IMAGE CREDIT: NASA; ESA; Z. LEVAY AND R. VAN DER MAREL, STSCI; T. HALLAS; AND A. MELLINGER

THE "INSIDER'S" VIEW OF THE MILKY WAY

ALYSSA A. GOODMAN, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

TWO-SLIDE INTRODUCTION TO THE "INSIDER'S" VIEW OF THE MILKY WAY

FOR THEORISTS

Distance to M101 ~ 7 Mpc

● ALMA-like resolution

10 kpc

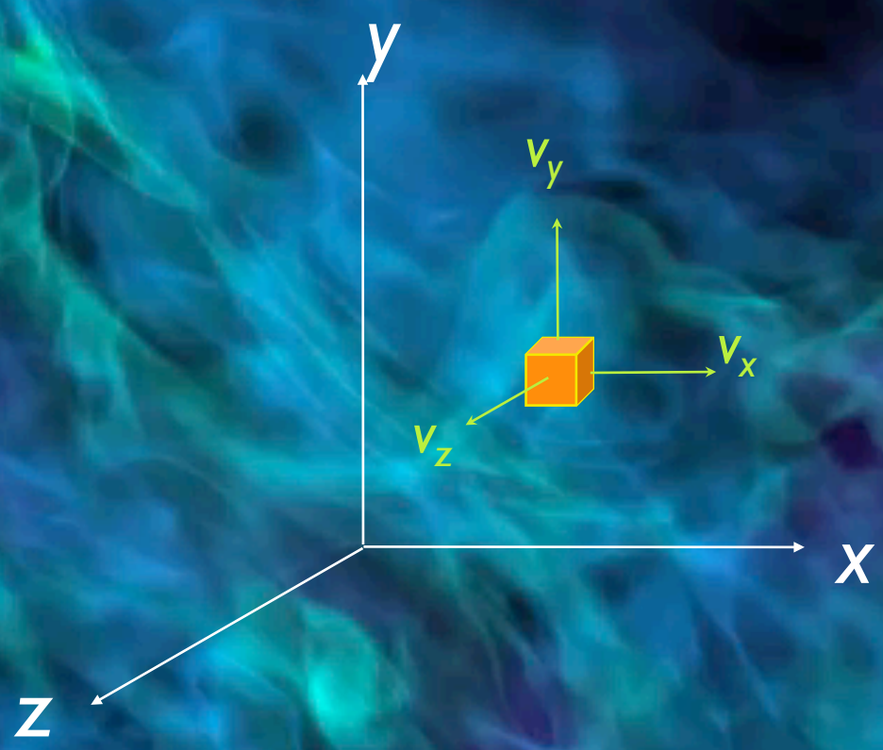
1 kpc

60 kpc

M101 hires STScI-PRC2006-10a.jpg

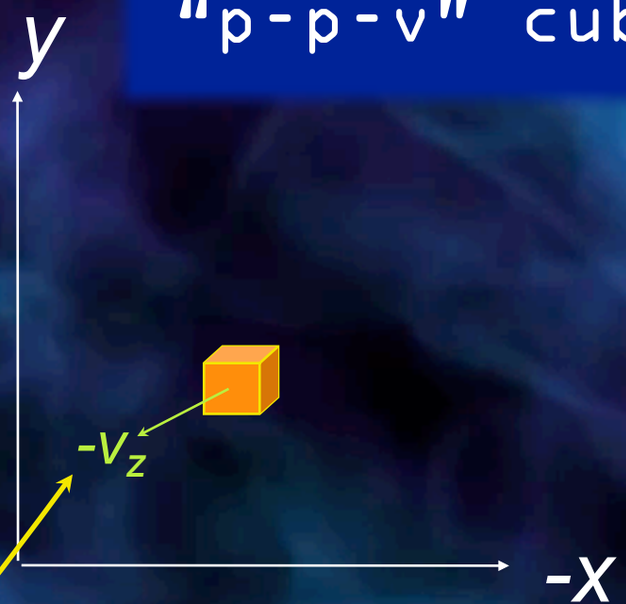
"Three" Dimensions: Spectral-Line Mapping

We wish we could measure…



But we can measure…

"p-p-v" cubes



v_z *only* from "spectral-line maps"

Hydrodynamic AMR Simulation, courtesy Stella Offner

IMAGE CREDIT: NASA; ESA; Z. LEVAY AND R. VAN DER MAREL, STSCI; T. HALLAS; AND A. MELLINGER

THE "INSIDER'S" VIEW OF THE MILKY WAY

ALYSSA A. GOODMAN, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS

THE BONES OF THE MILKY WAY

THE GRAND PLAN

The Milky Way

The Milky Way
(Artist's Conception)

Ringberg Castle, Bavaria
"Early Phases of Star Formation"
July 2012

de-jargonification

Who's Nessie?

What's an "infrared dark cloud"?

QUESTION *Andi B* ctic Plane"?

ANSWER *no one*

AG decides to look into this and...

"Is Nessie Parallel to the Galactic Plane?"

The Astrophysical Journal Letters, 719:L185–L189, 2010 August 20 doi:10.1088/2041-8205/719/2/L185

THE "NESSIE" NEBULA: CLUSTER FORMATION IN A FILAMENTARY INFRARED DARK CLOUD

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[2] Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA; e-chambers@northwestern.edu
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[4] I. Physikalisches Institut, Universität zu Köln, 50937 Köln, Germany; simonr@ph1.uni-koeln.de
Received 2010 April 13; accepted 2010 July 21; published 2010 August 3

ABSTRACT

The "Nessie" Nebula is a filamentary infrared dark cloud (IRDC) with a large aspect ratio of over 150:1 (1.°5 × 0.°01 or 80 pc × 0.5 pc at a kinematic distance of 3.1 kpc). Maps of HNC (1–0) emission, a tracer of dense molecular gas, made with the Australia Telescope National Facility Mopra telescope, show an excellent morphological match to the mid-IR extinction. Moreover, because the molecular line emission from the entire nebula has the same radial velocity to within ±3.4 km s^{-1}, the nebula is a single, coherent cloud and not the chance alignment of multiple unrelated clouds along the line of sight. The Nessie Nebula contains a number of compact, dense molecular cores which have a characteristic projected spacing of ~4.5 pc along the filament. The theory of gravitationally bound gaseous cylinders predicts the existence of such cores, which, due to the "sausage" or "varicose" fluid instability, fragment from the cylinder at a characteristic length scale. If turbulent pressure dominates over thermal pressure in Nessie, then the observed core spacing matches theoretical predictions. We speculate that the formation of high-mass stars and massive star clusters arises from the fragmentation of filamentary IRDCs caused by the "sausage" fluid instability that leads to the formation of massive, dense molecular cores. The filamentary molecular gas clouds often found near high-mass star-forming regions (e.g., Orion, NGC 6334, etc.) may represent a later stage of IRDC evolution.

Key words: ISM: clouds – stars: formation

Jackson et al. 2010

Monster to Bone

There should be >1000 more of these to find...a full skeleton perhaps?

milkywaybones.org

WORKING DRAFT OPEN SCIENCE ARTICLE AUTHOREA.COM/249

The Bones of the Milky Way

Goodman, Alves, Beaumont, Benjamin, Borkin, Burkert, Dame, Jackson, Kauffmann, Robitaille 2013

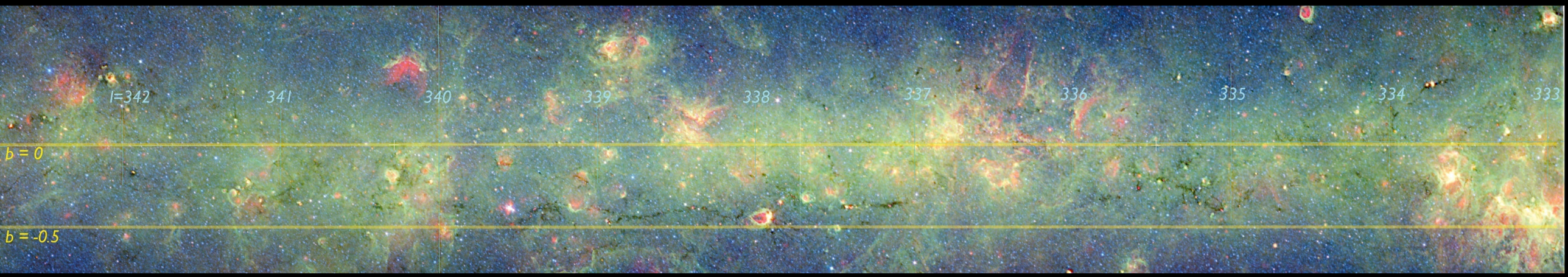
This article will be submitted to the Astrophysical Journal in November 2013.
The current online version is citable as an online "Authorea" preprint, and you can use the article's URL to do that.

Abstract

ABSTRACT

The very long, thin infared dark cloud ``Nessie'' is even longer than had been previously claimed, and an analysis of its Galactic location suggests that it lies 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 imagery from the Spitzer Space Telescope shows that this IRDC is at least 2, and possibly as many as 8 times longer than had originally been claimed by Nessie's discoverers, Jackson et al. (2010); its aspect ratio is therefore at least 150:1, and possibly as large as 800:1. A careful accounting for both the Sun's offset from the Galactic plane (~ 25 pc) and the Galactic center's offset from the $(l^{II}, b^{II}) = (0, 0)$ position defined by the IAU in 1959 shows that the latitude of the true Galactic mid-plane at the 3.1 kpc distance to the Scutum-Centaurus Arm is not $b = 0$, but instead closer to $b = -0.5$, which is the latitude of Nessie to within a few pc. Apparently, Nessie lies *in* the Galactic mid-plane. An analysis of the radial velocities of low-density (CO) and high-density (NH_3) gas associated with the Nessie dust feature suggests that Nessie runs along the Scutum-Centaurus Arm in position-position-velocity space, which means it likely forms a dense 'spine' of the arm in real space as well. No galaxy-scale simulation to date has the spatial resolution to predict a Nessie-like feature, but extant simulations do suggest that highly elongated over-dense filaments should be associated with a galaxy's spiral arms. Nessie is situated in the closest major spiral arm to the Sun toward the inner Galaxy, and appears almost perpendicular to our line of sight, making it the easiest feature of its kind to detect from our location (a shadow of an Arm's bone, illuminated by the Galaxy beyond). Although the Sun's (~ 25 pc) offset from the Galactic plane is not large in comparison with the half-thickness of the plane as traced by Population I objects such as GMCs and HII regions (~ 200 pc; Rix et al. (2013)), it may be significant compared with an extremely thin layer that might be traced out by Nessie-like "bones" of the Milky Way. Future high-resolution extinction and molecular line data may therefore allow us to exploit the Sun's position above the plane to gain a (very foreshortened) view ``from above'' of dense gas in Milky Way's disk and its structure.

ApJ version submitted Nov 2013; open version on Authorea.com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338
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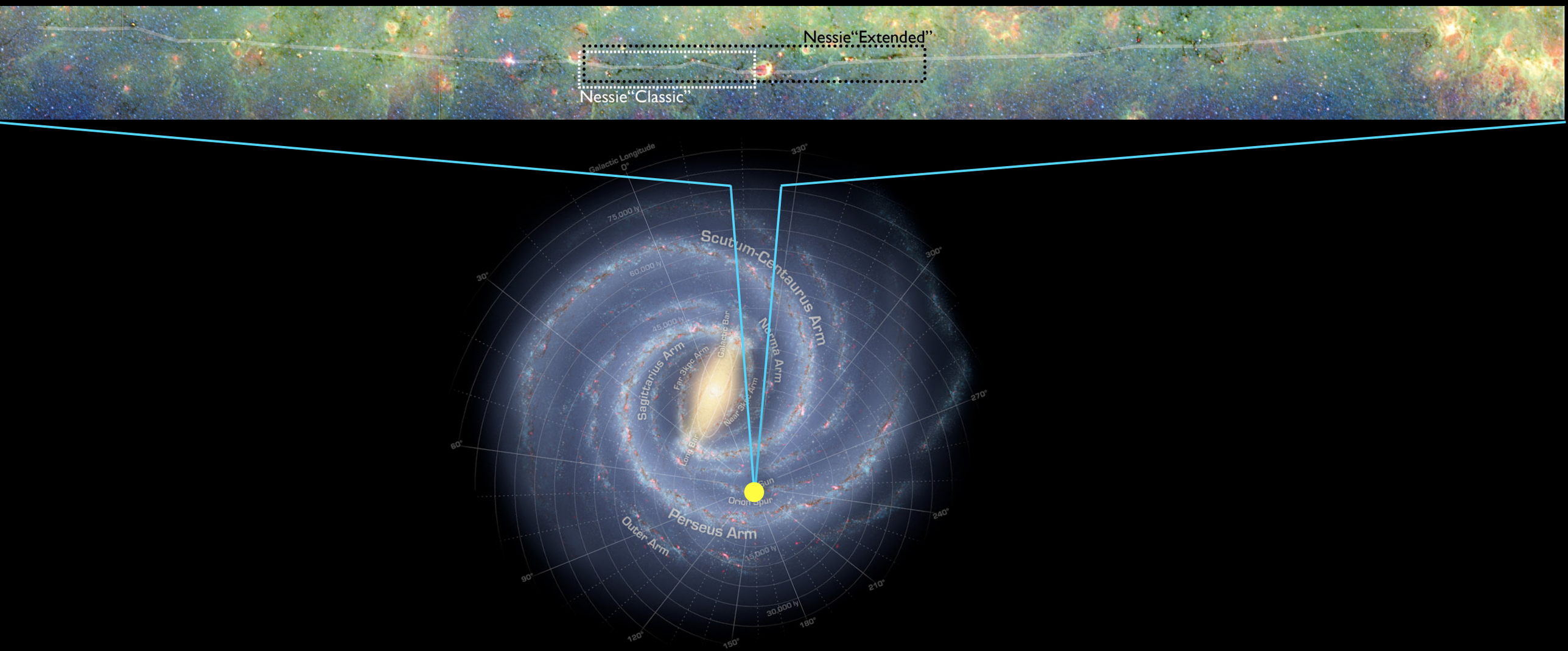
336
335
334
333
b = 0
b = -0.5


