## GLUEING TOGETHER THE SKELETON OF THE MILKY WAY

# Alyssa A. Goodman Harvard-Smithsonan Center for Astrophysics Radcliffe Institute for Advanced Study @aagie







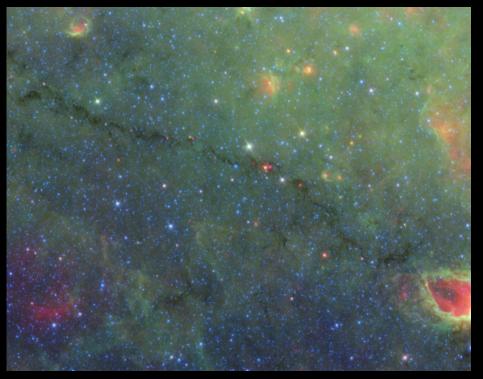
I missed Monday's talk...what did you say?

I'm a particle physicist...what's a "galactic plane"? What's a "rotation curve"? How do you measure all this stuff? Why should I care?

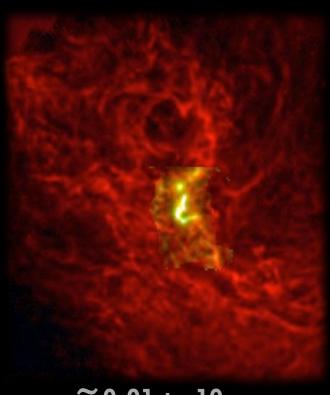
I'm an astronomer...and I only care a little about the Galaxy— can I just see more on that cool software you showed too briefly on Monday?

## TODAY

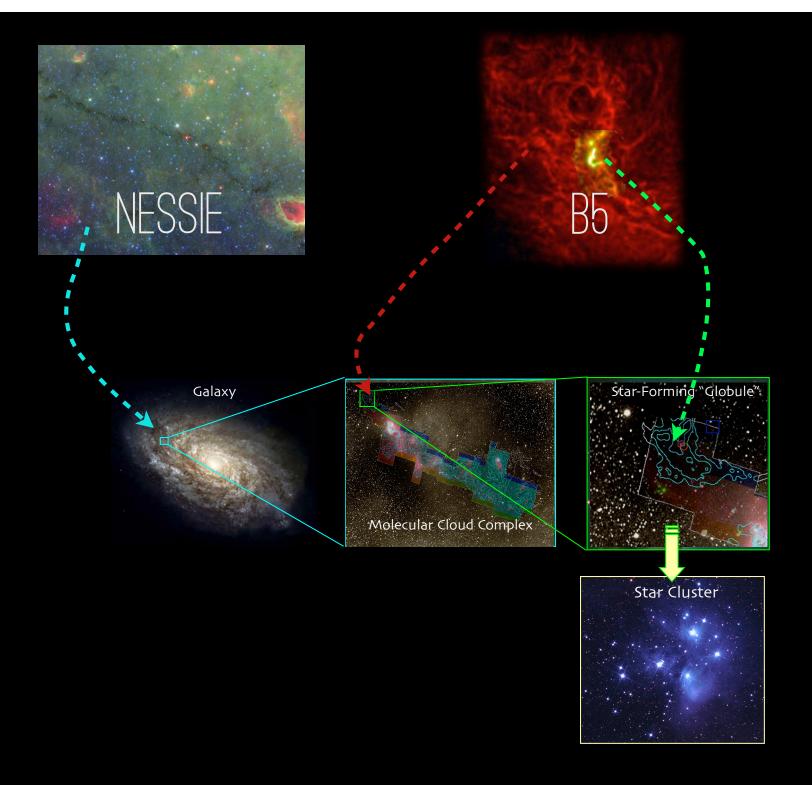
## MONDAY



>100 pc



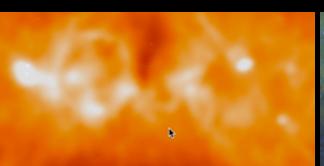
~0.01 to 10 pc

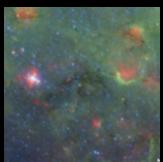


## MEASUREMENTS

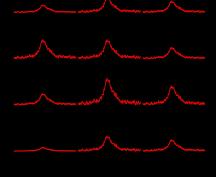


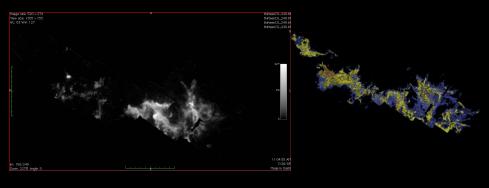






Gas

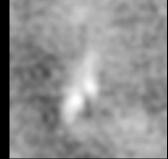




"Stars"







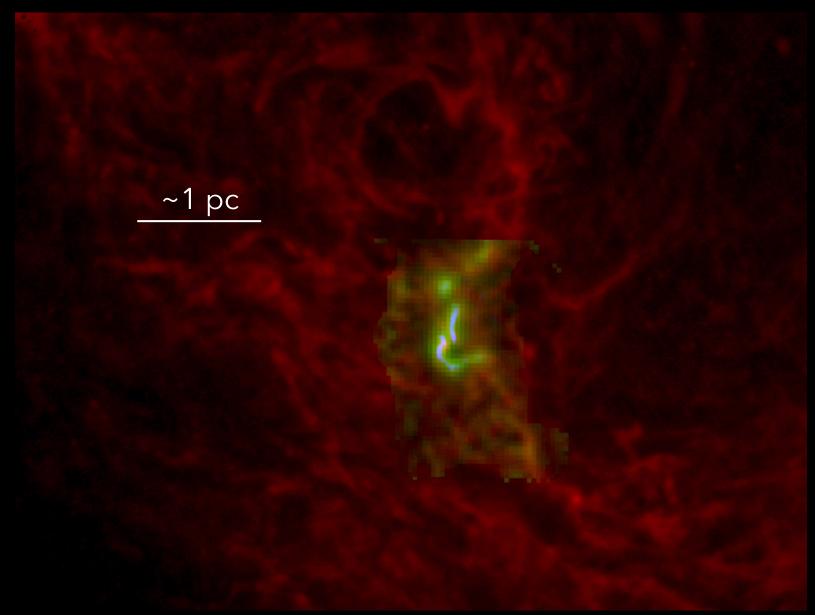
I missed Monday's talk...what did you say?

I'm a particle physicist...what's a "galactic plane"? What's a "rotation curve"? How do you measure all this stuff? Why should I care?

I'm an astronomer...and I only care a little about the Galaxy— can I just see more on that cool software you showed too briefly on Monday?

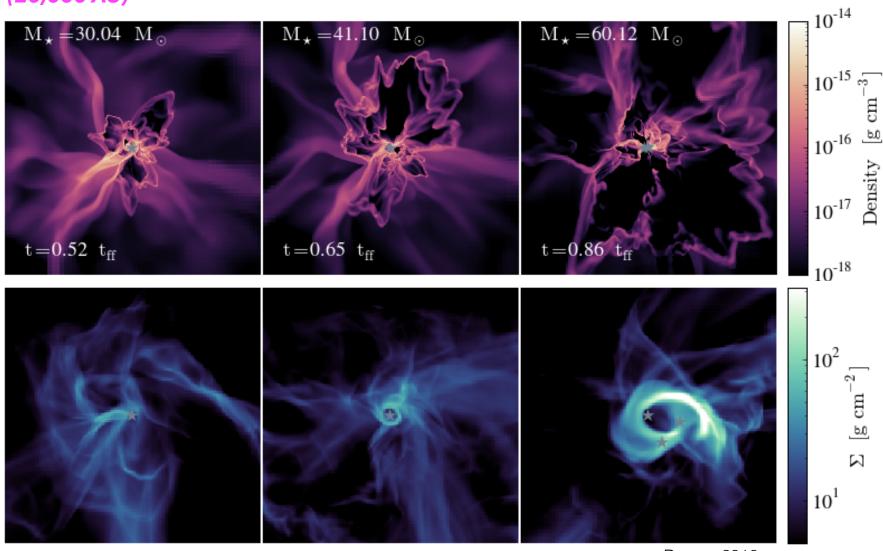
## MONDAY: There are no collapsing spheres in star formation ...and it's probably a much faster process than we thought.

blue =VLA ammonia (high-density gas); green=GBT ammonia (lower-res high-density gas); red=Herschel 250 micron continuum (dust)



Mass delivered to star via infalling dense filaments, RT instabilities, and disk accretion.

(20,000 AU)<sup>2</sup>



 $(3,000 AU)^2$ 

Rosen+2016

I missed Monday's talk...what did you say?

I'm a particle physicist...what's a "galactic plane"? What's a "rotation curve"? How do you measure all this stuff? Why should I care?

I'm an astronomer...and I only care a little about the Galaxy— can I just see more on that cool software you showed too briefly on Monday?

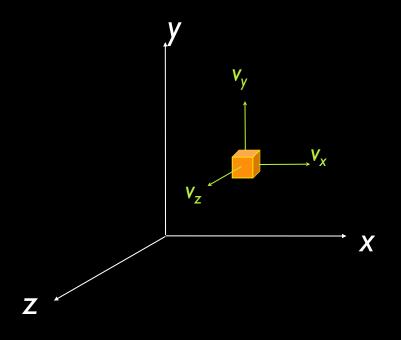


The Milky Way (Artist's Conception)

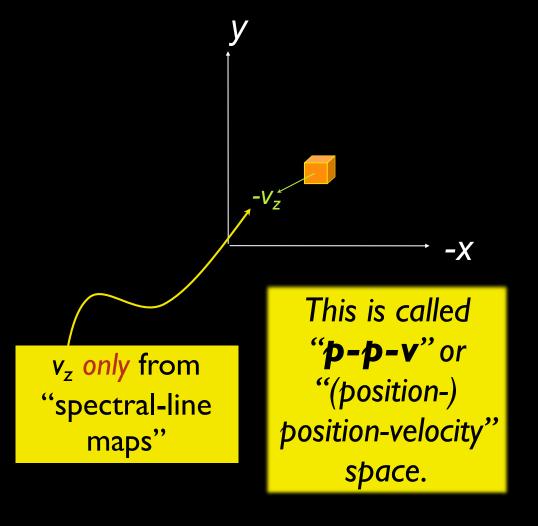


### P-P-V SPACE & SPECTRAL-LINE MAPPING (FROM MONDAY)

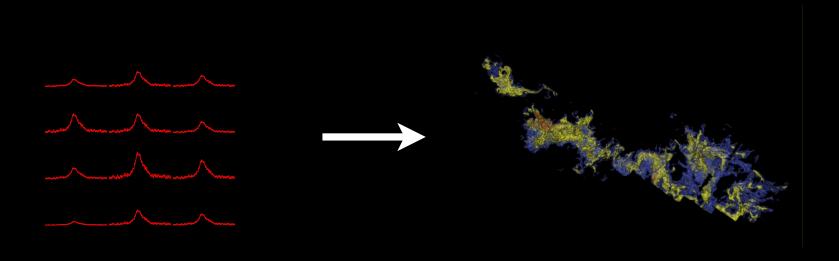
We wish we could measure...



