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The Bones of the Milky Way

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

with collaborators at (alphabetically by insitution):

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 Insitute for Astronomy: Thomas Robitaille

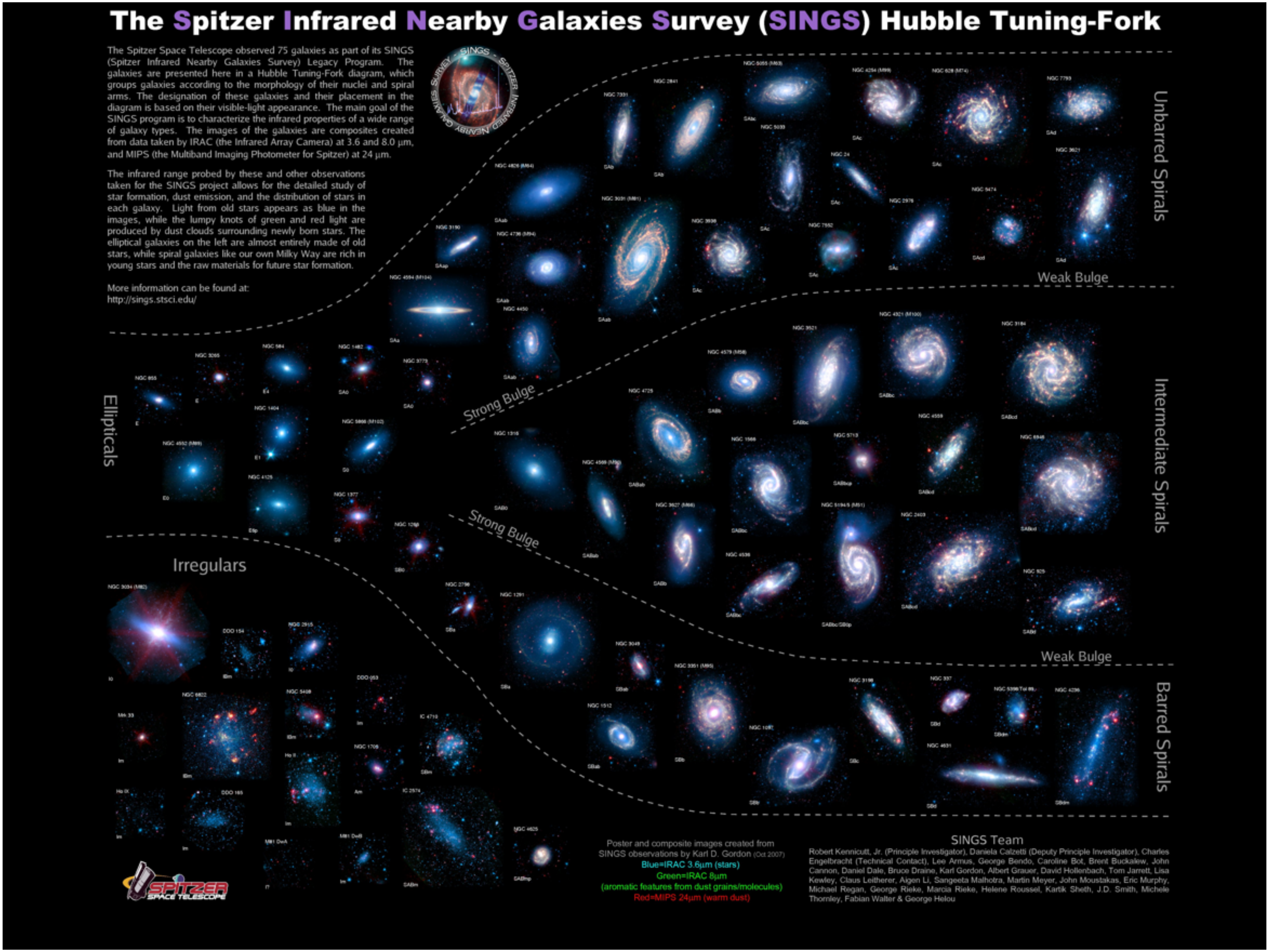
U. Munich: Andreas Burkert

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 Hershcel


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/
SINGS - SPITZER INFRARED NEARBY GALAXIES SURVEY
Unbarred Spirals
Weak Bulge
Strong Bulge
Intermediate Spirals
Strong Bulge
Weak Bulge
Barred Spirals
Ellipticals
Irregulars
Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (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, Aigen 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
SPITZER SPACE TELESCOPE

1936: “The Realm of the Nebulae” by Edwin Hubble

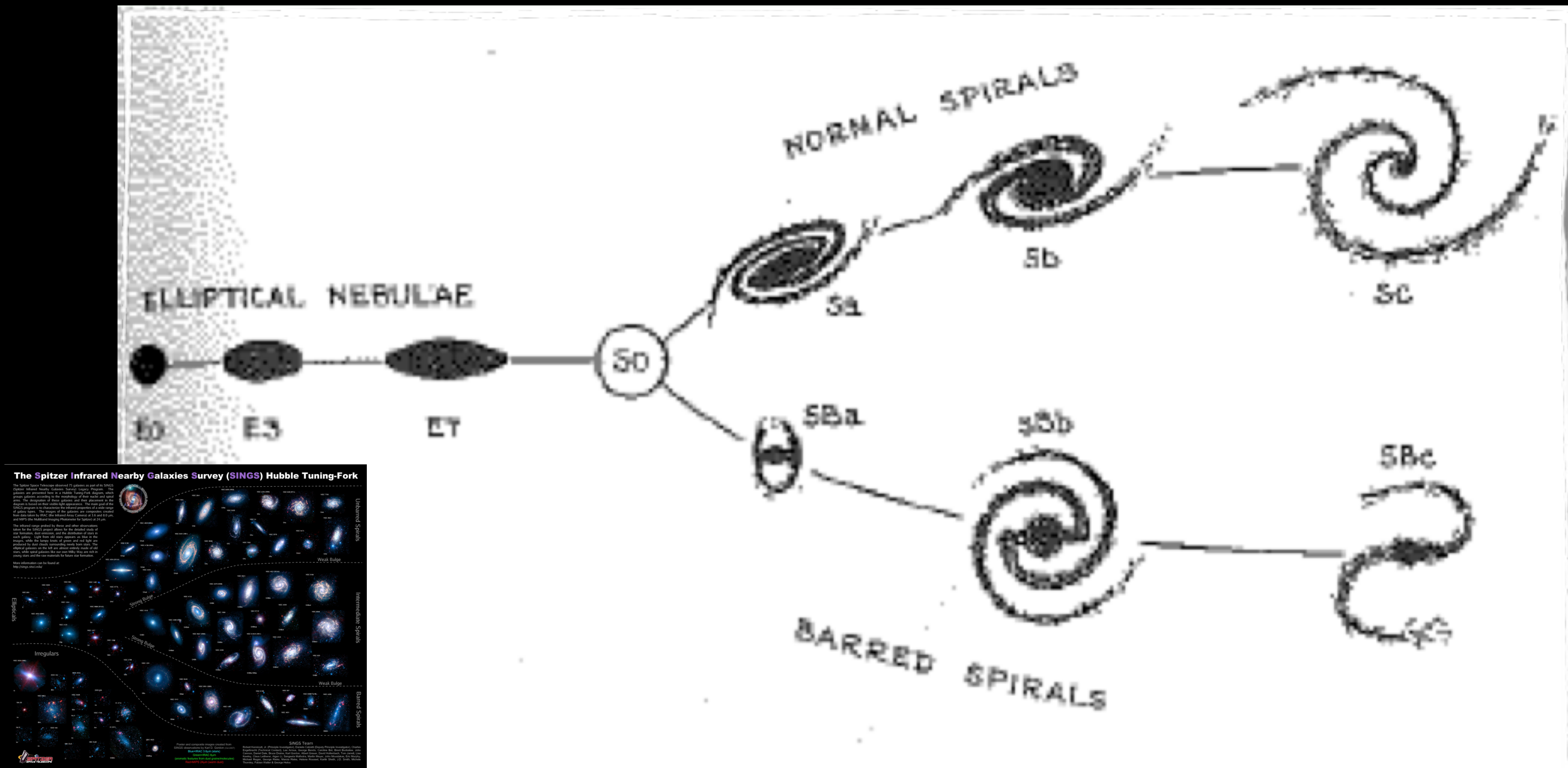


FIG. 1. *The Sequence of Nebular Types.*

The diagram is a schematic representation of the sequences of classification. A few nebulæ 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 nebulæ 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

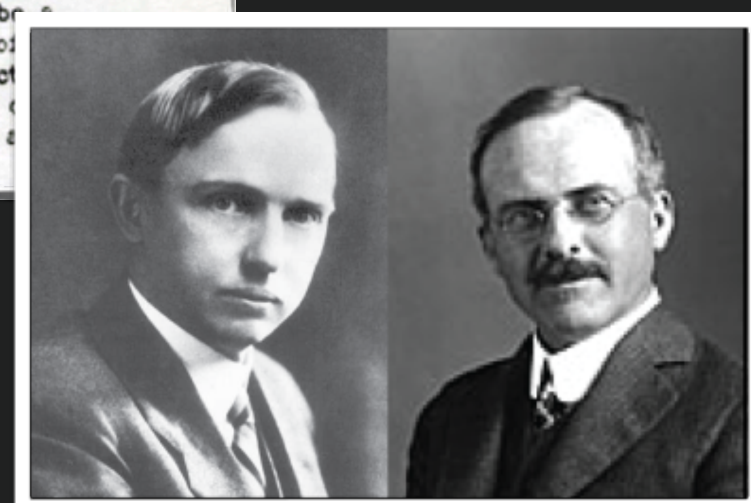
For Files

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.

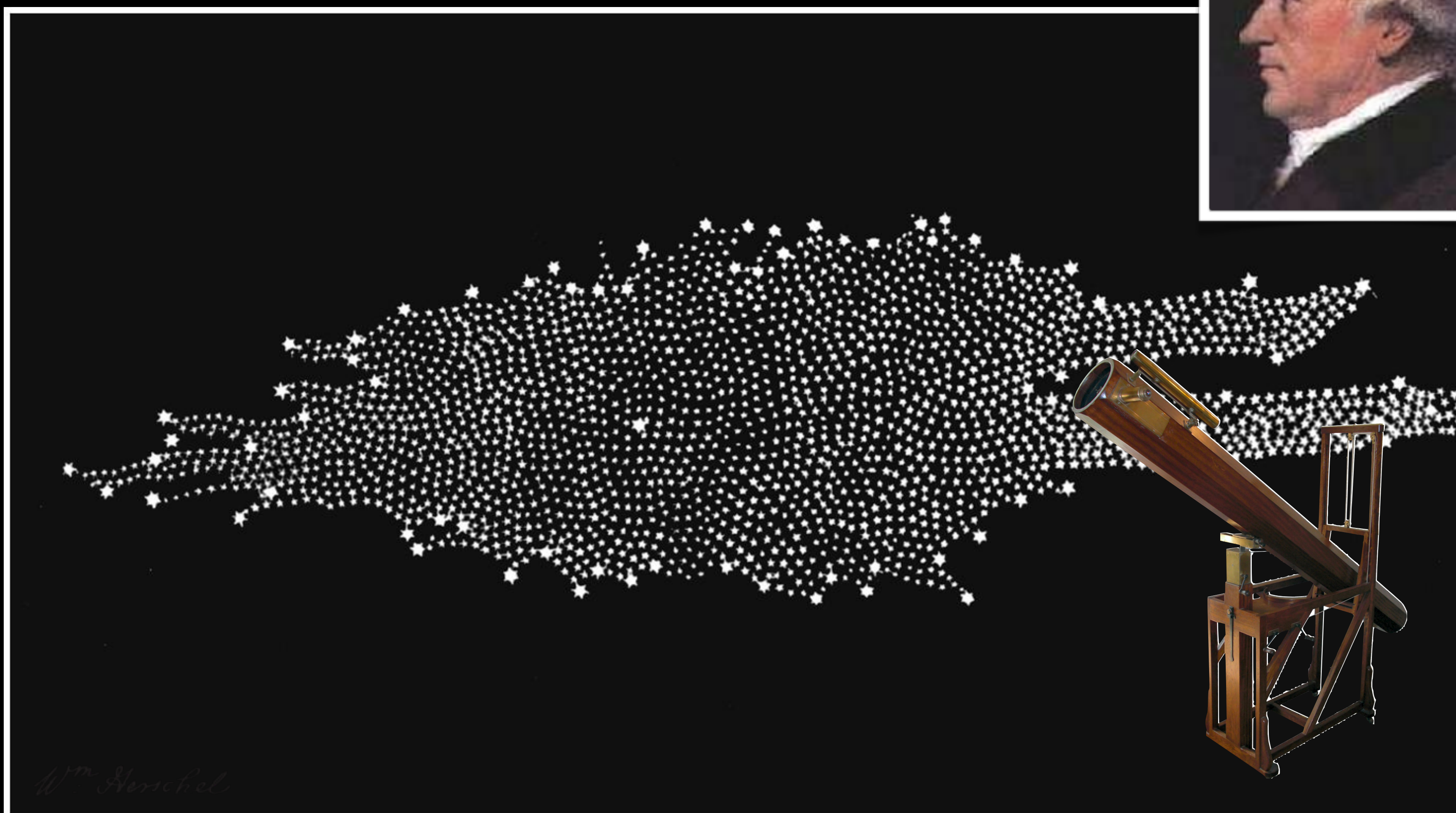
In this public meeting, Dr. Harlow Shapley of the Mt. Wilson Solar Observatory, will discuss recently secured evidence pointing to the dimensions of our galaxy of stars, known popularly as the Milky Way, which he believes to be ten times greater than is held in the older theories concerning the dimensions 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 o
numerous universes would see our Milky Way as a spiral nebula. The lect
these two learned astronomers will be followed by a general discussion
the auditors present who are interested in the development of this new
in scientific research.

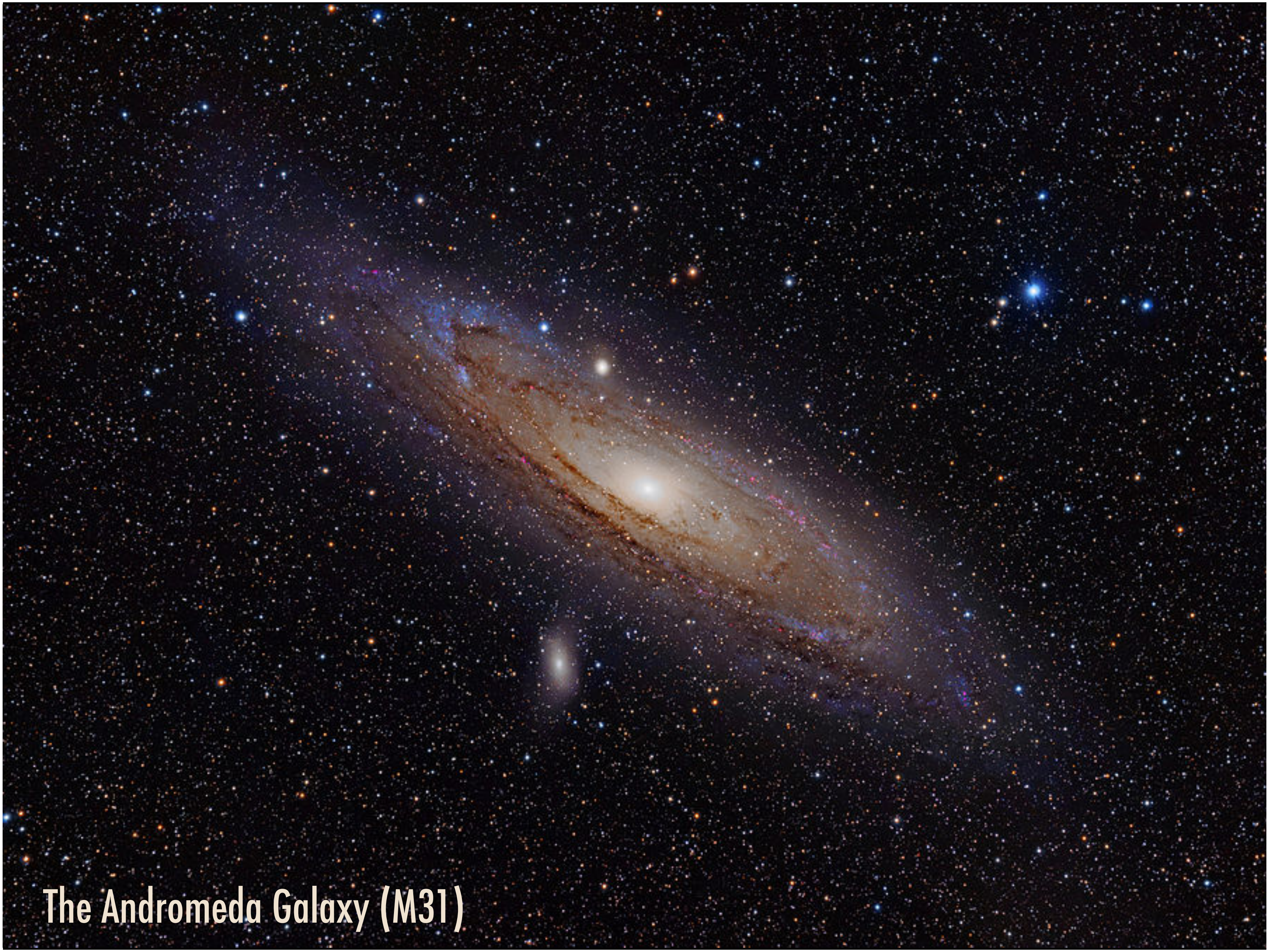


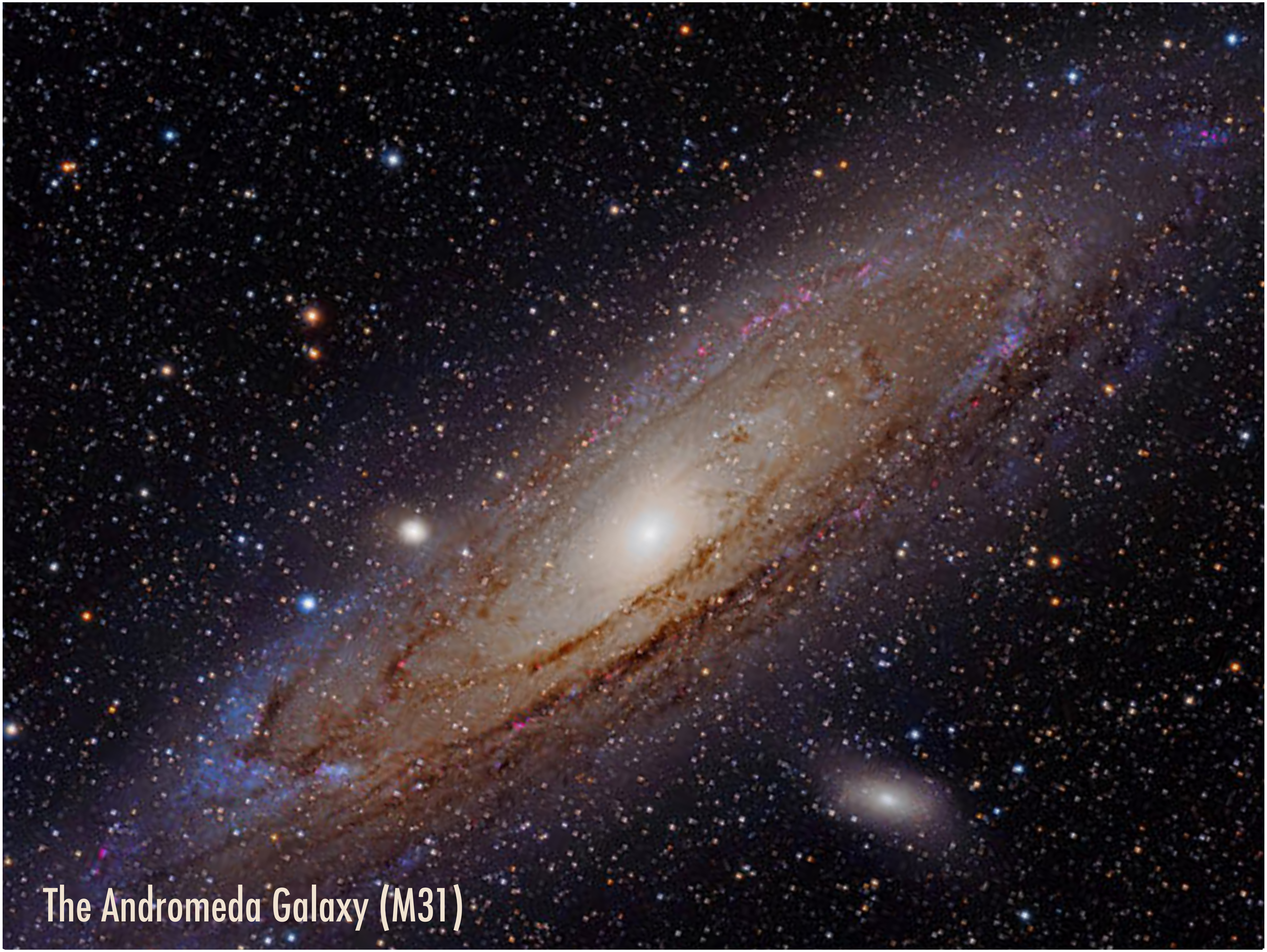
The Shapley-Curtis Debate at the Smithsonian Natural History Museum, 1920

