glue-ing together the Universe

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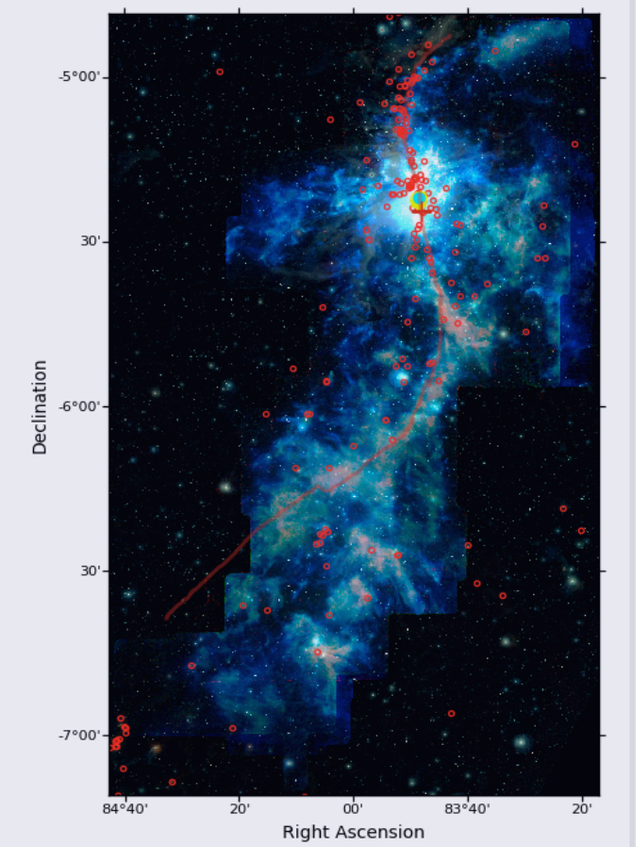
Tab 1 | Tab 3



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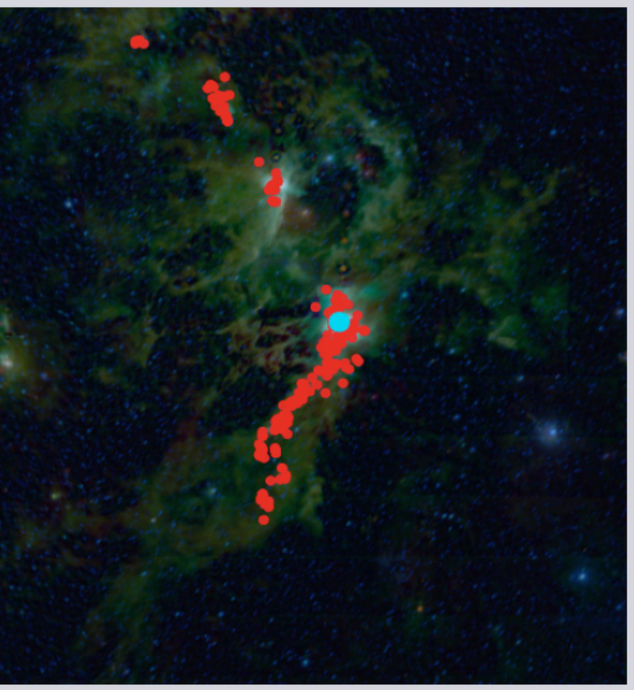
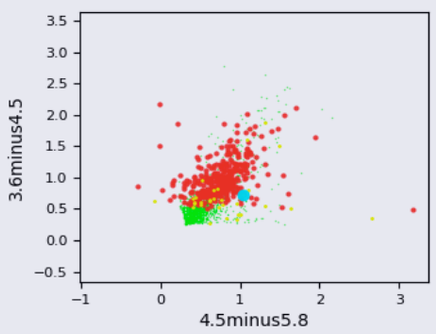


2D Scatter



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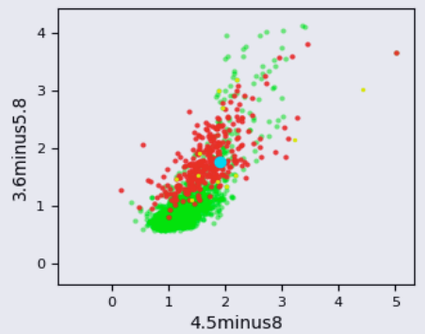

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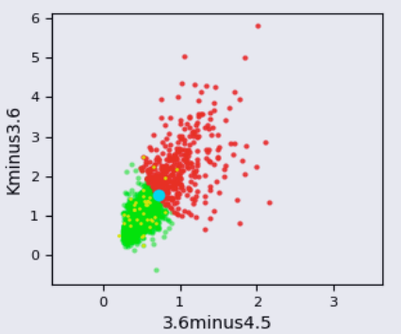

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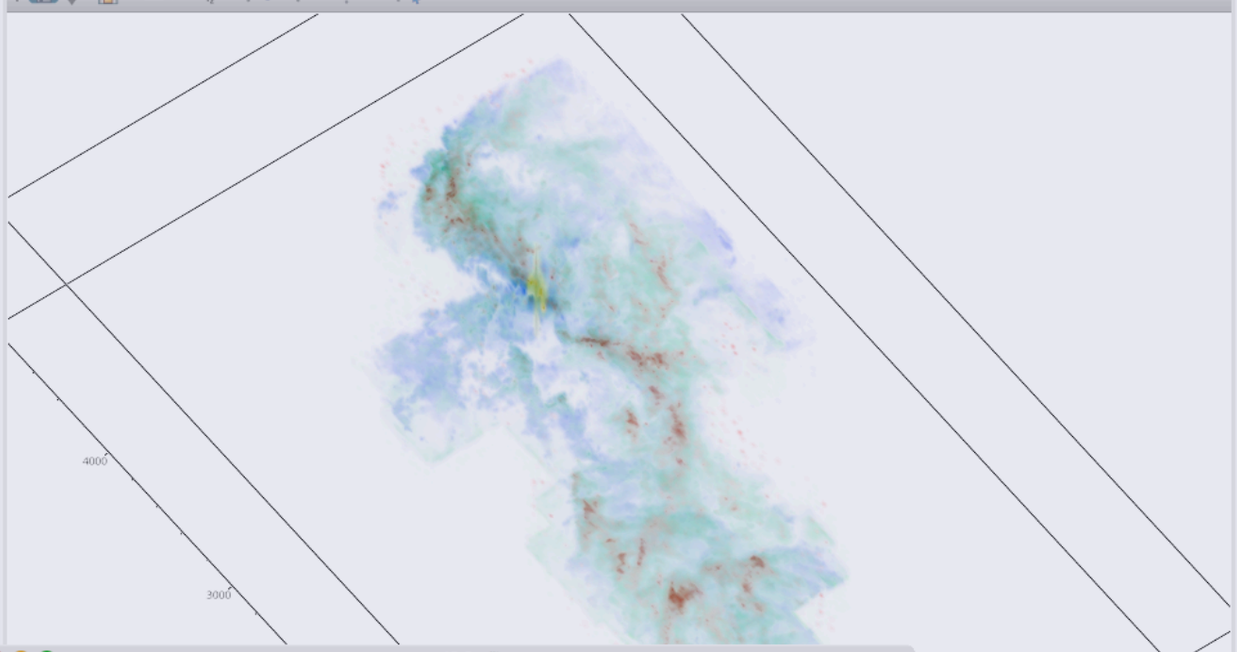

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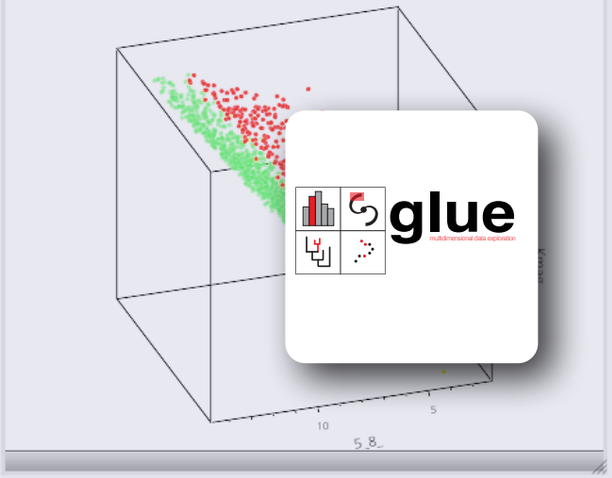
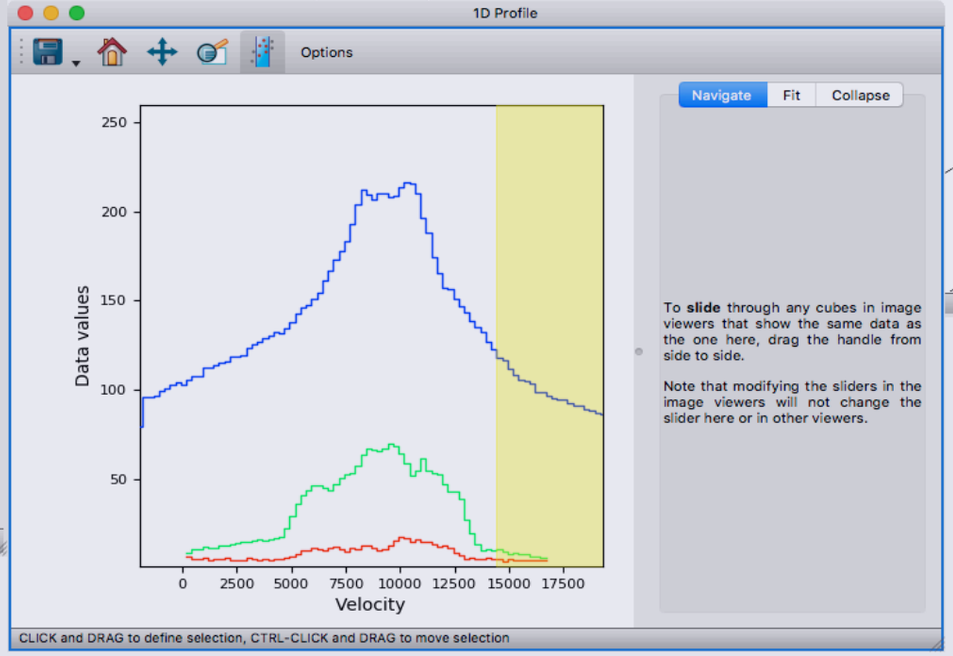


1D Profile

Options



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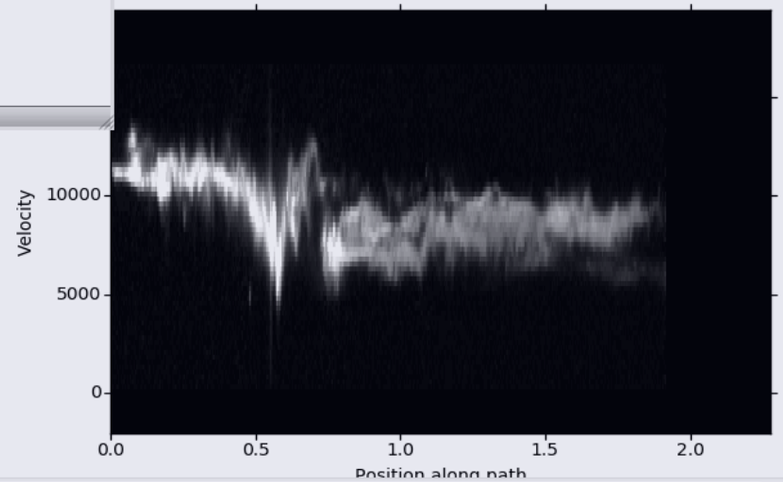
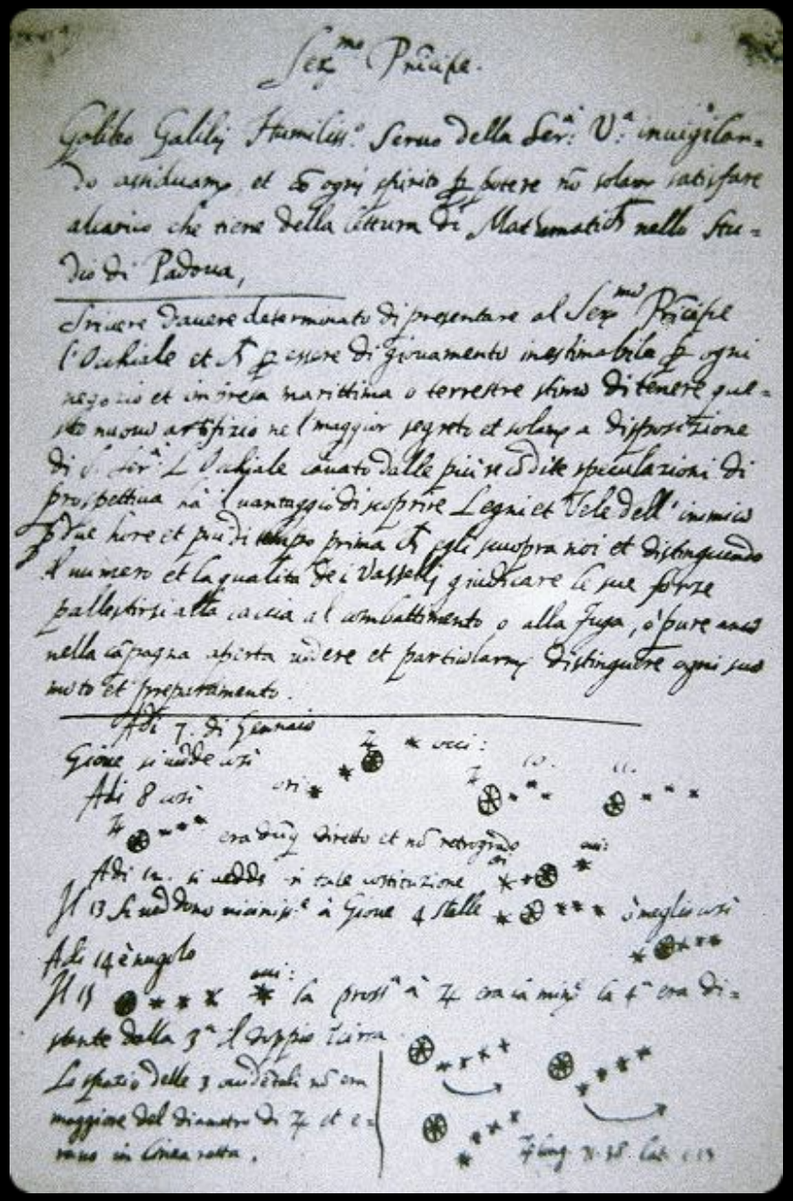


Galileo, Jupiter's Moons, "3D" thinking

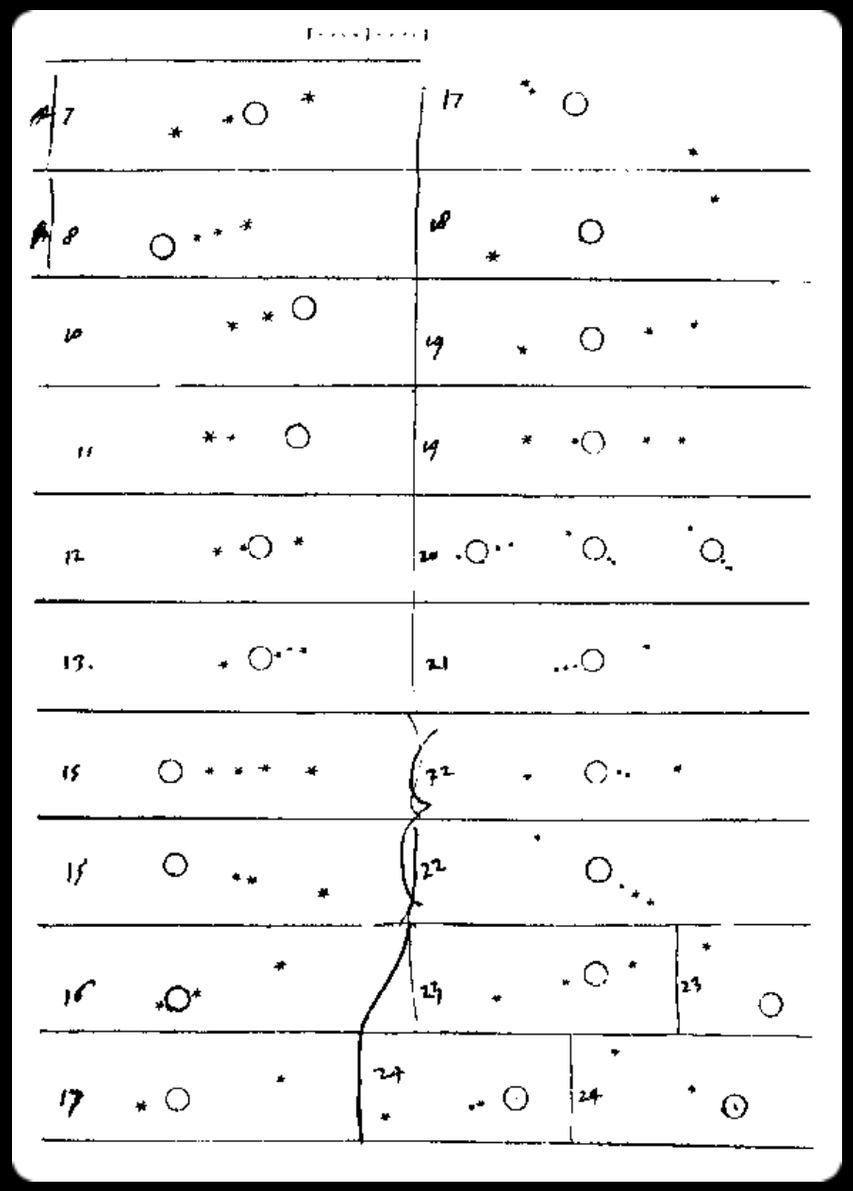


Sen^mo Prencipe.

Galileo Galilei Humilis.^mo Servo della Ser.^tà V.^a umigliss.^mo
Do ardisco, et da ogni spirito [illegible] devere nō solam.^te sodisfare
alcuno che versi della Letteratura di Mathematica nello Stu-
dio di Padova,

Sendo venuto determinato di presentare al Ser.^mo Prencipe
l'Archiale et N.^ro essere di giovamento inestimabile p.^r ogni
negotio et impresa marittima o terrestre stimo di tenerle qual-
che nuovo artificio nel maggior segretto et solam.^te a disposizione
di V.^ra A.^za Archiale cavato dalle più sottili speculazioni di
prospettiva con quantaggio di ispetrie Legni et Vele dell'inimici
p.^r due hore et più di tempo prima di quelli scuoprirli et distinguendo
il numero et la qualità de i Vasselli giudicare le sue forze
per potersi alla caccia al combattimento o alla fuga, o pure anco
nella campagna aperta vedere et particolarm.^te distinguere ogni sua
moto et preparamento.

Adi 7. di Genaro
Giove si vedde così
Adi 8 così
Adi 10. si vedde in tale costituzione
Il 13 fu nuovam.^te mirato à Giove 4 stelle disposte così
Adi 14 è retto
Il 15 la prossim.^a à ♃ era più picc.^la la 4.^a era di-
stante dalla 3.^a doppio spatio
Lo spatio delle 3 suddette nō era
maggiore del diametro di ♃ et e-
rano in linea retta.