Nessie "Extended"
Nessie "Classic"
Galactic Longitude
0°
30°
60°
90°
120°
150°
180°
210°
240°
270°
300°
330°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Galactic Bar
Far 3kpc Arm
Near 3kpc Arm
Long Bar
Sun
Orion Spur

Aspect Ratio for longest version of Nessie is 800:1

Table 1: Estimates of Nessie's Density and Mass

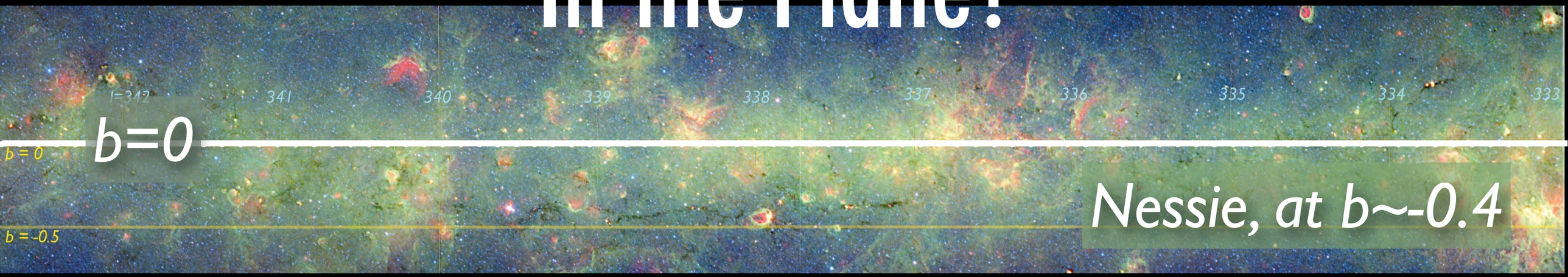
Assumptions:	*Baryonic mass of Milky Way (Msuns)*	*1.25E+11*
	Distance to Nessie (pc)	*3,100*

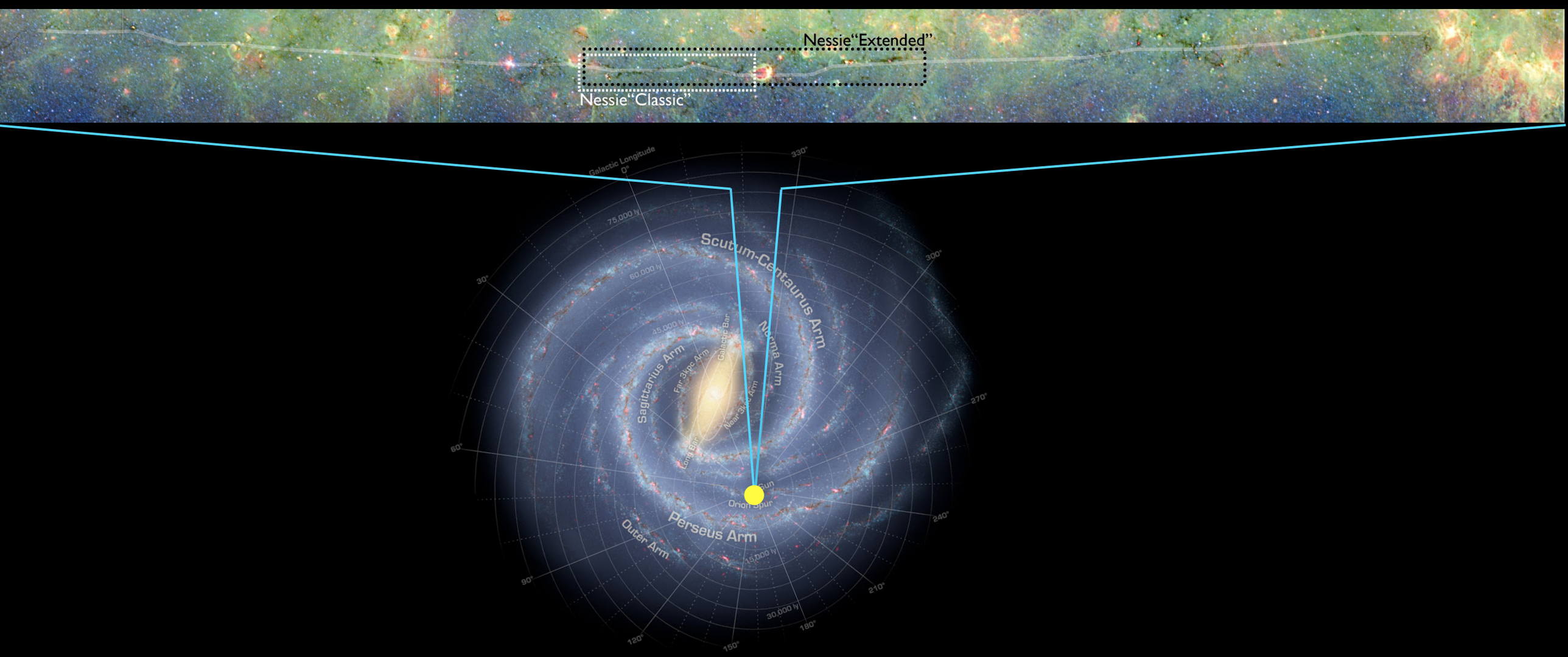
Nickname	Length *deg*	Radius *deg*	Length *pc*	Radius *pc*	Average density *cm^-3*	H2 column density *cm^-2*	Equiv. Av *mag*	Mass *Msuns*	Mass per unit length *Msuns/pc*	# to equal mass of Milky Way	aspect ratio
for innermost Spitzer IRDC...											
"Nessie Classic"	1.5	0.005	81	0.3	1E+5	8E+22	81	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

"In the Plane?"


l=342
341
340
339
338
337
336
335
334
333
b=0
b = 0
b = -0.5
Nessie, at b~-0.4


Nessie "Extended"
Nessie "Classic"
Galactic Longitude
0°
30°
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210°
240°
270°
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330°
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60,000 ly
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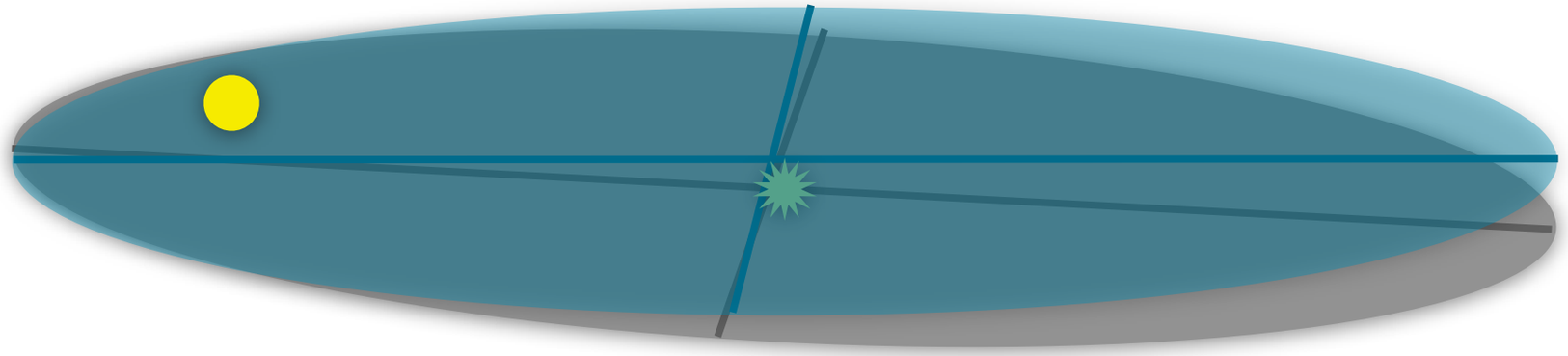
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Norma Arm
Sagittarius Arm
Perseus Arm
Outer Arm
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Long Bar
Sun
Orion Spur

"In the Plane?"

"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 ~25 pc "above" the IAU Milky Way Plane

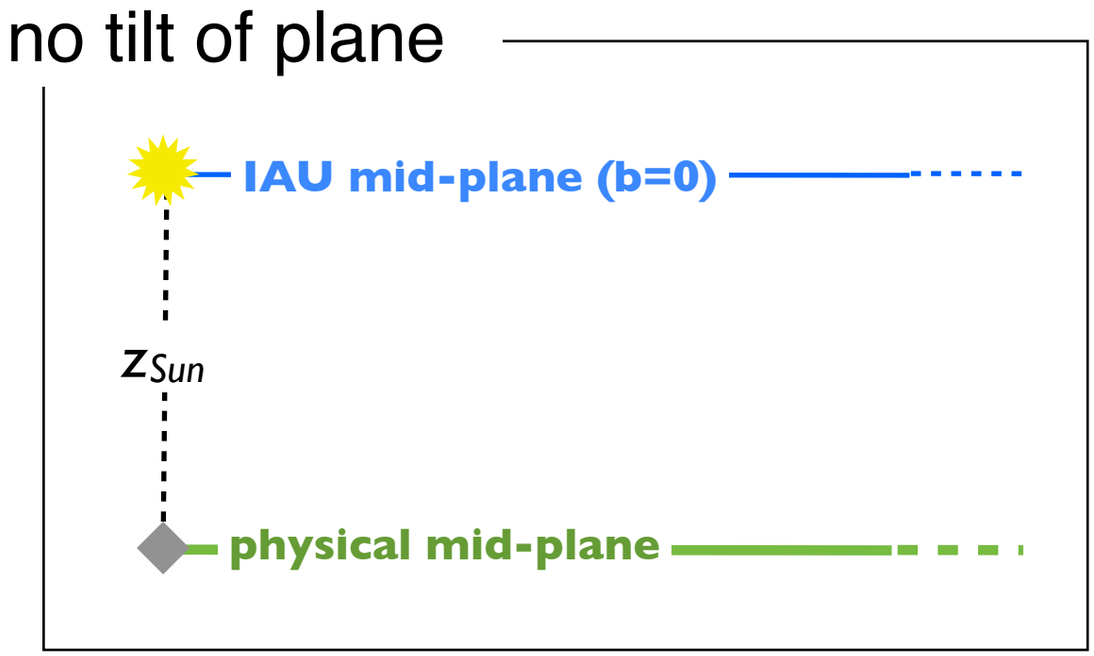
+

Galactic Center is ~7 pc offset from the IAU Milky Way Center

=

The Galactic Plane is not exactly where you'd think it is when you look at the sky, and...

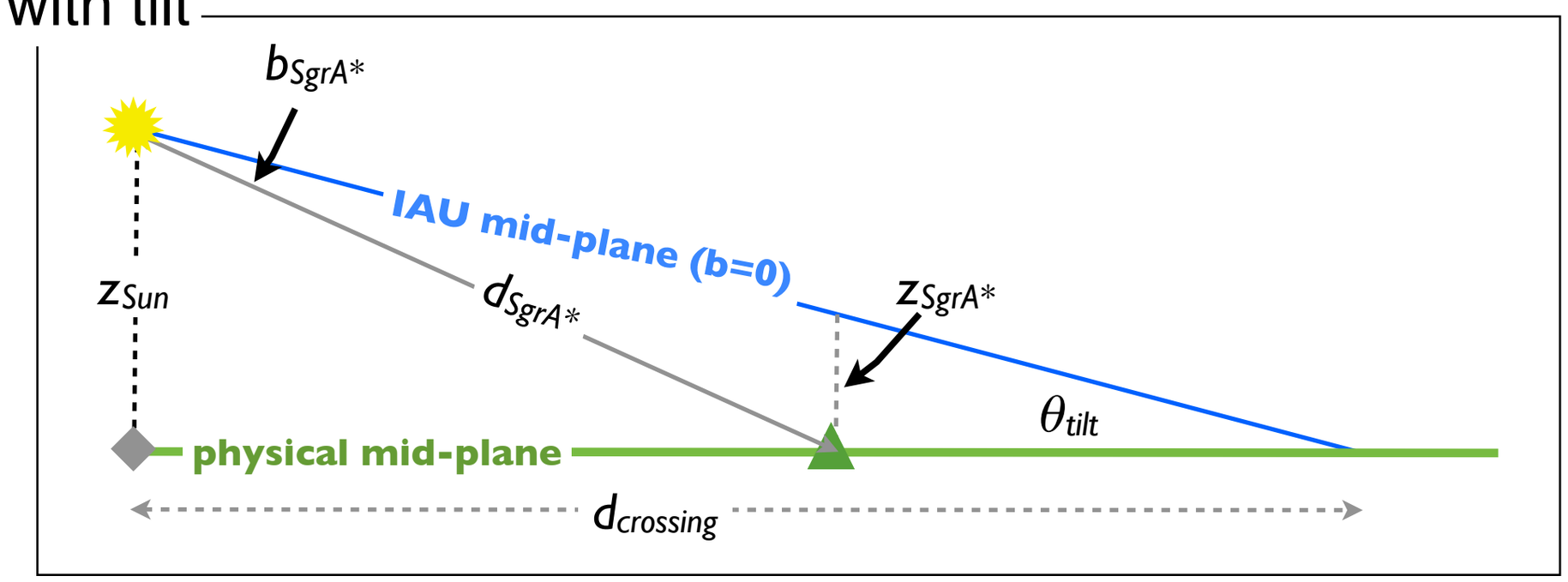
"In the Plane?"



