

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

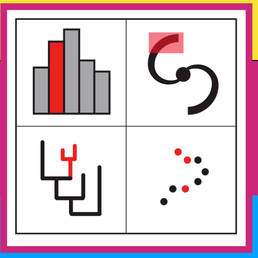
NEW Milky Way

what it looks like

how we know

why it matters



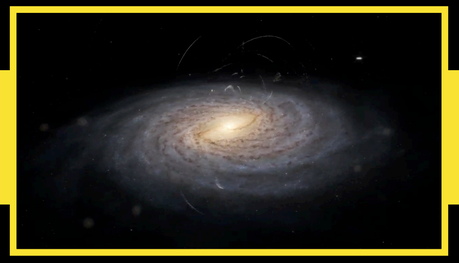


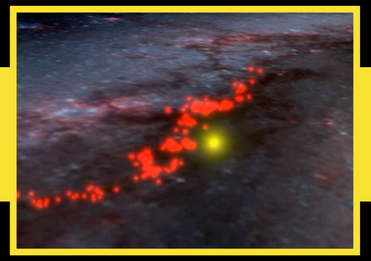
Alyssa Goodman, Center for Astrophysics | Harvard & Smithsonian

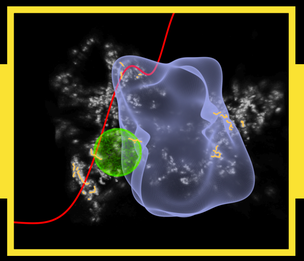
featuring especially the work of João **Alves**++., Shmuel **Bialy**, Andi **Bukert** ++., Gordian **Edenhofer**, Torsten **Enßlin** ++, Doug **Finkbeiner** ++., Michael **Foley**, Ralf **Konietzka**, Reimar Leike, Theo **O'Neill**, Juan **Soler**, Catherine **Zucker** & the **glue** team

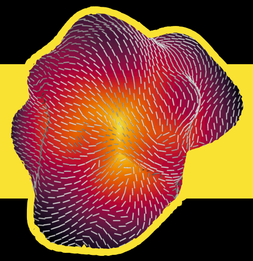
The NEW Milky Way

what it looks like



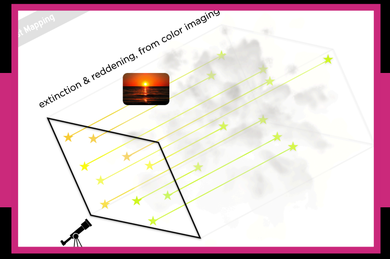




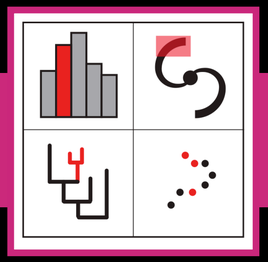


how we know

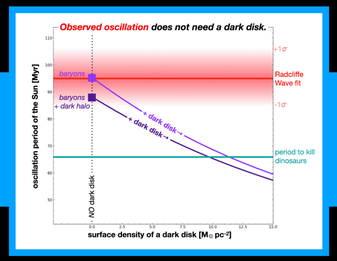


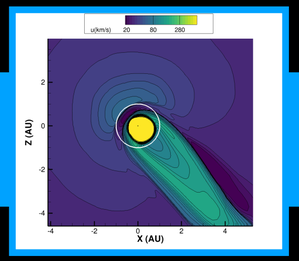


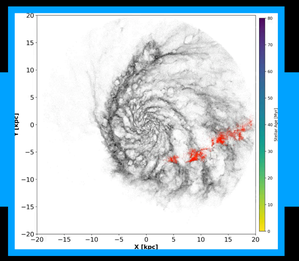


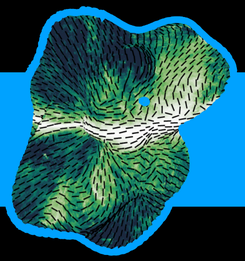


why it matters

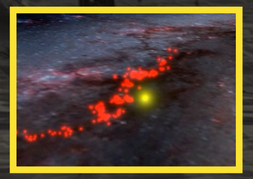




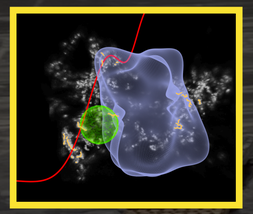




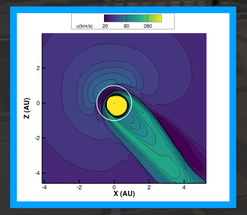
WHAT'S NEW?



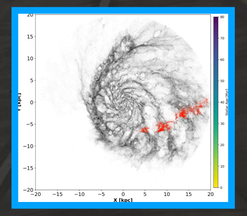
Arms of galaxies (1) look like they "wave," and (2a) they move like that too. (2b) There appears to be almost no dark matter in the Milky Way's disk.)



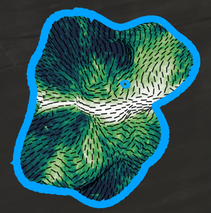
(3a) Feedback from supernovae & winds are as important as theorists said it was 50 years ago, even though observers didn't believe them. (3b) Star forming clouds may largely form at the intersection of feedback bubbles.



(4a) The Sun is "just passing through" our Local Bubble & Earth's (4b, planets') radiation history is determined by this kind of "interstellar weather."



(5) Parts (arms?) of galaxies that appear "near each other" today, did NOT start out that way. Pattern speeds are deceiving.

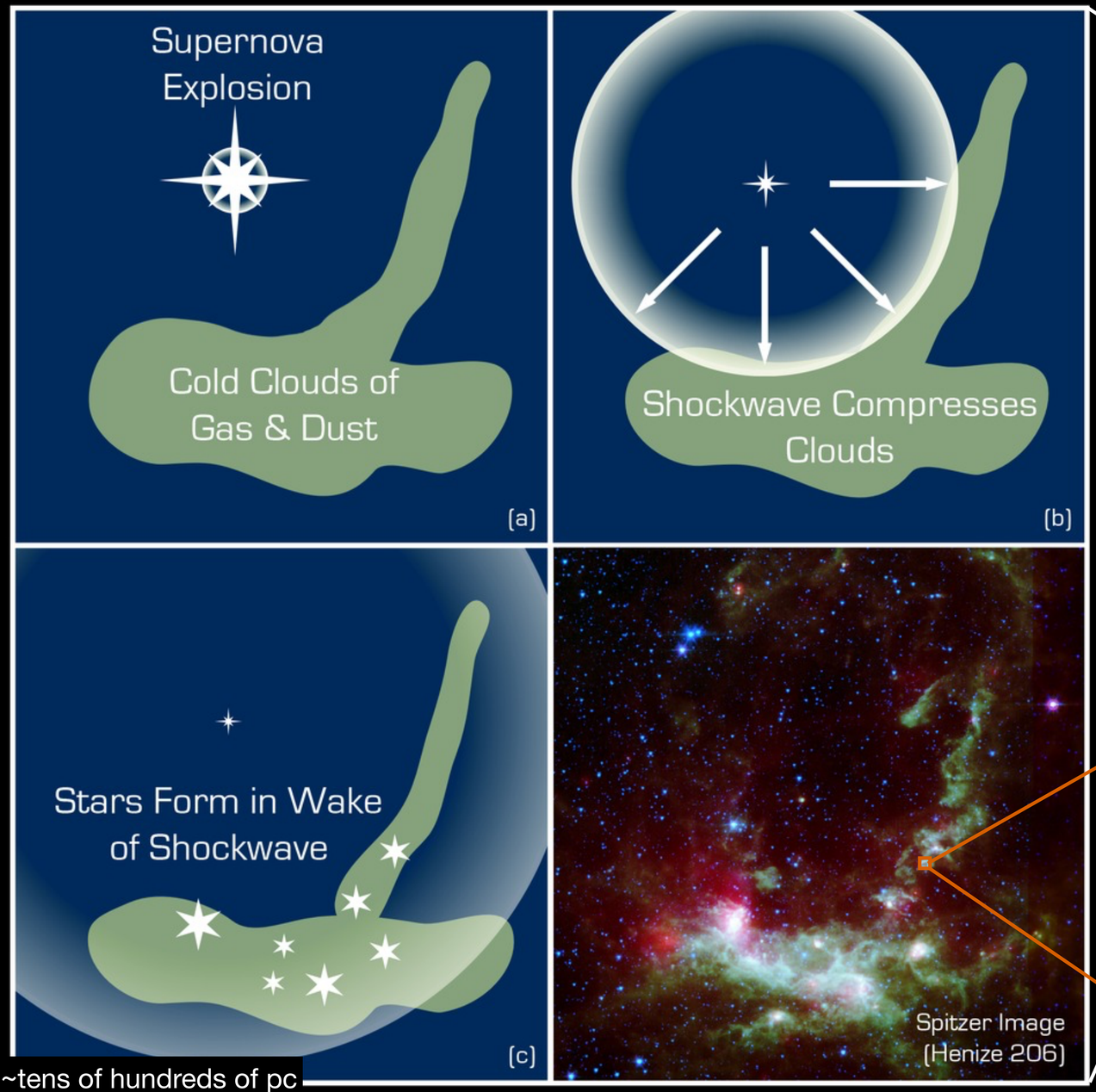


(6) Magnetic fields appear swept-up into feedback bubble's surfaces.

QUICK(!) BACKGROUND

1. STAR FORMATION
2. LIMITATIONS OF “P-P-V” SPACE

STAR FORMATION



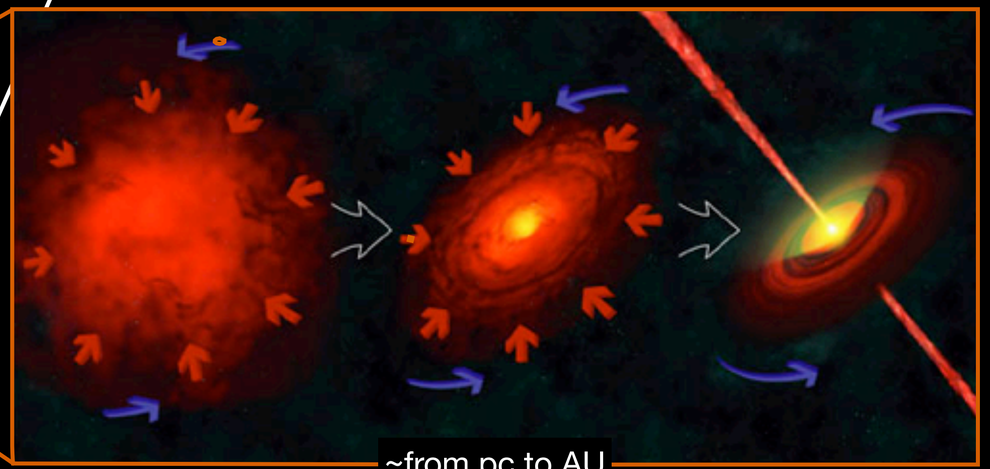
~tens of hundreds of pc

Credit: NASA/JPL-Caltech/R. Hurt (SSC-Caltech) **Spitzer Space Telescope • ssc2004-04b**

~tens of kpc



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



~from pc to AU

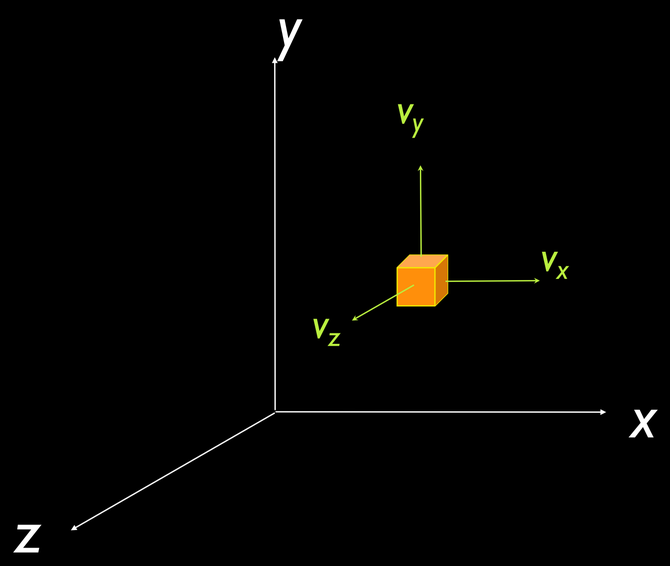
©Adison-Wesley 2004

p-p-v space

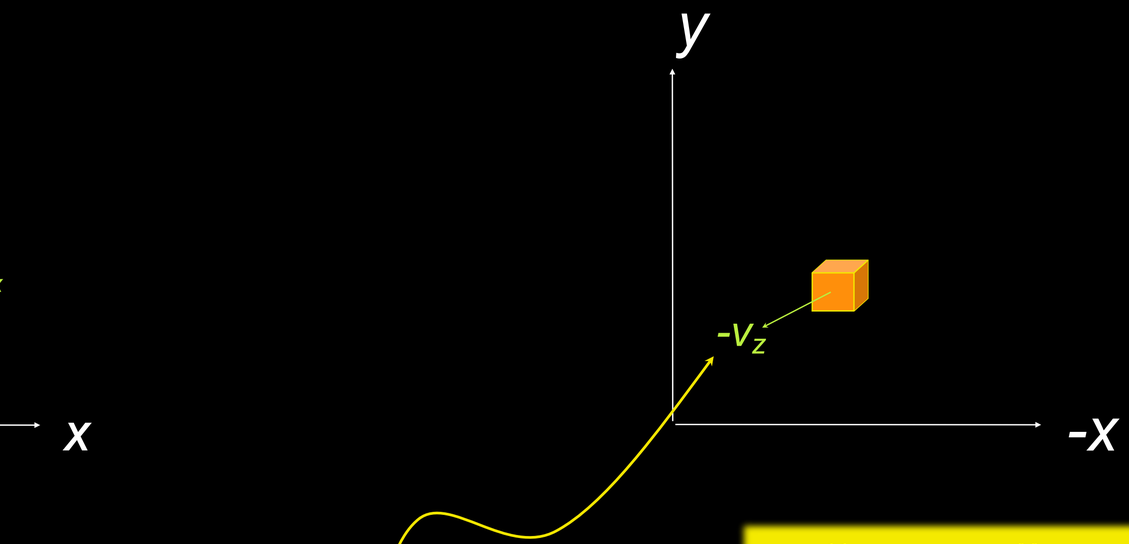
SPECTRAL-LINE MAPPING

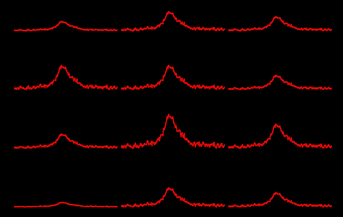
(re: LIMITATIONS OF "P-P-V" SPACE)

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



p-p-v space: "3D"





v_z *only* from "spectral-line maps" (Doppler)

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

"p-p-v"= position-position-velocity data

"kinematic distance" only

HI

Oort et al 1958

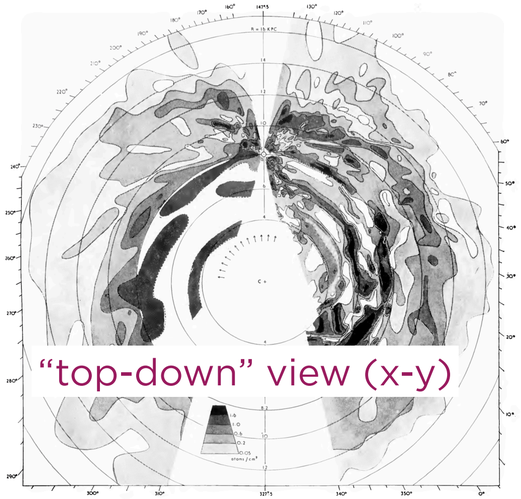
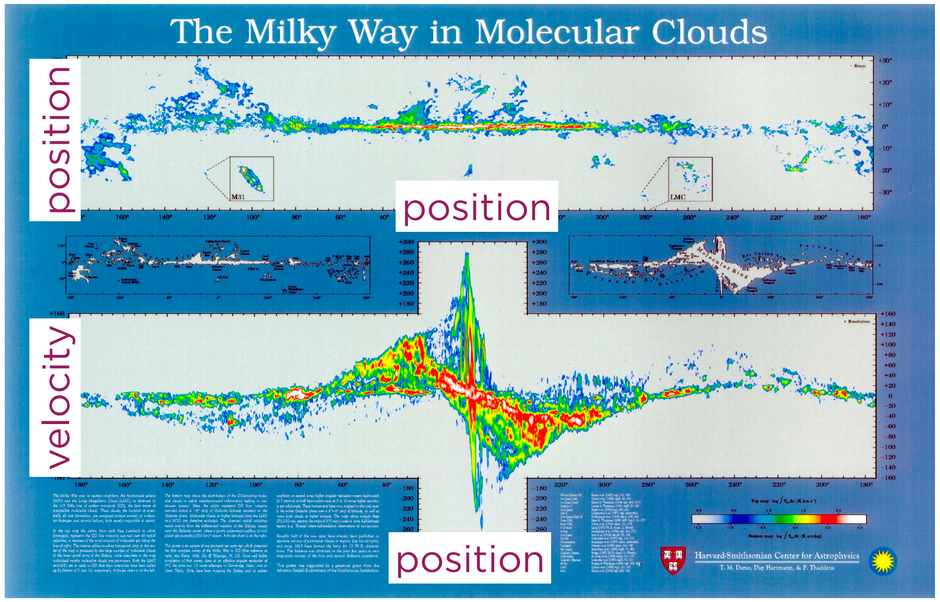


FIG. 4.—*Distribution of neutral hydrogen in the Galactic System. The maximum densities in the z-direction are projected on the galactic plane, and contours are drawn through the points.*

CO

Dame et al 2001



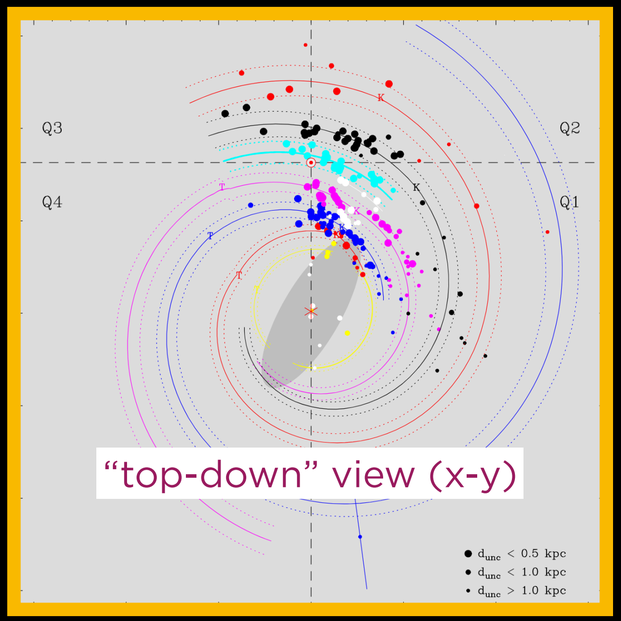
p-p-p = true 3D space data

true distance



Maser VLBI parallax

today's "gold standard" for distance measurement



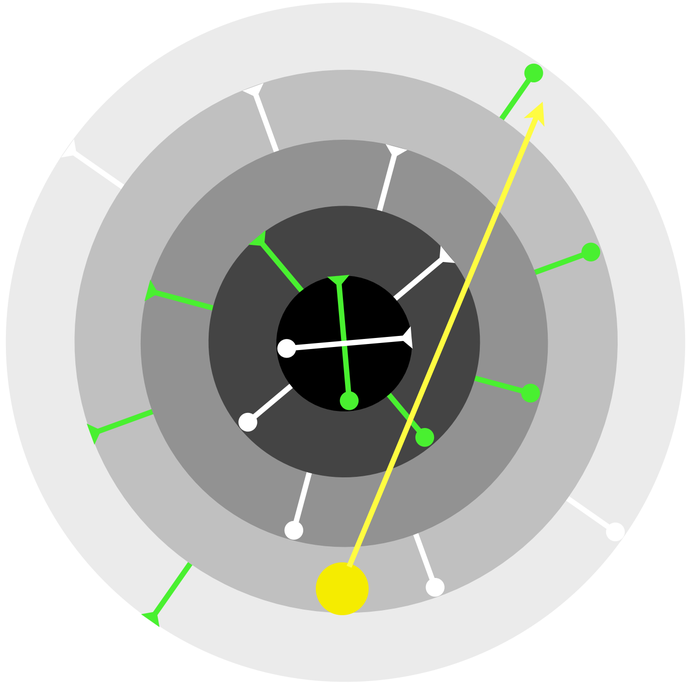
Reid et al. 2019

kinematic distance

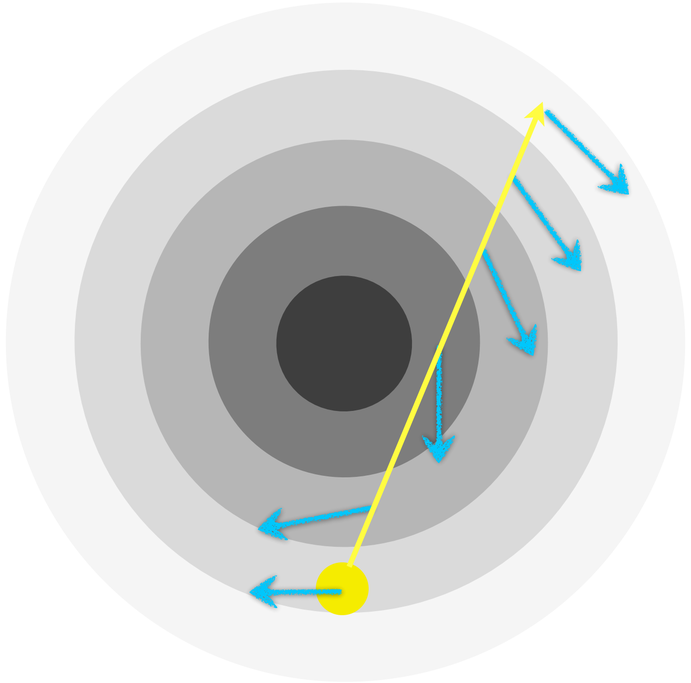
A galaxy as viewed from its outskirts…



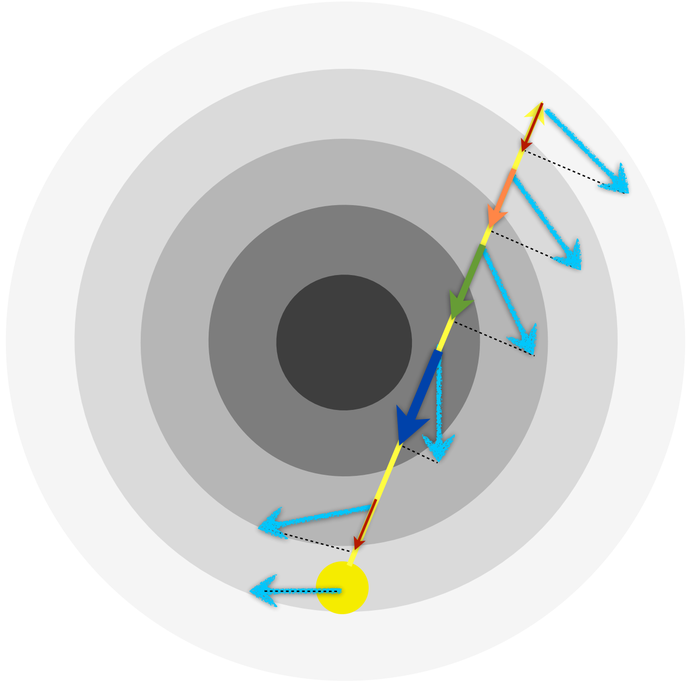
kinematic distance

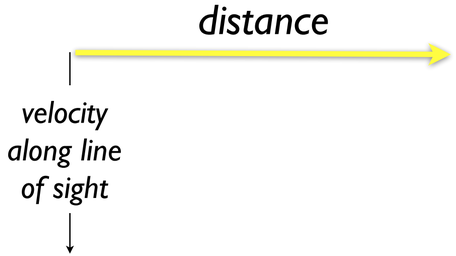


kinematic distance



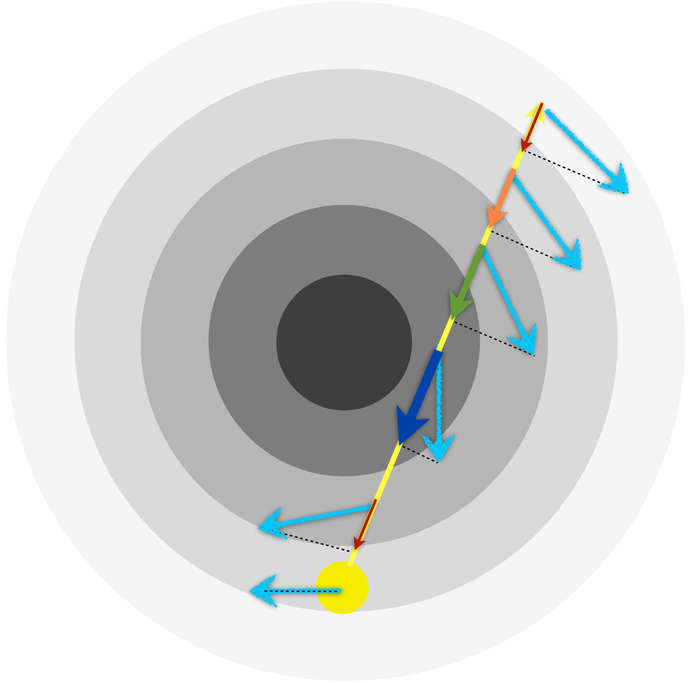
kinematic distance

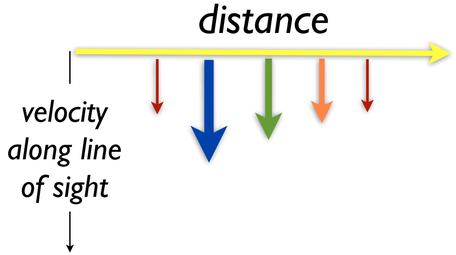




kinematic distance

Not useful for *detailed* structure within a galaxy.
(in the same way that the Hubble Flow doesn't work on small scales).