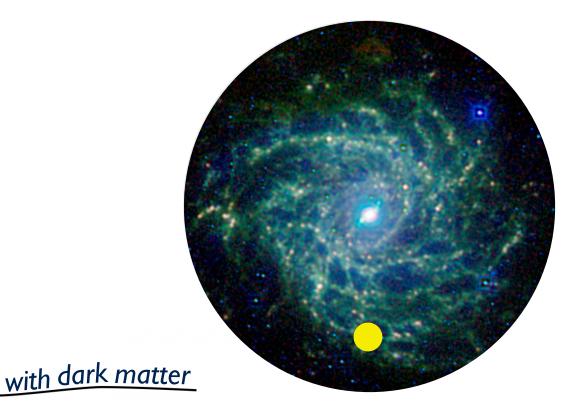
But we can measure...



## P-P-V SPACE & SPECTRAL-LINE MAPPING



### Translating "p-p-v" to real space in our Galaxy...

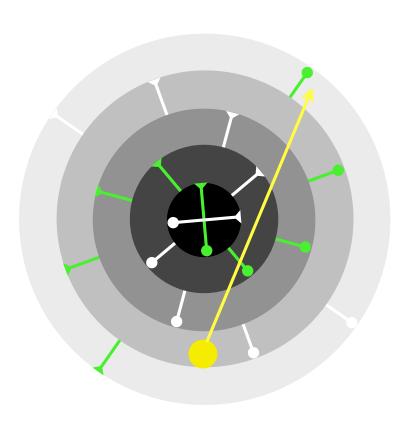


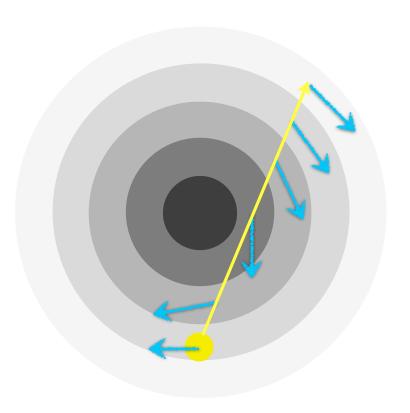
Velocity

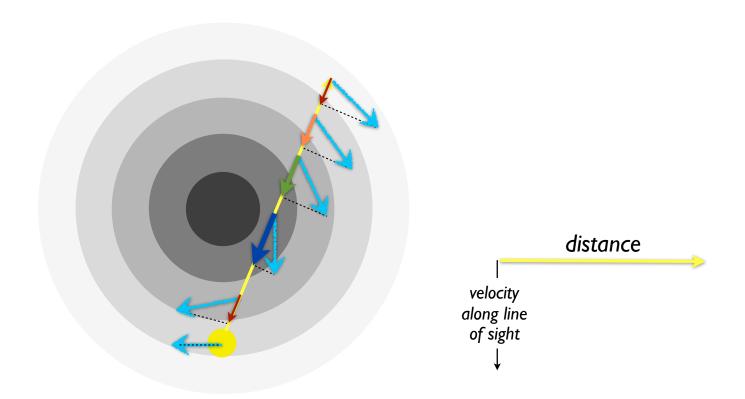
· · no dark matter

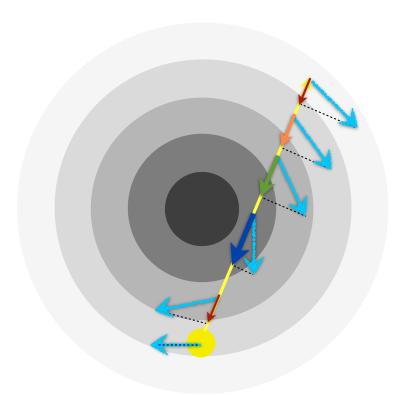
...using its "rotation curve"

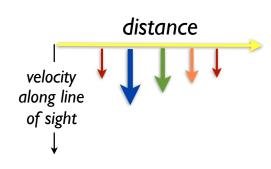
Distance



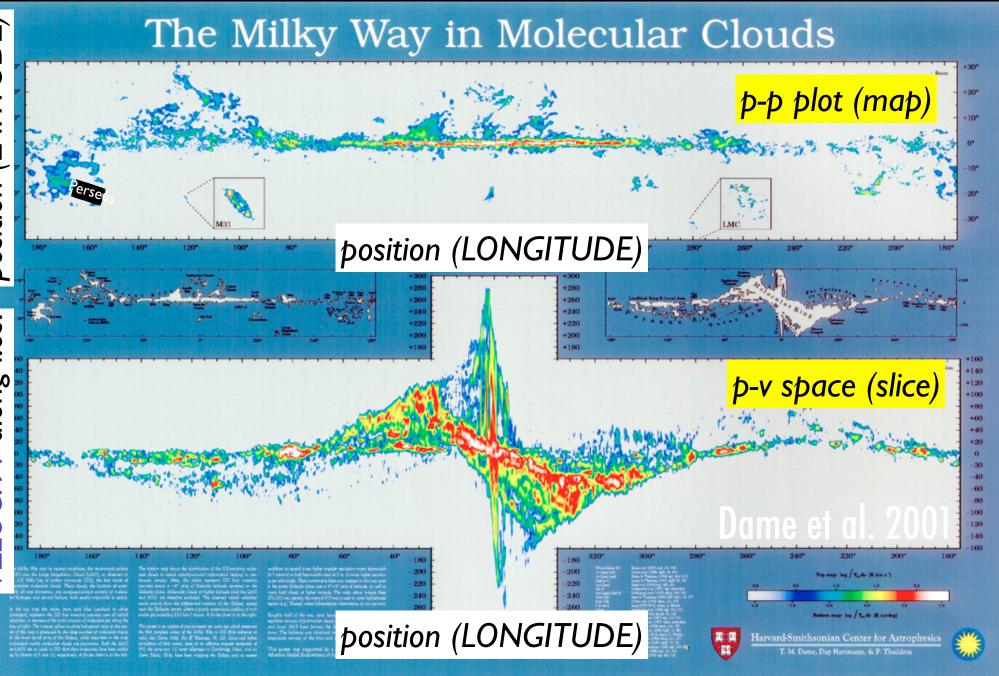








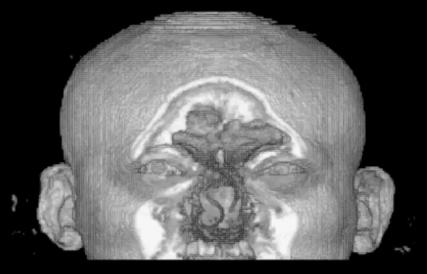
### Molecular Gas & the most famous "p-p-v" poster ever

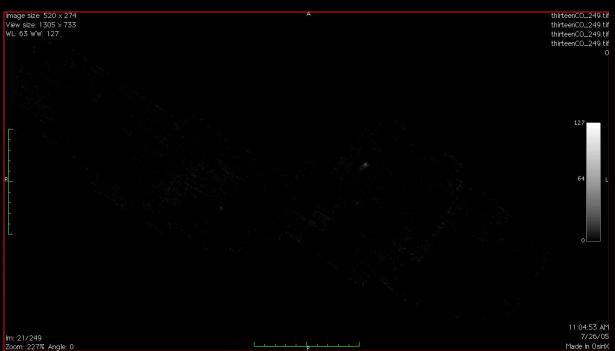


## ASTRONOMICAL MEDICINE

### "Keith"

### "Perseus"

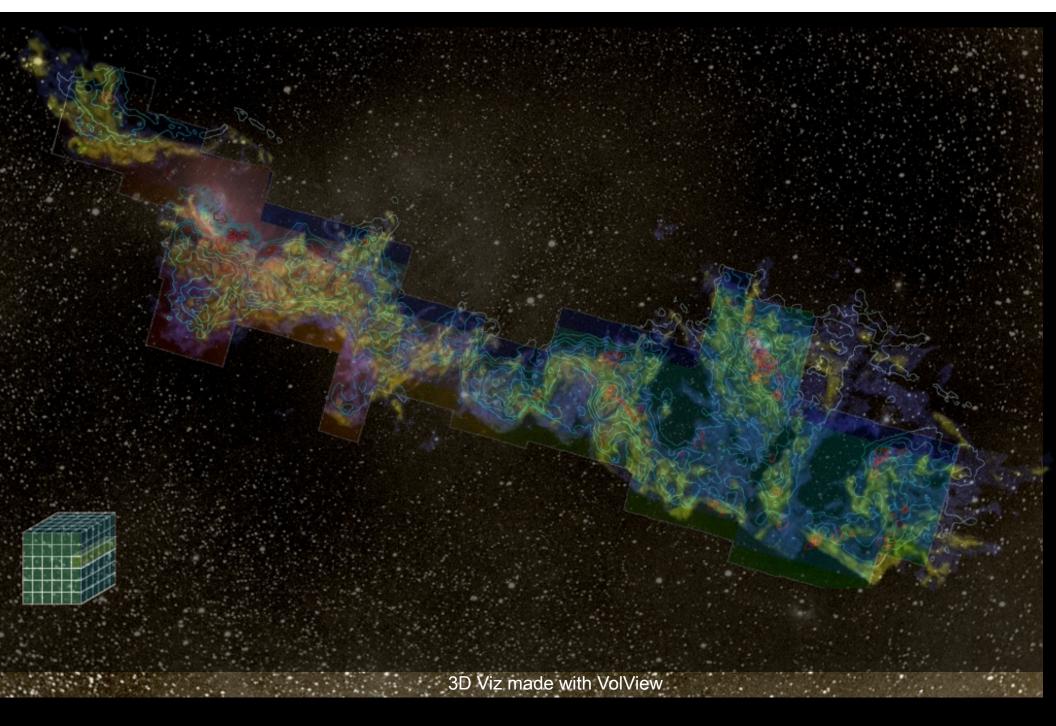




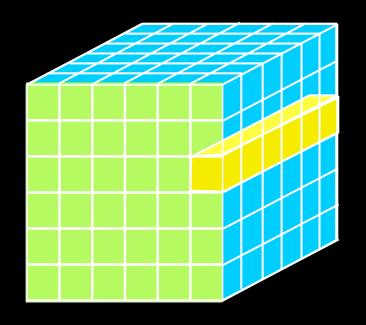
"z" is depth into head

"z" is line-of-sight velocity

mm peak (Enoch et al. 2006) ASTRONOMICAL MEDICINE O mage size: 520 x 274 sub-mm peak (Hatchell iew size: 1305 x 733 et al. 2005, Kirk et al. 2006) L: 63 WW: 127 13CO (Ridge et al. 2006) mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.) Optical image (Barnard 1927) oom: 227% Angle: 0







### DATA-DIMENSIONS-DISPLAY

D: Columns = "Spectra", "SEDs" or "Time Series" (x-y Graphs)

**2D**: Faces or Slices = "Images"

3D: Volumes = "3D Renderings", "2D Movies"

**4D**: Time Series of Volumes = "3D Movies"

## 2009 3D PDF INTERACTIVITY IN A "PAPER"

**LETTERS** NATURE|Vol 457|1 January 2009

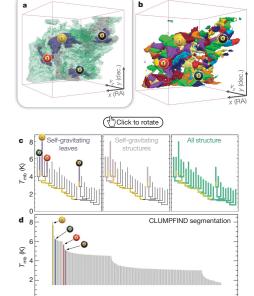


Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' featureidentification algorithms as applied to <sup>13</sup>CO emission from the L1448 region of Perseus. a, 3D visualization of the surfaces indicated by colours in the dendrogram shown in c. Purple illustrates the smallest scale selfgravitating structures in the region corresponding to the leaves of the dendrogram; pink shows the smallest surfaces that contain distinct selfgravitating 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  $T_{\rm mb}$  (main-beam temperature) test-level values for which the virial parameter is less than 2. The x-y locations of the four 'selfgravitating' leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position–position–velocity  $(p-p-\nu)$  space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (c) to track hierarchical structure, d shows a pseudodendrogram 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  $(-0.5 \text{ km s}^{-1})$  to back  $(8 \text{ km s}^{-1})$ .

