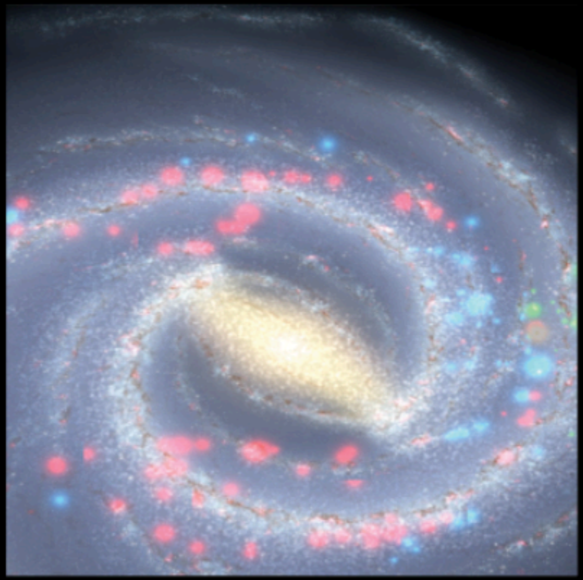
C I E R A

CENTER FOR
INTERDISCIPLINARY
EXPLORATION AND
RESEARCH IN
ASTROPHYSICS

Fall 2012 Interdisciplinary Colloquium

"THE CLOSE RELATIONSHIP BETWEEN HEART DISEASE AND SEA MONSTERS"

(or, why good high-dimensional data visualization can solve almost any problem!)



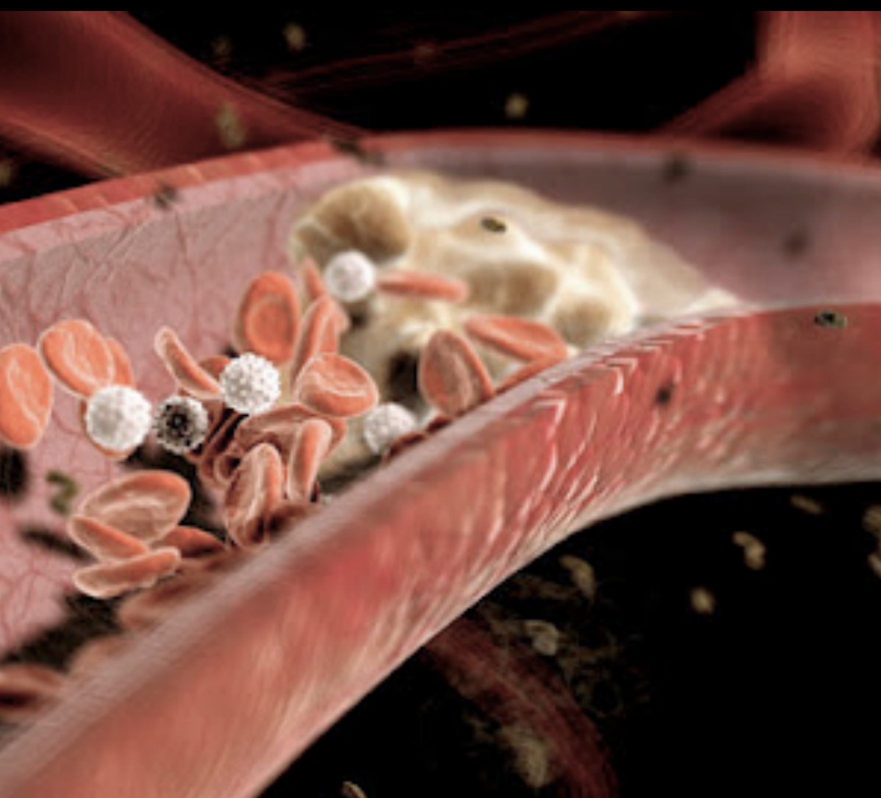
This talk will explore the role of high-dimensional data visualization in a variety of research areas. In fields as diverse as Astronomy, Medicine, Geology, and Genomics, the progress of research is now limited more by the speed of data analysis and understanding than it is by data acquisition. Rich online resources offer not only ever-larger tables of numbers, but also images, movies, and other high-dimensional data streams. And, most results of previous research are available on-demand thanks to a growing wealth of digitized literature. The talk will offer real-world scenarios, focusing in particular on examples from Astronomy (including sea monsters in the sky) and Medicine (including how your doctor *should* look at your heart), where high-dimensional linked-view data visualization tools, such as the WorldWide Telescope and Glue software packages, have quickened the pace of insight.

Friday, November 30th
at 11:00am
Technological Institute
2145 Sheridan Road, Room F160

Dr. Alyssa A. Goodman
Harvard-Smithsonian Center for Astrophysics

The Close Relationship between Heart Disease and Sea Monsters*

**or, why good high-dimensional data visualization can solve almost any problem!*



Alyssa A. Goodman

Harvard-Smithsonian Center for Astrophysics

Relative Strengths

Pattern Recognition
Creativity

Calculations

"e-Science"

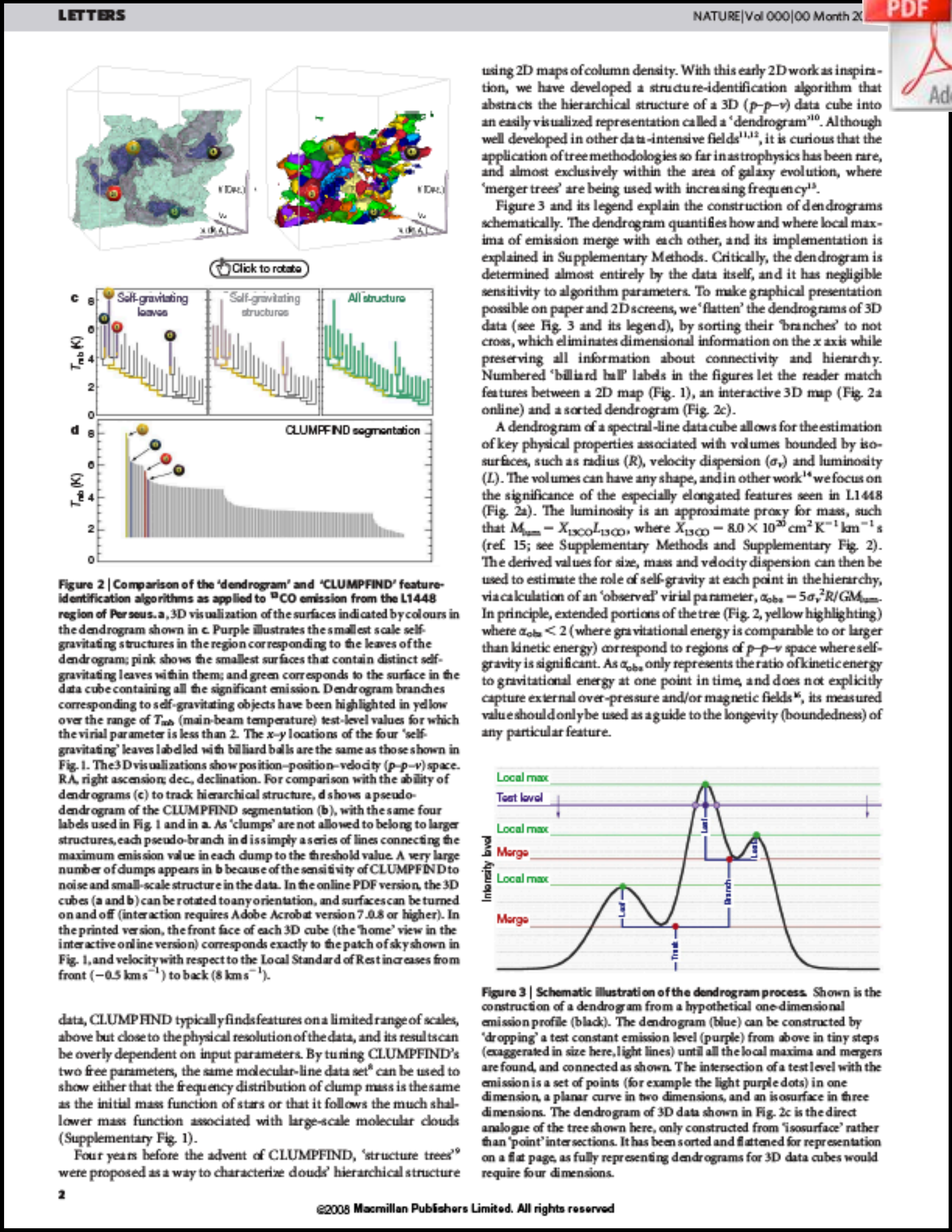


Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. **a**, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating structures in the region corresponding to the leaves of the dendrogram; pink shows the smallest surfaces that contain distinct self-gravitating leaves within them; and green corresponds to the surface in the data cube containing all the significant emission. Dendrogram branches corresponding to self-gravitating objects have been highlighted in yellow over the range of T_{mb} (main-beam temperature) test-level values for which the virial parameter is less than 2. The *x*–*y* locations of the four 'self-gravitating' leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position–position–velocity (*p*–*p*–*v*) space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (**c**) to track hierarchical structure, **d** shows a pseudo-dendrogram of the CLUMPFIND segmentation (**b**), with the same four labels used in Fig. 1 and in **a**. As 'clumps' are not allowed to belong to larger structures, each pseudo-branch in **d** is simply a series of lines connecting the maximum emission value in each clump to the threshold value. A very large number of clumps appears in **b** because of the sensitivity of CLUMPFIND to noise and small-scale structure in the data. In the online PDF version, the 3D cubes (**a** and **b**) can be rotated to any orientation, and surfaces can be turned on and off (interaction requires Adobe Acrobat version 7.0.8 or higher). In the printed version, the front face of each 3D cube (the 'home' view in the interactive online version) corresponds exactly to the patch of sky shown in Fig. 1, and velocity with respect to the Local Standard of Rest increases from front (-0.5 km s^{-1}) to back (8 km s^{-1}).

data, CLUMPFIND typically finds features on a limited range of scales, above but close to the physical resolution of the data, and its results can be overly dependent on input parameters. By tuning CLUMPFIND's two free parameters, the same molecular-line data set[8] can be used to show either that the frequency distribution of clump mass is the same as the initial mass function of stars or that it follows the much shallower mass function associated with large-scale molecular clouds (Supplementary Fig. 1).

Four years before the advent of CLUMPFIND, 'structure trees'[9] were proposed as a way to characterize clouds' hierarchical structure using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that abstracts the hierarchical structure of a 3D (*p*–*p*–*v*) data cube into an easily visualized representation called a 'dendrogram'[10]. Although well developed in other data-intensive fields[11,12], it is curious that the application of tree methodologies so far in astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where 'merger trees' are being used with increasing frequency[13].

Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is explained in Supplementary Methods. Critically, the dendrogram is determined almost entirely by the data itself, and it has negligible sensitivity to algorithm parameters. To make graphical presentation possible on paper and 2D screens, we 'flatten' the dendrograms of 3D data (see Fig. 3 and its legend), by sorting their 'branches' to not cross, which eliminates dimensional information on the *x* axis while preserving all information about connectivity and hierarchy. Numbered 'billiard ball' labels in the figures let the reader match features between a 2D map (Fig. 1), an interactive 3D map (Fig. 2a online) and a sorted dendrogram (Fig. 2c).

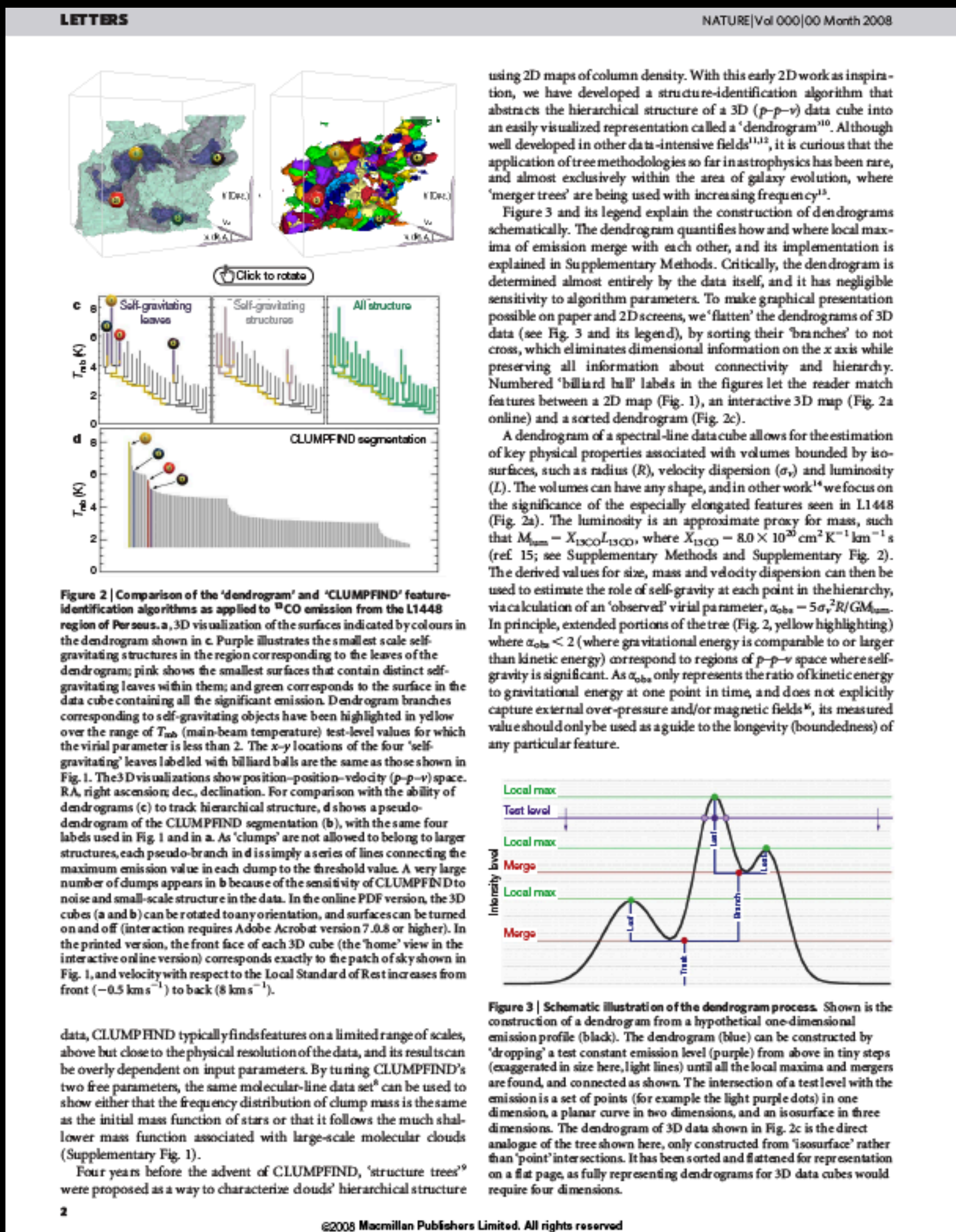
A dendrogram of a spectral-line data cube allows for the estimation of key physical properties associated with volumes bounded by isosurfaces, such as radius (R), velocity dispersion (σ_v) and luminosity (L). The volumes can have any shape, and in other work[14] we focus on the significance of the especially elongated features seen in L1448 (Fig. 2a). The luminosity is an approximate proxy for mass, such that $M_{lum} = X_{13CO}L_{13CO}$, where $X_{13CO} = 8.0 \times 10^{20}$ cm^2 K^{-1} km^{-1} s (ref. 15; see Supplementary Methods and Supplementary Fig. 2). The derived values for size, mass and velocity dispersion can then be used to estimate the role of self-gravity at each point in the hierarchy, via calculation of an 'observed' virial parameter, $\alpha_{obs} = 5\sigma_v^2R/GM_{lum}$. In principle, extended portions of the tree (Fig. 2, yellow highlighting) where $\alpha_{obs} < 2$ (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of *p*–*p*–*v* space where self-gravity is significant. As α_{obs} only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic fields[16], its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in size here, light lines) until all the local maxima and mergers are found, and connected as shown. The intersection of a test level with the emission is a set of points (for example the light purple dots) in one dimension, a planar curve in two dimensions, and an isosurface in three dimensions. The dendrogram of 3D data shown in Fig. 2c is the direct analogue of the tree shown here, only constructed from 'isosurface' rather than 'point' intersections. It has been sorted and flattened for representation on a flat page, as fully representing dendrograms for 3D data cubes would require four dimensions.

Goodman et al. 2009: 1st 3D PDF in Nature

“High-dimensional” or “Multivariate” Data

(Astronomy=Biology)



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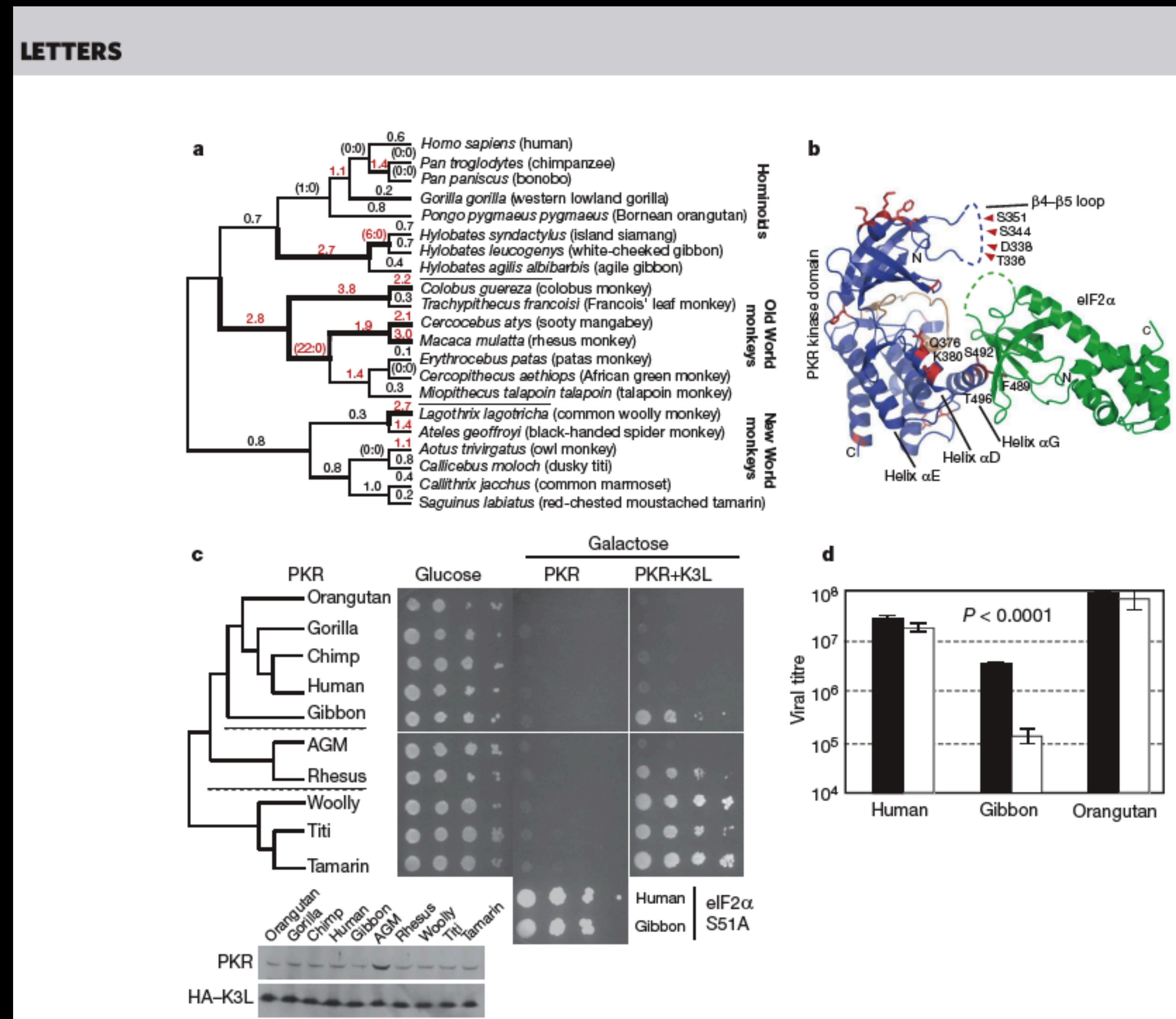
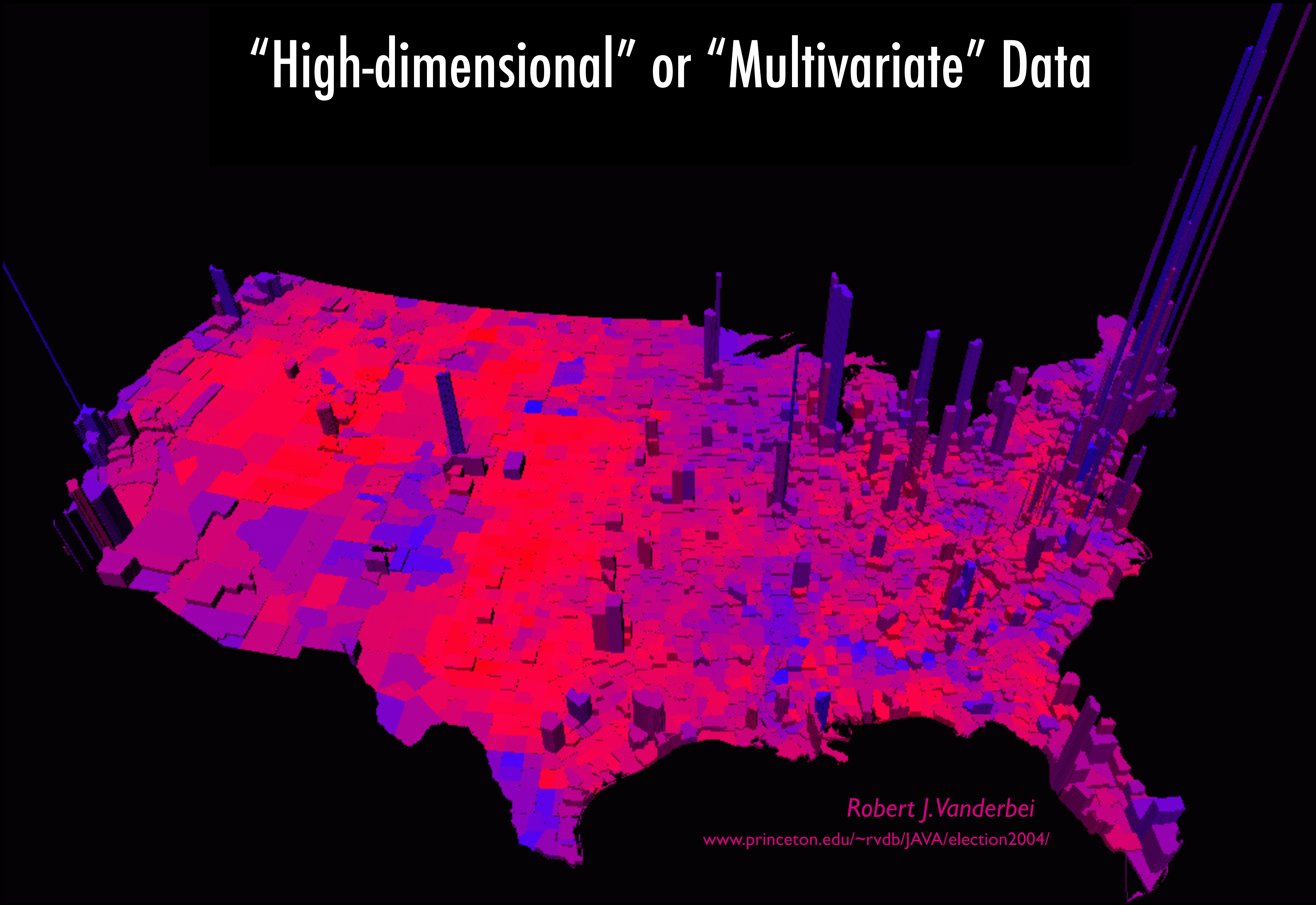


Goodman et al. *Nature*, 2009

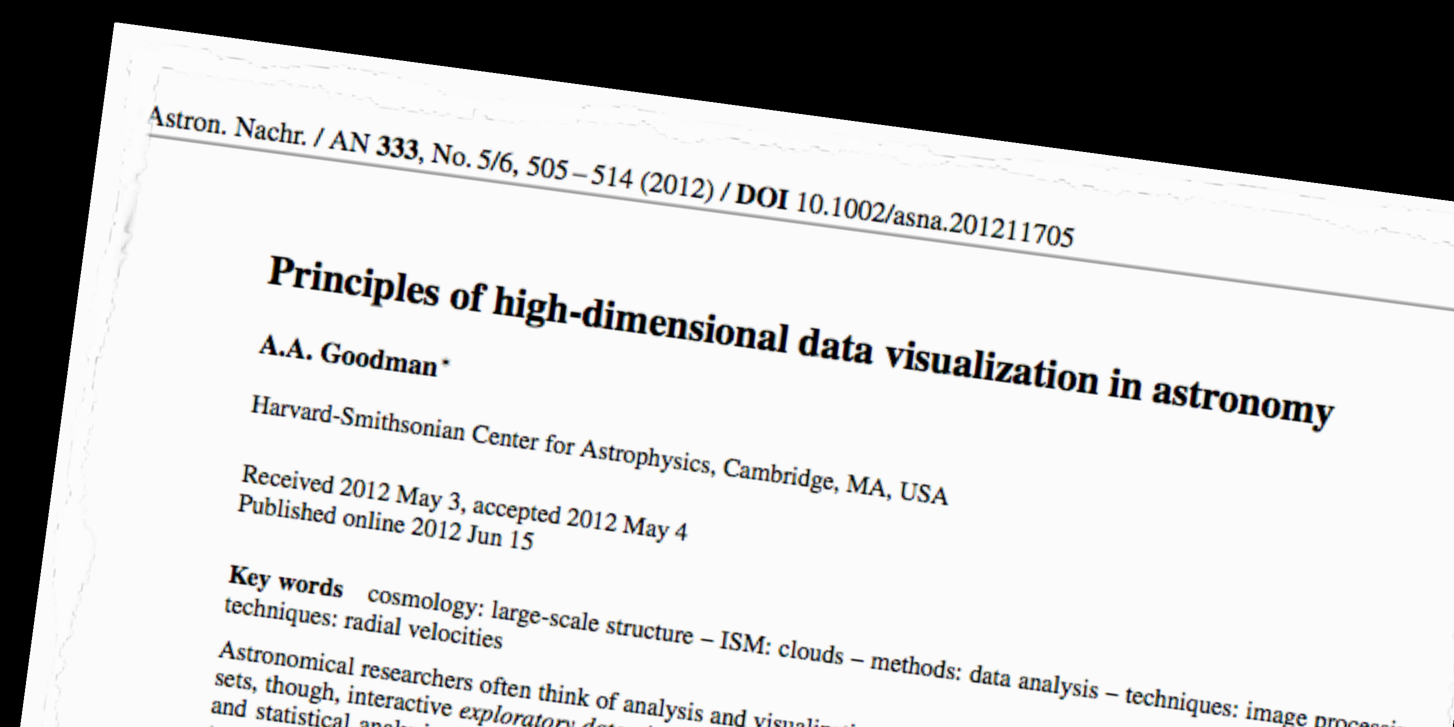
Elde et al. *Nature*, 2008

“High-dimensional” or “Multivariate” Data



This map displays 2 quantities as a function of 2 spatial dimensions....Is that 4 dimensions?

