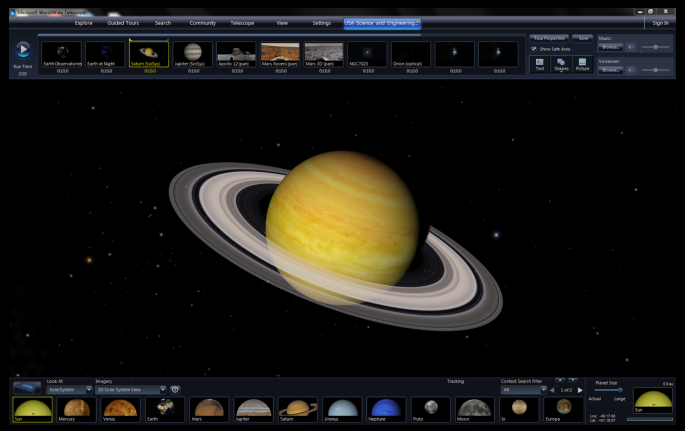

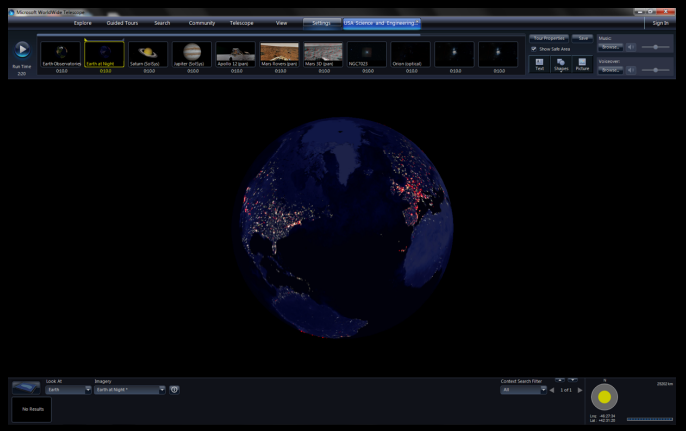

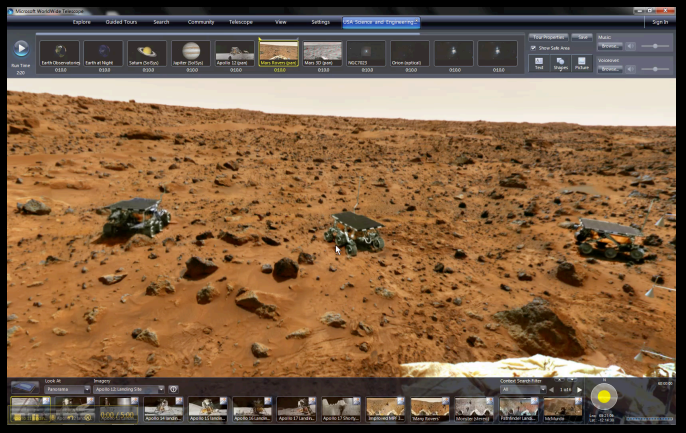

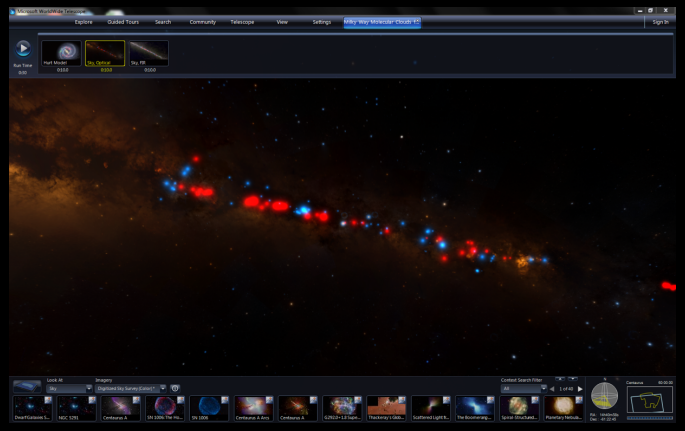

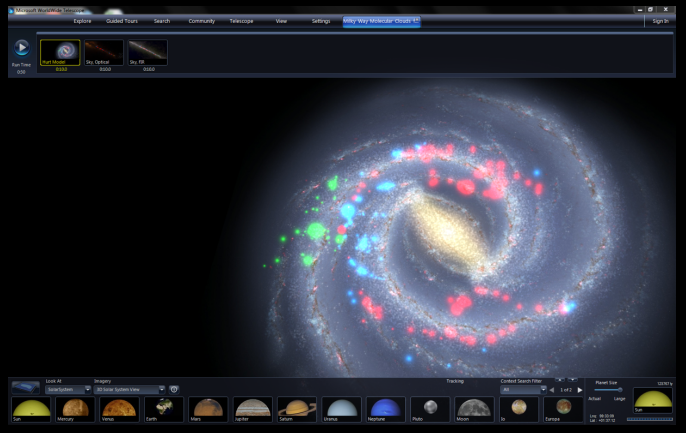

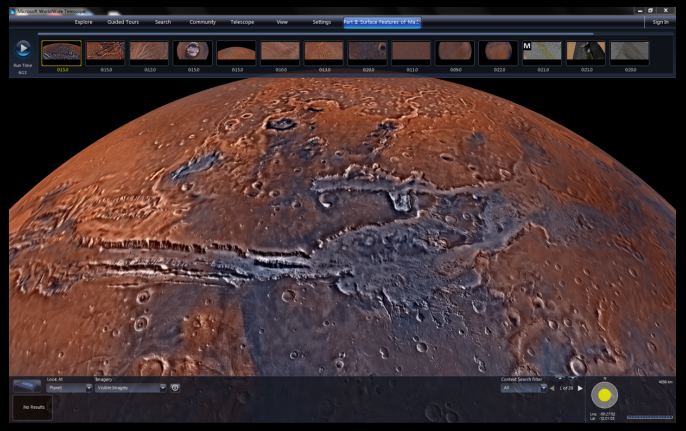

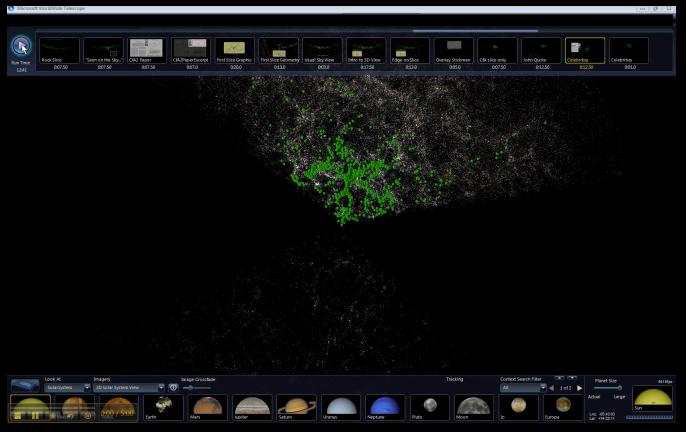

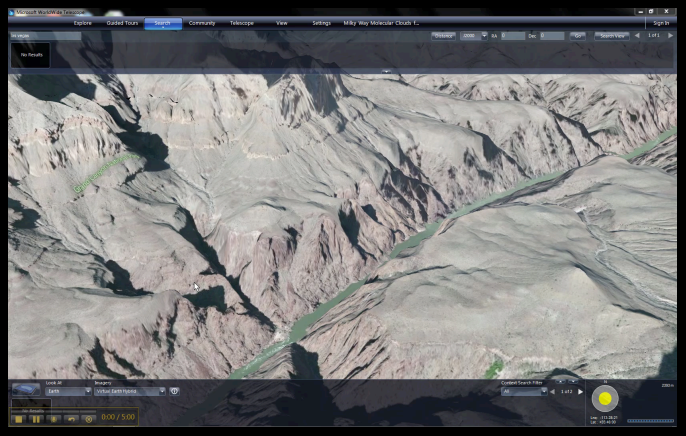

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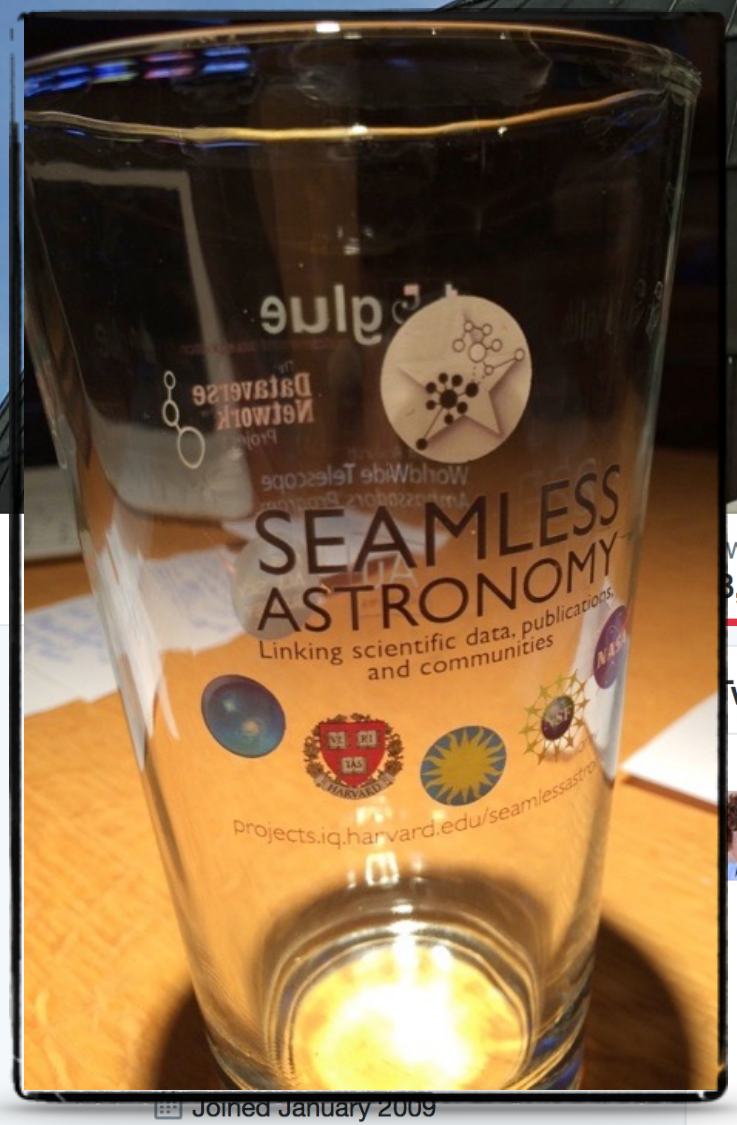

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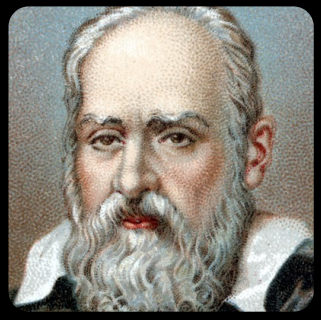

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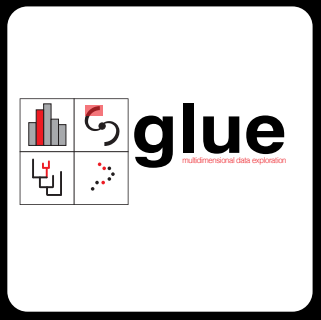
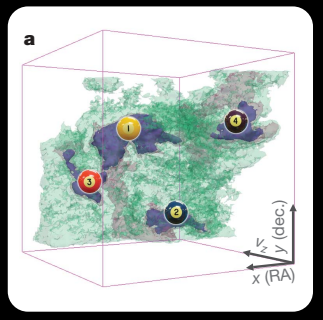
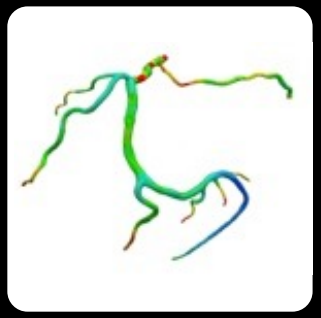

glue
multidimensional data exploration


a
y (dec.)
x (RA)



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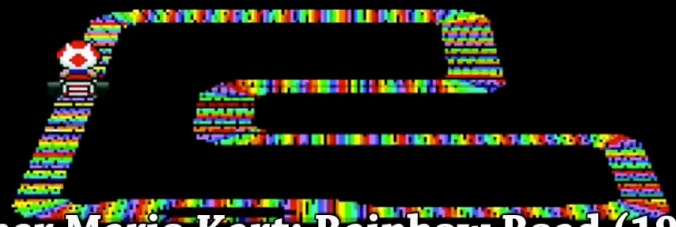
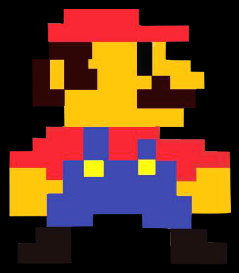
1992



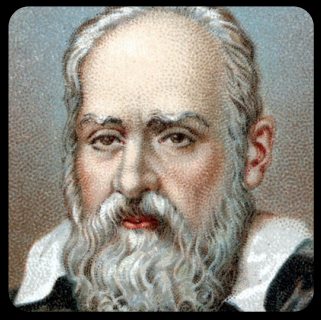
Super Mario Kart: Rainbow Road (1992)

2014

Mario Kart 8: Rainbow Road (2014)



Mario franchise, copyright Nintendo



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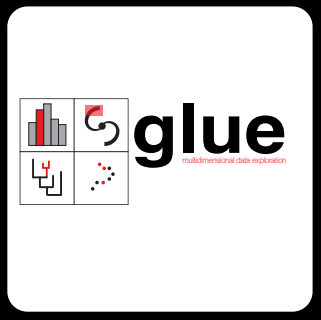
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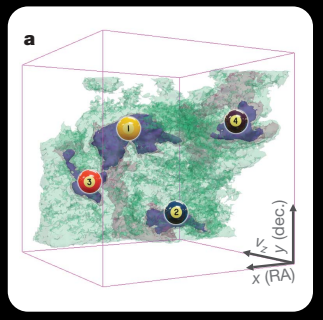
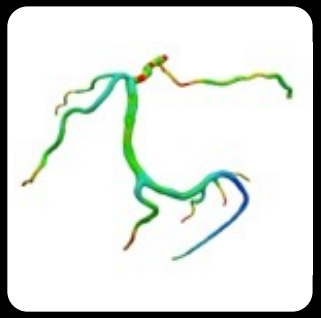
multidimensional data exploration


a
y (dec.)
x (RA)



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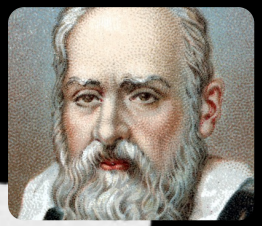
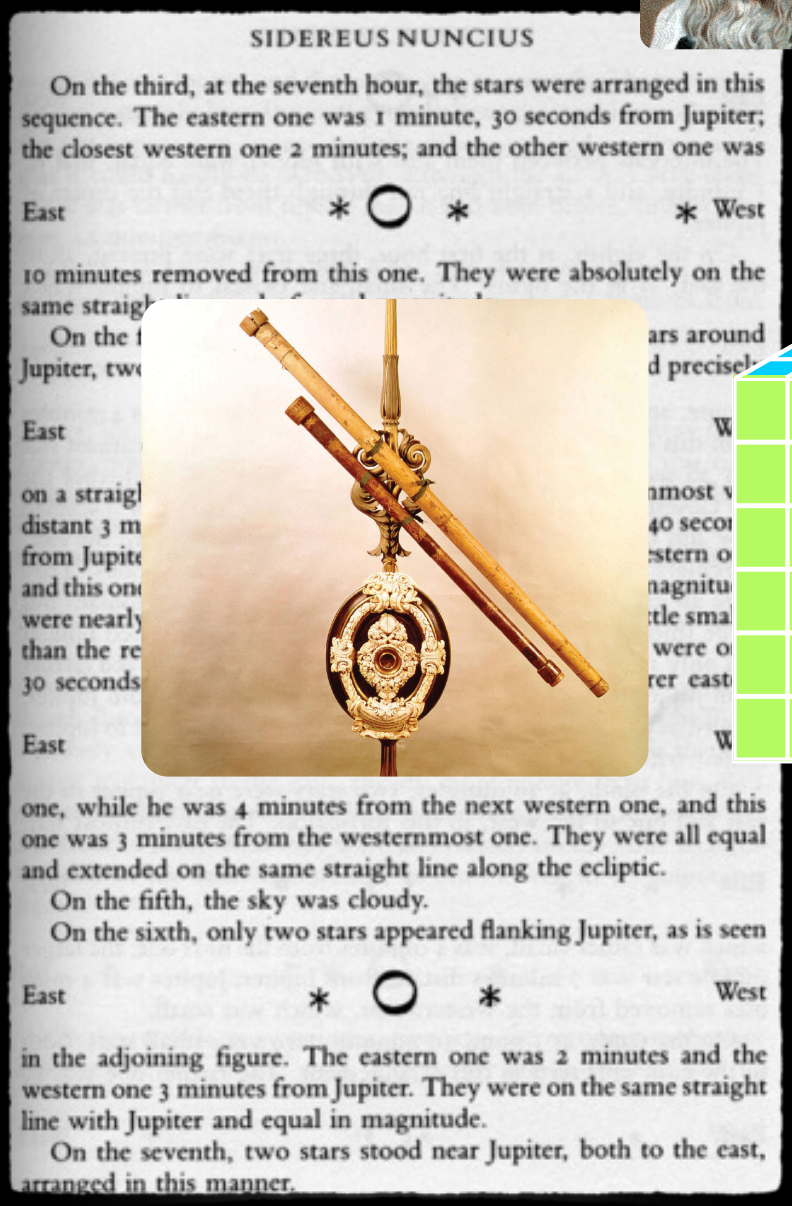
17th Century





SIDEREUS NUNCIUS

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 straigh

On the f ars around Jupiter, two d precisel

East W

on a straigl most v distant 3 m 40 secon from Jupite stern o and this one agnitu were nearly tle smal than the re were o 30 seconds rer east

East W

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.