Sun

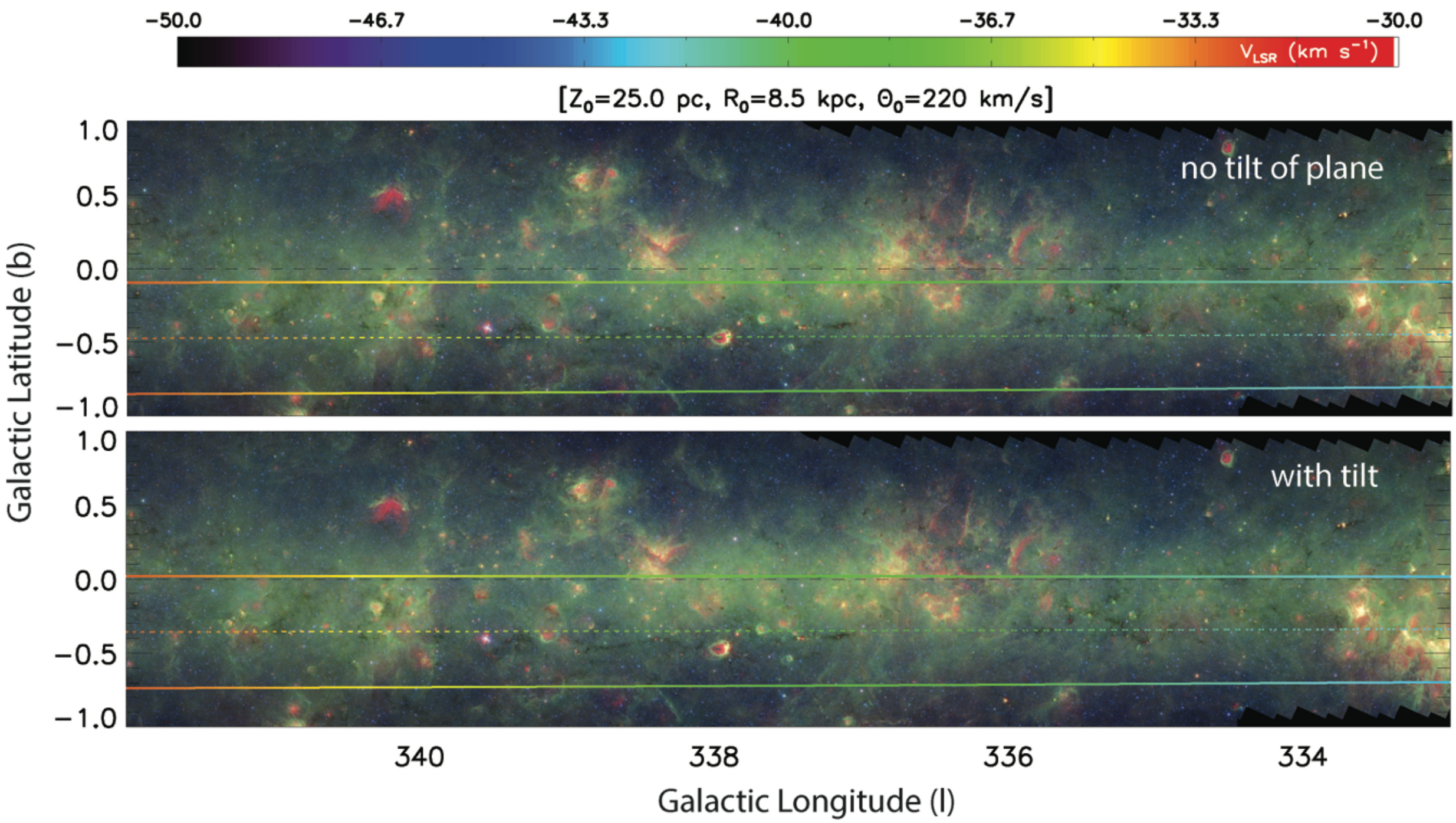
Projection of Sun onto physical midplane

Location of SgrA*

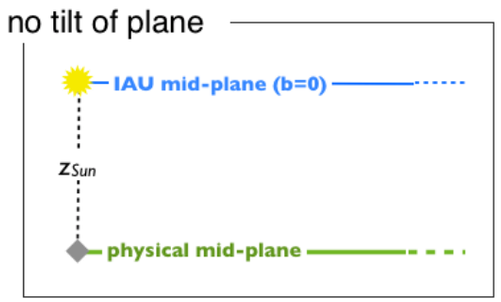


Goodman et al. 2013, see MilkyWayBones.org

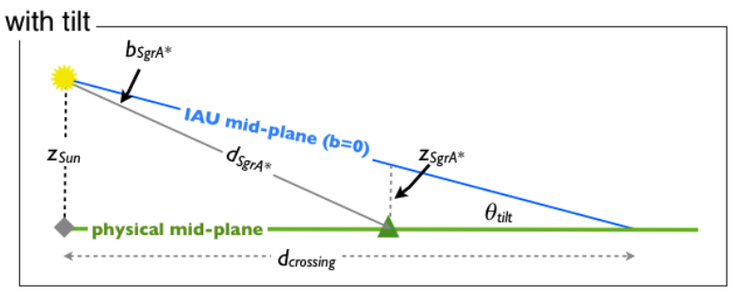
"In the Plane?"

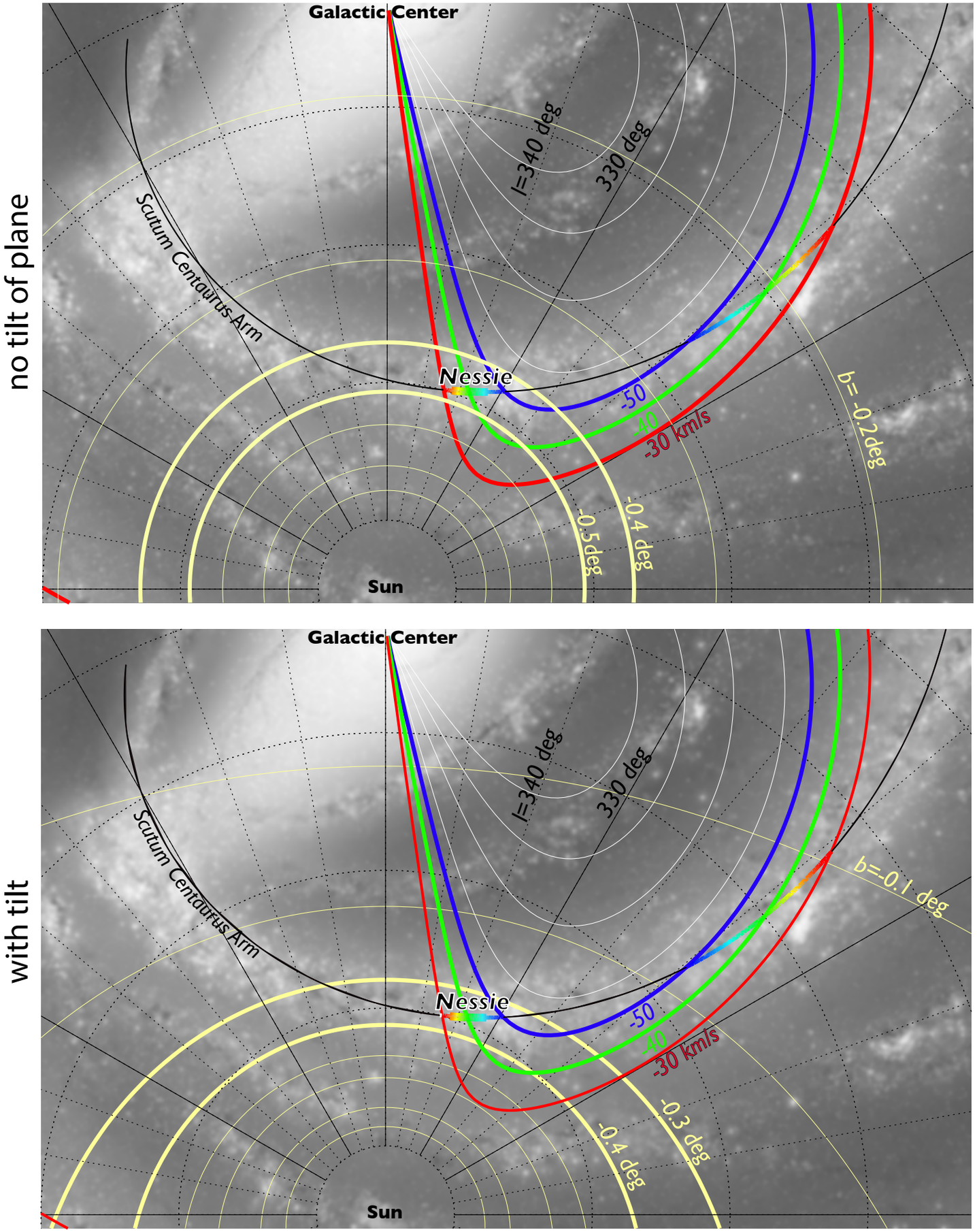


Goodman et al. 2013, see MilkyWayBones.org



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

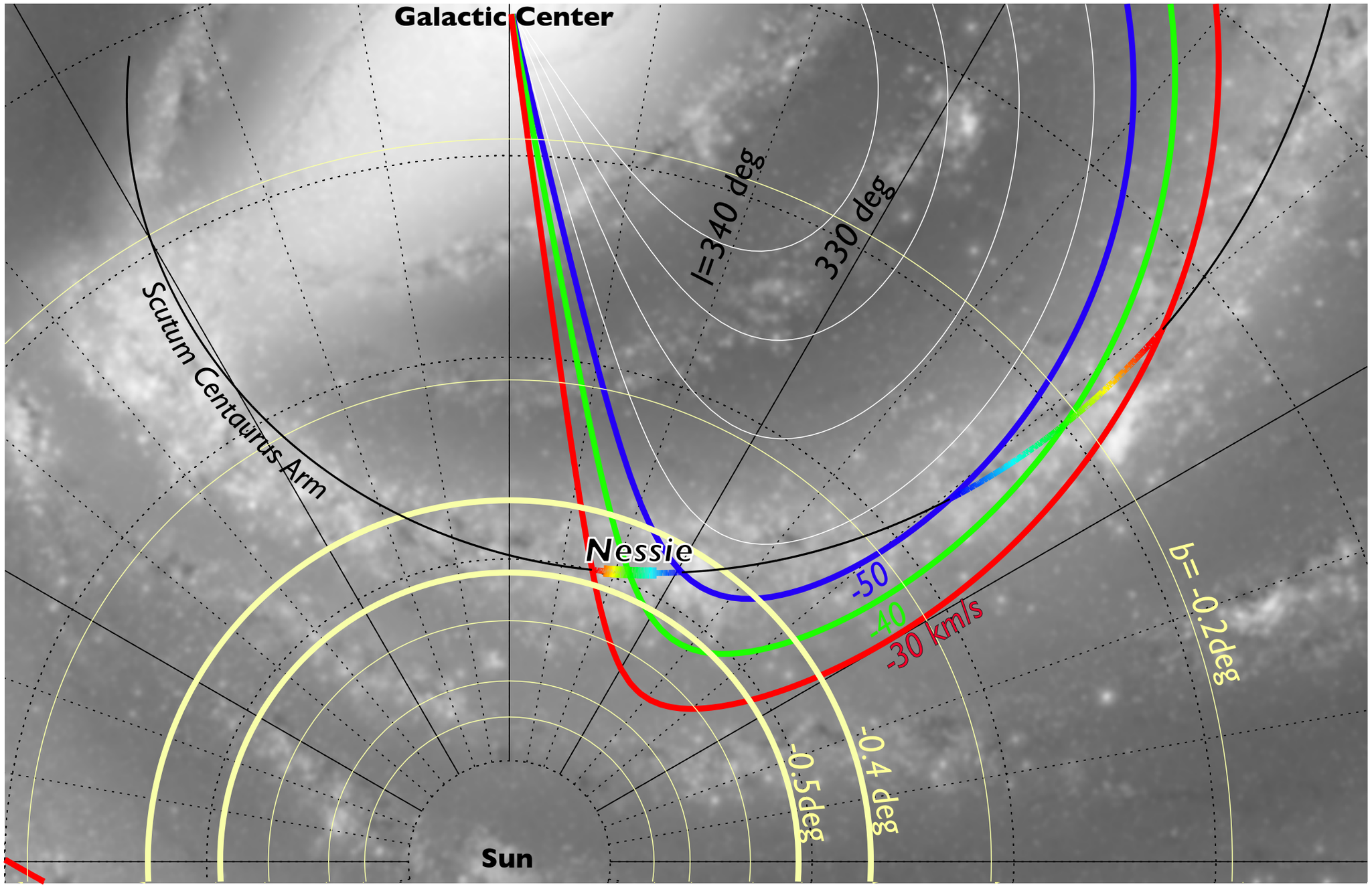




Goodman et al. 2013, see MilkyWayBones.org

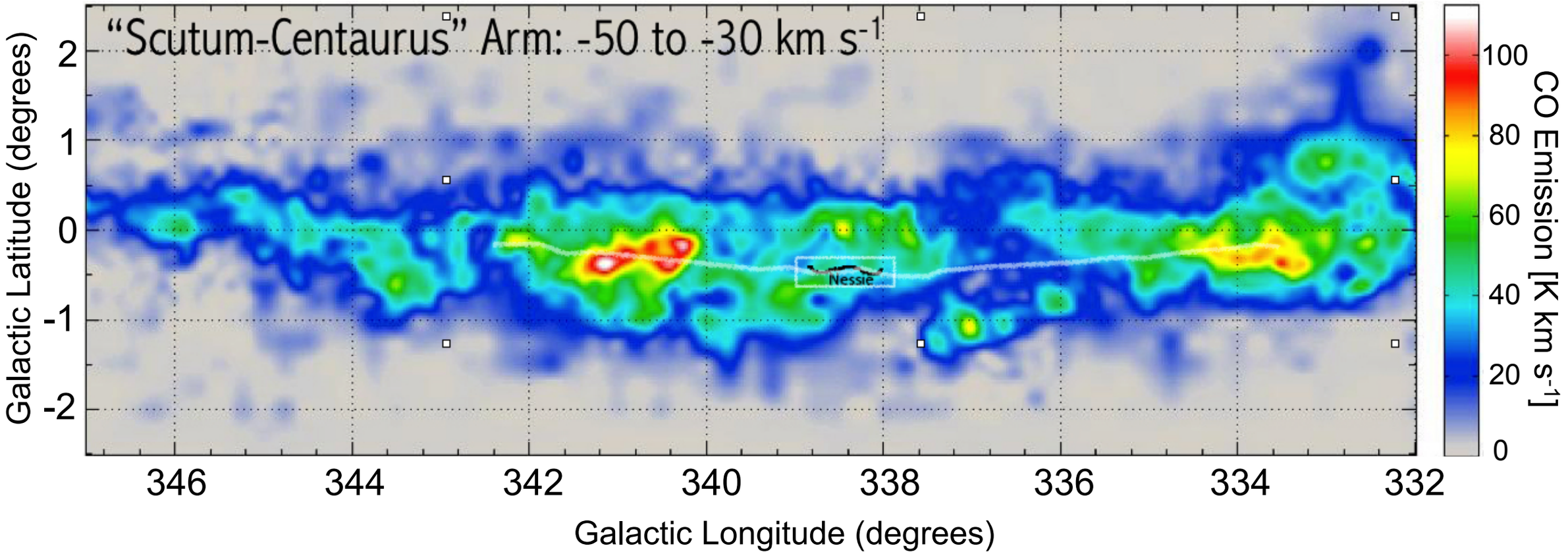
Predictions in "3D"

