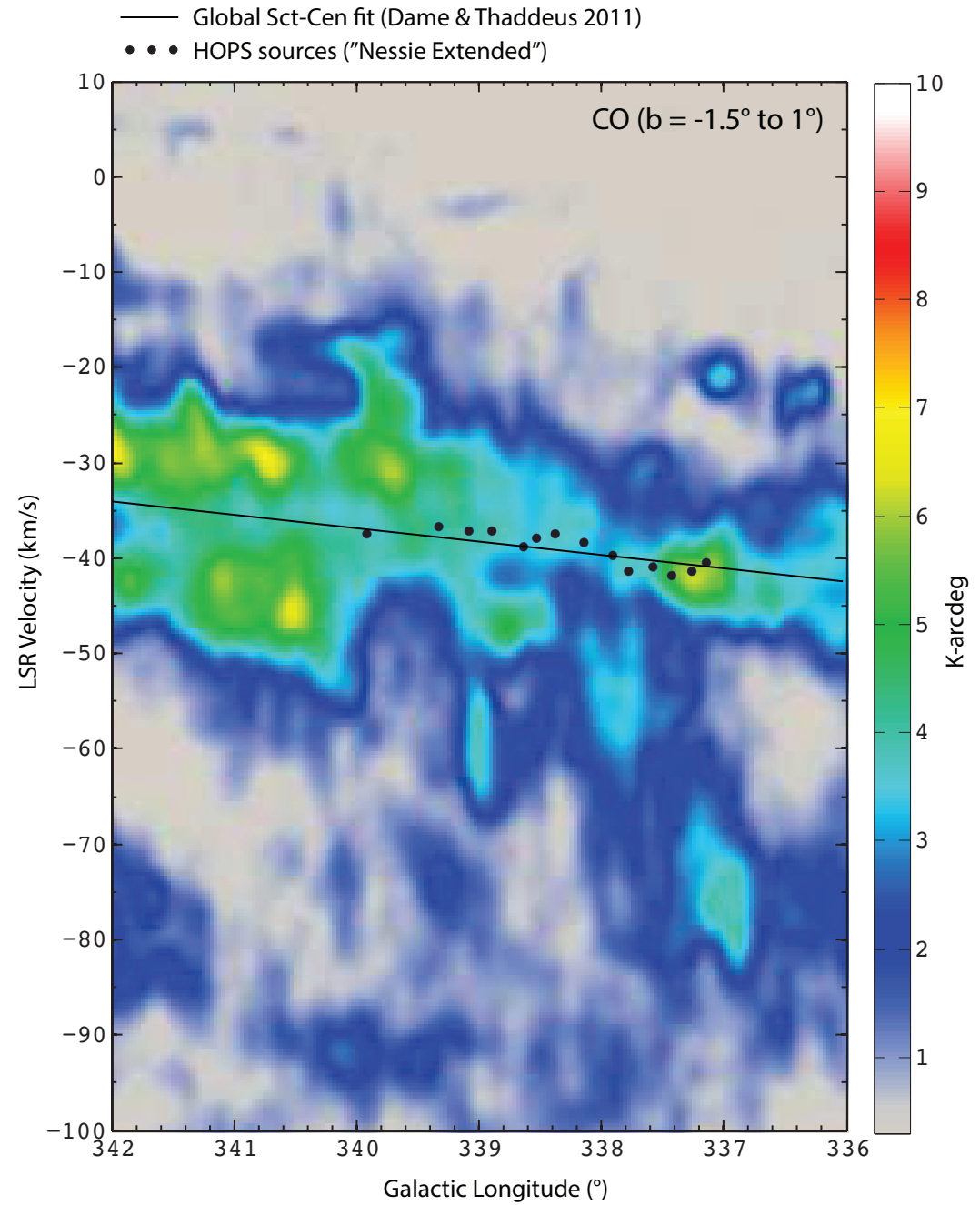
$z=0.00$

Formation of a Milky-Way-like Galaxy (Stars)



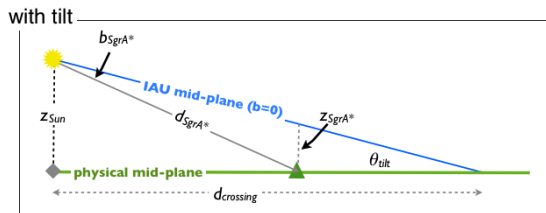
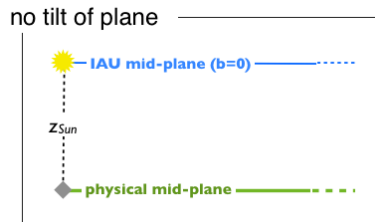
http://www.tapir.caltech.edu/~phopkins/Site/Movies_cosmo.html

...eerily precisely...