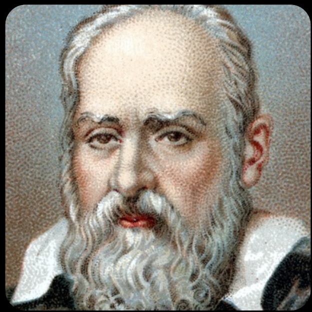
On the sixth, only two stars appeared flanking Jupiter, as is seen

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.

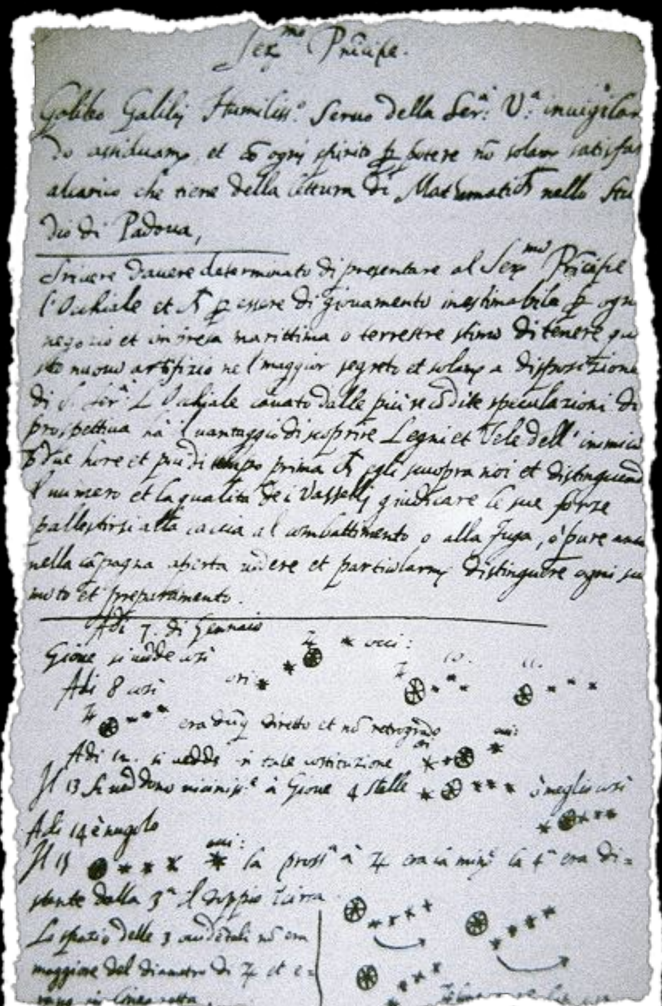
On the seventh, two stars stood near Jupiter, both to the east, arranged in this manner.

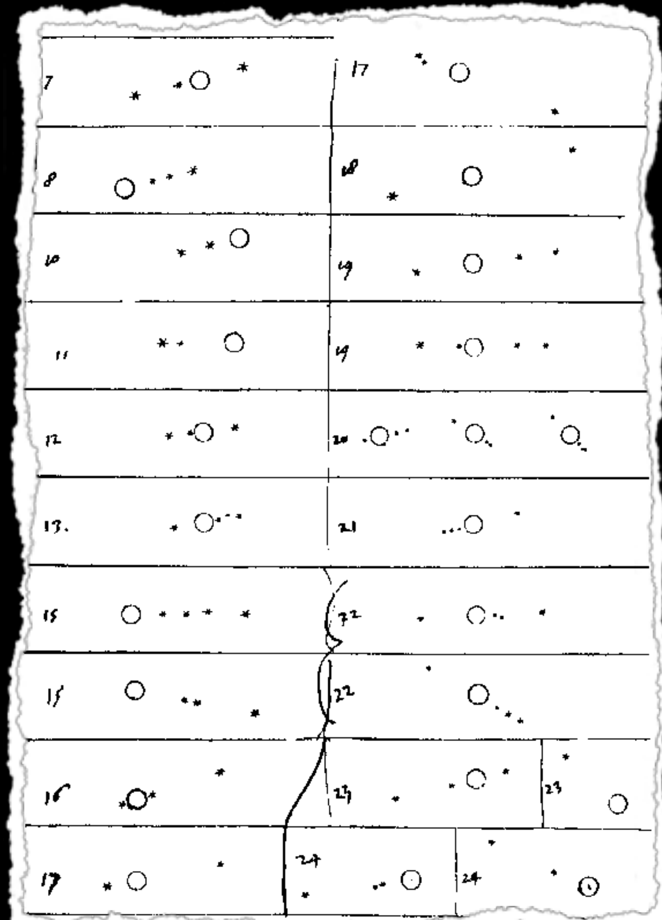
21st Century

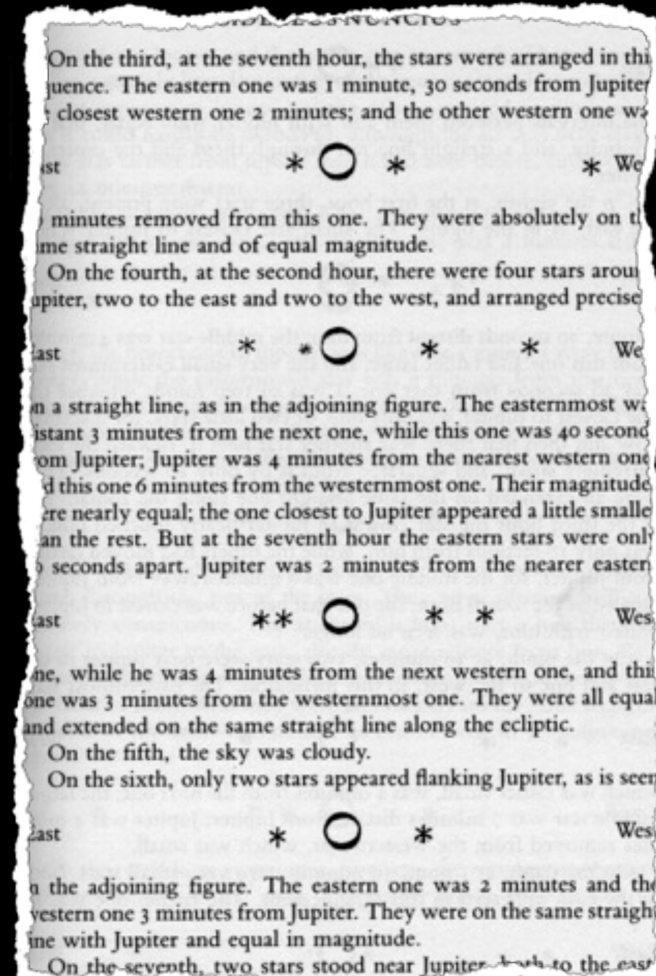


GALILEO GALILEI

(1564–1642)







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

ist * O * * We

minutes removed from this one. They were absolutely on t
me straight line and of equal magnitude.

On the fourth, at the second hour, there were four stars arou
upiter, two to the east and two to the west, and arranged precise

East * *O * * We

n a straight line, as in the adjoining figure. The easternmost w
istant 3 minutes from the next one, while this one was 40 second
om Jupiter; Jupiter was 4 minutes from the nearest western one
d this one 6 minutes from the westernmost one. Their magnitude
ere nearly equal; the one closest to Jupiter appeared a little smalle
an the rest. But at the seventh hour the eastern stars were only
seconds apart. Jupiter was 2 minutes from the nearer easter

East ** O * * Wes

ne, while he was 4 minutes from the next western one, and thi
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.

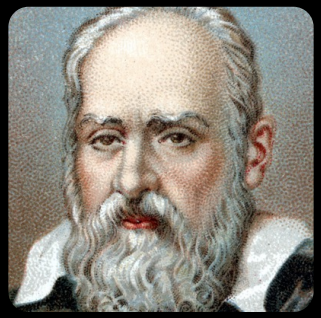
On the sixth, only two stars appeared flanking Jupiter, as is seen

East * O * Wes

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

On the seventh, two stars stood near Jupiter, both to the east

Notes for & re-productions of Siderius Nuncius



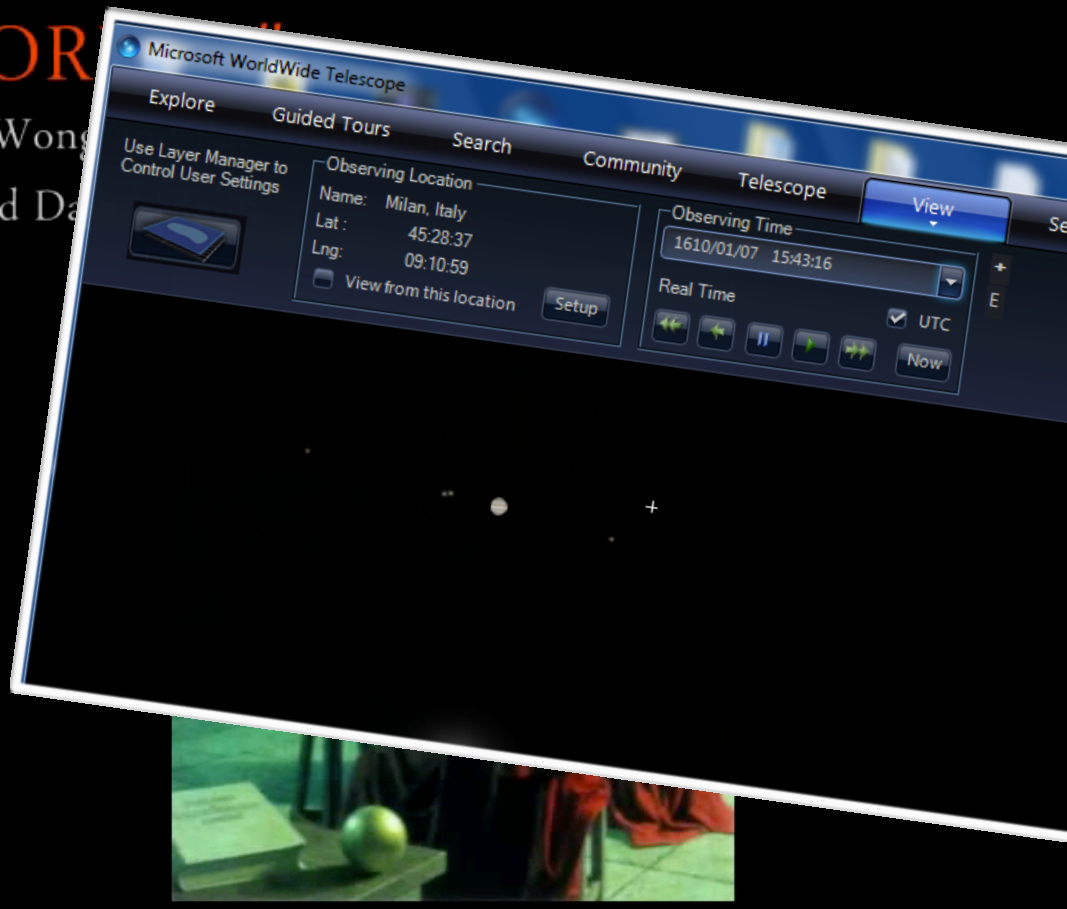
GALILEO GALILEI

(1564-1642)

GALILEO'S "NEW OR

Created by Alyssa Goodman, Curtis Wong

with advice from Owen Gingerich and Da

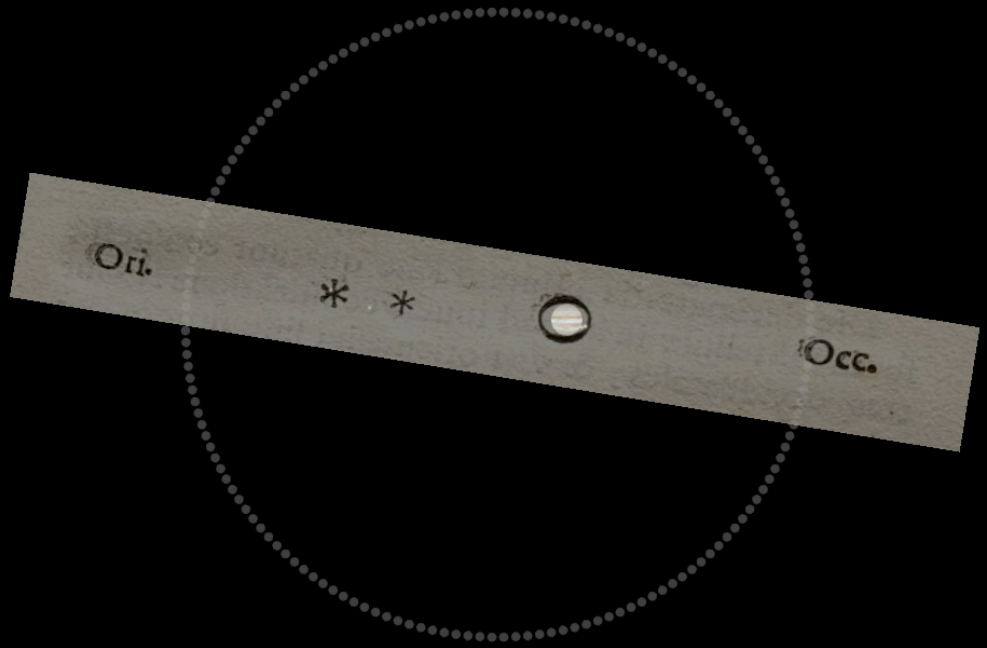


Galileo's New Order, A WorldWide Telescope Tour by Goodman, Wong & Udomprasert 2010
Microsoft Research WWT Software (~now "OpenWWT"): Wong (inventor), Fay (architect), et al.

GALILEO GALILEI

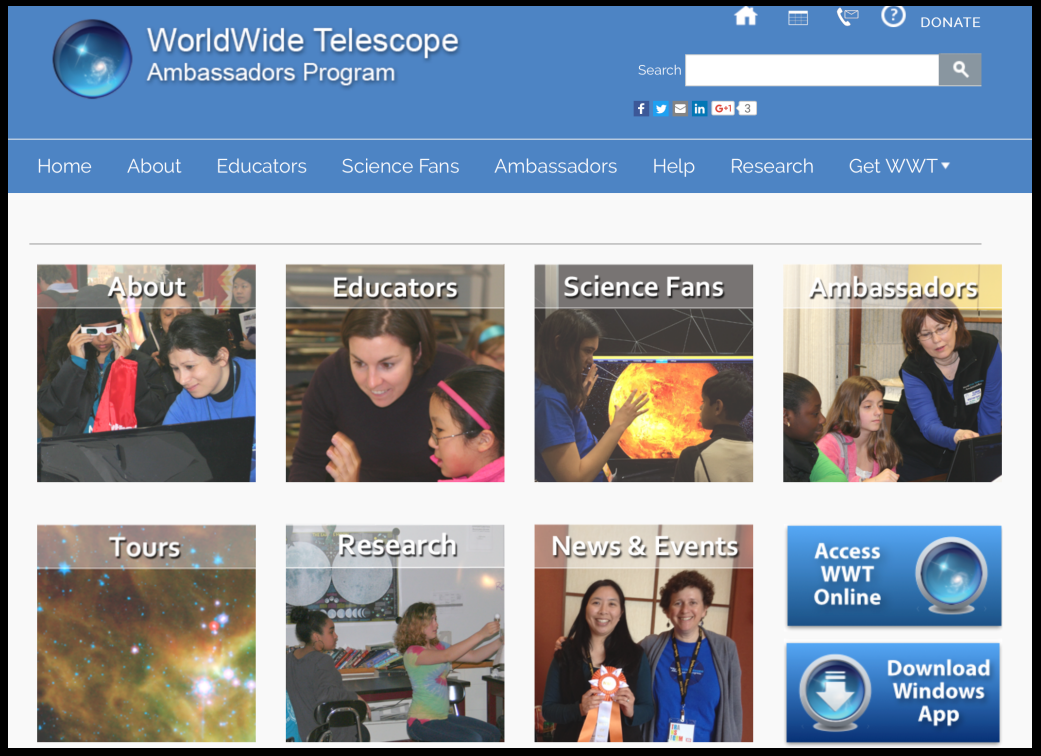
(1564-1642)

January 11, 1610

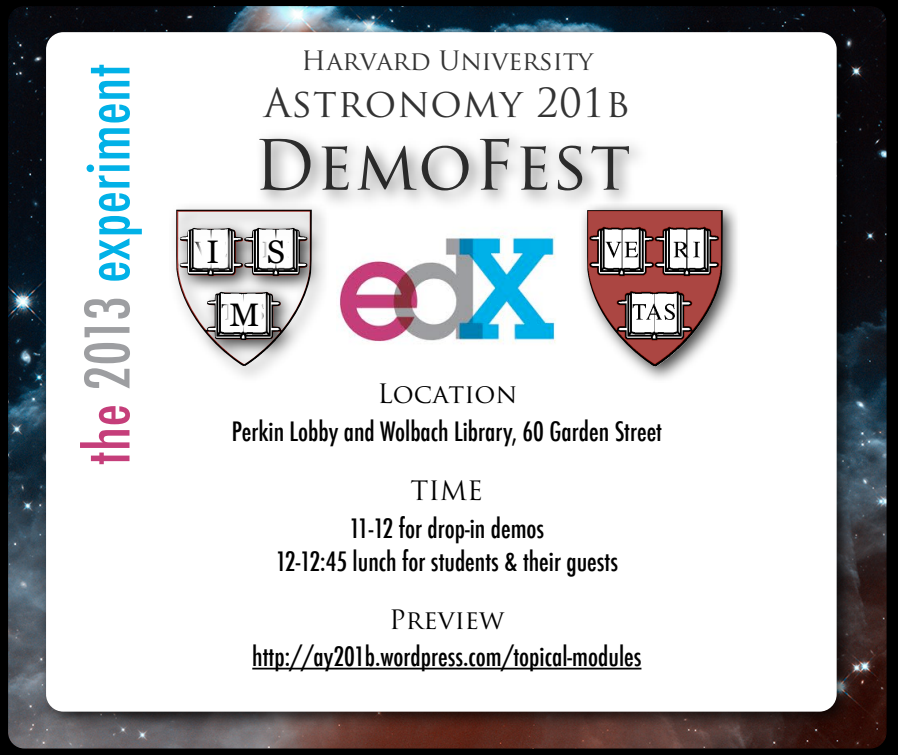


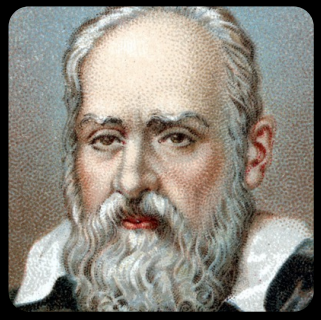
Galileo's New Order, A WorldWide Telescope Tour by Goodman, Wong & Udomprasert 2010
Microsoft Research WWT Software (~now "OpenWWT"): Wong (inventor), Fay (architect), et al.

WWT Ambassadors

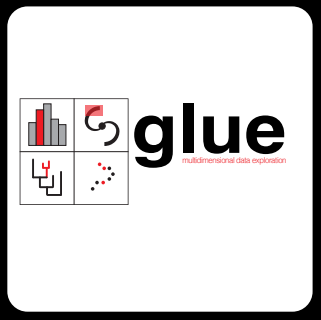


online learning





WorldWide Telescope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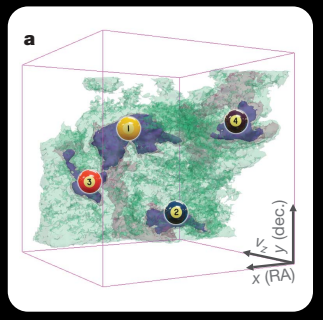
multidimensional data exploration


a
y (dec.)
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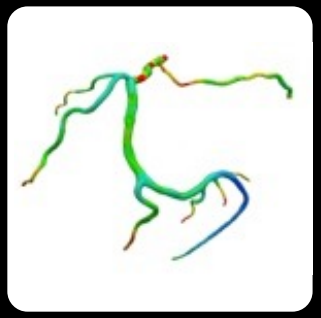

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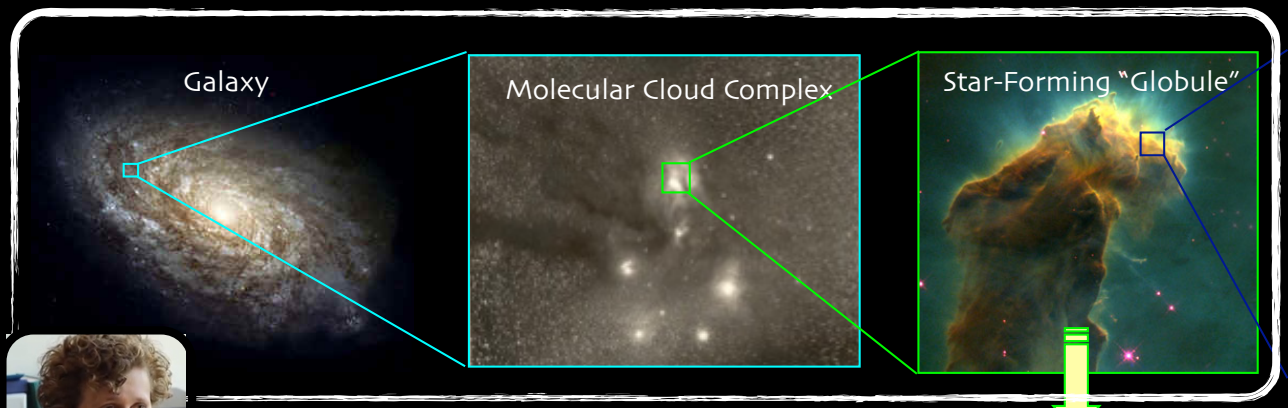
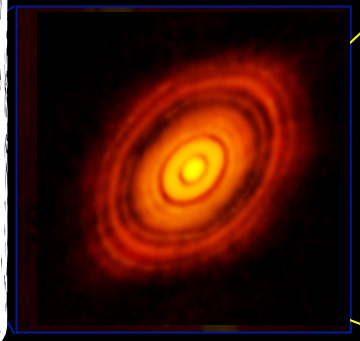
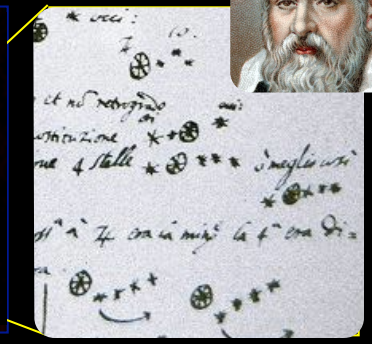
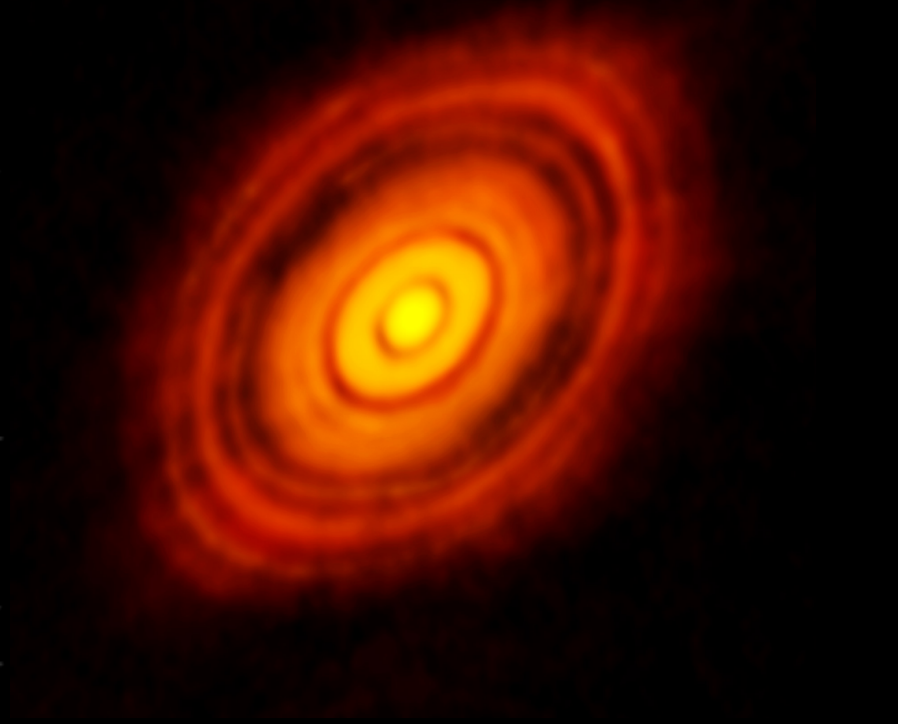
STAR & PLANET FORMATION IN GALAXIES IN 1 SLIDE





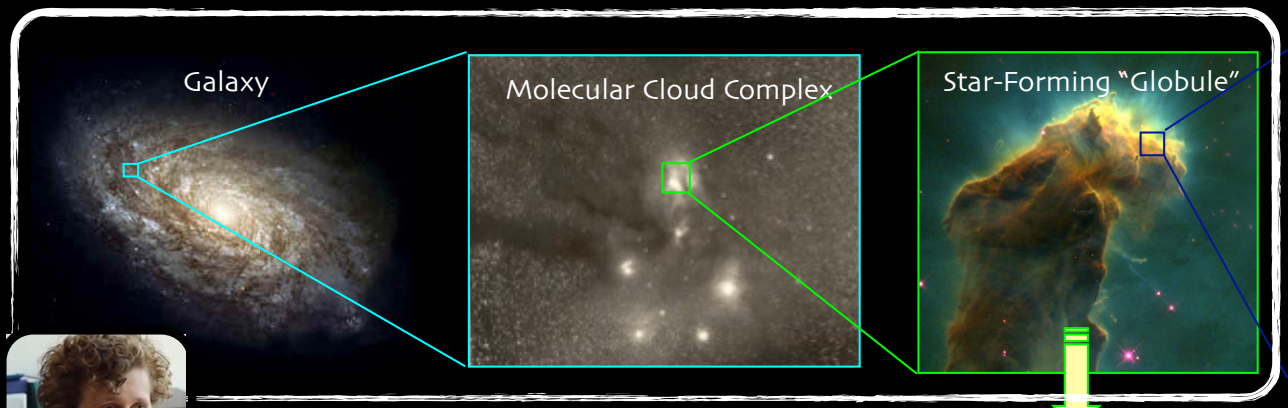


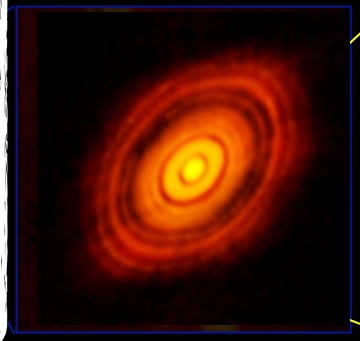
Artist's Rendering 2004
(based on theory & simulations, credit R. Hurt)

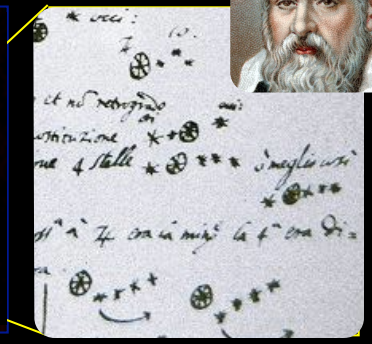


Real ALMA data 2014

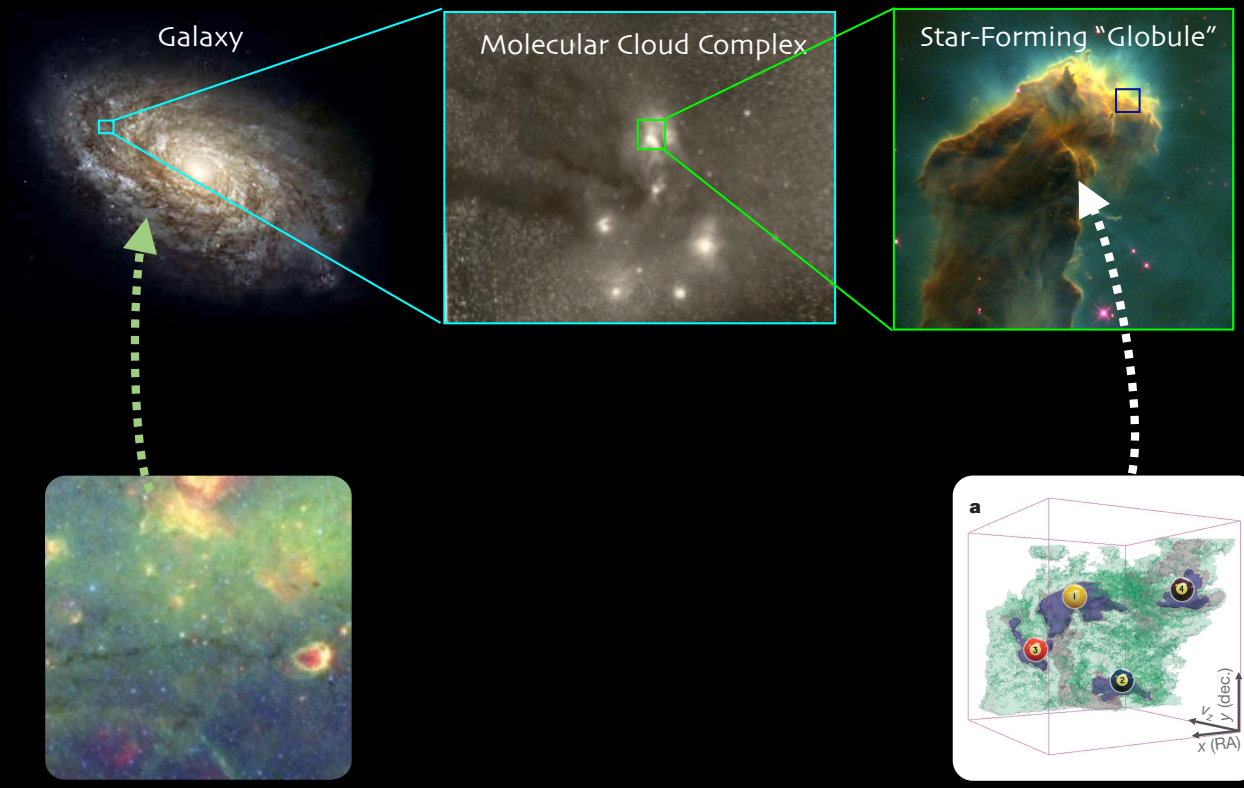
STAR & PLANET FORMATION IN GALAXIES IN 1 SLIDE

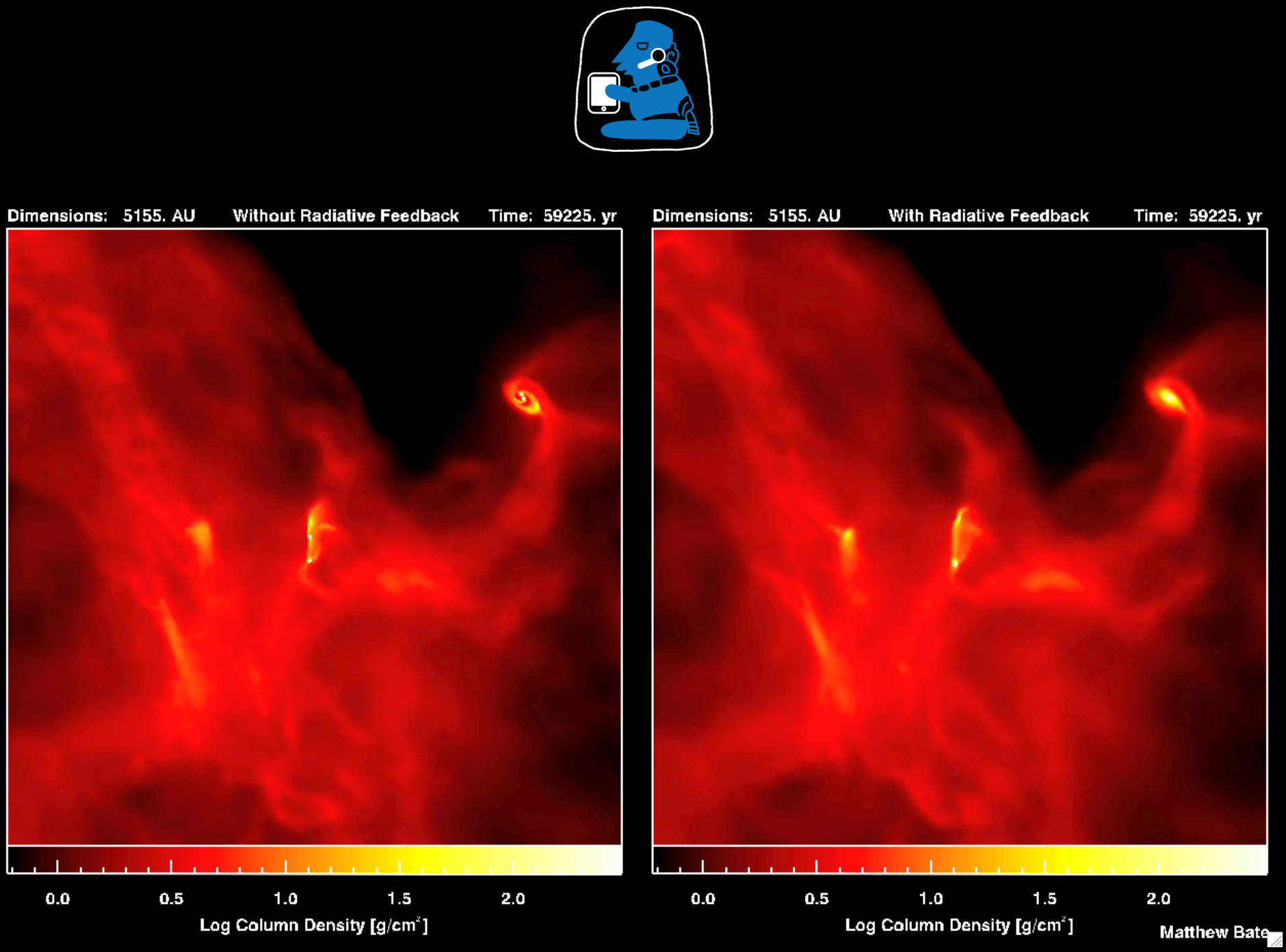






"SEEING SCIENCE"

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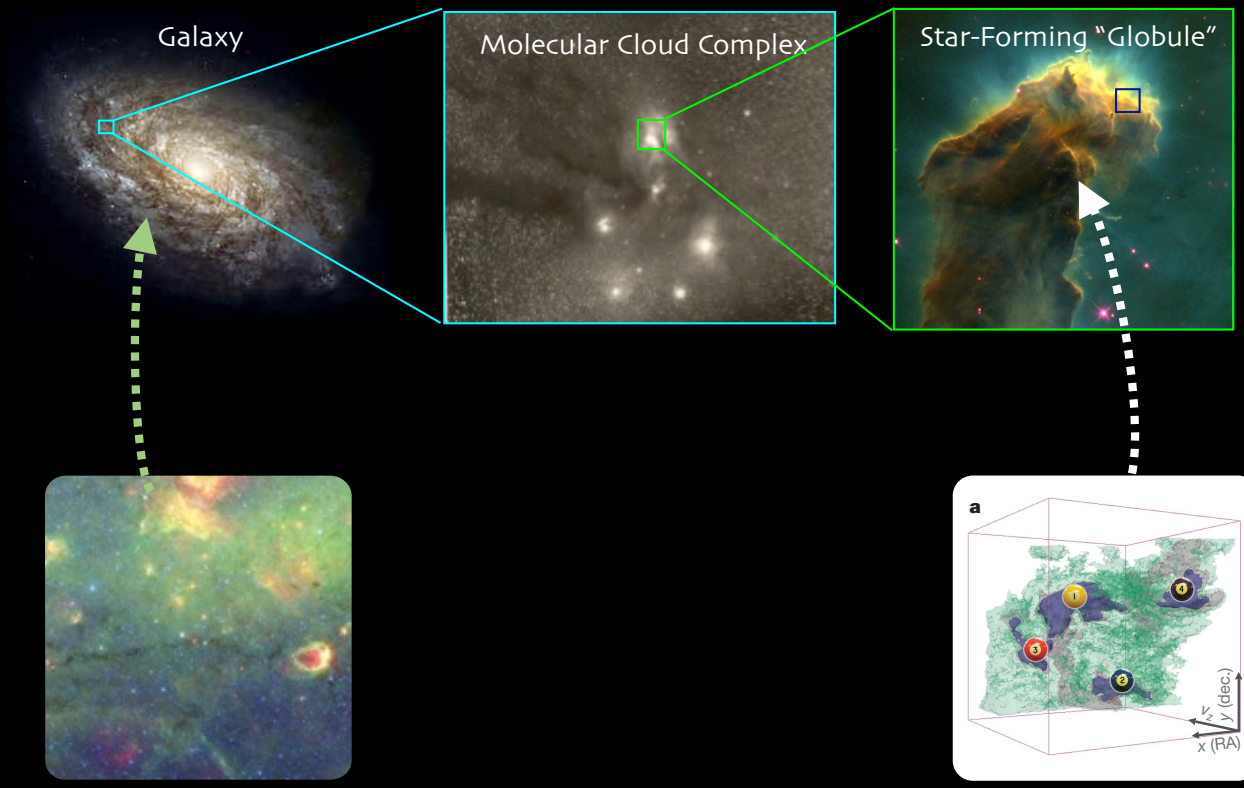
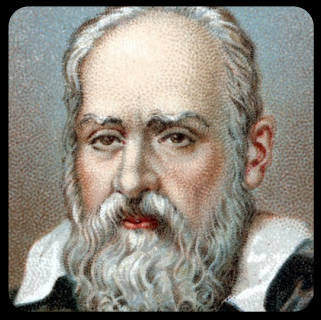
Matthew Bate

"SEEING SCIENCE"





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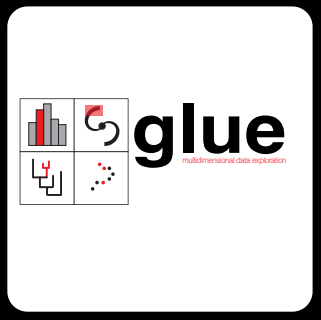
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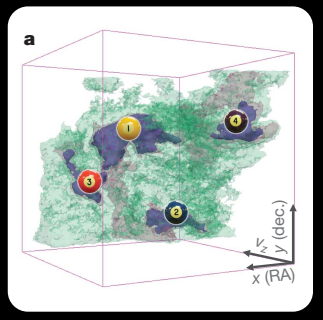
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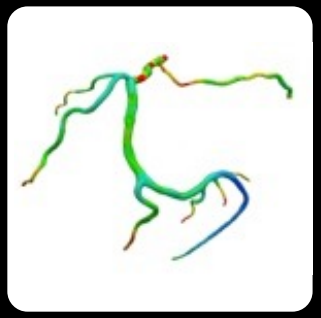

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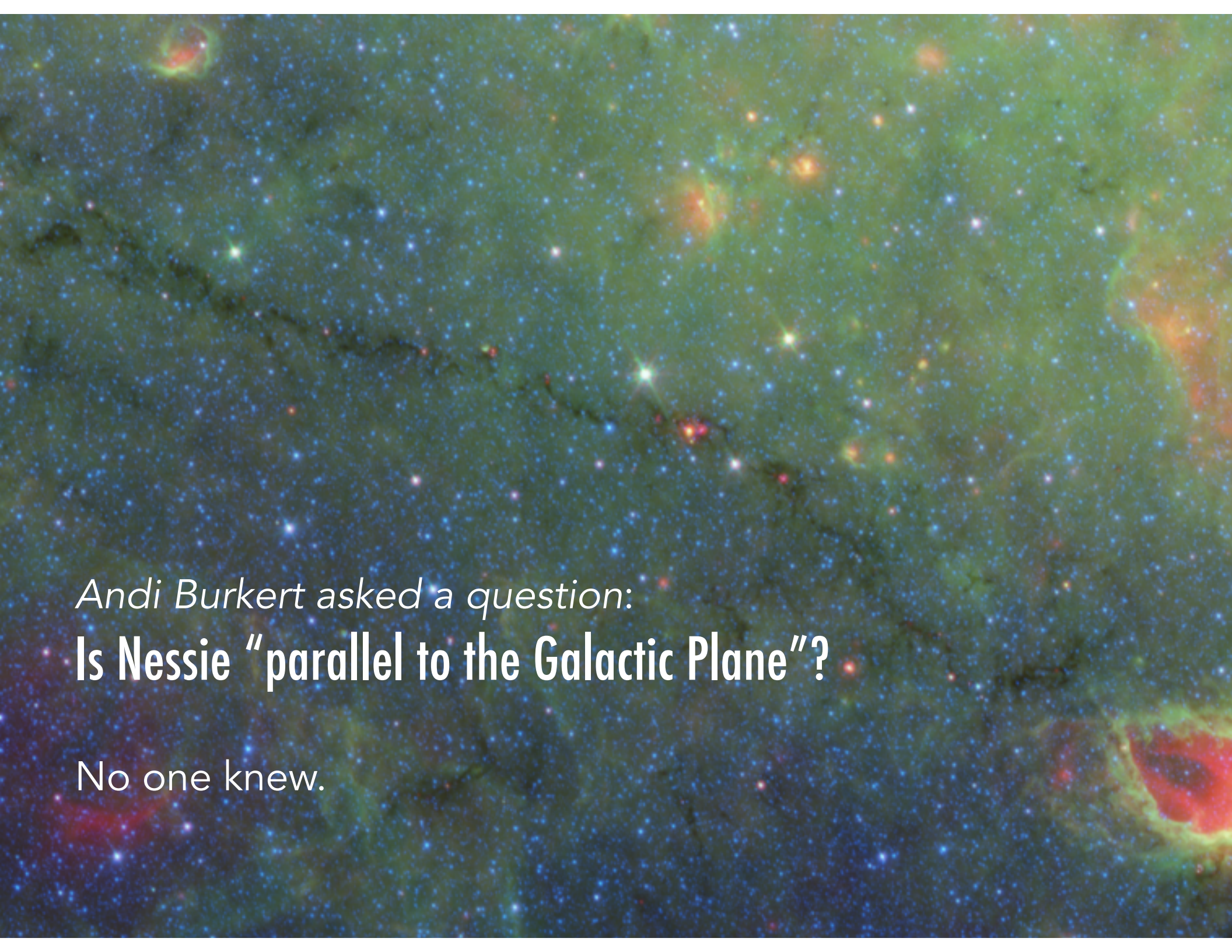
Once upon a time (2012), in an enchanted castle (in Bavaria)

...at a conference about
"The Early Phases of Star Foration"



Andi Burkert asked a question:

Is Nessie "parallel to the Galactic Plane"?

No one knew.

THE MILKY WAY

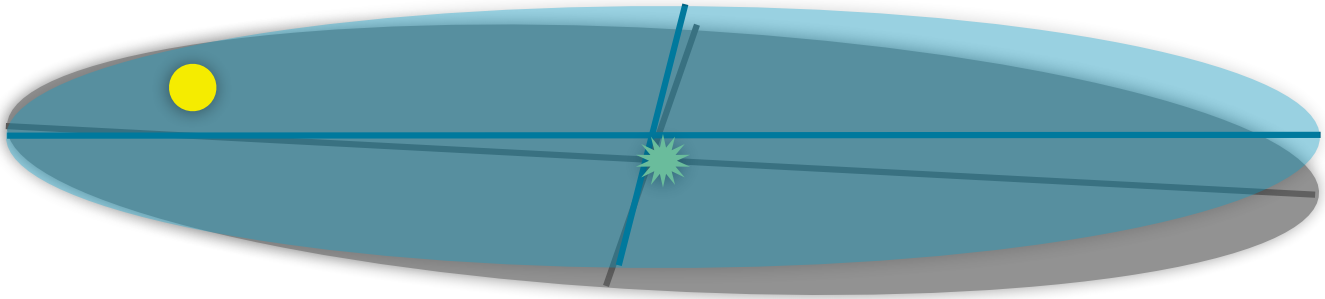
“Galactic Plane”

The Milky Way
(Artist's Conception)

"Is Nessie Parallel to the Galactic Plane?"

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. *[Blaauw et al. 1959]*

Sun is ~75 light years "above" the IAU Milky Way Plane

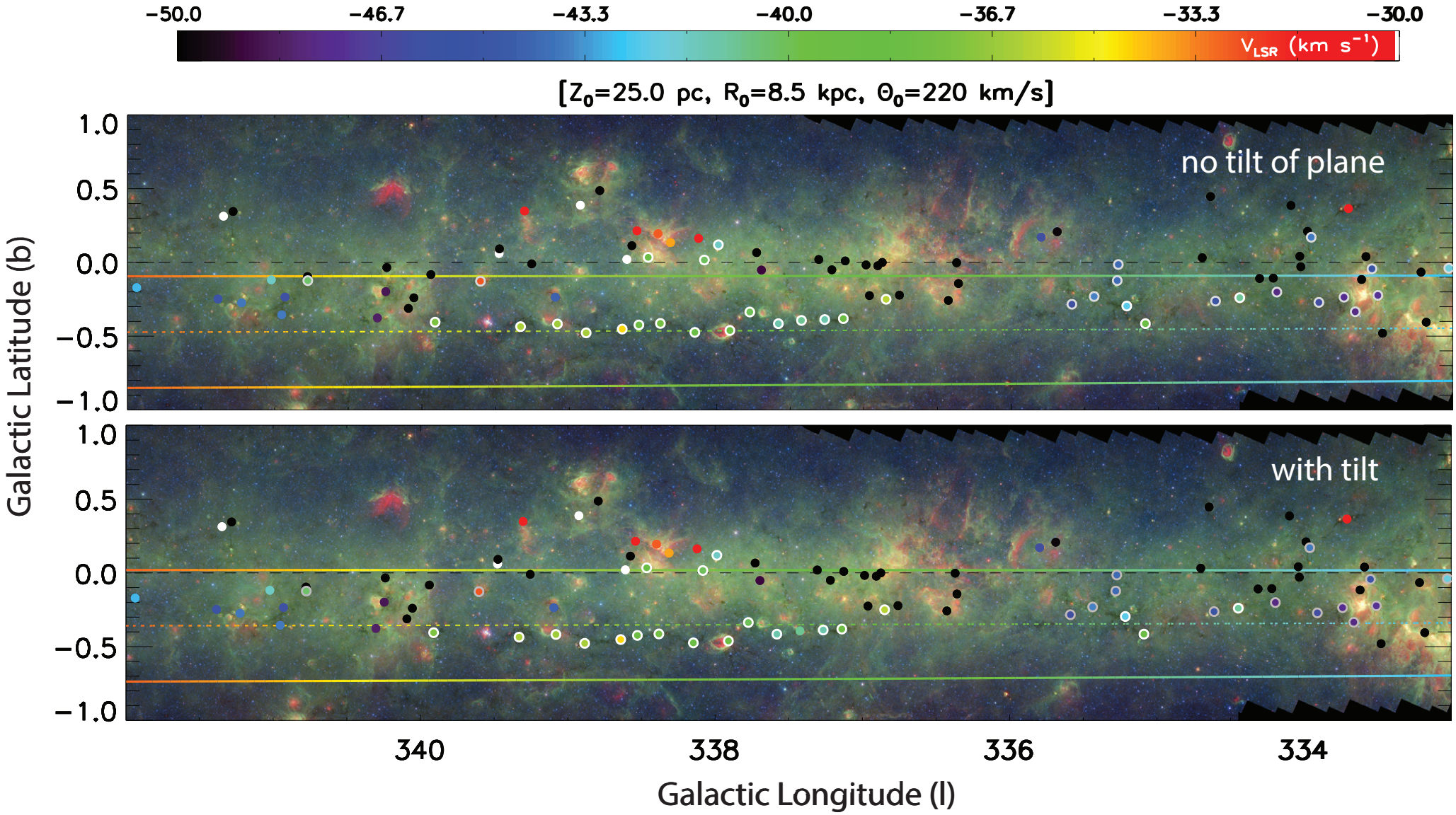
+

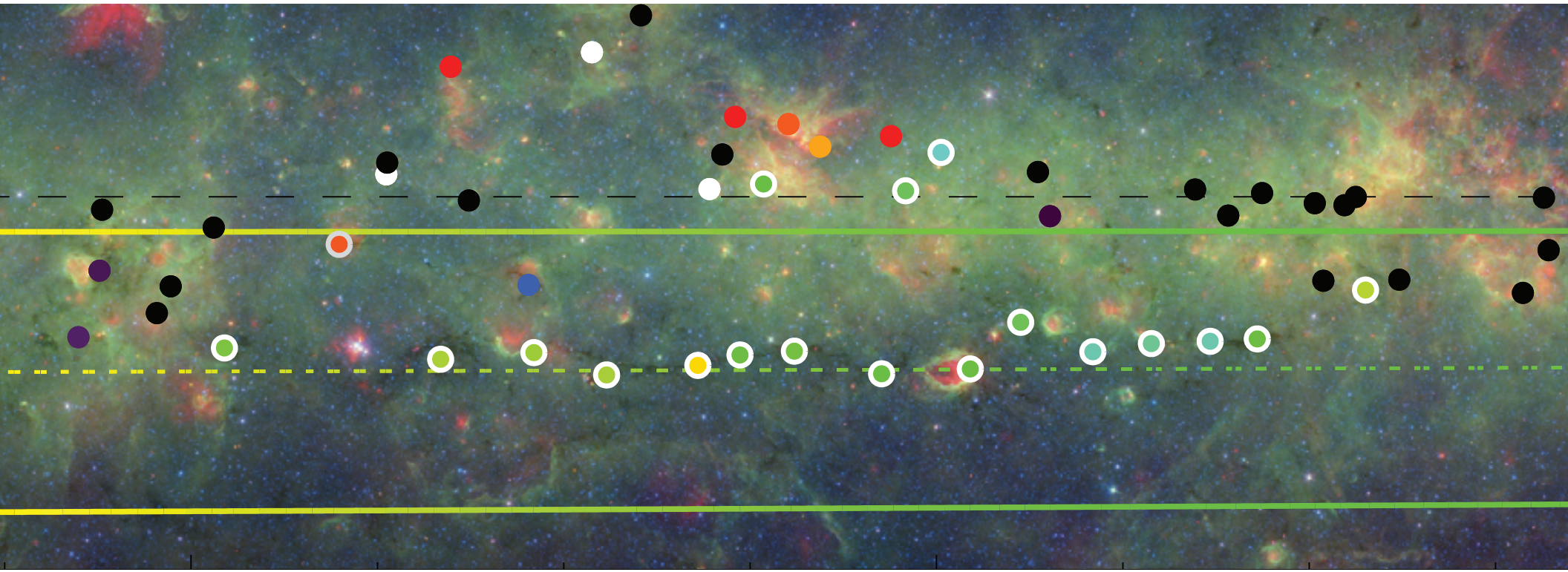
Galactic Center is ~20 light years offset from the IAU Milky Way Center

=

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!



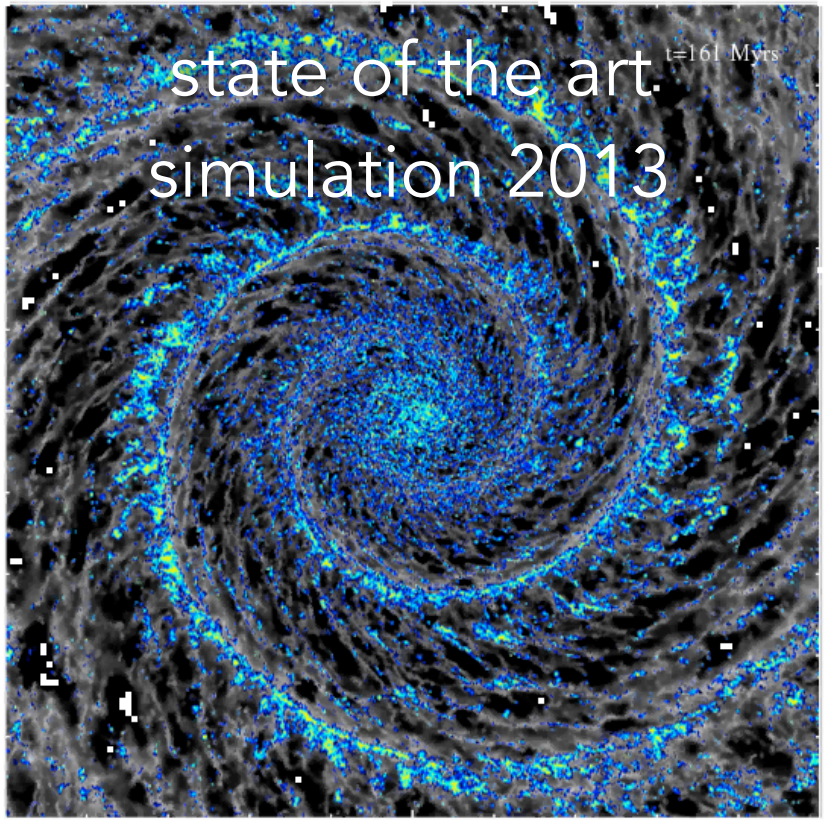


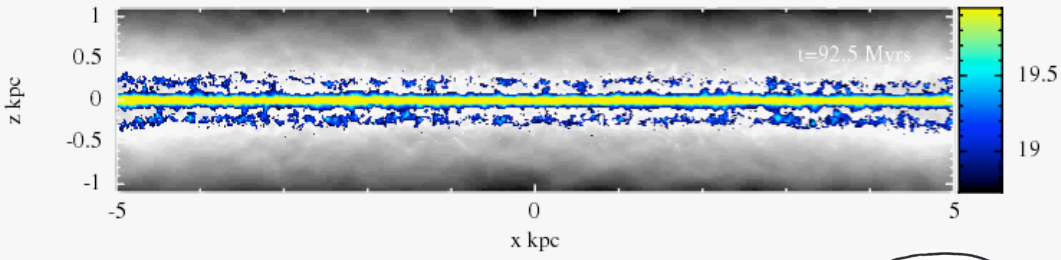
...eerily precisely...

How do we know the velocities?

A full 3D skeleton?

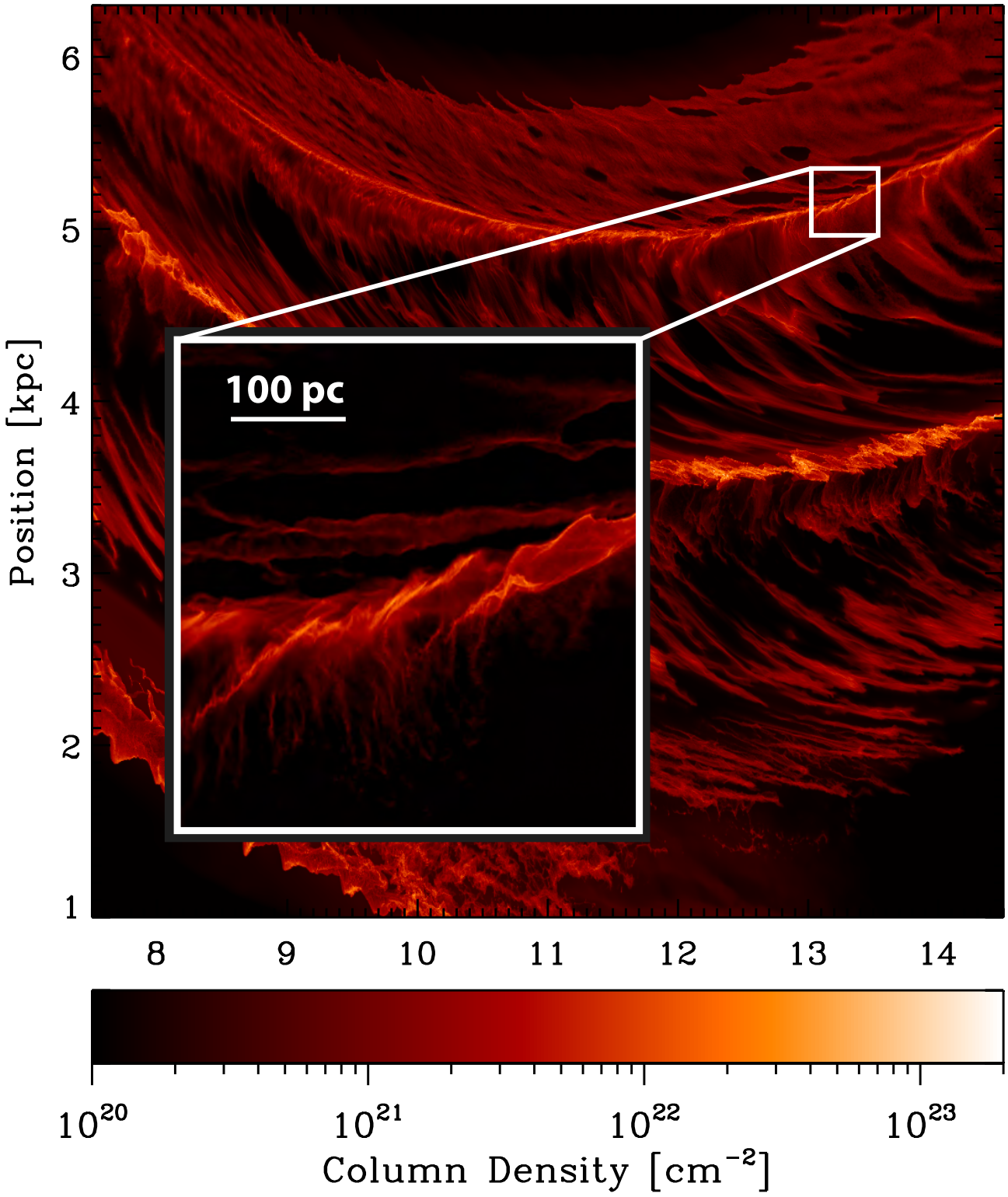
(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas





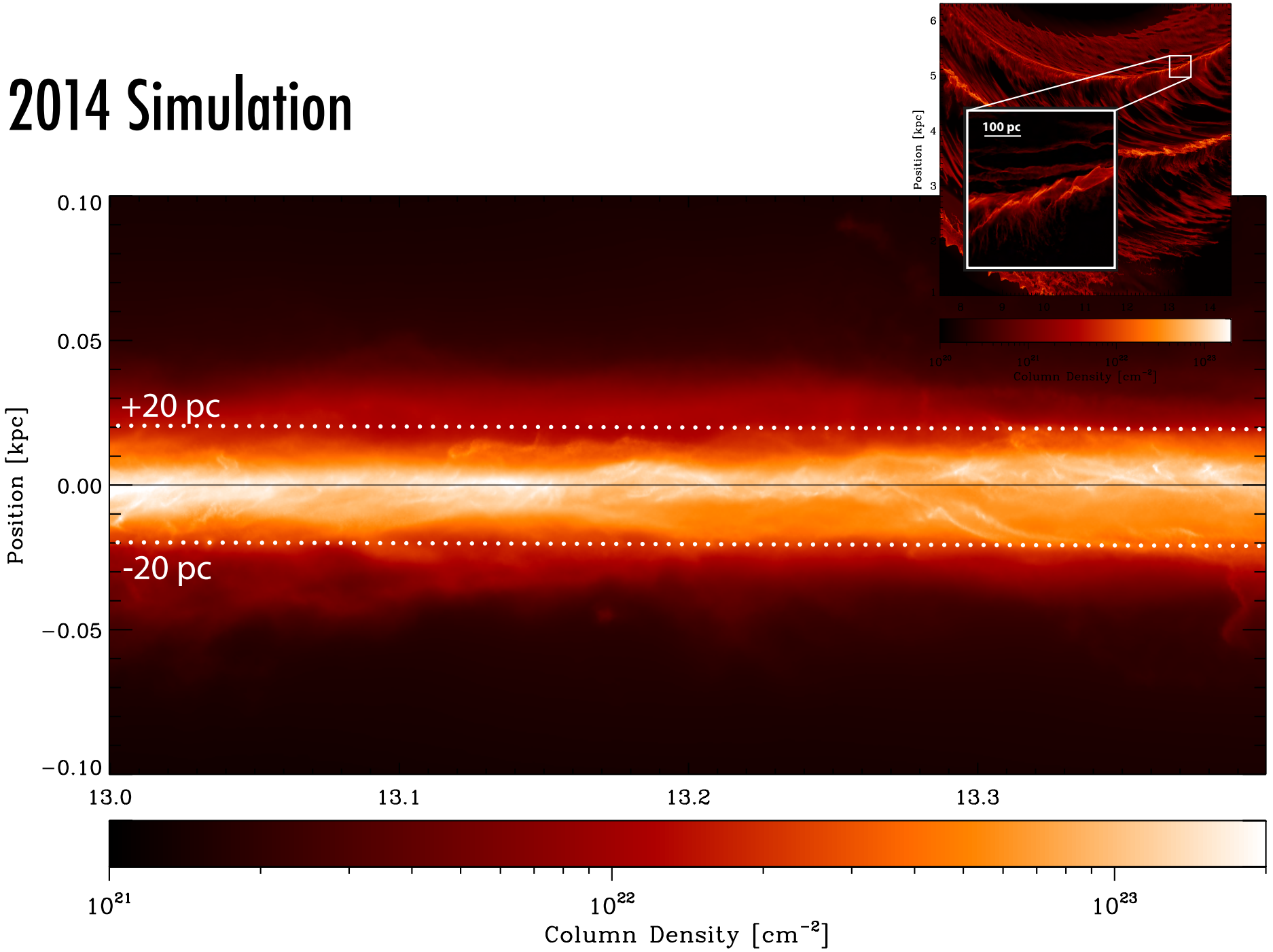
simulations courtesy Clare Dobbs

2014 Simulation



Smith et al. 2014, using AREPO

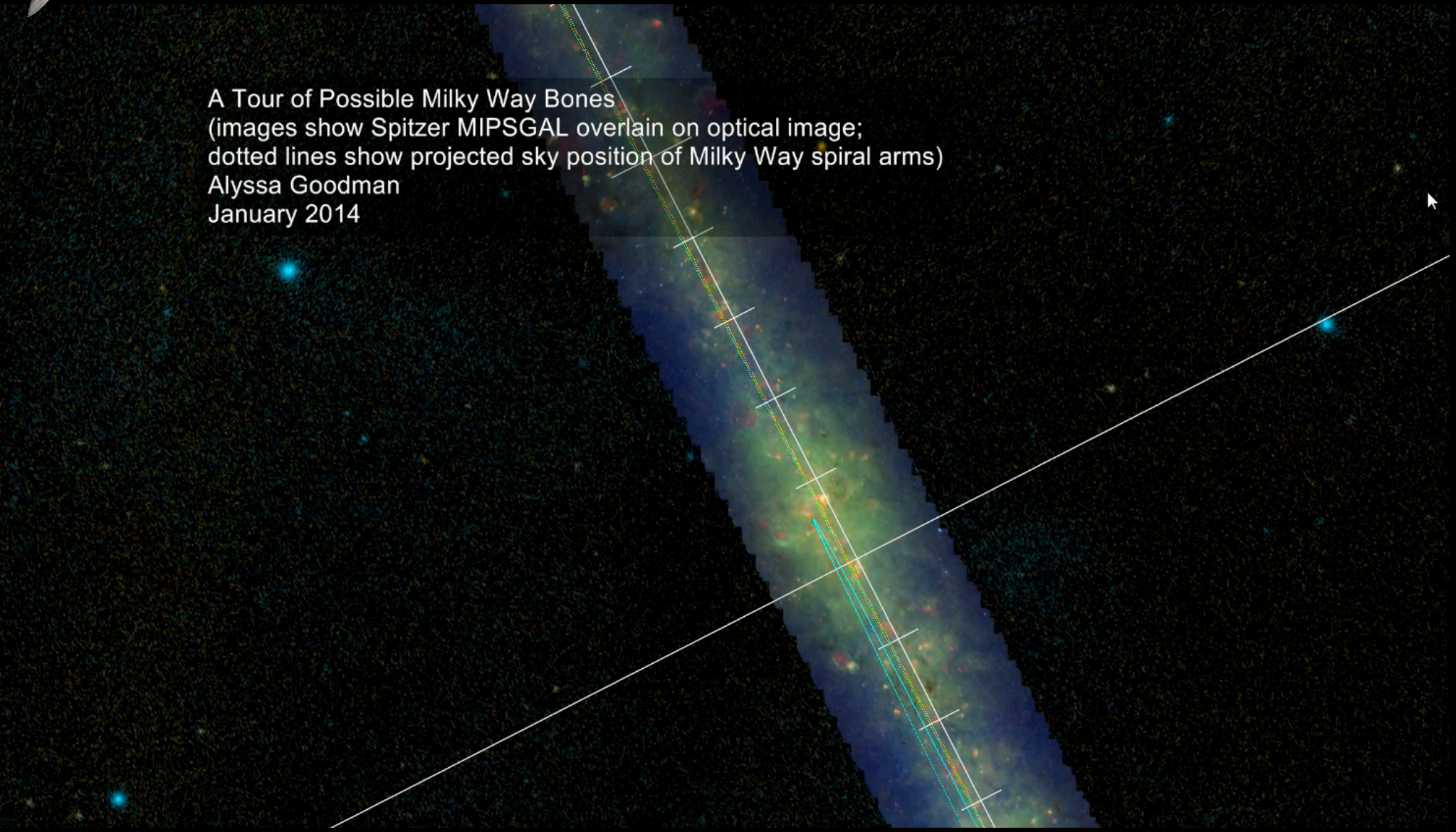
2014 Simulation



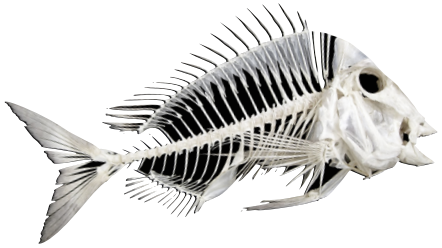
Smith et al. 2014, using AREPO

Can we find more bones?

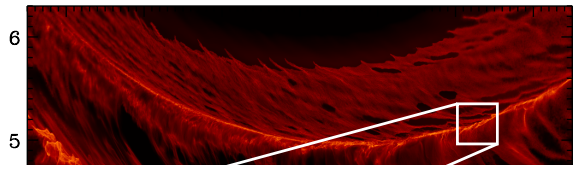
A Tour of Possible Milky Way Bones
(images show Spitzer MIPSGAL overlain on optical image;
dotted lines show projected sky position of Milky Way spiral arms)
Alyssa Goodman
January 2014



[demo]



Short Answer: Yes



The Astrophysical Journal, 815:23 (25pp), 2015 December 10 doi:10.1088/0004-637X/815/1/23
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THE SKELETON OF THE MILKY WAY

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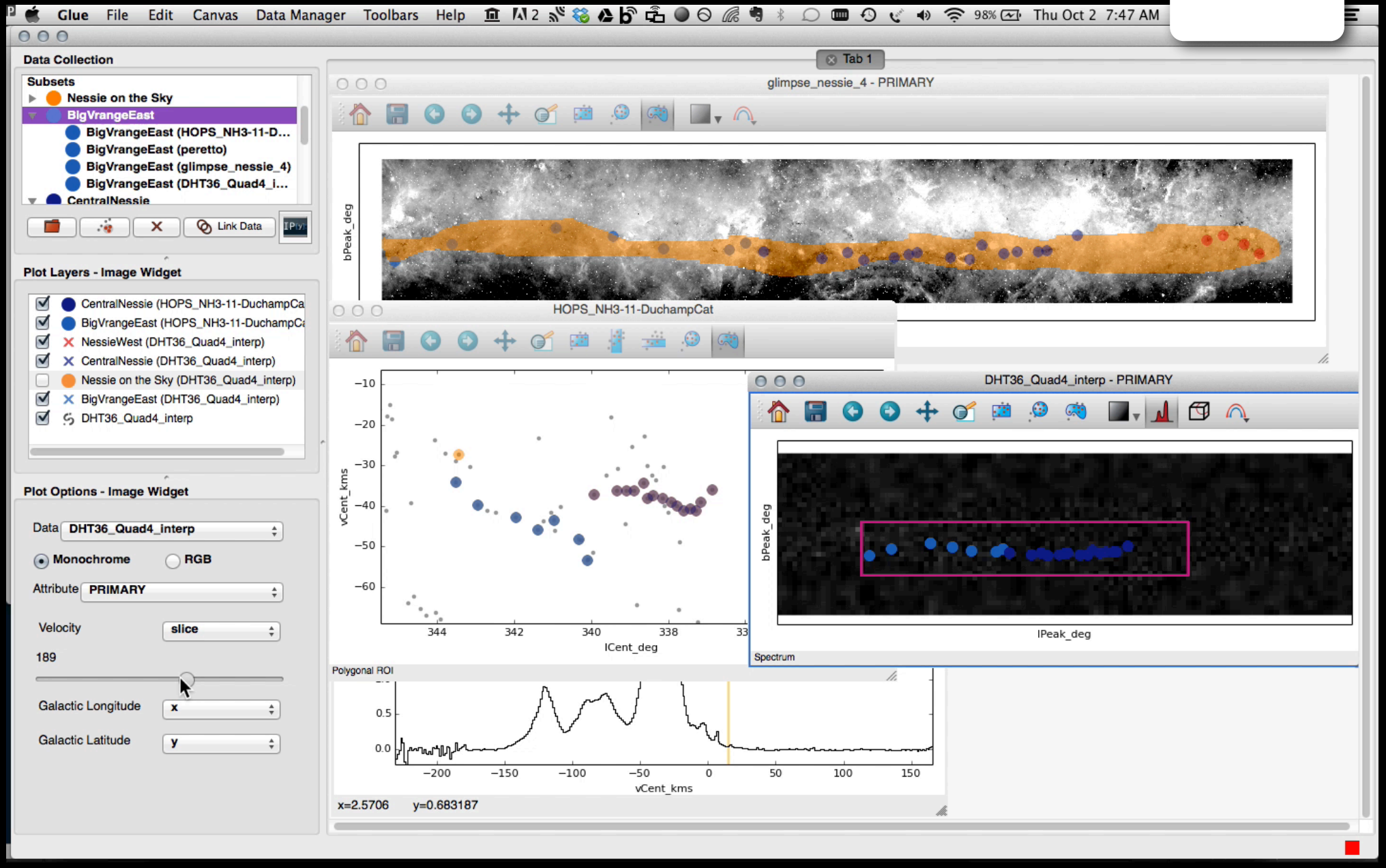
Received 2015 June 27; accepted 2015 September 21; published 2015 December 3

ABSTRACT

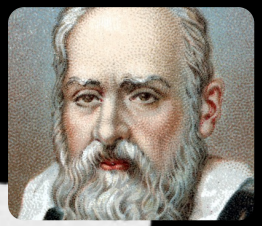
Recently, Goodman et al. argued that the very long, very thin infrared dark cloud "Nessie" lies directly in the Galactic midplane and runs along the Scutum–Centaurus Arm in position–position–velocity (*p–p–v*) space as traced by lower-density CO and higher-density NH_3 gas. Nessie was presented as the 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_2H^+, HCO^+, and NH_3 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 $\geqslant$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

HOW DID WE DO IT? (LINKED VIEWS)



17th Century



SIDEREUS NUNCIUS

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 straigh

On the f ars around
Jupiter, twe d precisely

East West

on a straigl nmost was
distant 3 m 40 seconds
from Jupite stern one,
and this on nagnitudes
were nearly tle smaller
than the re were only
30 seconds rer 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

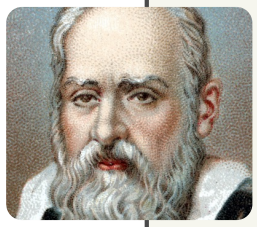
East * ○ * West

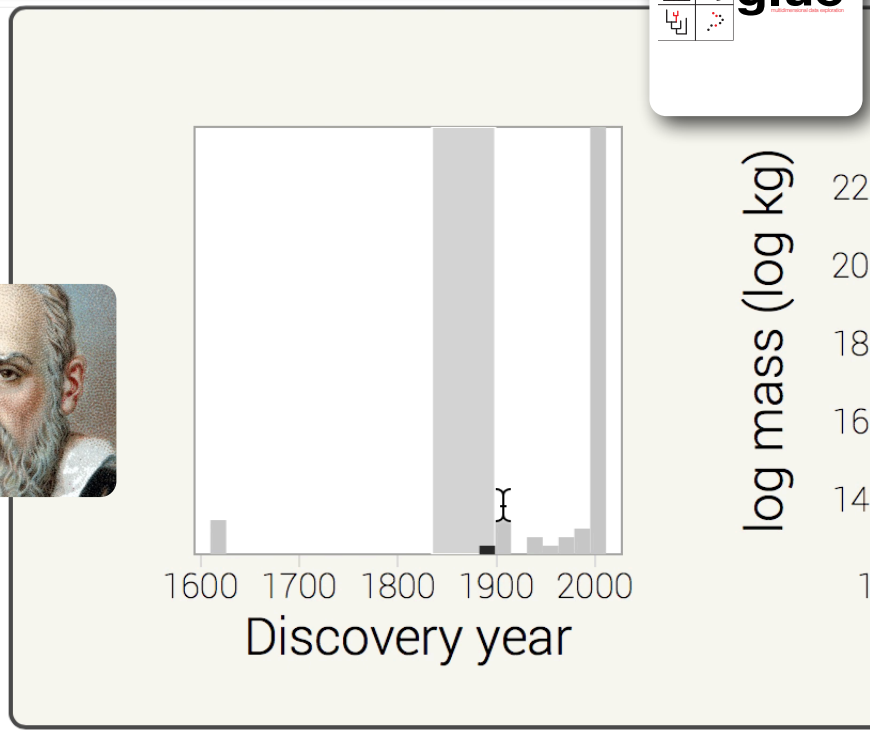
in the adjoining figure. The eastern one was 2 minutes and the western one 3 minutes from Jupiter. They were on the same straight line with Jupiter and equal in magnitude.

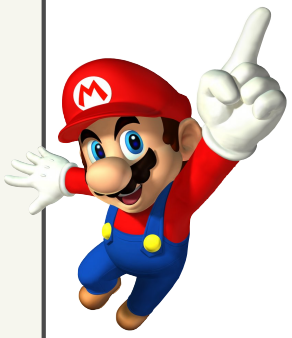
On the seventh, two stars stood near Jupiter, both to the east, arranged in this manner.

21st Century

LINKED VIEWS OF HIGH-DIMENSIONAL DATA





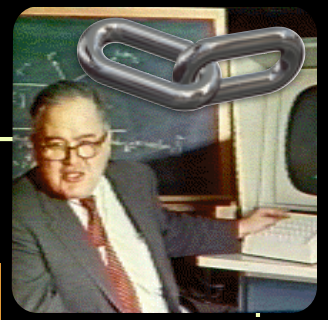


Four Centuries of Discovery | **A Chasm in Mass** | Little Siblings | Close Cousins | The Strangers

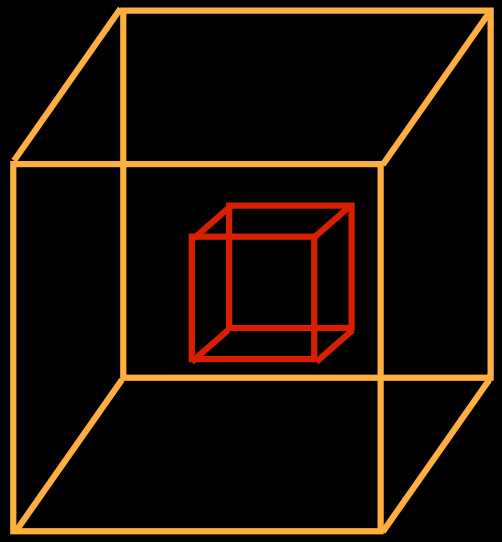
While telescopes improved dramatically toward 1900, no further moons were discovered, as the Galilean satellites are 10,000 times more massive than the next most massive moon, Himalia.

Au
Authorea

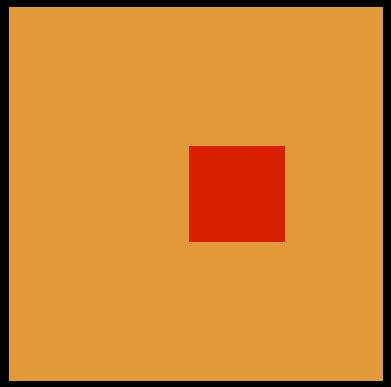
LINKED VIEWS OF HIGH-DIMENSIONAL DATA



John Tukey

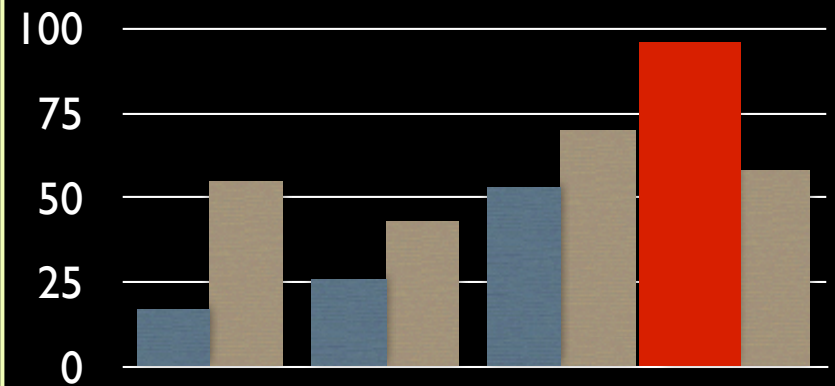


3D

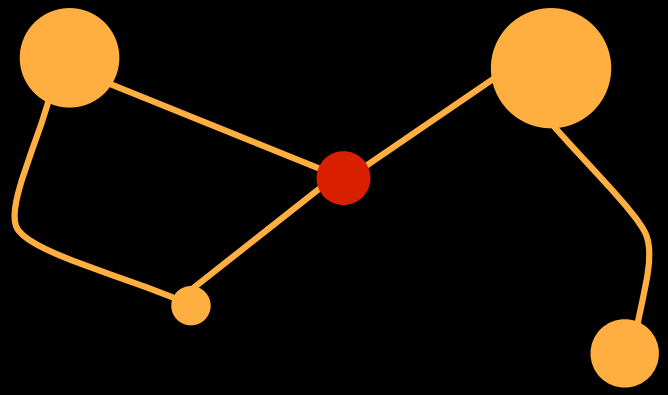


2D

Statistics



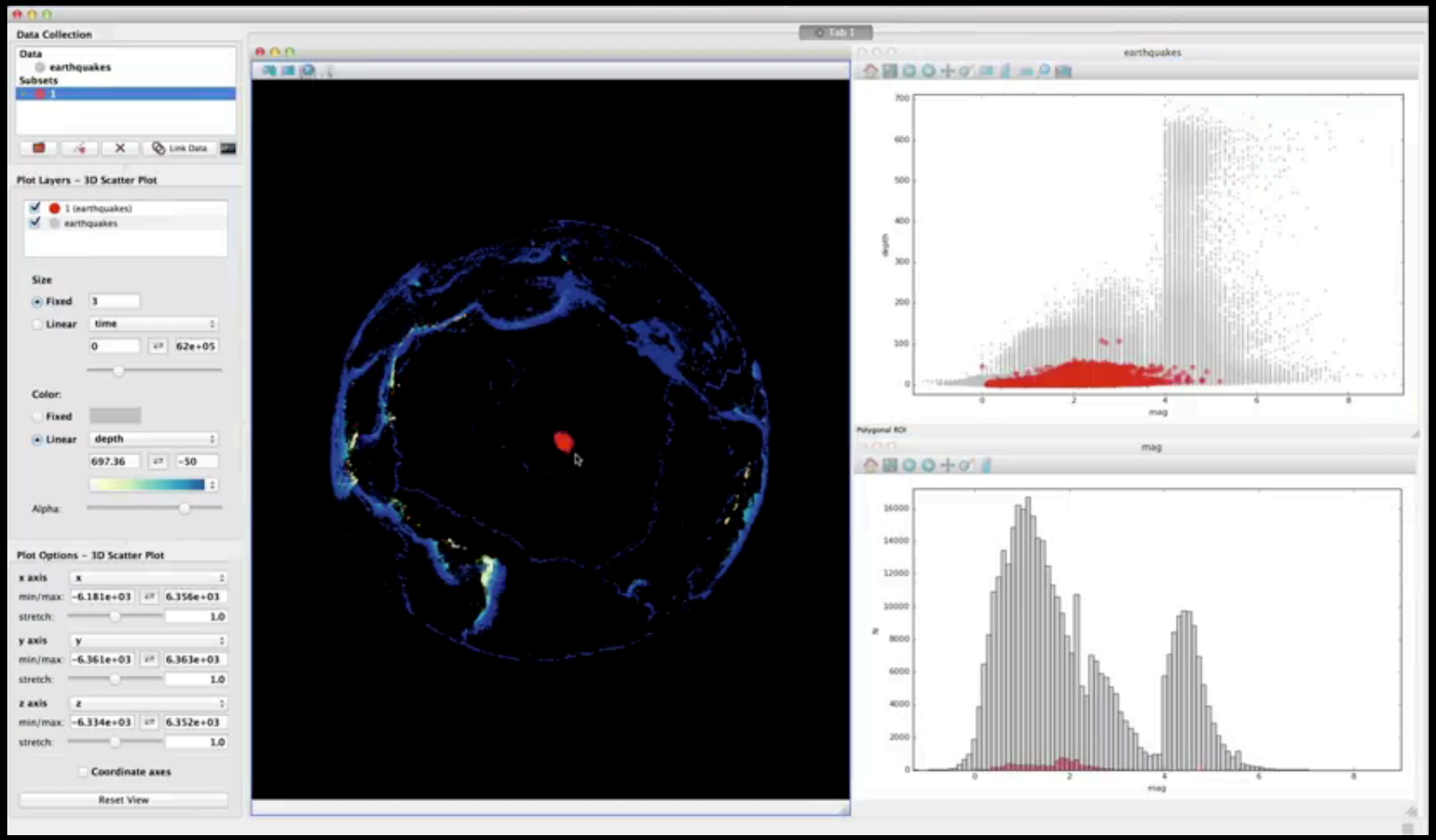
Data Abstraction



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

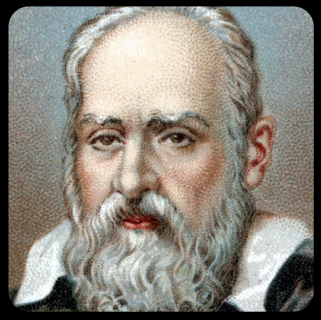
LINKED VIEWS OF HIGH-DIMENSIONAL DATA (IN PYTHON)

GLUE

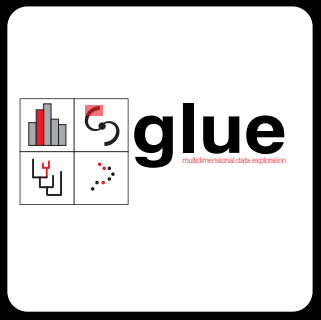


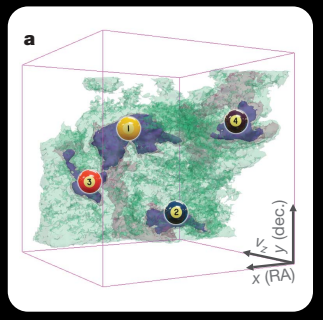
video by Tom Robitaille, lead glue developer

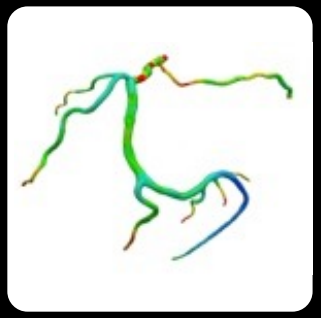
glue created by: C. Beaumont, M. Borkin, P. Qian, T. Robitaille, and A. Goodman, PI



WorldWide Telescope


glue
multidimensional data exploration

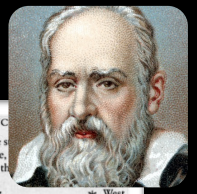

a
y (dec.)
x (RA)



Au
Authorea

SCHOLARLY COMMUNICATION

1610



SIDEREUS NUNC

On the third, at the seventh hour, the s
sequence. The eastern one was 1 minute,
the closest western one 2 minutes; and th

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 st
30 seconds apart. Jupiter was 2 minutes from the

East ** ○ * *

one, while he was 4 minutes from the next western
one was 3 minutes from the westernmost one. They
and extended on the same straight line along the ecl

On the fifth, the sky was cloudy.

On the sixth, only two stars appeared flanking Ju

East * ○ *

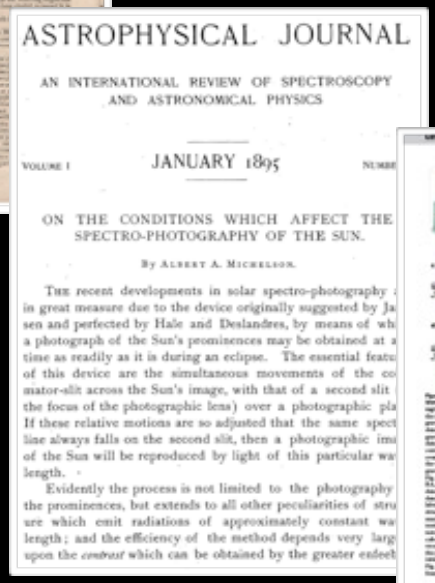
in the adjoining figure. The eastern one was 2 mi
western one 3 minutes from Jupiter. They were on th
line with Jupiter and equal in magnitude.

On the seventh, two stars stood near Jupiter, bo
arranged in this manner.

1665

PHILOSOPHICAL TRANSACTIONS

1895



ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME I JANUARY 1895 NUMBE

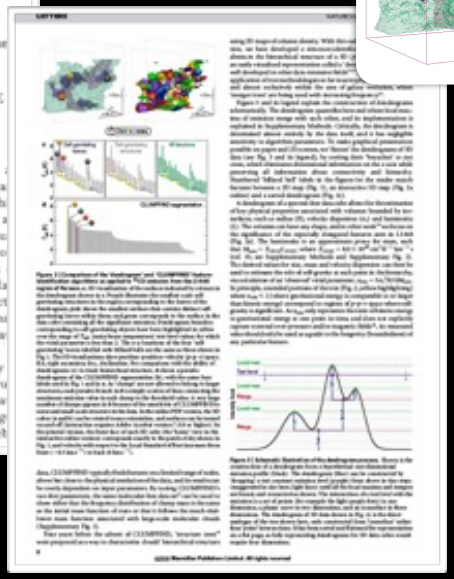
ON THE CONDITIONS WHICH AFFECT THE SPECTRO-PHOTOGRAPHY OF THE SUN.

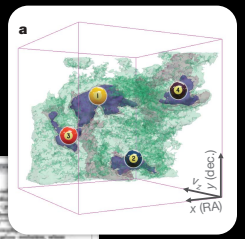
By Albert A. Michelson.

The recent developments in solar spectro-photography
in great measure due to the device originally suggested by Ja
sen and perfected by Hale and Deslandres, by means of wh
a photograph of the Sun's prominences may be obtained at a
time as readily as it is during an eclipse. The essential featu
of this device are the simultaneous movements of the co
mator-slit across the Sun's image, with that of a second slit
the focus of the photographic lens) over a photographic pla
If these relative motions are so adjusted that the same spect
line always falls on the second slit, then a photographic ima
of the Sun will be reproduced by light of this particular wa
length.

Evidently the process is not limited to the photography
the prominences, but extends to all other peculiarities of stru
ure which emit radiations of approximately constant wa
length; and the efficiency of the method depends very larg
upon the *contrast* which can be obtained by the greater endeel

2009





2009

3D PDF

INTERACTIVITY

IN A "PAPER"

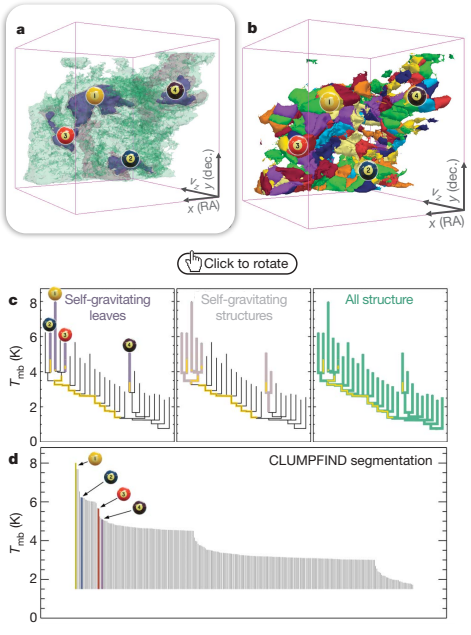


Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. a, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating 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 t… schematically. The dendrogram qua… ima of emission merge with each… explained in Supplementary Meth… determined almost entirely by t… sensitivity to algorithm paramet… possible on paper and 2D screen… data (see Fig. 3 and its legend… cross, which eliminates dimen… preserving all information… Numbered 'billiard ball' lab… features between a 2D map… online) and a sorted dendr…

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

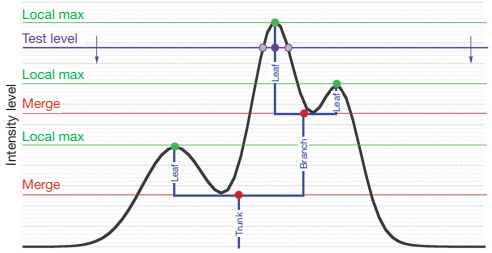


Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in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

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

Create
1 / 4
131%
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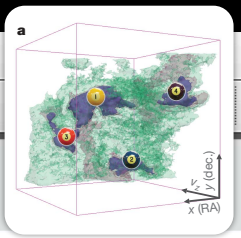


Vol 457|1 January 2009|doi:10.1038/nature07609

LETTERS

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

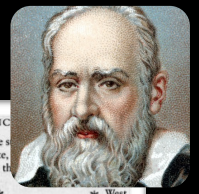
Alyssa A. Goodman[1,2], Erik W. Rosolowsky[2,3], Michelle A. Borkin[1]†, Jonathan B. Foster[2], Michael Halle[1,4], Jens Kauffmann[1,2] & Jaime E. Pineda[2]

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

SCHOLARLY COMMUNICATION

1610



SIDEREUS NUNC

On the third, at the seventh hour, the s
sequence. The eastern one was 1 minute,
the closest western one 2 minutes; and th

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 st
30 seconds apart. Jupiter was 2 minutes from the

East ** ○ * *

one, while he was 4 minutes from the next western one was 3 minutes from the westernmost one. They and extended on the same straight line along the ec

On the fifth, the sky was cloudy.

On the sixth, only two stars appeared flanking Ju

East * ○ *

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

On the seventh, two stars stood near Jupiter, bo arranged in this manner.

1665

PHILOSOPHICAL TRANSACTIONS

1895

ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME I JANUARY 1895 NUMBE

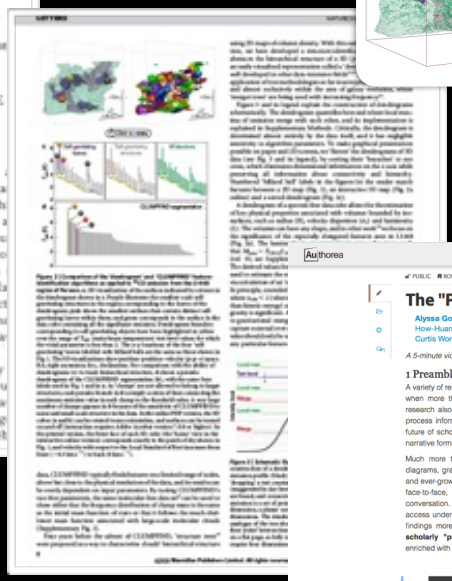
ON THE CONDITIONS WHICH AFFECT THE SPECTRO-PHOTOGRAPHY OF THE SUN.

By Albert A. Michelson.

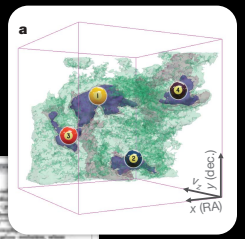
The recent developments in solar spectro-photography in great measure due to the device originally suggested by Ja sen and perfected by Hale and Deslandres, by means of wh a photograph of the Sun's prominences may be obtained at a time as readily as it is during an eclipse. The essential featu of this device are the simultaneous movements of the co mator-slit across the Sun's image, with that of a second slit the focus of the photographic lens) over a photographic pla If these relative motions are so adjusted that the same spect line always falls on the second slit, then a photographic ima of the Sun will be reproduced by light of this particular wa length.

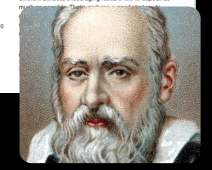
Evidently the process is not limited to the photography the prominences, but extends to all other peculiarities of stru ure which emit radiations of approximately constant wa length; and the efficiency of the method depends very larg upon the *contrast* which can be obtained by the greater endeet

2009



2015

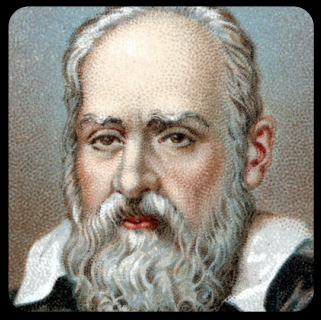




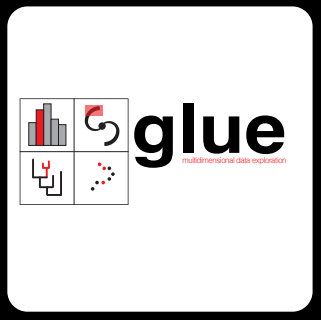
WorldWide Telescope

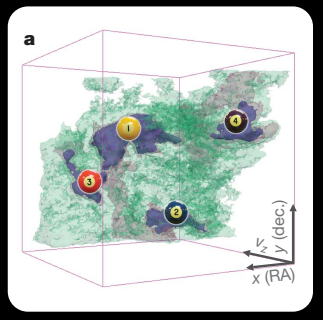
glue

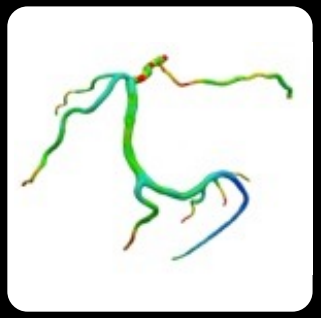
Au Authorea



WorldWide Telescope


glue
multidimensional data exploration


a
y (dec.)
x (RA)



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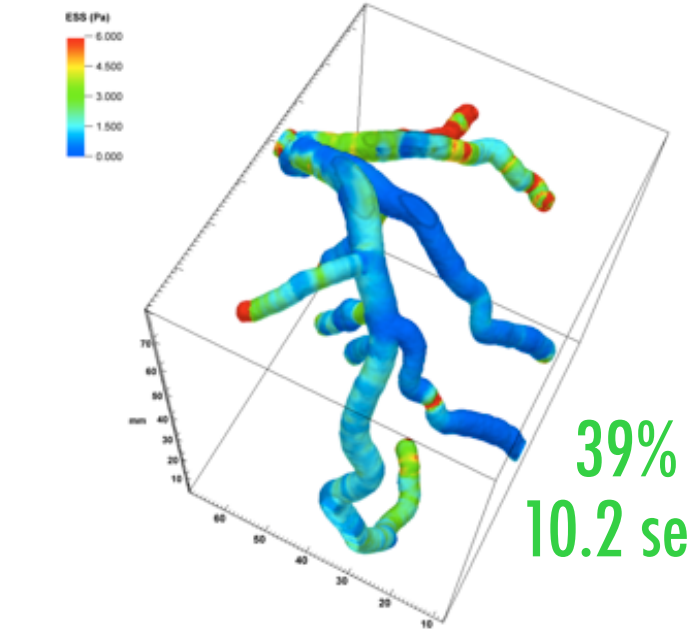
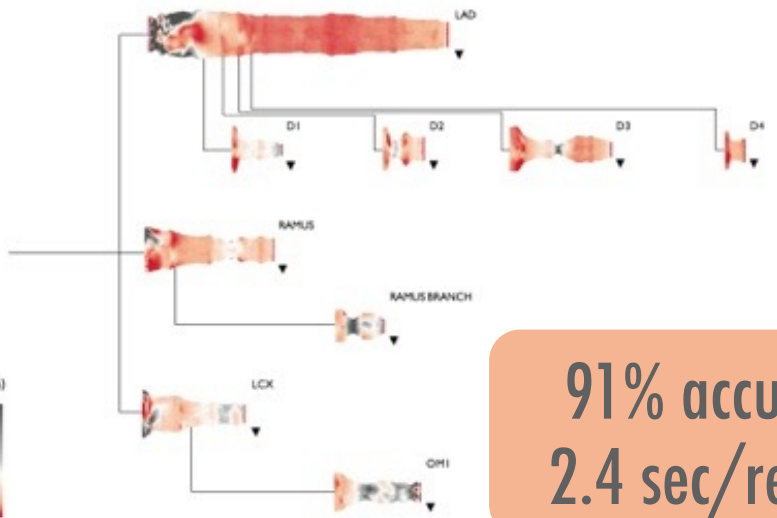
Authorea

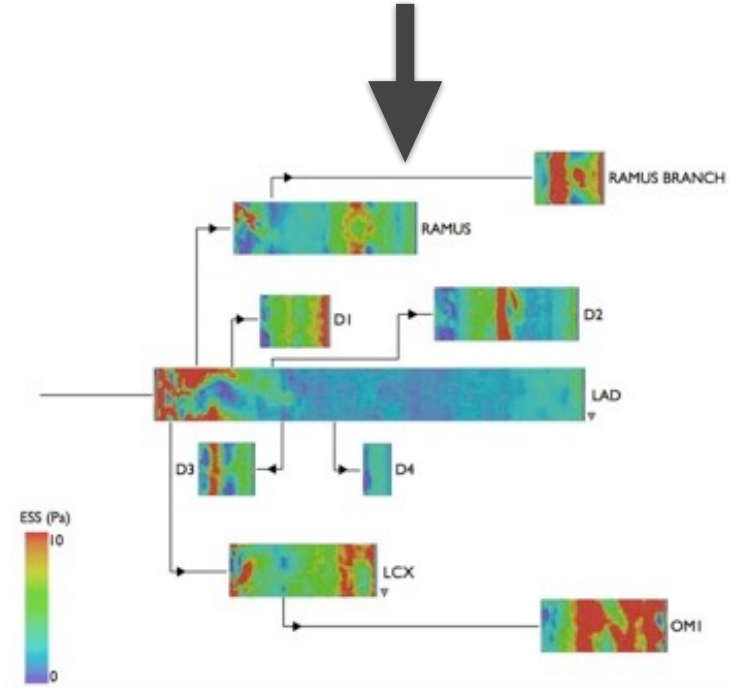
ASTRONOMICAL MEDICINE

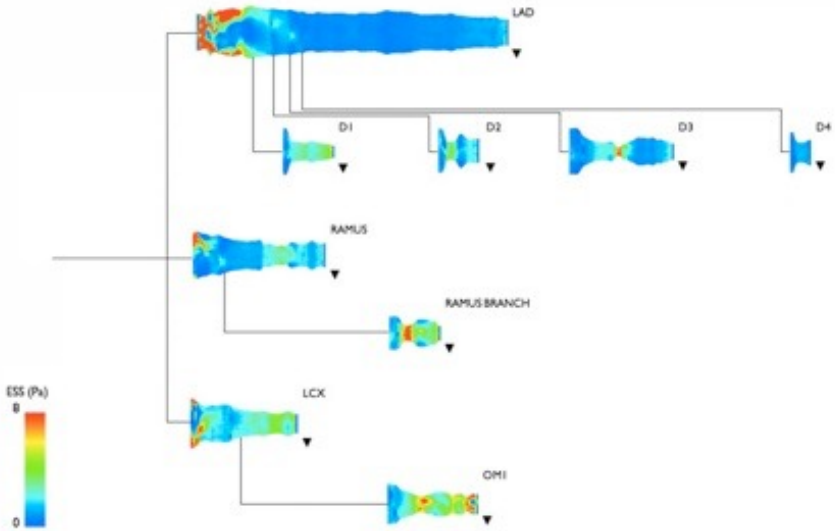


39% accurate
10.2 sec/region



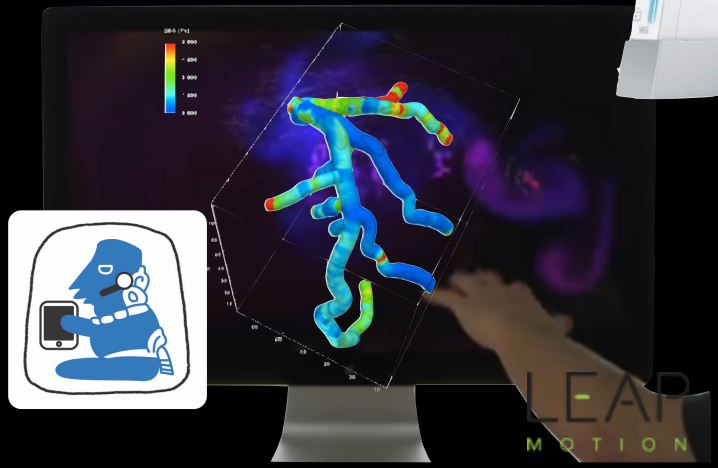
91% accurate
2.4 sec/region



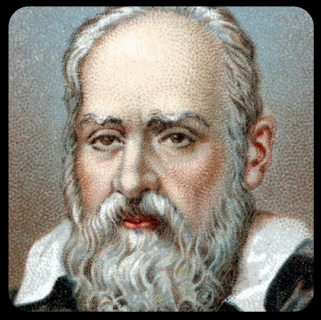


Borkin et al. 2011
cf. colorbrewer2.org

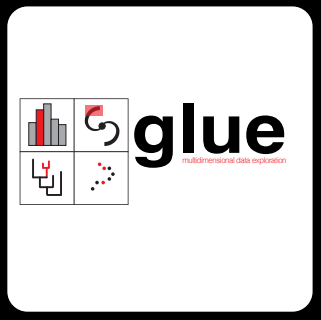
NOW WE JUST NEED TO SOLVE "3D SELECTION"

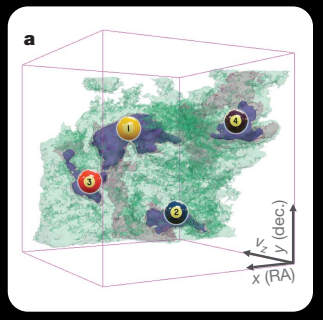


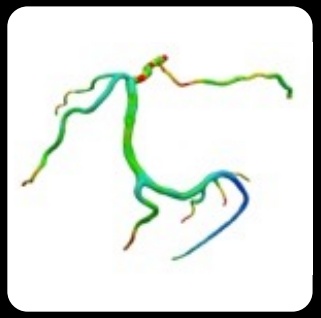
Microsoft
HoloLens



WorldWide Telescope


glue
multidimensional data exploration


a
y (dec.)
x (RA)



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HARVARD gazette

An academic reality show

'PredictionX' brings together faculty from across the University to discuss the human need to know the future

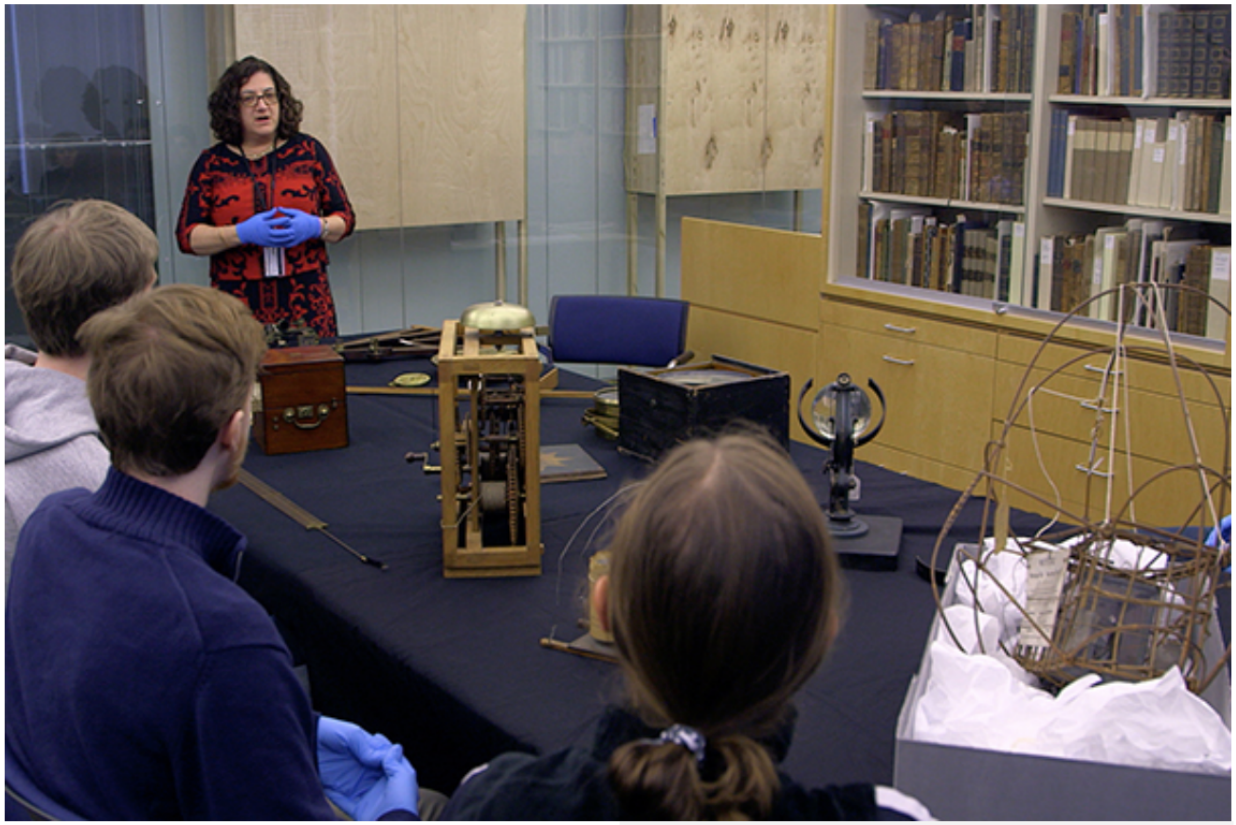


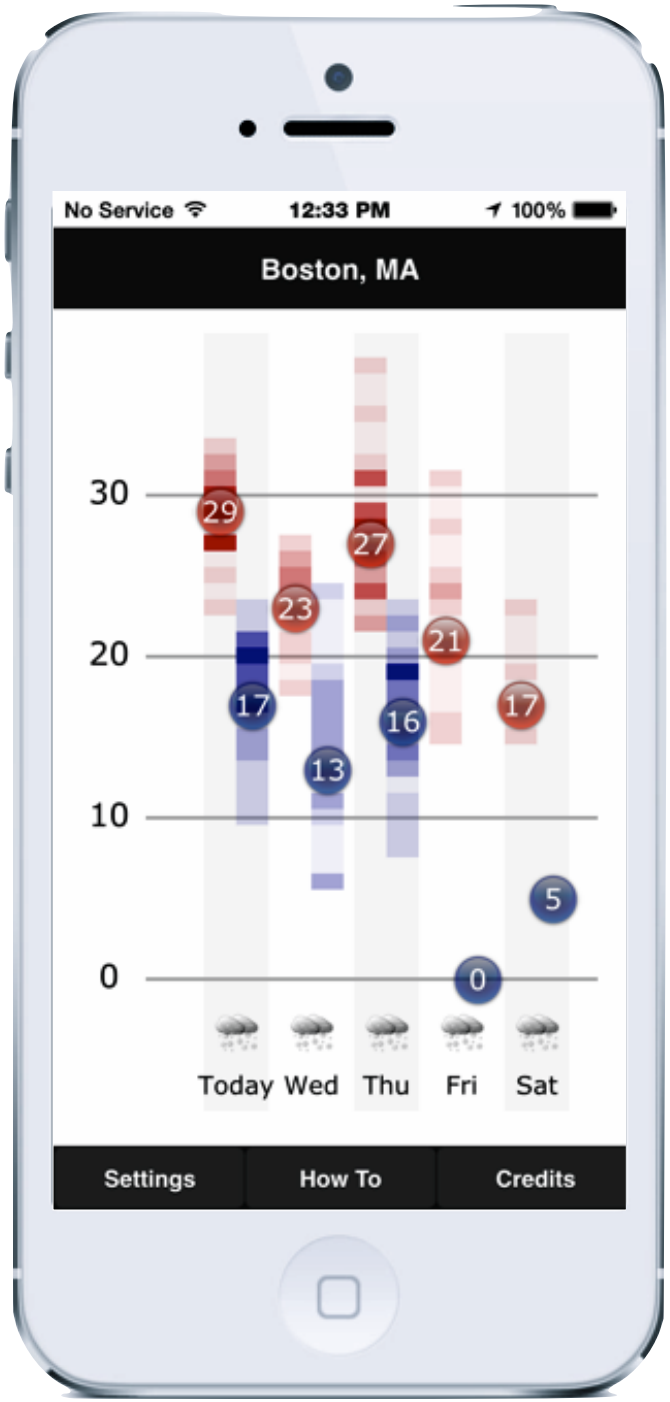
Photo courtesy of HarvardX

Professor Sara Schechner shows students compasses, sextants, and a variety of other instruments that sailors used to measure and

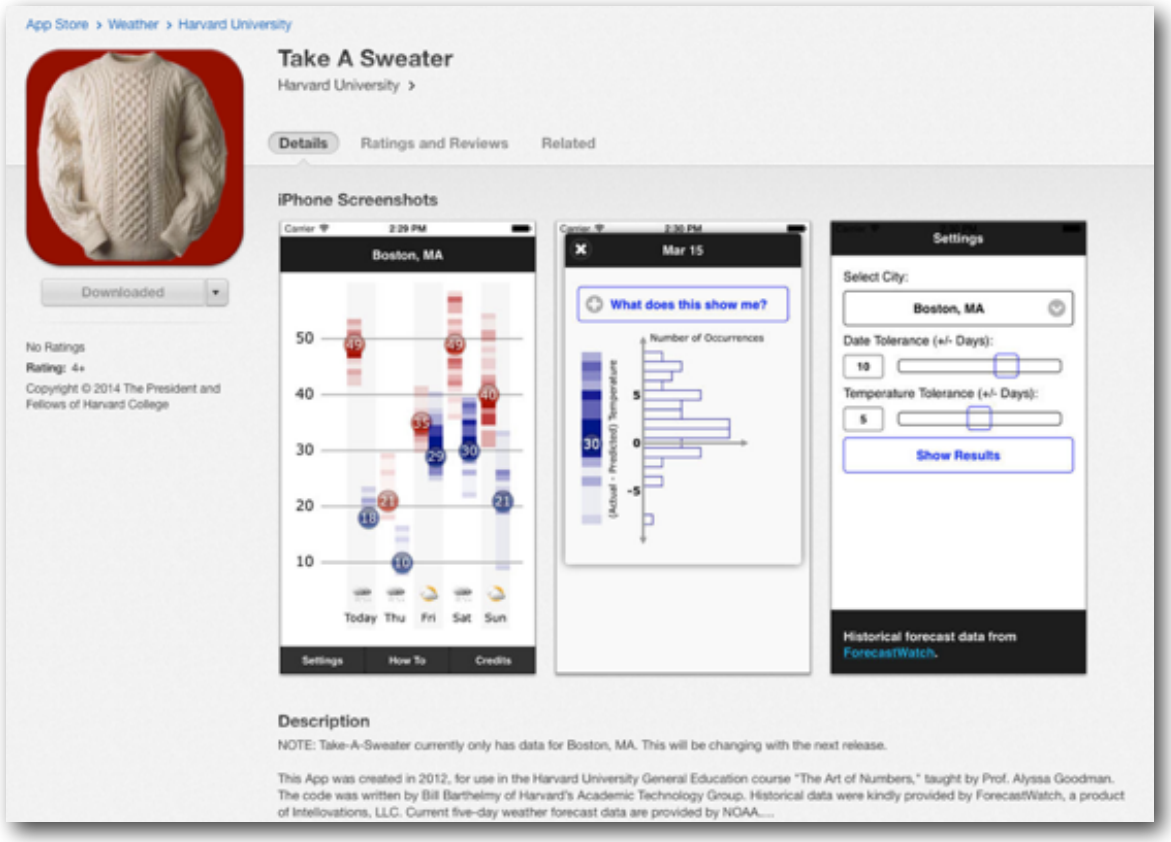
November 13, 2015 |

By Brett Milano, Harvard Correspondent

In a Science Center lecture hall at Harvard, anthropologist Rowan Flad

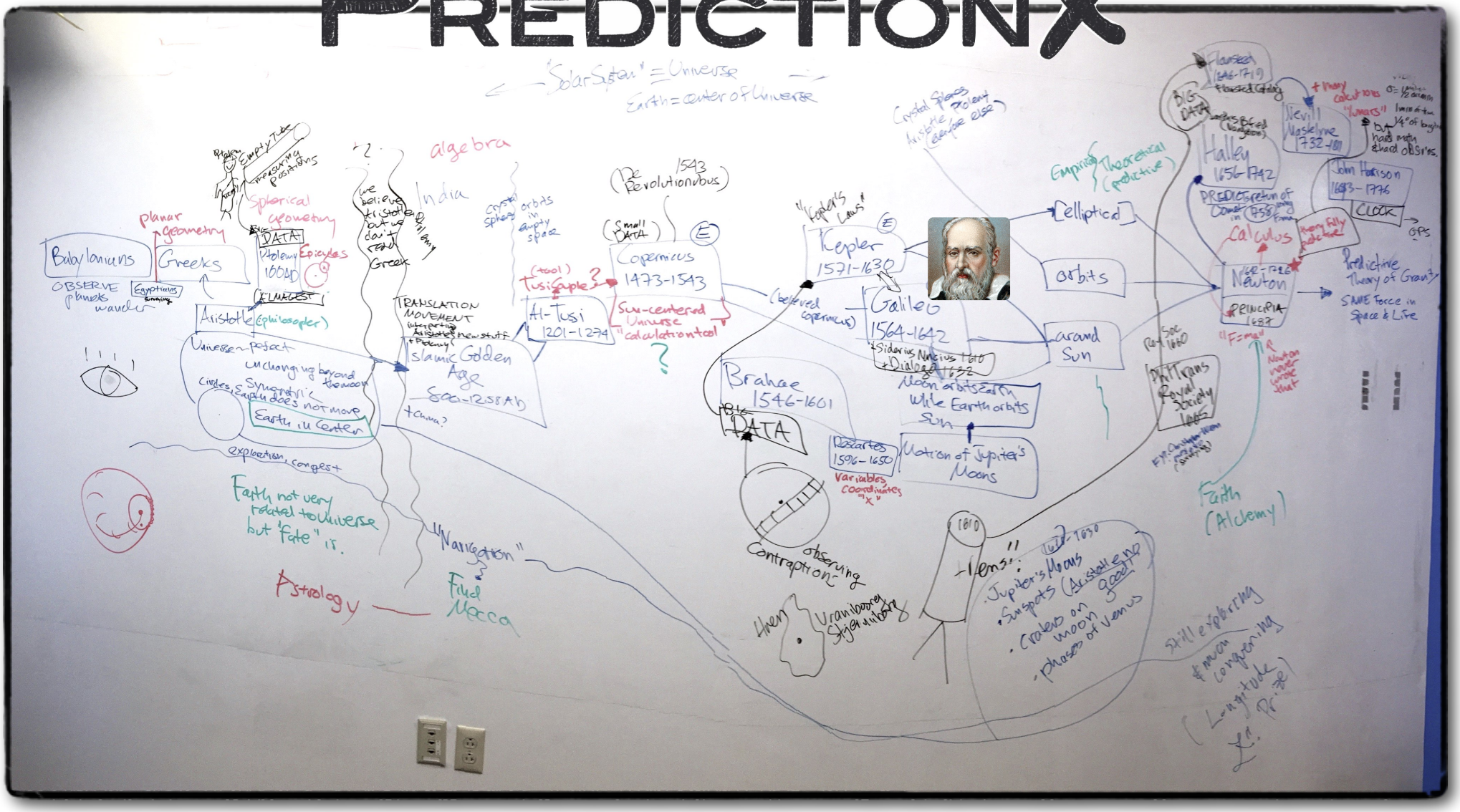


PredictionX



takeasweater.com, and "TakeASweater" in the Apple App Store

PredictionX

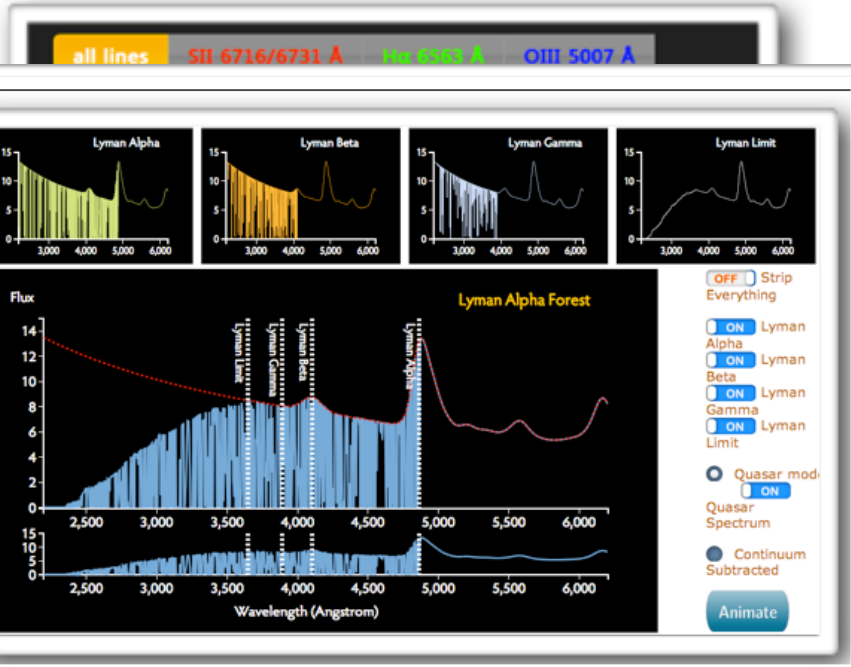


EDUCATION, 2016+

online learning

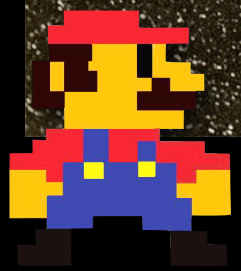
WWT Ambassadors

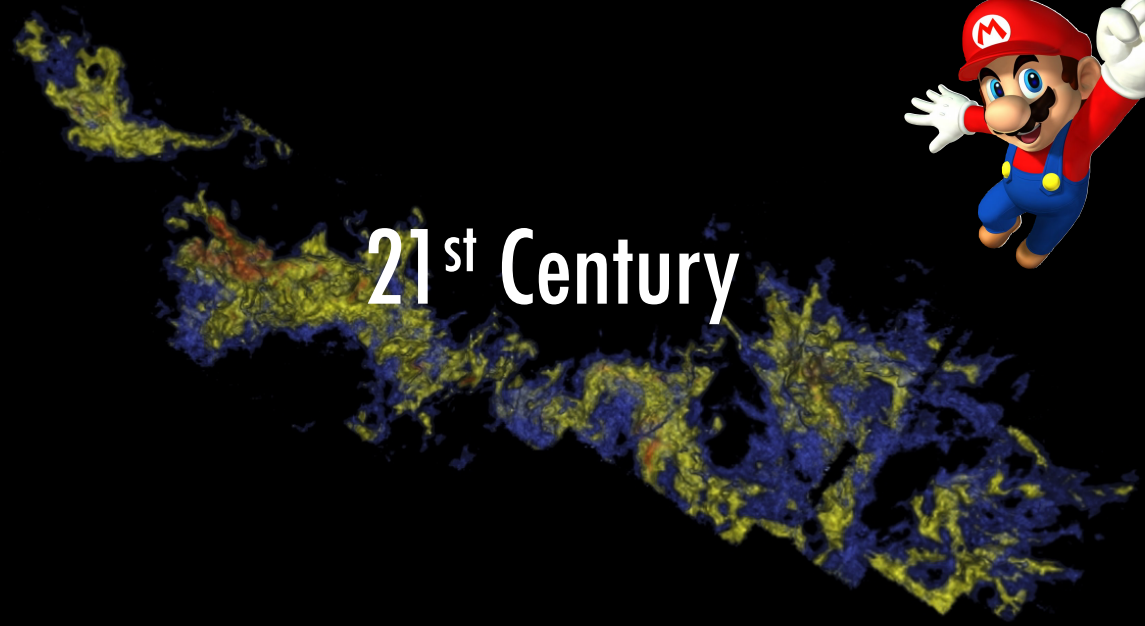
Stephen



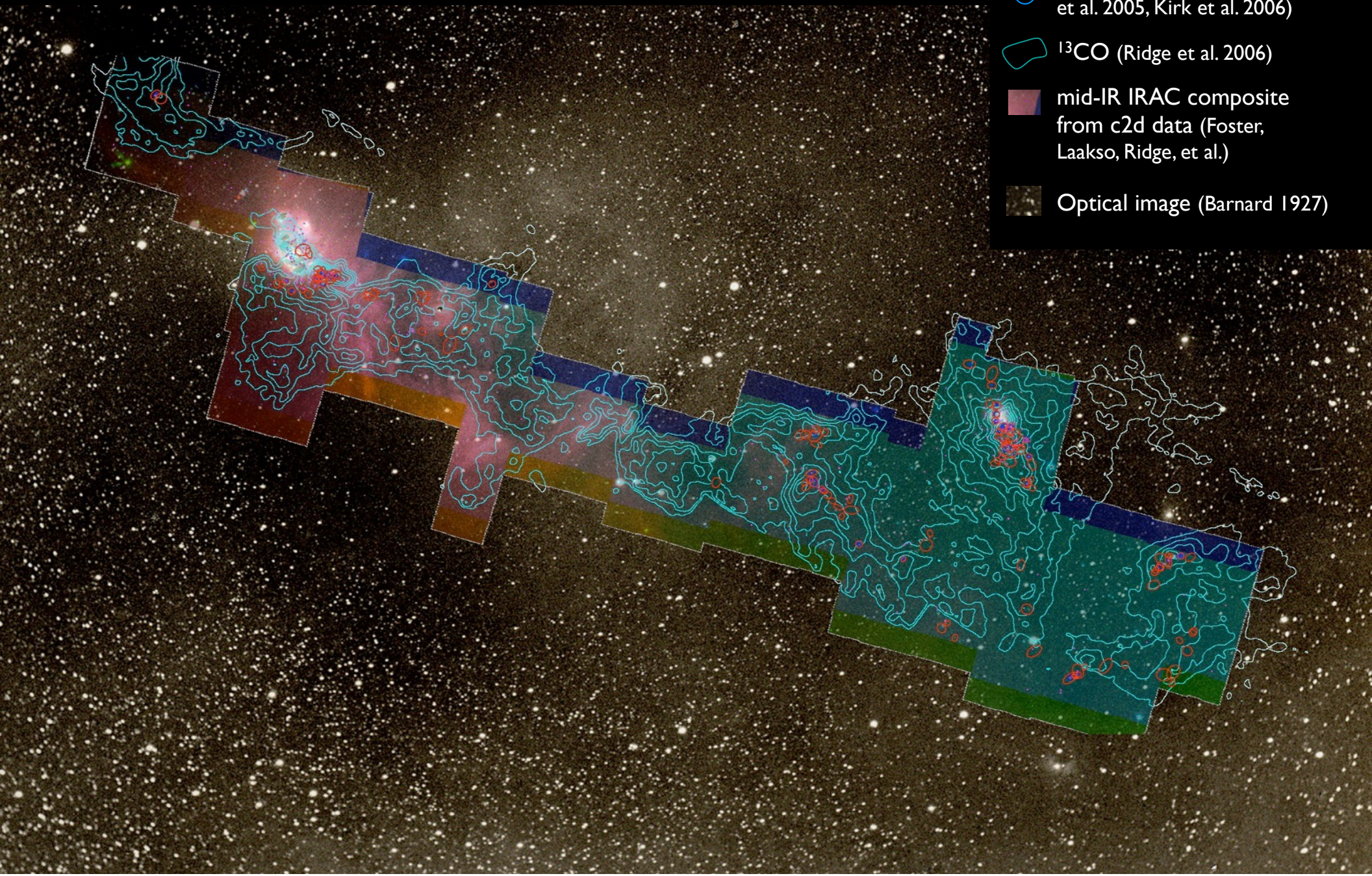
see: A New Approach to Developing Interactive Software Modules through Graduate Education, Sanders, Faesi & Goodman 2013

20th Century




21st Century

WIDE DATA


COMPLETE
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)

COMPLETE Coverage Tool (WWT)

COMPLETE Data Available

Center on Perseus | Center on Ophichus | Center on Serpens

Full-Cloud Data (Phase I, All Data Available)

Dataset	Show	Perseus	Ophiuchus	Serpens	Link
GBT: HI Data Cube	☑	√	√	∅	Data
IRAS: Av/Temp Maps	☑	√	√	√	Data
FCRAO: 12CO	☑	√	√	√	Data
FCRAO: 13CO		√	√	√	Data
JCMT: 850 microns	☑	√	√	∅	Data
Spitzer c2d: IRAC 1,3 (3.6,5.8 μm)	☑	√	√	√	Data
Spitzer c2d: IRAC 2,4 (4.5,8 μm)	☑	√	√	√	Data
CSO/Bolocam: 1.2-mm	☑	√	∅	∅	Data
Spitzer MIPS: Derived Dust Map	☑	√	∅	∅	Data

Targeted Regions (Phase II, Some Data Not Yet Available)

CTIO/Calar Alto: NIR (J,H,Ks)	☑	√	√	∅	Data
IRAM 30-m: N2H+ and C18O	☑	√	∅	∅	Data
IRAM 30-m: 1.1-mm continuum	☑	√	∅	∅	Data
Megacam/MMT: r,i,z images	☑	√	∅	∅	Data

Catalogs & Pointed Surveys

NH3 Pointed Survey	☐	√	∅	∅	Data
YSO Candidate list (c2d)	☐	√	√	√	Data