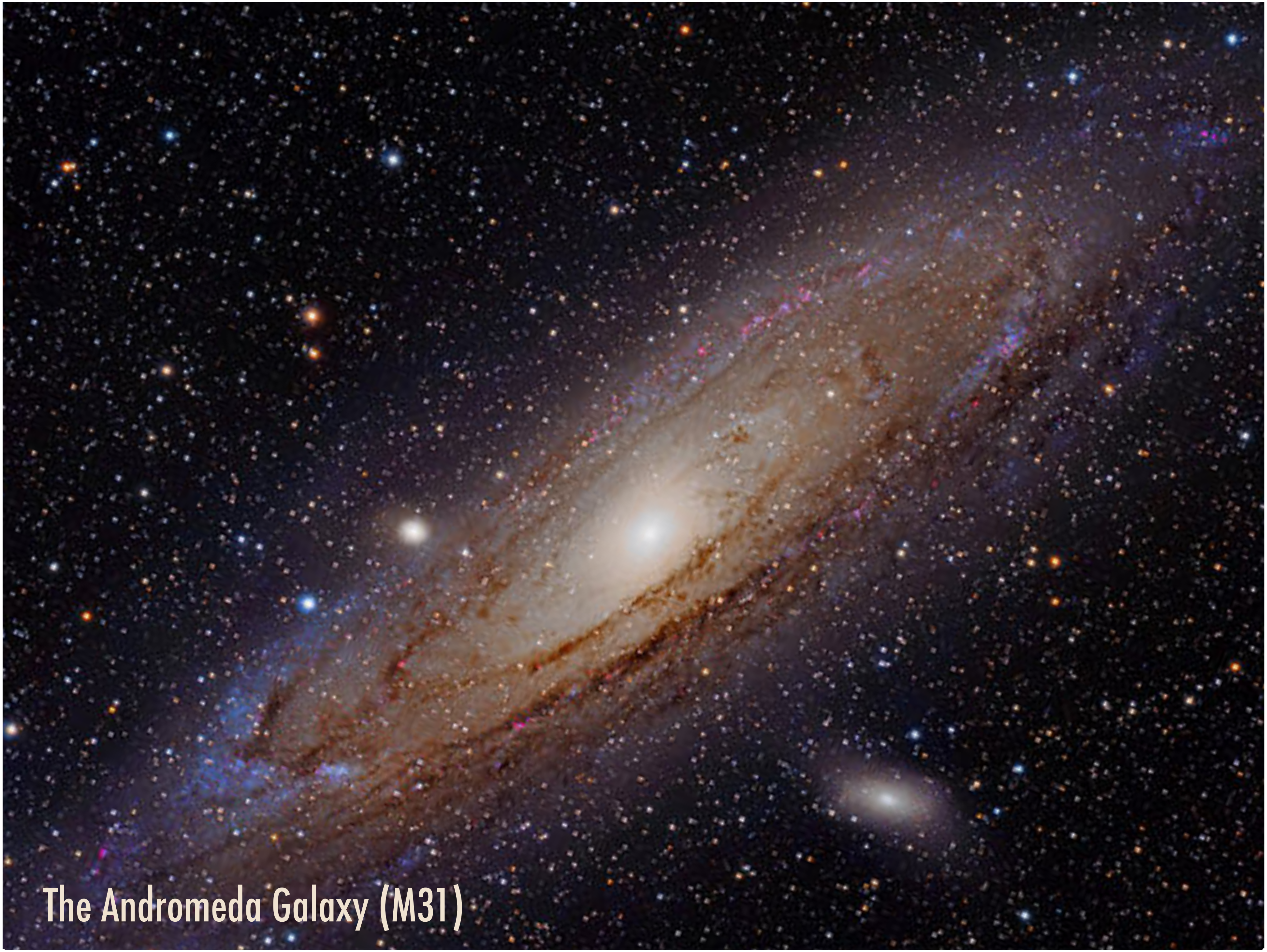
William Herschel's Milky Way Galaxy in 1781

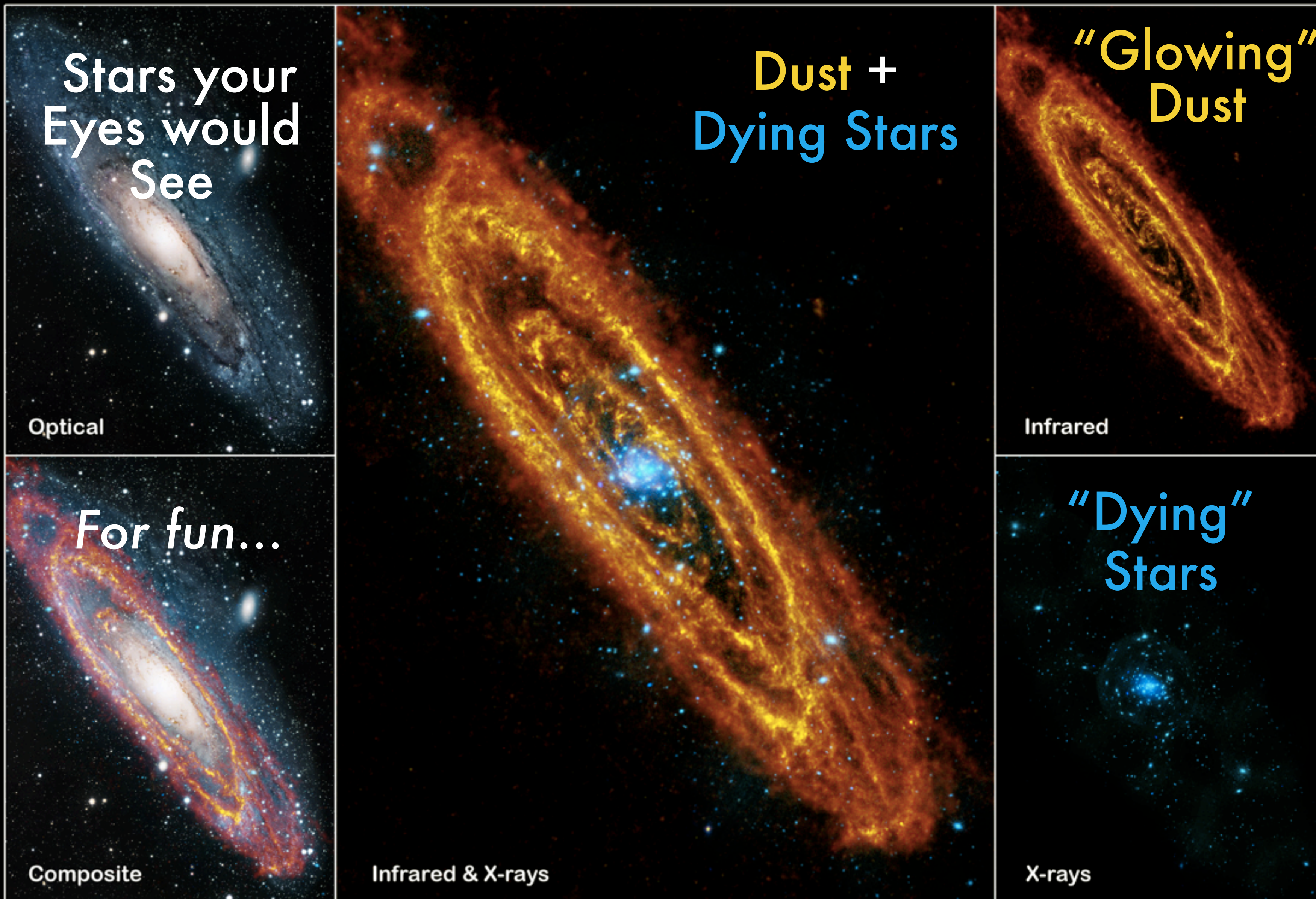


More info at http://cosmology.carnegiescience.edu/timeline/1781 (Herschel); http://cosmology.carnegiescience.edu/timeline/1920 (Shapley-Curtis)


The Andromeda Galaxy (M31)

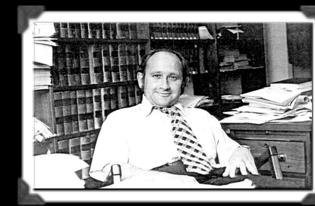

The Andromeda Galaxy (M31)

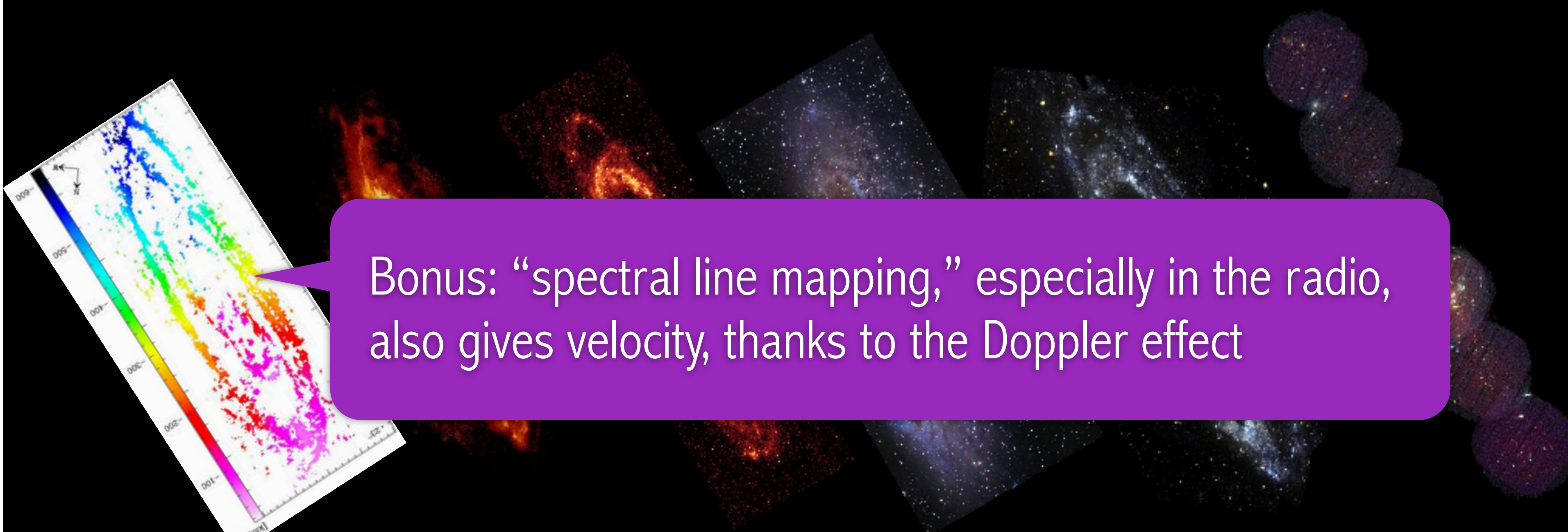

The Andromeda Galaxy (M31)



The Andromeda Galaxy (M31)

Gas, Dust, Stars at Many Wavelengths





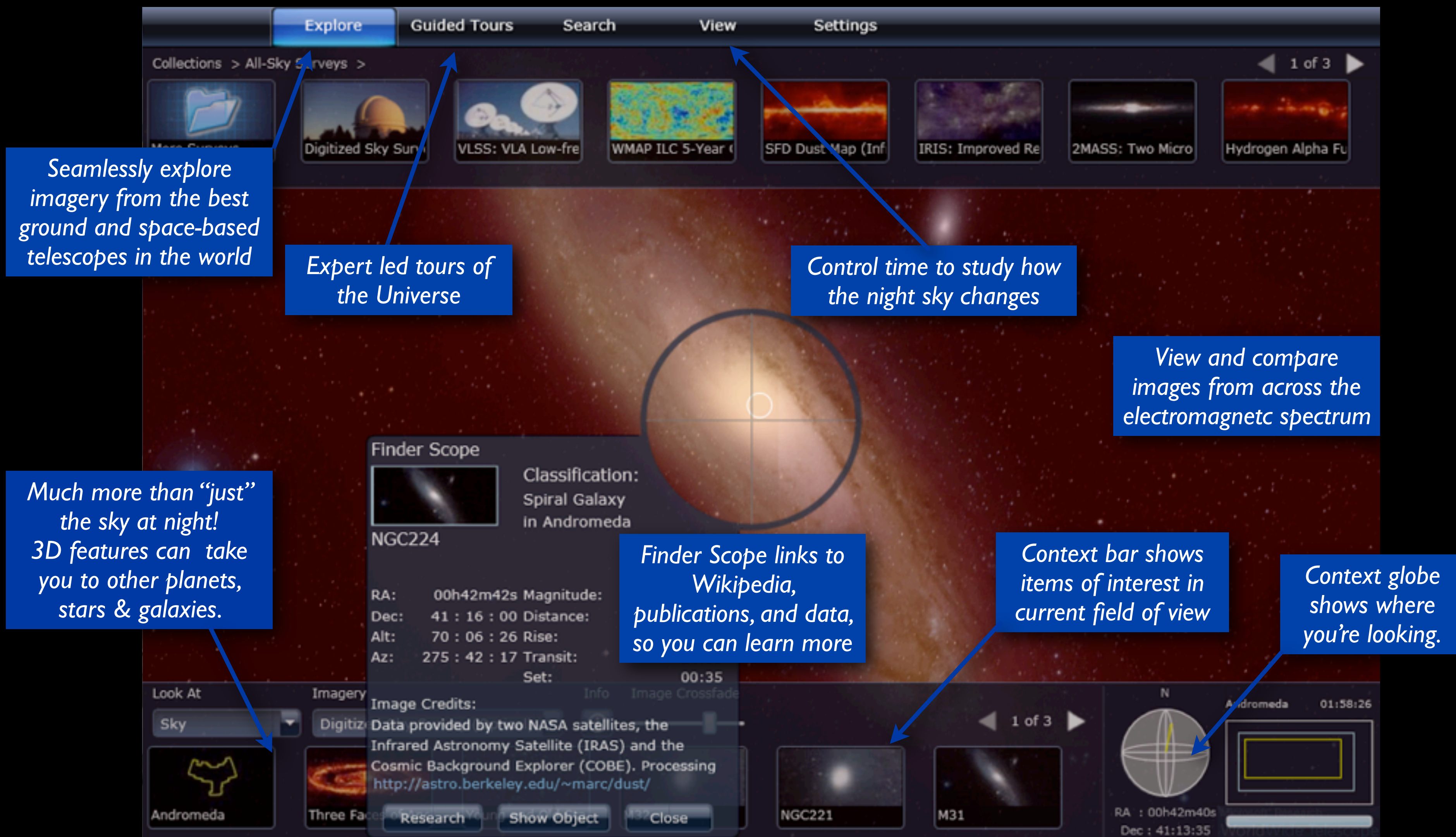
Bonus: “spectral line mapping,” especially in the radio, also gives velocity, thanks to the Doppler effect

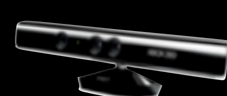
Microsoft® Research

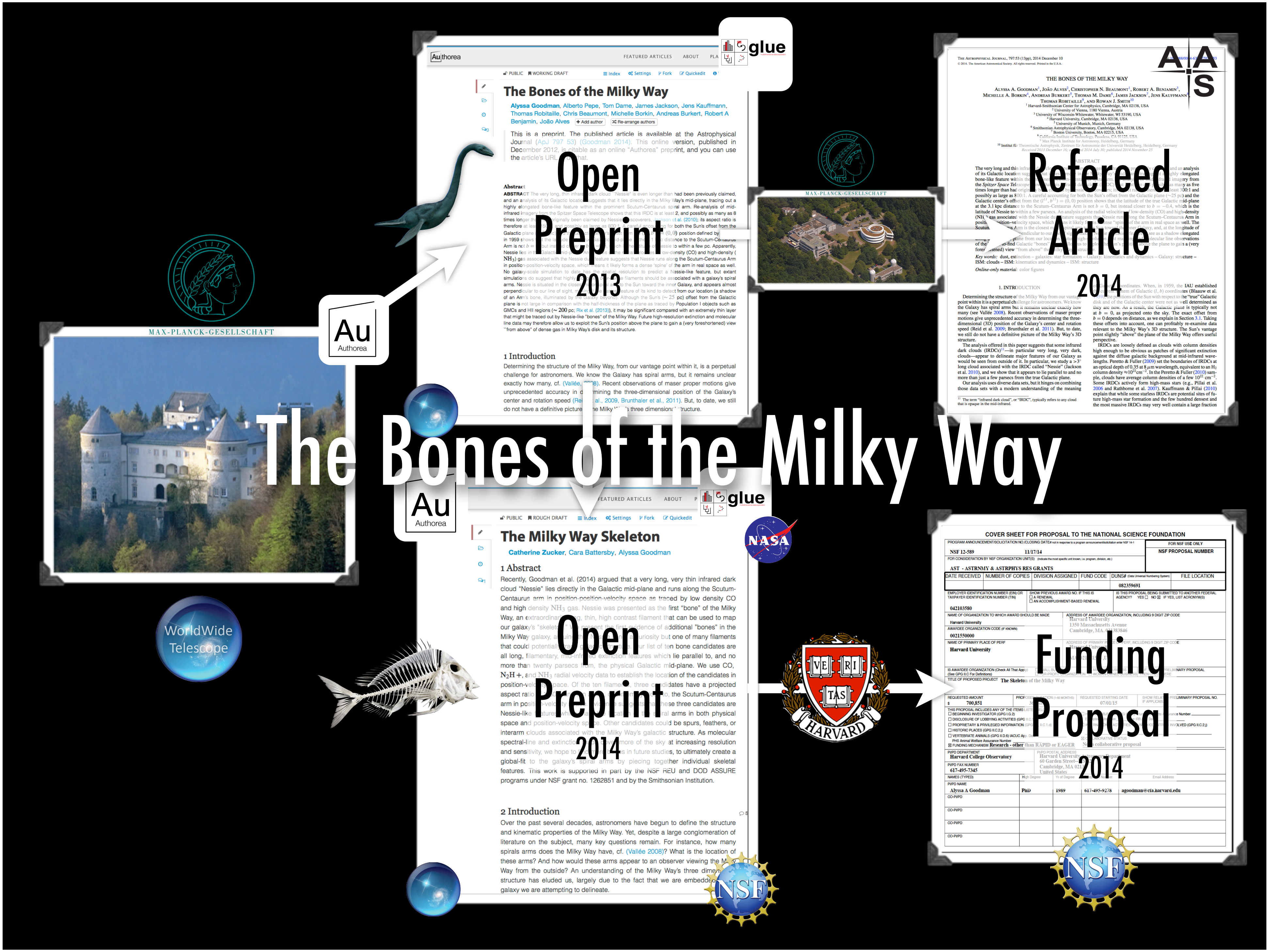
WorldWide Telescope

[demo]

