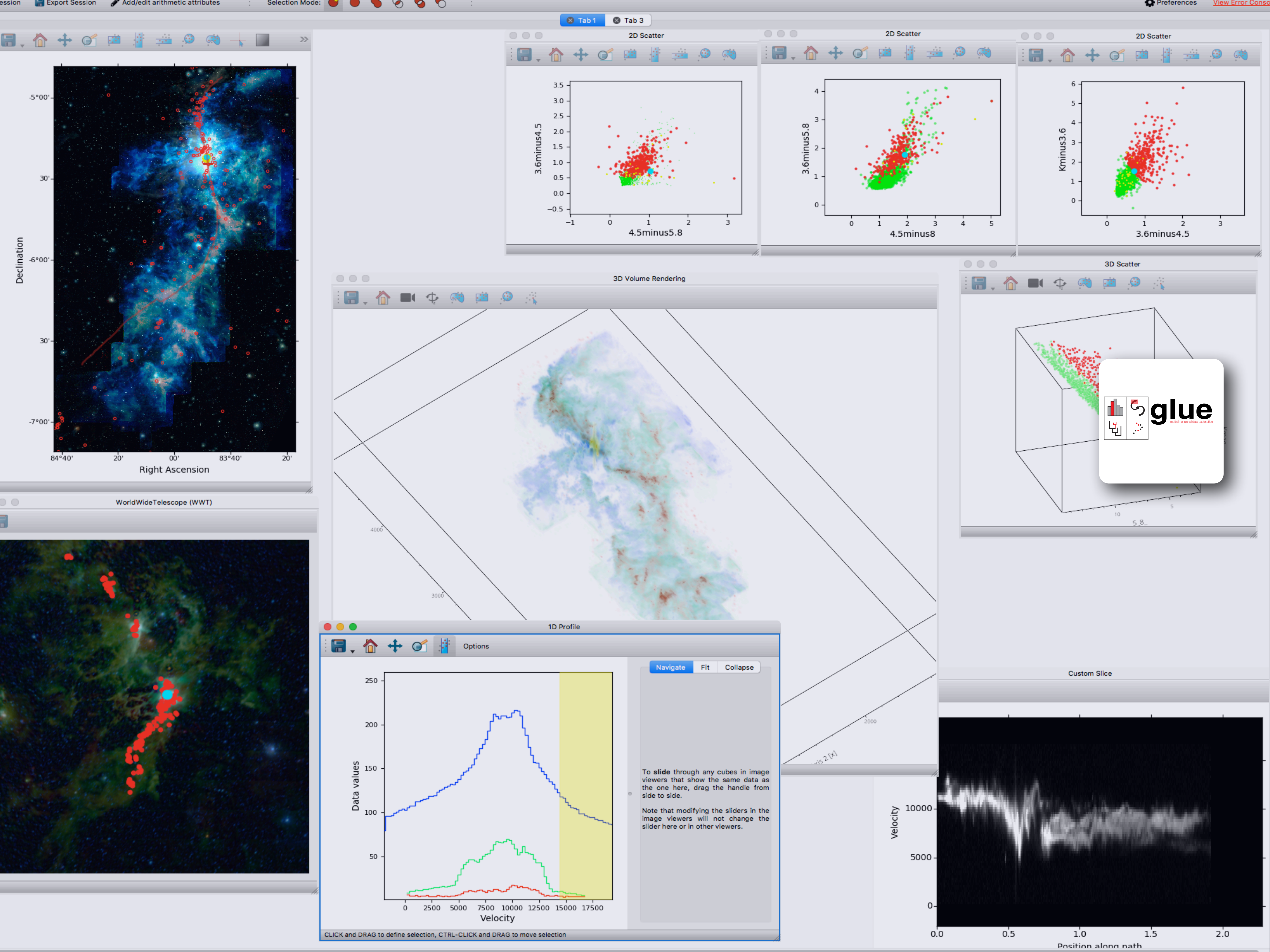
glue-ing together the Universe

Alyssa A. Goodman
Center for Astrophysics | Harvard & Smithsonian, Radcliffe Insitute for Advanced Study,
HDSI Steering Committee & glue solutions, inc.

@AlyssaAGoodman


Export Session
Add/edit arithmetic attributes
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View Error Console
Tab 1
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2D Scatter
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4.5minus5.8
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3.6minus4.5
3D Volume Rendering
3D Scatter
glue
WorldWideTelescope (WWT)
1D Profile
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To slide through any cubes in image viewers that show the same data as the one here, drag the handle from side to side.
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CLICK and DRAG to define selection, CTRL-CLICK and DRAG to move selection
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Velocity
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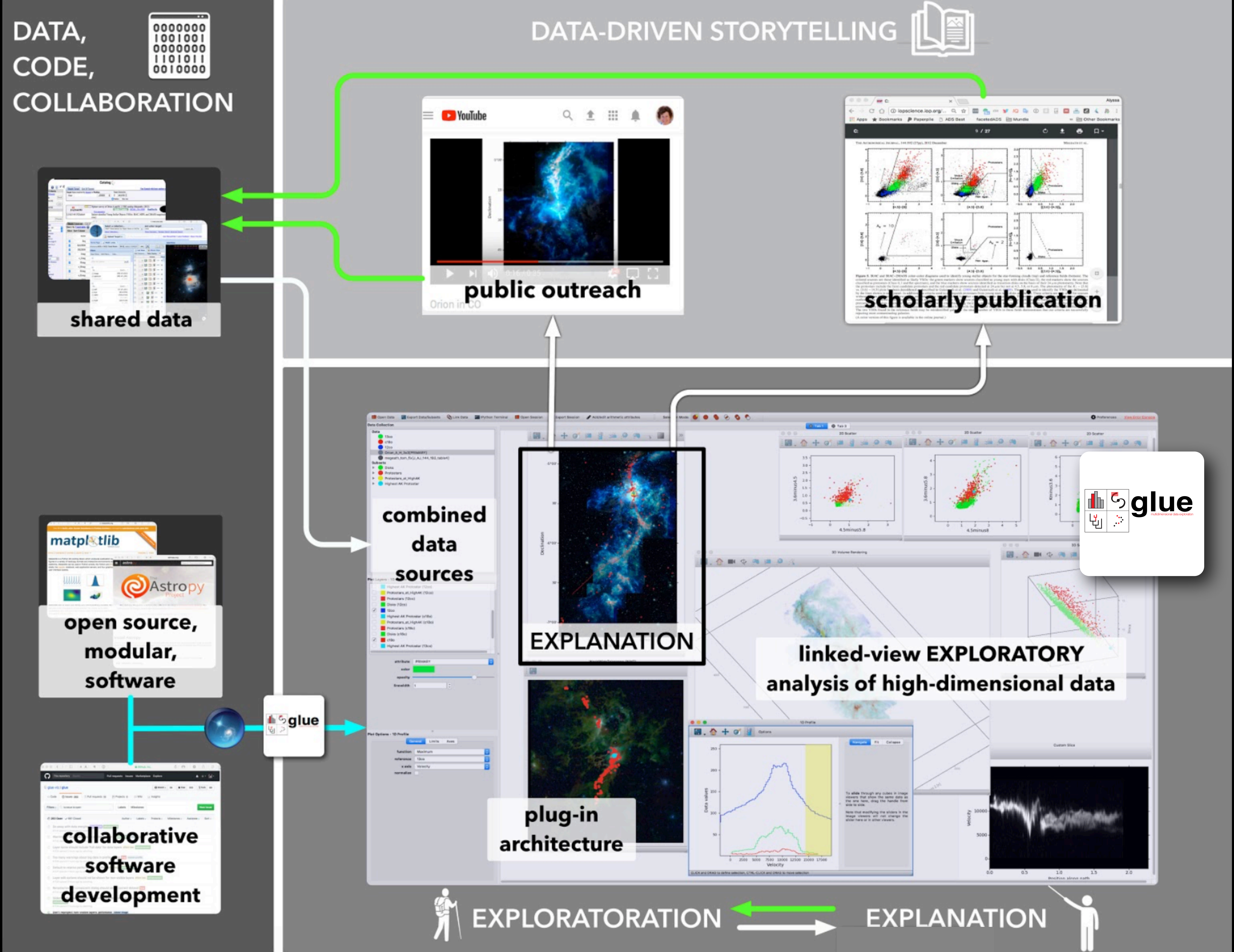
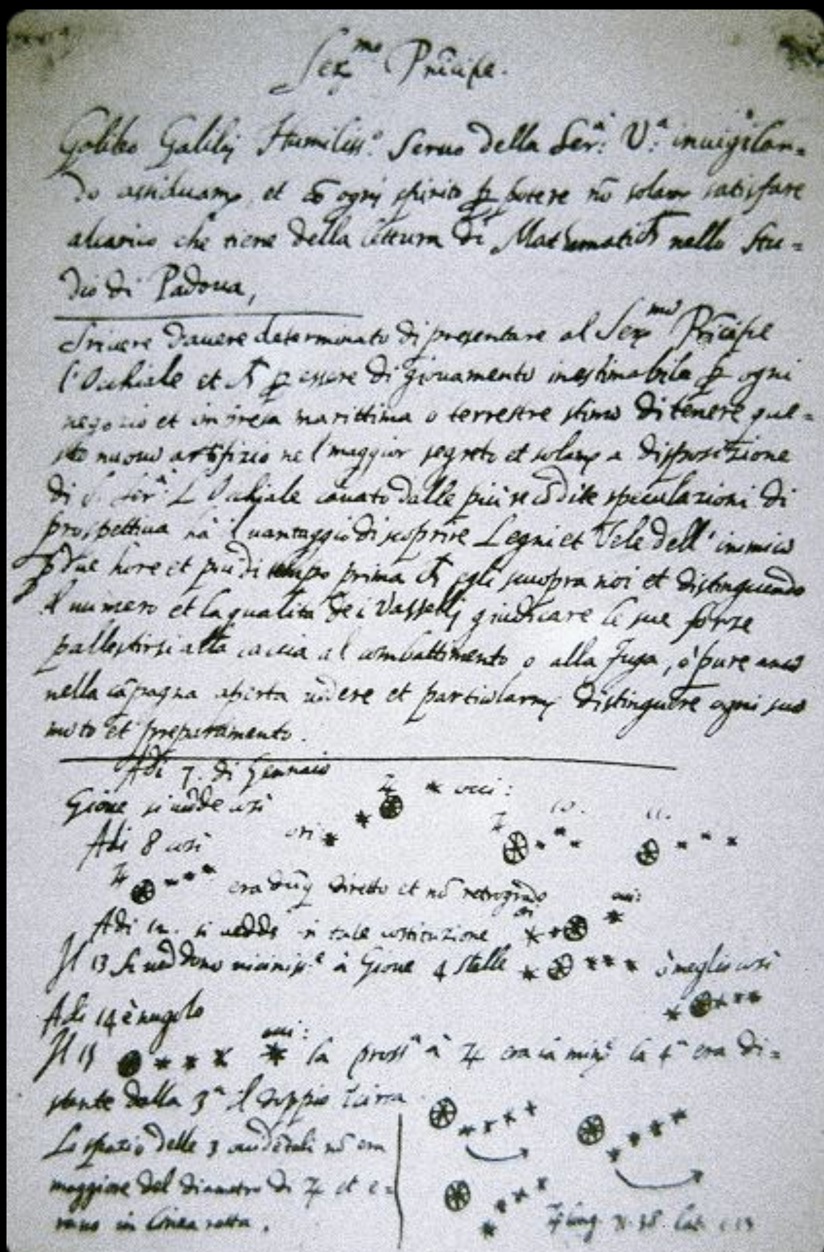
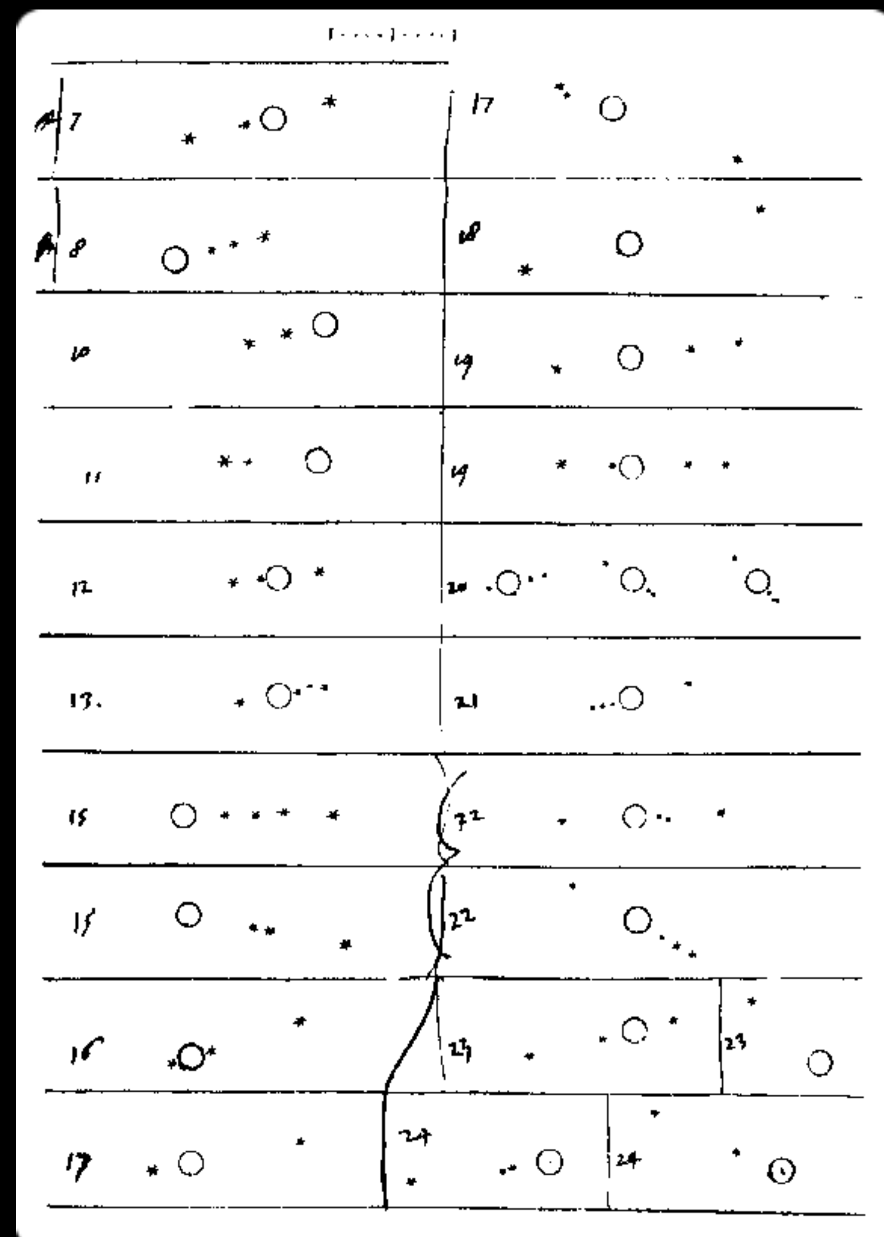
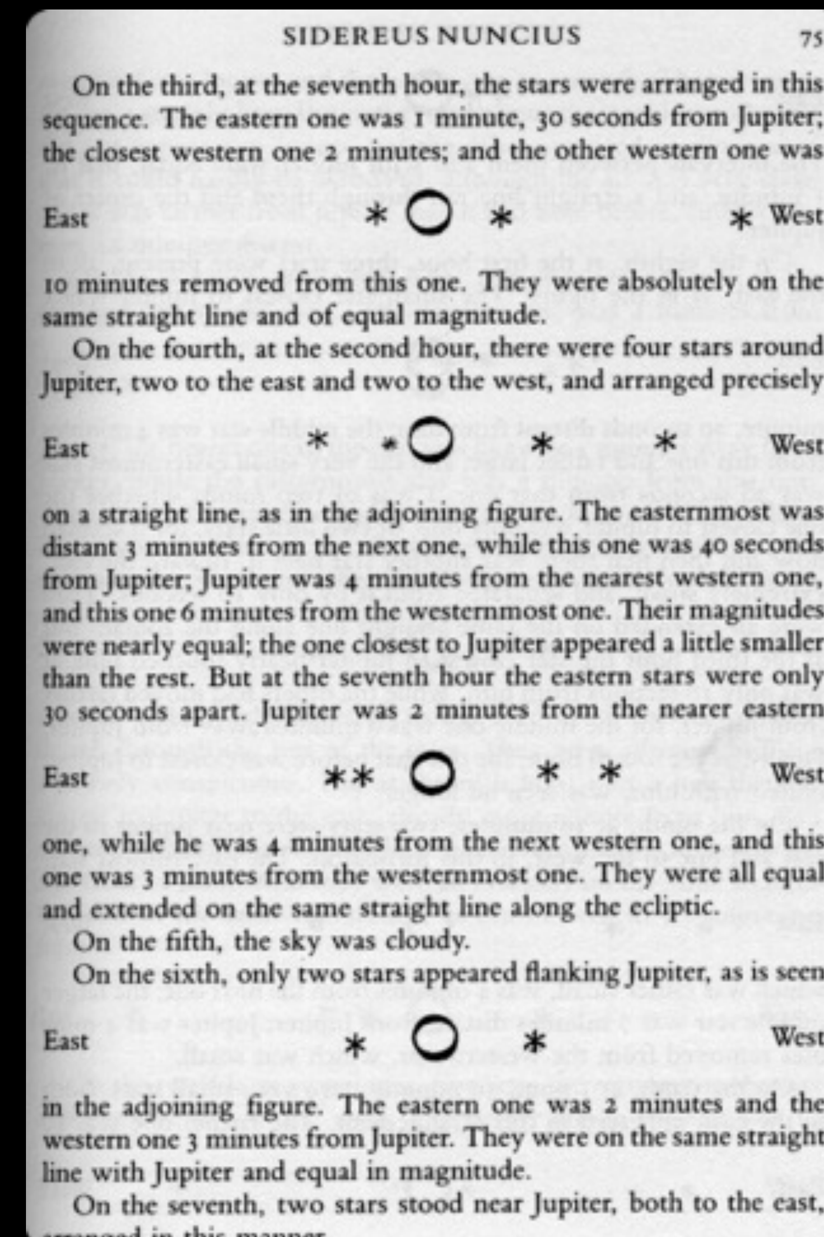