Including Galactic Center offset)



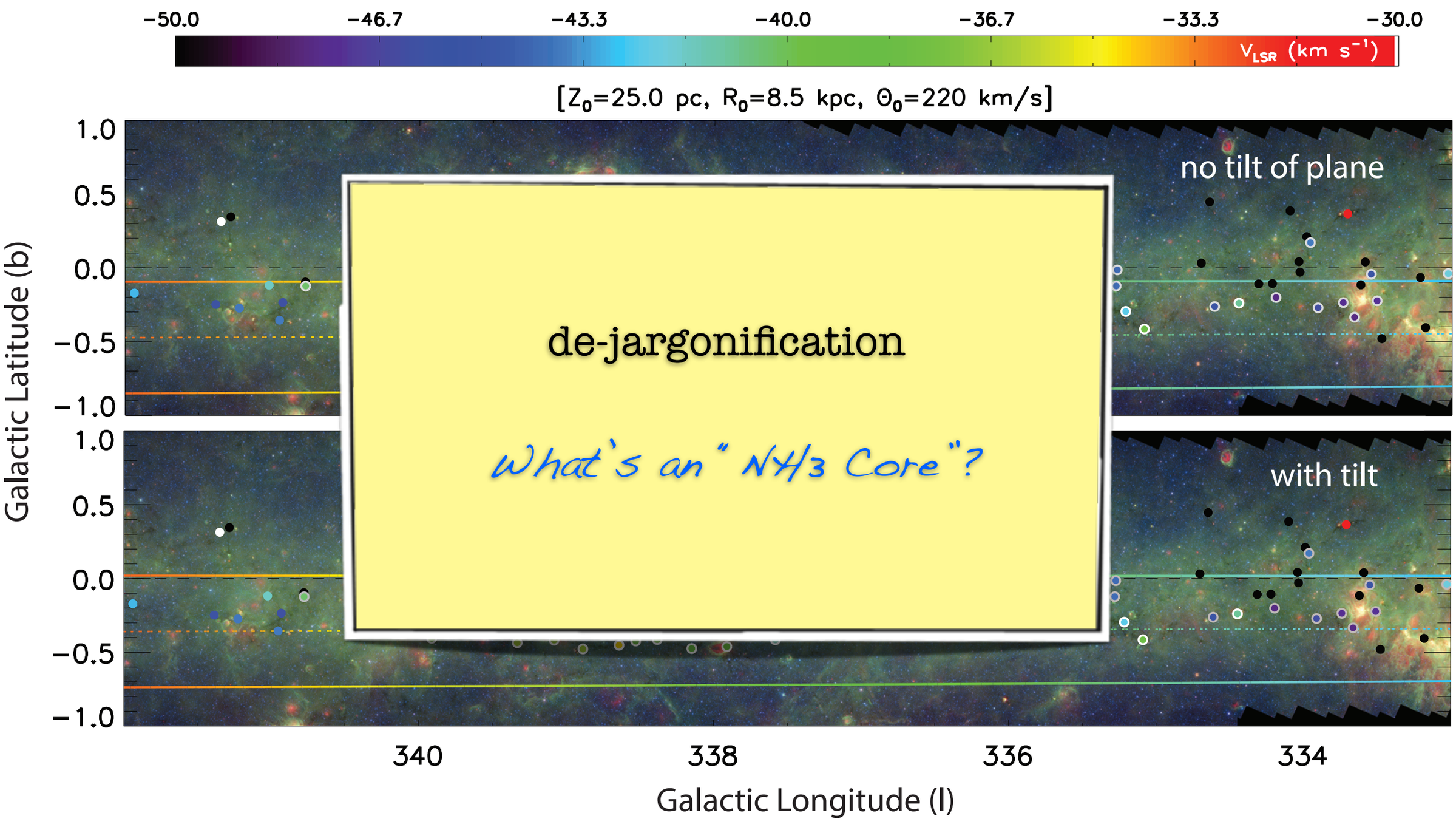
Goodman et al. 2013, see MilkyWayBones.org

Test in "3D": Is Nesssie at the Right Velocity? (CO)



Goodman et al. 2013, see MilkyWayBones.org

Test in "3D": Is Nesssie at the Right Velocity? (NH_3 Cores)



Goodman et al. 2013, see MilkyWayBones.org

−50.0 −46.7 −43.3 −40.0 −36.7

[Z_0=25.0 pc, R_0=8.5 kpc, Θ_0=220 km/s]

Galactic Latitude (b)

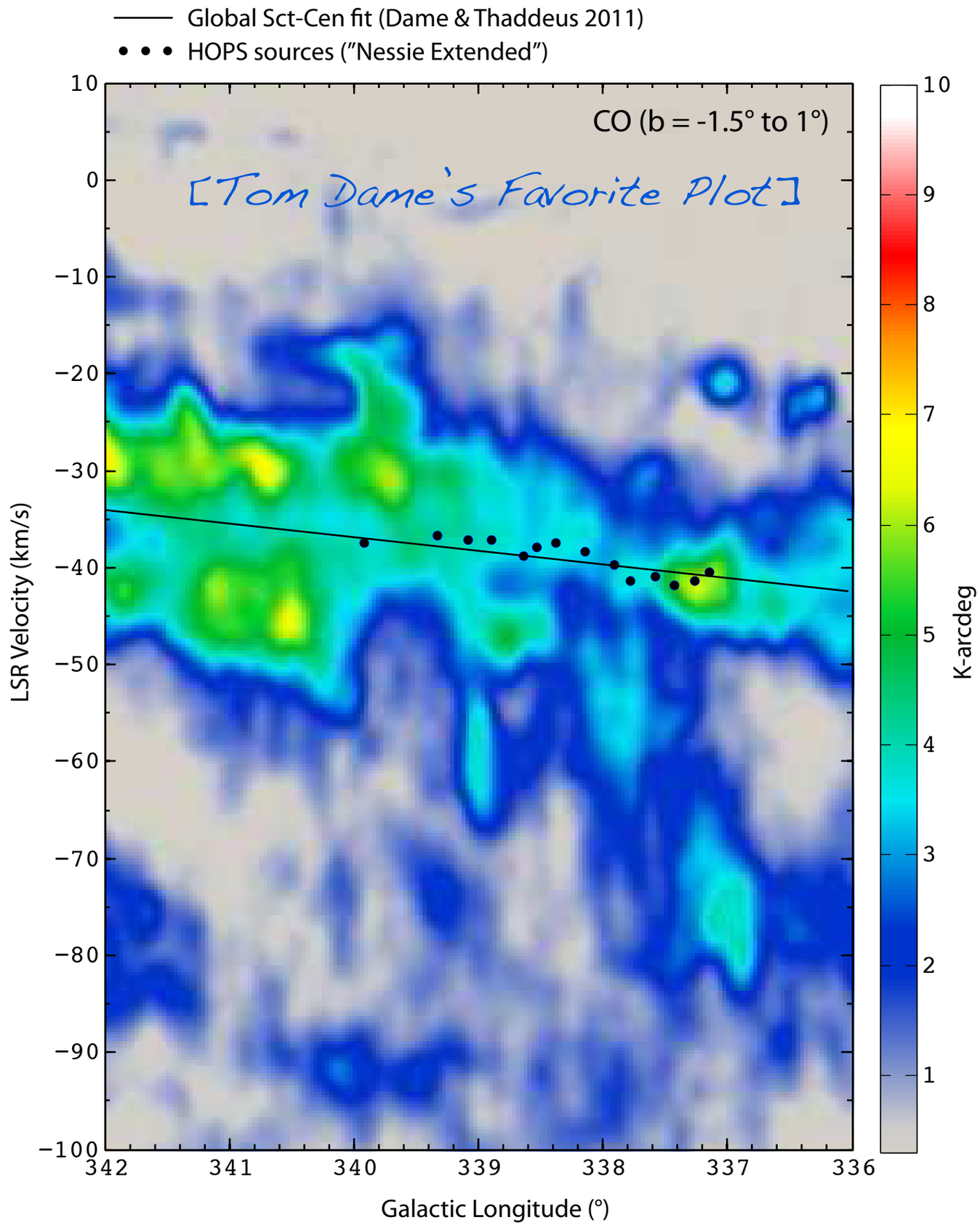
1.0
0.5
0.0
−0.5
−1.0

340 338 336

Galactic Longitude (l)

Goodman et al. 2013, see MilkyWayBones.org

Test in "3D": Is Nesssie at the Right Velocity? (CO & NH_3)



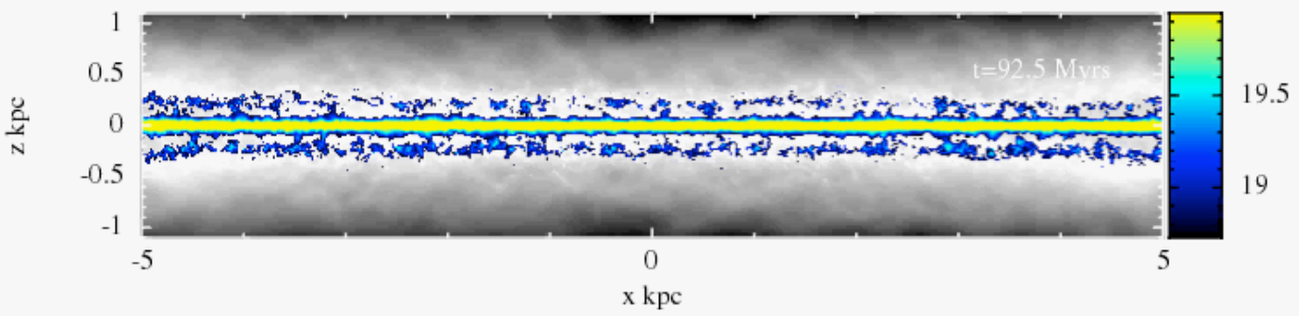
Goodman et al. 2013, see MilkyWayBones.org

Nessie is a Bone of the Milky Way

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

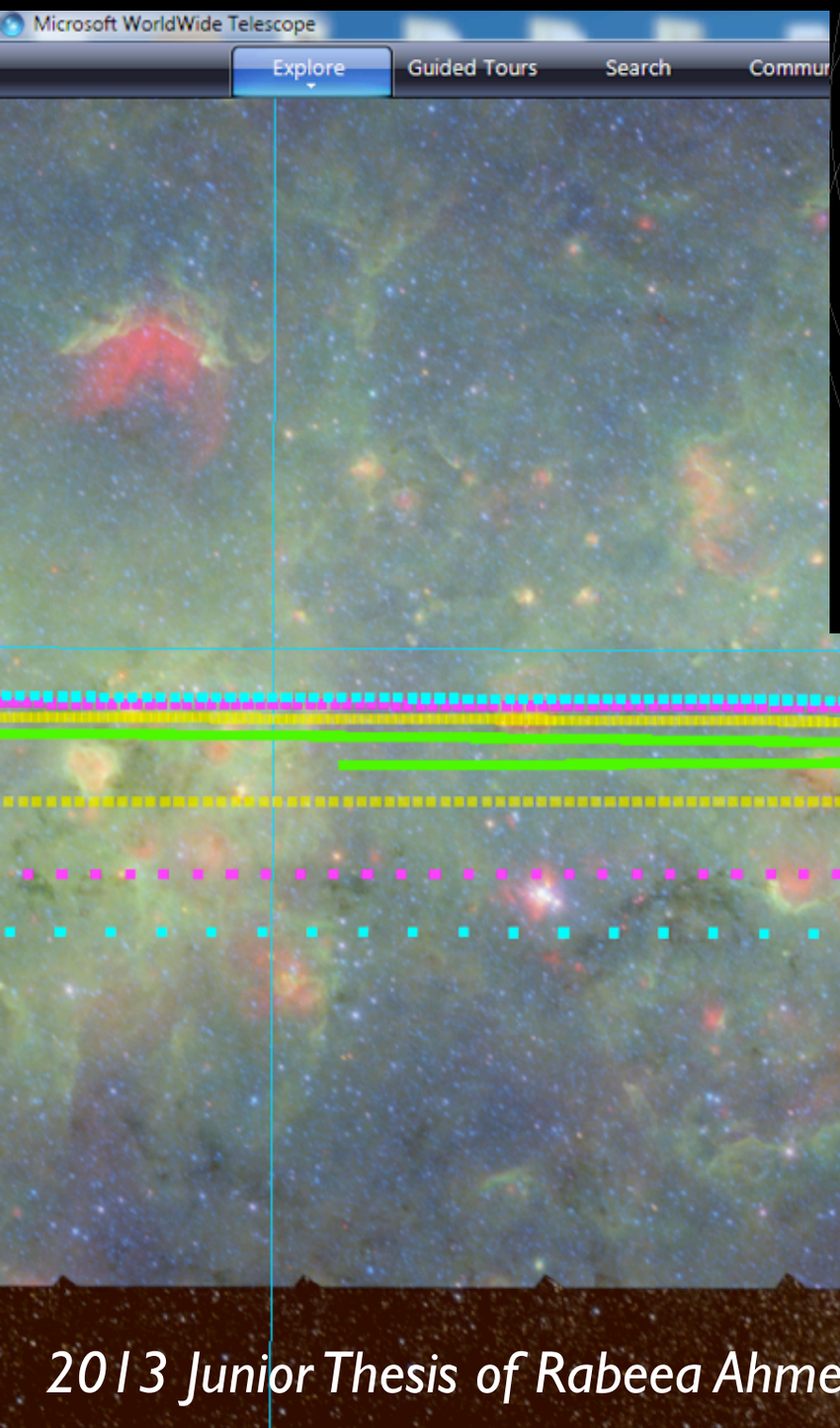
What does that mean?

