The New Milky Way, in 3D

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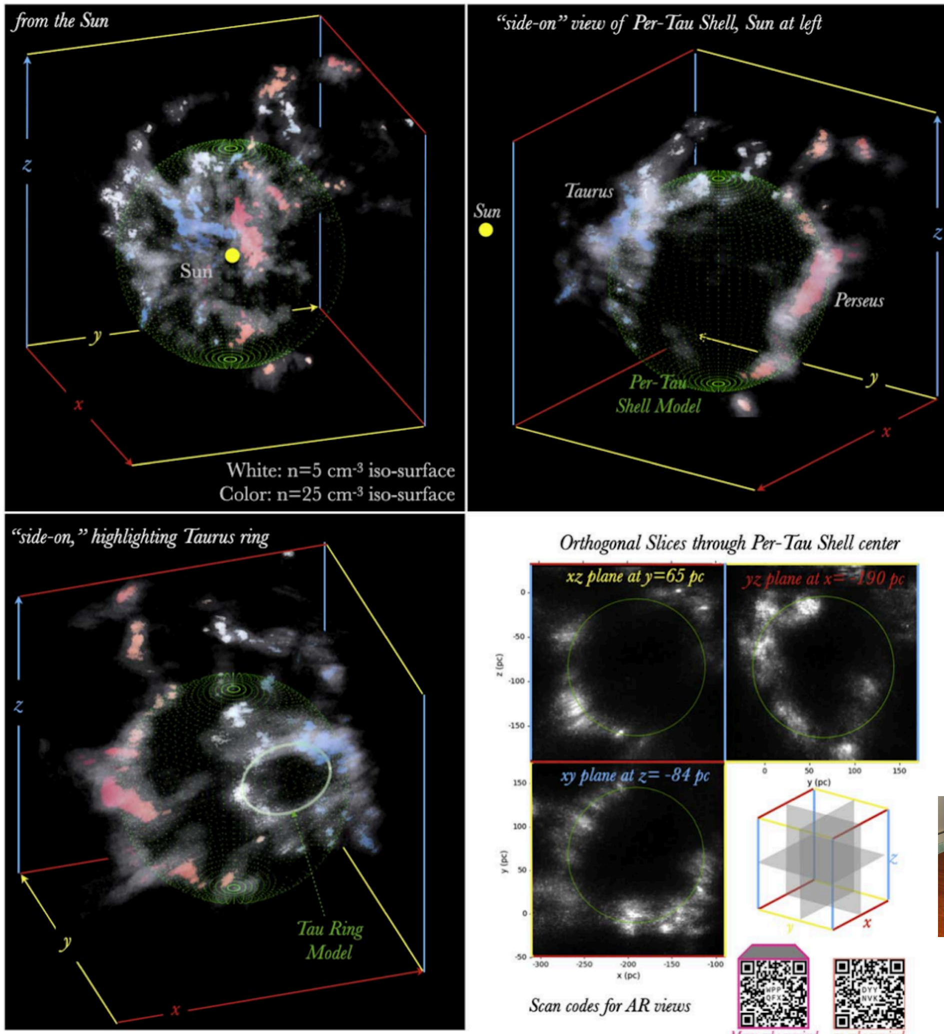
with many thanks to:
João Alves, John Bally, Cara Battersby, Gus Beane, Chris Beaumont, Bob Benjamin, Ted Bergin, Shmuel Bialy, Michelle Borkin, Andi Burkert, Shlomo Cahlon, Jon Carifio, Kaustav Das, Tom Dame, Elena D'Onghia, Gordian Edenhofer, Torsten Enβlin, Jonathan Fay, Douglas Finkbeiner, John Forbes, Michael Foley, Greg Green, Josefa Groβschedl, Mike Grudić, James Jackson, Sarah Jeffreson, Jens Kauffmann, Diana Khimey, Ralf Konietzka, Eric Koch, Charles Lada, Reimar Leike, Stefan Meingast, Josh Peek, Stephen Portillo, Mark Reid, Tom Rice, Tom Robitaille, Eddie Schlafly, Vadim Semenov, Maya Skarbinski, Rowan Smith, Juan Soler, Josh Speagle, Alan Tu, Cameren Swiggum, Patricia Udomprasert, Peter Williams, Curtis Wong & Catherine **Zucker**!

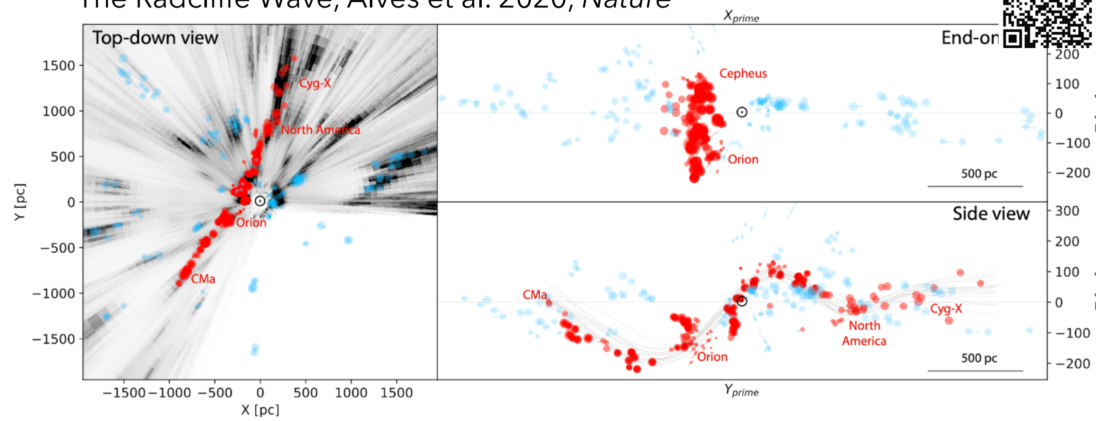
@AlyssaAGoodman

What is the true spatial and kinematic distribution of dense gas in the Milky Way, and how does it relate to star formation, and galactic structure?

The Perseus-Taurus Supershell
Bialy et al. 2021, *ApJL*

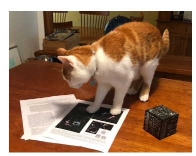


The Radcliffe Wave, Alves et al. 2020, *Nature*

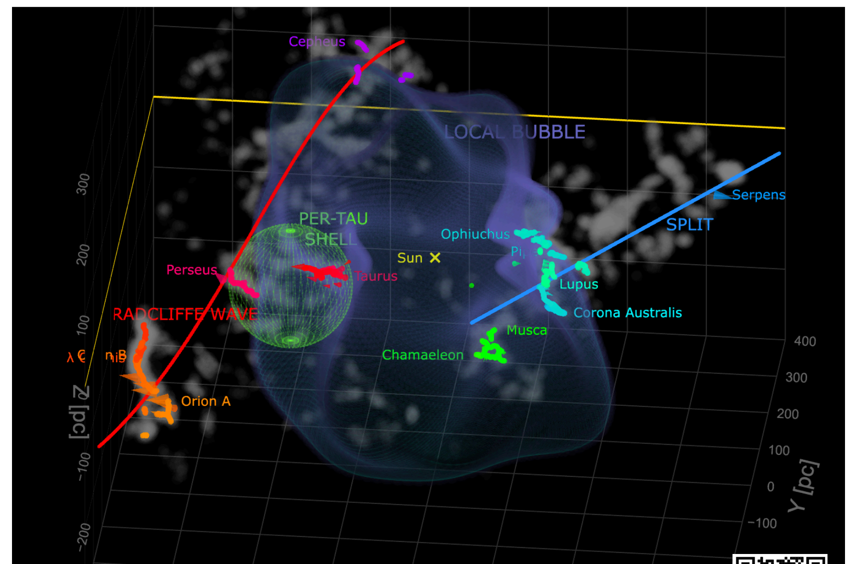


tinyurl.com/AG-2-24-22

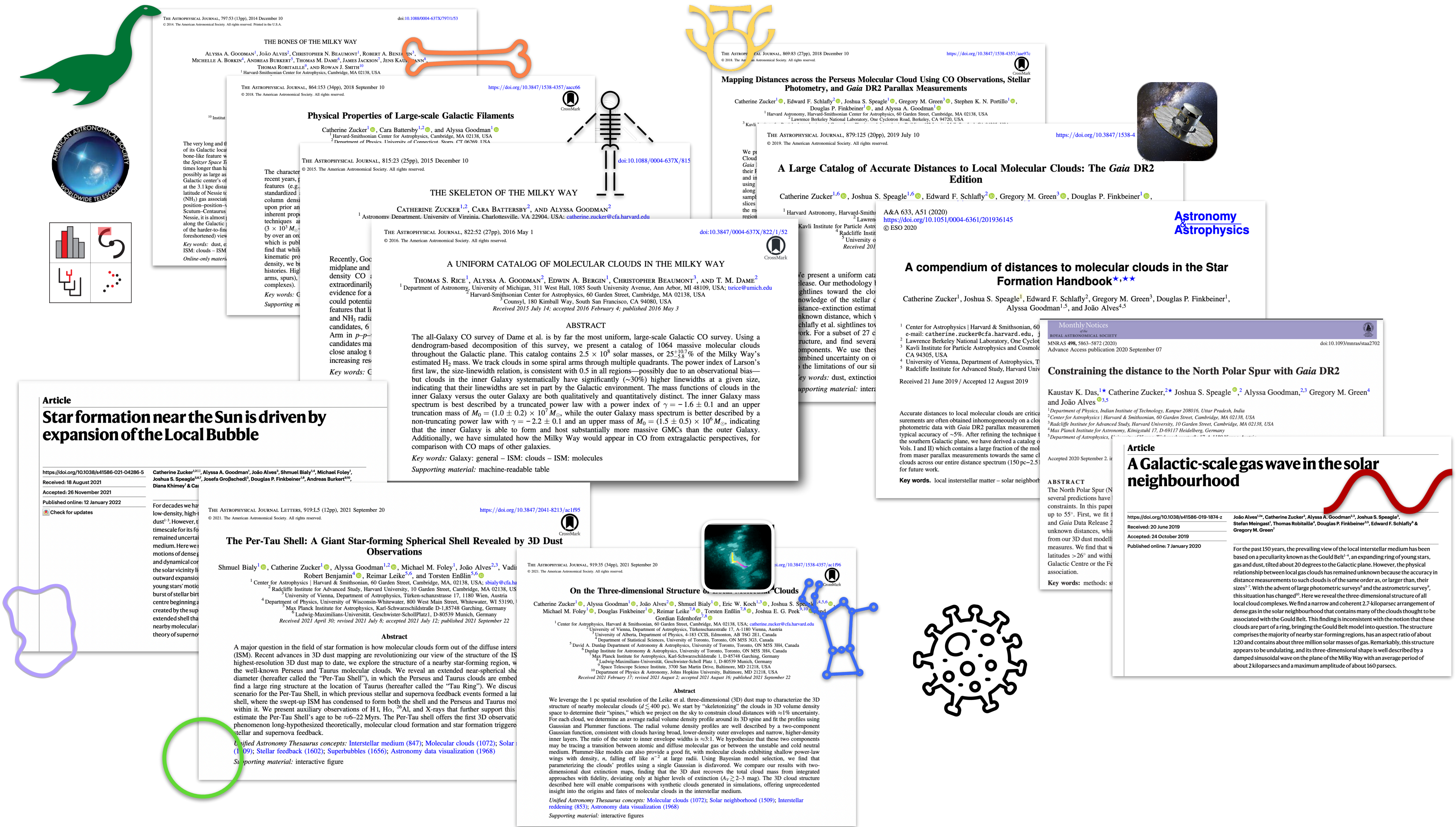
QR code for today's handout

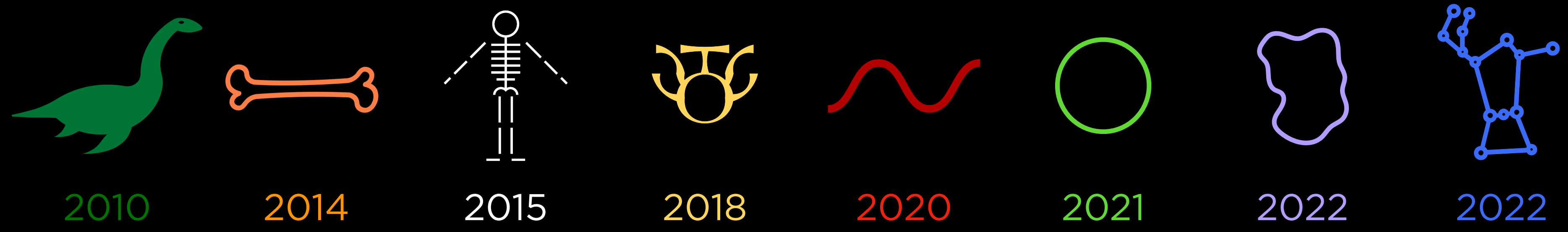


←AR Codes

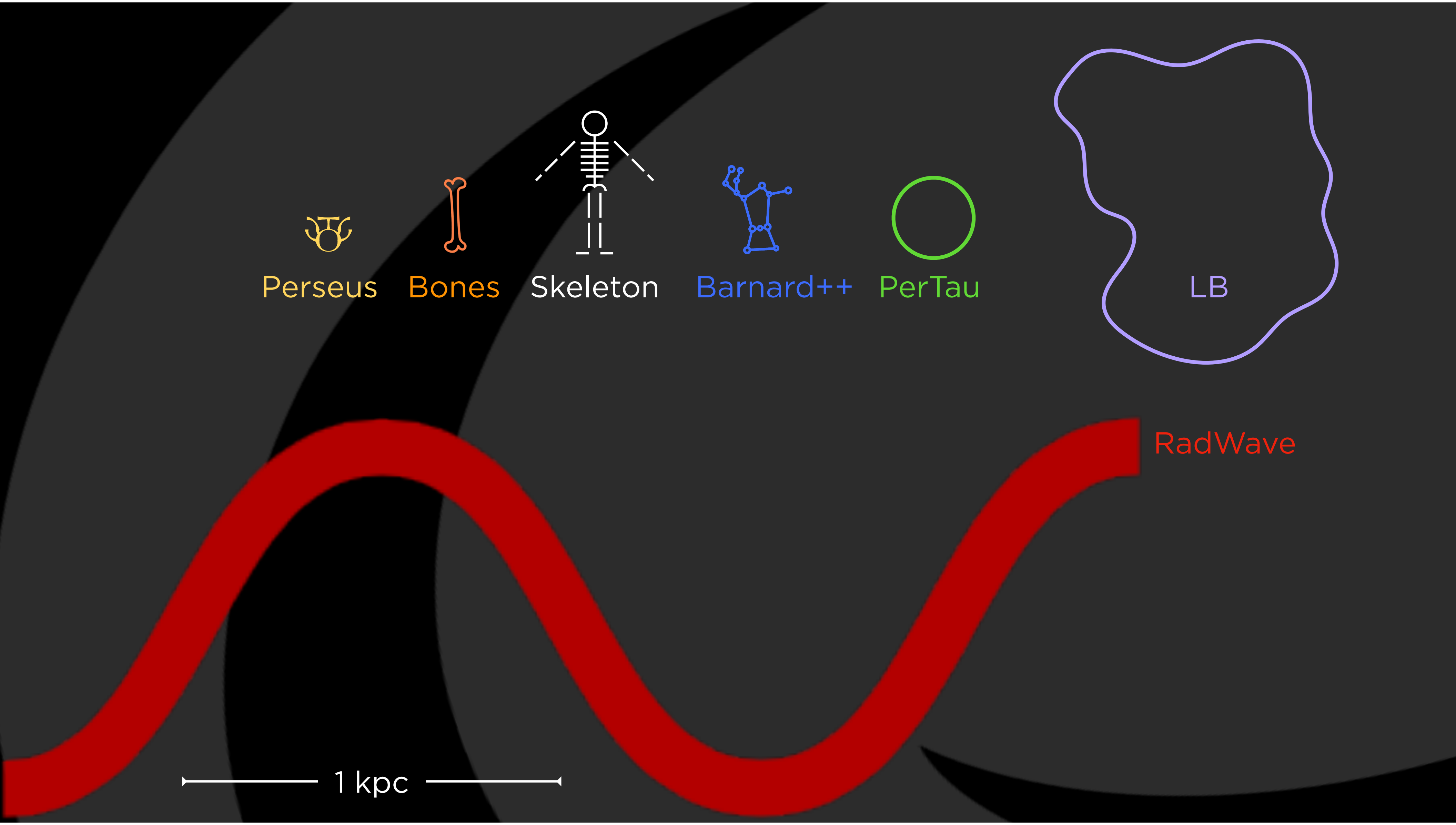


The Local Bubble in Context
Zucker et al. 2022, *Nature*

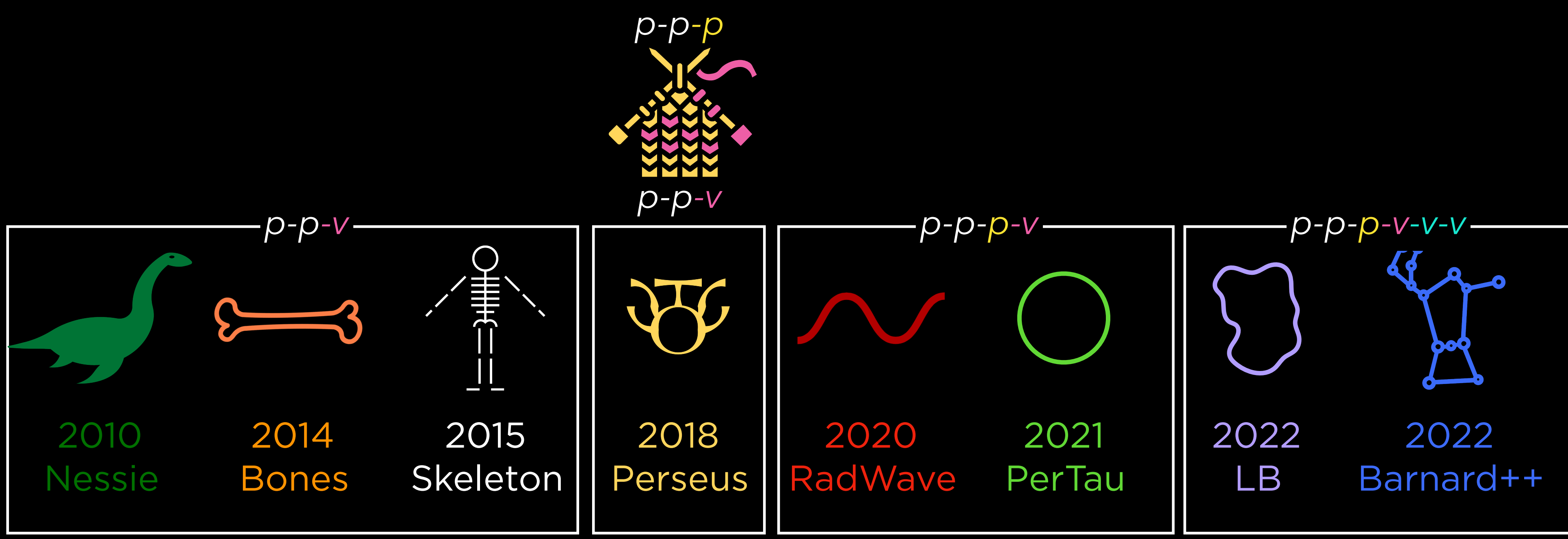

The Bones of the Milky Way
Physical Properties of Large-scale Galactic Filaments
The Skeleton of the Milky Way
A Uniform Catalog of Molecular Clouds in the Milky Way
Mapping Distances across the Perseus Molecular Cloud Using CO Observations, Stellar Photometry, and Gaia DR2 Parallax Measurements
A Large Catalog of Accurate Distances to Local Molecular Clouds: The Gaia DR2 Edition
Astronomy & Astrophysics
A compendium of distances to molecular clouds in the Star Formation Handbook
Constraining the distance to the North Polar Spur with Gaia DR2
Article
Star formation near the Sun is driven by expansion of the Local Bubble
The Per-Tau Shell: A Giant Star-forming Spherical Shell Revealed by 3D Dust Observations
On the Three-dimensional Structure of Local Molecular Clouds
Article
A Galactic-scale gas wave in the solar neighbourhood


2010
2014
2015
2018
2020
2021
2022
2022


Nessie
Bones
Skeleton
Perseus
RadWave
PerTau
LB
Barnard++

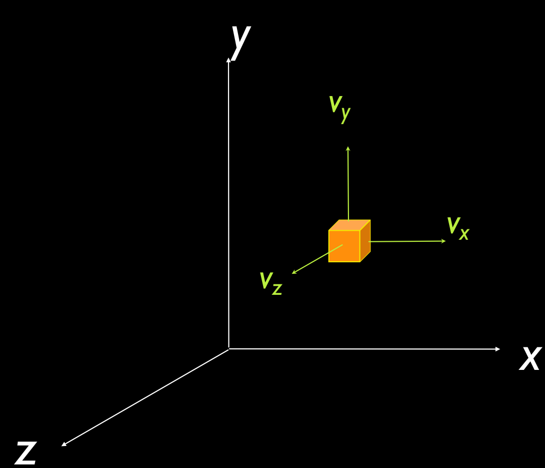

Perseus
Bones
Skeleton
Barnard++
PerTau
LB
RadWave
1 kpc

The New Milky Way, in 3D, 4D & 6D

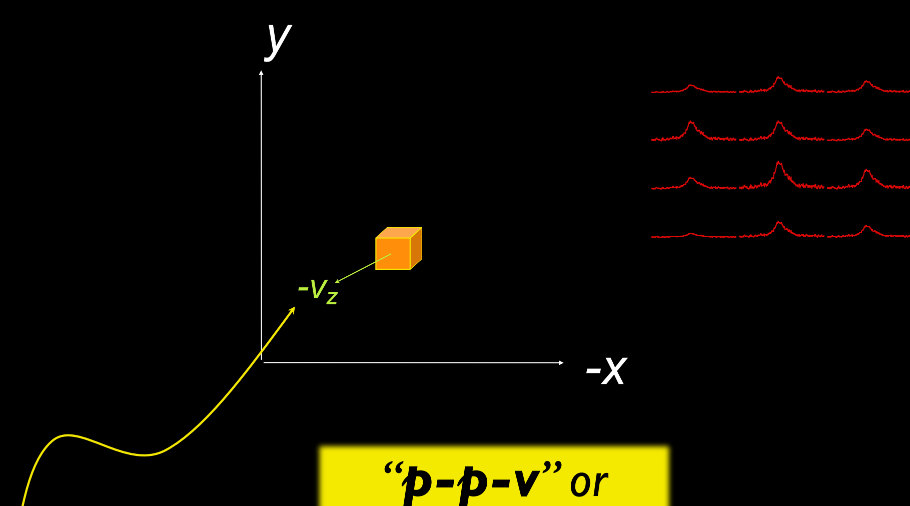


Spectral-line mapping

true 3D <u>with</u> velocities: 6D



p-p-v space: "3D"



v_z *only* from "spectral-line maps"

"***p-p-v***" *or* *"position-position-velocity" space* *"p-p-v"*= position-position-velocity data

"kinematic distance" only

HI

Oort et al 1958

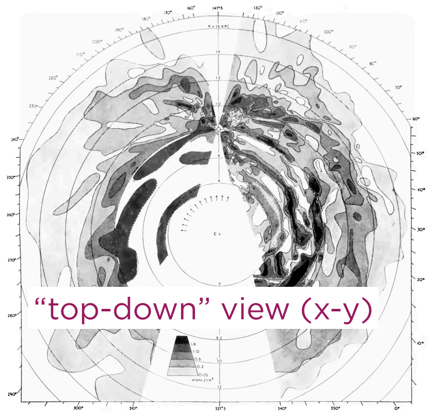
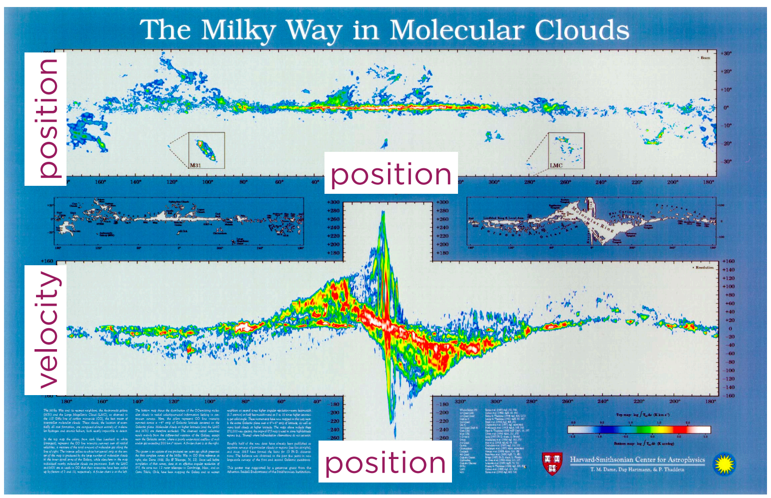


FIG. 4.—Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.