Data • Dimensions • Display


Astron. Nachr. / AN **333**, No. 5/6, 505 – 514 (2012) / **DOI** 10.1002/asna.201211705

Principles of high-dimensional data visualization in astronomy

A.A. Goodman*

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA

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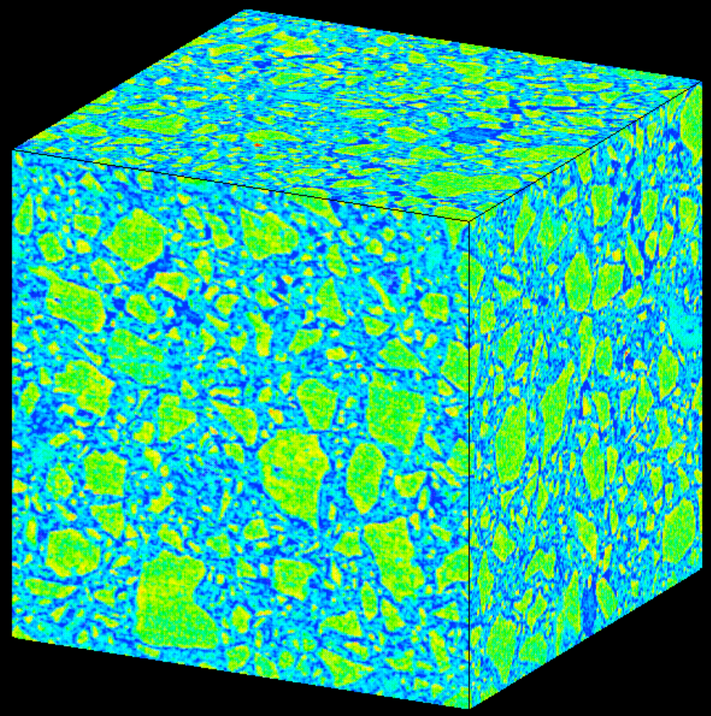
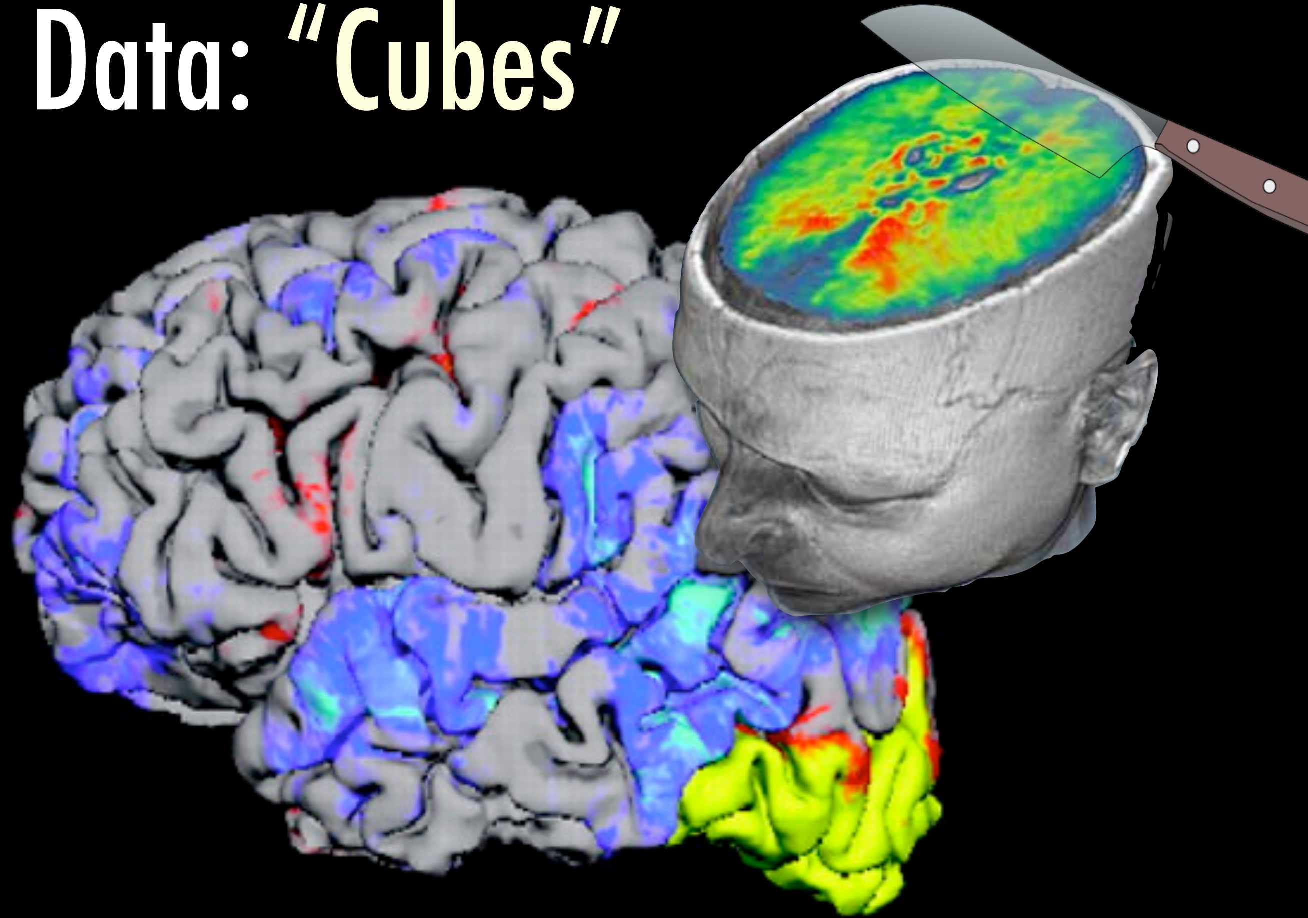
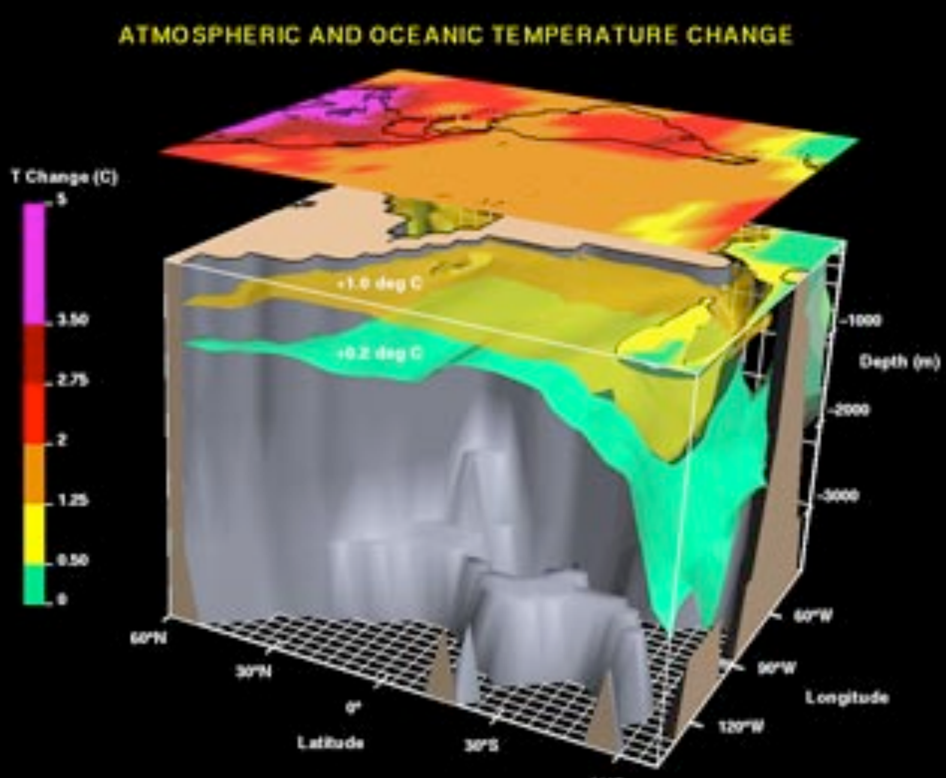
Key words cosmology: large-scale structure – ISM: clouds – methods: data analysis – techniques: image processing
techniques: radial velocities

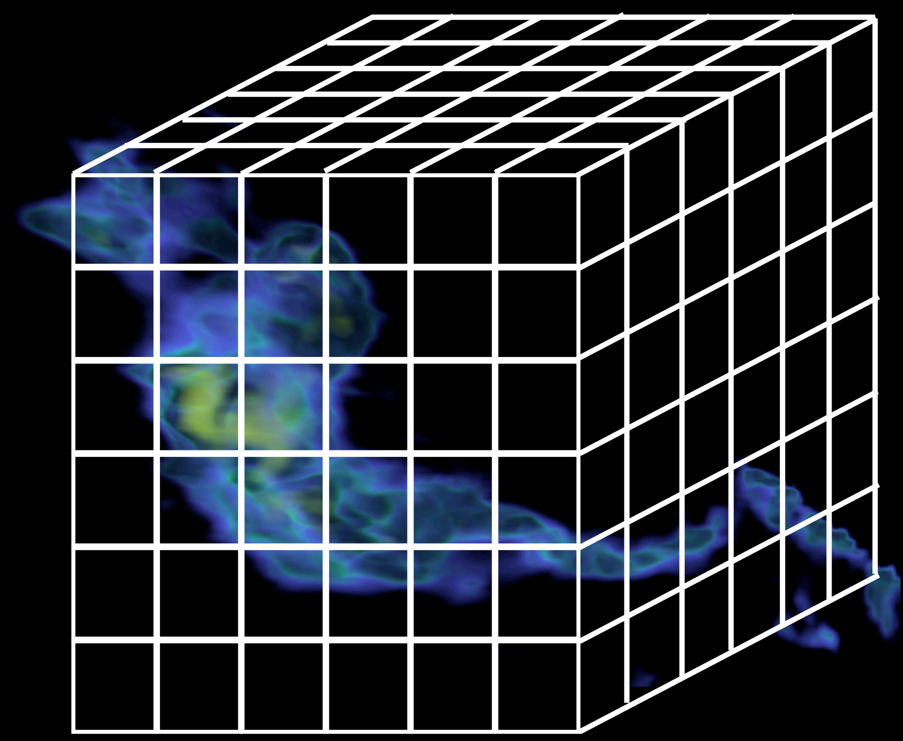
Astronomical researchers often think of analysis and visualiz
sets, though, interactive *exploratory* d
and statistical anal

High-Dimensional Data: "Cubes"

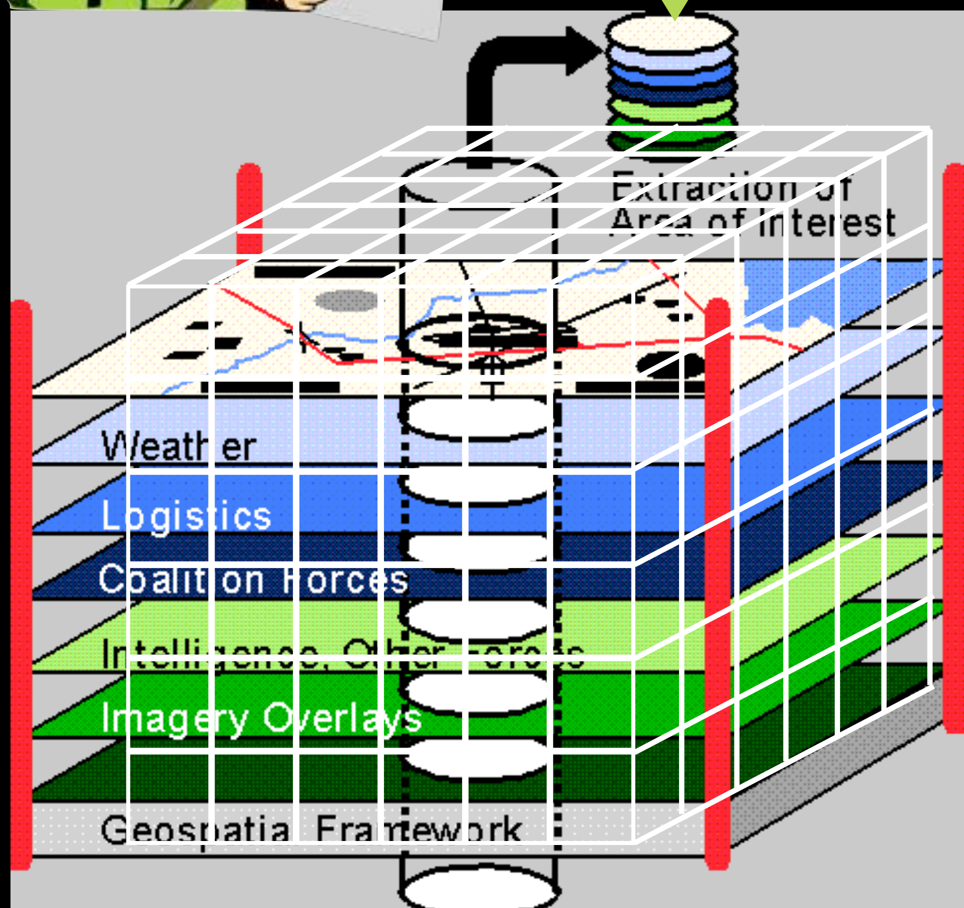




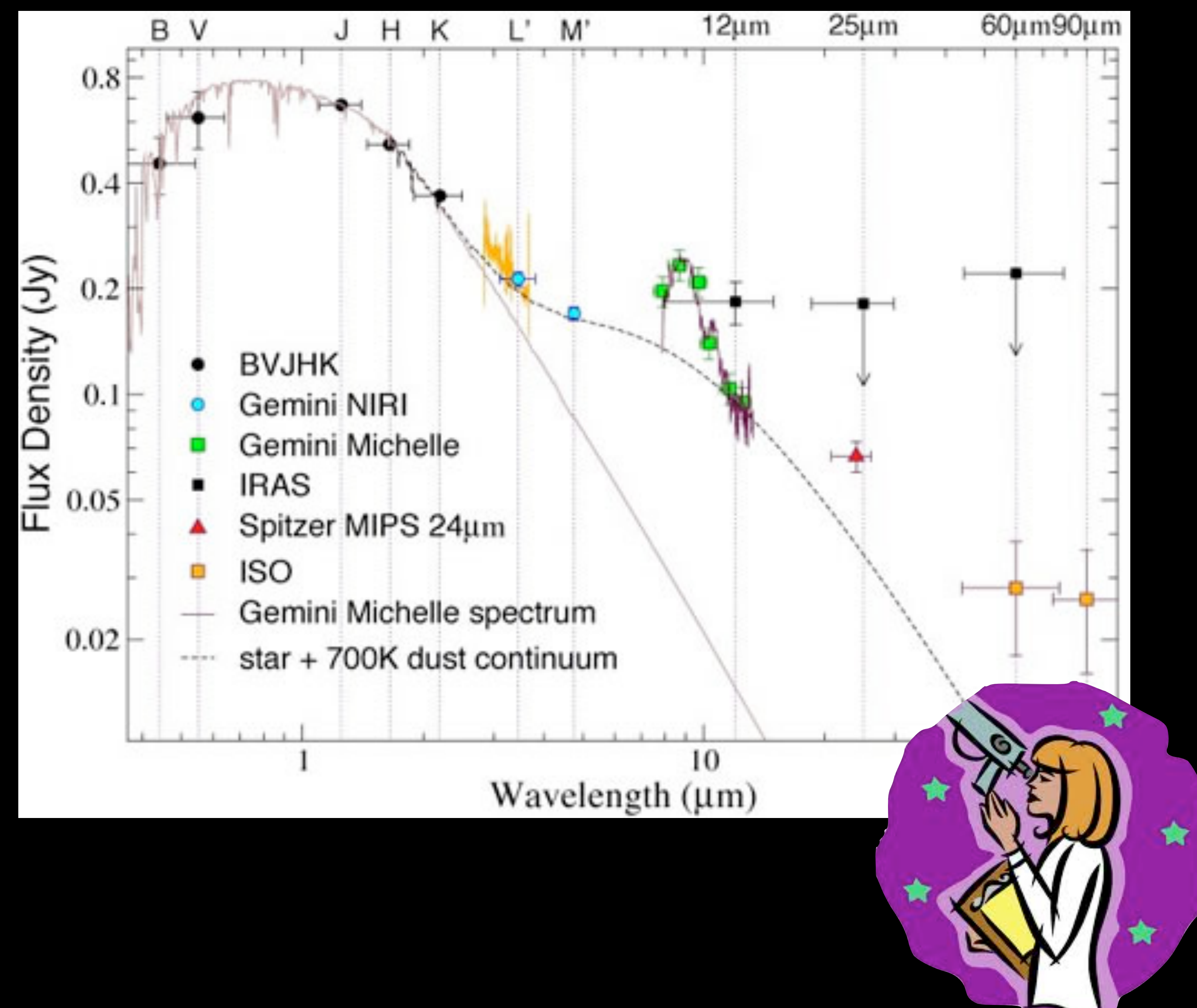


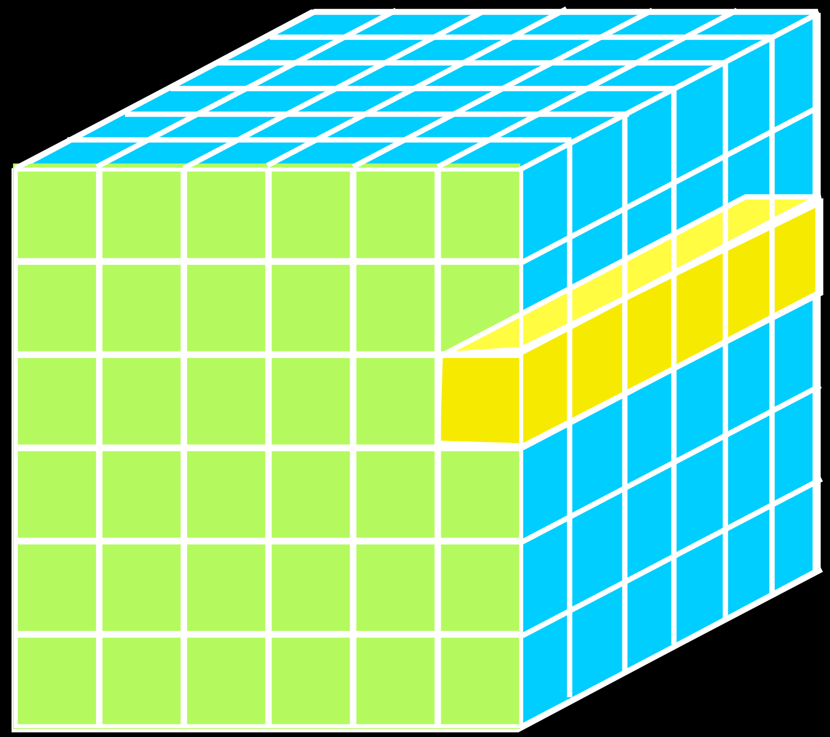


This 1-D “Bore”



is a “spectral energy distribution”





GENERALLY

1D: Columns = “Spectra”, “SEDs” or “Time Series”

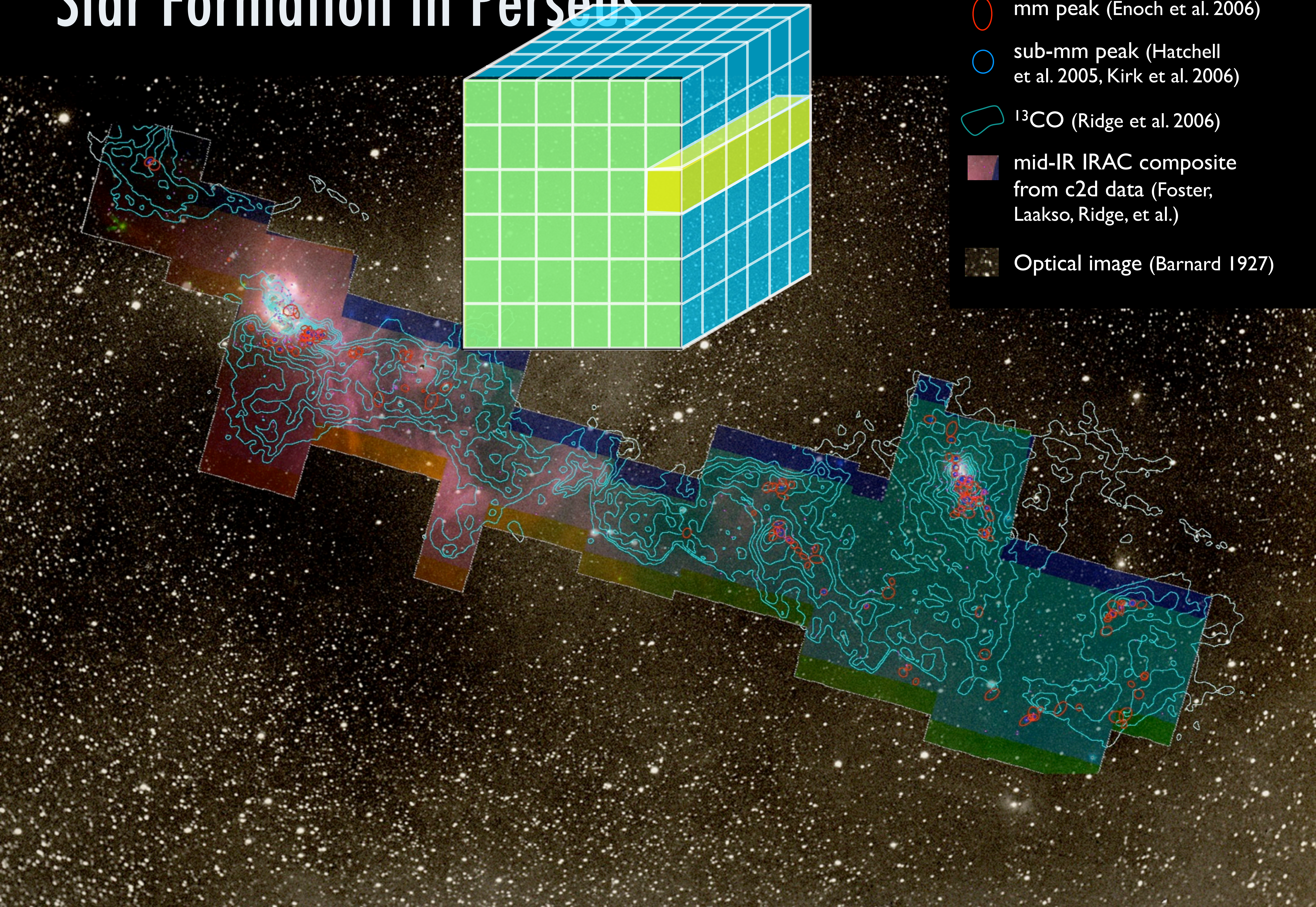
2D: Faces or Slices = “Images”

3D: Volumes = “3D Renderings”, “2D Movies”

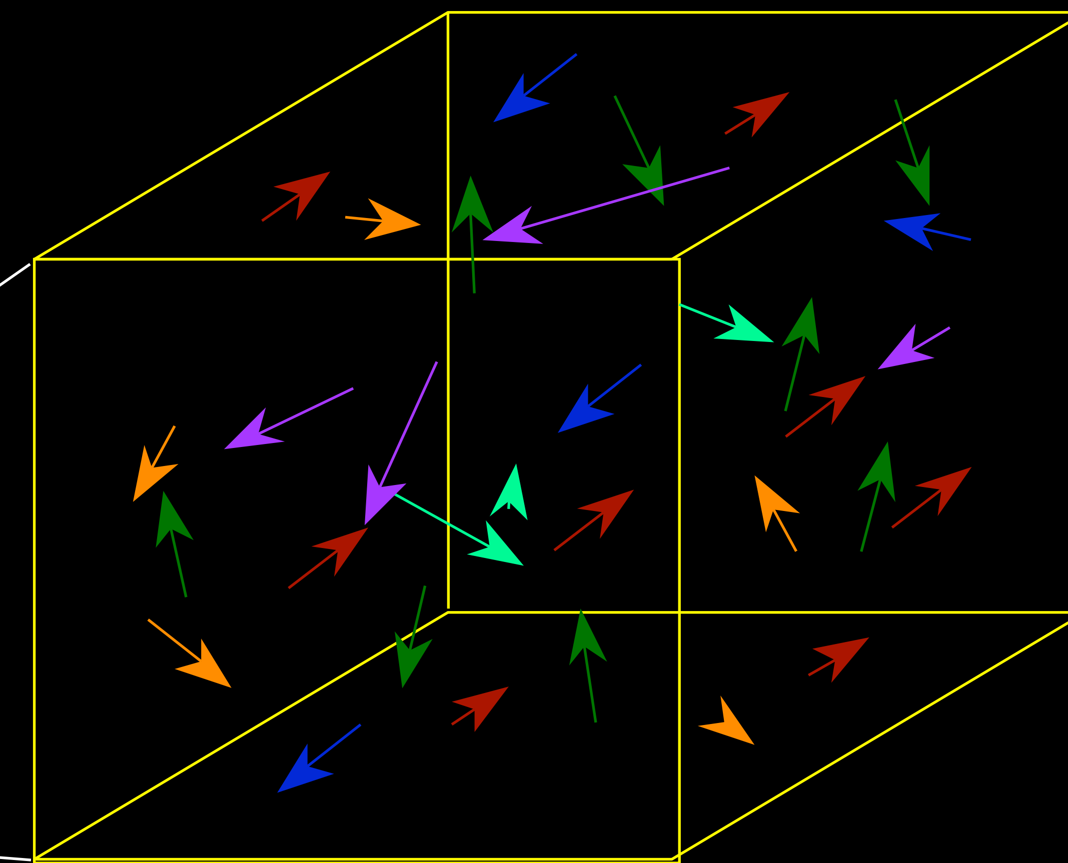
4D: Time Series of Volumes = “3D Movies”