On the third, at the seventh hour, the stars were arranged in this sequence. The eastern one was 1 minute, 30 seconds from Jupiter; the closest western one 2 minutes; and the other western one was

East * ○ * * West

10 minutes removed from this one. They were absolutely on the same straight line and of equal magnitude.

On the fourth, at the second hour, there were four stars around Jupiter, two to the east and two to the west, and arranged precisely

East * * ○ * * West

on a straight line, as in the adjoining figure. The easternmost was distant 3 minutes from the next one, while this one was 40 seconds from Jupiter; Jupiter was 4 minutes from the nearest western one, and this one 6 minutes from the westernmost one. Their magnitudes were nearly equal; the one closest to Jupiter appeared a little smaller than the rest. But at the seventh hour the eastern stars were only 30 seconds apart. Jupiter was 2 minutes from the nearer eastern

East ** ○ * * West

one, while he was 4 minutes from the next western one, and this one was 3 minutes from the westernmost one. They were all equal and extended on the same straight line along the ecliptic.

On the fifth, the sky was cloudy.

On the sixth, only two stars appeared flanking Jupiter, as is seen

East * ○ * West

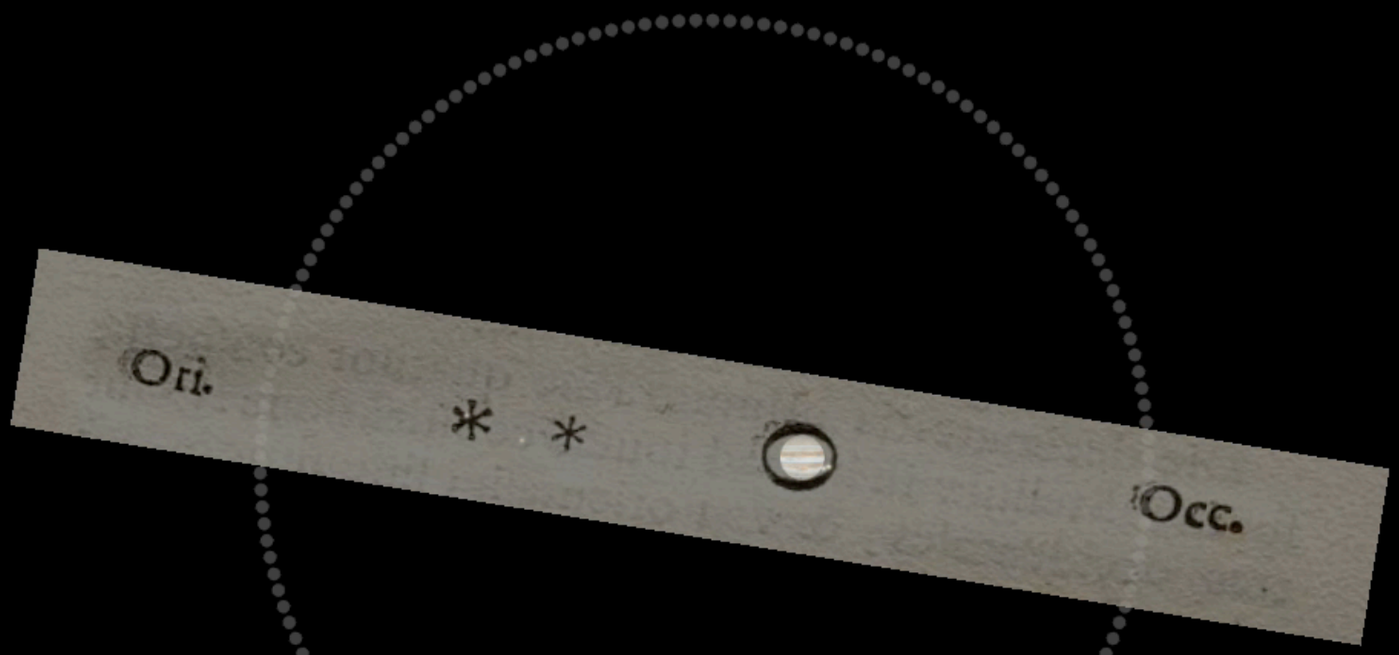
in the adjoining figure. The eastern one was 2 minutes and the western one 3 minutes from Jupiter. They were on the same straight line with Jupiter and equal in magnitude.

On the seventh, two stars stood near Jupiter, both to the east, arranged in this manner.

Notes for & re-productions of Siderius Nuncius

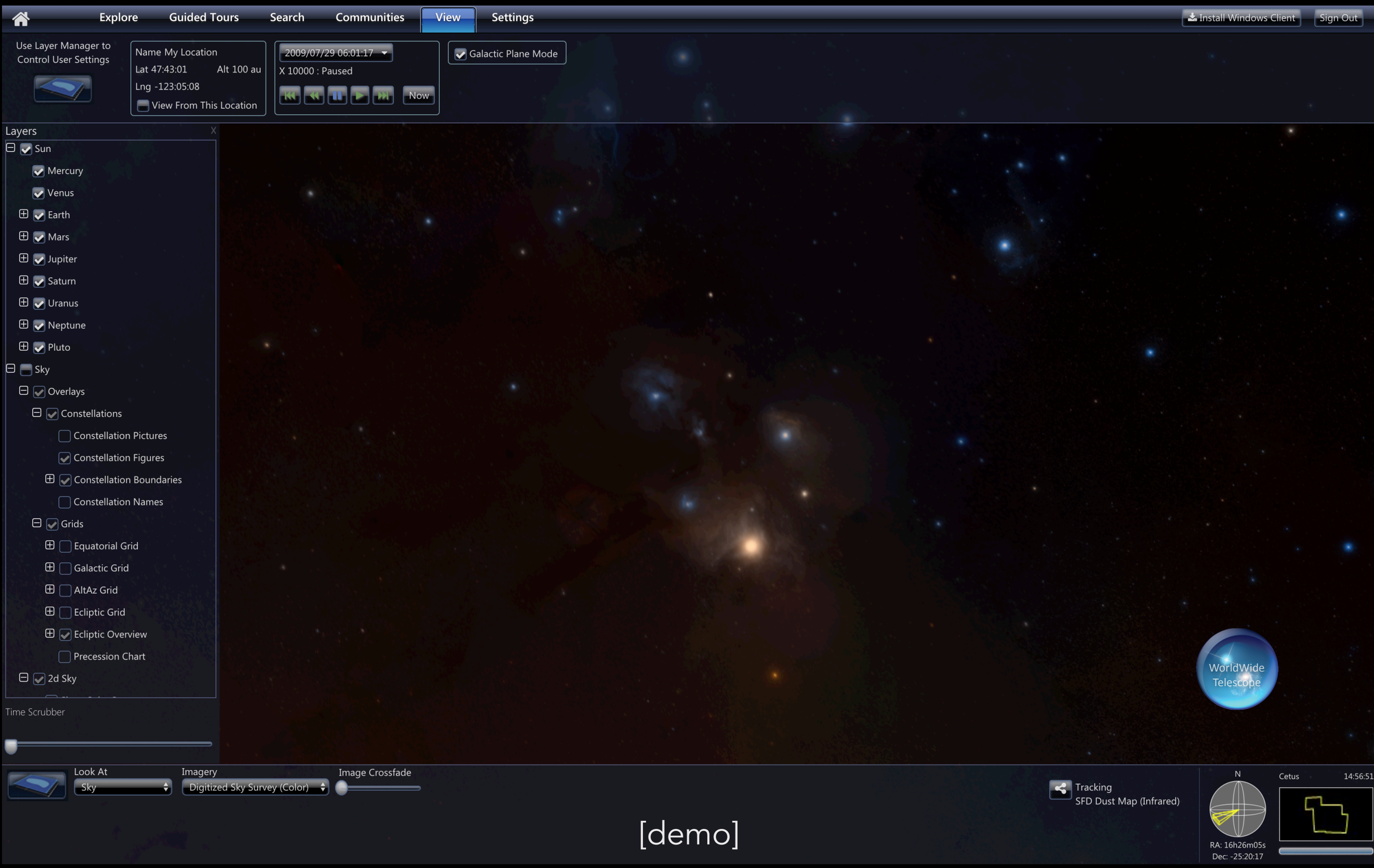
Galileo's 3D thinking, in WorldWide Telescope

January 11, 1610



Galileo's New Order, A WorldWide Telescope Tour by Goodman, Wong & Udomprasert 2010
WWT Software Wong (inventor, MS Research), Fay (architect, MS Research), et al., now open source, hosted by AAS
see wwtambassadors.org for more on WWT Outreach

The Sky at Many Wavelengths in a “WorldWide Telescope”



[demo]

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VIS 2018

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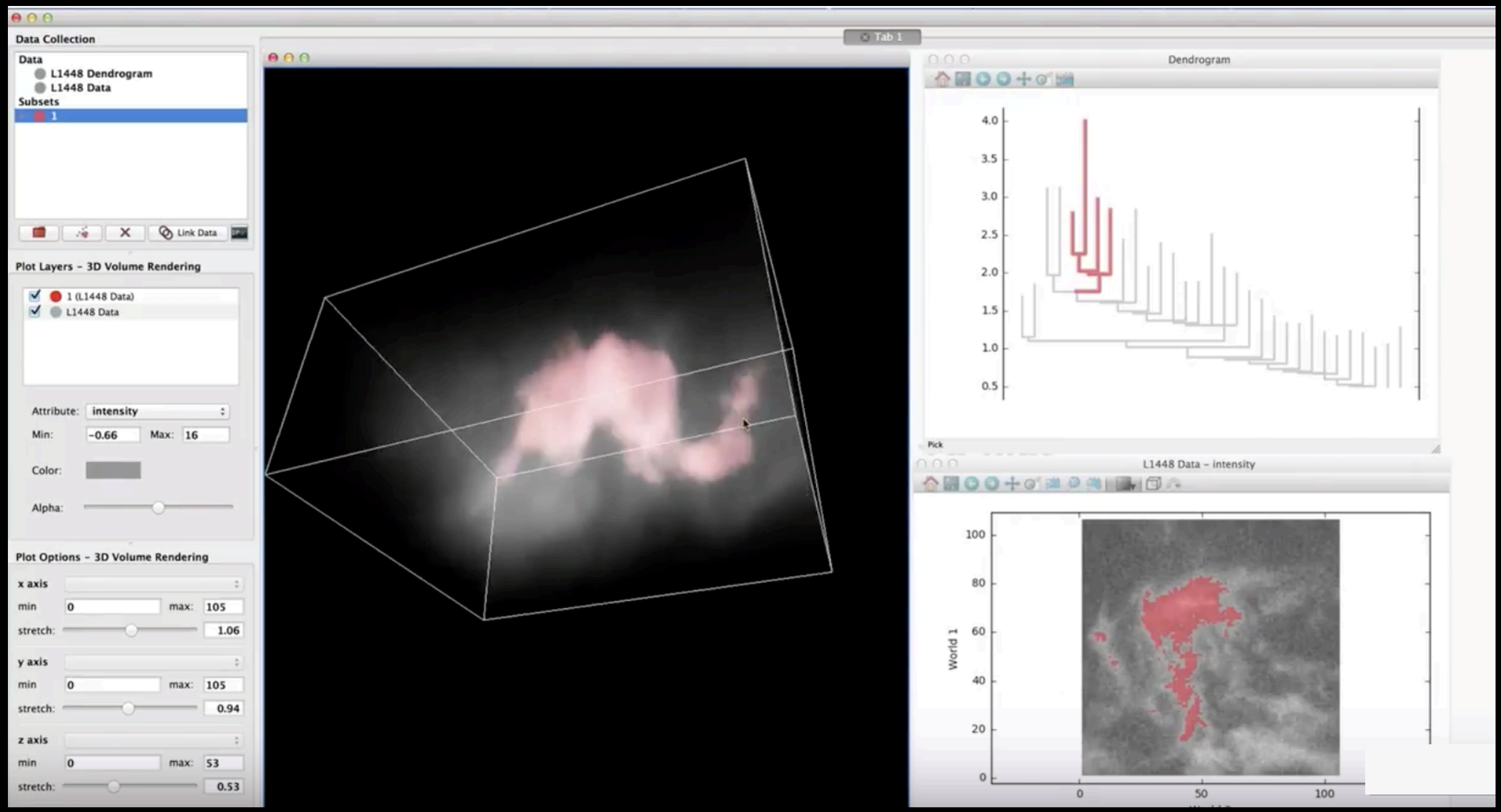

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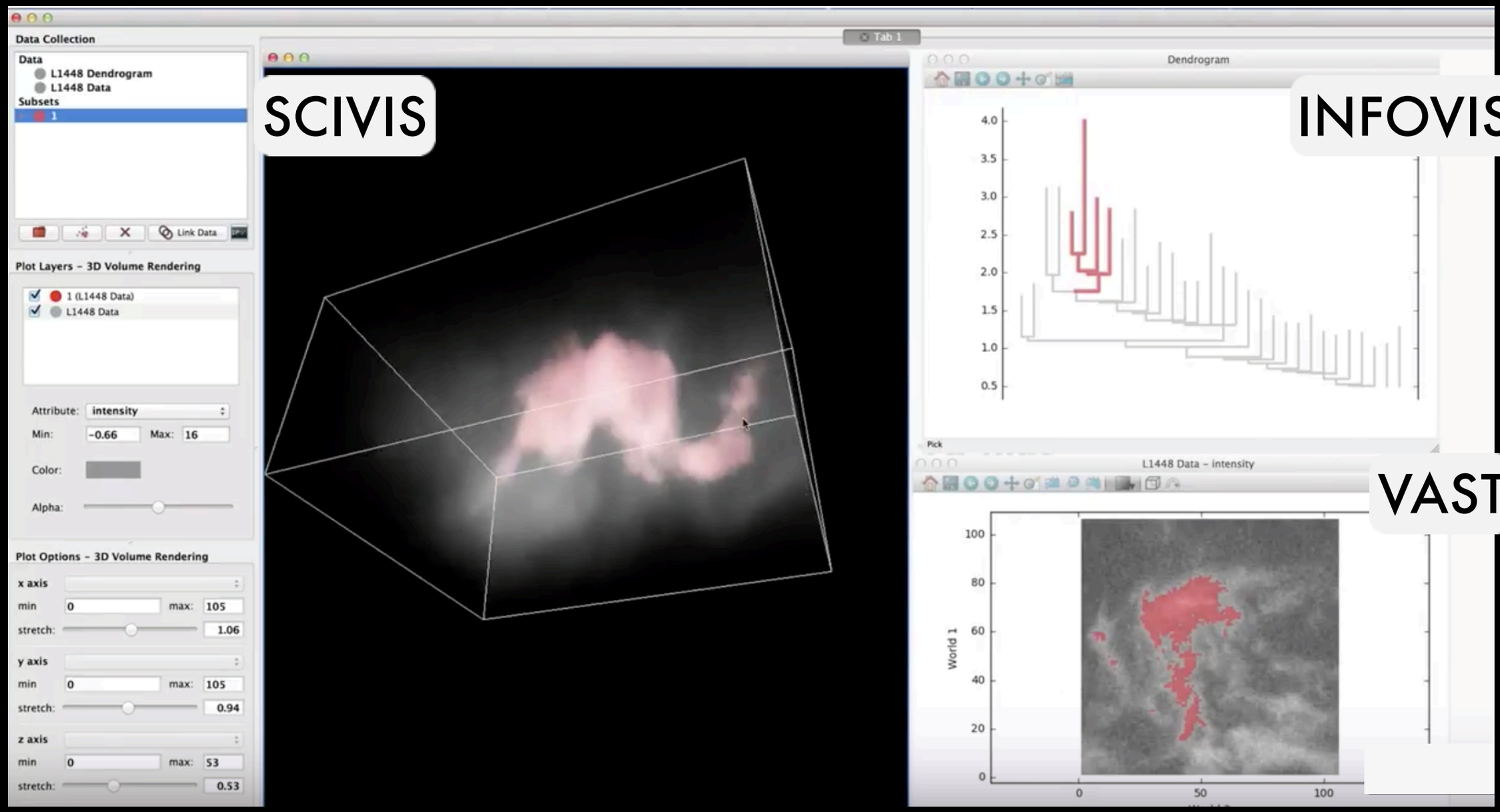

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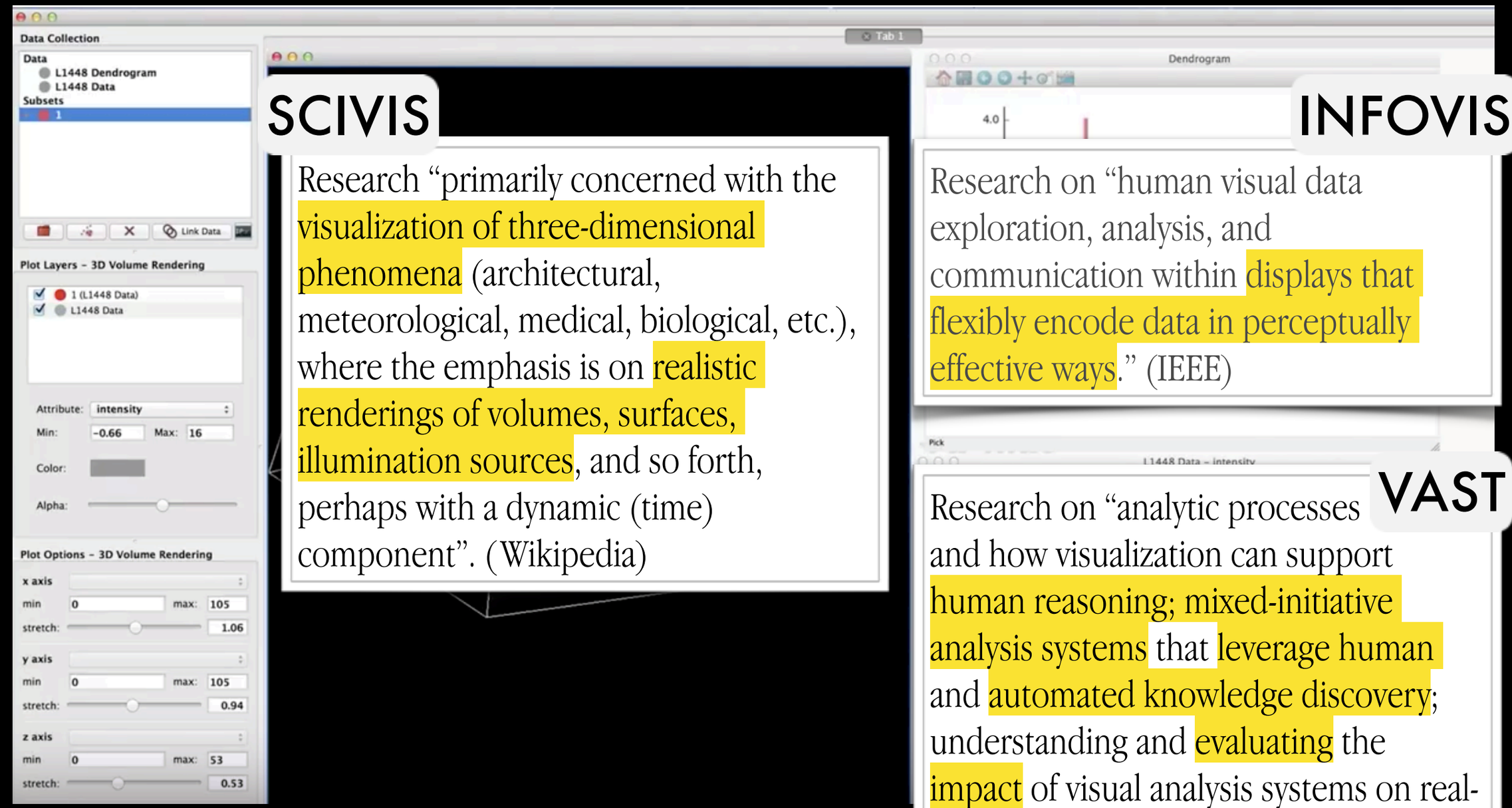