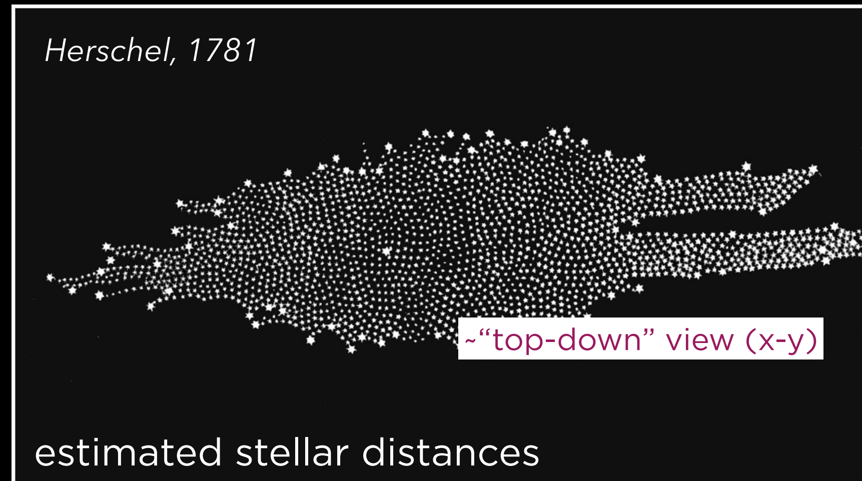
CO

Dame et al 2001



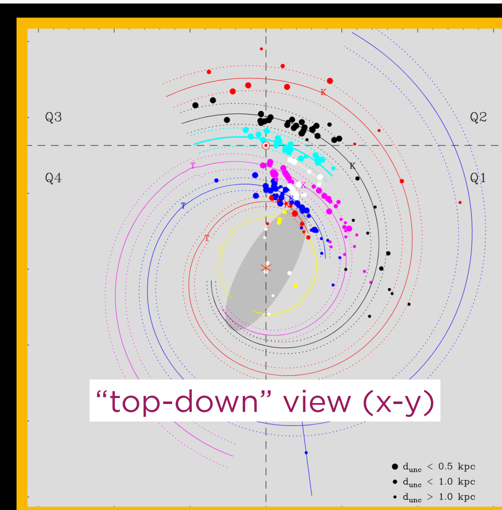
p-p-p = true 3D space data

true distance



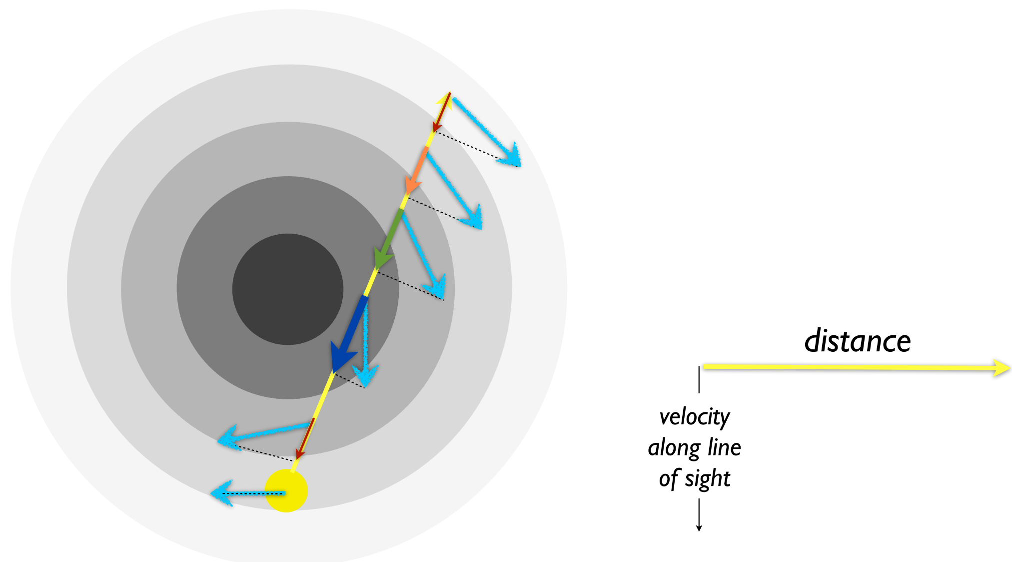
Maser VLBI parallax

today's "gold standard" for distance measurement



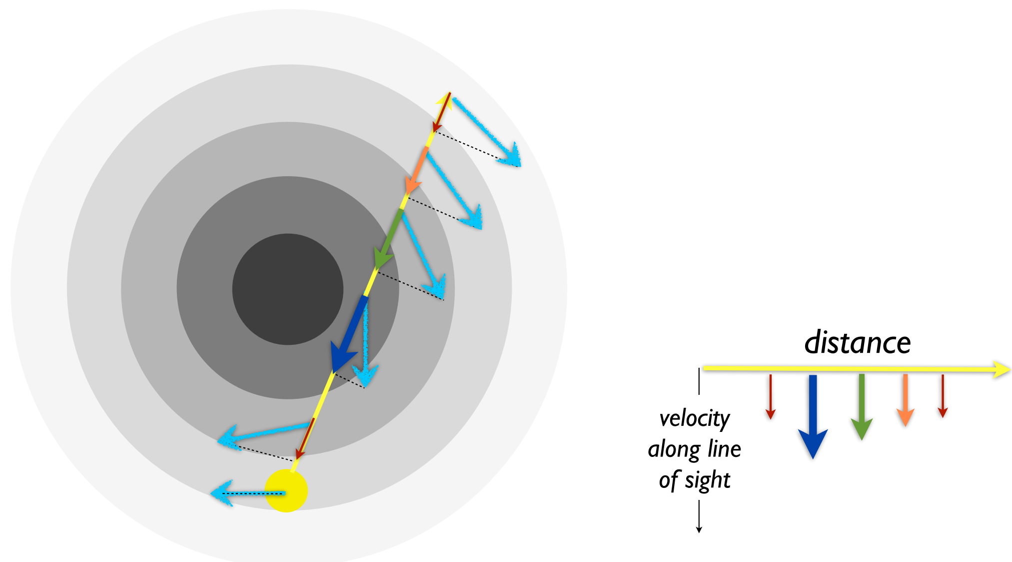
Reid et al. 2019

kinematic distance

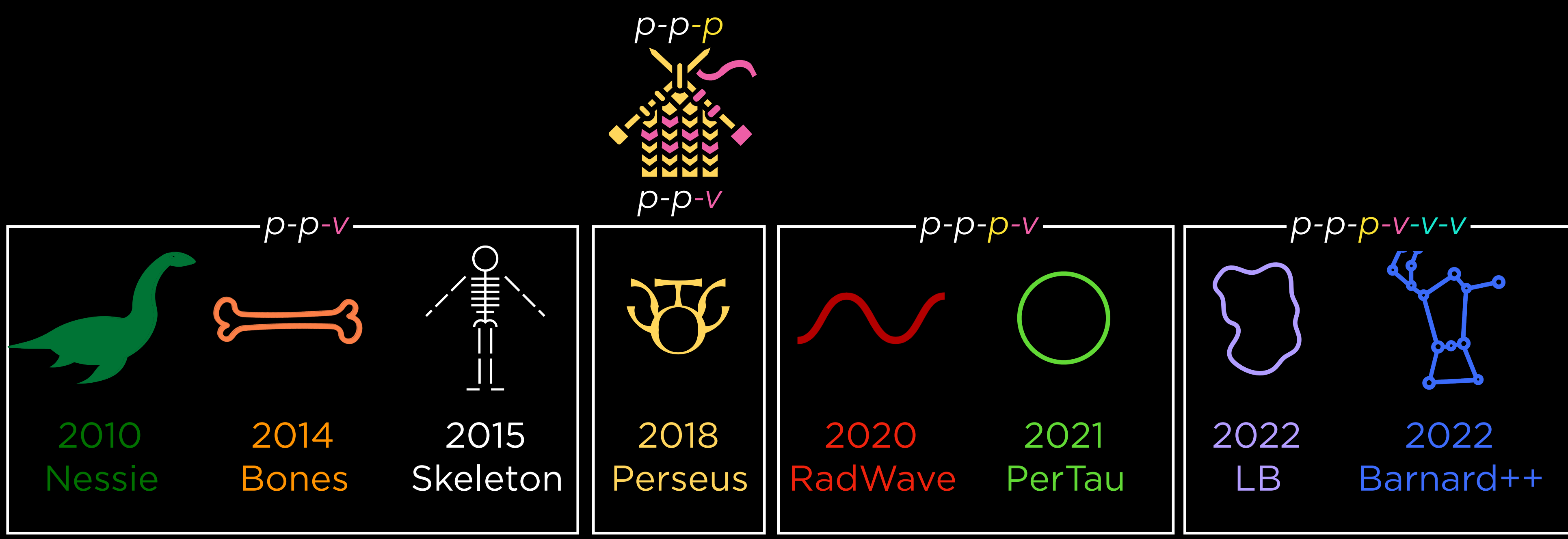


kinematic distance

Not useful for individual molecular cloud structures
(in the same way that the Hubble Flow doesn't work on small scales).



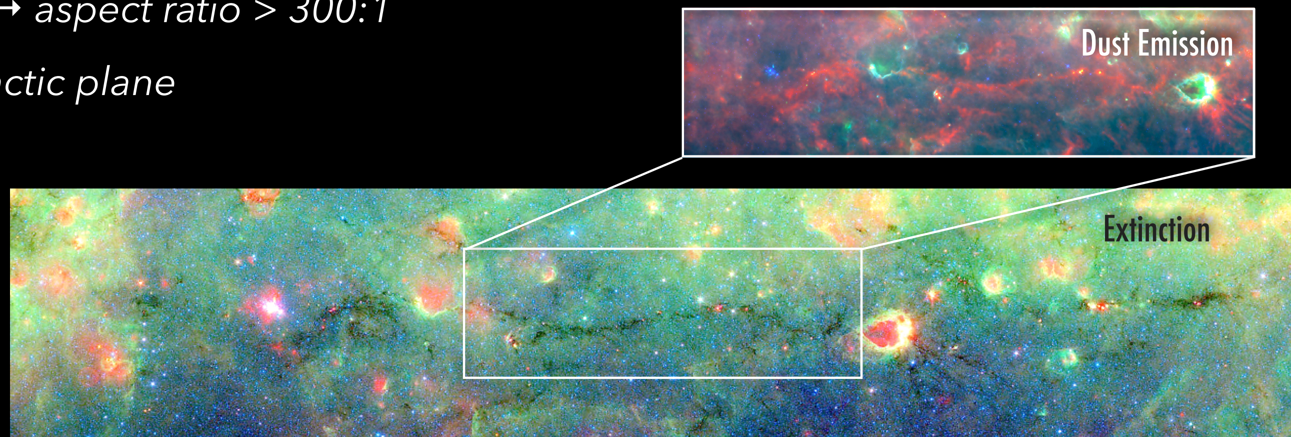
The New Milky Way, in 3D, 4D & 6D



Nessie is a "Bone" of the Milky Way

160+ pc long, < 1 pc wide → aspect ratio > 300:1

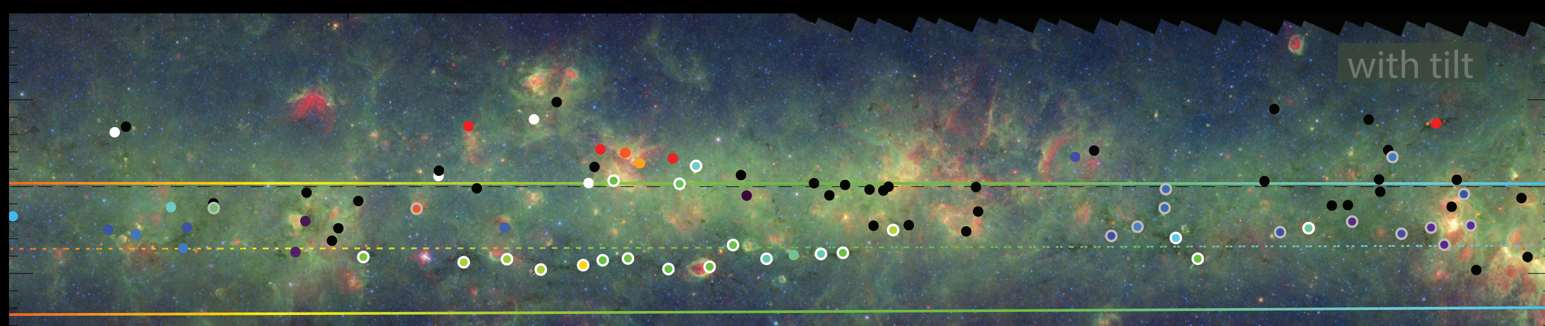
appears to lie in "exact" galactic plane



"p-p-v"

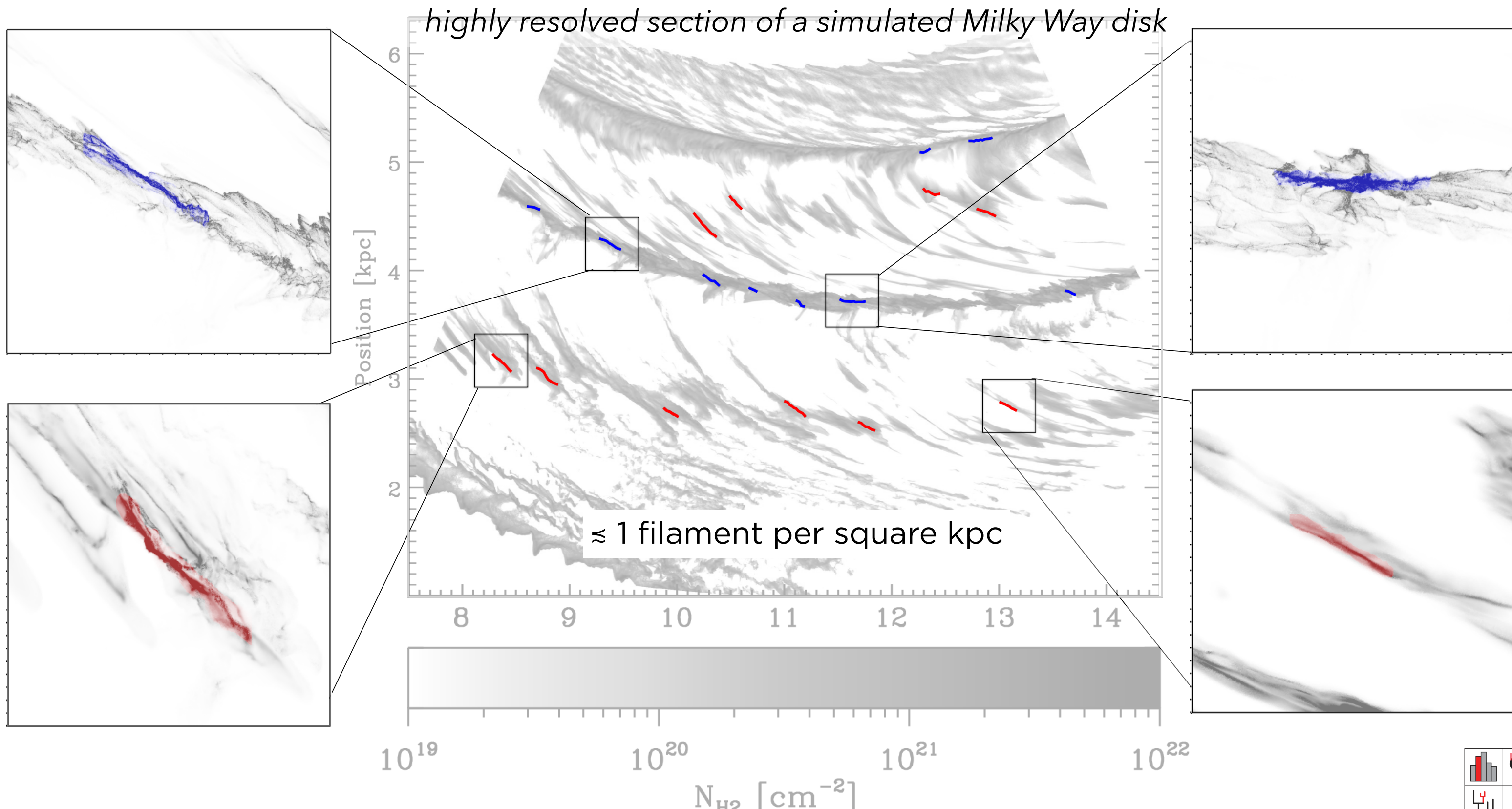
colored **dots** show spectral line measurements' agreement with velocities predicted by Galactic rotation;

velocity-colored **lines** show ±20 pc from true Galactic plane

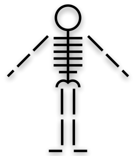


Discovery of Nessie IRDC: Jackson et al. 2010; extension & characterization as "Bone" in Milky Way's plane: Goodman et al. 2014

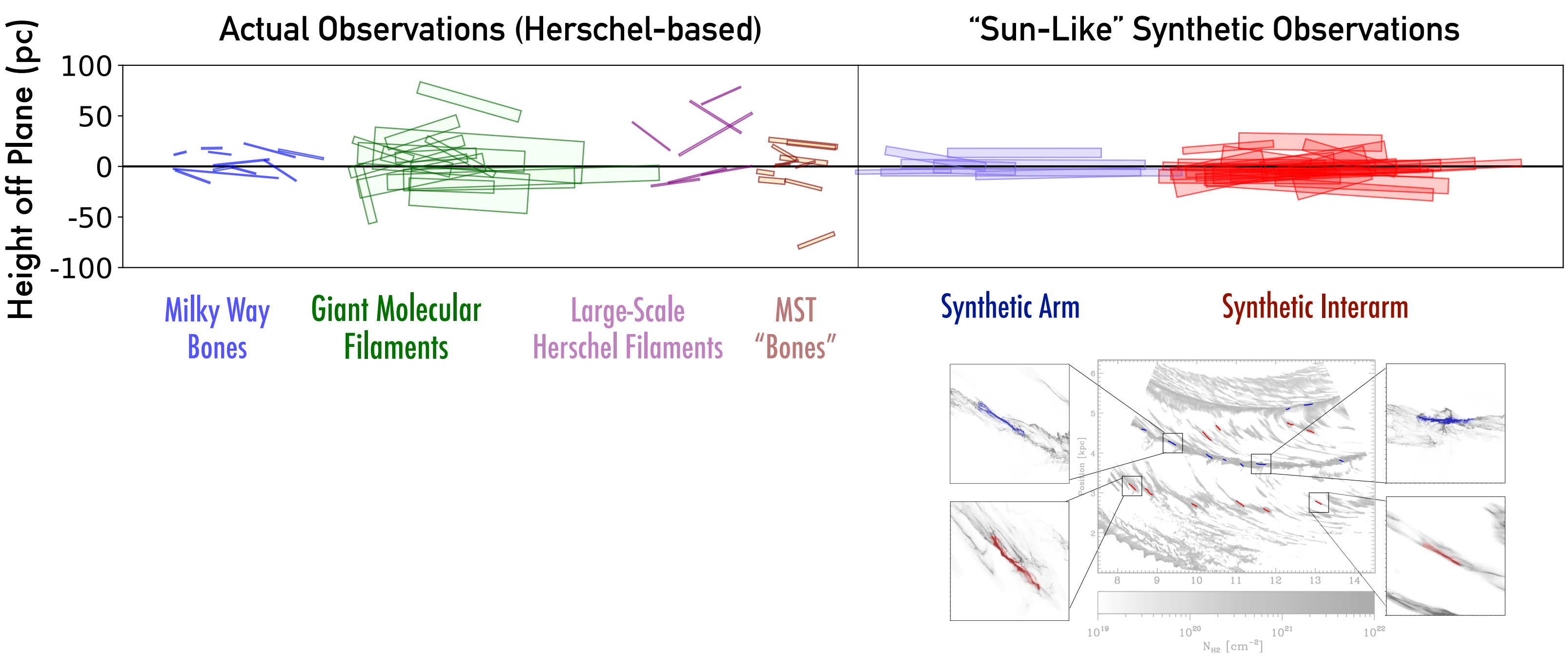
A simulated "skeleton"



Simulation: Smith et al. 2014; filament characterization Zucker, Smith & Goodman 2019.

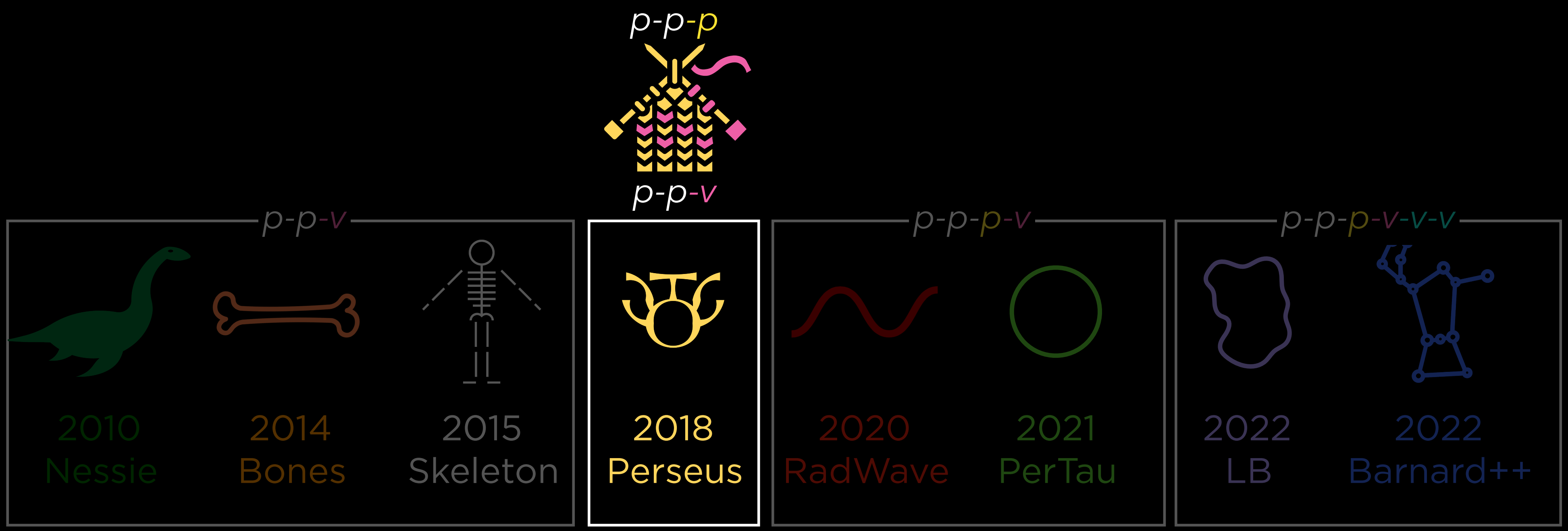


Observations show a far greater variety of filaments…
(not all super-skinny, highly-elongated, “Bones”)



Simulation: Smith et al. 2014; filament characterization Zucker, Smith & Goodman 2019.