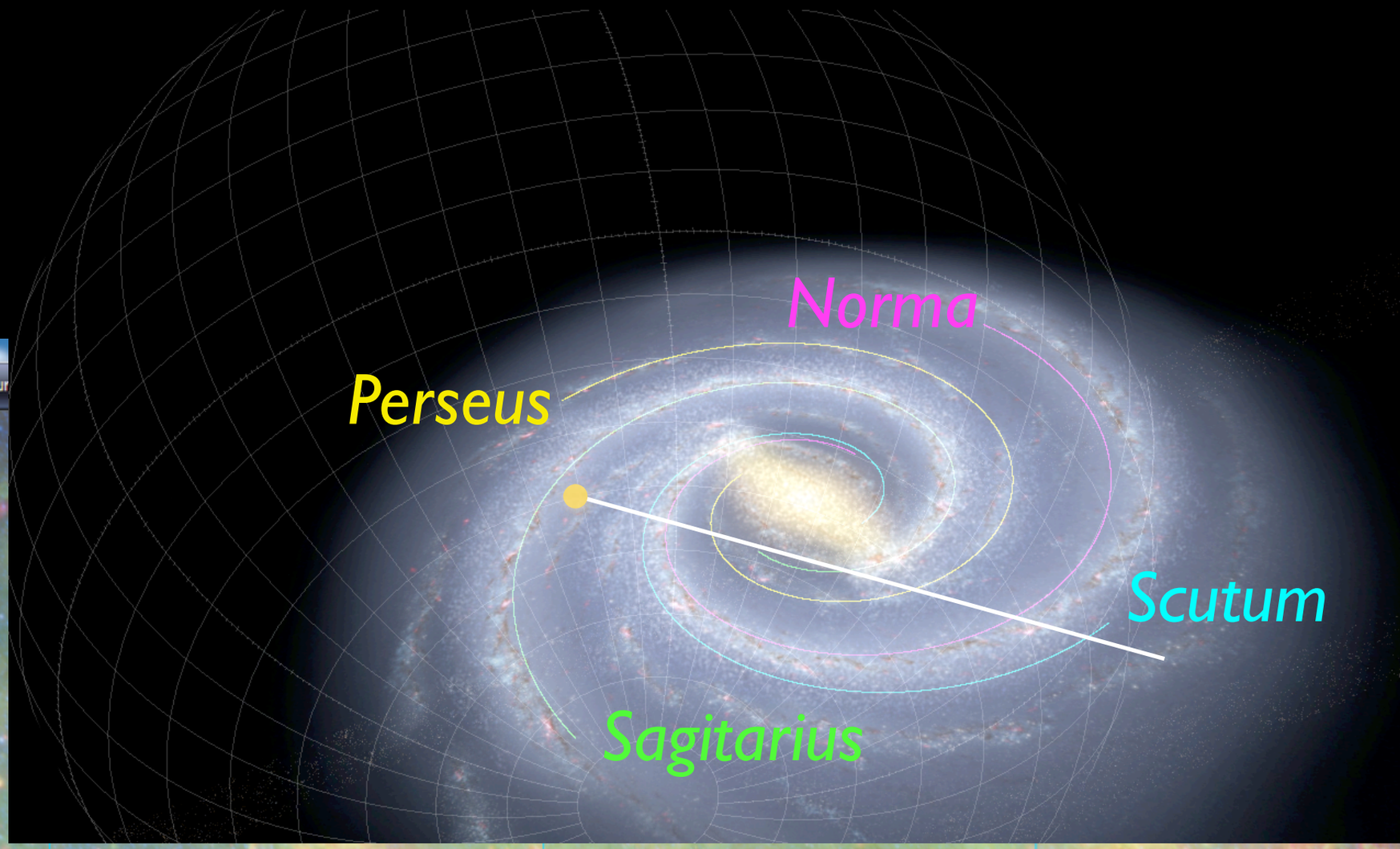
(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas



Dobbs & Pringle 2013

Other Arms?
Other Nessies?

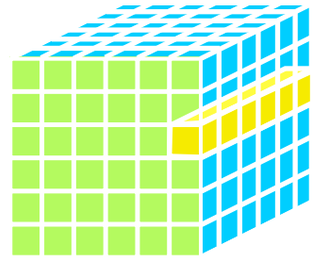


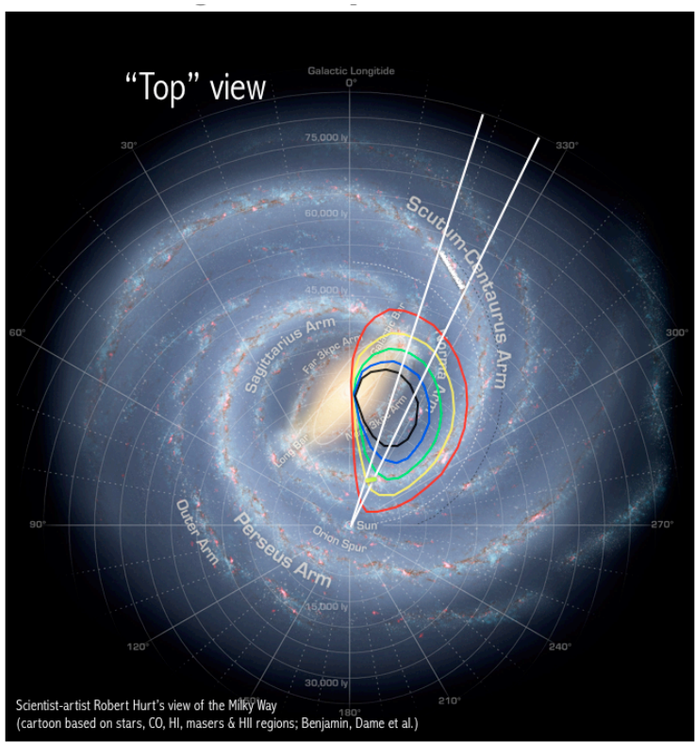


2013 Junior Thesis of Rabeea Ahmed, Harvard

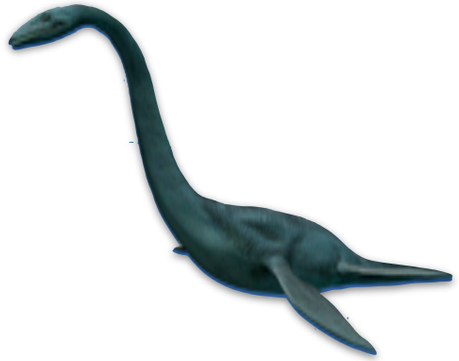
"The Making of" the Bones of the Milky Way

SEAMLESS ASTRONOMY
Linking scientific data, publications, and communities

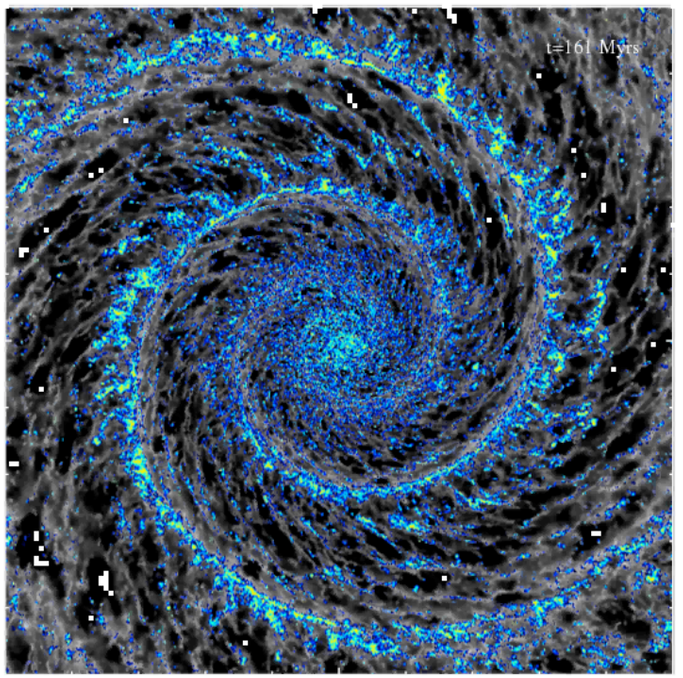




-20
-40
-60
-80
-100

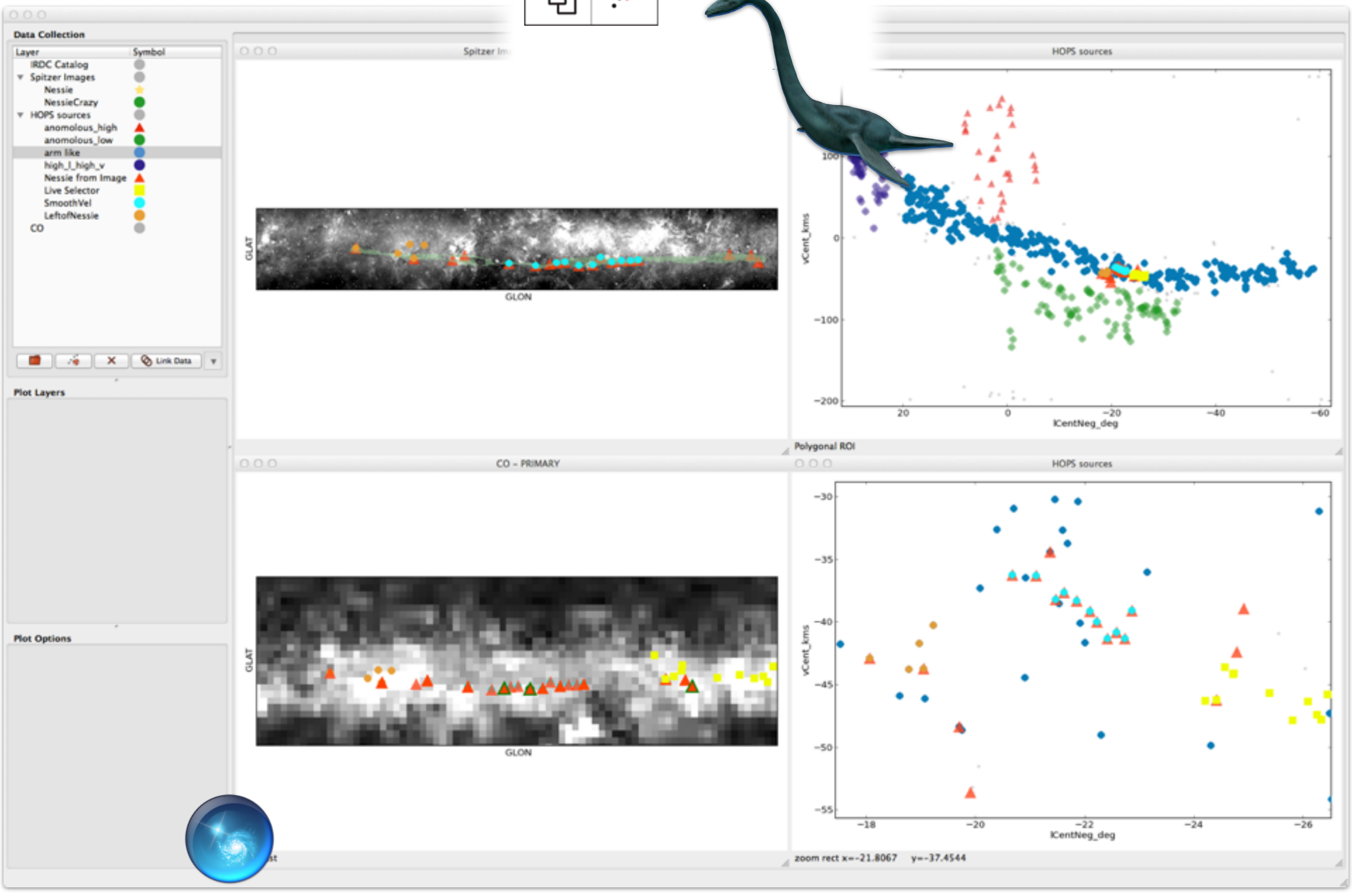


glue
multidimensional data exploration



glue

multidimensional data exploration



http://www.glueviz.org/en/latest/

Glue collaboration: ***Beaumont****, Borkin, Goodman, Pfister, Robitaille*

THE BONES OF THE MILKY WAY

THE GRAND PLAN

The Astrophysical Journal, 745:69 (16pp), 2012 January 20 doi:10.1088/0004-637X/745/1/69