DATA,
CODE,
COLLABORATION
DATA-DRIVEN STORYTELLING
shared data
public outreach
scholarly publication
combined
data
sources
EXPLANATION
linked-view EXPLORATORY
analysis of high-dimensional data
plug-in
architecture
open source,
modular,
software
collaborative
software
development
glue
matplotlib
Astropy
EXPLORATORATION
EXPLANATION

Galileo, Jupiter’s Moons, “3D” thinking






SIDEREUS NUNCIUS 75

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

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

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

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

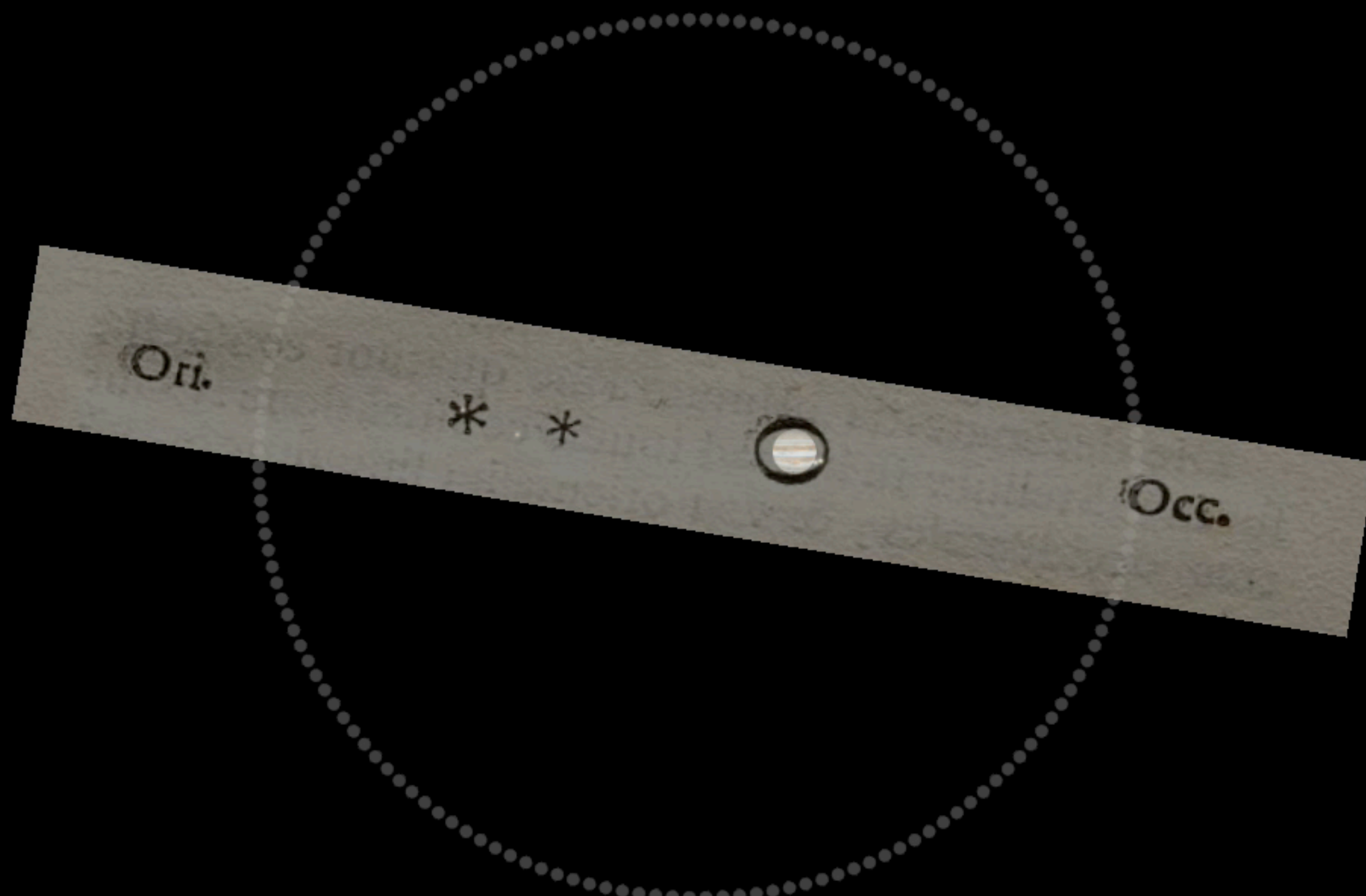
in the adjoining figure. The eastern one was 2 minutes and the western one 3 minutes from Jupiter. They were on the same straight line with Jupiter and equal in magnitude.

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

Notes for & re-productions of Siderius Nuncius

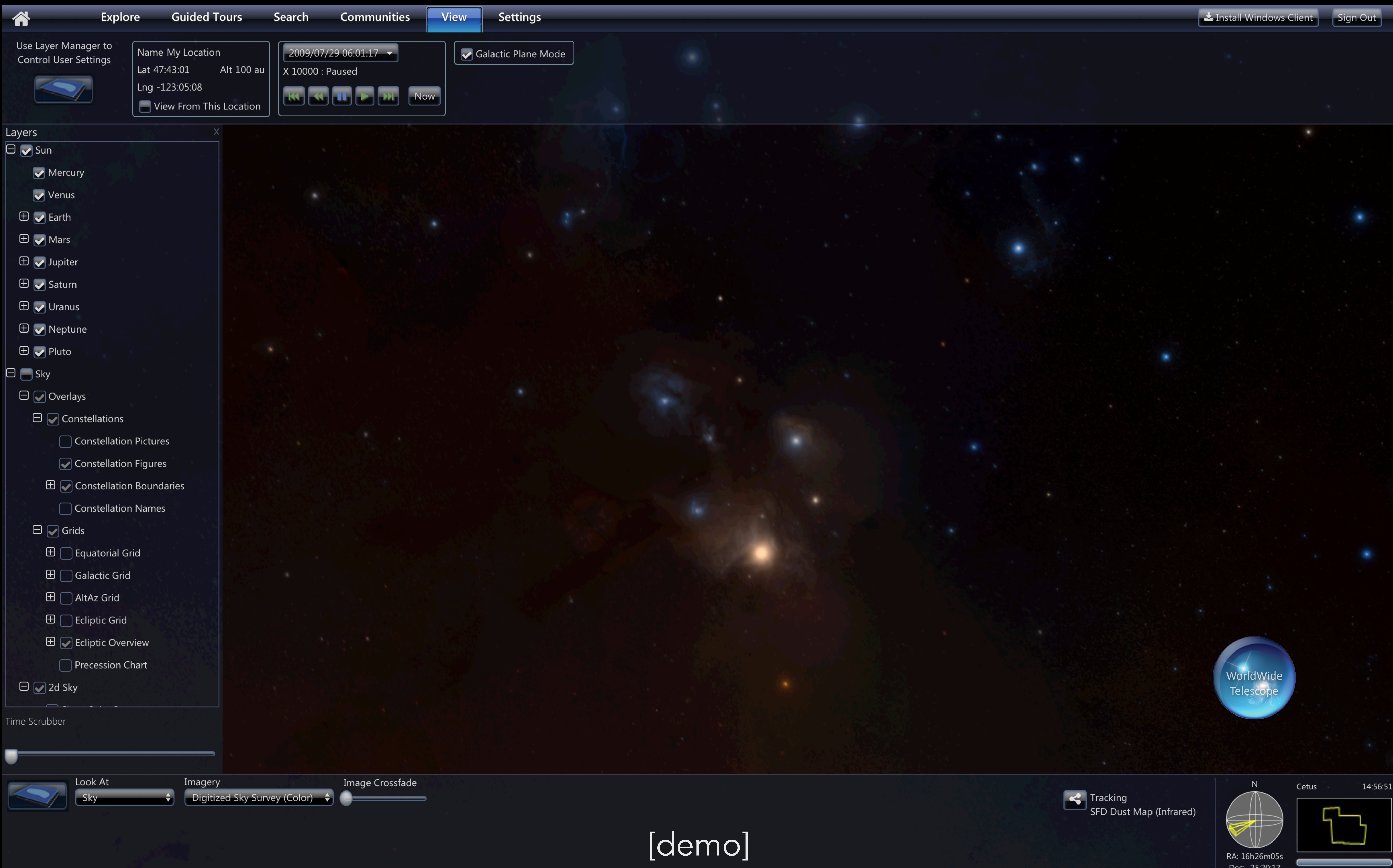
Galileo's 3D thinking, in WorldWide Telescope

January 11, 1610

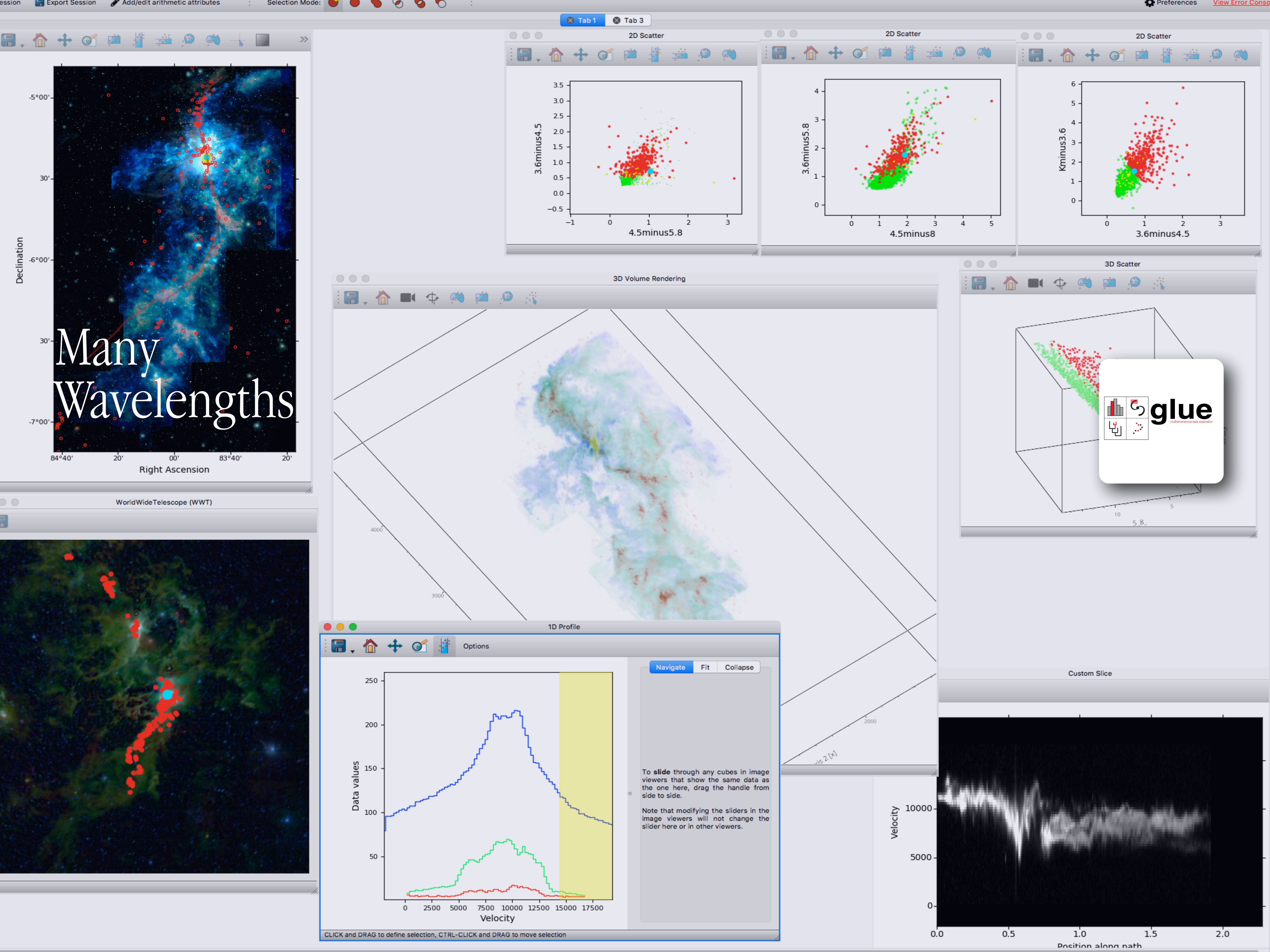


Galileo's New Order, A WorldWide Telescope Tour by Goodman, Wong & Udomprasert 2010
WWT Software Wong (inventor, MS Research), Fay (architect, MS Research), et al., now open source, hosted by AAS
see wwtambassadors.org for more on WWT Outreach

The Sky at Many Wavelengths in a “WorldWide Telescope”



[demo]



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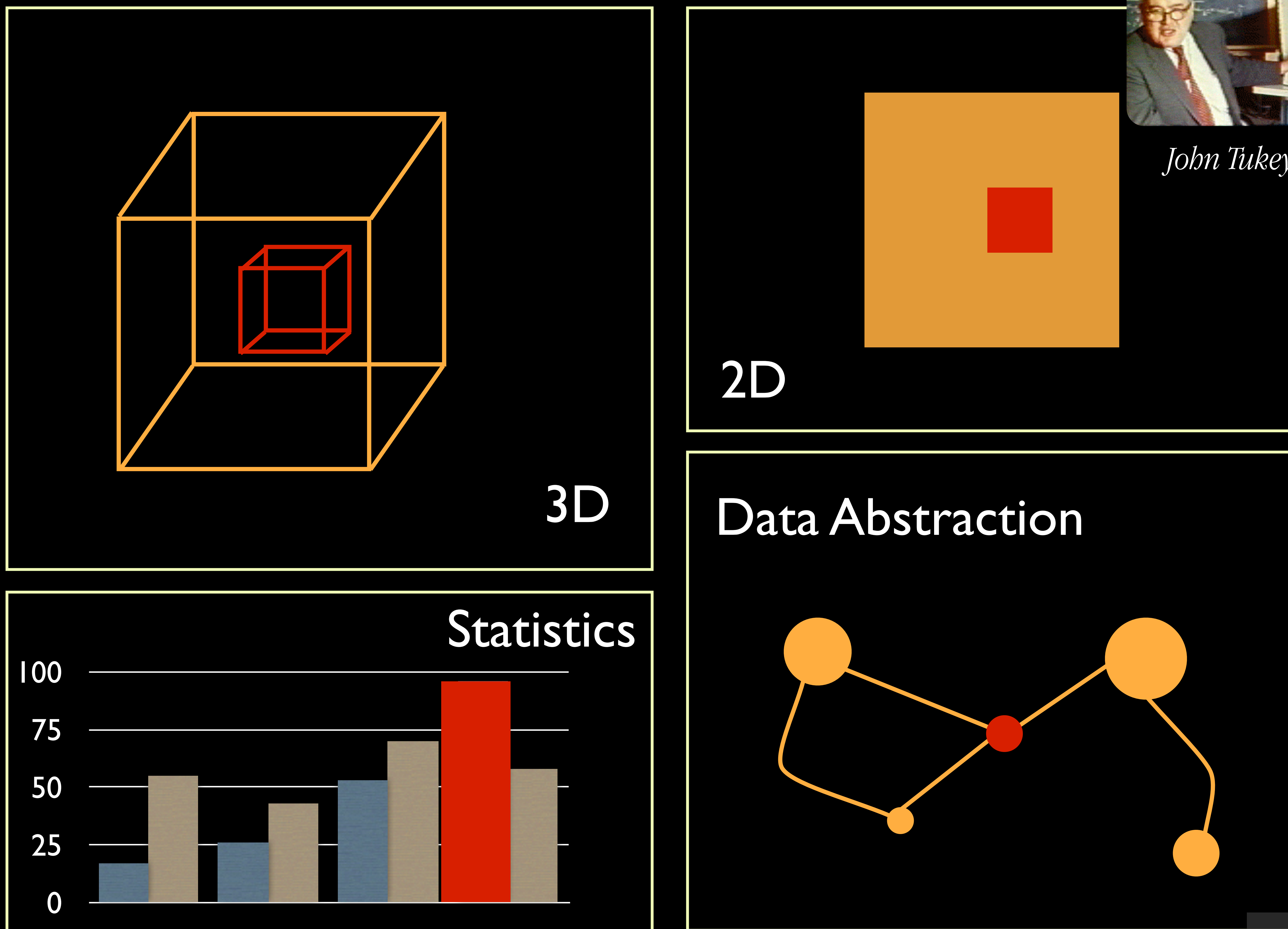
Velocity
Position along path