The New Milky Way, in 3D, 4D & 6D



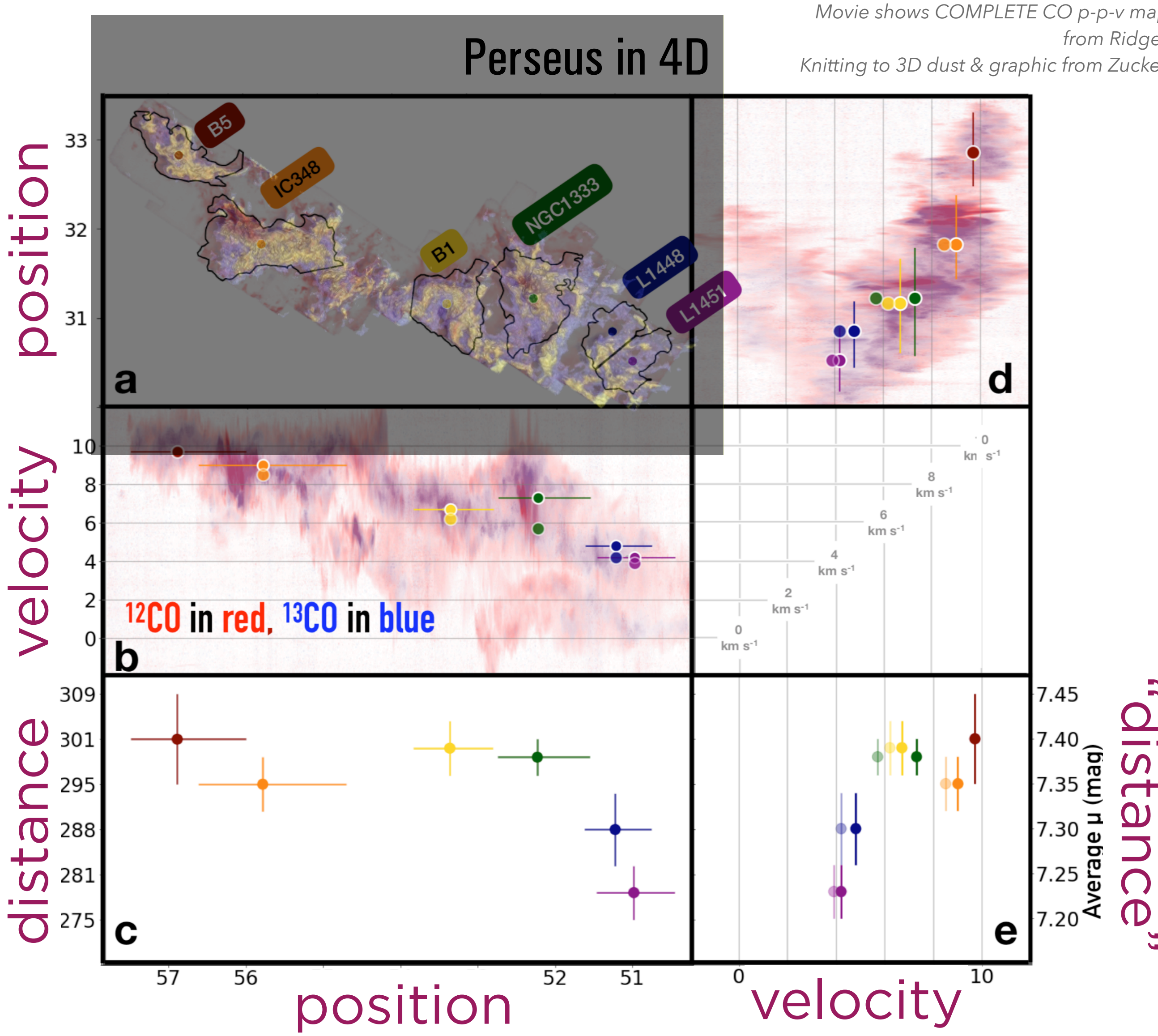
p-p-p

p-p-v

2018
Perseus

The Dataverse® Project

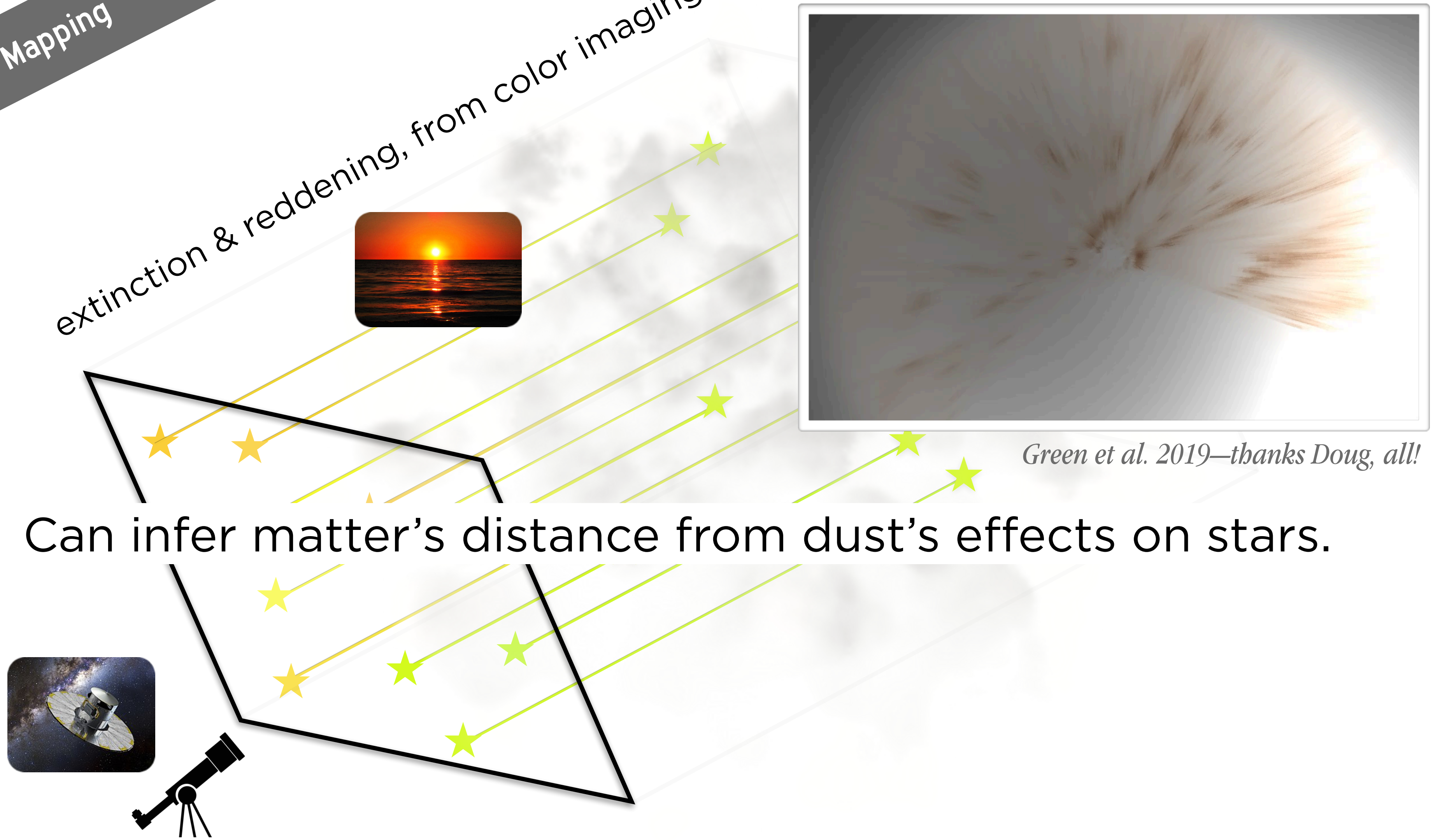
Movie shows COMPLETE CO p-p-v map of Perseus from Ridge et al. 2006;
Knitting to 3D dust & graphic from Zucker et al. 2018



How does 3D Dust Mapping work, and why is Gaia so helpful?

3D Dust Mapping

extinction & reddening, from color imaging



Green et al. 2019—thanks Doug, all!

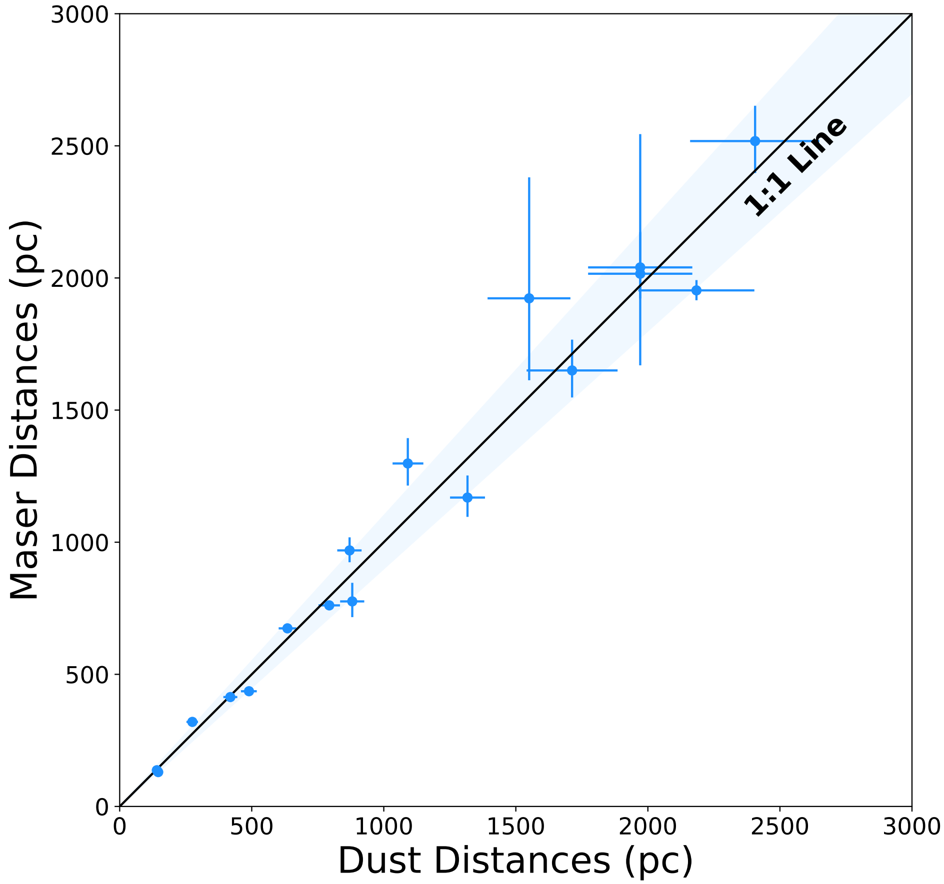
Can infer matter's distance from dust's effects on stars.

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

Can you trust 3D dust?

*thanks Doug, Greg, Eddie, Josh, Catherine...

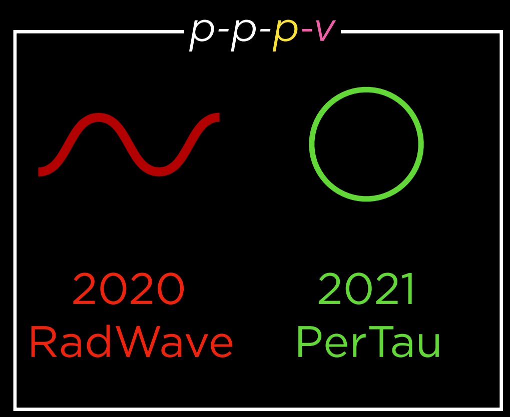
requires **special** regions on the Sky (HII regions with masers)

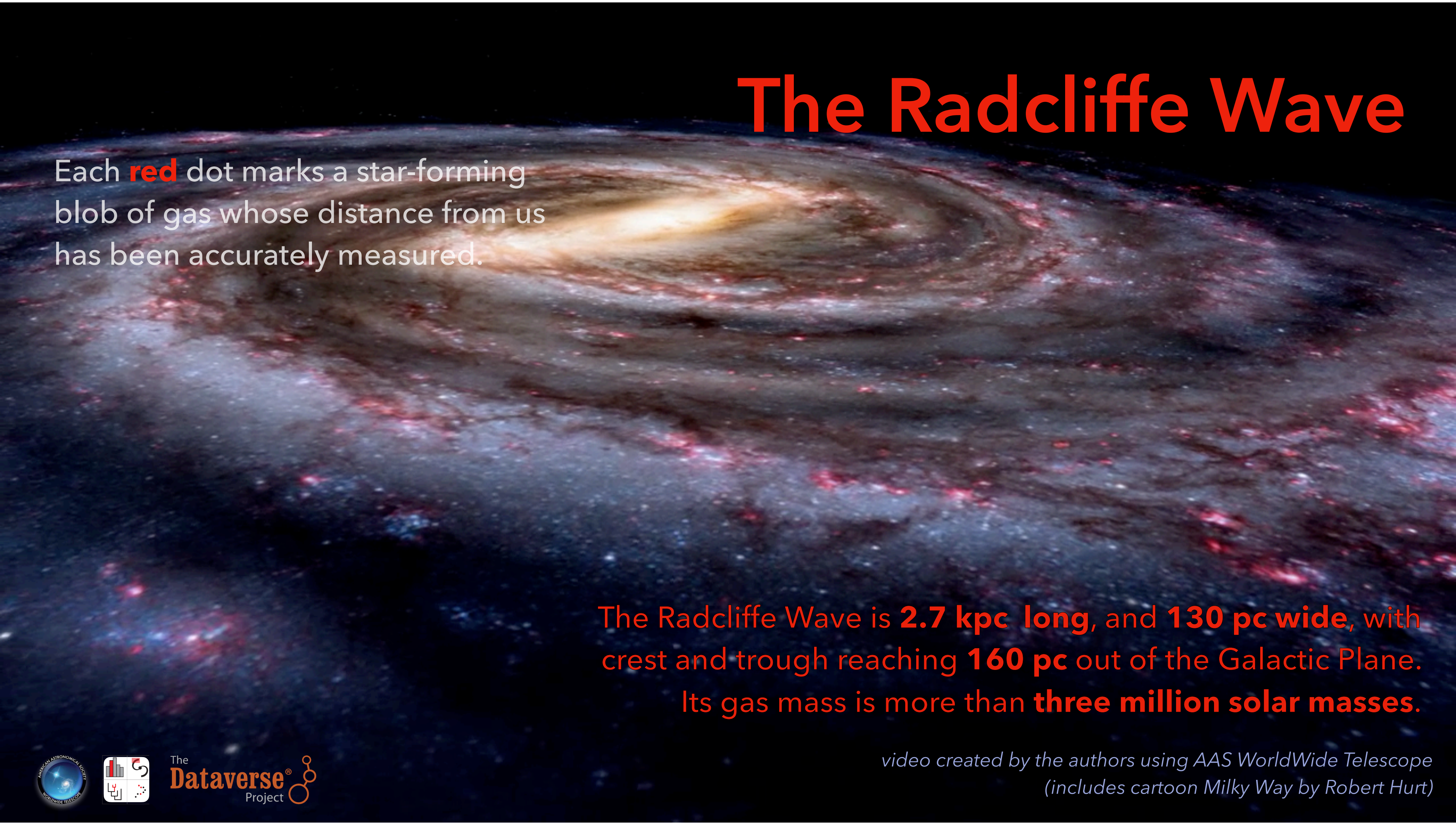


can be used **anywhere** there's dust & measurable stellar properties

Zucker et al. 2019

What can be learned from good 3D dust maps + spectral-line gas maps?




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 2.7 kpc long, and 130 pc wide, with crest and trough reaching 160 pc out of the Galactic Plane. Its gas mass is more than three million solar masses.
The Dataverse Project
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

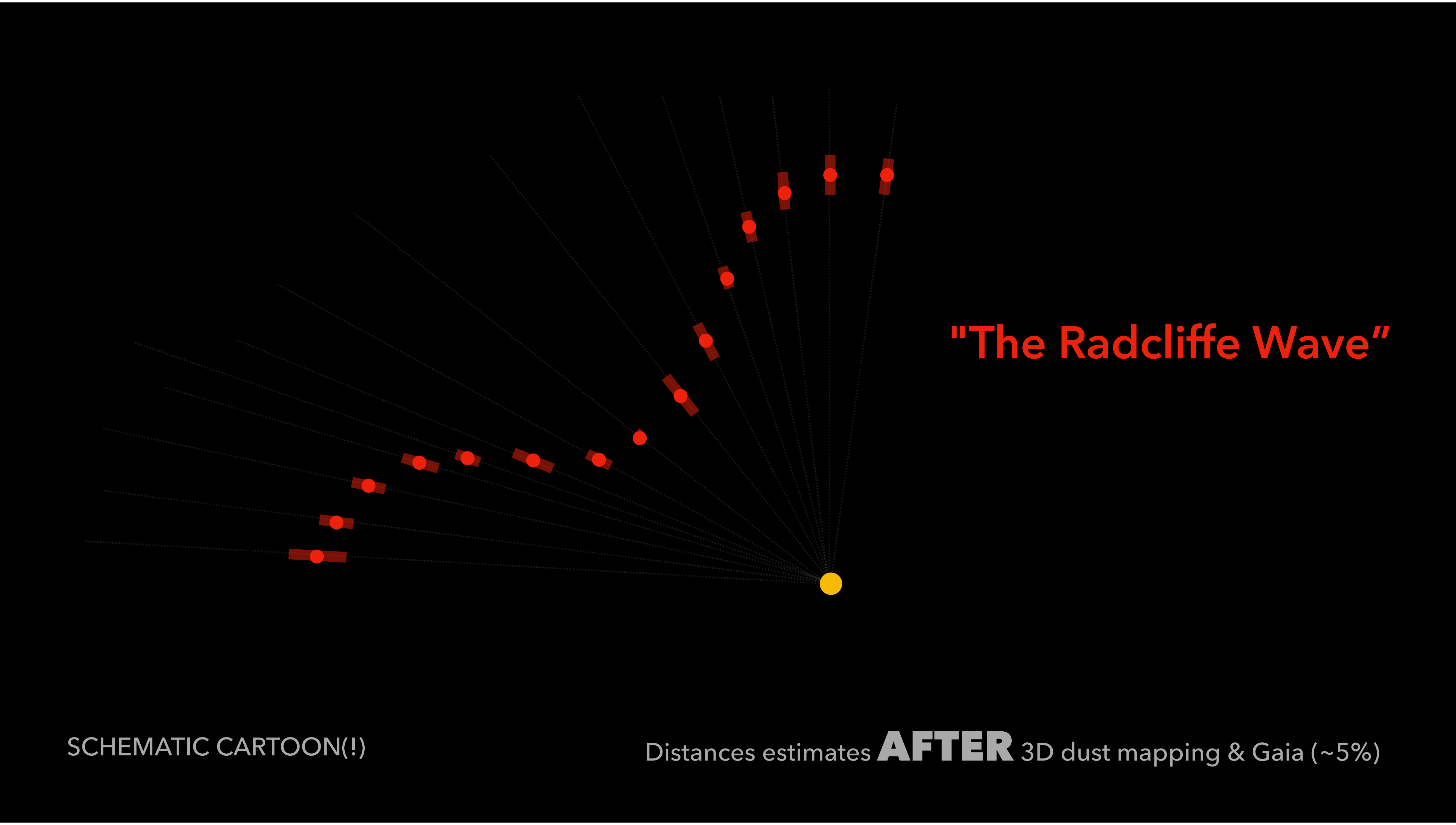
DISTANCES!!

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

Uncertain Distances

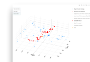
SCHEMATIC CARTOON(!)

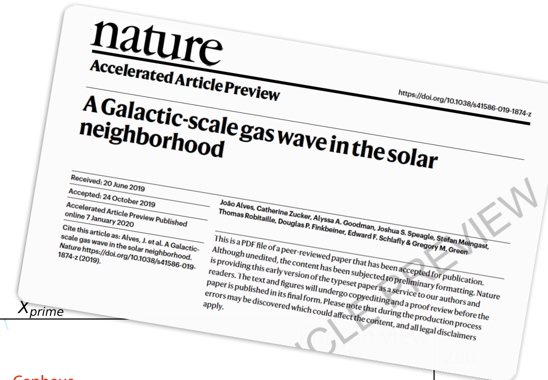
Distances estimates **BEFORE** 3D dust mapping & Gaia (~30%)


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

The Radcliffe Wave

click the figure to launch interactive…




nature

Accelerated Article Preview

https://doi.org/10.1038/s41586-019-1874-z

A Galactic-scale gas wave in the solar neighborhood

Received: 20 June 2019

Accepted: 24 October 2019

Accelerated Article Preview Published online 7 January 2020

Cite this article as: Alves, J. et al. A Galactic-scale gas wave in the solar neighborhood. *Nature* https://doi.org/10.1038/s41586-019-1874-z (2019).

João Alves, Catherine Zucker, Alyssa A. Goodman, Joshua S. Speagle, Stefan Meingast, Thomas Robitaille, Douglas P. Finkbeiner, Edward F. Schlafly & Gregory M. Green

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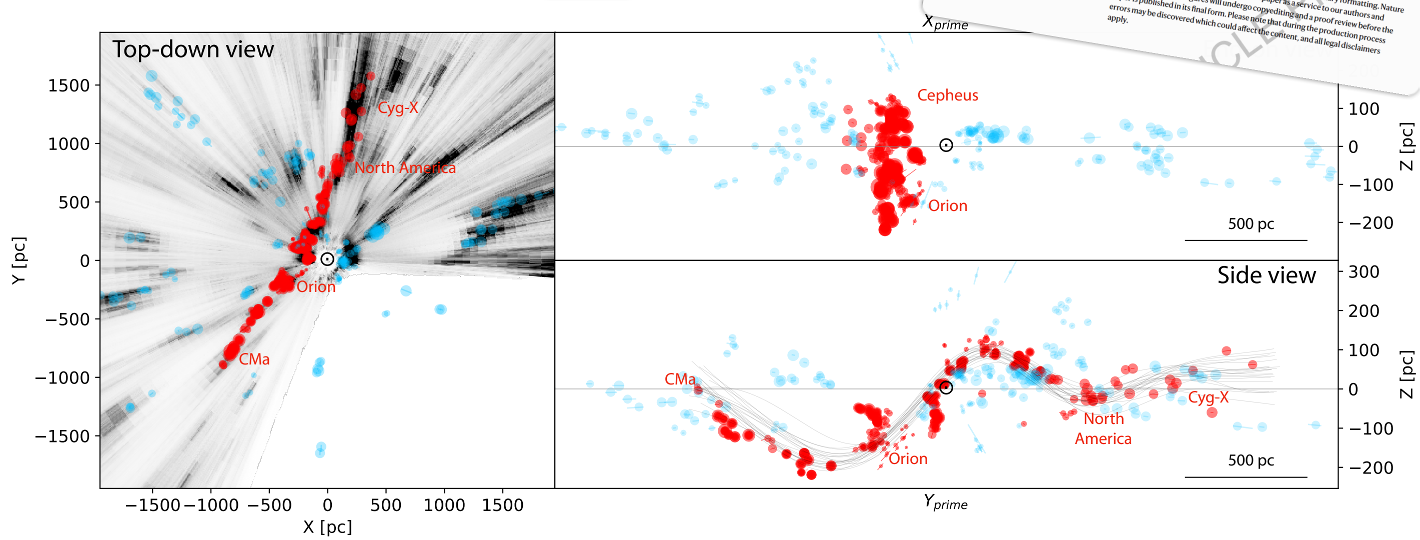


RADWAVE

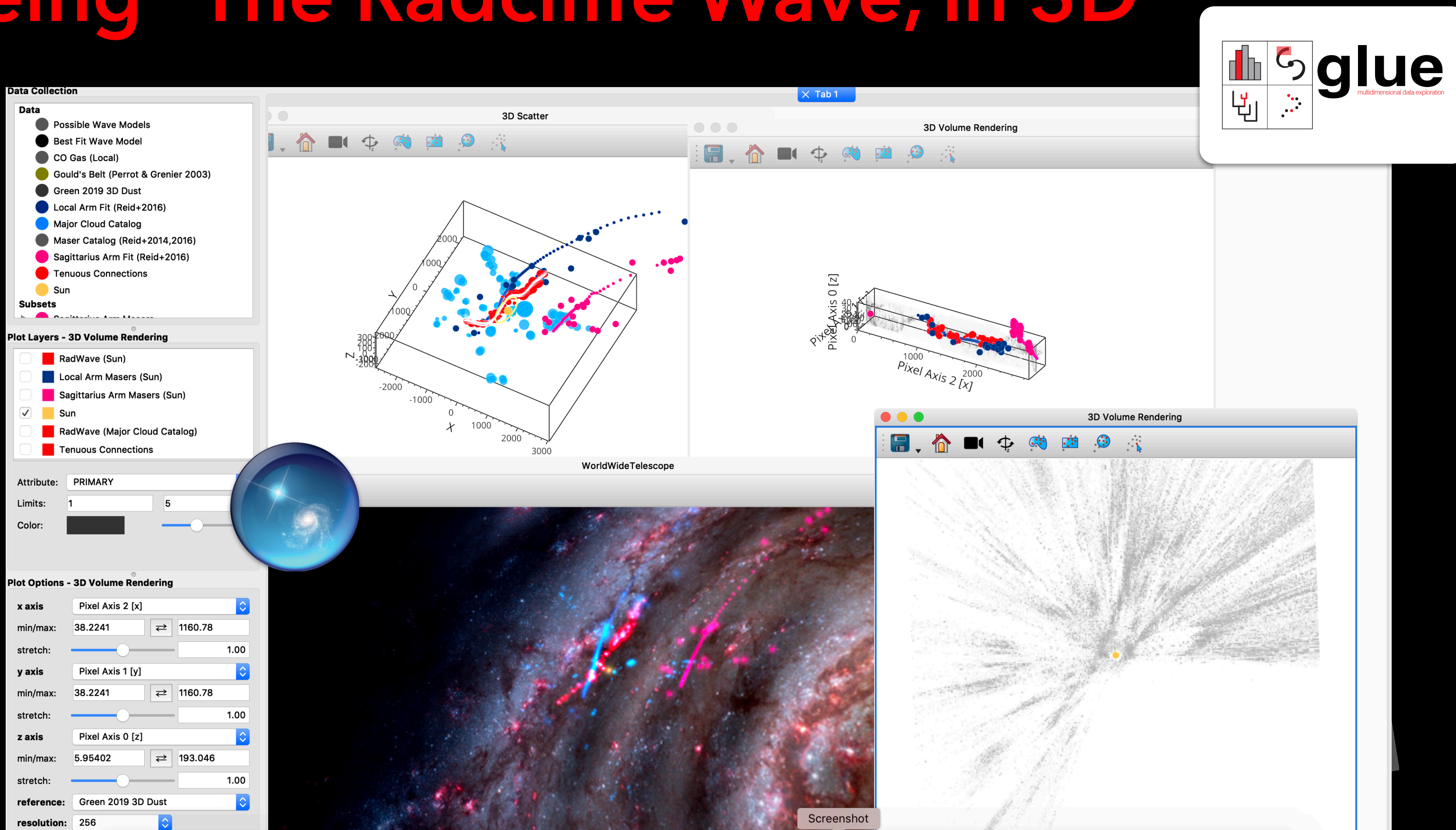
Surprising wave-like arrangement of star-forming gas *is* the “Local Arm” of the Milky Way.