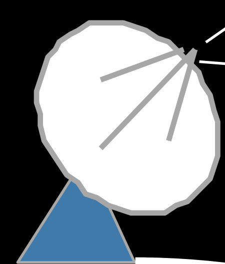
Star Formation in Perseus

COMPLETE

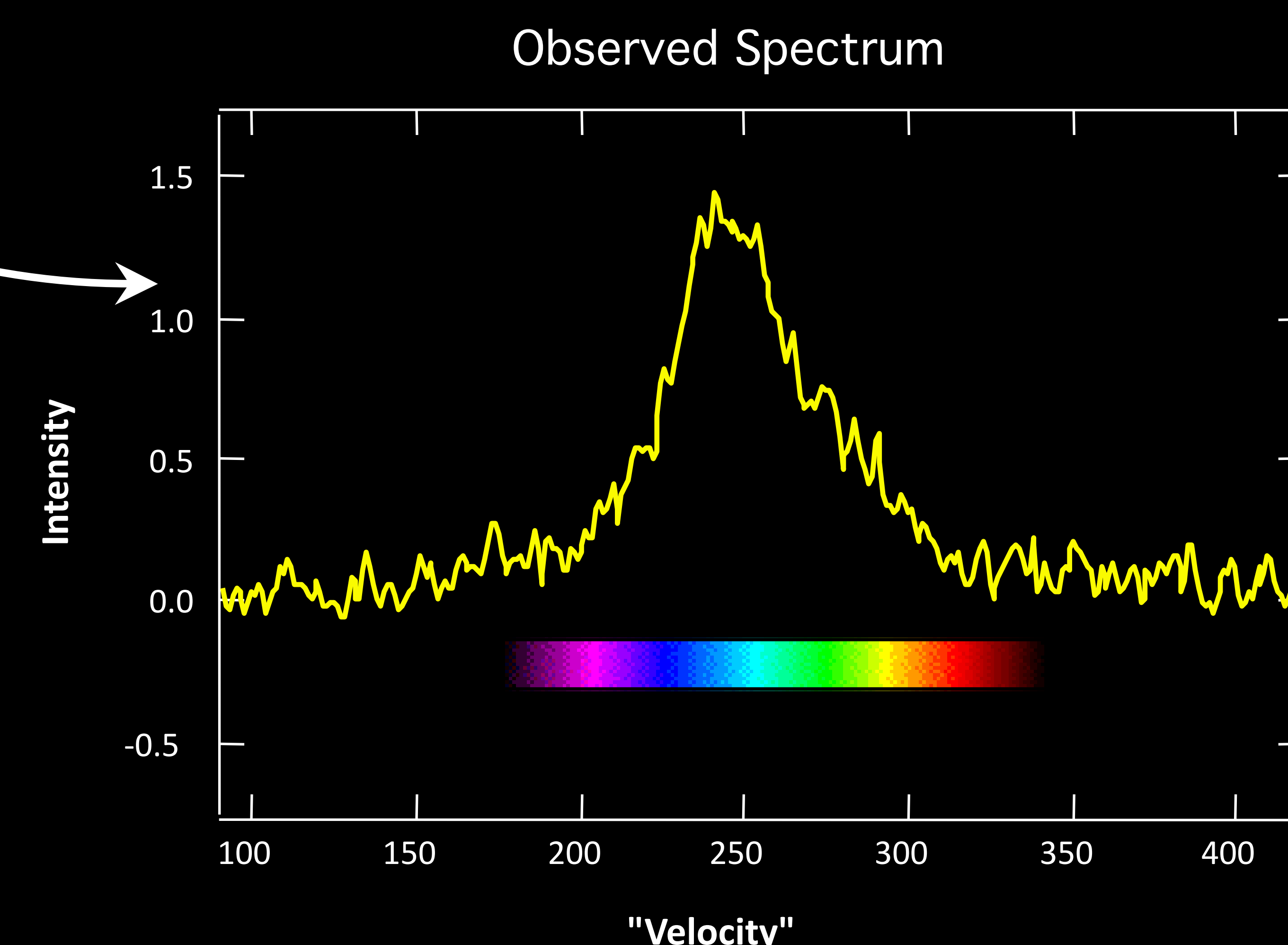


Velocity from Spectroscopy



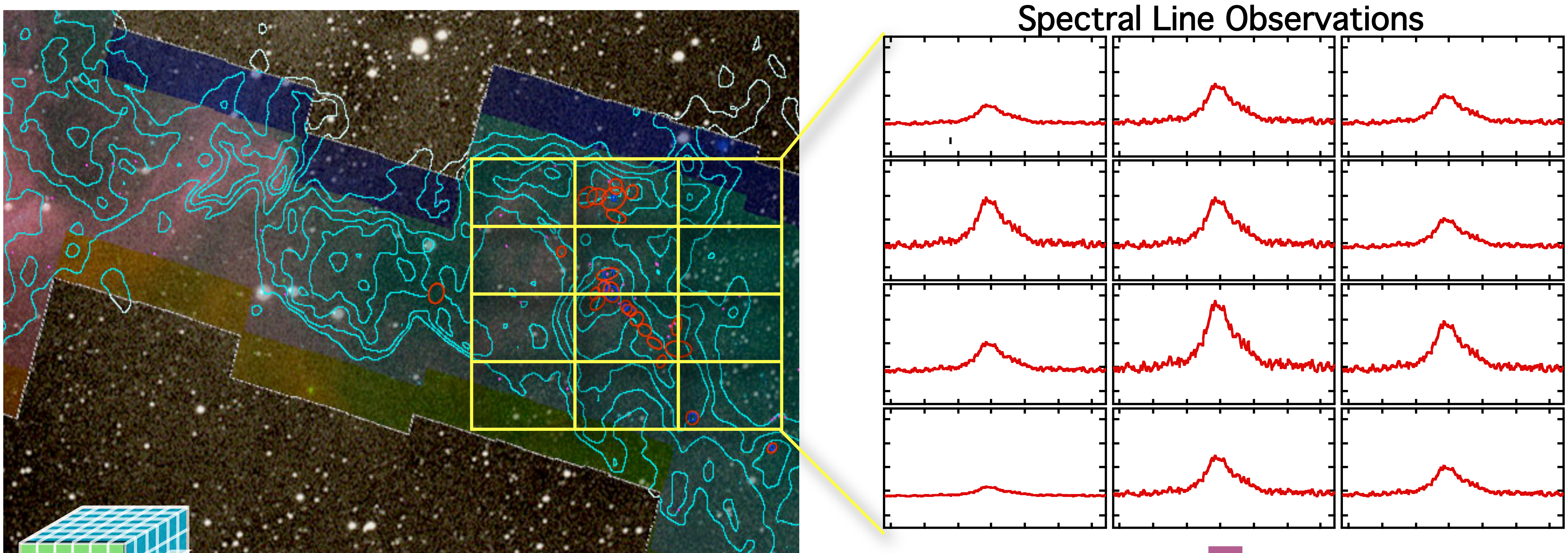


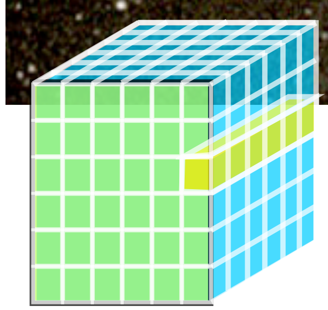
Telescope + Spectrometer

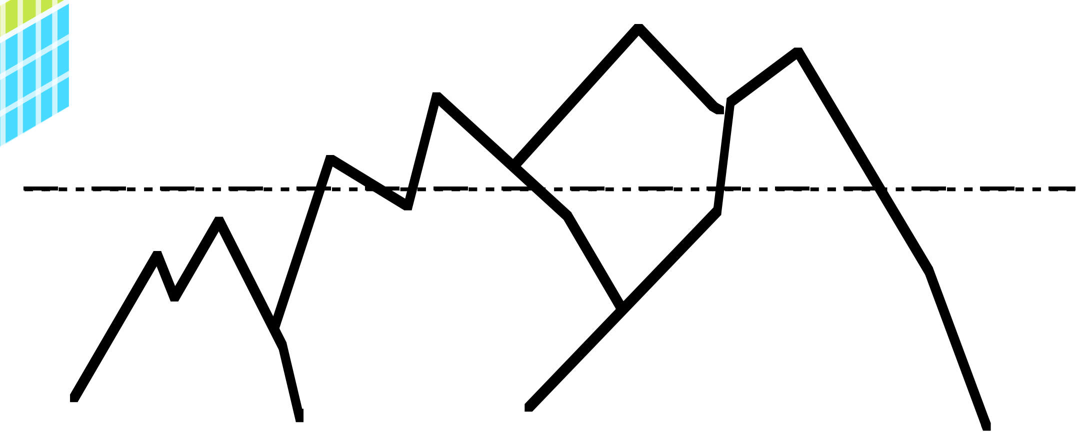


All thanks to Doppler

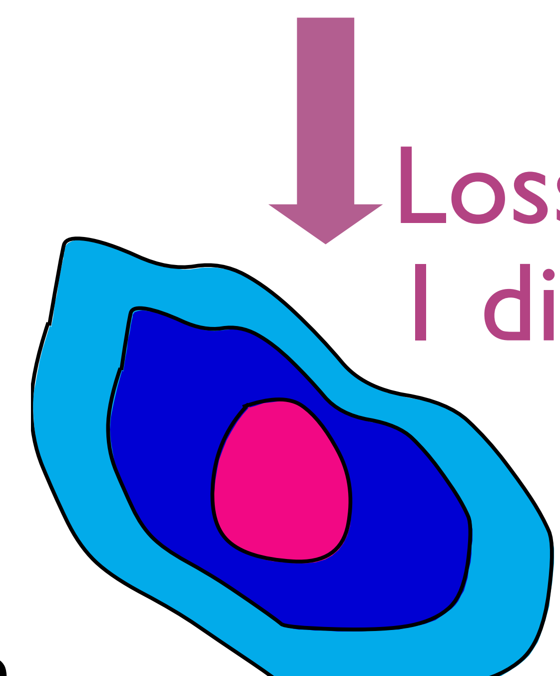
Spectral-Line Mapping



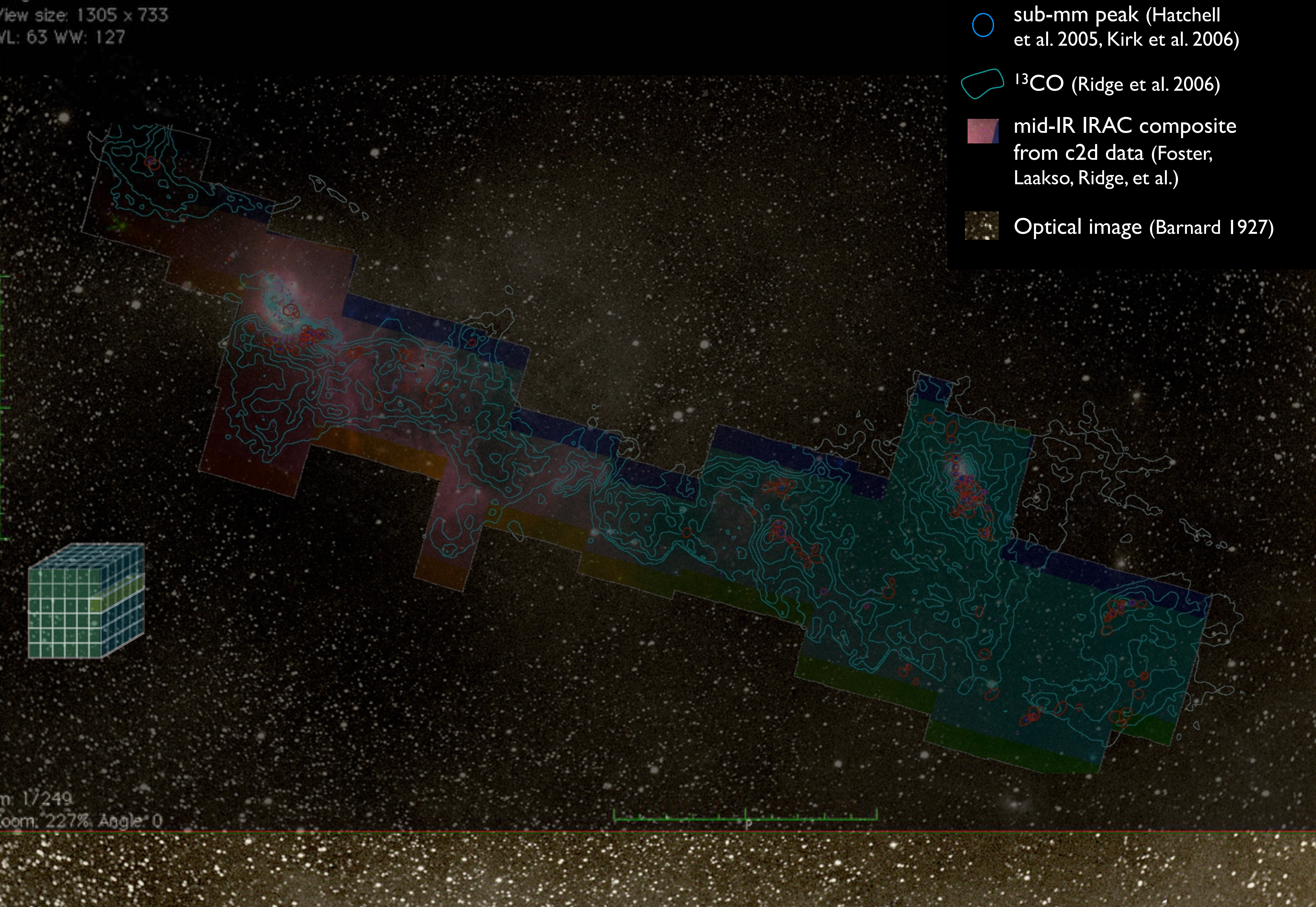




No loss of information

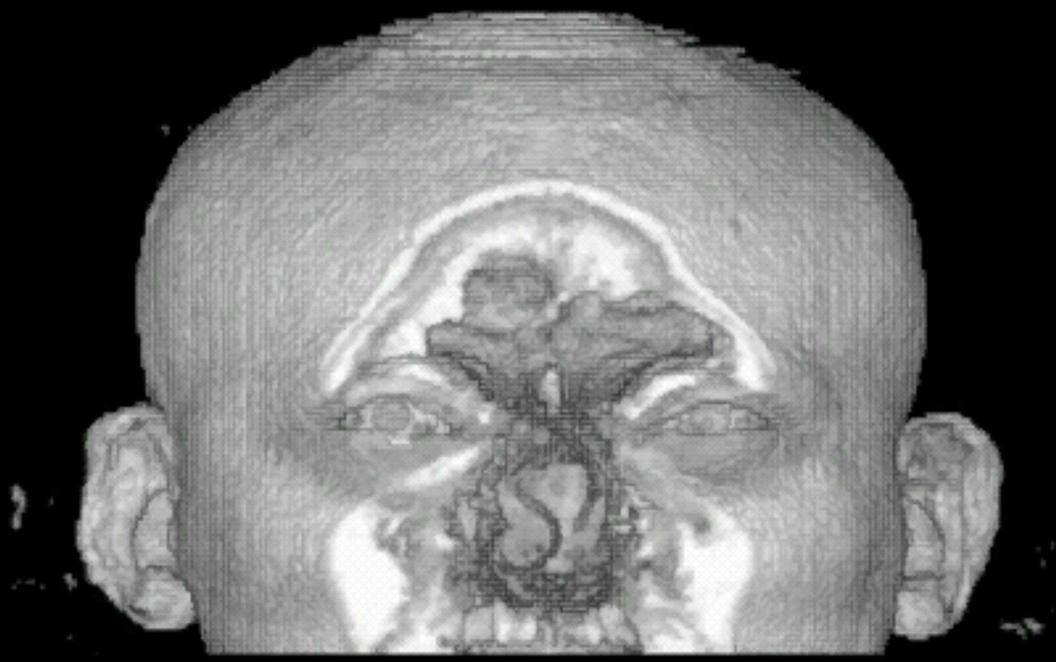


COMPLETE Perseus



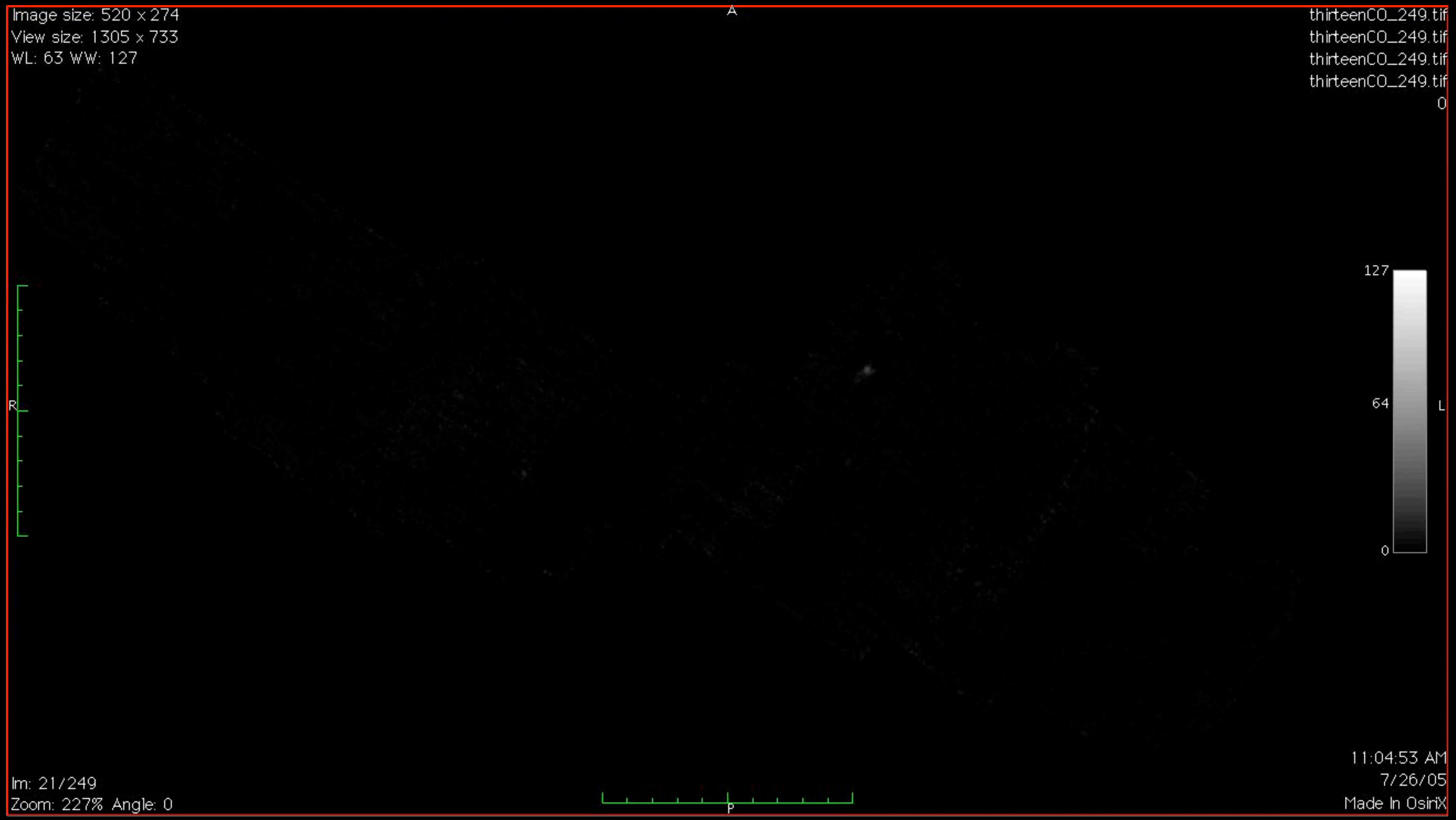
"Astronomical Medicine"

"KEITH"



"z" is depth into head

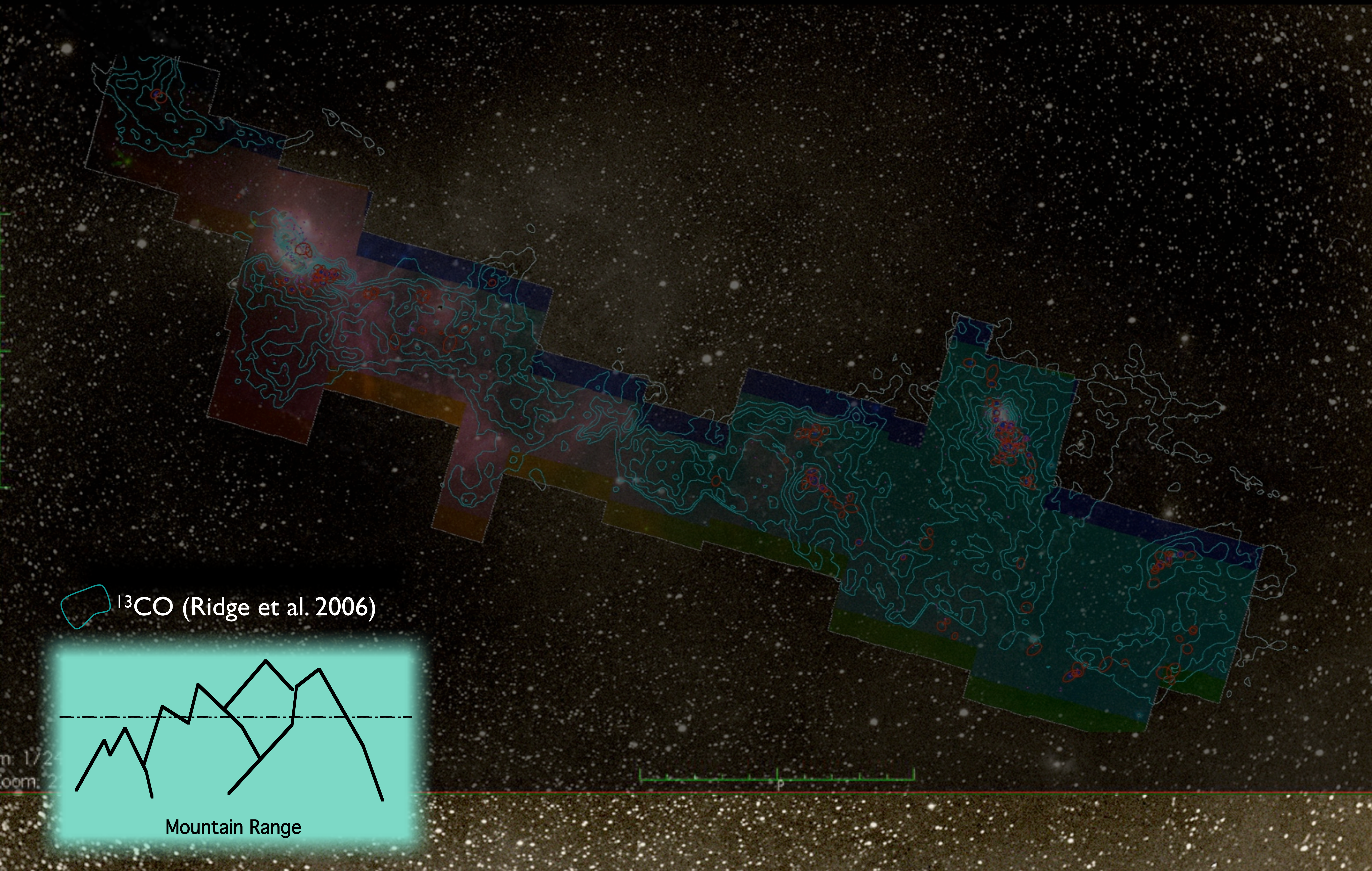
"PERSEUS"

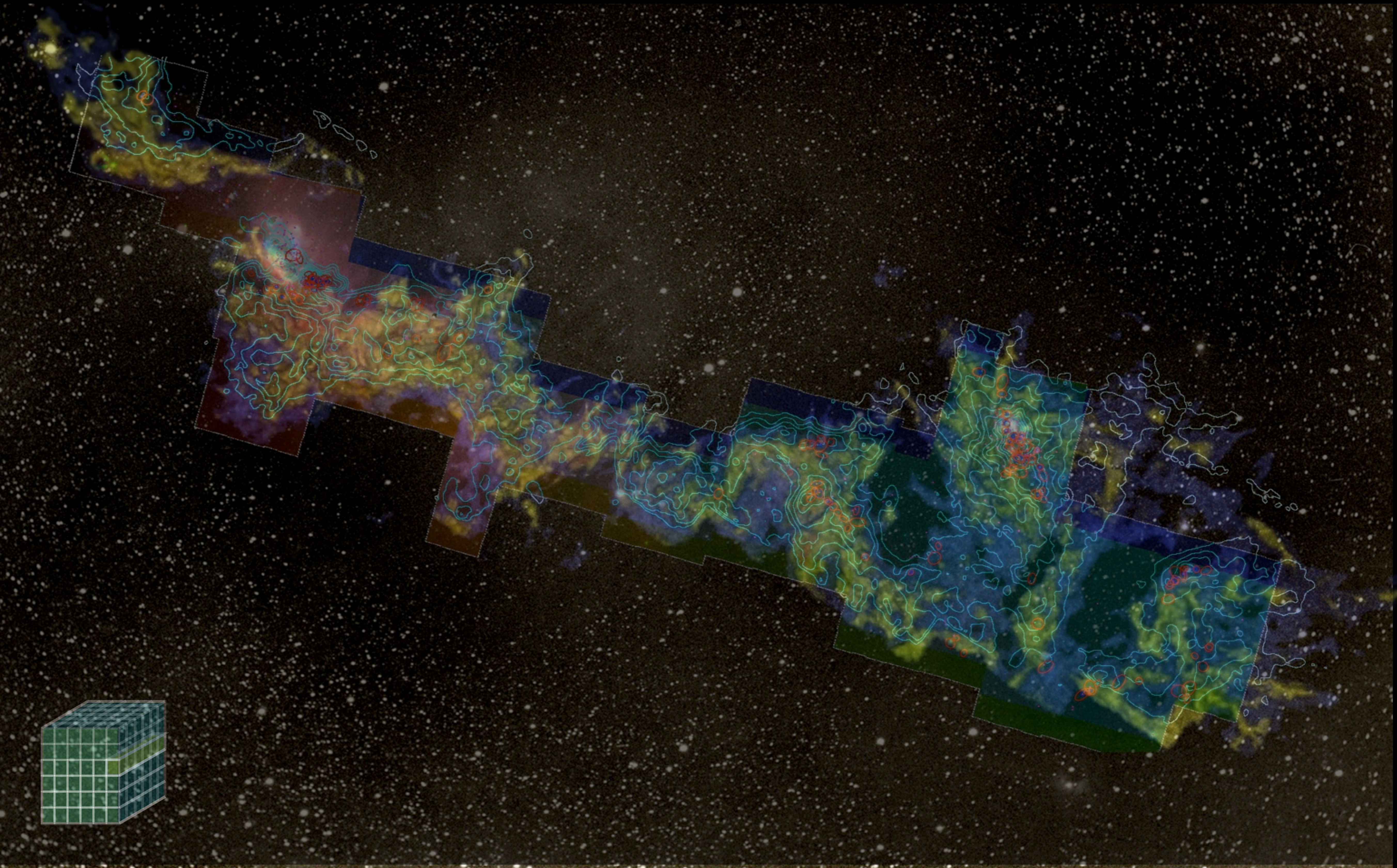


"z" is line-of-sight velocity

http://am.iic.harvard.edu/

COMPLETE Perseus

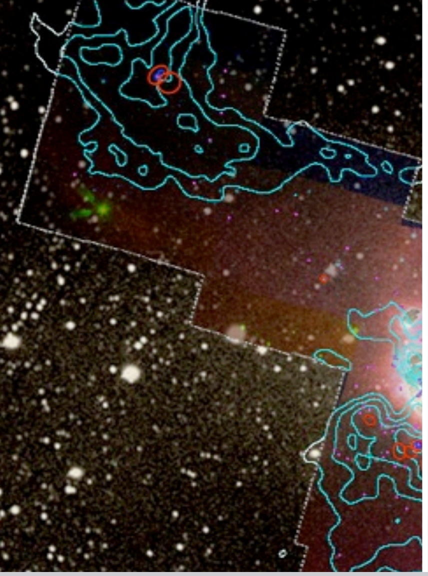


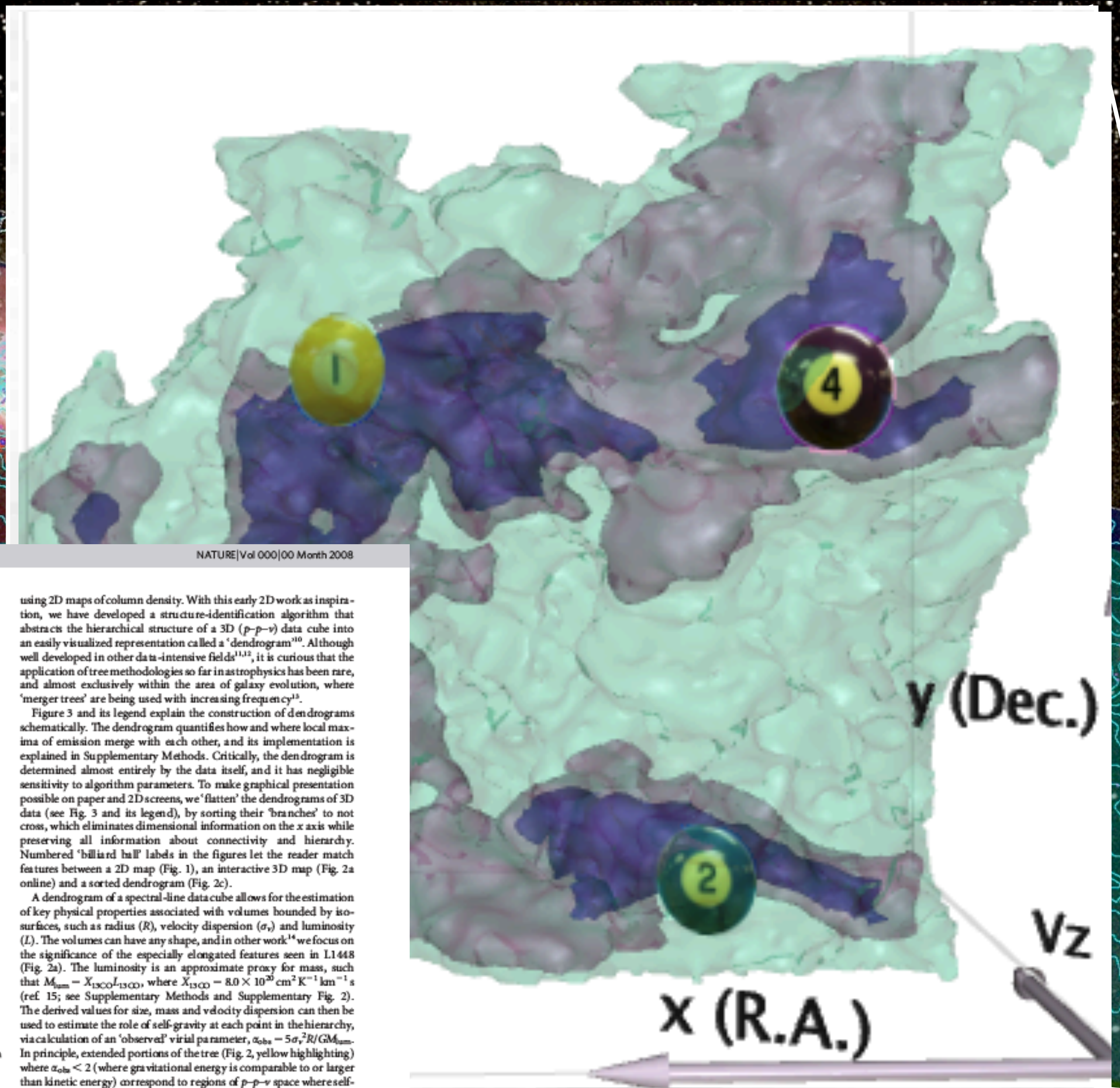


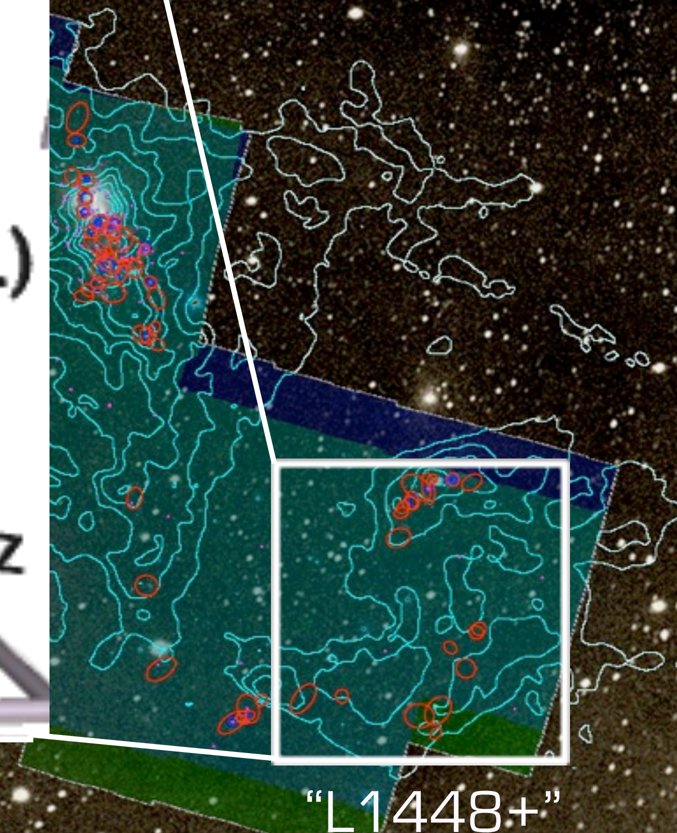
3D Viz made with VolView

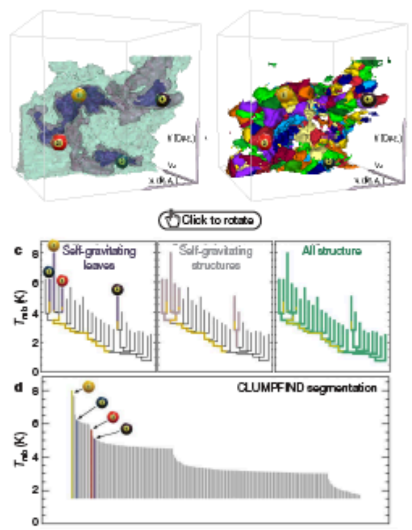
AstronomicalMedicine@IIC

COMPLETE









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Four years before the advent of CLUMPFIND, 'structure trees'[9] were proposed as a way to characterize clouds' hierarchical structure using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that abstracts the hierarchical structure of a 3D (p–p–v) data cube into an easily visualized representation called a 'dendrogram'[10]. Although well developed in other data-intensive fields[11,12], it is curious that the application of tree methodologies so far in astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where 'merger trees' are being used with increasing frequency[13].

Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is explained in Supplementary Methods. Critically, the dendrogram is determined almost entirely by the data itself, and it has negligible sensitivity to algorithm parameters. To make graphical presentation possible on paper and 2D screens, we 'flatten' the dendrograms of 3D data (see Fig. 3 and its legend), by sorting their 'branches' to not cross, which eliminates dimensional information on the x axis while preserving all information about connectivity and hierarchy. Numbered 'billiard ball' labels in the figures let the reader match features between a 2D map (Fig. 1), an interactive 3D map (Fig. 2a online) and a sorted dendrogram (Fig. 2c).

A dendrogram of a spectral-line data cube allows for the estimation of key physical properties associated with volumes bounded by isosurfaces, such as radius (R), velocity dispersion (σ_v) and luminosity (L). The volumes can have any shape, and in other work[14] we focus on the significance of the especially elongated features seen in L1448 (Fig. 2a). The luminosity is an approximate proxy for mass, such that $M_{lum} = X_{13CO} L_{13CO}$, where $X_{13CO} = 8.0 \times 10^{20}\ \mathrm{cm^{2}\,K^{-1}\,km^{-1}\,s}$ (ref. 15; see Supplementary Methods and Supplementary Fig. 2). The derived values for size, mass and velocity dispersion can then be used to estimate the role of self-gravity at each point in the hierarchy, via calculation of an 'observed' virial parameter, $\alpha_{obs} = 5\sigma_v^2 R/GM_{lum}$. In principle, extended portions of the tree (Fig. 2, yellow highlighting) where $\alpha_{obs} < 2$ (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of p–p–v space where self-gravity is significant. As α_{obs} only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic fields[16], its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

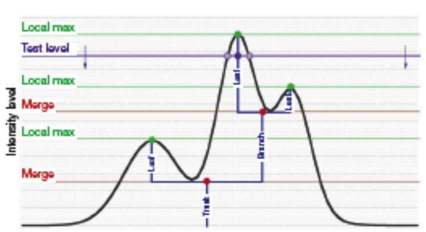
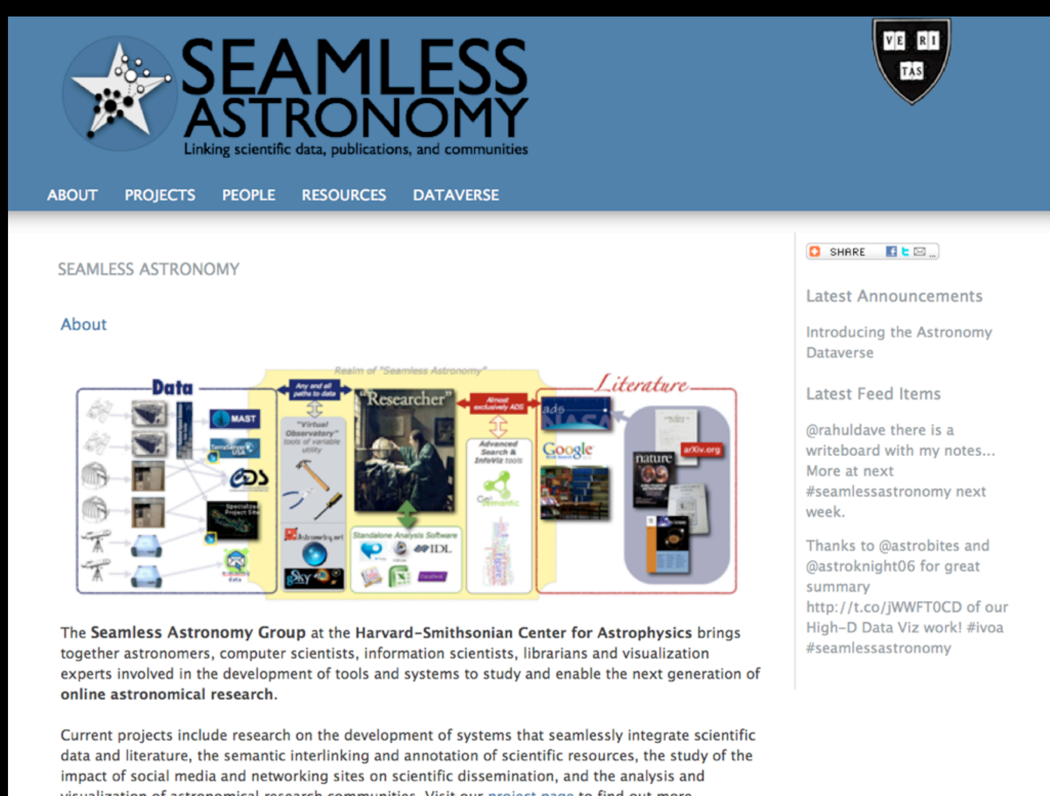


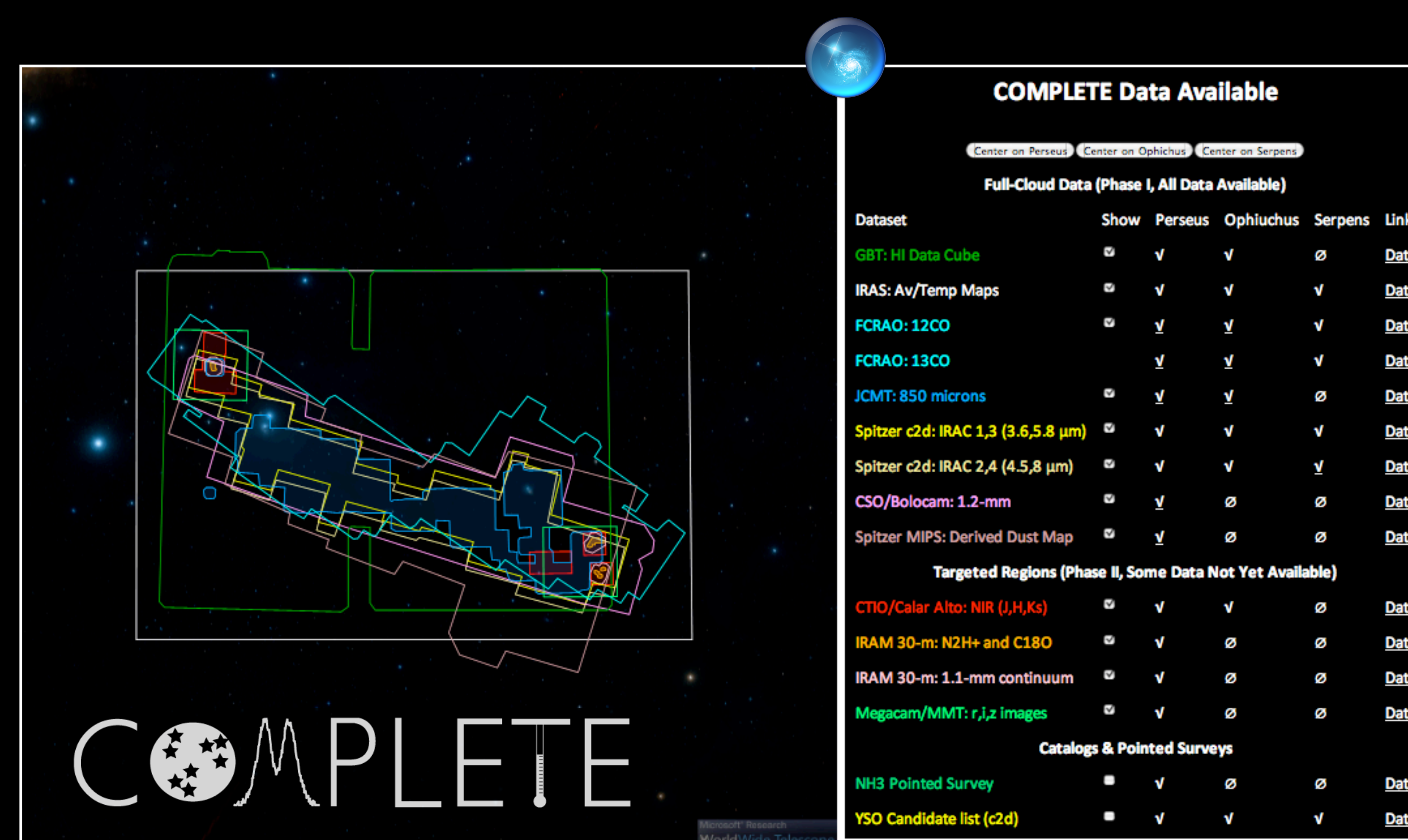
Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in size here, light lines) until all the local maxima and mergers are found, and connected as shown. The intersection of a test level with the emission is a set of points (for example the light purple dots) in one dimension, a planar curve in two dimensions, and an isosurface in three dimensions. The dendrogram of 3D data shown in Fig. 2c is the direct analogue of the tree shown here, only constructed from 'isosurface' rather than 'point' intersections. It has been sorted and flattened for representation on a flat page, as fully representing dendrograms for 3D data cubes would require four dimensions.