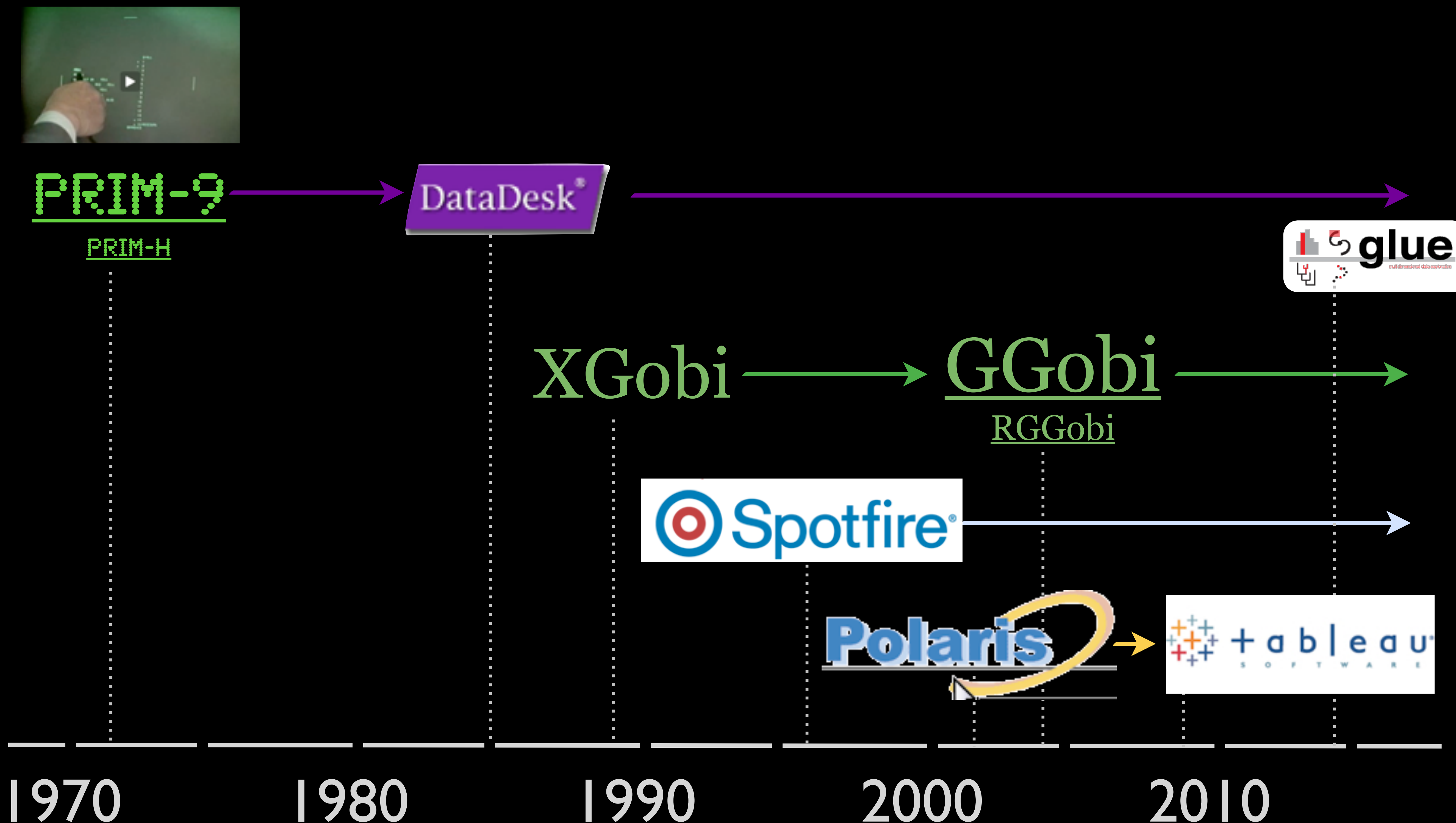
Linked Views of High-dimensional Data

John Tukey



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

JOHN TUKEY'S LEGACY



"3D PDF" (Nature, 2009)

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Tools Comment Share

Vol 457 | 1 January 2009 | doi:10.1038/nature07609

nature

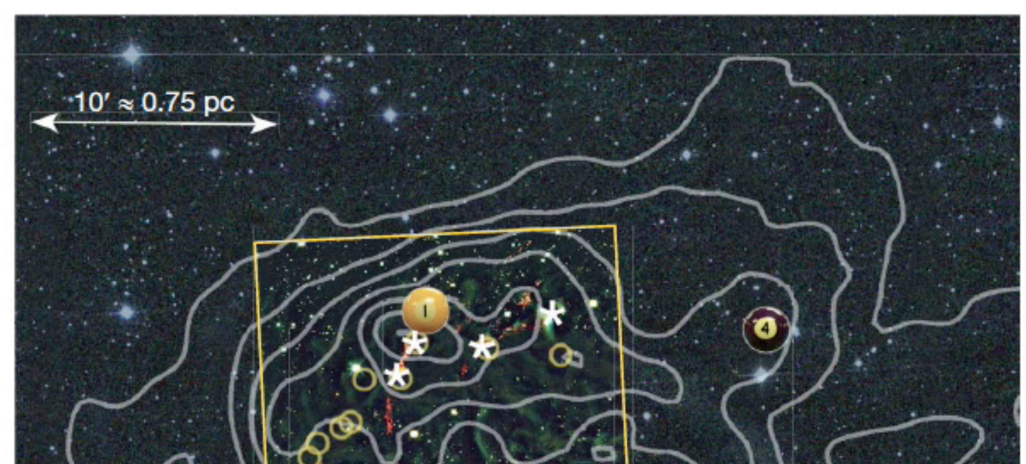
LETTERS

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



2009

3D PDF

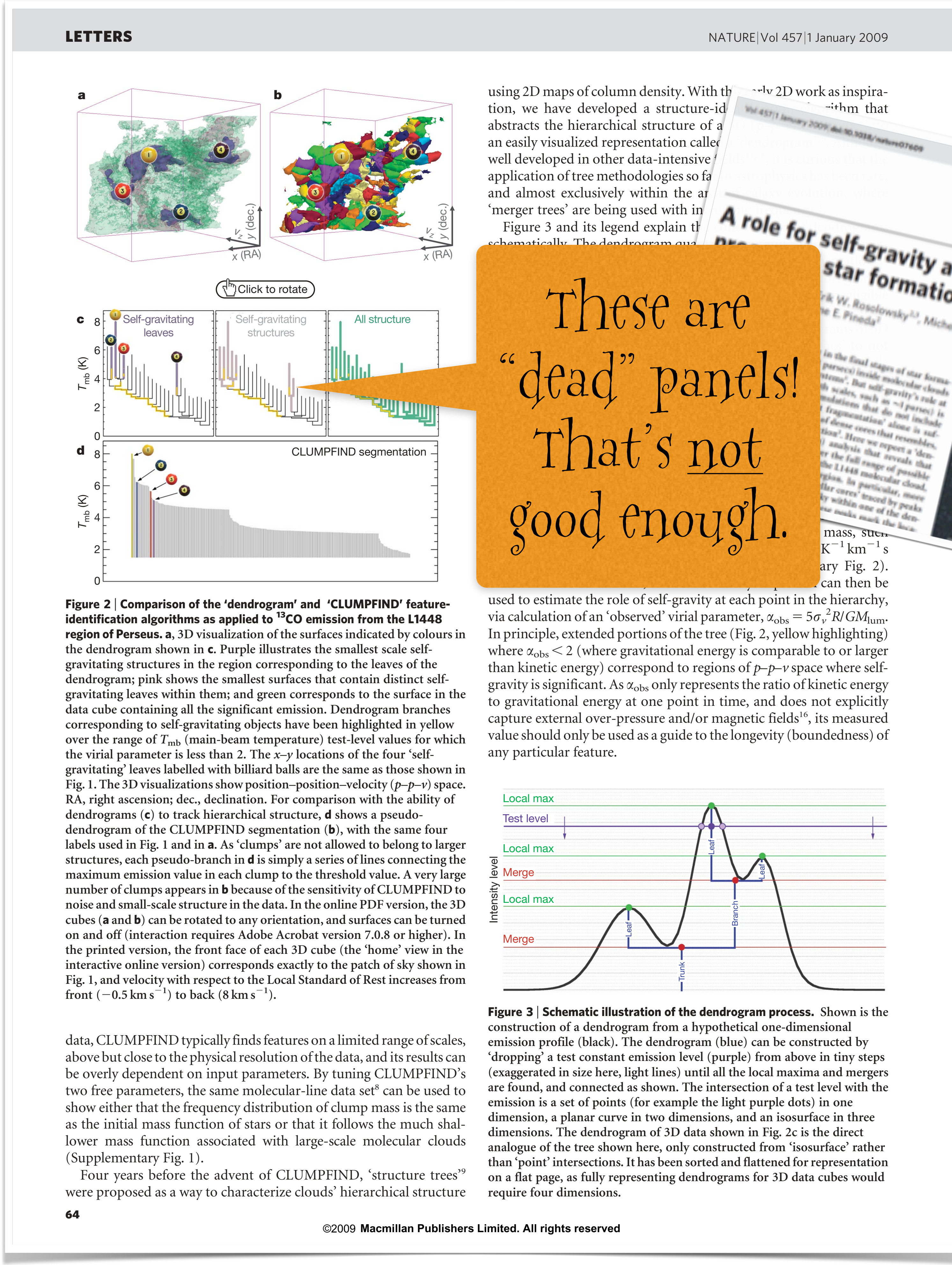


Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. **a**, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating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

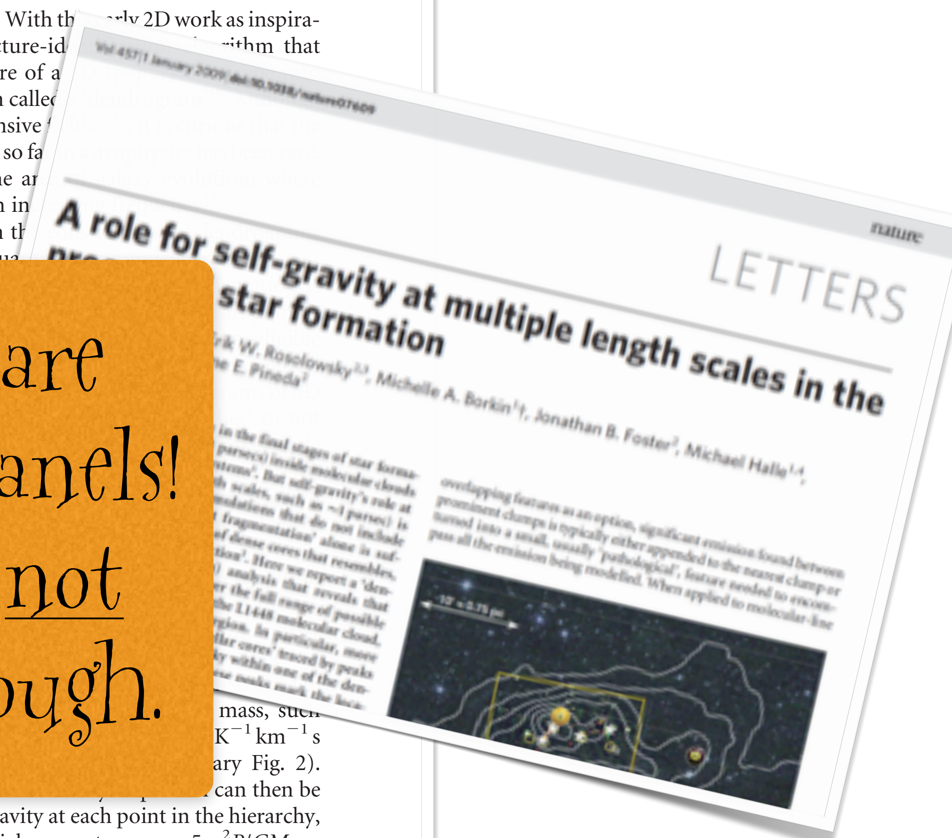
Four years before the advent of CLUMPFIND, 'structure trees'[9] were proposed as a way to characterize clouds' hierarchical structure using 2D maps of column density. With th[…]rly 2D work as inspiration, we have developed a structure-id[…]rithm that abstracts the hierarchical structure of a […] an easily visualized representation calle[…] well developed in other data-intensive […] application of tree methodologies so fa[…] and almost exclusively within the a[…] 'merger trees' are being used with in[…]

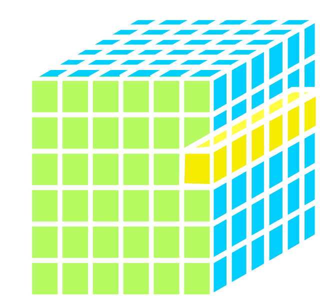
Figure 3 and its legend explain th[…] schematically. The dendrogram qua[…]

[…] mass, such […] 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.

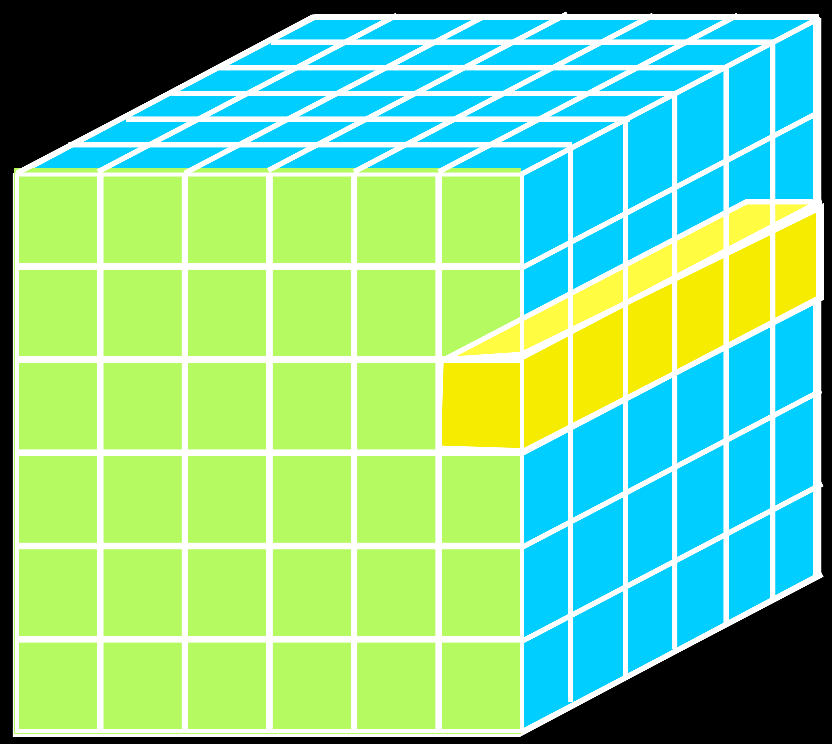
Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in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

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





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



"DATA, DIMENSIONS, DISPLAY"

1D: Columns = "Spectra", "SEDs" or "Time Series"

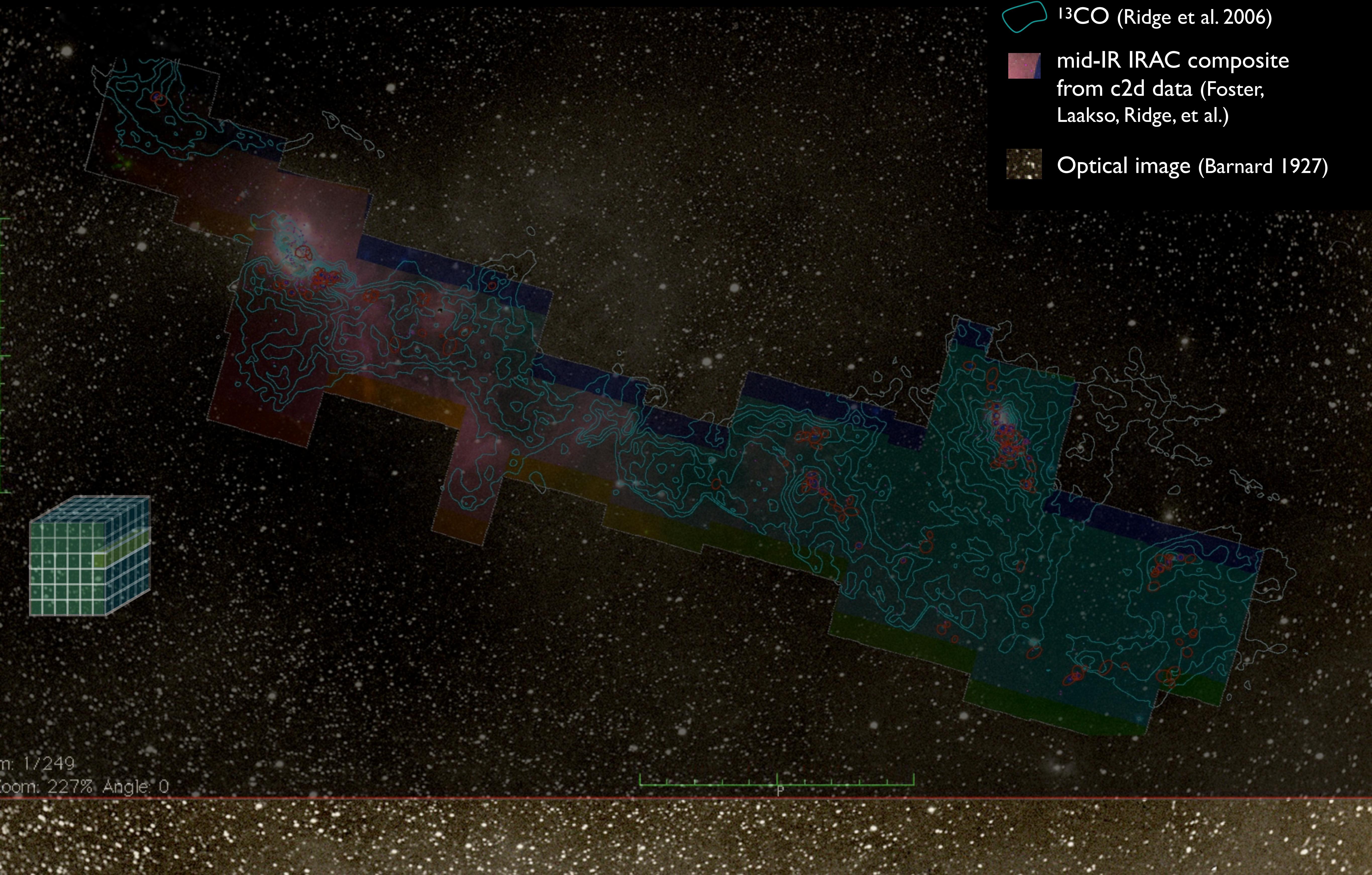
2D: Faces or Slices = "Images"

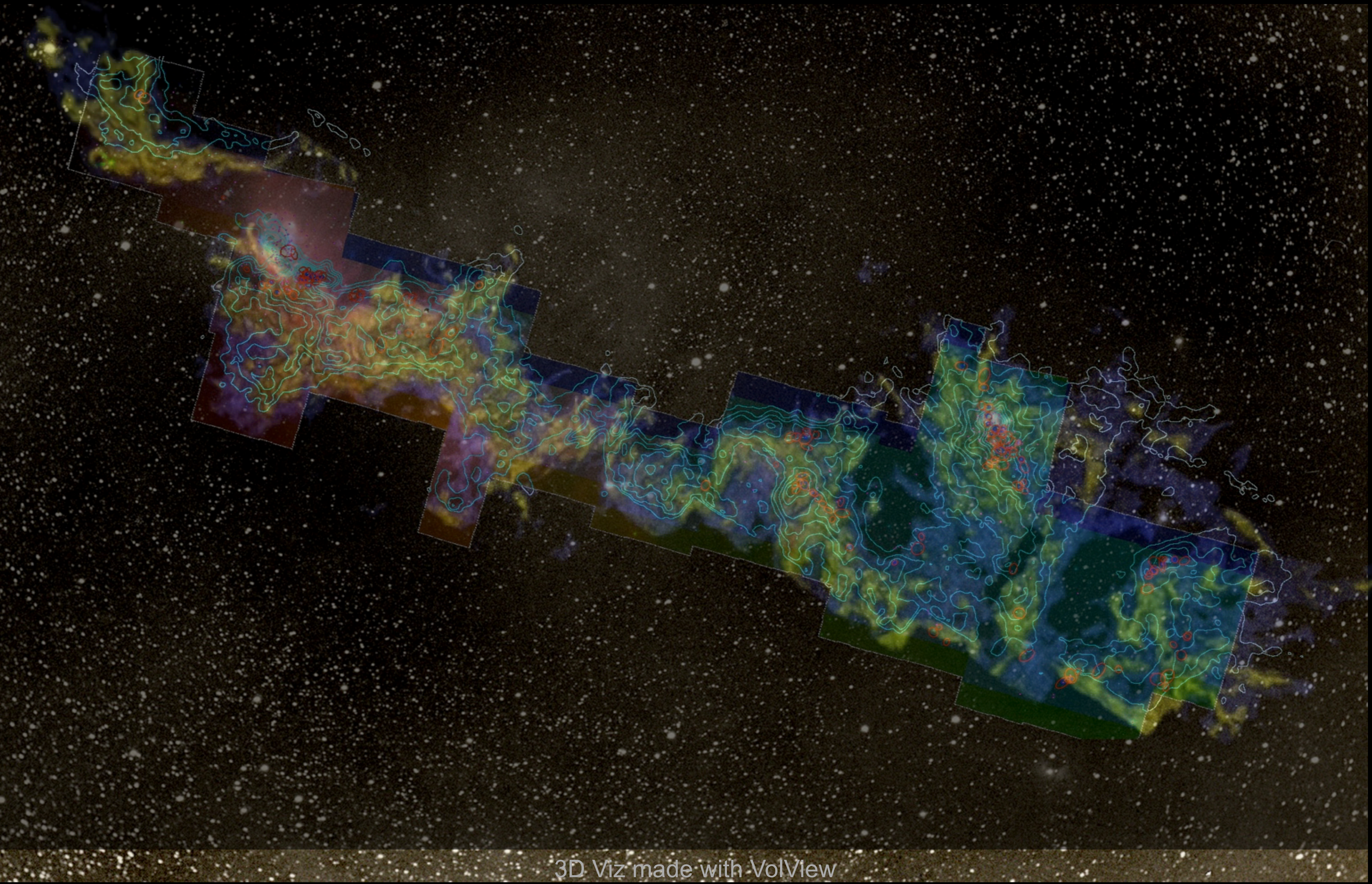
3D: Volumes = "3D Renderings", "2D Movies"

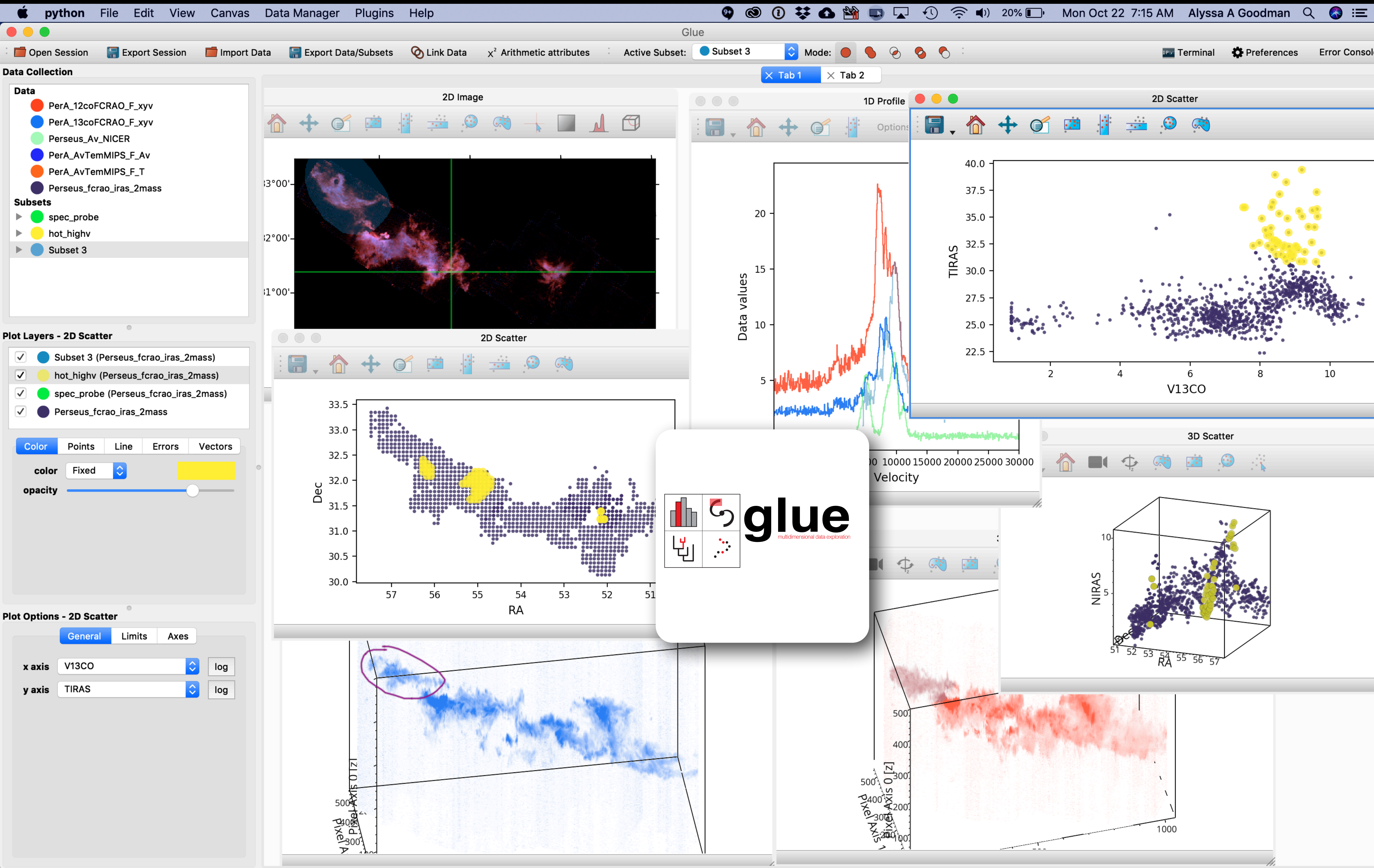
4D: Time Series of Volumes = "3D Movies"

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)




3D Viz made with VolView


python File Edit View Canvas Data Manager Plugins Help
Mon Oct 22 7:15 AM Alyssa A Goodman
Glue
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Export Session
Import Data
Export Data/Subsets
Link Data
Arithmetic attributes
Active Subset:
Subset 3
Mode:
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Error Console
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V13CO
3D Scatter
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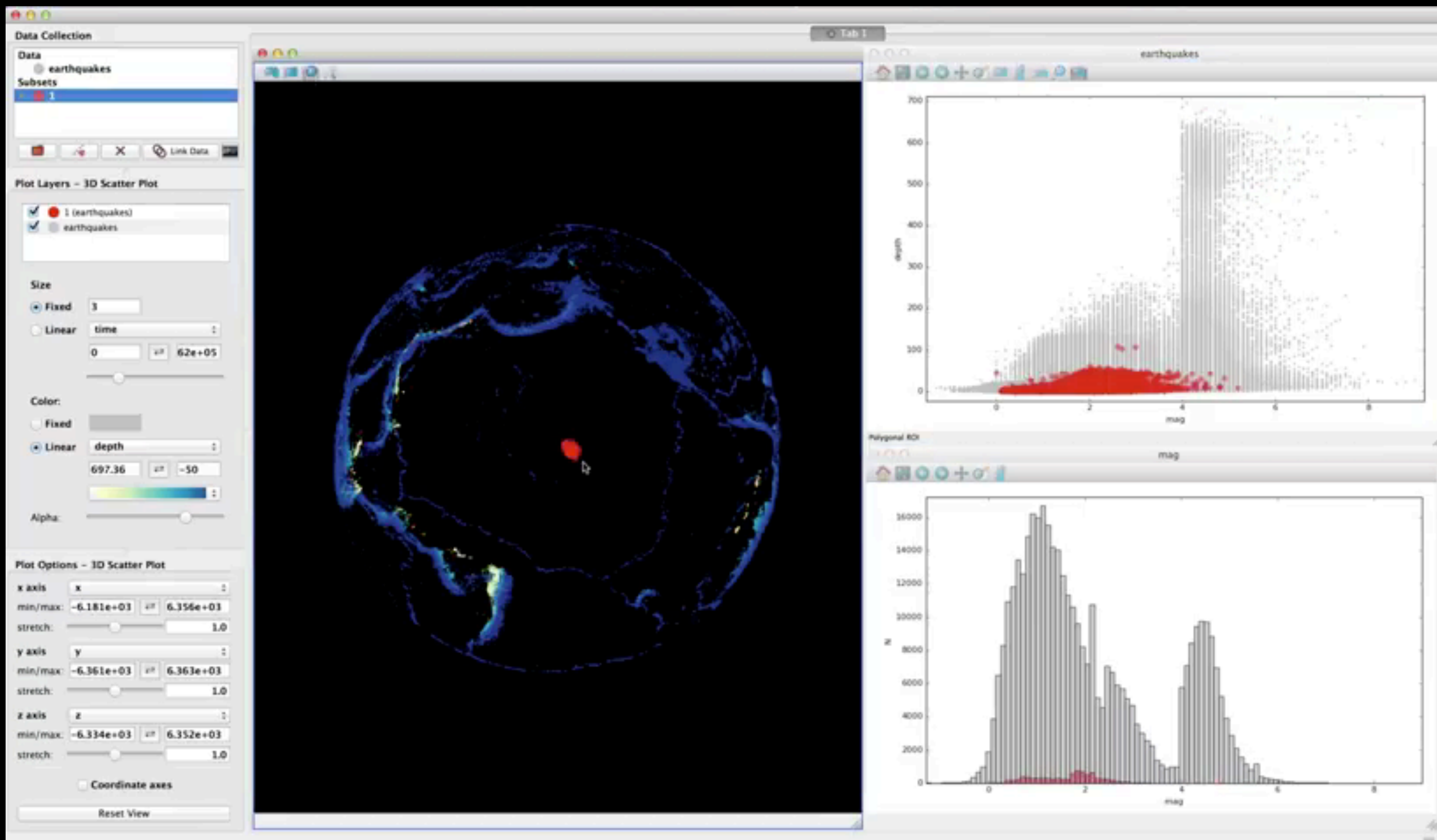
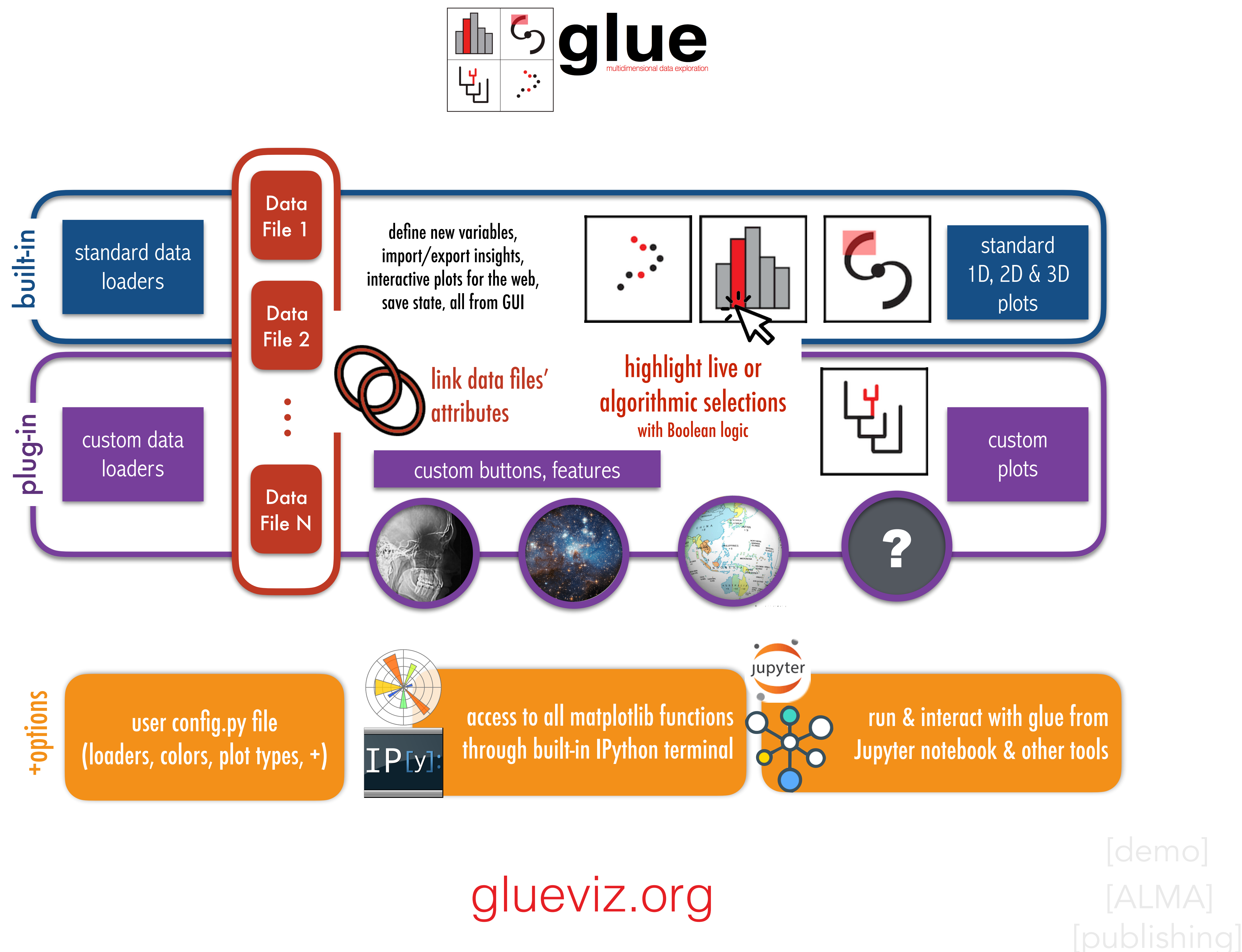
glue
multidimensional data exploration

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



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
plug-in
custom data loaders
link data files' attributes
highlight live or algorithmic selections
with Boolean logic
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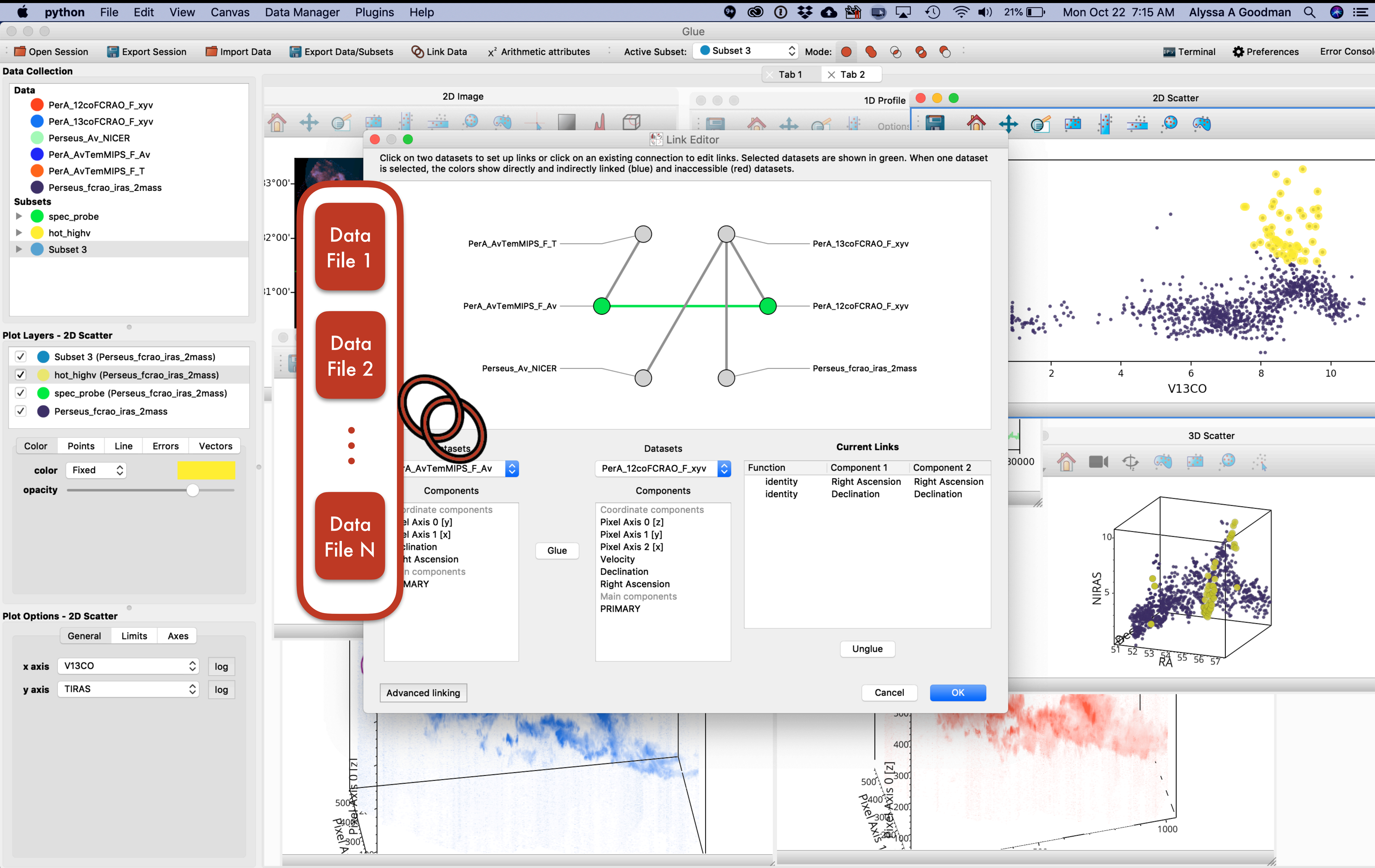
IP[y]:
access to all matplotlib functions through built-in IPython terminal
jupyter
run & interact with glue from Jupyter notebook & other tools
glueviz.org
[demo]
[ALMA]
[publishing]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1D Profile
2D Scatter
3D Scatter
Link Editor
Click on two datasets 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.
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Pixel Axis 1 [y]
Pixel Axis 2 [x]
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Declination
Right Ascension
Main components
PRIMARY
Glue
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Function
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Component 2
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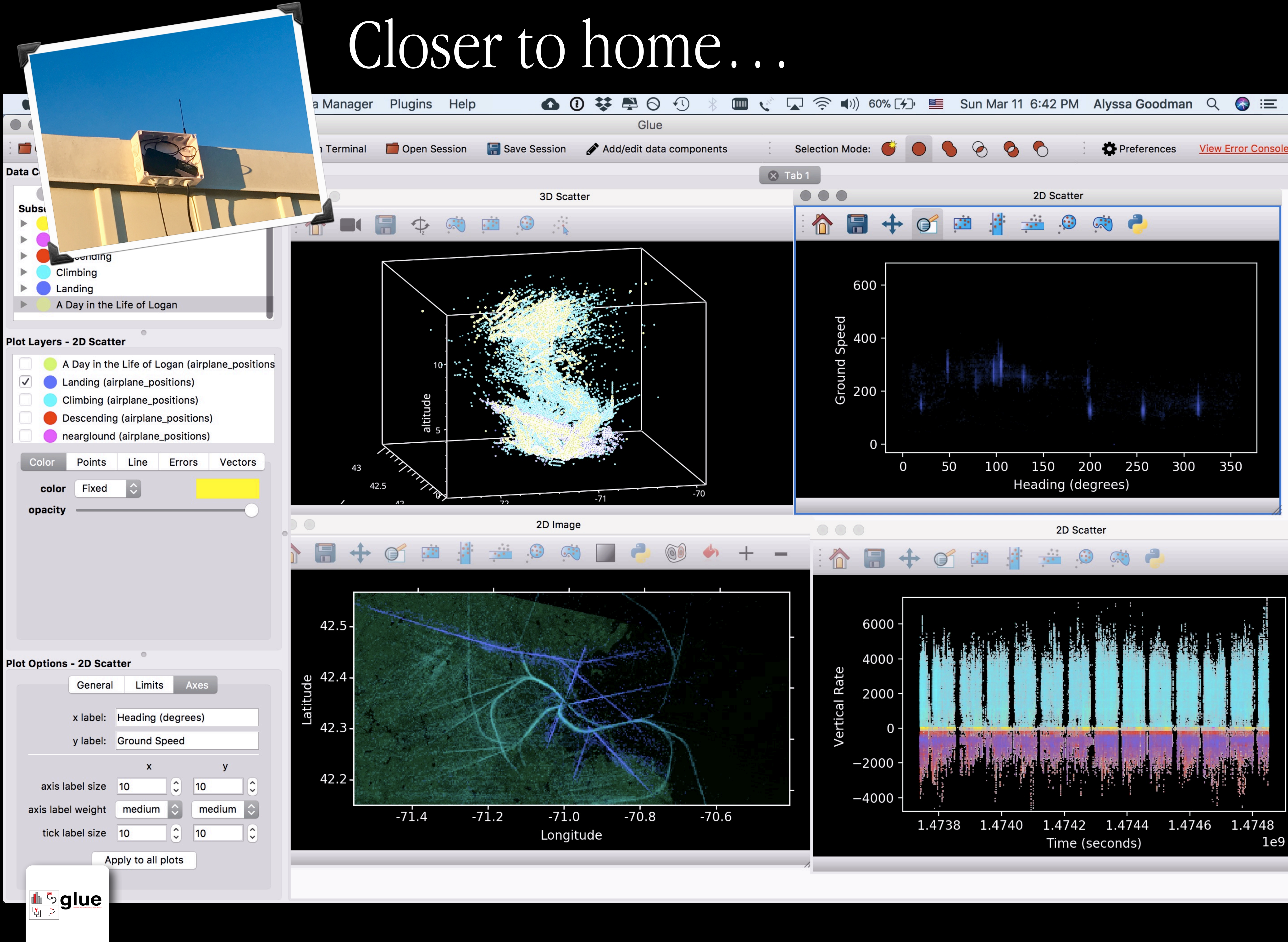
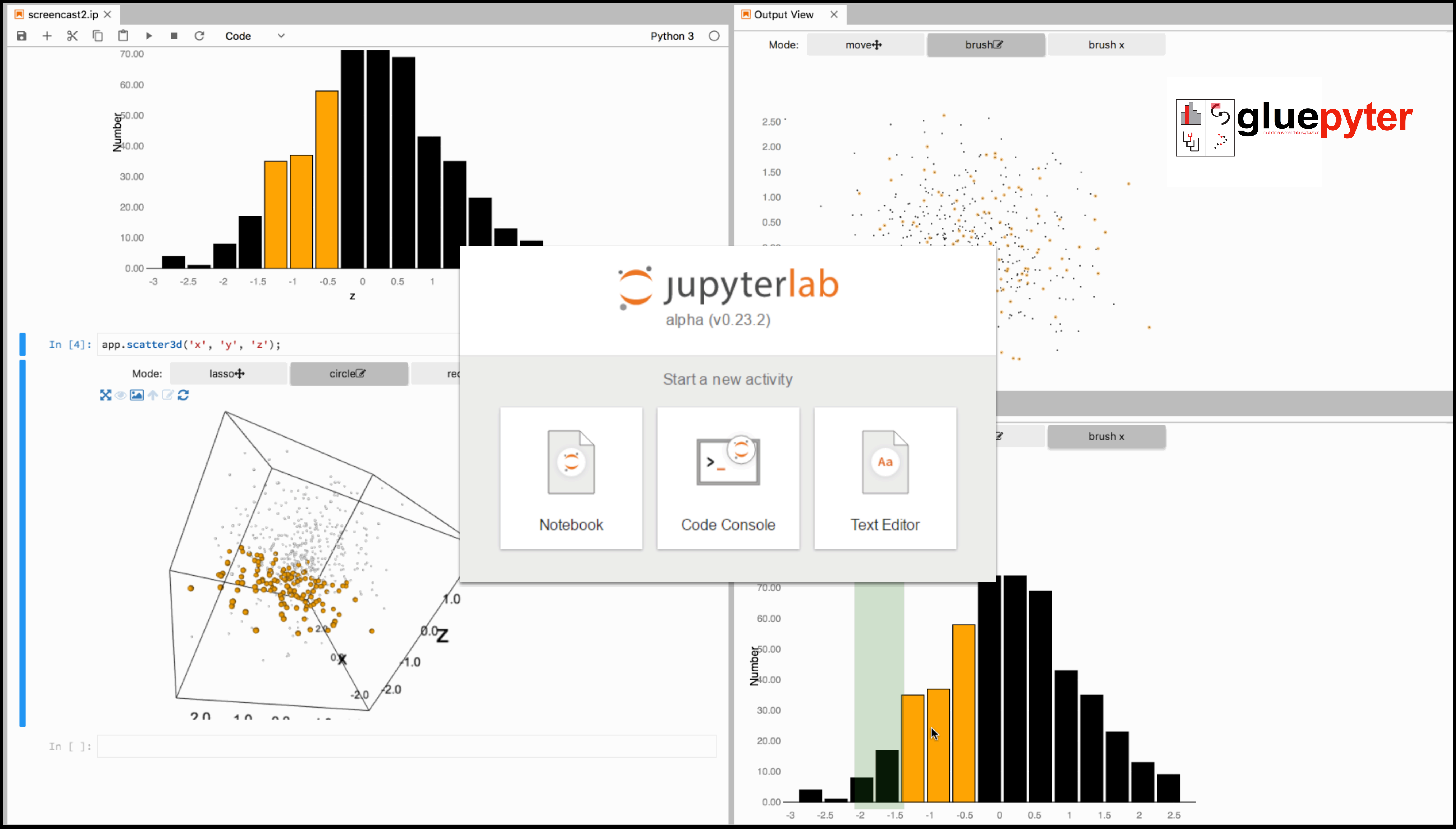
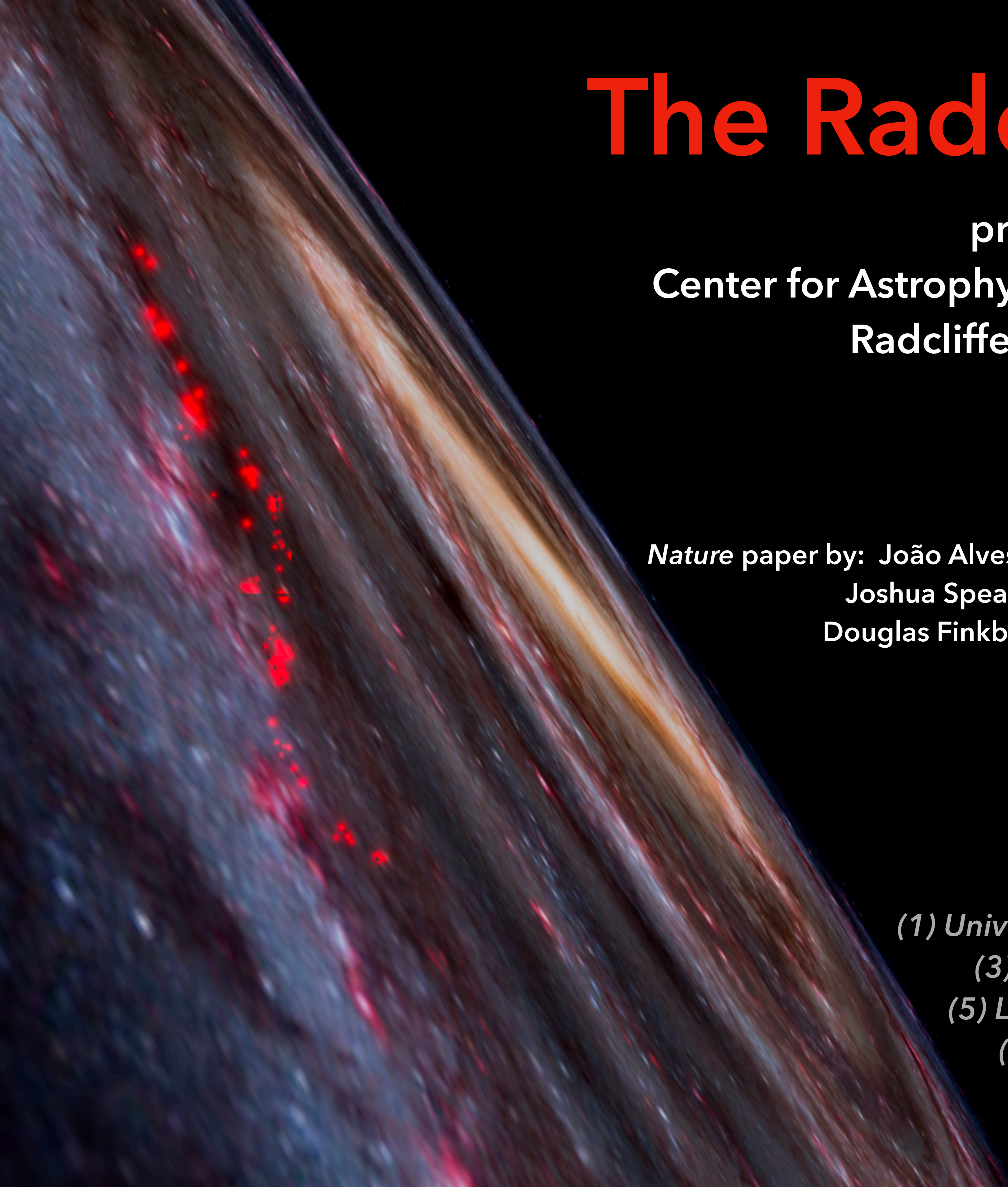
Closer to home…



“glupyter”: glue in the browser



Video courtesy of Maarten Breddels, consulting developer



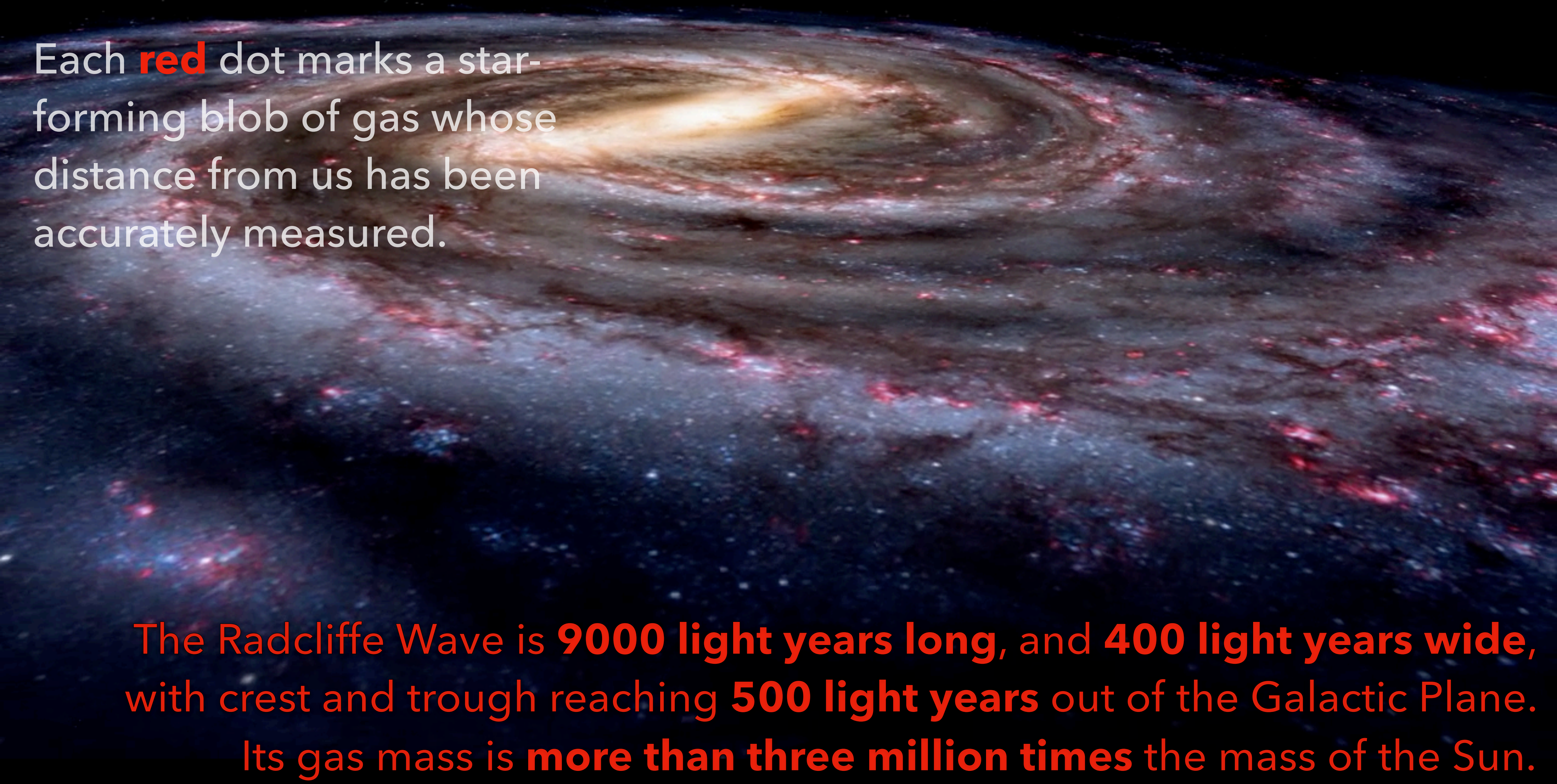
The Radcliffe Wave

presented by Alyssa Goodman,
Center for Astrophysics | Harvard & Smithsonian,
Radcliffe Institute for Advanced Study

Nature paper by: João Alves[1,3], Catherine Zucker[2], Alyssa Goodman[2,3], Joshua Speagle[2], Stefan Meingast[1], Thomas Robitaille[4], Douglas Finkbeiner[3], Edward Schlafly[5] & Gregory Green[6]

representing
(1) University of Vienna; (2) Harvard University; (3) Radcliffe Insitute; (4) Aperio Software; (5) Lawrence Berkeley National Laboratory; (6) Kavli Insitute for Particle Physics and Cosmology

The Radcliffe Wave



Each **red** dot marks a star-forming blob of gas whose distance from us has been accurately measured.