worldwidetelescope.org

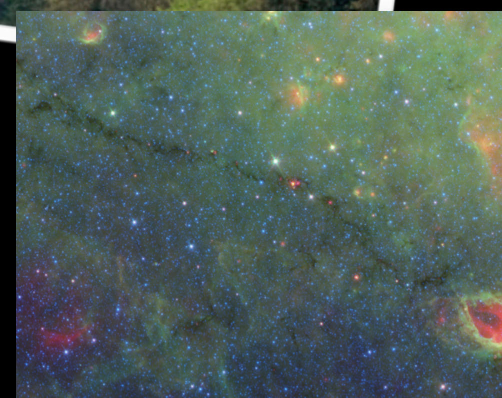


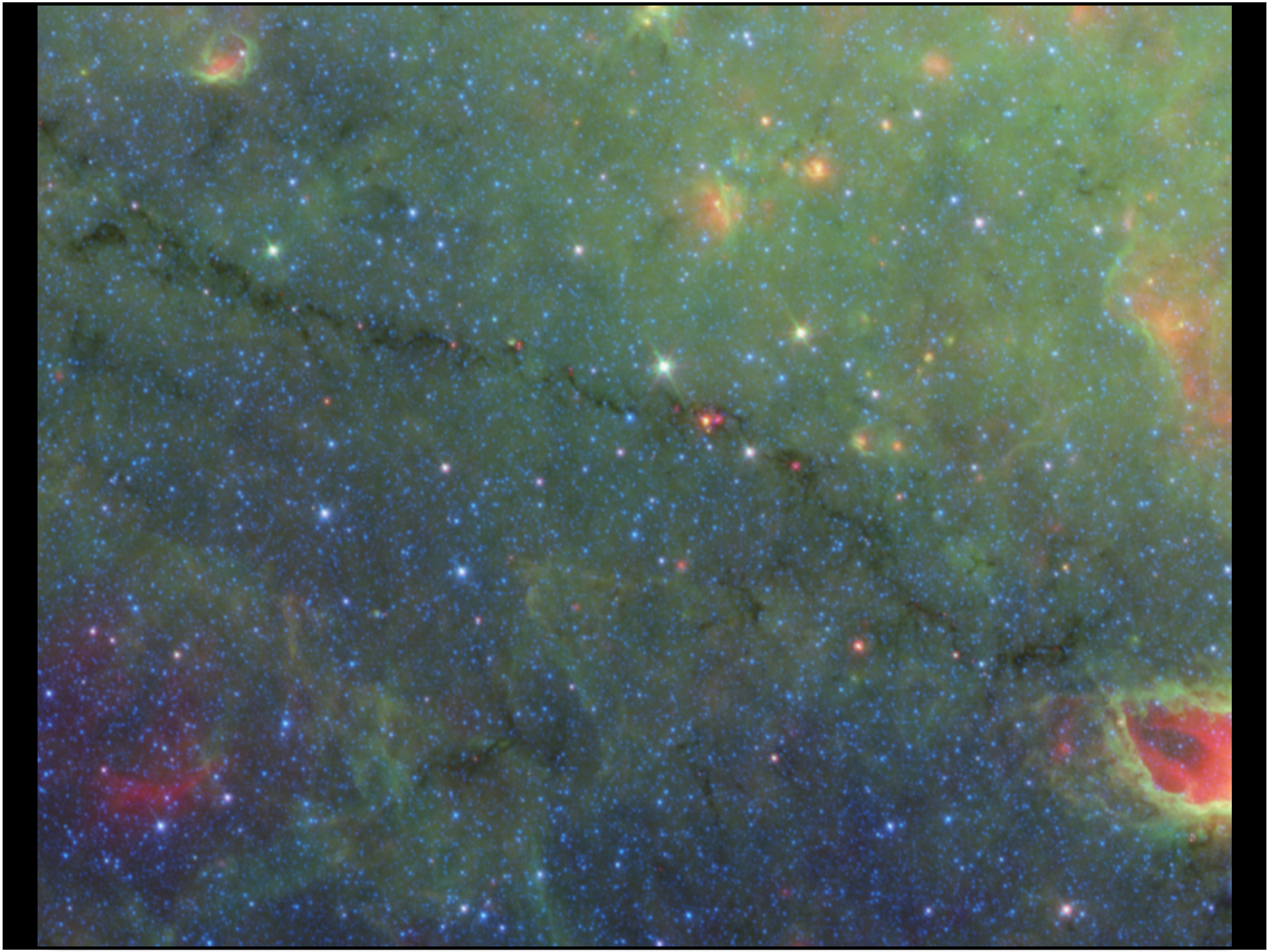



The Bones of the Milky Way
Open Preprint 2013
Refereed Article 2014
Open Preprint 2014
Funding Proposal 2014
MAX-PLANCK-GESELLSCHAFT
WorldWide Telescope
Au Authorea
glue
The Bones of the Milky Way
The Milky Way Skeleton
Catherine Zucker, Cara Battersby, Alyssa Goodman
COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION
NASA
HARVARD
NSF
AAS

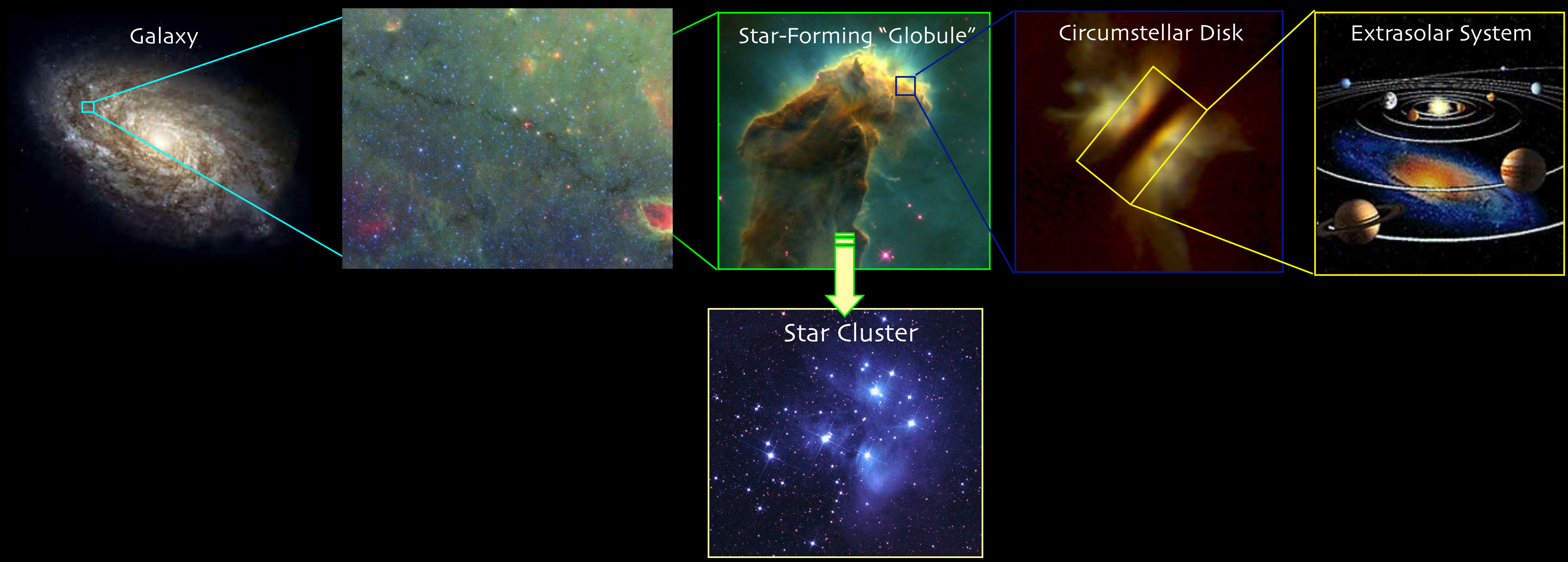
Once upon a time (2012), in an enchanted castle (in Bavaria)

...at a conference about star formation





Star and Planet Formation



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

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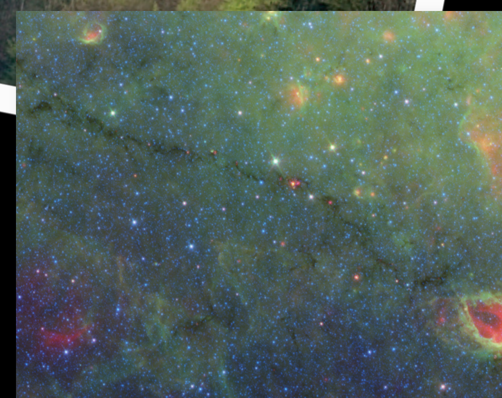


QUESTION *Andi Burkert*: Is Nessie "parallel to the Galactic Plane"?

ANSWER *no one* immediately knew the answer!

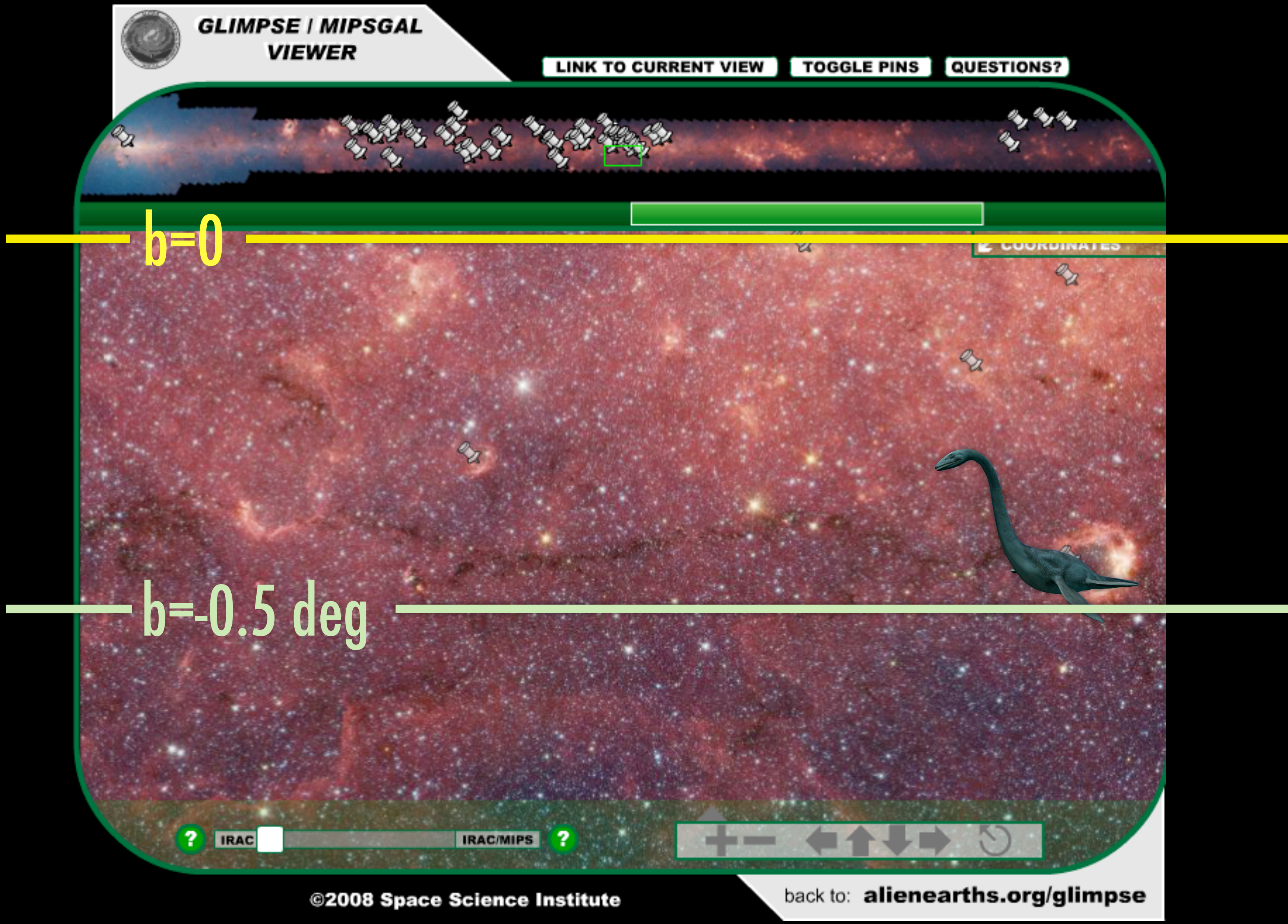
The Milky Way

“Galactic Plane”

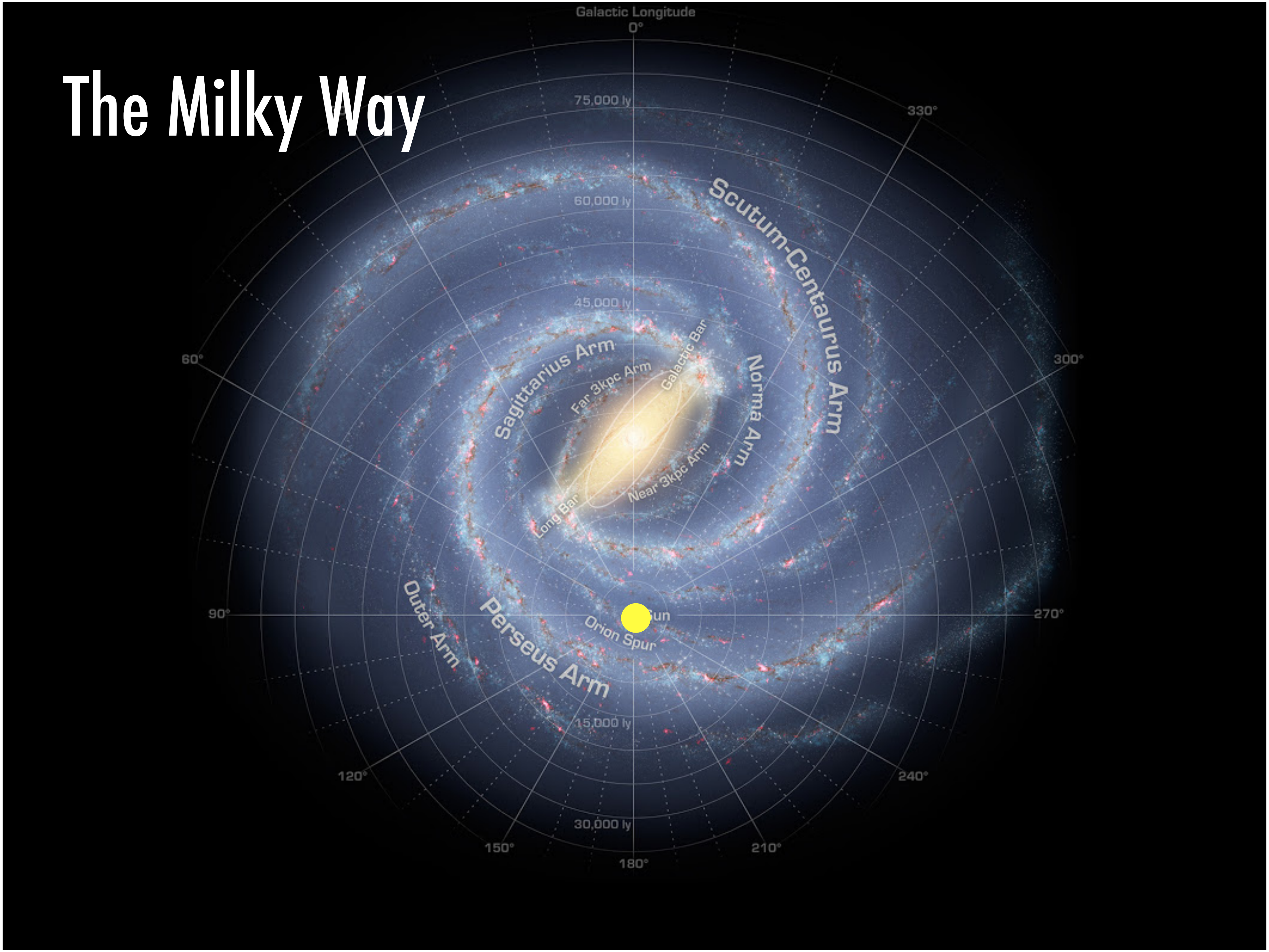
The Milky Way
(Artist's Conception)

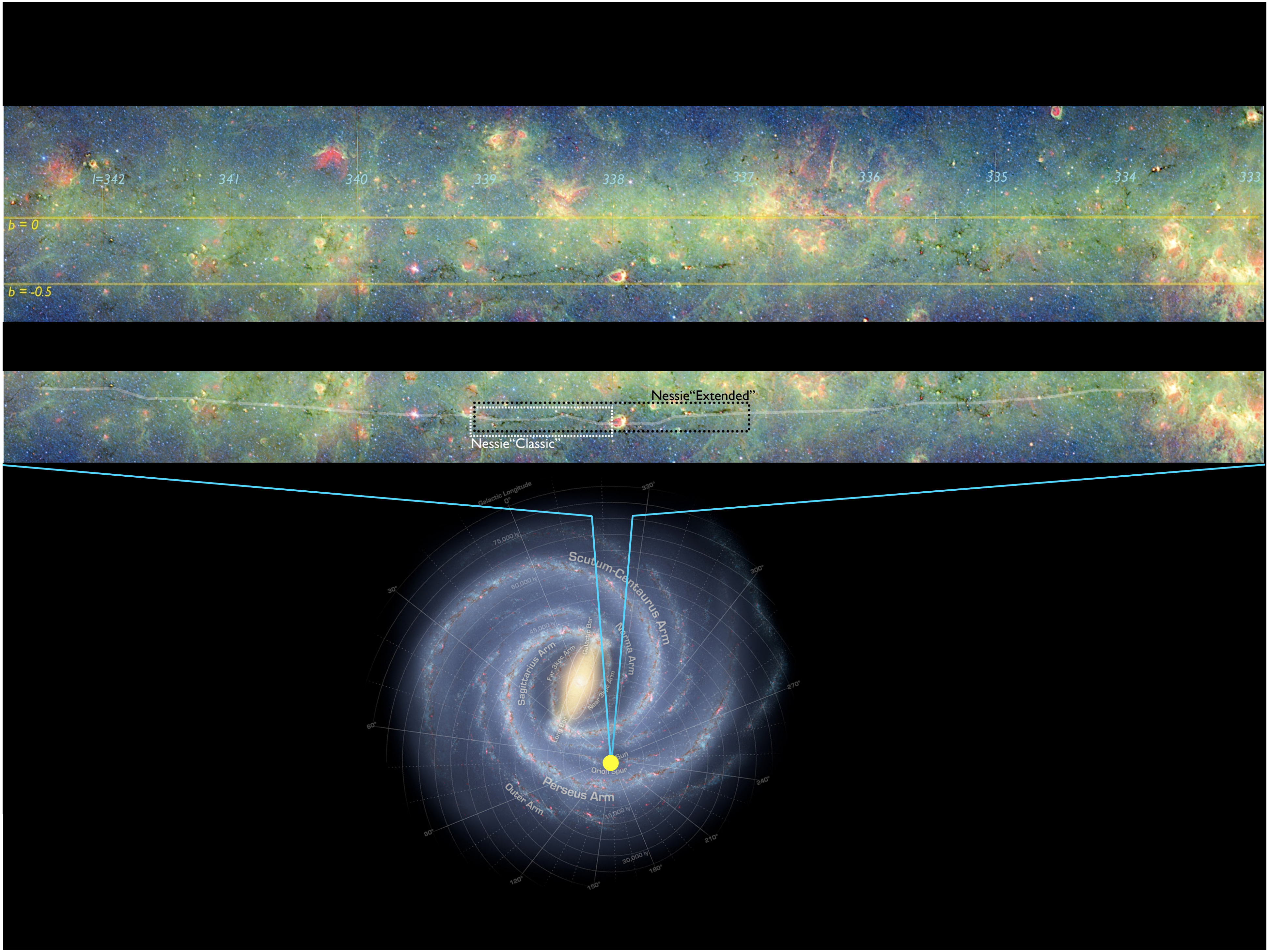
“Is Nessie Parallel to the Galactic Plane?”

