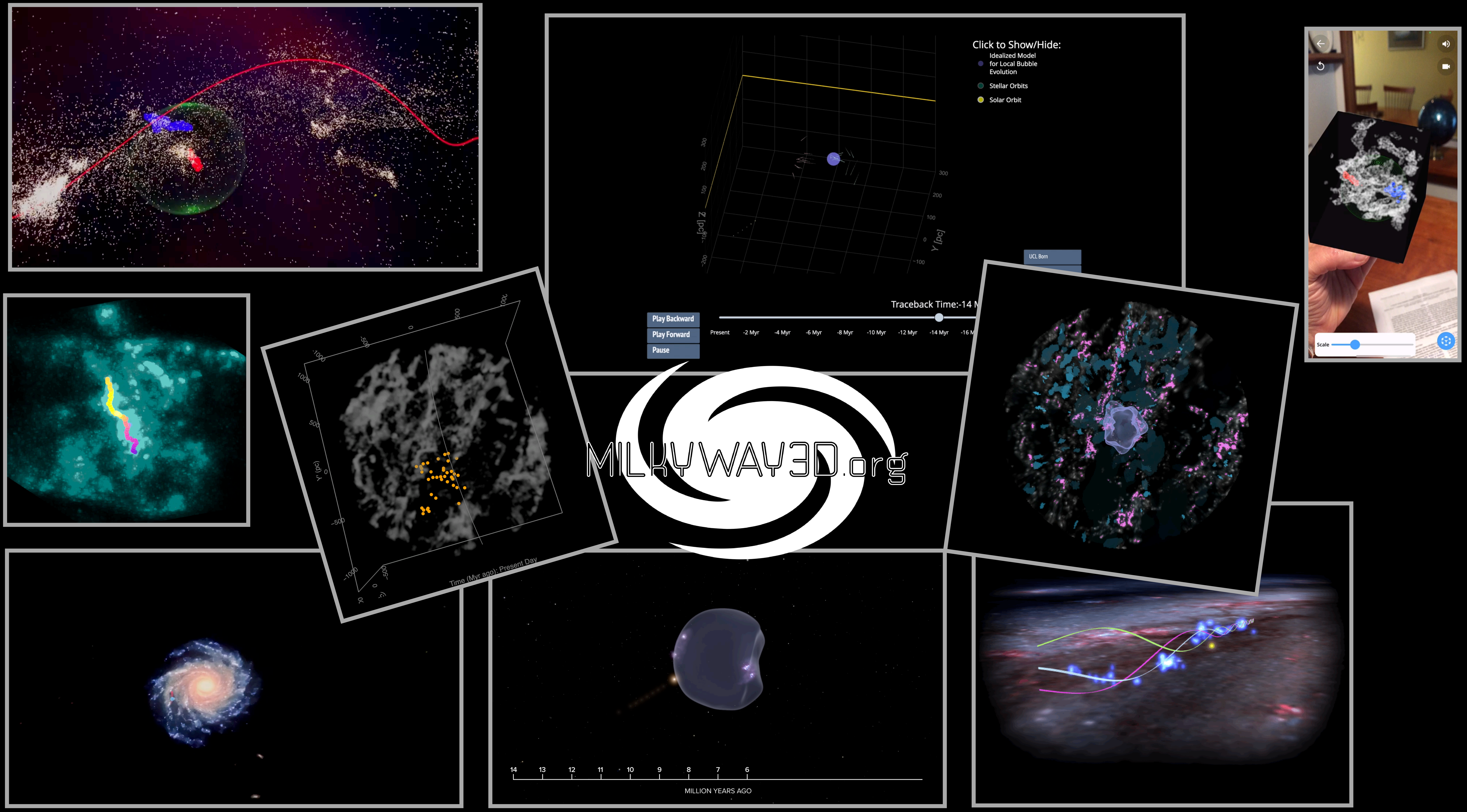


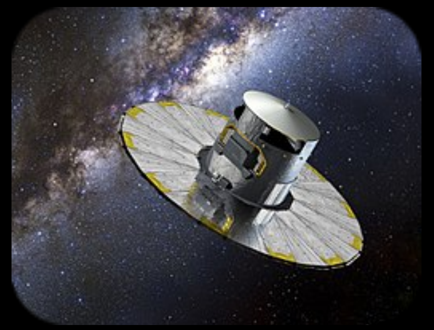
Zucker et al. 2021, Bialy et al. 2021; Zucker et al. 2022, Konietizka et al. 2024, O'Neill et al. 2024, Swiggum et al. 2024

…s ago, no one knew that. . .

Th… …ant (2.7 kpc-long) "wave" of star-forming regions (Alves et al. 2020, named "The Ra… …e") waving up & down (P=90 Myr; Konietzka et al. 2024) along the "Local Arm" o… …Way, the Sun passed through it ~13 Myr ago (Maconi et al. 2024*); and a magn… …uns along it (Panopolou 2024*).

Nearly all star forming regio… …50 pc of the Sun lie on the "surface" of the Local Bubble (Zucker et al. 2022), … …tually a Local Chimney (O'Neill et al. 2024*), and we can estimate what its B-fi… …like, in 3D (O'Neill et al. 2024*).

The Perseus and Taurus star-forming regions lie on… …sides of a "shell," with Perseus in the Radcliffe Wave, and Taurus smooshed betw… …ocal Bubble & the "PerTau Shell" (Bialy et al. 2021).



"Most nearby young star clusters formed in three massive complexes" (Swiggum et al. 2024*).

submitted, embargoed, or in prep, ask…

AAS Meeting Madison, earlier this week, for my colleagues

TONIGHT: *Making a 3D Movie of the Star-Forming Milky Way I never thought I'd see, with my friends*

MILKYWAY3D.org

Catherine Zucker, Center for Astrophysics | Harvard & Smithsonian; Jacqueline Faherty, American Museum of Natural History; Joao Alves, University of Vienna; Brian Abbott, American Museum of Natural History; Micah Acinapura, American Museum of Natural History; Robert Benjamin, University of Wisconsin, Whitewater; Gordian Edenhofer, Max Planck Insitute for Astrophysics–> CfA; Carter Emmart, American Museum of Natural History; Douglas Finkbeiner, Center for Astrophysics | Harvard & Smithsonian; Ralf Konietzka, Center for Astrophysics | Harvard & Smithsonian; Theo O'Neill, Center for Astrophysics | Harvard & Smithsonian; Andrew Saydjari, Center for Astrophysics | Harvard & Smithsonian–>IAS; Robert Hurt, IPAC, and the Full MilkyWay3D.org Team, ++…see "Collaborators" at MilkyWay3D.org.

Alyssa A. Goodman Center for Astrophysics | Harvard & Smithsonian


with my friends

star-forming nebulae

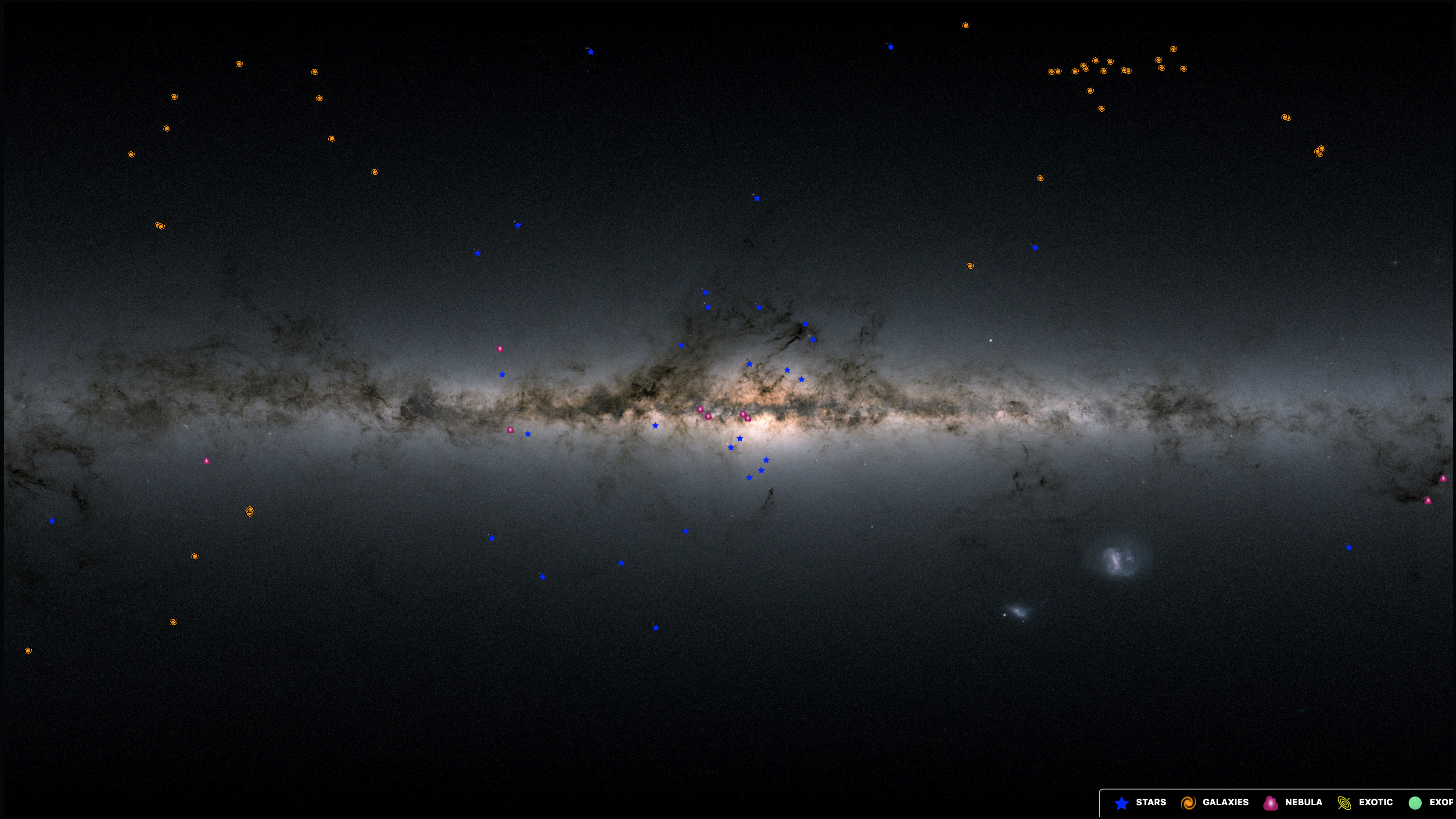
“Messier” Objects

galaxies

Mes·sier, Charles
| ˈmesiə, mesye, ˌmesēˈā, mesˌyā |
(1730–1817), French astronomer. He discovered a number of nebulae, galaxies, and star clusters, which he designated by M numbers.