A UNIVERSAL, LOCAL STAR FORMATION LAW IN GALACTIC CLOUDS, NEARBY GALAXIES, HIGH-REDSHIFT DISKS, AND STARBURSTS

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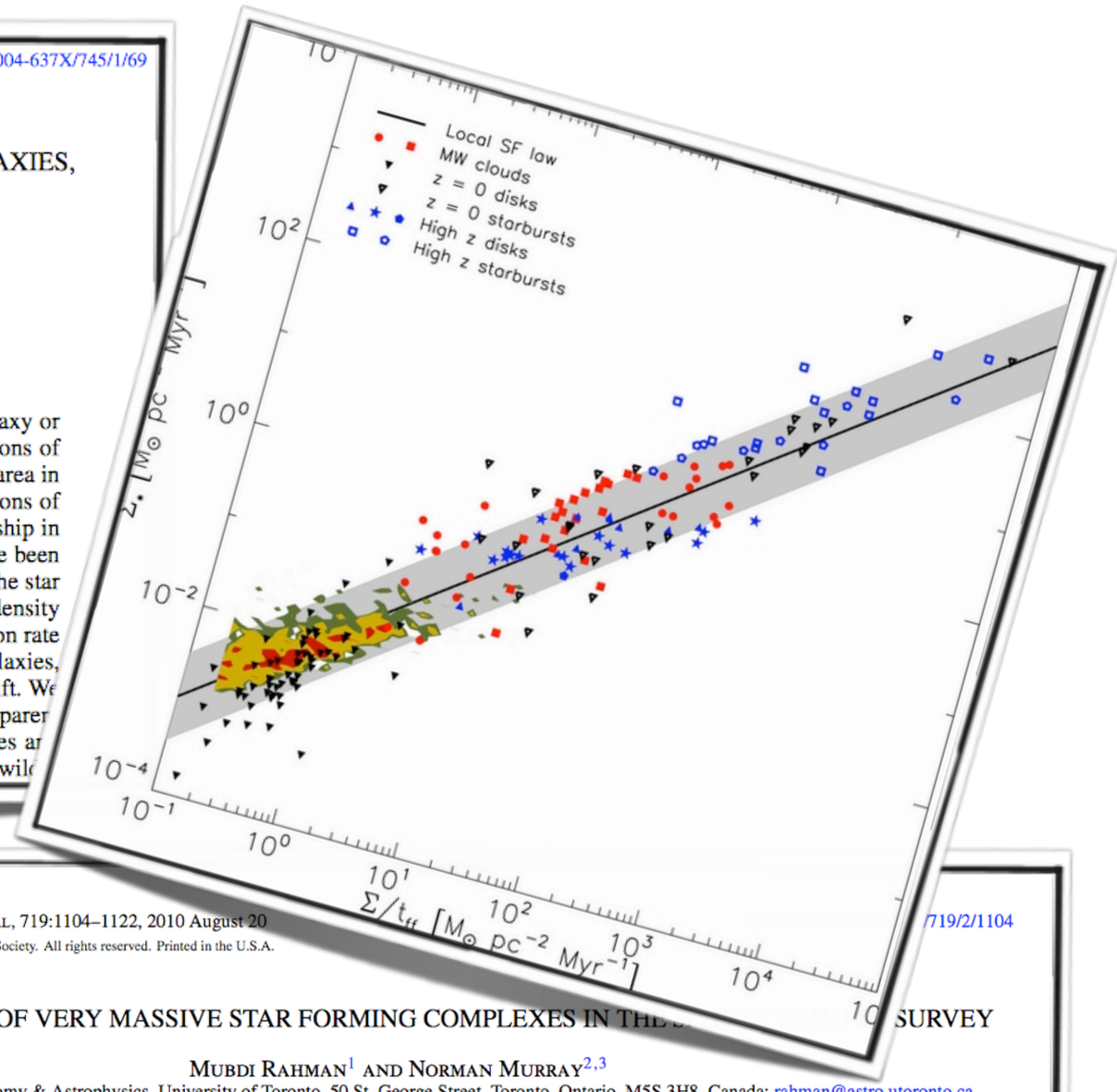
Received 2011 September 16; accepted 2011 October 18; published 2011 December 29

ABSTRACT

Star formation laws are rules that relate the rate of star formation in a particular region, either an entire galaxy or some portion of it, to the properties of the gas, or other galactic properties, in that region. While observations of Local Group galaxies show a very simple, local star formation law in which the star formation rate per unit area in each patch of a galaxy scales linearly with the molecular gas surface density in that patch, recent observations of both Milky Way molecular clouds and high-redshift galaxies apparently show a more complicated relationship in which regions of equal molecular gas surface density can form stars at quite different rates. These data have been interpreted as implying either that different star formation laws may apply in different circumstances, that the star formation law is sensitive to large-scale galaxy properties rather than local properties, or that there are high-density thresholds for star formation. Here we collate observations of the relationship between gas and star formation rate from resolved observations of Milky Way molecular clouds, from kpc-scale observations of Local Group galaxies, and from unresolved observations of both disk and starburst galaxies in the local universe and at high redshift. We show that all of these data are in fact consistent with a simple, *local, volumetric* star formation law. The apparent variations stem from the fact that the observed objects have a wide variety of three-dimensional size scales and degrees of internal clumping, so even at fixed gas column density the regions being observed can have wild



THE GRAND PLAN

Motivation–

What's the Star Formation "Law"? (Is there one?)

ournal, 719:1104–1122, 2010 August 20 /719/2/1104

PLE OF VERY MASSIVE STAR FORMING COMPLEXES IN THE SURVEY

Mubdi Rahman[1] and Norman Murray[2,3]
[1] Department of Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, Ontario, M5S 3H8, Canada; rahman@astro.utoronto.ca
[2] Canadian Institute for Theoretical Astrophysics, 60 St. George Street, University of Toronto, Toronto, ON M5S 3H8, Canada; murray@cita.utoronto.ca
Received 2010 April 17; accepted 2010 June 24; published 2010 July 26

ABSTRACT

We examine the 13 most luminous sources in the *WMAP* free–free map using the *Spitzer* GLIMPSE and *Midcourse Space Experiment* surveys to identify massive star formation complexes, emitting one-third of the Galactic free–free luminosity. We identify star-forming complexes (SFCs) by a combination of bubble morphology in 8 μm emission and radio recombination line radial velocities. We find 40 SFCs associated with our *WMAP* sources and determine unique distances up to 31. We interpret the bubbles as evidence for radial expansion. The radial velocity distribution for each source allows us to measure the intrinsic speed of a complex's expansion. This speed is consistent with the size and age of the bubbles. The high free–free luminosities, combined with negligible synchrotron emission, demonstrate that the bubbles are not driven by supernovae. The kinetic energy of the largest bubbles is a substantial fraction of that measured in the older superbubbles found by Heiles. We find that the energy injected into the interstellar medium by our bubbles is similar to that required to maintain turbulent motion in the gas disk inside 8 kpc. We report a number of new SFCs powered by massive ($M_* > 10^4\ M_\odot$) star clusters. We measure the scale height of the Galactic O stars to be $h_* = 35 \pm 5$ pc. We determine an empirical relationship between the 8 μm and free–free emission of the form $F_{8\,\mu\mathrm{m}} \propto F_{\mathrm{ff}}^2$. Finally, we find that the bubble geometry is more consistent with a spherical shell rather than a flattened disk.

Key words: H II regions – infrared: ISM – stars: formation

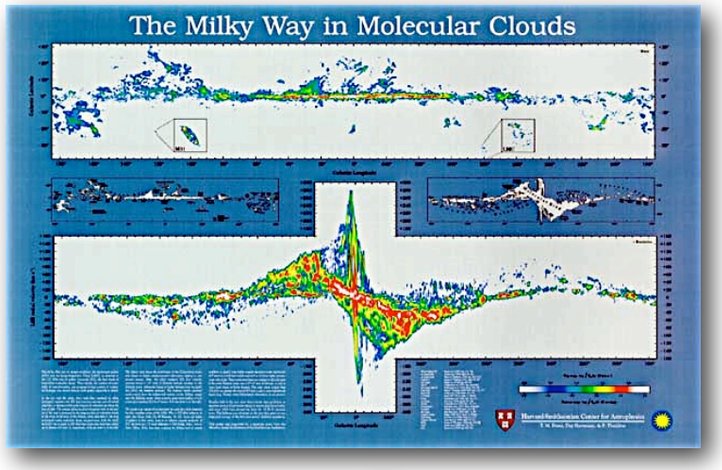
Online-only material: color figures, machine-readable table

THE GRAND PLAN

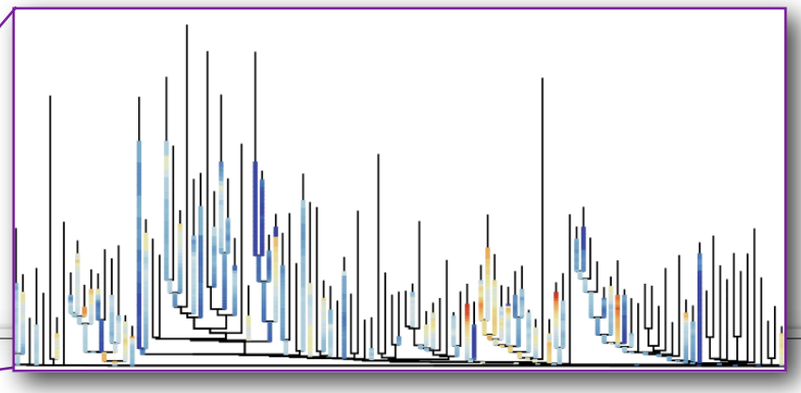
CONSPIRATORS

Alves,Beaumont, Benjamin, Bergin, Dame, Faesi, Finkbeiner, Goodman, Offner, Reid, Rice, Robitaille, Rosolowsky

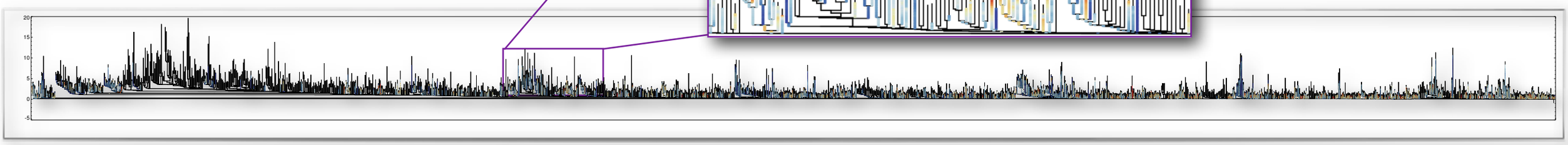
THE GRAND PLAN



CO Map of Milky Way

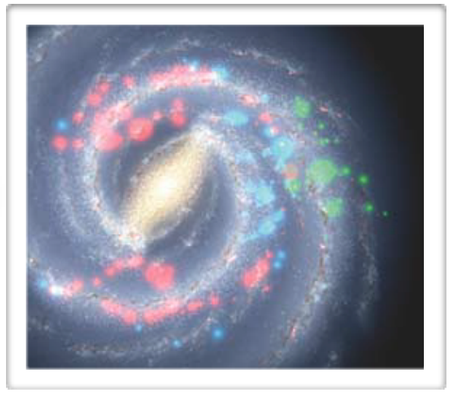


Structure Tree in p-p-v space

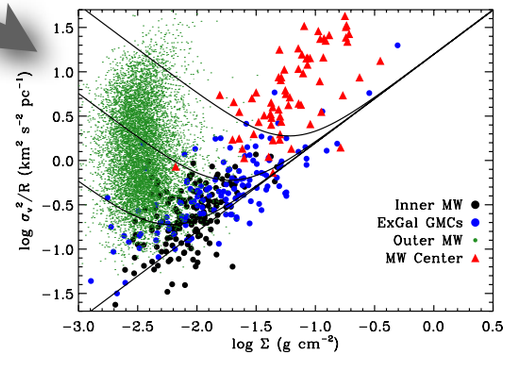


Hierarchical Catalog

distance assignments...



3D Viz



Analysis

e.g. pressure, SFE

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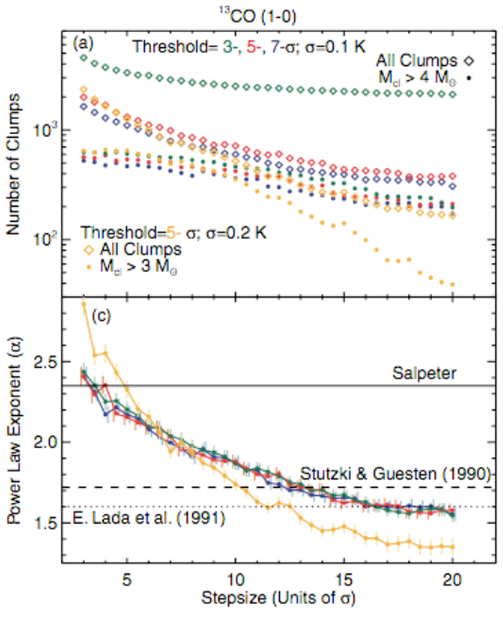
CAVEAT EMPTOR

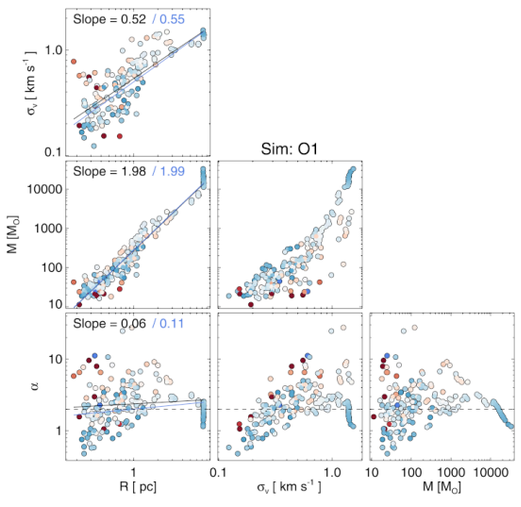
no structure-finding routine is perfect



e.g. Pineda et al. 2009

dendrograms are at least hierarchical, and much better than CLUMPFIND

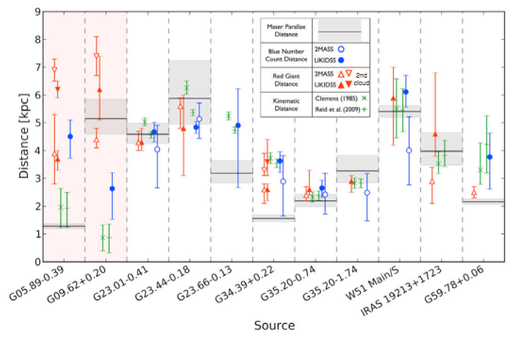
p-p-v space is not a great proxy for p-p-p space