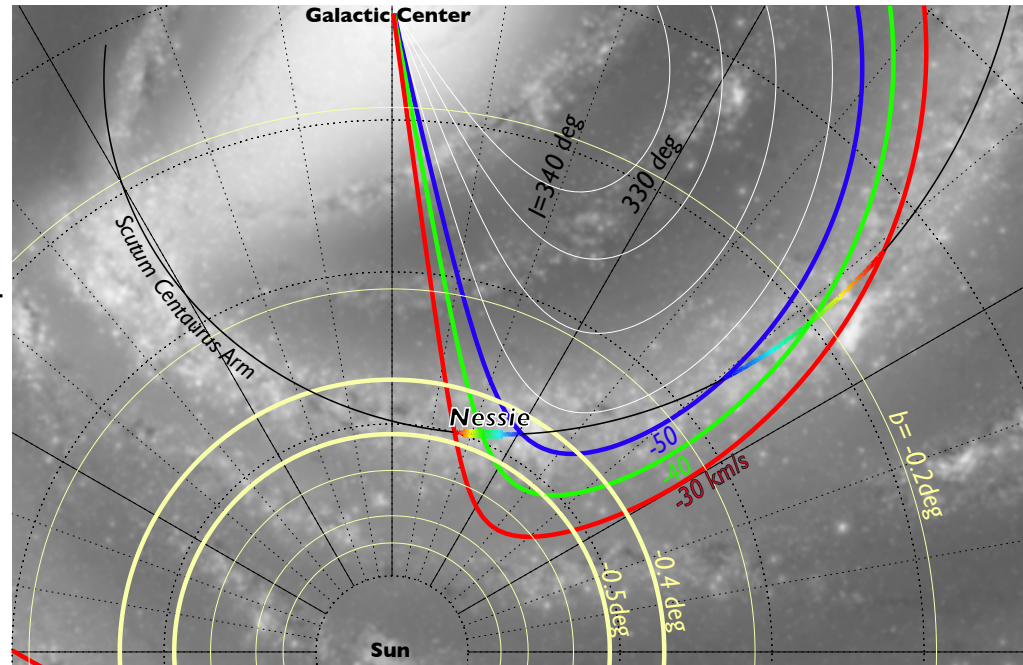


Goodman et al. 2013, see MilkyWayBones.org

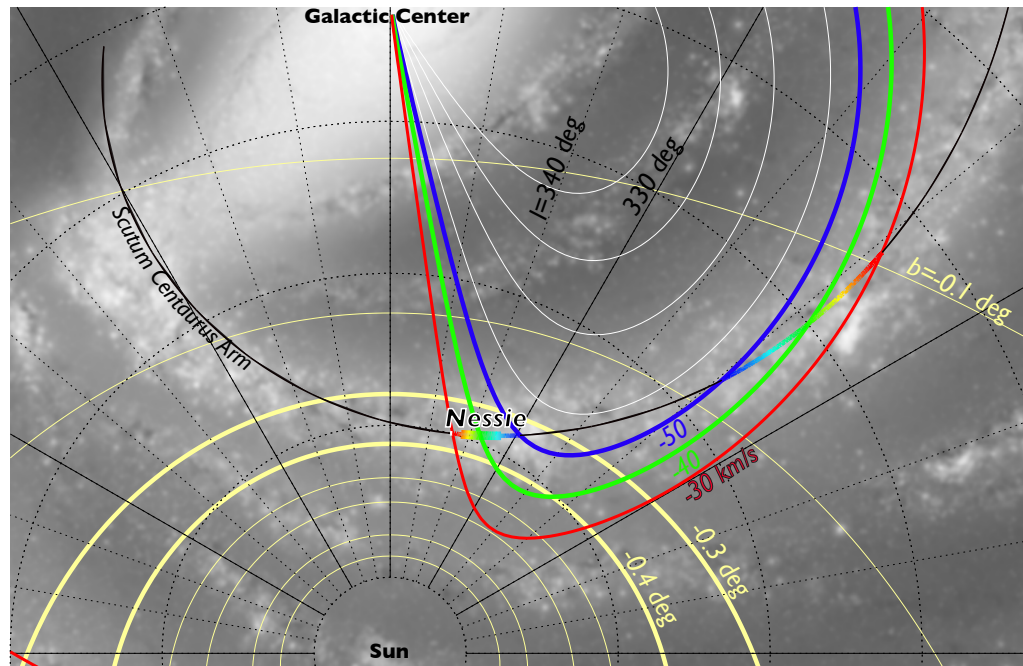
Predictions in "3D" (p-p-v space)