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

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)

The Dataverse Project

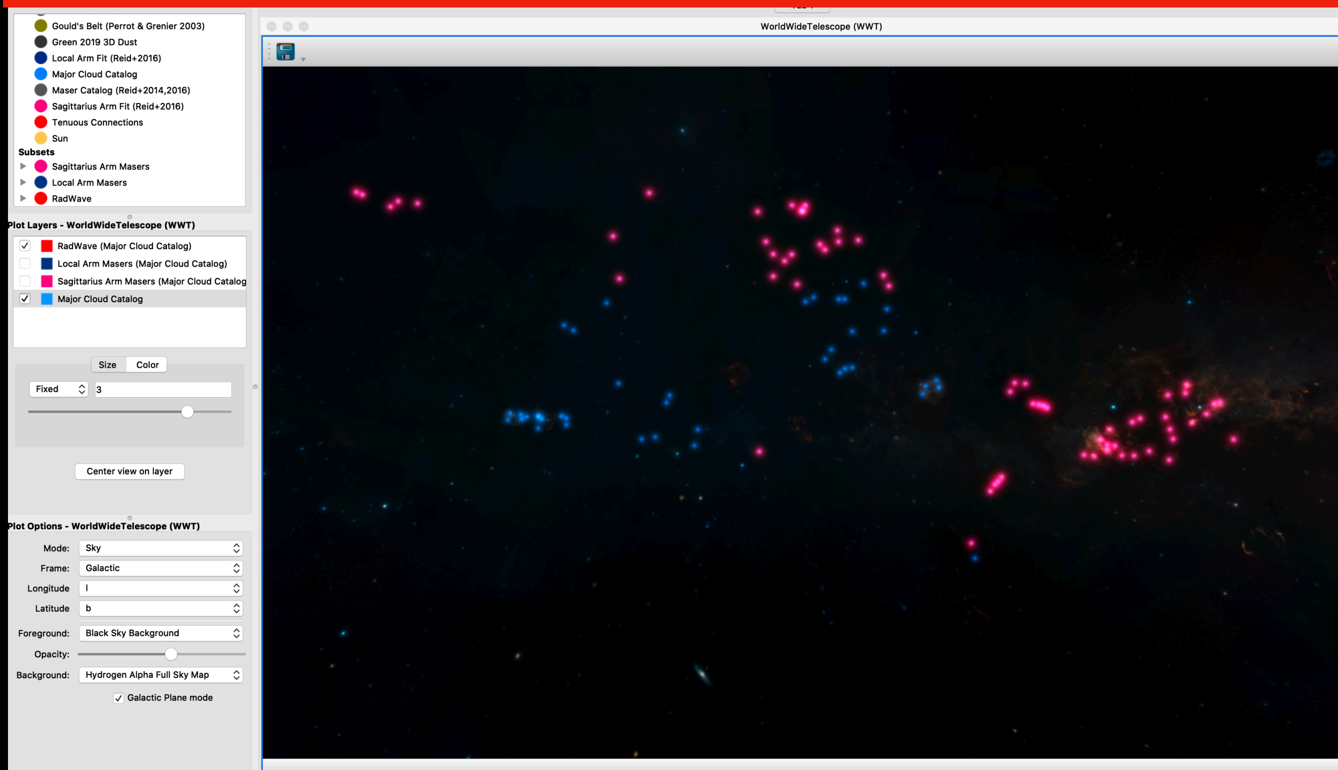
"Seeing" The Radcliffe Wave, in 3D



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

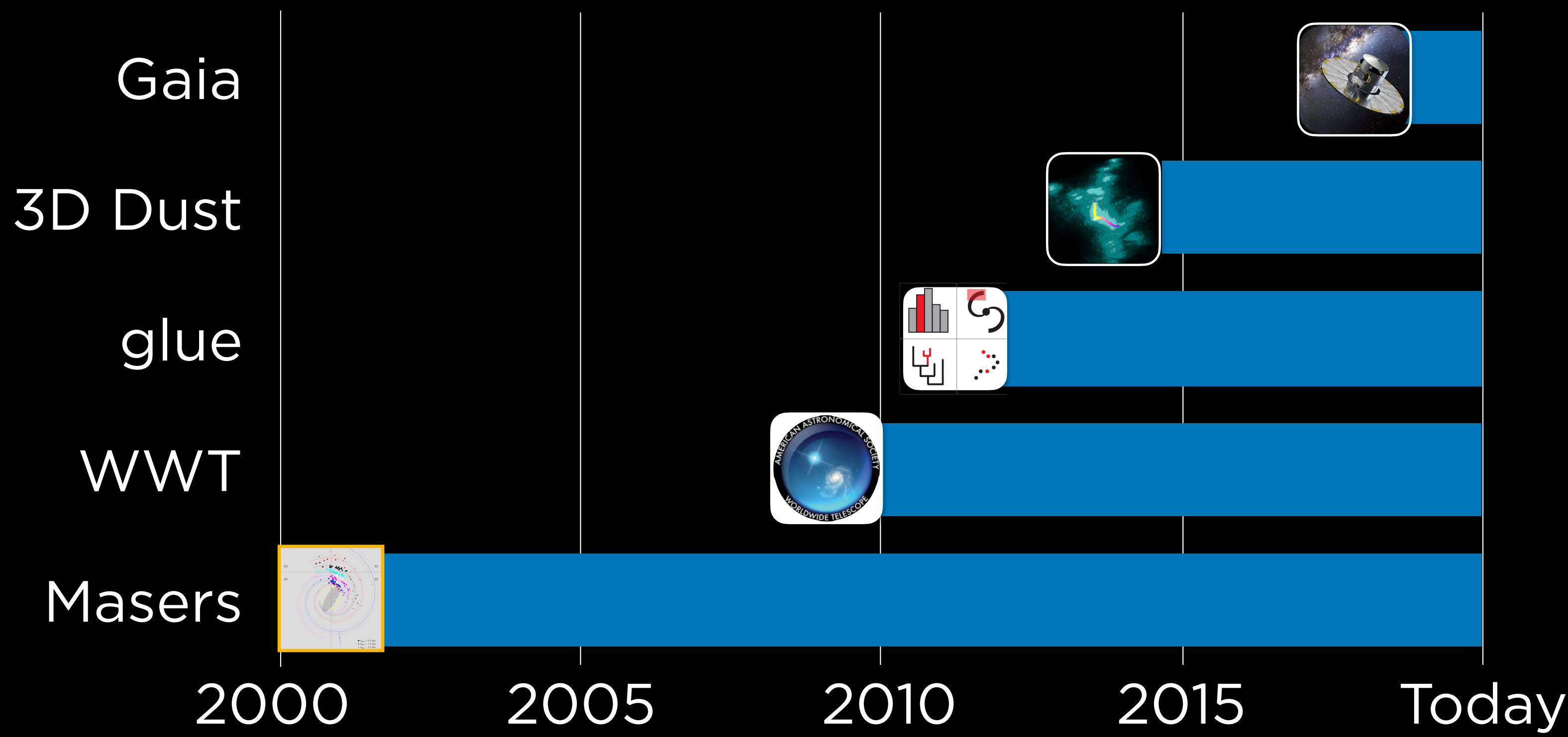
WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

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

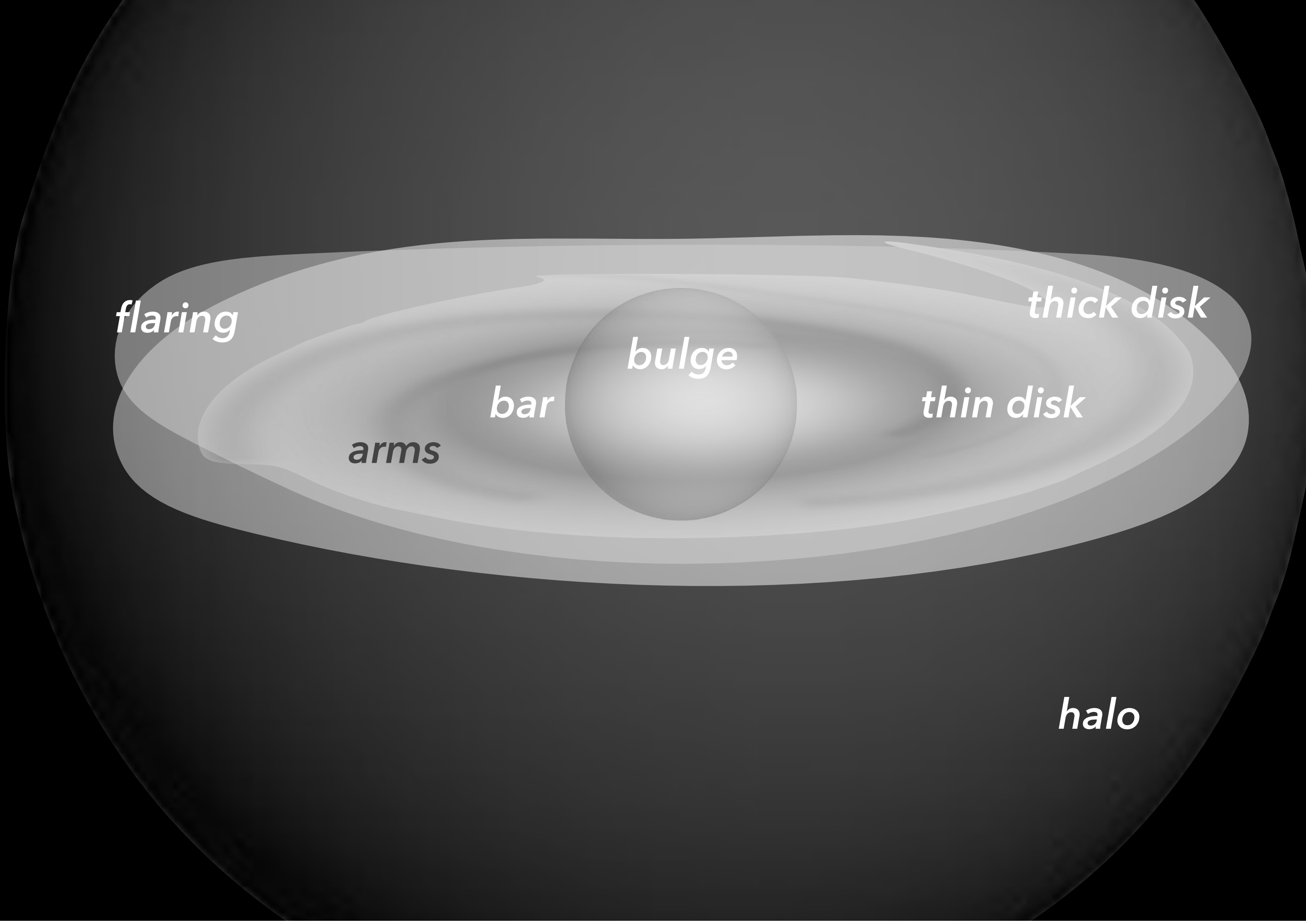


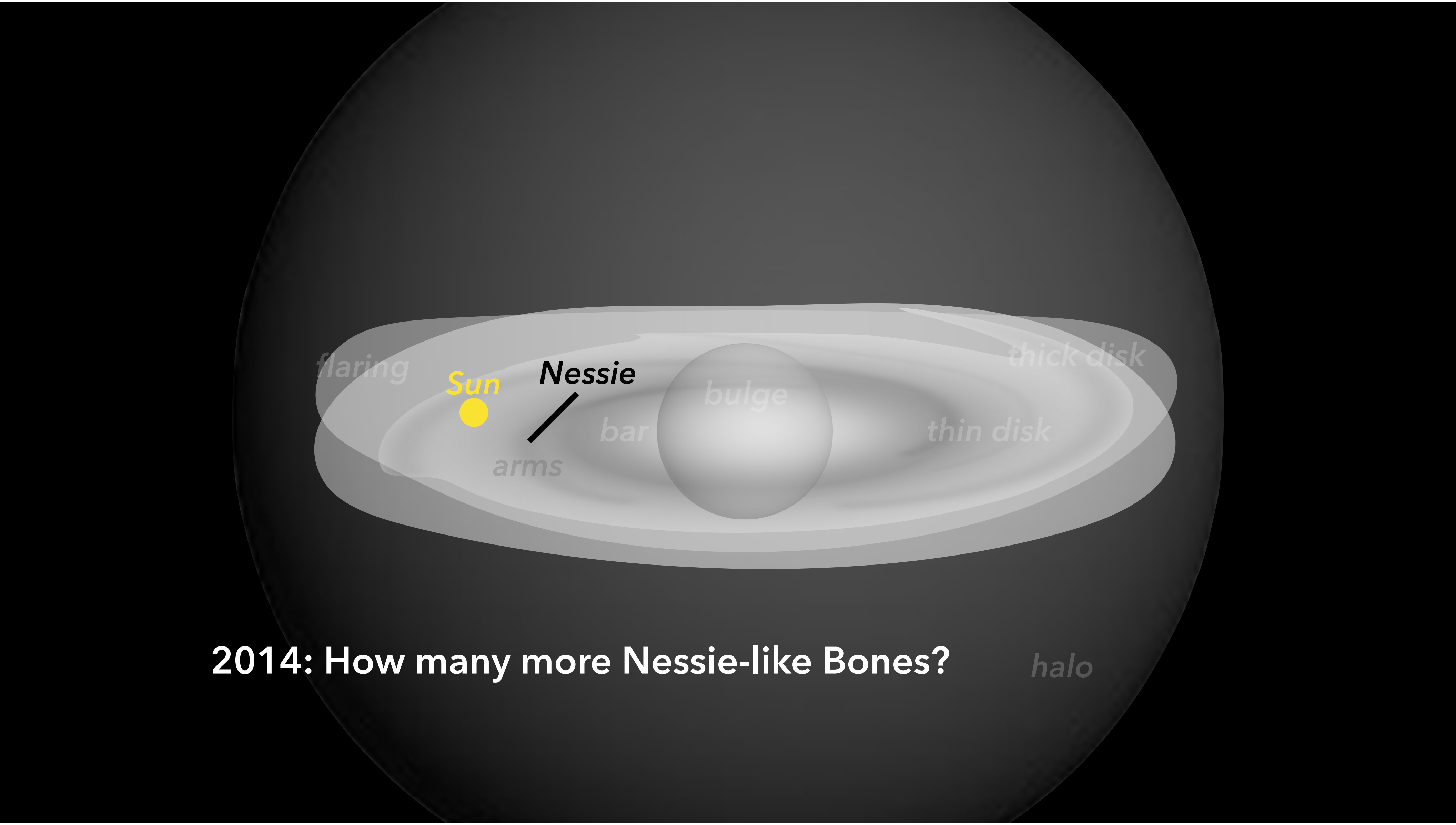
AAS WorldWide Telescope: worldwidetelescope.org glue: glueviz.org

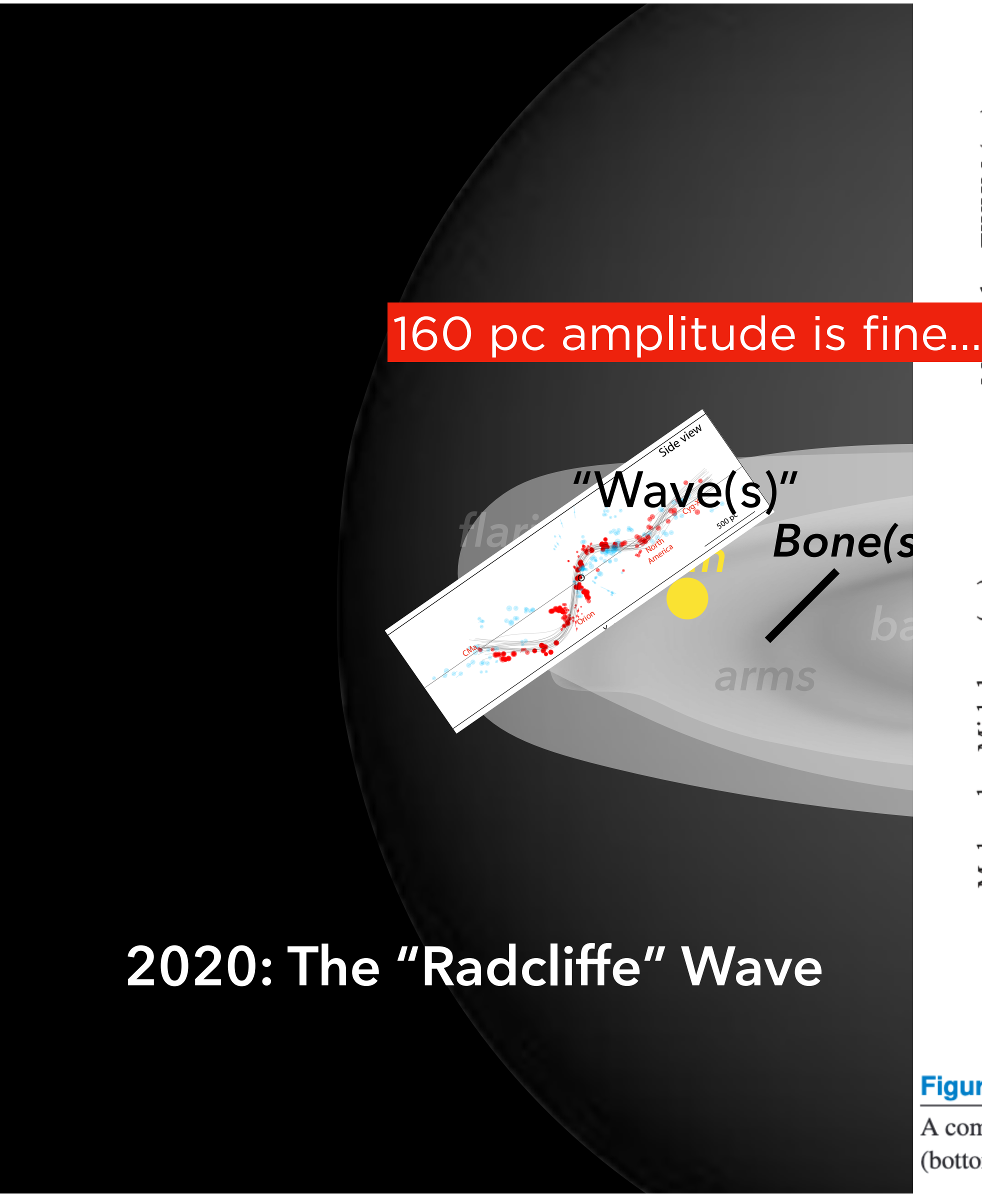
WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

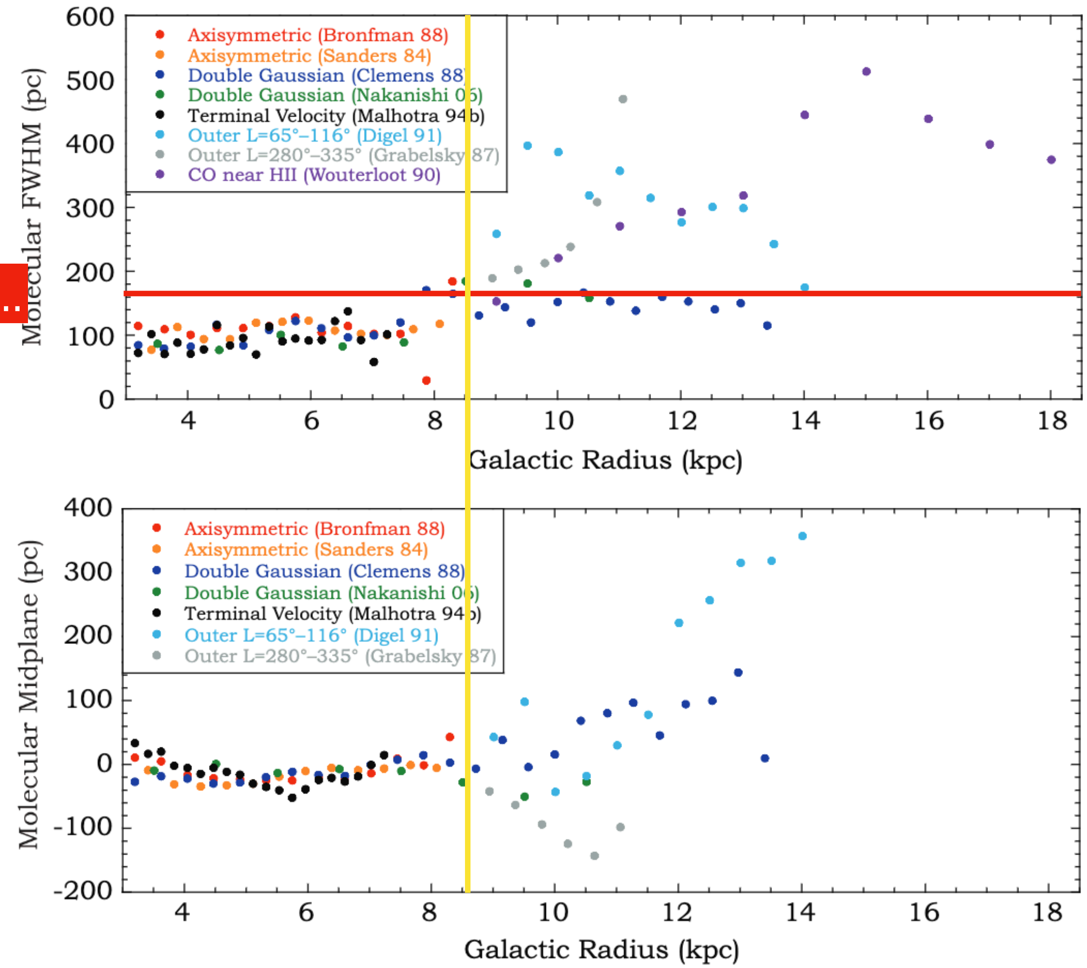


Milky Way Structure as we “know” it.




flaring
Sun
Nessie
bulge
thick disk
bar
thin disk
arms
2014: How many more Nessie-like Bones?
halo





Heyer & Dame 2015

Figure 6

A comparison of measurements of the thickness of the molecular gas layer (top) and its midplane displacement (bottom) as functions of Galactic radius. References in the legend are abbreviated to the first author and year.

Open Questions

What is the ORIGIN of the Radcliffe Wave? Collision? Feedback? Other??

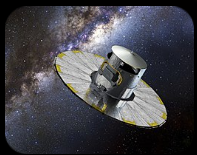
Gus Beane's & Sarah Jeffreson's synthetic Milky Ways;
Alan Tu's & Ralf Konietzka's estimates of wave motion; "The Radcliffe Wave at Radcliffe," coming in 2022, including Andi Burkert, Joao Alves, Catherine Zucker & several others

Do other parts of the Milky Way show this wavy structure? How about other galaxies? How can we SEARCH?

Eric Koch's ALMA proposal; Beane, Jeffreson simulations

What do "waves " mean for the STAR-FORMING HISTORIES of galaxies?

Good question! First maybe we should make some waves in simulations?...



What happens to the Milky Way, according to Gaia? (consider time scales..)

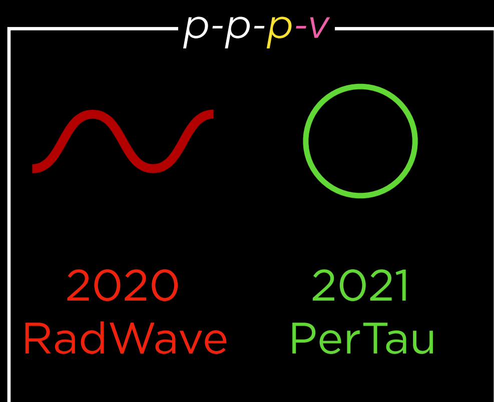
"The Global Dynamical Atlas of the Milky Way mergers: Constraints from Gaia EDR3 based orbits of globular clusters, stellar streams and satellite galaxies", Khyati Malhan et al., Astrophysical Journal 926, 2 (2022)

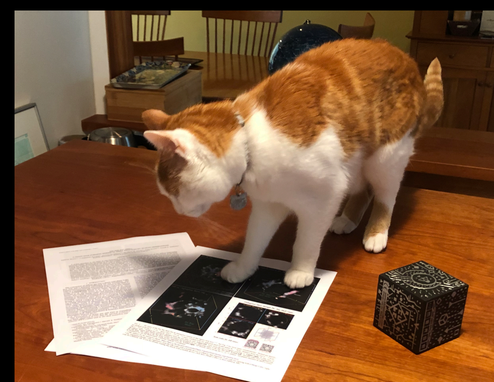
DOI: 10.3847/1538-4357/ac4d2a
arXiv: https://arxiv.org/abs/2202.07660
MPIA press release: https://www.mpia.de/5830900/news_publ...

cf. work of Naidu, Conroy, et al. at the CfA
youtube.com/watch?v=eemvYBcQUIM&list=PPSV

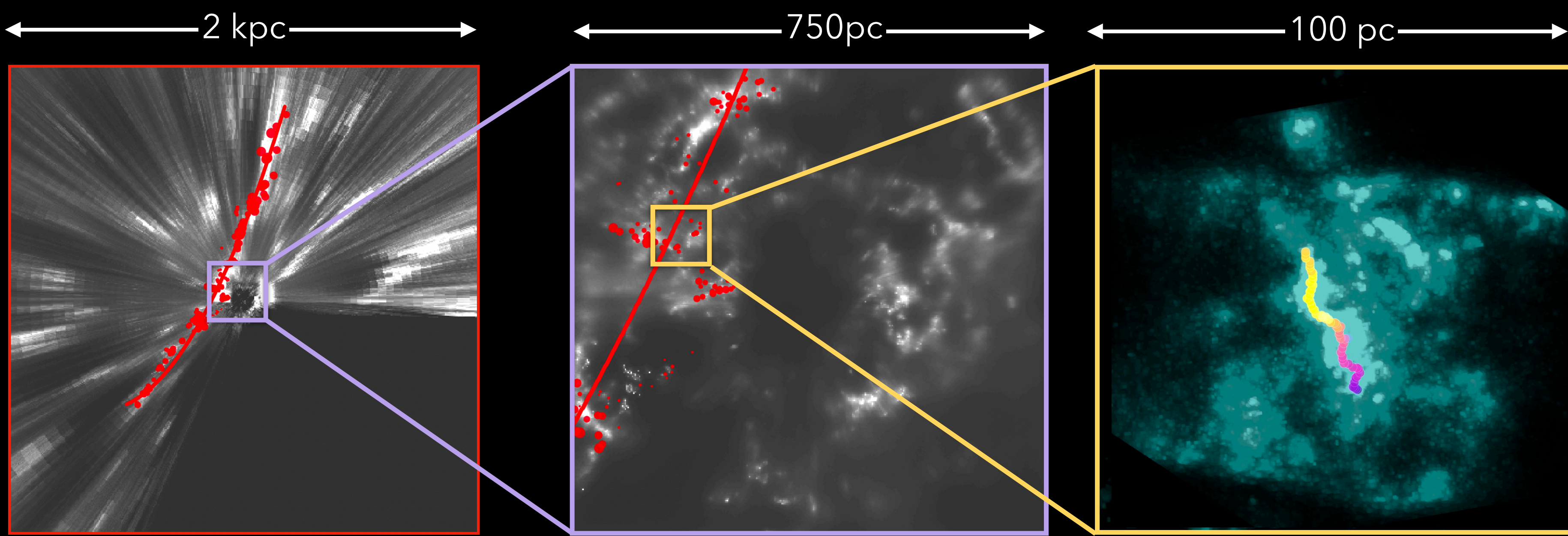
Credits: S. Payne-Wardenaar / K. Malhan, MPIA

Impatient to know about the cat photo?
First, we need to improve distance resolution.