COMPLETE

“Rich Online Resources”

offer not only ever-larger tables of numbers, but also images, movies, and other high-dimensional data streams.
And, most results of previous research are available on-demand thanks to a growing wealth of digitized literature.





[NGC 1333/theastrodata demo]

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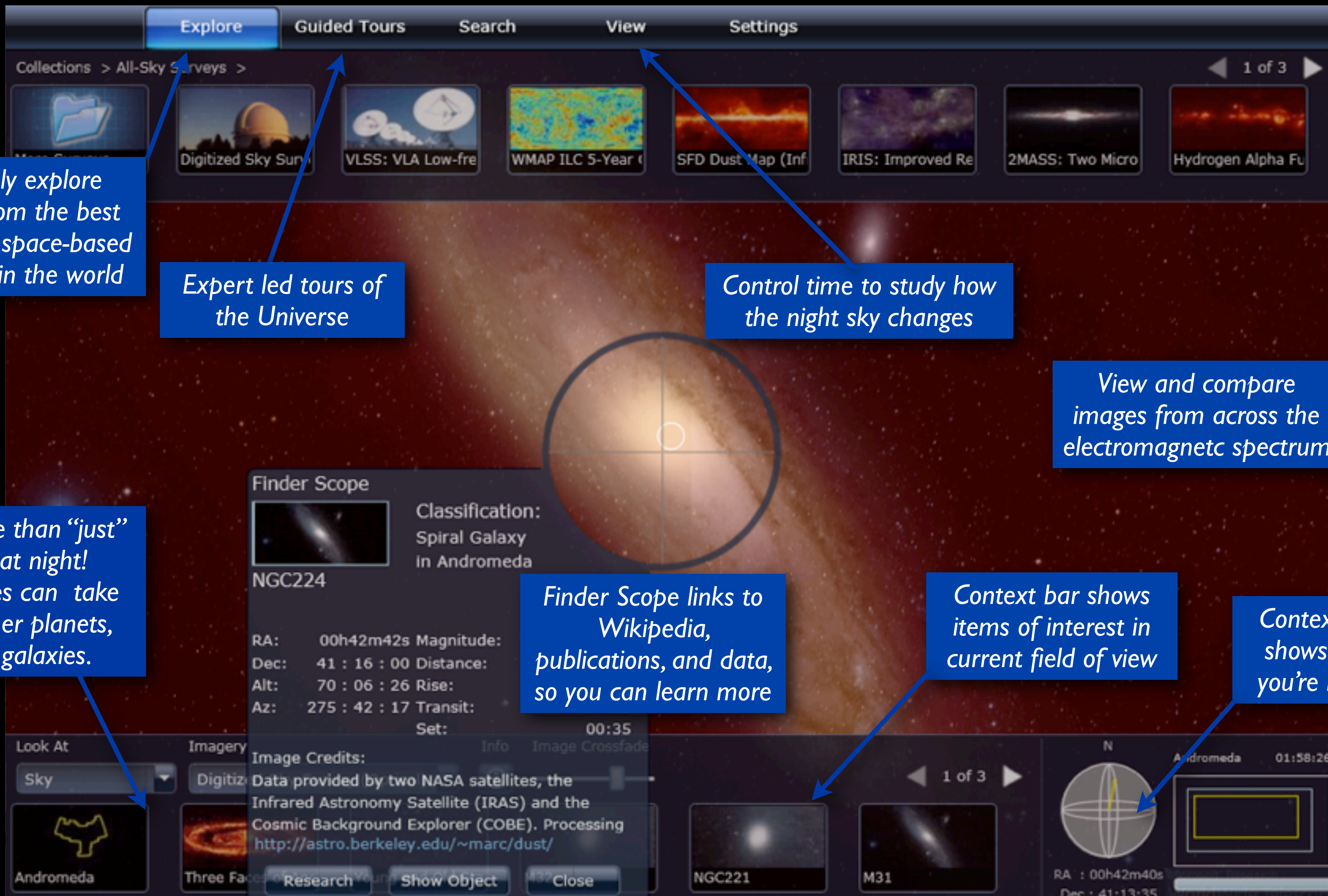

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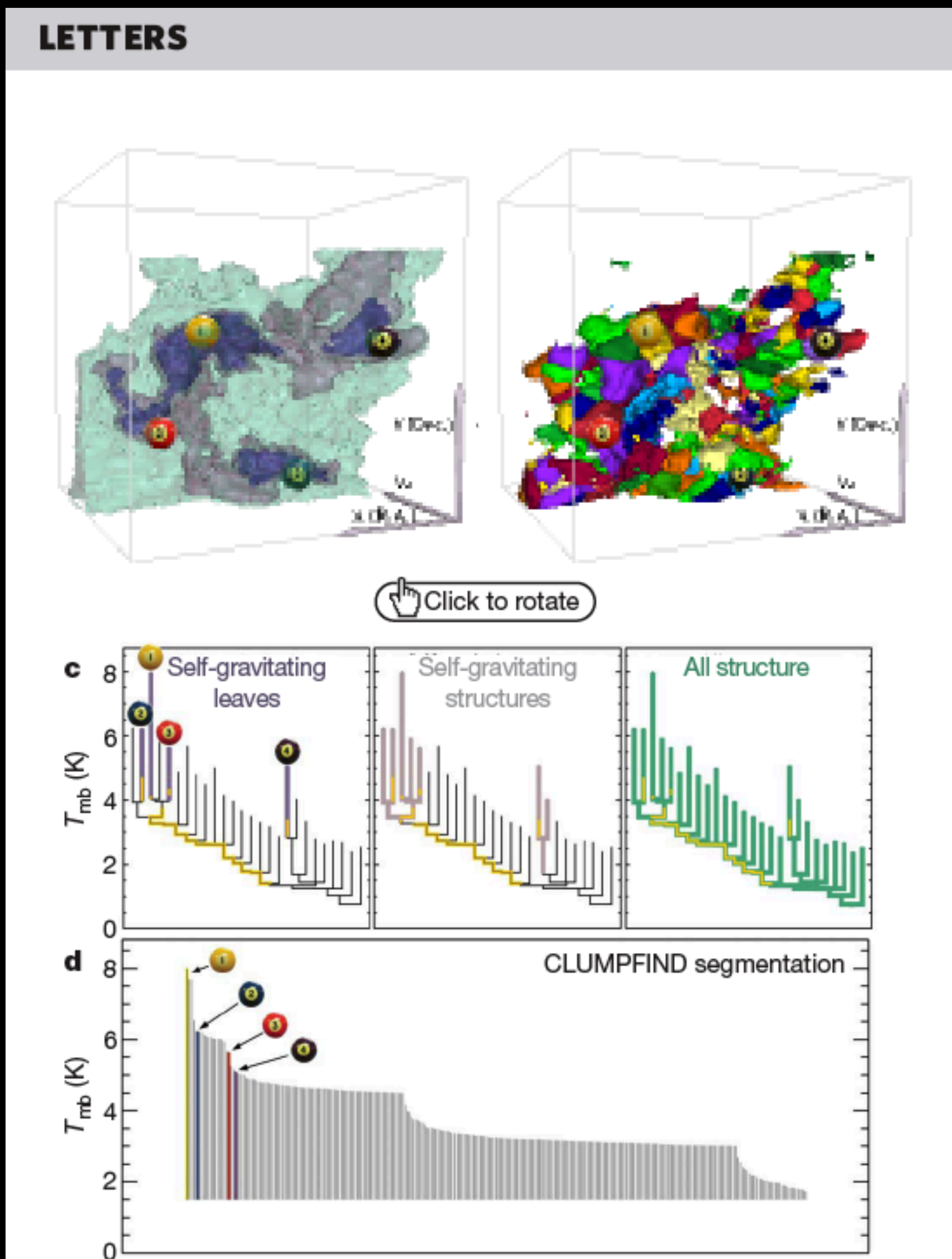
Context globe shows where you're looking.

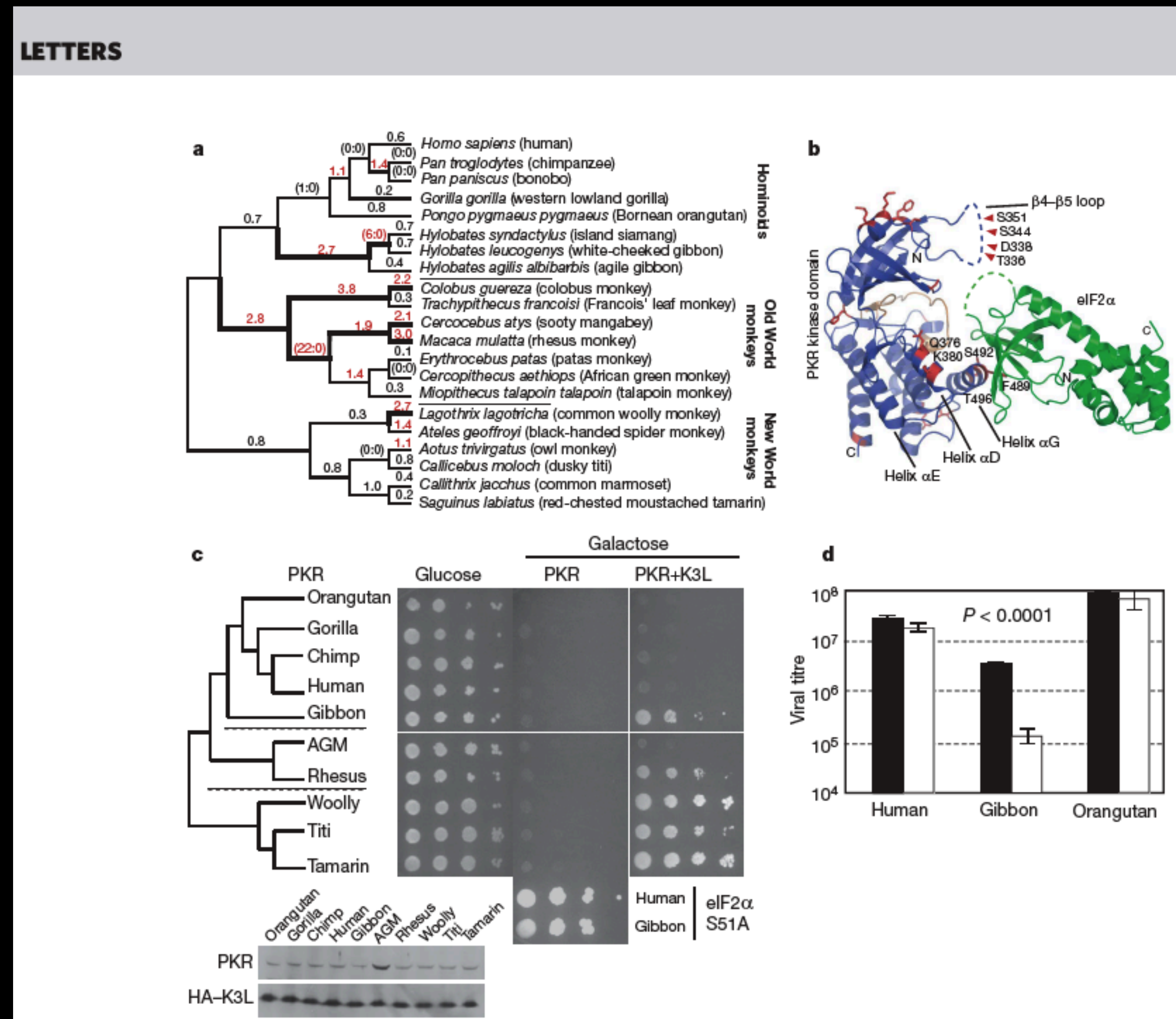

Heart Disease & Sea Monsters

"High-dimensional" or "Multivariate" Data

(Astronomy=Biology)



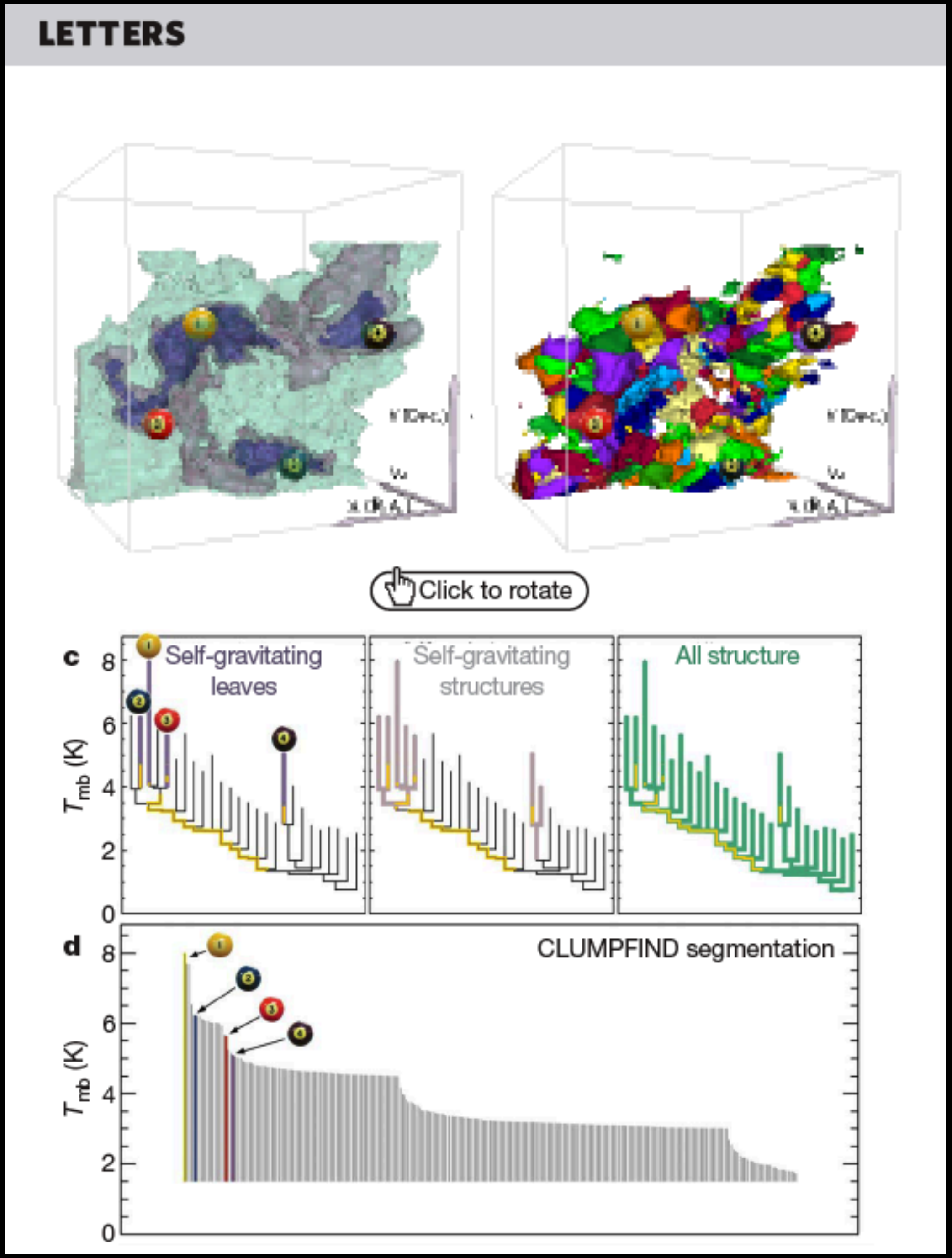
Goodman et al. *Nature*, 2009



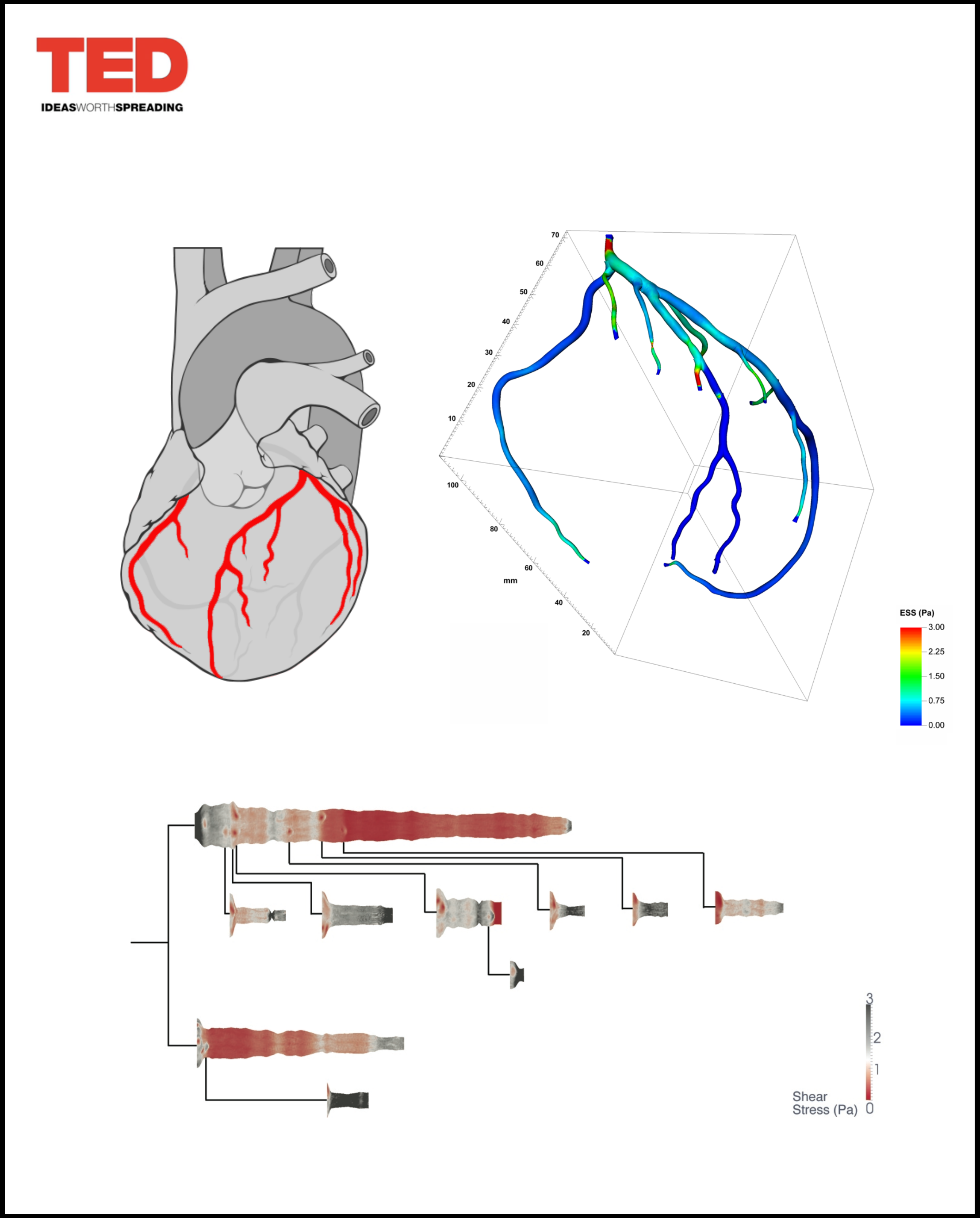
Elde et al. *Nature*, 2008

"High-dimensional" or "Multivariate" Data

(Astronomy=Medicine)

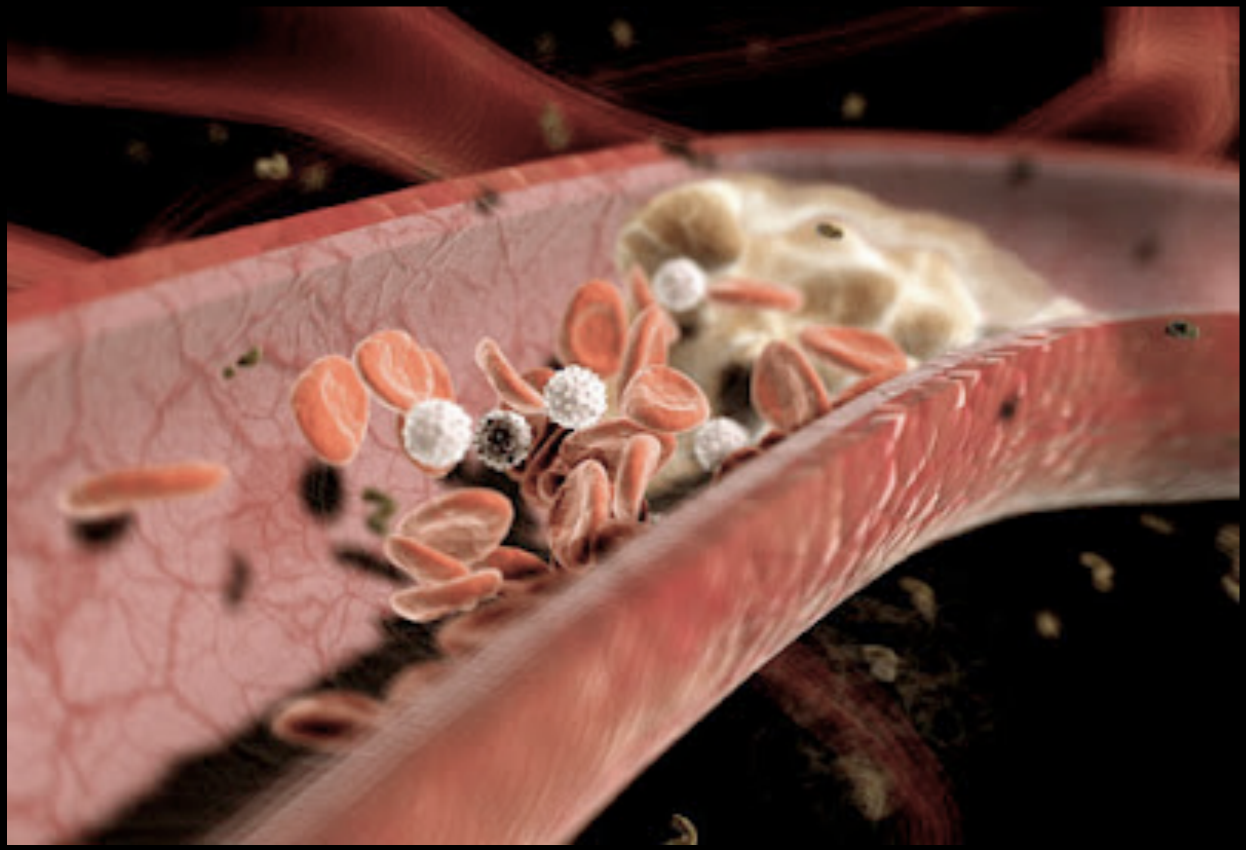


Goodman et al. *Nature*, 2009



Borkin et al. *IEEE Viz*, 2011

Saving Lives

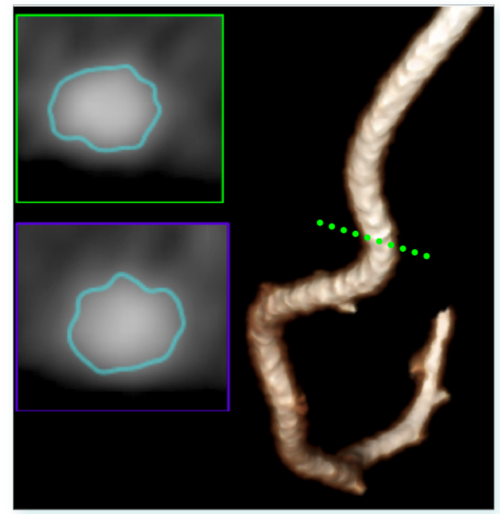


Michelle Borkin

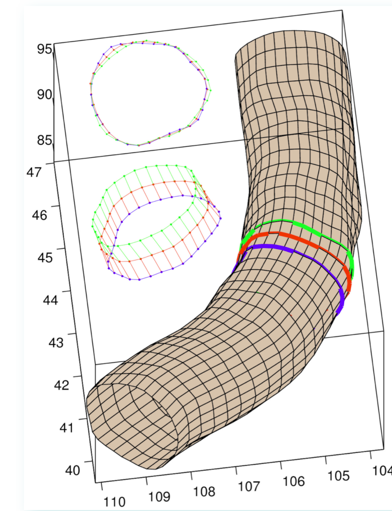
Harvard School of Engineering & Applied Science Ph.D. student,
supervised by Alyssa Goodman (Astronomer) & Hanspeter Pfister (Computer Scientist)

Patients Troubled Hearts, in 3D

Obtain patient CT data

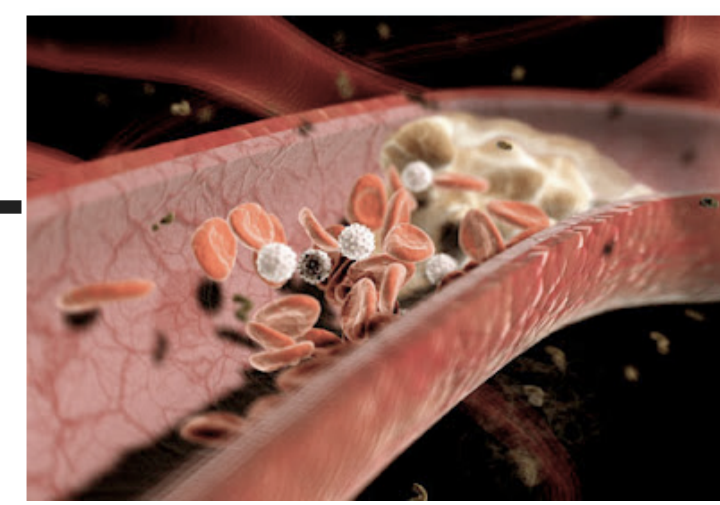


Segment arteries

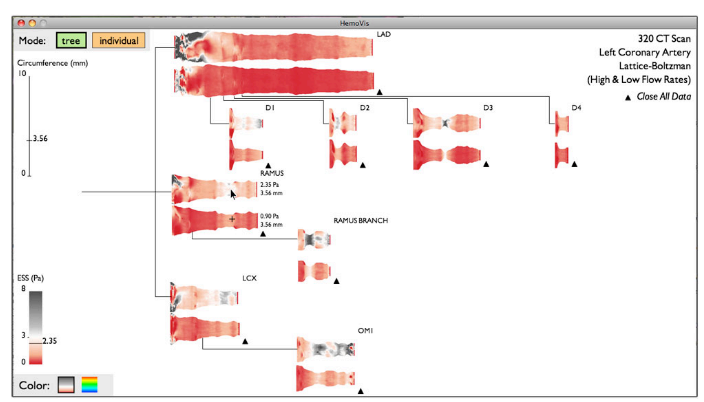


Generate patient geometries

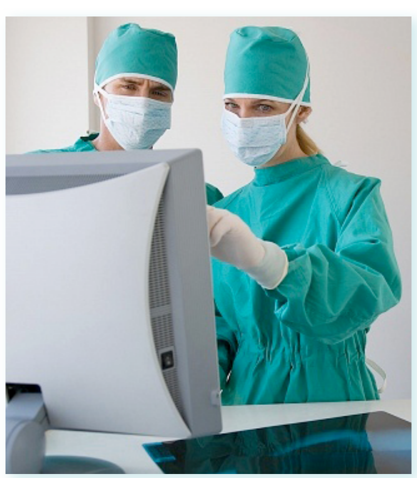
Patient specific flow simulation



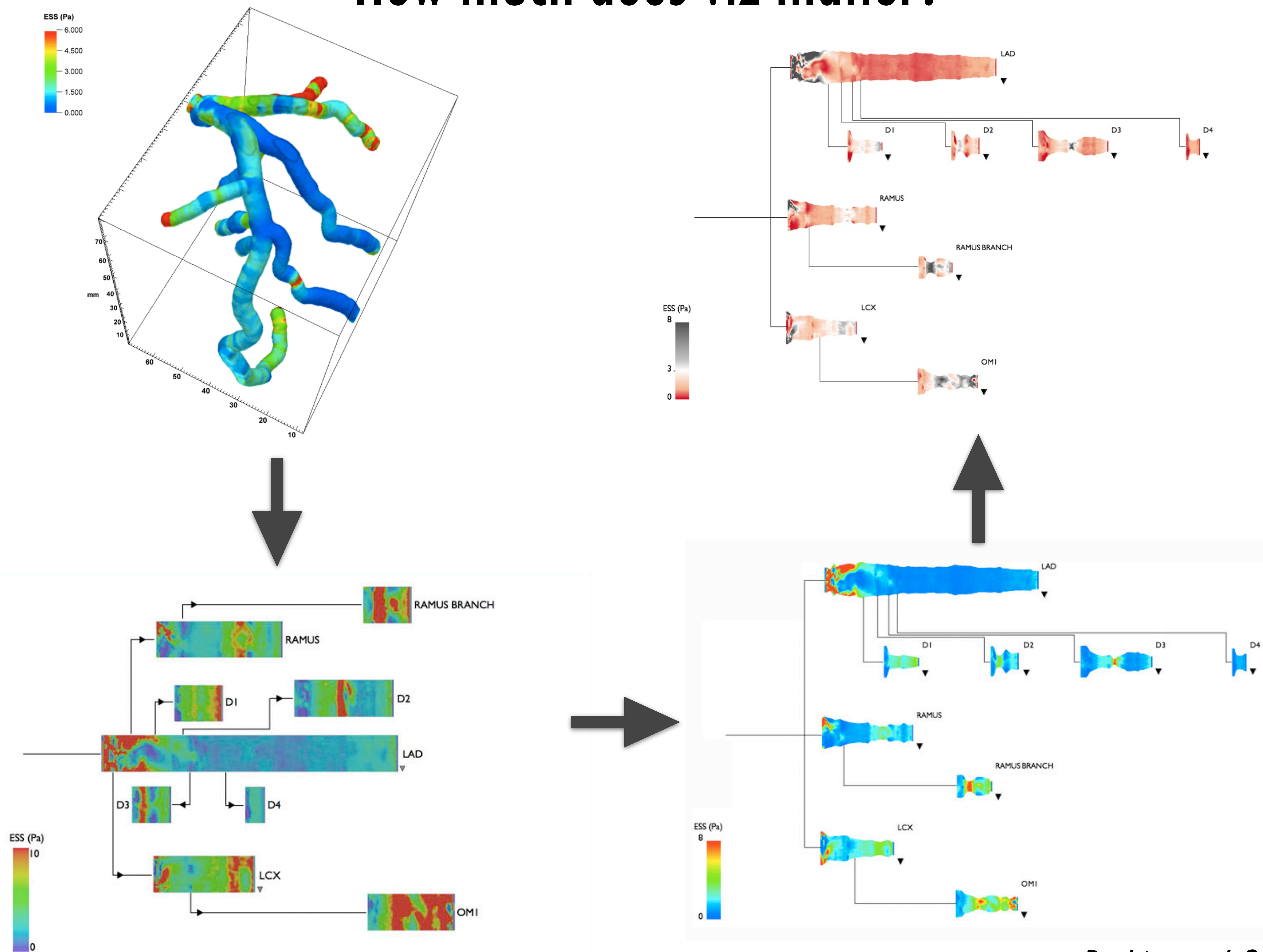
Visualize/analyze data



Clinical decision



How much does viz matter?