QUICK(!) BACKGROUND

1. STAR FORMATION
2. LIMITATIONS OF “P-P-V” SPACE

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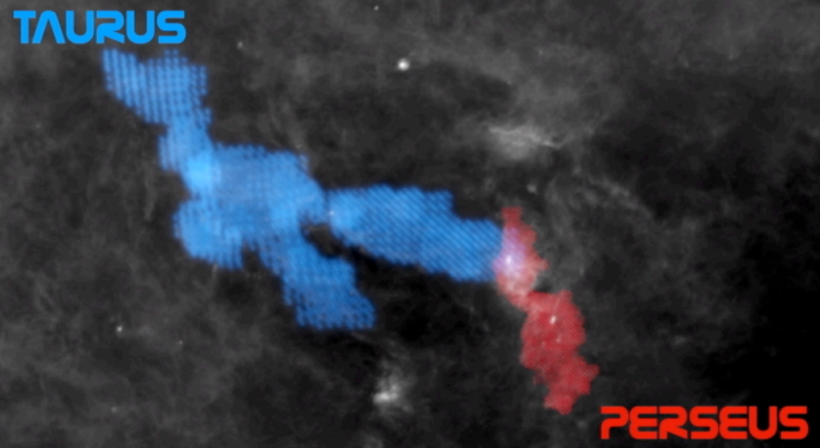
e.g. THE PER-TAU DECEPTION/REVELATION

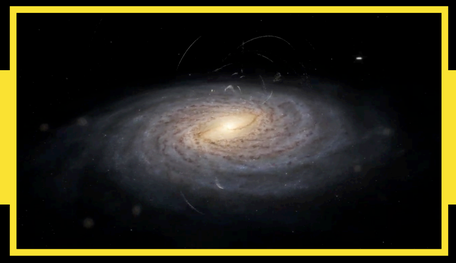
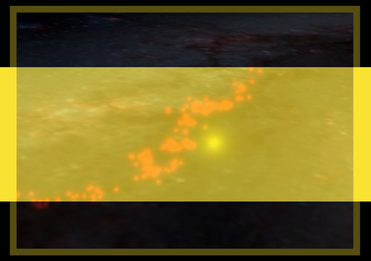
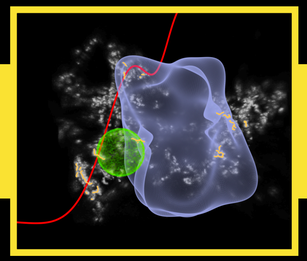
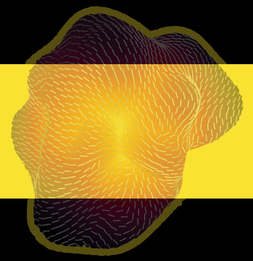
THE LIMITATION/DECEPTION: Spectral line maps show the parts of TAURUS & PERSEUS that “touch” as seen on the sky to be at the SAME line-of-sight velocity.

THE REVELATION: “3D dust mapping” shows …

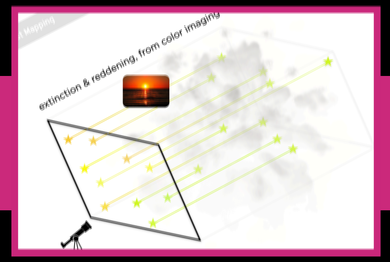


The NEW Milky Way

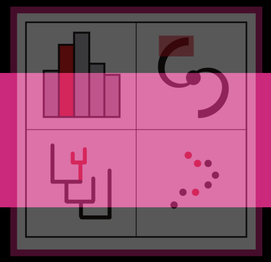
what it looks like

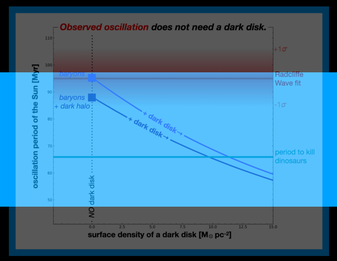
how we know

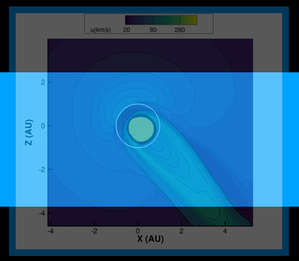



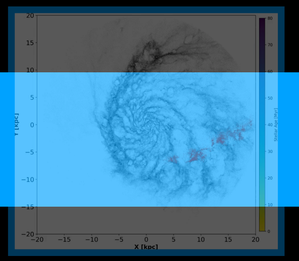


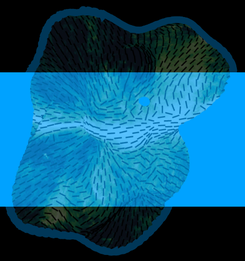


why it matters





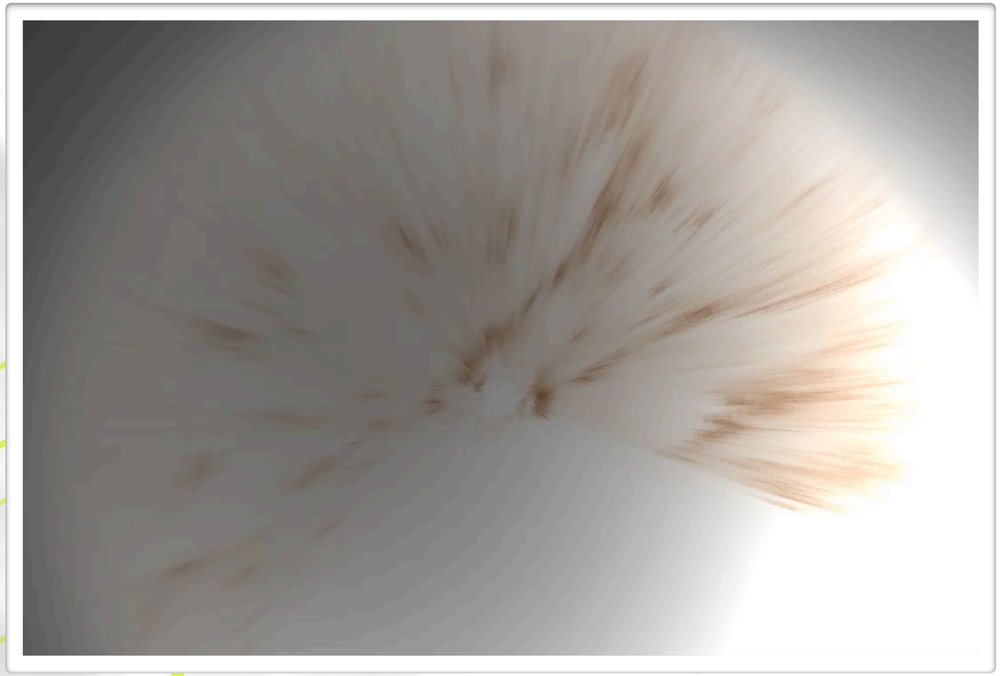




3D Dust Mapping

extinction & reddening, from color imaging

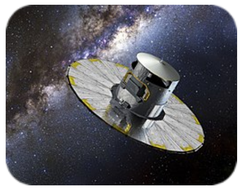


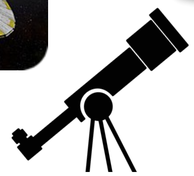


Green et al. 2019

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

Ask Torsten Enβlin for much more information!





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

Glue (/Users/aagoodman/Library/CloudStorage/GoogleDrive-goodman.alyssa@gmail.com/.shortcut-targets-by-id/1e4RysNClnsaerZT11AaNJ9GKPS9q7vZg/MilkyWay3D.ORG/Sessions/munich_d

Open Session | Export Session | Import Data | Export Data/Subsets | Link Data | x² Arithmetic attributes | Active Subset: None/Create New (the next selection will create a subset)

Data Collection

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- Reid2019_ApJ_885_131_LocalArmFit_MW3D[HDU1]
- Reid2019_ApJ_885_131_SGNArmFit_MW3D[HDU1]
- Reid2019_ApJ_885_131_MW3D[HDU1]
- Hunt2023_arXiv_2303.13424_MW3D[HDU1]
- Lallement2019_A+A_625_A135_Split_MW3D[HDU1]
- Edenhofer_2023_3D_Dust_XYZ_Revised-2

Subsets

Plot Layers - 3D Volume Rendering

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- [x] Zucker2021_ApJ_919_35_spines_MW3D[HDU1]
- [x] Bialy2021_ApJL_919_L5_MW3D[HDU1]
- [x] Pelgrims2020_A+A_636_A17_lmax10_MW3D[HDU1]
- [x] Alves2020_Nat_578_237_MW3D[HDU1]
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Limits: 5.89626e-08 | 0.00643762

Color:

Plot Options - 3D Volume Rendering

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min/max: -73.9532 ⇄ 812.953

stretch: 1.00

y axis Pixel Axis 1 [y]

min/max: -73.9532 ⇄ 812.953

stretch: 1.00

z axis Pixel Axis 0 [z]

min/max: -54.101 ⇄ 593.101

stretch: 1.00

reference: Leike2020_A+A_639_A138_xyz_cube_MW3D

resolution: 256

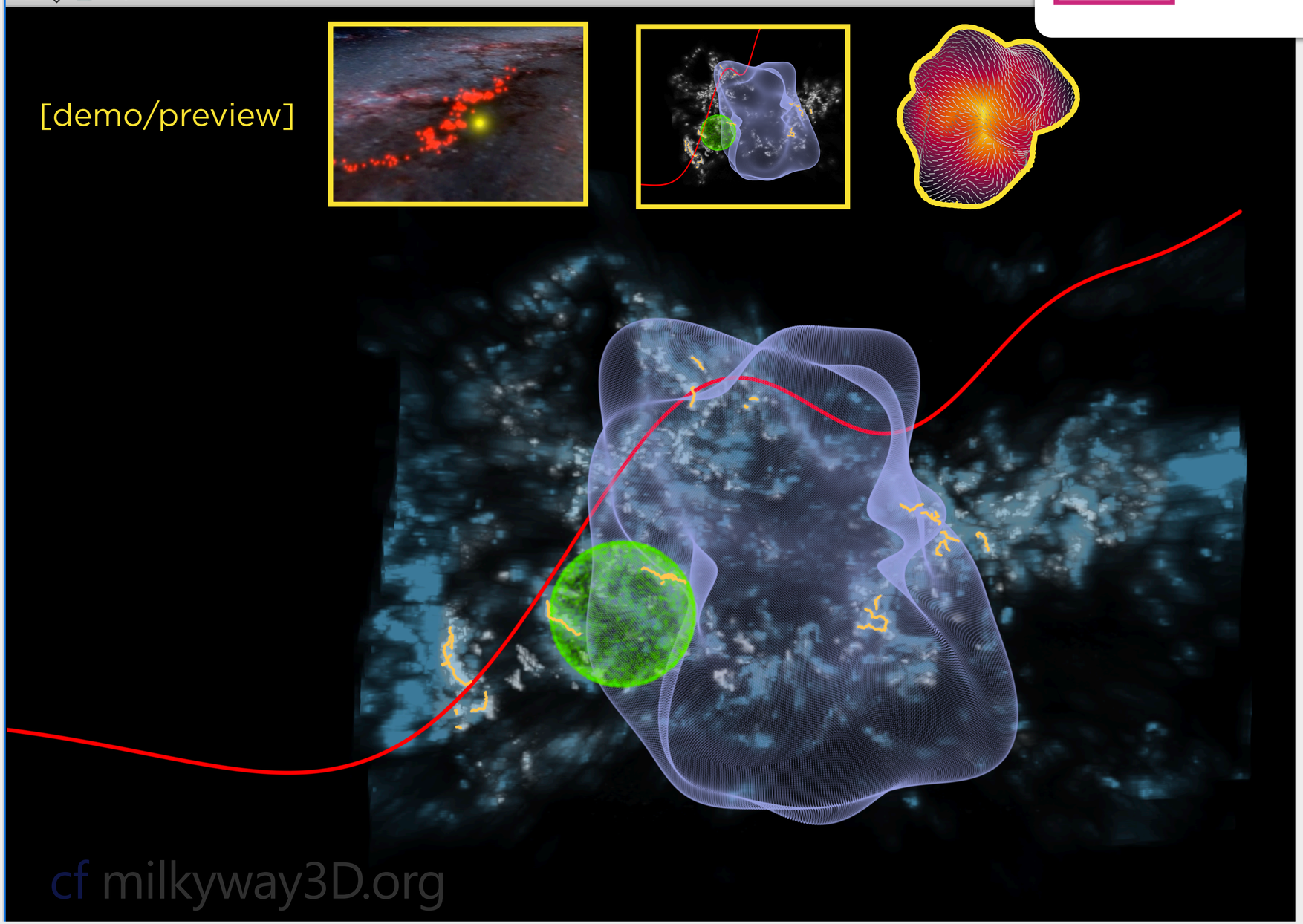
- [x] Native aspect ratio
- [ ] Perspective
- [ ] Downsample when panning

Line Width 1

- [ ] Show axes

Tab 1 | Tab 2 | Tab 3

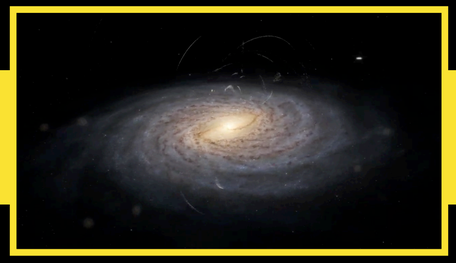
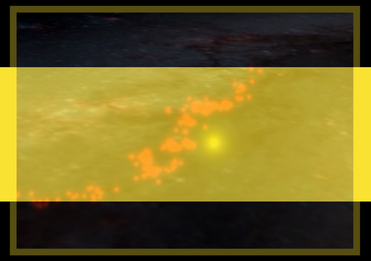
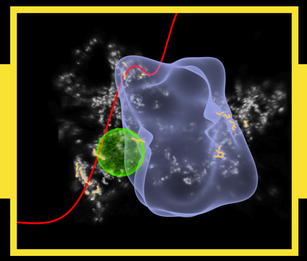
3D Volume Rendering



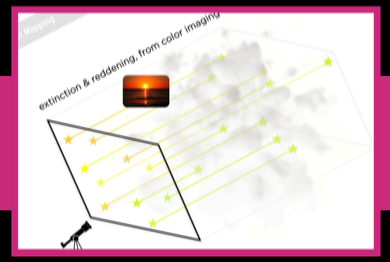
glue
multidimensional data exploration

The NEW Milky Way

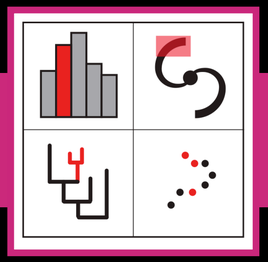
what it looks like

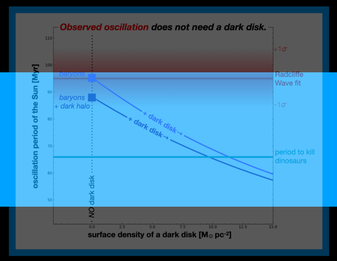

how we know

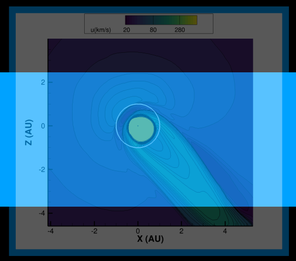



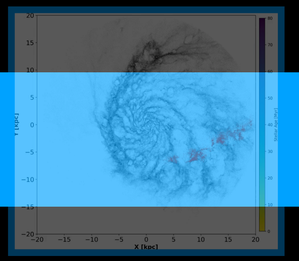


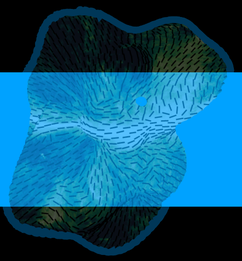


why it matters

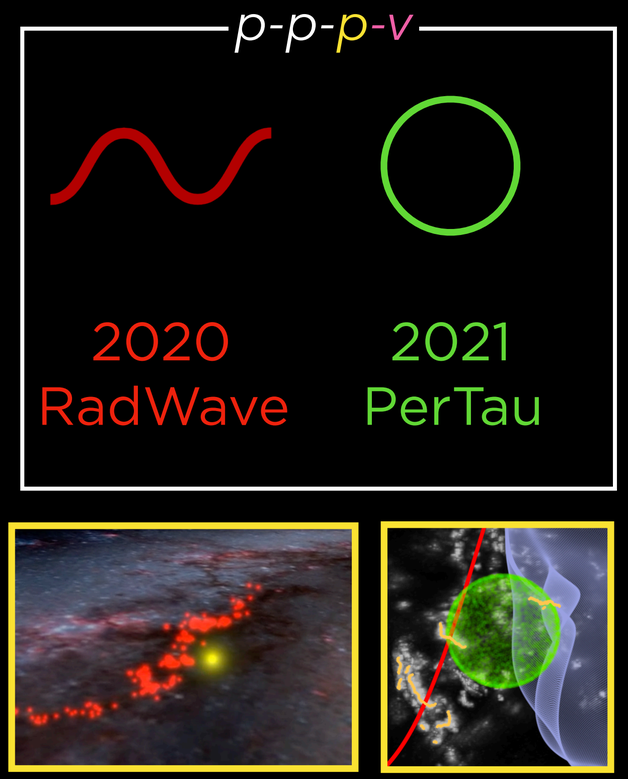




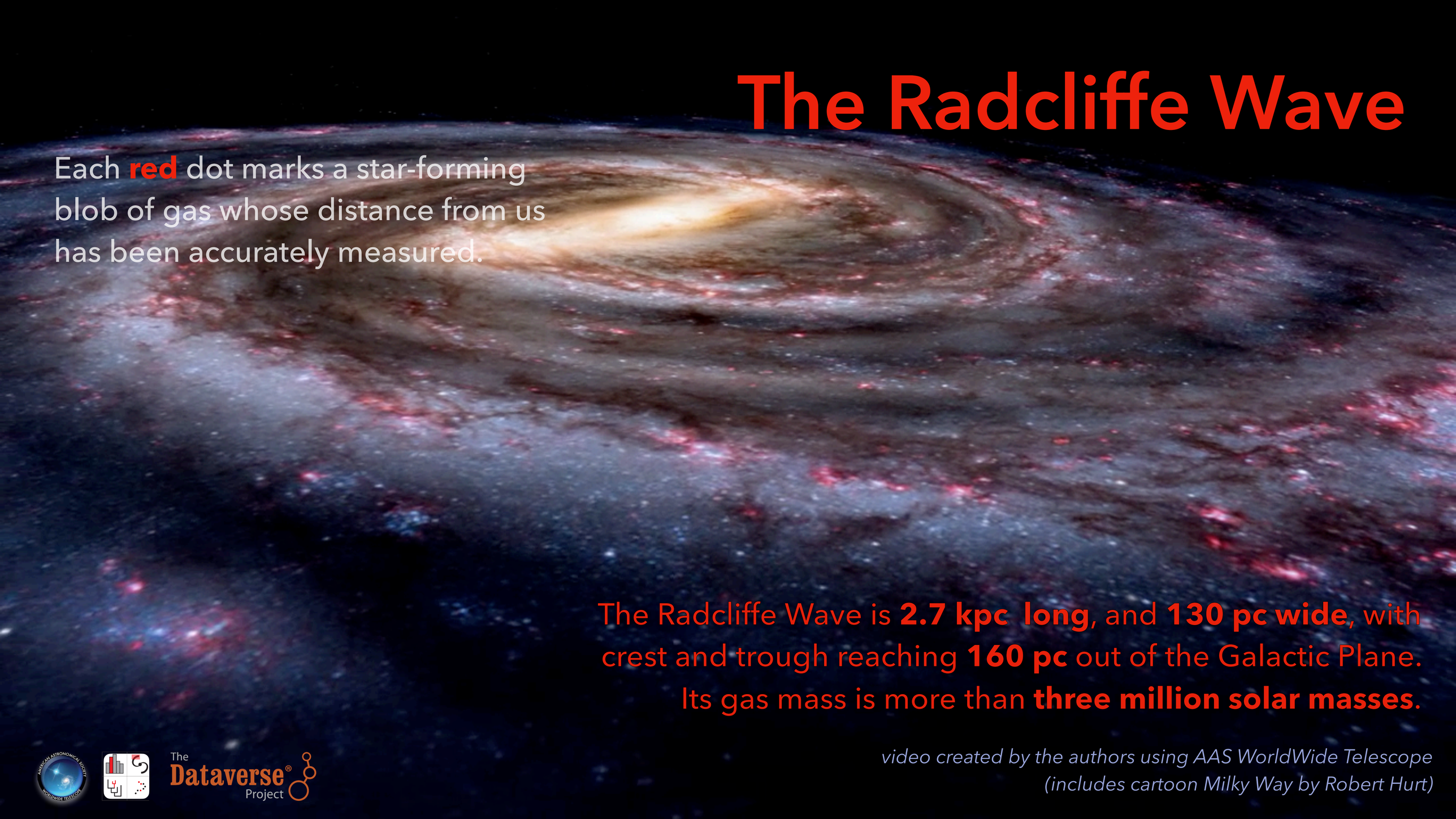




What can be learned from good 3D dust maps + spectral-line gas maps?



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**.

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

The Radcliffe Wave (as of 2020!)

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!!

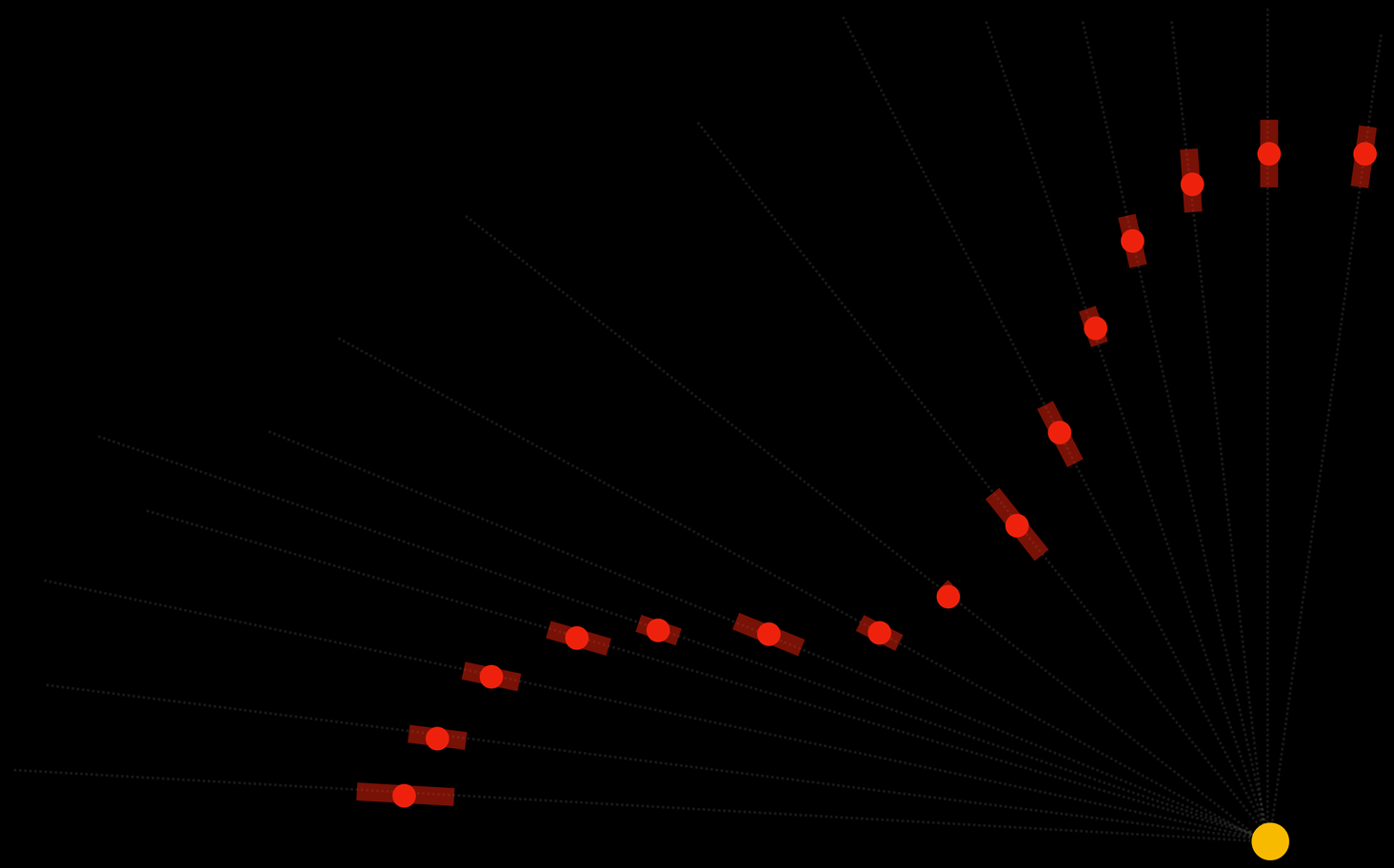
We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.



Uncertain Distances

SCHEMATIC CARTOON(!)

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



"The Radcliffe Wave"

SCHEMATIC CARTOON(!)

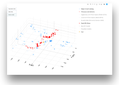
Distances estimates **AFTER** 3D dust mapping & Gaia (~5%)

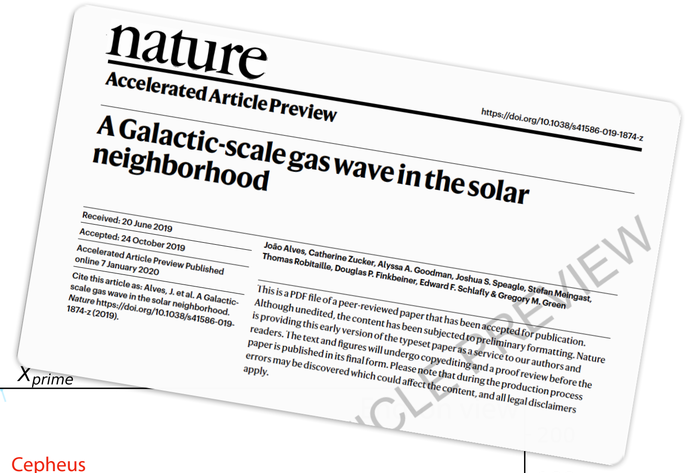
The Radcliffe Wave

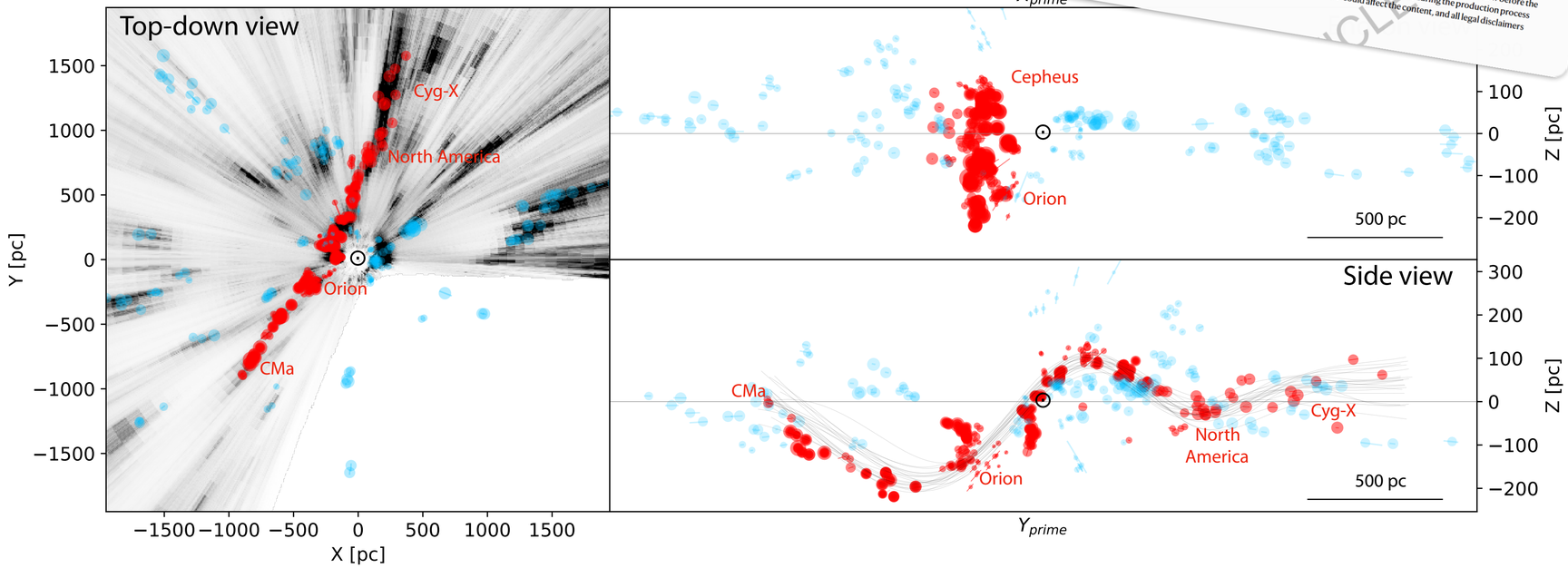
RADWAVE

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

click the figure to launch interactive…







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)

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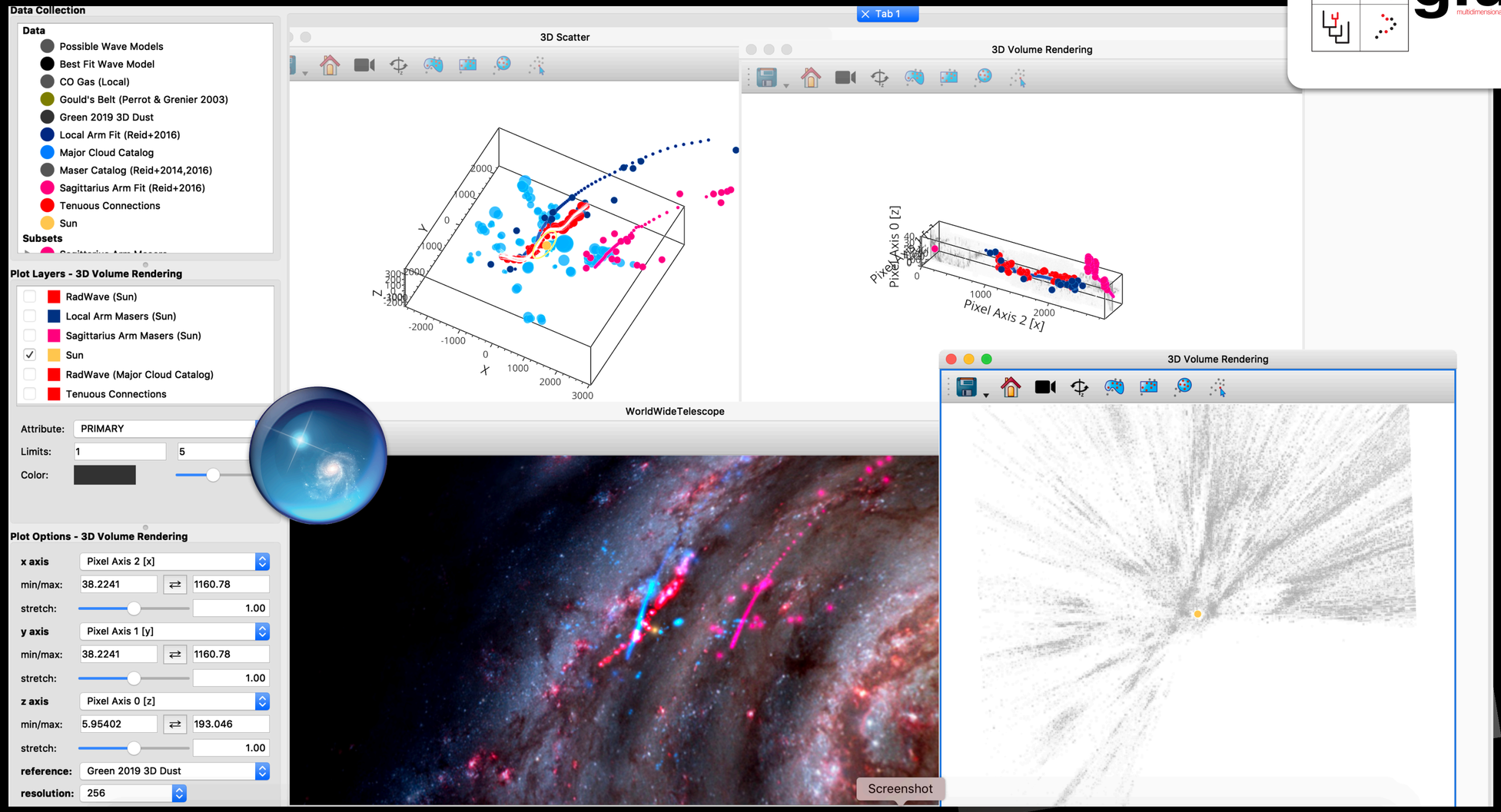
“Seeing” The Radcliffe Wave, in 3D

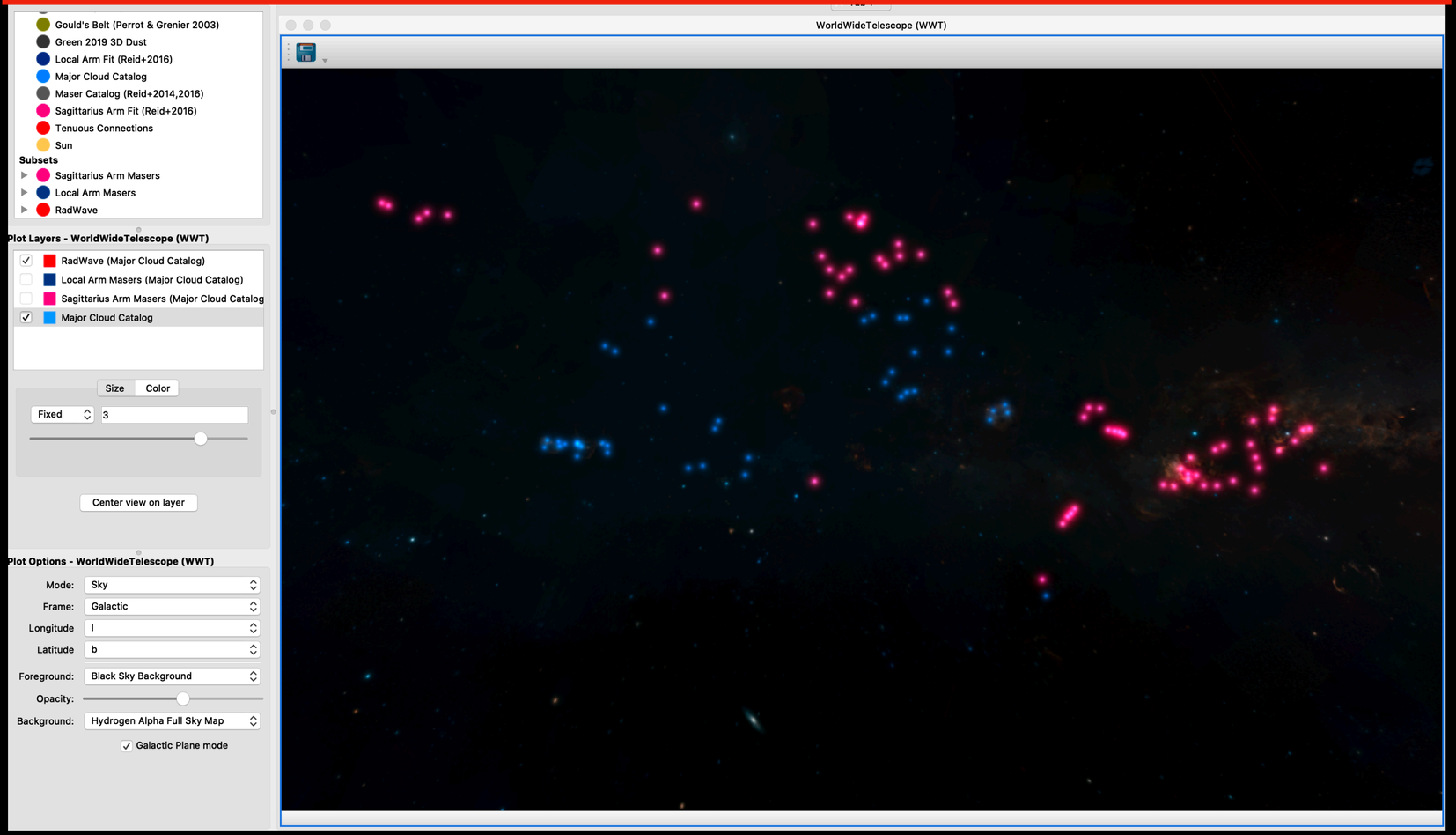


AAS WorldWide Telescope: worldwidetelescope.org

glue: glueviz.org

WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

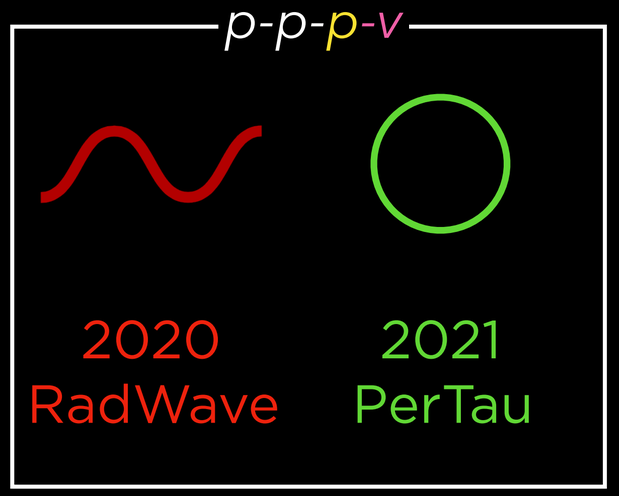
It's not apparent in 2D on the Sky.

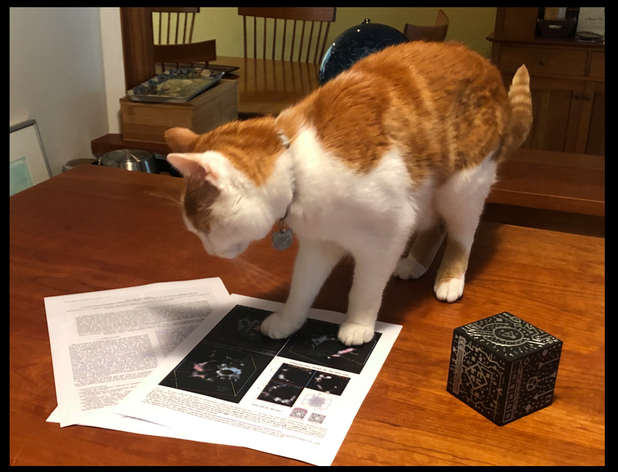


AAS WorldWide Telescope: worldwidetelescope.org

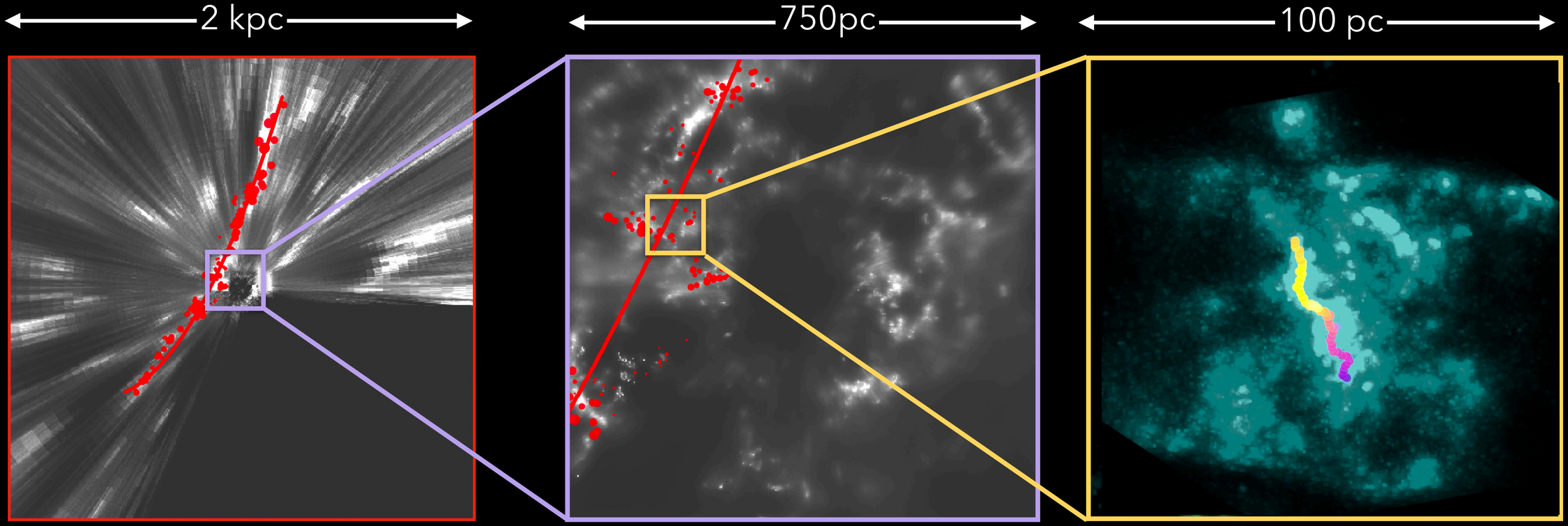
glue: glueviz.org

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





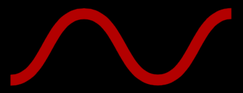
2019 to 2021: from distances to shapes

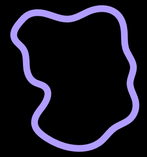


Zucker et al. 2020; Zucker & Speagle et al. 2019; Alves et al. 2020; Green et al. ***2019***

Leike, Glatzle, & Enßlin ***2020***

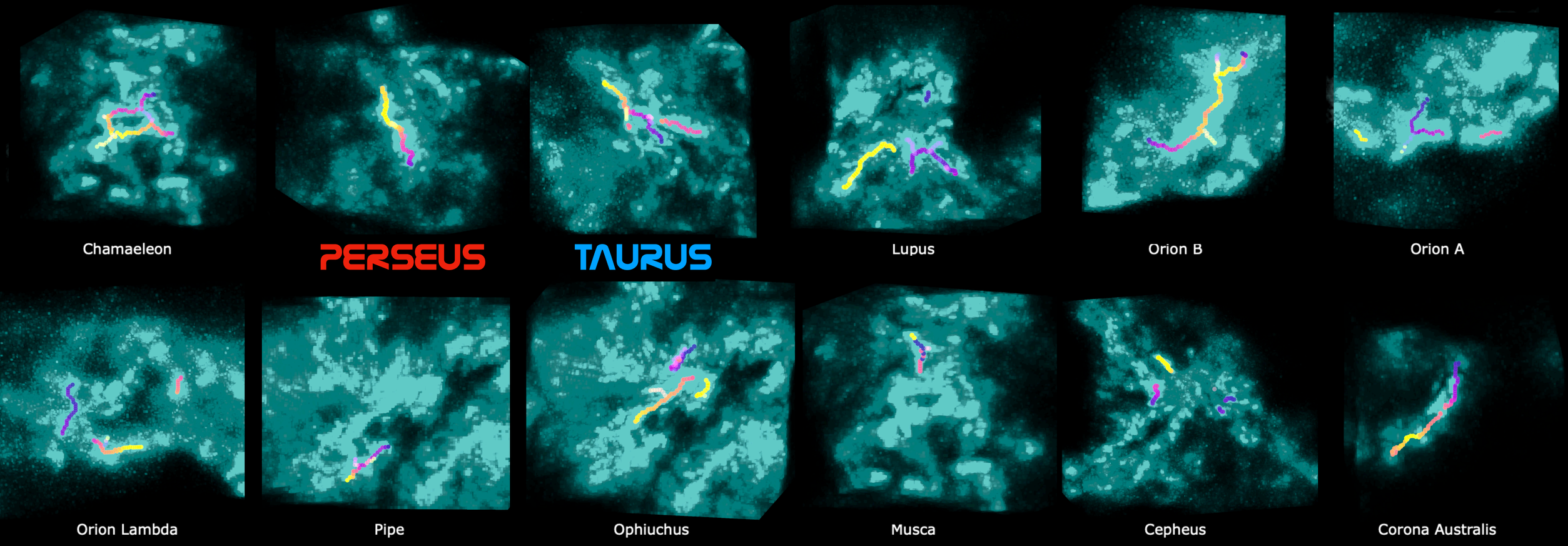
Zucker et al. ***2021****; Leike, Glatzle, & Enßlin 2020*







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



Zucker et al. ***2021***

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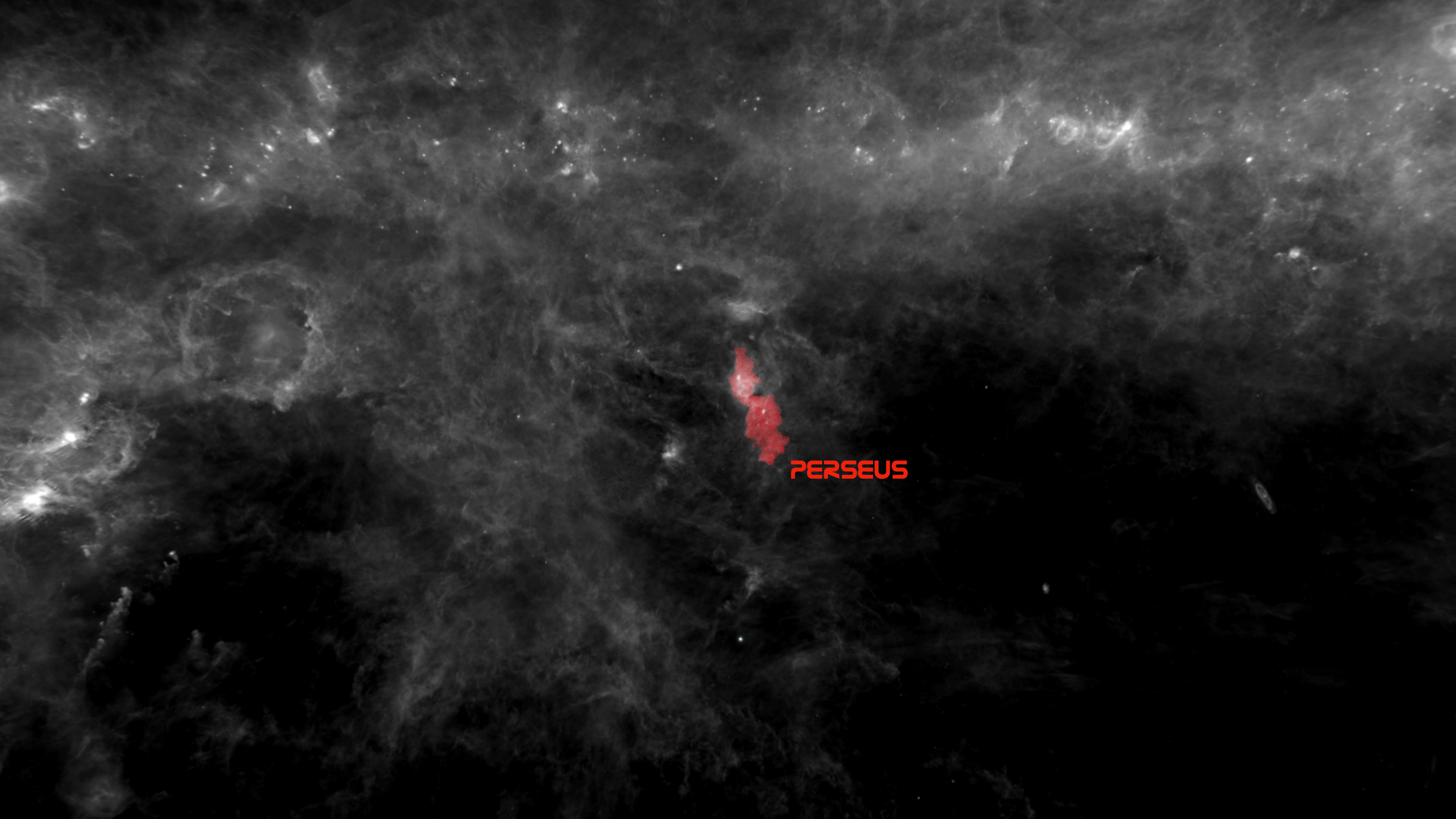
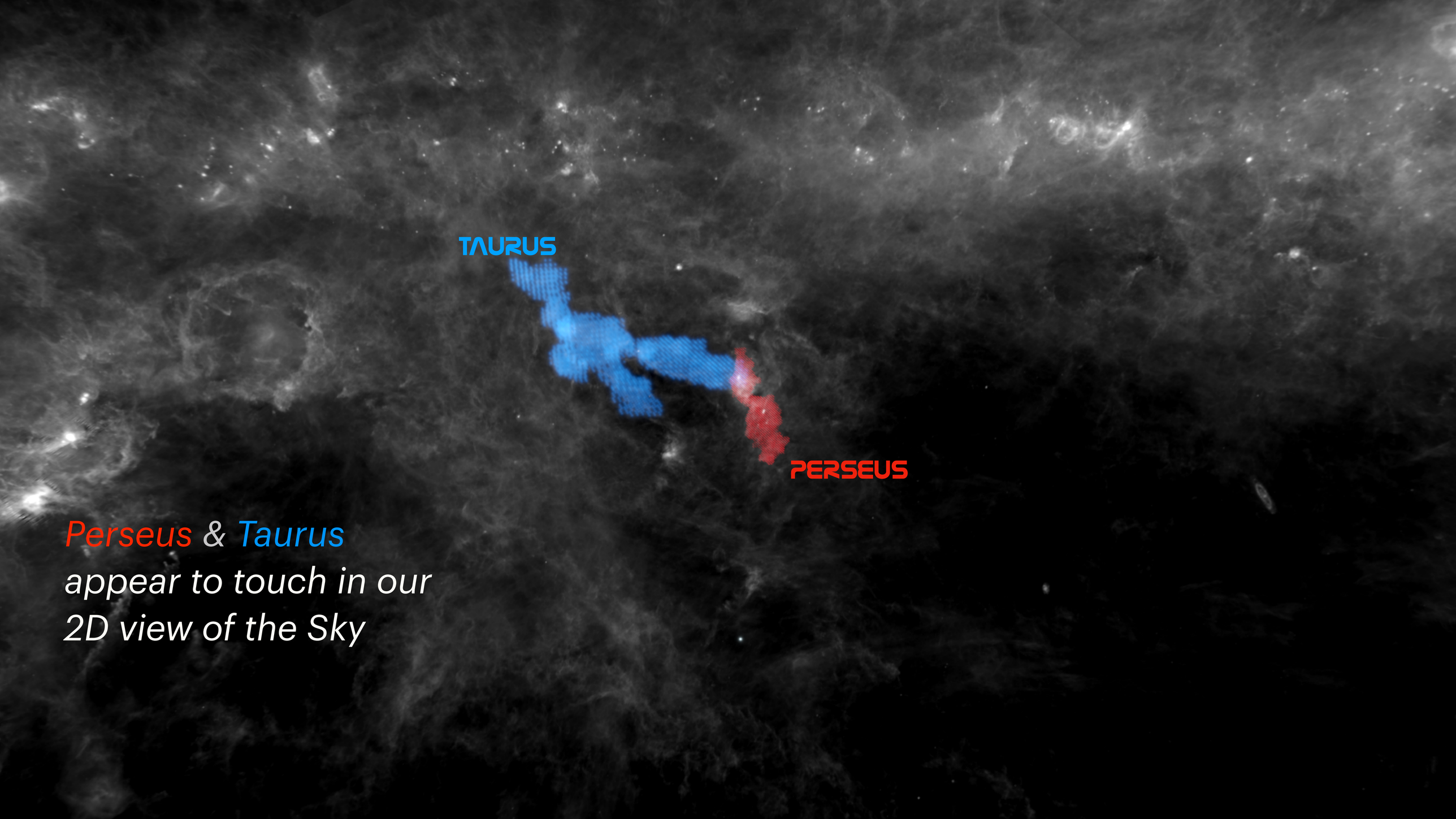
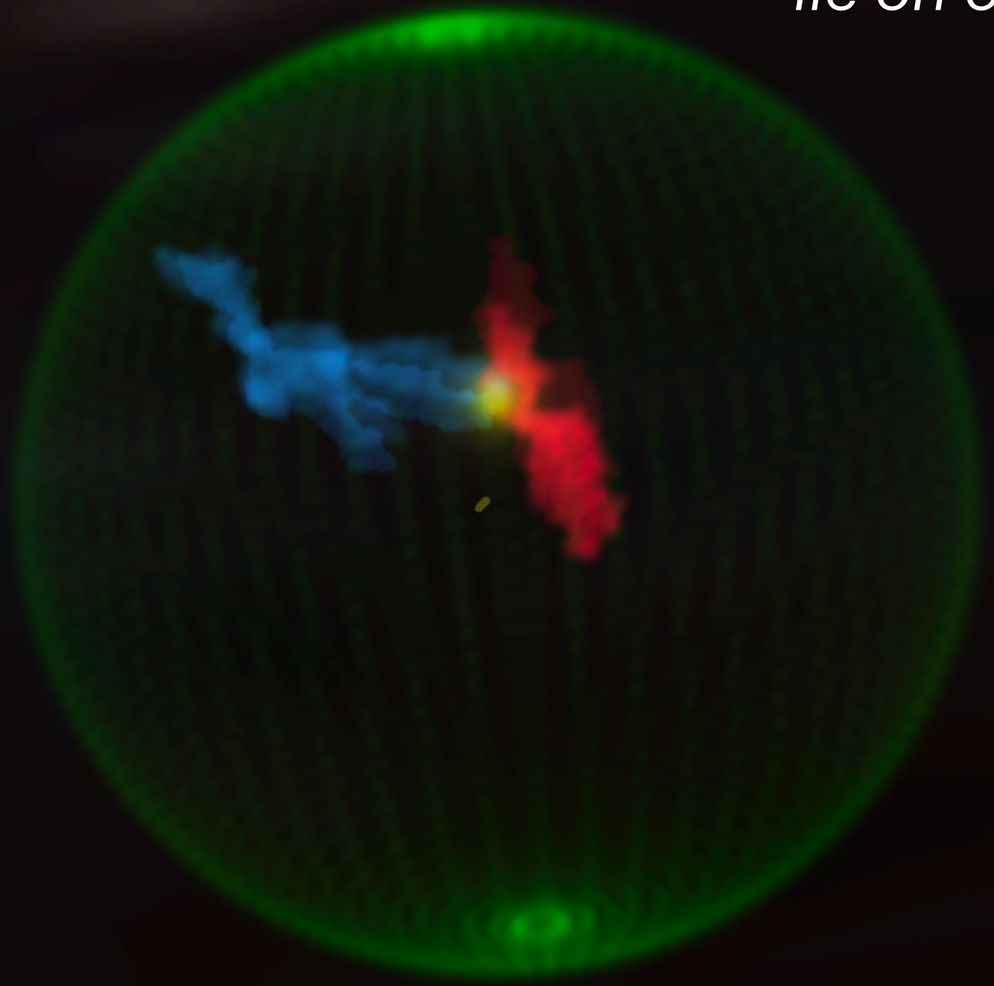

PERSEUS



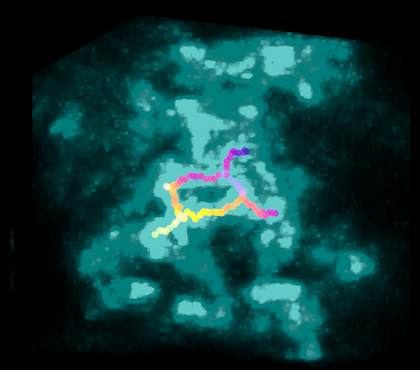
Perseus & *Taurus*
appear to touch in our
2D view of the Sky

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

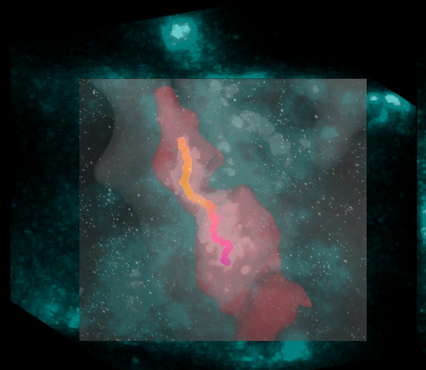


Bialy et al. 2021

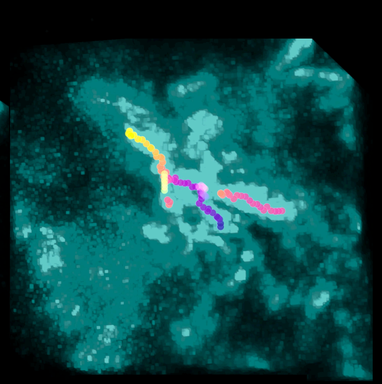

animation by Jasen Lux Chambers



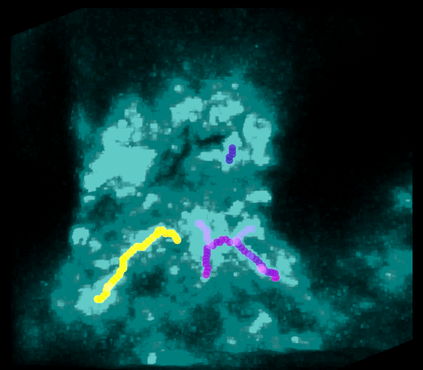
Chamaeleon



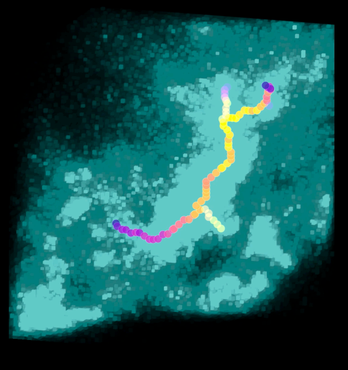
PERSEUS



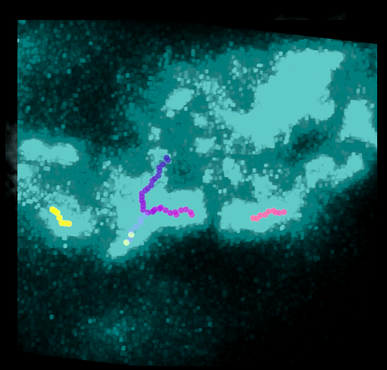
TAURUS



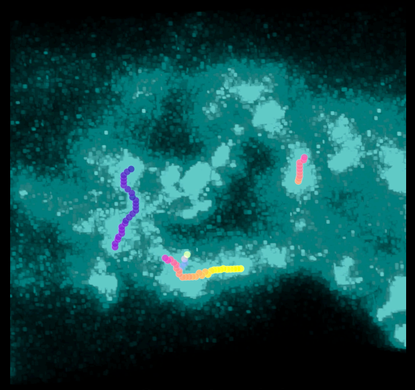
Lupus



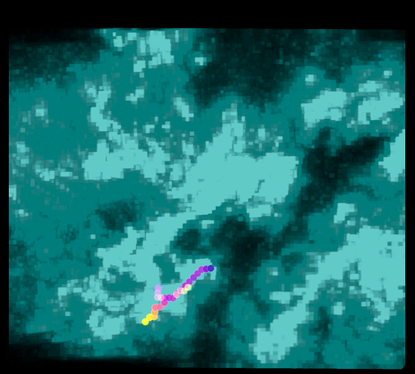
Orion B



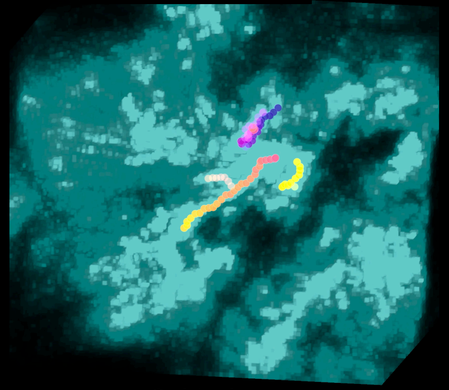
Orion A



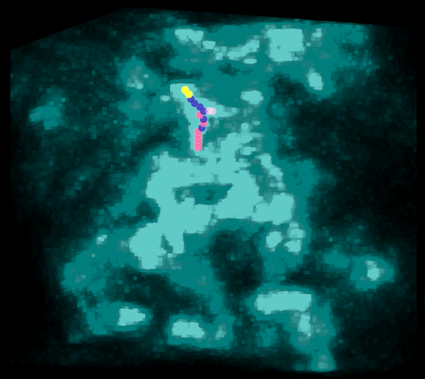
Orion Lambda



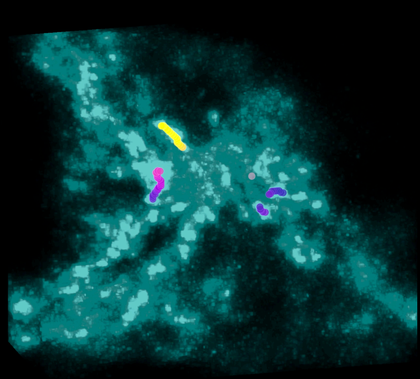
Pipe



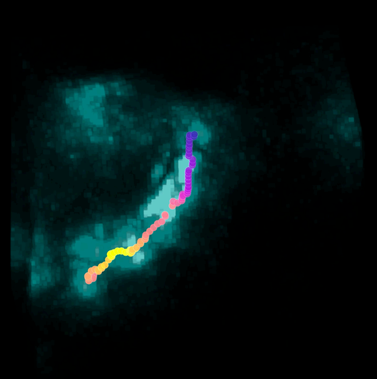
Ophiuchus



Musca



Cepheus



Corona Australis

Zucker et al. ***2021***

The Dataverse® Project

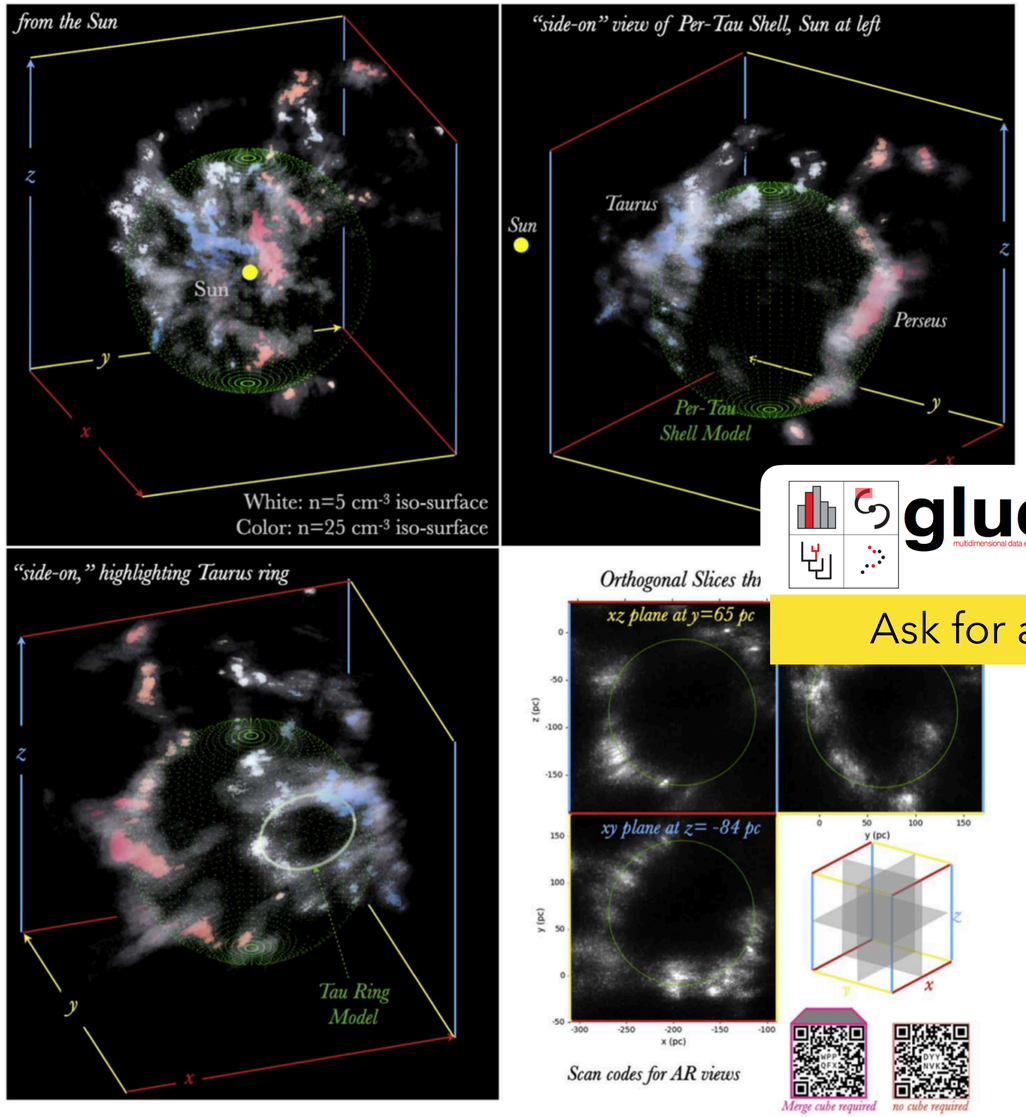


Figure 2. 3D views of the Per-Tau shell (for an interactive version[8] of this figure click here [9]; see Figure 5 for more static visualizations). Plotted are density iso-surfaces at levels $n = 5$ cm^{-3} (gray) and $n = 25$ cm^{-3} (color), overlaid with our spherical-shell model, radius $R_s = 78$ 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.

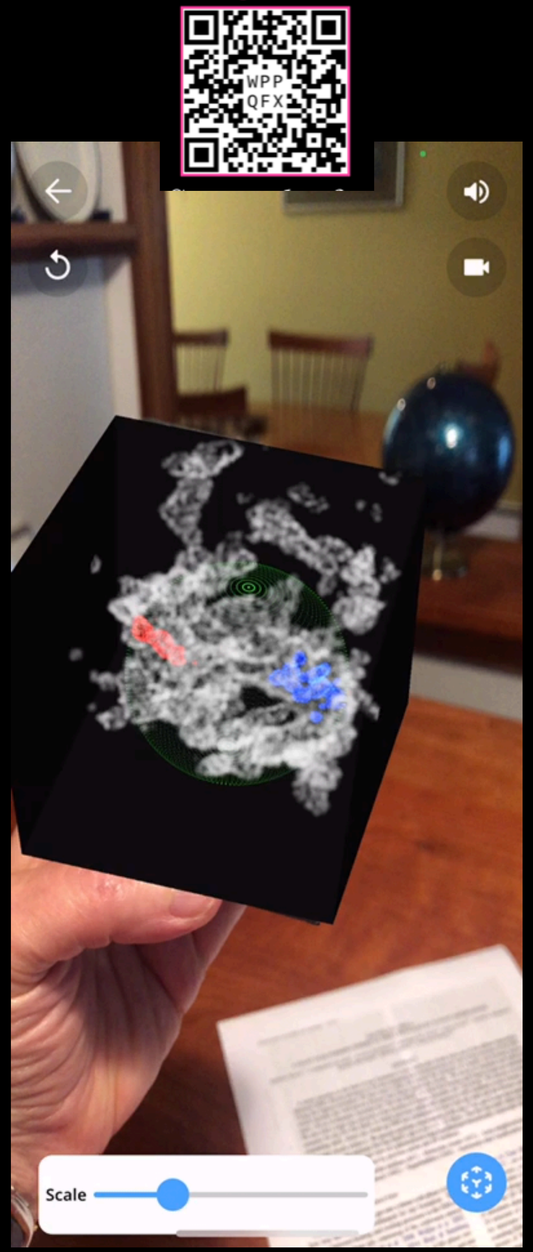
2. *Tau Ring:* in a sky projection the Tau Ring is seen almost edge-on. The near side of the Tau Ring connects with the main body of Taurus at $d \approx 150$ pc, whereas the farthest part extends to $d \approx 220$ pc.

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

glue multidimensional data exploration → COSPACES

Ask for a demo later, please.

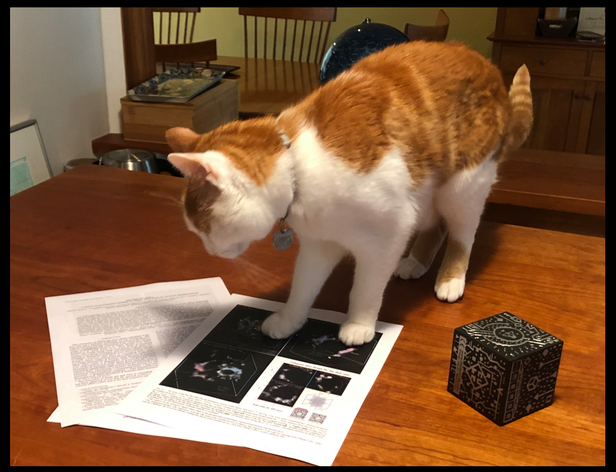


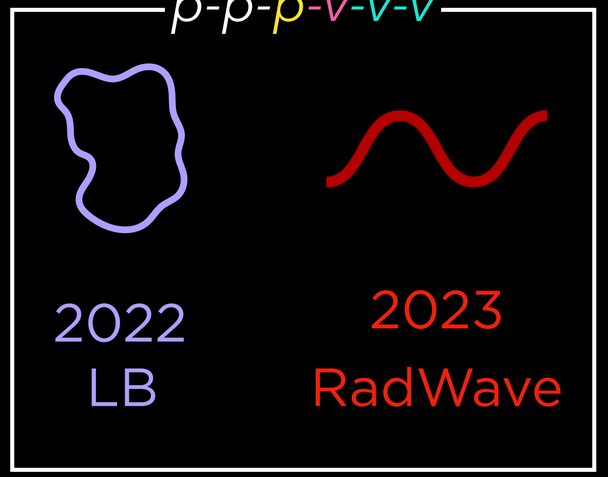


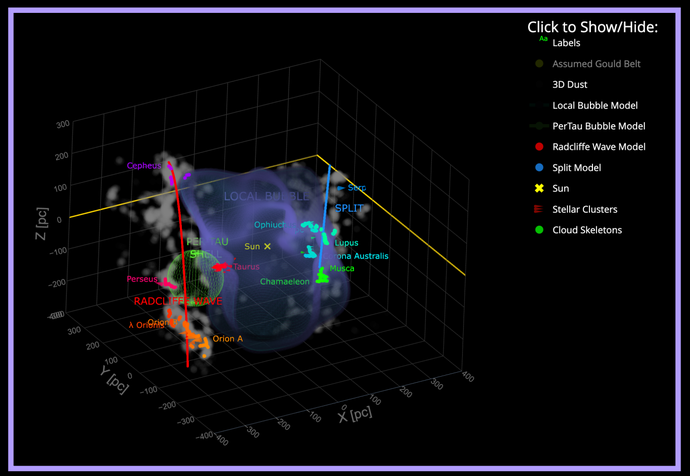
Bialy et al. 2021

The Dataverse® Project

What's even better than a cat photo?

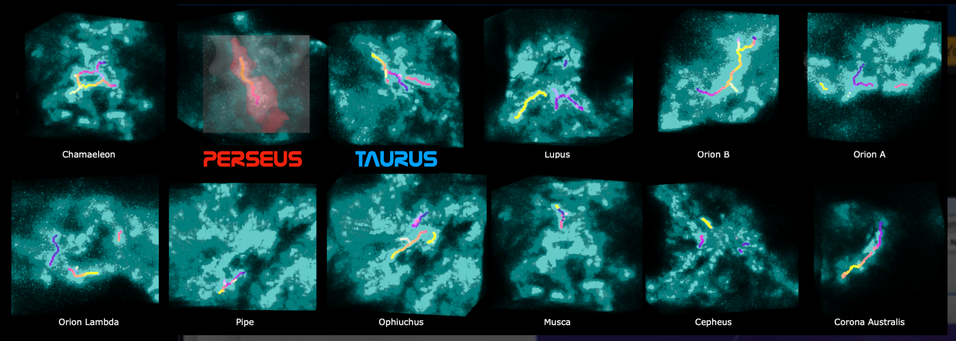






How about interactive 6D figures showing how stars form all around us?

But first, a confession.





THE NEW YORK TIMES, TUESDAY, JANUARY 25, 2022

D4

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.

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.

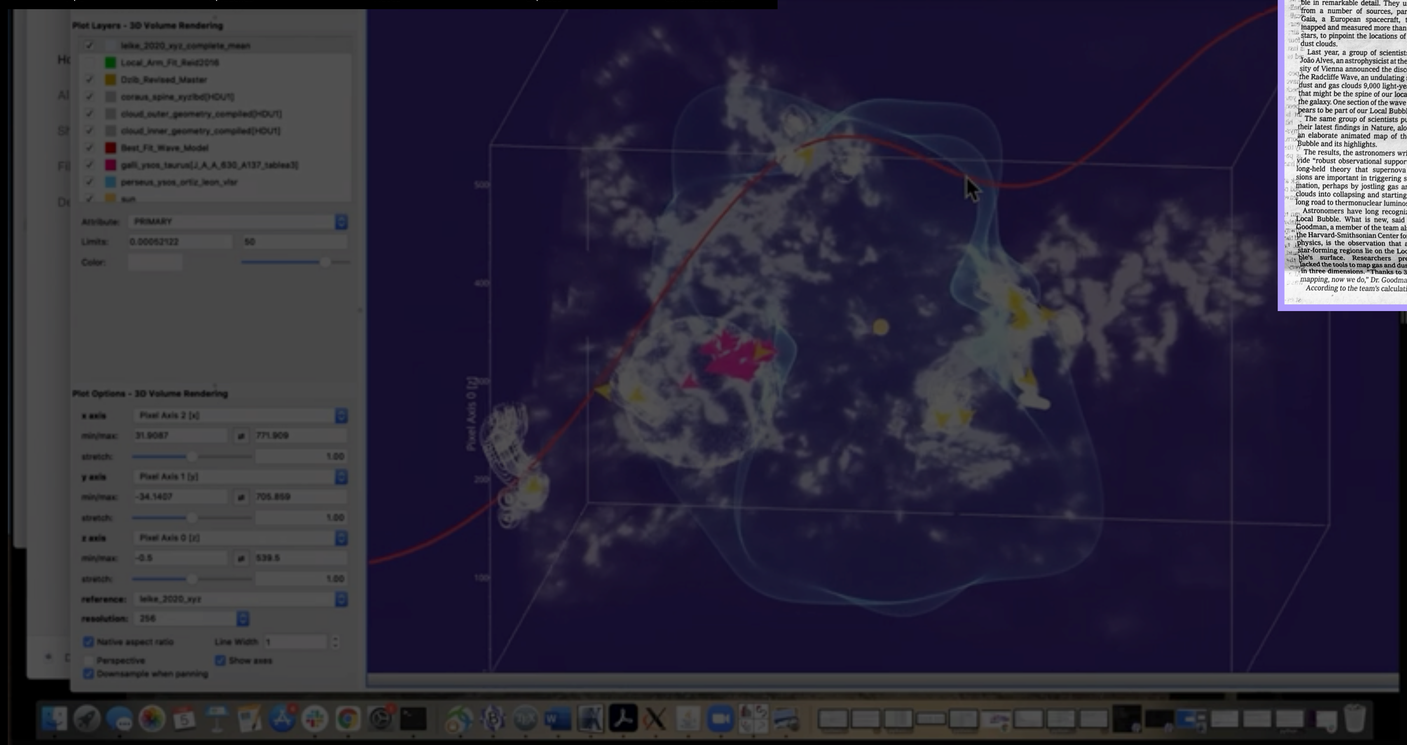
"The sun is moving at a significantly different velocity than the average of the stars and gas in the solar neighborhood," he noted. This would enable it to catch up and pass — or be passed by — the bubble.

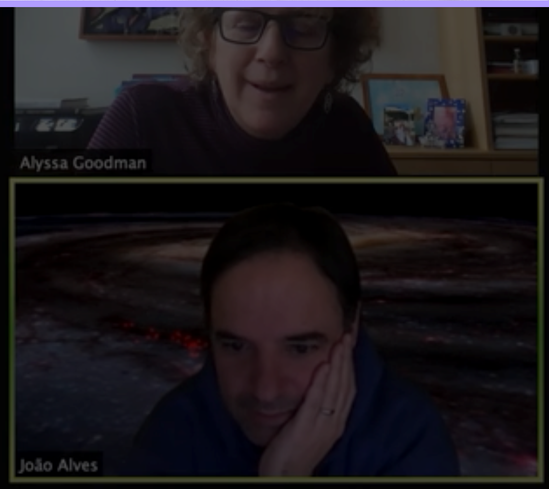
"It was a revelation," Dr. Goodman said, "how kooky the sun's path really is compared with a simple circle."

NYT, January 25, 2022

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.

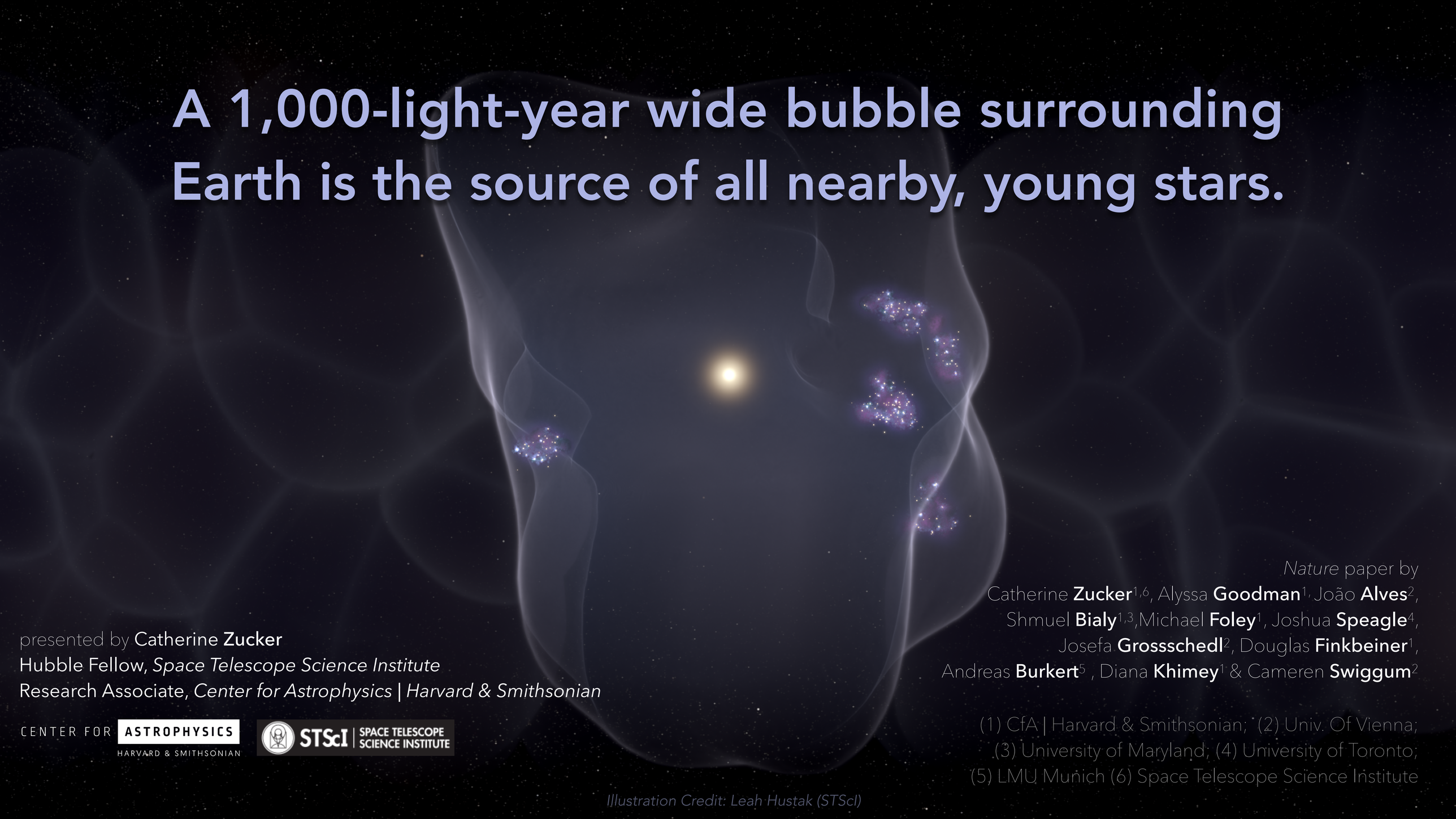
NASA





2022
LB

A 1,000-light-year wide bubble surrounding Earth is the source of all nearby, young stars.



presented by Catherine **Zucker**
Hubble Fellow, *Space Telescope Science Institute*
Research Associate, *Center for Astrophysics | Harvard & Smithsonian*

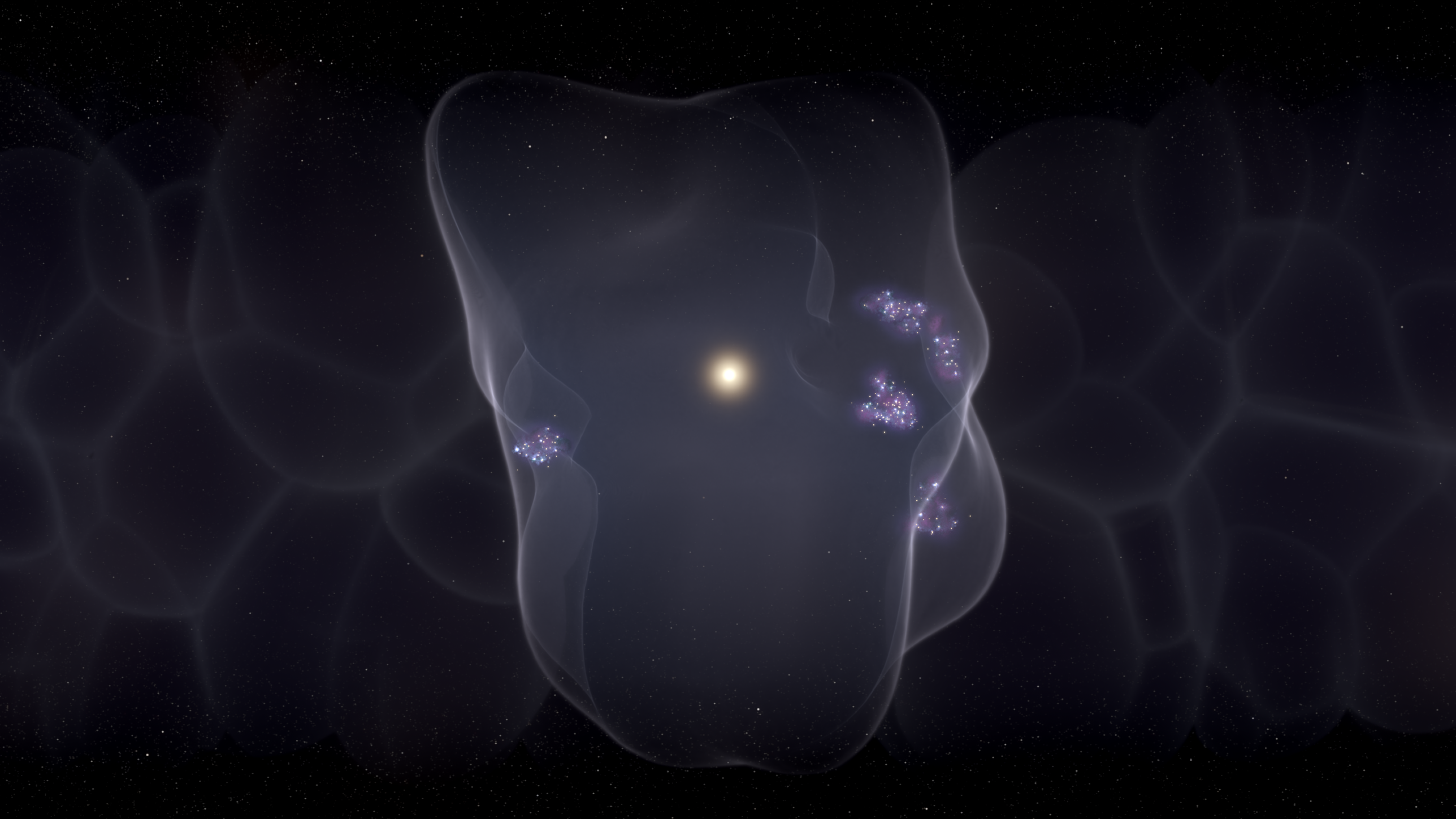
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

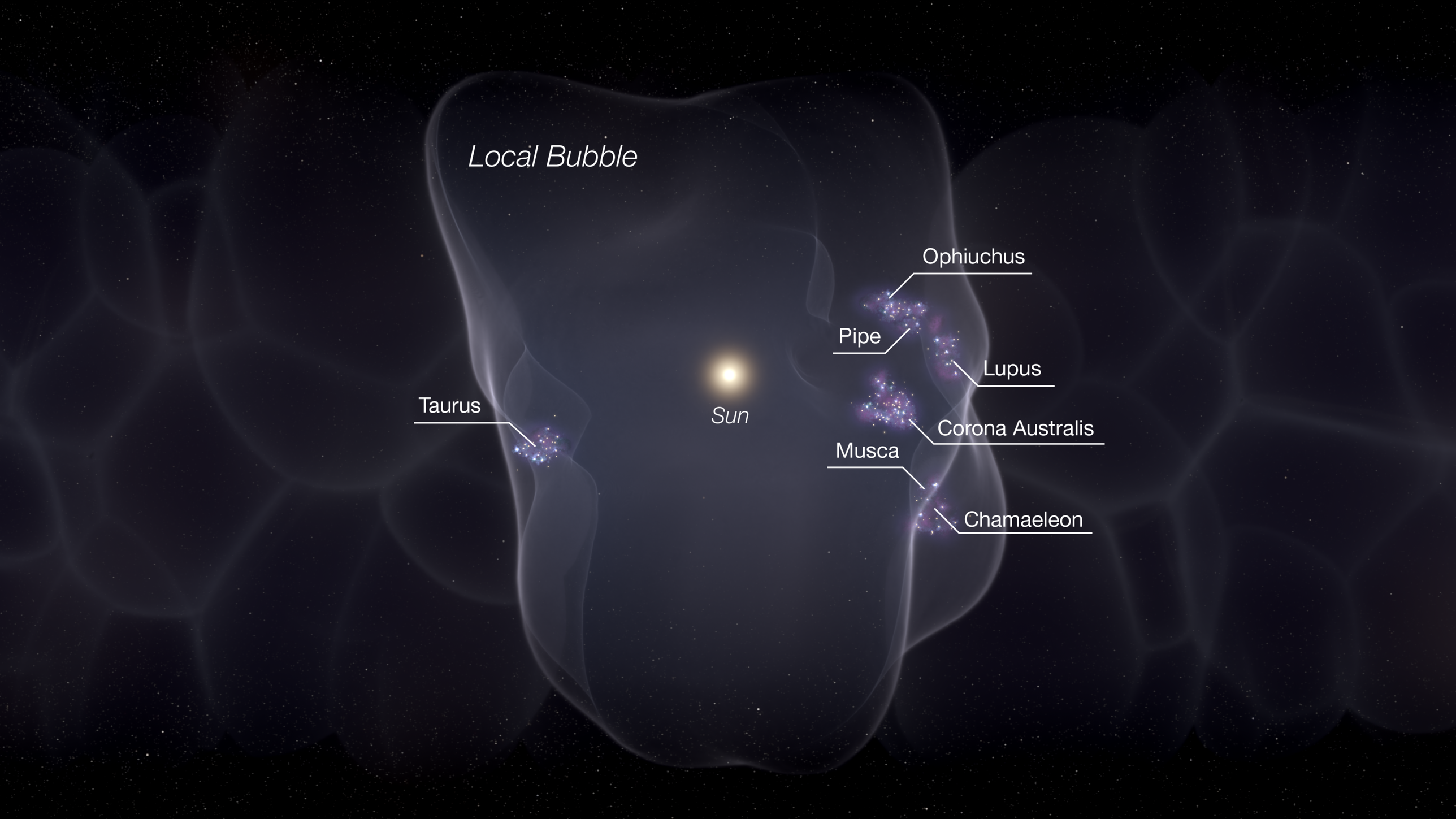
STScI | SPACE TELESCOPE SCIENCE INSTITUTE

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

Illustration Credit: Leah Hustak (STScI)




Local Bubble
Ophiuchus
Pipe
Lupus
Taurus
Sun
Corona Australis
Musca
Chamaeleon

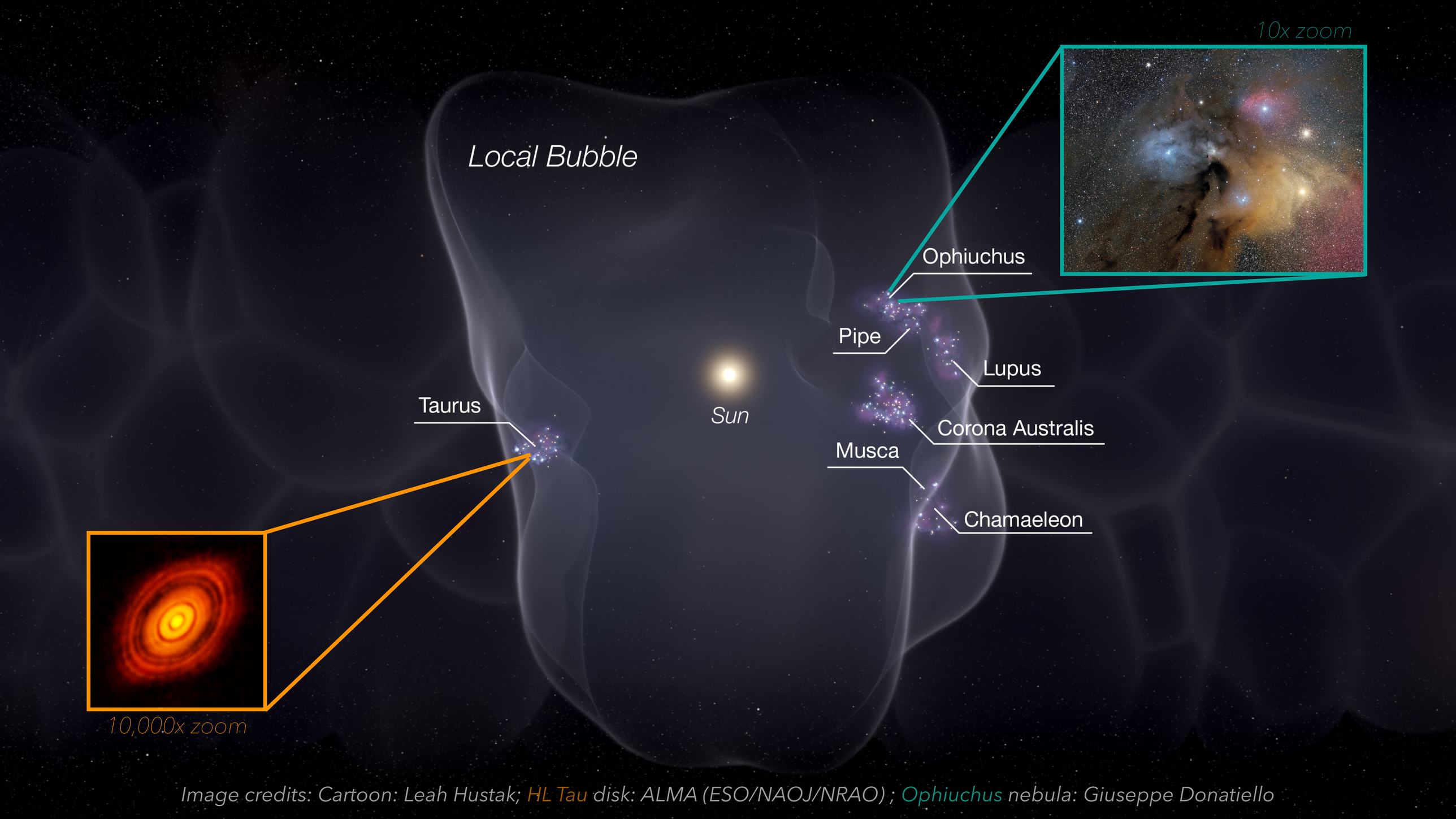
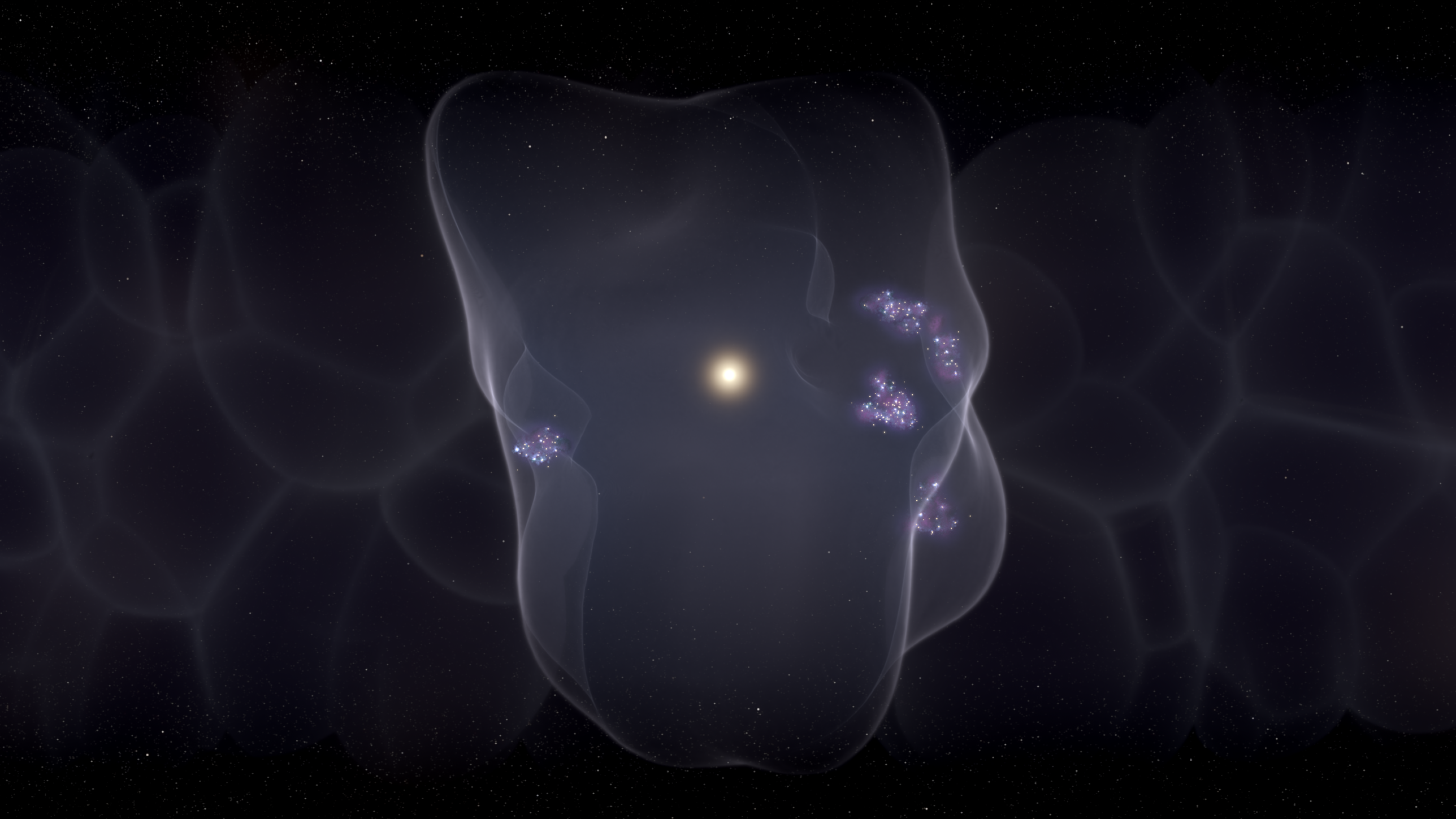


Image credits: Cartoon: Leah Hustak; HL Tau disk: ALMA (ESO/NAOJ/NRAO) ; Ophiuchus nebula: Giuseppe Donatiello



We can reconstruct the evolutionary history of our Galactic neighborhood.

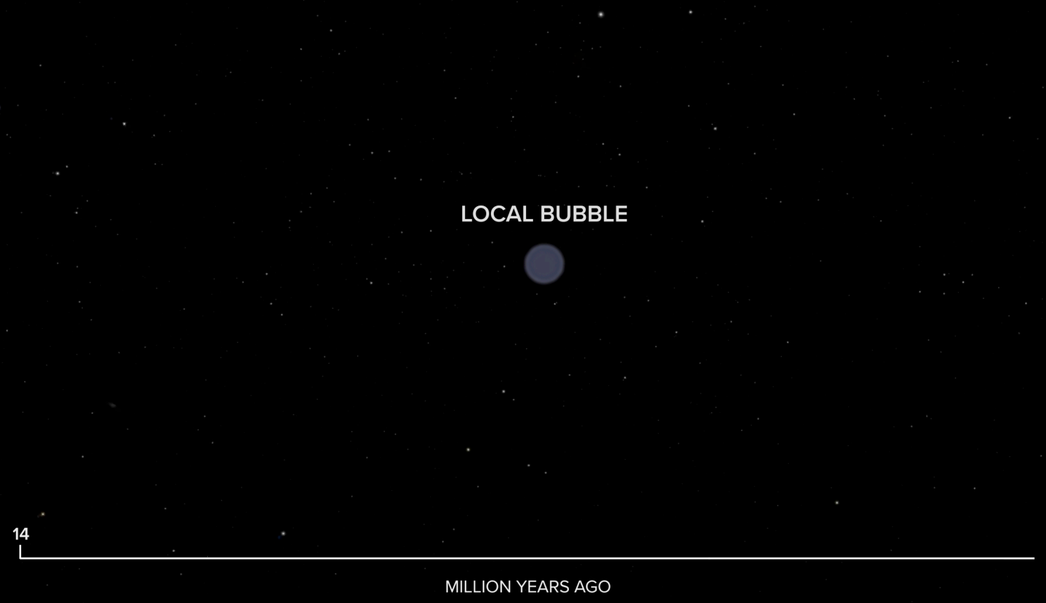


We can reconstruct the evolutionary history of our Galactic neighborhood.

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

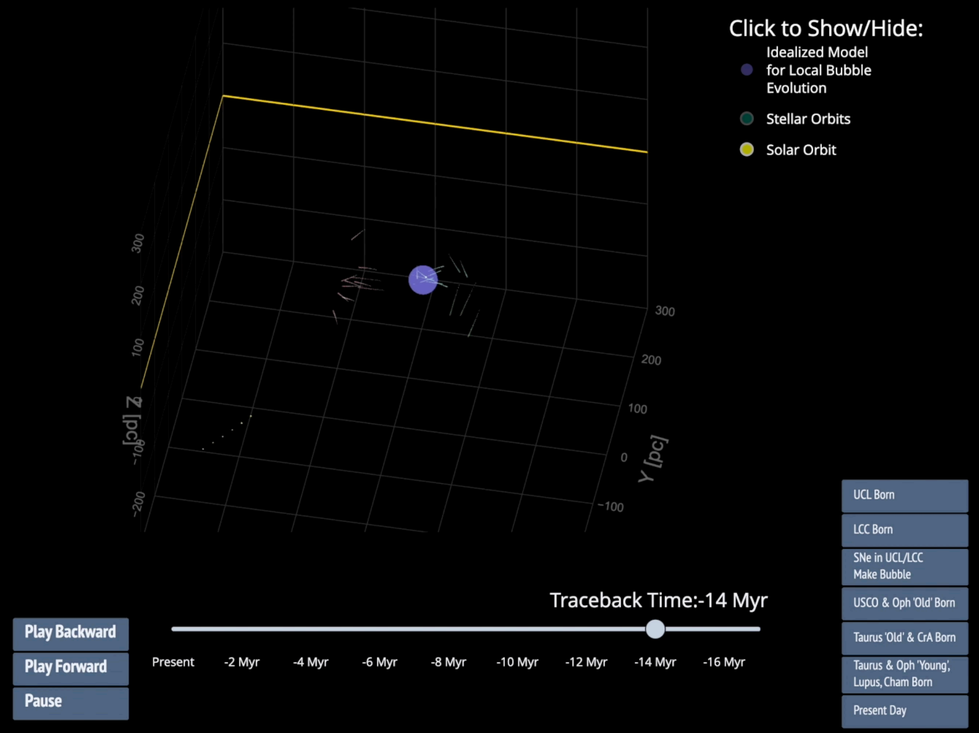


“Cartoon”



“Real Data”

(Zucker et al. 2022, *Nature*)



[try the interactive figure]

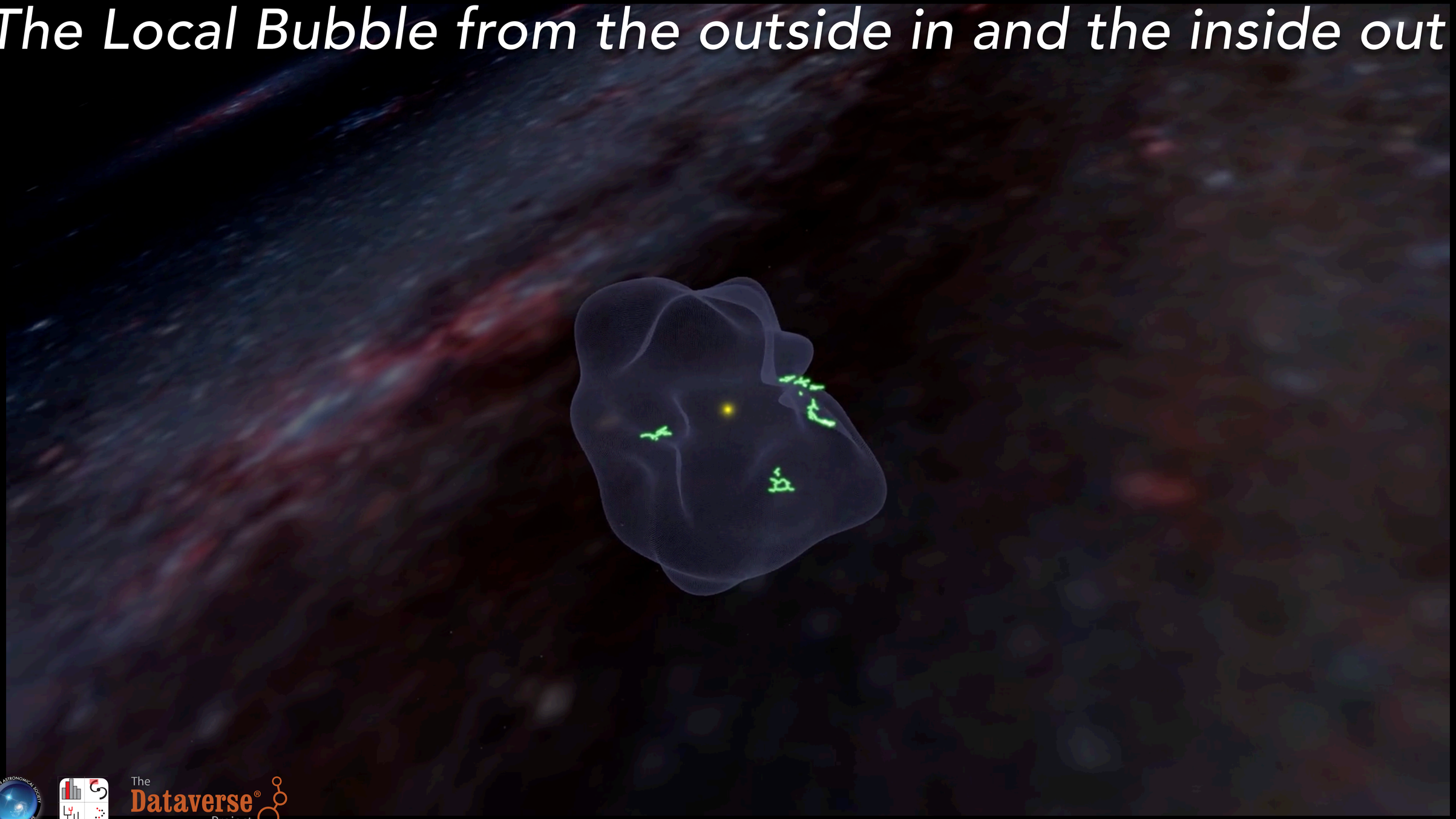
glue → plotly

The Local Bubble from the outside in and the inside out



The Dataverse® Project

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.



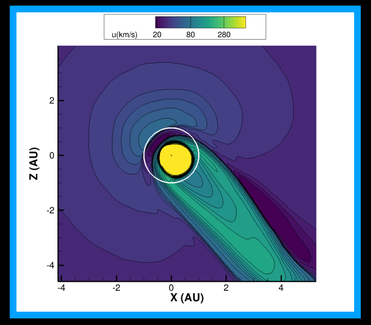
How did the Sun wind up in the bubble? (by accident)

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?

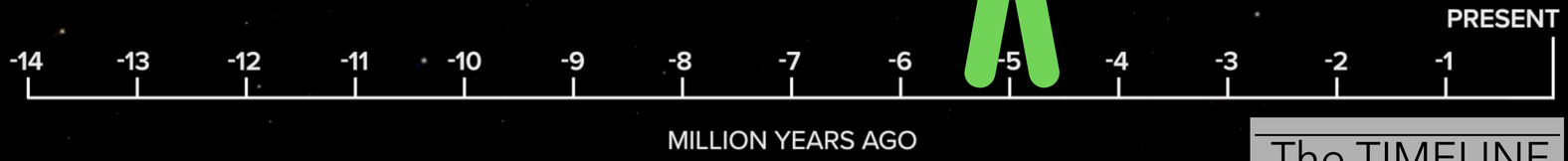


See Opher et al. 2023 (Heliosphere shrinks as Sun passes through Local Bubble, exposes Earth!)



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

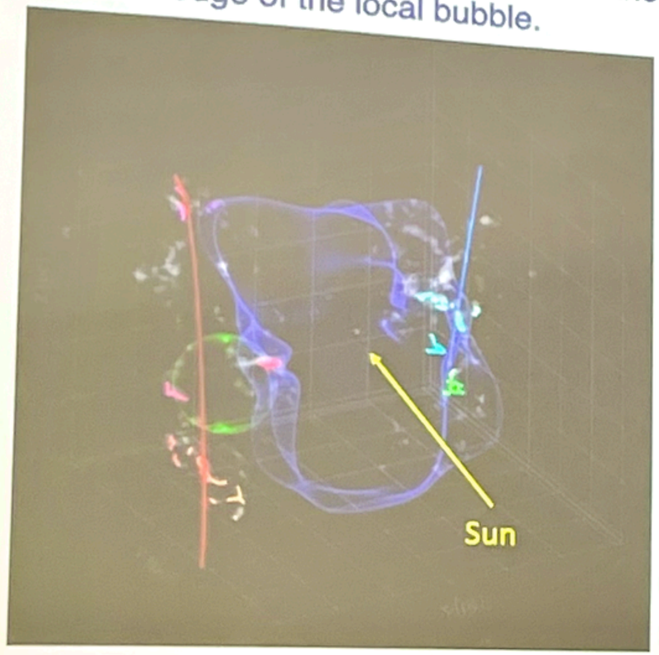
We can now explain how all nearby star formation began

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

Molecular cloud formation from compressions induced by expanding giant bubbles

Most star forming molecular clouds in the solar neighborhood (d<500 pc) are at the edge of the local bubble.

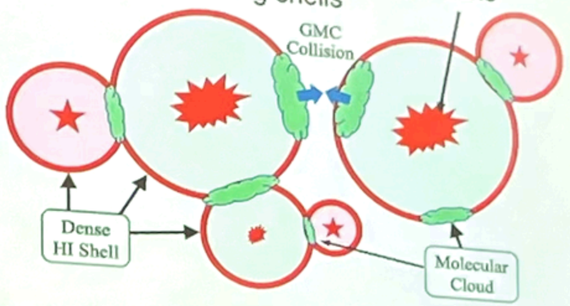


Zucker et al. 2022

Inutsuka+2015

Network of expanding shells

Multiple Supernova explosions



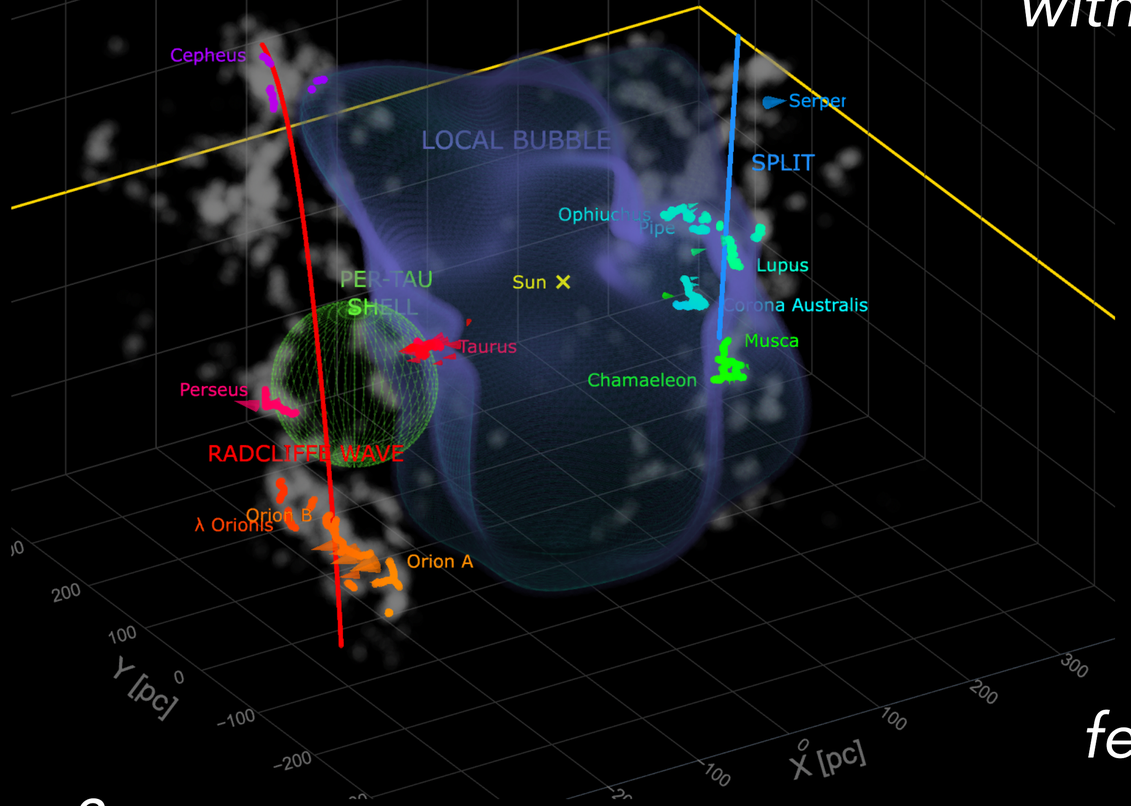
Giant bubbles (~50-100 pc) shaping the ISM of the galaxy



Doris Arzoumanian earlier today at MPE, thanks!

"Next" *(way back in 2022!)*

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



How do we SEARCH for other bubbles?

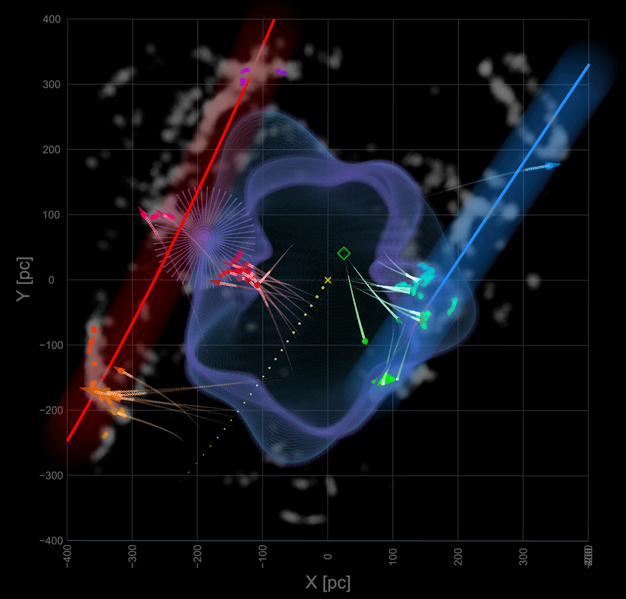
How do these bubbles INTERACT with each other?

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]

And back in 2022,
we wondered:
What (MAYBE!) caused the prior star formation that caused the SNe that caused the Local Bubble?



Traceback Time:Present

Play Reverse Pause

Present -1 Myr -2 Myr -3 Myr -4 Myr -5 Myr -6 Myr -7 Myr -8 Myr -9 Myr -10 Myr -11 Myr -12 Myr -13 Myr -14 Myr -15 Myr -16 Myr -17 Myr -18 Myr -19 Myr -20 Myr

Click to see what MIGHT have happened...

Then, in 2023…

1. Andi Burkert sent Ralf Konietzka to Cambridge.
2. We realized the RadWave is so big that p-p-p-v from CO is useful enough to suggest oscillation.
3. Joao Alves et al. made really, really, good 6D clusters of young stars using Gaia.
4. Ralf found the RadWave IS oscillating — and drifting outward from the Galactic Center.
5. BONUS: also, dark matter probably didn't kill the dinosaurs.

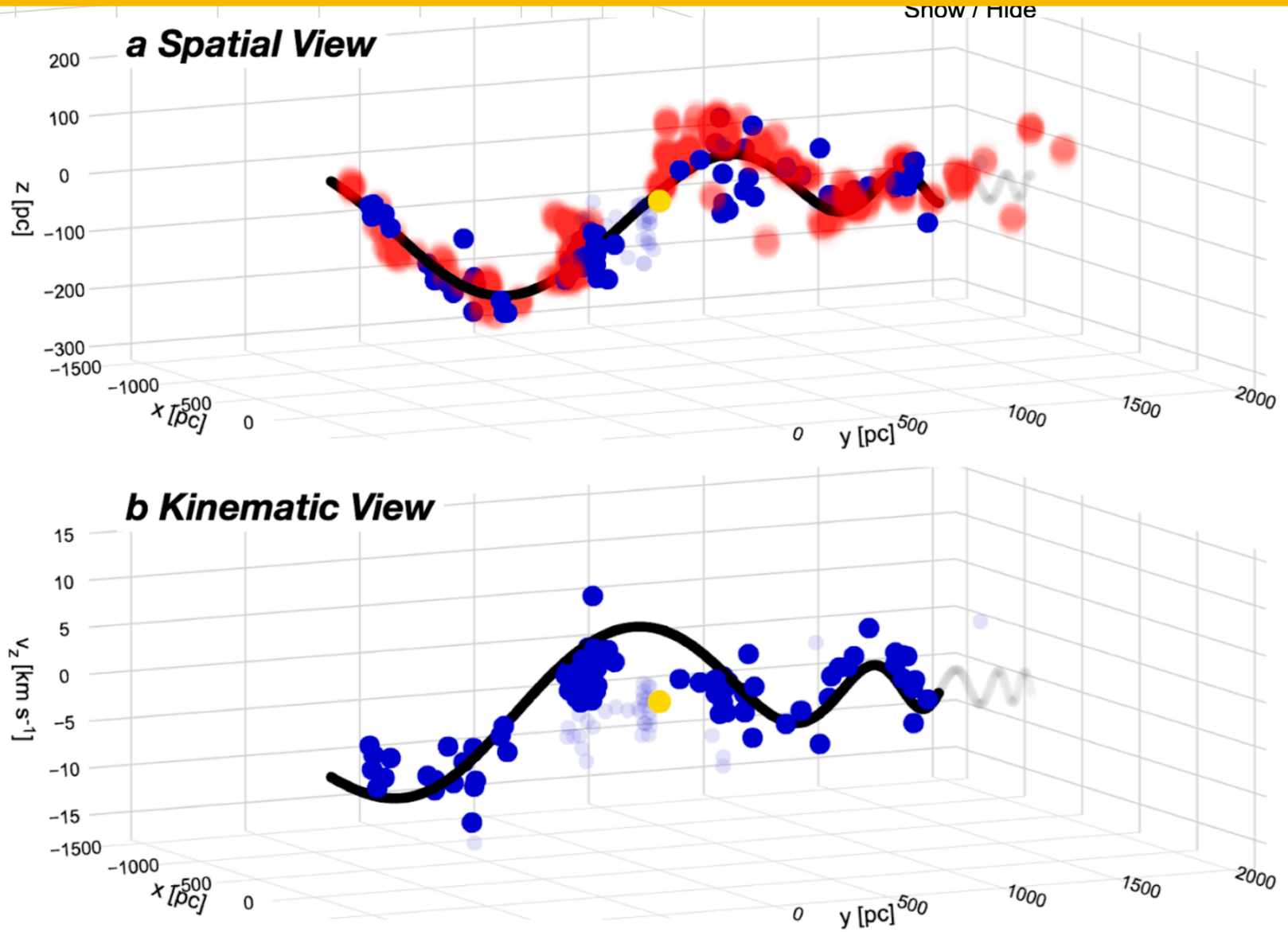
Konietzka, R., Goodman, A., Zucker, C., Burkert, A., Alves, J., Foley, M., Swiggum, C. 2023. To be submitted to Nature, June 2023. **The Radcliffe Wave is Oscillating**

Embargoed—please do not share—this slide will be removed from slides online.

Phase Space Analysis of the Local Interstellar Medium

The Oscillation of the Radcliffe Wave

Ralf Konietzka



Master's Thesis
at the Faculty of Physics
Ludwig-Maximilians-University of Munich

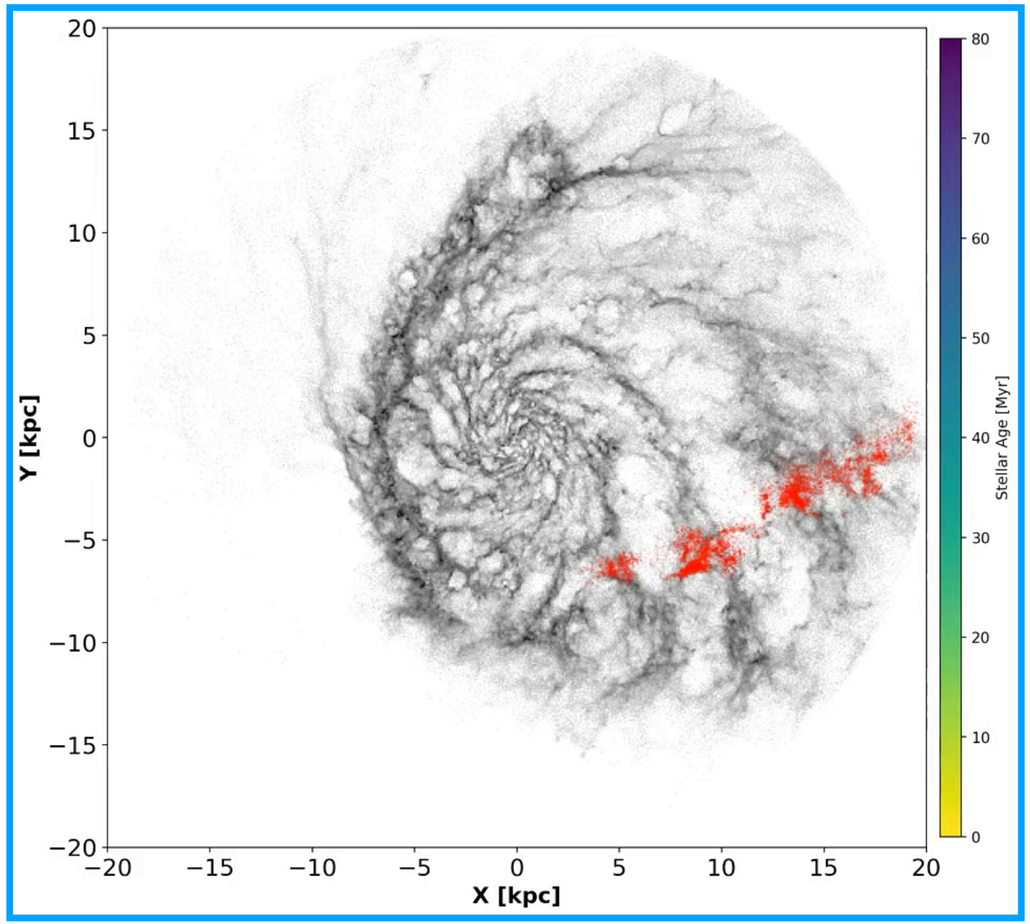
Submitted by
Ralf Konietzka
born in Nuremberg

Supervised by
Prof. Dr. Alyssa Goodman
Prof. Dr. Andreas Burkert

Munich, June 12, 2023

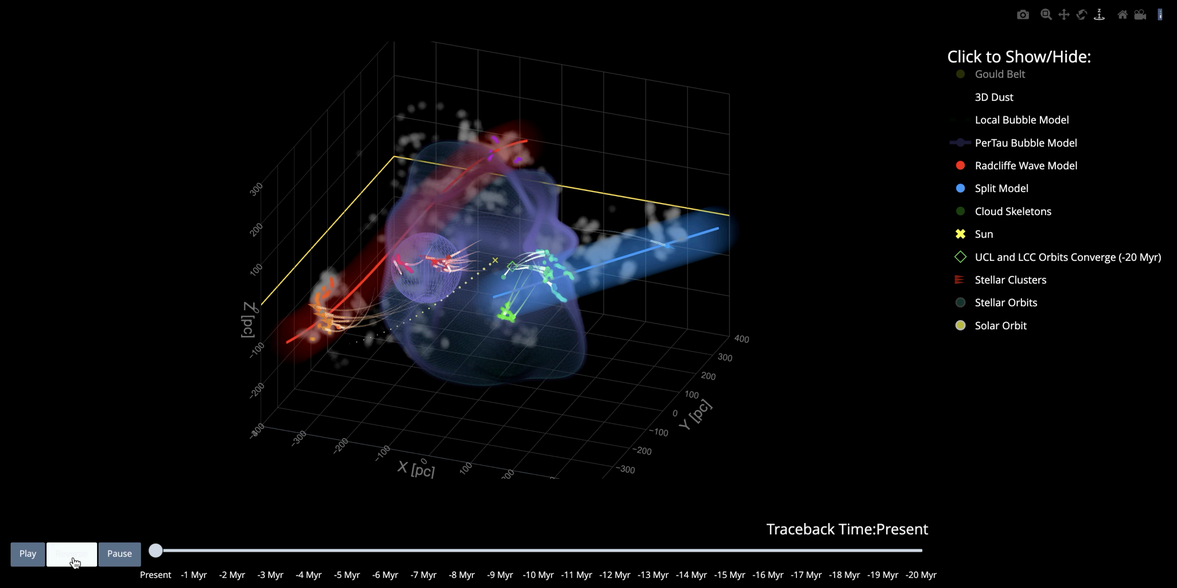
Konietzka, R., Goodman, A., Zucker, C., Burkert, A., Alves, J., Foley, M., Swiggum, C. 2023. To be submitted to Nature, June 2023. The Radcliffe Wave is Oscillating

“Snapshots” can be deceiving– pattern speed is NOT real motion!



Loebman and Zucker, AG et al 2023

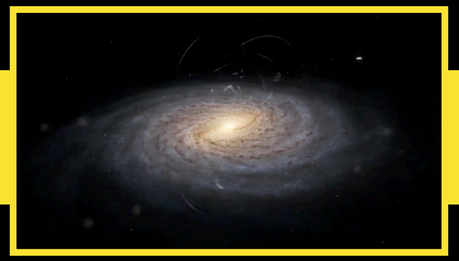
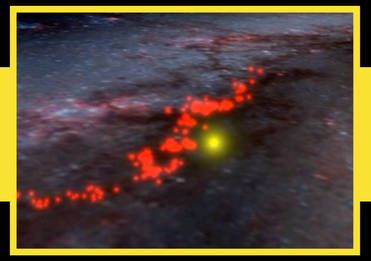
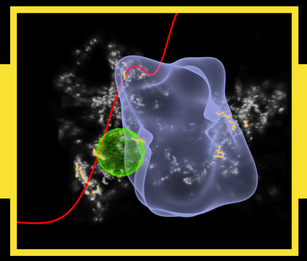
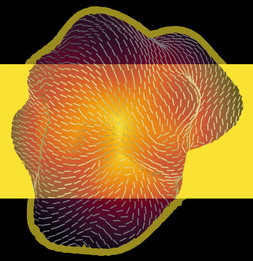
“Crazy” stuff *IS* happening?!



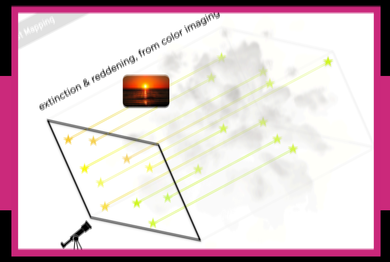
https://faun.rc.fas.harvard.edu/czucker/Interactive_Figure3_Alyssa.html, based on Zucker et al. 2022 (& now Konietzka et al. 2023)

The NEW Milky Way

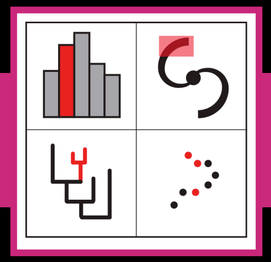
what it looks like

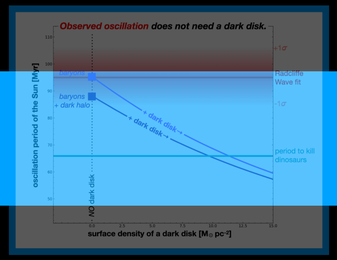
how we know

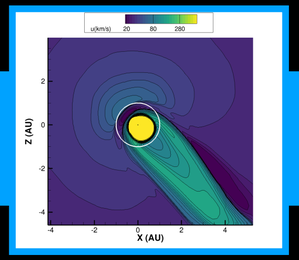



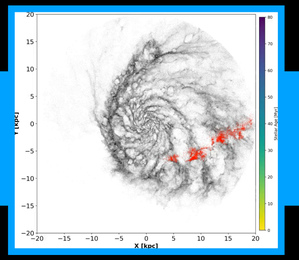


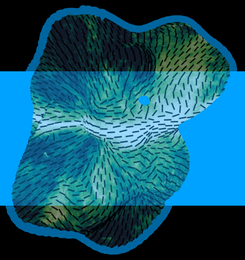


why it matters

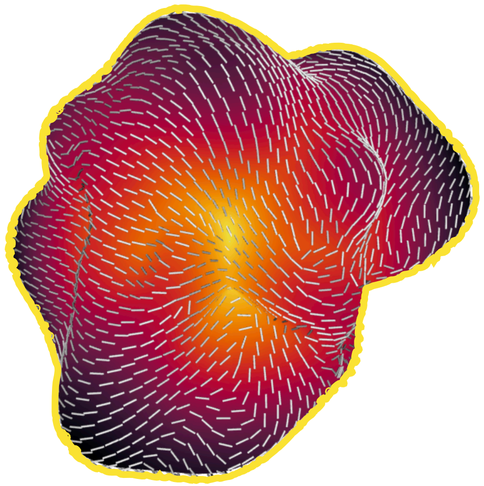








A 3D Map of the Local Bubble's Magnetic Field



Explore Interactive Figures from the paper

Figure 1: Local-to-total Extinction Ratio

Figure 3: 3D Vector Field

Figure 4: Environment

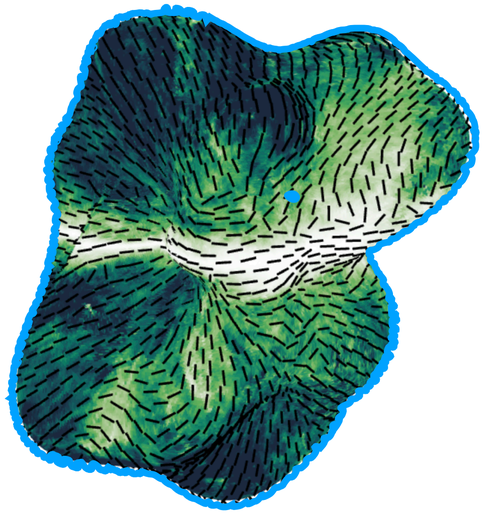
Figure 5: Distance

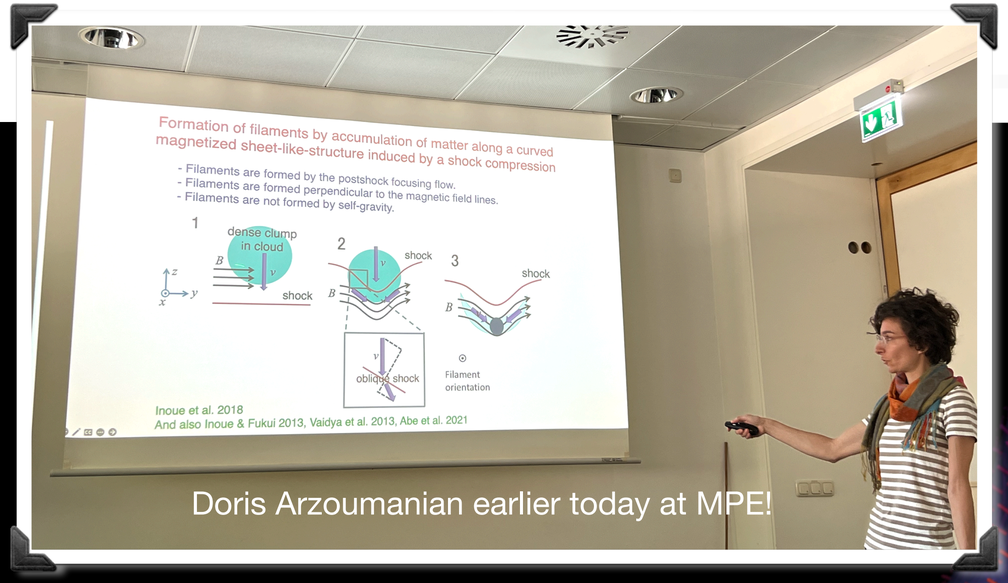
Figure 6: Inclination from plane-of-the-sky, Gamma

Figure 7: Polarization fraction p

Figure 8: Dispersion S

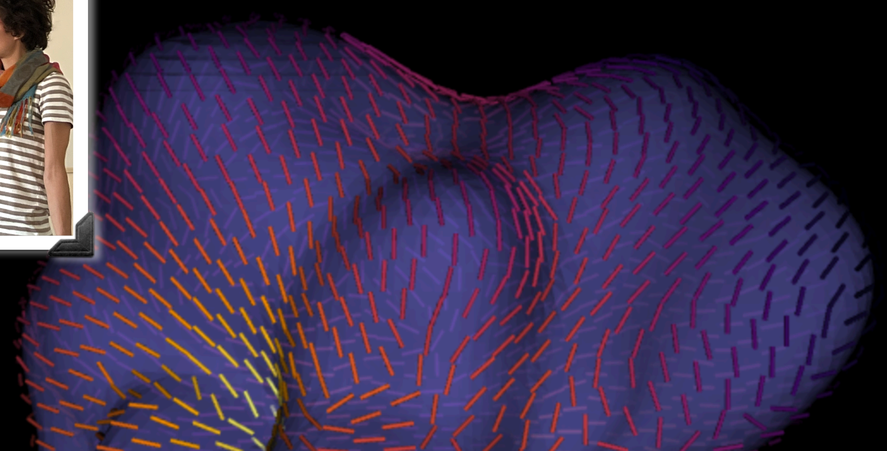
Figure 12: Background Starlight





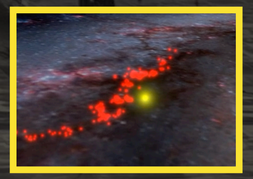
Doris Arzoumanian earlier today at MPE!

https://theo-oneill.github.io/magneticlocalbubble/

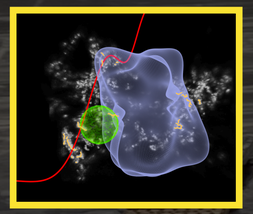


O'Neill et al. 2023

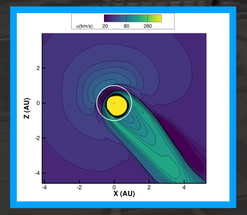
WHAT'S NEW?



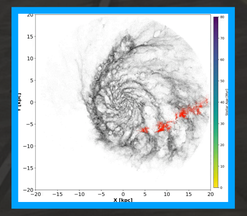
Arms of galaxies (1) look like they "wave," and (2a) they move like that too. (2b) There appears to be almost no dark matter in the Milky Way's disk.)



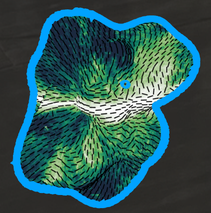
(3a) Feedback from supernovae & winds are as important as theorists said it was 50 years ago, even though observers didn't believe them. (3b) Star forming clouds may largely form at the intersection of feedback bubbles.



(4a) The Sun is "just passing through" our Local Bubble & Earth's (4b, planets') radiation history is determined by this kind of "interstellar weather."

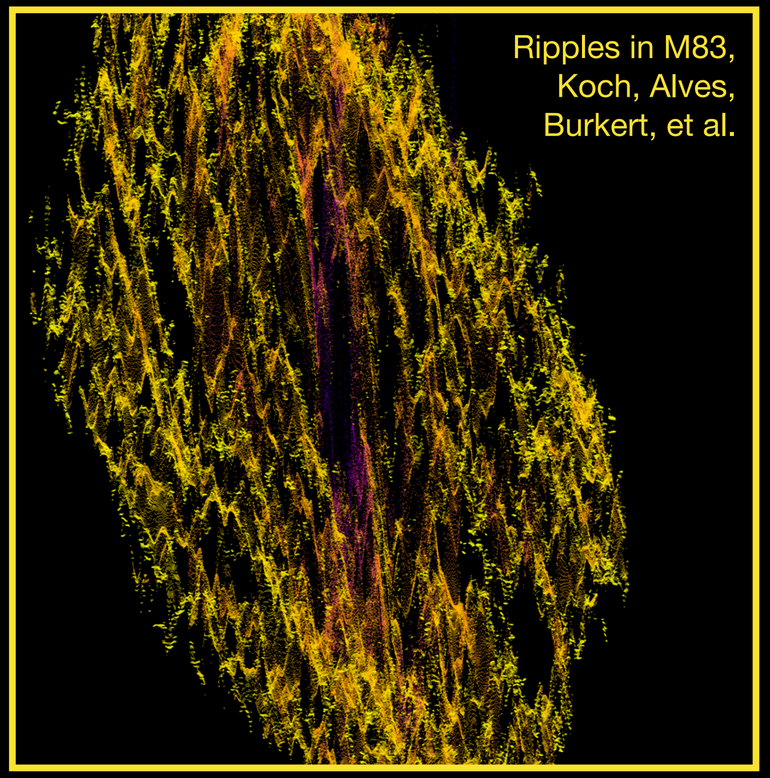


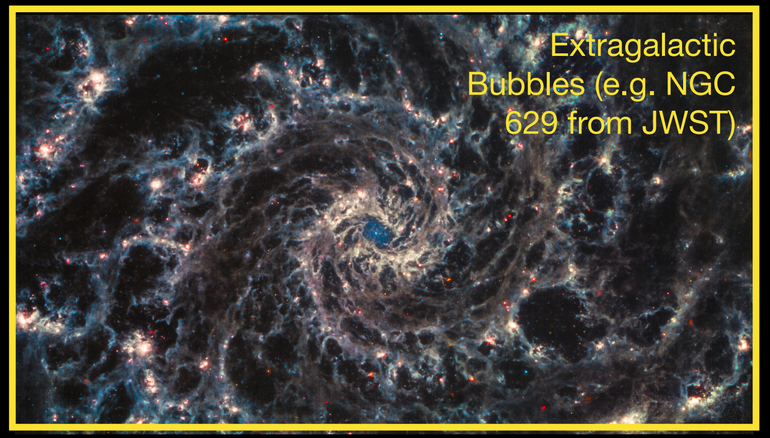
(5) Parts (arms?) of galaxies that appear "near each other" today, did NOT start out that way. Pattern speeds are deceiving.



(6) Magnetic fields appear swept-up into feedback bubble's surfaces.

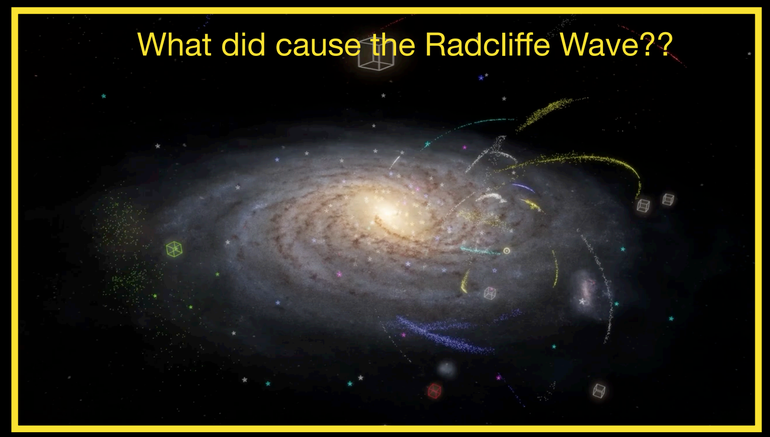
WHAT'S NEXT? (2023 edition)



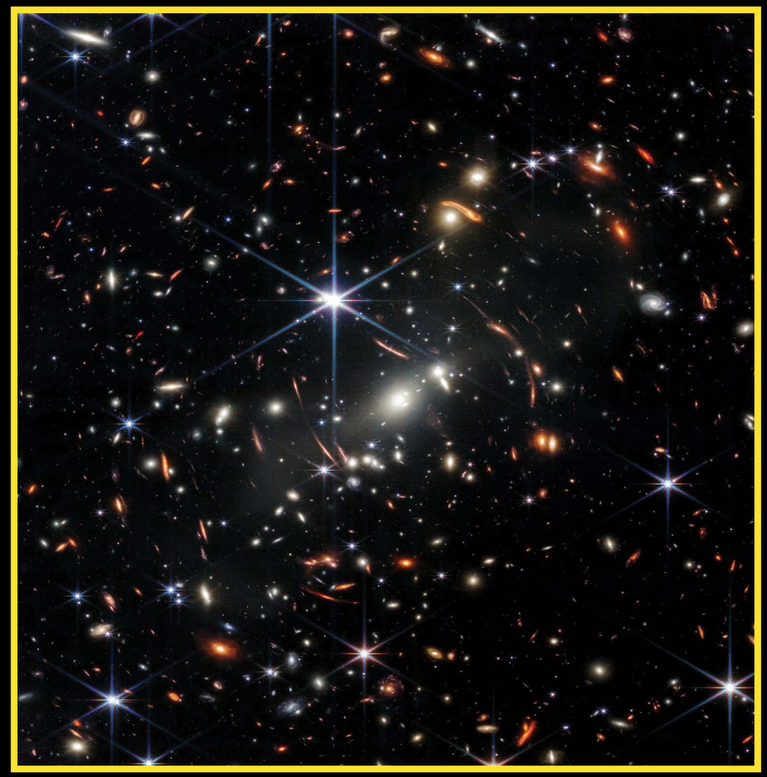


milkyway3d.org (ask me to say more!)



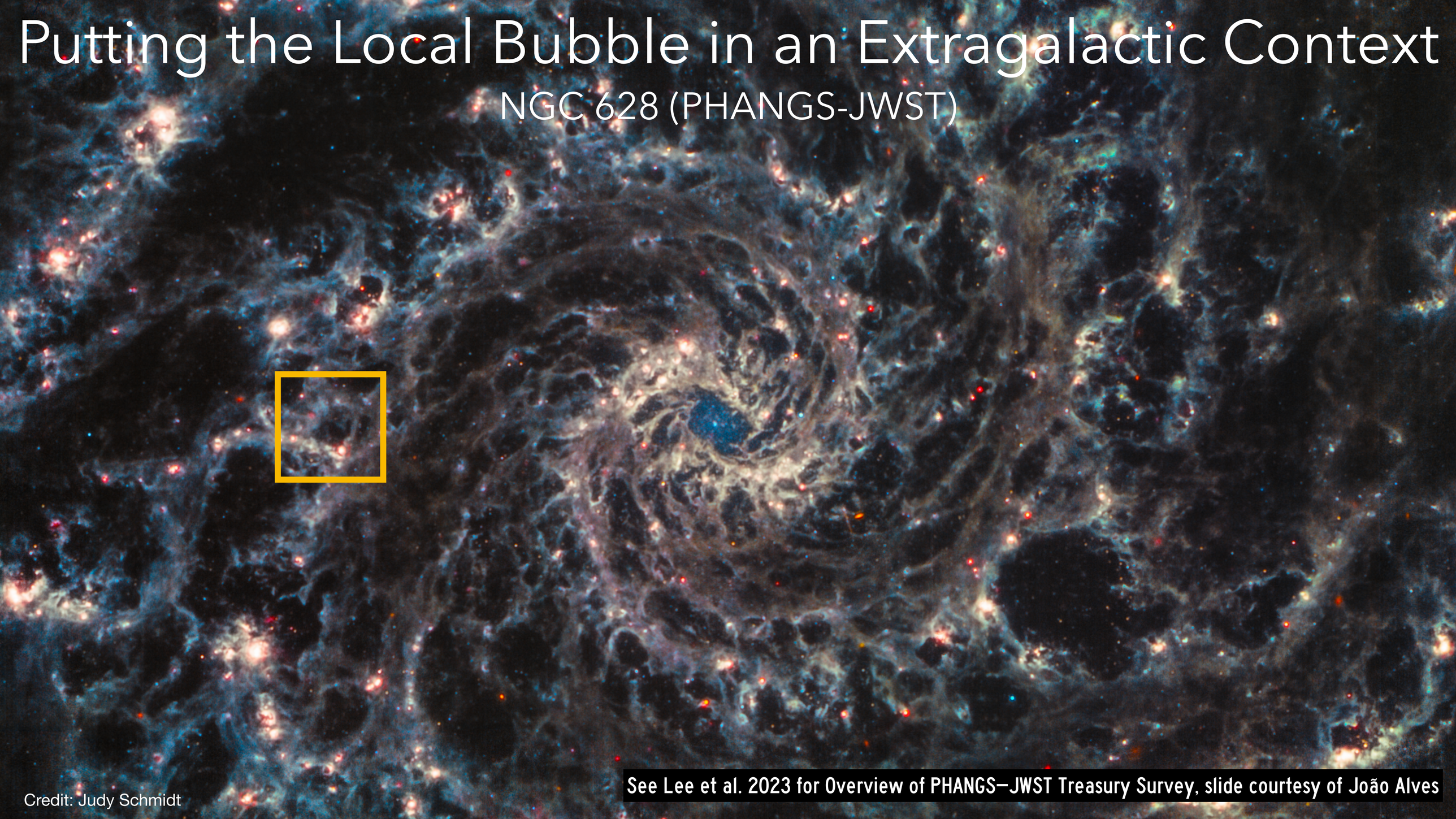


How does a detailed understanding of time-resolved topography of MW stars & gas help extragalactic modeling?



Putting the Local Bubble in an Extragalactic Context

NGC 628 (PHANGS-JWST)



Credit: Judy Schmidt

See Lee et al. 2023 for Overview of PHANGS–JWST Treasury Survey, slide courtesy of João Alves

OpenSpace

glue

AMERICAN ASTRONOMICAL SOCIETY
WORLDWIDE TELESCOPE

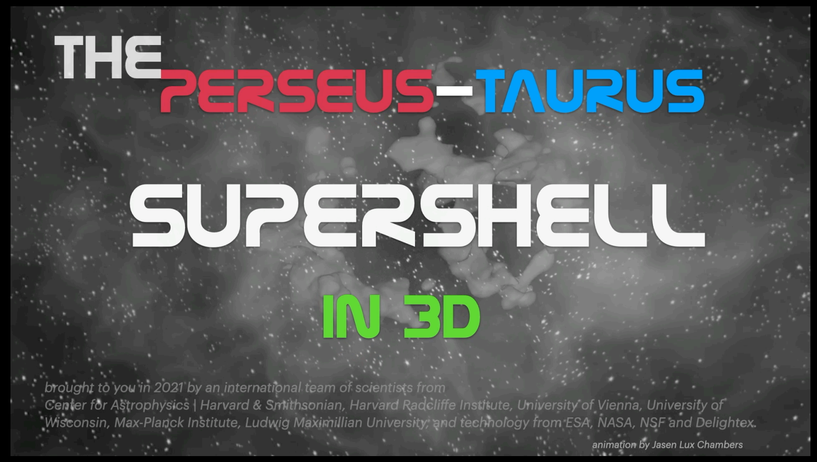


Flying through the "New" Milky Way

more information about our collaboration at milkyway3D.org

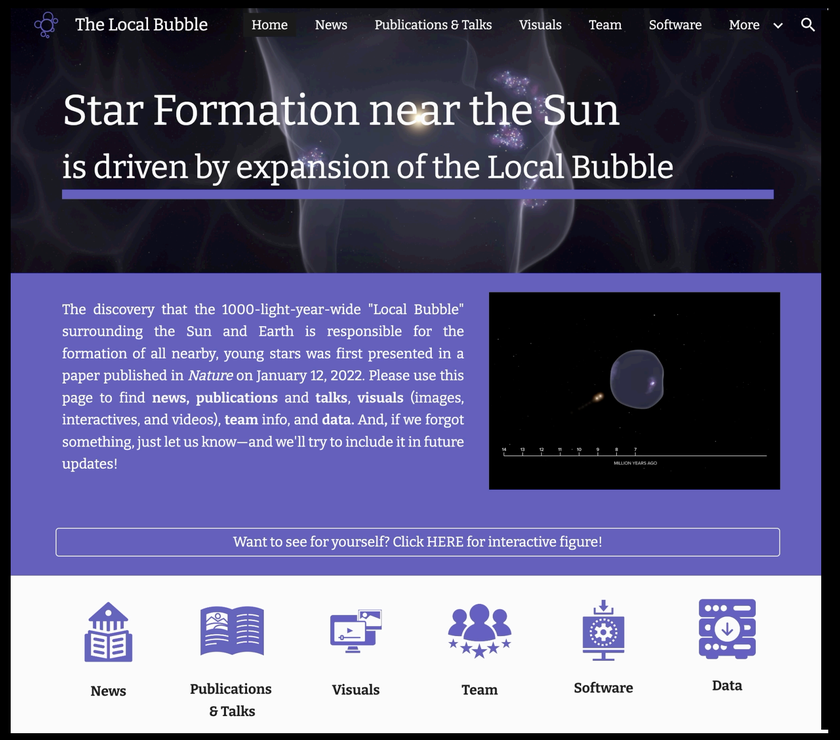
The New Milky Way online
(as of 1/23)

2021

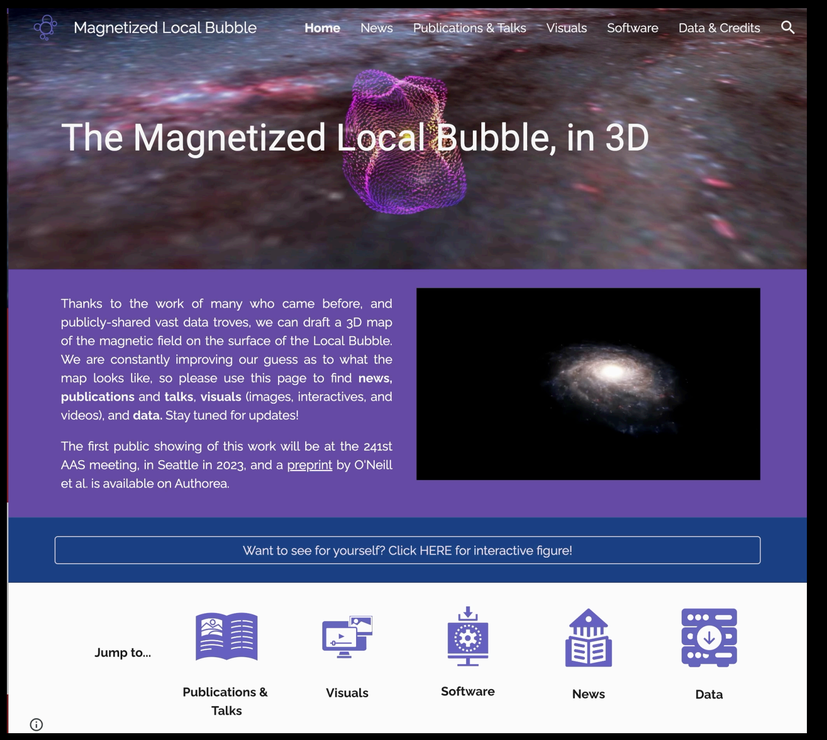




2020

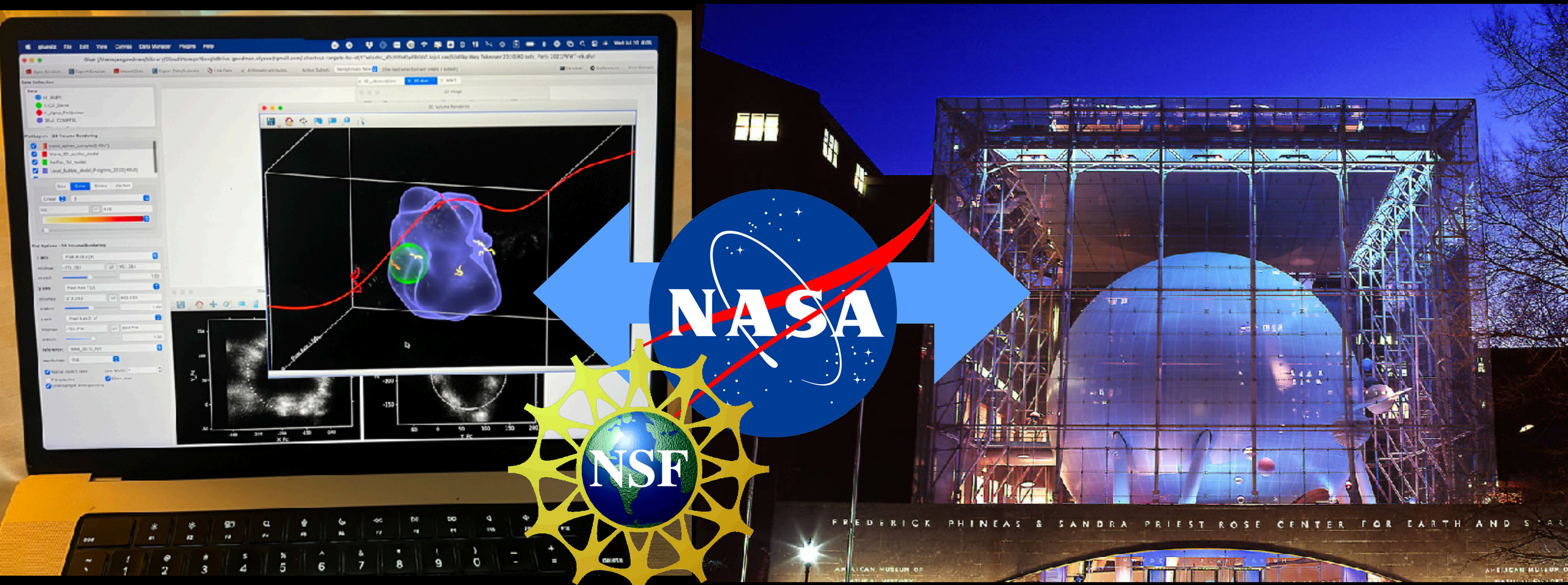


2022



2023 (today!)


H + He
Main Sequence


glue
multidimensional data exploration
OpenSpace
AMERICAN ASTRONOMICAL SOCIETY
WORLDWIDE TELESCOPE
NASA
NSF
FREDERICK PHINEAS & SANDRA PRIEST ROSE CENTER FOR EARTH AND



Welcome to a new view of the Milky Way... in 3D!

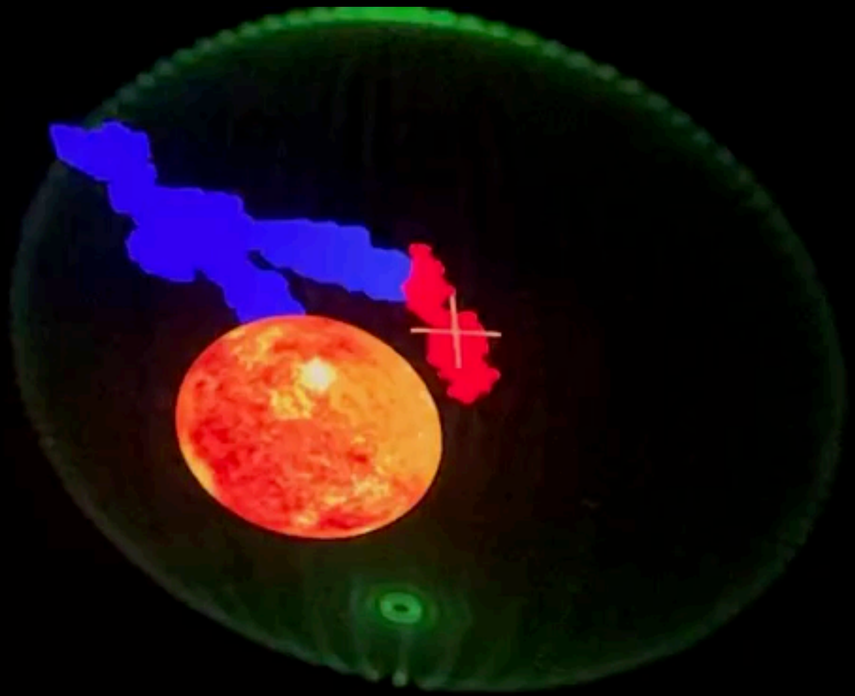
Soon, milkyway3d.org will serve as a hub for the interconnected set of outreach, education, and research resources that will result from the interconnections we're in the process of making.

Our project includes new software development; approaches to data sharing; and scientific research questions propelling our collaboration forward.

milkyway3D.org




glue
Multidimensional data exploration
OpenSpace





AAS AMERICAN ASTRONOMICAL SOCIETY
WORLDWIDE TELESCOPE

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multidimensional data exploration

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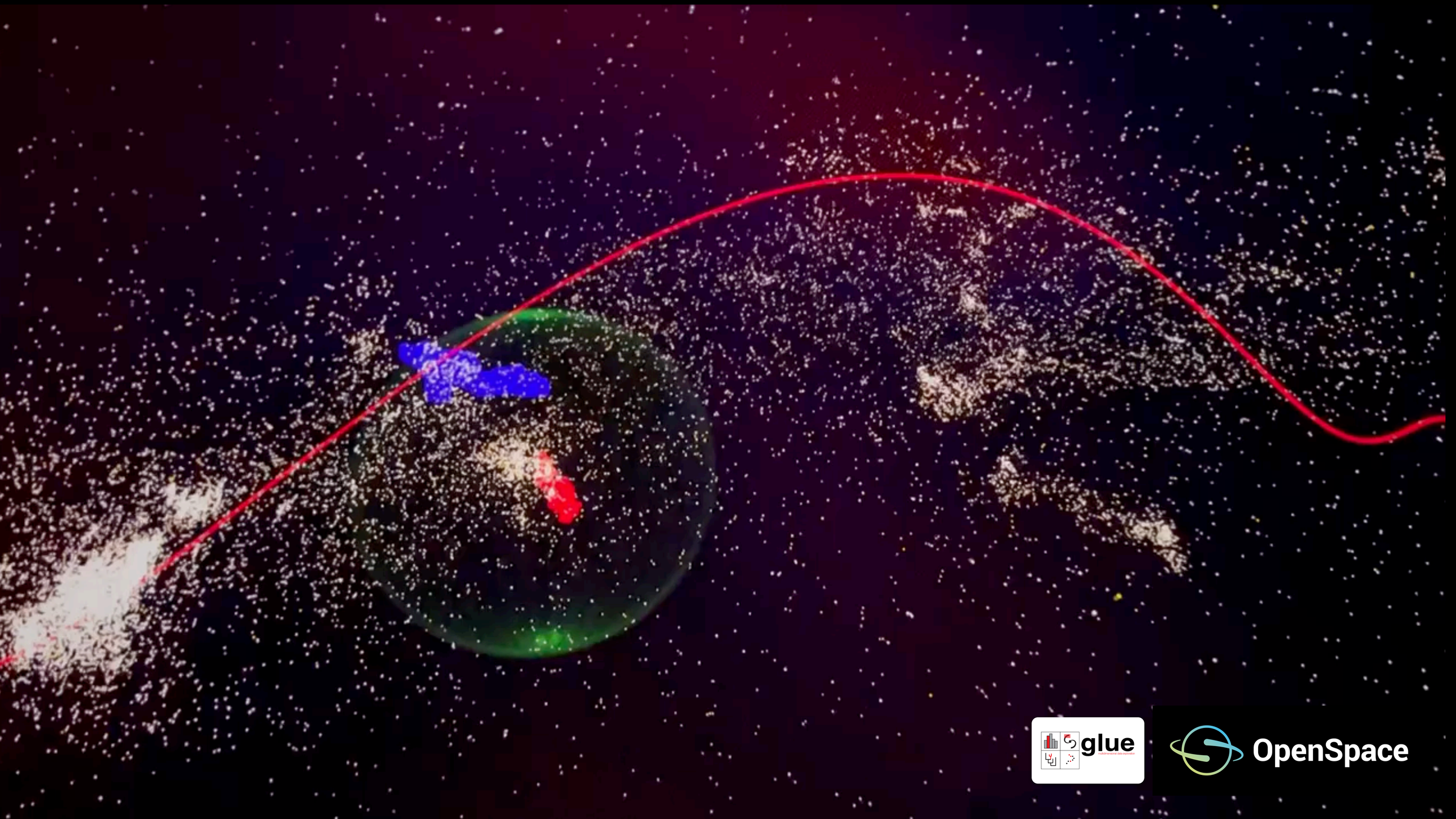
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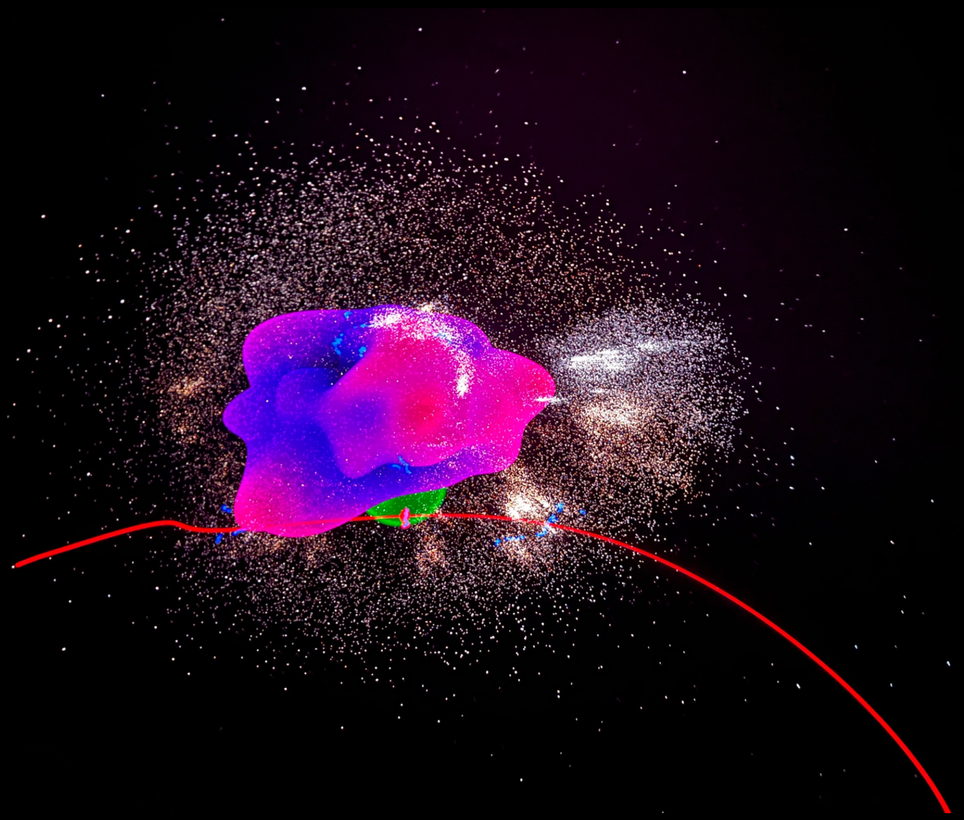
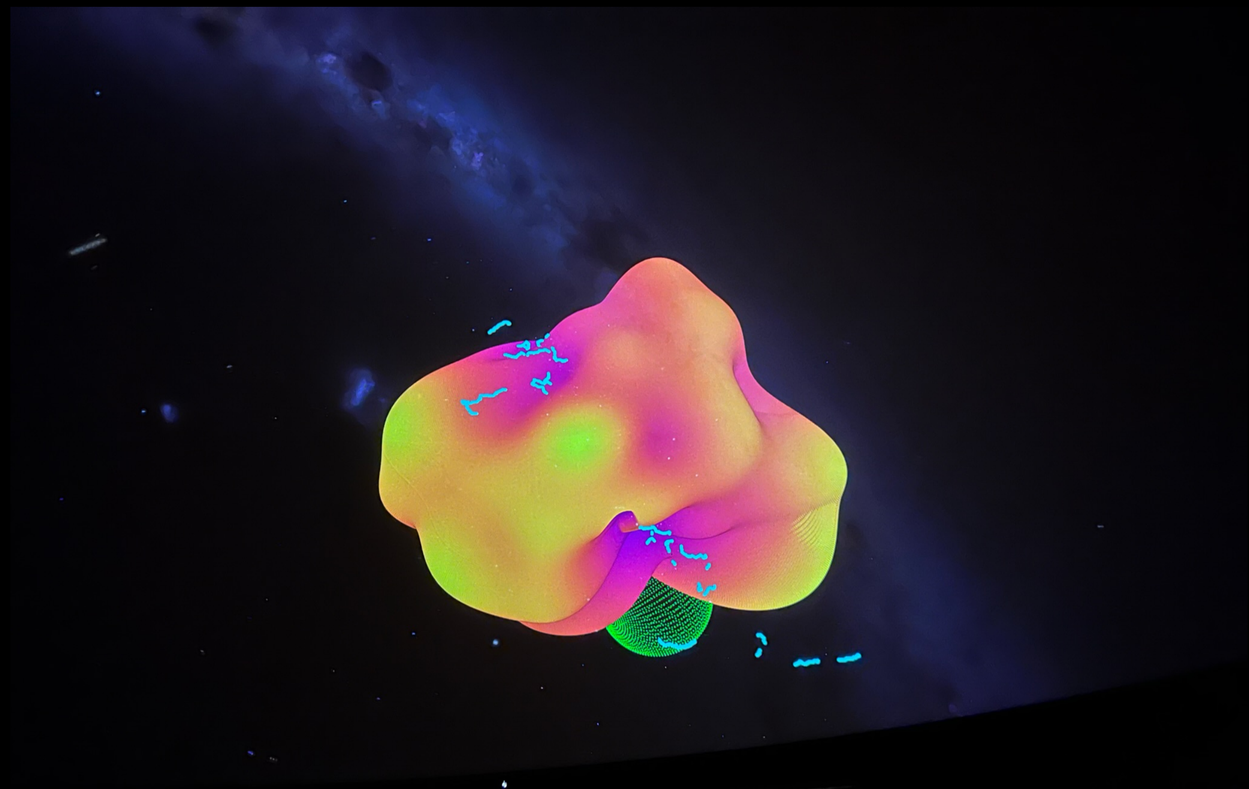




glue
multidimensional data exploration

OpenSpace





***great* 1D, 2D** and **3D** data manipulation, flexible architecture facilitating plug-ins, data transfer, and interactive data exploration; "glupyter" flavor runs in web pages

glue
multidimensional data exploration

CosmicDS

plug-in in-use on Hayden Planetarium dome

AMERICAN ASTRONOMICAL SOCIETY
WORLDWIDE TELESCOPE

plug-in shows WWT images in context in 3.

OpenSpace

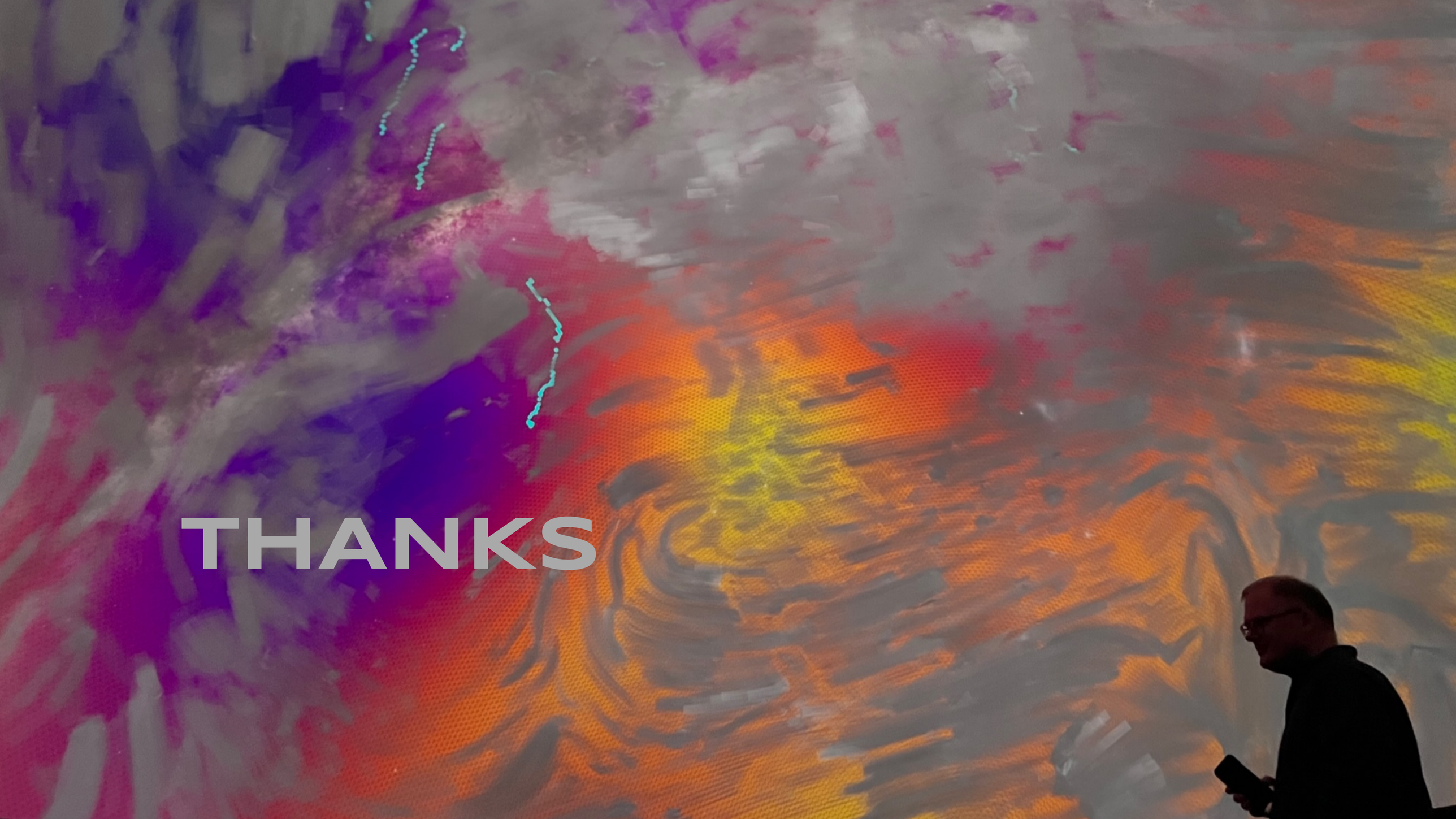
***great* 2D** object and all-sky images
limited 3D functionality

limited 2D all-sky images
***great* 3D** functionality

The "Perseus-Taurus Superbubble"
a demo of the need for 2D-3D contextualization functionality



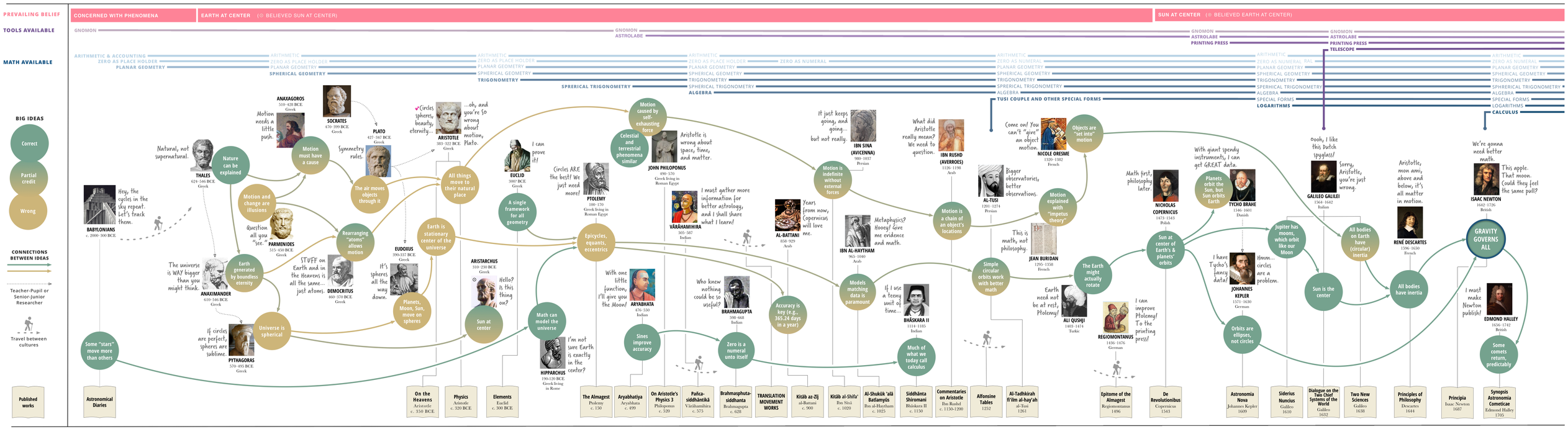
This video was composited using the WWT and OpenSpace, making some use of prototype plug-ins, but 2D and 3D imagery was aligned manually by experts. As a generalizable STEM concept, it explains the deceptive "forced perspective" made possible in when objects at very different distances, in 3D, appear to touch in 2D.


THANKS

The Path to Newton

PREDICTIONX
predictionx.org

The Path to Newton



© Harvard University, created by Alyssa Goodman, Jais Brohinsky, Drew Lichtenstein & Katie Peek, re-use is allowed, with attribution, version 1, 2019

demo: path-to.org or LabXchange™ Science and learning–connected.

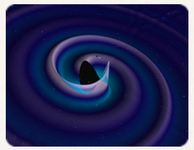
Opinion

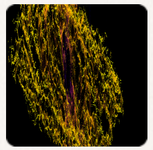
The New Universe

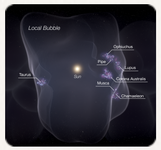
MEMPHIS, SUNDAY OCTOBER 23, 2022

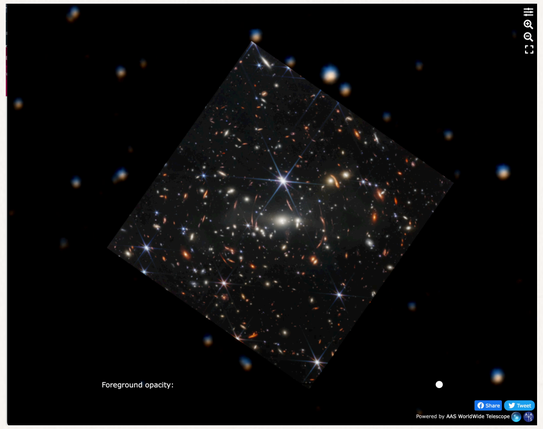
WHAT DO EXPENSIVE NEW TELESCOPES DO FOR HUMANITY TODAY?

Are mega-projects like ALMA, LIGO, JWST, and Gaia worth the billions?



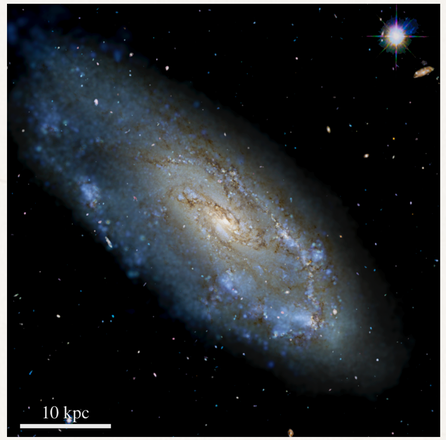


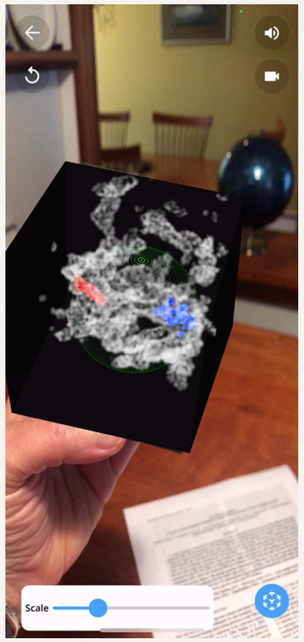




ARE COMPUTERS THE NEW TELESCOPES?

New galaxies in-silico, the early Universe without physics, and new stars forming in your hand.



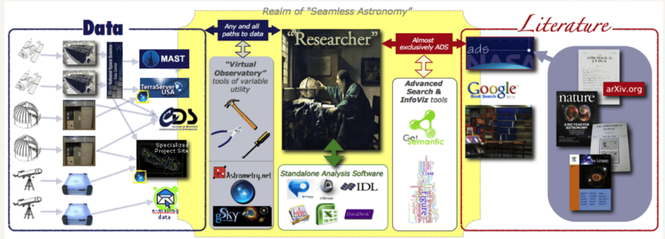


IS ASTROPHYSICS BEING (RE)ORGANIZED?

Lone stargazers are a rarer and rarer breed in professional astronomy. Teams and data scientists seem the way of the future, and tools that talk to each other are essential.

SEAMLESS ASTRONOMY

Linking scientific data, publications, and communities



Editor: Alyssa Goodman, Center for Astrophysics | Harvard & Smithsonian, @AlyssaAGoodman

ARE COMPUTERS THE NEW TELESCOPES?

The Path to Newton

PREVAILING BELIEF

TOOLS AVAILABLE

MATH AVAILABLE

CONCERNED WITH PHENOMENA

EARTH AT CENTER (☉ BELIEVED SUN AT CENTER)

GNOMON

GNOMON
ASTROLABE

ARITHMETIC & ACCOUNTING
ZERO AS PLACE HOLDER
PLANAR GEOMETRY

ARITHMETIC
ZERO AS PLACE HOLDER
PLANAR GEOMETRY
SPHERICAL GEOMETRY

ARITHMETIC
ZERO AS PLACE HOLDER
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPRERICAL TRIGONOMETRY

ARITHMETIC
ZERO AS PLACE HOLDER
ZERO AS NUMERAL
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPHERICAL TRIGONOMETRY
ALGEBRA

BIG IDEAS

Correct

Partial credit

Wrong

CONNECTIONS BETWEEN IDEAS

Teacher-Pupil or Senior-Junior Researcher

Travel between cultures

Published works



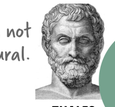
Hey, the cycles in the sky repeat. Let's track them.

BABYLONIANS
c. 2000–300 BCE

Some "stars" move more than others

Astronomical Diaries

Natural, not supernatural.



THALES
624–546 BCE
Greek

Nature can be explained

Motion and change are illusions

Earth generated by boundless eternity



The universe is WAY bigger than you might think.

ANAXIMANDER
610–546 BCE
Greek

Universe is spherical



If circles are perfect, spheres are sublime.

PYTHAGORAS
570–495 BCE
Greek

Motion needs a little push.



ANAXAGOROS
510–428 BCE
Greek

Motion must have a cause



Question all you "see."

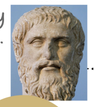
PARMENIDES
515–450 BCE
Greek

Rearranging "atoms" allows motion



SOCRATES
470–399 BCE
Greek

Symmetry rules.



PLATO
427–347 BCE
Greek

The air moves objects through it



STUFF on Earth and in the Heavens is all the same... just atoms.

DEMOCRITUS
460–370 BCE
Greek



It's spheres all the way down.

EUDOXUS
390-337 BCE
Greek

Planets, Moon, Sun, move on spheres

Earth is stationary center of the universe



Circles, spheres, beauty, eternity...

ARISTOTLE
383–322 BCE
Greek

...oh, and you're so wrong about motion, Plato.

All things move to their natural place



Hello? Is this thing on?

ARISTARCHUS
310–230 BCE
Greek

Sun at center



I can prove it!

EUCLID
300? BCE
Greek

A single framework for all geometry

Motion caused by self-exhausting force

Celestial and terrestrial phenomena similar



Aristotle is wrong about space, time, and matter.

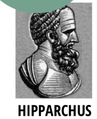
JOHN PHILOPONUS
490–570
Greek living in Roman Egypt



Circles ARE the best! We just need more!

PTOLEMY
100–170
Greek living in Roman Egypt

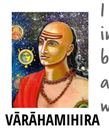
Epicycles, equants, eccentrics



I'm not sure Earth is exactly in the center?

HIPPARCHUS
190-120 BCE
Greek living in Rome

Math can model the universe



I must gather more information for better astrology, and I shall share what I learn!

VĀRĀHAMIHIRA
505–587
Indian

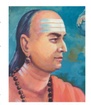


Years from now, Copernicus will love me.

AL-BATTANI
858–929
Arab

It just kee going, a going but not reall

Motion is indefinite without external forces



With one little function, I'll give you the Moon!

ARYABHATA
476–550
Indian

Sines improve accuracy



Who knew nothing could be so useful?

BRAHMAGUPTA
598–668
Indian

Zero is a numeral unto itself

Accuracy is key (e.g., 365.24 days in a year)

On the Heavens
Aristotle
c. 350 BCE

Physics
Aristotle
c. 320 BCE

Elements
Euclid
c. 300 BCE

The Almagest
Ptolemy
c. 150

Aryabhatiya
Aryabhata
c. 499

On Aristotle's Physics 3
Philoponus
c. 520

Pañca-siddhāntikā
Vārāhamihira
c. 575

Brahmasphuta-siddhanta
Brahmagupta
c. 628

TRANSLATION MOVEMENT WORKS

Kitāb az-Zīj
al-Battani
c. 900

Kitāb
Ibn
c.

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)

GNOMON
ASTROLABE
PRINTING PRESS

ARITHMETIC
ZERO AS PLACE HOLDER
ZERO AS NUMERAL
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ALGEBRA
TUSI COUPLE AND OTHER SPECIAL FORMS
LOGARITHMS



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It just keeps going, and going... but not really.



IBN SINA (AVICENNA)
980–1037
Persian

Motion is indefinite without external forces



Metaphysics? Hooey! Give me evidence and math.

IBN AL-HAYTHAM
965–1040
Arab

Models matching data is paramount

What did Aristotle really mean? We need to question.



IBN RUSHD (AVERROES)
1126–1198
Arab

Motion is a chain of an object's locations



Bigger observatories, better observations.

AL-TUSI
1201–1274
Persian

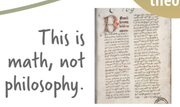
Simple circular orbits work with better math

Come on! You can't "give" an object motion.



NICOLE ORESME
1320–1382
French

Objects are "set into" motion



This is math, not philosophy.

JEAN BURIDAN
1295–1358
French

Motion explained with "impetus theory"

With giant spendy instruments, I can get GREAT data.

Math first, philosophy later.



NICHOLAS COPERNICUS
1473–1543
Polish

Sun at center of Earth's & planets' orbits

Planets orbit the Sun, but Sun orbits Earth



TYCHO BRAHE
1546–1601
Danish

Jupiter has moons, which orbit like our Moon

I have Tycho's fancy data!



Hmm... circles are a problem.

JOHANNES KEPLER
1571–1630
German

Orbits are ellipses, not circles



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BRAHMAGUPTA
598–668
Indian

Zero is a numeral unto itself

If I use a teeny unit of time...



BHĀSKARA II
1114–1185
Indian

Much of what we today call calculus

Earth need not be at rest, Ptolemy!



ALI QUSHJI
1403–1474
Turkic

The Earth might actually rotate



I can improve Ptolemy! To the printing press!

REGIOMONTANUS
1436–1476
German

Epitome of the Almagest
Regiomontanus
1496

Physics
Aristotle
c. 320 BCE

Elements
Euclid
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The Almagest
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c. 150

Aryabhatiya
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Ibn Sīnā
c. 1020

Al-Shukūk 'alā Batlamyūs
Ibn al-Haytham
c. 1025

Siddhānta Shiromani
Bhāskara II
c. 1150

Commentaries on Aristotle
Ibn Rushd
c. 1150-1200

Alfonsine Tables
1252

Al-Tadhkirah fi'ilm al-hay'ah
al-Tusi
1261

De Revolutionibus
Copernicus
1543

Astronomia Nova
Johannes Kepler
1609

Siderius Nuncius
Galileo
1610

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PREDICTIONX

SUN AT CENTER (⊕ BELIEVED EARTH AT CENTER)

GNOMON
ASTROLABE
PRINTING PRESS
TELESCOPE

ARITHMETIC
ZERO AS NUMERAL
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPHERICAL TRIGONOMETRY
ALGEBRA
SPECIAL FORMS
LOGARITHMS
CALCULUS

TUSI COUPLE AND OTHER SPECIAL FORMS

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Zero is a numeral unto itself

Much of what we today call calculus

Planets orbit the Sun, but Sun orbits Earth

Jupiter has moons, which orbit like our Moon

All bodies on Earth have (circular) inertia

Sun is the center

All bodies have inertia

GRAVITY GOVERNS ALL

Some comets return, predictably

It just keeps going, and going... but not really.

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980–1037
Persian

What did Aristotle really mean? We need to question.

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1546–1601
Danish

I have Tycho's fancy data!

Hmm... circles are a problem.

JOHANNES KEPLER
1571–1630
German

Oooh, I like this Dutch spyglass!

Sorry, Aristotle, you're just wrong.

GALILEO GALILEI
1564–1642
Italian

Aristotle, mon ami, above and below, it's all matter in motion.

RENÉ DESCARTES
1596–1650
French

We're gonna need better math.

This apple. That moon. Could they feel the same pull?

ISAAC NEWTON
1642–1726
British

I must make Newton publish!

EDMOND HALLEY
1656–1742
British

I can improve Ptolemy! To the printing press!

REGIOMONTANUS
1436–1476
German

Earth need not be at rest, Ptolemy!

ALI QUSHJI
1403–1474
Turkic

If I use a teeny unit of time...

BHĀSKARA II
1114–1185
Indian

Years from now, Copernicus will love me.

AL-BATTANI
858–929
Arab

Metaphysics? Hooey! Give me evidence and math.

IBN AL-HAYTHAM
965–1040
Arab

BRAHMAGUPTA
598–668
Indian

Epitome of the Almagest
Regiomontanus
1496

De Revolutionibus
Copernicus
1543

Astronomia Nova
Johannes Kepler
1609

Siderius Nuncius
Galileo
1610

Dialogue on the Two Chief Systems of the World
Galileo
1632

Two New Sciences
Galileo
1638

Principles of Philosophy
Descartes
1644

Principia
Isaac Newton
1687

Synopsis Astronomia Cometicae
Edmond Halley
1705

Brahmasphuta-siddhanta
Brahmagupta
c. 628

TRANSLATION MOVEMENT WORKS

Kitāb az-Zīj
al-Battani
c. 900

Kitāb al-Shifa'
Ibn Sīnā
c. 1020

Al-Shukūk 'alā Batlamyūs
Ibn al-Haytham
c. 1025

Siddhānta Shiromani
Bhāskara II
c. 1150

Commentaries on Aristotle
Ibn Rushd
c. 1150-1200

Alfonsine Tables
1252

Al-Tadhkirah fi'ilm al-hay'ah
al-Tusi
1261

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PREDICTIONX

“ARE COMPUTERS THE NEW TELESCOPES?”

GNOMON
ASTROLABE
PRINTING PRESS
TELESCOPE

ARITHMETIC
ZERO AS NUMERAL
PLANAR GEOMETRY
SPHERICAL GEOMETRY
TRIGONOMETRY
SPHRERICAL TRIGONOMETRY
ALGEBRA
SPECIAL FORMS
LOGARITHMS
CALCULUS

ELECTRONIC COMPUTERS

NUMERICAL SIMULATION
BAYESIAN STATISTICS
INTERACTIVE DATA VISUALIZATION
AI/MACHINE LEARNING

I like Dutch glass!

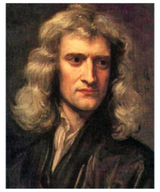


Sorry, Aristotle, you’re just wrong.

GALILEI

Aristotle, mon ami, above and below, it’s all matter

We’re gonna need better math.



This apple. That moon. Could they feel the same pull?

The Padua Rainbow