SCIVIS

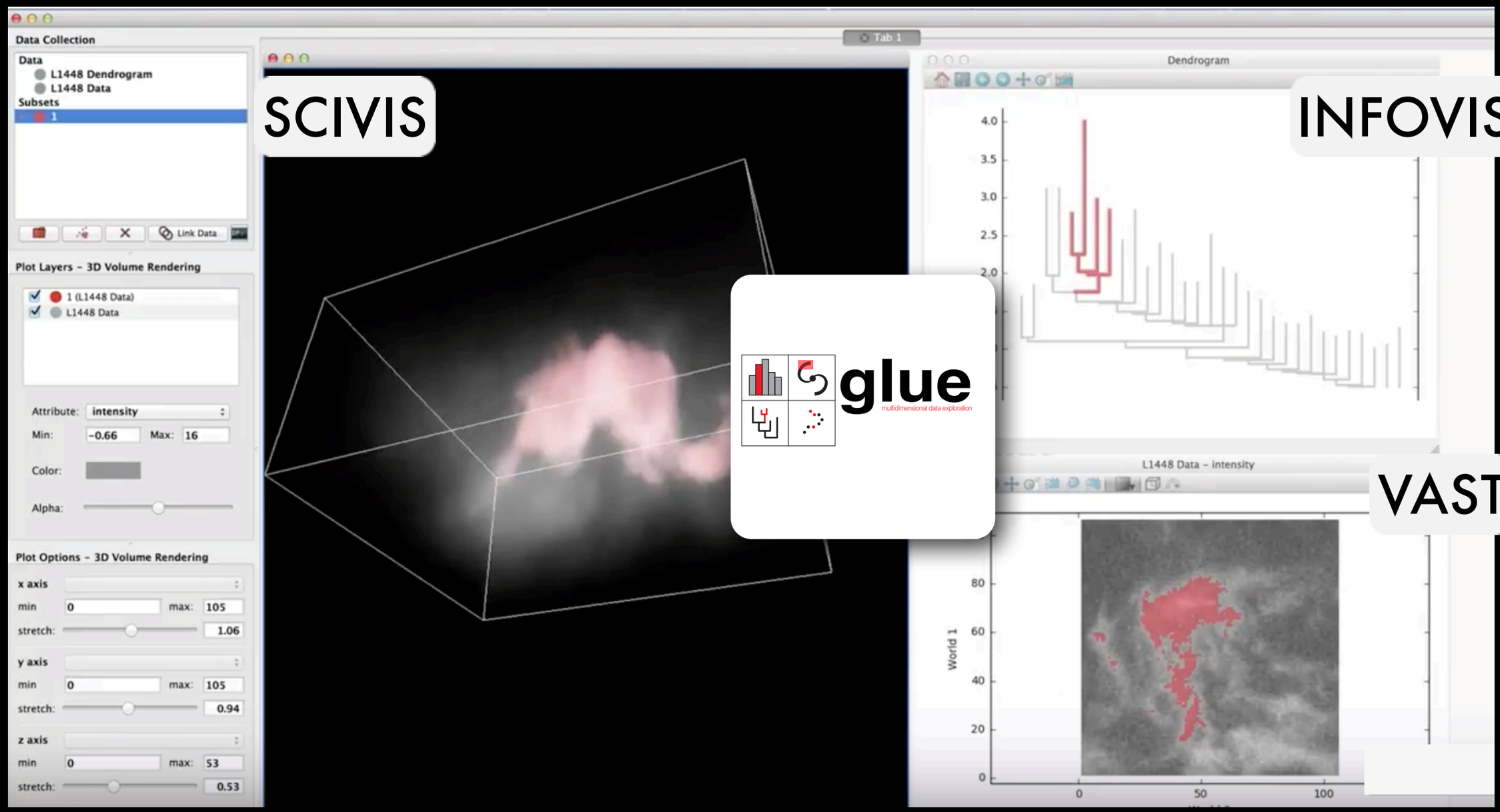
Research "primarily concerned with the visualization of three-dimensional phenomena (architectural, meteorological, medical, biological, etc.), where the emphasis is on realistic renderings of volumes, surfaces, illumination sources, and so forth, perhaps with a dynamic (time) component". (Wikipedia)

INFOVIS

Research on "human visual data exploration, analysis, and communication within displays that flexibly encode data in perceptually effective ways." (IEEE)

VAST

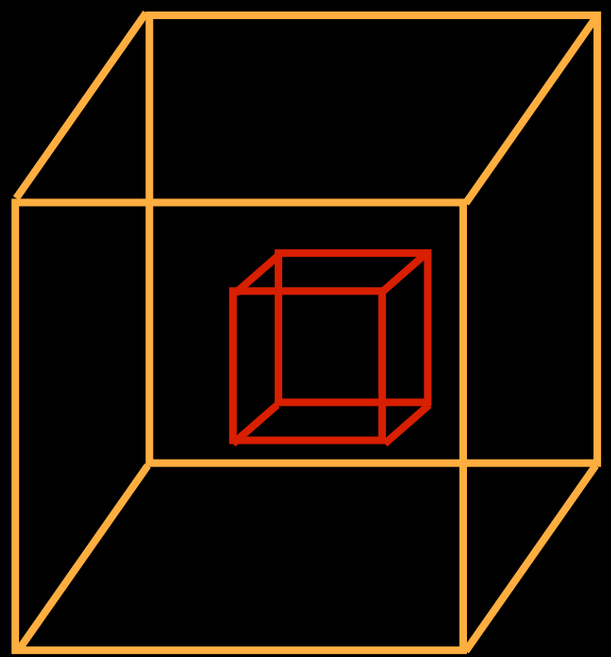
Research on "analytic processes and how visualization can support human reasoning; mixed-initiative analysis systems that leverage human and automated knowledge discovery; understanding and evaluating the impact of visual analysis systems on real-world applications." (IEEE)



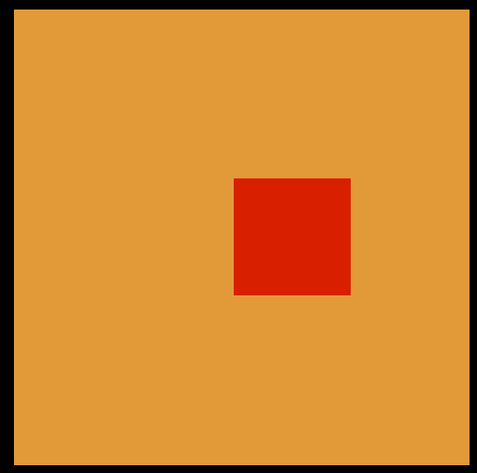
core glue contributors: C. Beaumont, M. Borkin, M. Breddels, A. Goodman, T. Robitaille

Linked Views of High-dimensional Data

John Tukey



3D



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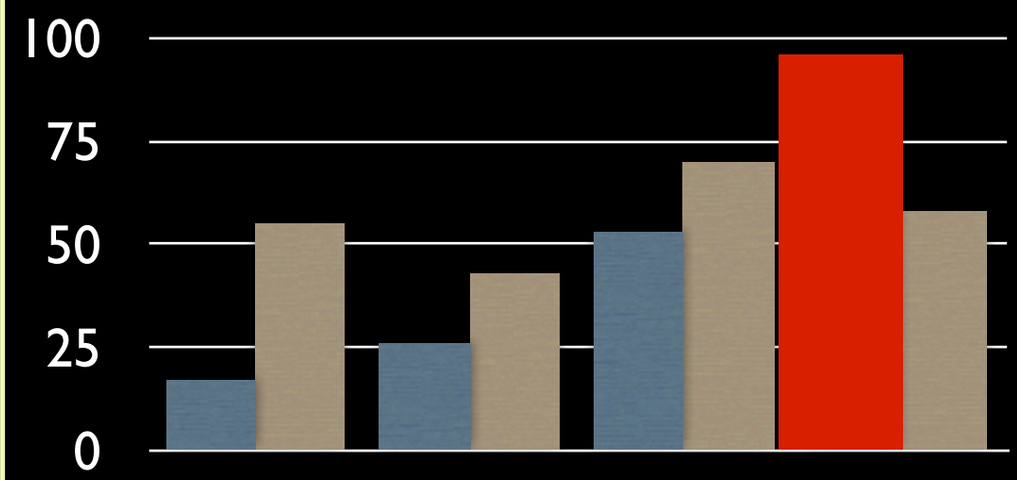

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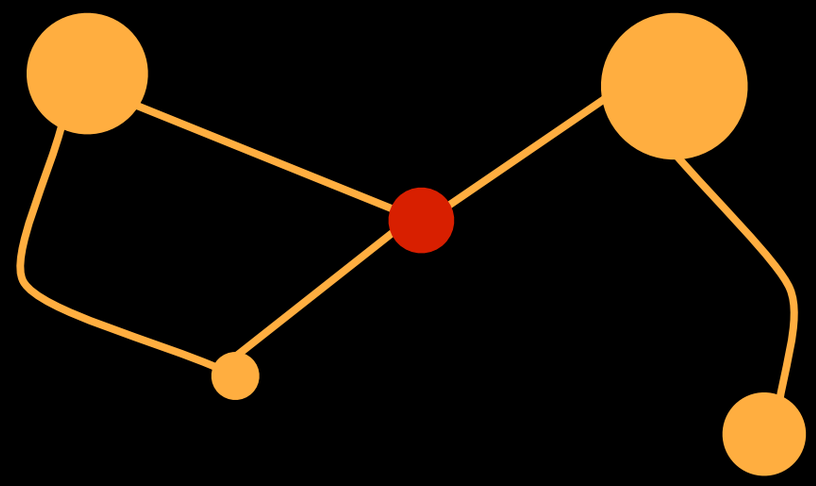
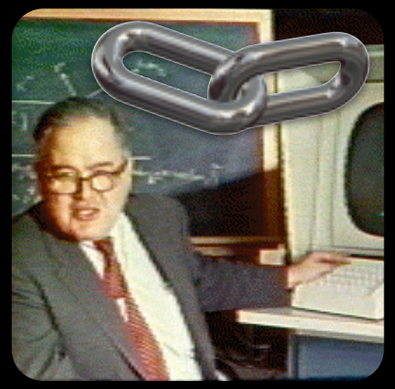


figure, by M. Borkin, reproduced from Goodman 2012, "Principles of High-Dimensional Data Visualization in Astronomy"

JOHN TUKEY'S LEGACY



PRIM-9

PRIM-H

DataDesk®

"AstroMed"
@VIS

glue
multidimensional data exploration

XGobi → GGobi →

RGGobi

Spotfire®

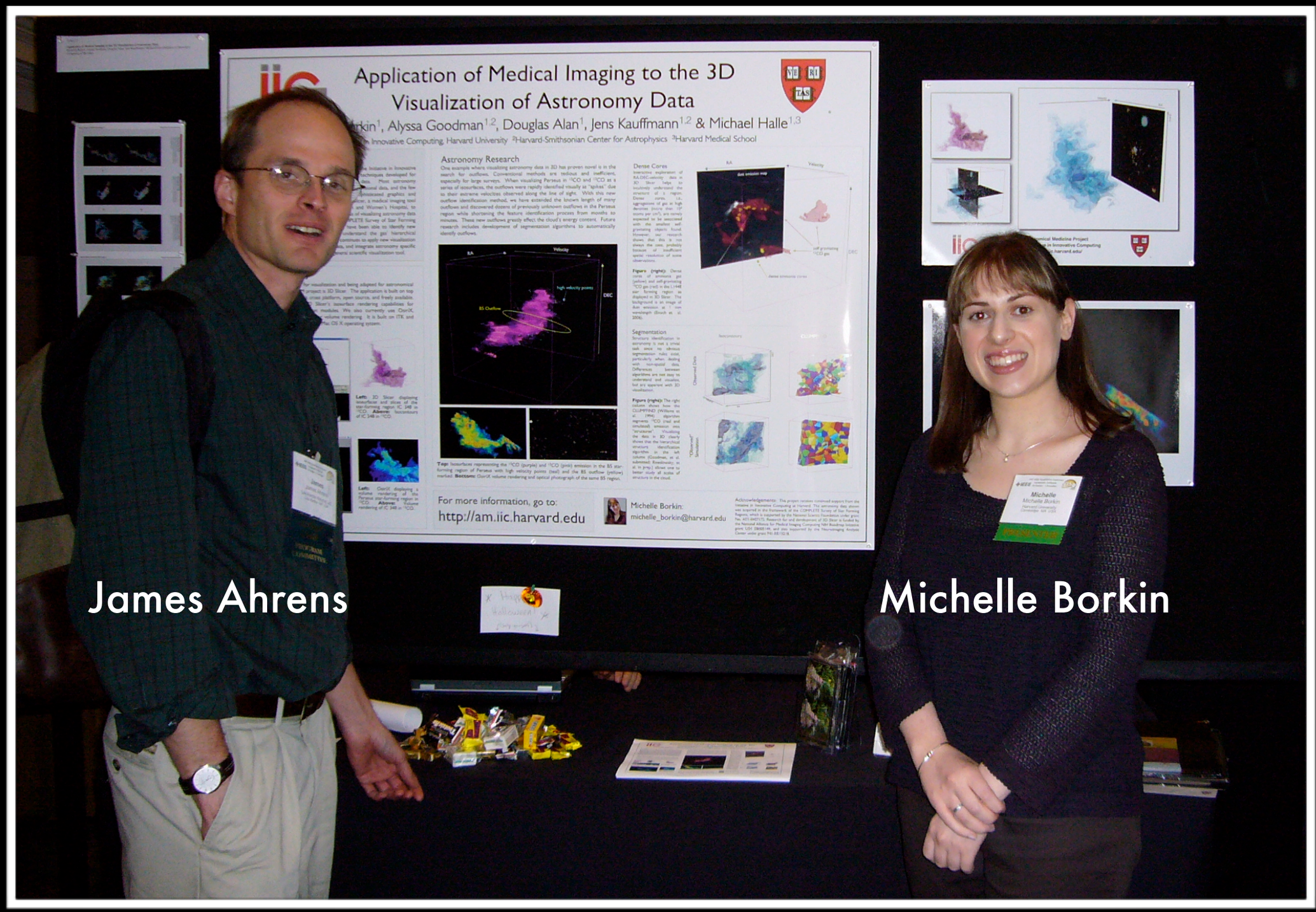
Polaris →

+ableau
SOFTWARE

IEEE VIS
established

1970 1980 1990 2000 2010

“AstroMed” @IEEVIS 2007



James Ahrens

Michelle Borkin

Application of Medical Imaging to the 3D Visualization of Astronomy Data

Michelle Borkin[1], Alyssa Goodman[1,2], Douglas Alan[1], Jens Kauffmann[1,2] & Michael Halle[1,3]

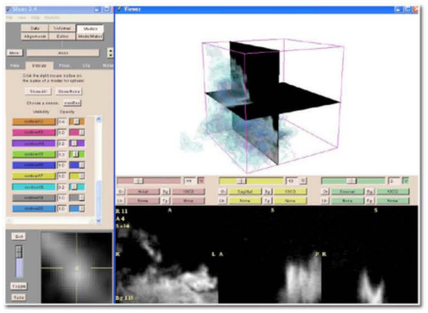
[1]Initiative in Innovative Computing, Harvard University [2]Harvard-Smithsonian Center for Astrophysics [3]Harvard Medical School

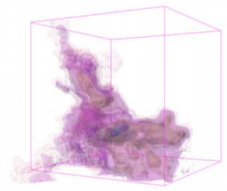
Summary

As part of the Astronomical Medicine (AM) project at the Initiative in Innovative Computing at Harvard, 3D visualization and analytical techniques developed for medical imaging have been applied to astronomy data. Most astronomy visualization applications and tools are only for two dimensional data, and the few available for three dimensional visualization lack sophisticated graphics and rendering capabilities. In applying programs like 3D Slicer, a medical imaging tool developed at the Surgical Planning Lab at Brigham and Women's Hospital, to astronomy data we have demonstrated the usefulness of visualizing astronomy data in 3D. Using molecular line maps from the COMPLETE Survey of Star Forming Regions of the Perseus star-forming region, we have been able to identify new outflows and shells from young stars, and understand the gas' hierarchical structure. The Astronomical Medicine project continues to apply new visualization and segmentation techniques to astronomy data, and integrate astronomy specific features into 3D Slicer paving the way for a general scientific visualization tool.

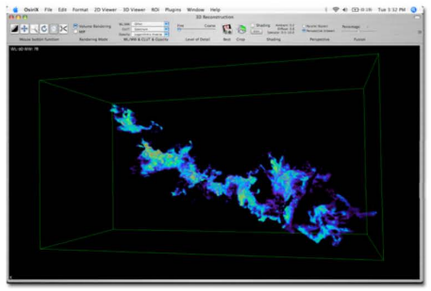
Visualization Tools

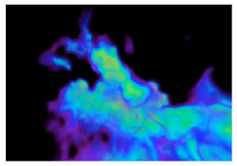
The primary tool being used for visualization and being adapted for astronomical visualization as part of the AM project is 3D Slicer. The application is built on top of the VTK and ITK toolkits, is cross platform, open source, and freely available. We have primarily utilized 3D Slicer's isosurface rendering capabilities for visualization, and its segmentation modules. We also currently use OsiriX, another medical imaging program, for volume rendering. It is built on ITK and VTK, and is open sourced for Apple's Mac OS X operating system.





Left: 3D Slicer displaying isosurfaces and slices of the star-forming region IC 348 in ^{13}CO. **Above:** Isocontours of IC 348 in ^{13}CO.

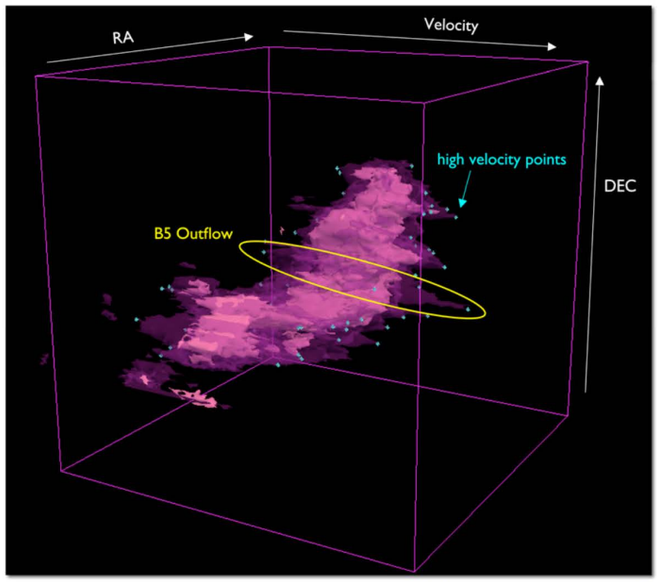


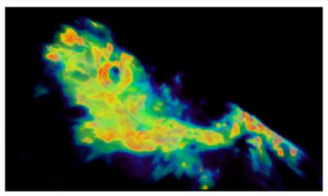


Left: OsiriX displaying a volume rendering of the Perseus star-forming region in ^{12}CO. **Above:** Volume rendering of IC 348 in ^{13}CO.

Astronomy Research

One example where visualizing astronomy data in 3D has proven novel is in the search for outflows. Conventional methods are tedious and inefficient, especially for large surveys. When visualizing Perseus in ^{12}CO and ^{13}CO as a series of isosurfaces, the outflows were rapidly identified visually as "spikes" due to their extreme velocities observed along the line of sight. With this new outflow identification method, we have extended the known length of many outflows and discovered dozens of previously unknown outflows in the Perseus region while shortening the feature identification process from months to minutes. These new outflows greatly effect the cloud's energy content. Future research includes development of segmentation algorithms to automatically identify outflows.



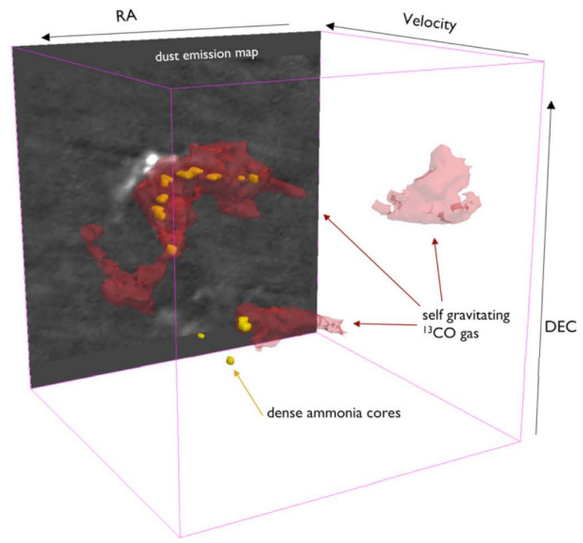


Top: Isosurfaces representing the ^{12}CO (purple) and ^{13}CO (pink) emission in the B5 star-forming region of Perseus with high velocity points (teal) and the B5 outflow (yellow) marked. **Bottom:** OsiriX volume rendering and optical photograph of the same B5 region.

Dense Cores

Interactive exploration of RA-DEC-velocity data in 3D Slicer helps to intuitively understand the structure of a region. Dense cores, i.e., aggregations of gas at high densities (more than 10^5 atoms per cm^3), are naively expected to be associated with the smallest self-gravitating objects found. However, our research shows that this is not always the case, probably because of insufficient spatial resolution of some observations.

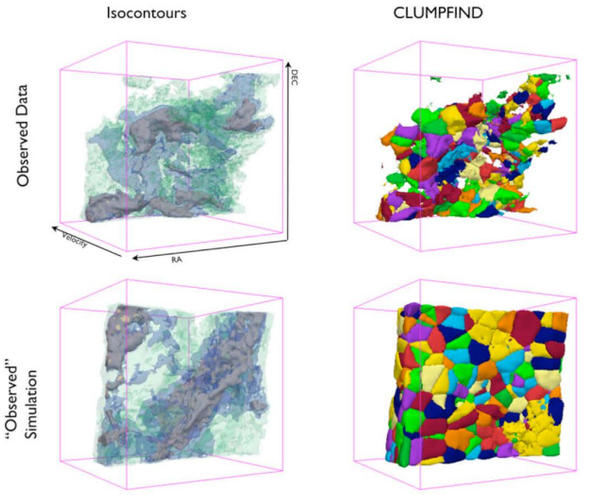
Figure (right): Dense cores of ammonia gas (yellow) and self-gravitating ^{13}CO gas (red) in the L1448 star forming region as displayed in 3D Slicer. The background is an image of dust emission at 1 mm wavelength (Enoch et al. 2006).



Segmentation

Structure identification in astronomy is not a trivial task since no obvious segmentation rules exist, particularly when dealing with non-spatial data. Differences between algorithms are not easy to understand and visualize, but are apparent with 3D visualization.

Figure (right): The right column shows how the CLUMPFIND (Williams et al. 1994) algorithm segments ^{13}CO (real and simulated) emission into "structures". Visualizing the data in 3D clearly shows that the hierarchical structure identification algorithm in the left column (Goodman, et al. submitted; Rosolowsky, et al. in prep.) allows one to better study all scales of structure in the cloud.



For more information, go to:
http://am.iic.harvard.edu

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"3D PDF" (Nature, 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[1,2], Erik W. Rosolowsky[2,3], Michelle A. Borkin[1]†, Jonathan B. Foster[2], Michael Halle[1,4], Jens Kauffmann[1,2] & Jaime E. Pineda[2]

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[1]. 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 function[2]. 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 ^{13}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[3] 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

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2009

3D PDF

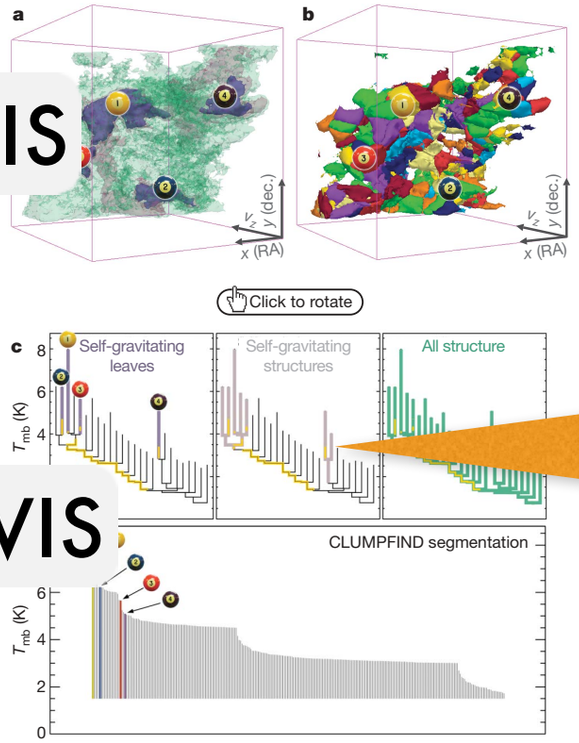

Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. a, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating 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 ($-0.5\,\mathrm{km\,s^{-1}}$) to back ($8\,\mathrm{km\,s^{-1}}$).

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] ...roposed as a way to characterize clouds' hierarchical structure

using 2D maps of column density. With th...rly 2D work as inspiration, we have developed a structure-id...ithm that abstracts the hierarchical structure of a... an easily visualized representation calle... well developed in other data-intensive ... application of tree methodologies so fa... and almost exclusively within the ar... 'merger trees' are being used with in...

Figure 3 and its legend explain th... schematically. The dendrogram qua...

...mass, stu... $\mathrm{K^{-1}\,km^{-1}\,s}$ ...ary Fig. 2). ...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.

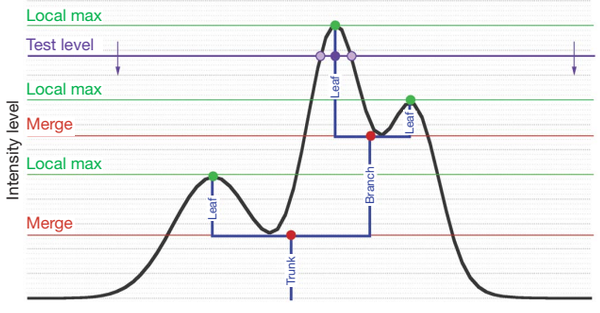

Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in 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.

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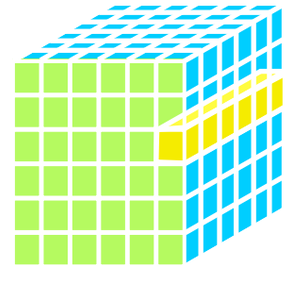
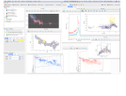
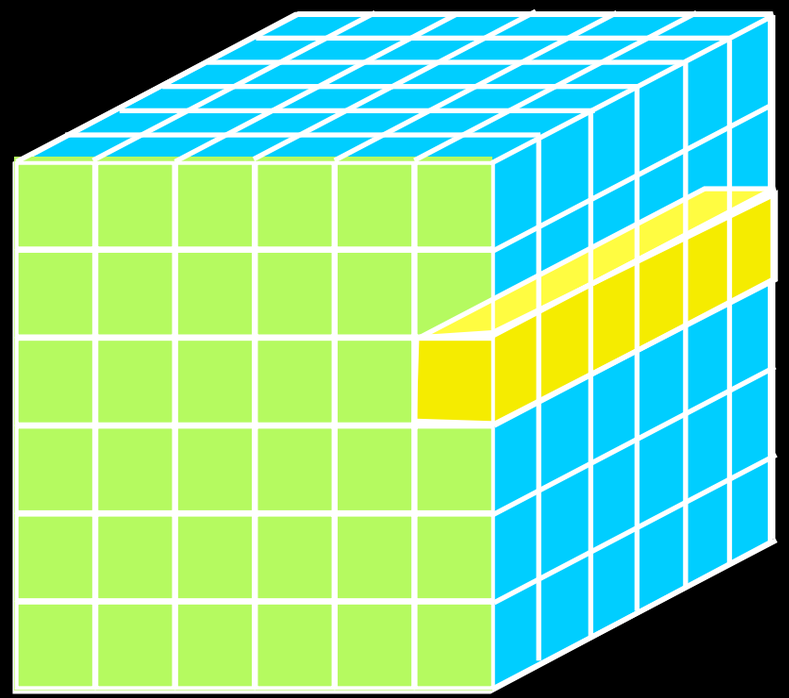
These are "dead" panels! That's not good enough.





VAST

Goodman et al. 2009, Nature,
cf: Fluke et al. 2009



"DATA, DIMENSIONS, DISPLAY"

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”

WIDE DATA, "IN 3D"

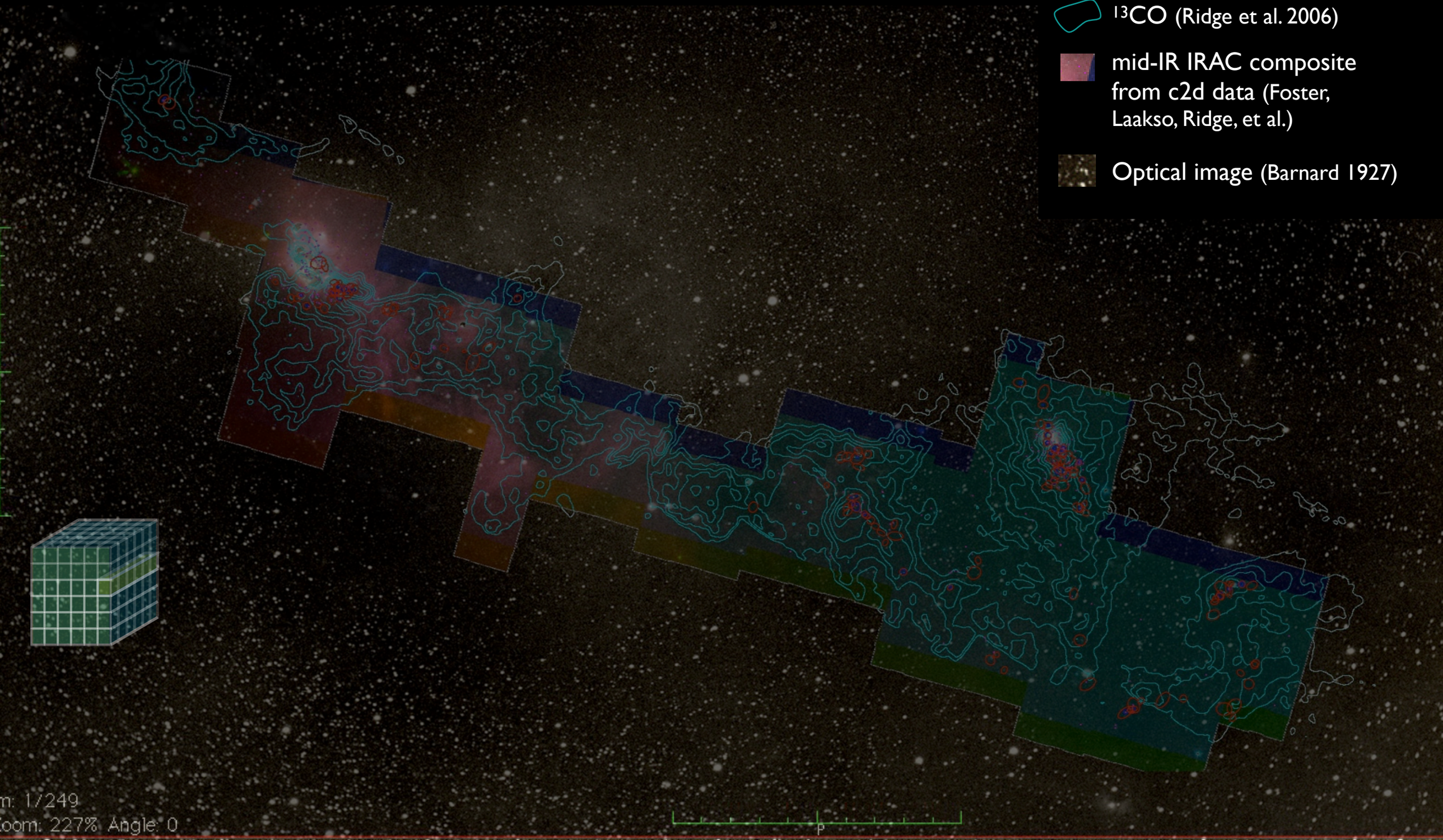
mm peak (Enoch et al. 2006)

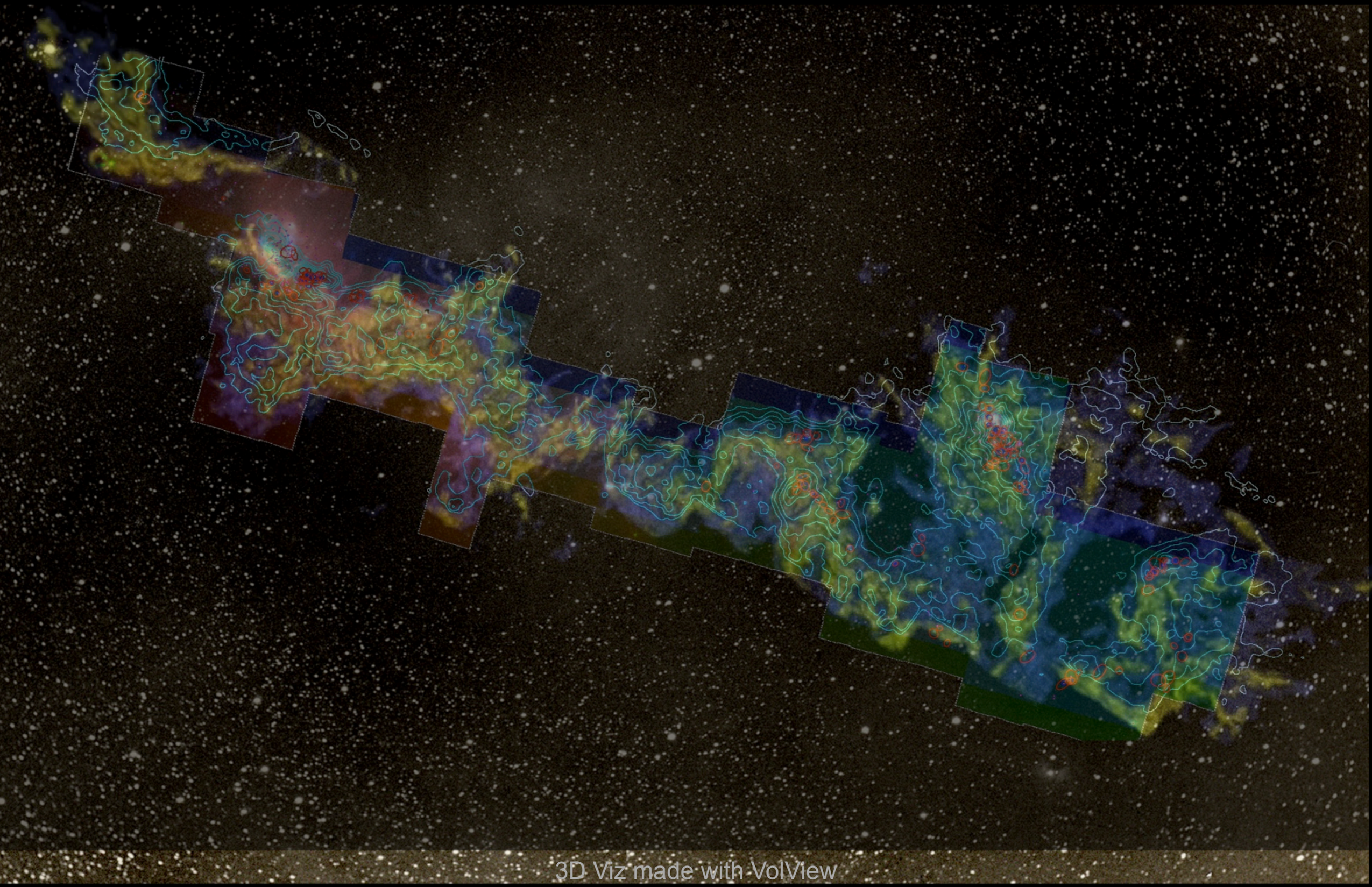
sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)

^{13}CO (Ridge et al. 2006)

mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.)

Optical image (Barnard 1927)





AstronomicalMedicine@IIG

COMPLETE

python File Edit View Canvas Data Manager Plugins Help

20% Mon Oct 22 7:15 AM Alyssa A Goodman

Glue

Open Session | Export Session | Import Data | Export Data/Subsets | Link Data | Arithmetic attributes | Active Subset: Subset 3 | Mode: | Terminal | Preferences | Error Console

Data Collection

Data
- PerA_12coFCRAO_F_xyv
- PerA_13coFCRAO_F_xyv
- Perseus_Av_NICER
- PerA_AvTemMIPS_F_Av
- PerA_AvTemMIPS_F_T
- Perseus_fcrao_iras_2mass

Subsets
- spec_probe
- hot_highv
- Subset 3

Plot Layers - 2D Scatter
- Subset 3 (Perseus_fcrao_iras_2mass)
- hot_highv (Perseus_fcrao_iras_2mass)
- spec_probe (Perseus_fcrao_iras_2mass)
- Perseus_fcrao_iras_2mass

Color | Points | Line | Errors | Vectors

color: Fixed

opacity

Plot Options - 2D Scatter

General | Limits | Axes

x axis: V13CO log

y axis: TIRAS log

Tab 1 | Tab 2

2D Image

2D Scatter

Dec

RA

1D Profile

Options

Data values

Velocity

2D Scatter

TIRAS

V13CO

3D Scatter

NIRAS

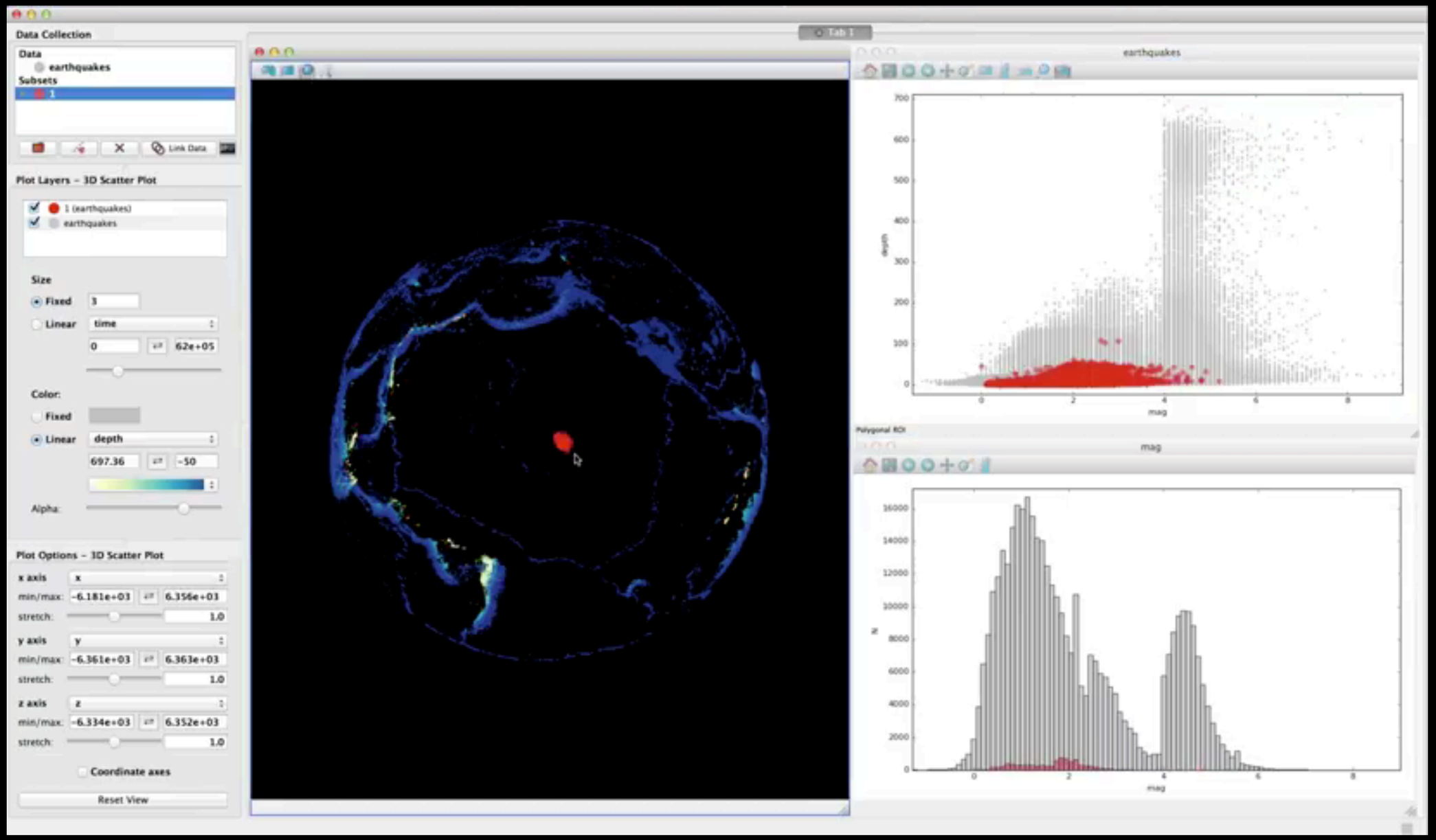
RA

glue

multidimensional data exploration

Linked Views of High-dimensional Data (in Python)

glue

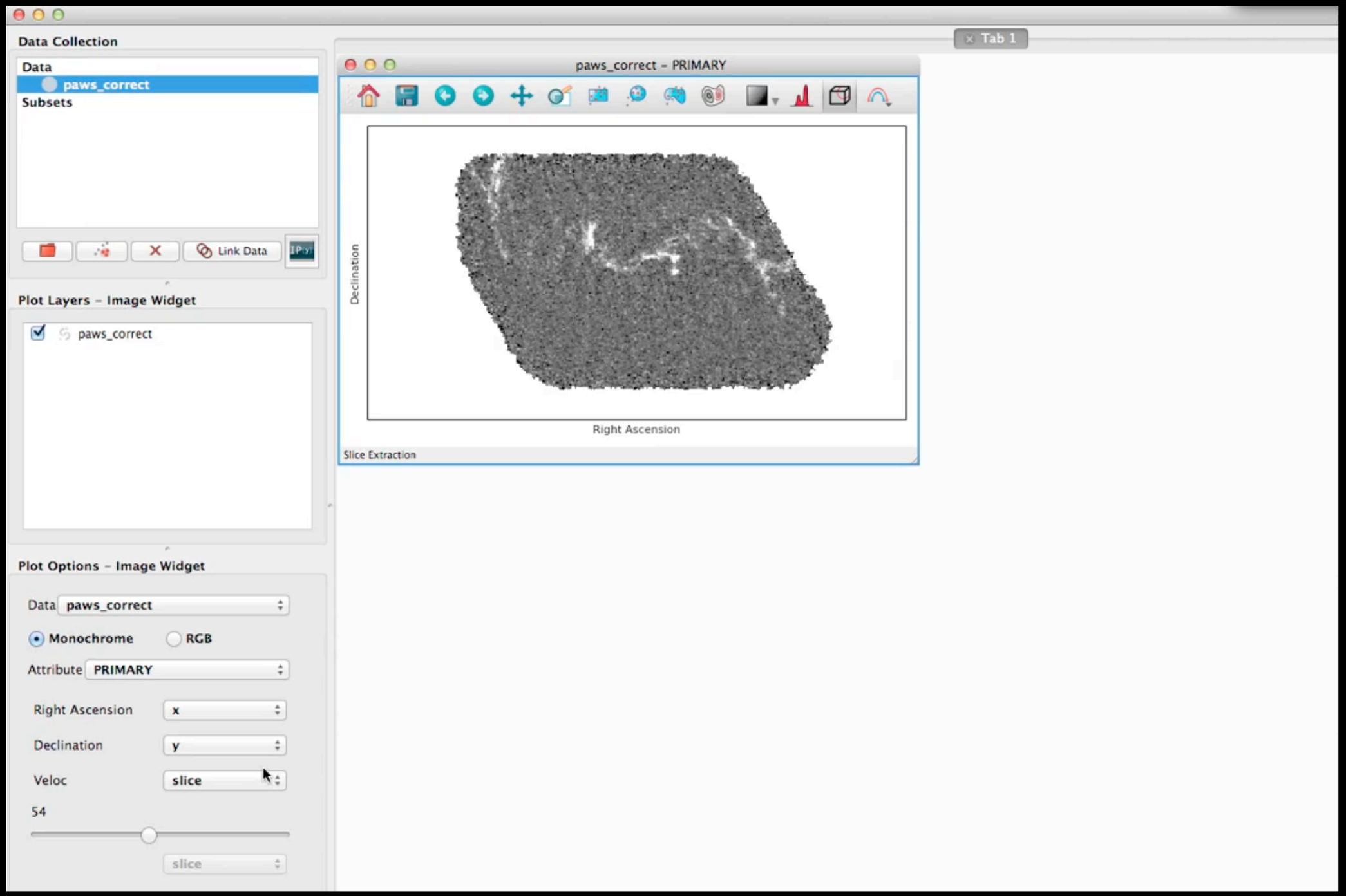


video by Tom Robitaille, lead glue developer

glue created by: C. Beaumont, M. Borkin, M. Breddels, P. Qian, T. Robitaille, and A. Goodman, PI

Linked Views of High-dimensional Data (in Python)

glue



video by Chris Beaumont, glue developer

glue created by: C. Beaumont, M. Borkin, M. Breddels, P. Qian, T. Robitaille, and A. Goodman, PI

glue

multidimensional data exploration

built-in

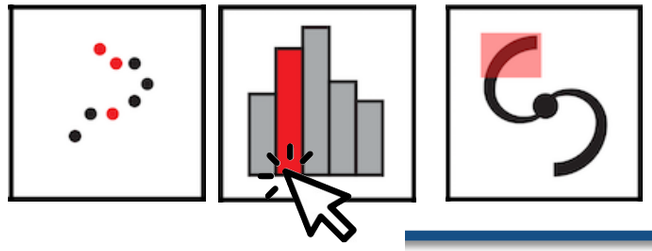
standard data loaders

Data File 1

Data File 2

Data File N

define new variables, import/export insights, interactive plots for the web, save state, all from GUI



standard 1D, 2D & 3D plots

link data files' attributes

highlight live or algorithmic selections with Boolean logic

plug-in

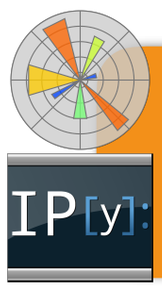
custom data loaders

custom buttons, features

custom plots

+options

user config.py file (loaders, colors, plot types, +)



access to all matplotlib functions through built-in IPython terminal

jupyter

run & interact with glue from Jupyter notebook & other tools

glueviz.org

[demo]
[ALMA]
[publishing]

python File Edit View Canvas Data Manager Plugins Help 21% Mon Oct 22 7:15 AM Alyssa A Goodman

Glue

Open Session | Export Session | Import Data | Export Data/Subsets | Link Data | Arithmetic attributes | Active Subset: Subset 3 | Mode: | Terminal | Preferences | Error Console

Data Collection

Data
- PerA_12coFCRAO_F_xyv
- PerA_13coFCRAO_F_xyv
- Perseus_Av_NICER
- PerA_AvTemMIPS_F_Av
- PerA_AvTemMIPS_F_T
- Perseus_fcrao_iras_2mass

Subsets
- spec_probe
- hot_highv
- Subset 3

Plot Layers - 2D Scatter
- Subset 3 (Perseus_fcrao_iras_2mass)
- hot_highv (Perseus_fcrao_iras_2mass)
- spec_probe (Perseus_fcrao_iras_2mass)
- Perseus_fcrao_iras_2mass

Color | Points | Line | Errors | Vectors

color: Fixed

opacity

Plot Options - 2D Scatter

General | Limits | Axes

x axis: V13CO log

y axis: TIRAS log

Tab 1 | Tab 2

2D Image

1D Profile

2D Scatter

Link Editor

Click on two datasets to set up links or click on an existing connection to edit links. Selected datasets are shown in green. When one dataset is selected, the colors show directly and indirectly linked (blue) and inaccessible (red) datasets.

PerA_AvTemMIPS_F_T — PerA_13coFCRAO_F_xyv

PerA_AvTemMIPS_F_Av — PerA_12coFCRAO_F_xyv

Perseus_Av_NICER — Perseus_fcrao_iras_2mass

Data File 1

Data File 2

Data File N

Datasets: PerA_AvTemMIPS_F_Av

Components

Coordinate components
el Axis 0 [y]
el Axis 1 [x]
clination
ht Ascension
n components
MARY

Glue

Datasets: PerA_12coFCRAO_F_xyv

Components

Coordinate components
Pixel Axis 0 [z]
Pixel Axis 1 [y]
Pixel Axis 2 [x]
Velocity
Declination
Right Ascension
Main components
PRIMARY

Current Links

Function	Component 1	Component 2
identity	Right Ascension	Right Ascension
identity	Declination	Declination

Unglue

Advanced linking | Cancel | OK

V13CO

3D Scatter

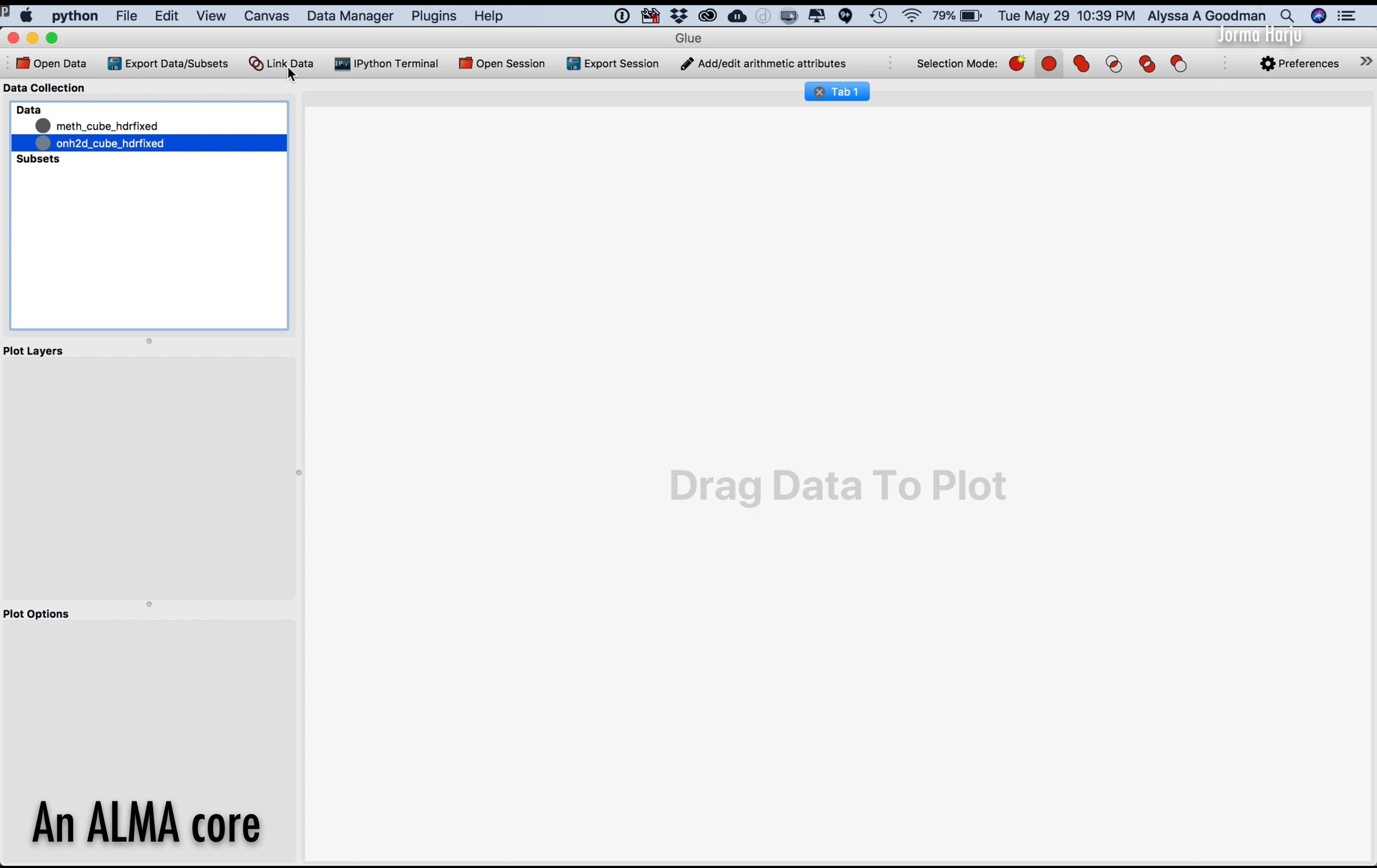
NIRAS

RA

Pixel Axis 0 [z]

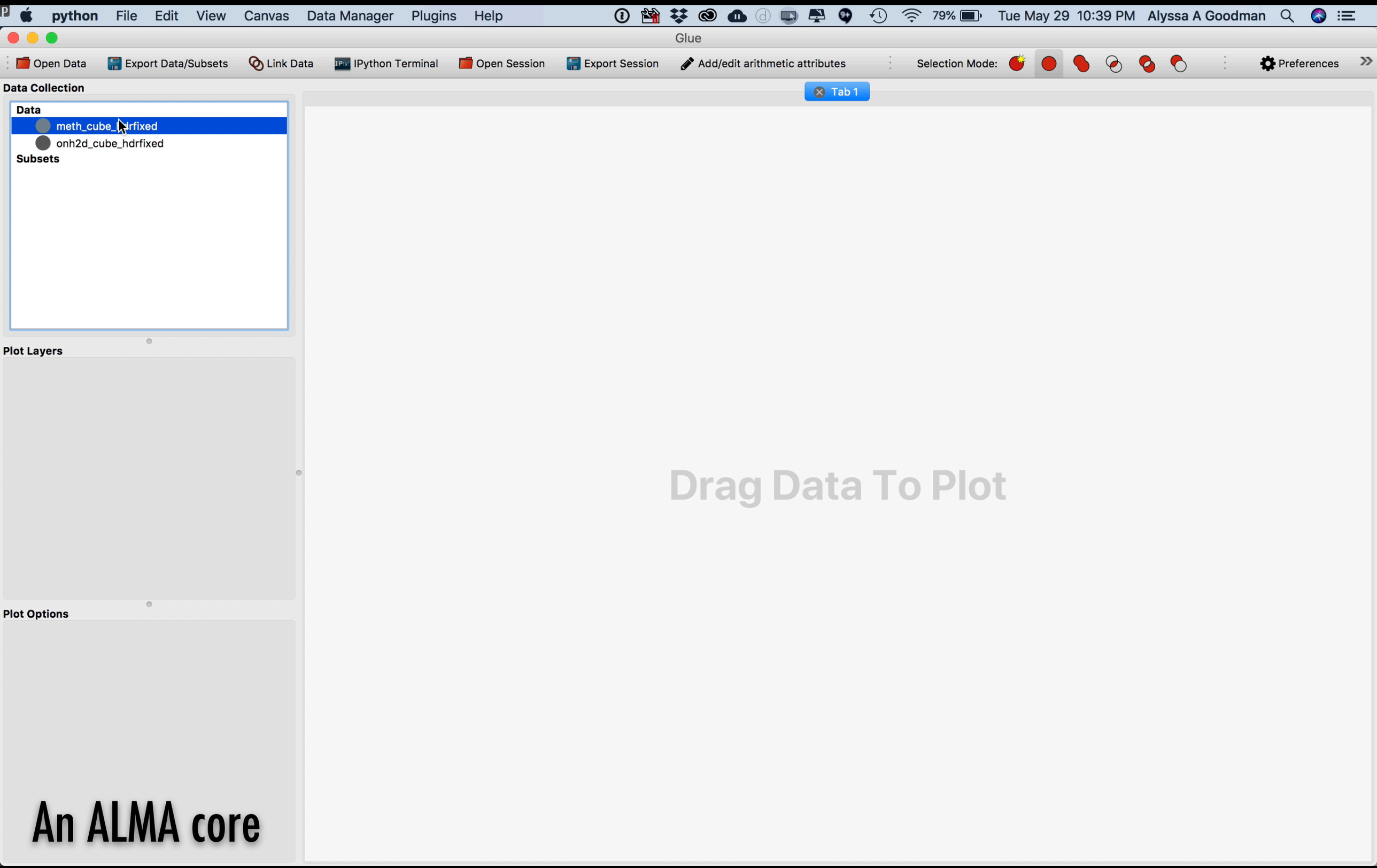
Pixel Axis 1 [y]

"No merging of data sets—just glue them."



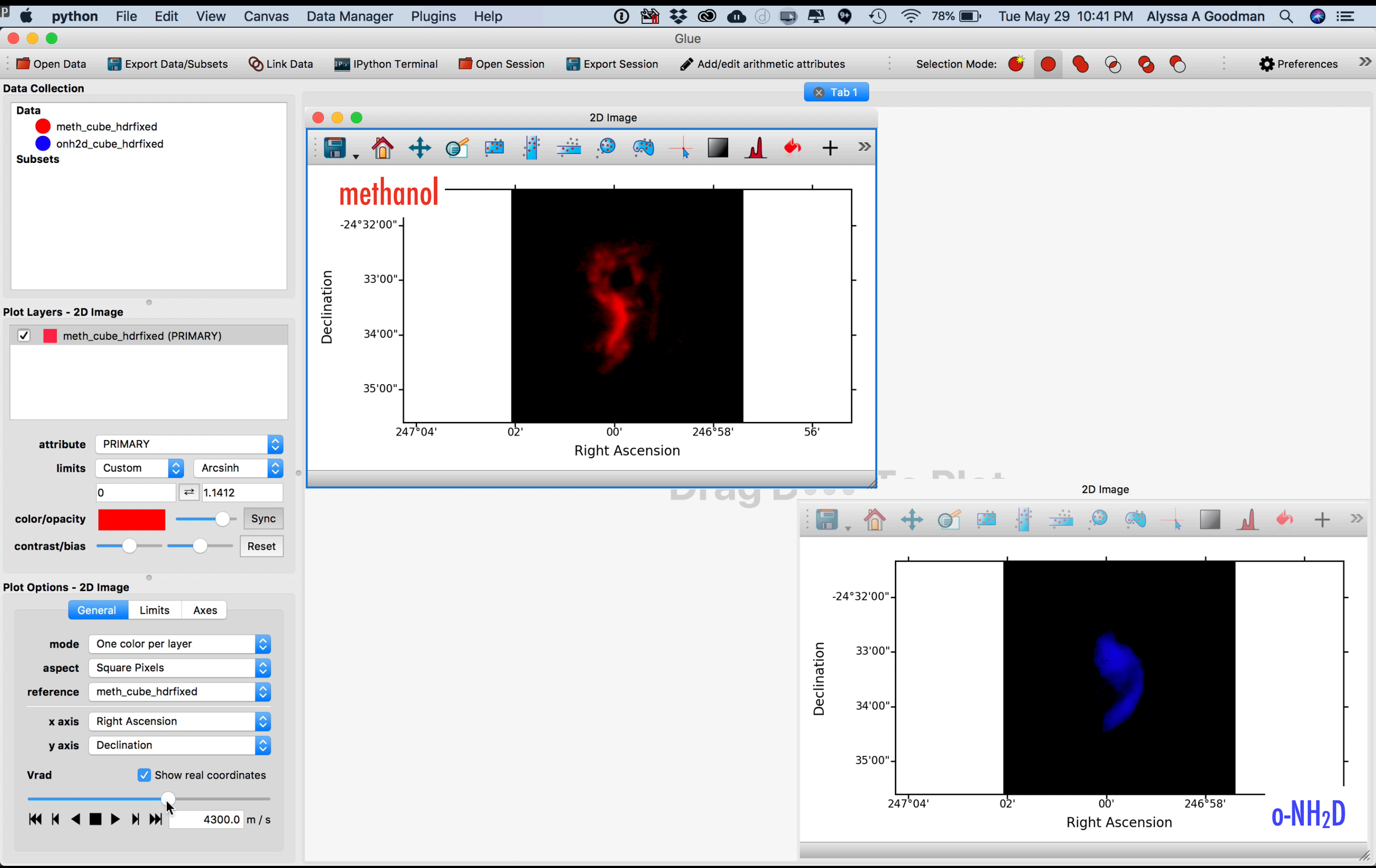
An ALMA core

Just drag to visualize, e.g. series of 2D "channel maps."

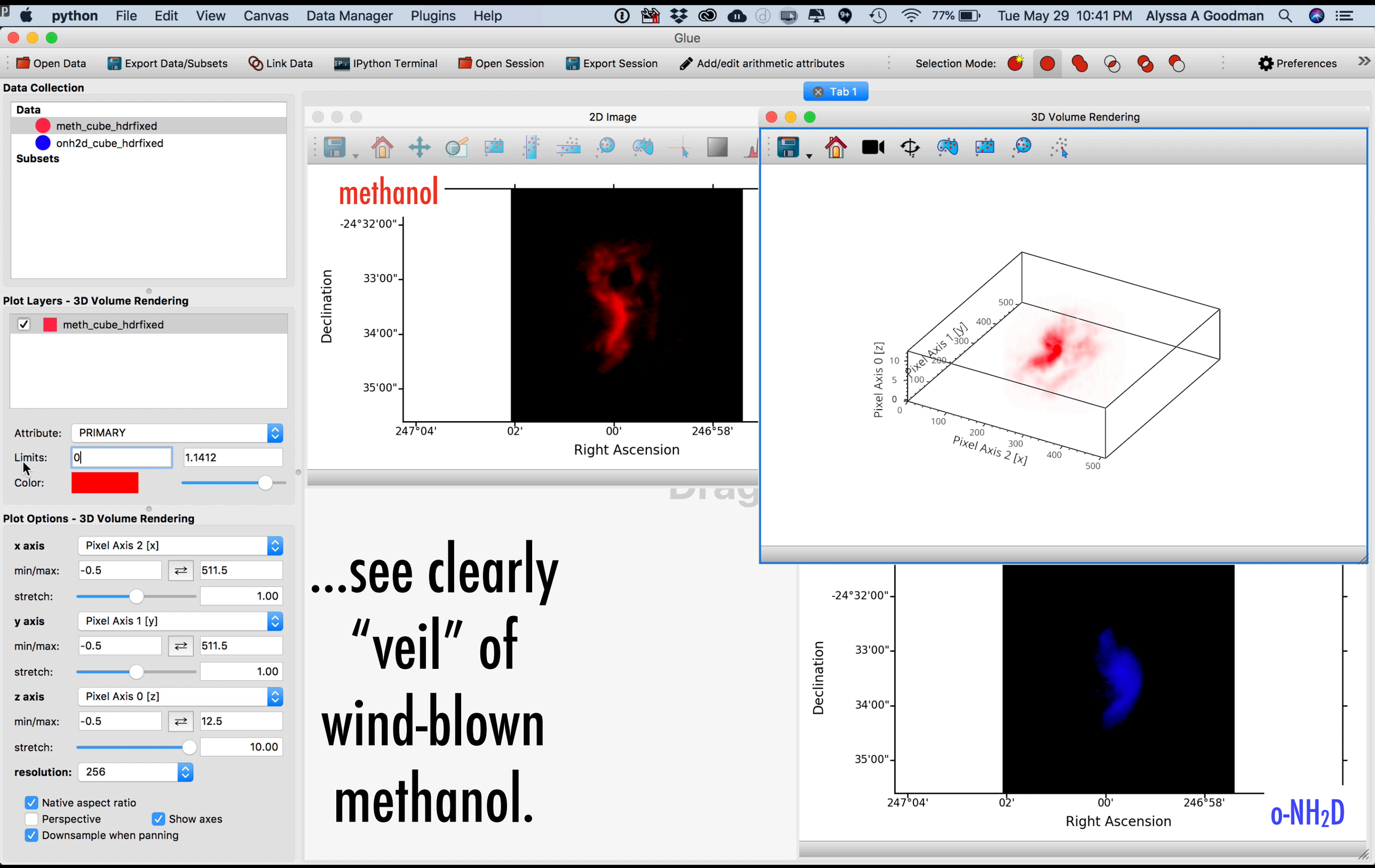


An ALMA core

Adjust so each tracer is a different color.

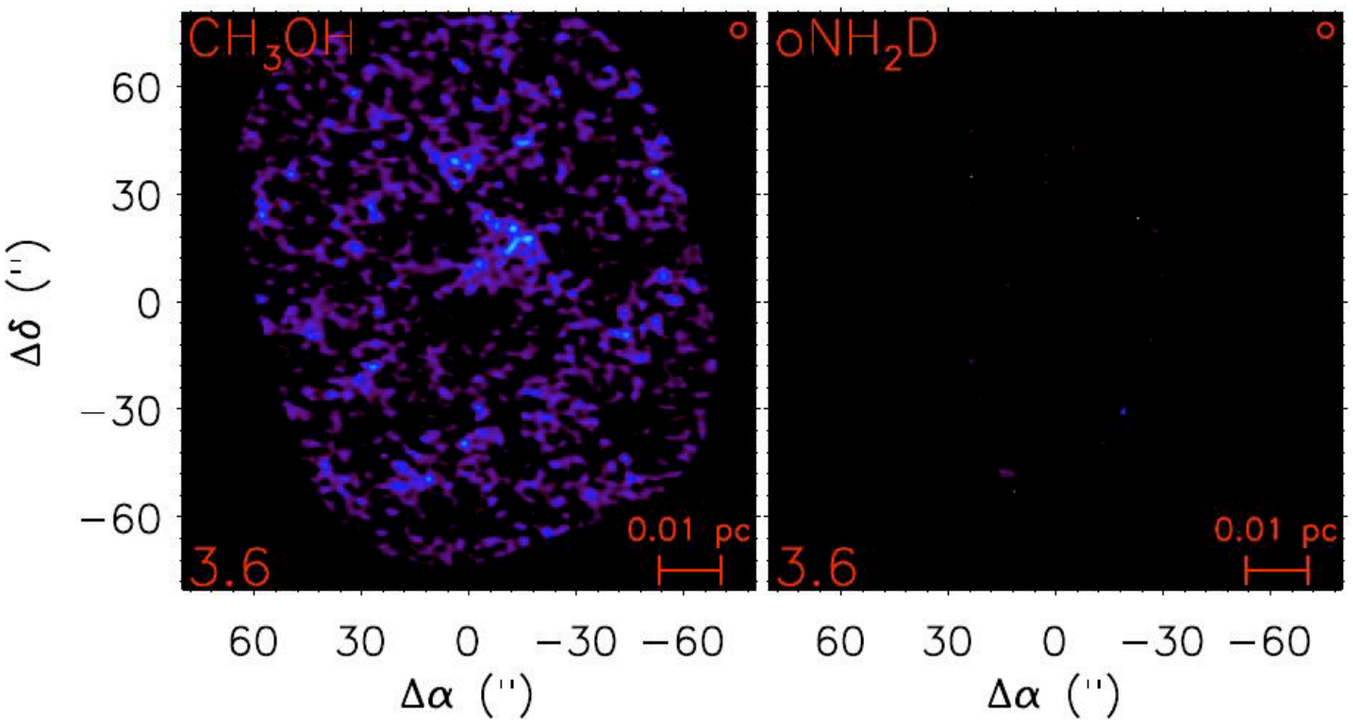


Create 3D views...

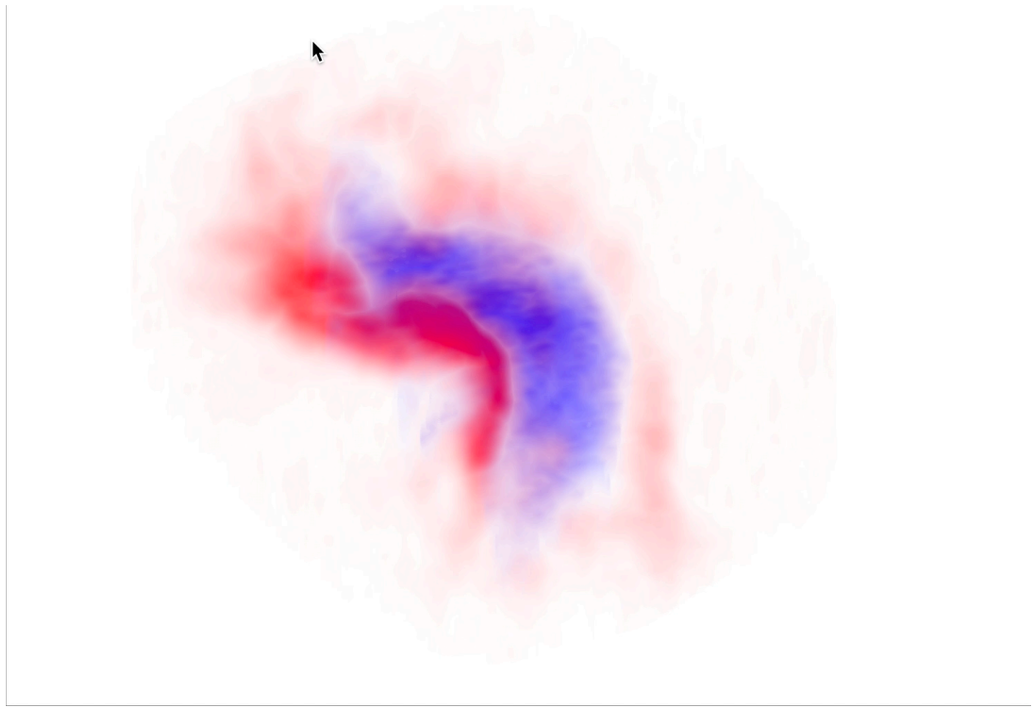


...see clearly "veil" of wind-blown methanol.

Traditional Rainbow Channel maps



glue



glue

multidimensional data exploration

built-in

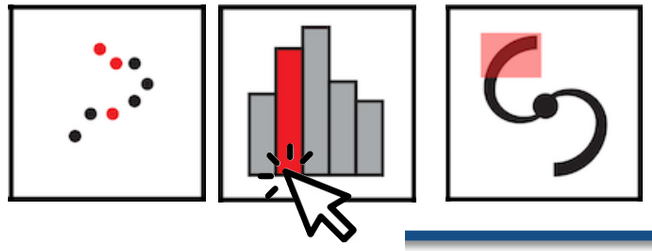
standard data loaders

Data File 1

Data File 2

Data File N

define new variables, import/export insights, interactive plots for the web, save state, all from GUI



standard 1D, 2D & 3D plots

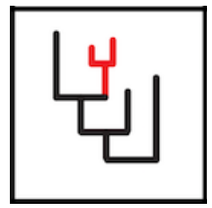
link data files' attributes

highlight live or algorithmic selections with Boolean logic

plug-in

custom data loaders

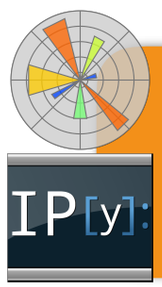
custom buttons, features



custom plots

+options

user config.py file (loaders, colors, plot types, +)



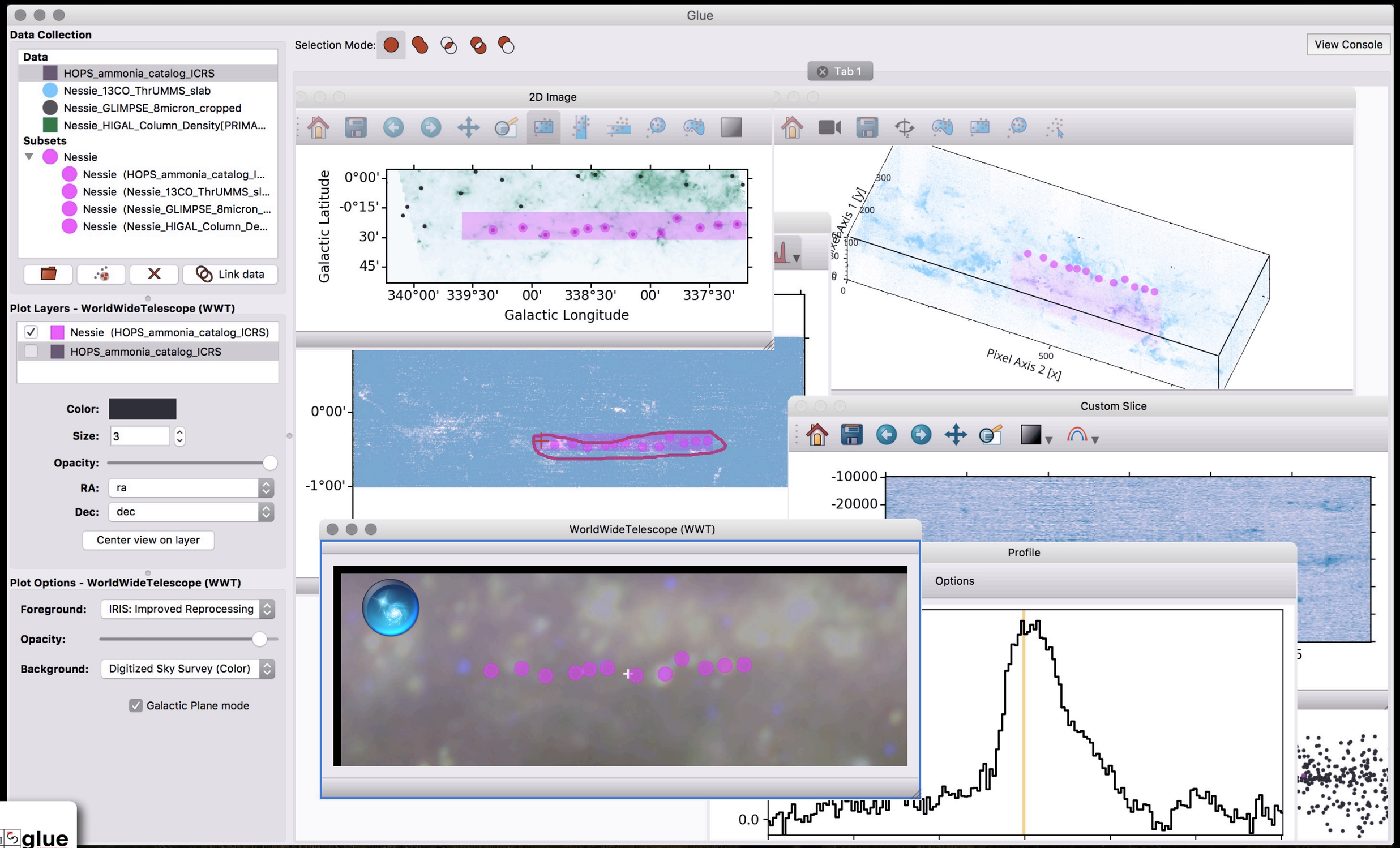
access to all matplotlib functions through built-in IPython terminal

run & interact with glue from Jupyter notebook & other tools

glueviz.org

[demo]
[ALMA]
[publishing]

WorldWide Telescope as a plug-in



My FBI file. . .

Manager Plugins Help 60% Sun Mar 11 6:42 PM Alyssa Goodman

Glue

Terminal Open Session Save Session Add/edit data components Selection Mode: Preferences View Error Console

Tab 1

Climbing
Landing
A Day in the Life of Logan

Plot Layers - 2D Scatter

- A Day in the Life of Logan (airplane_positions
- [x] Landing (airplane_positions)
- Climbing (airplane_positions)
- Descending (airplane_positions)
- neargound (airplane_positions)

Color | Points | Line | Errors | Vectors

color: Fixed

opacity

Plot Options - 2D Scatter

General | Limits | Axes

x label: Heading (degrees)

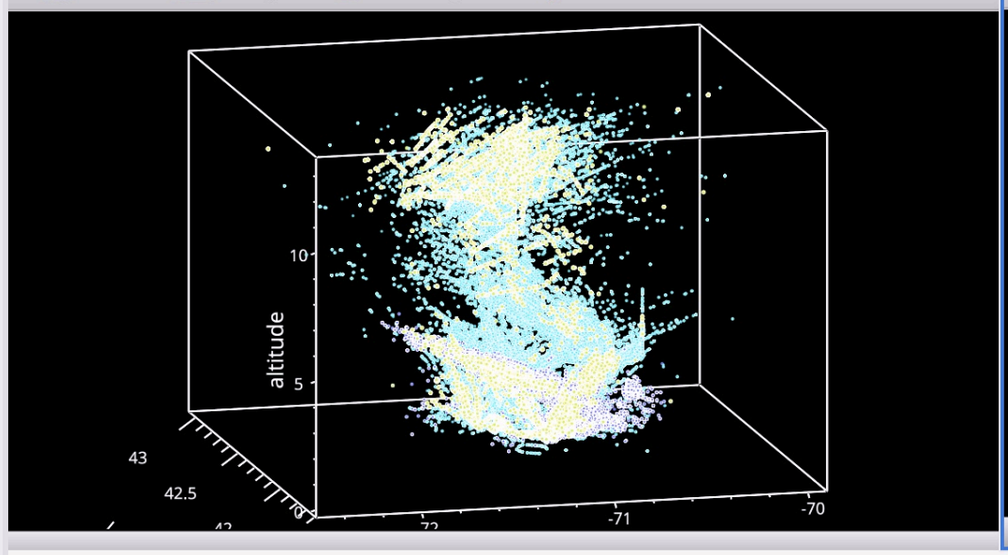
y label: Ground Speed

	x	y
axis label size	10	10
axis label weight	medium	medium
tick label size	10	10

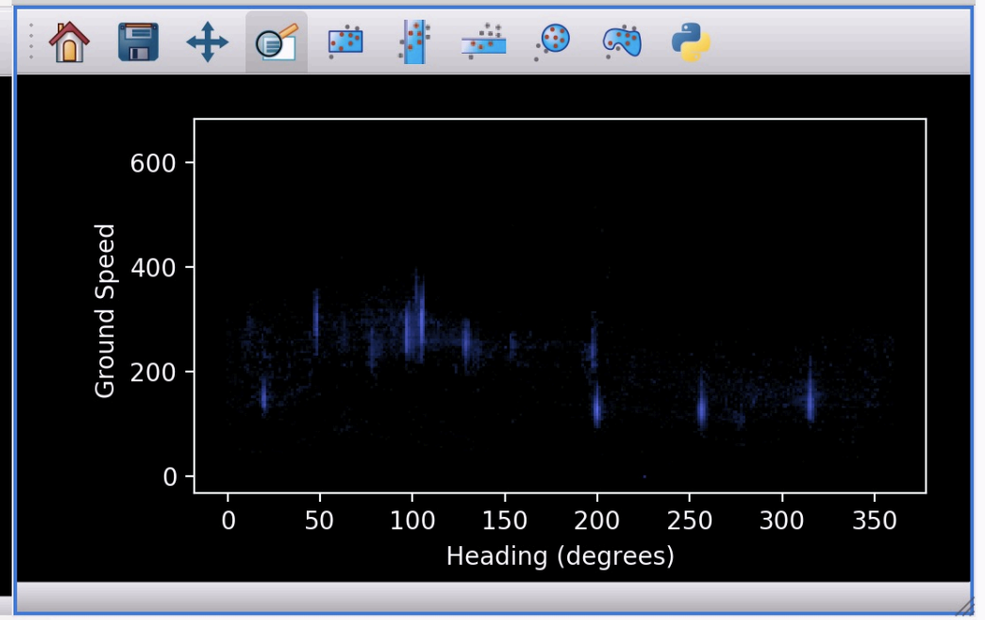
Apply to all plots

glue

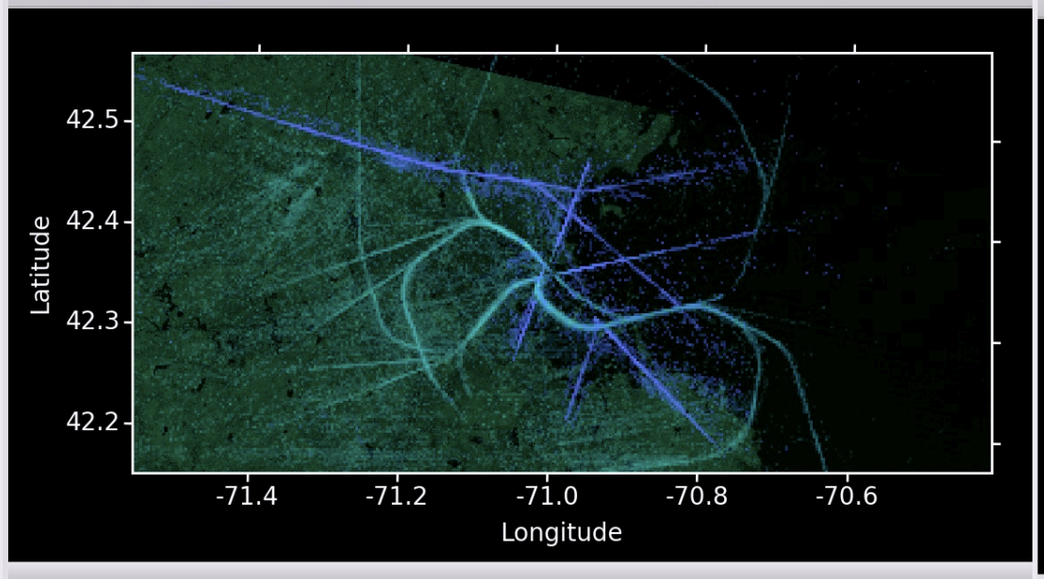
3D Scatter



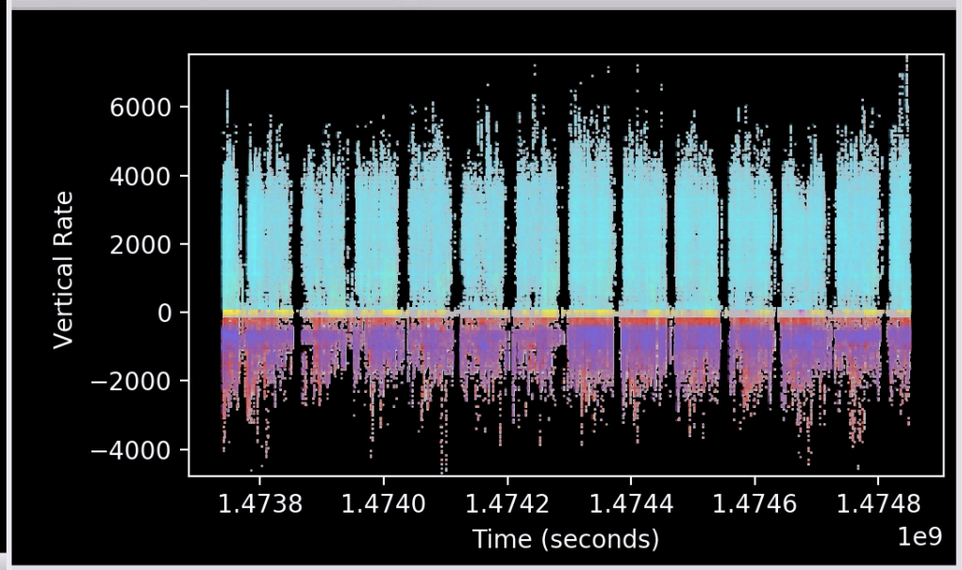
2D Scatter



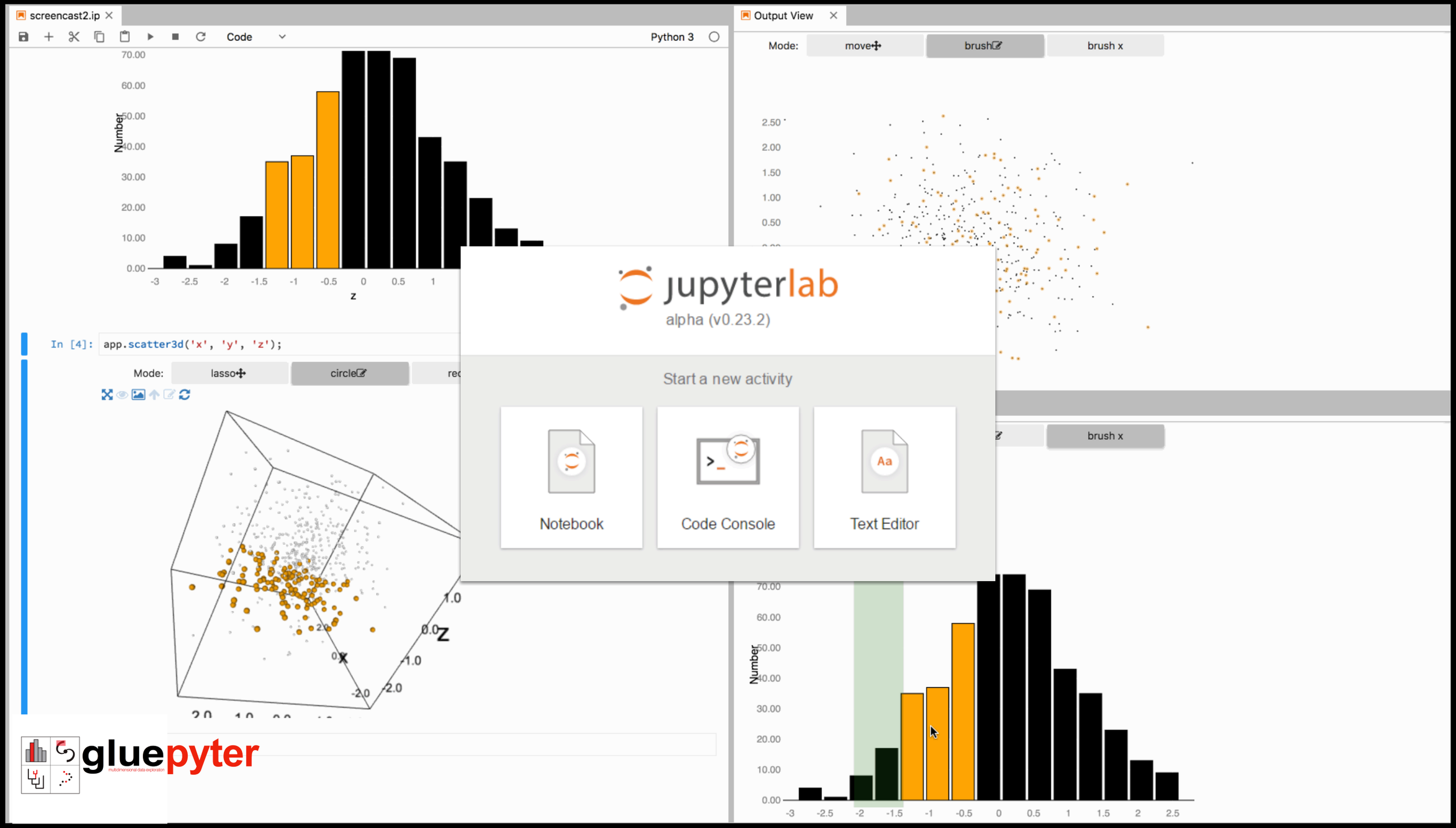
2D Image



2D Scatter



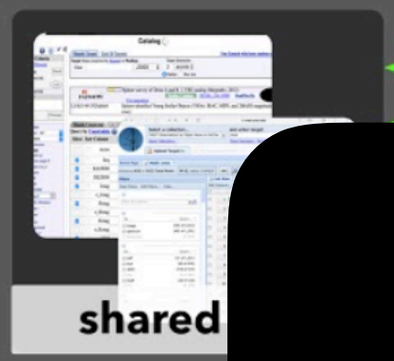
Coming next: glue in the browser

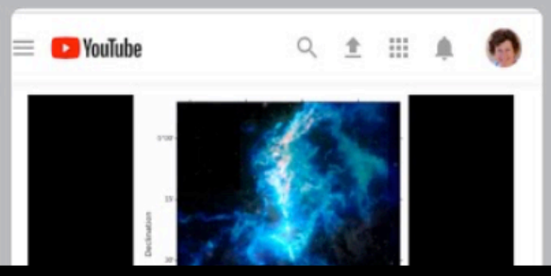


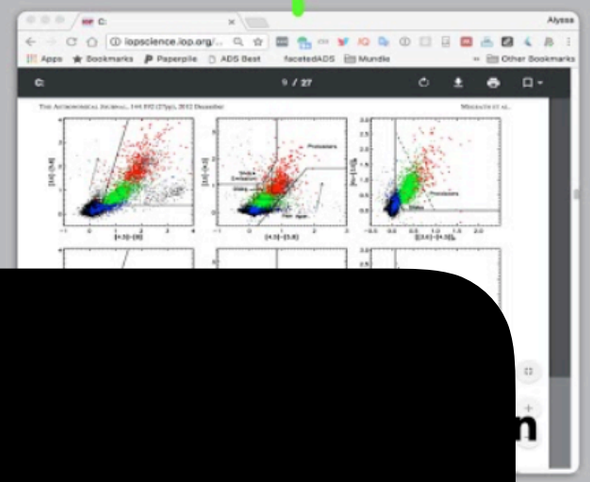
Video courtesy of Maarten Breddels, consulting developer

DATA,
CODE,
COLLABORATION

DATA-DRIVEN STORYTELLING



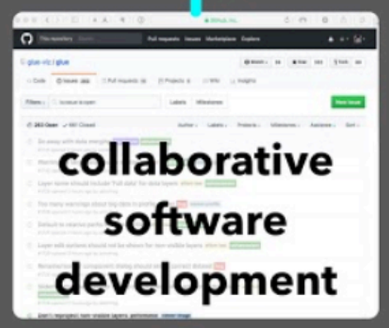


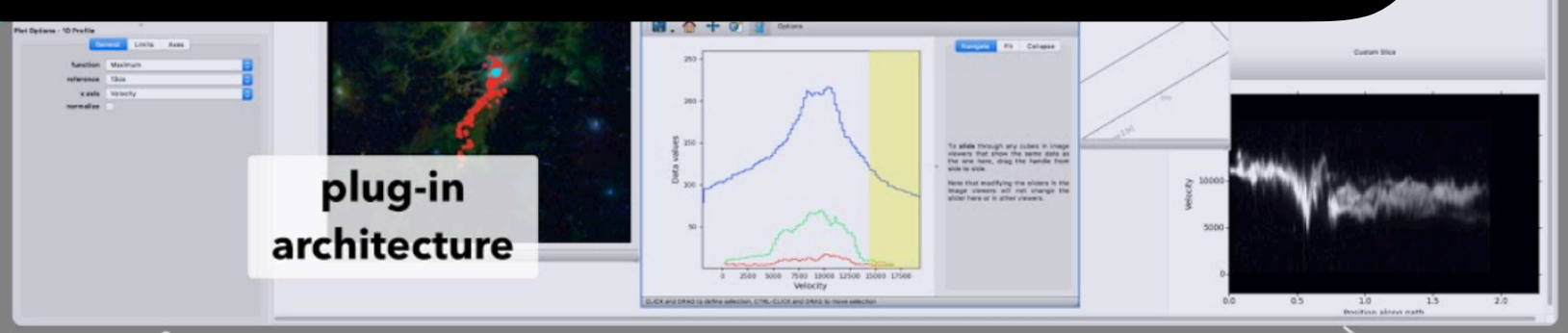


This is all possible, and happening now.

Not for everyone, though.

Critical to *evaluate adoption* & *refine* solutions
Michelle Borkin is doing this for glue
—look for results in Borkin, Goodman, Munzner et al. 2019





EXPLORATORATION ⇄ EXPLANATION

glue-ing together the Universe

glueviz.org

get glue

Alyssa A. Goodman
Harvard-Smithsonian Center for Astrophysics + Radcliffe Insitute for Advanced Study
@AlyssaAGoodman

10QViz.org

≡ MENU

TEN QUESTIONS TO ASK WHEN CREATING A VISUALIZATION

The 10 Questions

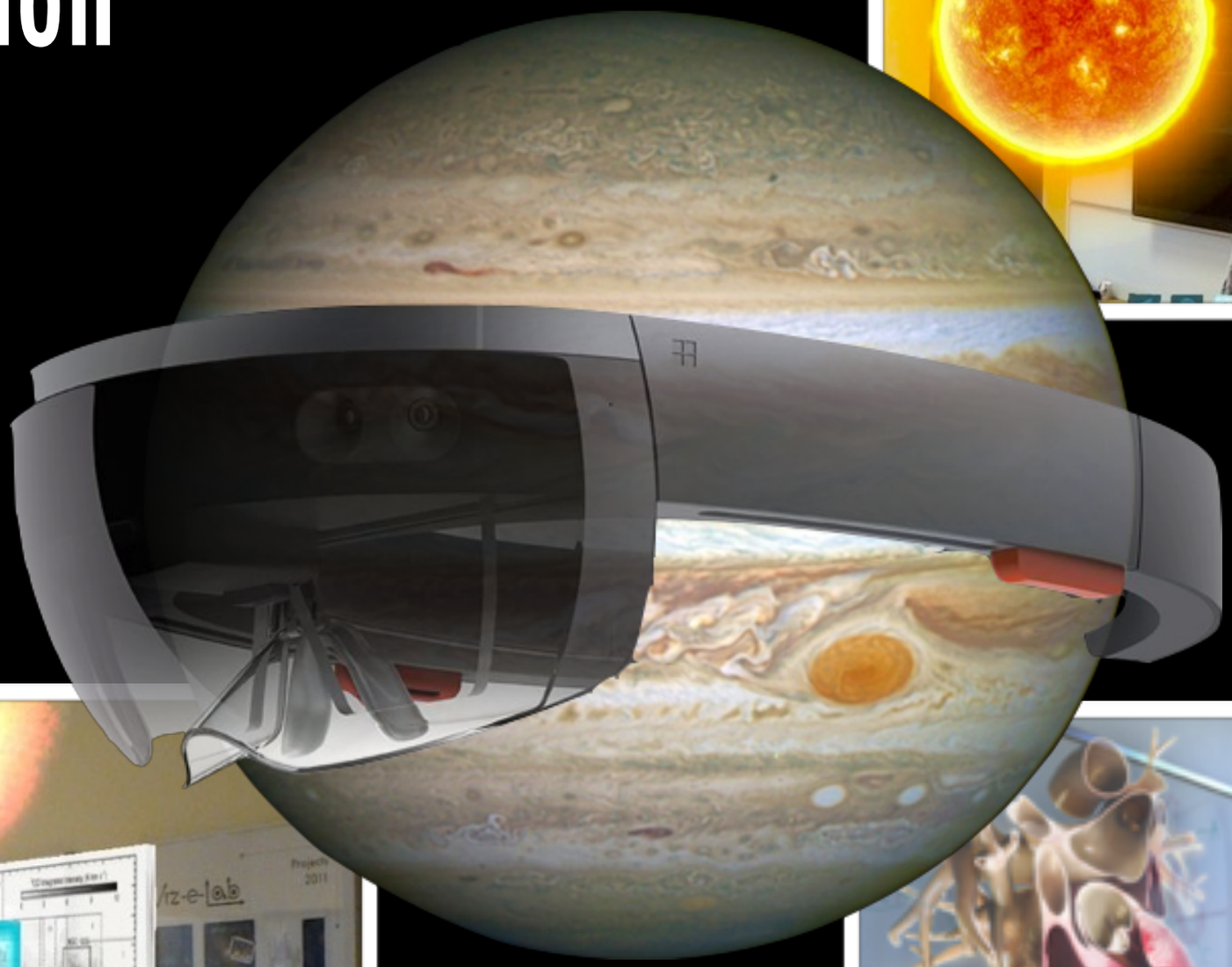
1. **Who** | Who is your audience? How expert will they be about the subject and/or display conventions?
2. **Explore-Explain** | Is your goal to explore, document, or explain your data or ideas, or a combination of these?
3. **Categories** |Do you want to show or explore pre-existing, known, human-interpretable, categories?
4. **Patterns** |Do you want to identify new, previously unknown or undefined patterns?
5. **Predictions & Uncertainty** | Are you making a comparison between data and/or predictions? Is representing uncertainty a concern?
6. **Dimensions** | What is the intrinsic number of dimensions (not necessarily spatial) in your data, and how many do you want to show at once?
7. **Abstraction & Accuracy** | Do you need to show all the data, or is summary or abstraction OK?
8. **Context & Scale** | Can you, and do you want to, put the data into a standard frame of reference, coordinate system, or show scale(s)?
9. **Metadata** | Do you need to display or link to non-quantitative metadata? (including captions, labels, etc.)
10. **Display Modes** | What display modes might be used in experiencing your display?