e.g. Beaumont et al. 2013

gross structure, and/or isoloated structure are/is OK

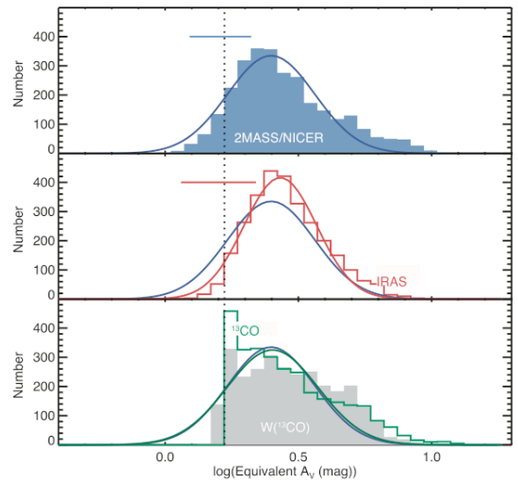
kinematic distances can be unreliable



e.g. Foster et al. 2012

combine kinematic distances with maser & extinction constraints

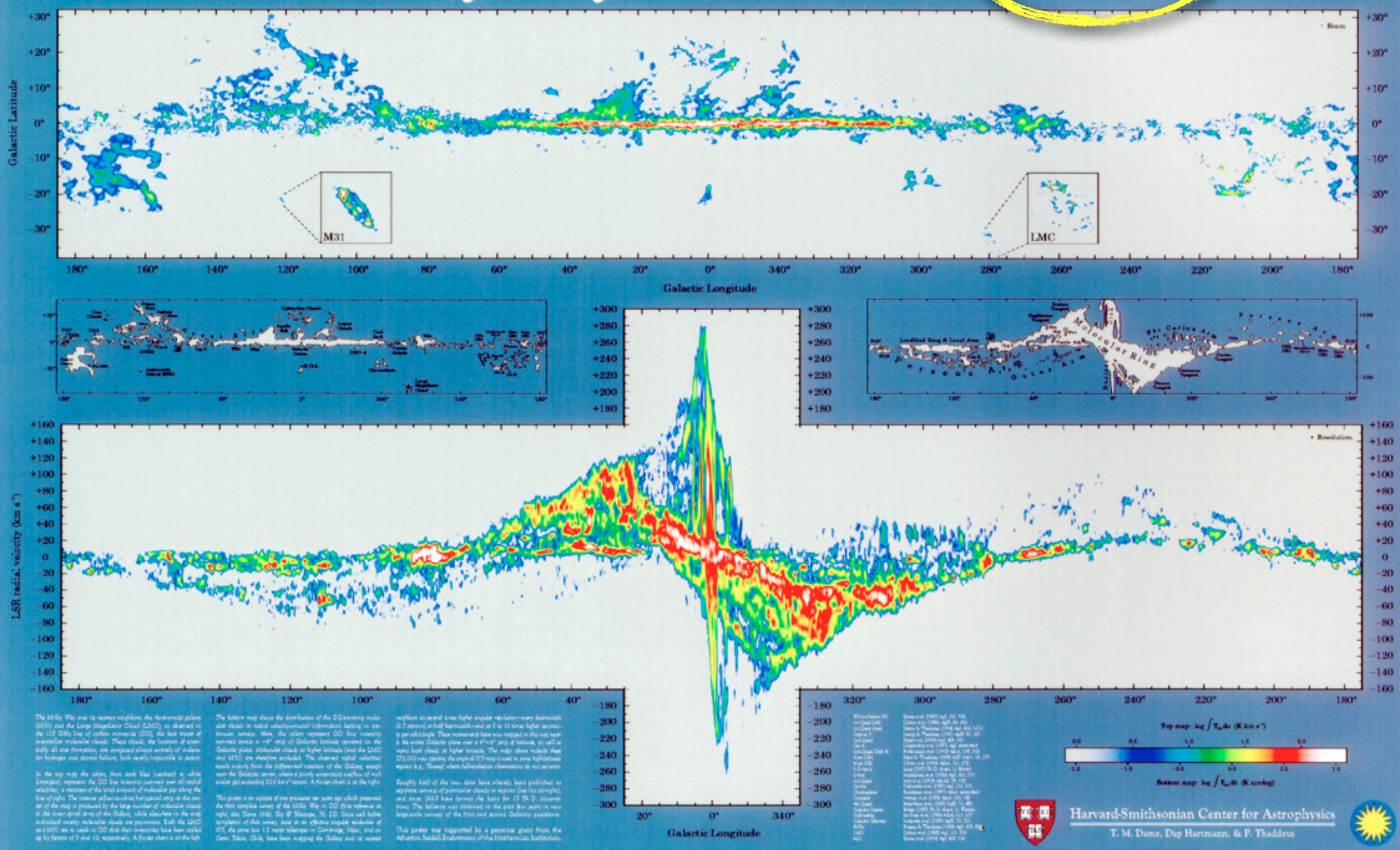
CO is a poor tracer of column density



e.g. Goodman et al. 2009

CO is our only handle on kinematics

The Milky Way in Molecular Clouds



The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), as observed in the 115 GHz line of carbon monoxide (CO), the best tracer of interstellar molecular clouds. These clouds, the location of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect.

In the top map the colors, from dark blue (weakest) to white (strongest), represent the CO line intensity summed over all radial velocities, a measure of the total amount of molecular gas along the line of sight. The intense yellow-to-white horizontal strip at the center of the map is produced by the large number of molecular clouds in the inner spiral arms of the Galaxy, while elsewhere in the map individual nearby molecular clouds are prominent. Both the LMC and M31 are so weak in CO that their intensities have been scaled up by factors of 3 and 10, respectively. A finder chart is at the left.

The bottom map shows the distribution of the CO-emitting molecular clouds in radial velocity-versus-sky (longitude) information lacking in continuum surveys. Here, the colors represent CO line intensity summed across a ~4° strip of Galactic latitude centered on the Galactic plane. Molecular clouds at higher latitude (and the LMC and M31) are therefore excluded. The observed radial velocities result mainly from the differential rotation of the Galaxy, except near the Galactic center, where a poorly understood outflow of molecular gas exceeding 200 km s⁻¹ occurs. A finder chart is at the right.

This poster is an update of one produced ten years ago which presented the first complete survey of the Milky Way in CO (first reference at right; also Dame 1988, Sky & Telescope, 76, 22). Data used before completion of that survey, done at an effective angular resolution of 0°.5, the same as our 1.2 meter telescope in Cambridge, Mass., and on Cerro Tololo, Chile, have been mapping the Galaxy and its nearest neighbors at several times higher angular resolution—every beamwidth (0.7 degrees) on half beamwidth—and at 5 to 10 times higher sensitivity per solid angle. These instruments have now mapped in this way nearly the entire Galactic plane over a 4°–6° strip of latitude, as well as many local clouds at higher latitude. The maps above include these 270,000 new spectra; the original 0°.5 map is used in some high-latitude regions (e.g., Draco) where full-resolution observations do not yet exist.

Roughly half of the new data have already been published as separate surveys of particular clouds or regions (see list at right), and since 1985 have formed the basis for 13 Ph.D. dissertations. The balance was obtained in the past few years in new large-scale surveys of the first and second Galactic quadrants.

This poster was supported by a generous grant from the Atherton Seidell Endowment of the Smithsonian Institution.

Harvard-Smithsonian Center for Astrophysics
T. M. Dame, Dap Hartmann, & P. Thaddeus

Dame et al. 2001

Dendrograms

intensity level

local max

test level

local max

merge

local max

merge

from Goodman et al. 2009

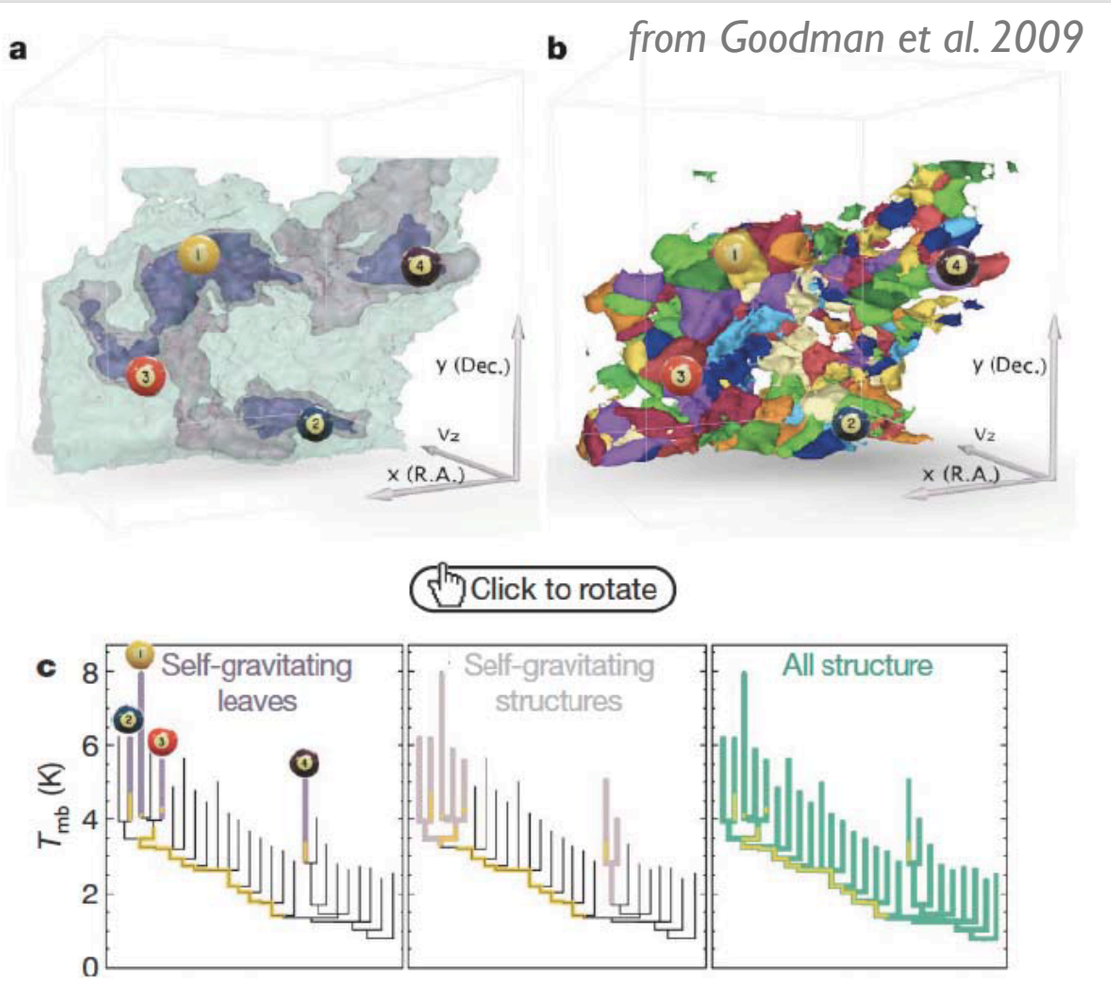
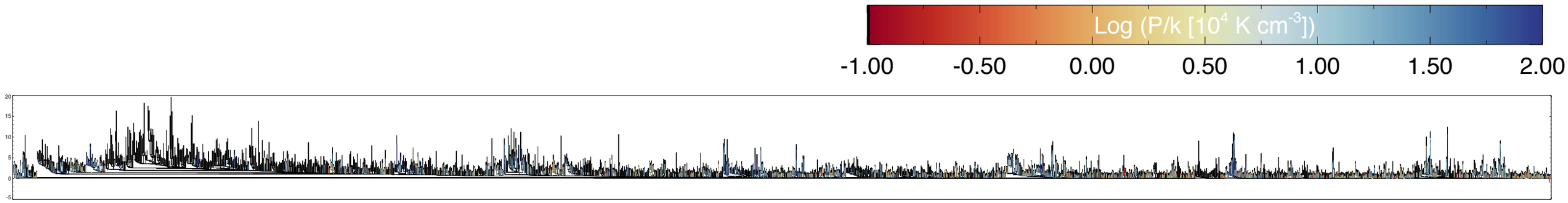


Figure 2 Dendrogram (a) and CLUMPFIND (b) decompositions of ^{13}CO in the L1448 region of Perseus shown in *p-p-v* space. Panels in (c) show dendrograms, colored to match surfaces in (a). Yellow highlights in (c) mark bound regions according to a virial analysis. In the published PDF version of Goodman et al. (2009b), this figure is interactive. Interested readers can download the paper from *Nature*, or visit tinyurl.com/Nature3Dpdf for a video demo.

Hierarchical "Segmentation"

Rosolowsky, Pineda, Kauffmann & Goodman 2008



(Pressure) Structure of Milky Way Clouds

Rice, Alves, Beaumont, Benjamin, Bergin, Dame, Faesi, Goodman, Offner, Reid, Robitaille, Rosolowsky 2013, in prep

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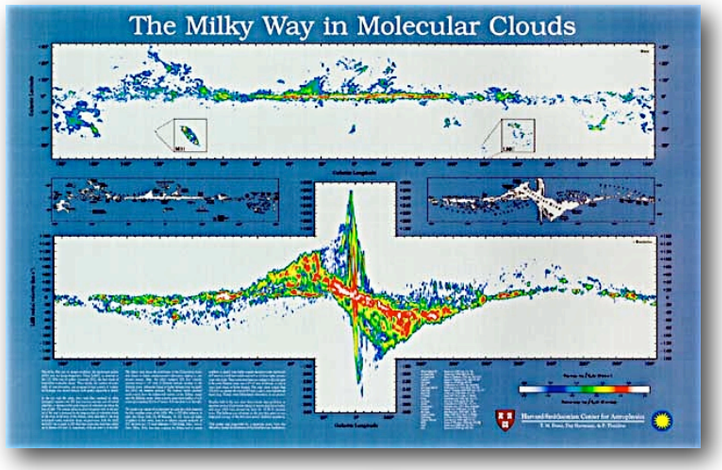

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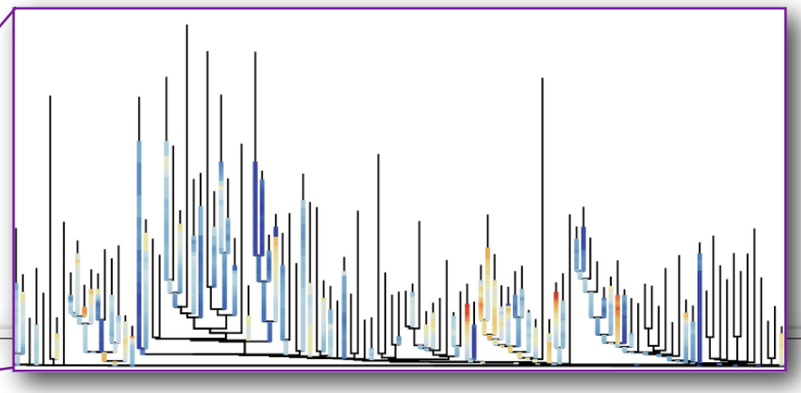