2019 to 2021: from distances to shapes

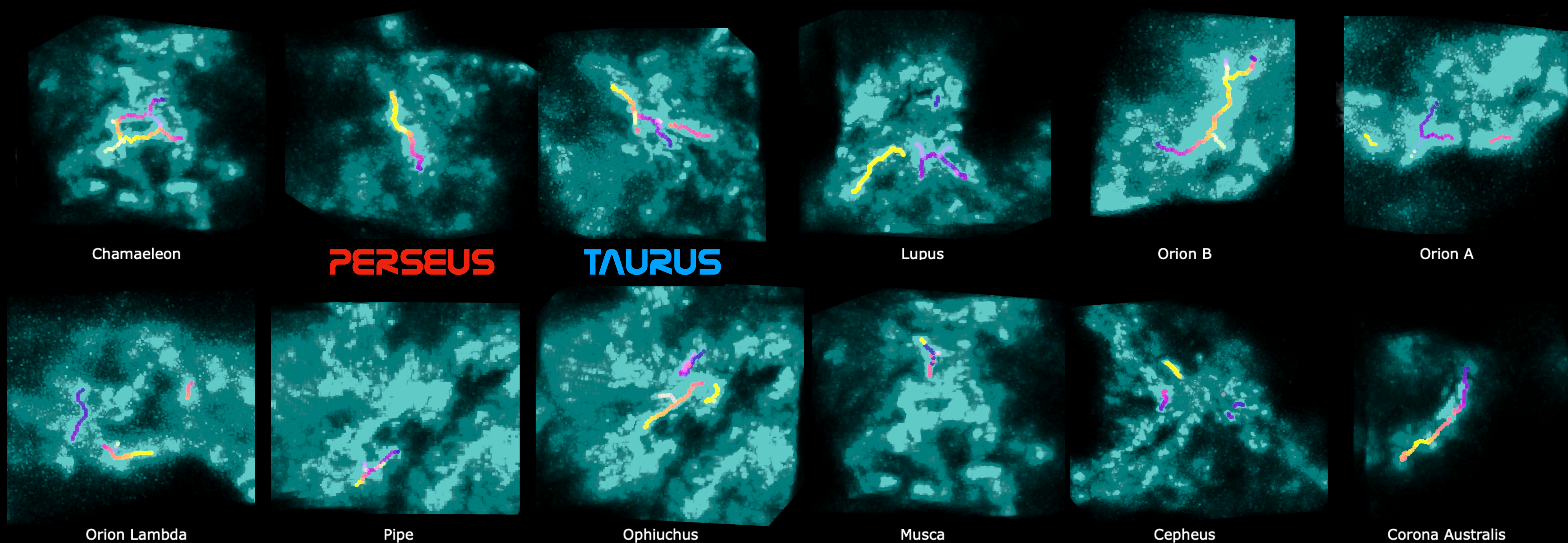


Zucker et al. 2020; Zucker & Speagle et al. 2019; Alves et al. 2020; Green et al. ***2019***

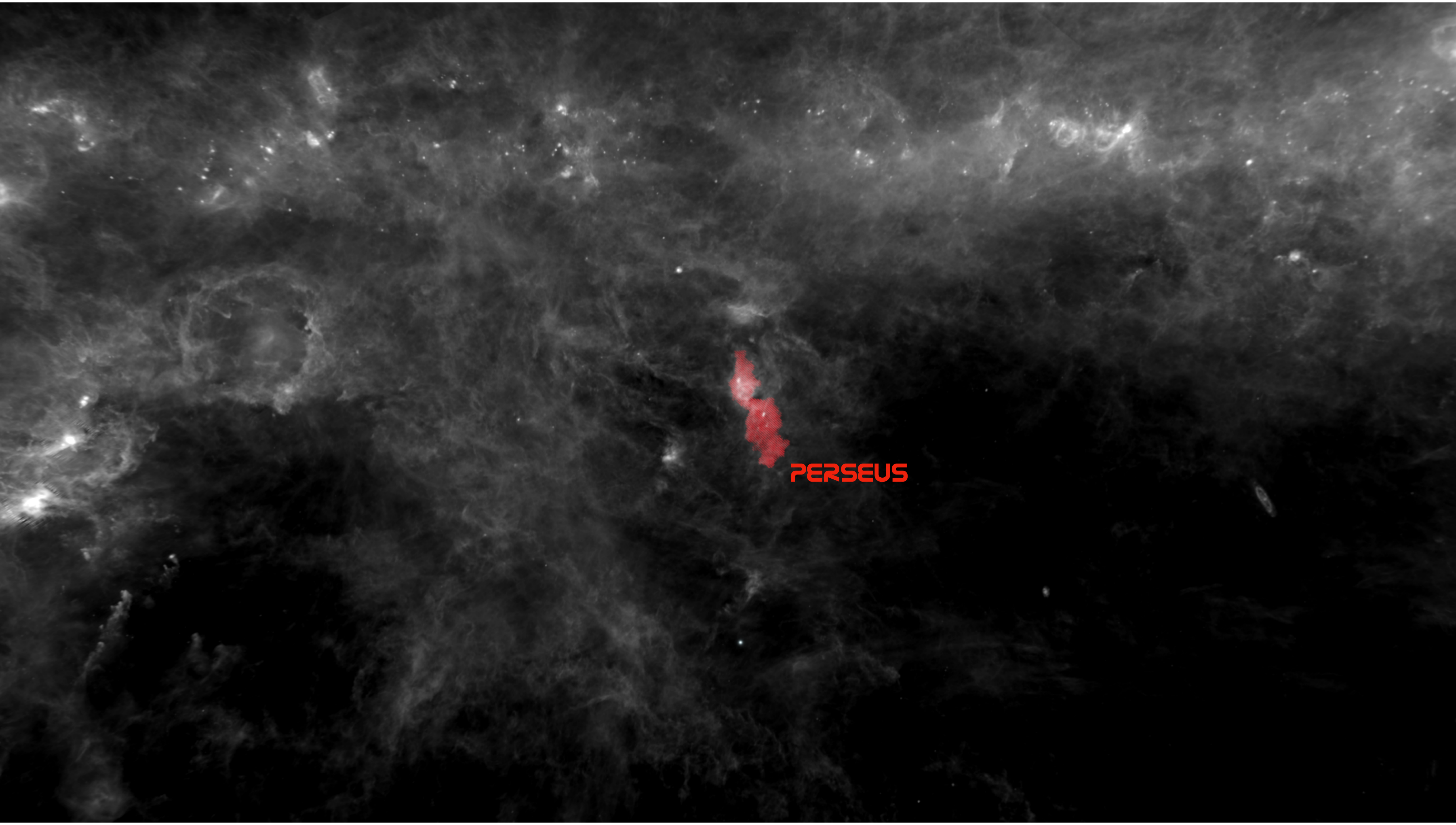
Leike, Glatzle, & Enßlin ***2020***

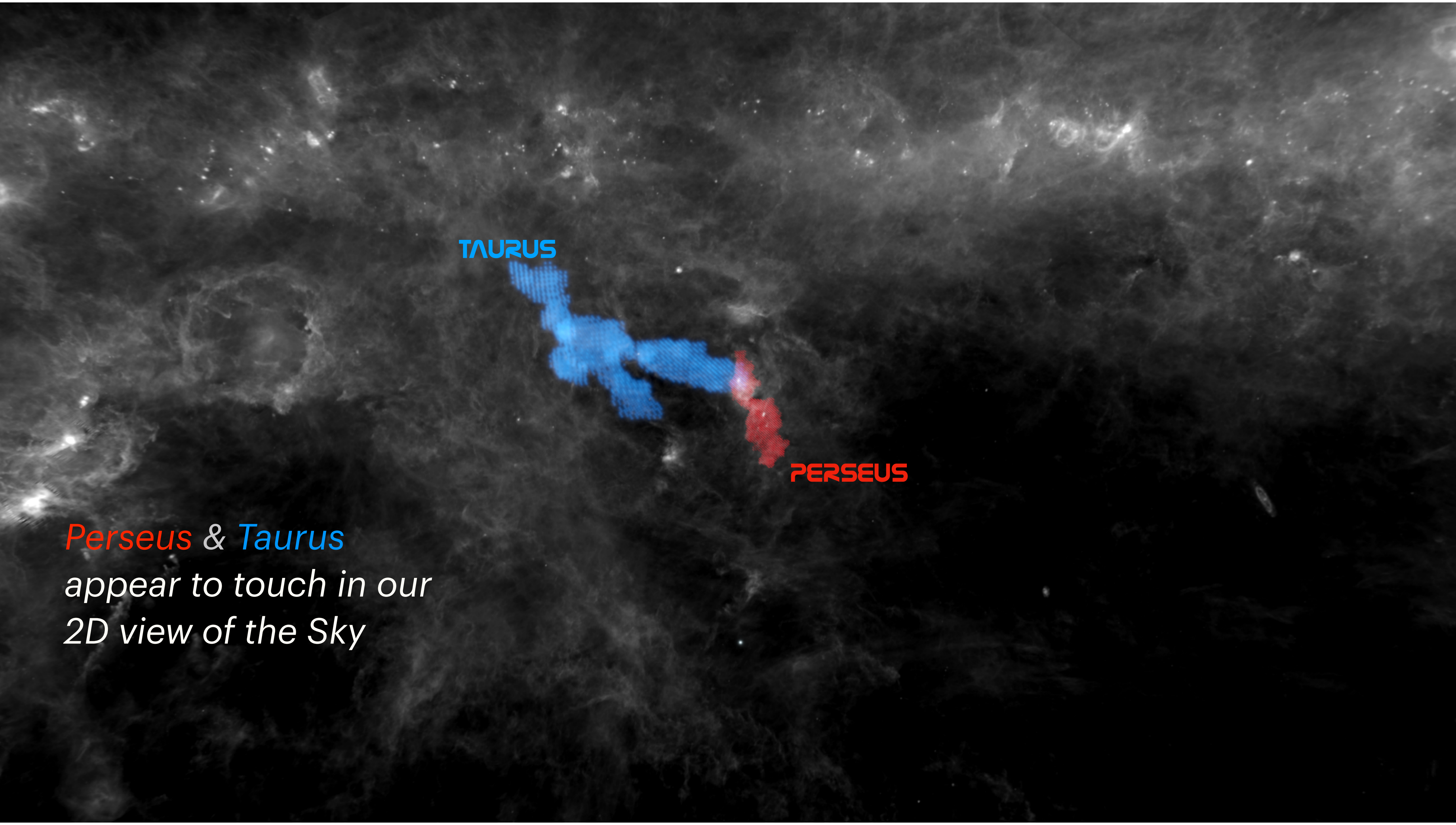
Zucker et al. ***2021****;*
Leike, Glatzle, & Enßlin 2020

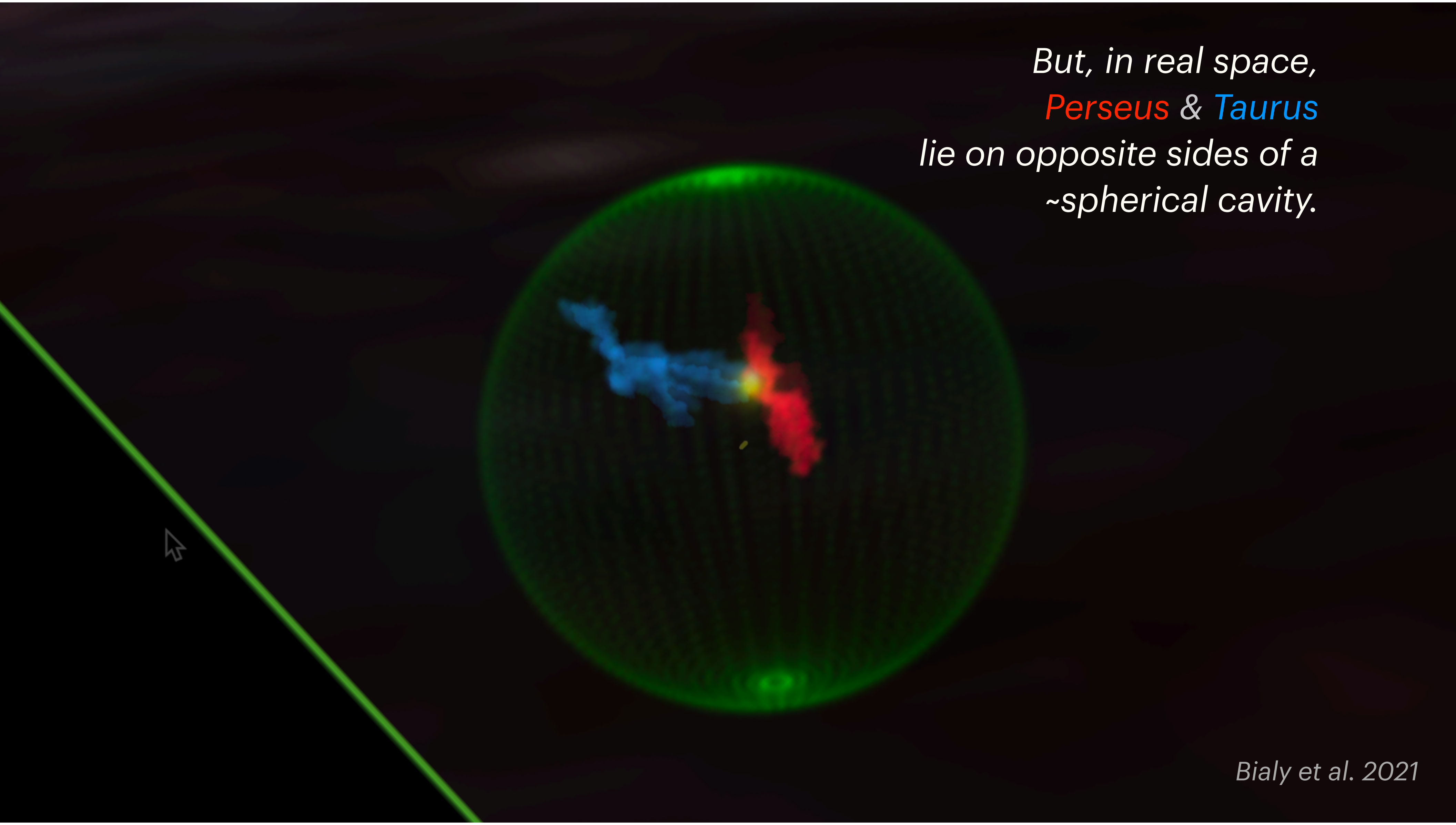
These are actual "p-p-p," pc-scale resolution, 3D maps of molecular clouds.

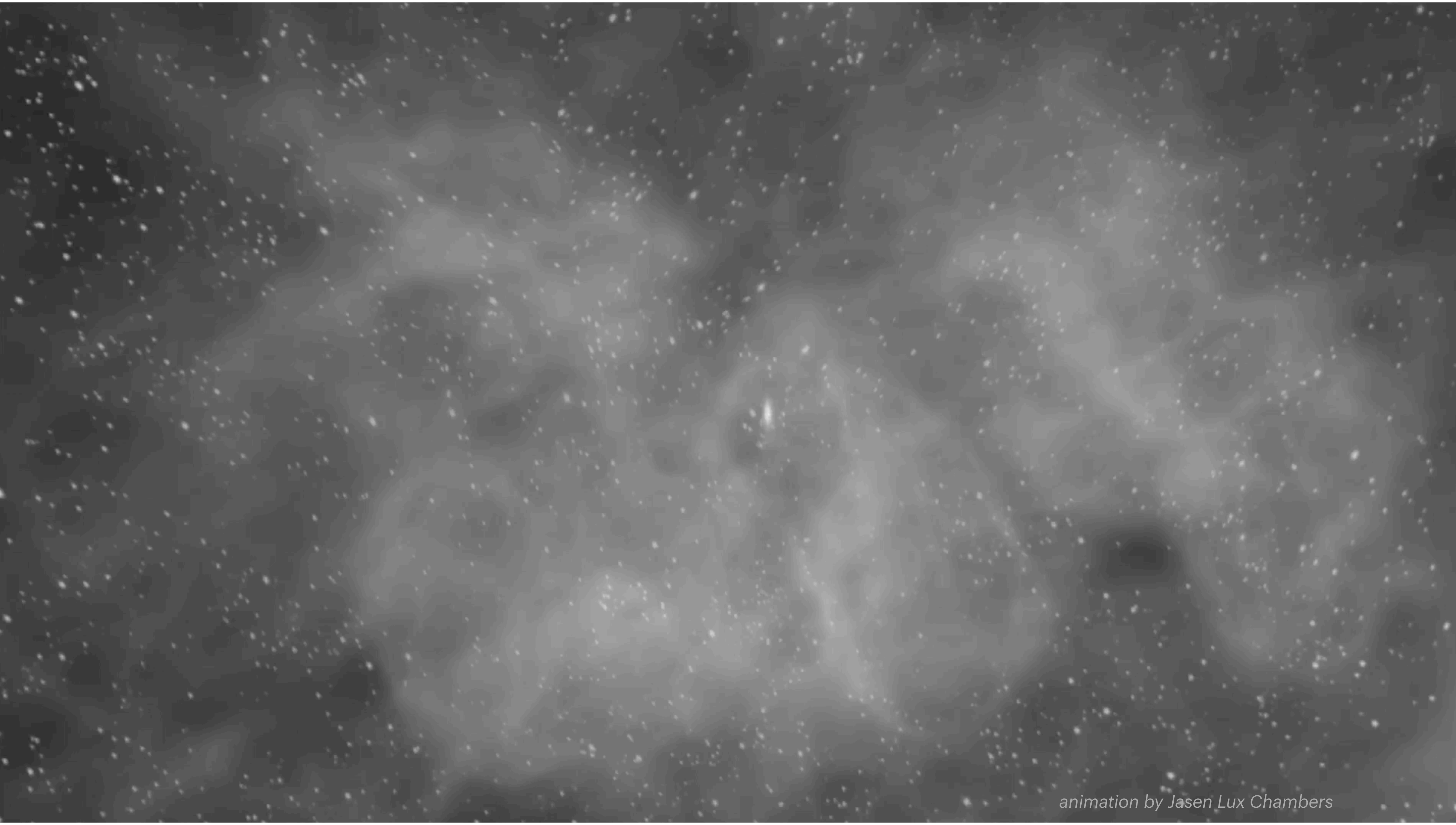


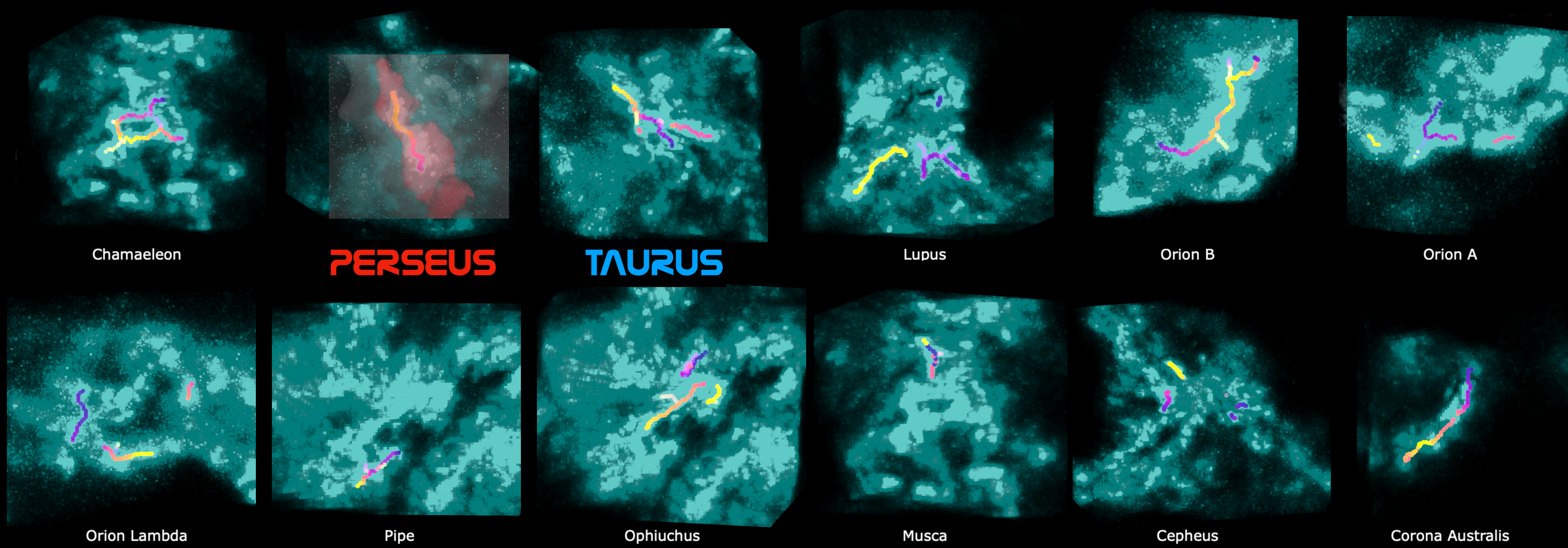
Zucker et al. ***2021***


PERSEUS


TAURUS
PERSEUS
Perseus & Taurus
appear to touch in our
2D view of the Sky

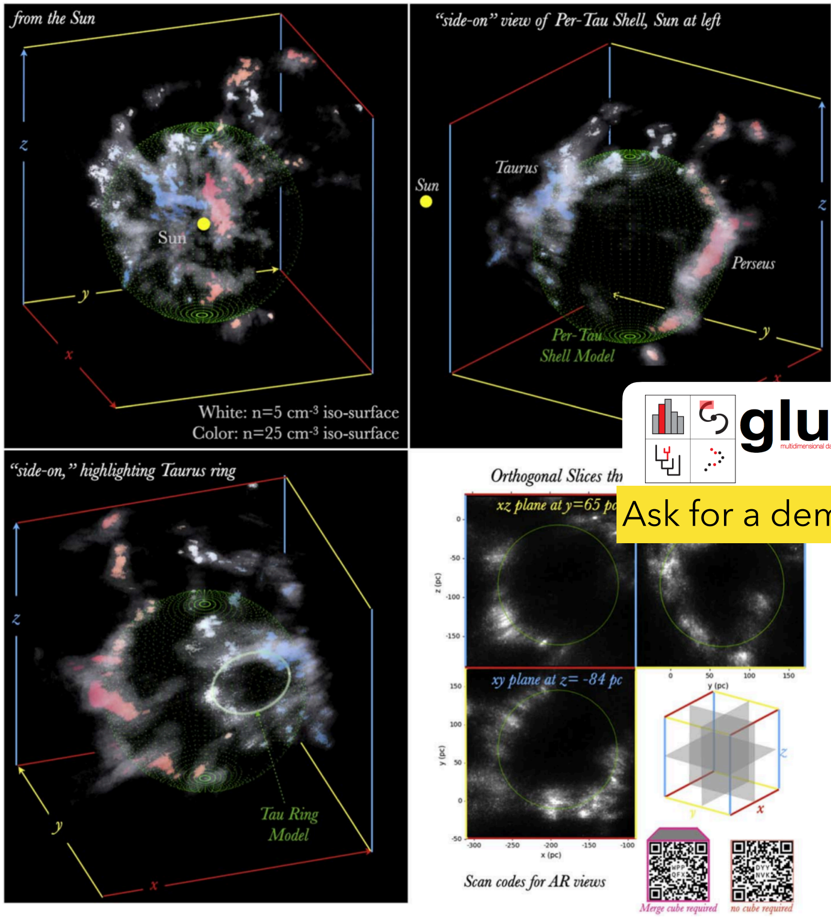

But, in real space,
Perseus & Taurus
lie on opposite sides of a
~spherical cavity.
Bialy et al. 2021


animation by Jasen Lux Chambers



Zucker et al. ***2021***

The Dataverse® Project



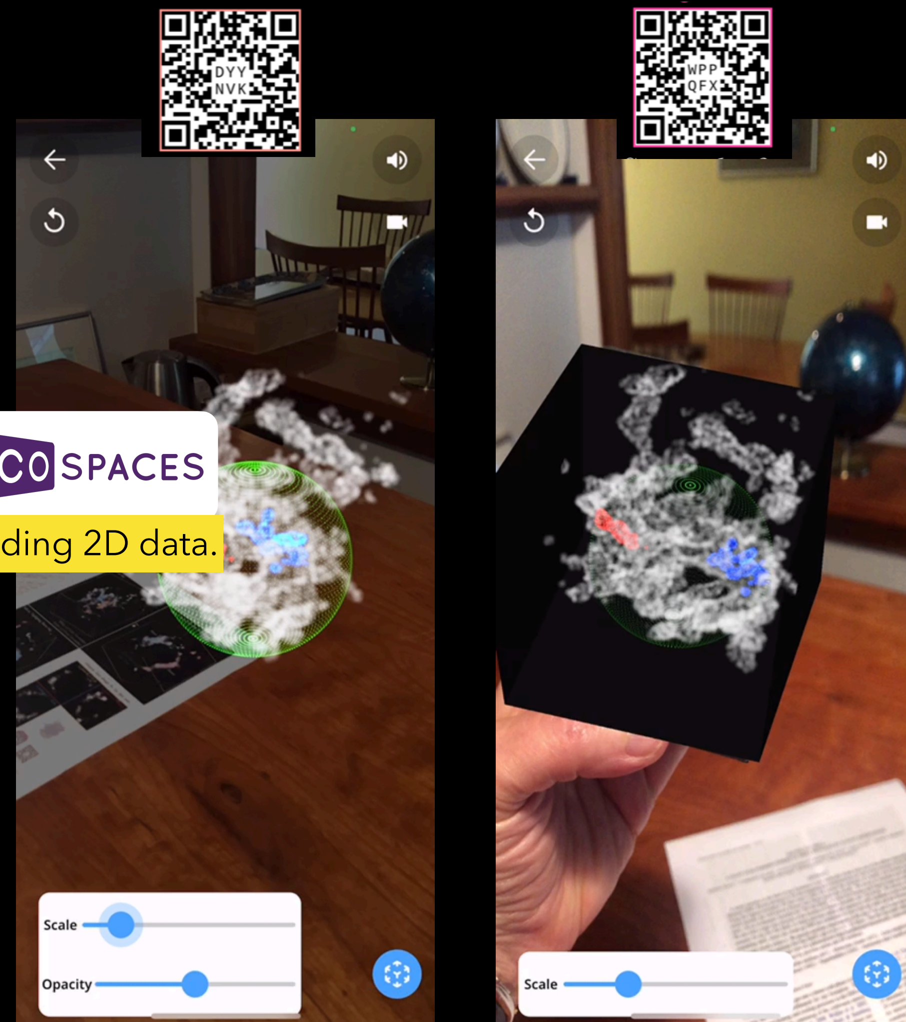
glue → CoSpaces

Ask for a demo later, including 2D data.