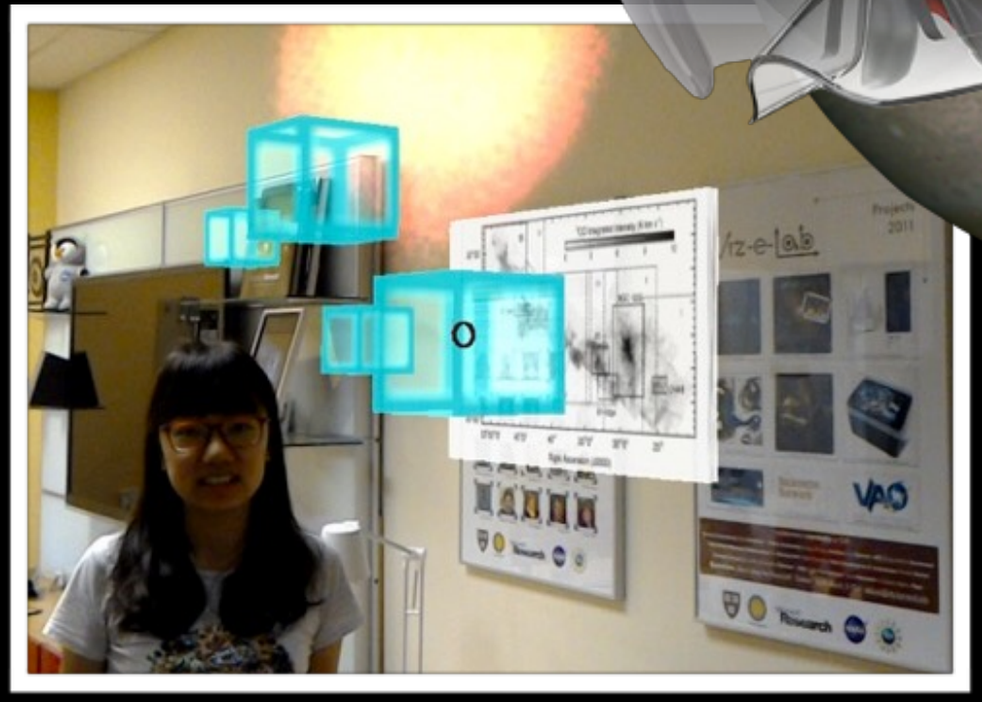
Join the 10QViz Conversation!

*To learn more about this site, please visit the **About** page.*

To read an in-process manuscript giving the scholarship behind the recommendations on this site, see Coltekin & Goodman 2018.

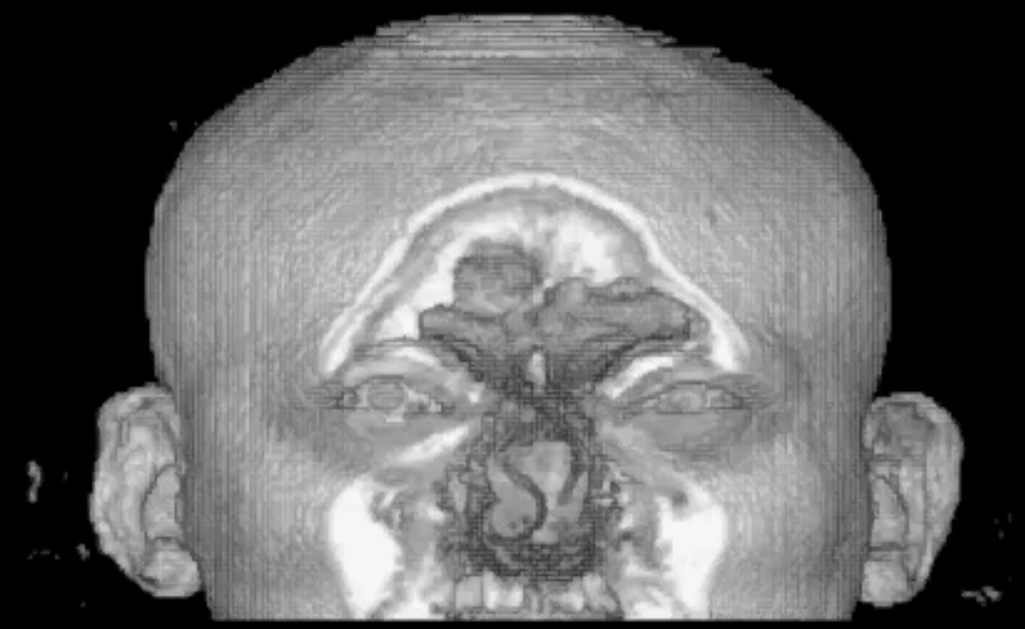
The challenge of 3D Selection





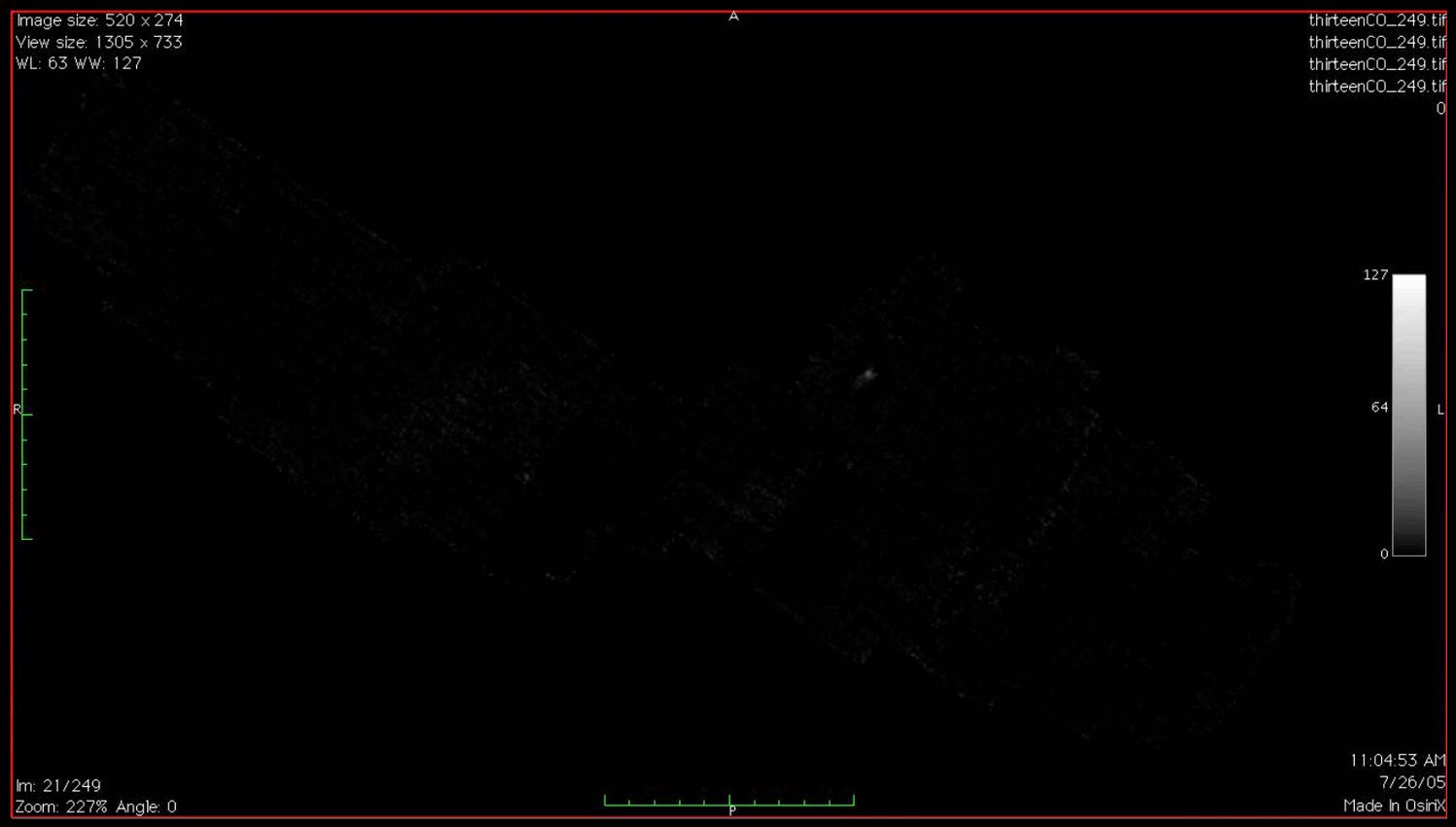
ASTRONOMICAL MEDICINE

“KEITH”



“z” is depth into head

“PERSEUS”



“z” is line-of-sight velocity

ASTRONOMICAL MEDICINE

mage size: 520 x 274
iew size: 1305 x 733
L: 63 WW: 127

mm peak (Enoch et al. 2006)

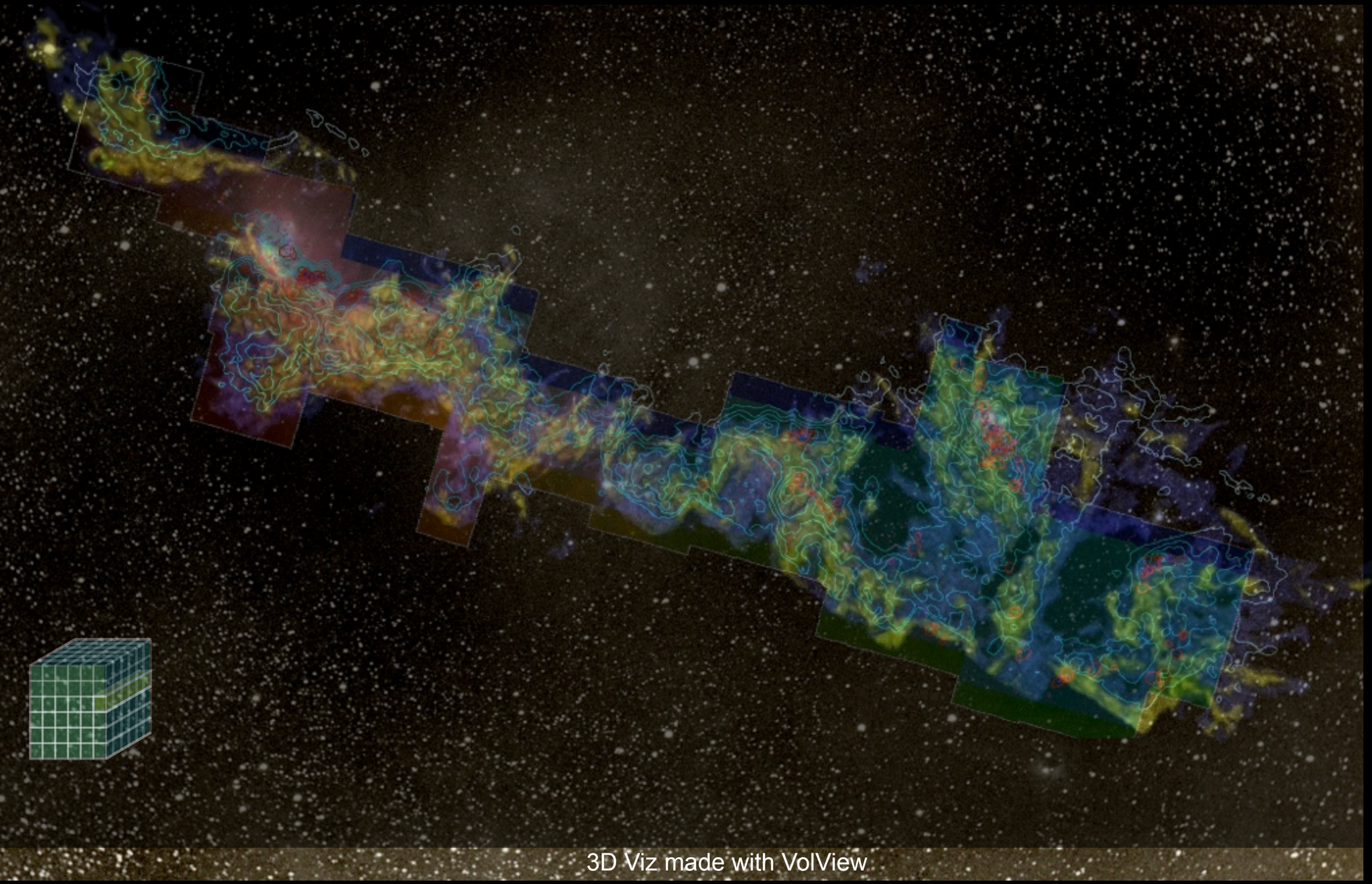
sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)

^{13}CO (Ridge et al. 2006)

mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.)

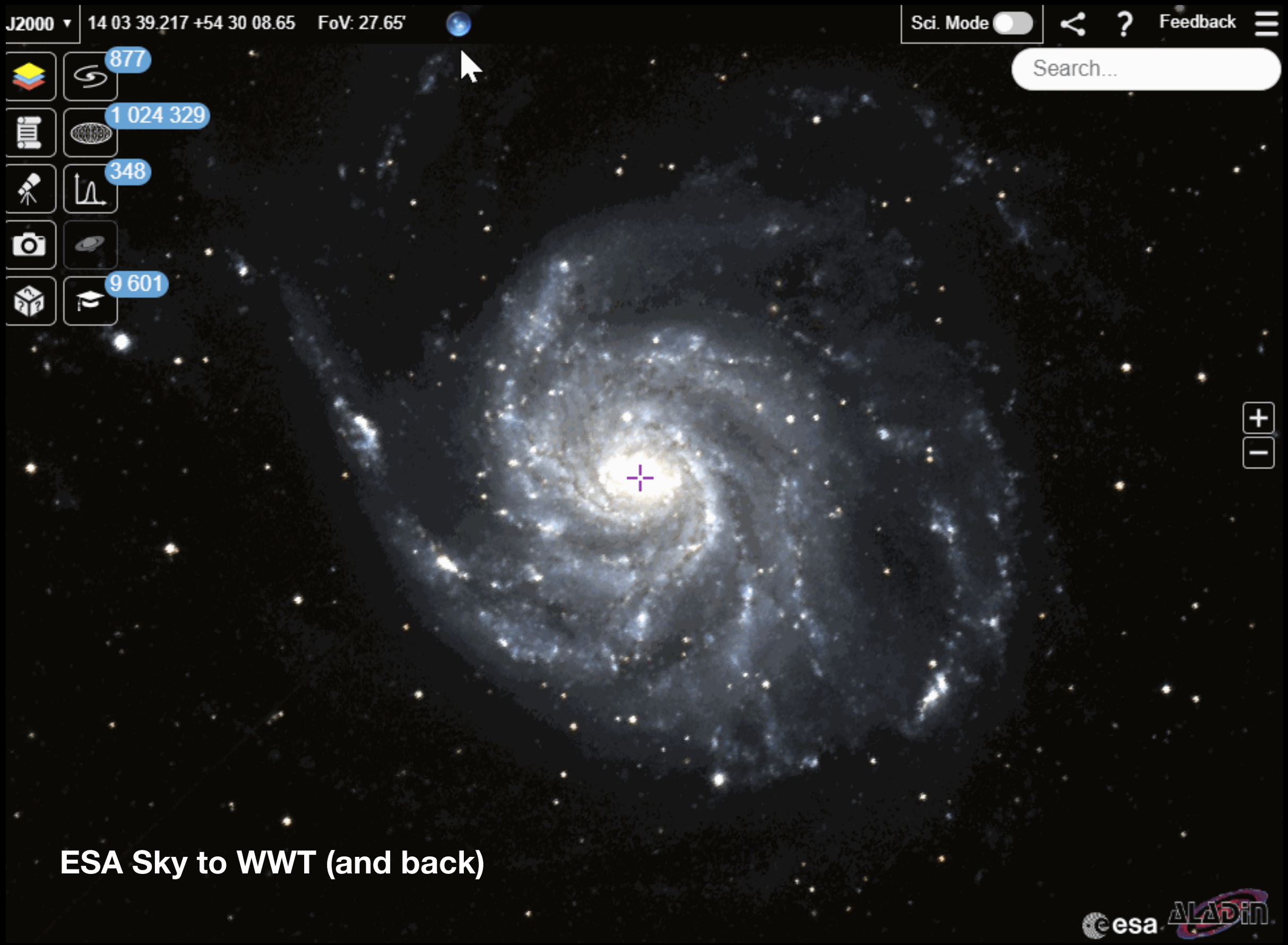
Optical image (Barnard 1927)

n: 1/249
oom: 227% Angle: 0



3D Viz made with VolView

COMPLETE


J2000
14 03 39.217 +54 30 08.65
FoV: 27.65'
Sci. Mode
Feedback
Search...
877
1 024 329
348
9 601
ESA Sky to WWT (and back)
esa
ALADIN