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

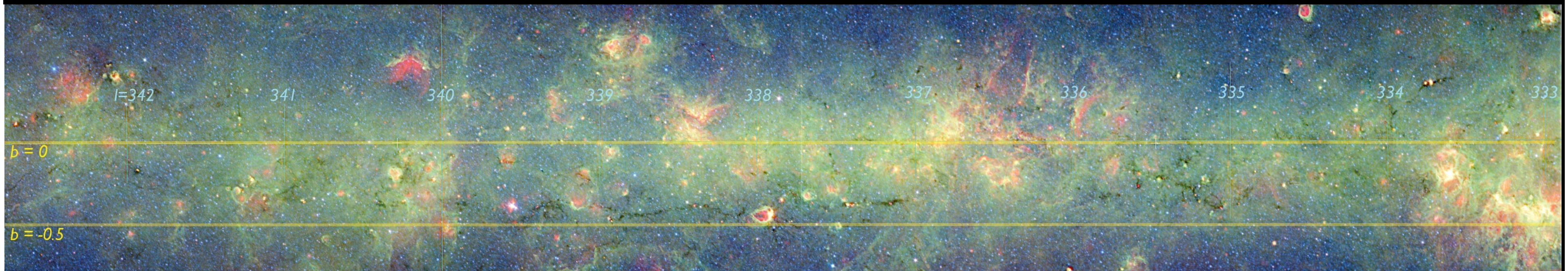


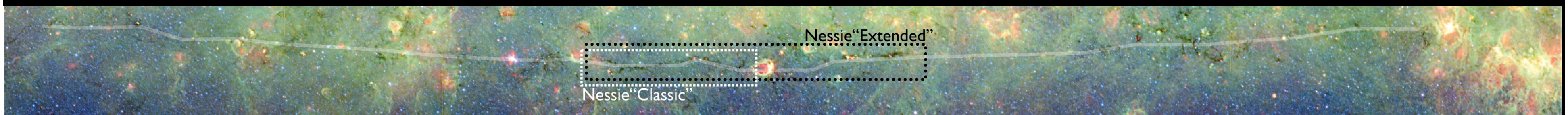
The Milky Way





l=342
341
340
339
338
337
336
335
334
333
b = 0
b = -0.5
Nessie"Extended"
Nessie"Classic"
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Galactic Bar
Sun
Orion Spur
Galactic Longitude





"Nessie Extended"

~500 light years long & 1.5 light years thick

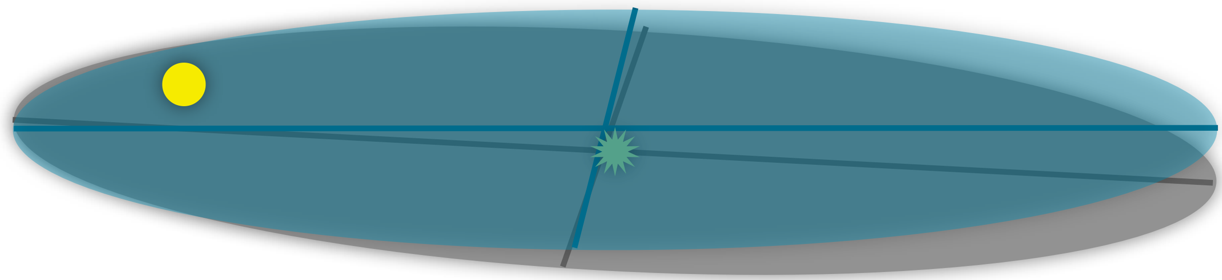
300:1 axial ratio

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]*

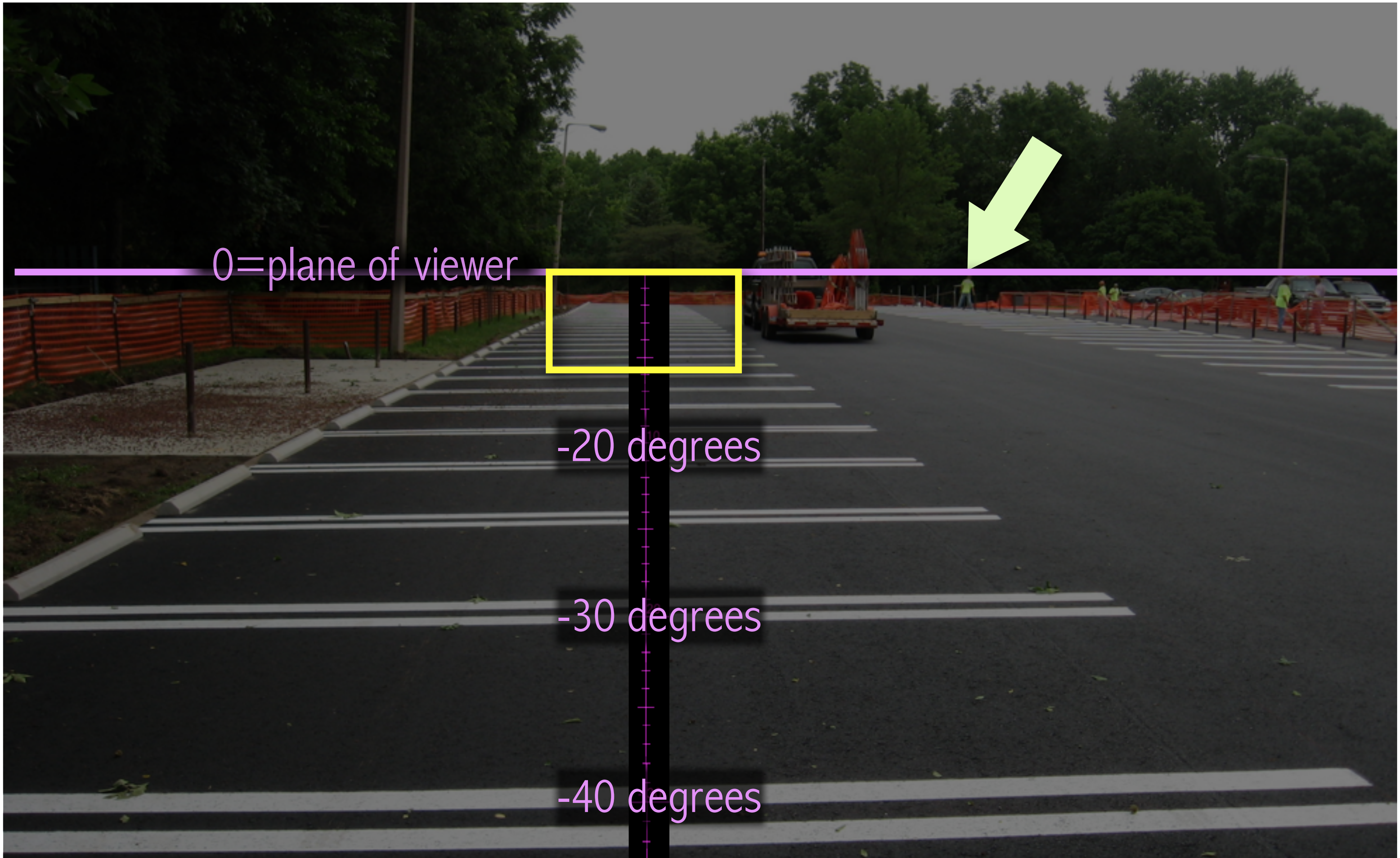
Sun is ~75 light years "above" the IAU Milky Way Plane

\+

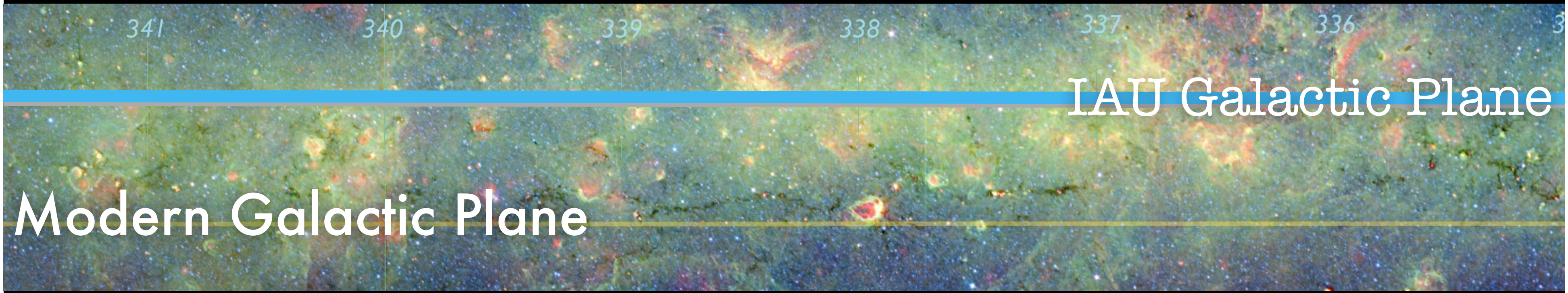
Galactic Center is ~20 light years offset from the IAU Milky Way Center

=

The **Galactic Plane is not quite where you'd think it is** when you look at the sky



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

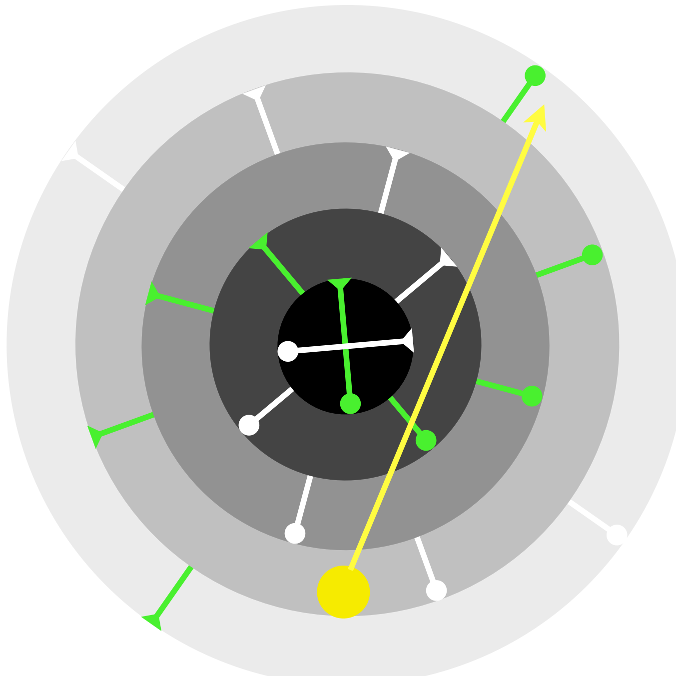


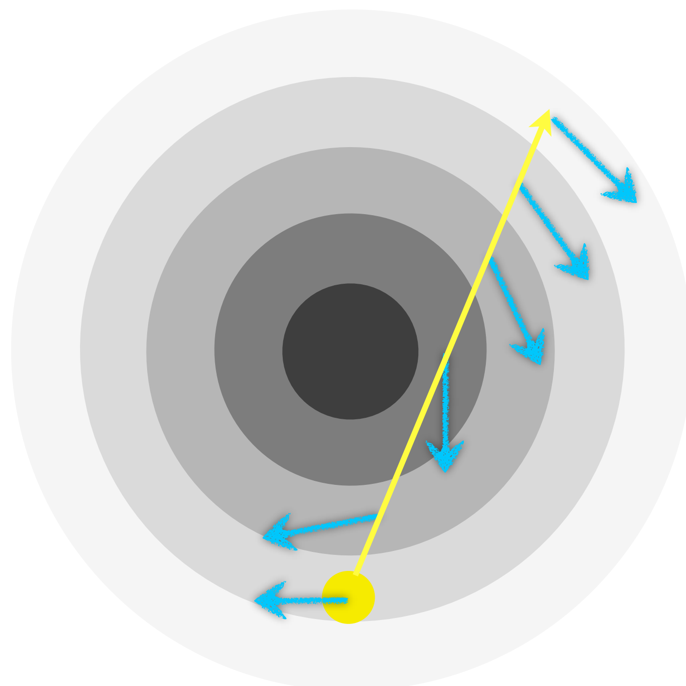
Yes, Nessie is EXACTLY in the Galactic Plane!

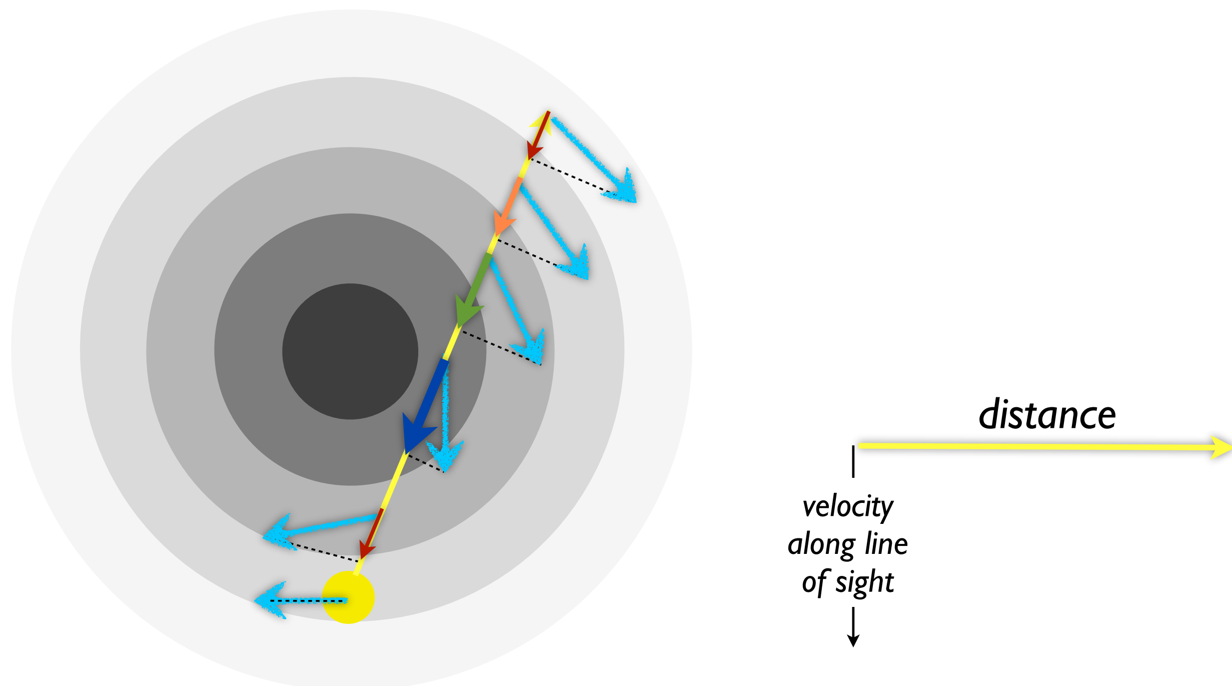
What about its distance?

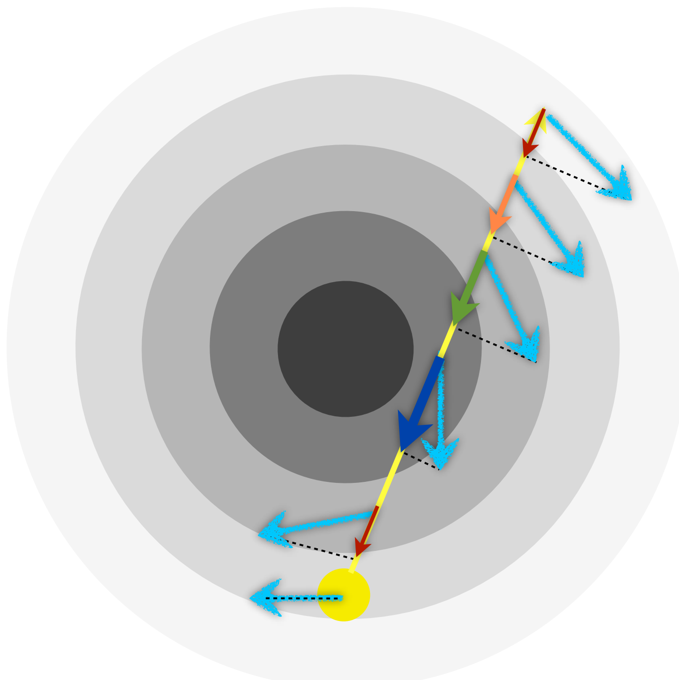
we can use “radial velocities” to estimate distance in a rotating galaxy...

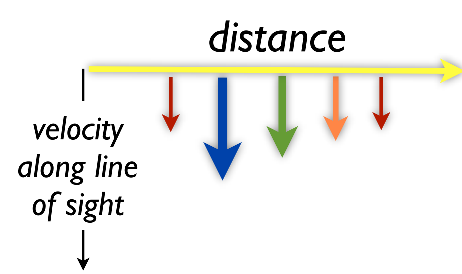
A Rotating (Spiral) Galaxy Observed from its Outskirts...