The Radcliffe Wave is **9000 light years long**, and **400 light years wide**, with crest and trough reaching **500 light years** out of the Galactic Plane. Its gas mass is **more than three million times** the mass of the Sun.

video created by the authors using AAS WorldWide Telescope
(includes cartoon Milky Way by Robert Hurt)

The Radcliffe Wave

ACTUALLY 2 IMPORTANT DEVELOPMENTS

DISTANCES!!

We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.

Zucker et al. 2019; 2020

RADWAVE

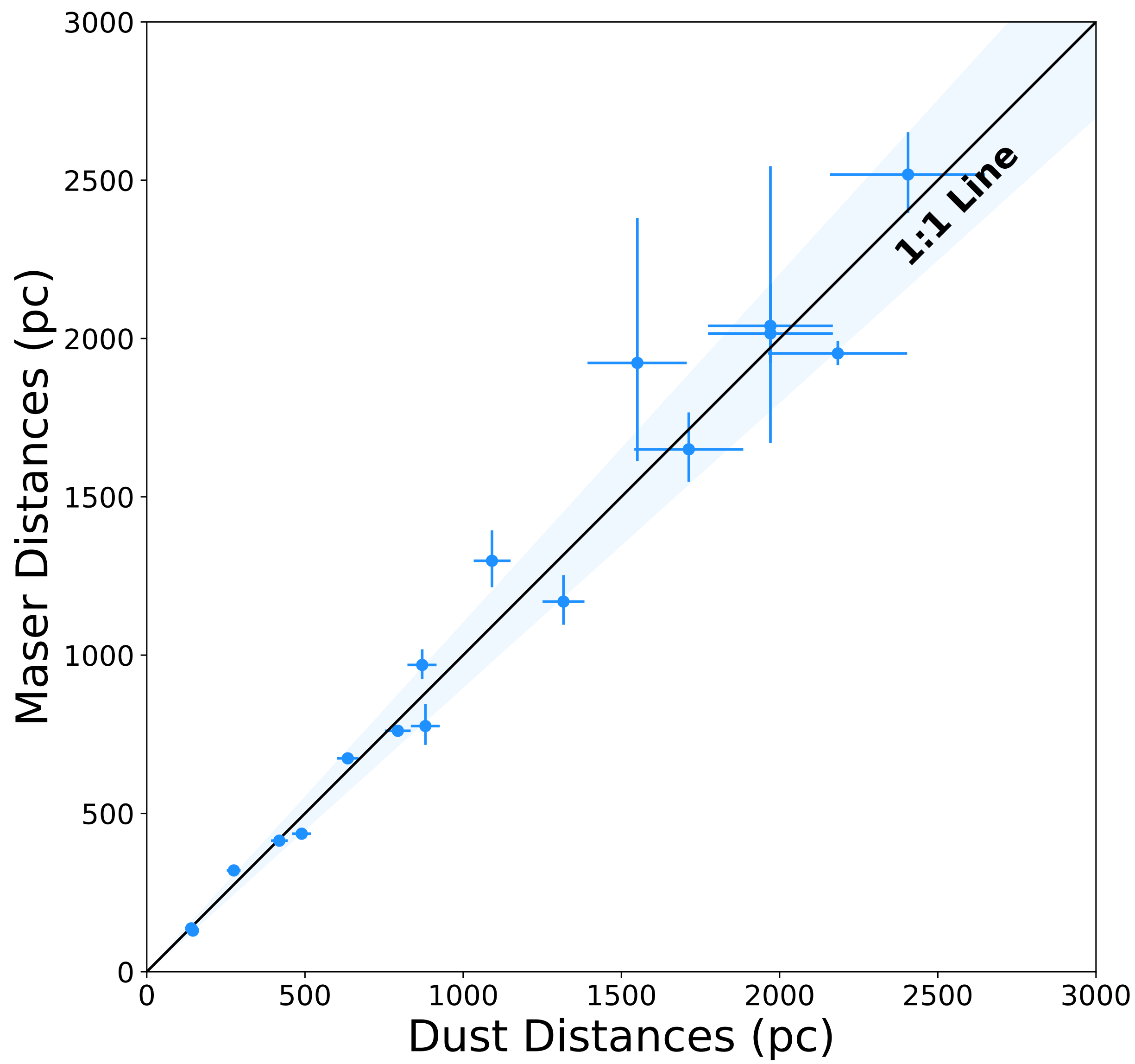
Surprising wave-like arrangement of star-forming gas *is* the "Local Arm" of the Milky Way.

Alves et al. 2020

DISTANCES!!

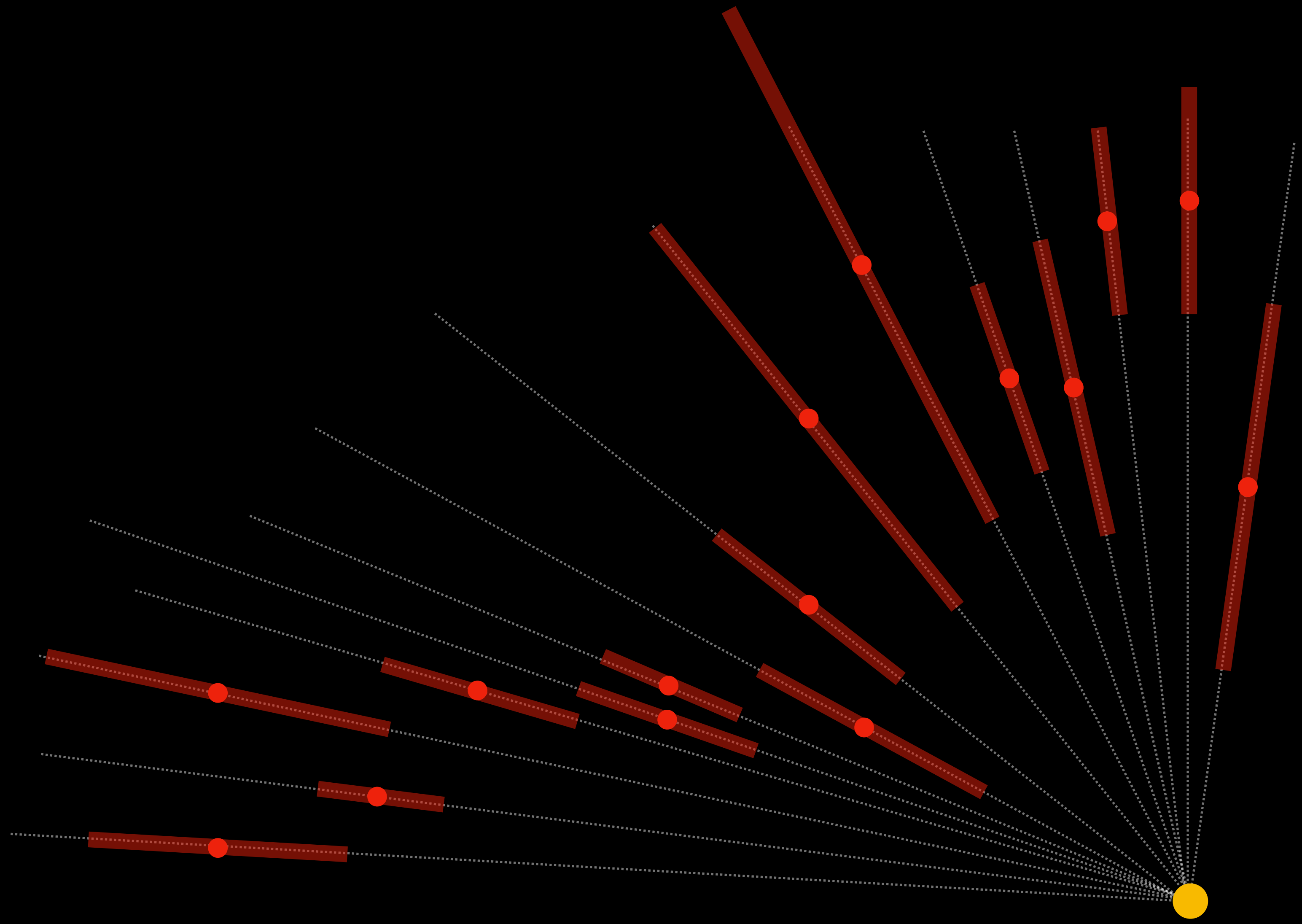
We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.

requires **special** regions on the Sky (HII regions with masers)



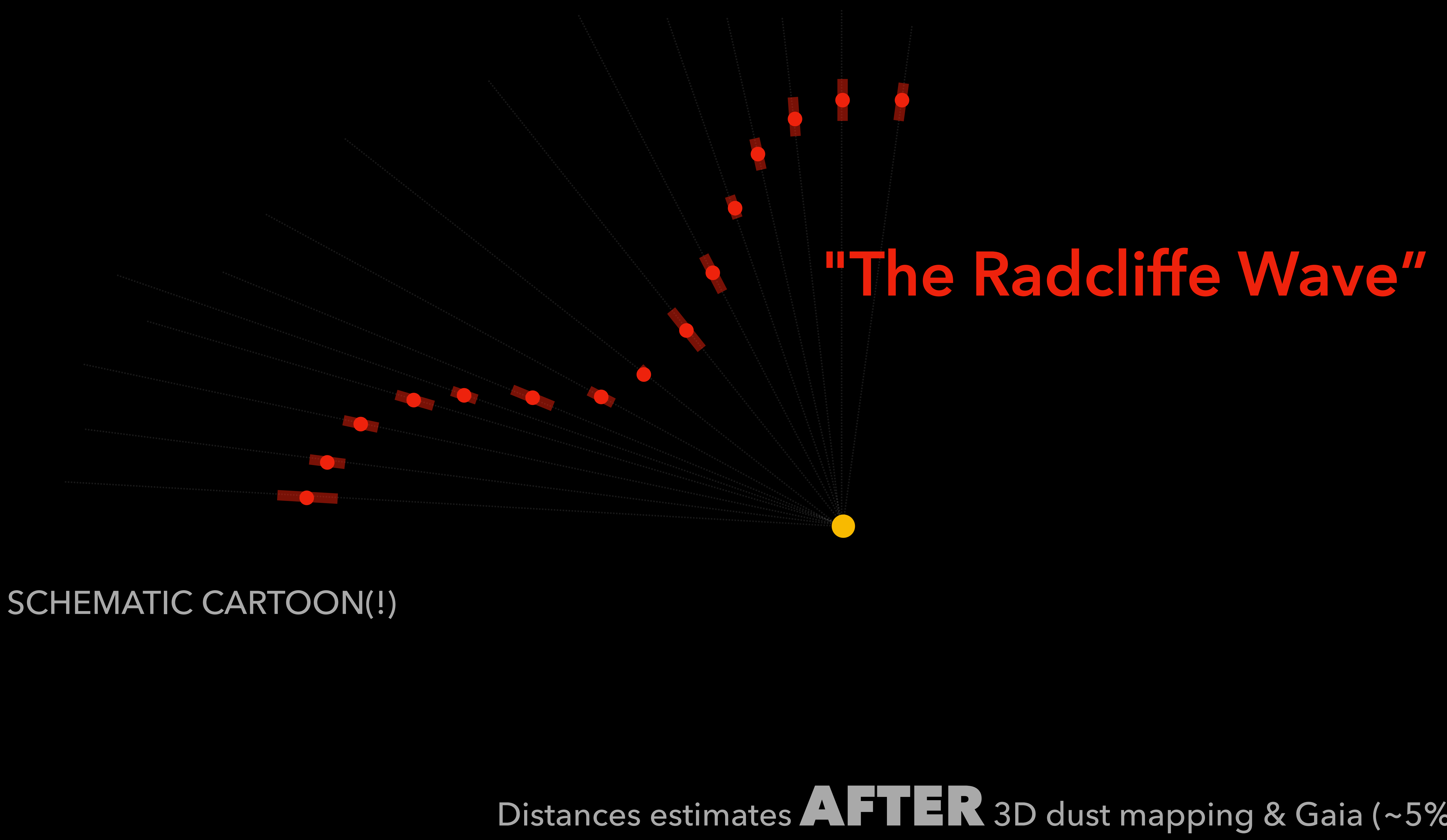
can be used **anywhere** there's dust & measurable stellar properties

Zucker et al. 2019



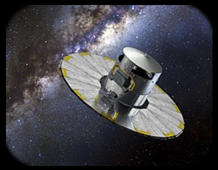
Uncertain Distances

SCHEMATIC CARTOON(!)


"The Radcliffe Wave"
SCHEMATIC CARTOON(!)
Distances estimates AFTER 3D dust mapping & Gaia (~5%)

HOW= 3D dust mapping*

+ Gaia*

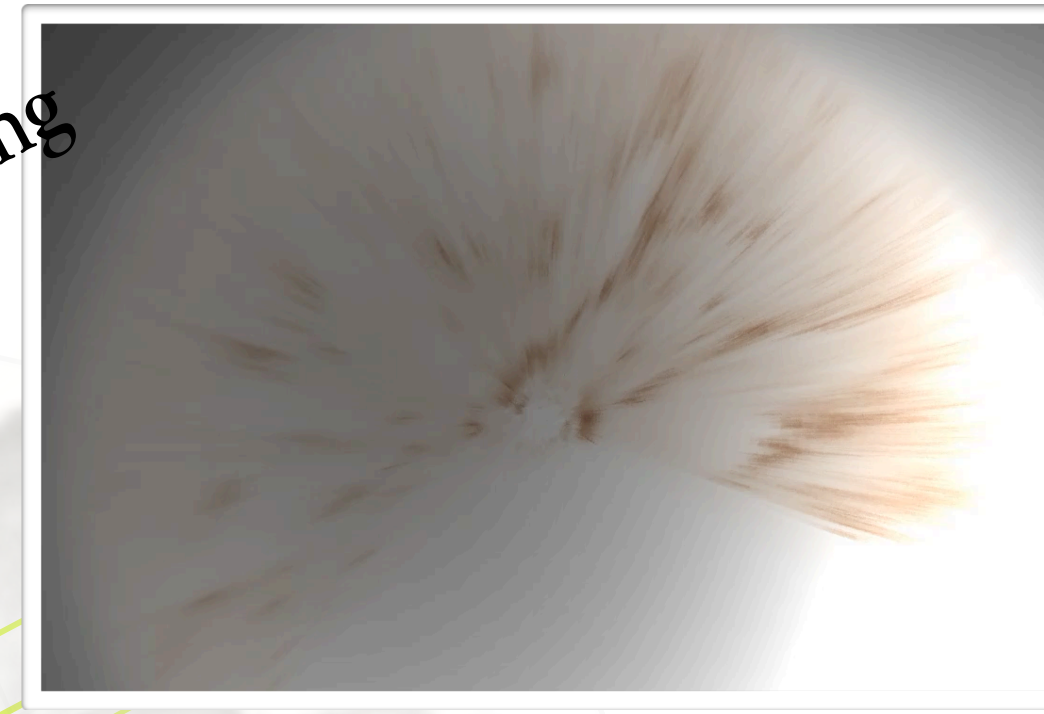


+ glue*

+ WorldWide Telescope

*2 million CPU hours, Harvard   *800 million stars, ESA   *NASA/JWST, NSF   *Microsoft Research, NSF, AAS

Extinction & Reddening, from Color Imaging



Green et al. 2019

Can infer matter’s distance from *dust’s* effects on stars.

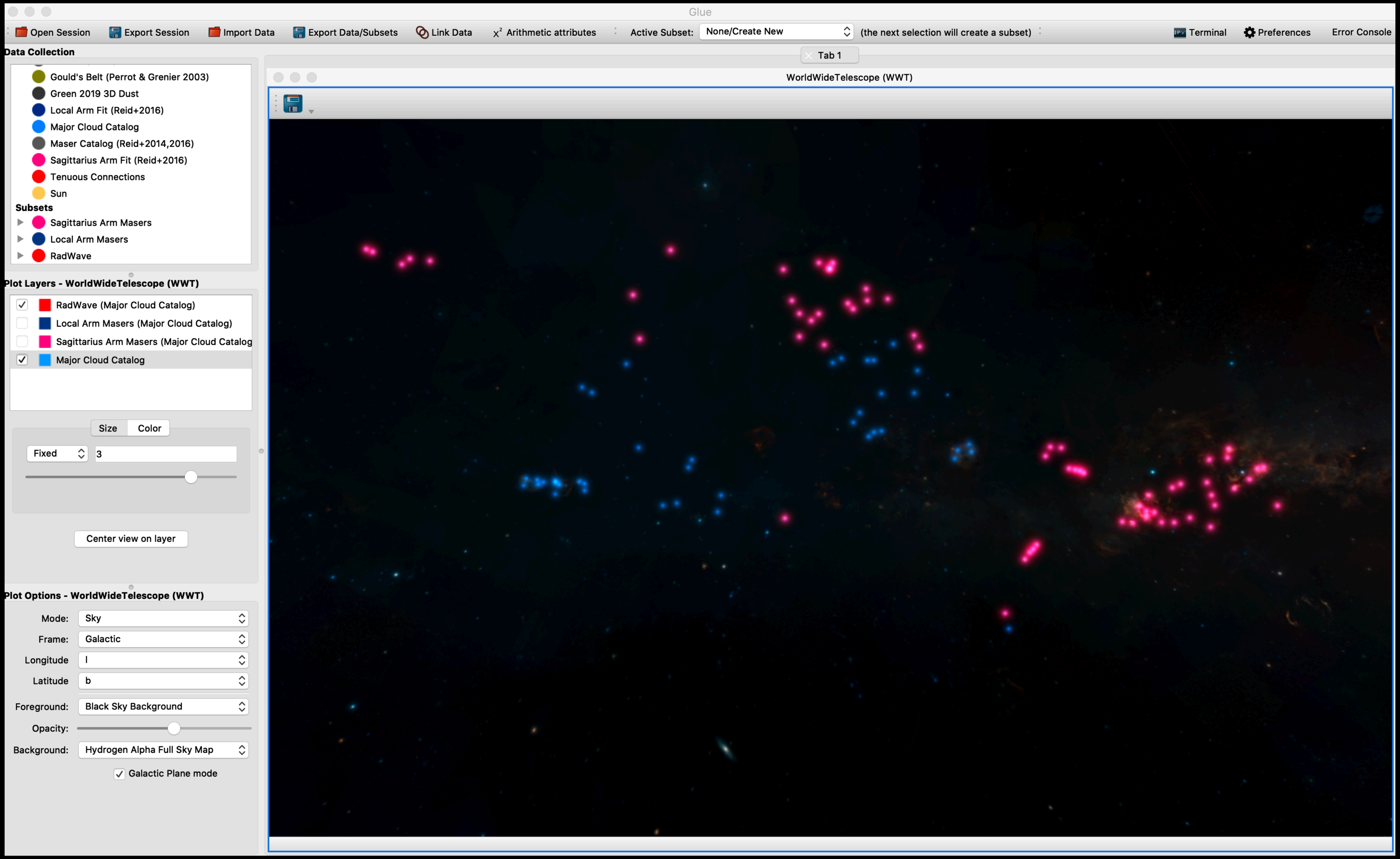
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

“Seeing” The Radcliffe Wave, in 3D

AAS WorldWide Telescope: worldwidetelescope.org glue: glueviz.org

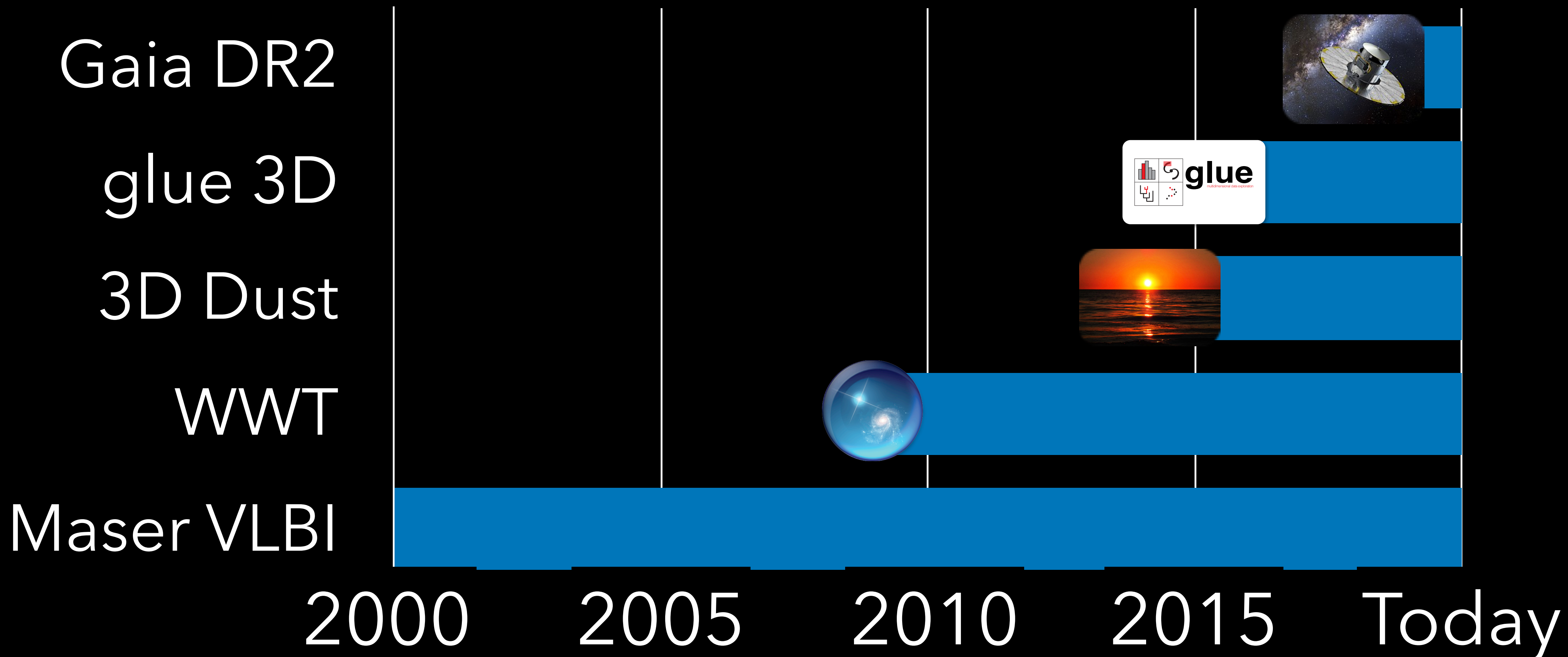
WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

It's not apparent in 2D on the Sky.



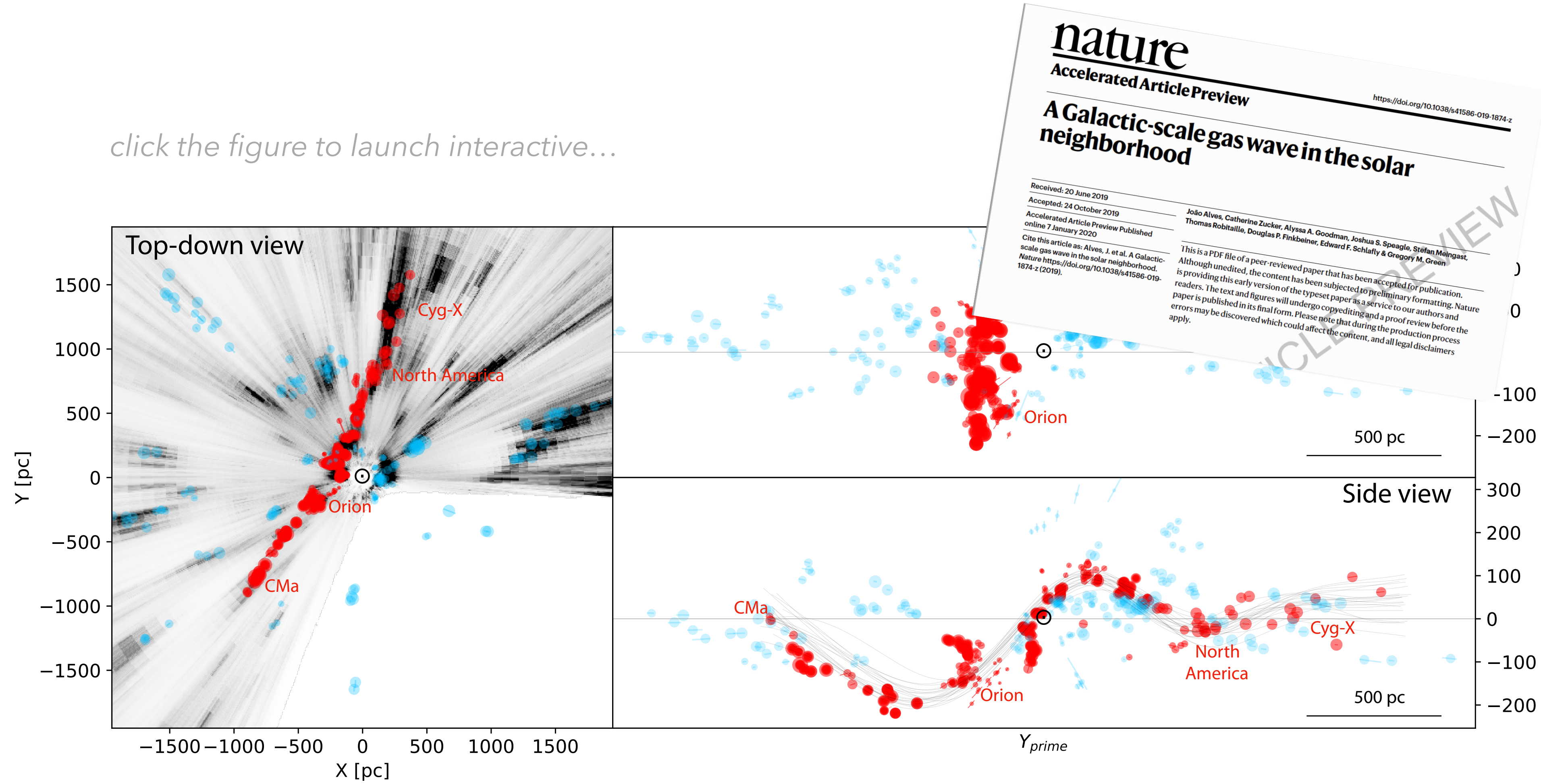
AAS WorldWide Telescope: worldwidetelescope.org   glue: glueviz.org

WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?



The Radcliffe Wave

click the figure to launch interactive…



RADWAVE
Surprising **wave-like arrangement** of star-forming gas *is* the "Local Arm" of the Milky Way.

João Alves, Catherine Zucker, Alyssa Goodman, Joshua Speagle, Stefan Meingast, Thomas Robitaille, Douglas Finkbeiner, Edward F. Schlafly, and Gregory Green 2020, *Nature* (7 January 2020)

Alves et al. *Nature* paper & two distance catalog papers by Zucker et al. (2019, 2020) include several interactive figures (via plot.ly & bokeh), and deep links to data (on Dataverse) and code (on GitHub) inspired by AAS "Paper of the Future" (Goodman et al. 2015)

RADWAVE
Surprising
wave-like
arrangement
of star-forming
gas *is* the
“Local Arm” of
the Milky Way.

“So What,” for Astronomers?

demise of “Gould's Belt”

end to 100-year-old paradigm

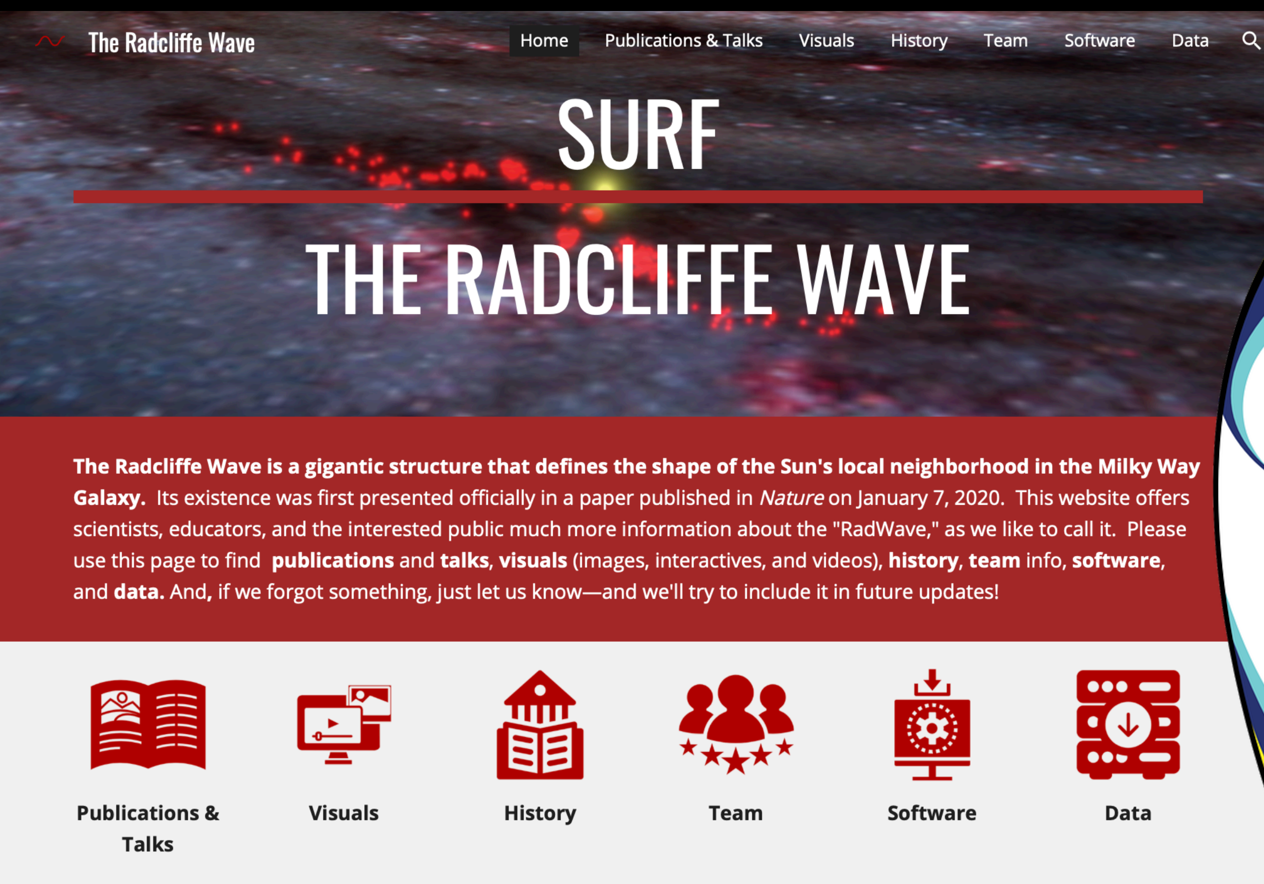
“Local Arm" not shaped as we thought it was, locally

arm is “straight" from top-down

big wave in “arm” never previously observed

wave’s origin unknown (collision? dark matter? accretion?)

SURF the Radcliffe Wave



It appears that the Sun, on its galactic orbit, crossed the Radcliffe Wave 13 million years ago, and may cross it again in the future.

video created by the authors using AAS WorldWide Telescope (includes cartoon Milky Way by Robert Hurt)

Find slides, papers, videos, WWT Tours, and much more at:
tinyurl.com/RadWave

glue-ing together the Universe

get glue

glueviz.org

glue
solutions
inc.

gluesolutions.io

video version of these slides at: tinyurl.com/goodmanWiDS2020

10QViz.org

≡ MENU

TEN QUESTIONS TO ASK WHEN CREATING A VISUALIZATION

The 10 Questions

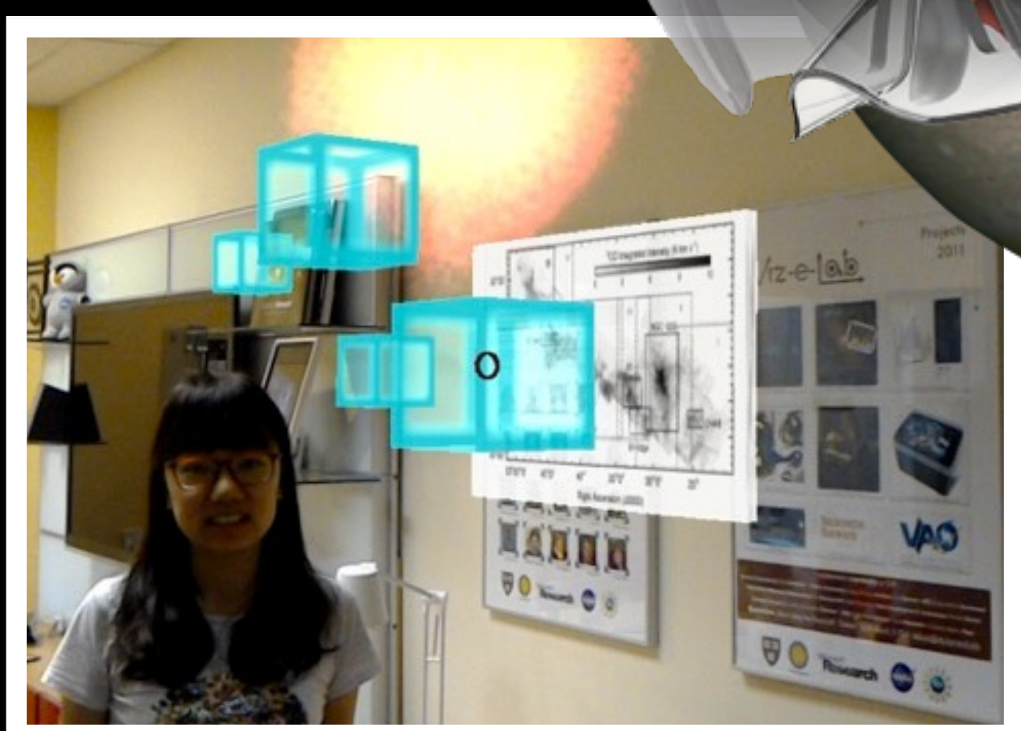
1. **Who** | Who is your audience? How expert will they be about the subject and/or display conventions?
2. **Explore-Explain** | Is your goal to explore, document, or explain your data or ideas, or a combination of these?
3. **Categories** |Do you want to show or explore pre-existing, known, human-interpretable, 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.*

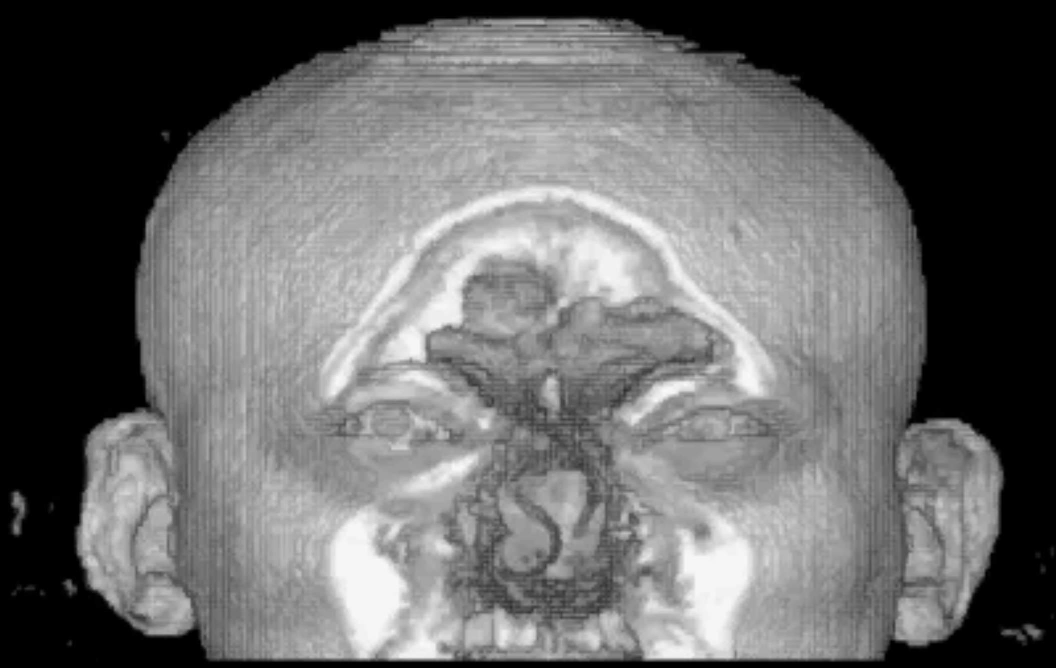
To read an in-process manuscript giving the scholarship behind the recommendations on this site, see Coltekin & Goodman 2018.

The challenge of 3D Selection



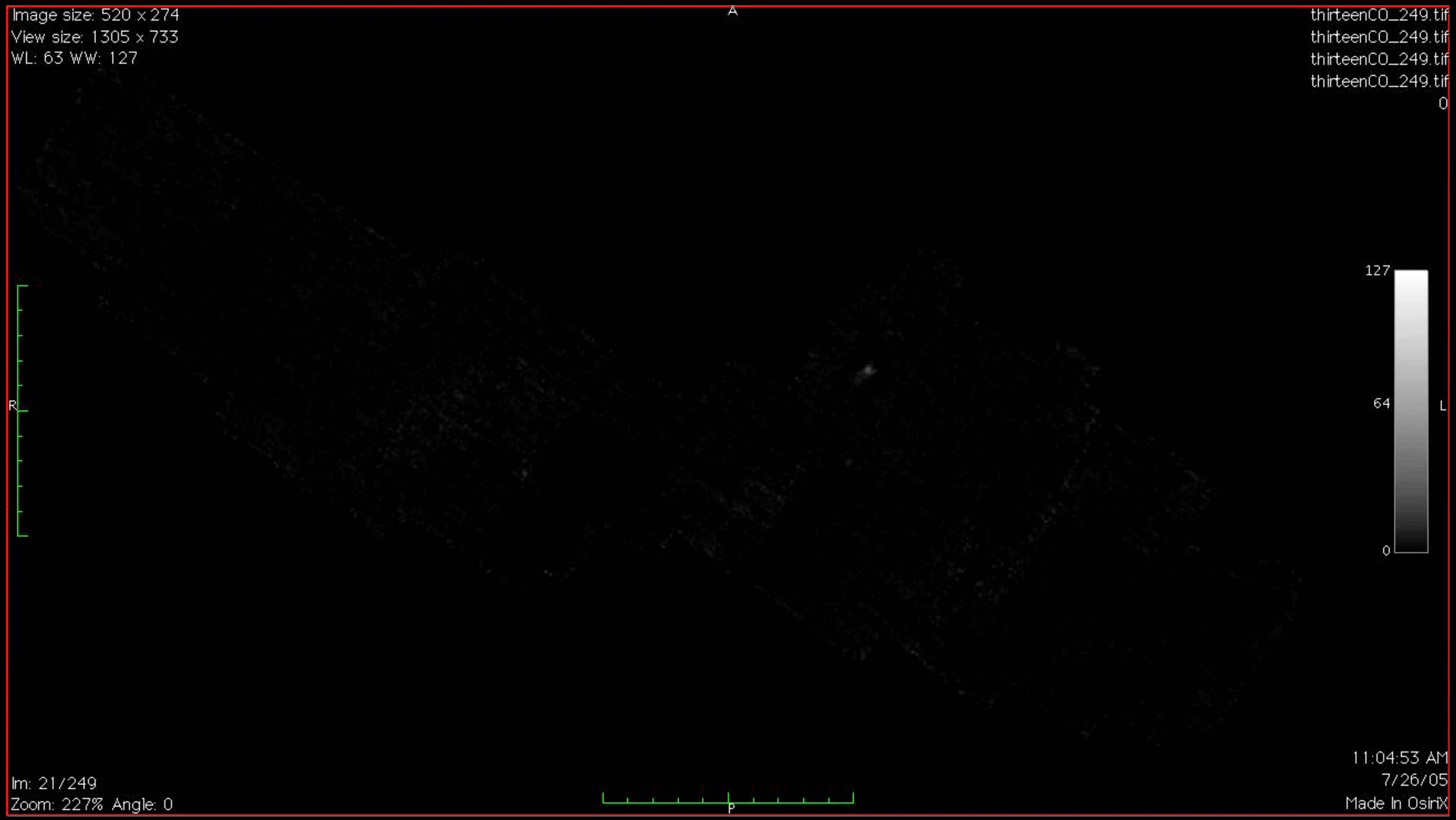
ASTRONOMICAL MEDICINE

"KEITH"



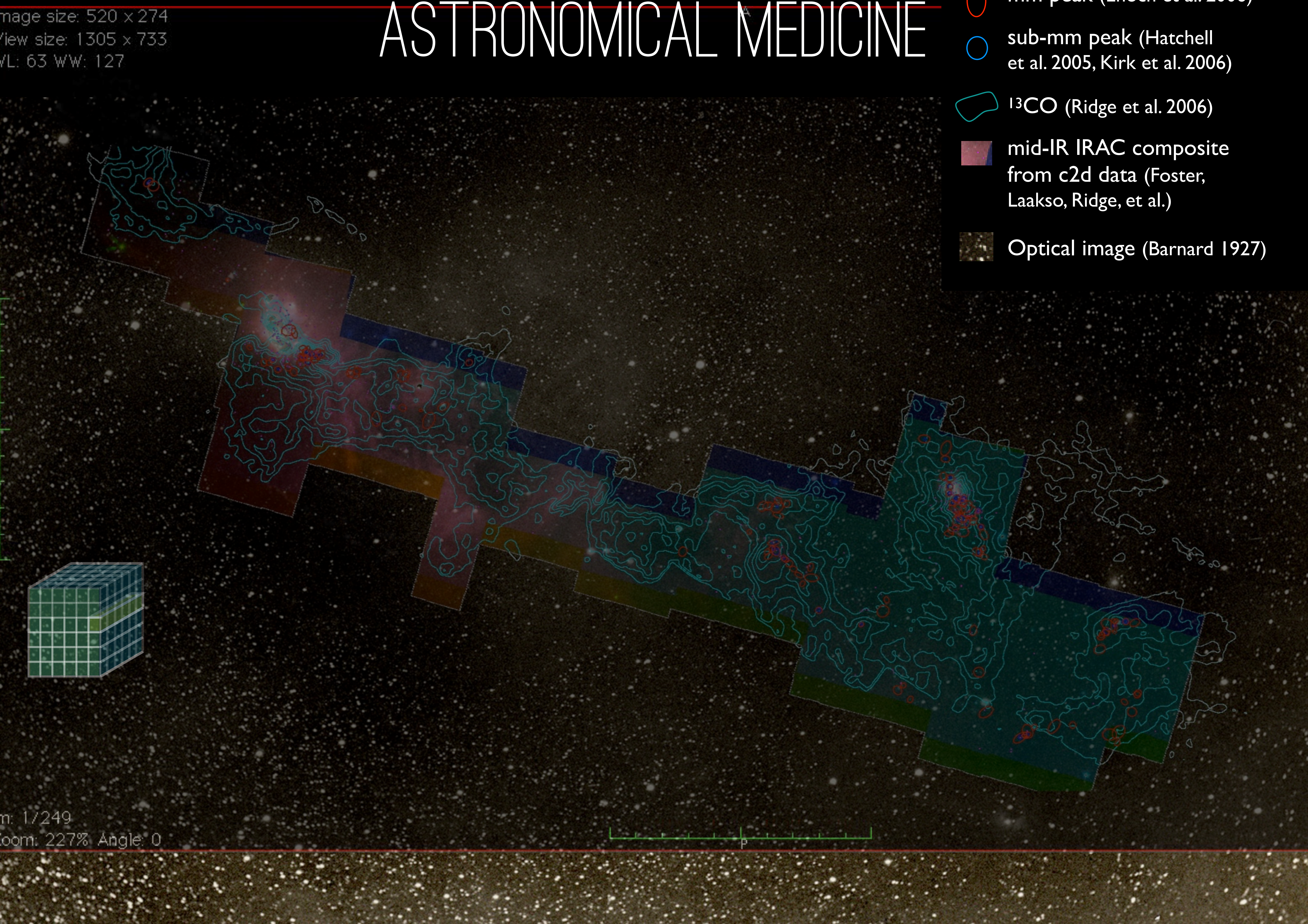
"z" is depth into head

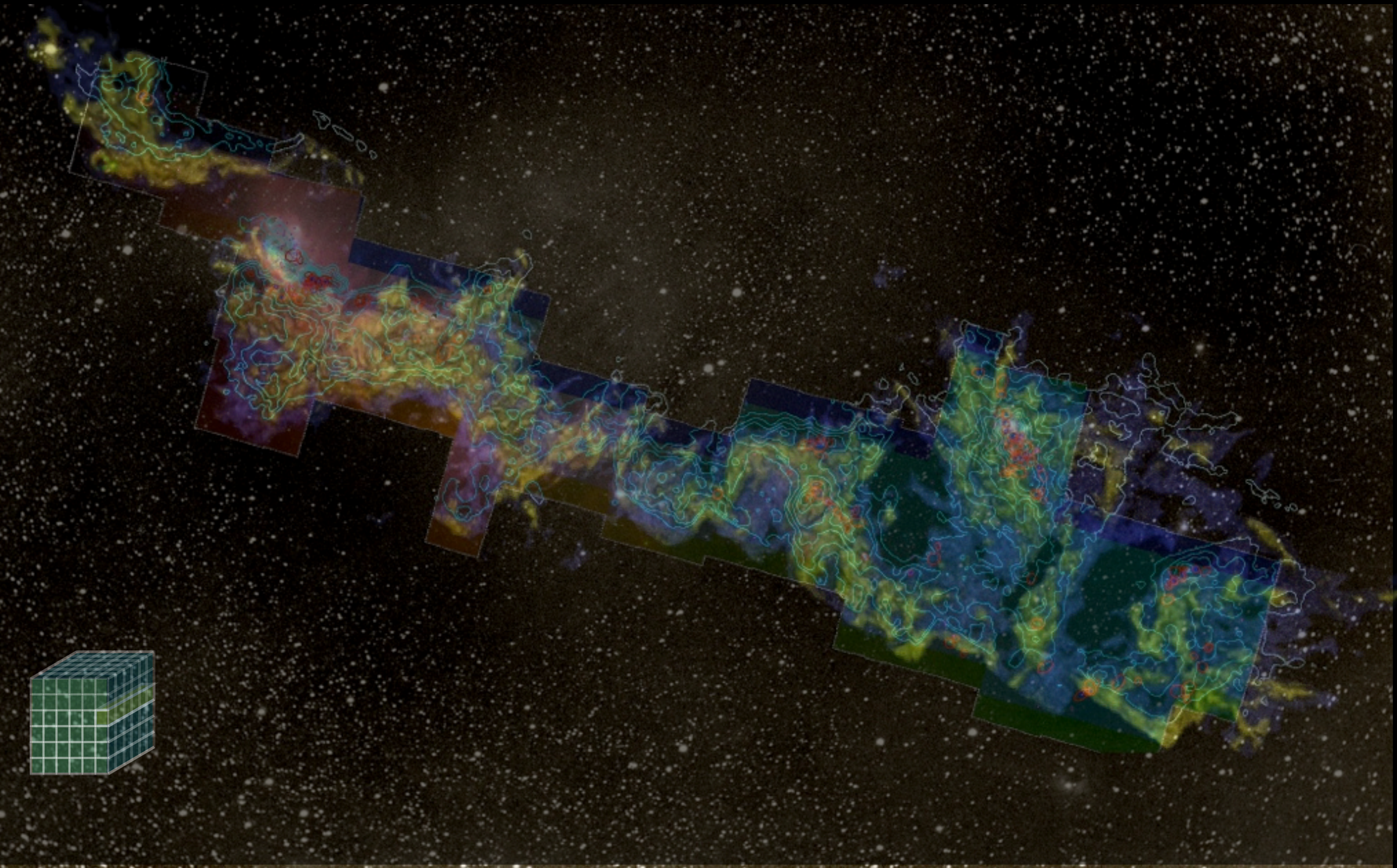
"PERSEUS"



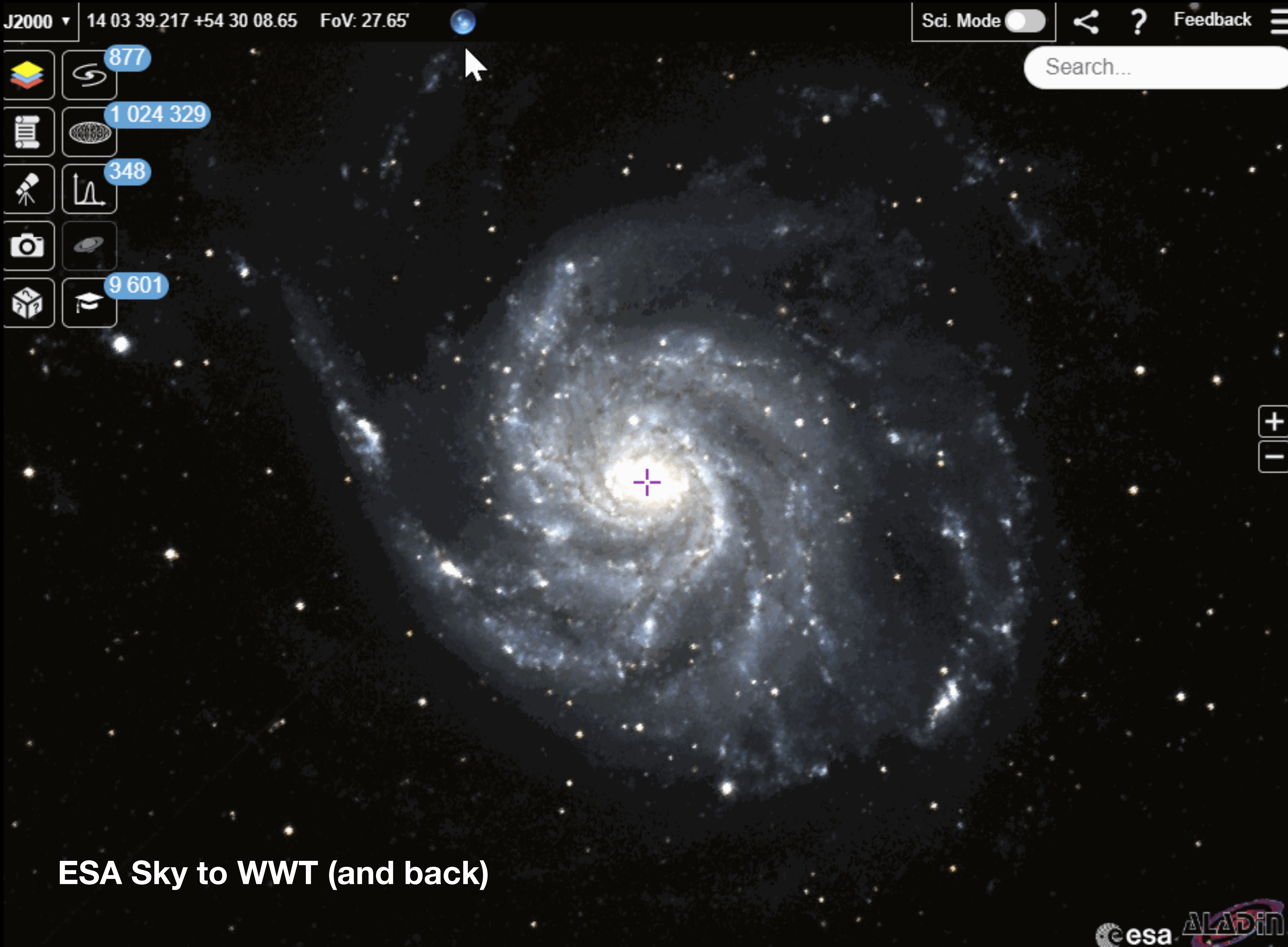
"z" is line-of-sight velocity

ASTRONOMICAL MEDICINE




3D Viz made with VolView

COMPLETE



ESA Sky to WWT (and back)