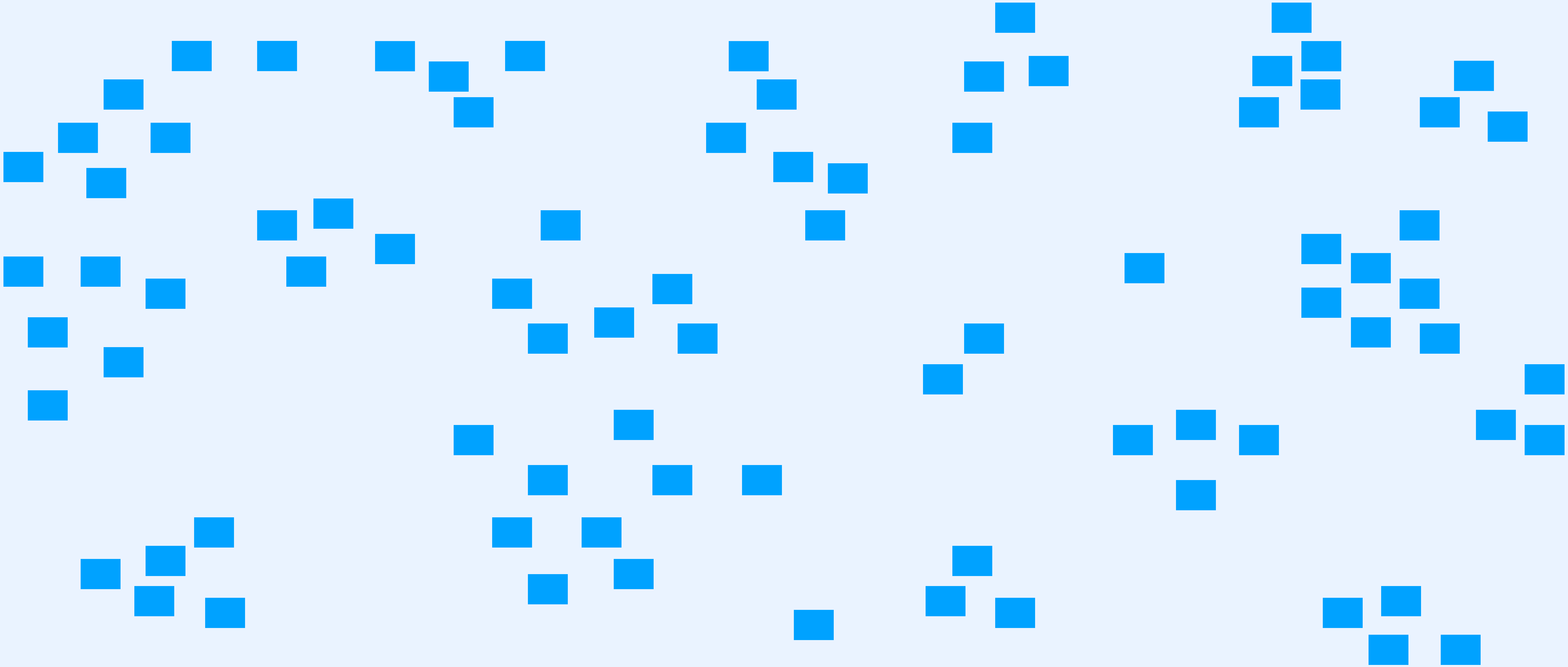
mess·y | ˈmesē | adjective (**messier** | ˈmesēər |, **messiest** | ˈmesēist |)
1 untidy or dirty: *his messy hair*.
- generating or involving mess or untidiness: *stripping wallpaper can be a* **more**

images all from Hubble Space Telescope

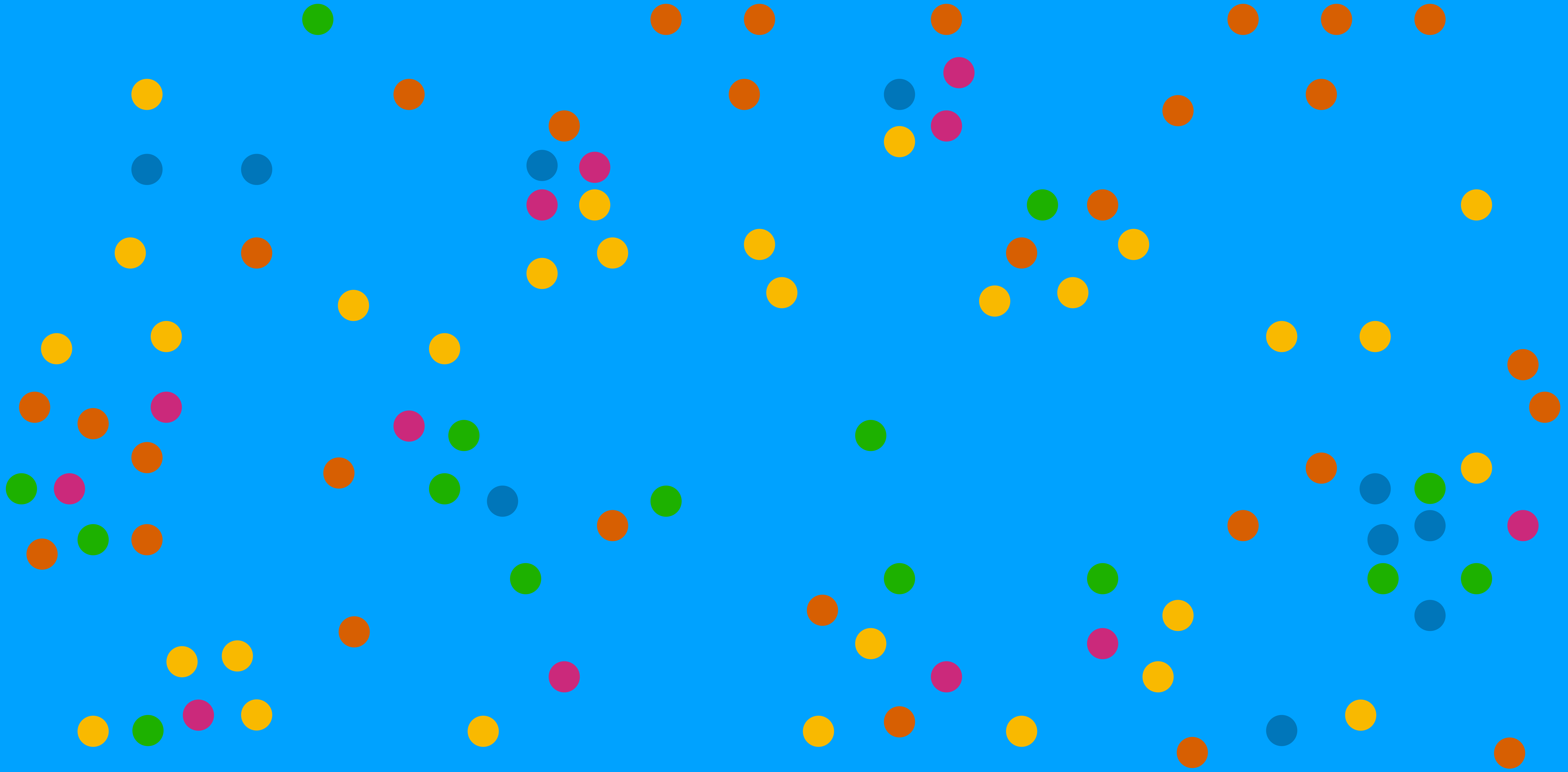

STARS
GALAXIES
NEBULA
EXOTIC
EXOP

WHERE ARE WE?

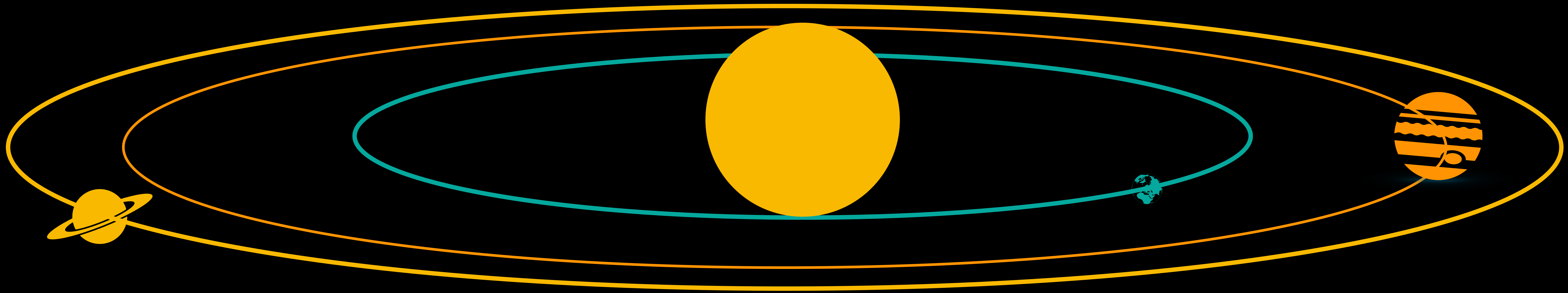
WHERE ARE WE?



our **Universe** contains MANY billions of **galaxies**

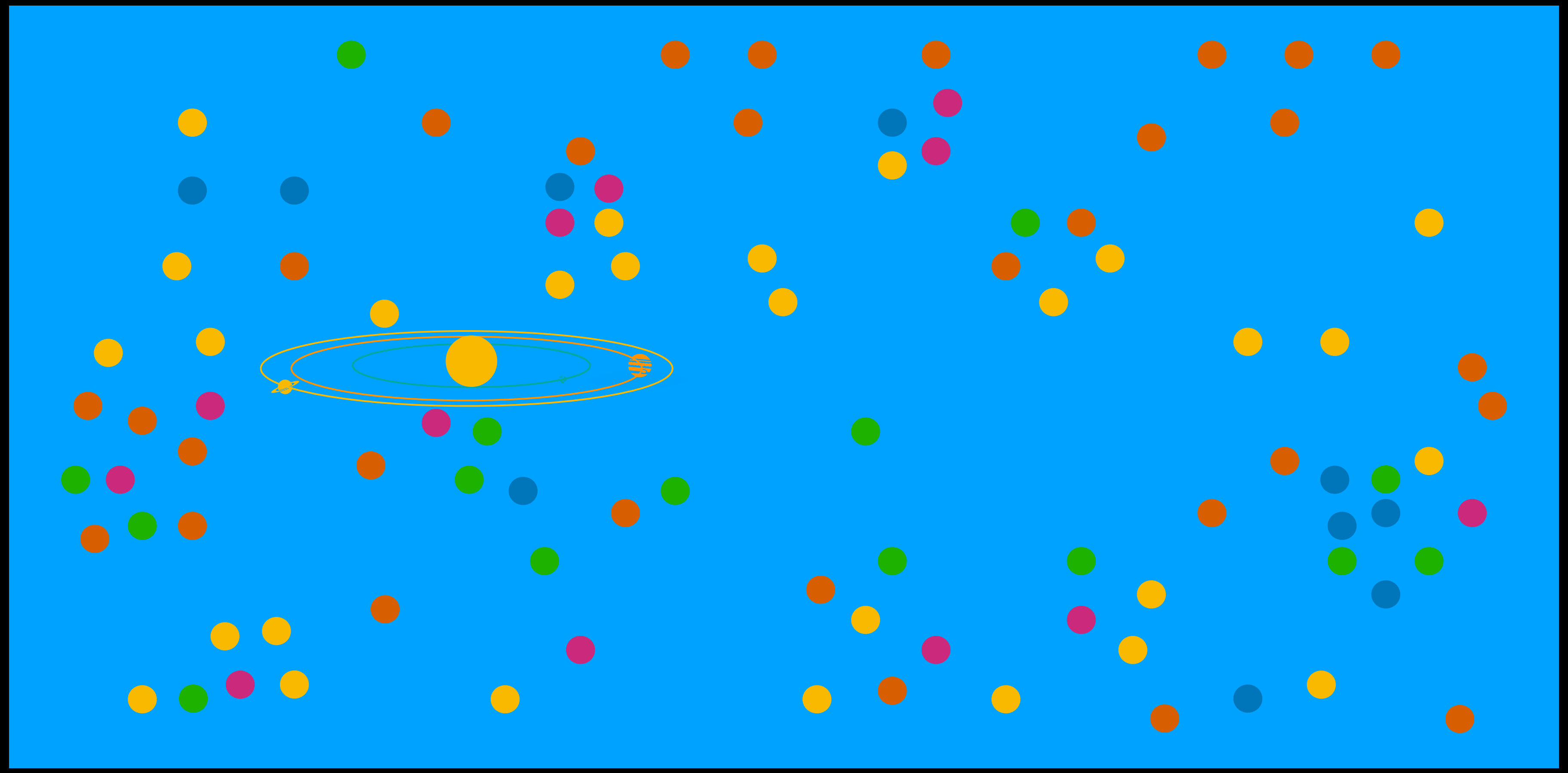


ours is called “The Milky Way” and it contains about 1 hundred billion stars

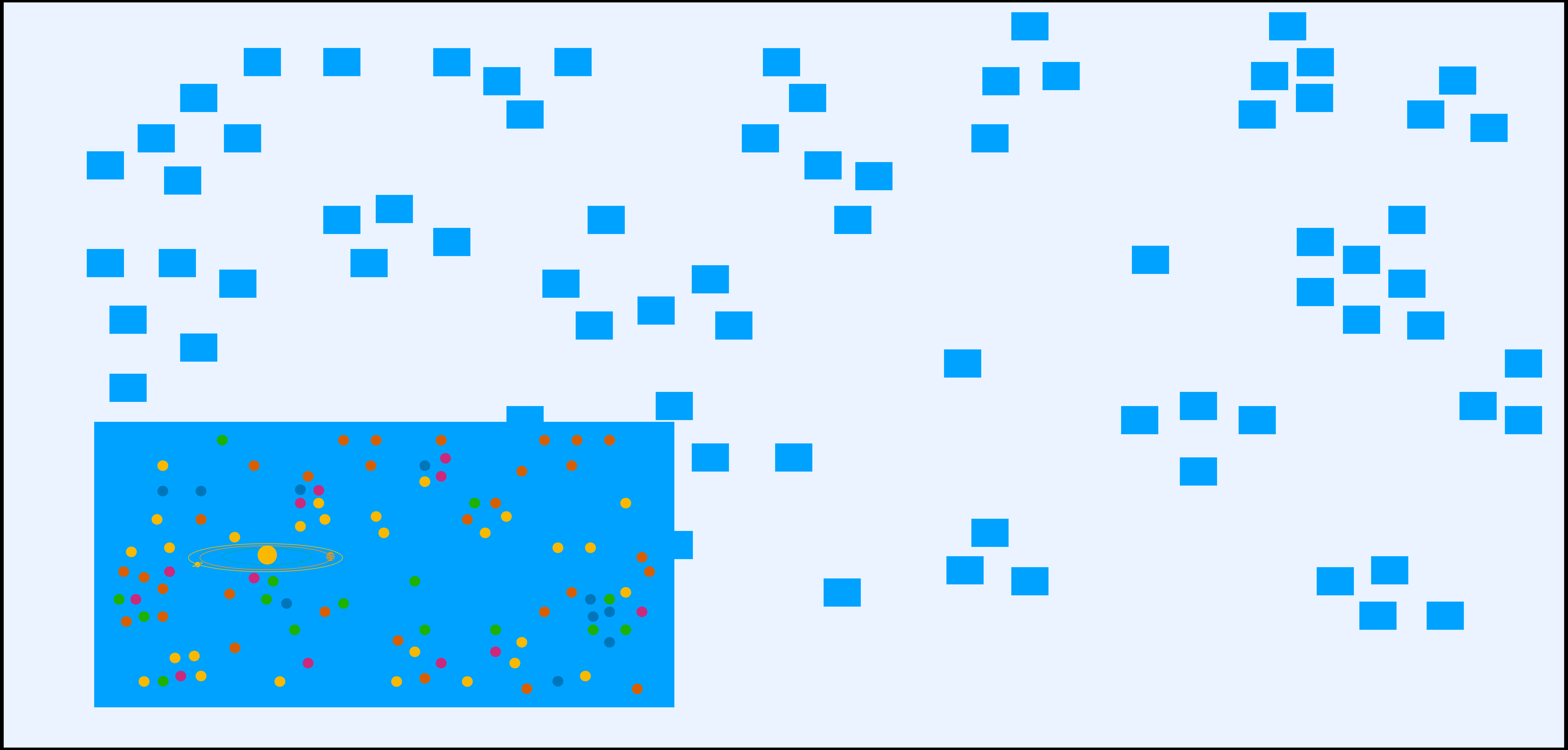


around most of the stars are systems of planets (ours is called “**The Solar System**”)

our home planet is **Earth**

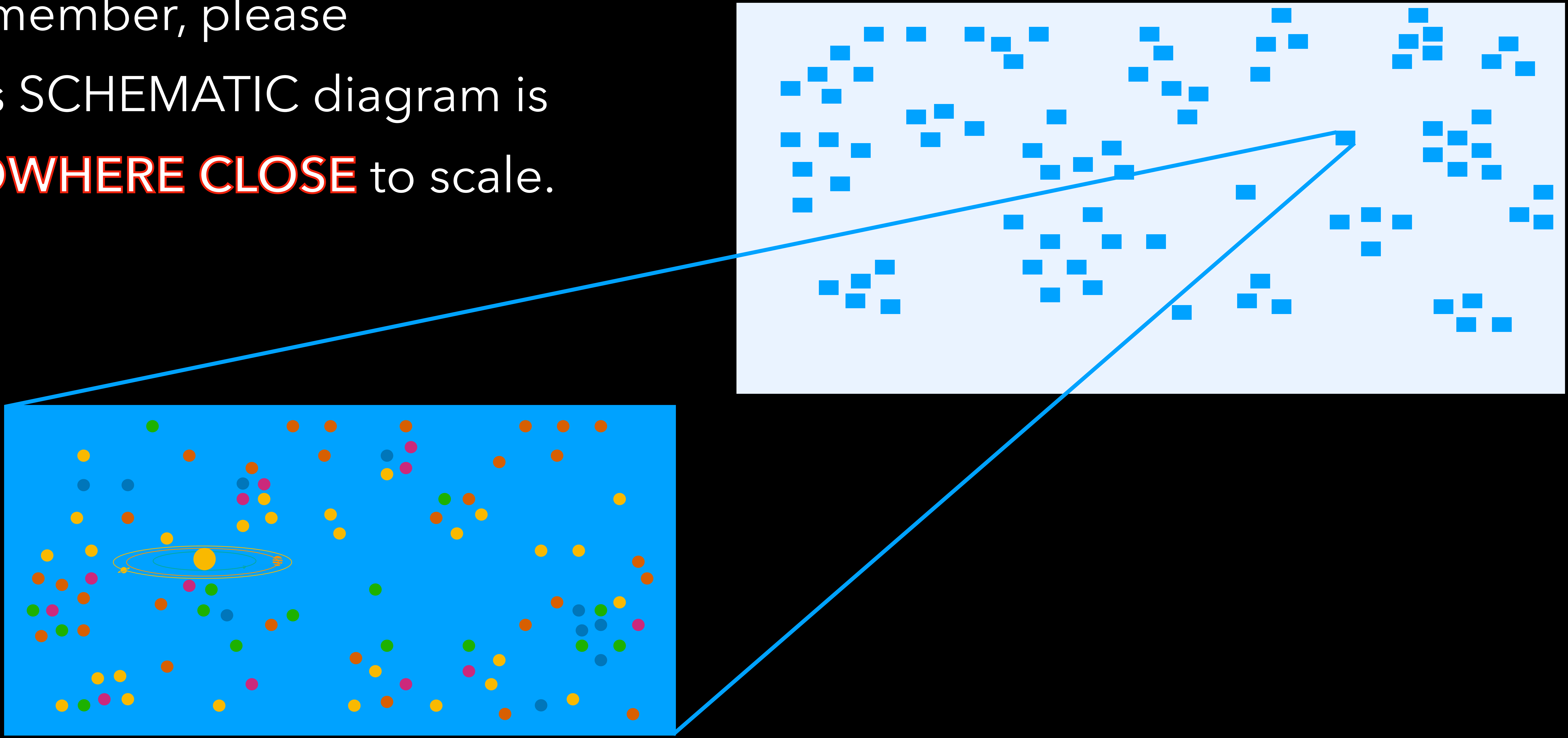


Earth resides in the Solar System, around the Sun, which is one of MANY stars, INSIDE the Milky Way,



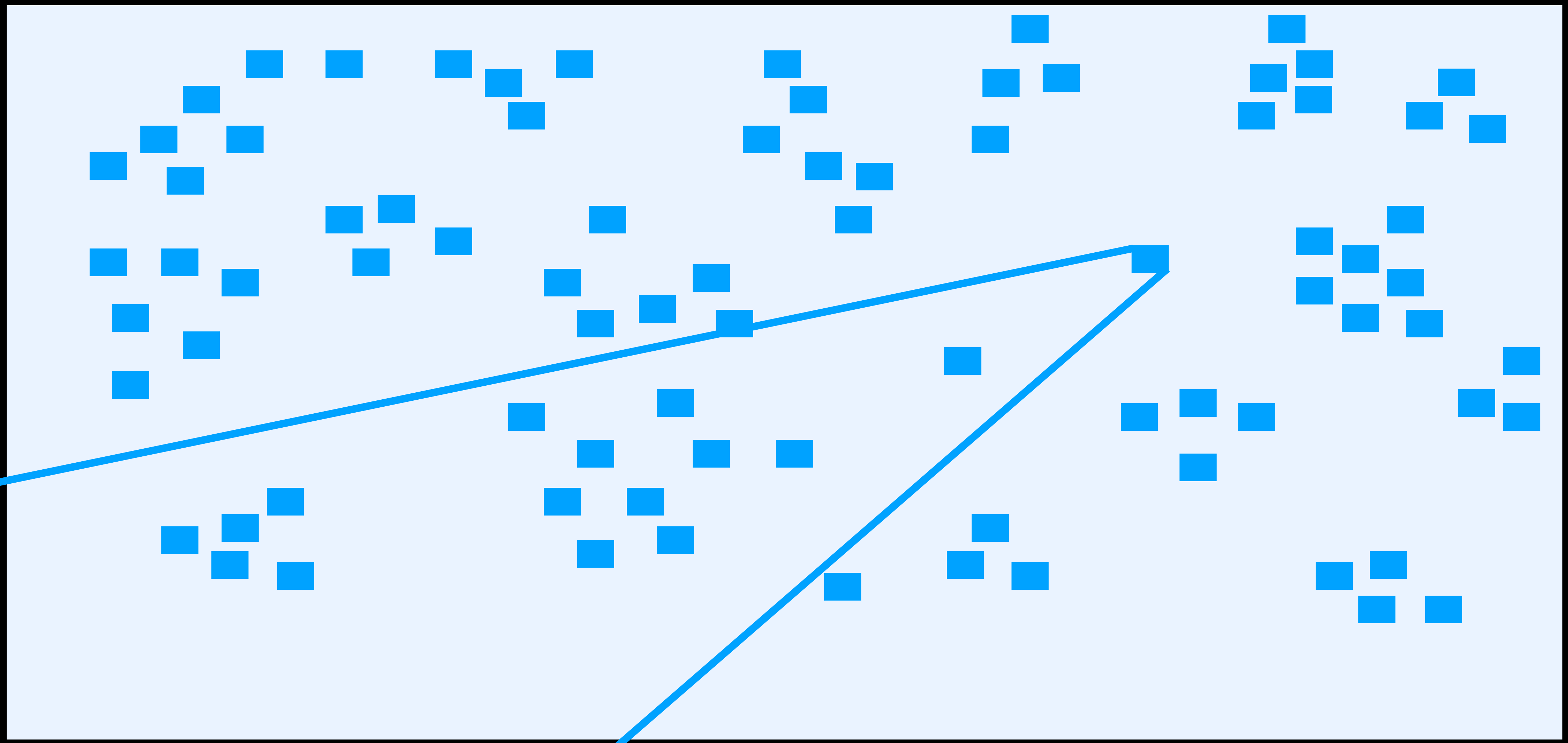
Earth resides in the Solar System, around the Sun, which is one of MANY stars, INSIDE the Milky Way, which is one of MANY galaxies, in our Universe

Remember, please
this SCHEMATIC diagram is
NOWHERE CLOSE to scale.



Earth resides in the Solar System, around the Sun, which is one of MANY stars,
INSIDE the Milky Way, which is one of MANY galaxies, in our Universe

And, actually, that boring blue box likely looks something more like this…



…cartoon!

…and we are buried INSIDE the Milky Way.


c. 1910
“the Star-Forming Milky Way I never thought I'd see”
Image credit: E.E. Barnard, published 1919


c. 2010
WorldWide Telescope
Explore
Guided Tours
Search
Communities
View
Settings
Support WWT
Sign Out
Use Layer Manager to Control User Settings
Name My Location
Lat 42:34:13
Alt 100.0m
Lng -88:33:18
View From This Location
Setup
2024/06/12 20:54:30
Real Time
Now
Galactic Plane Mode
View in ESASky
esa
Layers
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
Sky
Overlays
Constellations
Constellation Pictures
Constellation Figures
Constellation Boundaries
Constellation Names
Grids
Equatorial Grid
Galactic Grid
AltAz Grid
Time Scrubber
Astrometry.net
WORLDWIDE TELESCOPE
Look At
Sky
Imagery
Digitized Sky Survey (Color)
Image Crossfade
Tracking
Bar-pt1-pl013_sm.jpg
1 of 13
N
Ophiuchus
RA: 16h27m42.9s
Dec: -23:09:36
Comet Wilson-H...
Rho Oph
Rho Oph
Rho Ophiuchus c...
Spirals with a tale...
Elia 2-27
Rho Ophiuchi clo...
Infant Solar Syste...
Infant solar syste...
Rho Ophiuchi
Rho Ophiuchi
2MASS J162813...

E. E. Barnard

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XLIX — JANUARY 1919 — NUMBER 1

ON THE DARK MARKINGS OF THE SKY
WITH A CATALOGUE OF 182 SUCH OBJECTS

By E. E. BARNARD

It would be unwise to assume that all the dark places shown on photographs of the sky are due to intervening opaque masses between us and the stars. In a considerable number of cases no other explanation seems possible, but some of them are doubtless only vacancies.

I do not think it necessary to urge the fact that there are obscuring masses of matter in space. This has been quite definitely proved in my former papers on this subject. If any doubt remains of this it will perhaps be readily dispelled by a close examination of the photographs previously printed. The conclusive ones I think are:

1. The photograph of the nebula about Nu Scorpii[1] which clearly shows partial and complete obscuration by the great wing-like nebula that covers much of the immediate region of Nu Scorpii and extends southward to the great nebula of Rho Ophiuchi.

2. The region of Rho Ophiuchi, where a large space of sky is blotted out by a great and beautiful nebula.[2] The fact of obscuration is clearly evident here, for wherever a trace of the nebula

[1] *Astrophysical Journal*, 31, 1910, Plate I, facing p. 8.

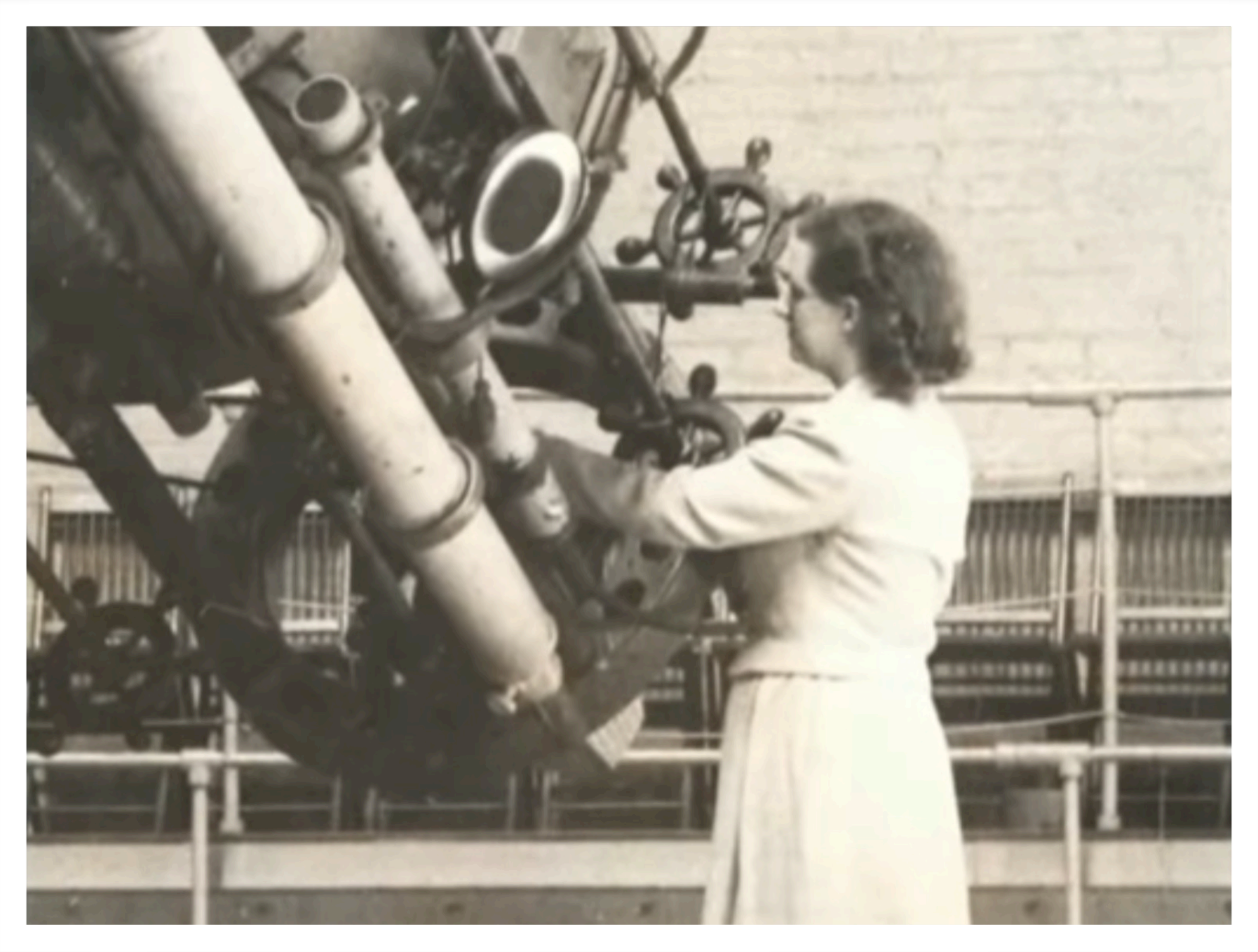
[2] *Ibid.*, Plate IIa, facing p. 10.

Astrometry.net
WORLDWIDE TELESCOPE

@Yerkes, 1920

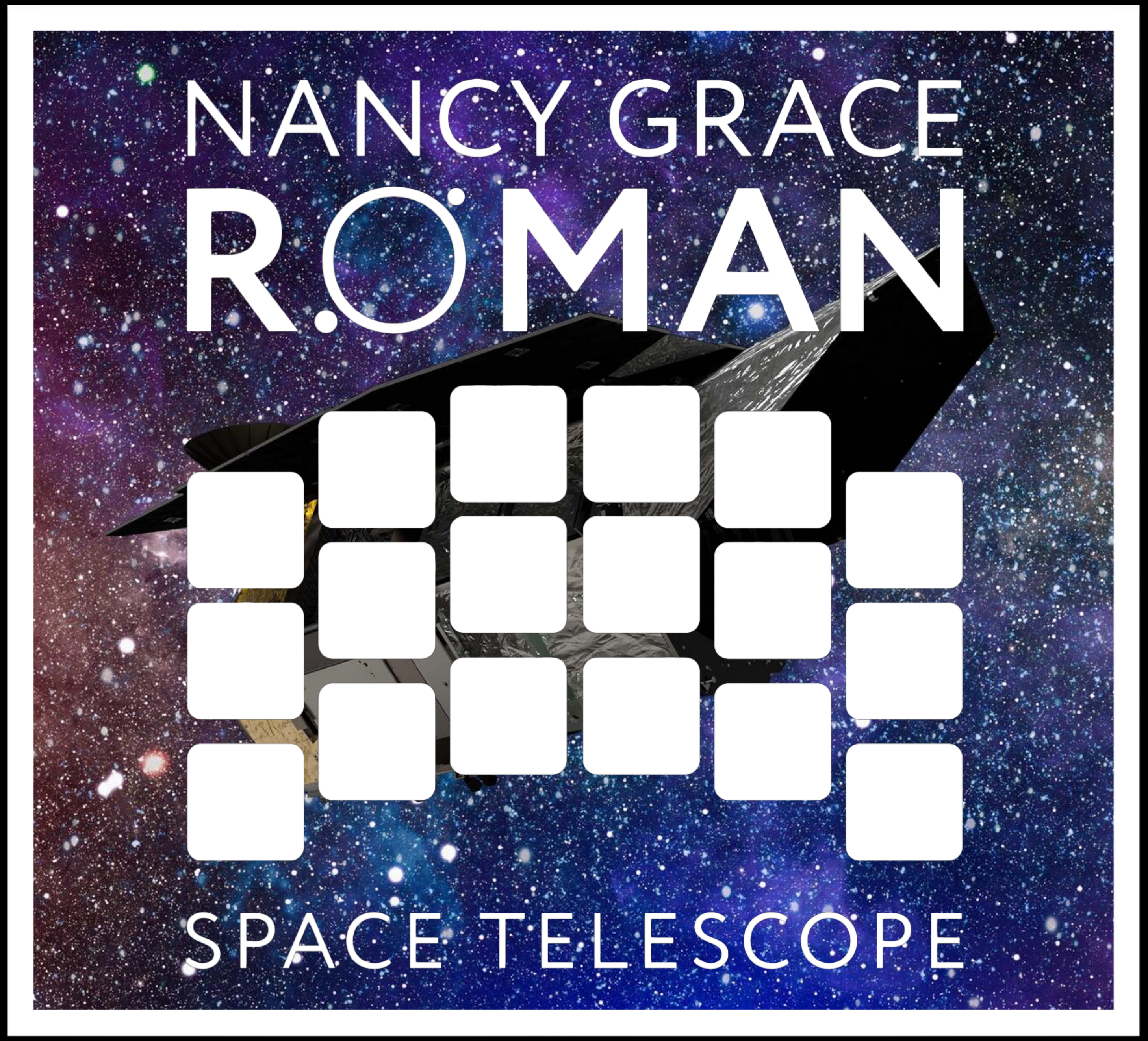

YERKES·OBSERVATORY
UNIVERSITY·OF·CHICAGO
18
95
CLOSED FOR
A PRIVATE
EVENT

Nancy Grace Roman



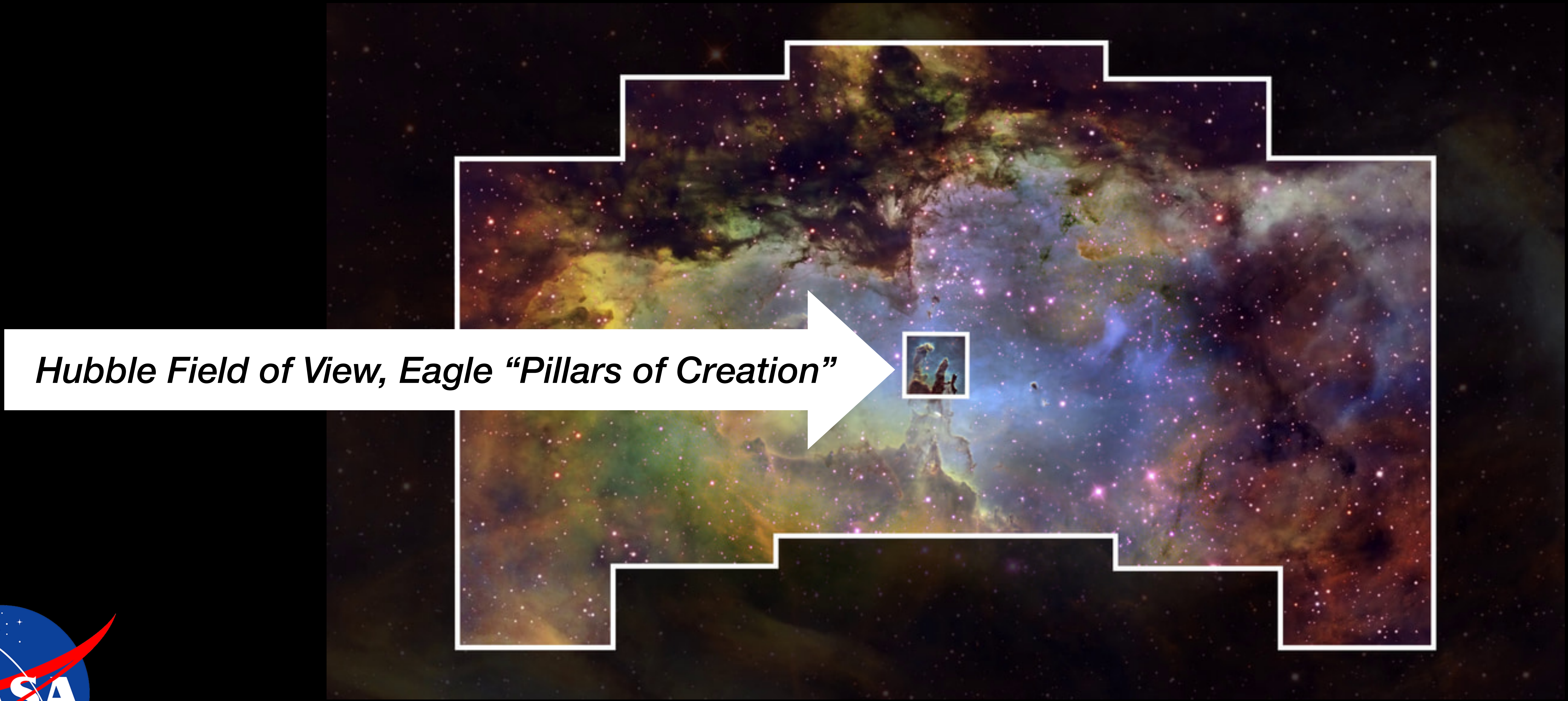
@Yerkes, 1948

with her accomplishment,
The Hubble Space Telescope,
launched 1990



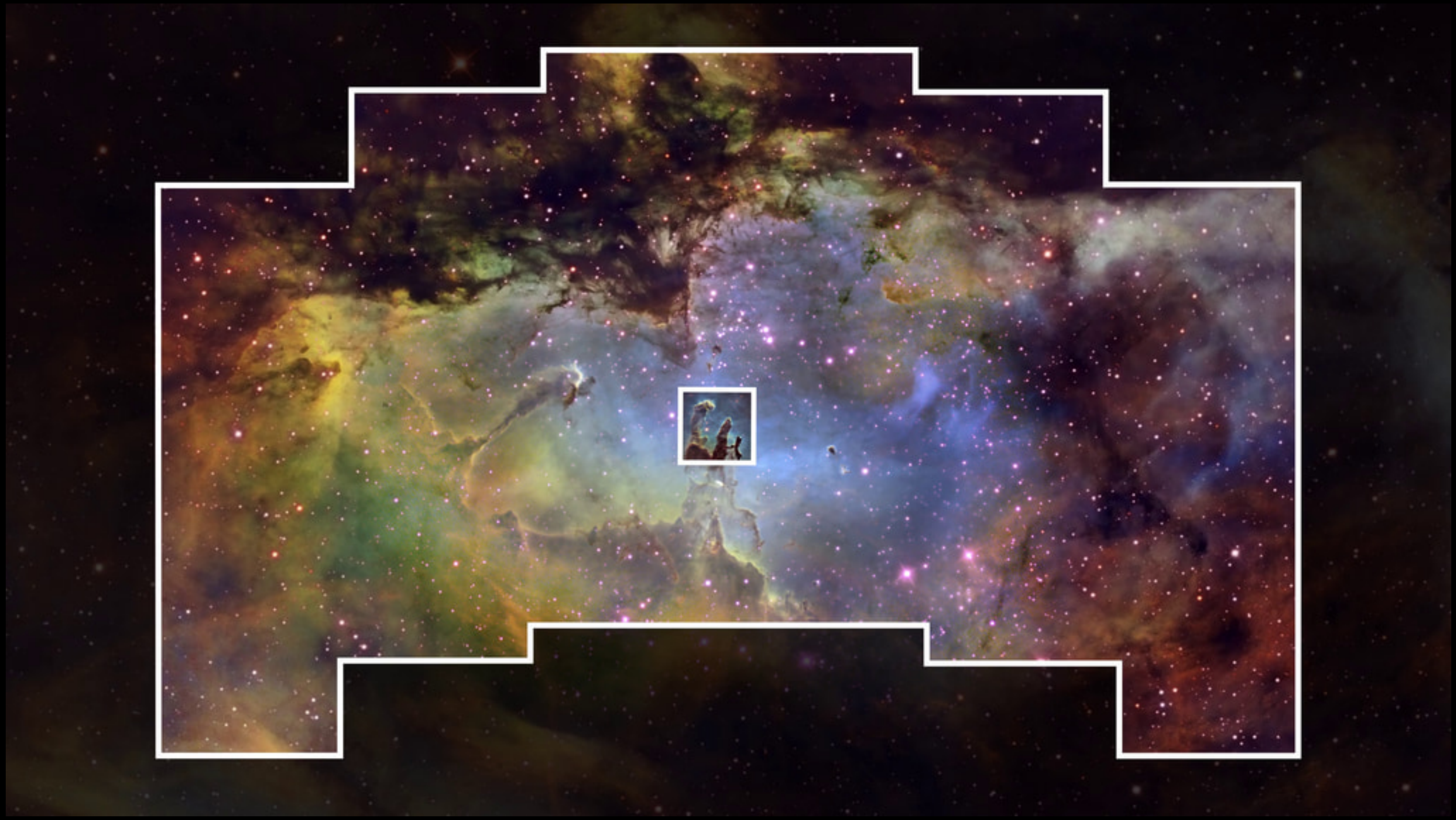
coming in ~2026

NANCY GRACE ROMAN

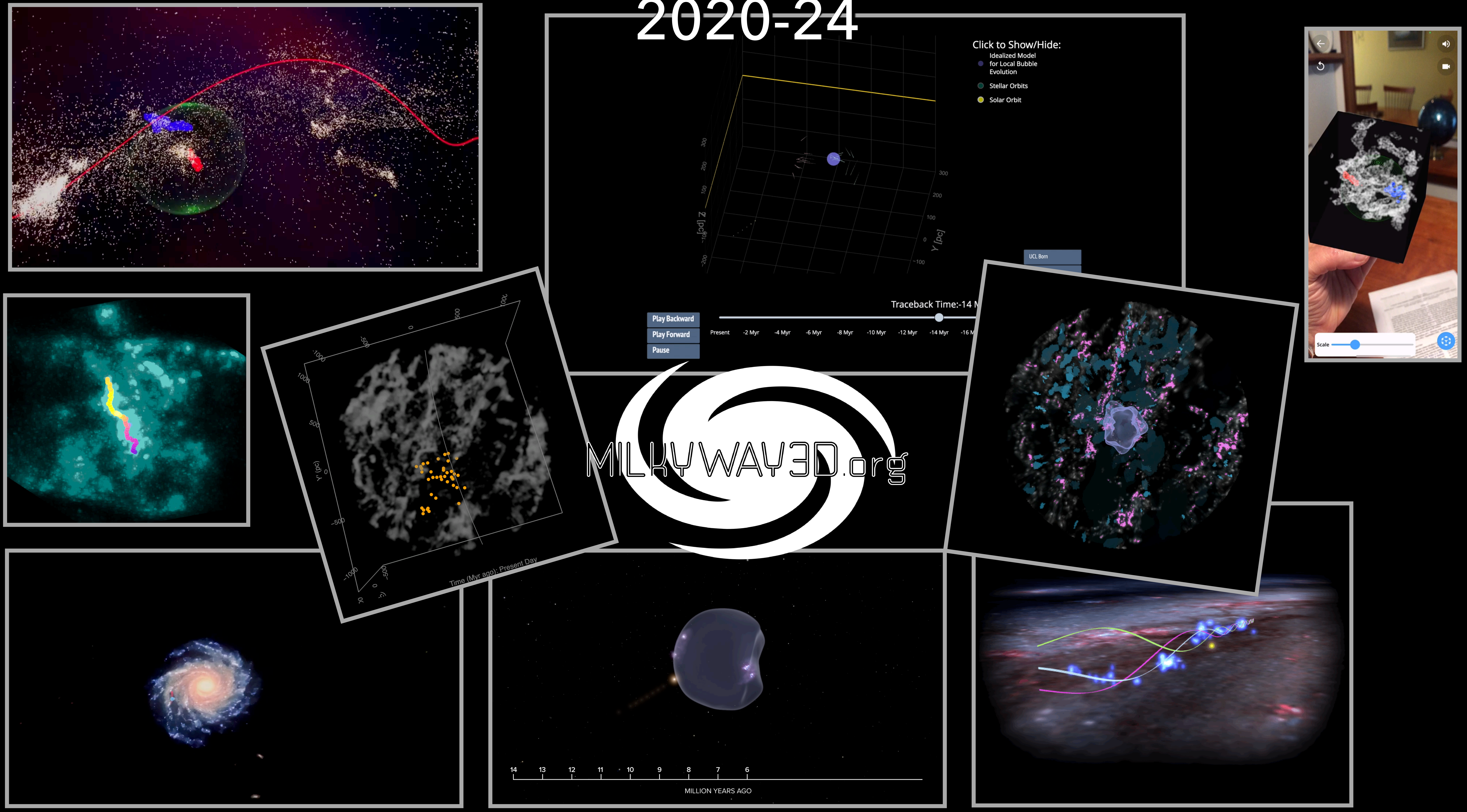


SPACE TELESCOPE

While this is wonderful, it's a 2D view. Not good enough.



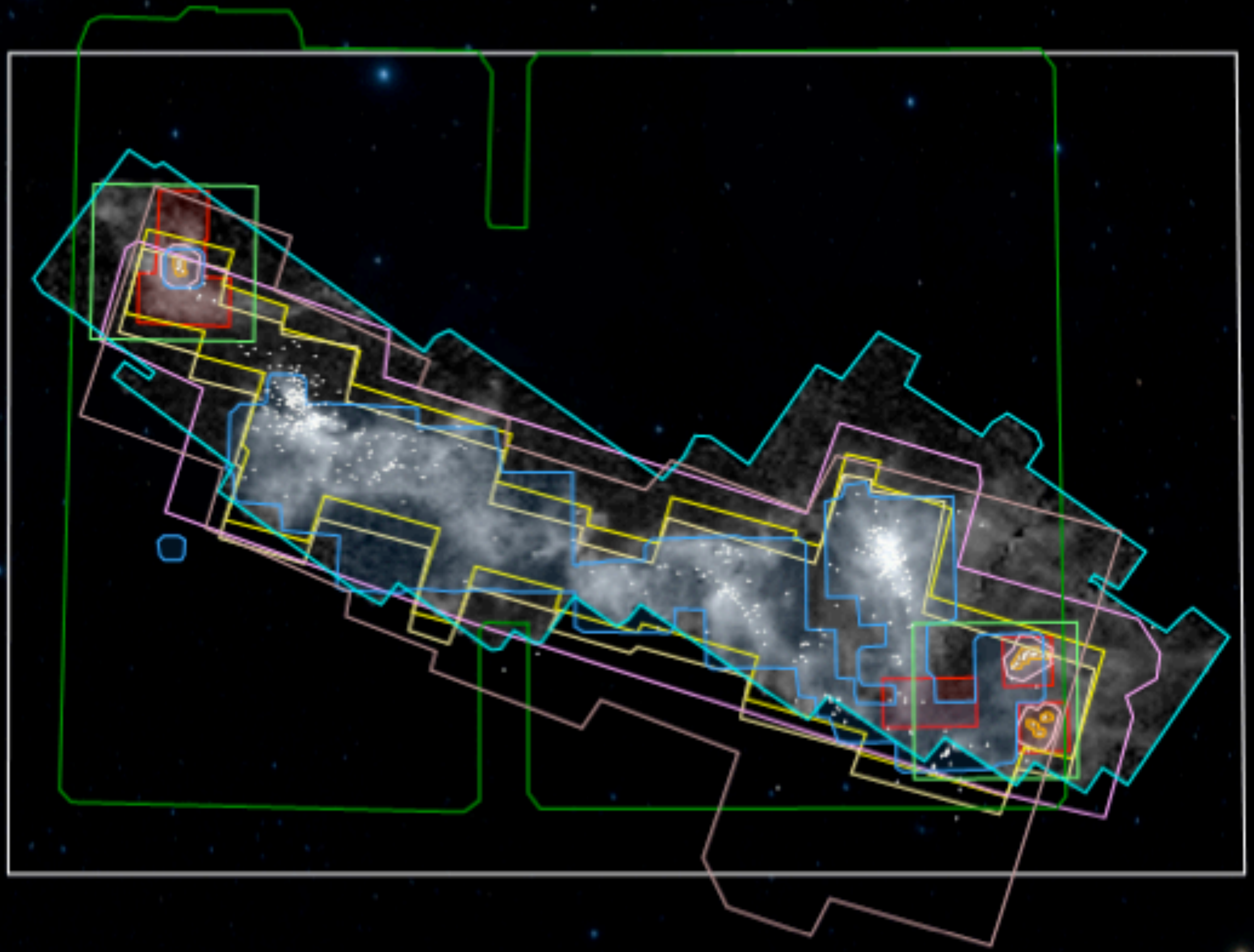
2020-24



Zucker et al. 2021, Bialy et al. 2021; Zucker et al. 2022, Konietizka et al. 2024, O'Neill et al. 2024, Swiggum et al. 2024

But first, let's go back a decade+

2011



Completely

COMPLETE

Alyssa Goodman,
Harvard-Smithsonian Center for Astrophysics

Microsoft Research WorldWide Telescope

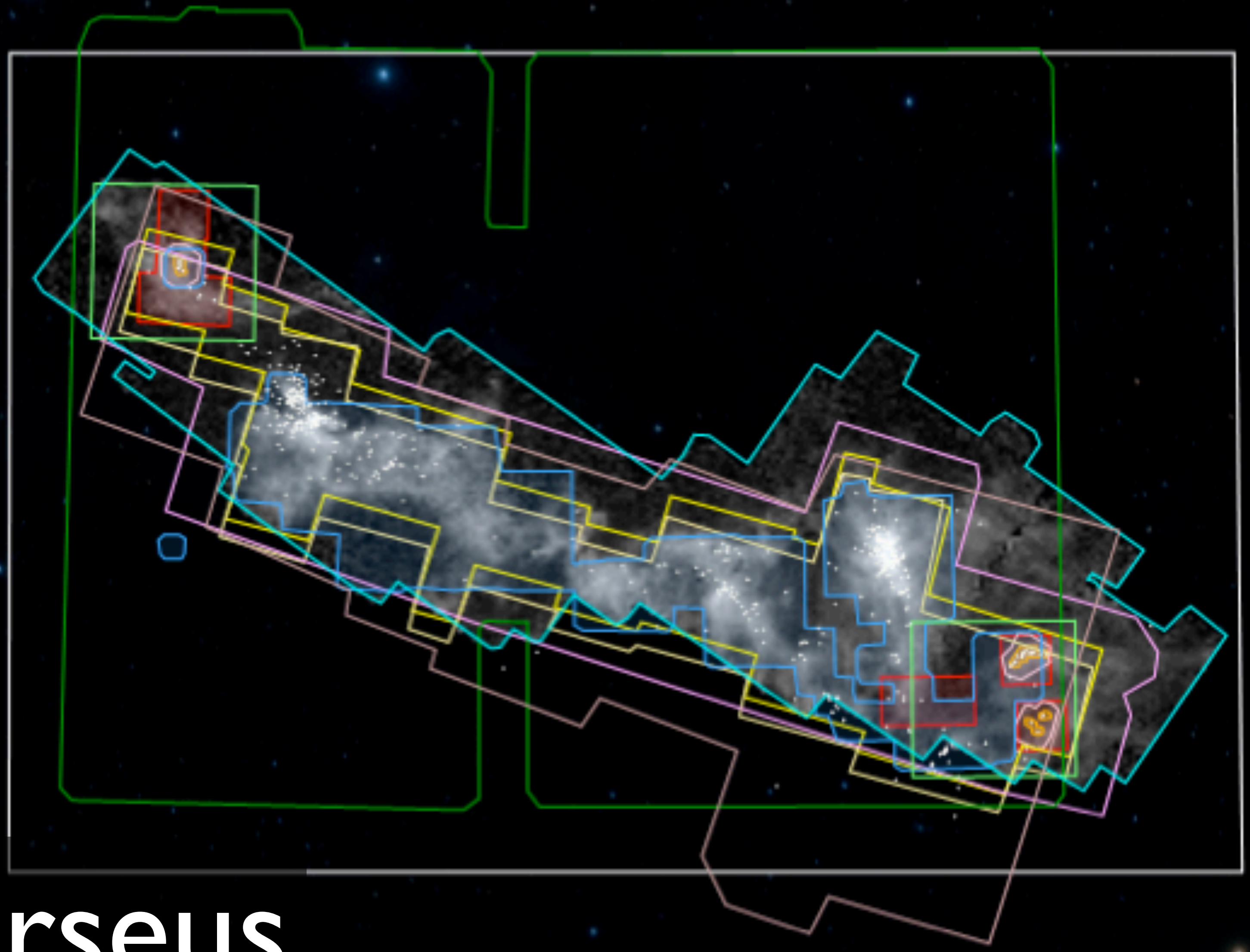
COMPLETE
up to Fall 2011

Joao **Alves**
Héctor **Arce**
Chris **Beaumont***
Michelle **Borkin***
Paola **Caselli**
James **Di Francesco**
Jonathan **Foster***
Alyssa **Goodman** (PI)
Mark **Heyer**
Doug **Johnstone**
Jens **Kauffmann**
Helen **Kirk***
Di **Li**
Jaime **Pineda***
Naomi **Ridge**
Erik **Rosolowsky**
Scott **Schnee***
Rahul **Shetty**
Mario **Tafalla**