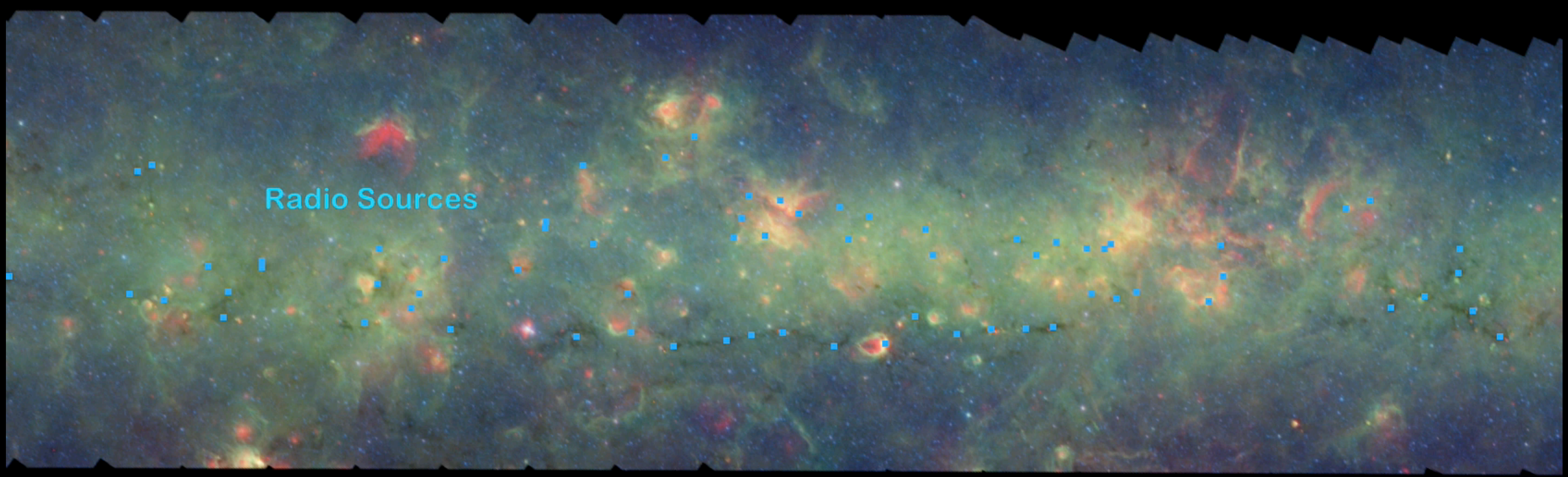



distance
velocity
along line
of sight

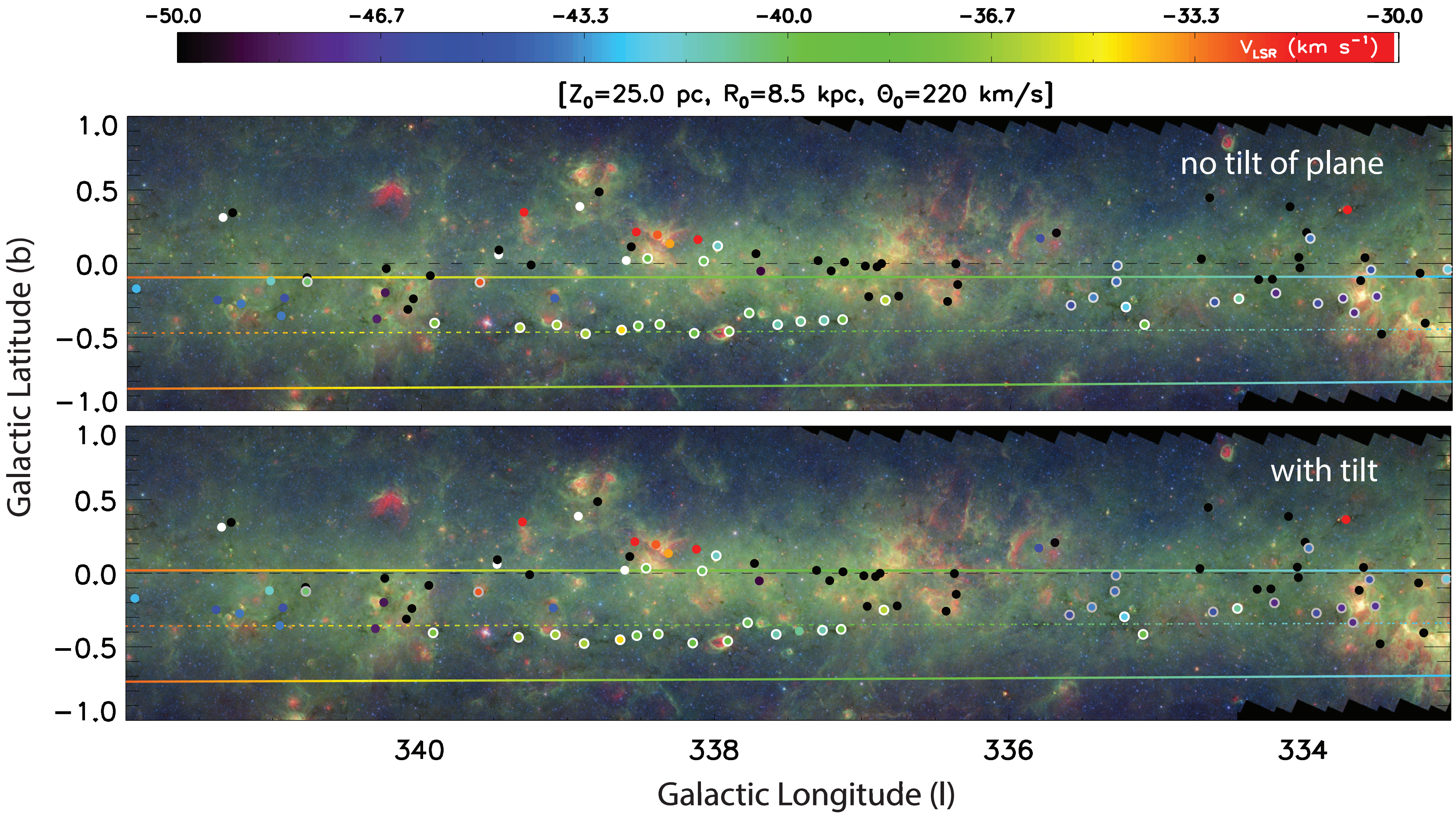


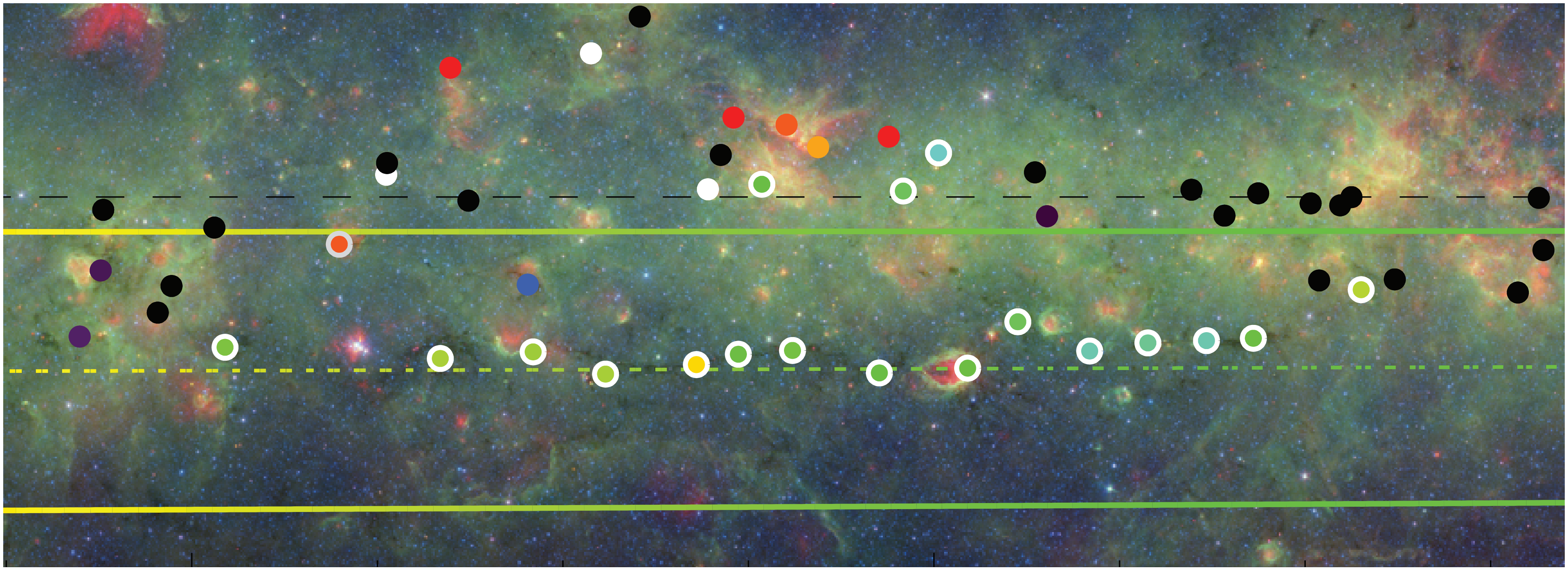

distance
velocity
along line
of sight

Velocity to Distance



In the plane and at the distance of spiral arm!



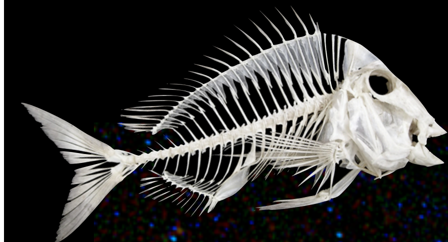


...eerily precisely...

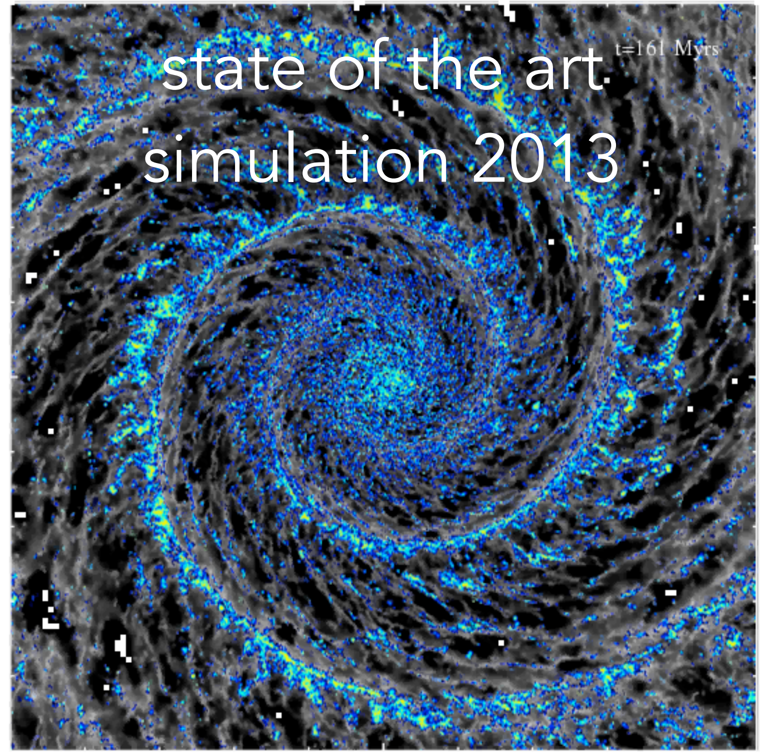
Monster to Bone

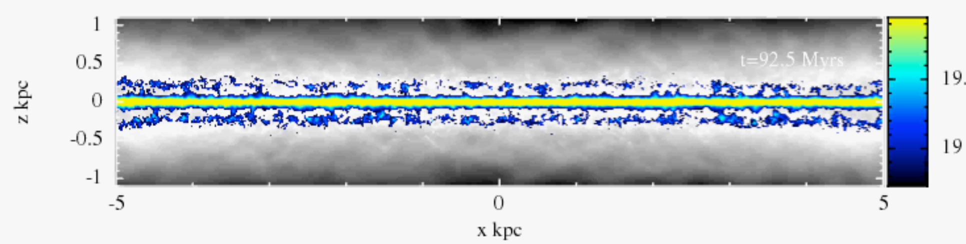
There could be 1000s more of these to find...a full skeleton perhaps?

A full 3D skeleton?



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

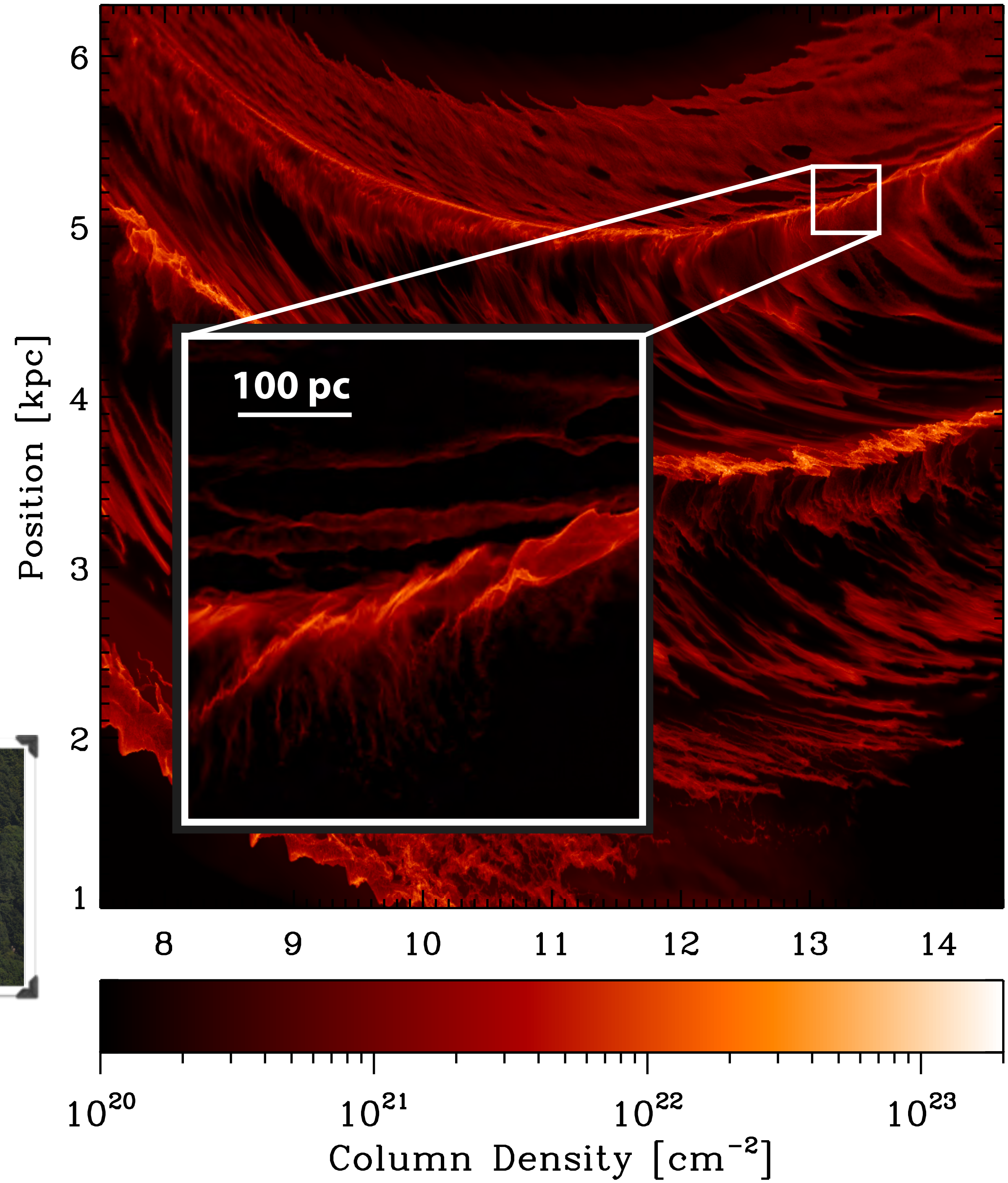




simulations courtesy Clare Dobbs

New!

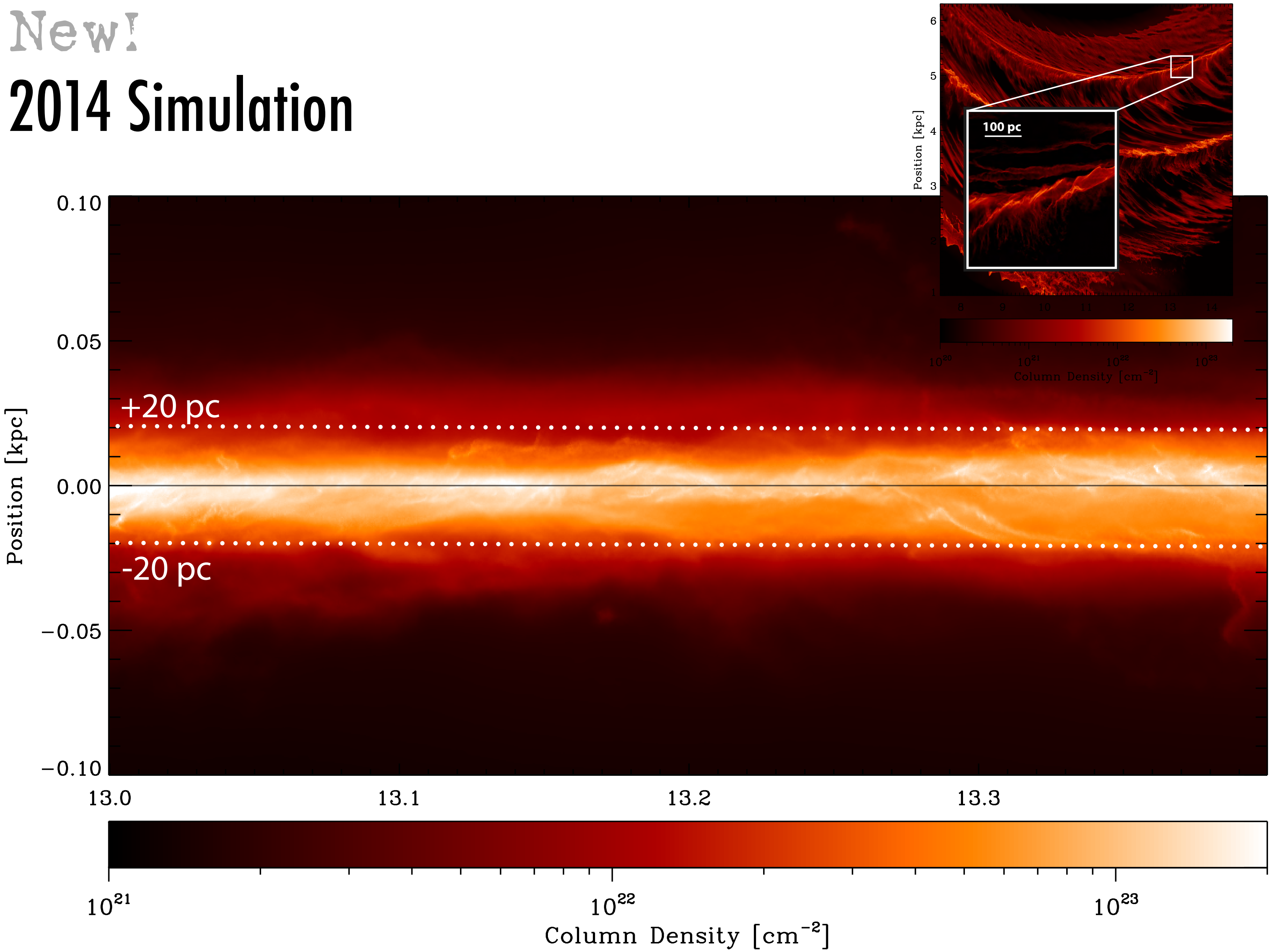
2014 Simulation



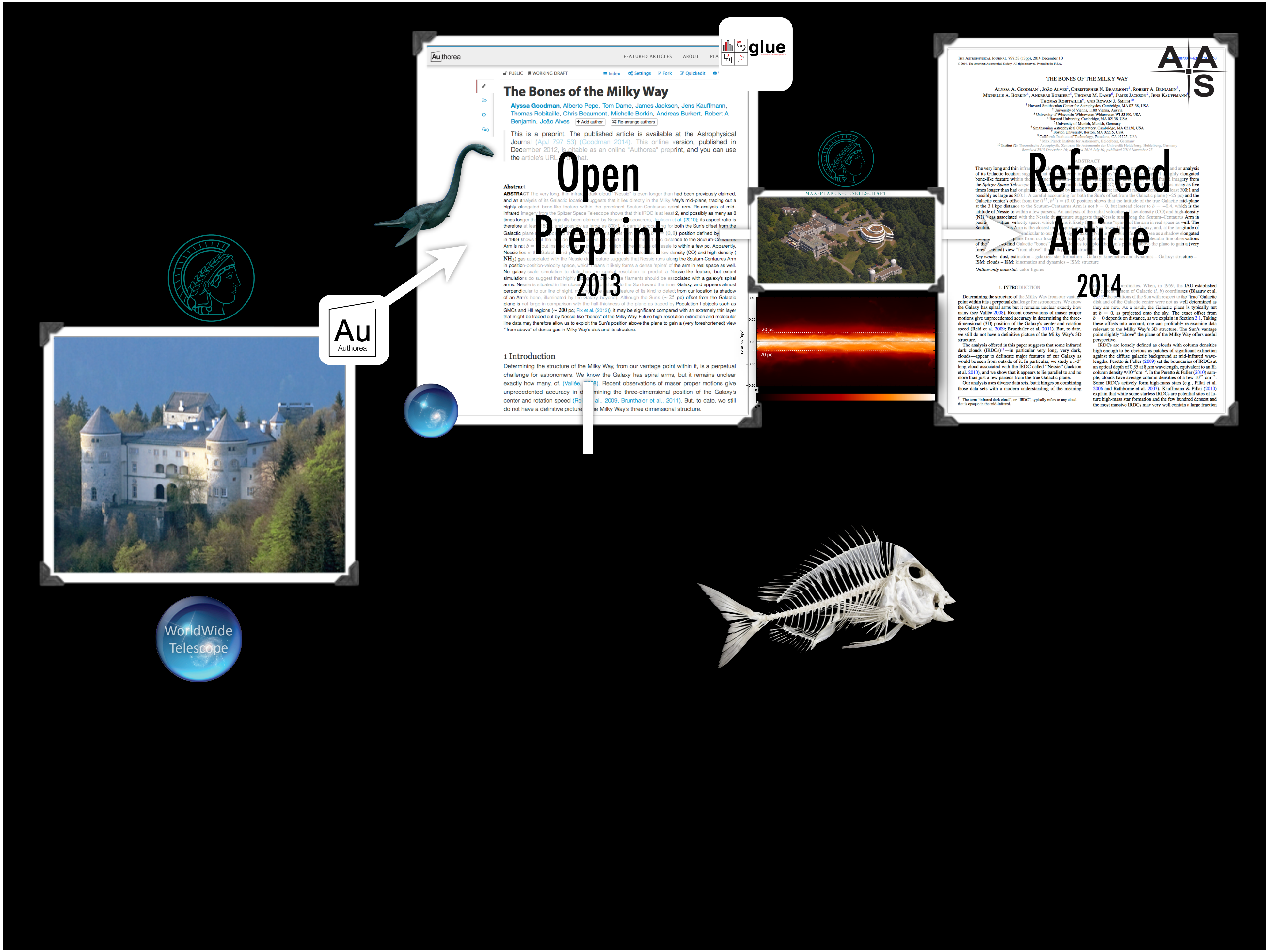
Smith et al. 2014, using AREPO

New!