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 set8 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 th tion, we have developed a structure-id abstracts the hierarchical structure of a an easily visualized representation called well developed in other data-intensive application of tree methodologies so fa and almost exclusively within the ar A role for self-gravity at multiple length scales in the 'merger trees' are being used with in

arly 2D work as inspira-

-ithm that

process of star formation

Alyssa A. Goodman (-) Erk W. Rosolowsky (-) Michelle A. Borkin't, Jonathan B. Foster', Michael Halle (-)

Figure 3 and its legend explain the schematically. The dendrogram qua ima of emission merge with each explained in Supplementary Meth determined almost entirely by the sensitivity to algorithm parameter possible on paper and 2D screen data (see Fig. 3 and its legend cross, which eliminates dimenpreserving all information Numbered 'billiard ball' labe features between a 2D map online) and a sorted dendre

A dendrogram of a spectr of key physical properties surfaces, such as radius (k).

(L). The volumes can have any shape, the significance of the especially elongated features (Fig. 2a). The luminosity is an approximate proxy for mass, that  $M_{\text{lum}} = X_{13\text{CO}} L_{13\text{CO}}$ , where  $X_{13\text{CO}} = 8.0 \times 10^{20} \text{ cm}^2 \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ (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 selfgravity is significant. As  $\alpha_{obs}$  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 fields16, its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

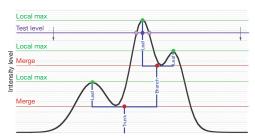


Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in 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, Nature, cf: Fluke et al. 2009 Vol 457 | 1 January 2009 | doi:10.1038/nature07609

nature

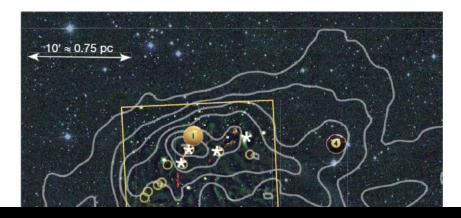
LETTERS

## A role for self-gravity at multiple length scales in the process of star formation

Alyssa A. Goodman<sup>1,2</sup>, Erik W. Rosolowsky<sup>2,3</sup>, Michelle A. Borkin<sup>1</sup>†, Jonathan B. Foster<sup>2</sup>, Michael Halle<sup>1,4</sup>, Jens Kauffmann<sup>1,2</sup> & Jaime E. Pineda<sup>2</sup>

Self-gravity plays a decisive role in the final stages of star formation, where dense cores (size ~0.1 parsecs) inside molecular clouds collapse to form star-plus-disk systems<sup>1</sup>. But self-gravity's role at earlier times (and on larger length scales, such as ~1 parsec) is unclear; some molecular cloud simulations that do not include self-gravity suggest that 'turbulent fragmentation' alone is sufficient to create a mass distribution of dense cores that resembles, and sets, the stellar initial mass function2. Here we report a 'dendrogram' (hierarchical tree-diagram) analysis that reveals that self-gravity plays a significant role over the full range of possible scales traced by <sup>13</sup>CO observations in the L1448 molecular cloud, but not everywhere in the observed region. In particular, more than 90 per cent of the compact 'pre-stellar cores' traced by peaks of dust emission<sup>3</sup> are projected on the sky within one of the dendrogram's self-gravitating 'leaves'. As these peaks mark the locations of already-forming stars, or of those probably about to form, a self-gravitating cocoon seems a critical condition for their exist.

overlapping features as an option, significant emission found between prominent clumps is typically either appended to the nearest clump or turned into a small, usually 'pathological', feature needed to encompass all the emission being modelled. When applied to molecular-line





FEATURED ARTICLES

ABOUT

PLANS

BLOG

FEEDB/



© Settings P Fork ☑ Quickedit

Word Count

42 Comment



B 0

SH1

#### The "Paper" of the Future

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 X Re-arrange authors

A 5-minute video demonsration of this paper is available at this YouTube link.

03

#### 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.

### Cognition Paper of the Future

Konrad Hinsen 3 days ago · Public

Many good suggestions, but if the goal is "long-lasting rich records of scientific discourse", a more careful and critical attitude towards electronic artifacts is appropriate. I do see it concerning videos, but not a word on the much more critical situation in software. Archiving source code is not sufficient: all the dependencies, plus the complete build environment, would have to be conserved as well to make things work a few years from now. An "executable figure" in the form of an IPython notebook wil...

#### Merce Crosas 3 days ago · Public

Konrad, good points; this has been a concern for the community working on reproducibility. Regarding data repositories, Dataverse handles long-term preservation and access of data files in the following way: 1) for some data files that the repository recognizes (such as R Data, SPSS, STATA), which depend on a statistical package, the system converts them into a preservation format (such as a tab/CSV format). Even though the original format is also saved and can be accessed, the new preservation format gua...

more

#### Konrad Hinsen 1 day ago · Public

That sounds good. I hope more repositories will follow the example of Dataverse. Figshare in particular has a very different attitude, encouraging researchers to deposit as much as possible. That's perhaps a good strategy to change habits, but in the long run it could well backfire when people find out in a few years that 90% of those deposits have become useless.

Christine L. Borgman 4 months ago · Private

"publications"

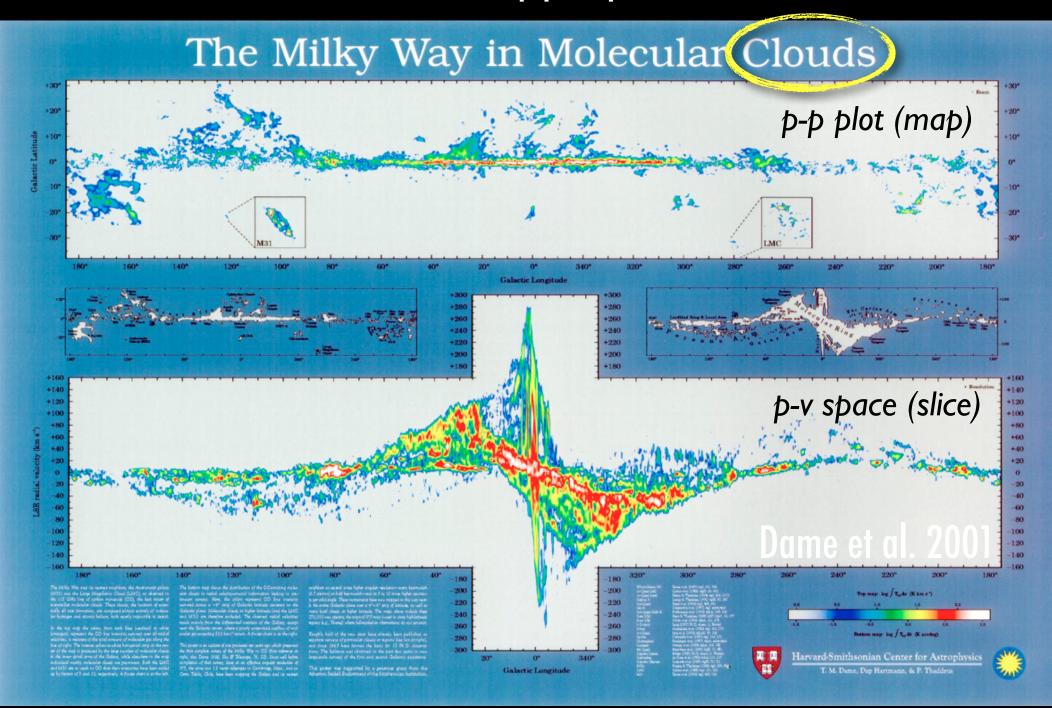


Ē

7()15

(you may have missed this Monday)

## Molecular Gas & the most famous "p-p-v" poster ever



### Molecular Gas "Clouds"

### Rice et al. 2016

video: Matt Pasquini



#### warning: velocity-distance conversions in this movie make assumptions that are accident-prone

THE ASTROPHYSICAL JOURNAL, 822:52 (27pp), 2016 May 1 © 2016. The American Astronomical Society. All rights reserved.

doi:10.3847/0004-637X/822/1/52



#### A UNIFORM CATALOG OF MOLECULAR CLOUDS IN THE MILKY WAY

THOMAS S. RICE<sup>1</sup>, ALYSSA A. GOODMAN<sup>2</sup>, EDWIN A. BERGIN<sup>1</sup>, CHRISTOPHER BEAUMONT<sup>3</sup>, AND T. M. DAME<sup>2</sup>

Department of Astronomy, University of Michigan, 311 West Hall, 1085 South University Avenue, Ann Arbor, MI 48109, USA; tsrice@umich.edu

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Counsyl, 180 Kimball Way, South San Francisco, CA 94080, USA

Received 2015 July 14; accepted 2016 February 4: published 2016 May 3

#### ABSTRACT

The all-Galaxy CO survey of Dame et al. is by far the most uniform, large-scale Galactic CO survey. Using a dendrogram-based decomposition of this survey, we present a catalog of 1064 massive molecular clouds throughout the Galactic plane. This catalog contains  $2.5 \times 10^8$  solar masses, or  $25^{+10.7}_{-5.8}\%$  of the Milky Way's estimated  $H_2$  mass. We track clouds in some spiral arms through multiple quadrants. The power index of Larson's first law, the size-linewidth relation, is consistent with 0.5 in all regions—possibly due to an observational bias—but clouds in the inner Galaxy systematically have significantly (~30%) higher linewidths at a given size, indicating that their linewidths are set in part by the Galactic environment. The mass functions of clouds in the inner Galaxy versus the outer Galaxy are both qualitatively and quantitatively distinct. The inner Galaxy mass spectrum is best described by a truncated power law with a power index of  $\gamma = -1.6 \pm 0.1$  and an upper truncation mass of  $M_0 = (1.0 \pm 0.2) \times 10^7 M_{\odot}$ , while the outer Galaxy mass spectrum is better described by a non-truncating power law with  $\gamma = -2.2 \pm 0.1$  and an upper mass of  $M_0 = (1.5 \pm 0.5) \times 10^6 M_{\odot}$ , indicating that the inner Galaxy is able to form and host substantially more massive GMCs than the outer Galaxy. Additionally, we have simulated how the Milky Way would appear in CO from extragalactic perspectives, for comparison with CO maps of other galaxies.