Borkin et al. 2011

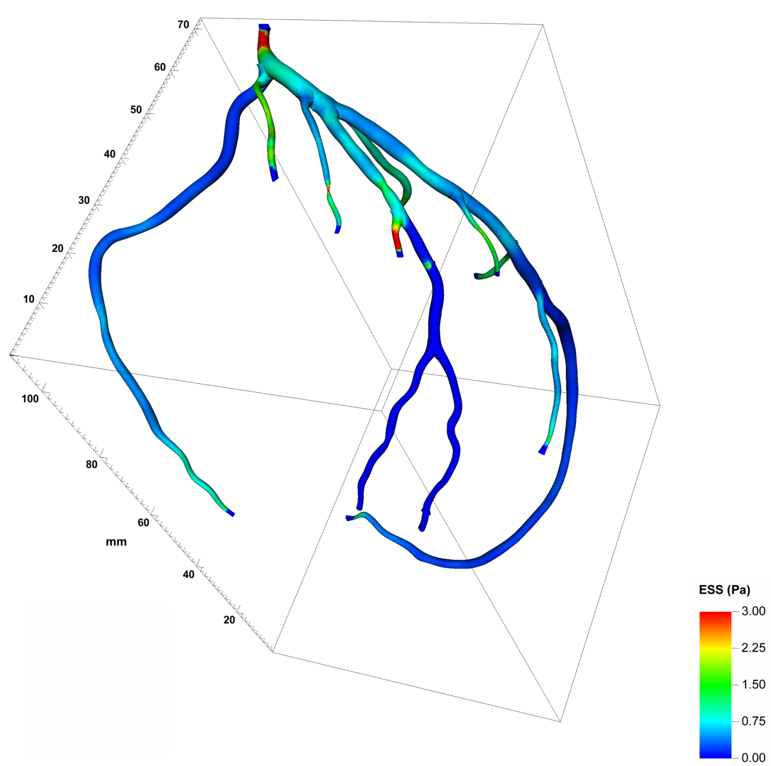
Accuracy

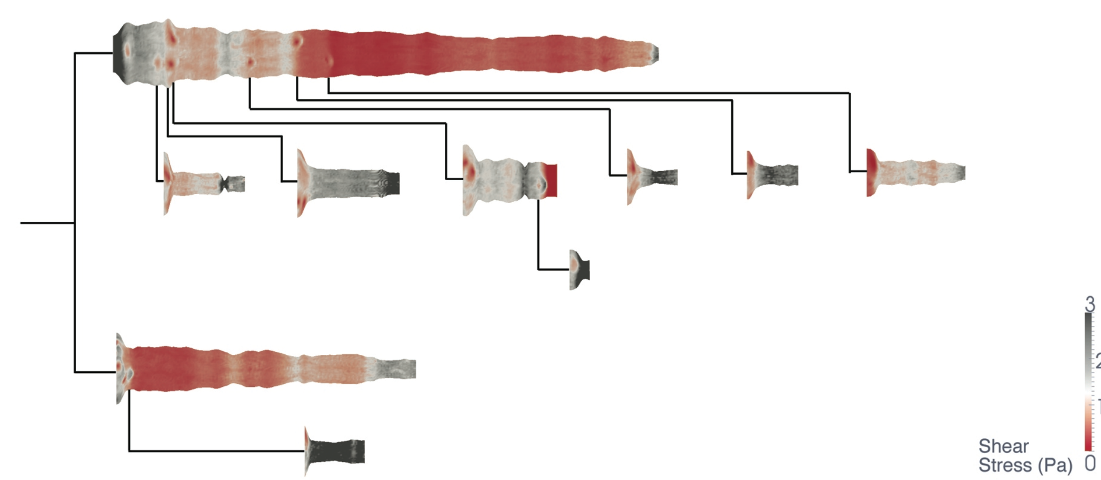
Strong effect of **dimensionality** on accuracy

And strong effect of **color**...

39% *percent low ESS regions found* 62%

91%





Borkin et al. 2011

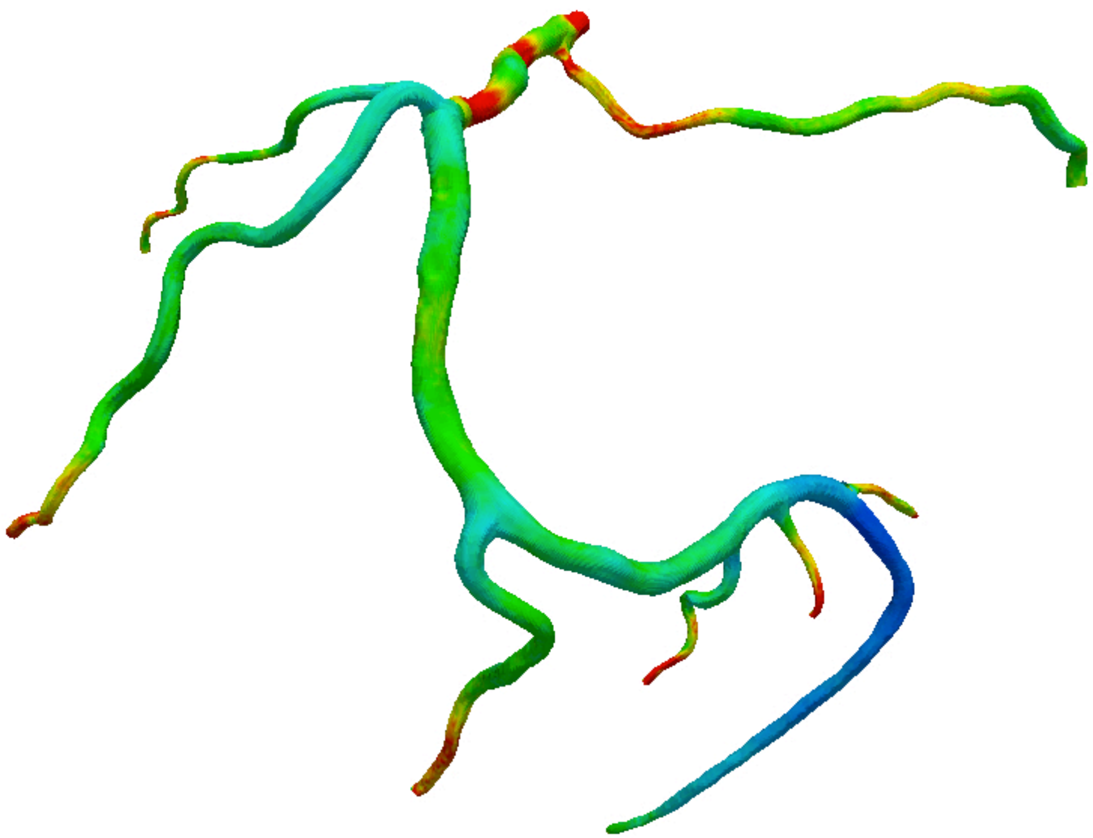
Efficiency

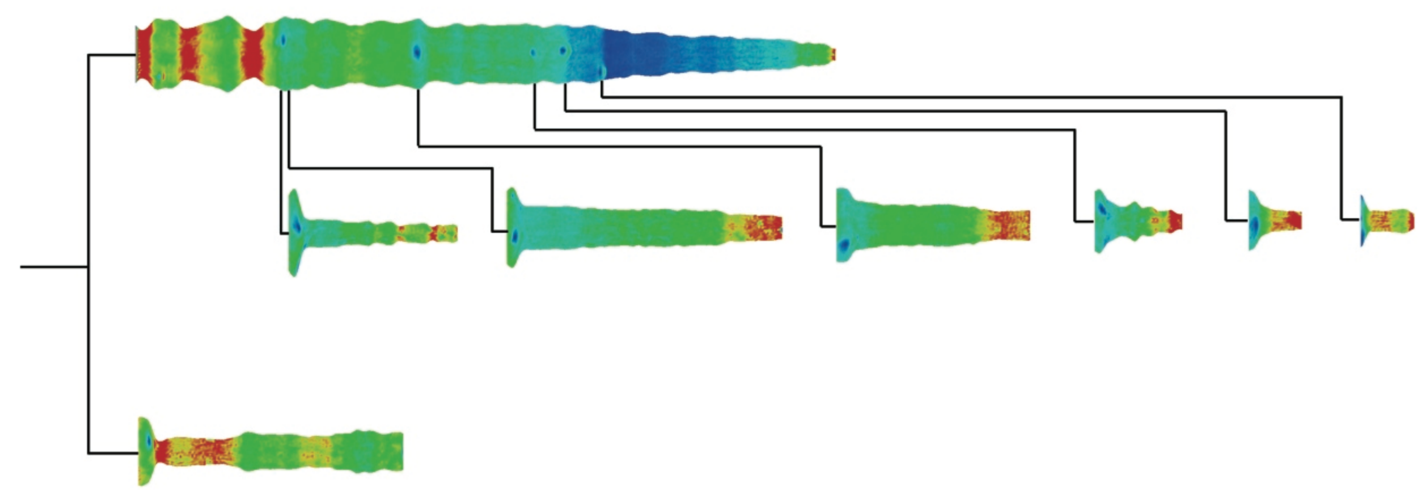
Participants more **efficient** in **2D**.

Rainbow color map has greater detriment in 3D.

10.2 sec/region
5.6 sec/region

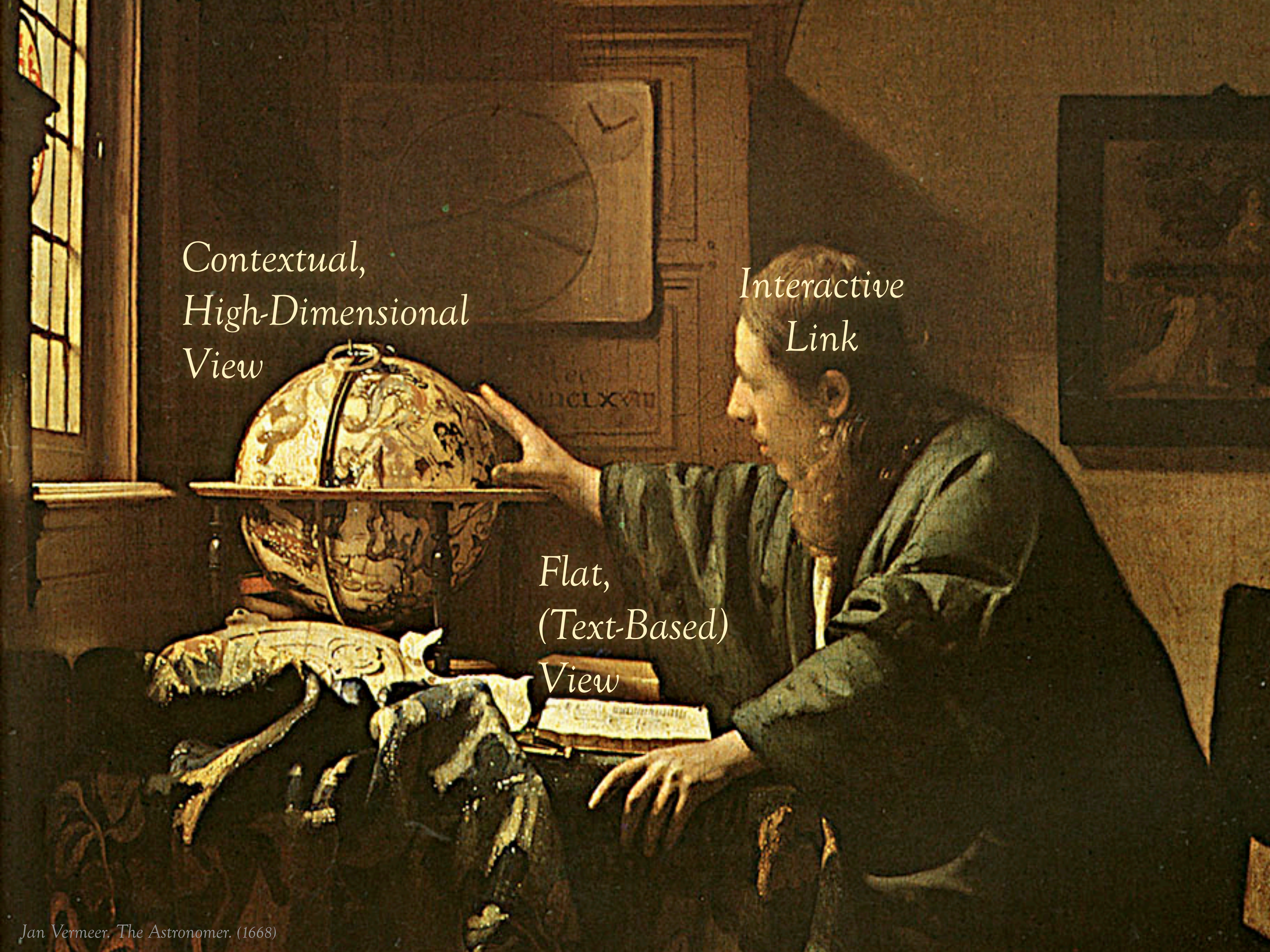
2.6 sec/region
2.4 sec/region



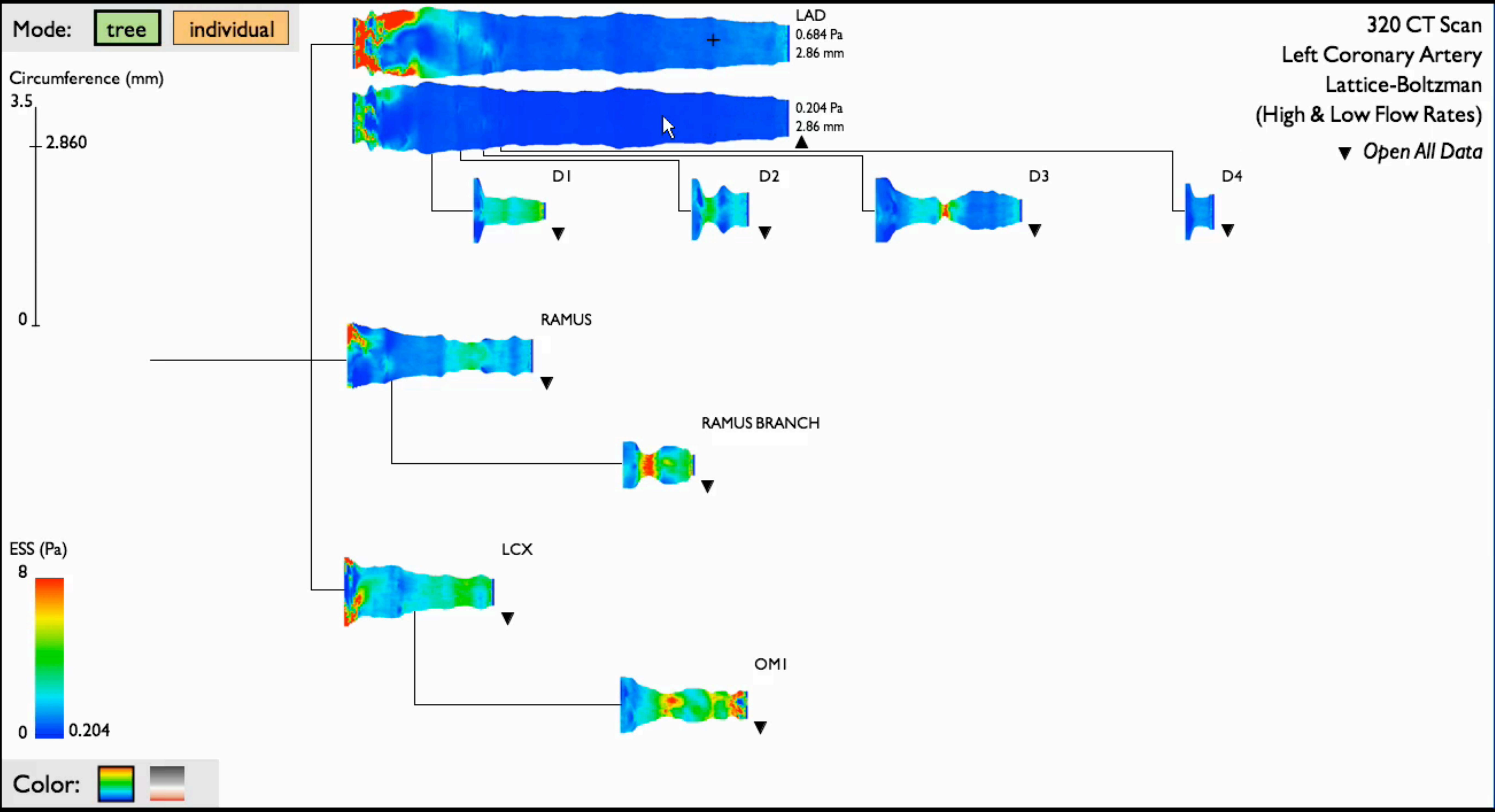


BUT–3D still essential for sugical planning.

Borkin et al. 2011

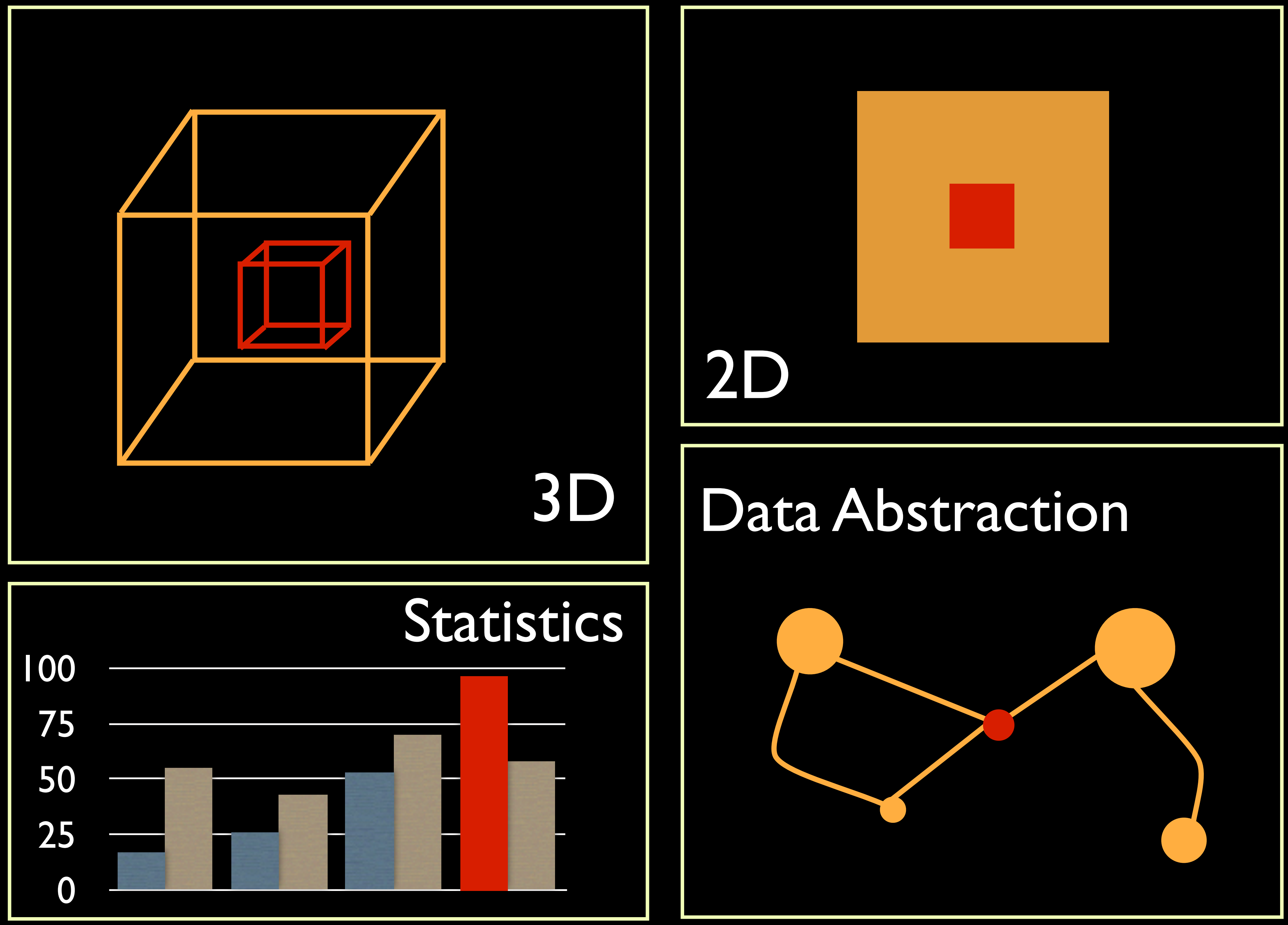


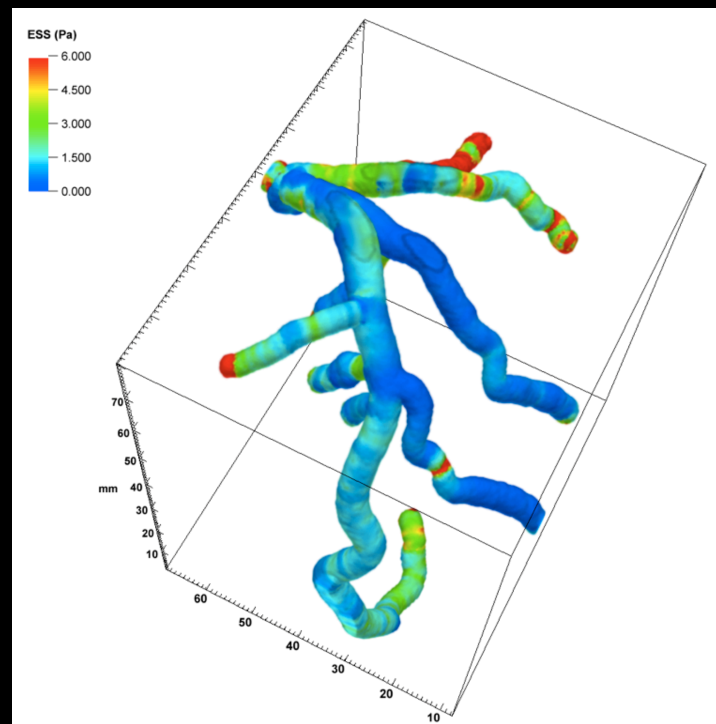
Jan Vermeer. The Astronomer. (1668)



Borkin et al. 2011

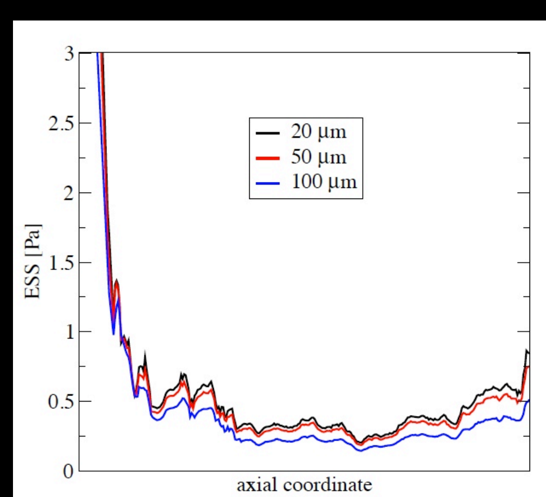
"Linked Views"

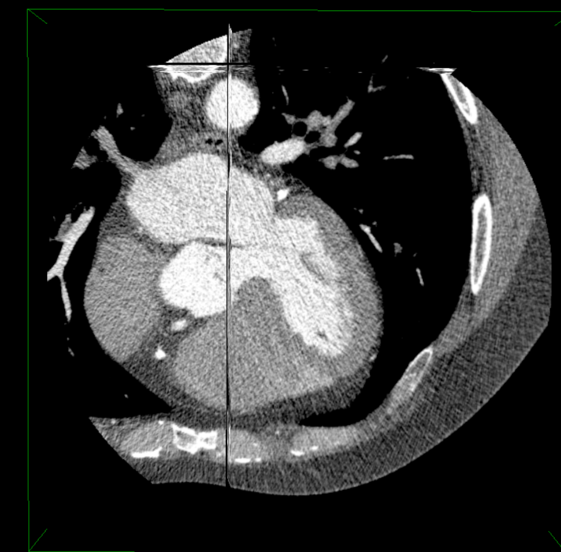




3D

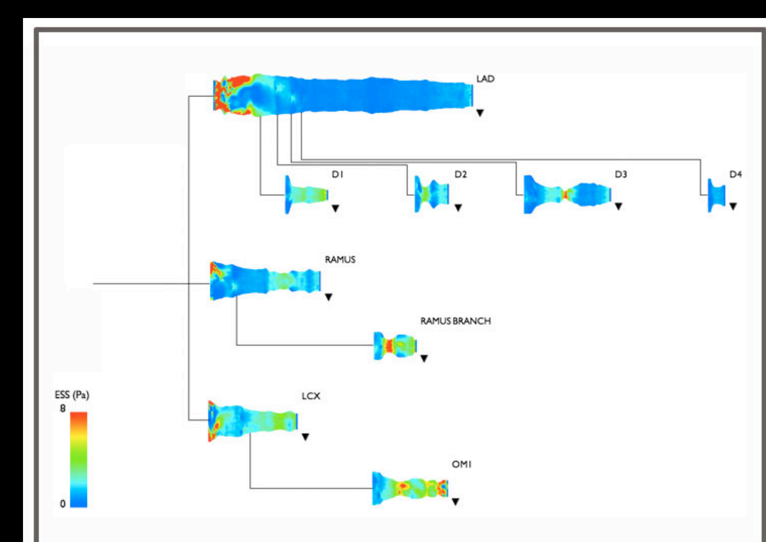
Statistics

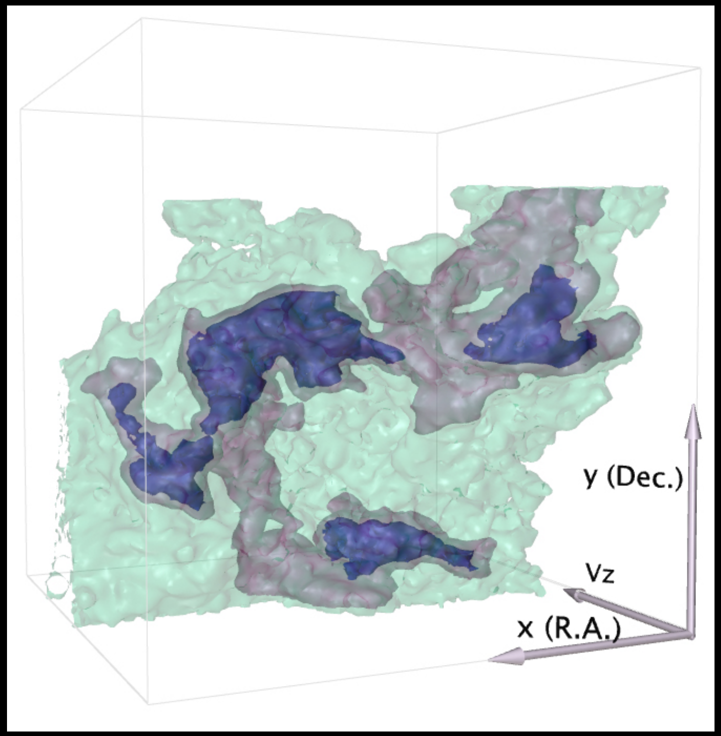




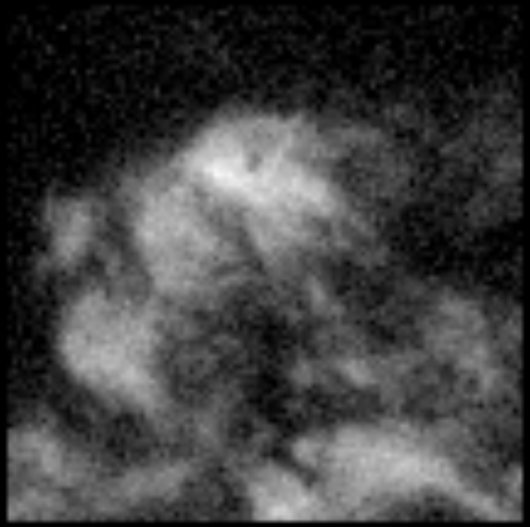
2D

Data Abstraction



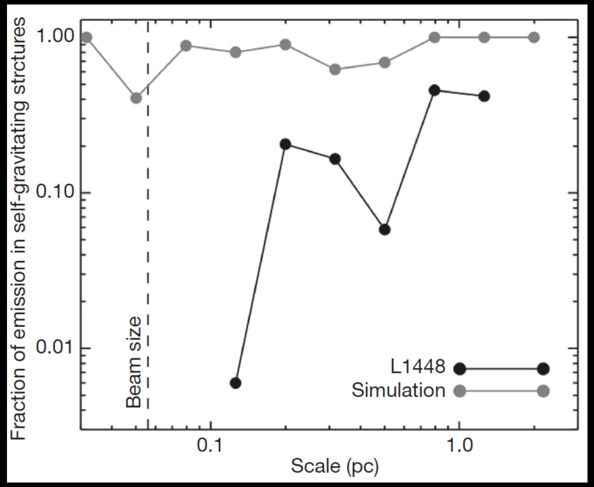


3D

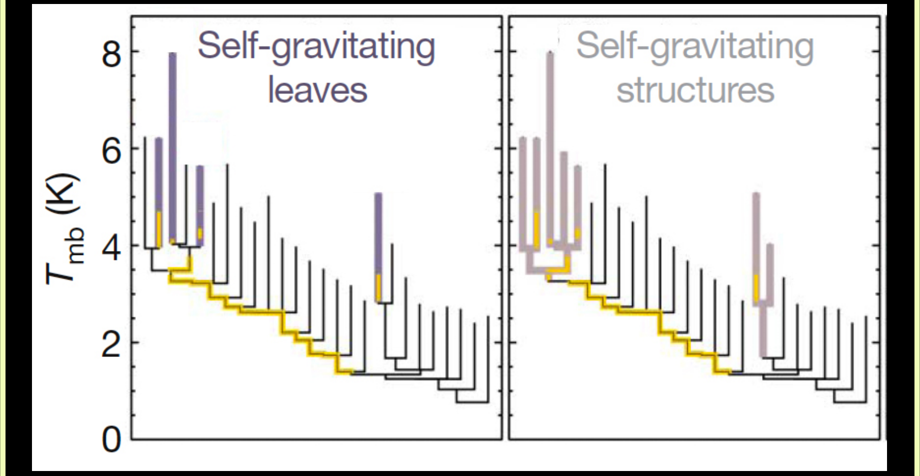


2D

Statistics



Data Abstraction

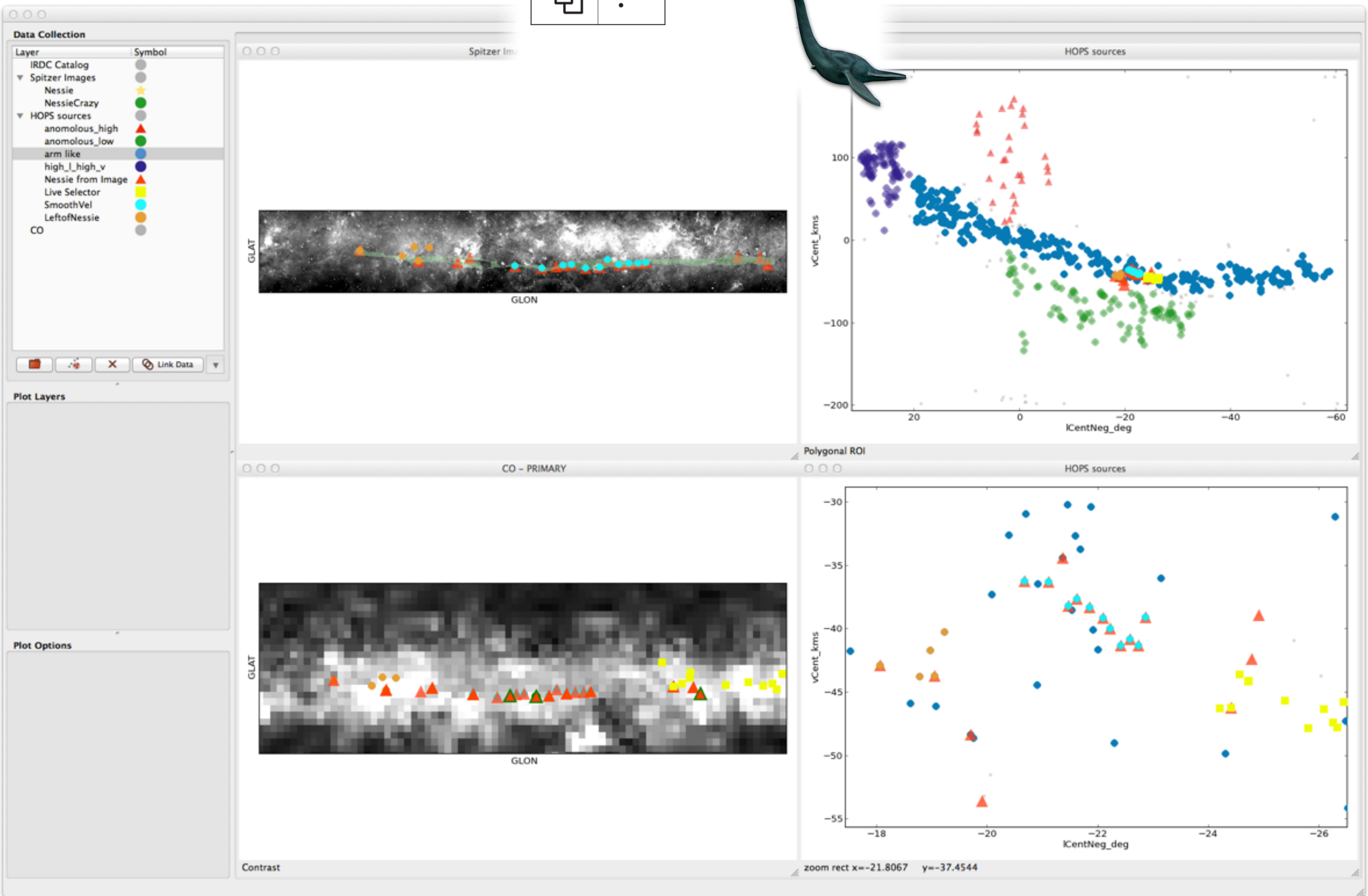


How?

glue

multidimensional data exploration

glue
multidimensional data exploration



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

The Bones of the Milky Way

Alyssa A. Goodman
Harvard-Smithsonian Center for Astrophysics
with Joao F. Alves, Christopher Beaumont, Robert A. Benjamin, Michelle A. Borkin, Andreas Burkert, Thomas M. Dame, Jens Kauffmann & Thomas Robitaille

fish skeleton images from
www.helterskeletons.com

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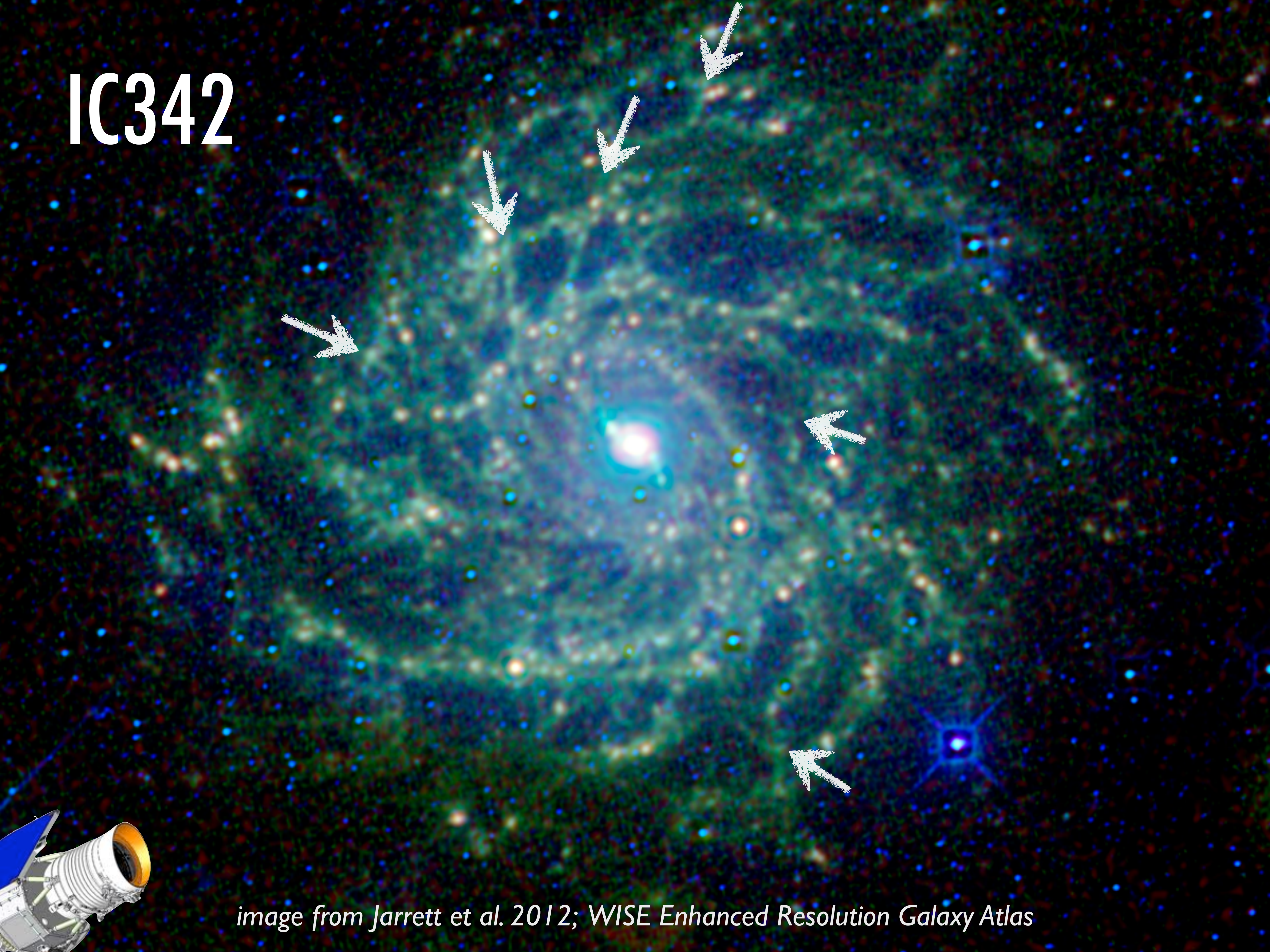

image from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas

Once upon a time in an enchanted castle by a lake, a sea monster…

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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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 ($1\overset{\circ}{.}5 \times 0\overset{\circ}{.}01$ or 80 pc $\times$ 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 $\sim$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

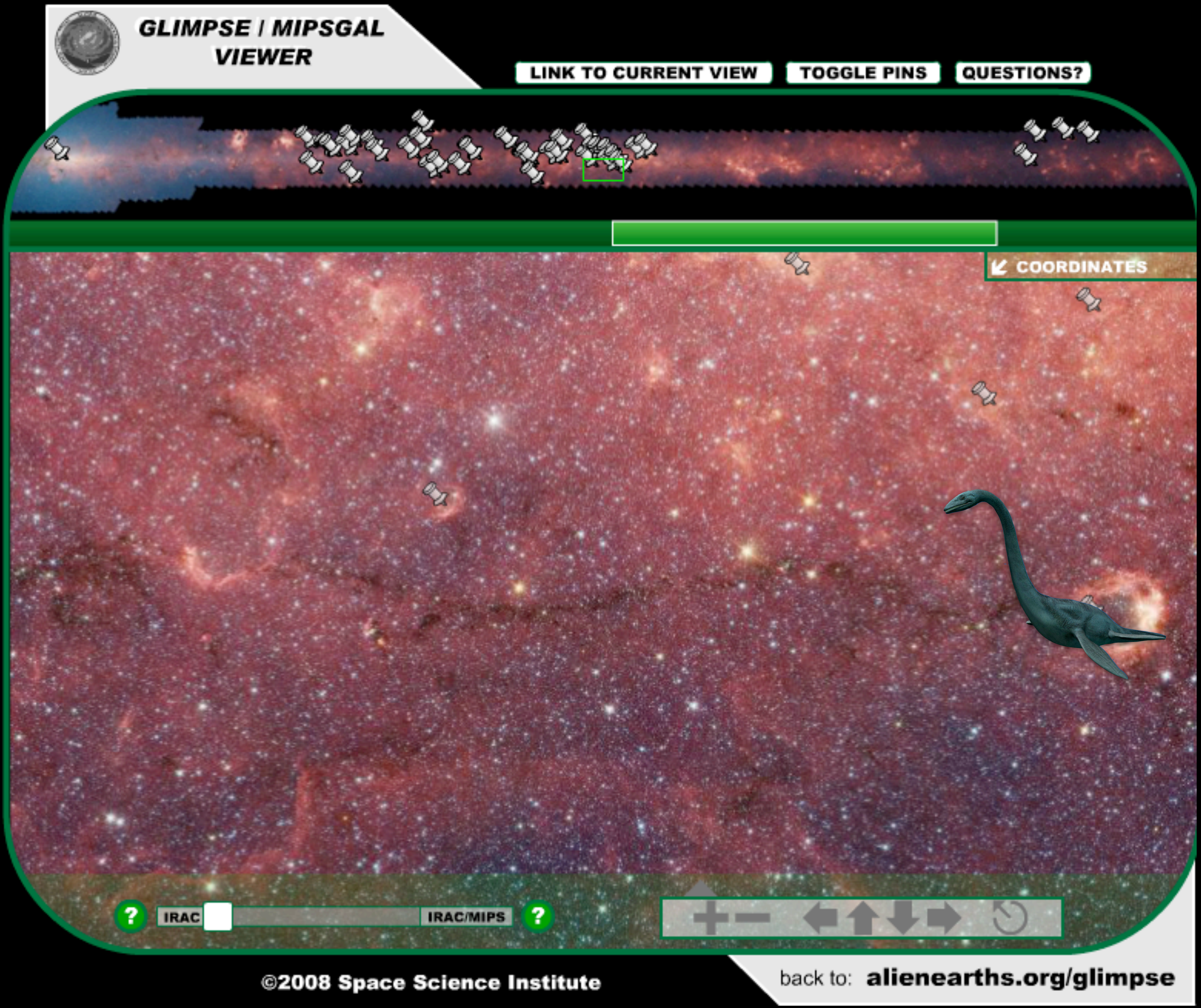
Ringberg Castle, Bavaria
"Early Phases of Star Formation"
July 2012

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

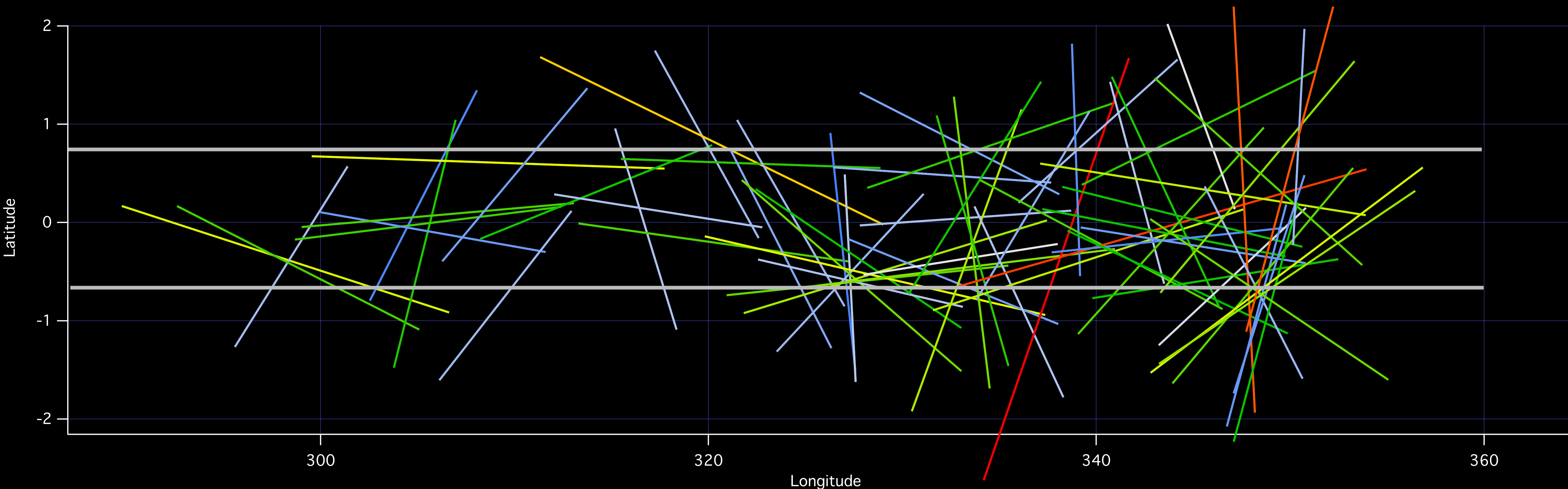
ANSWER *no one* immediately knew the answer!

AG decides to look into this and...

Quick Answer: Yes, looks like it is...



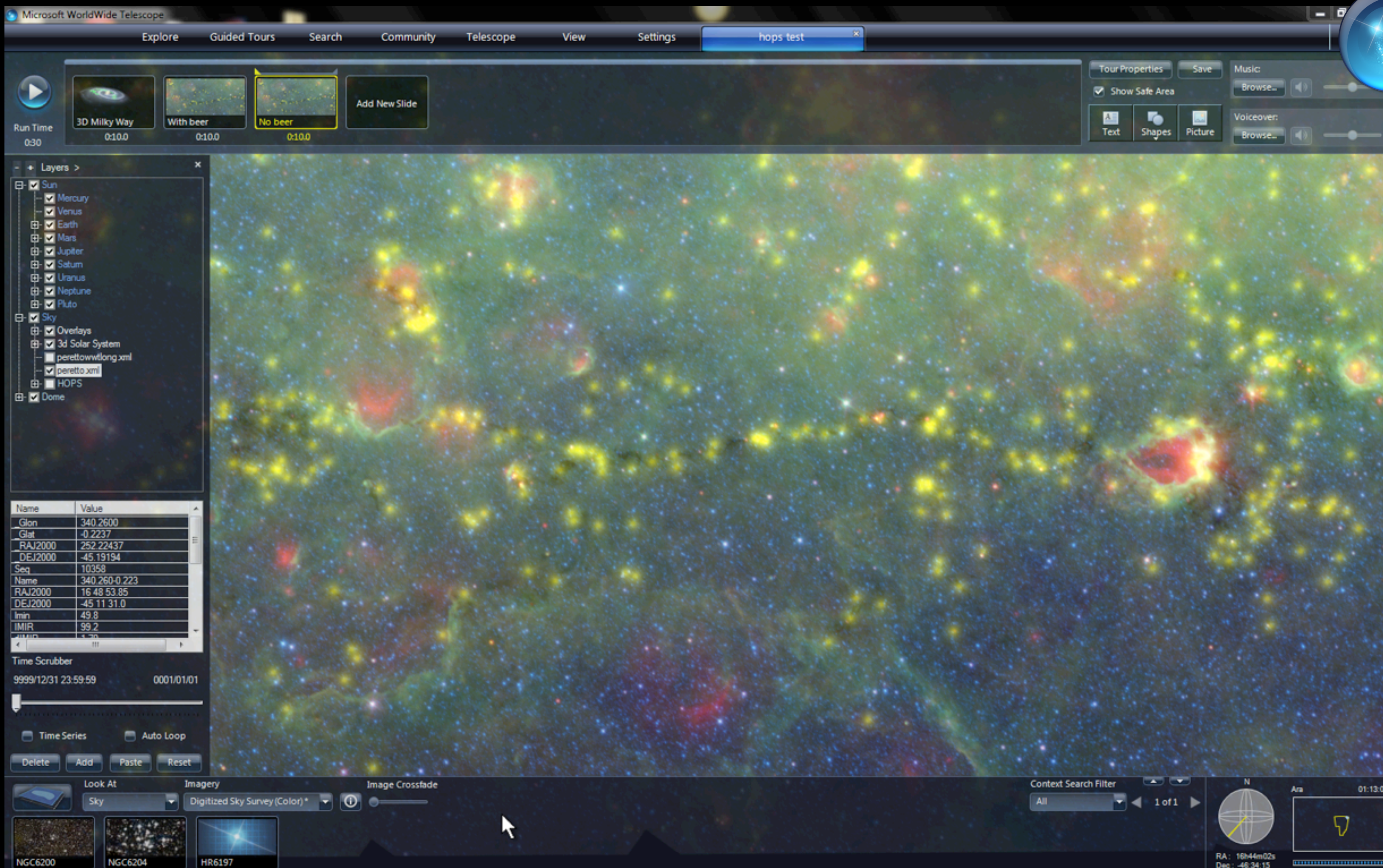
Are others too?



filtering out only "long" Peretto & Fuller clouds, and showing their orientation (color~length)

Huh? Let's look...

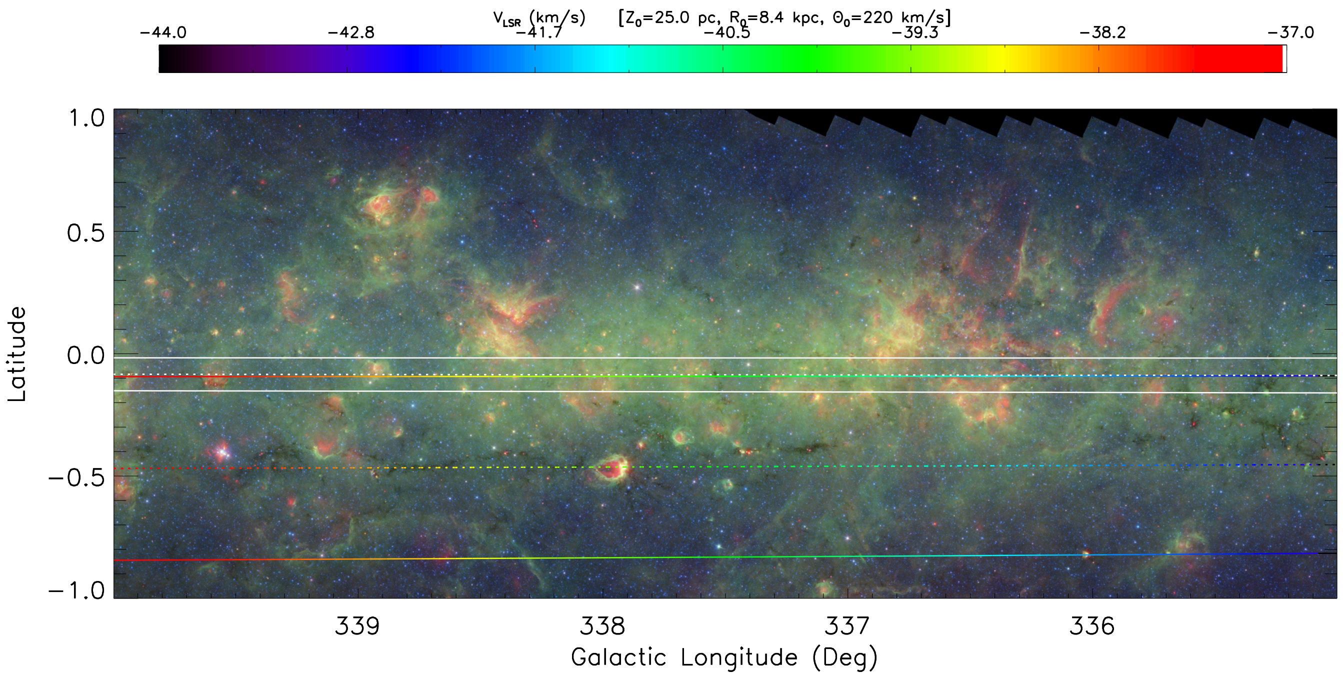
WWT



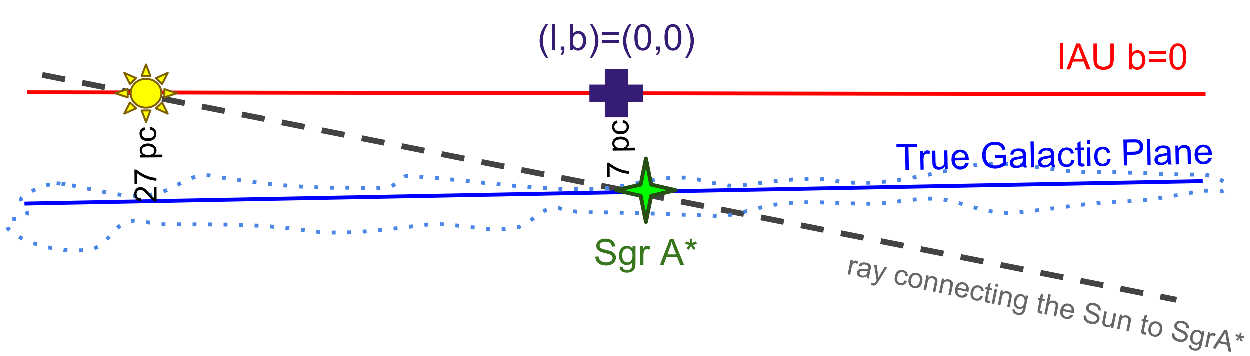
[Demo: Much more to Nessie than meets the eye!]

Where is "Nessie," in 3D?

How close to "in" the plane?

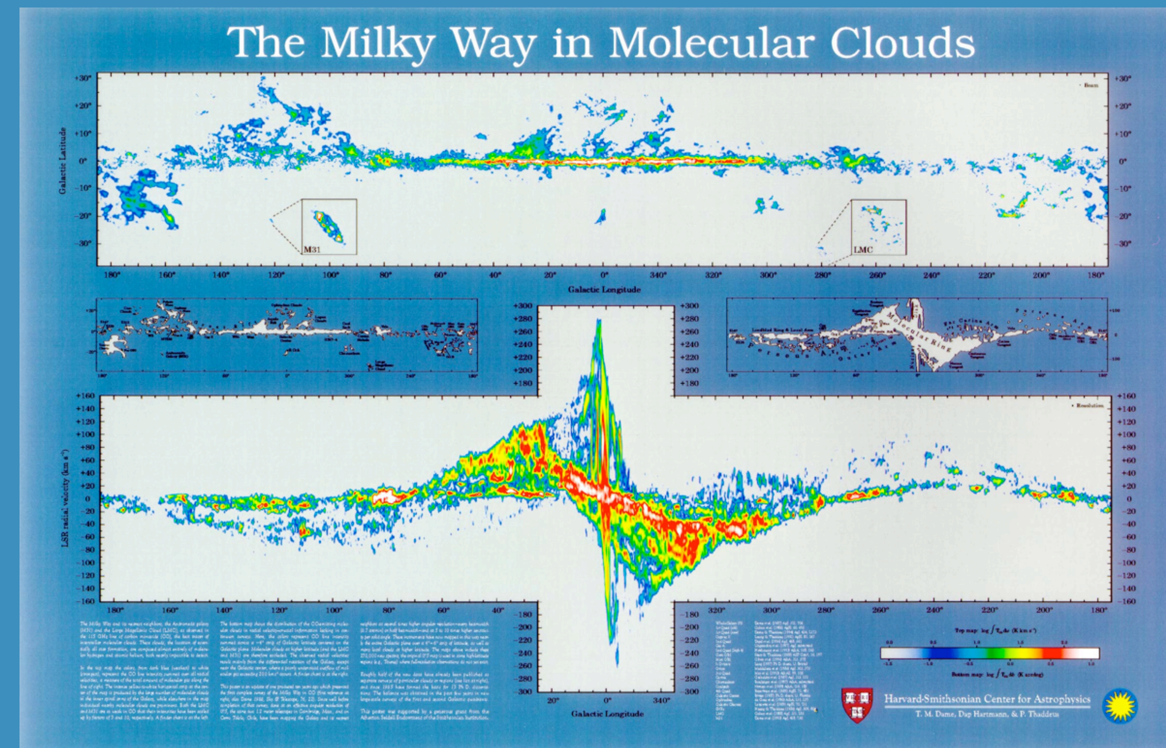


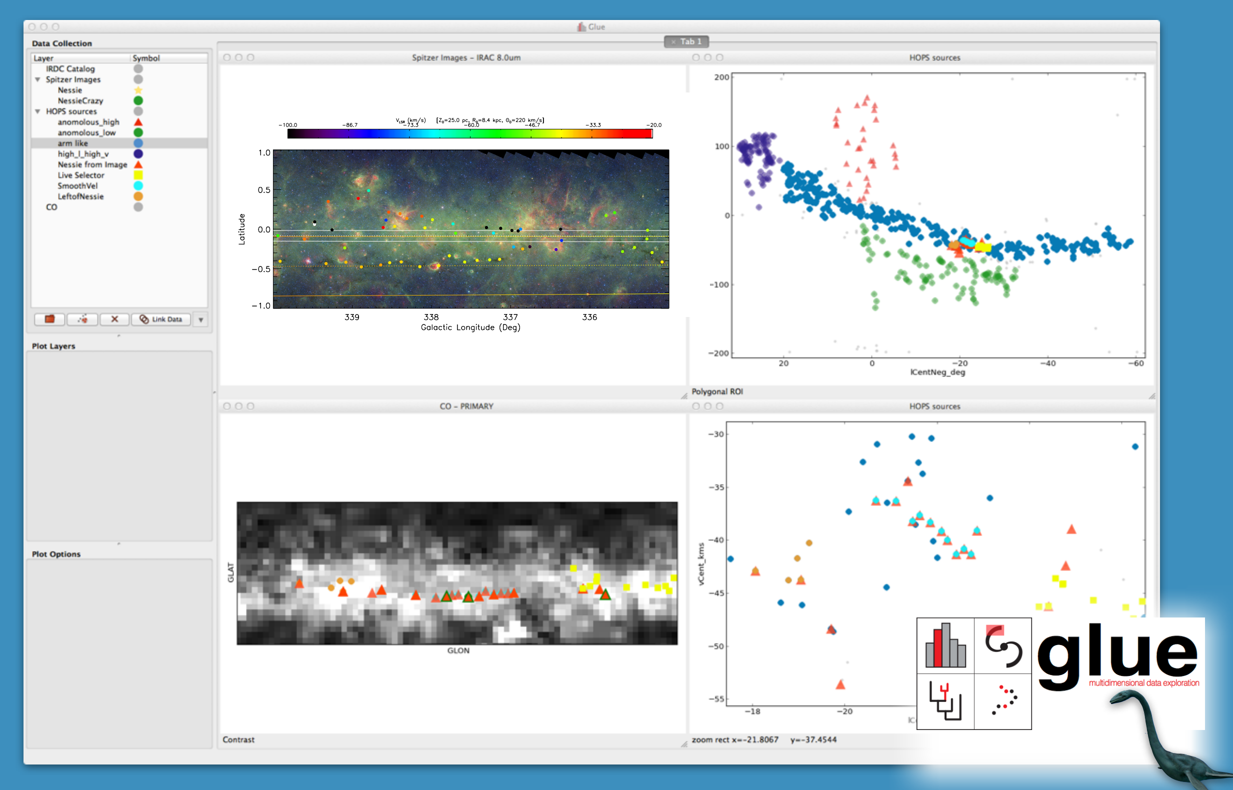
Drawing is schematic--NOT to scale



Notes:
IAU b=0 set from HI, which is uncertain by ~0.1 degrees
tilt of red w.r.t. blue would be (20/8400)*180/pi=0.13 degrees

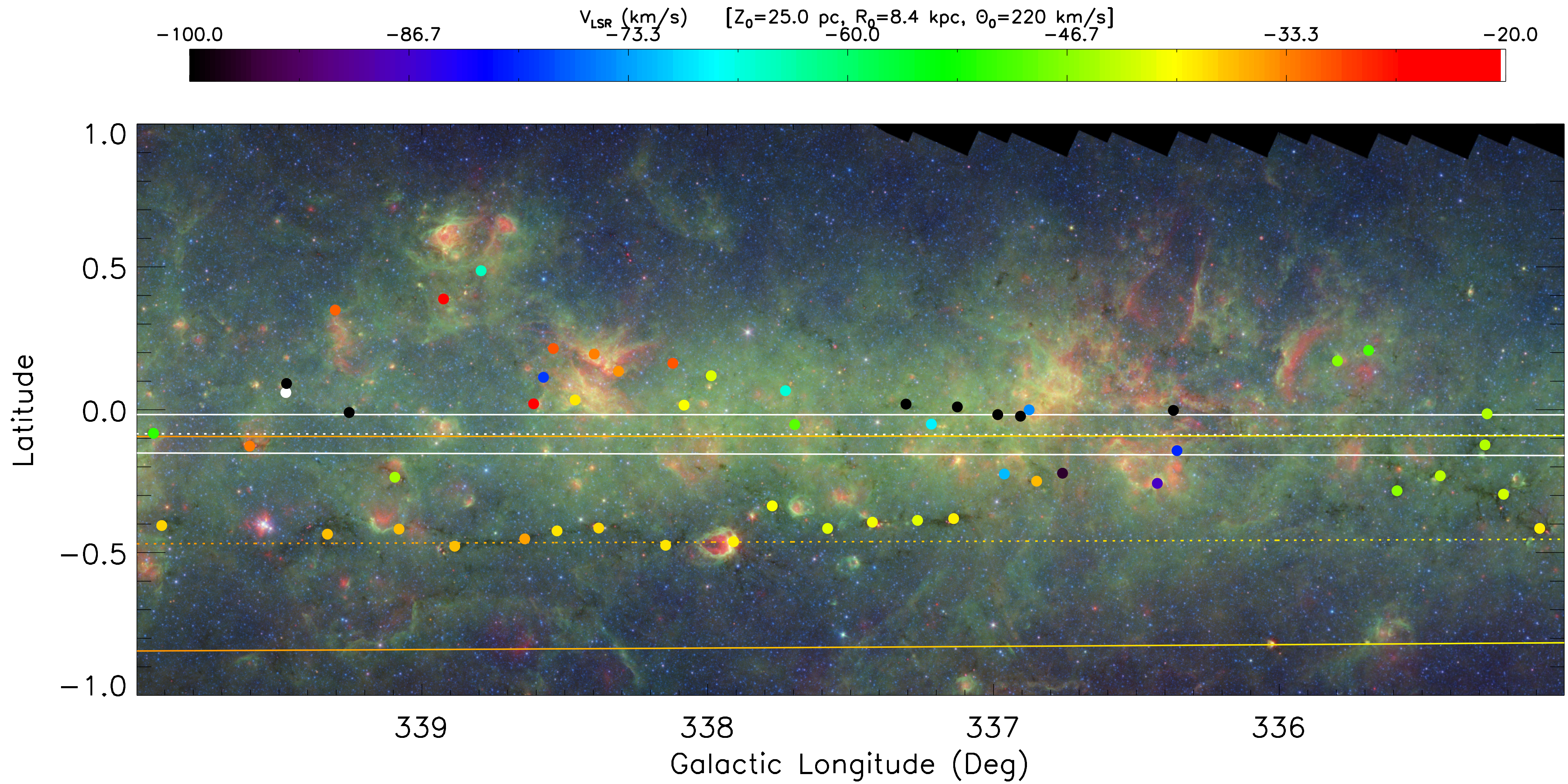
At what distance & inclination to l.o.s?





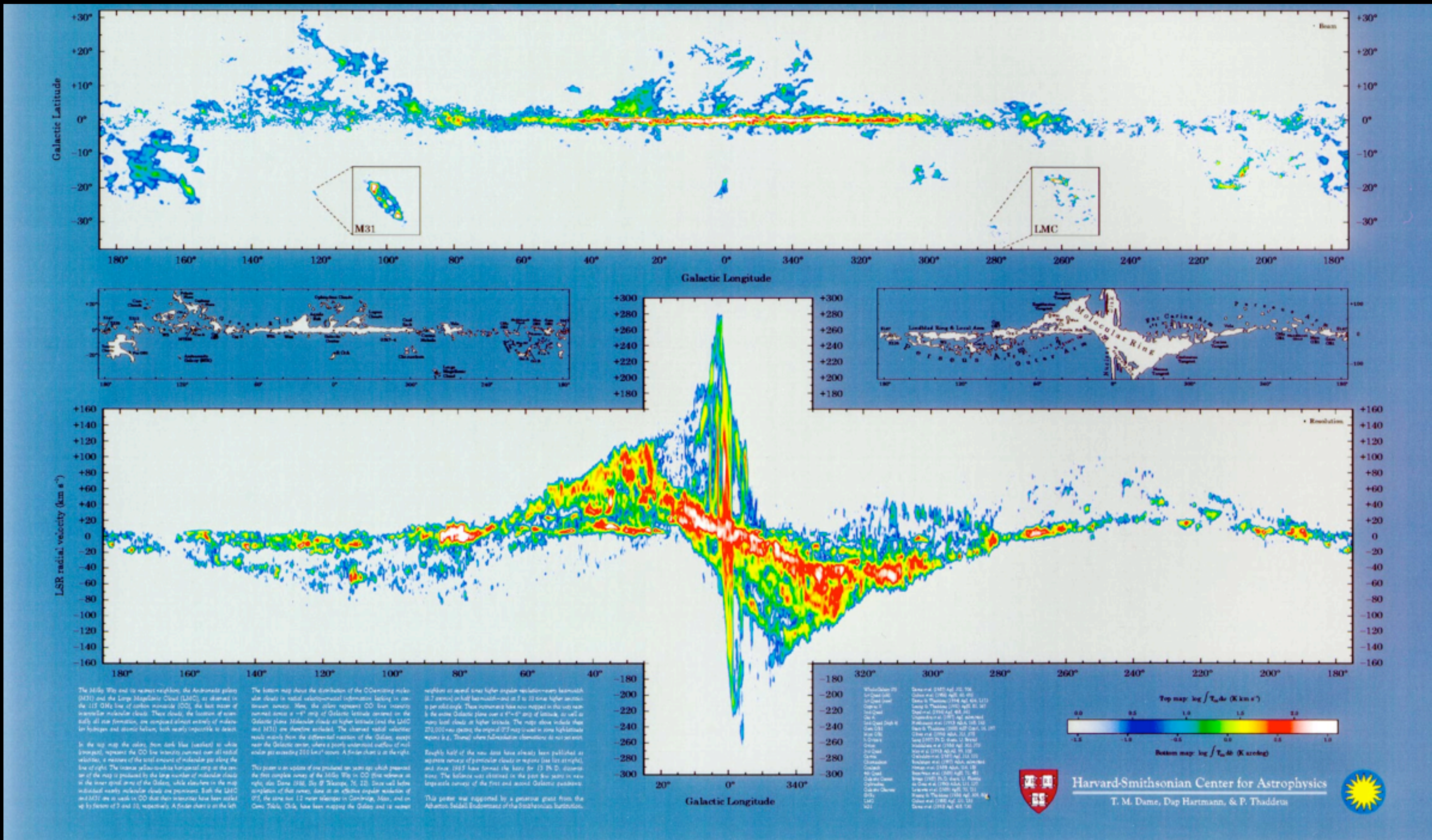
Where is "Nessie," in 3D?

Velocity contratints on distance & inclination to l.o.s



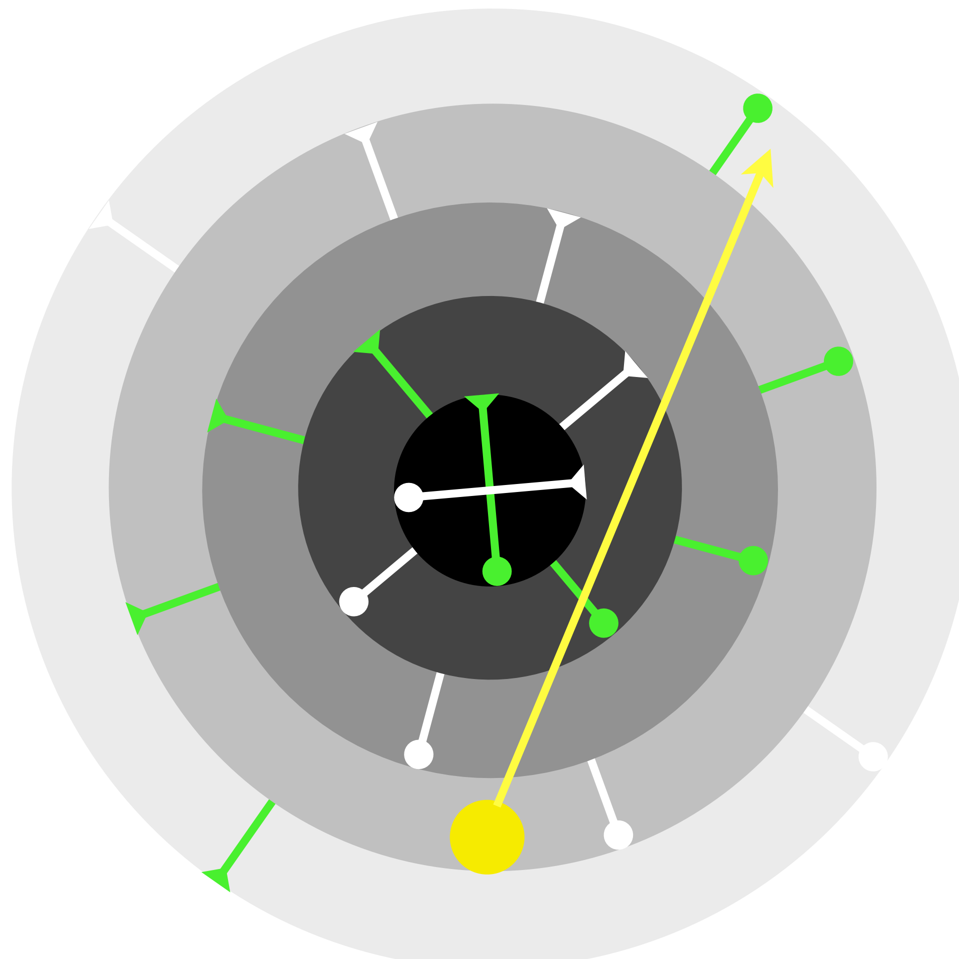
colored dots show HOPS data (dense gas velocities) from Purcell et al. 2012

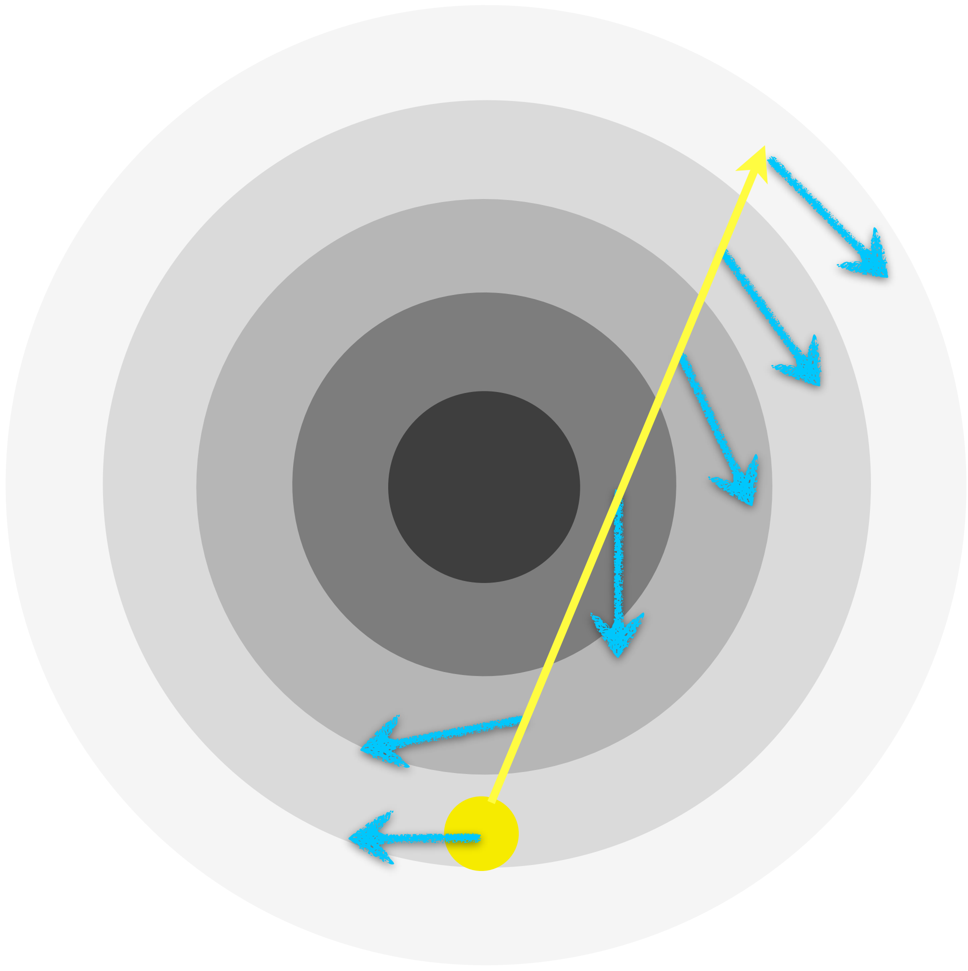
Milky Way Gas Kinematics 101

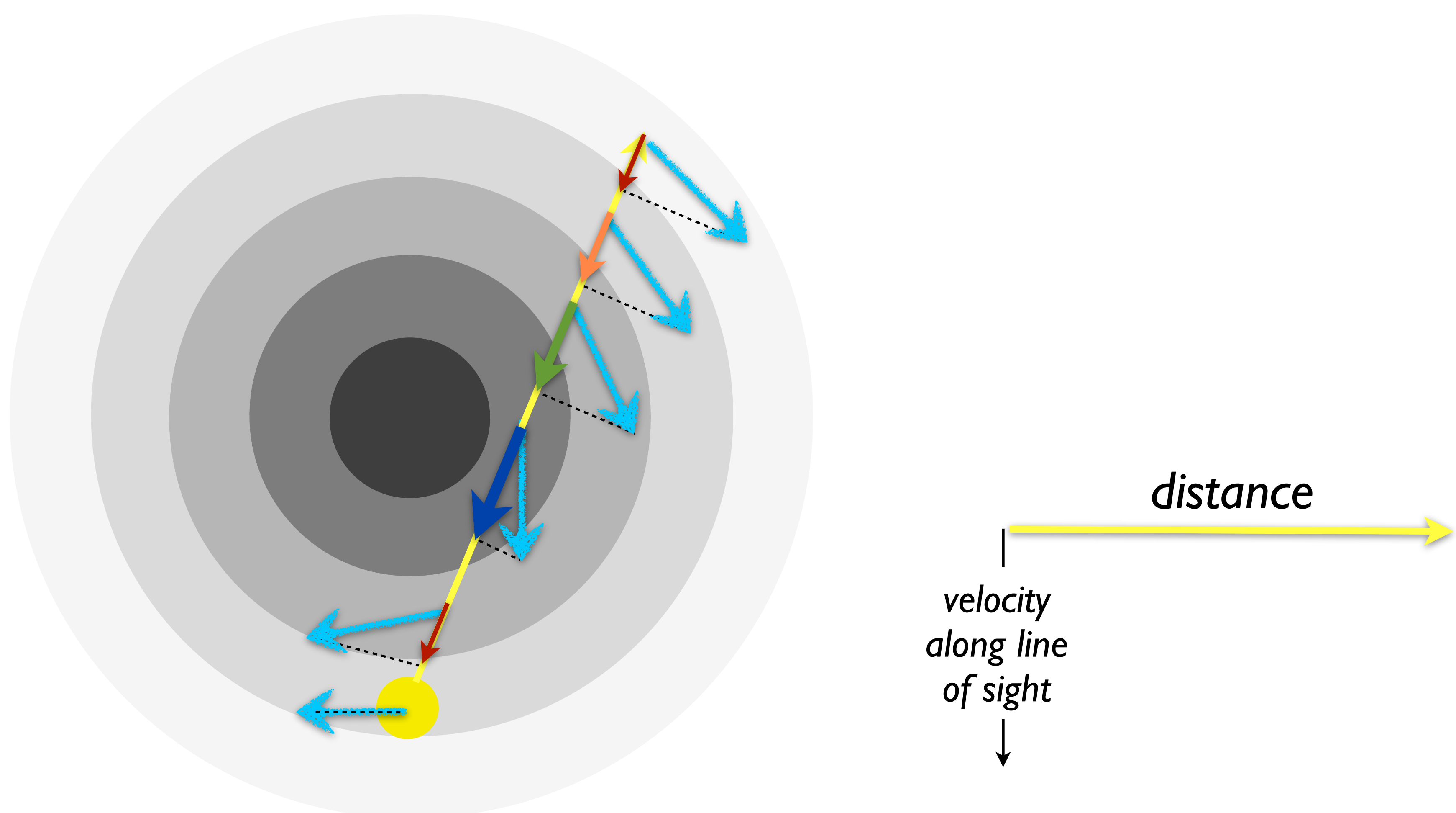


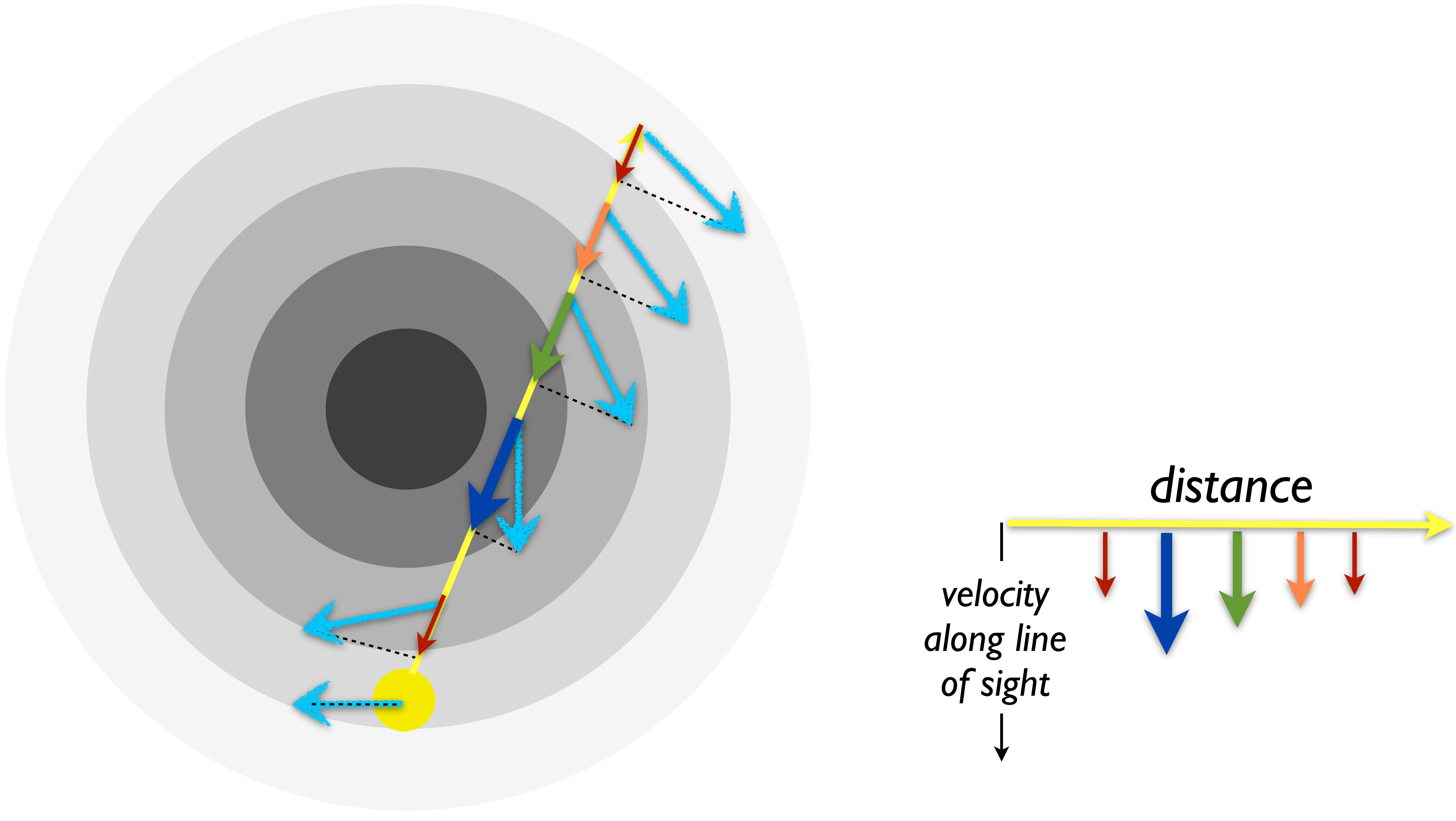
Dame et al. 2001

A Spiral Galaxy Observed from its Outskirts...

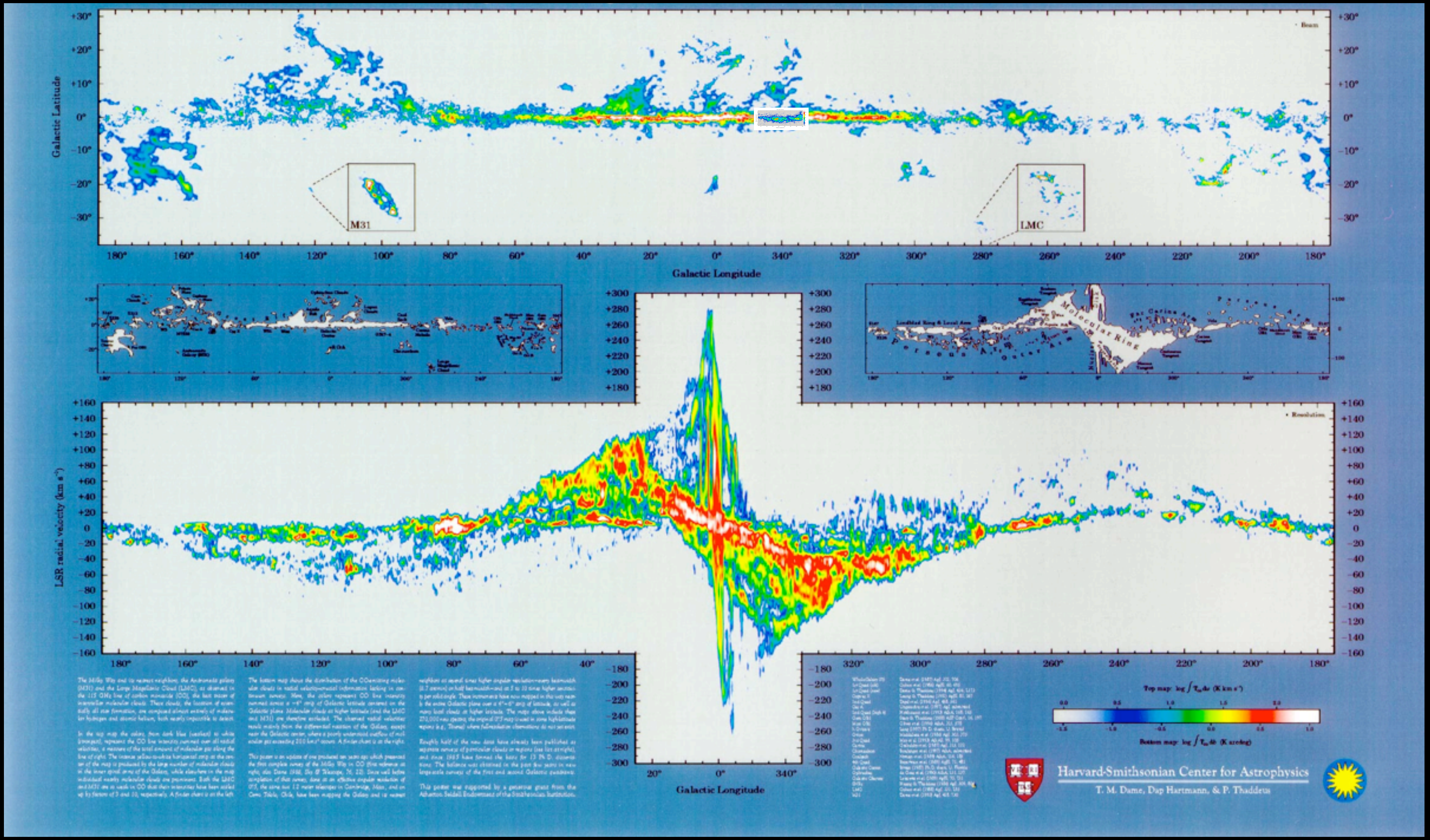




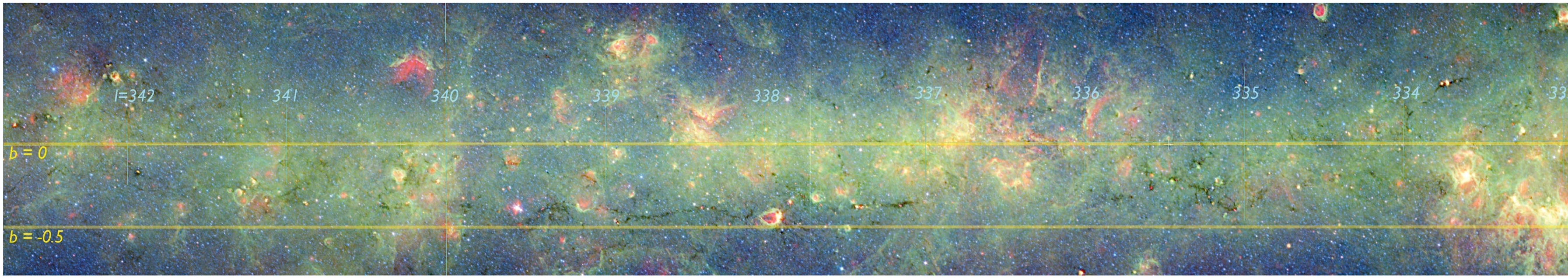

distance
velocity
along line
of sight


distance
velocity
along line
of sight

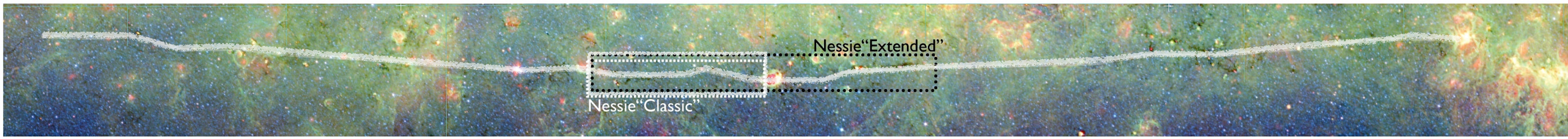
Milky Way Gas Kinematics 101

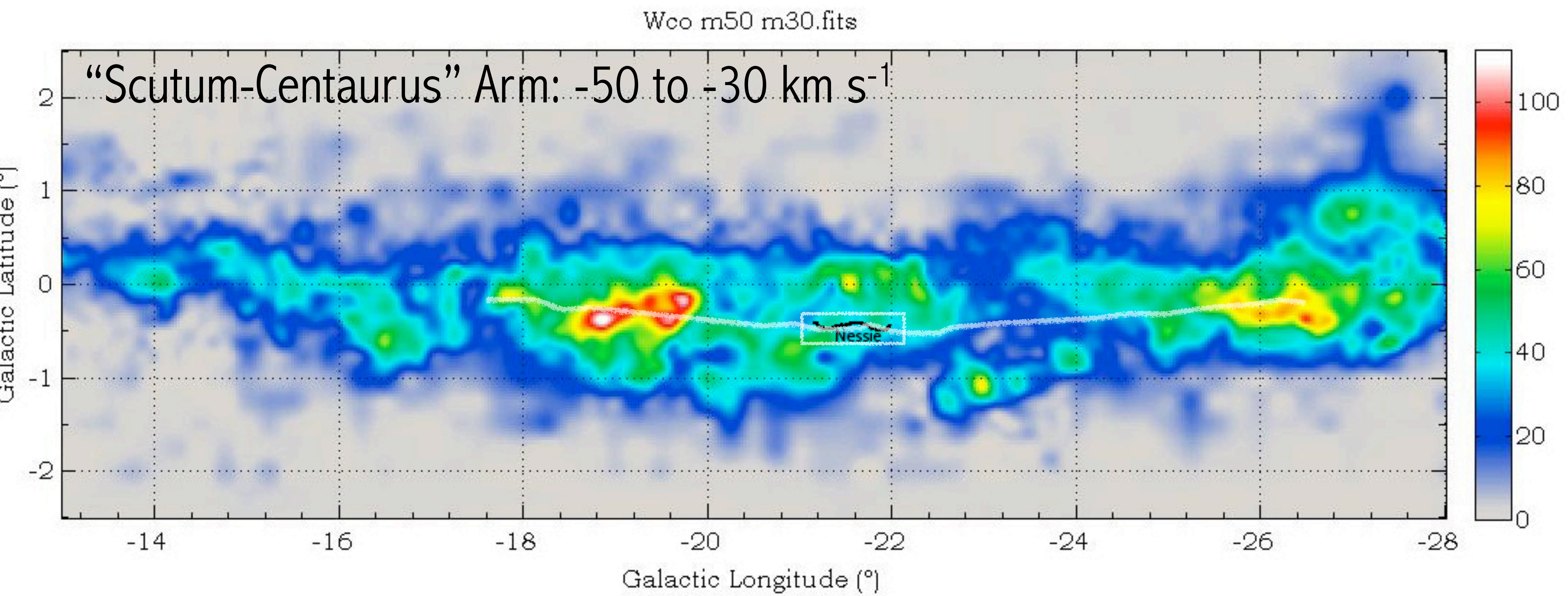


Dame et al. 2001

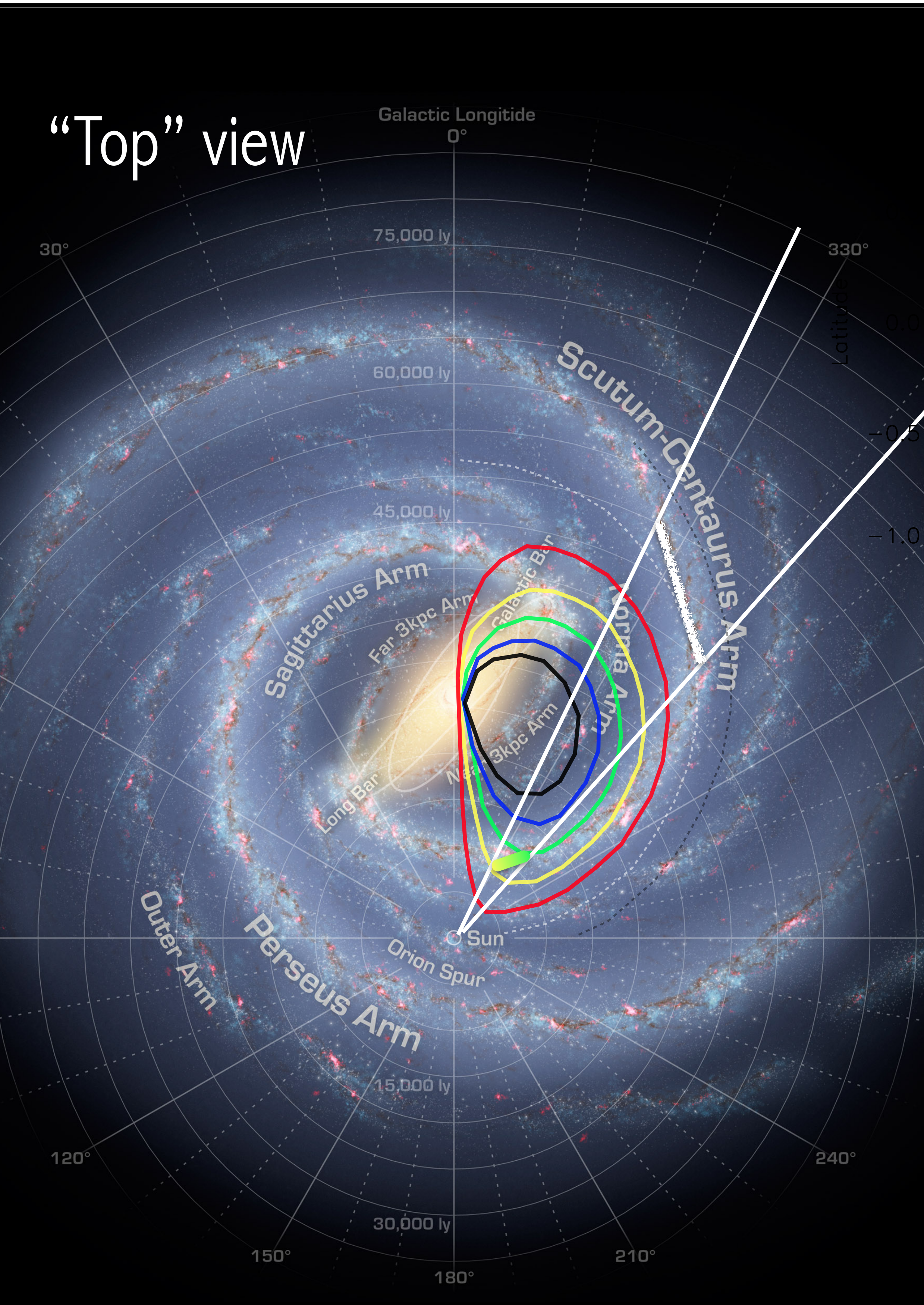


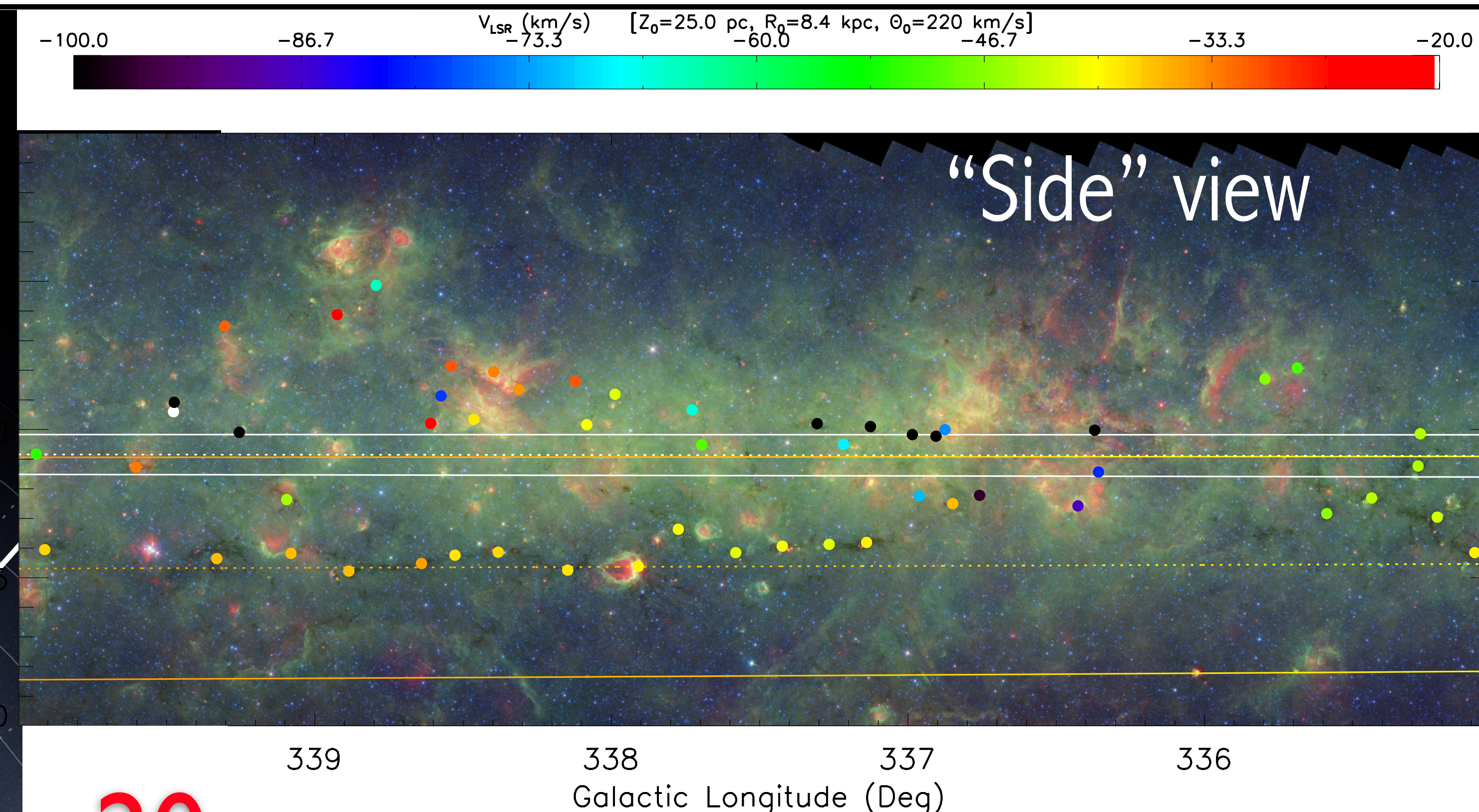
1 degree ~ 60 pc at 3.5 kpc





Using Velocity Constraints





-20

-40

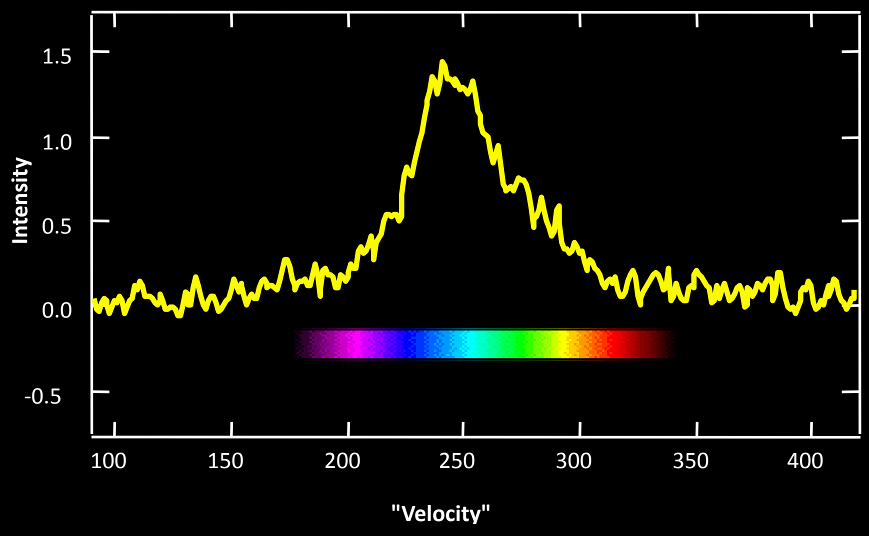
-60

-80

-100

Left: Scientist-artist Robert Hurt's view of the Milky Way
(cartoon based on stars, CO, HI, masers & HII regions; Benjamin, Dame et al.)


IC342
image from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas



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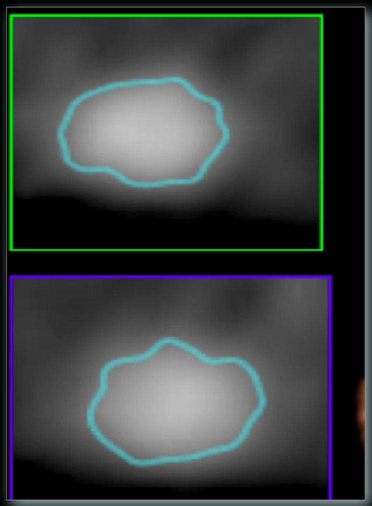

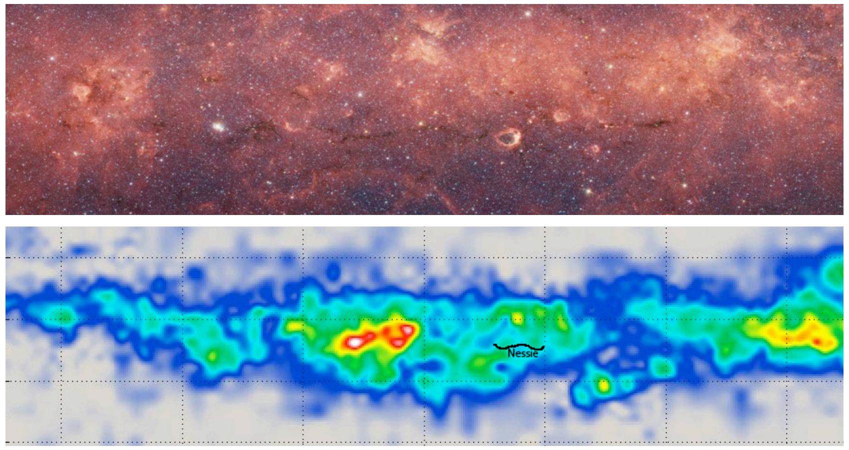

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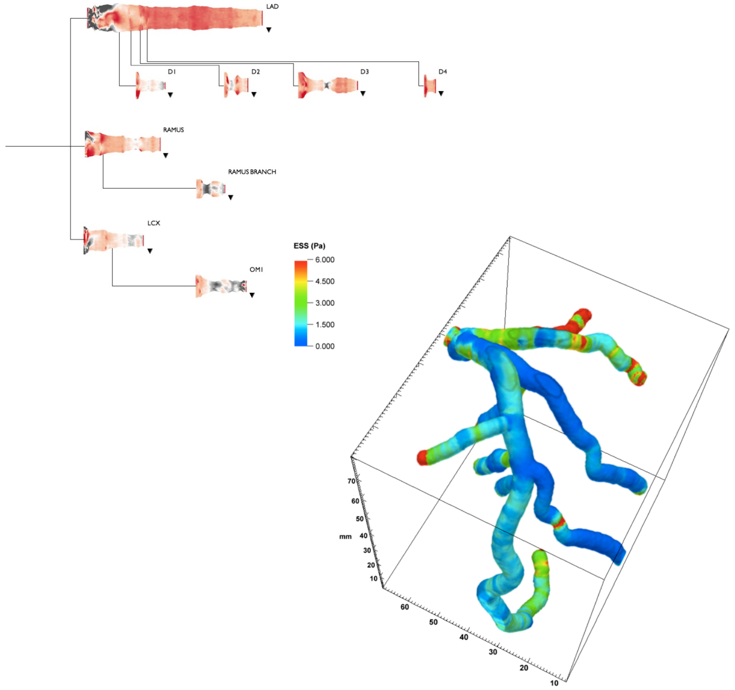
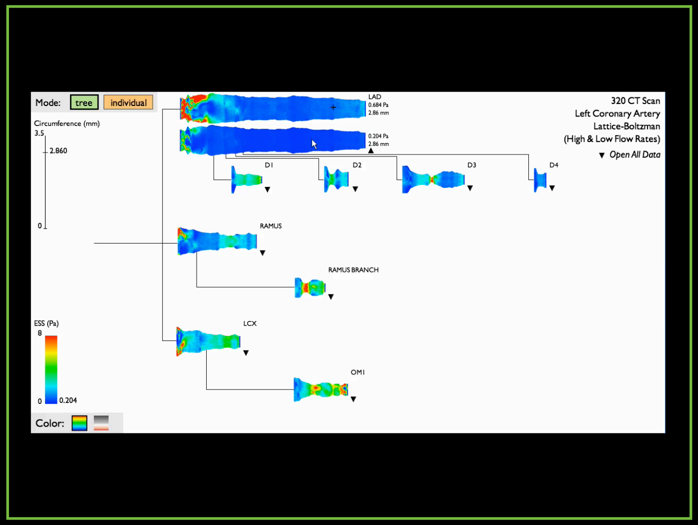
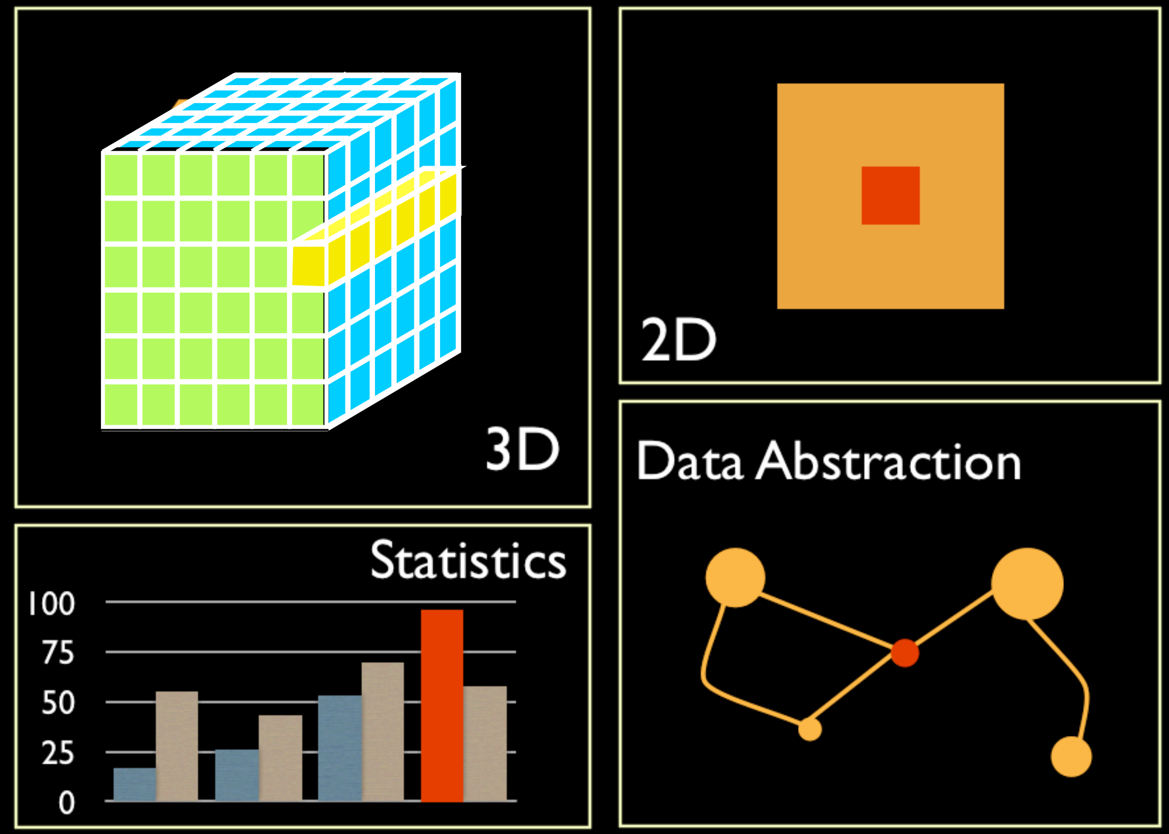


Display

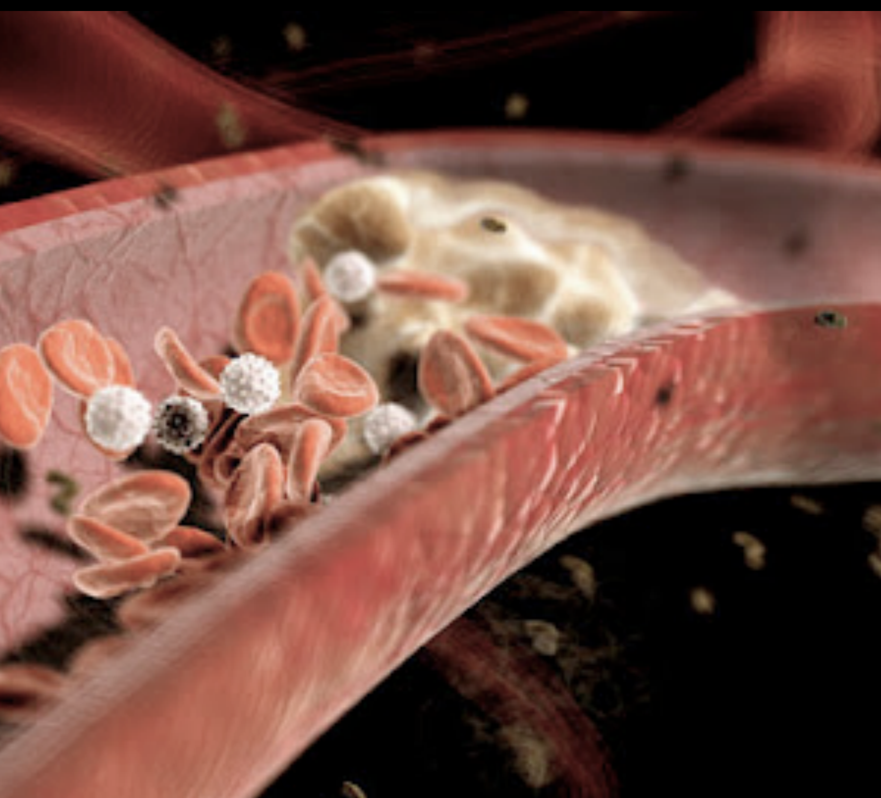




glue
multidimensional data exploration

The Close Relationship between Heart Disease and Sea Monsters*

**or, why good high-dimensional data visualization can solve almost any problem!*



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Principles of high-dimensional data visualization in astronomy

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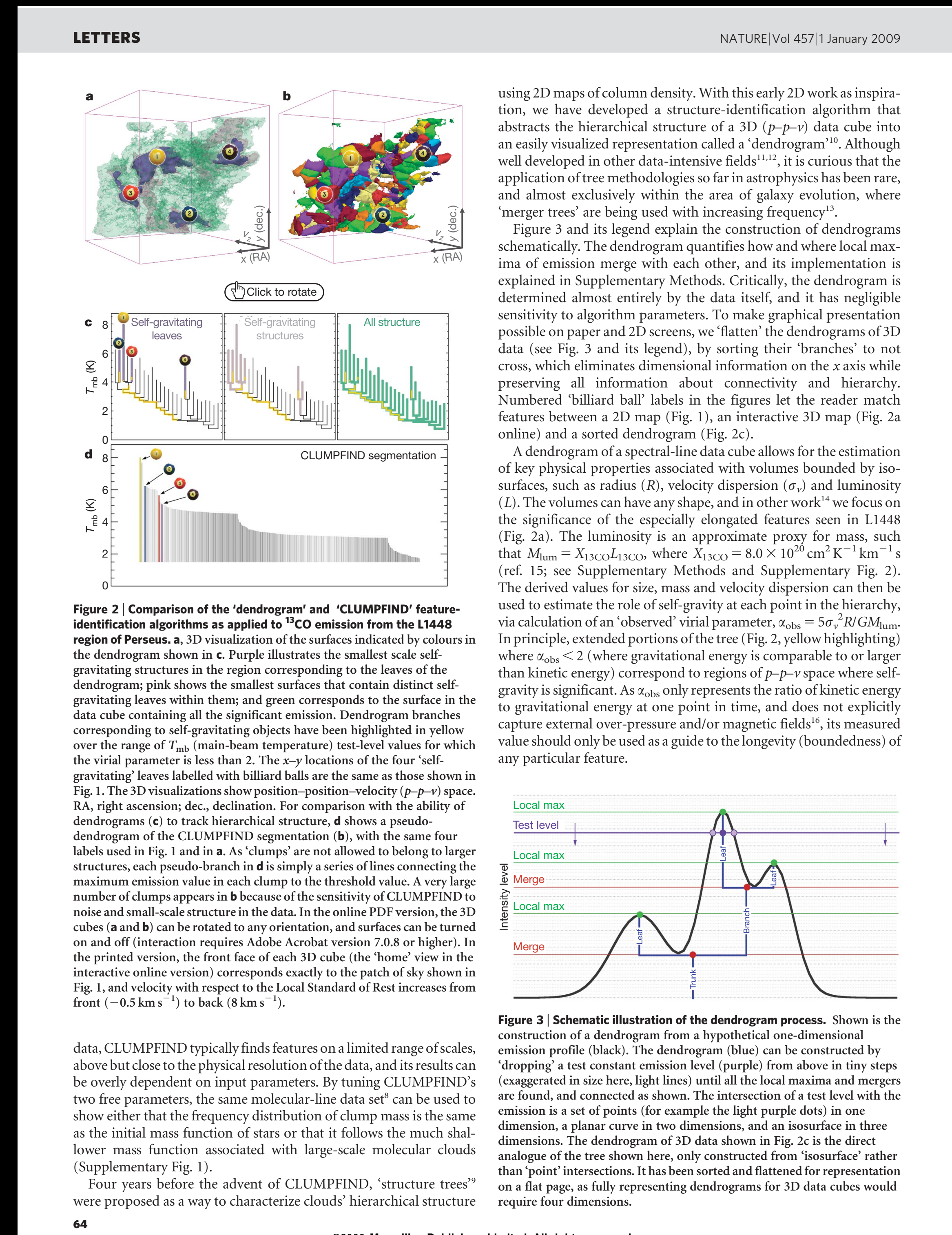
Key words cosmology: large-scale structure – ISM: clouds – methods: data analysis – techniques: image processing – techniques: radial velocities

Astronomical researchers often think of analysis and visualization as separate tasks. In the case of high-dimensional data sets, though, interactive *exploratory data visualization* can give far more insight than an approach where data processing and statistical analysis are followed, rather than accompanied, by visualization. This paper attempts to charts a course toward "linked view" systems, where multiple views of high-dimensional data sets update live as a researcher selects, highlights, or otherwise manipulates, one of several open views. For example, imagine a researcher looking at a 3D volume visualization of simulated or observed data, and simultaneously viewing statistical displays of the data set's properties (such as an x-y plot of temperature vs. velocity, or a histogram of vorticities). Then, imagine that when the researcher selects an interesting group of points in any one of these displays, that the same points become a highlighted subset in all other open displays. Selections can be graphical or algorithmic, and they can be combined, and saved. For tabular (ASCII) data, this kind of analysis has long been possible, even though it has been under-used in astronomy. The bigger issue for astronomy and other "high-dimensional" fields, though, is that no extant system allows for full integration of images and data cubes within a linked-view environment. The paper concludes its history and analysis of the present situation with suggestions that look toward cooperatively-developed open-source modular software as a way to create an evolving, flexible, high-dimensional, linked-view visualization environment useful in astrophysical research.

3D Selection

- Wh
- How
- How ... on?

What does "Publication-Quality" Graphics Mean in an Interactive 3D World?



Click to rotate

Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. a, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating structures in the region corresponding to the leaves of the dendrogram; pink shows the smallest surfaces that contain distinct self-gravitating leaves within them; and green corresponds to the surface in the data cube containing all the significant emission. Dendrogram branches corresponding to self-gravitating objects have been highlighted in yellow over the range of T_{mb} (main-beam temperature) test-level values for which the virial parameter is less than 2. The x–y locations of the four 'self-gravitating' leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position–position–velocity (p–p–v) space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (**c**) to track hierarchical structure, **d** shows a pseudo-dendrogram of the CLUMPFIND segmentation (**b**), with the same four labels used in Fig. 1 and in **a**. As 'clumps' are not allowed to belong to larger structures, each pseudo-branch in **d** is simply a series of lines connecting the maximum emission value in each clump to the threshold value. A very large number of clumps appears in **b** because of the sensitivity of CLUMPFIND to noise and small-scale structure in the data. In the online PDF version, the 3D cubes (**a** and **b**) can be rotated to any orientation, and surfaces can be turned on and off (interaction requires Adobe Acrobat version 7.0.8 or higher). In the printed version, the front face of each 3D cube (the 'home' view in the interactive online version) corresponds exactly to the patch of sky shown in Fig. 1, and velocity with respect to the Local Standard of Rest increases from front ($-0.5\ km\ s^{-1}$) to back ($8\ km\ s^{-1}$).

data, CLUMPFIND typically finds features on a limited range of scales, above but close to the physical resolution of the data, and its results can be overly dependent on input parameters. By tuning CLUMPFIND's two free parameters, the same molecular-line data set[8] can be used to show either that the frequency distribution of clump mass is the same as the initial mass function of stars or that it follows the much shallower mass function associated with large-scale molecular clouds (Supplementary Fig. 1).

Four years before the advent of CLUMPFIND, 'structure trees'[9] were proposed as a way to characterize clouds' hierarchical structure using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that abstracts the hierarchical structure of a 3D (p–p–v) data cube into an easily visualized representation called a 'dendrogram'[10]. Although well developed in other data-intensive fields[11,12], it is curious that the application of tree methodologies so far in astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where 'merger trees' are being used with increasing frequency[13].

Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is explained in Supplementary Methods. Critically, the dendrogram is determined almost entirely by the data itself, and it has negligible sensitivity to algorithm parameters. To make graphical presentation possible on paper and 2D screens, we 'flatten' the dendrograms of 3D data (see Fig. 3 and its legend), by sorting their 'branches' to not cross, which eliminates dimensional information on the x axis while preserving all information about connectivity and hierarchy. Numbered 'billiard ball' labels in the figures let the reader match features between a 2D map (Fig. 1), an interactive 3D map (Fig. 2a online) and a sorted dendrogram (Fig. 2c).

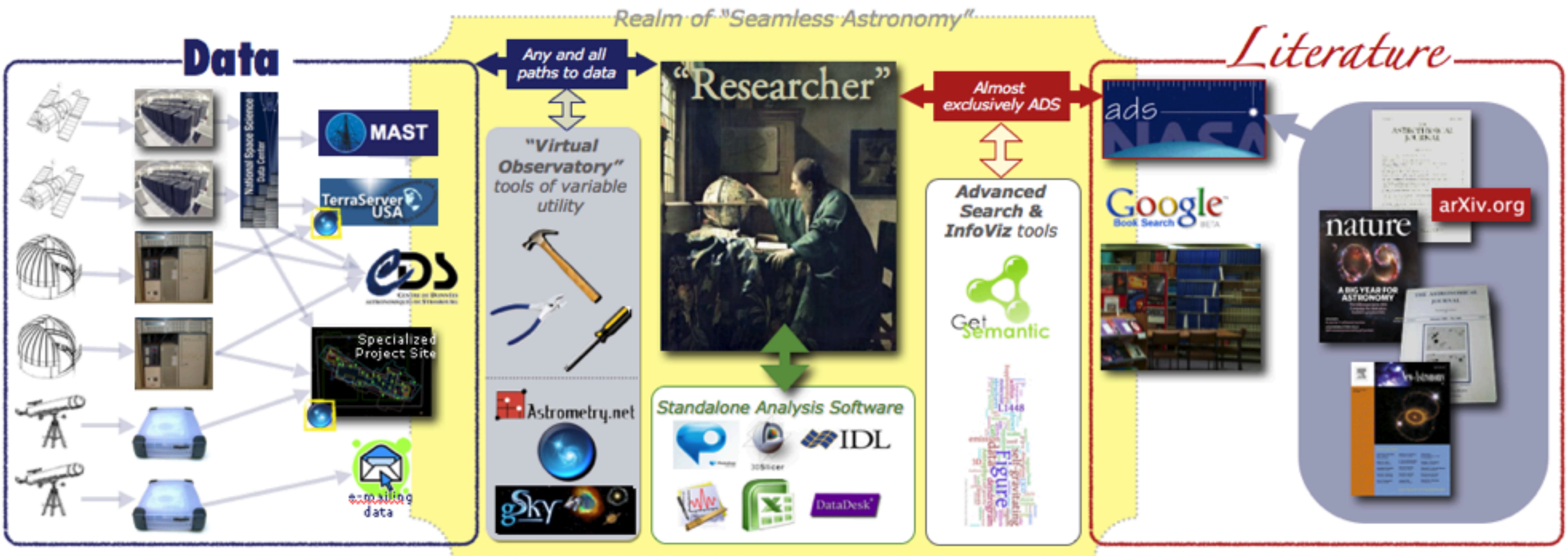
A dendrogram of a spectral-line data cube allows for the estimation of key physical properties associated with volumes bounded by isosurfaces, such as radius (R), velocity dispersion (σ_v) and luminosity (L). The volumes can have any shape, and in other work[14] we focus on the significance of the especially elongated features seen in L1448 (Fig. 2a). The luminosity is an approximate proxy for mass, such that $M_{lum} = X_{13CO} L_{13CO}$, where $X_{13CO} = 8.0 \times 10^{20}\ cm^2\ K^{-1}\ km^{-1}\ s$ (ref. 15; see Supplementary Methods and Supplementary Fig. 2). The derived values for size, mass and velocity dispersion can then be used to estimate the role of self-gravity at each point in the hierarchy, via calculation of an 'observed' virial parameter, $\alpha_{obs} = 5\sigma_v{}^2 R/GM_{lum}$. In principle, extended portions of the tree (Fig. 2, yellow highlighting) where $\alpha_{obs} < 2$ (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of p–p–v space where self-gravity is significant. As α_{obs} only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic fields[16], its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in size here, light lines) until all the local maxima and mergers are found, and connected as shown. The intersection of a test level with the emission is a set of points (for example the light purple dots) in one dimension, a planar curve in two dimensions, and an isosurface in three dimensions. The dendrogram of 3D data shown in Fig. 2c is the direct analogue of the tree shown here, only constructed from 'isosurface' rather than 'point' intersections. It has been sorted and flattened for representation on a flat page, as fully representing dendrograms for 3D data cubes would require four dimensions.

*Goodman, Rosolowsky, Borkin, Foster, Halle, Kauffmann & Pineda, **Nature**, 2009*

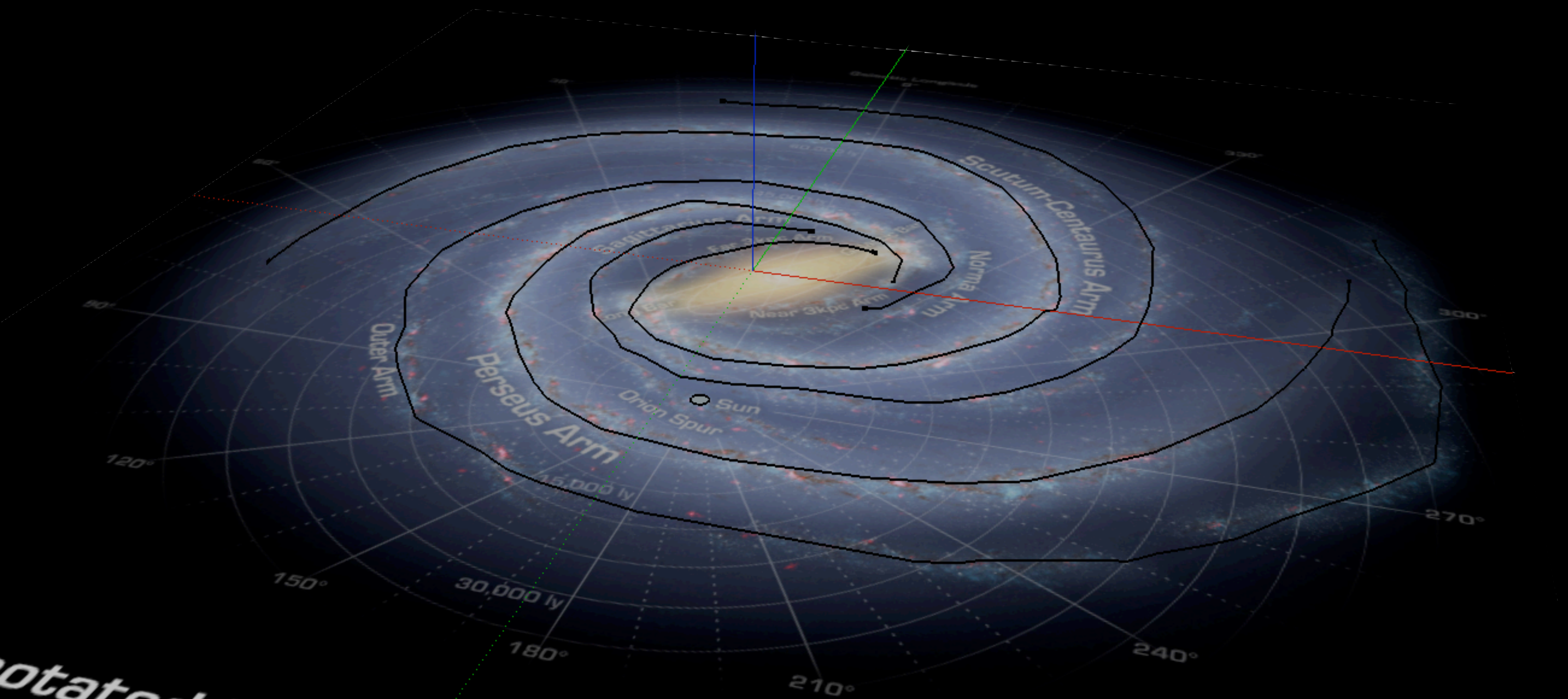
SEAMLESS ASTRONOMY

Linking scientific data, publications, and communities

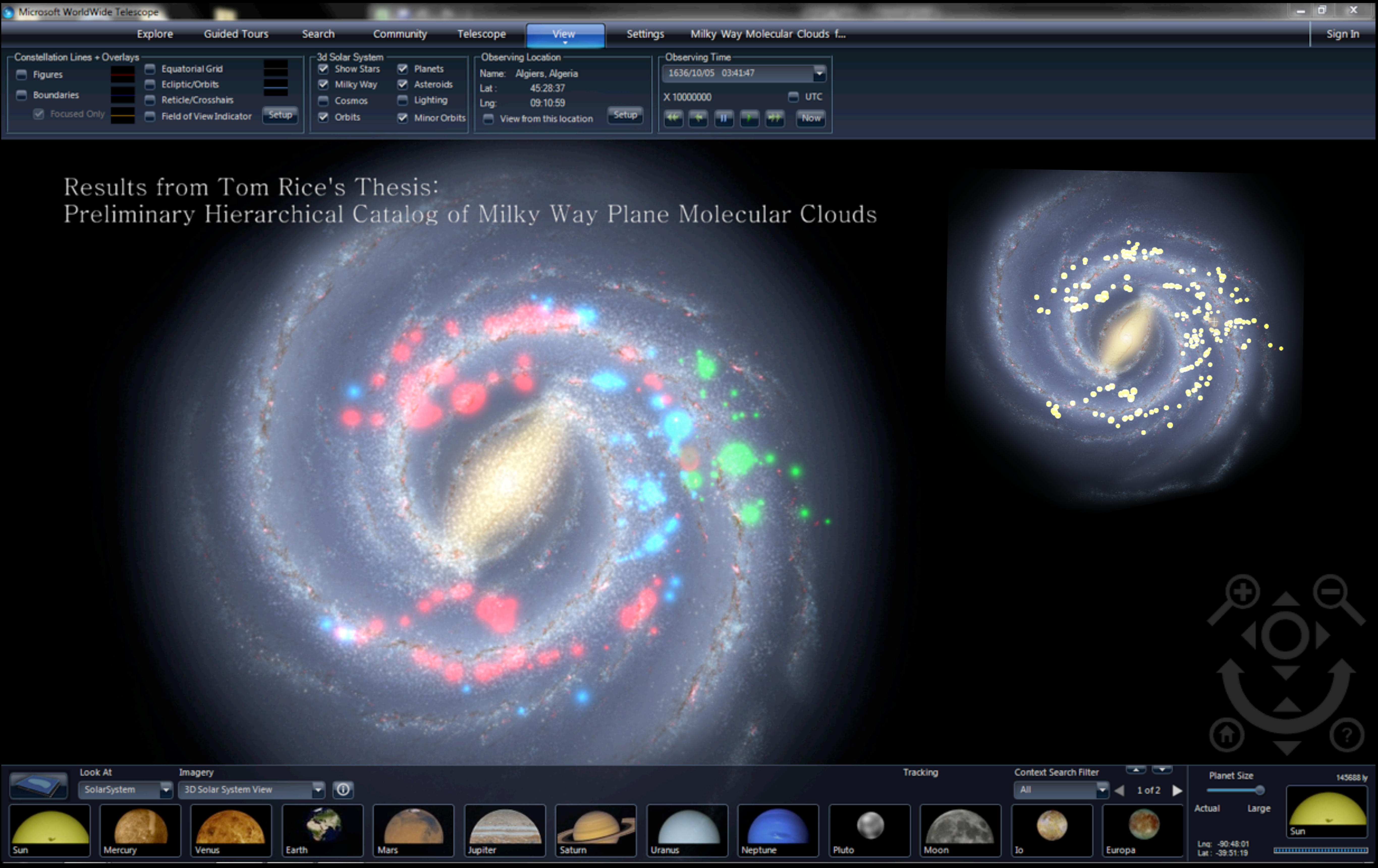


projects.iq.harvard.edu/seamlessastronomy/

UNIVERSE3D.org



Value of “Linked Views” from Harvard Undergrad Thesis* Work



*thesis of Tom Rice, ’12, awarded Hoopes Prize