Figure 2. 3D views of the Per-Tau shell (for an interactive version[8] of this figure click here [9]; see Figure 5 for more static visualizations). Plotted are density iso-surfaces at levels $n = 5$ cm^{-3} (gray) and $n = 25$ cm^{-3} (color), overlaid with our spherical-shell model, radius $R_s = 78$ pc, distance from the Sun $d = 218$ pc. The $n = 25$ cm^{-3} surfaces are colored by distance from the Sun (blue-to-red). Top-left panel: view from the Sun (compare with Figure 1). Top-right panel: a side view of the region. Perseus and Taurus and their diffuse envelopes are arranged on two opposing sides of the Per-Tau shell. Bottom-left panel: another side view emphasizing the Tau Ring. The ellipse is the Tau Ring model (Appendix B). Bottom-right panel: 2D density slices along the xy, xz, yz planes. All planes intersect at shell's center. In all panels xyz are the Heliocentric Cartesian Galactic Coordinates.

2. *Tau Ring:* in a sky projection the Tau Ring is seen almost edge-on. The near side of the Tau Ring connects with the main body of Taurus at $d \approx 150$ pc, whereas the farthest part extends to $d \approx 220$ pc.

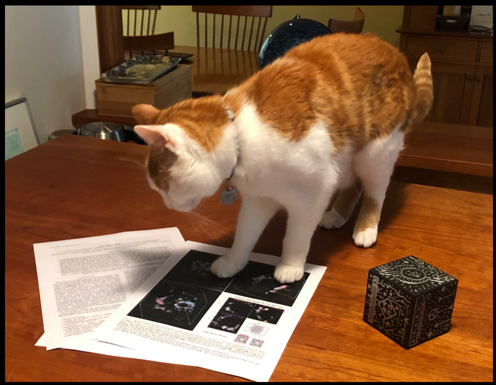
3. *The Fictitious Connection*: A filament seems to connect Taurus to Perseus. This connection is only a coincidental projection effect, where in actuality the filament is located at the distance of Taurus, and does not physically connect

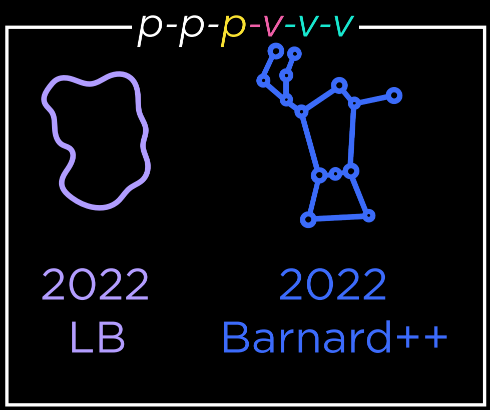


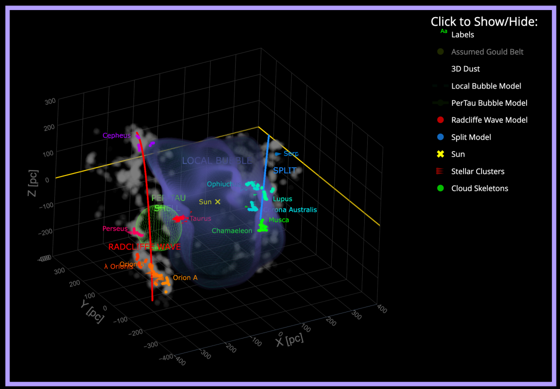
Bialy et al. 2021

The Dataverse Project

What’s even better than a cat photo?

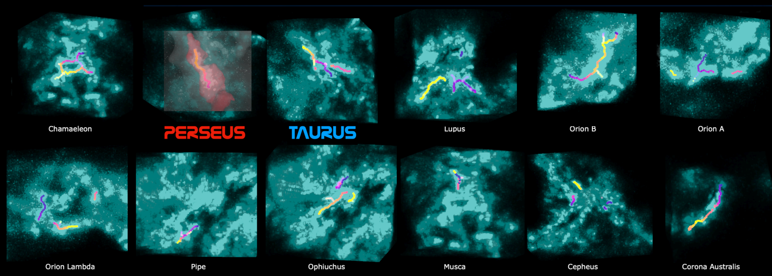






How about interactive 6D figures showing how stars form all around us?

But first, a confession.



D4 THE NEW YORK TIMES, TUESDAY, JANUARY 25, 2022

OUT THERE | DENNIS OVERBYE

Where Our Bubble Ends, Our Understanding Begins

By mapping a region devoid of gas and dust, scientists learn more about star formation.

LEAH HUSTAK (STSCI)/CFA

JUST A BIT TOO LATE for New Year celebrations, astronomers have discovered that the Milky Way galaxy, our home, is, like champagne, full of bubbles.

As it happens, our solar system is passing through the center of one of these bubbles. Fourteen million years ago, according to the astronomers, a firecracker chain of supernova explosions drove off all the gas and dust from a region roughly 1,000 light-years wide, leaving it bereft of the material needed to produce new generations of stars.

As a result, all the baby stars in our neighborhood can be found stuck on the edges of this bubble. There, the staccato force of a previous generation of exploding stars has pushed gas clouds together into forms dense enough to collapse under their own ponderous if diffuse gravity and condense enough to ignite, as baby stars. Our sun, 4.5 billion years old, drifts through the middle of this space in a coterie of aged stars.

"This is really an origin story," Catherine Zucker said in a news release from the Harvard-Smithsonian Center for Astrophysics. "For the first time, we can explain how all nearby star formation began."

Dr. Zucker, now at the Space Telescope Science Institute in Baltimore, led a team that mapped what they call the Local Bubble in remarkable detail. They used data from a number of sources, particularly Gaia, a European spacecraft, that has mapped and measured more than a billion stars, to pinpoint the locations of gas and dust clouds.

Last year, a group of scientists led by João Alves, an astrophysicist at the University of Vienna announced the discovery of the Radcliffe Wave, an undulating string of dust and gas clouds 9,000 light-years long that might be the spine of our local arm of the galaxy. One section of the wave now appears to be part of our Local Bubble.

The same group of scientists published their latest findings in Nature, along with an elaborate animated map of the Local Bubble and its highlights.

The results, the astronomers write, provide "robust observational support" for a long-held theory that supernova explosions are important in triggering star formation, perhaps by jostling gas and dust clouds into collapsing and starting on the long road to thermonuclear luminosity.

Astronomers have long recognized the Local Bubble. What is new, said Alyssa Goodman, a member of the team also from the Harvard-Smithsonian Center for Astrophysics, is the observation that all local star-forming regions lie on the Local Bubble's surface. Researchers previously lacked the tools to map gas and dust clouds in three dimensions. "Thanks to 3-D dust-mapping, now we do," Dr. Goodman said.

According to the team's calculations, the Local Bubble began 14 million years ago with a massive supernova, the first of about 15; massive stars died and blew up. Their blast waves cleared out the region. There are now no stars younger than 14 million years in the bubble, Dr. Goodman said.

The bubble continues to grow at about 4 miles a second. "Still, more supernovae are expected to take place in the near future, like Antares, a red supergiant star near the edge of the bubble that could go any century now," Dr. Alves said. "So the Local Bubble is not 'done.'"

With a score of well-known star-forming regions sitting on the surface of the bubble, the next generation of stars is securely on tap.

The team plans to go on and map more bubbles in the our Milky Way flute of champagne. There must be more, Dr. Goodman said, because it would be too much of a coincidence for the sun to be smack in the middle of the only one.

The sun's presence in this one is nonetheless coincidental, Dr. Alves said. Our star wandered into the region only five million years ago — long after most of the action — and will exit about five million years from now.

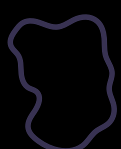
The motions of the stars are more irregular than commonly portrayed, as they are bumped gravitationally by other stars, clouds and the like, Dr. Alves said.

"The sun is moving at a significantly different velocity than the average of the stars and gas in the solar neighborhood," he noted. "This would enable it to catch up and pass — or be passed by — the bubble.

"It was a revelation," Dr. Goodman said, "how kooky the sun's path really is compared with a simple circle."

NASA

Above, an illustration of the Local Bubble, which formed in the Milky Way, left, when supernova explosions drove off all the gas and dust from a 1,000-light-year-wide region.



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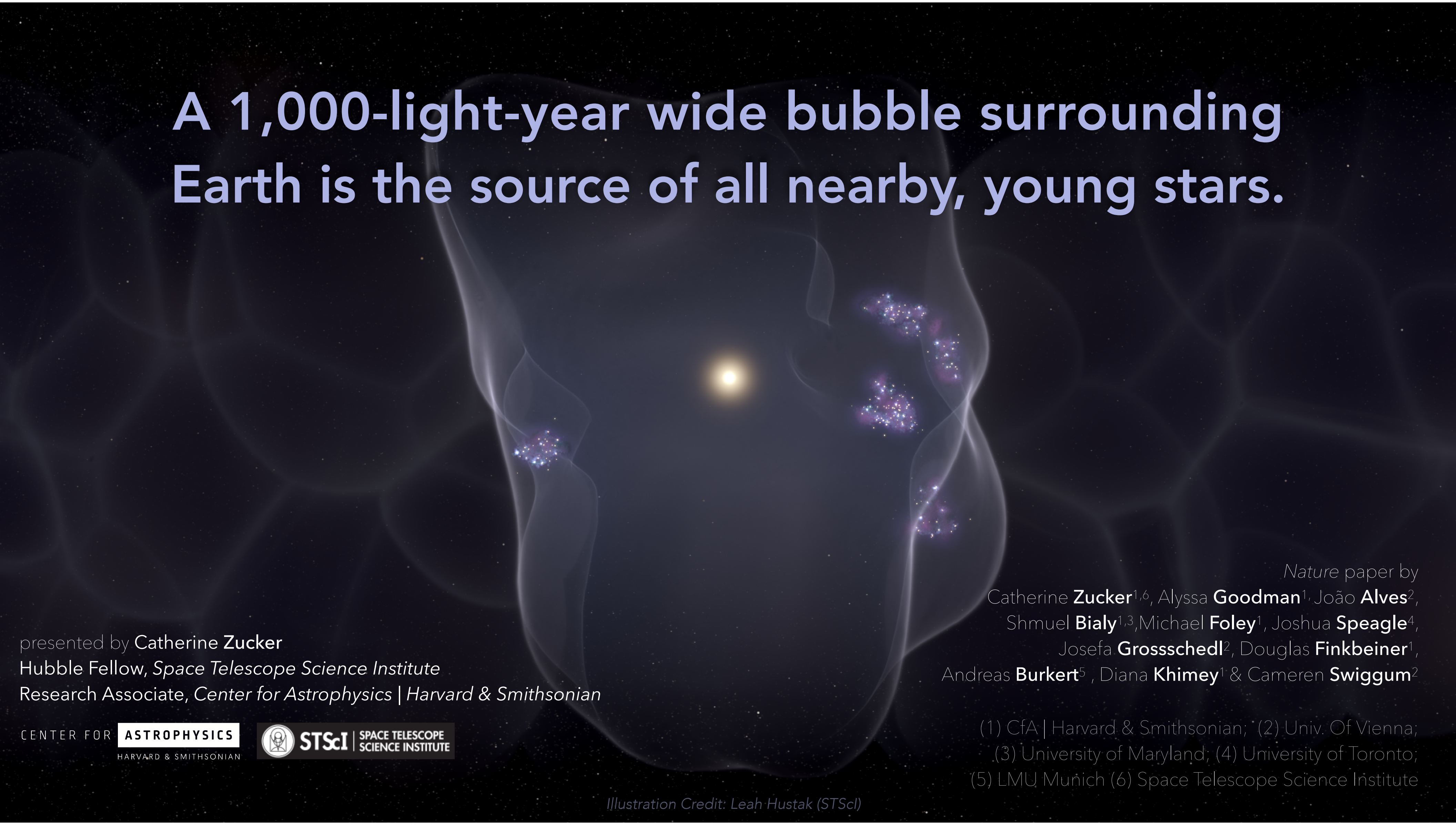
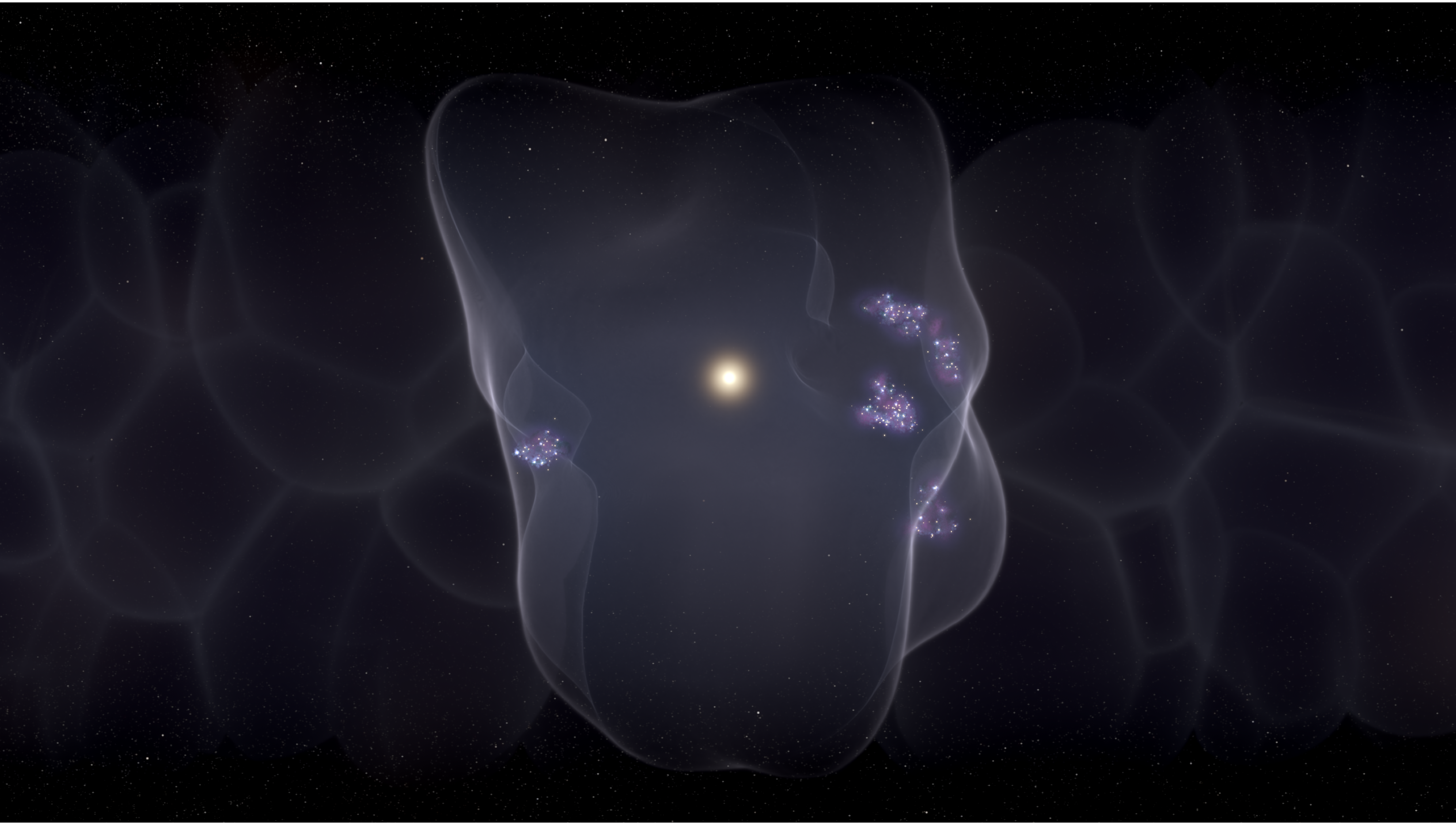
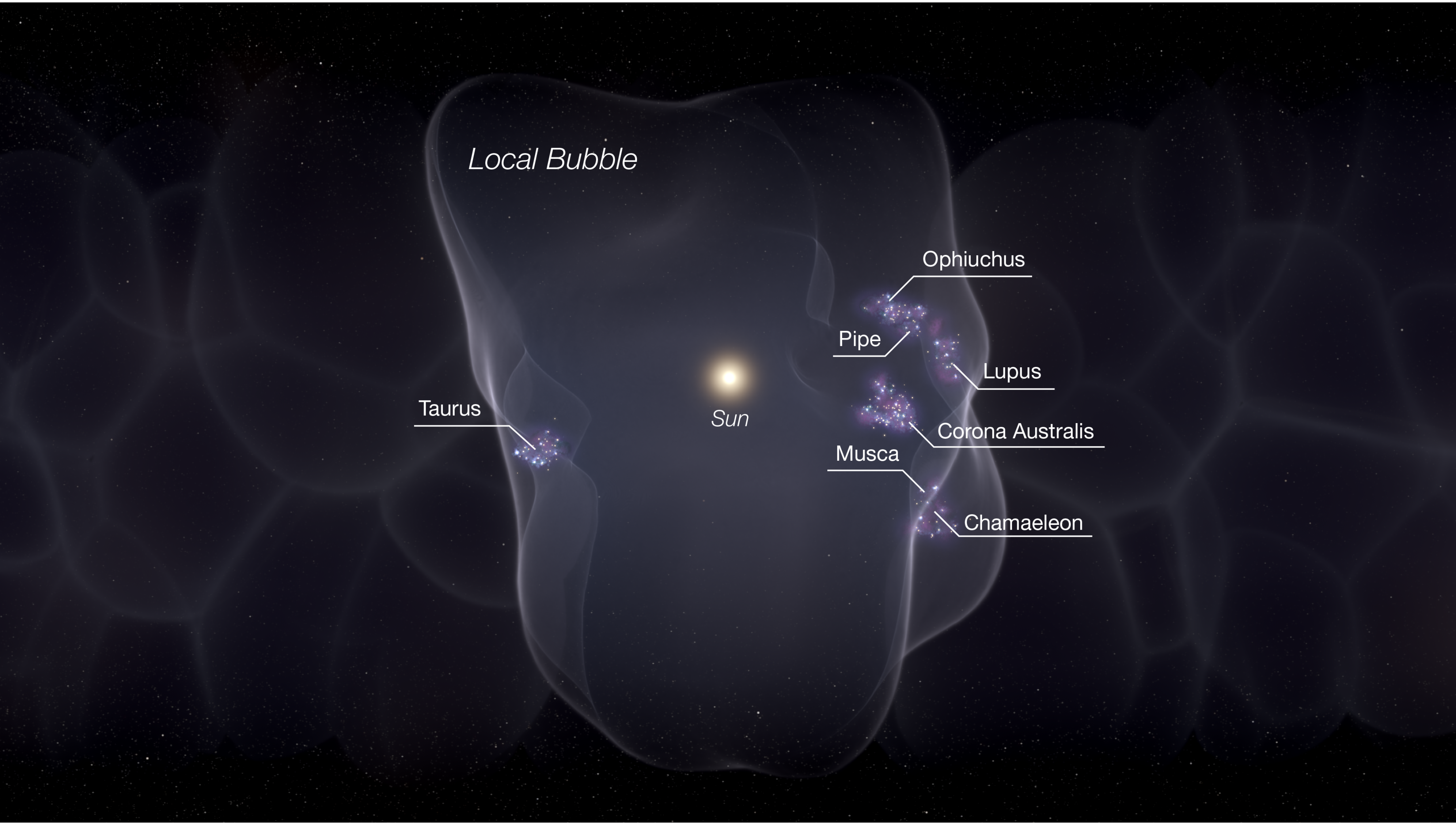
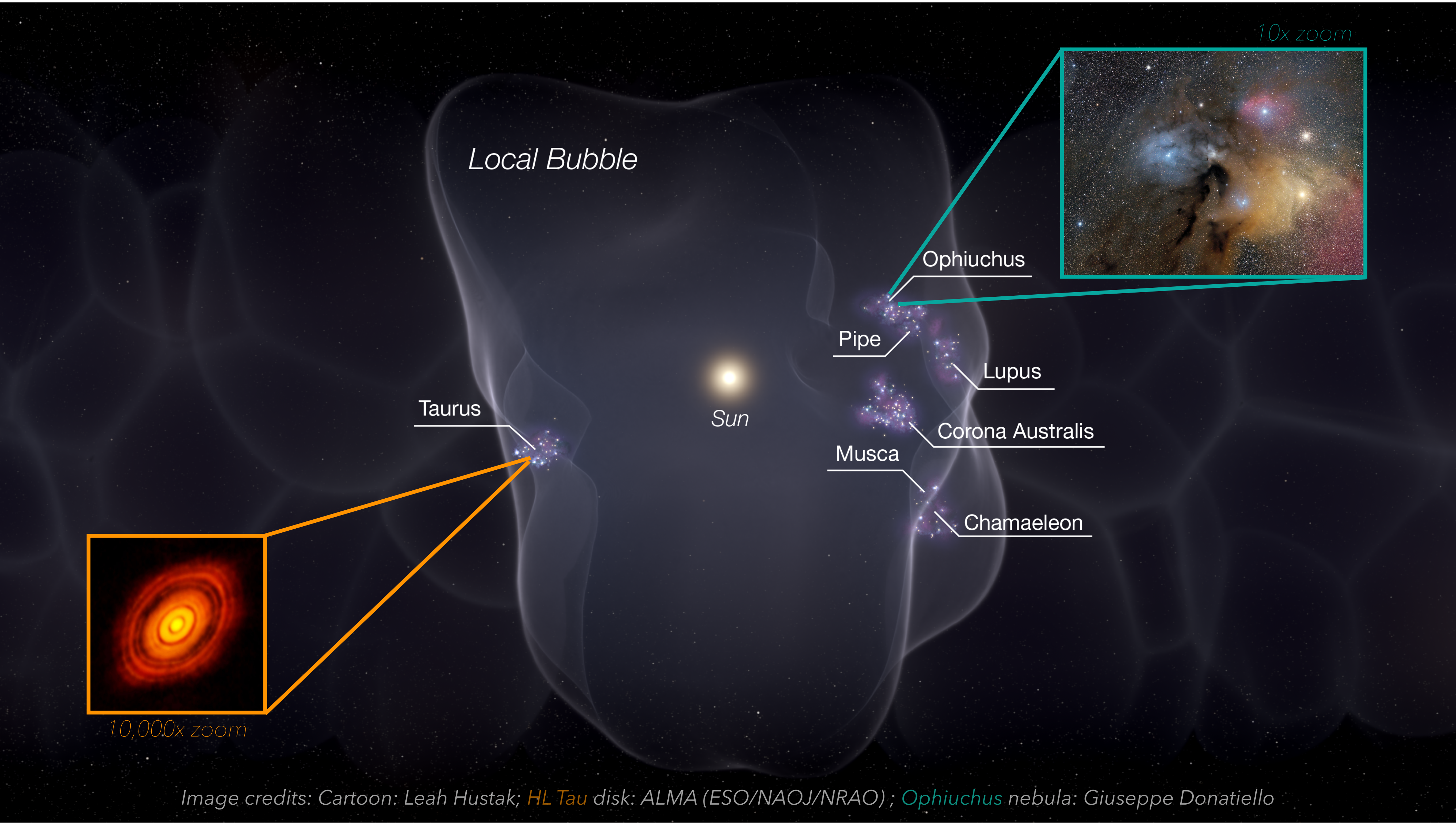
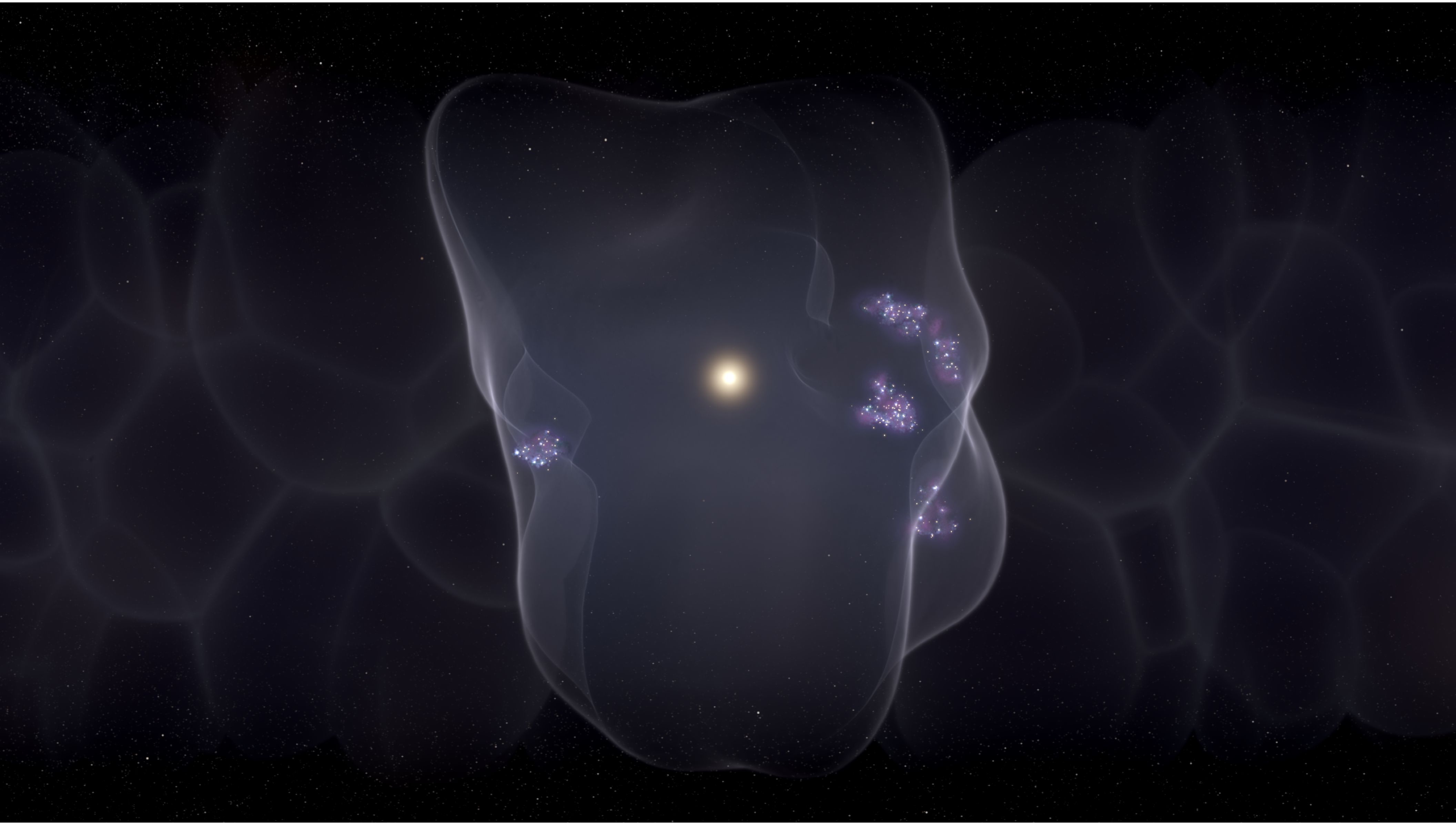