Key words: Galaxy: general - ISM: clouds - ISM: molecules

Supporting material: machine-readable table

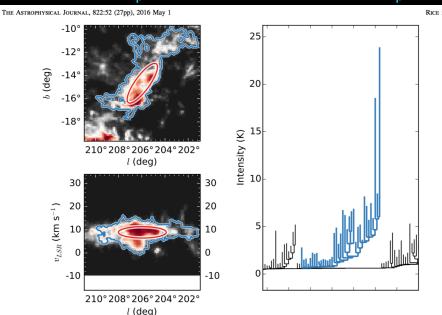


Figure 2. Example dendrogram extraction of Orion B: a nearby, well-studied giant molecular cloud. Top left: (l, b) thumbnail of the cloud and its neighboring region as seen on the sky. Bottom left: (l, v) thumbnail of the same region. Right: dendrogram cutout, with Orion B's structures highlighted in blue. The pixels corresponding to the highlighted dendrogram structures are outlined in the blue contour (in projection); a representative ellipse is drawn in red, with semimajor axis length equal to the second moment along each relevant dimension (as calculated in Section 2.2). Data come from DHT Survey #27 (the Orion complex).

 $(\alpha, \beta, x, y, z) = (97.1^{\circ} - 177.0^{\circ} 700 \,\mathrm{pc} 69 \,\mathrm{pc} 70 \,\mathrm{pc})$ 

### "3D Dust Mapping" (now Pan Starrs, soon Gaia)

THE ASTROPHYSICAL JOURNAL, 810:25 (23pp), 2015 September 1

© 2015. The American Astronomical Society. All rights reserved.

doi:10.1088/0004-637X/810/1/25

#### A THREE-DIMENSIONAL MAP OF MILKY WAY DUST

GREGORY M. GREEN<sup>1</sup>, EDWARD F. SCHLAFLY<sup>2</sup>, DOUGLAS P. FINKBEINER<sup>1</sup>, HANS-WALTER RIX<sup>2</sup>, NICOLAS MARTIN<sup>2,3</sup>,
WILLIAM BURGETT<sup>4</sup>, PETER W. DRAPER<sup>5</sup>, HEATHER FLEWELLING<sup>6</sup>, KLAUS HODAPP<sup>6</sup>, NICHOLAS KAISER<sup>6</sup>, ROLF PETER KUDRITZKI<sup>6</sup>,

EUGENE MAGNIER<sup>6</sup>, NIGEL METCALFE<sup>5</sup>, PAUL PRICE<sup>7</sup>, JOHN TONRY<sup>6</sup>, AND RICHARD WAINSCOAT<sup>6</sup>

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA; ggreen@cfa.harvard.edu

Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Observatoire astronomique de Strasbourg, Université de Strasbourg, CNRS, UMR 7550, 11 rue de l'Université, F-67000 Strasbourg, France

GMTO Corporation, 251 S. Lake Ave., Suite 300, Pasadena, CA 91101, USA

Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK

Institute for Astronomy, University of Hawaii at Manoa, 2680 Woodlawn Dr., Honolulu, HI 96822, USA

Princeton University Observatory, 4 Ivy Lane, Peyton Hall, Princeton University, Princeton, NJ 08544, USA

Received 2015 February 24: accepted 2015 July 2: published 2015 August 26

Green, Schlafly, Finkbeiner, Rix et al. 2015

-30° -15° +0° +15° +30°

## GLUEING TOGETHER

## THE MILKY WAY

CO dendrogram

HII regions (recomb lines)

3D dust

masers (Bessel)

Stellar Positions
(Gaia)

with Catherine Zucker, Doug Finkbeiner, Tom Dame, Mark Reid, et al.



# GLUEING TOGETHER (SKELETON OF THE) THE MILKY WAY

CO dendrogram

HII regions (recomb lines)

3D dust



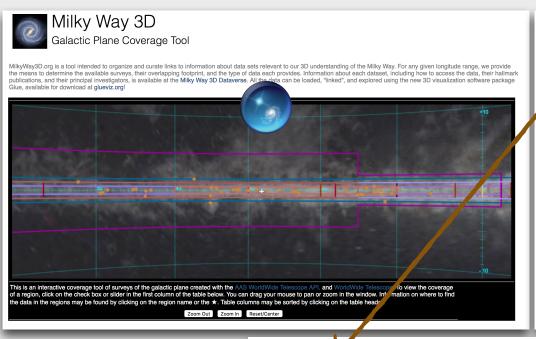
masers (Bessel)

Stellar Positions (Gaia)

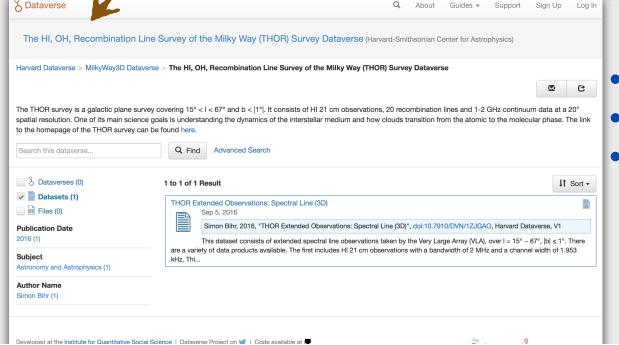
with Catherine Zucker, Doug Finkbeiner, Tom Dame, Mark Reid, et al.



## milkyway3d.org







- free & open
- online now
- contactC. Zucker toadd yoursurvey

# GLUEING TOGETHER (SKELETON OF THE) THE MILKY WAY

CO dendrogram

HII regions (recomb lines)

3D dust



masers (Bessel)

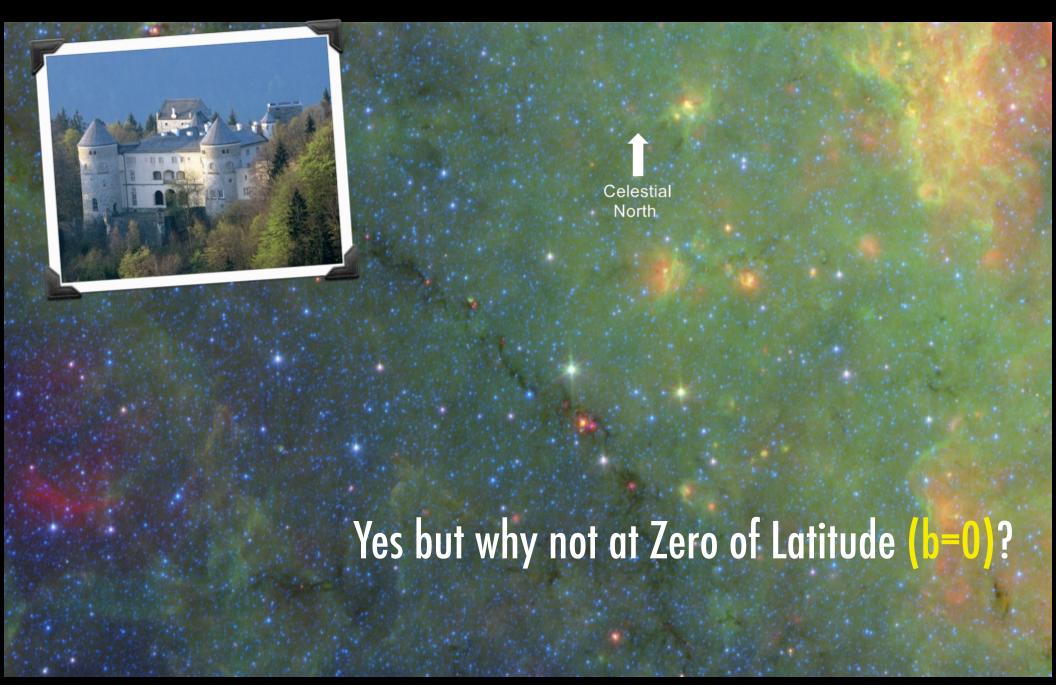
Stellar Positions (Gaia)

with Catherine Zucker, Doug Finkbeiner, Tom Dame, Mark Reid, et al.



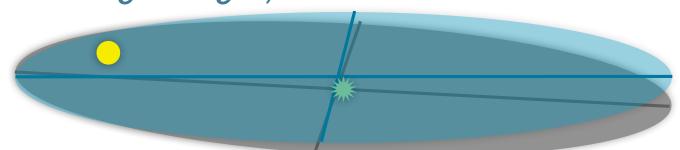
## "Is Nessie Parallel to the Galactic Plane?" -A. Burkert, 2012





## 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.

[Blaquw et al. 1959]

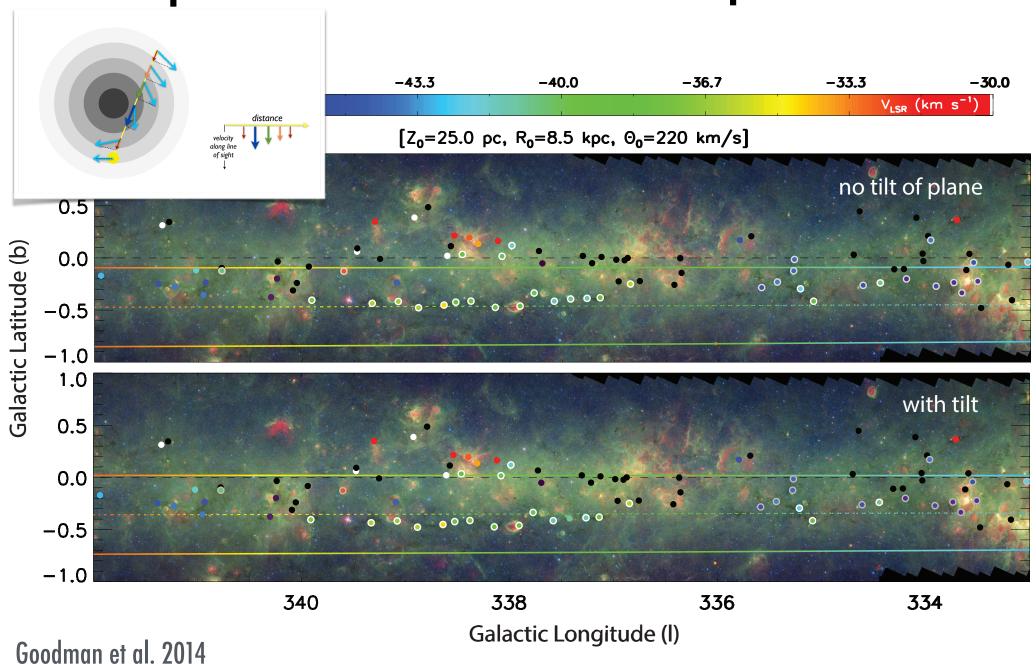
Sun is
~25 pc
"above" the
IAU Milky Way
Plane