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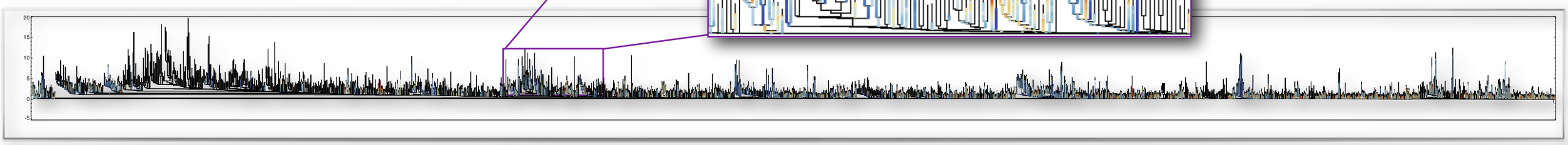

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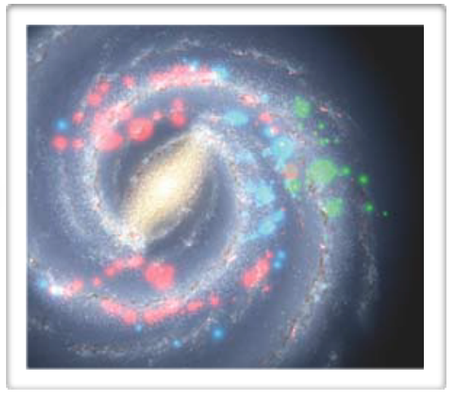
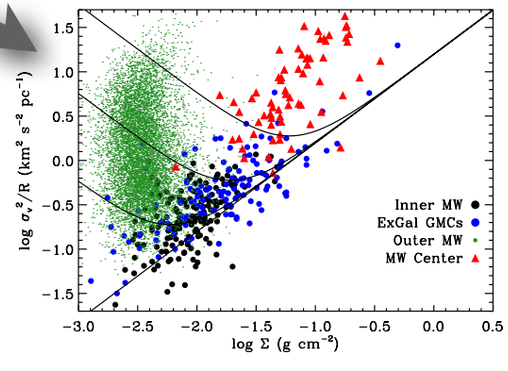


3D Viz



Analysis

e.g. pressure, SFE

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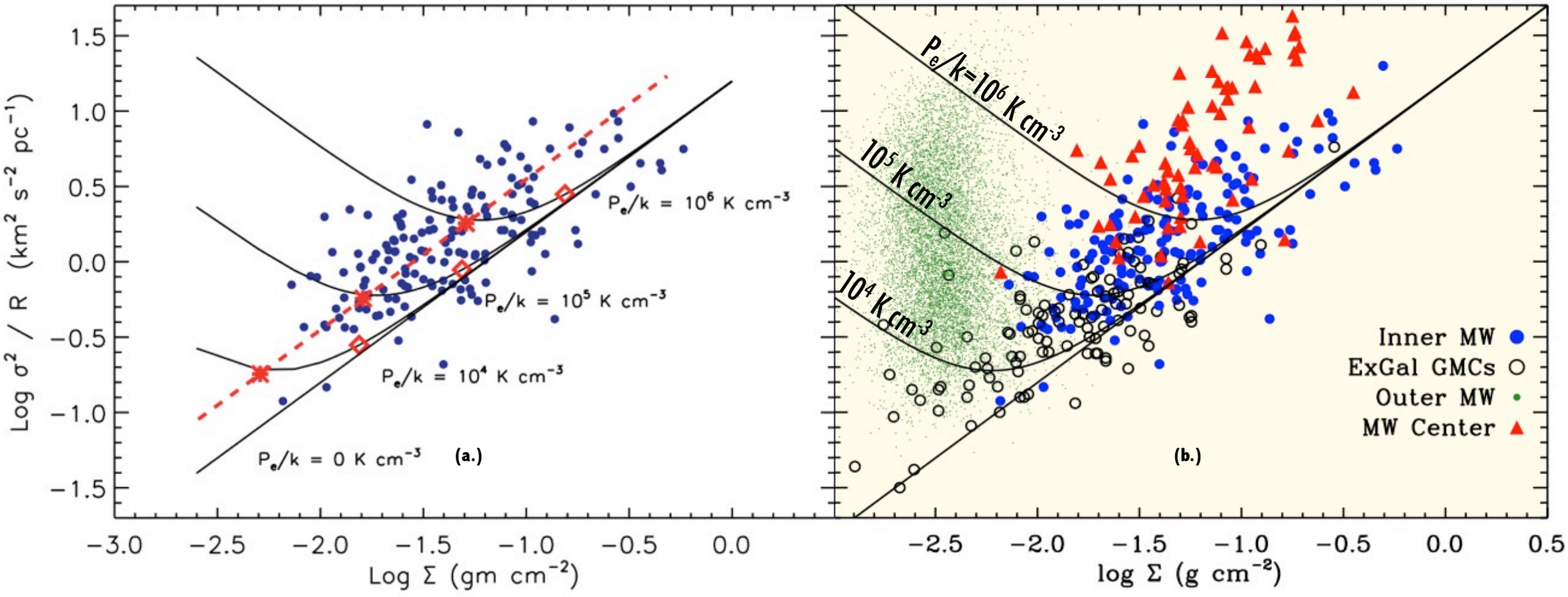
PRESSURE?



cf. Heyer et al. 2009; Field, Blackman & Keto 2011

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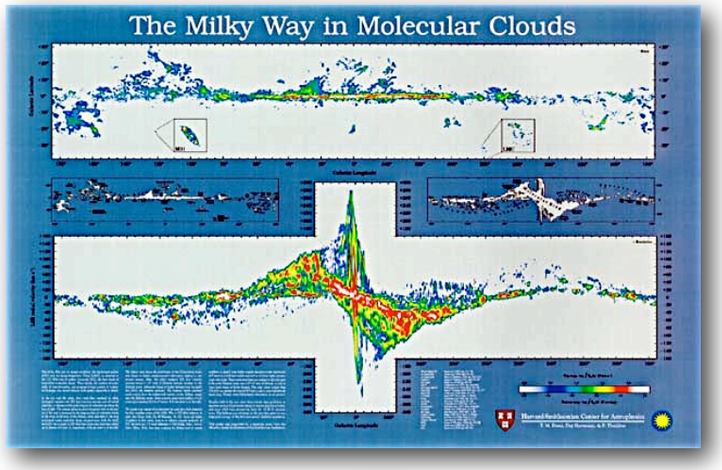

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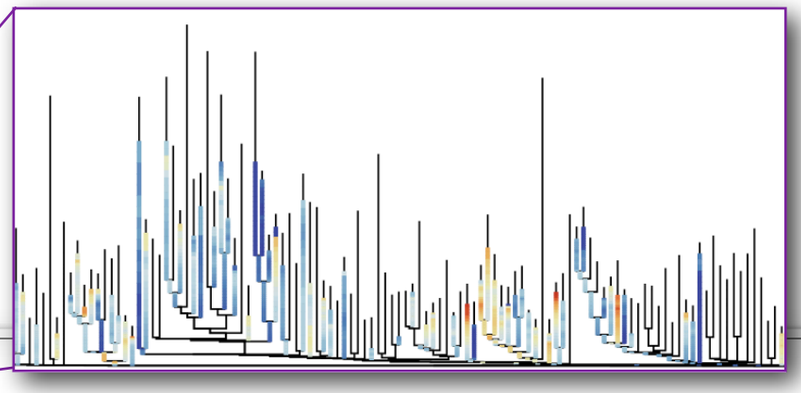

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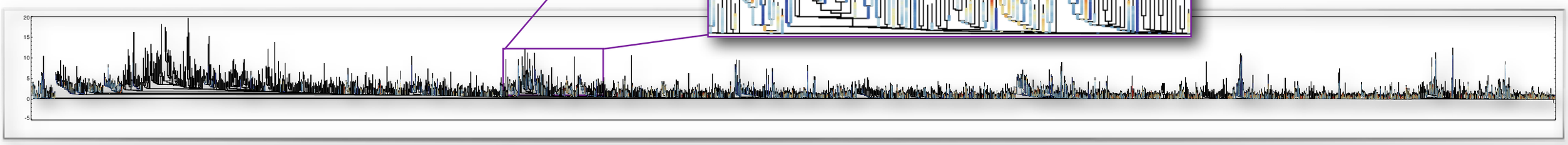

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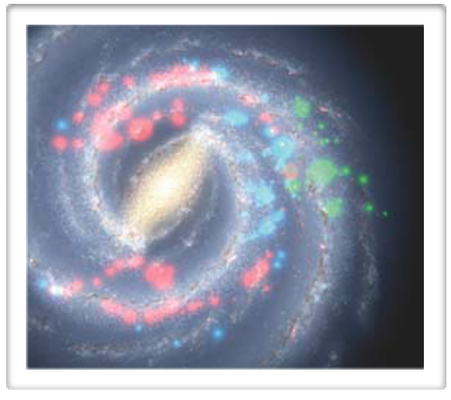

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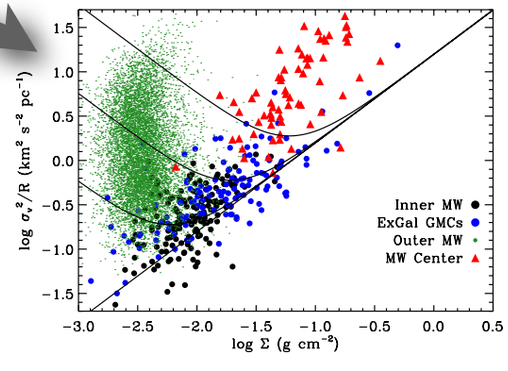

Analysis

e.g. pressure, SFE

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The intention of Universe3D.org is to host links to web content that enable the enhancement of our three-dimensional view of the Universe. Feel free to join in and edit--Wikipedia-style!

Recently added Dataset

Methanol MultiBeam Survey The Methanol MultiBeam Survey is a sensitive survey of massive young stars in the Milky Way Galaxy to detect methanol masers. The survey is carried out by
cover a 4-MHz band, corres
channels each separated by
scanned more than once wi
velocities are searched. A s
hydroxyl (OH) is observed in parallel with the methanol band

The galaxy's an
A team of as
Milky Way G
Thu, 21 Nov
Comet ISON un
New images
days.
Wed, 20 Nov
MicroObservato
The comet re
Wed, 20 Nov 2013 02:00:00 GMT

News

Survey Coverage of the Milky Way

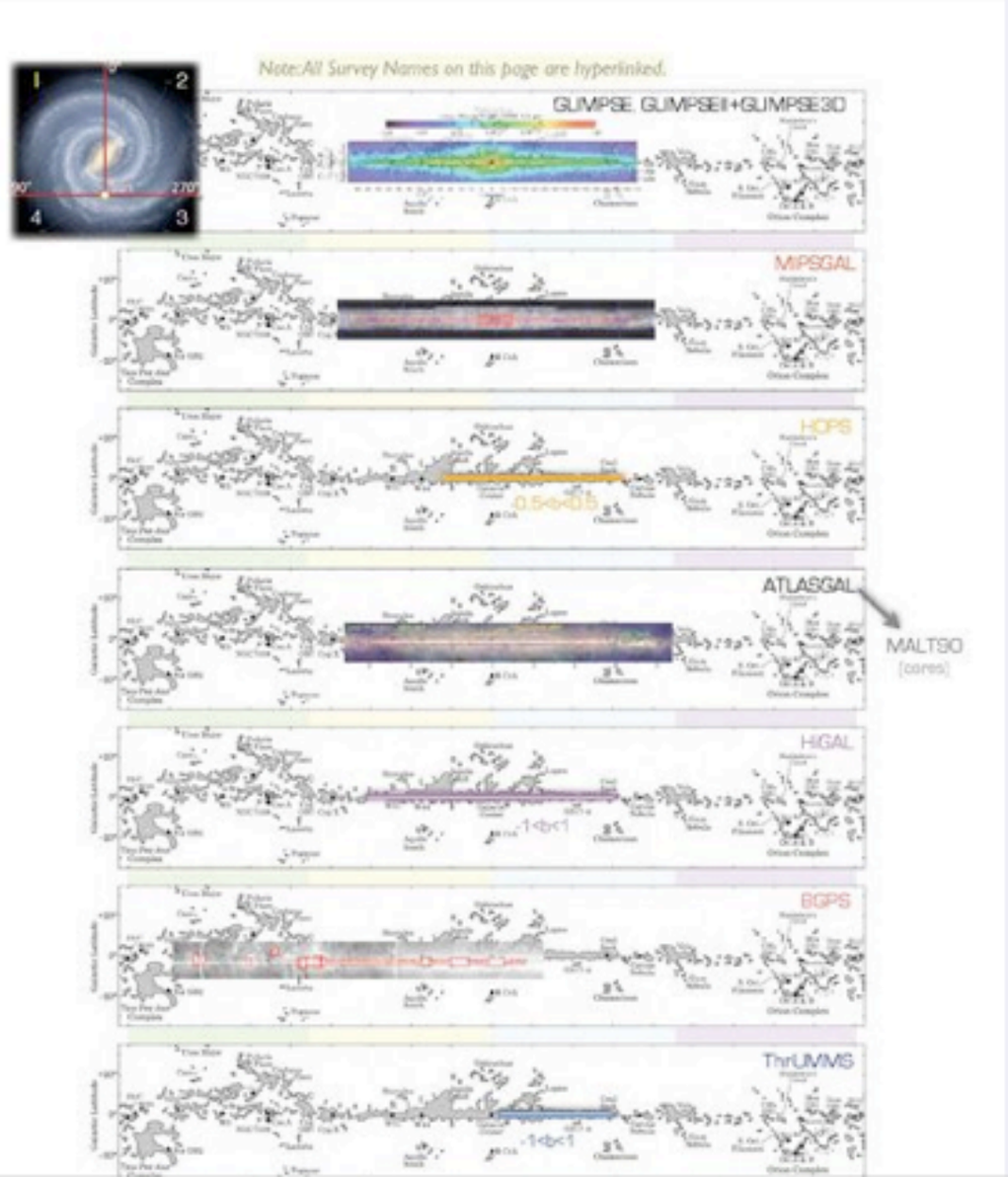

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IMAGE CREDIT: NASA; ESA; Z. LEVAY AND R. VAN DER MAREL, STSCI; T. HALLAS; AND A. MELLINGER

THE "INSIDER'S" VIEW OF THE MILKY WAY

ALYSSA A. GOODMAN, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS