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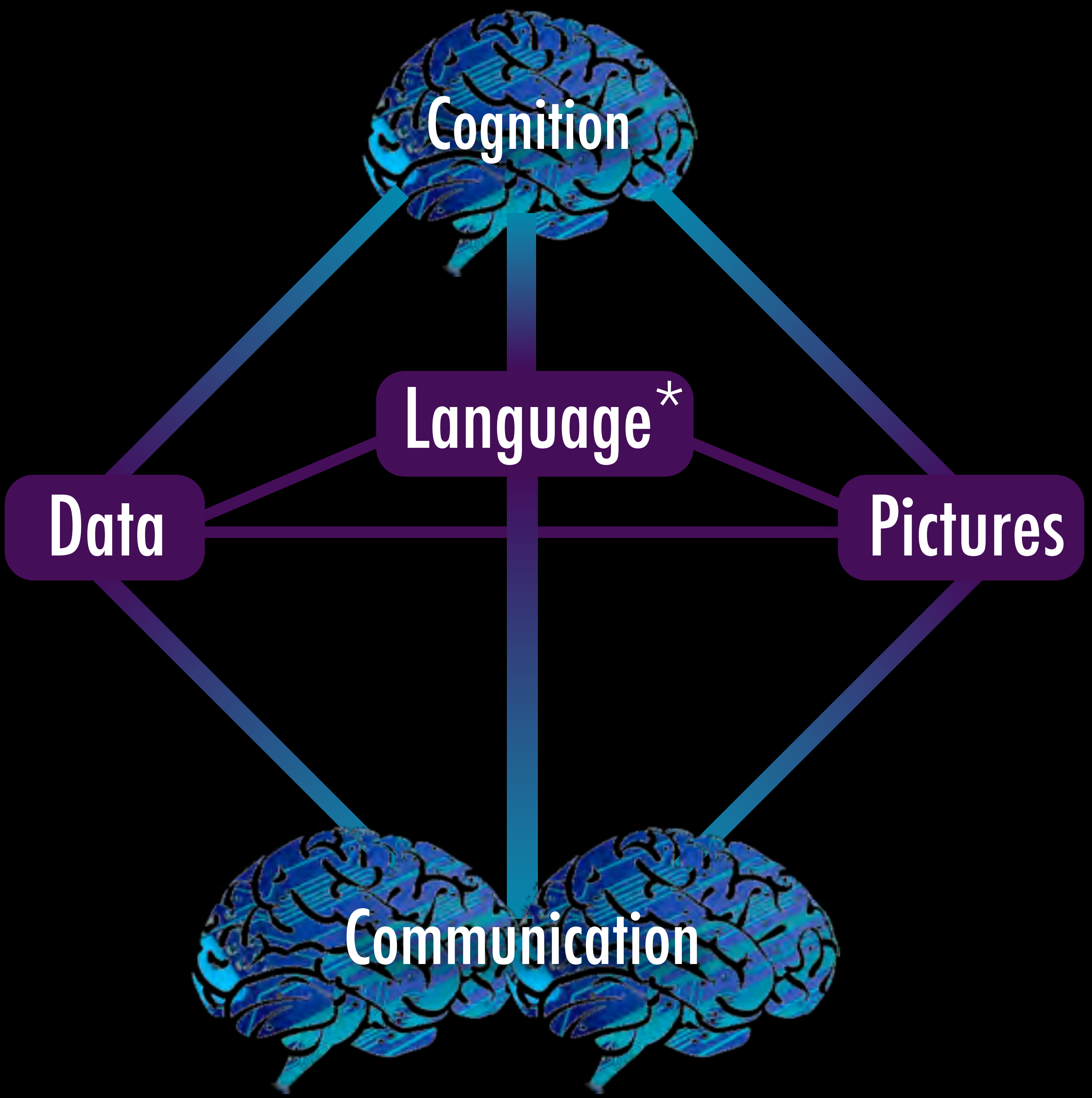
SEEING STARS FORM IN THE MILKY WAY

ALYSSA A. GOODMAN
HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS @AAGIE

RELATIVE STRENGTHS

Pattern Recognition
Creativity

Calculations



*"Language" includes words & math

"LINKING VISUALIZATION & UNDERSTANDING IN ASTRONOMY"


SEEING
STARS FORM
IN
THE MILKY WAY


WorldWide Telescope
ZOONIVERSE
glue
multidimensional data exploration
a
x (RA)
y (dec.)
edX
ADS
ALL SKY
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SEEING STARS FORM IN THE MILKY WAY

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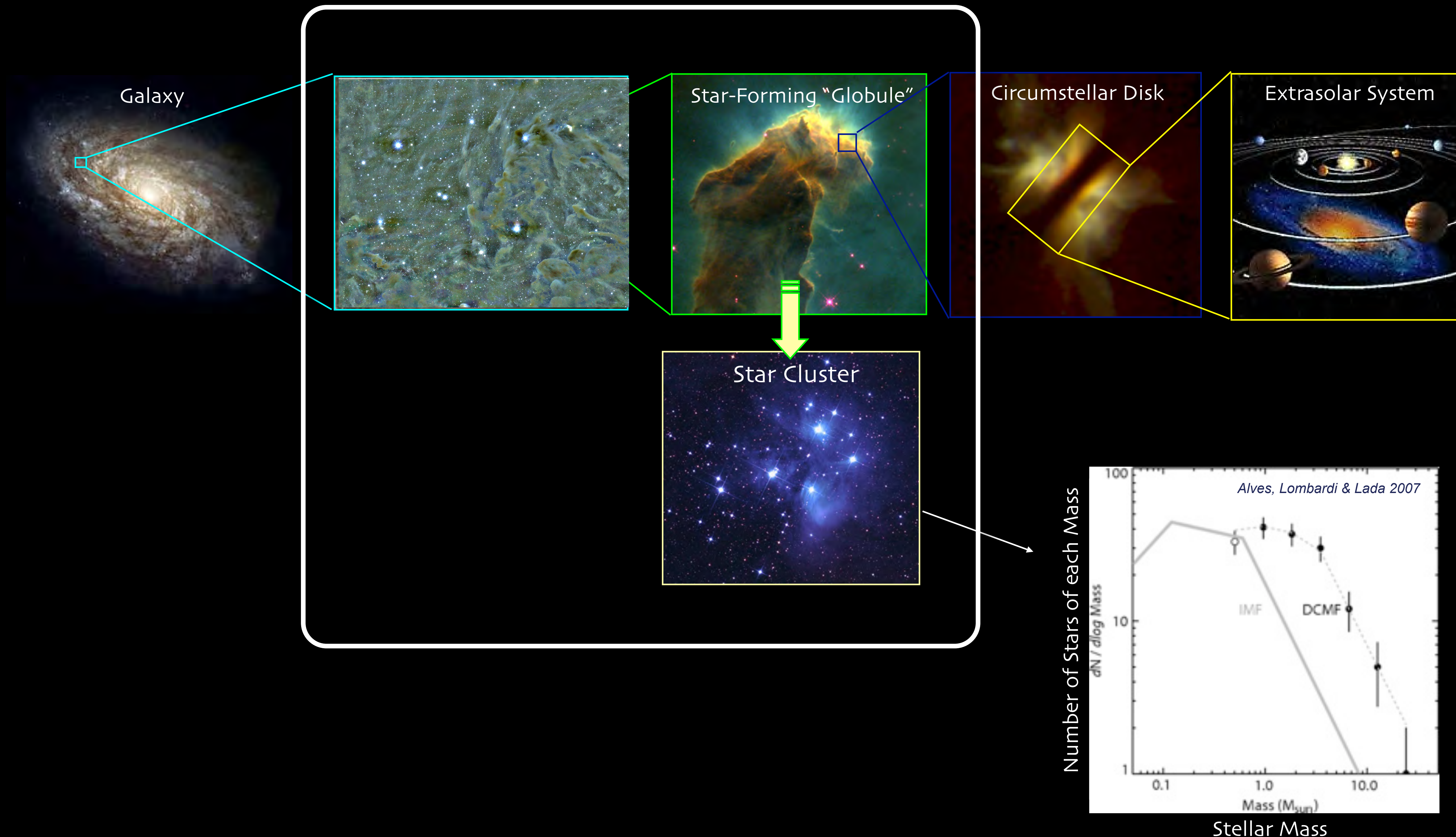
THE MILKY WAY

"Galactic Plane"

The Milky Way
(Artist's Conception)


SEEING
STARS FORM
IN
THE MILKY WAY

HOW STARS FORM



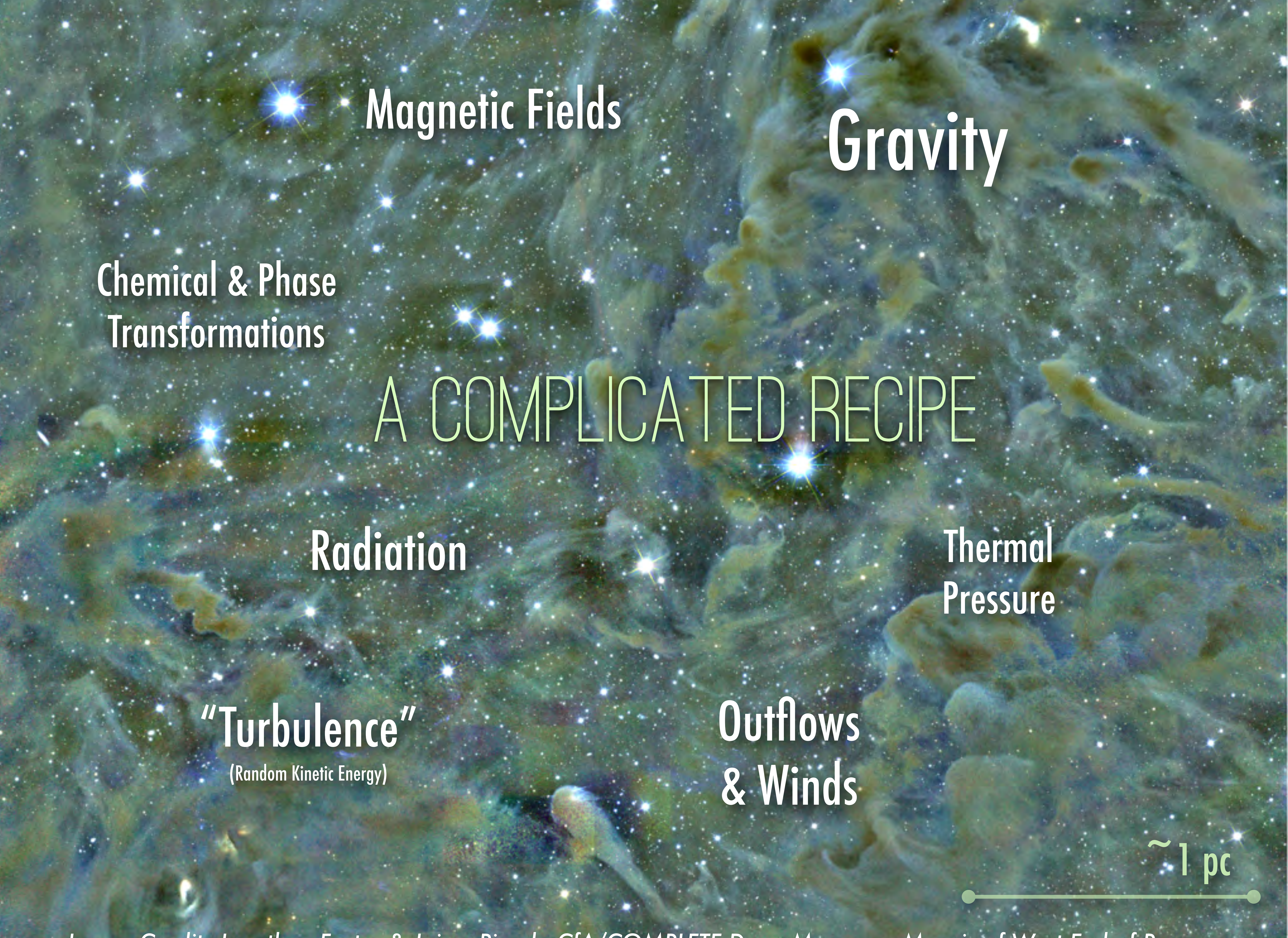


Image Credit: Jonathan Foster & Jaime Pineda CfA/COMPLETE Deep Megacam Mosaic of West End of Perseus

A COMPLICATED RECIPE

STARS

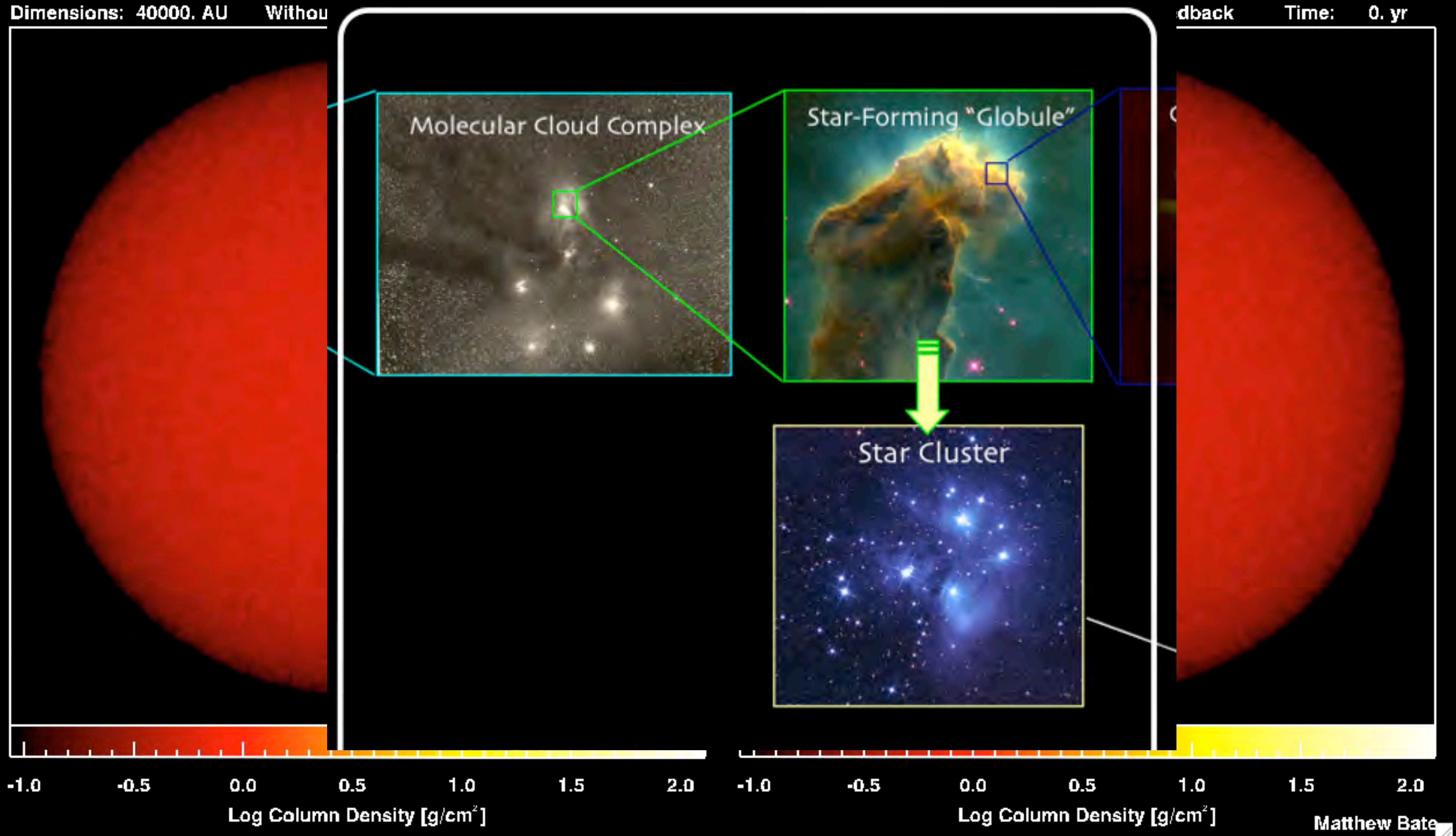
prep time: without galaxy formation, ~**1 Million years** (If you want to form your own Galaxy first, allow at least 10 billion years extra.)

ingredients: gas, dust, photons, and a touch of dark matter

equipment: gravity, magnetic fields, thermodynamics, chemical reactions

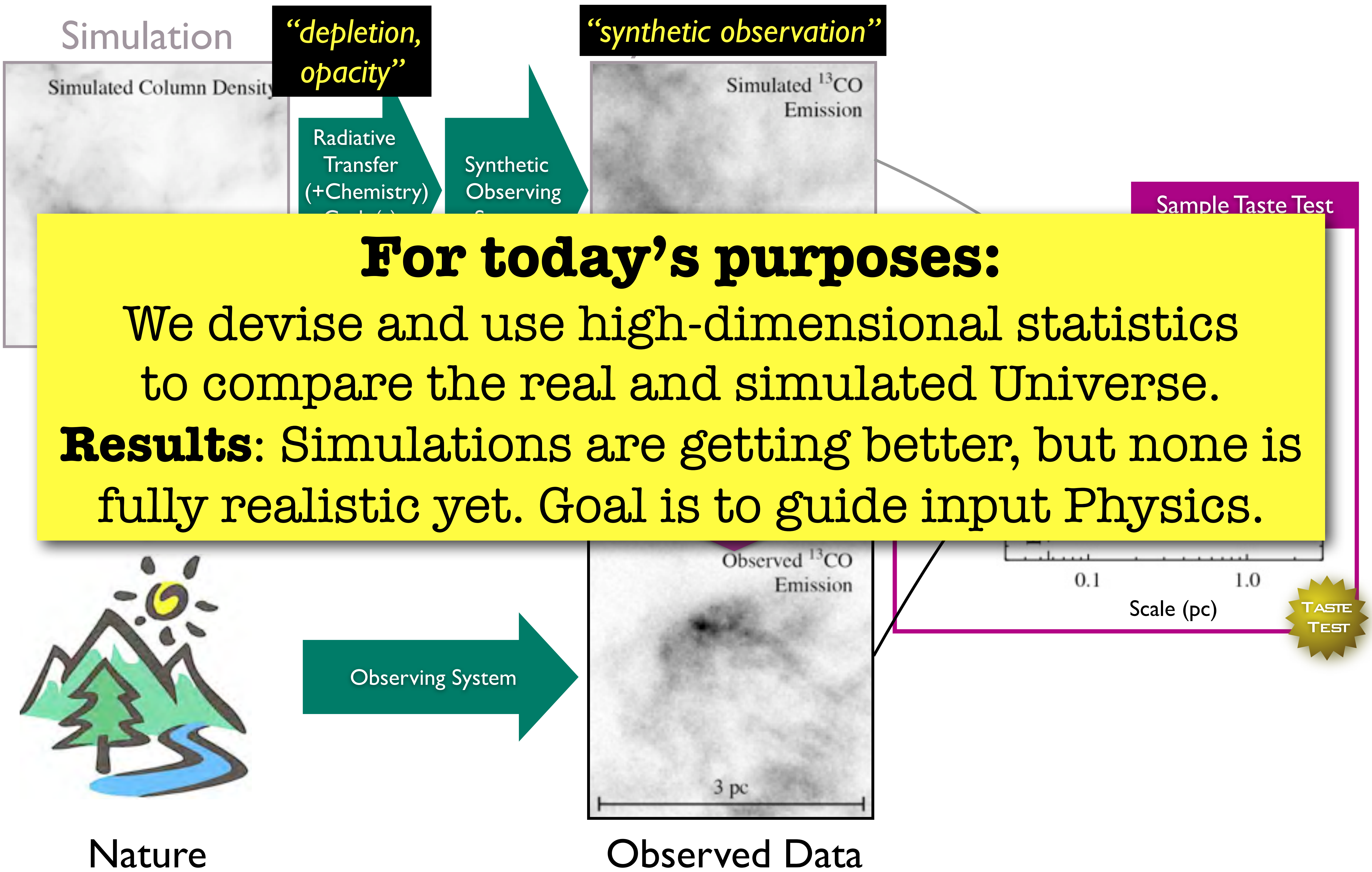
instructions: mix all above ingredients, using equipment “as needed”, stir well, using turbulence generated by stellar winds, Galactic shear, and more. Beware of shocks.

PRIMITIVE COOKING, WITH "SIMPLE" RECIPES



Simulations of Bate 2009

THE "TASTE-TESTING" PROCESS



For today's purposes:

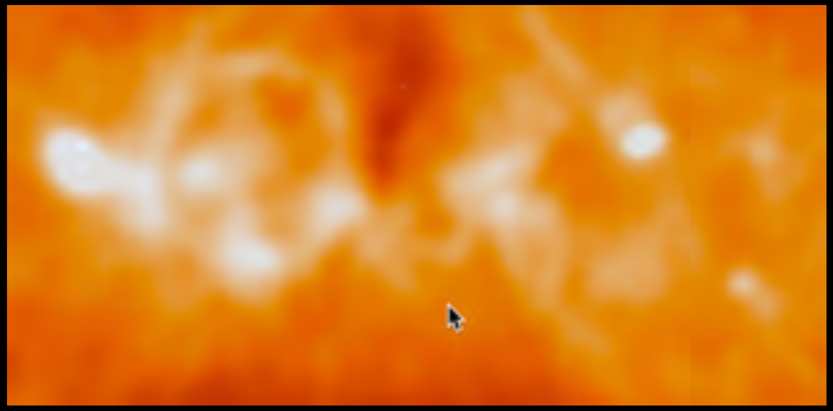
We devise and use high-dimensional statistics to compare the real and simulated Universe.

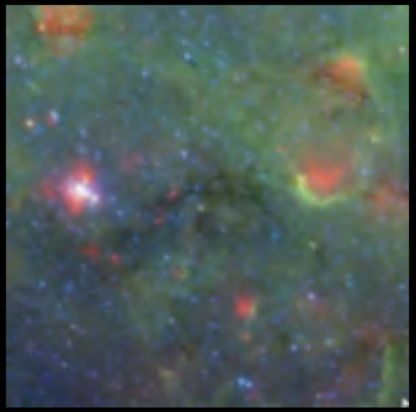
Results: Simulations are getting better, but none is fully realistic yet. Goal is to guide input Physics.


SEEING
STARS FORM
IN
THE MILKY WAY

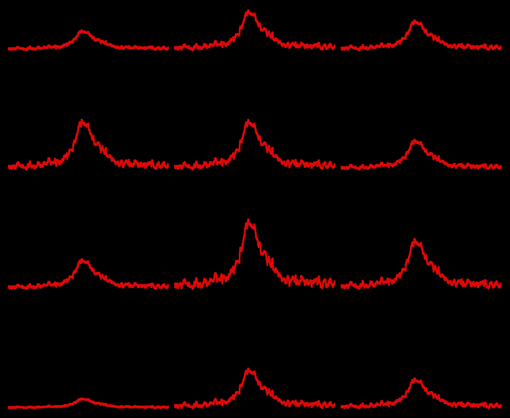
WHAT WE SEE

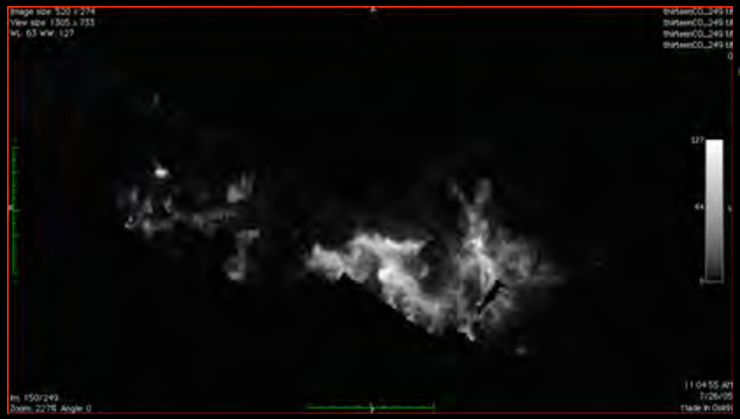
Dust

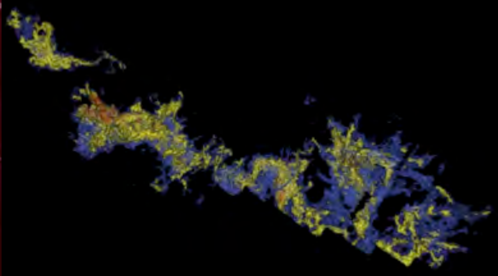




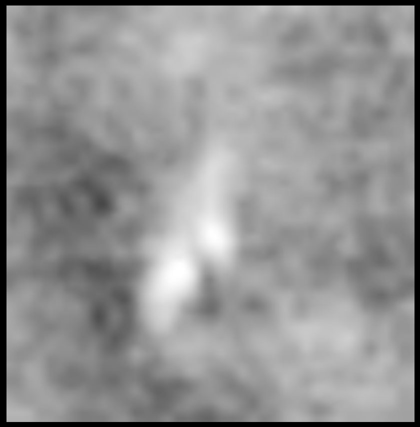
Gas



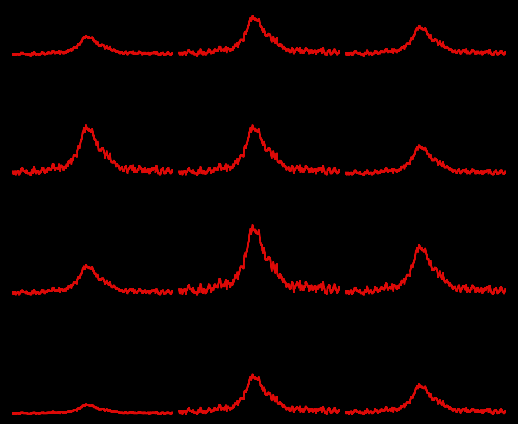


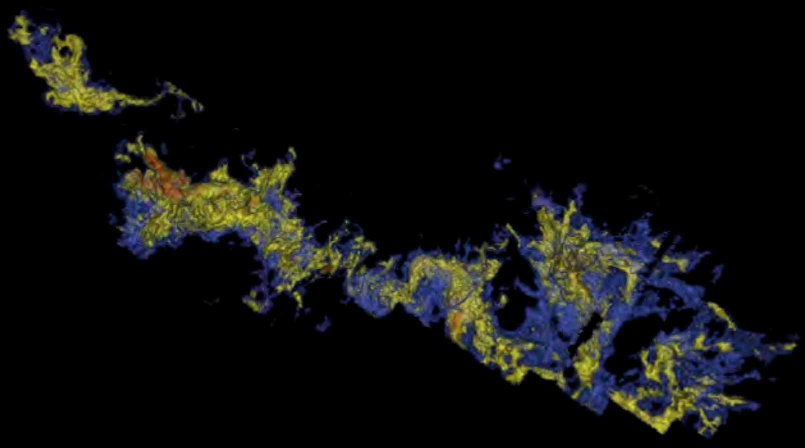


“Stars”



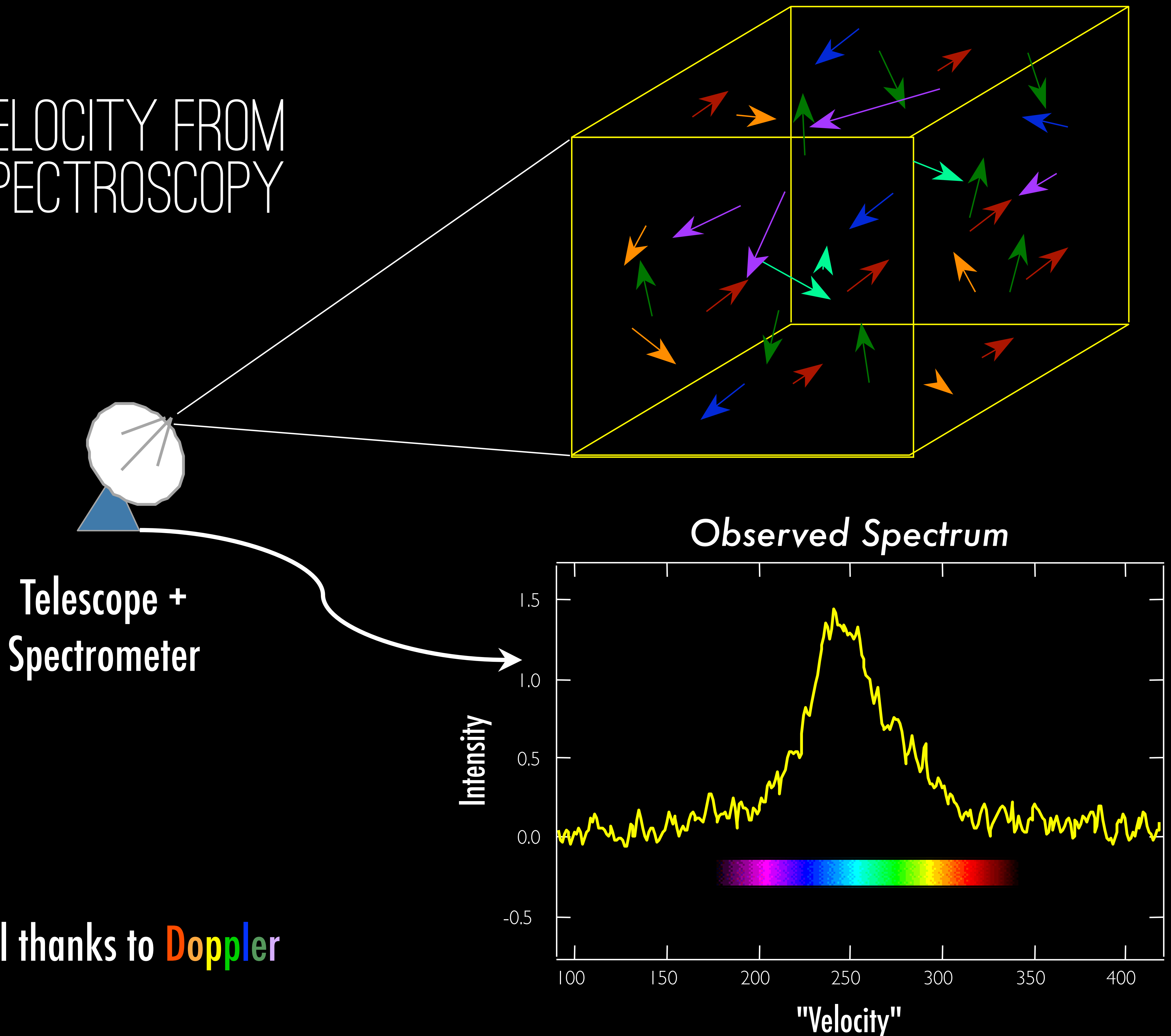
HOW WE "SEE"





IN 3D

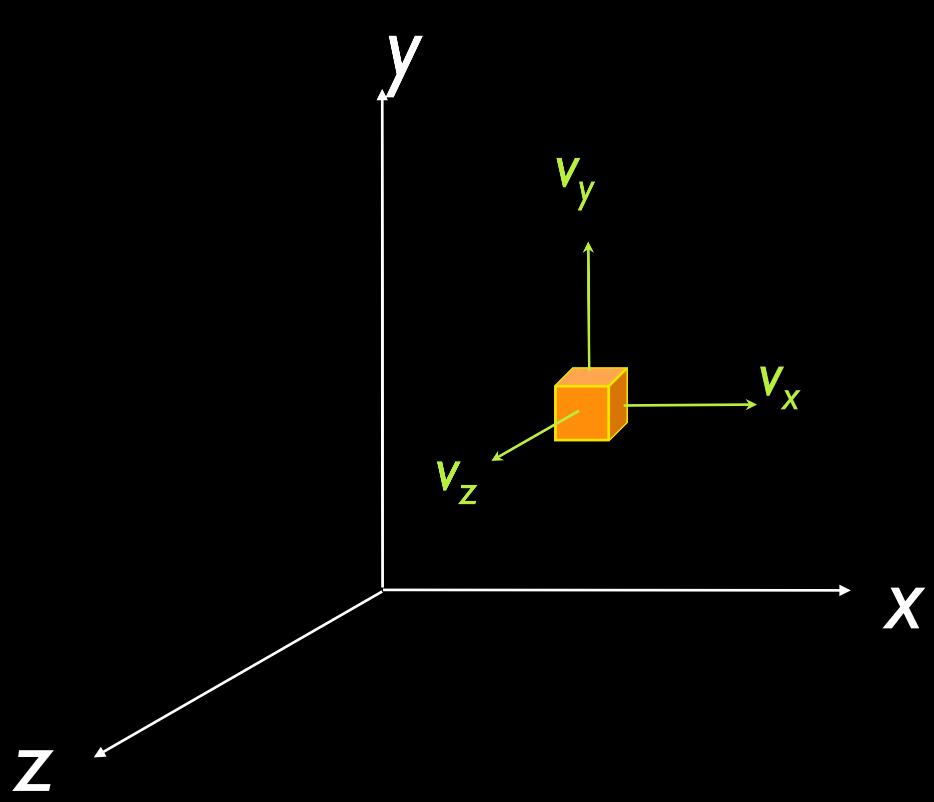
VELOCITY FROM SPECTROSCOPY



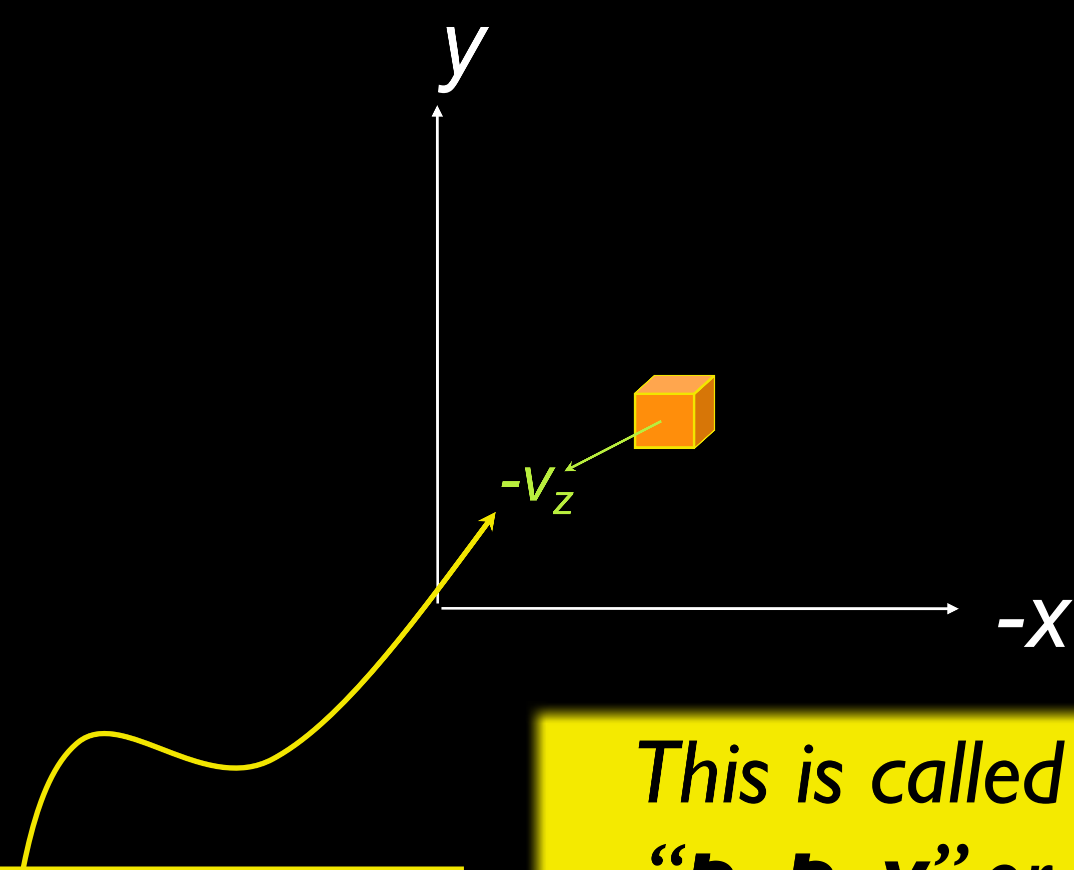
All thanks to Doppler

SPECTRAL-LINE MAPPING

We <u>wish</u> we could measure…



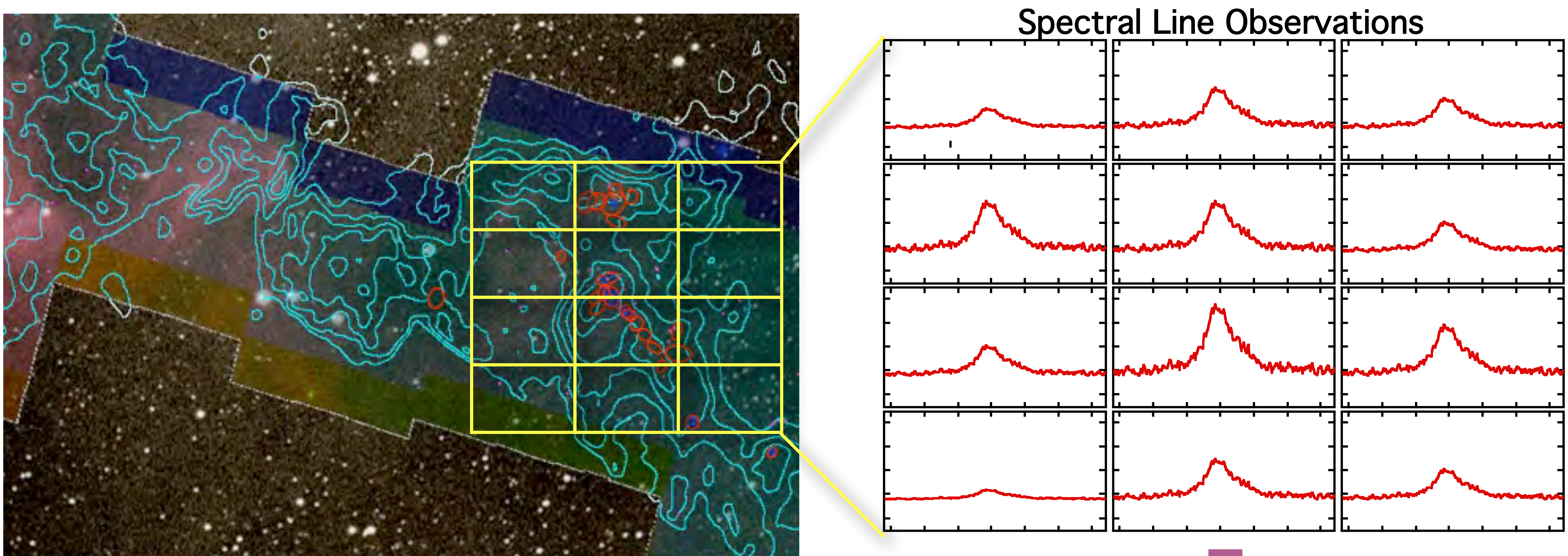
But we <u>can</u> measure…

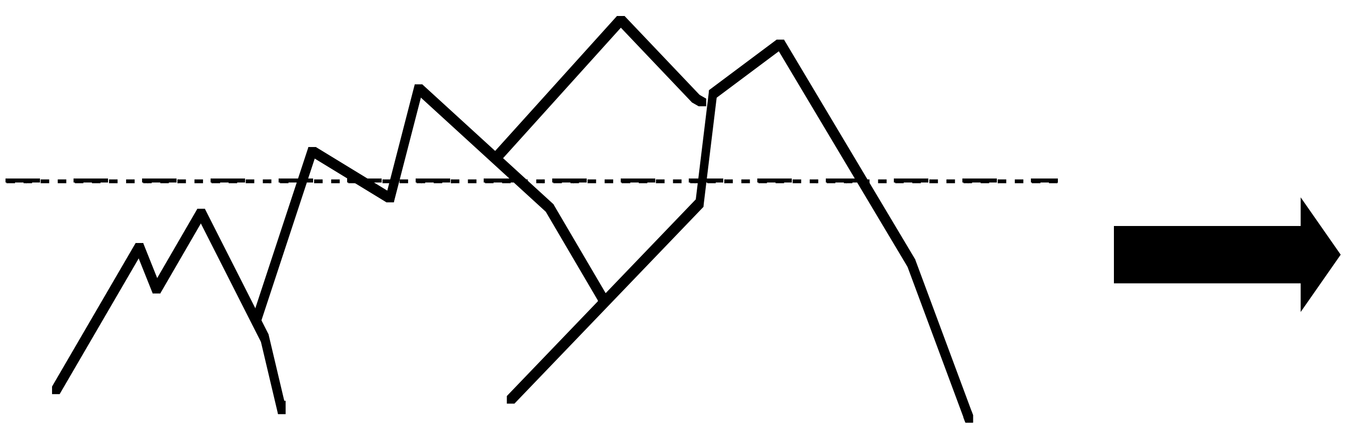


v_z *only* from "spectral-line maps"

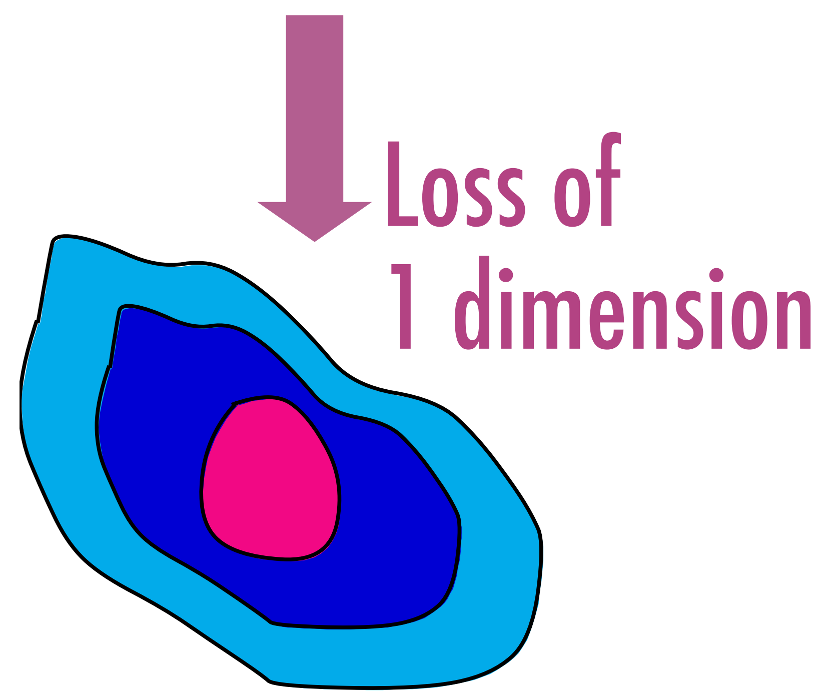
*This is called "**p-p-v**" or "position-position-velocity" space.*

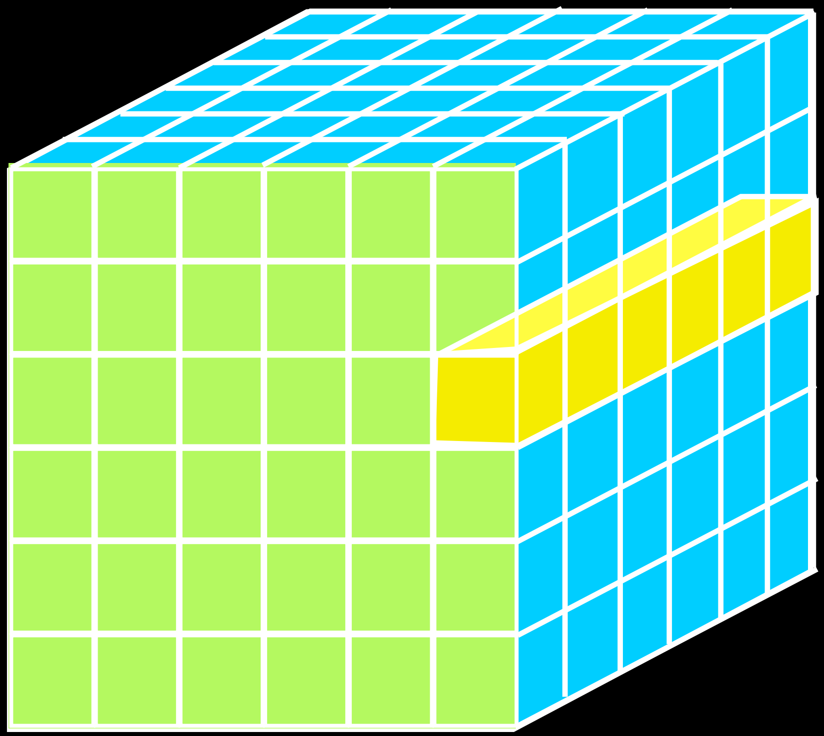
SEEING IN P-P-V SPACE





No loss of information





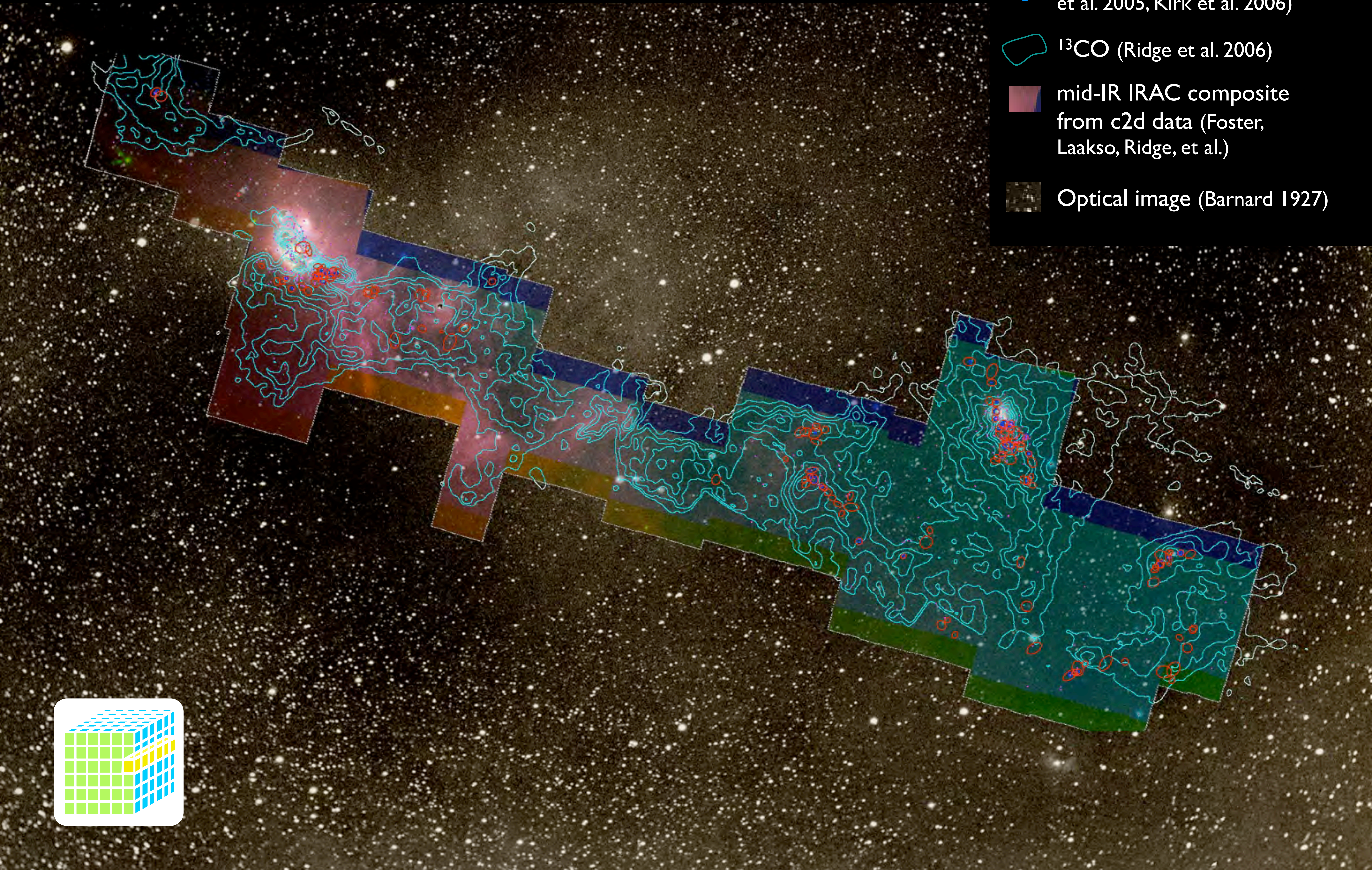
DATA-DIMENSIONS-DISPLAY

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"

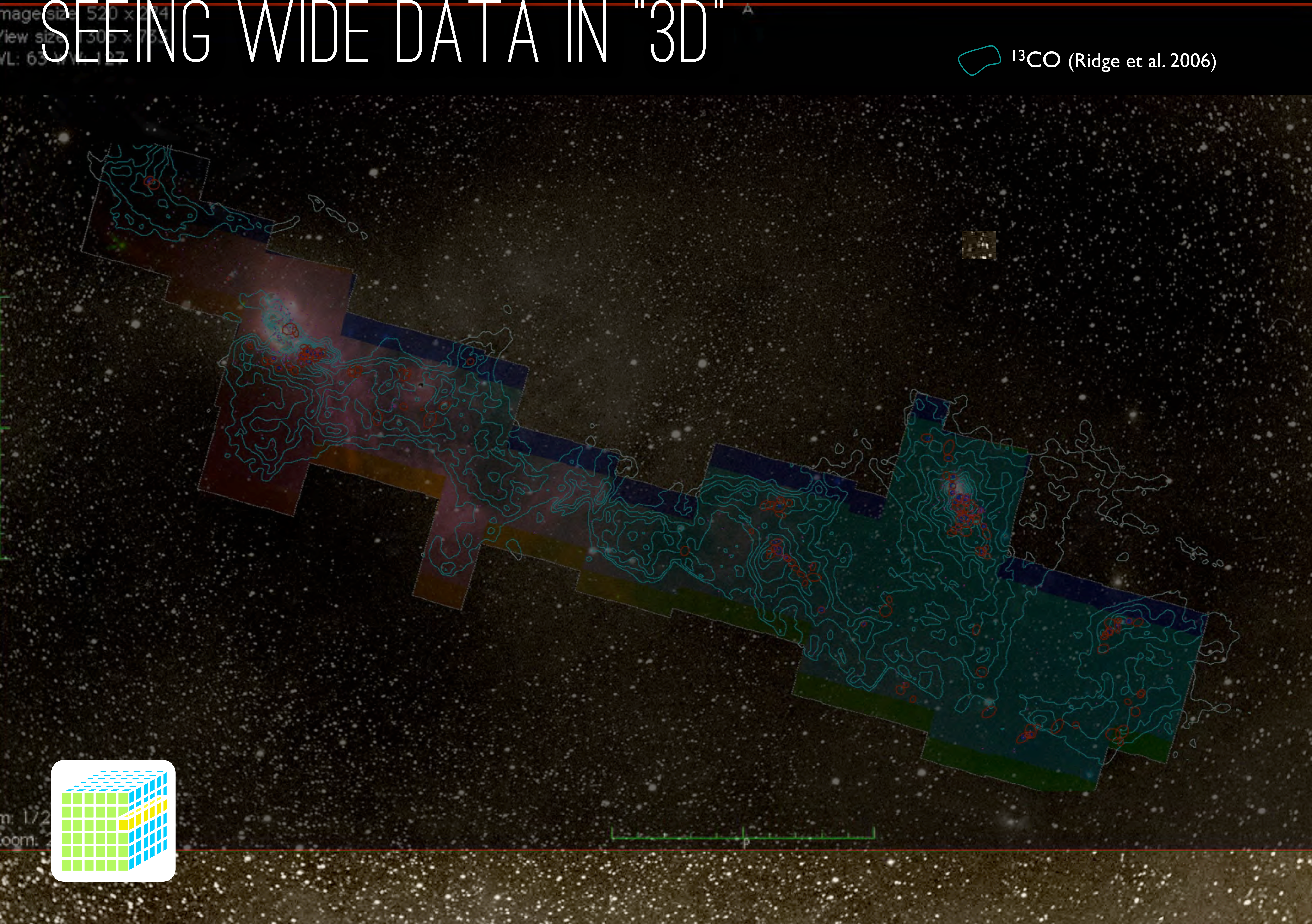
SEEING WIDE DATA IN "3D"

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)

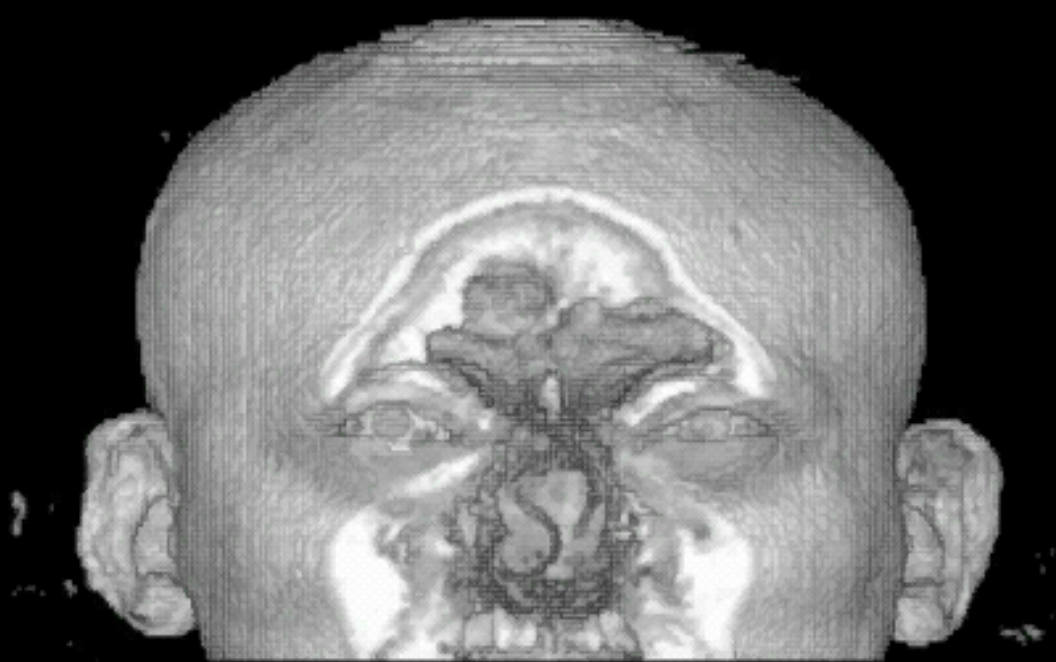


SEEING WIDE DATA IN "3D"



ASTRONOMICAL MEDICINE

"KEITH"

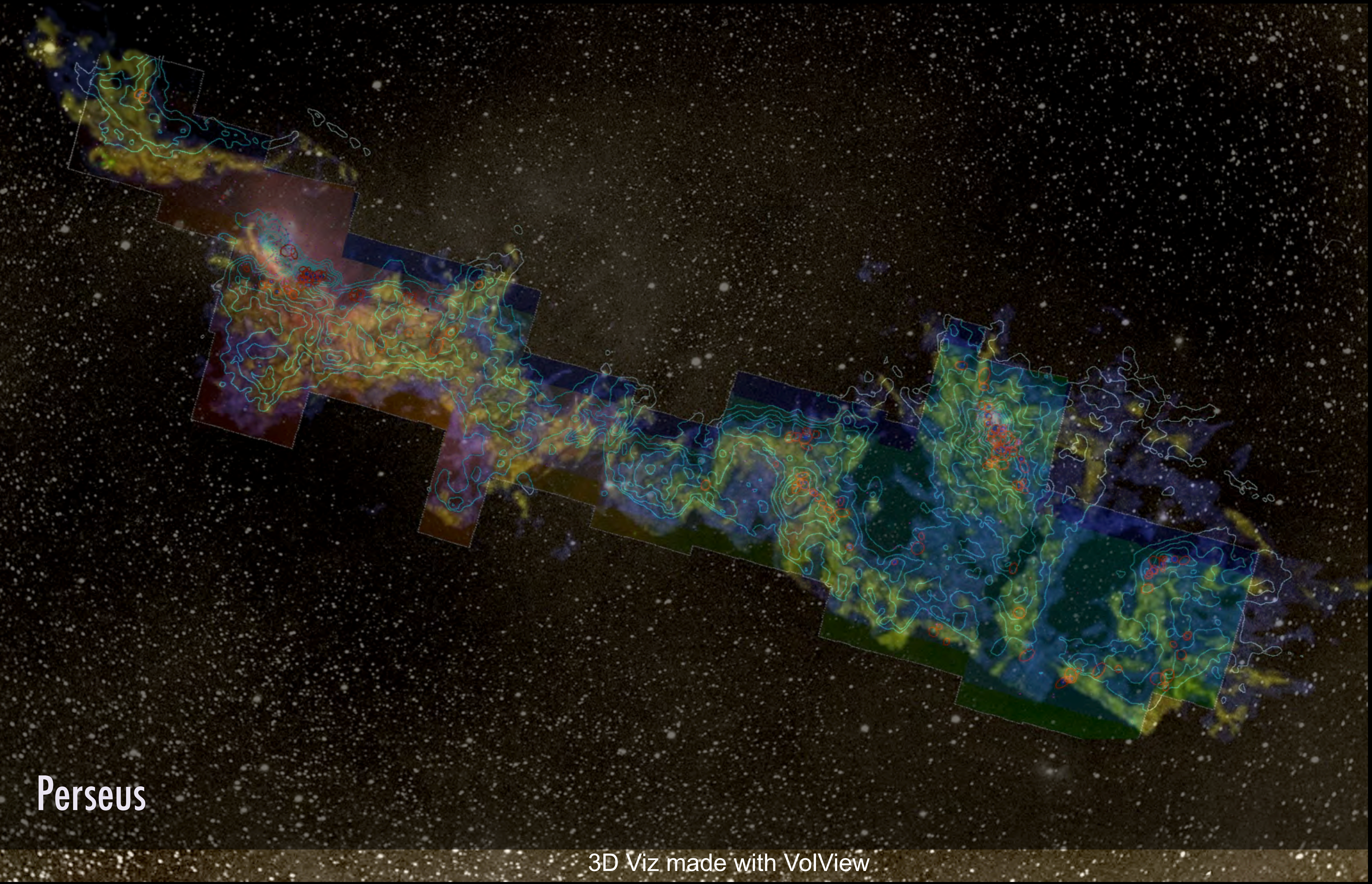


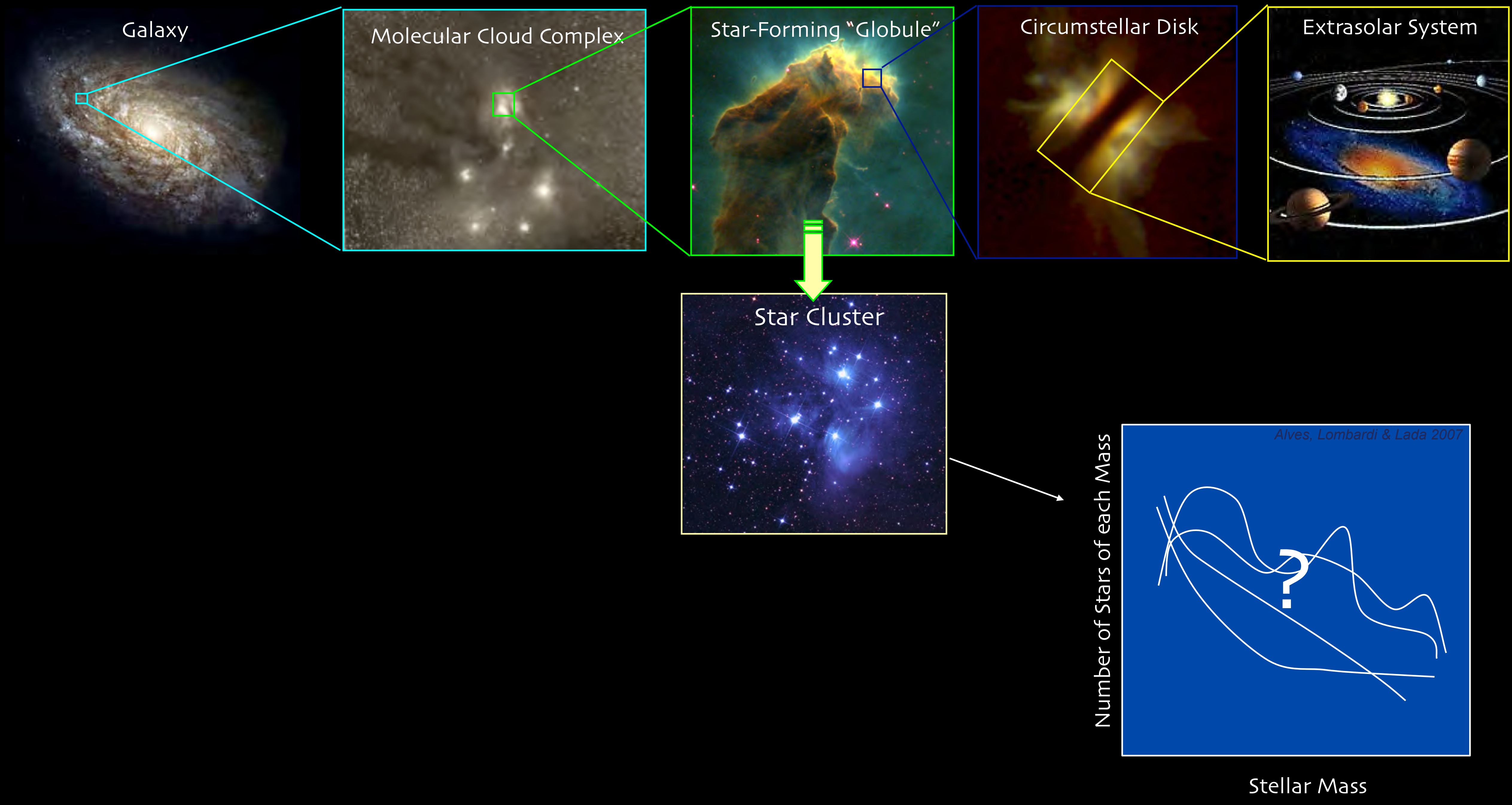
"z" is depth into head

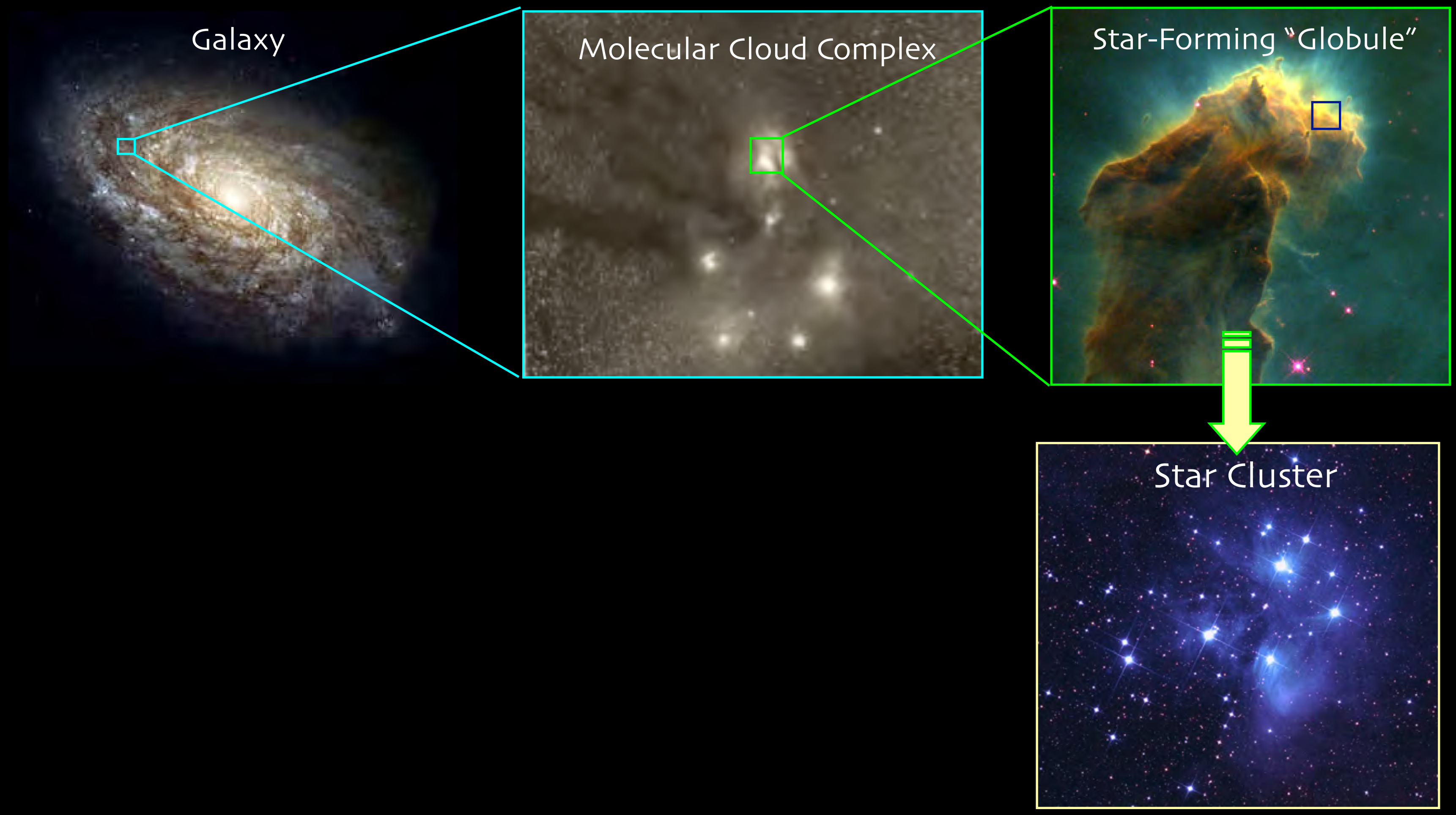
"PERSEUS"

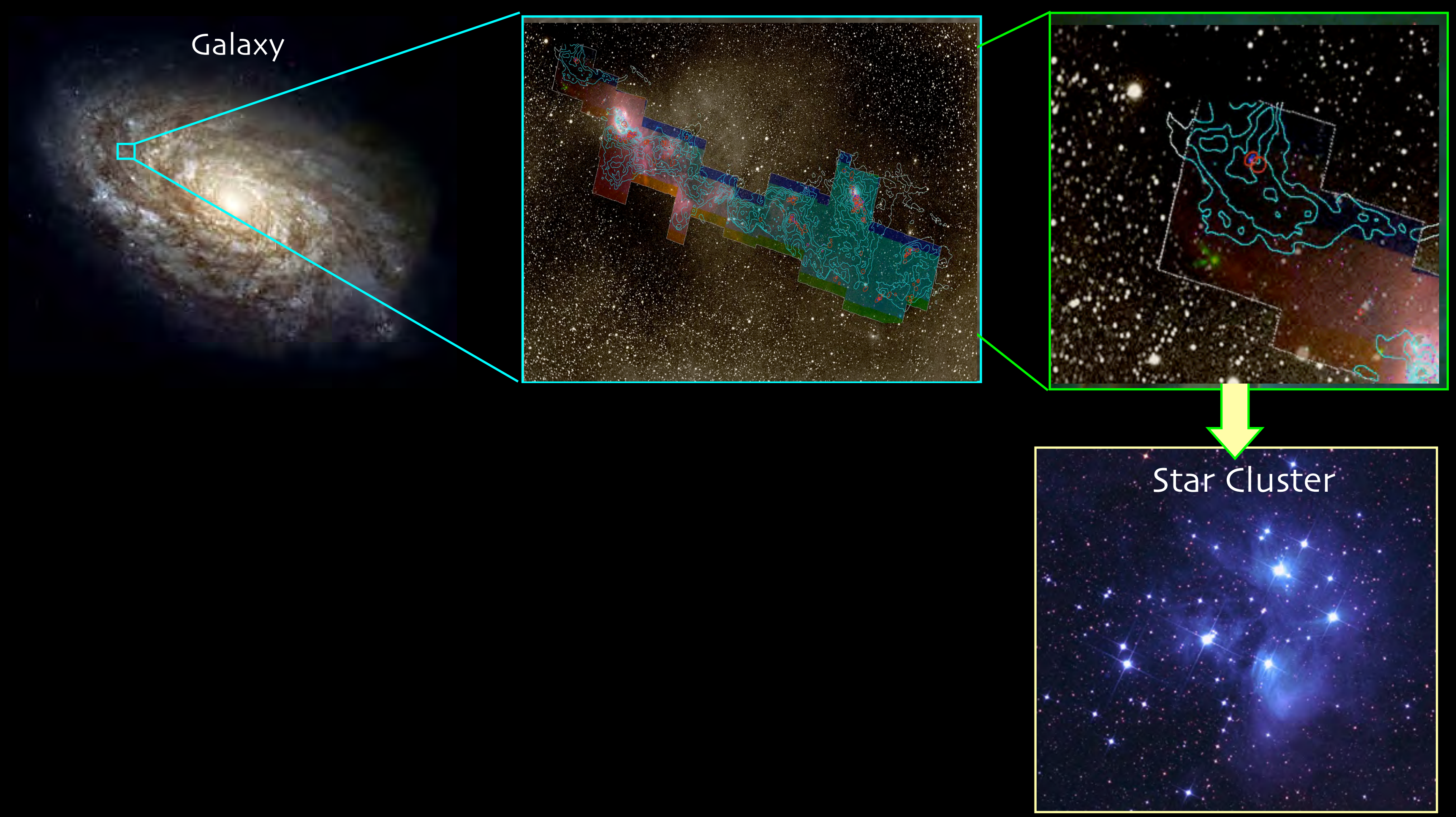
"z" is line-of-sight velocity

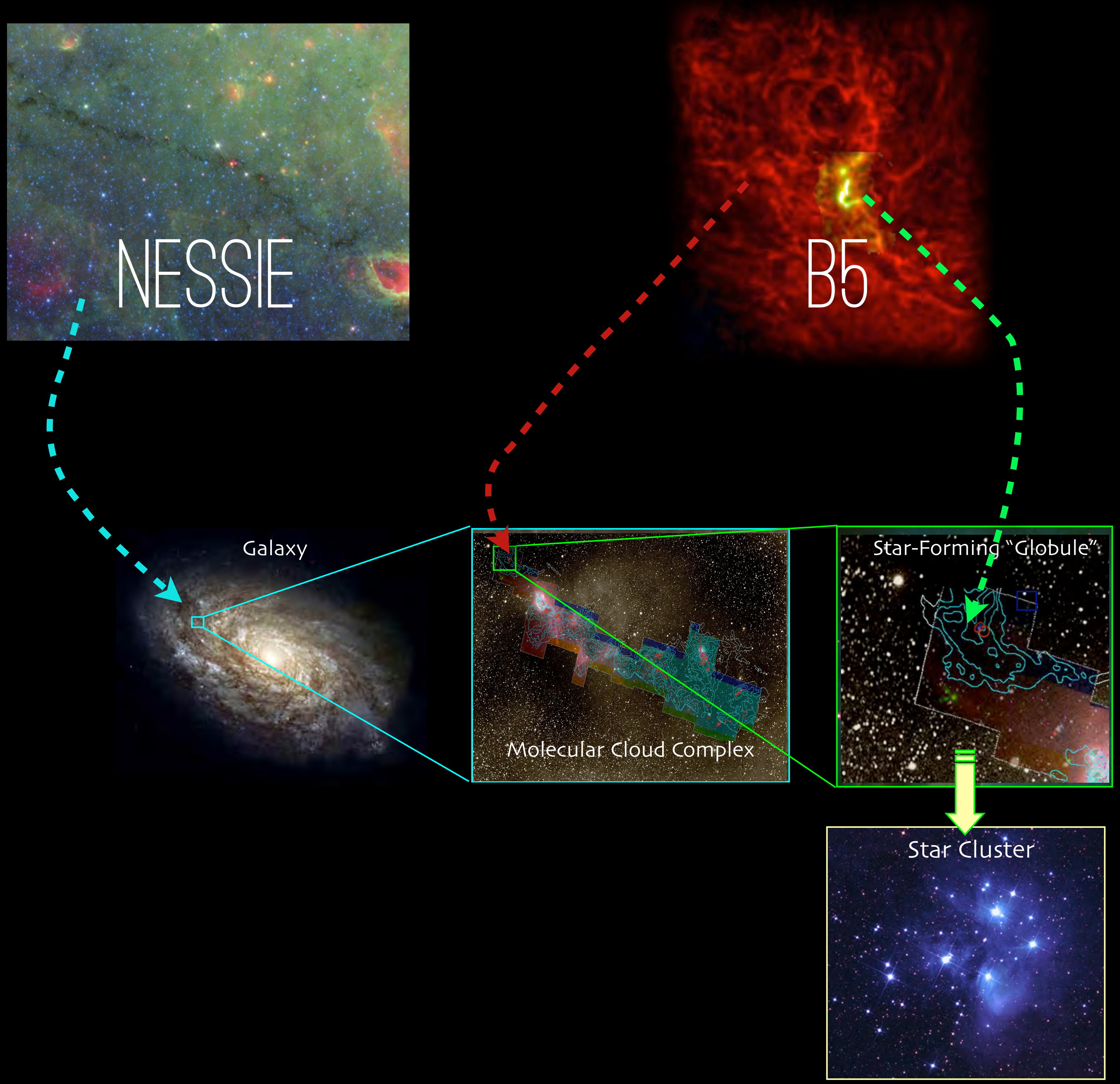
"AstroMed" collaborators include Douglas Alan, Chris Beaumont, Michelle Borkin, Jonathan Foster, Michael Halle, Nick Holliman, Jens Kauffmann, Jaime Pineda, Tudor Platon, Erik Rosolowsky, and more


Perseus
3D Viz made with VolView


Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Circumstellar Disk
Extrasolar System
Star Cluster
Alves, Lombardi & Lada 2007
?
Number of Stars of each Mass
Stellar Mass


Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Star Cluster


Galaxy
Star Cluster


NESSIE
B5
Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Star Cluster

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Science > Meetings > 2014 > Filamentary Structure in Molecular Clouds

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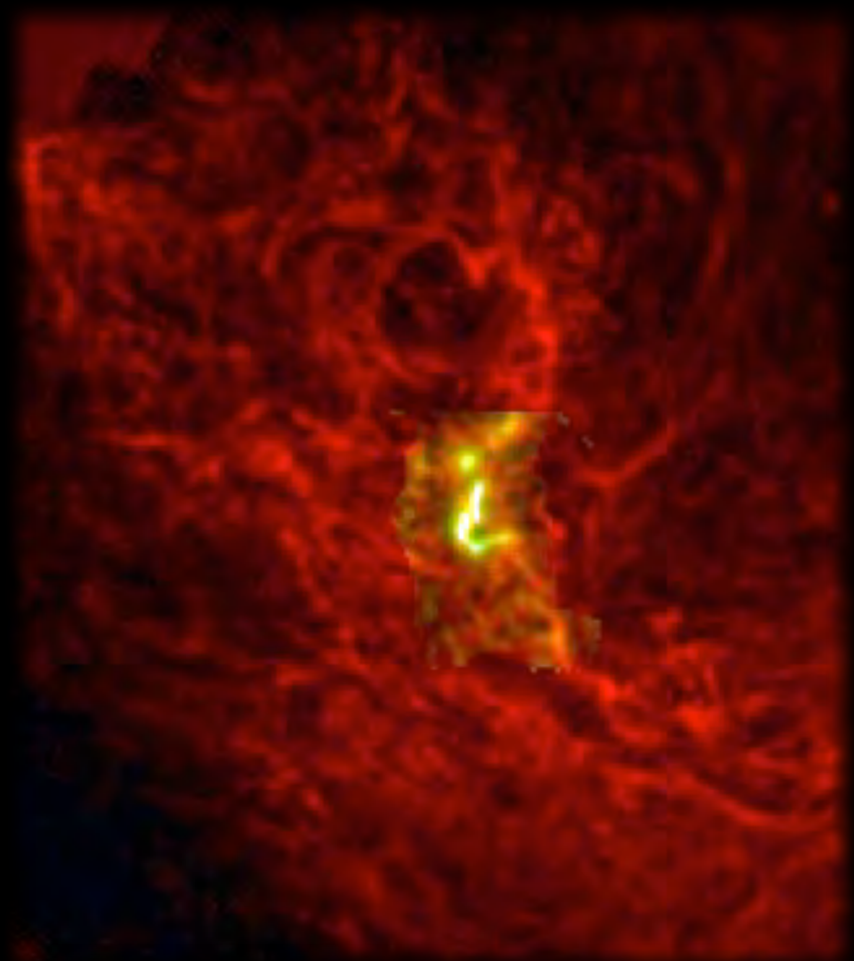
Filamentary Structure in Molecular Clouds

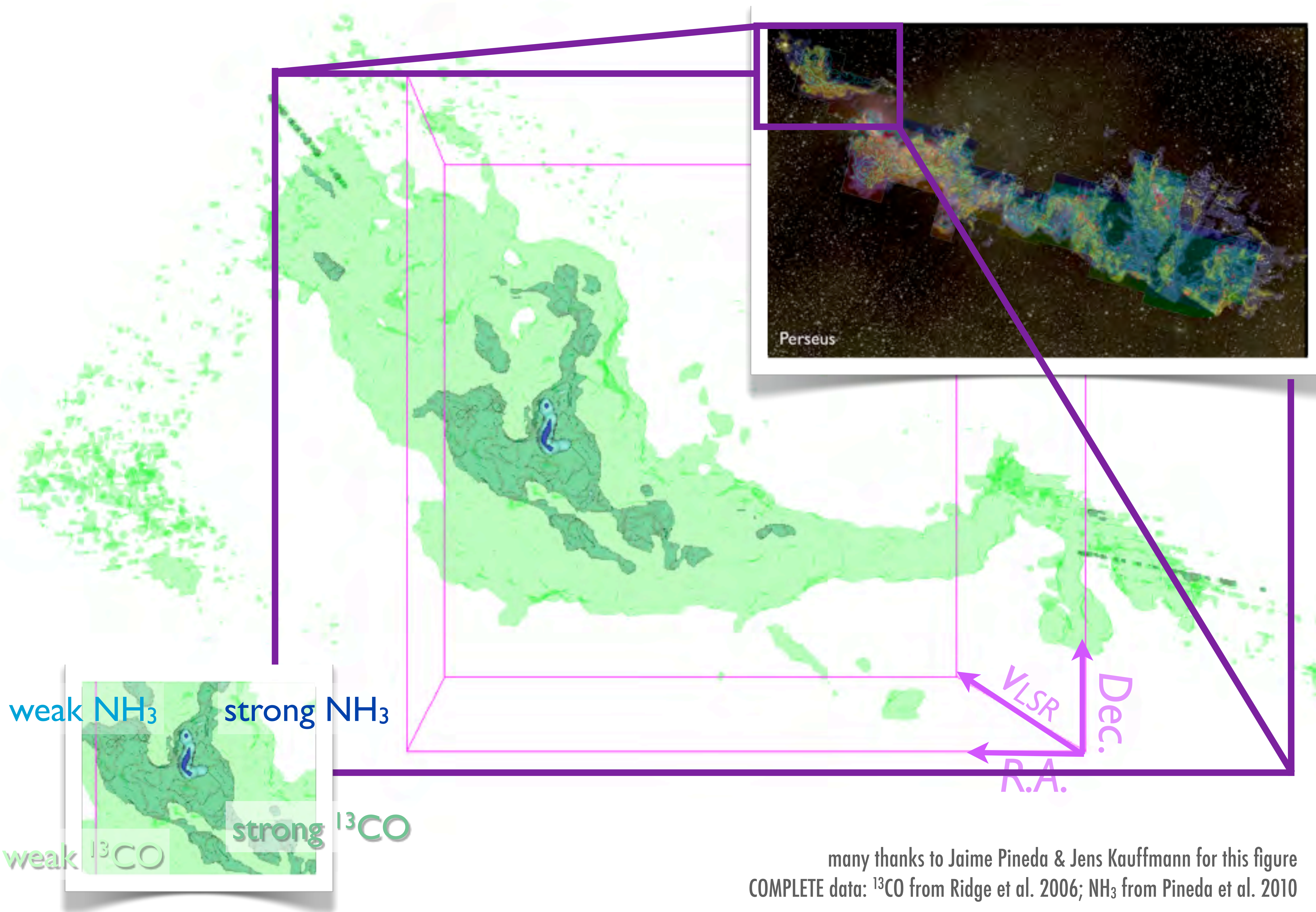
Dates: October 10 - 11, 2014
Location: NRAO Charlottesville Headquarters
520 Edgemont Road
Charlottesville, Virginia

COHERENT CORES
ISLANDS OF CALM IN TURBULENT SEAS(?)



The 30-year story: Myers & Benson 1983, Goodman et al. 1998, Pineda et al. 2010, 2011, 2014

POSITION-VELOCITY STRUCTURE OF THE B5 REGION IN PERSEUS

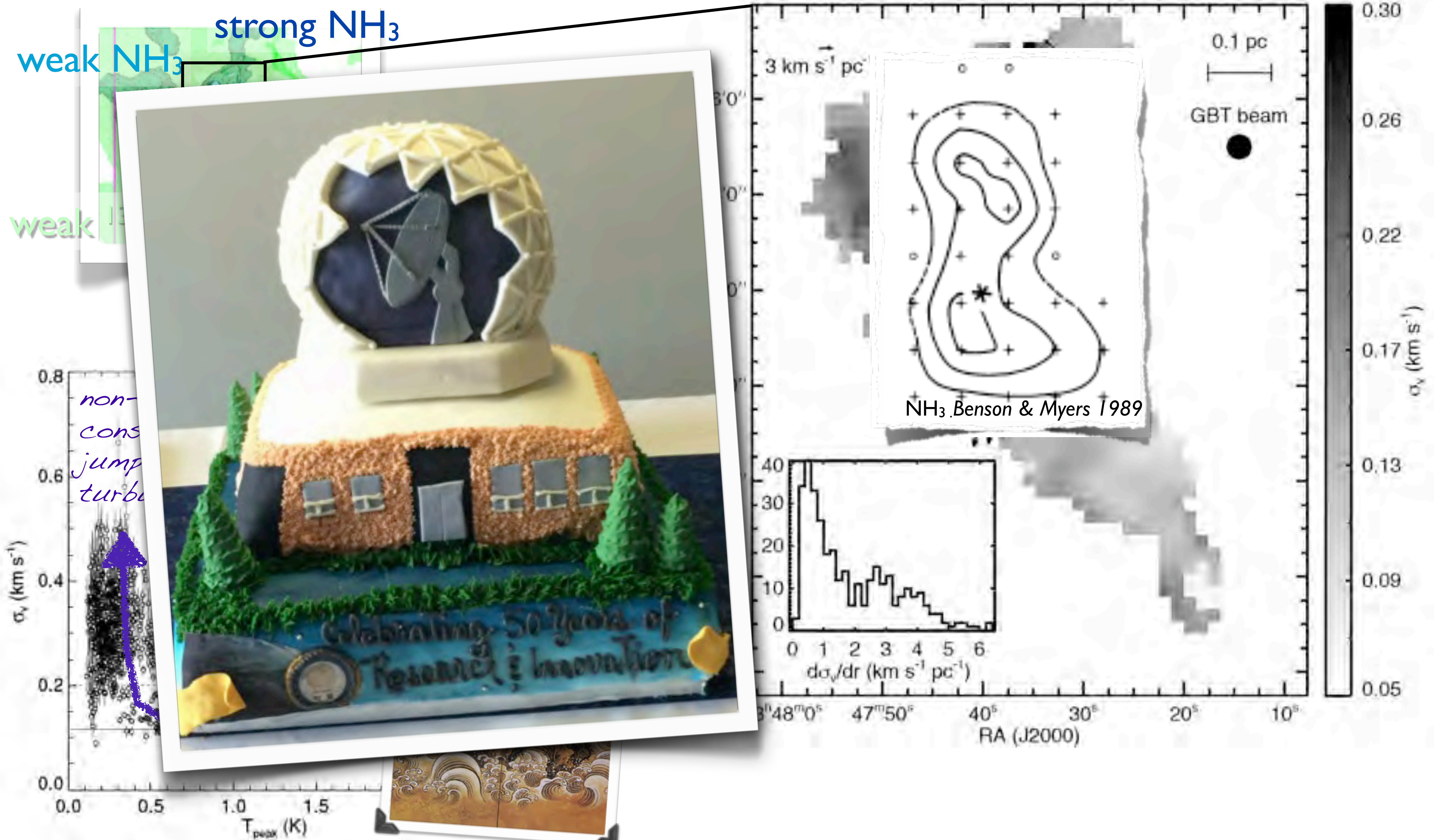


many thanks to Jaime Pineda & Jens Kauffmann for this figure

COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2010

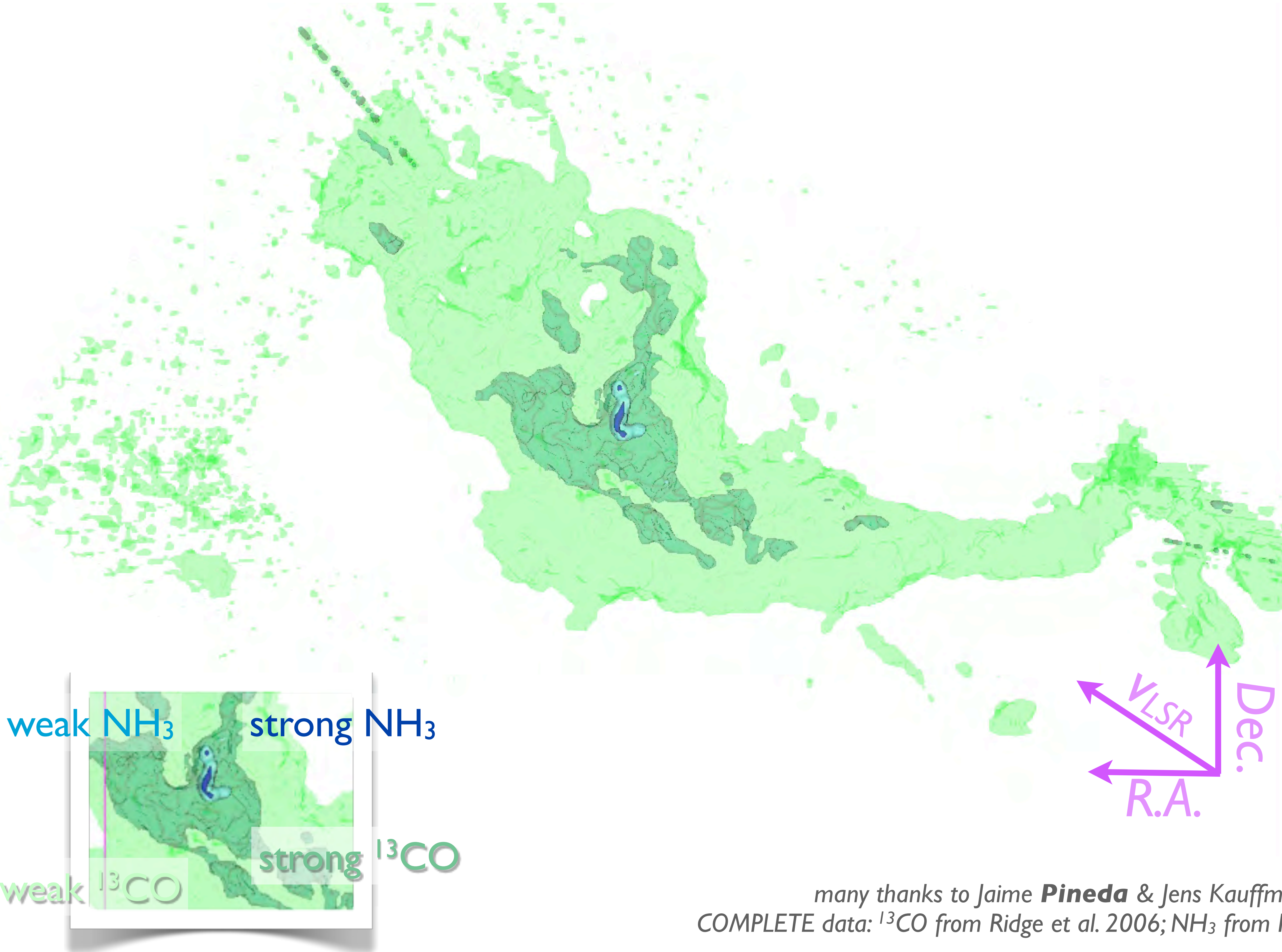
STRONG EVIDENCE FOR "VELOCITY COHERENCE" IN DENSE CORES

greyscale shows NH_3 velocity dispersion, arrows show gradient in dispersion



GBT NH_3 observations of the B5 core (Pineda et al. 2010)

POSITION-VELOCITY STRUCTURE OF THE B5 REGION IN PERSEUS



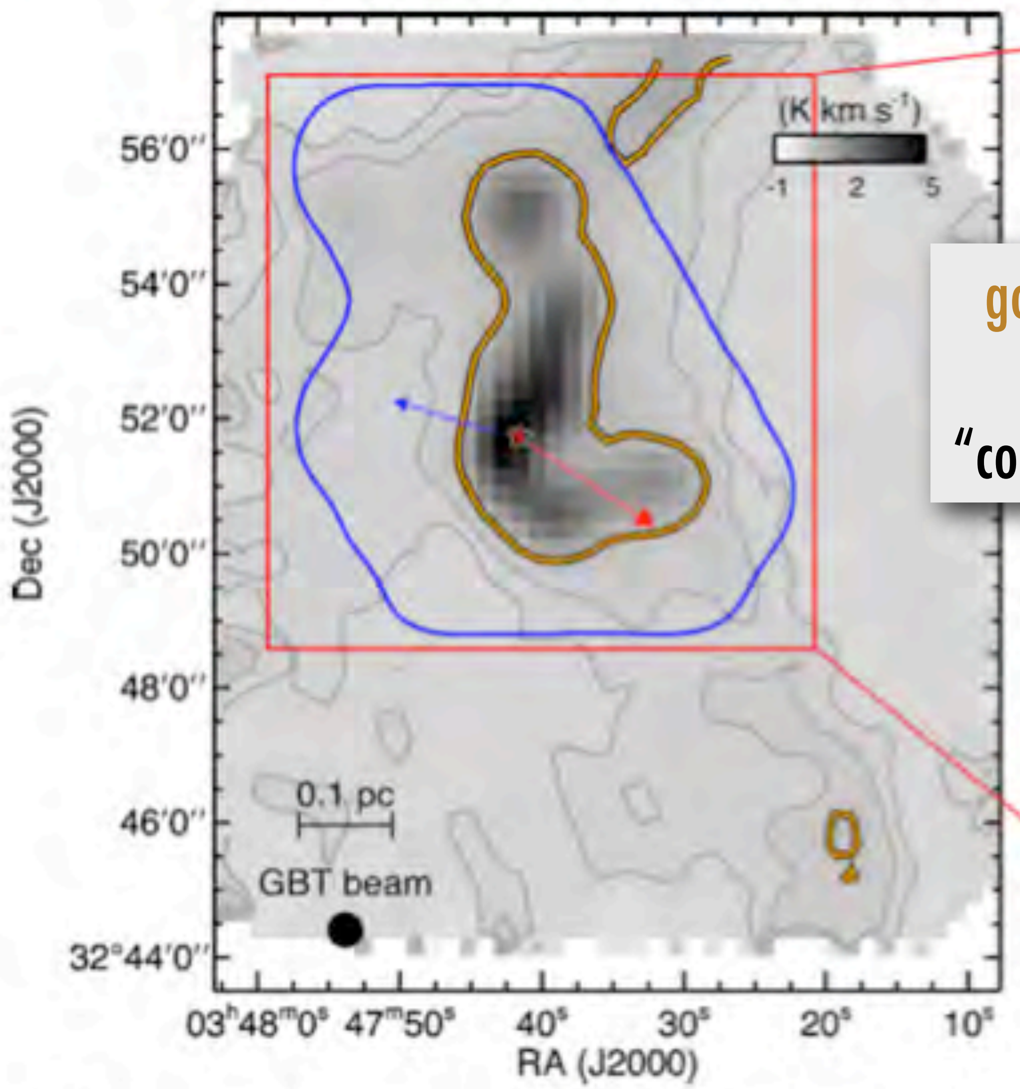
many thanks to Jaime ***Pineda*** *& Jens Kauffmann for this figure*

COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2010

BUT THEN… WE FOUND SUB-STRUCTURE

The Astrophysical Journal Letters, 739:L2 (5pp), 2011 September 20

Pineda et al.

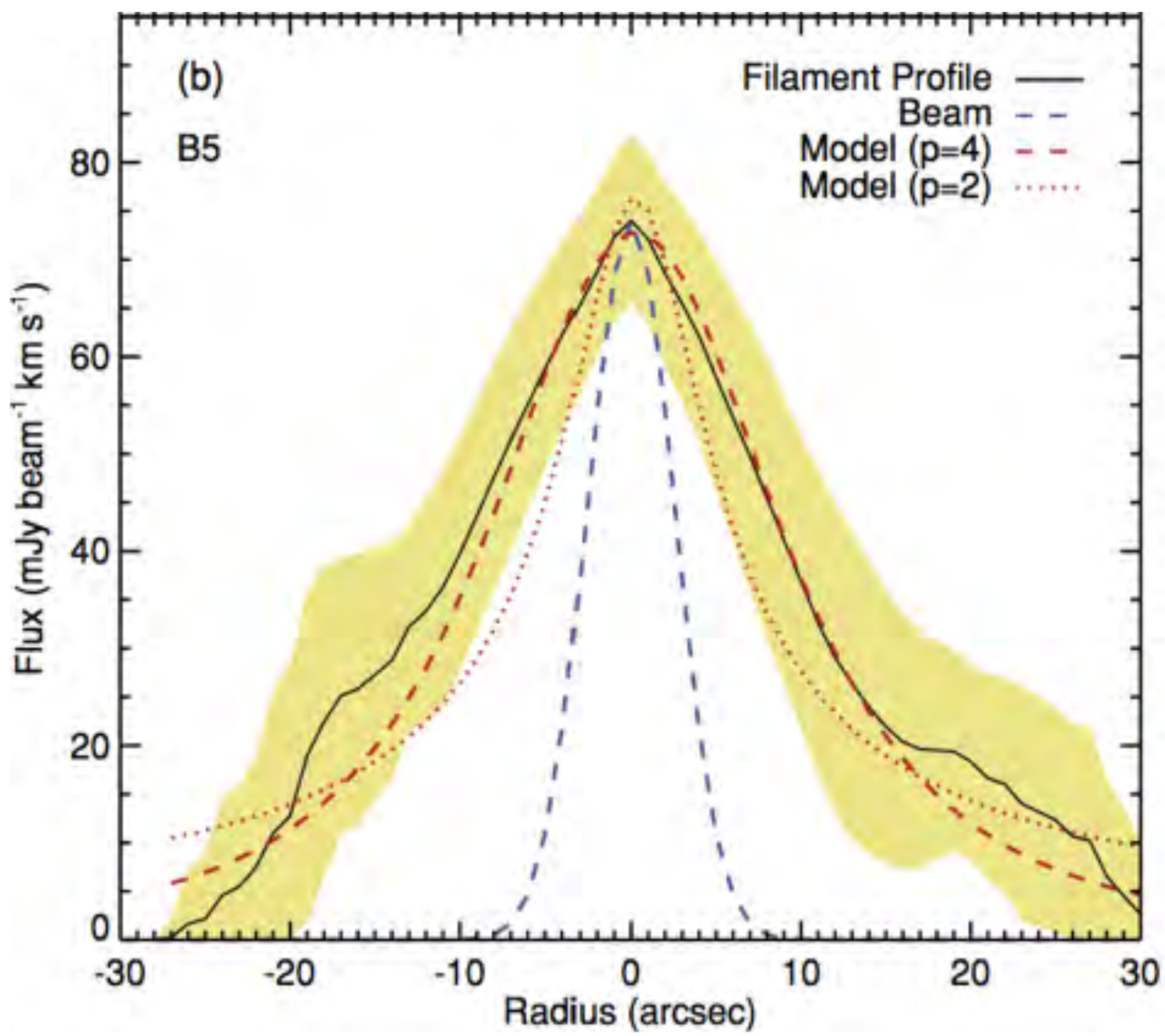


gold contour shows "coherent" core

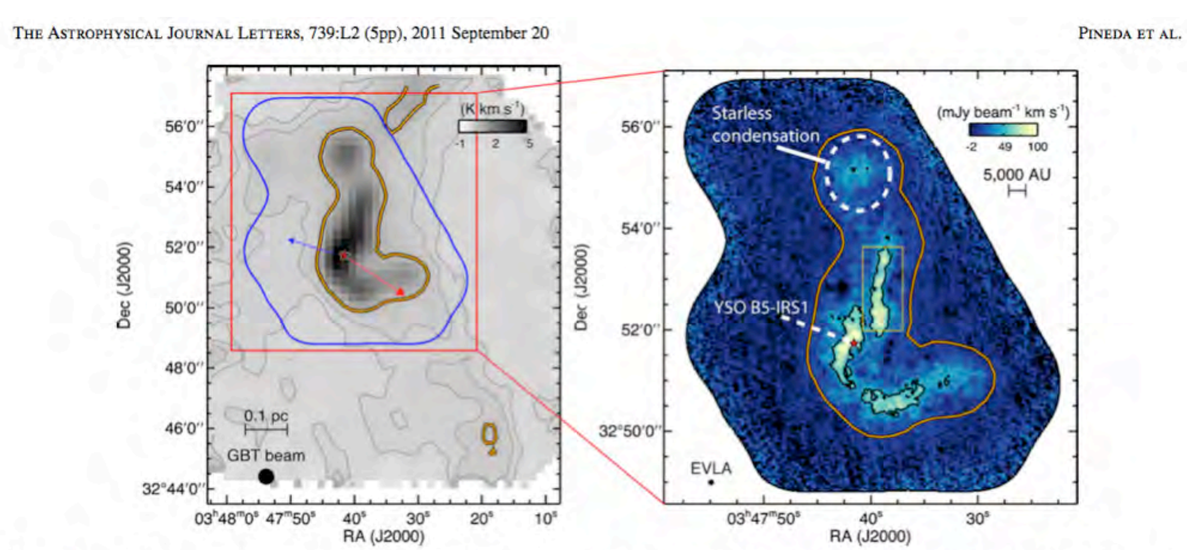
Figure 1. Left panel: integrated intensity map of B5 in NH_3 (1,1) obtained with GBT. Gray contours show the 0.15 and 0.3 K km s^{-1} level in NH_3 (1,1) integrated intensity. The orange contours show the region in the GBT data where the non-thermal velocity dispersion is subsonic. The young star, B5–IRS1, is shown by the star in both panels. The outflow direction is shown by the arrows. The blue contour shows the area observed with the EVLA and the red box shows the area shown in the right panel. Right panel: integrated intensity map of B5 in NH_3 (1,1) obtained combining the EVLA and GBT data. Black contour shows the 50 mJy beam^{-1} km s^{-1} level in NH_3 (1,1) integrated intensity. The yellow box shows the region used in Figure 4. The northern starless condensation is shown by the dashed circle.

Pineda et al. 2011

BUT MAYBE IT'S DIFFERENT?



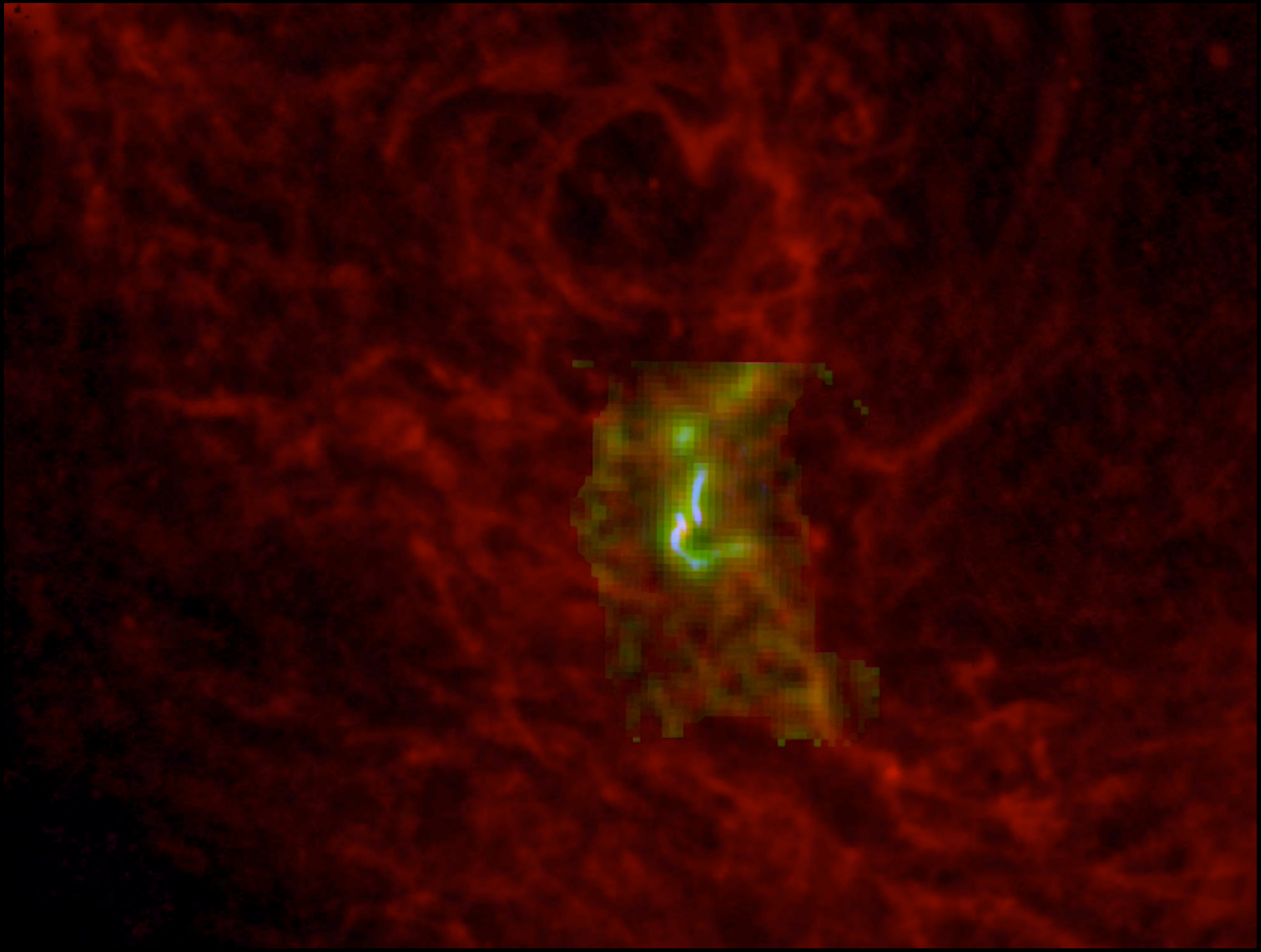
isothermal, hydrostatic filaments, not turbulent ones?



Pineda et al. 2011

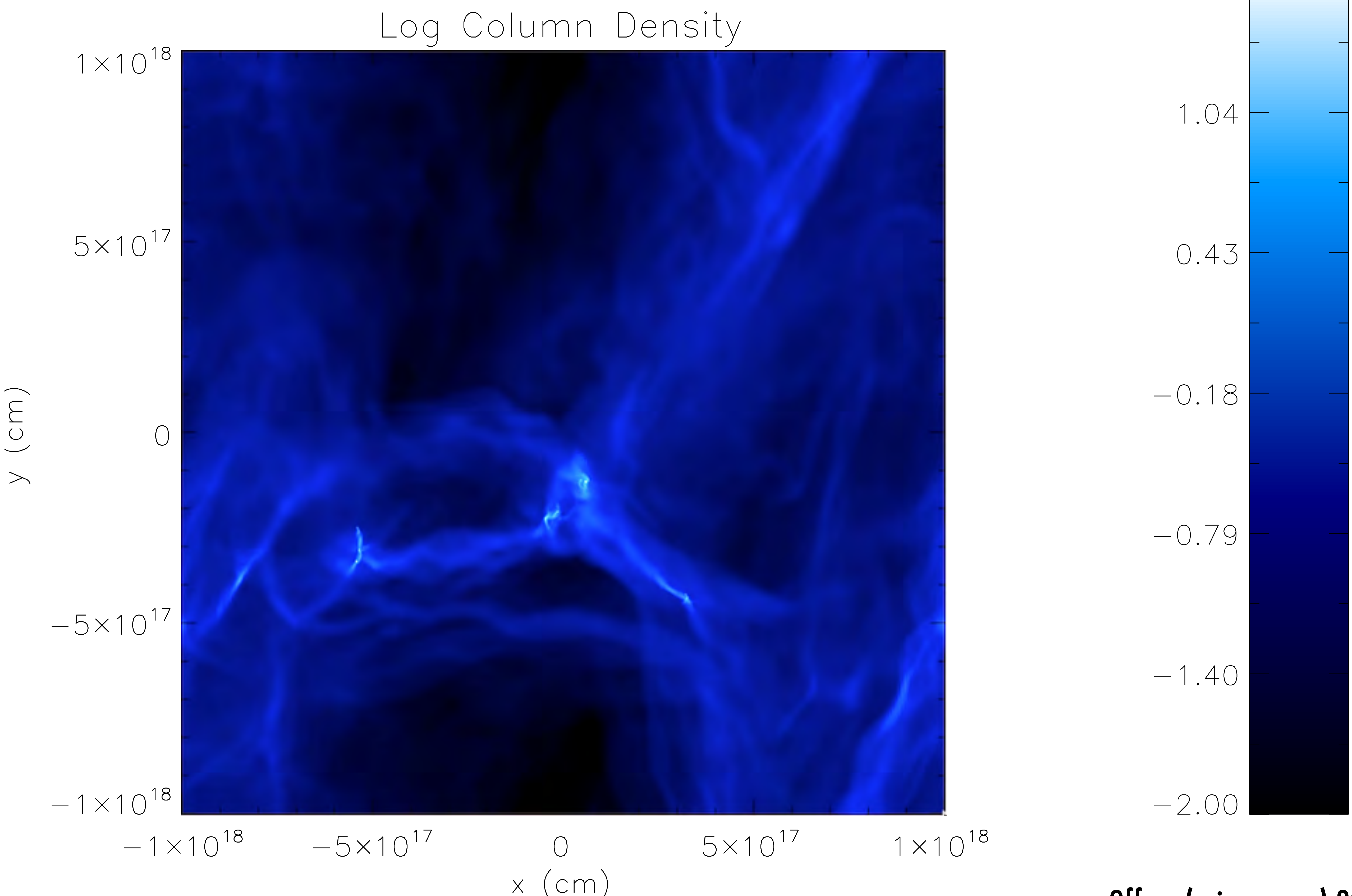
BUT WHAT IF FILAMENTS CONTINUE ACROSS "CORE" BOUNDARIES?!

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



Goodman, Chen, Offner & Pineda 2014 in prep.

B5-ISH SIMULATION (NO MAGNETIC FIELD)



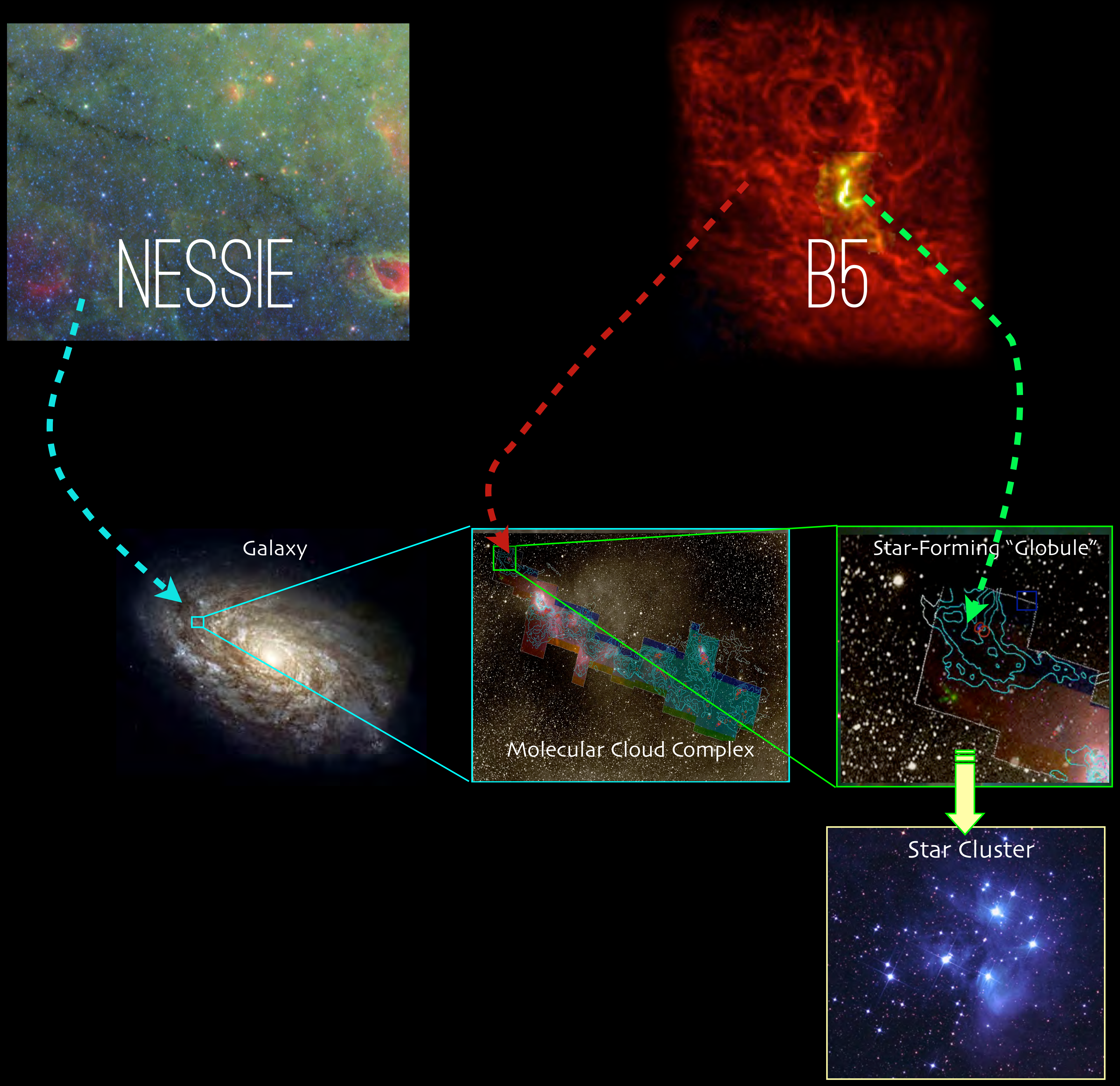
Offner (priv. comm.) 2014

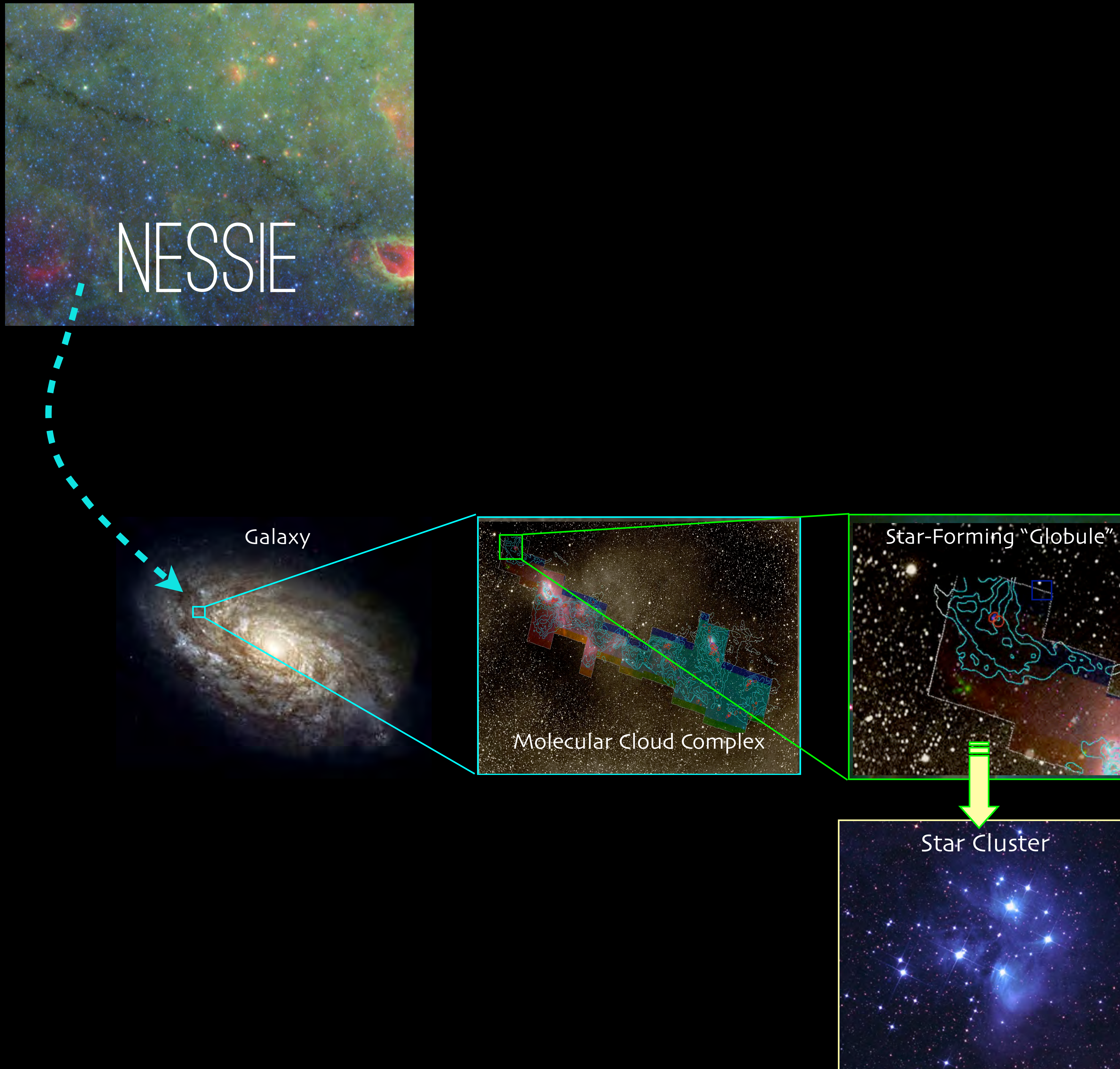
SHHH...

WE NOW ALSO KNOW THAT B5 IS FORMING A BOUND CLUSTER

[B5 image removed to comply with Nature "embargo" rules.]

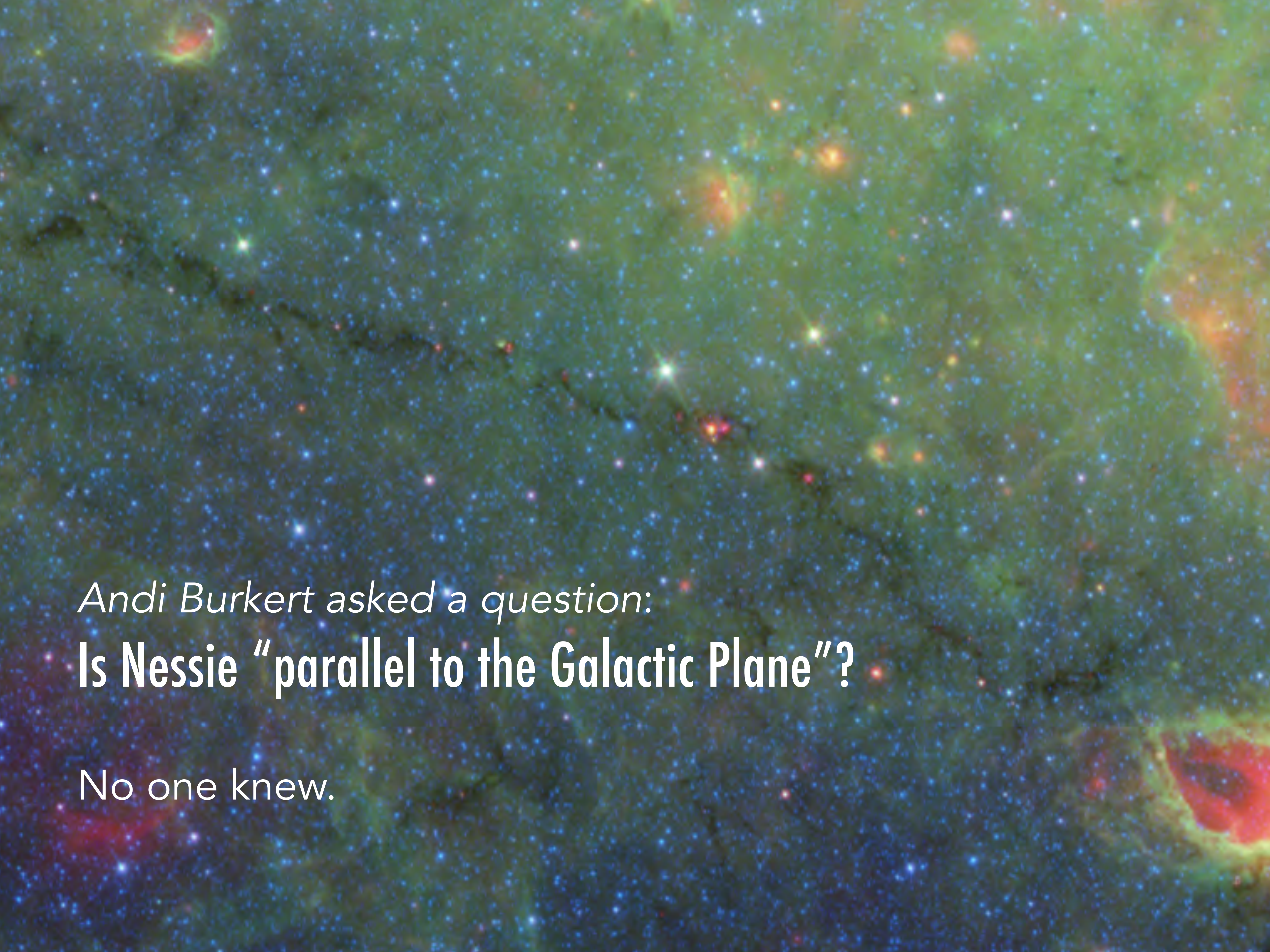
Pineda, Offner, Parker, Arce, Goodman, Caselli, Fuller, Bourke & Corder 2014, submitted to Nature (do not reproduce without permission)


NESSIE
B5
Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Star Cluster


NESSIE
Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Star Cluster

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

…at a conference about
“The Early Phases of Star Foration”

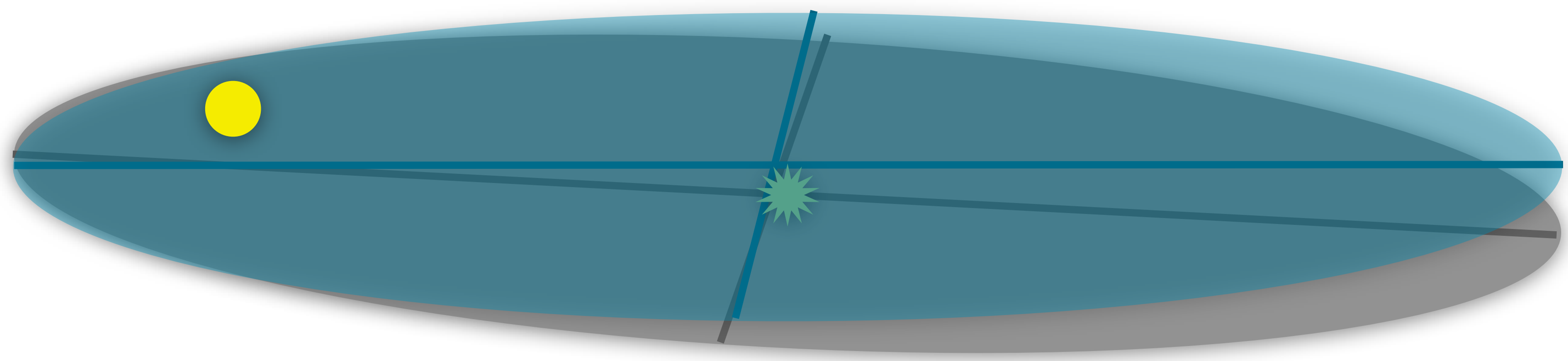

Andi Burkert asked a question:
Is Nessie “parallel to the Galactic Plane”?
No one knew.

The Milky Way

“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

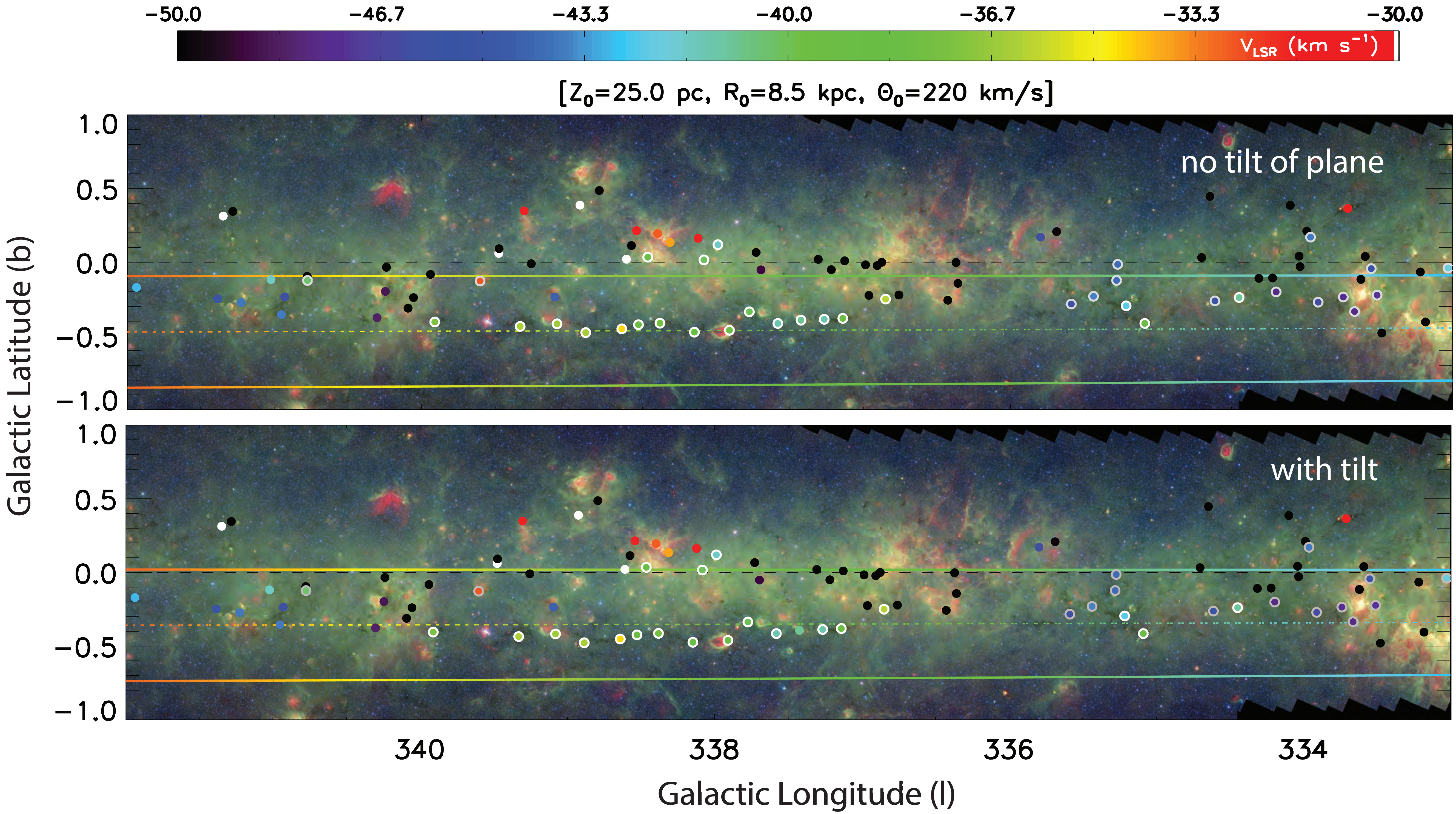
+

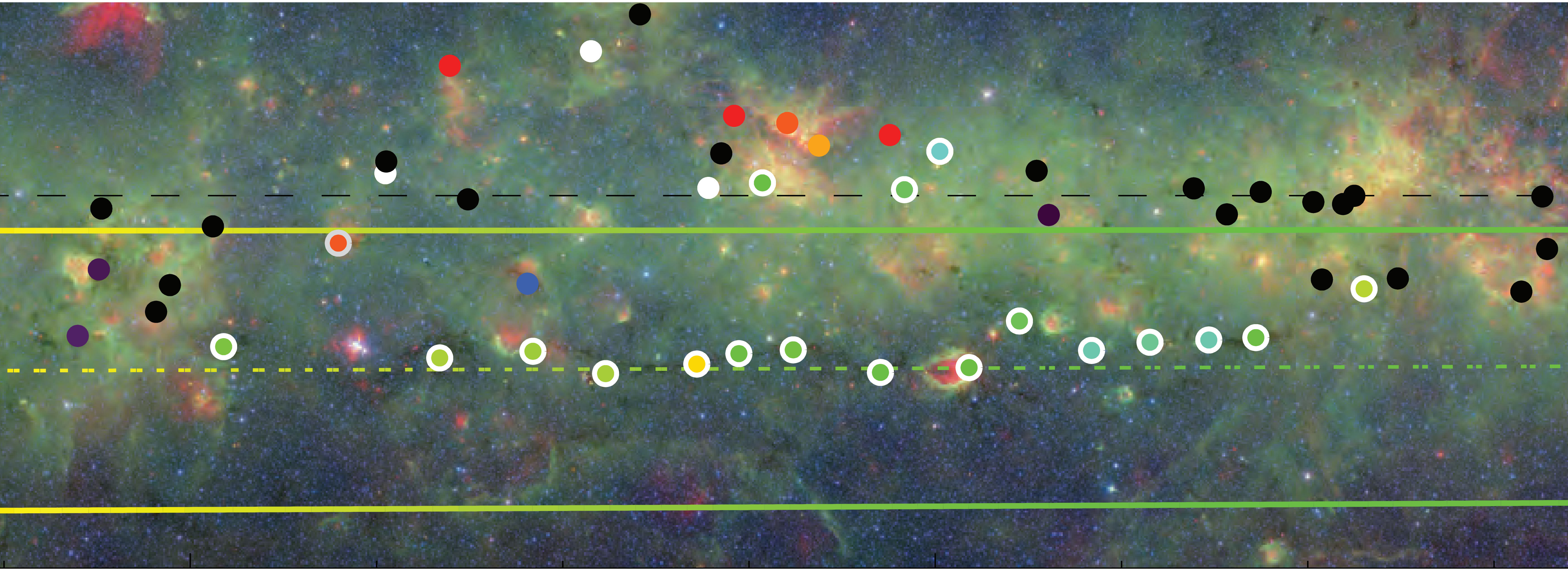
Galactic Center is ~20 light years offset from the IAU Milky Way Center

=

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!



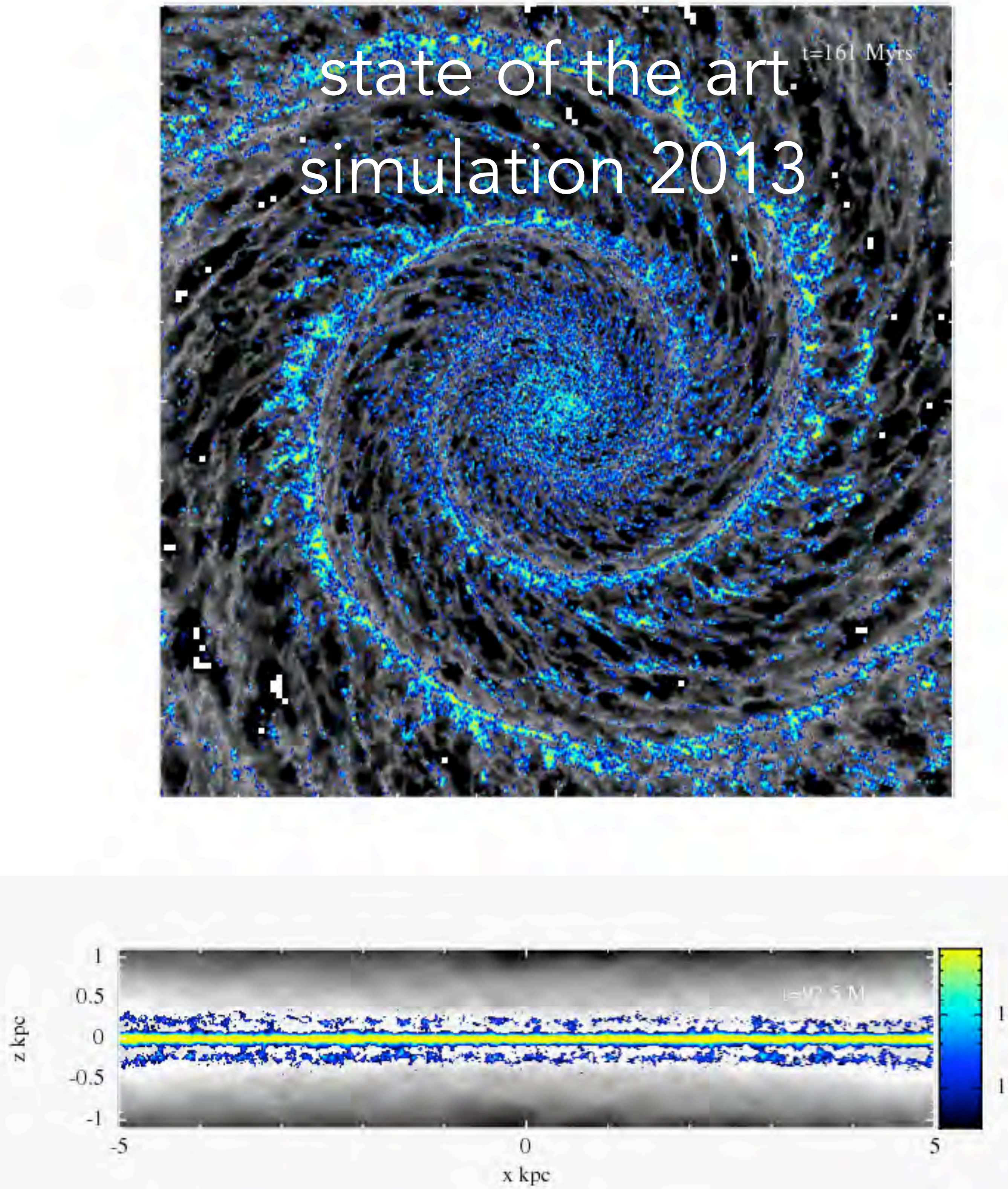


...eerily precisely...

How do we know the velocities?

A full 3D skeleton?

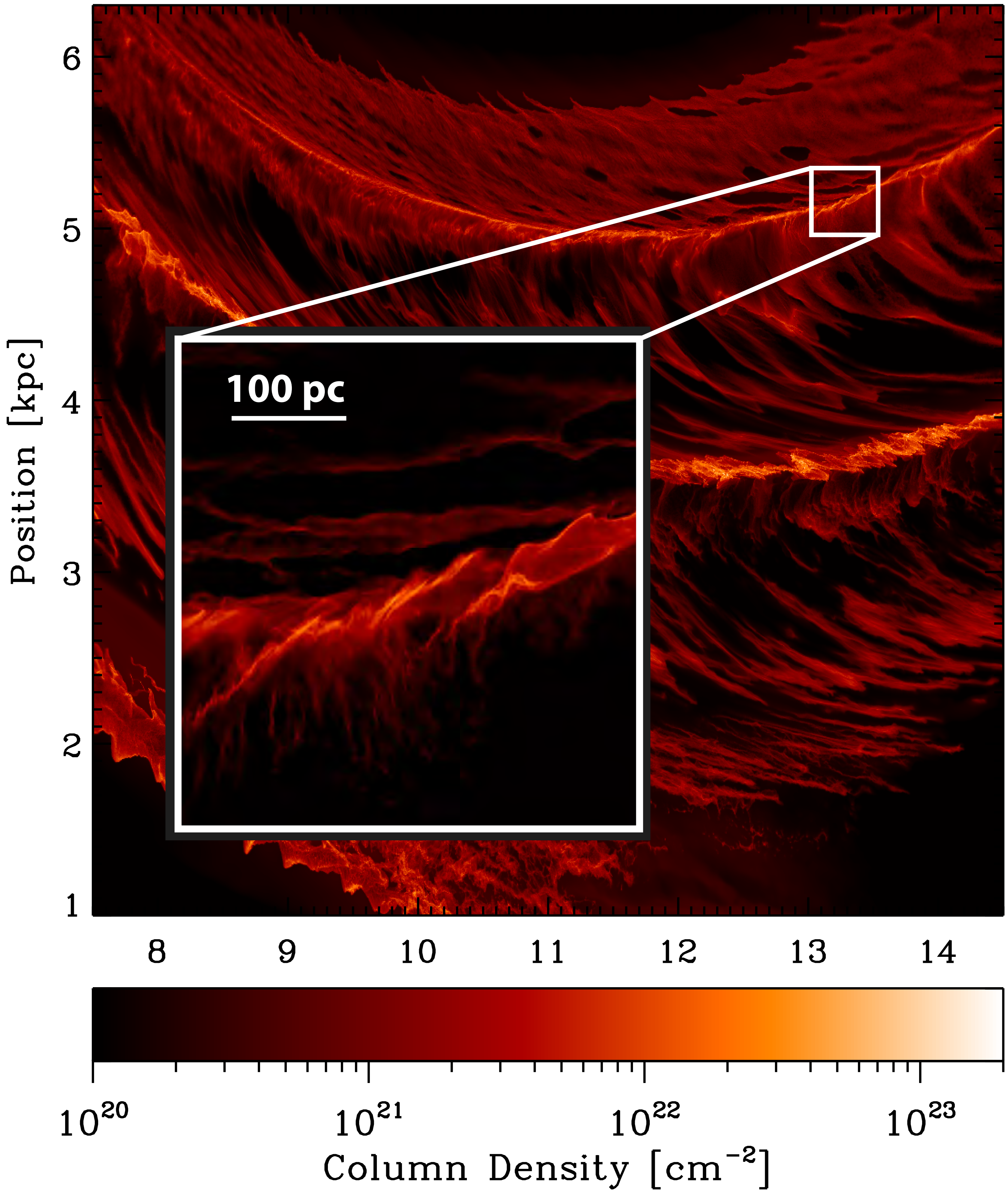
(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas



simulations courtesy Clare Dobbs

New!

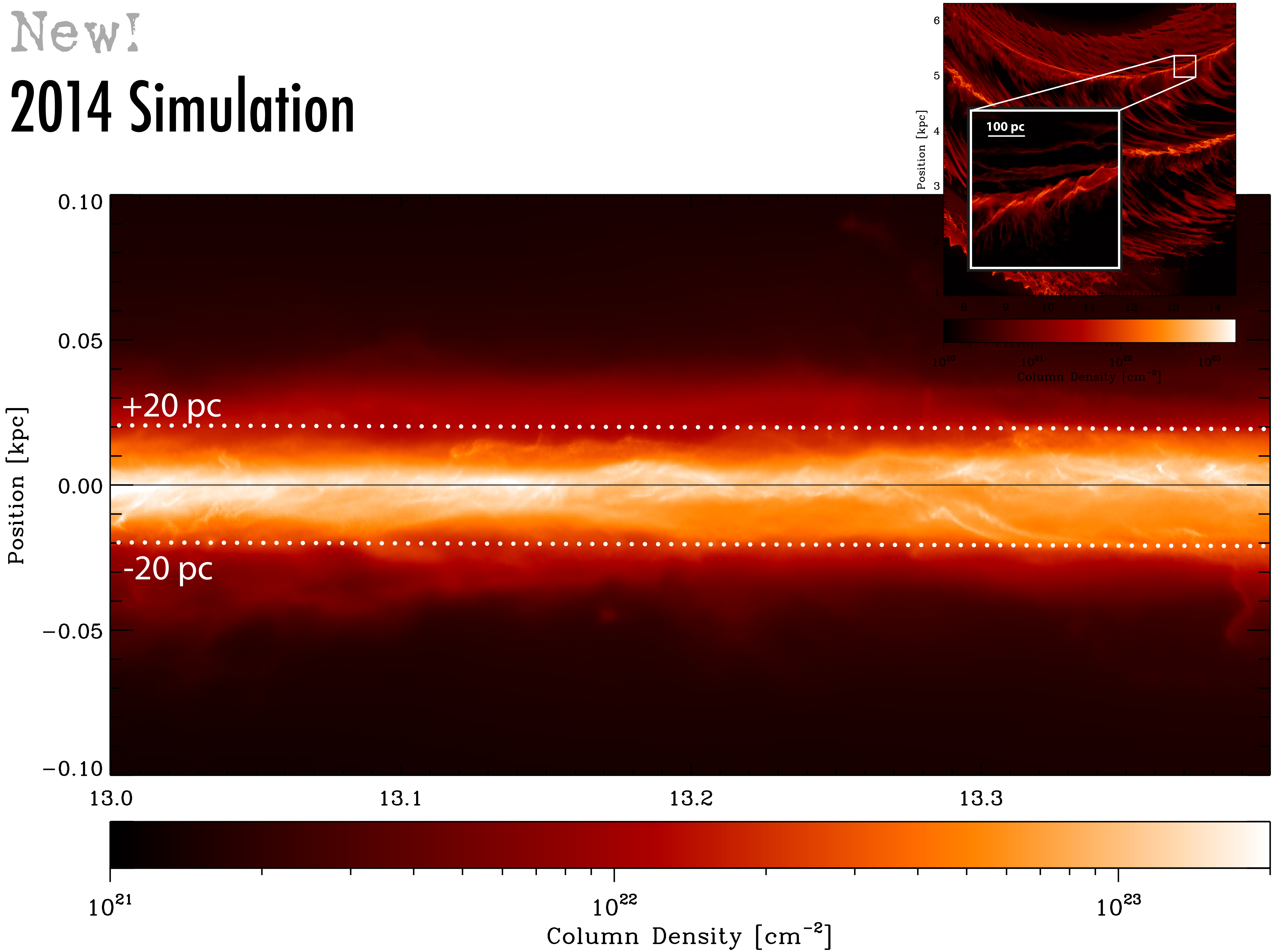
2014 Simulation



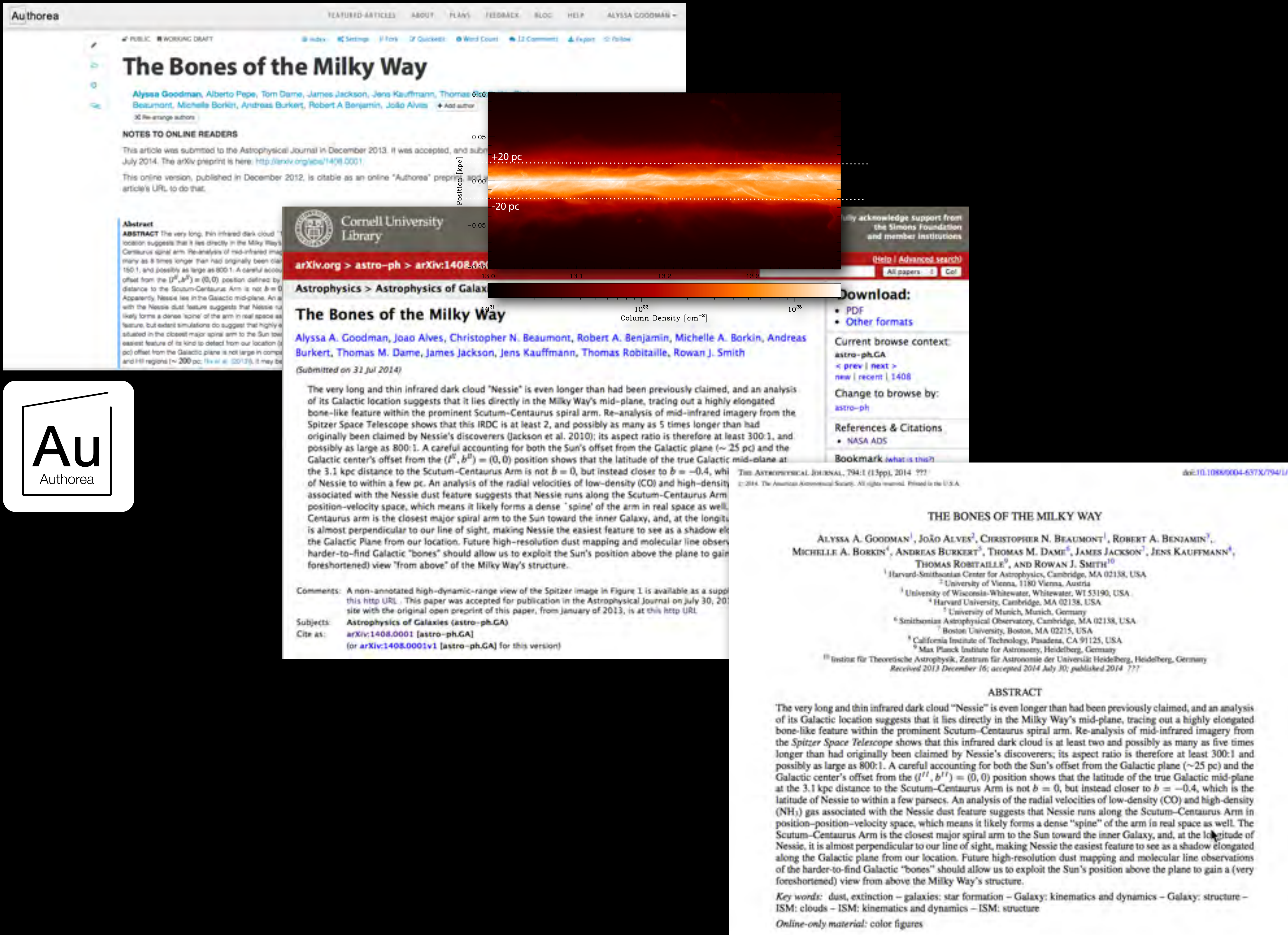
Smith et al. 2014, using AREPO

New!

2014 Simulation



Smith et al. 2014, using AREPO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Beaumont, Michelle Borkin, Andreas Burkert, Robert A Benjamin, João Alves
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Astrophysics > Astrophysics of Galaxies
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(Submitted on 31 Jul 2014)
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doi:10.1088/0004-637X/794/1/1
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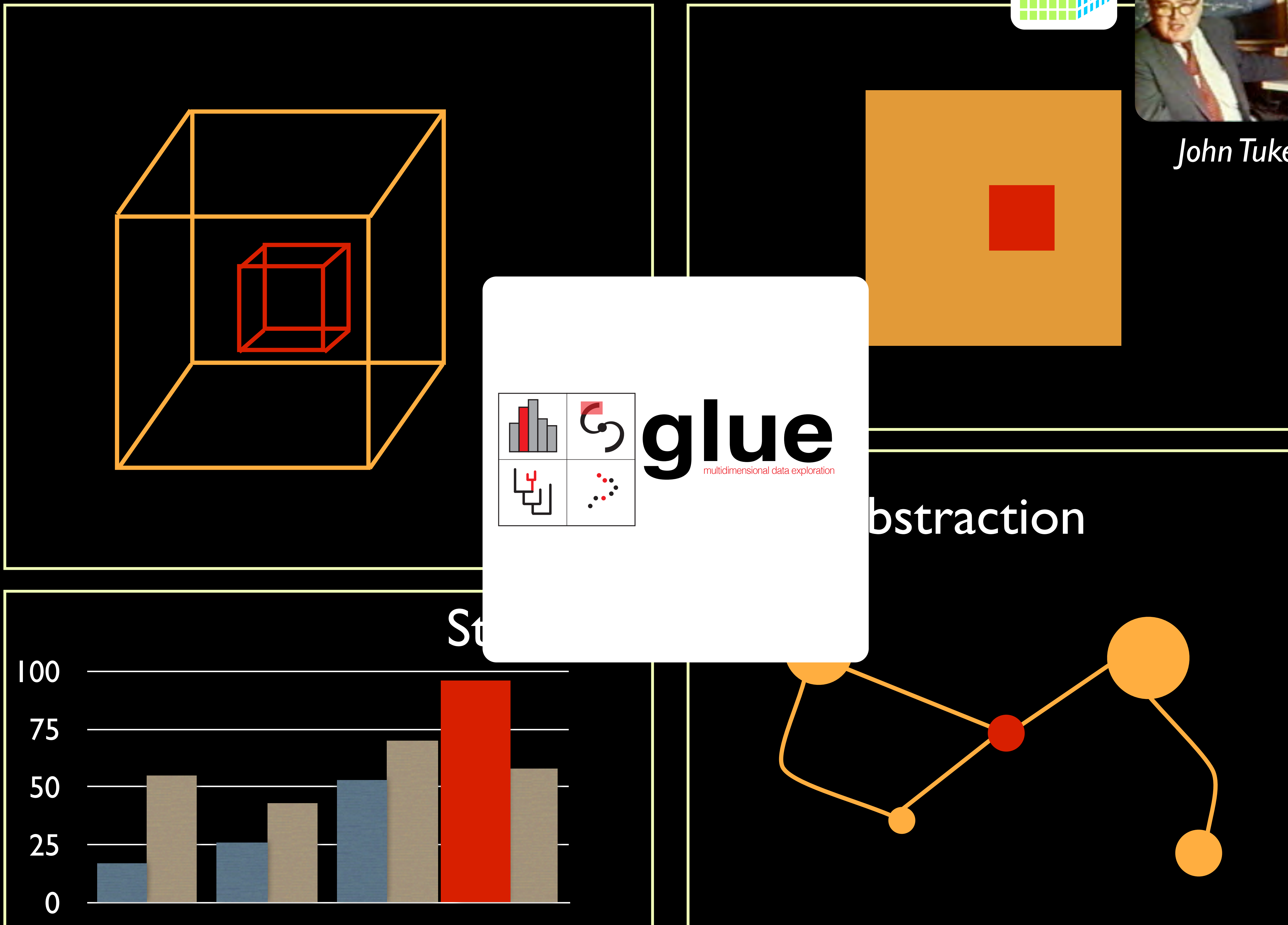
THE BONES OF THE MILKY WAY
ALYSSA A. GOODMAN[1], JOÃO ALVES[2], CHRISTOPHER N. BEAUMONT[1], ROBERT A. BENJAMIN[3], MICHELLE A. BORKIN[4], ANDREAS BURKERT[5], THOMAS M. DAME[6], JAMES JACKSON[7], JENS KAUFFMANN[8], THOMAS ROBITAILLE[9], AND ROWAN J. SMITH[10]
Received 2013 December 16; accepted 2014 July 30; published 2014 ???
ABSTRACT
The very long and thin infrared dark cloud "Nessie" is even longer than had been previously claimed, and an analysis of its Galactic location suggests that it lies directly in the Milky Way's mid-plane, tracing out a highly elongated bone-like feature within the prominent Scutum–Centaurus spiral arm. Re-analysis of mid-infrared imagery from the Spitzer Space Telescope shows that this infrared dark cloud is at least two and possibly as many as five times longer than had originally been claimed by Nessie's discoverers; its aspect ratio is therefore at least 300:1 and possibly as large as 800:1. A careful accounting for both the Sun's offset from the Galactic plane (~25 pc) and the Galactic center's offset from the (l^II, b^II) = (0, 0) position shows that the latitude of the true Galactic mid-plane at the 3.1 kpc distance to the Scutum–Centaurus Arm is not b = 0, but instead closer to b = −0.4, which is the latitude of Nessie to within a few parsecs. An analysis of the radial velocities of low-density (CO) and high-density (NH3) gas associated with the Nessie dust feature suggests that Nessie runs along the Scutum–Centaurus Arm in position–position–velocity space, which means it likely forms a dense "spine" of the arm in real space as well. The Scutum–Centaurus Arm is the closest major spiral arm to the Sun toward the inner Galaxy, and, at the longitude of Nessie, it is almost perpendicular to our line of sight, making Nessie the easiest feature to see as a shadow elongated along the Galactic plane from our location. Future high-resolution dust mapping and molecular line observations of the harder-to-find Galactic "bones" should allow us to exploit the Sun's position above the plane to gain a (very foreshortened) view from above the Milky Way's structure.
Key words: dust, extinction – galaxies: star formation – Galaxy: kinematics and dynamics – Galaxy: structure – ISM: clouds – ISM: kinematics and dynamics – ISM: structure
Online-only material: color figures