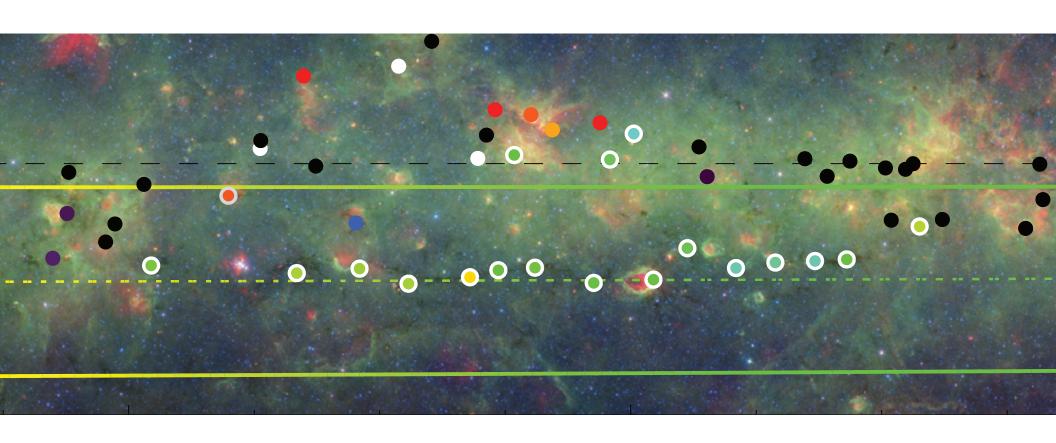
+

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

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

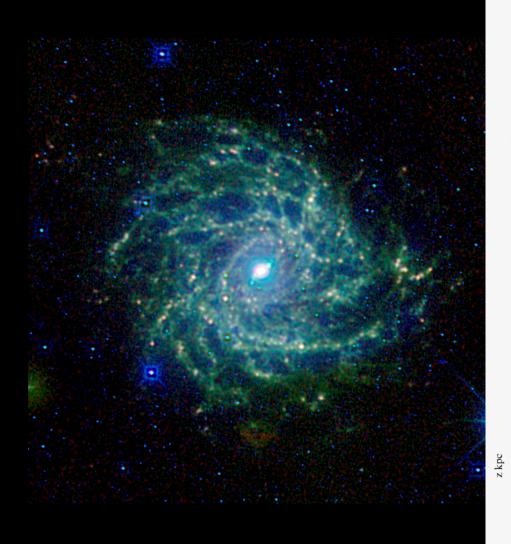
## In the plane! And at distance of spiral arm!



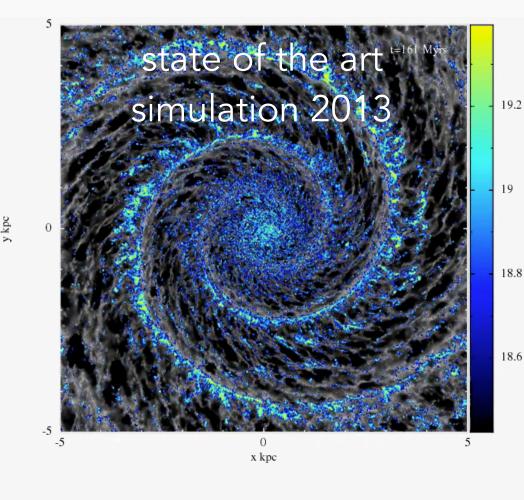


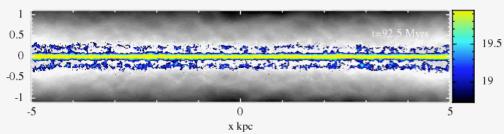
## ...eerily precisely...

## A full 3D skeleton?



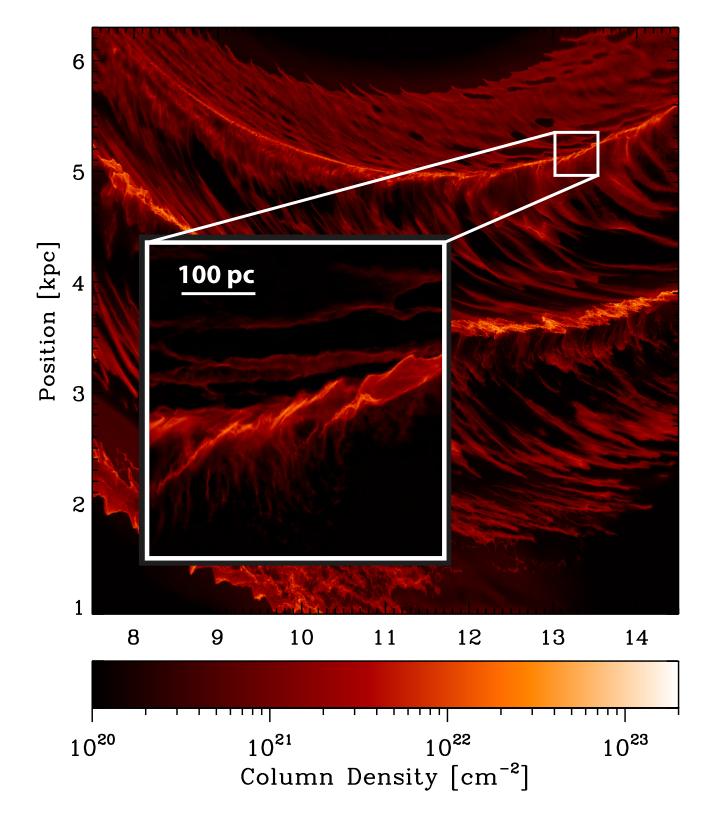
(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas

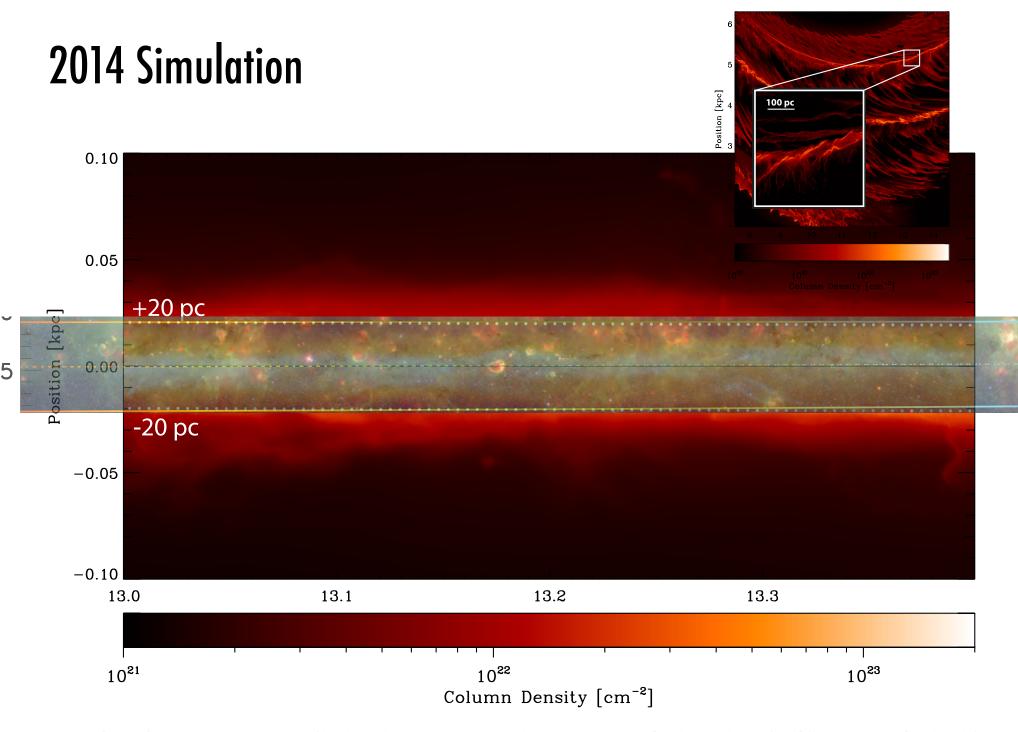




simulations courtesy Clare Dobbs

#### **2014 Simulation**





Smith et al. 2014, using AREPO (hydro+chemistry, imposed potential, no B-fields, no local (self-)gravity, no feedback)

#### THE BONES OF THE MILKY WAY

ALYSSA A. GOODMAN<sup>1</sup>, JOÃO ALVES<sup>2</sup>, CHRISTOPHER N. BEAUMONT<sup>1</sup>, ROBERT A. BENJAMIN<sup>3</sup>, MICHELLE A. BORKIN<sup>4</sup>, ANDREAS BURKERT<sup>5</sup>, THOMAS M. DAME<sup>6</sup>, JAMES JACKSON<sup>7</sup>, JENS KAUFFMANN<sup>8</sup>,

THOMAS ROBITAILLE<sup>9</sup>, AND ROWAN J. SMITH<sup>10</sup>

<sup>1</sup> Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

<sup>2</sup> University of Vienna, 1180 Vienna, Austria

<sup>3</sup> University of Wisconsin-Whitewater, Whitewater, WI 53190, USA

<sup>4</sup> Harvard University, Cambridge, MA 02138, USA

<sup>5</sup> University of Munich, Munich, Germany

<sup>6</sup> Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA

<sup>7</sup> Boston University, Boston, MA 02215, USA

<sup>8</sup> California Institute of Technology, Pasadena, CA 91125, USA

Max Planck Institute for Astronomy, Heidelberg, Germany
 Institut für Theoretische Astrophysik, Zentrum für Astronomie der Universiät Heidelberg, Heidelberg, Germany
 Received 2013 December 16; accepted 2014 July 30; published 2014 November 25

THE ASTROPHYSICAL JOURNAL, 815:23 (25pp), 2015 December 10 © 2015. The American Astronomical Society. All rights reserved.

doi:10.1088/0004-637X/815/1/23

#### THE SKELETON OF THE MILKY WAY

CATHERINE ZUCKER<sup>1,2</sup>, CARA BATTERSBY<sup>2</sup>, AND ALYSSA GOODMAN<sup>2</sup>

Astronomy Department, University of Virginia, Charlottesville, VA 22904, USA; catherine.zucker@cfa.harvard.edu

Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

Received 2015 June 27; accepted 2015 September 21; published 2015 December 3

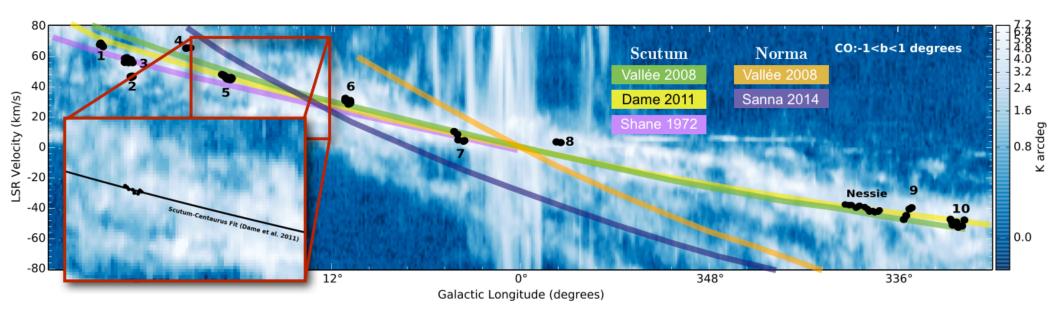
#### **ABSTRACT**

Recently, Goodman et al. argued that the very long, very thin infrared dark cloud "Nessie" lies directly in the Galactic midplane and runs along the Scutum–Centaurus Arm in position–position–velocity (p–p–v) space as traced by lower-density CO and higher-density NH<sub>3</sub> gas. Nessie was presented as the first "bone" of the Milky Way, an extraordinarily long, thin, high-contrast filament that can be used to map our Galaxy's "skeleton." Here we present evidence for additional bones in the Milky Way, arguing that Nessie is not a curiosity but one of several filaments that could potentially trace Galactic structure. Our 10 bone candidates are all long, filamentary, mid-infrared extinction features that lie parallel to, and no more than 20 pc from, the physical Galactic mid-plane. We use CO, N<sub>2</sub>H<sup>+</sup>, HCO<sup>+</sup>, and NH<sub>3</sub> radial velocity data to establish the three-dimensional location of the candidates in p–p–v space. Of the 10 candidates, 6 also have a projected aspect ratio of  $\geq$ 50:1; run along, or extremely close to, the Scutum–Centaurus Arm in p–p–v space; and exhibit no abrupt shifts in velocity. The evidence presented here suggests that these candidates mark the locations of significant spiral features, with the bone called filament 5 ("BC\_18.88-0.09") being a close analog to Nessie in the northern sky. As molecular spectral-line and extinction maps cover more of the sky at increasing resolution and sensitivity, it should be possible to find more bones in future studies.

Key words: Galaxy: kinematics and dynamics - Galaxy: structure - ISM: clouds

# 6 OUT OF 10 WWT-IDENTIFIED BONE CANDIDATES TURN OUT TO BE EXCELLENT IN "3D"

(POSITON-POSITION-VELOCITY SPACE)



#### PHYSICAL PROPERTIES OF LARGE-SCALE GALACTIC FILAMENTS

CATHERINE ZUCKER, CARA BATTERSBY, ALYSSA GOODMAN<sup>1</sup>

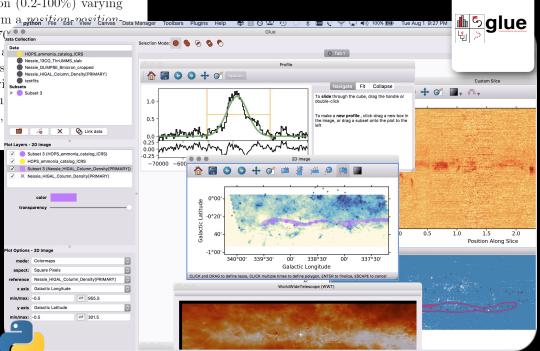
<sup>1</sup>Harvard-Smithsonian Center for Astrophysics

#### Abstract

The characterization of our Galaxy's longest filamentary gas features has been the subject of a number of studies in recent years, producing not only a sizeable sample of large-scale filaments, but also confusion as to whether all these features (e.g. "Bones", "Giant Molecular Filaments") are essentially the same. They are not. We undertake the first standardized analysis of the physical properties (densities, temperatures, morphologies, radial profiles) and kinematics of large-scale filaments in the literature. We expand and improve upon prior analyses by using the same data sets, techniques, and spiral arm models to disentangle the filaments' inherent properties from selection criteria and methodology. Our results suggest that the myriad filament finding techniques are uncovering different physical structures, with quantities length (10-268 pc), width (1-40 pc), mass  $(3 \times 10^3 \text{ M}_{\odot} - 1.1 \times 10^6 \text{ M}_{\odot})$ , aspect ratio (3:1 - 104:1), and dense gas fraction (0.2-100%) varying

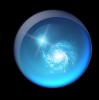
by at least an order of magnitude across the sample of 45 filaments. We perform a process of the filaments and find that while 60%-70 the filaments and find that while 60%-70 the Galaxy, only 30-45% also exhibit kinematic proximity to purported spiral space defined by aspect ratio, temperature, and density, we broadly distinguis egories, which could be indicative of different formation mechanisms or histori "Bone-like" filaments show the most potential for tracing gross spiral structu other categories could simply be large concentrations of molecular gas (GMCs,

# 2017 "The Bone Wars" (& glue)



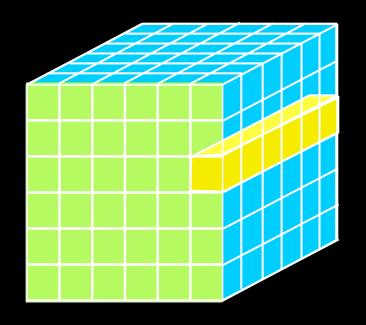
I missed Monday's talk...what did you say?

I'm a particle physicist...what's a "galactic plane"? What's a "rotation curve"? How do you measure all this stuff? Why should I care?





I'm an astronomer...and I only care a little about the Galaxy— can I just see more on that cool software you showed too briefly on Monday?



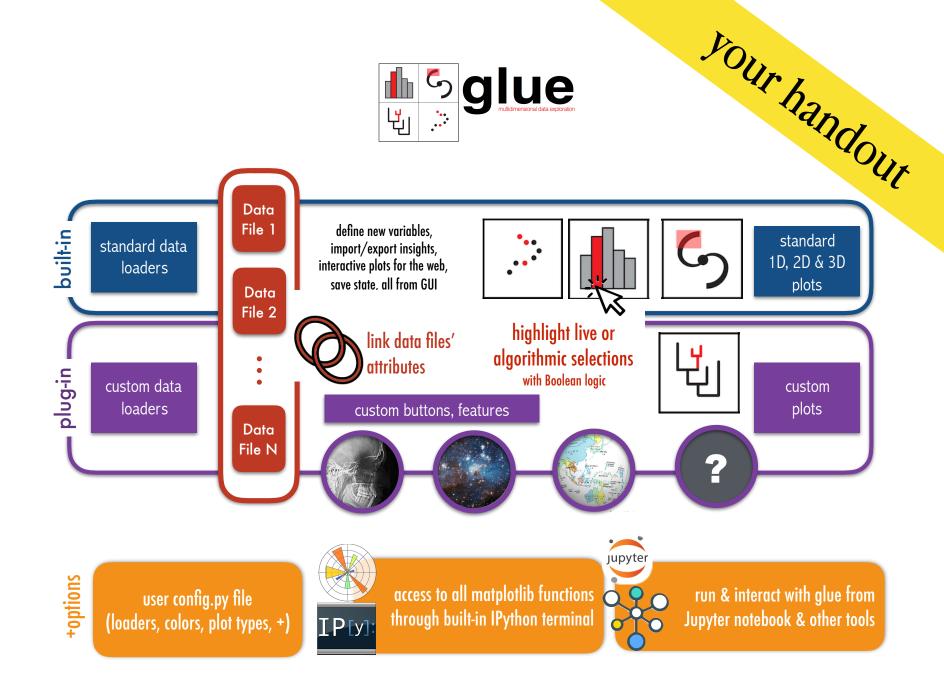
### DATA-DIMENSIONS-DISPLAY

D: Columns = "Spectra", "SEDs" or "Time Series" (x-y Graphs)

**2D**: Faces or Slices = "Images"

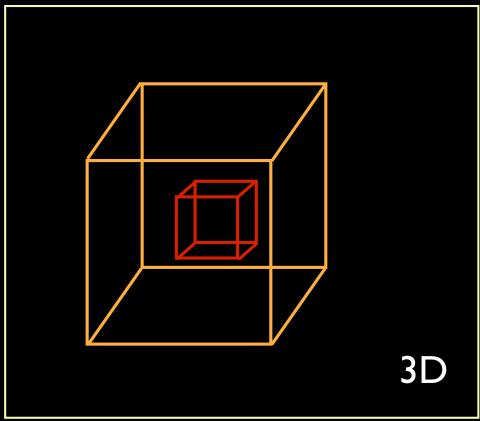
3D: Volumes = "3D Renderings", "2D Movies"

**4D**: Time Series of Volumes = "3D Movies"

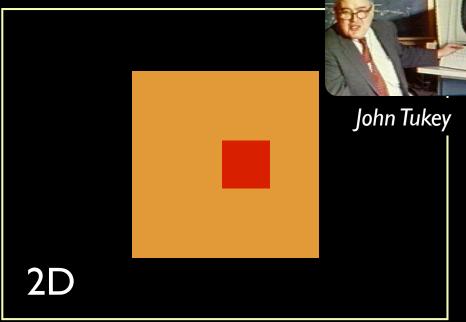


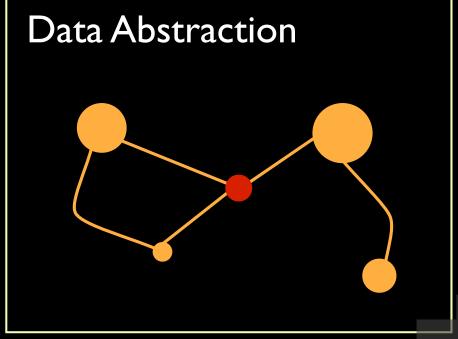
glueviz.org

#### LINKED VIEWS OF HIGH-DIMENSIONAL DATA

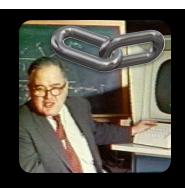




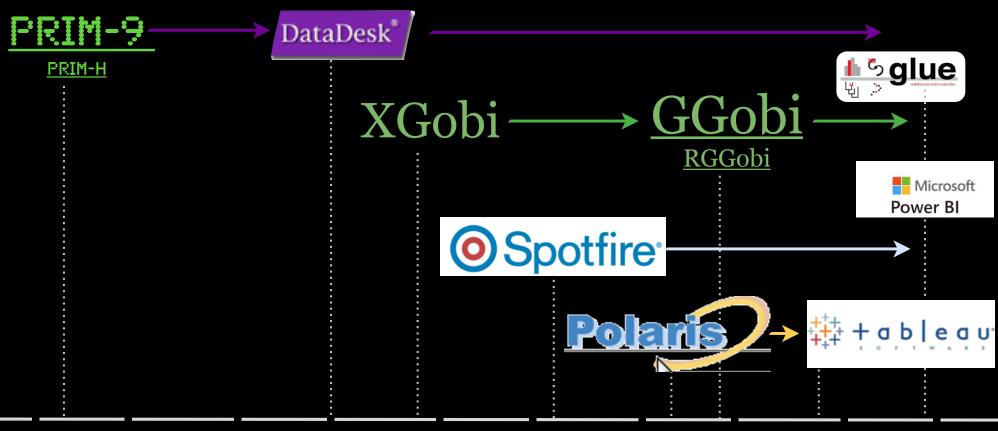




## JOHN TUKEY'S LEGACY





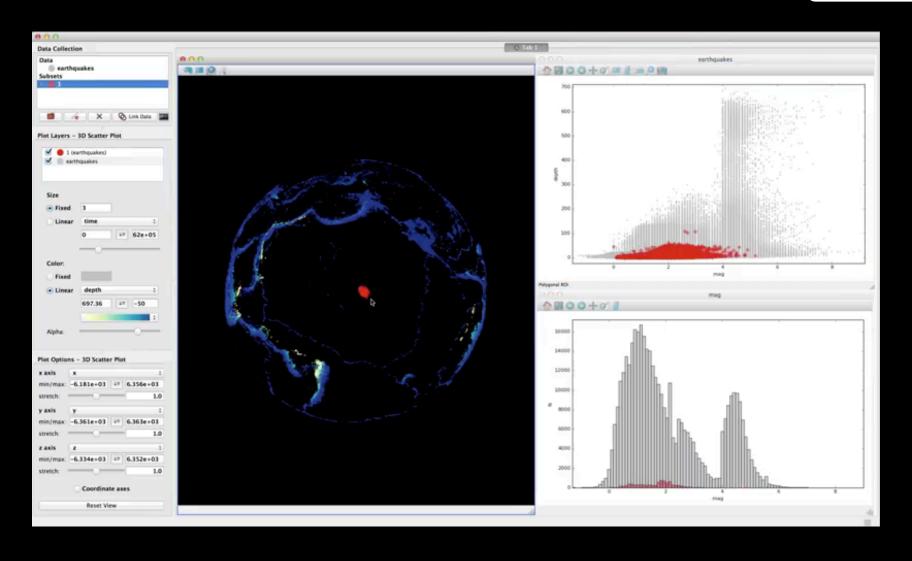


1970 1980 1990 2000

2010

# LINKED VIEWS OF HIGH-DIMENSIONAL DATA (IN PYTHON) GLUE



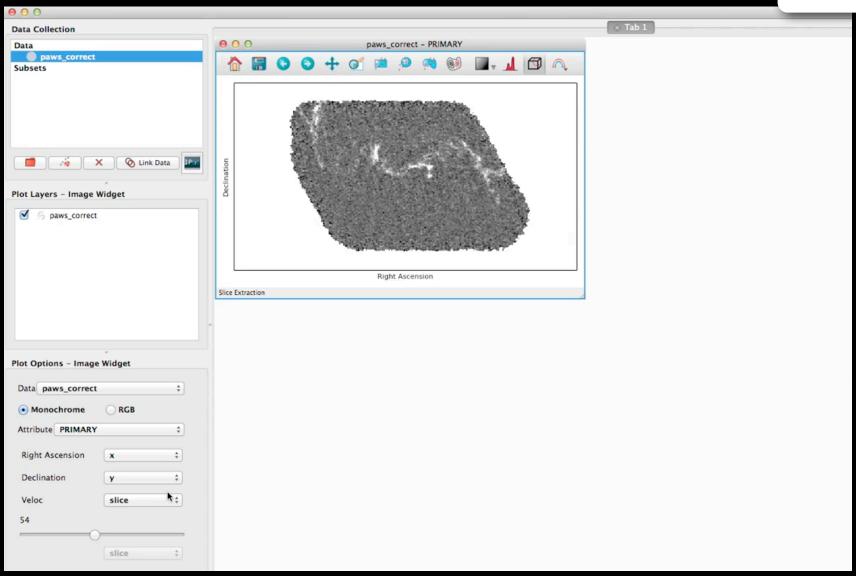


video by Tom Robitaille, lead glue developer glue created by: C. Beaumont, M. Borkin, P. Qian, T. Robitaille, and A. Goodman, Pl

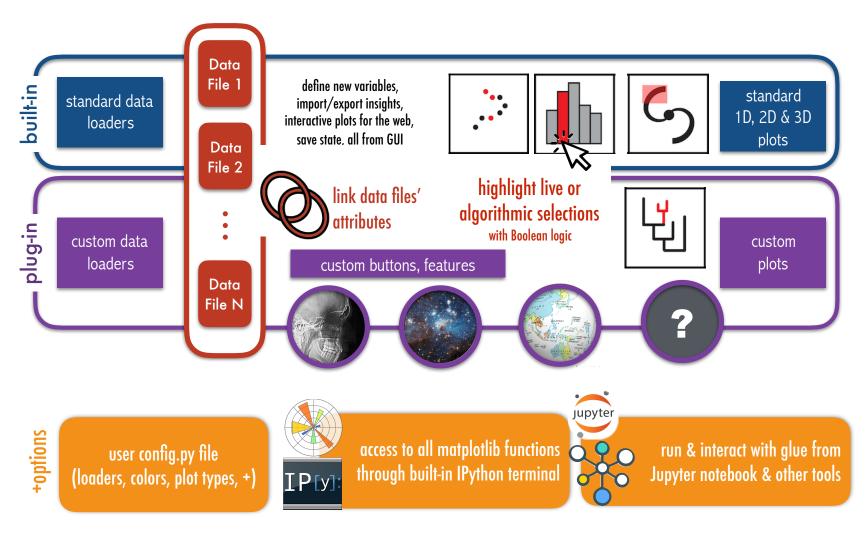
#### LINKED VIEWS OF HIGH-DIMENSIONAL DATA (IN PYTHON)

## GLUE



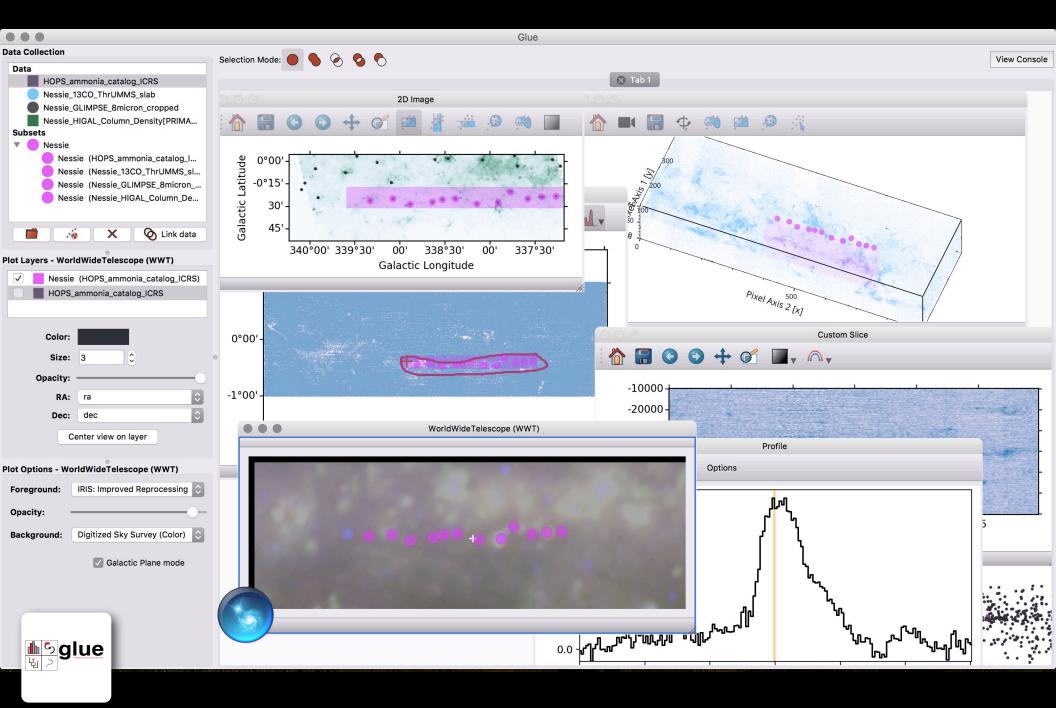






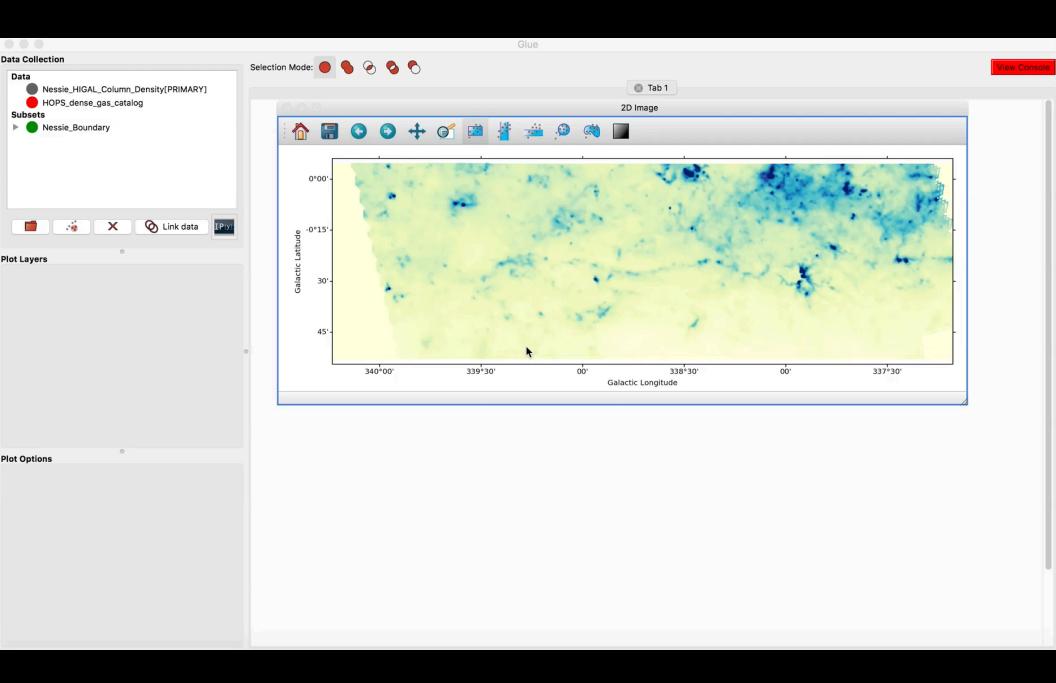
glueviz.org

#### NESSIE IN GLUE+WWT



## NESSIE IN GLUE+WWT







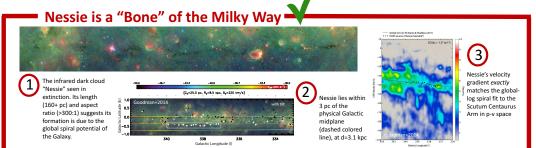
#### The Physical Properties of Large-Scale Galactic Filaments

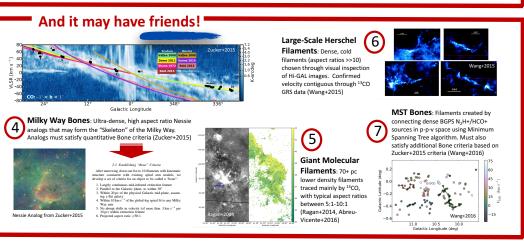


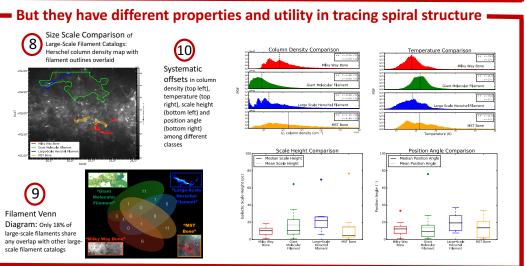
Catherine Zucker, Alyssa Goodman, Cara Battersby



Harvard-Smithsonian Center for As Tophysics



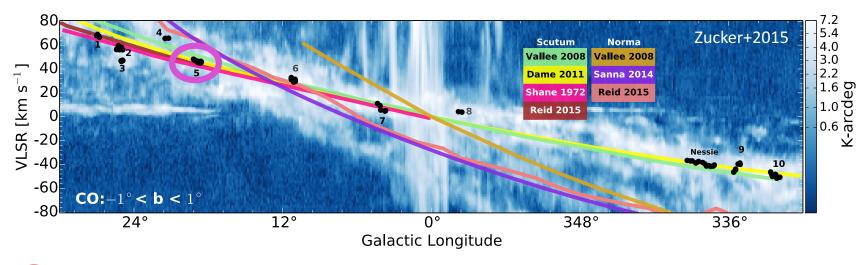




global spiral potential of the Galaxy.



#### And it may have friends!



Milky Way Bones: Ultra-dense, high aspect ratio Nessie analogs that may form the "Skeleton" of the Milky Way. Analogs must satisfy quantitative Bone criteria (Zucker+2015)

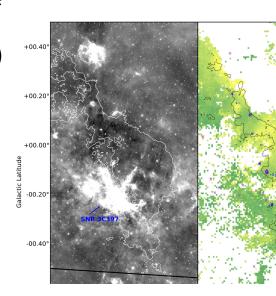




2.3. Establishing "Bone" Criteria

After narrowing down our list to 10 filaments with kinematic structure consistent with existing spiral arm models, we develop a set of criteria for an object to be called a "bone":

- 1. Largely continuous mid-infrared extinction feature
- 2. Parallel to the Galactic plane, to within 30°
- 3. Within 20 pc of the physical Galactic mid-plane, assuming a flat galaxy
- 4. Within 10 km s<sup>-1</sup> of the global-log spiral fit to any Milky Way arm

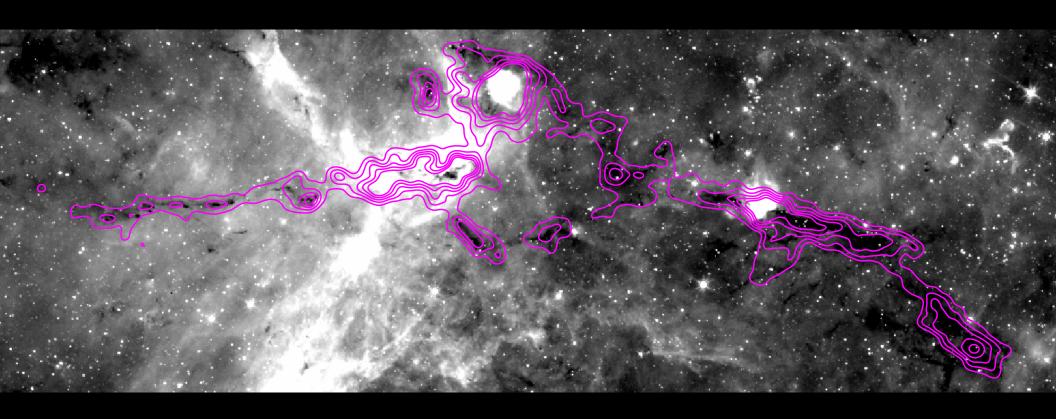


## FLAMENT 5"



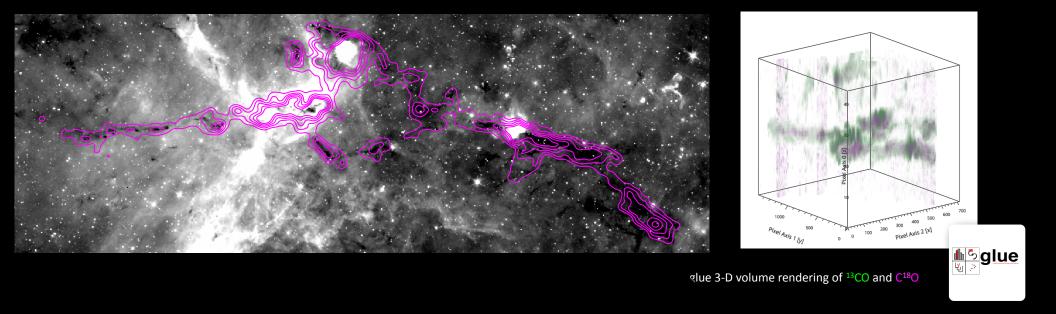
Battersby, Goodman, Zucker et al. in prep.

## "FILAMENT 5" WITH THE 30-M



Battersby, Goodman, Zucker et al. in prep.

## "FILAMENT 5" WITH THE 30-M



Battersby, Goodman, Zucker et al. in prep.



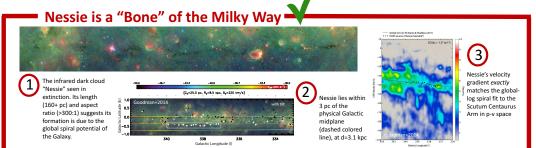
#### The Physical Properties of Large-Scale Galactic Filaments

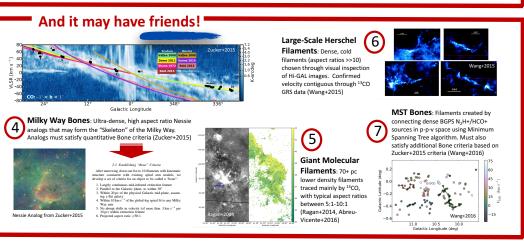


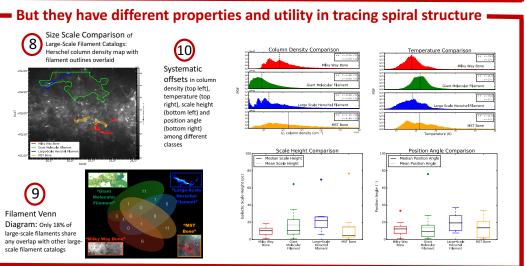
Catherine Zucker, Alyssa Goodman, Cara Battersby



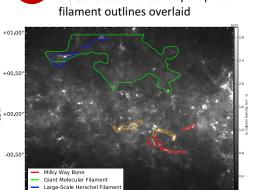
Harvard-Smithsonian Center for As Tophysics





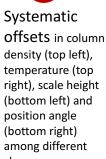


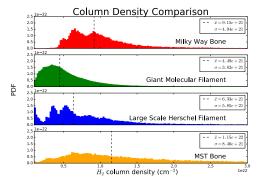
#### But they have different properties and utility in tracing spiral structure

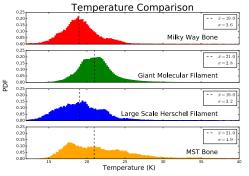


Size Scale Comparison of Large-Scale Filament Catalogs: Herschel column density map with

density (top left), classes



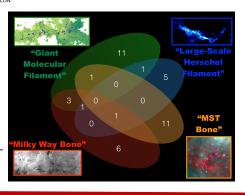


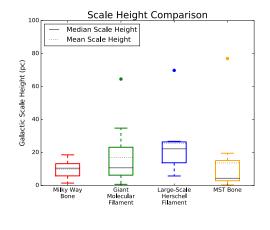


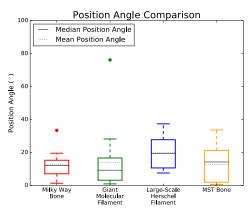


Filament Venn

Diagram: Only 18% of large-scale filaments share any overlap with other largescale filament catalogs

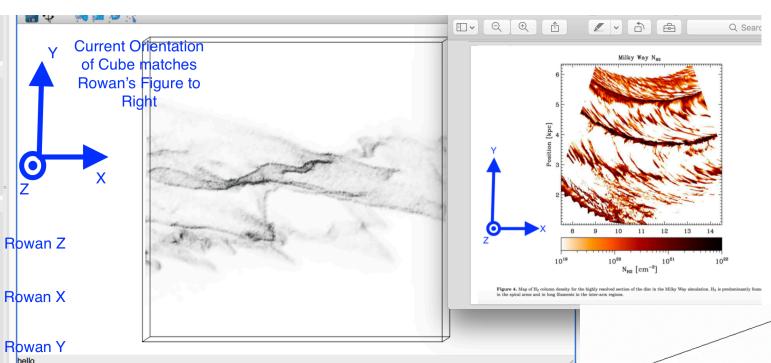






"Bones" tend to be closest to mid-plane, closest to "horizontal," coldest, and densest.

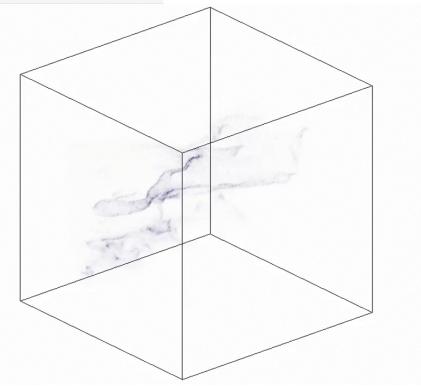
#### Next: What creates the Bones we observe?



<sup>5</sup> glue

brand new AREPO work...look for Zucker, Smith, Battersby, Goodman 2018

cf. simulation work by Moeckl & Burkert 2015, Duarte-Cabral & Dobbs 2016; + AREPO MHD simulation -ALMA polarimetry comparison from Hull et al. 2016, more...



# GLUEING TOGETHER THE SKELETON OF THE MILKY WAY

#### Alyssa A. Goodman **Harvard-Smithsonan Center for Astrophysics** Radcliffe Institute for Advanced Study @aagie