2014 Simulation



Smith et al. 2014, using AREPO



glue
The Bones of the Milky Way
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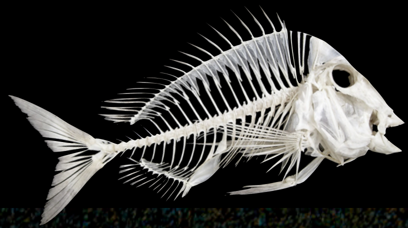
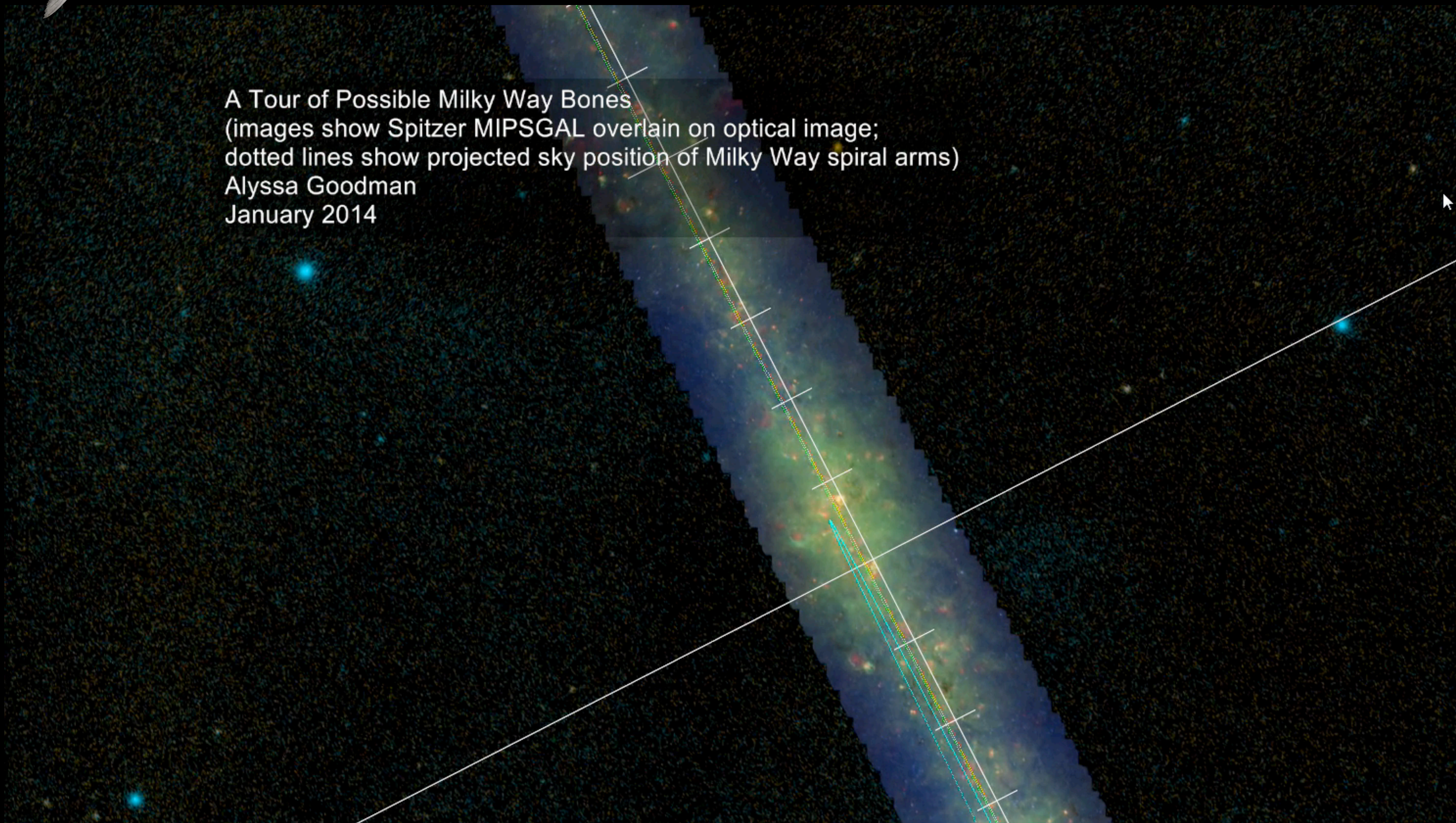
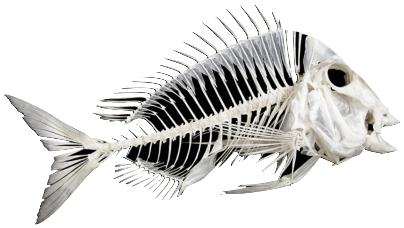
2014
THE BONES OF THE MILKY WAY
WorldWide
Telescope



Can we find more bones?

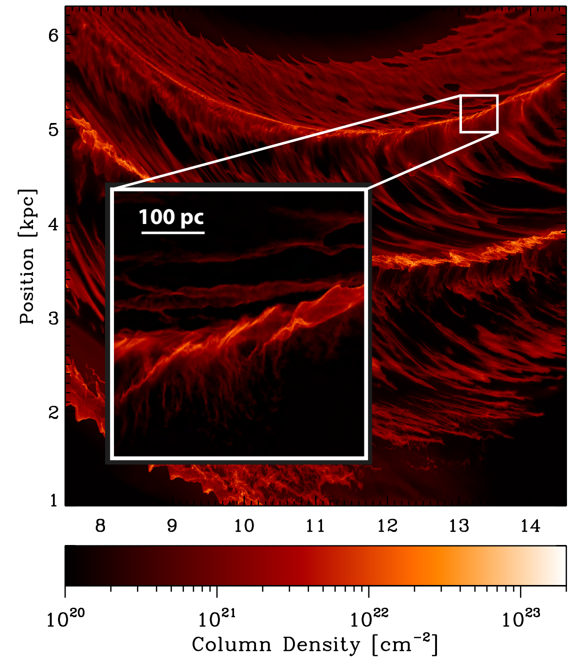


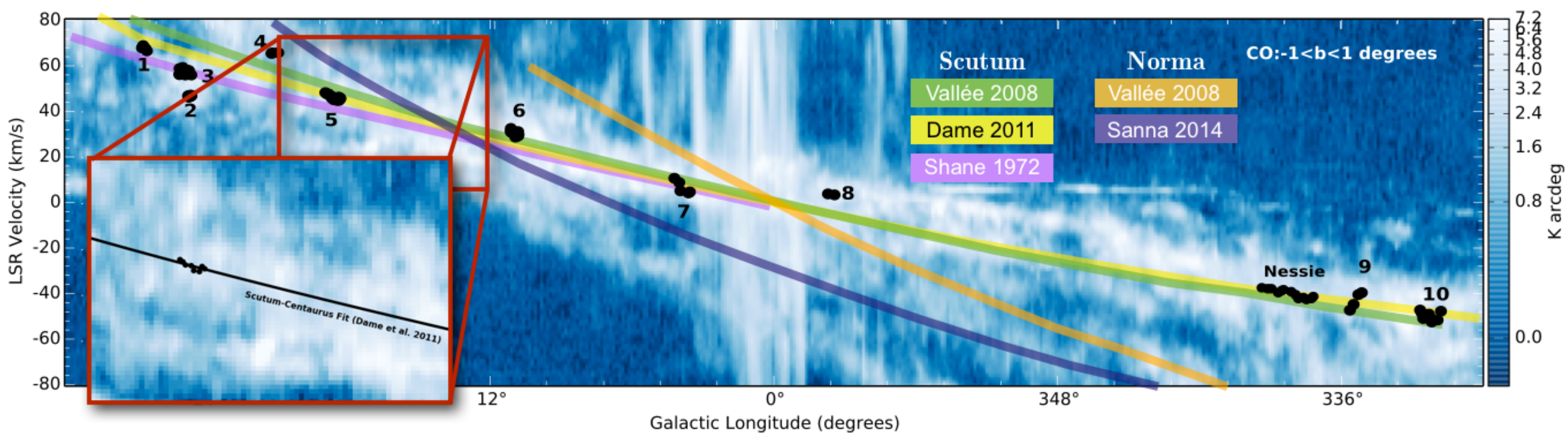
[demo]



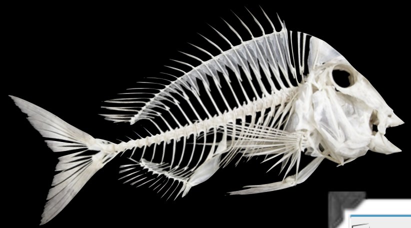
Short Answer: Yes

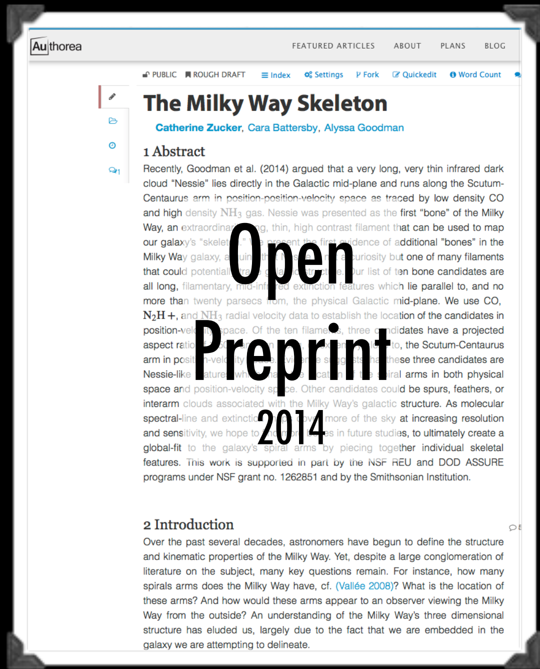
Both on the sky, and along the line of sight (so in "3D"), we find "bones" in the right places to give a detailed skeleton.

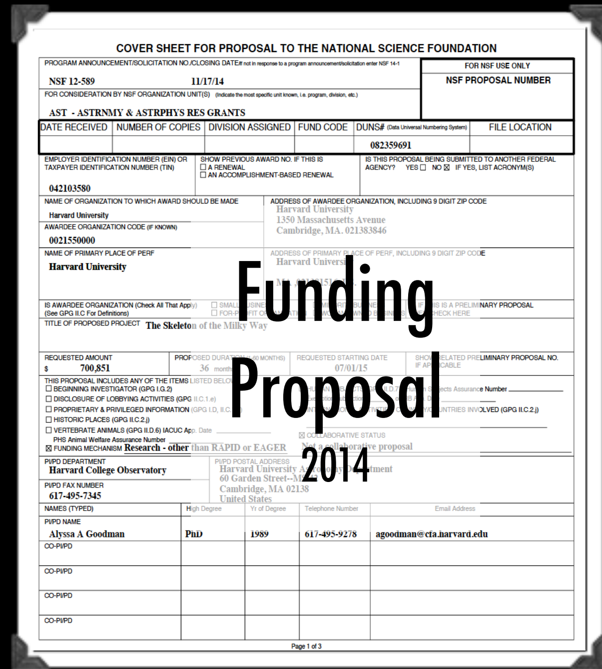


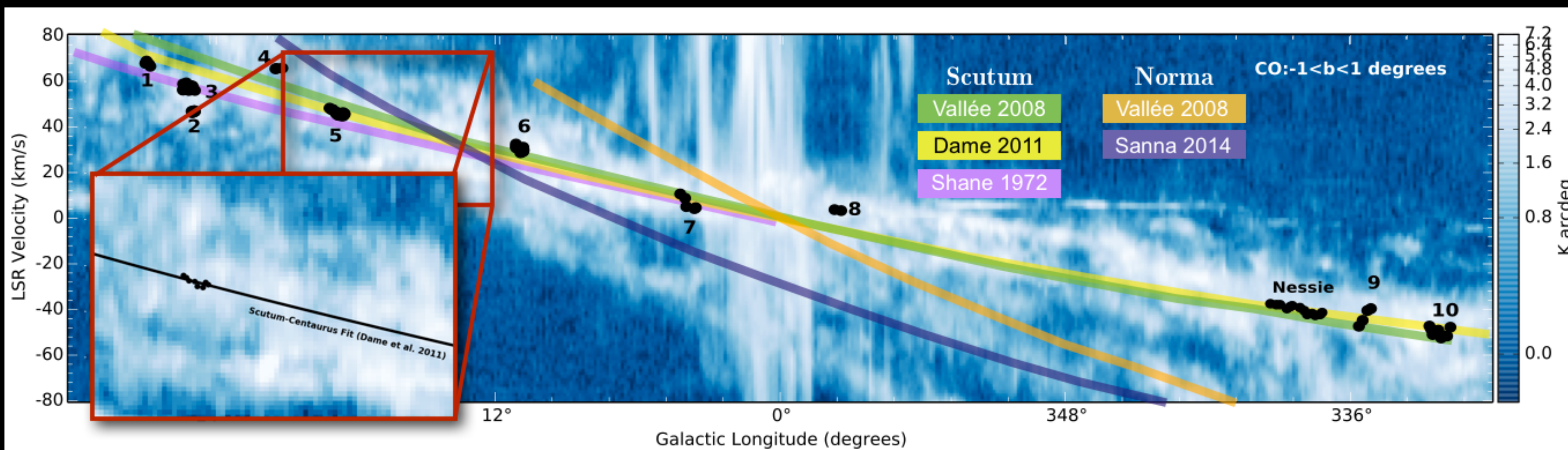


Longer Answer: (Also Yes).







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Proposal
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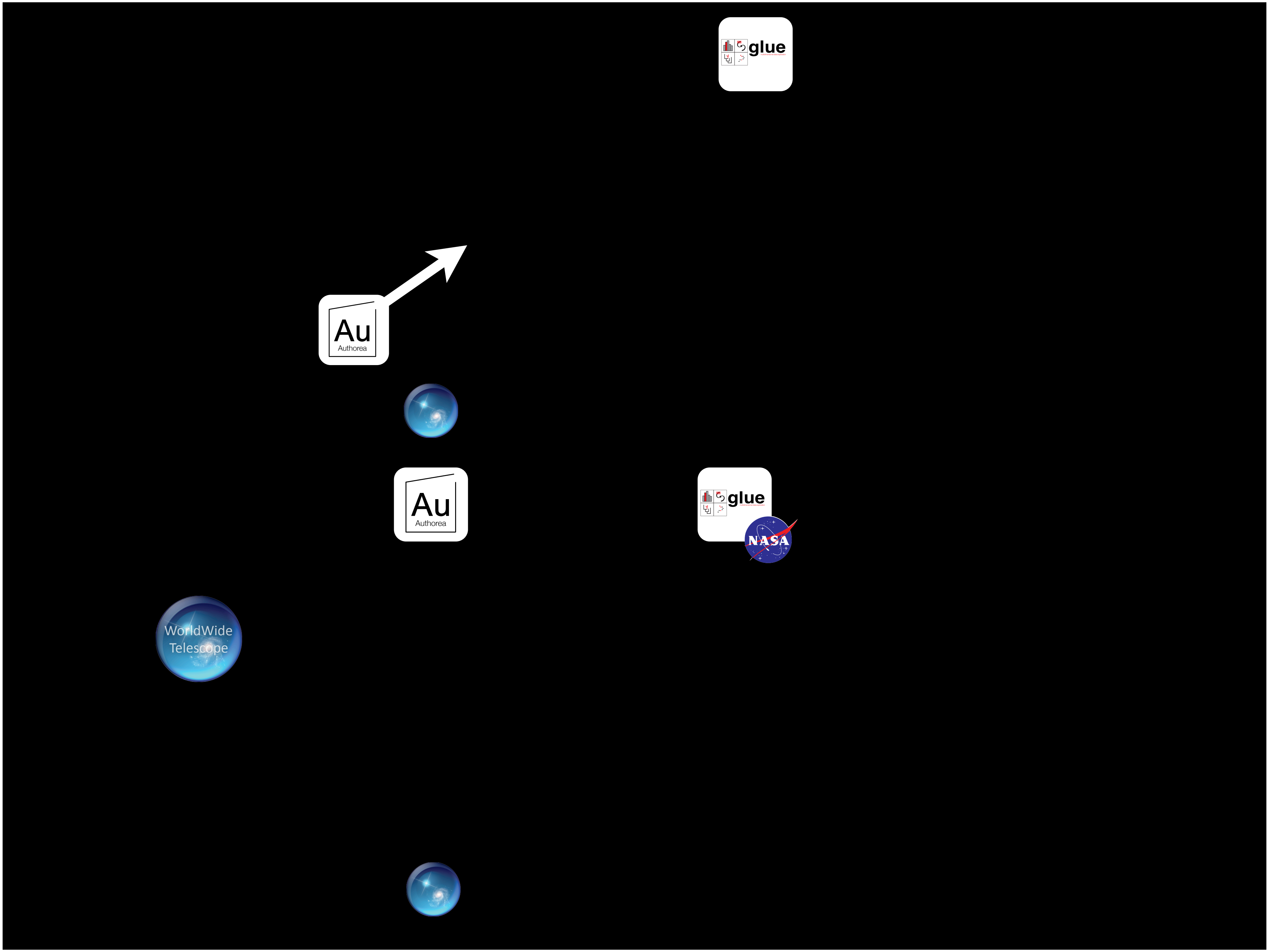
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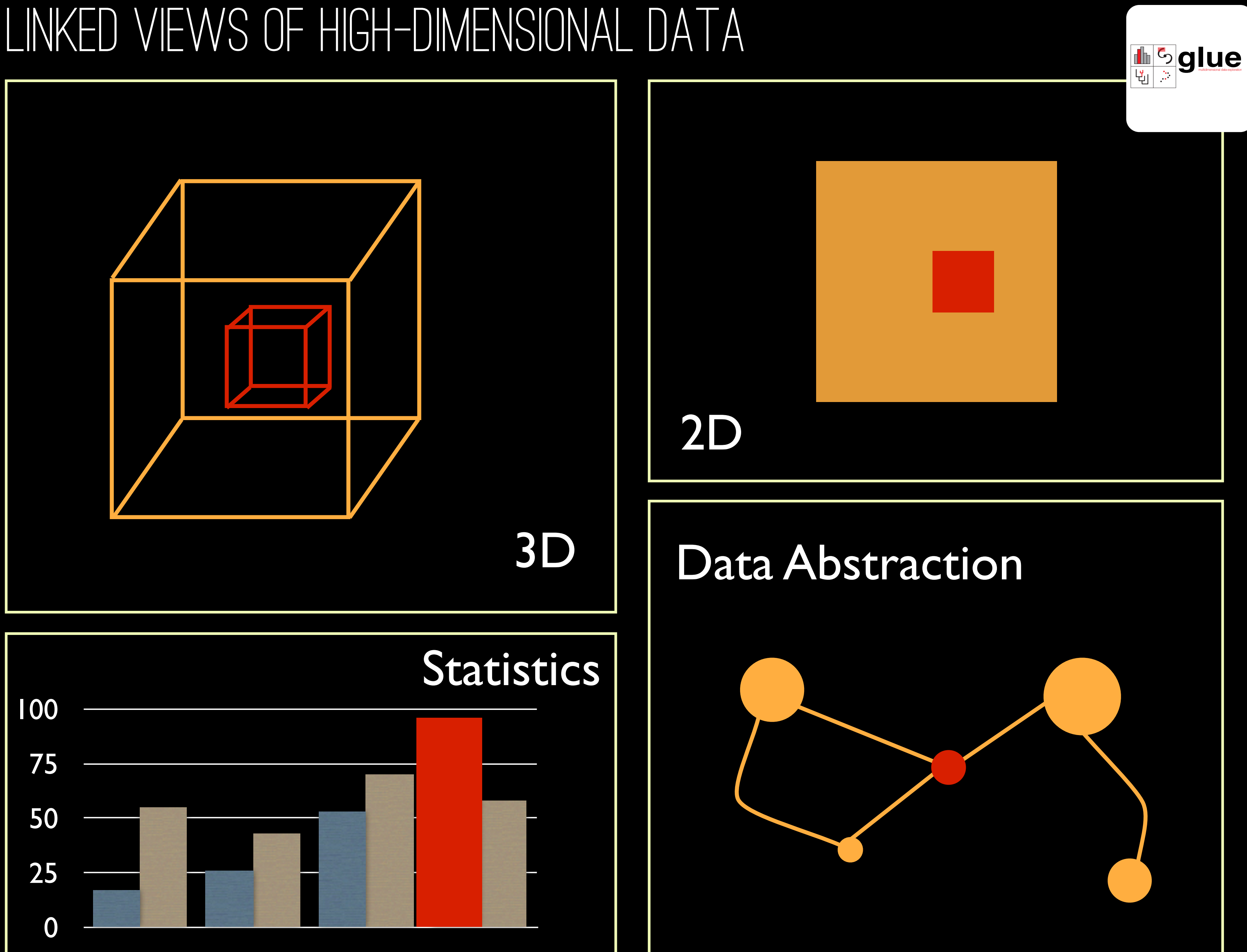
NASA
WorldWide
Telescope

SEAMLESS ASTRONOMY

Linking scientific data, publications, and communities

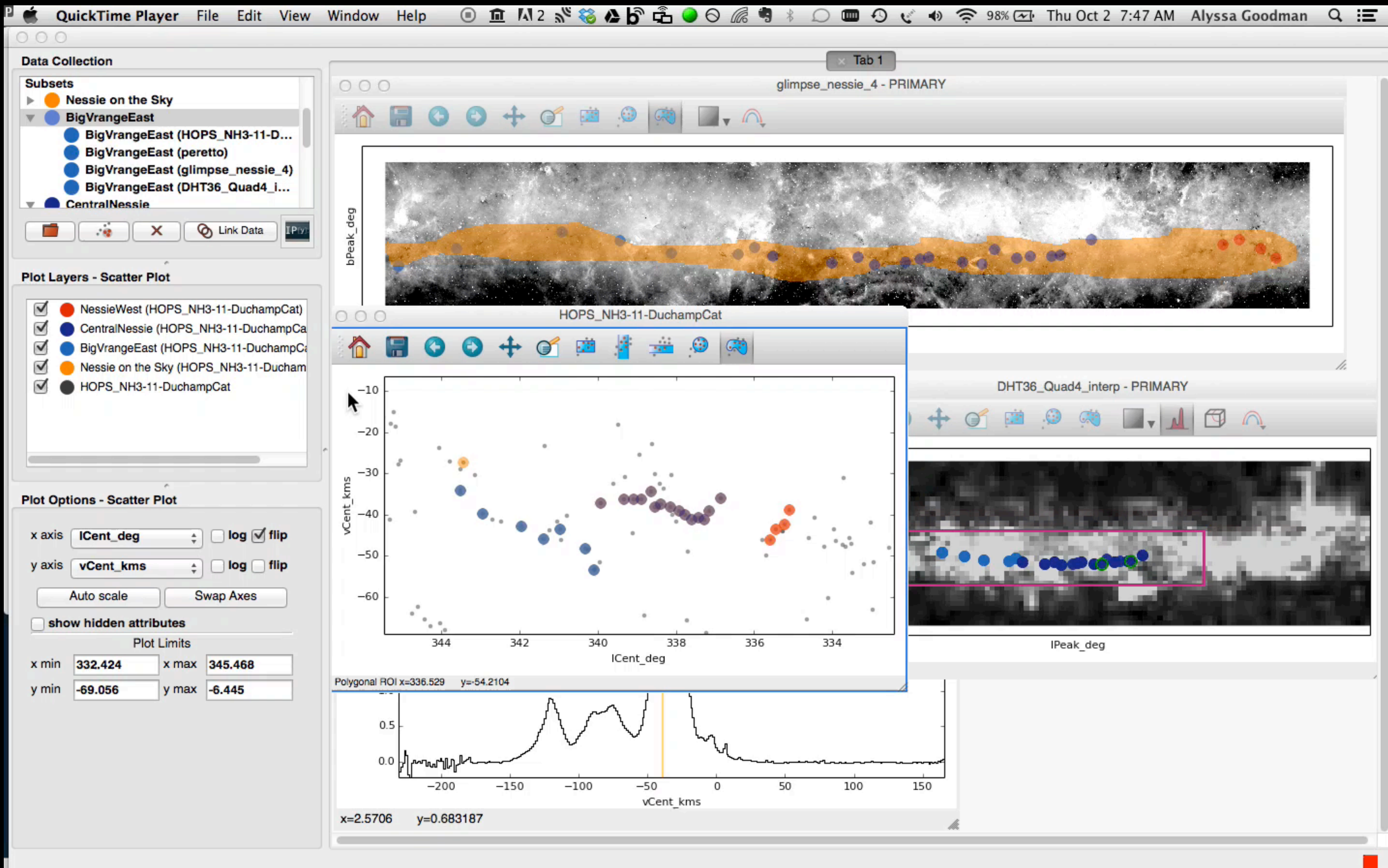
- Universe Information System
- Linked-View Visualization
- Open Collaborative Publishing

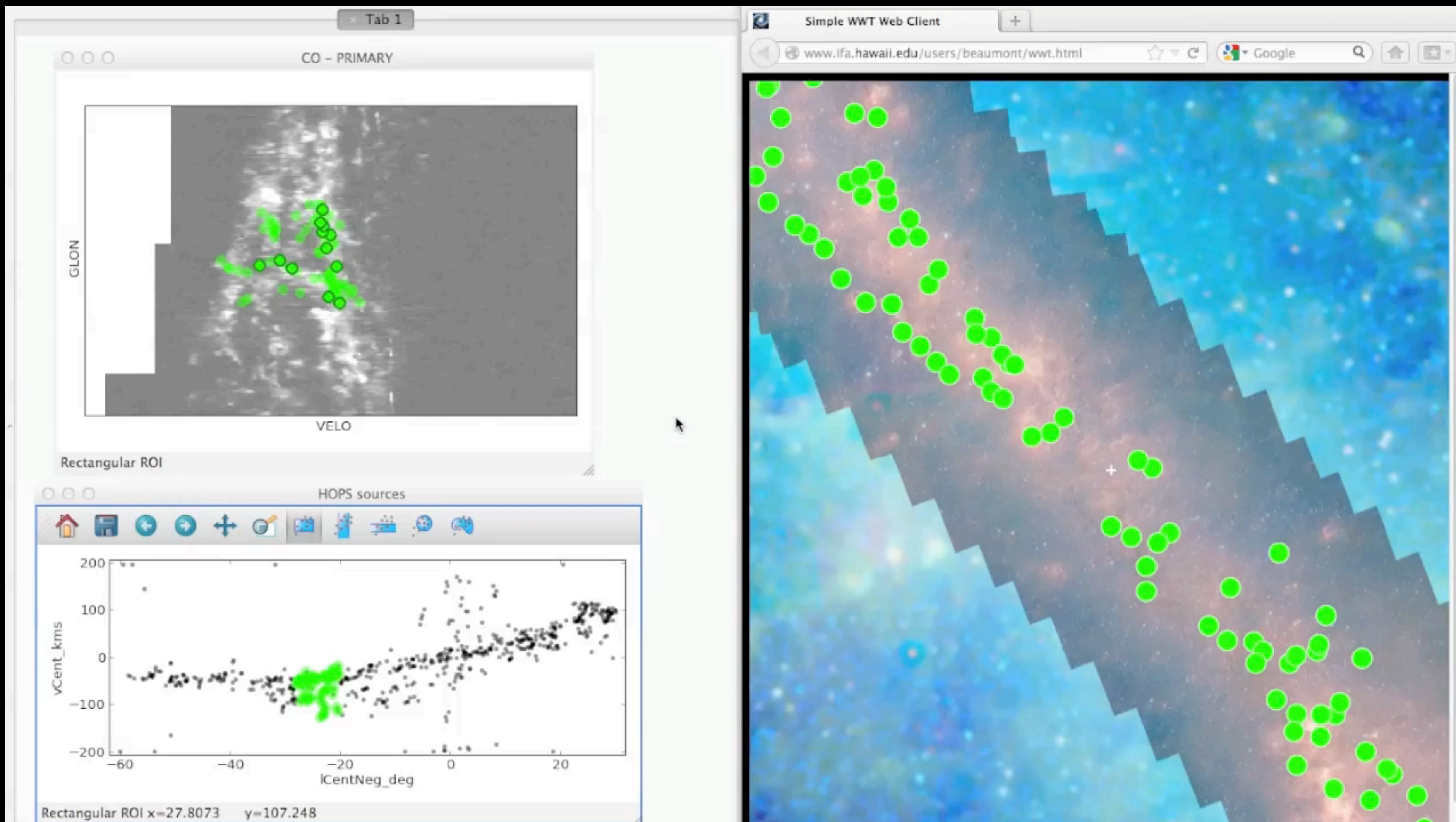
LINKED VIEWS OF HIGH-DIMENSIONAL DATA



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

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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 demonsration of this paper is available at this YouTube link.

2

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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 commuicate 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.

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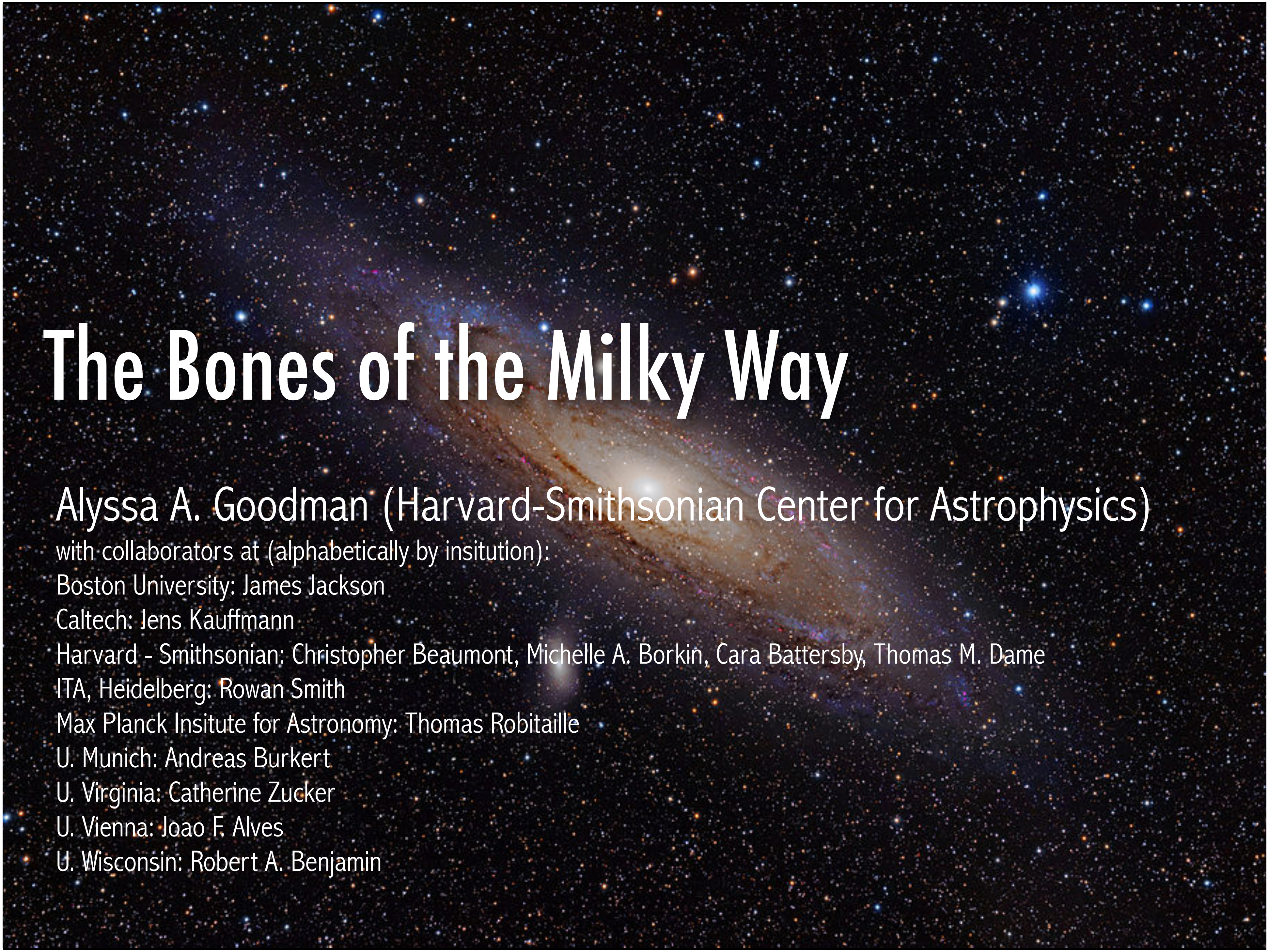
The Bones of the Milky Way: Credits

Seamless Astronomy-style tools used in this project

SEAMLESS ASTRONOMY
Linking scientific data, publications, and communities

- 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 Microsoft Research, NSF, NASA, VE RI TAS, Smithsonian

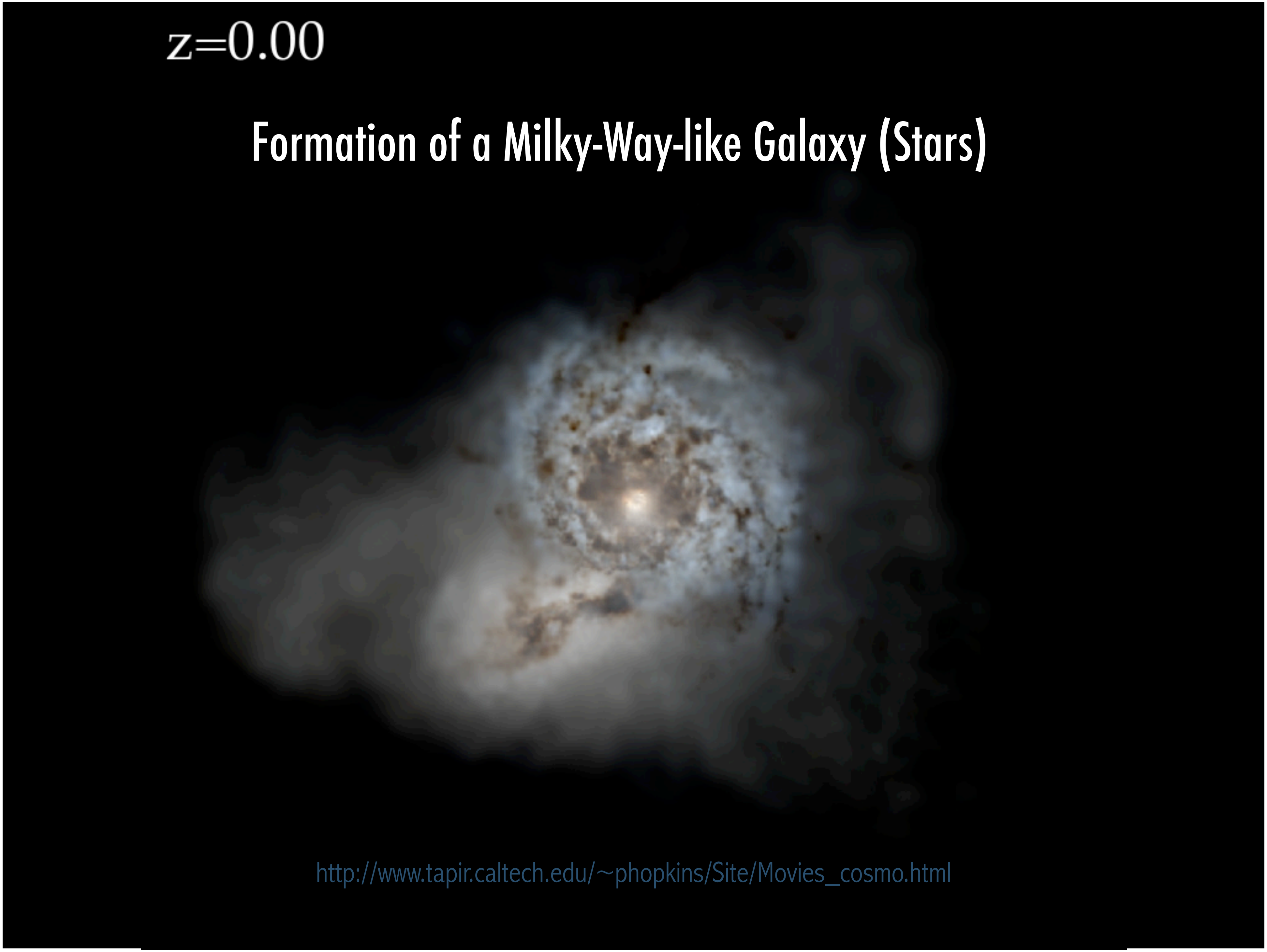


The Bones of the Milky Way

Alyssa A. Goodman (Harvard-Smithsonian Center for Astrophysics)
with collaborators at (alphabetically by insitution):
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 Insitute for Astronomy: Thomas Robitaille
U. Munich: Andreas Burkert
U. Virginia: Catherine Zucker
U. Vienna: Joao F. Alves
U. Wisconsin: Robert A. Benjamin

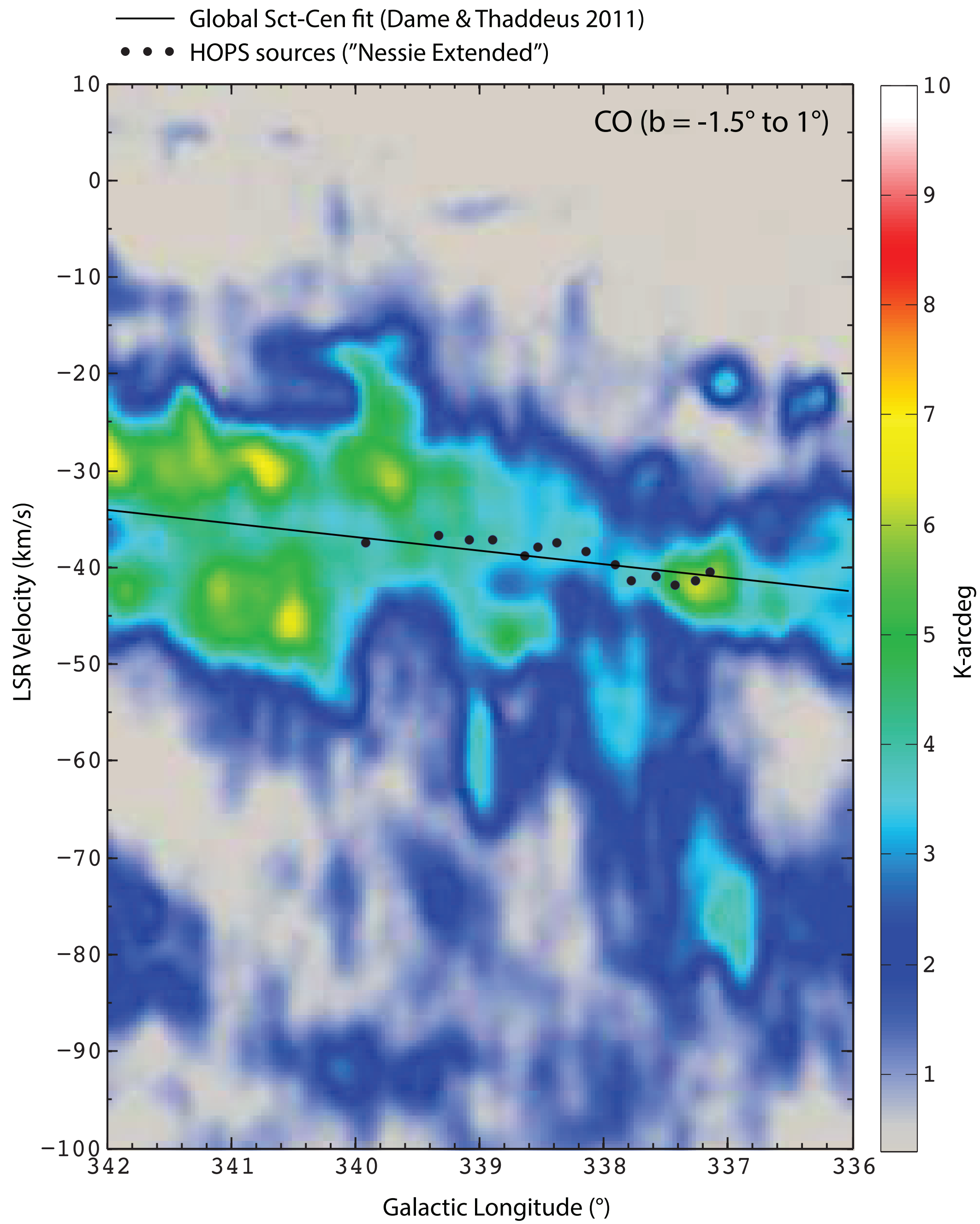
extra slides

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

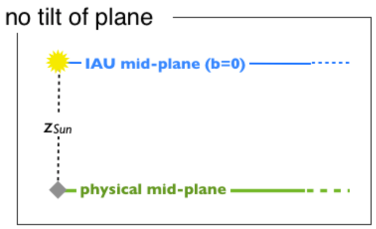


http://www.tapir.caltech.edu/~phopkins/Site/Movies_cosmo.html

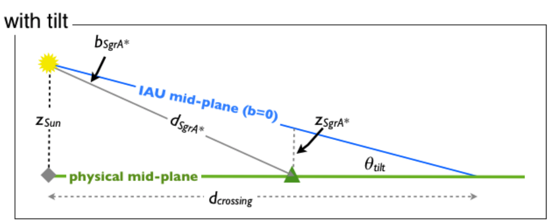
...eerily precisely...

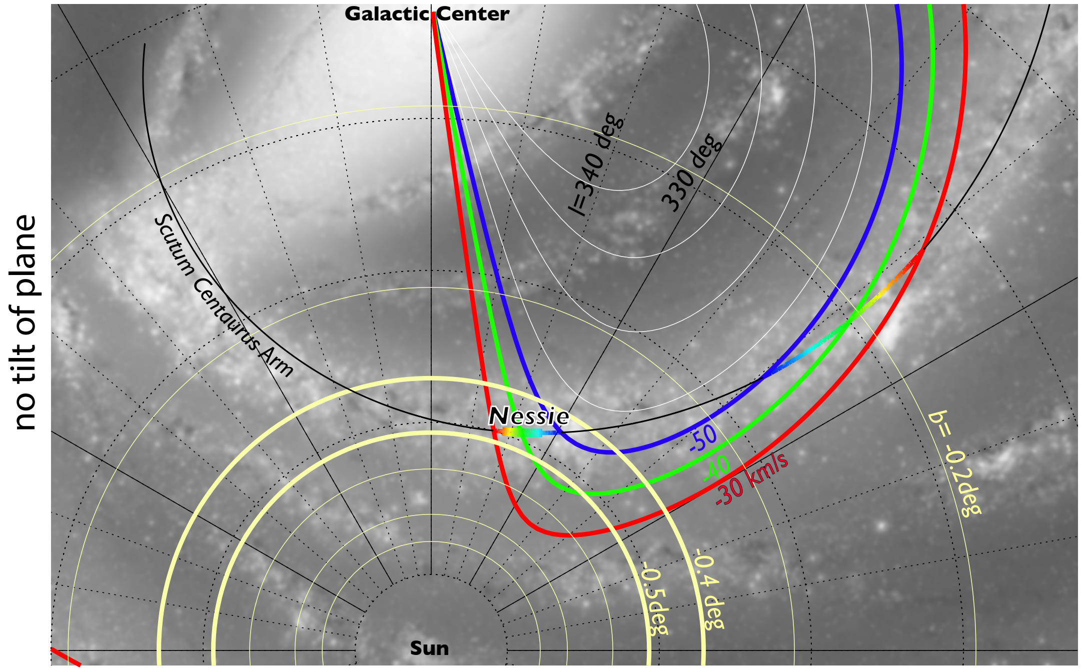


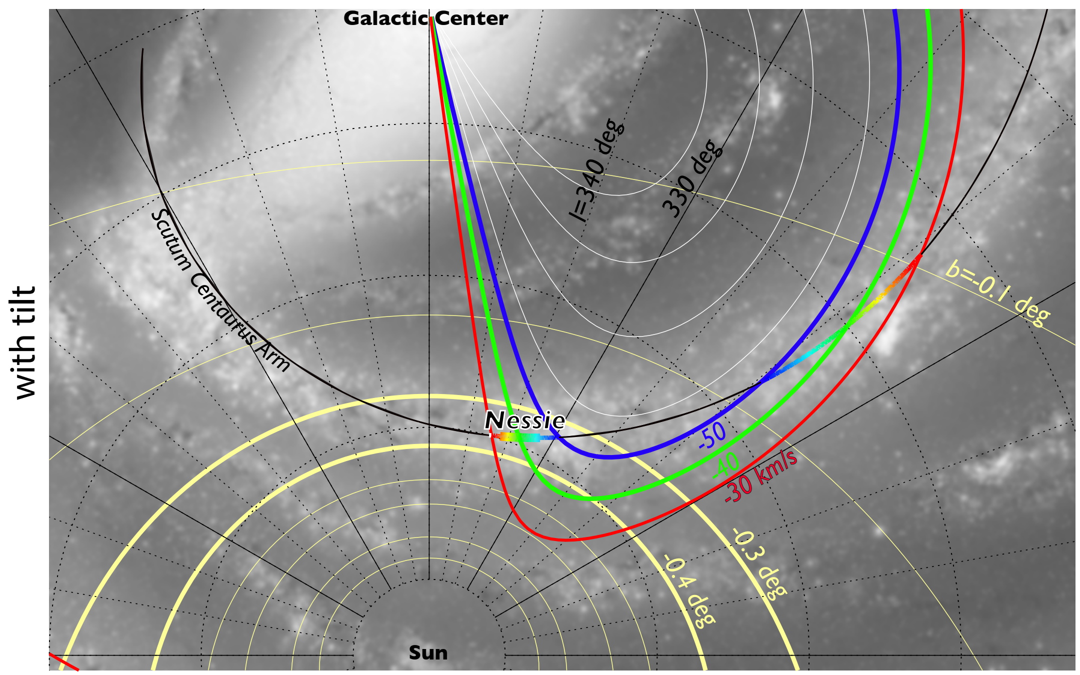
Goodman et al. 2013, see MilkyWayBones.org



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

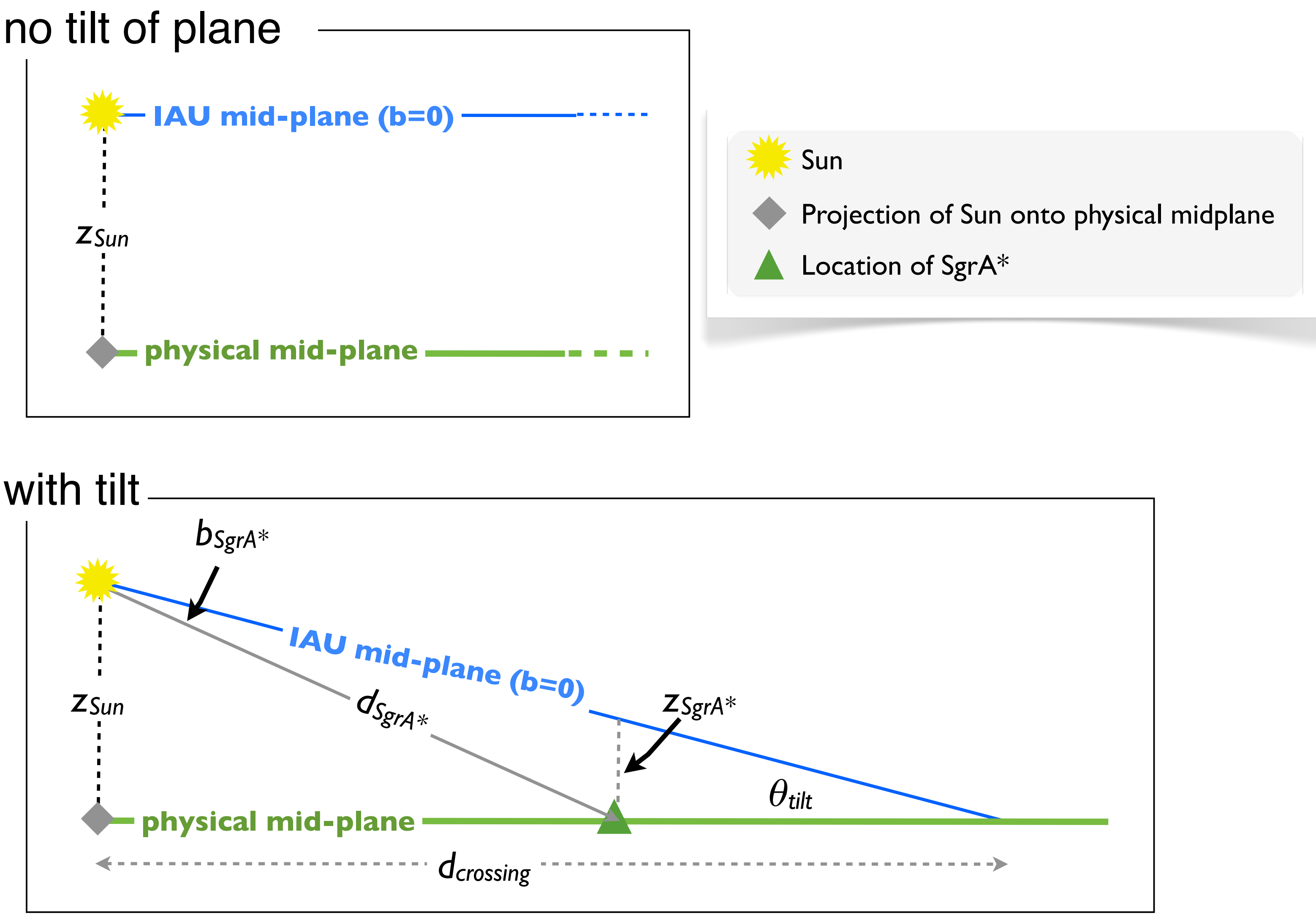






Goodman et al. 2013, see MilkyWayBones.org

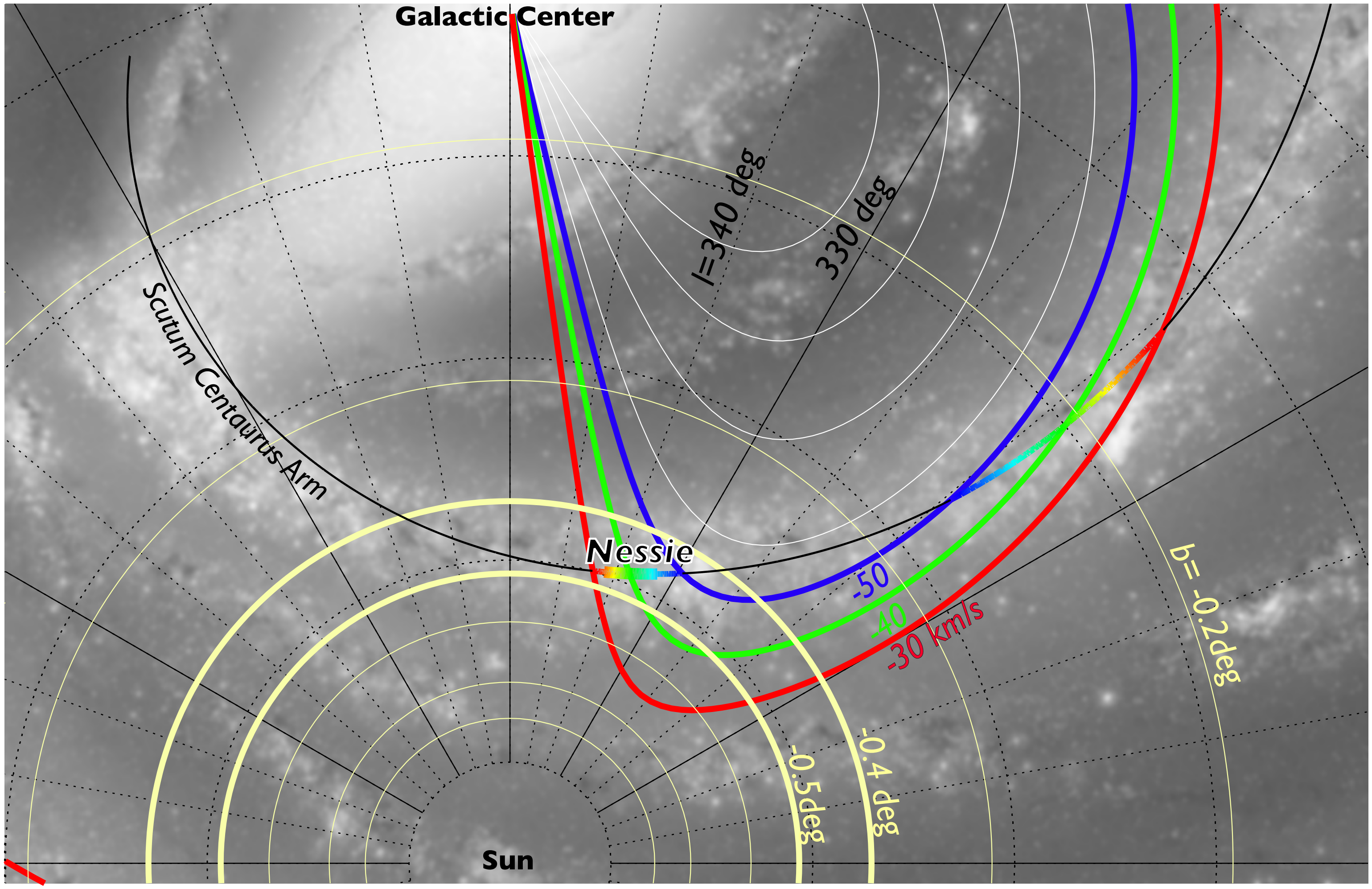
“In the Plane?”



Goodman et al. 2013, see MilkyWayBones.org

Predictions in "3D"

Including Galactic Center offset)



Goodman et al. 2013, see MilkyWayBones.org

Aspect Ratio for longest version of Nessie is 800:1

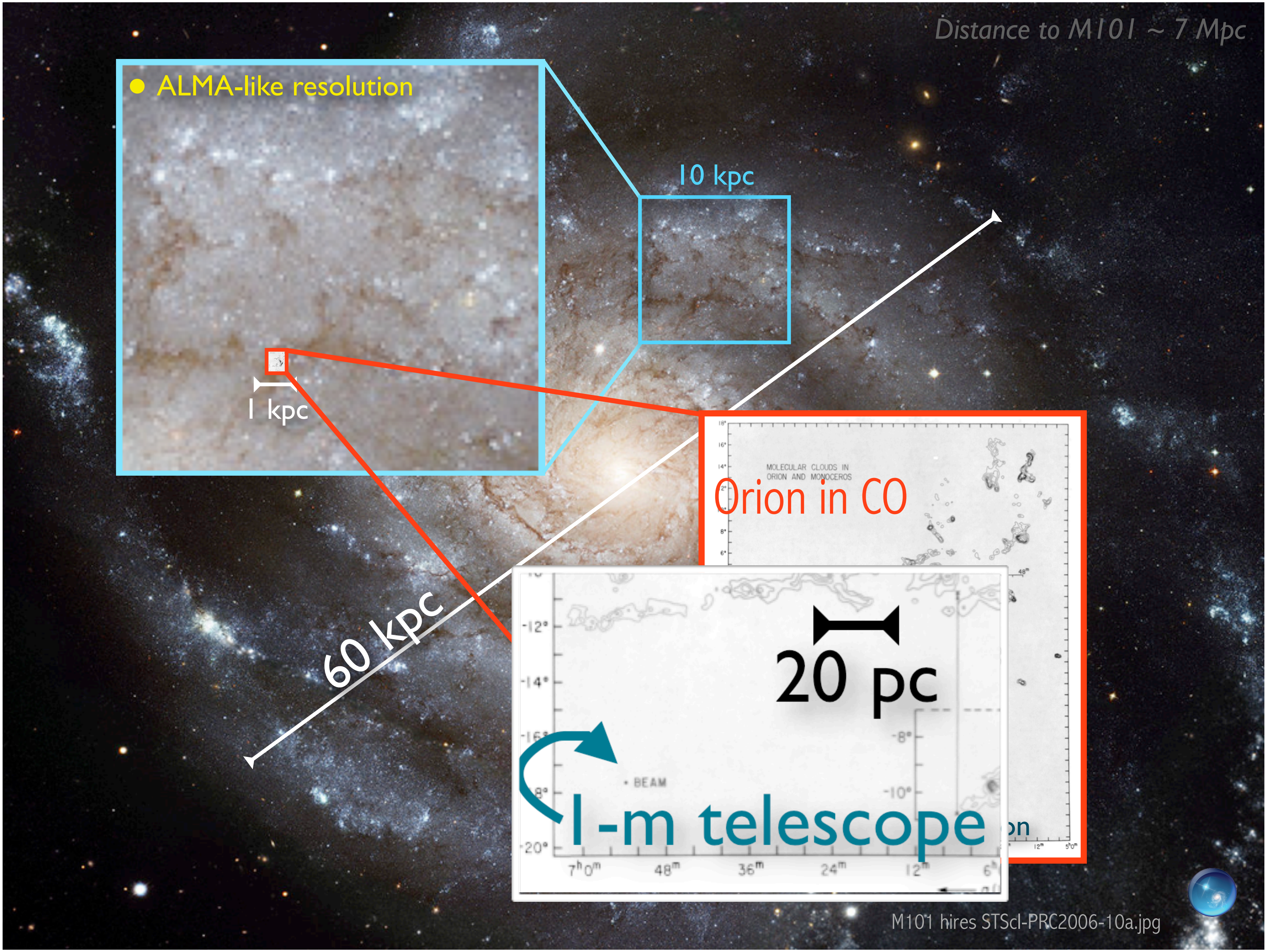
Table 1: Estimates of Nessie's Density and Mass

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**
	for innermost Spitzer IRDC...										
"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
	for envelope (width as observed in HNC, Jackson et al. 2010)...										
"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)

Goodman et al. 2013, see MilkyWayBones.org


Distance to M101 ~ 7 Mpc
ALMA-like resolution
10 kpc
1 kpc
60 kpc
MOLECULAR CLOUDS IN ORION AND MONOCEROS
Orion in CO
20 pc
BEAM
1-m telescope
M101 hires STScI-PRC2006-10a.jpg