A 1,000-light-year wide bubble surrounding Earth is the source of all nearby, young stars.
Nature paper by
Catherine **Zucker**[1,6], Alyssa **Goodman**[1], João **Alves**[2], Shmuel **Bialy**[1,3], Michael **Foley**[1], Joshua **Speagle**[4], Josefa **Grossschedl**[2], Douglas **Finkbeiner**[1], Andreas **Burkert**[5], Diana **Khimey**[1] & Cameren **Swiggum**[2]
(1) CfA | Harvard & Smithsonian; (2) Univ. Of Vienna; (3) University of Maryland; (4) University of Toronto; (5) LMU Munich (6) Space Telescope Science Institute
presented by Catherine **Zucker**
Hubble Fellow, *Space Telescope Science Institute*
Research Associate, *Center for Astrophysics* | *Harvard & Smithsonian*
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN
STScI SPACE TELESCOPE SCIENCE INSTITUTE
Illustration Credit: Leah Hustak (STScI)

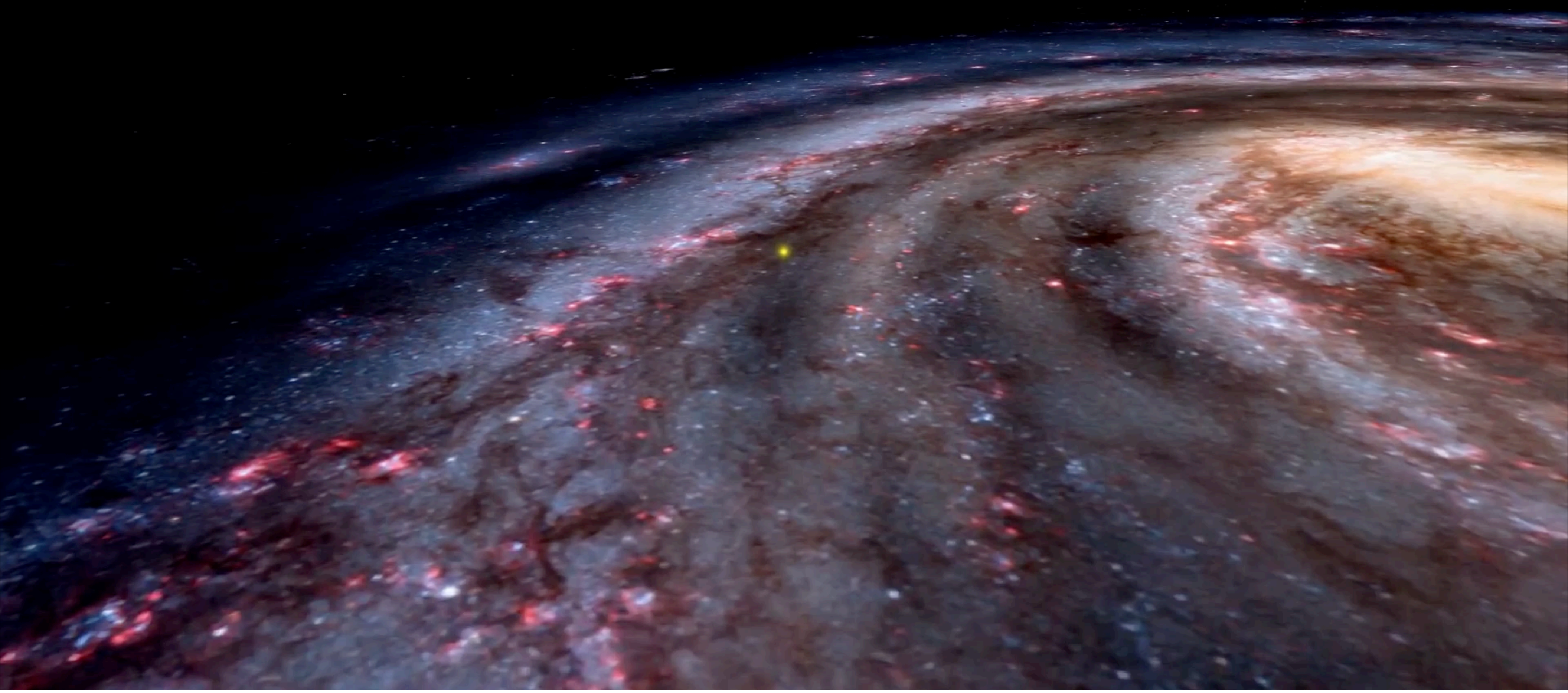



Local Bubble
Ophiuchus
Pipe
Lupus
Taurus
Sun
Corona Australis
Musca
Chamaeleon


10x zoom
Local Bubble
Ophiuchus
Pipe
Lupus
Taurus
Sun
Corona Australis
Musca
Chamaeleon
10,000x zoom
Image credits: Cartoon: Leah Hustak; HL Tau disk: ALMA (ESO/NAOJ/NRAO) ; Ophiuchus nebula: Giuseppe Donatiello



We can reconstruct the evolutionary history of our Galactic neighborhood.



We can reconstruct the **evolutionary history** of our Galactic neighborhood.

A chain of events beginning 14 million years ago with **powerful supernova explosions** created a **gigantic bubble** with a surface ripe for **star formation**

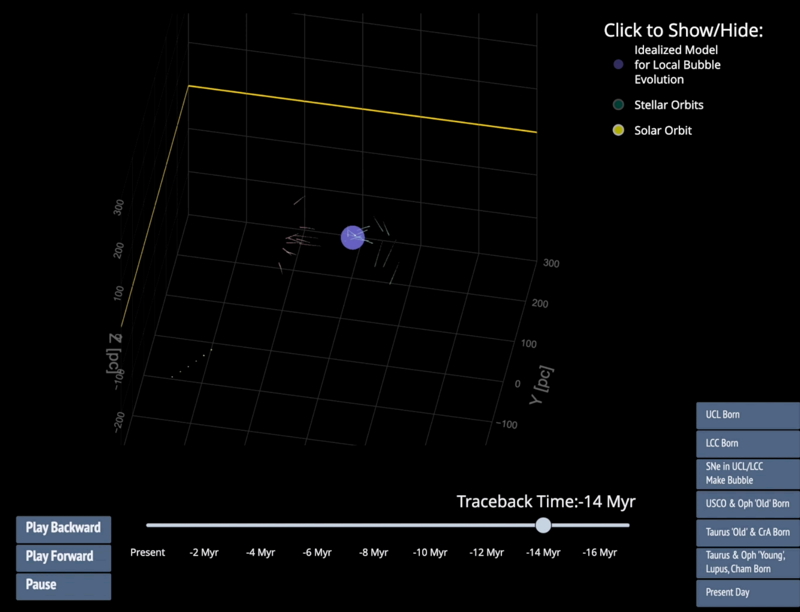
14

MILLION YEARS AGO

“Cartoon”

“Real Data”

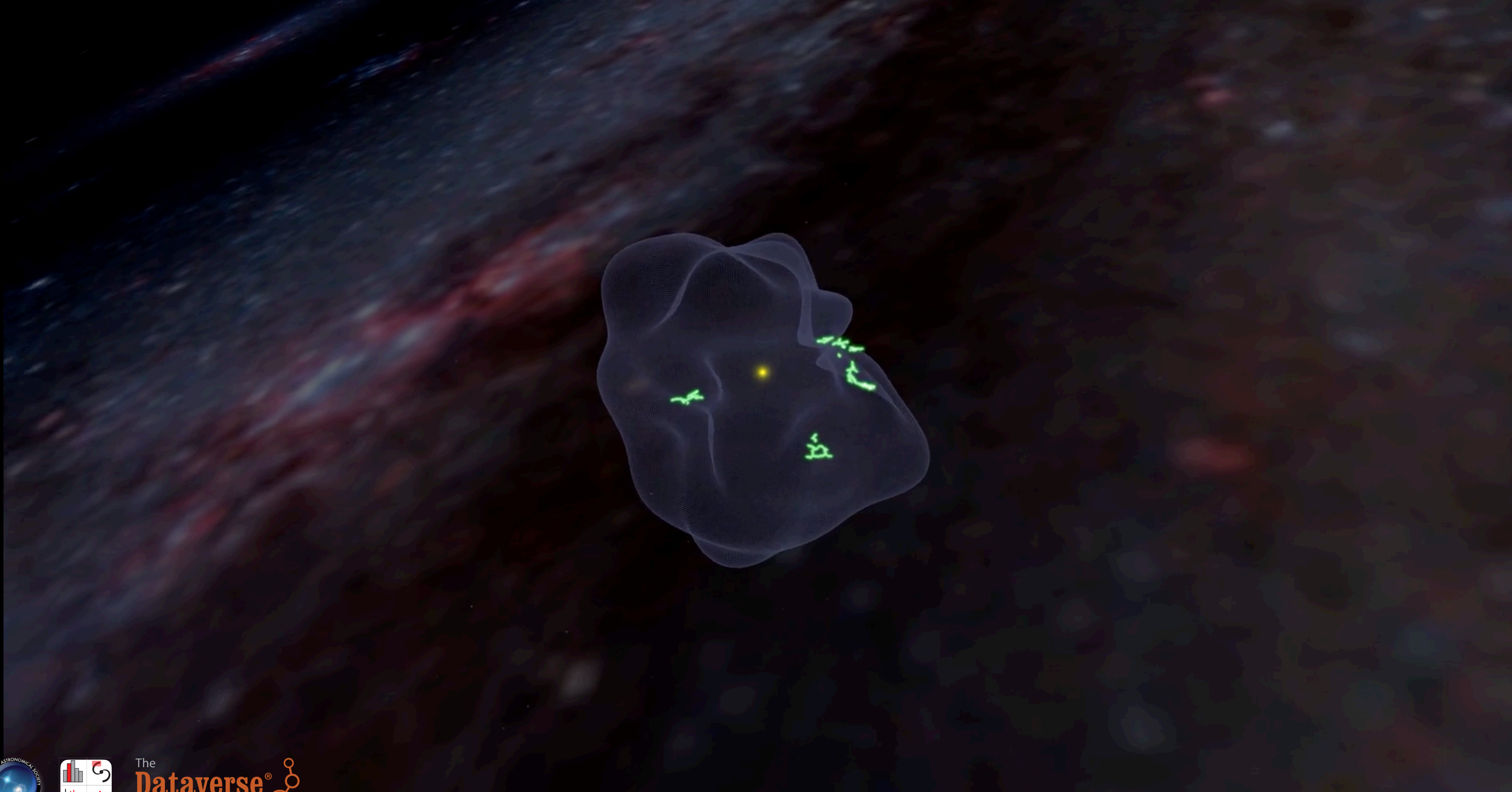
(Zucker et al. 2022, *Nature*)



[try the interactive figure]

The Local Bubble from the outside in and the inside out

The Local Bubble from the outside in and the inside out



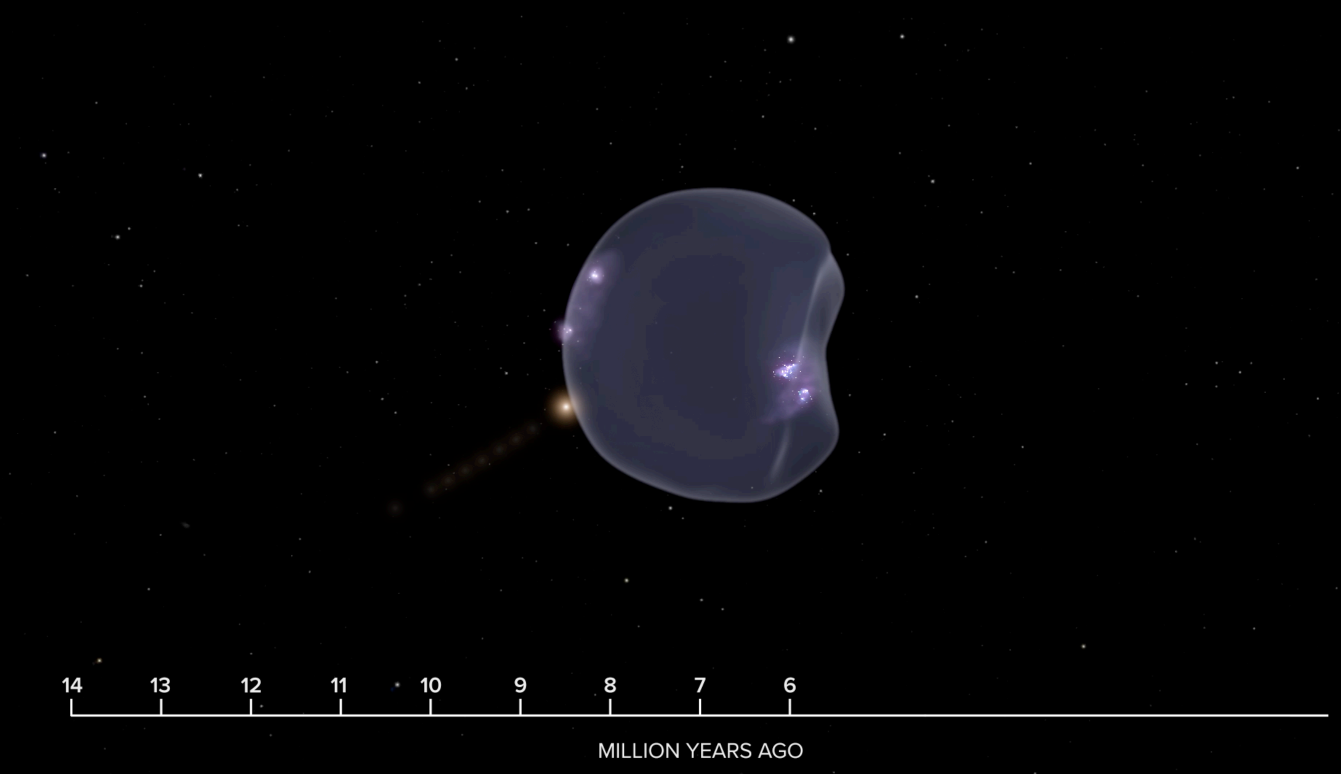
The Dataverse® Project

How did the Sun wind up in the bubble? (by accident)

The Sun was over 1,000 light years away when the bubble first started forming.

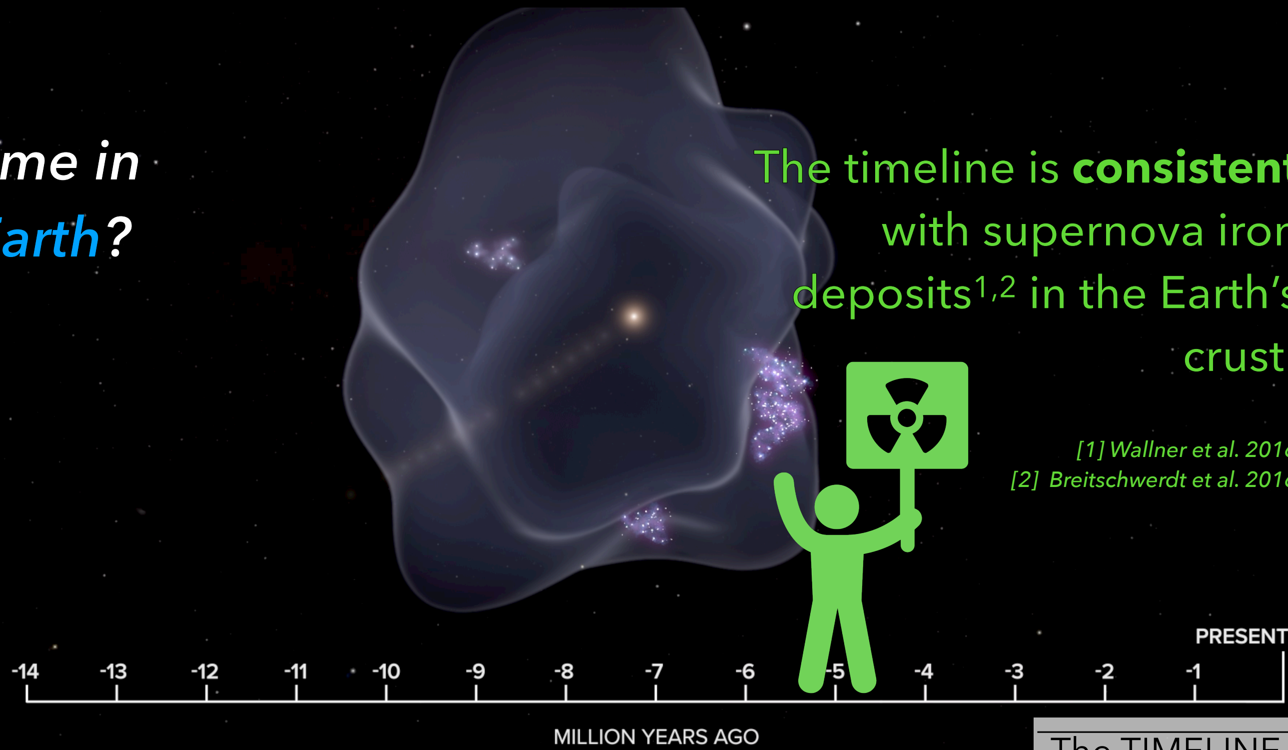
*How did the **Sun** wind up in the bubble? (by accident)*

The Sun entered the bubble 5 million years ago and now sits near the bubble's center.



How did the Sun wind up in the bubble? (by accident)

What does the Sun's time in the bubble mean for Earth?



The timeline is **consistent** with supernova iron deposits[1,2] in the Earth's crust!

[1] Wallner et al. 2016
[2] Breitschwerdt et al. 2016

The TIMELINE CONSORTIUM

So What?

In the present day, almost every single nearby, young star lies on the surface of the Local Bubble

We can now explain how all nearby star formation began

Supernovae can "sweep up" gas into dense clouds that ultimately form new stars (evidence for 50-year-old theory)

Sun's "luck" (centered in bubble) suggests that bubbles must be pervasive across the Galaxy, implying "bubbly" Milky Way

1977: C. McKee & J. Ostriker's Multiphase ISM

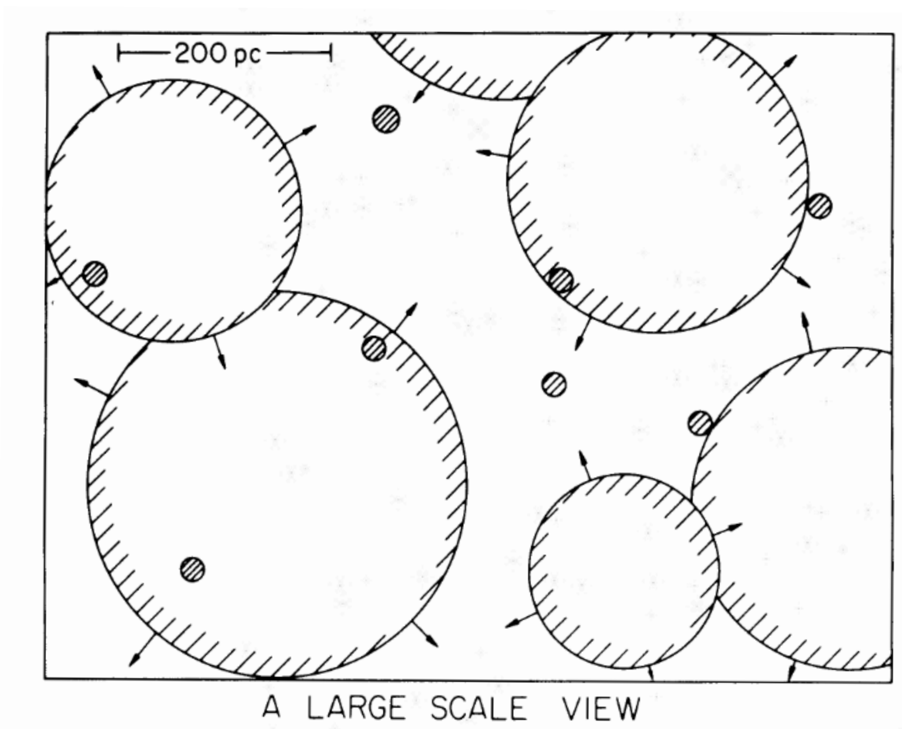


FIG. 3.—Large-scale structure of the interstellar medium. The scale here is 20 times greater than in Fig. 1: the region is 600 × 800 pc. Only SNRs with $R < R_c = 180$ pc and clouds with $a_0 > 7$ pc are shown. Altogether about 9000 clouds, most with $a_w \sim 2.1$ pc, would occur in a region this size.