no tilt of plane

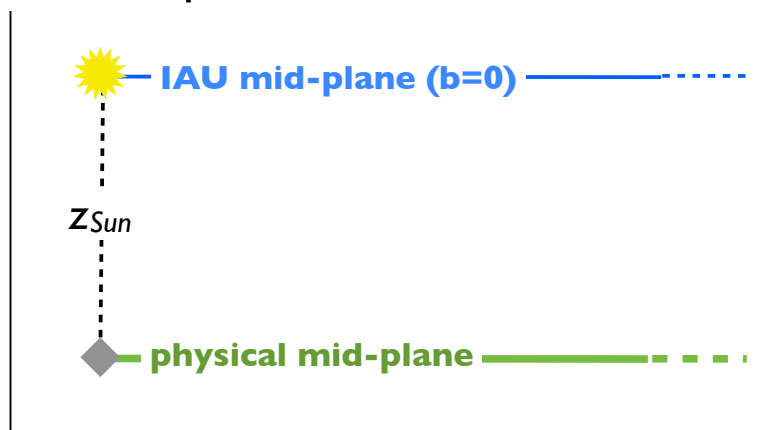





with tilt



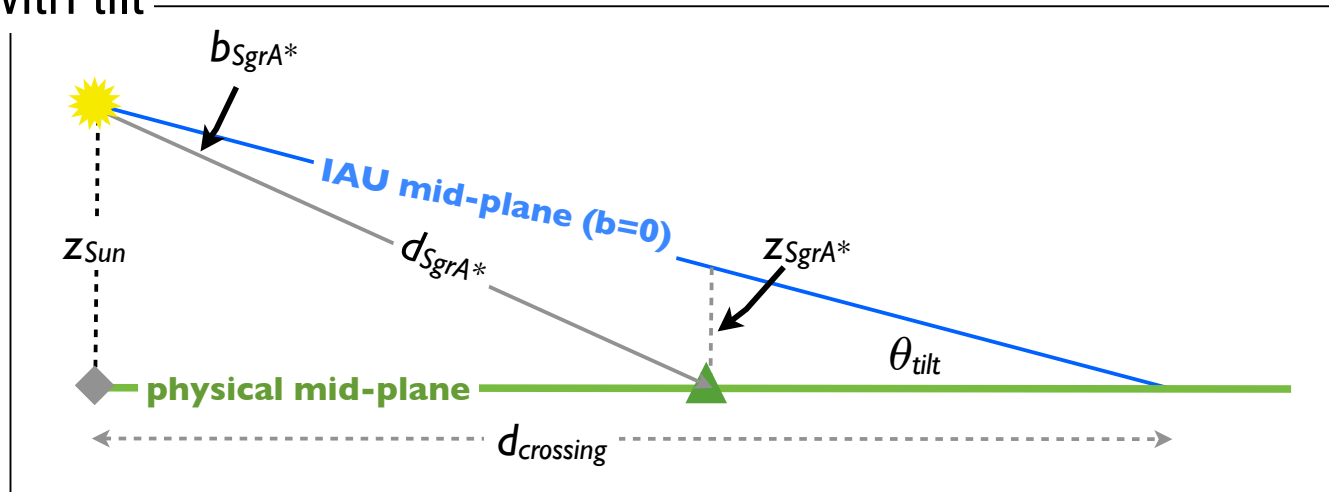
"In the Plane?"

no tilt of plane



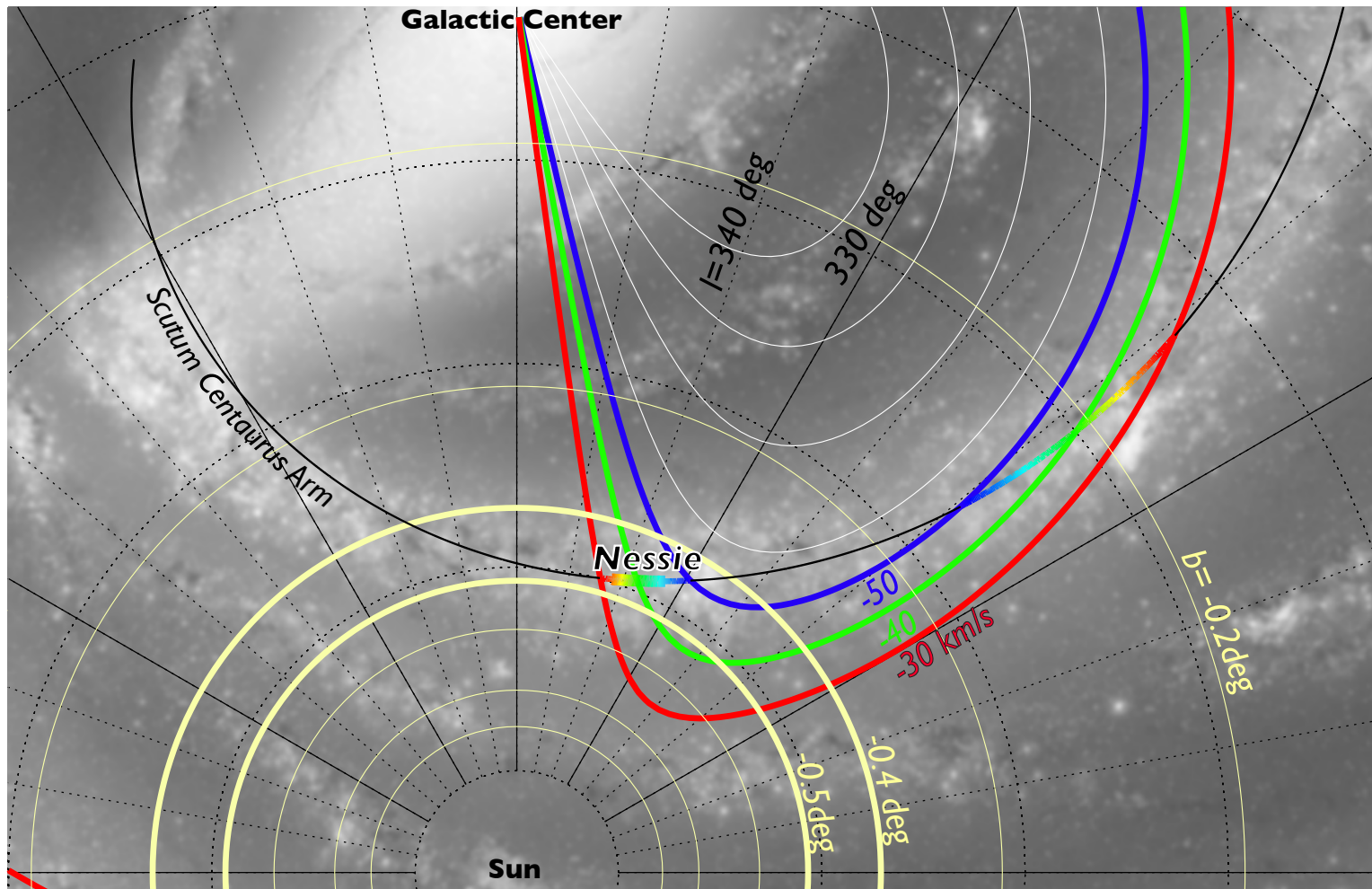
-  Sun
-  Projection of Sun onto physical midplane
-  Location of SgrA*

with tilt



Predictions in "3D"

Including Galactic Center offset)



Aspect Ratio for longest version of Nessie is 800:1

Table 1: Estimates of Nessie's Density and Mass

Assumptions:		Baryonic mass of Milky Way (Msuns)		1.25E+11		Distance to Nessie (pc)		3,100				
Nickname	Length deg	Radius deg	Length pc	Radius pc	Average density cm ⁻³	H2 column density cm ⁻²	Equiv. Av mag	Mass Msuns	Mass per unit length Msuns/pc	# to equal mass of Milky Way	aspect ratio	
<i>for innermost Spitzer IRDC...</i>												
"Nessie Classic"	1.5	0.005	81	0.3	1E+5	8E+22	81	1E+5	1,208	1E+6	150	
"Nessie Extended"	3	0.005	162	0.3	1E+5	8E+22	81	2E+5	1,208	6E+5	300	
"Nessie Optimistic"	8	0.005	431	0.3	1E+5	8E+22	81	5E+5	1,208	2E+5	800	
<i>for envelope (width as observed in HNC, Jackson et al. 2010)...</i>												
"Nessie Classic"	1.5	0.05	81	2.7	5E+2	4E+21	4	5E+4	604	3E+6	15	
"Nessie Extended"	3	0.05	162	2.7	5E+2	4E+21	4	1E+5	604	1E+6	30	
"Nessie Optimistic"	8	0.05	431	2.7	5E+2	4E+21	4	3E+5	604	5E+5	80	

and is very, very, thin: tenths of pc in diameter!!
(while 100s of pc long)

Distance to M101 ~ 7 Mpc

● ALMA-like resolution

10 kpc

1 kpc

Orion in CO

60 kpc

20 pc

l-m telescope