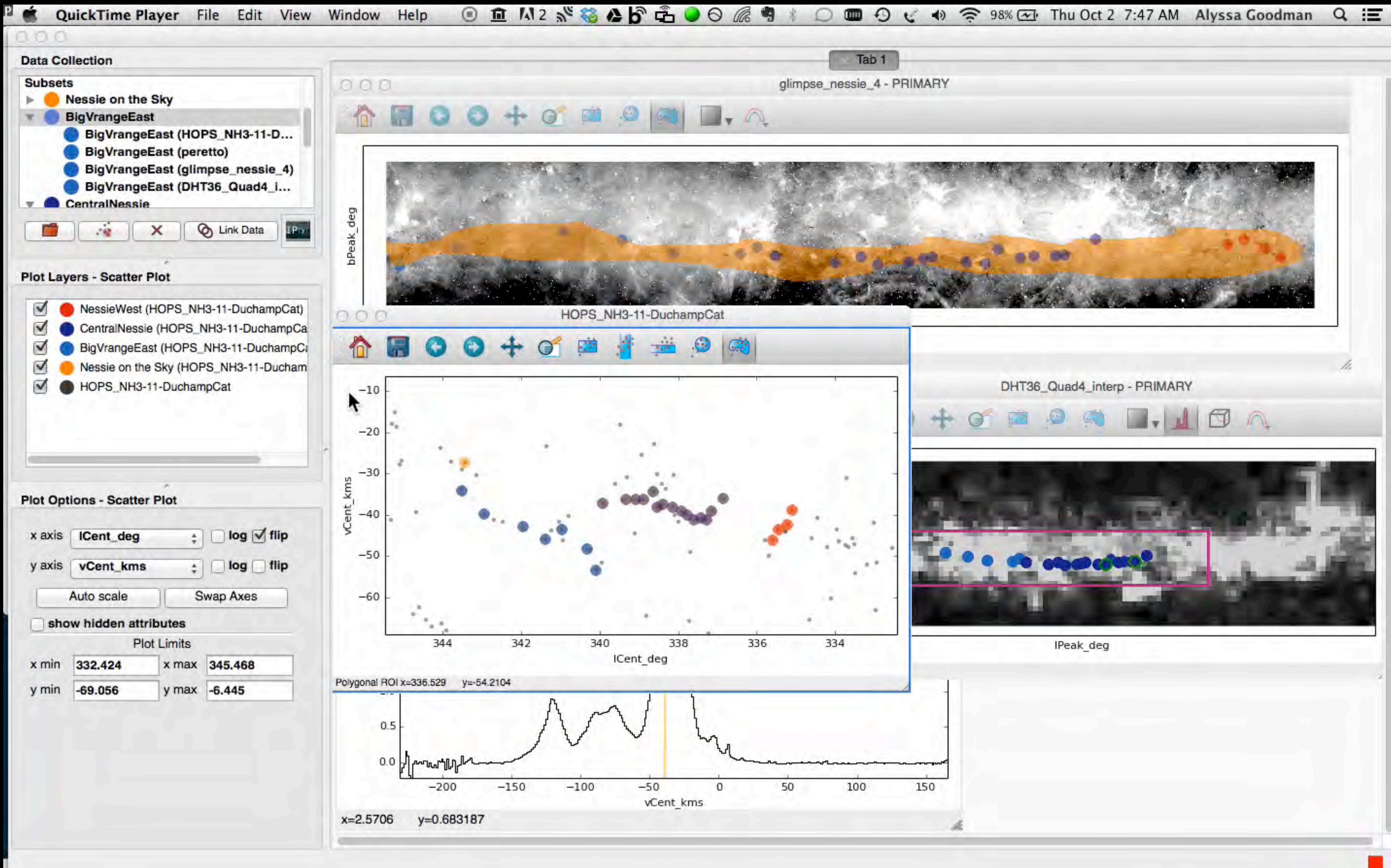
LINKED VIEWS OF HIGH-DIMENSIONAL DATA

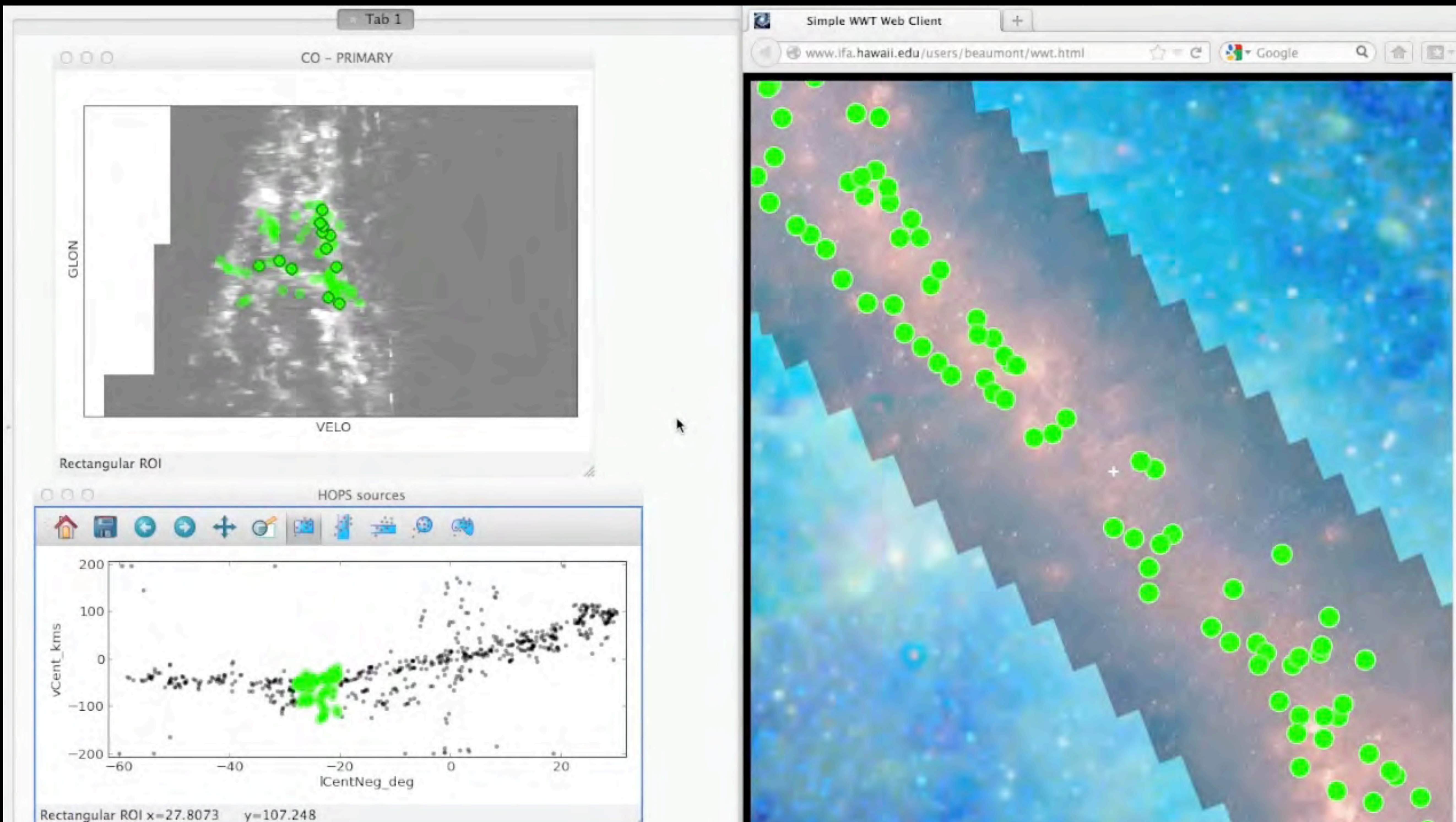
John Tukey



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

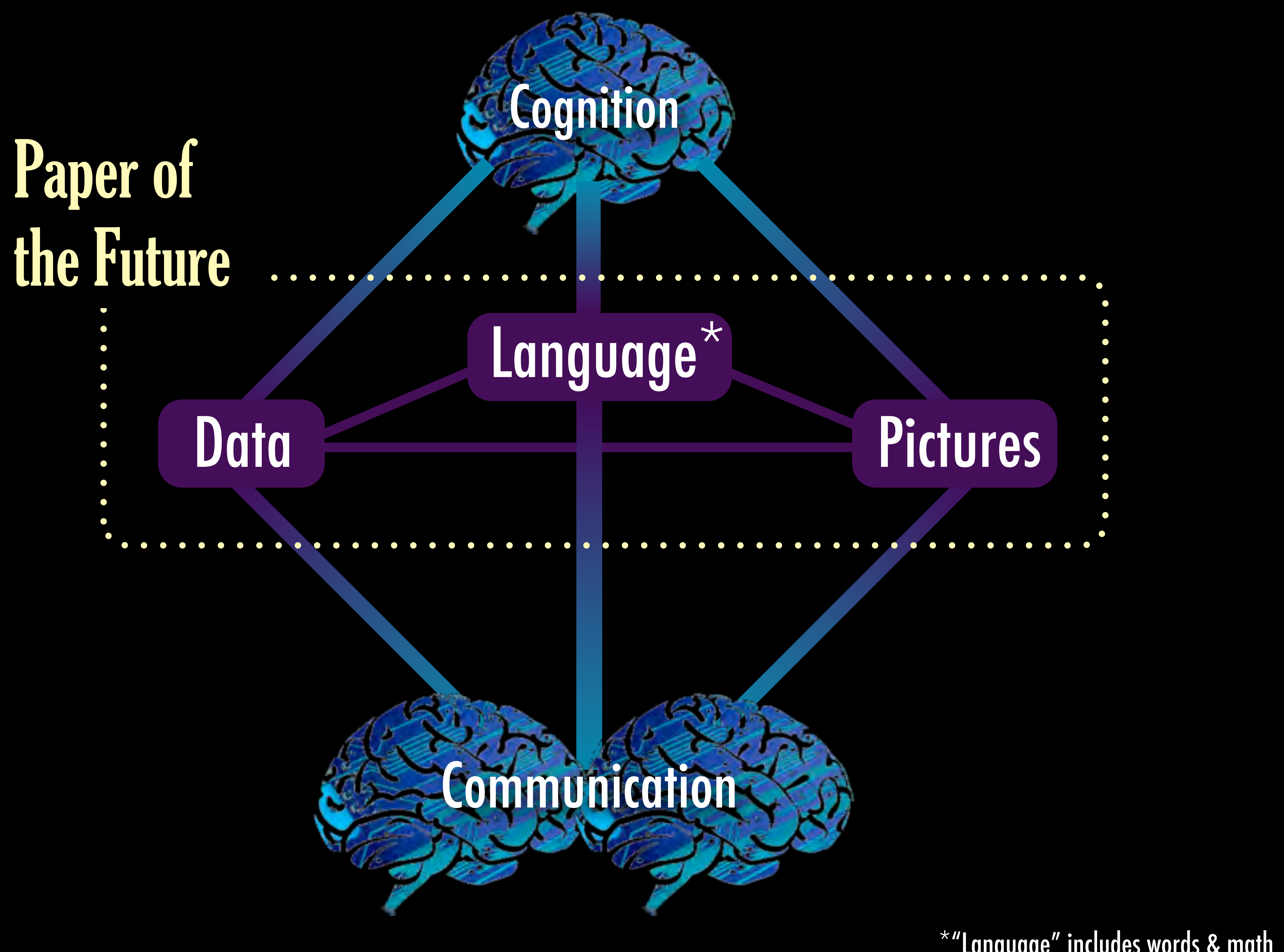
NESSIE IN GLUE





Video courtesy of Chris Beaumont, Lead Glue Architect

Nessie to B5, the movie.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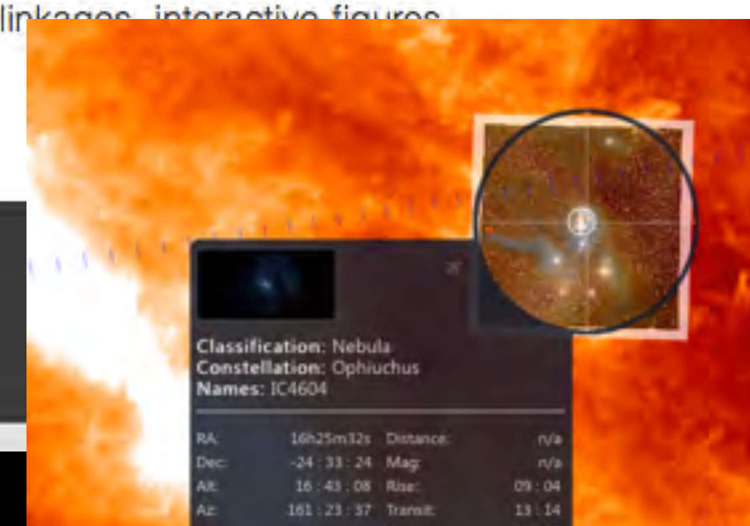
The "Paper" of the Future

Alyssa Goodman, Josh Peek, How-Huan Hope Chen, Alberto Accomazzi, Chris Beaumont, Christine L. Borgman, Merce Crosas, Christopher Erdmann, jfay@microsoft.com, August Muench, Alberto Pepe, Curtis Wong + Add author Re-arrange authors

1 Preamble

A variety of research on human cognition demonstrates that humans learn and communicate best when more than one processing sysetm (e.g. visual, auditory, touch) is used. And, related research also shows that, no matter how technical the material, most humans also retain and process information best when they can put a narrative "story" to it. So, when considering the future of scholarly communication, we should be careful not to do blithely away with the linear narrative format that articles and books have followed for centuries: instead, we should enrich it.

Much more than text is used to commuicate in Science. Figures, which include images, diagrams, graphs, charts, and more, have enriched scholarly articles since the time of Galileo, and ever-growing volumes of data underpin most scientific papers. When scientists communicate face-to-face, as in talks or small discussions, these figures are often the focus of the conversation. In the best discussions, scientists have the ability to manipulate the figures, and to access underlying data, in real-time, so as to test out various what-if scenarios, and to explain findings more clearly. **This short article explains—and shows with demonstrations—how scholarly "papers" can morph into long-lasting rich records of scientific discourse**, enriched with deep data and code linkages, interactive figures, audio, video, and commenting.



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SEEING STARS FORM IN THE MILKY WAY

ALYSSA A. GOODMAN
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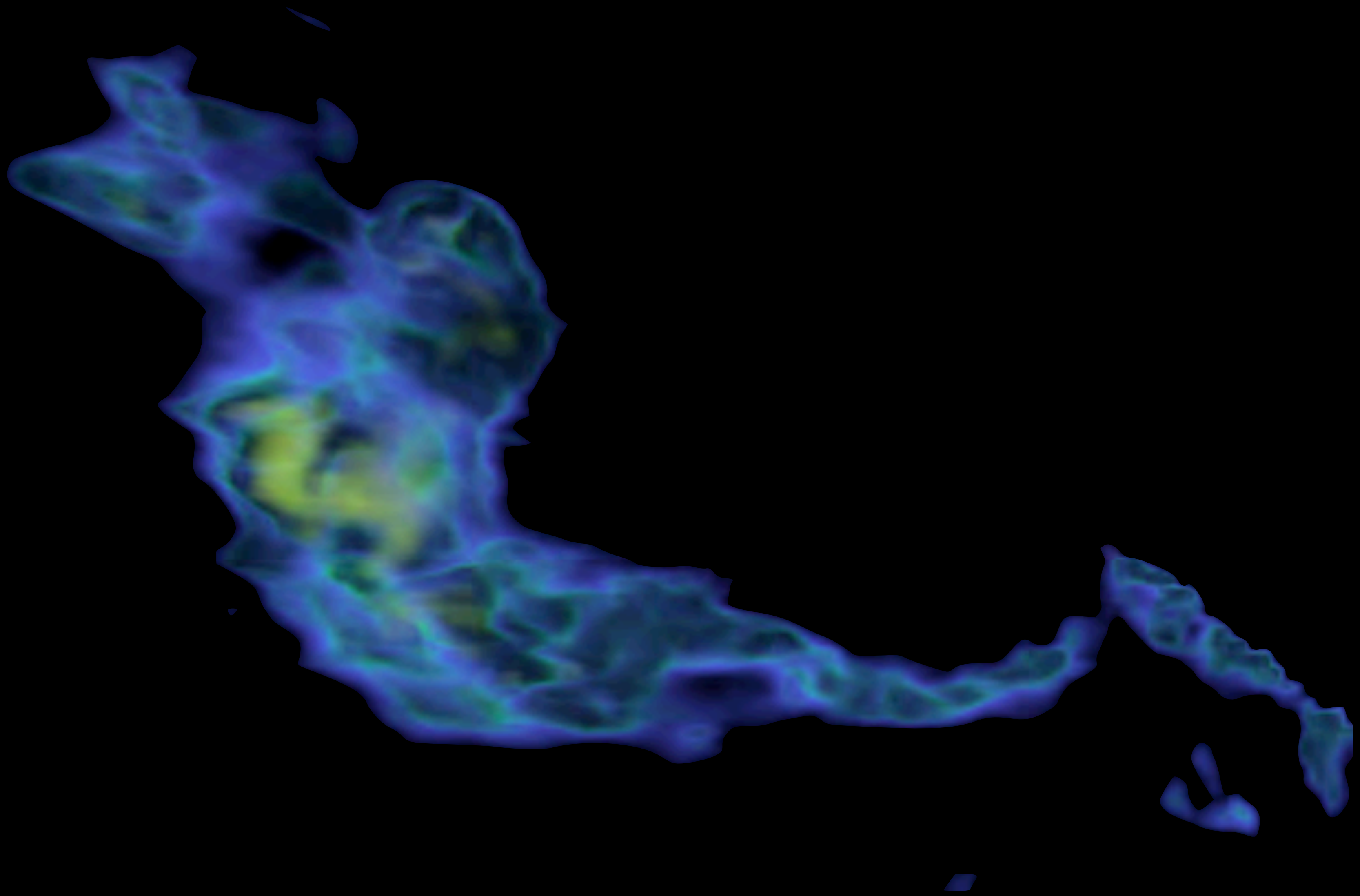
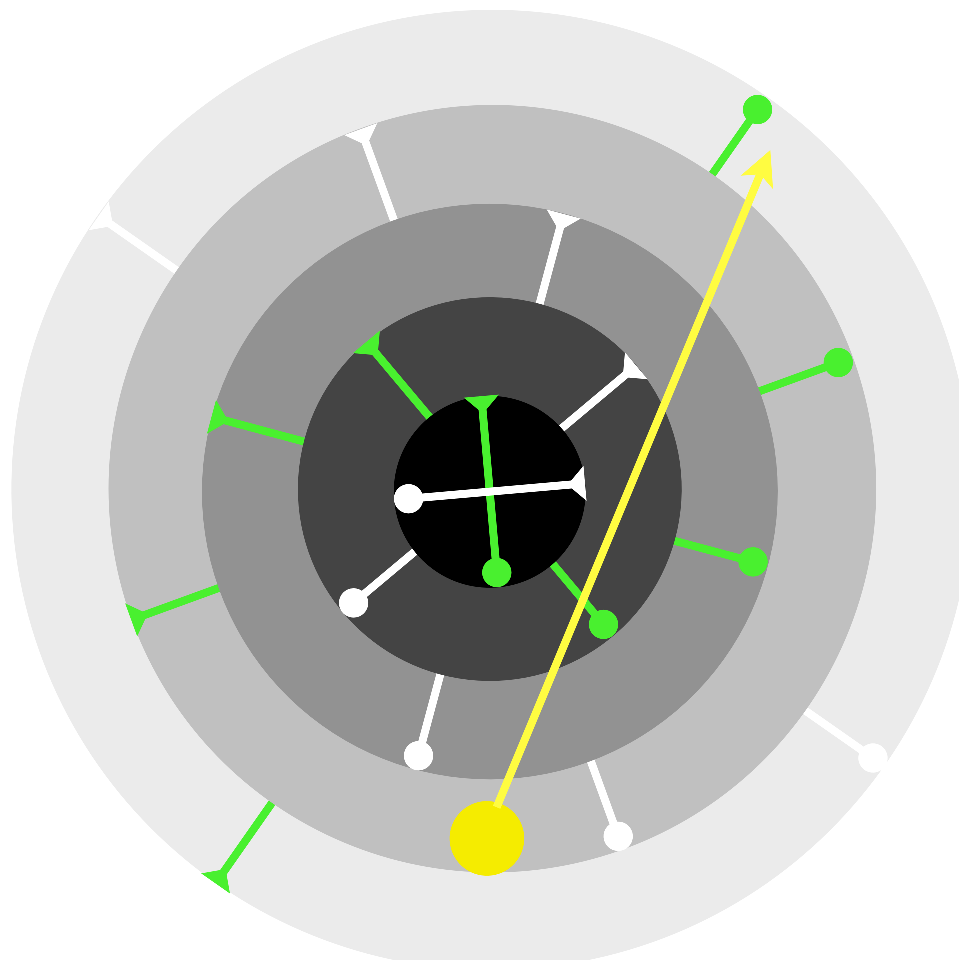
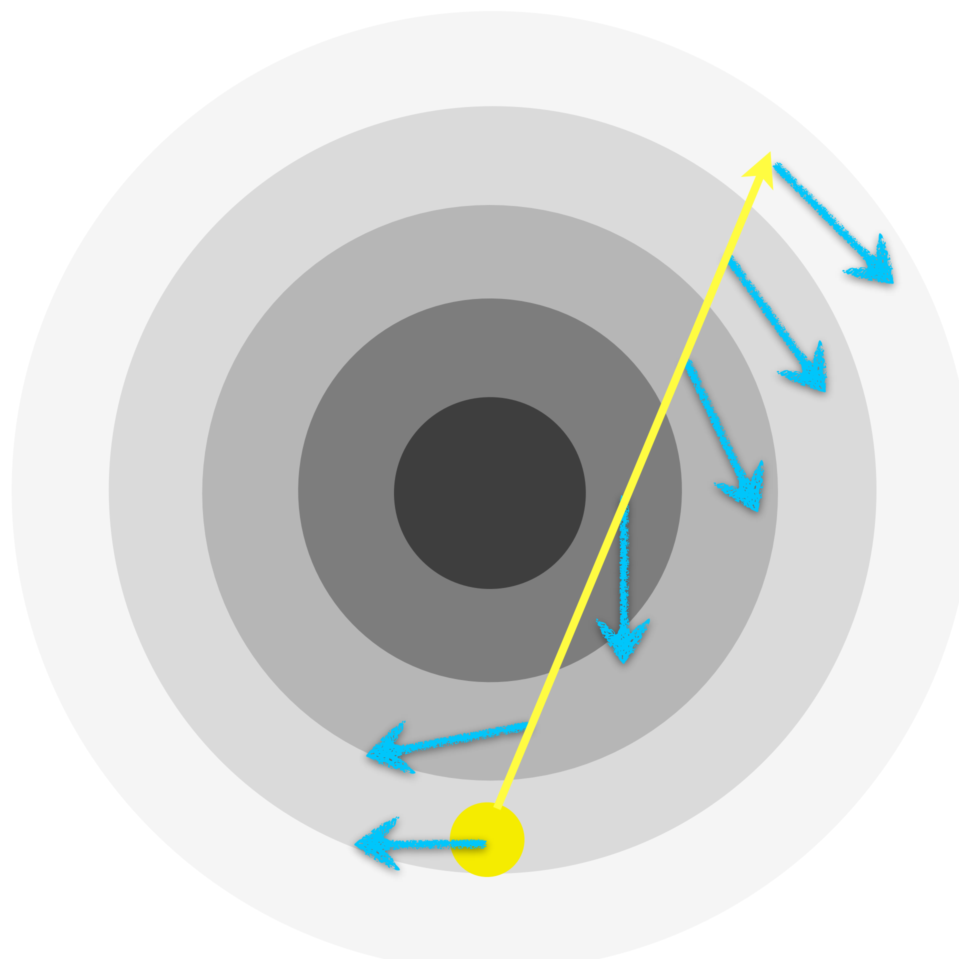
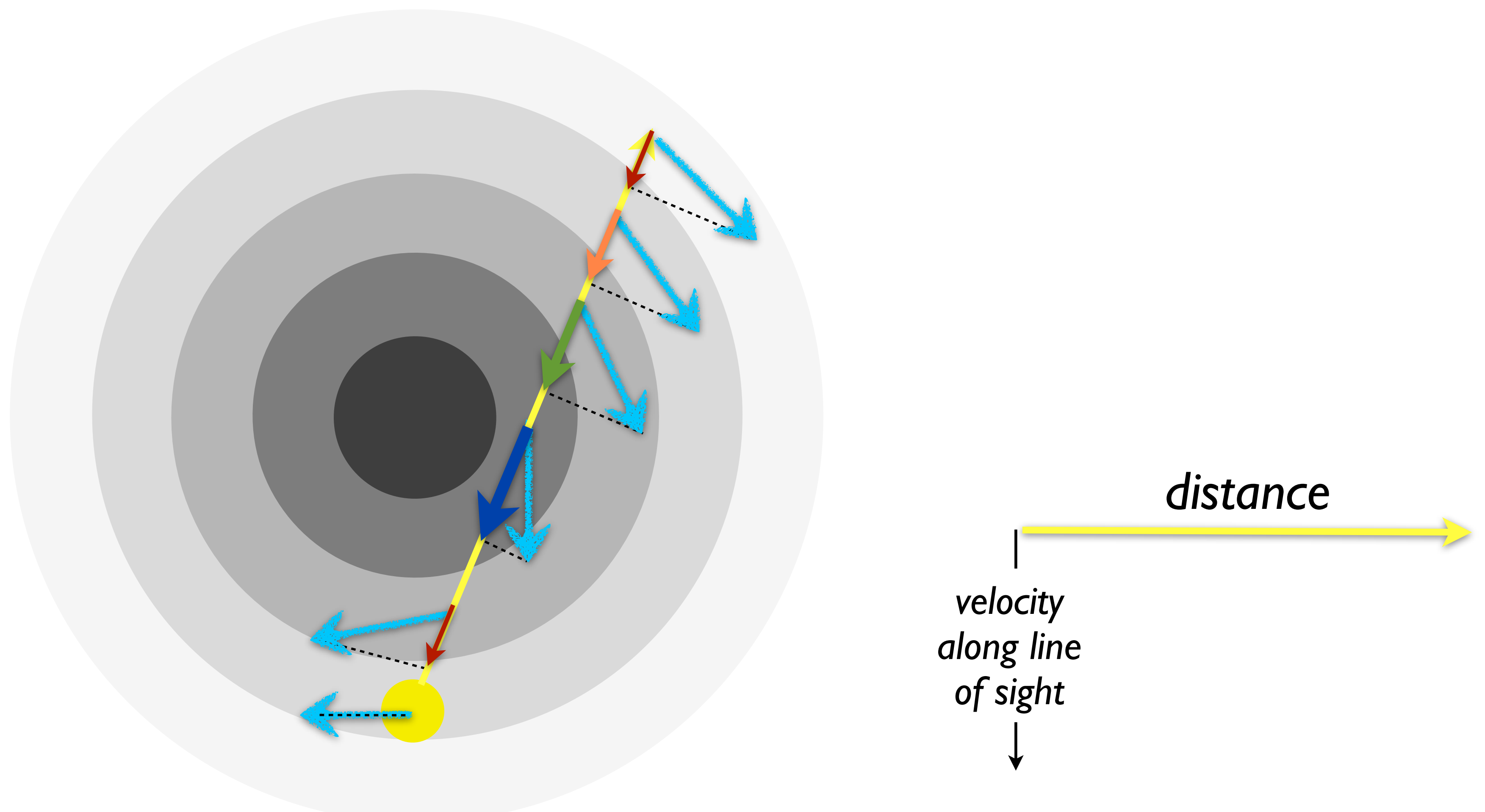
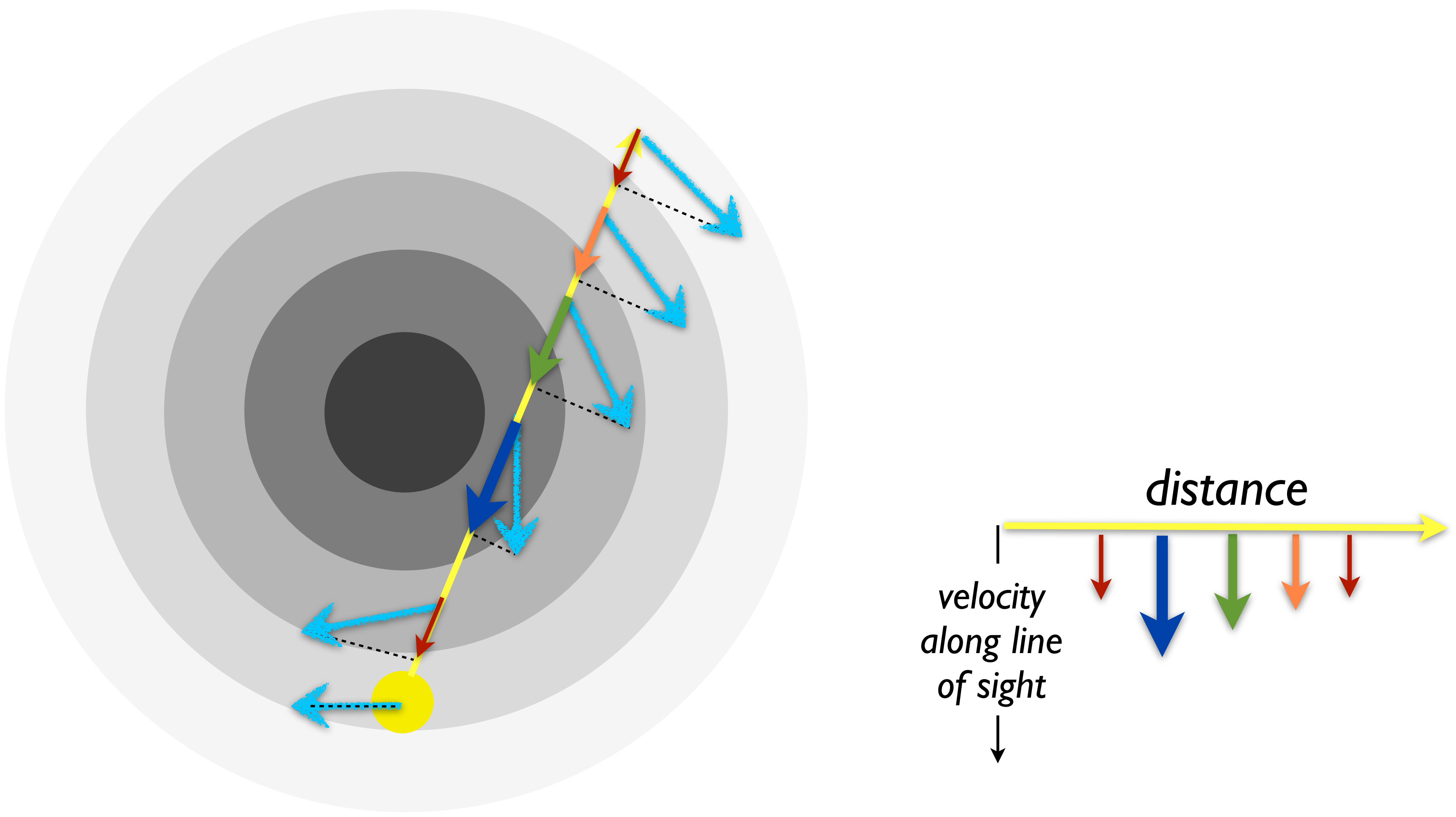


A Rotating (Spiral) Galaxy Observed from its Outskirts...






distance
velocity
along line
of sight



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