2017: C.-G. Kim & E. Ostriker's Multiphase ISM's evolution over 44 Myr

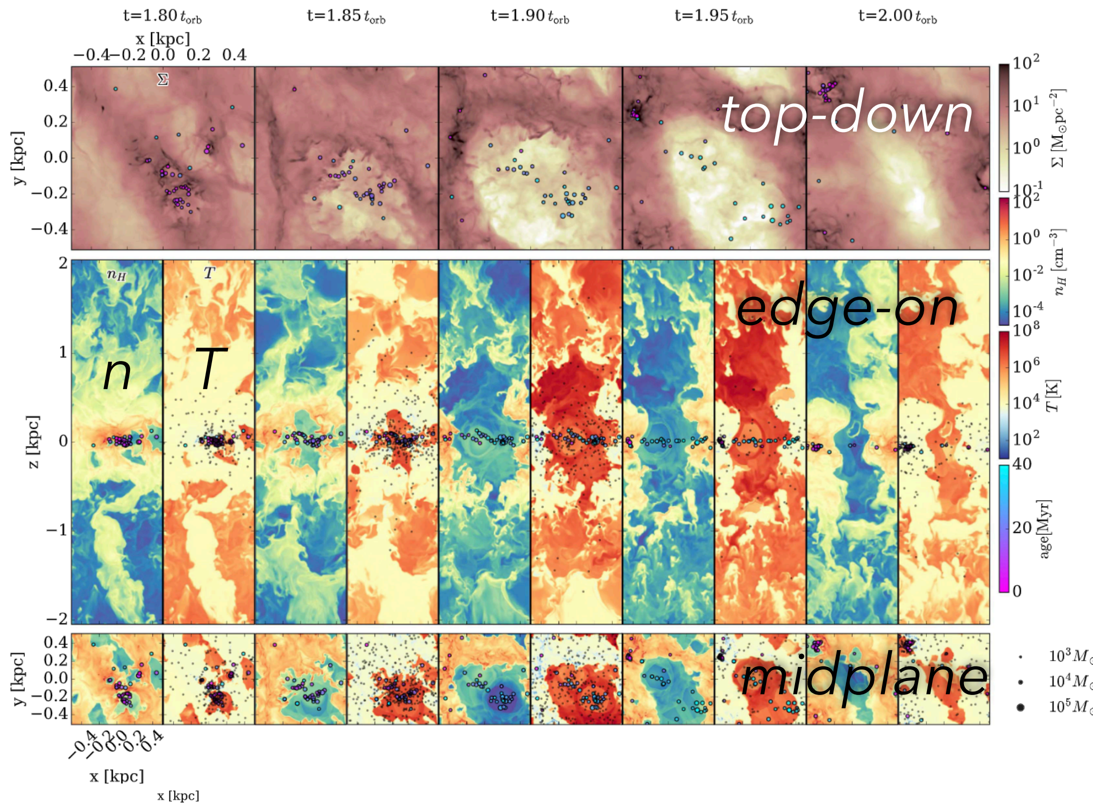
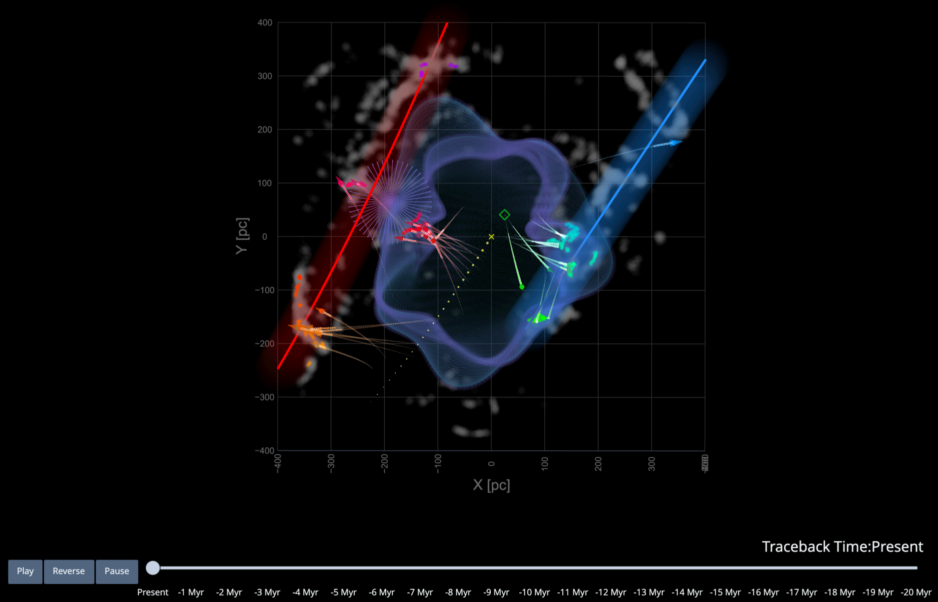


Figure 8. Time evolution of the ISM and young star population in the solar neighborhood model, shown at intervals of $\Delta t = 0.05 t_{orb} \approx 11$ Myr, from $t = 1.8 t_{orb} = 395$ Myr to $t = 2 t_{orb} = 439$ Myr. Top row: gas surface density Σ projected onto the XY ($\hat{x}$–$\hat{y}$) plane. Middle row: paired vertical slices (through $y = 0$) of number density n_H (left) and gas temperature T (right). Bottom row: paired midplane slices (through $z = 0$) of n_H (left) and T (right). In all panels, colored circles denote locations of all sink and star particles younger than 40 Myr (see the colorbar) projected onto each plane. The symbol size of sink/star particles denotes their mass (see legend). Runaway OB stars are shown as black dots only in the temperature panels for visual clarity.

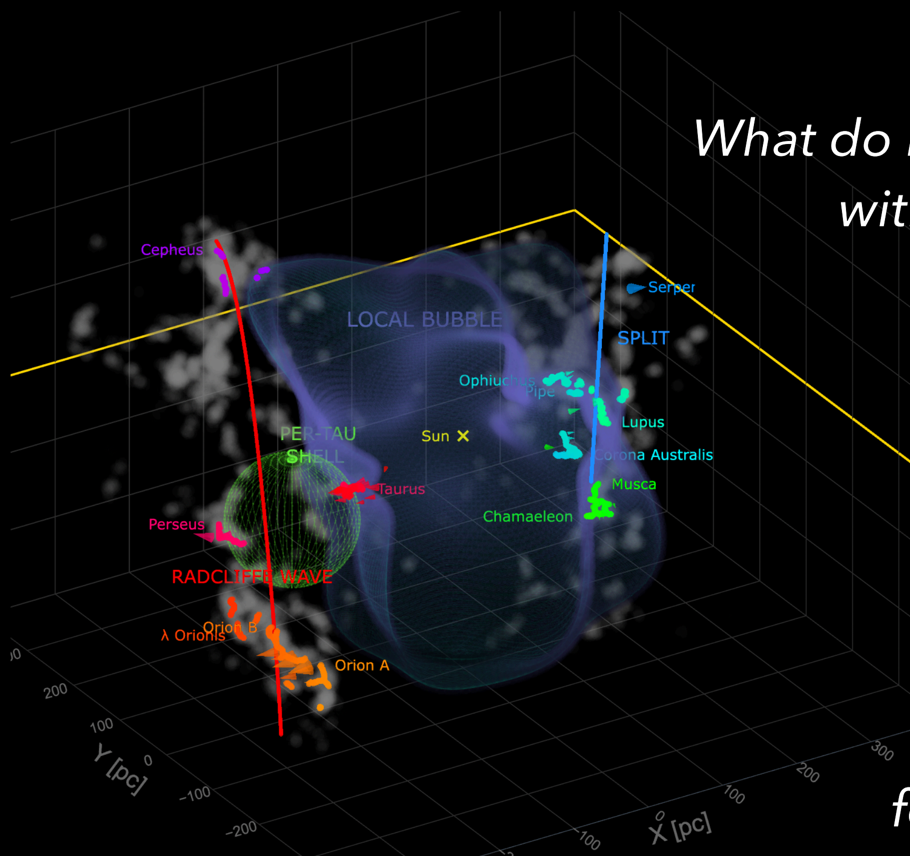
And what (MAYBE!) caused the prior star formation that caused the Sue that caused the Local Bubble?



Click to see what MIGHT have happened...

Next?

What do bubbles have to do with SPIRAL structure? Anything?



How do we SEARCH for other bubbles?

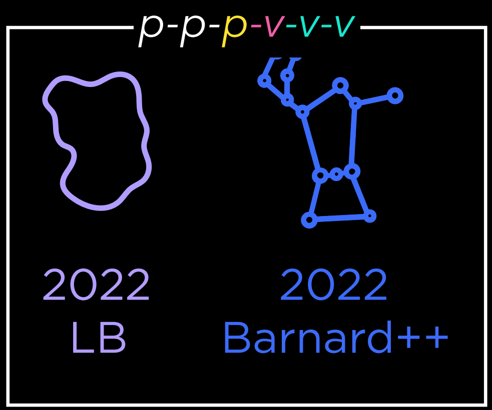
How do these bubbles INTERACT with each other?

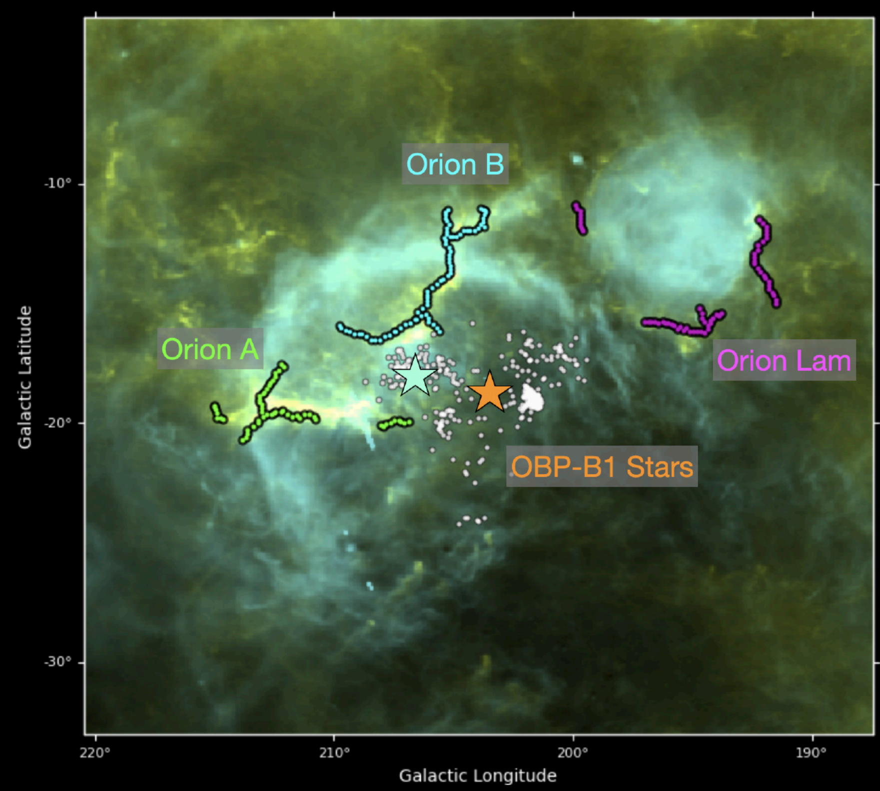
Can observations now measure supernova feedback's effect on galaxy EVOLUTION?

[try the interactive figure]

Local Bubble model [Pelgrims et al. 2020] , Superbubble expansion model [El-Badry et al. 2019], 3D Dust Maps [Leike et al. 2020, Lallement et al. 2019]

Next?





Foley et al. 2022:
A new 6D view of Barnard's Loop (& Orion)

Can we see these short term, “small”-scale, phenomena beyond the Milky Way?

PHANGS-MUSE, with ALMA, VLT; (cf PHANGS HST)

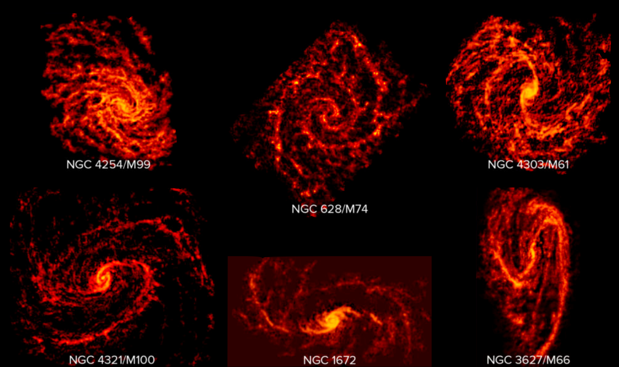
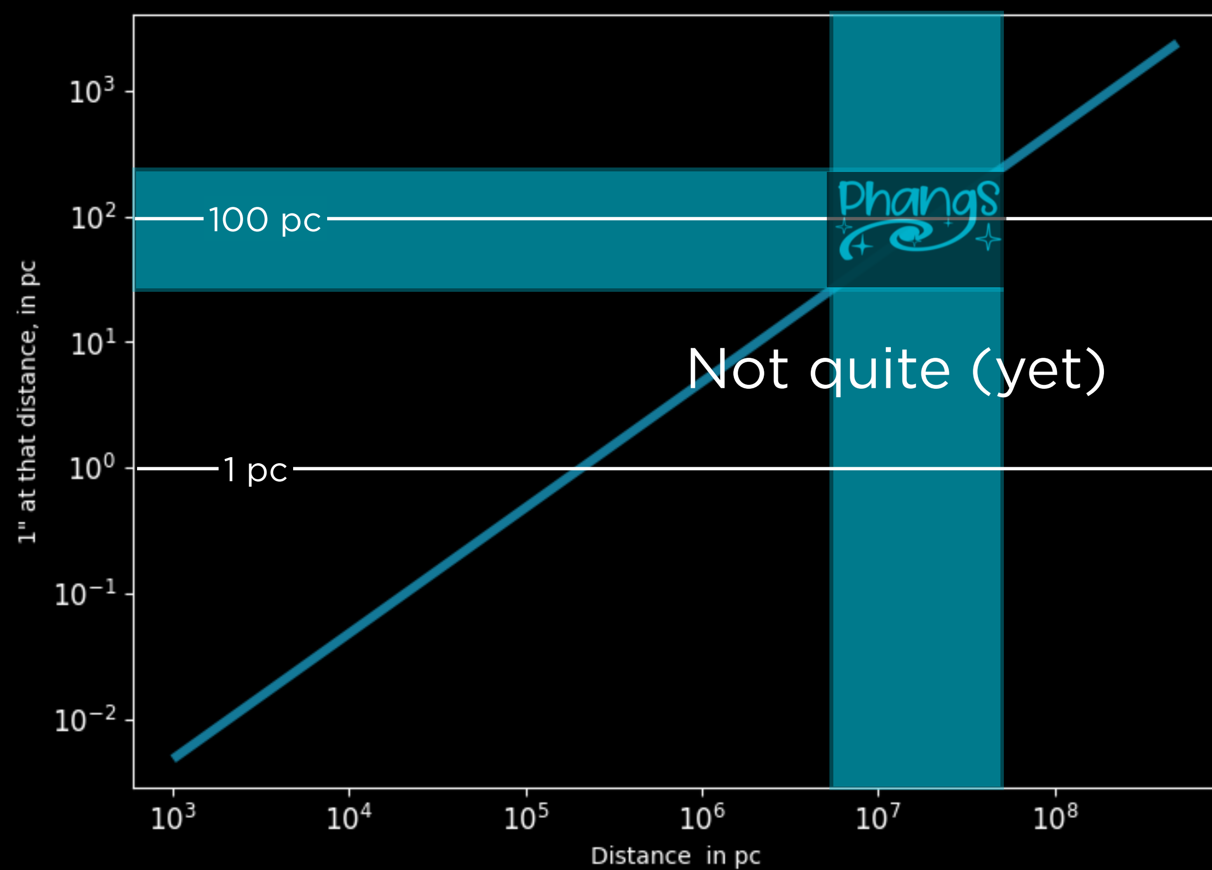
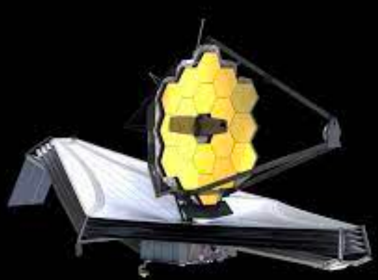


Image of carbon monoxide emission from six of the 74 galaxies in the PHANGS-ALMA survey. almascience.eso.org/alma-science/galaxies-and-galactic-nuclei



Zooming in on Phangs with JWST–
public data coming soon…



Webb Telescope

Jan 19, 2022

Capturing All That Glitters in Galaxies With NASA's Webb

An international research team will survey the stars, star clusters, and dust that lie within 19 nearby galaxies.

Spirals are some of the most captivating shapes in the universe. They appear in intricate seashells, carefully constructed spider webs, and even in the curls of ocean waves. Spirals on cosmic scales – as seen in galaxies – are even more arresting, not only for their beauty, but also for the overwhelming amount of information they contain. How do stars and star clusters form? Until recently, a complete answer used to lie out of reach, blocked by gas and dust. Within the first year of operations, NASA's James Webb Space Telescope will help researchers complete a more detailed sketch of the stellar life cycle with high-resolution infrared-light images of 19 galaxies.

The telescope will also provide a few key "puzzle pieces" that were missing until now. "JWST touches on so many different phases of the stellar life cycle – all in tremendous resolution," said Janice Lee, Gemini Observatory chief scientist at the National Science Foundation's NOIRLab in Tucson, Arizona. "Webb will reveal star formation at its very earliest stages, right when gas collapses to form stars and heats up the surrounding dust."

Lee is joined by David Thilker of the Johns Hopkins University in Baltimore, Maryland, Kathryn Kreckel of Heidelberg University in Germany, and 40 additional members of the multi-wavelength survey program known as PHANGS (Physics at High Angular resolution in Nearby GalaxieS). Their mission? Not only to unravel the mysteries of star formation with Webb's high-resolution infrared images, but also to share the datasets with the entire astronomical community to accelerate discovery.

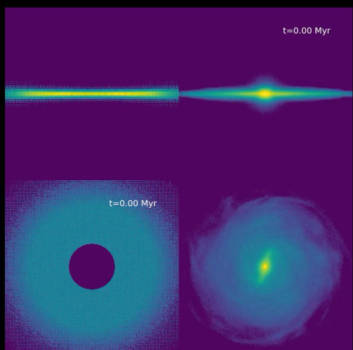
This image of spiral galaxy NGC 3351 combines observations from several observatories to reveal details about its stars and gas. Radio observations from the Atacama Large Millimeter/submillimeter Array (ALMA) show dense molecular gas in magenta. The Very Large Telescope's Multi Unit Spectroscopic Explorer (MUSE) instrument highlights where young massive stars illuminate their surroundings, set off in red. The Hubble Space Telescope's images highlight dust lanes in white and newly formed stars in blue. High-resolution infrared images from the Webb Space Telescope will help researchers identify where stars are forming behind dust and study the earliest stages of star formation in this galaxy.
Credits: Science: NASA, ESA, ESO-Chile, ALMA, NAOJ, NRAO; image processing: Joseph DePasquale (STScI)

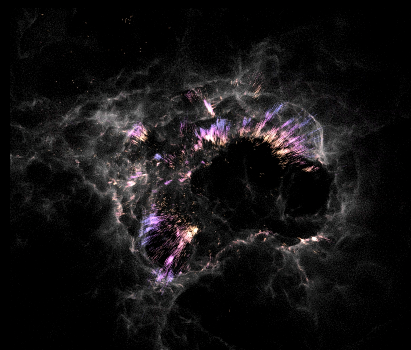
The Rhythms of Star Formation

PHANGS is novel, in part, because it brought together more than 100 international experts to study star formation from beginning to end. They are targeting galaxies that can be seen face-on from Earth and that are, on average, 50 million light-years away. The large collaboration began with microwave light images of 90 galaxies from the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile. Astronomers use this data to produce molecular gas maps to study the raw materials for star formation. Once the Very Large Telescope's Multi Unit Spectroscopic Explorer (MUSE) instrument, also in Chile, came online, they obtained data known as spectra to study later phases of star formation of 19 galaxies, particularly after star clusters have cleared nearby gas and dust. The space-based Hubble Space Telescope has provided visible and ultraviolet light observations of 38 galaxies to add high-resolution images of individual stars and star clusters.

The missing elements, which Webb will fill in, are largely in areas of the galaxies that are obscured by dust – regions where stars are actively beginning to form. "We're going to clearly see star clusters in the hearts of these dense molecular clouds that before we only had indirect evidence of," Thilker said. "Webb gives us a way to look inside these 'star factories' to see the freshly assembled star clusters and measure their properties before they evolve."

(Some of) what's next for the "New Milky Way" at Harvard/CfA/Radcliffe, and who to talk with to learn more…





Gus **Beane**: A Realistic Milky Way in AREPO

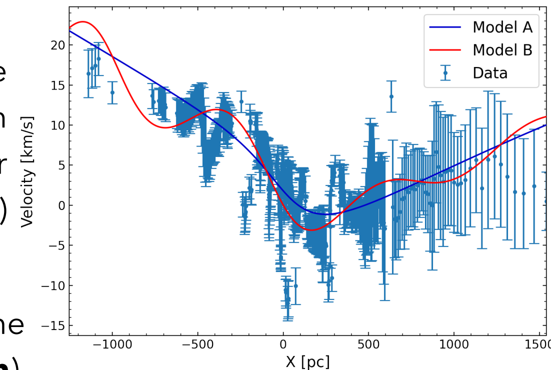
Michael **Foley**: Barnard's Loop in 3D, and similar structures in simulations

Next?

Harvard Radcliffe Institute

Goodman/Alves/Zucker: "The Radcliffe Wave at Radcliffe" (an Accelerator Workshop in 2022)

Ralf **Konietzka**: Are the Radcliffe Wave & the Split moving with respect to each other, and/or Galactic rotation? (2022)



2022 **REU**: The Magnetic Field of the Local Bubble, in 3D (with Jesse **Han**)

Shlomo **Cahlon**: 2-D vs. 3-D in Mass-Size Relations (2022)

Eric **Koch** : A 10-pc-scale–resolution follow up to PHANGS (2022 proposal to ALMA)

Alan **Tu**: Is the Radcliffe Wave Oscillating? (2022)

Sarah **Jeffreson &** Maya **Skarbinsk**i: Role of mergers in determining cloud properties, in simulations (2022)

Patricia **Udomprasert**: Cosmic "Data Stories" using the Radcliffe Wave data to teach data science to high-school/college students

CosmicDS

Apologies for not listing the MANY collaborators on each of these projects also here today–please introduce yourselves…

The New Milky Way, in 3D

Alyssa A. Goodman
Center for Astrophysics | Harvard & Smithsonian

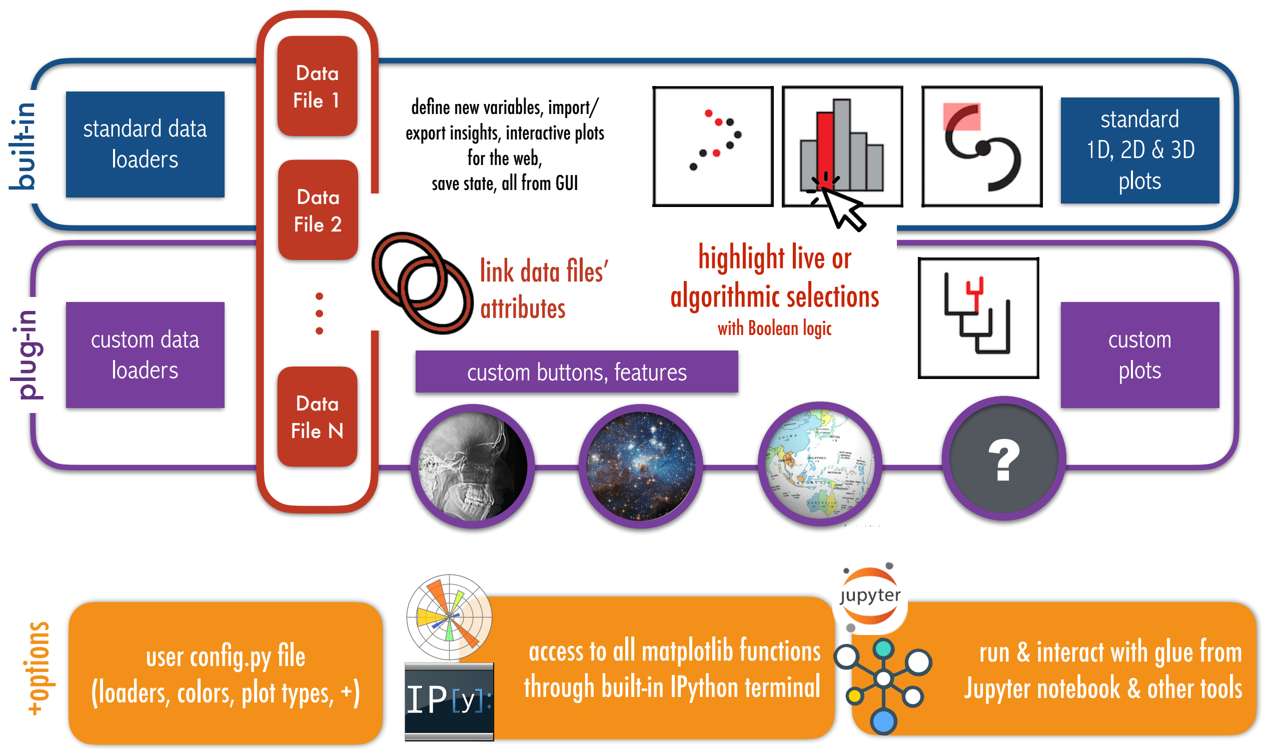
with many thanks to:
João Alves, John Bally, Cara Battersby, Gus Beane, Chris Beaumont, Bob Benjamin, Ted Bergin, Shmuel Bialy, Michelle Borkin, Andi Burkert, Shlomo Cahlon, Jon Carifio, Kaustav Das, Tom Dame, Elena D'Onghia, Gordian Edenhofer, Torsten Enβlin, Jonathan Fay, Douglas Finkbeiner, John Forbes, Michael Foley, Greg Green, Josefa Groβschedl, Mike Grudić, James Jackson, Sarah Jeffreson, Jens Kauffmann, Diana Khimey, Ralf Konietzka, Eric Koch, Charles Lada, Reimar Leike, Stefan Meingast, Josh Peek, Stephen Portillo, Mark Reid, Tom Rice, Tom Robitaille, Eddie Schlafly, Vadim Semenov, Maya Skarbinski, Rowan Smith, Juan Soler, Josh Speagle, Alan Tu, Cameren Swiggum, Patricia Udomprasert, Peter Williams, Curtis Wong & Catherine **Zucker**!

NASA NSF GORDON AND BETTY MOORE FOUNDATION Alfred P. Sloan FOUNDATION HDSI Harvard Data Science Initiative Harvard Radcliffe Institute CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

@AlyssaAGoodman

glue

multidimensional data exploration



glueviz.org

extra slides