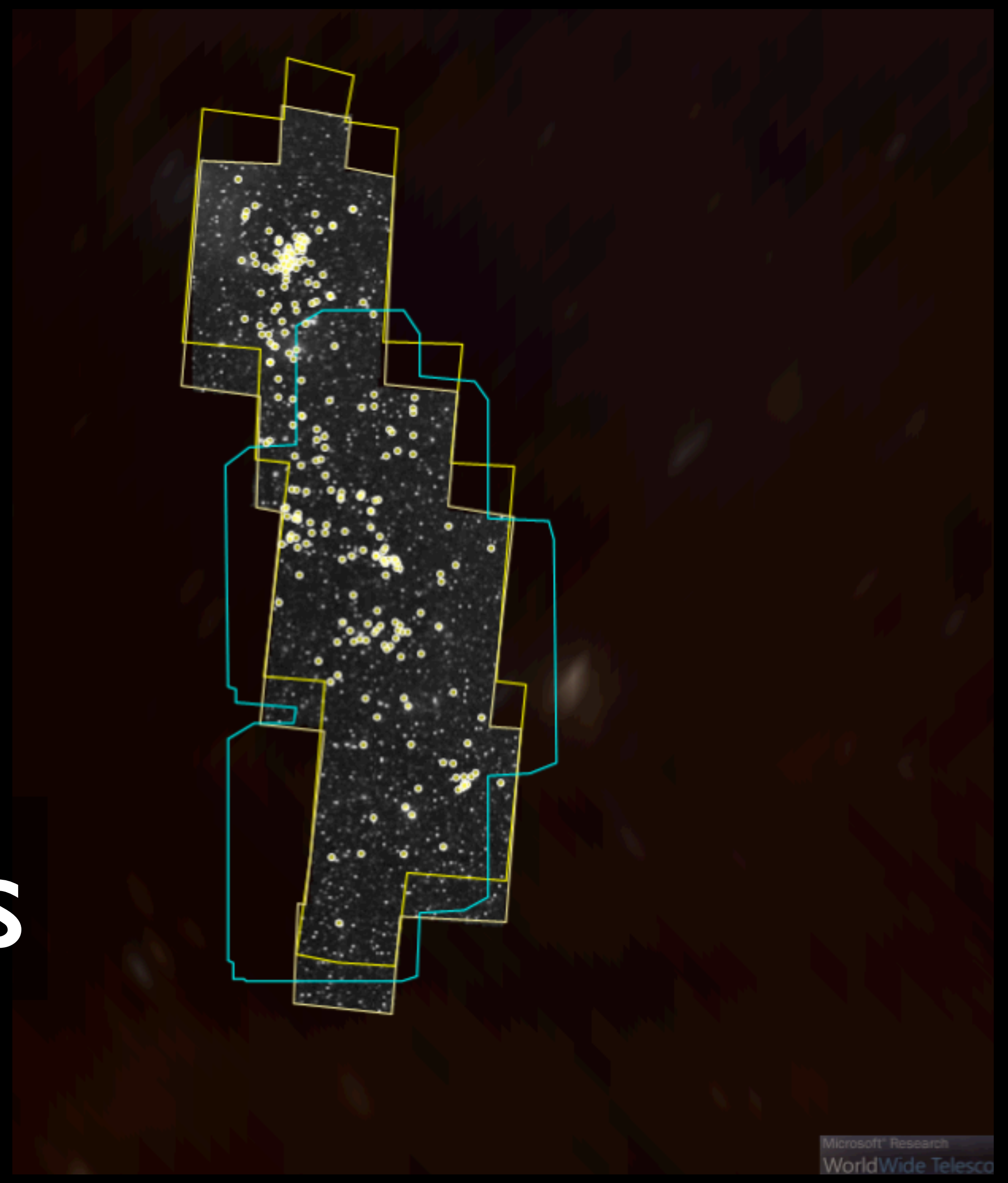
**=COMPLETE Ph.D.*

+many thanks to special friends of COMPLETE: Hope ***Chen****, Michael* ***Halle****, Marco* ***Lombardi****, Phil* ***Myers****, Stella* ***Offner****, Tom* ***Robitaille****,* ***c2d*** *Team, co-authors, undergrad interns...*

2011



Perseus



Serpens

Ophiuchus

COMPLETE

The **CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission Survey of Star-Forming Regions

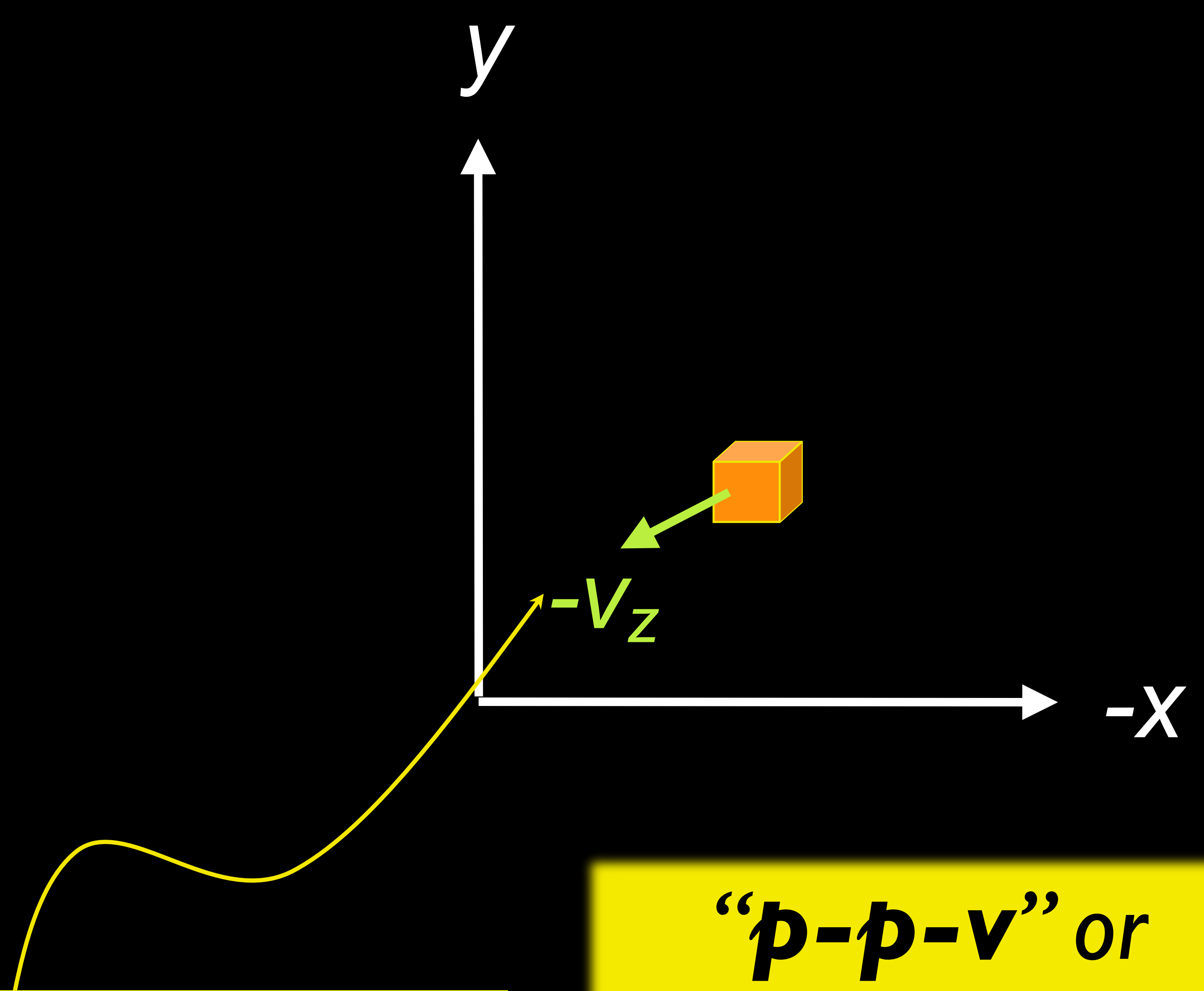
SIRTF Legacy: From Cores to Disks
c2d
CfA CIT IPAC JPL NAU UL UMd UT

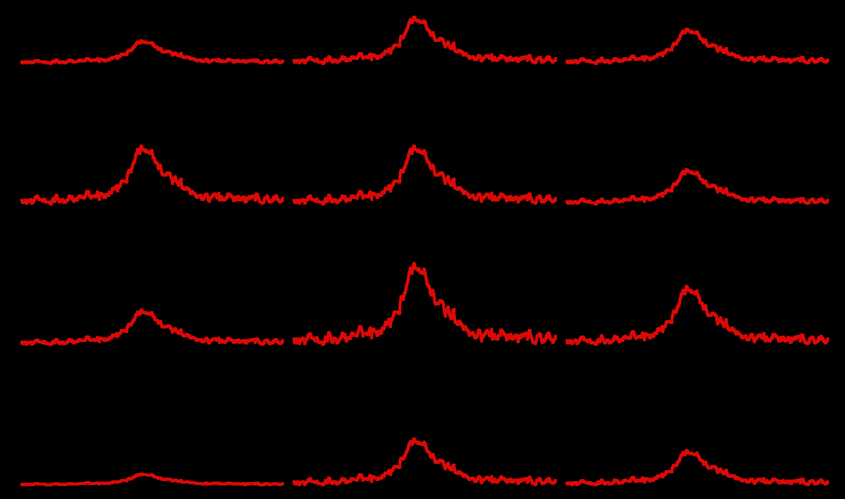
www.cfa.harvard.edu/COMPLETE
tinyurl.com/completepapers

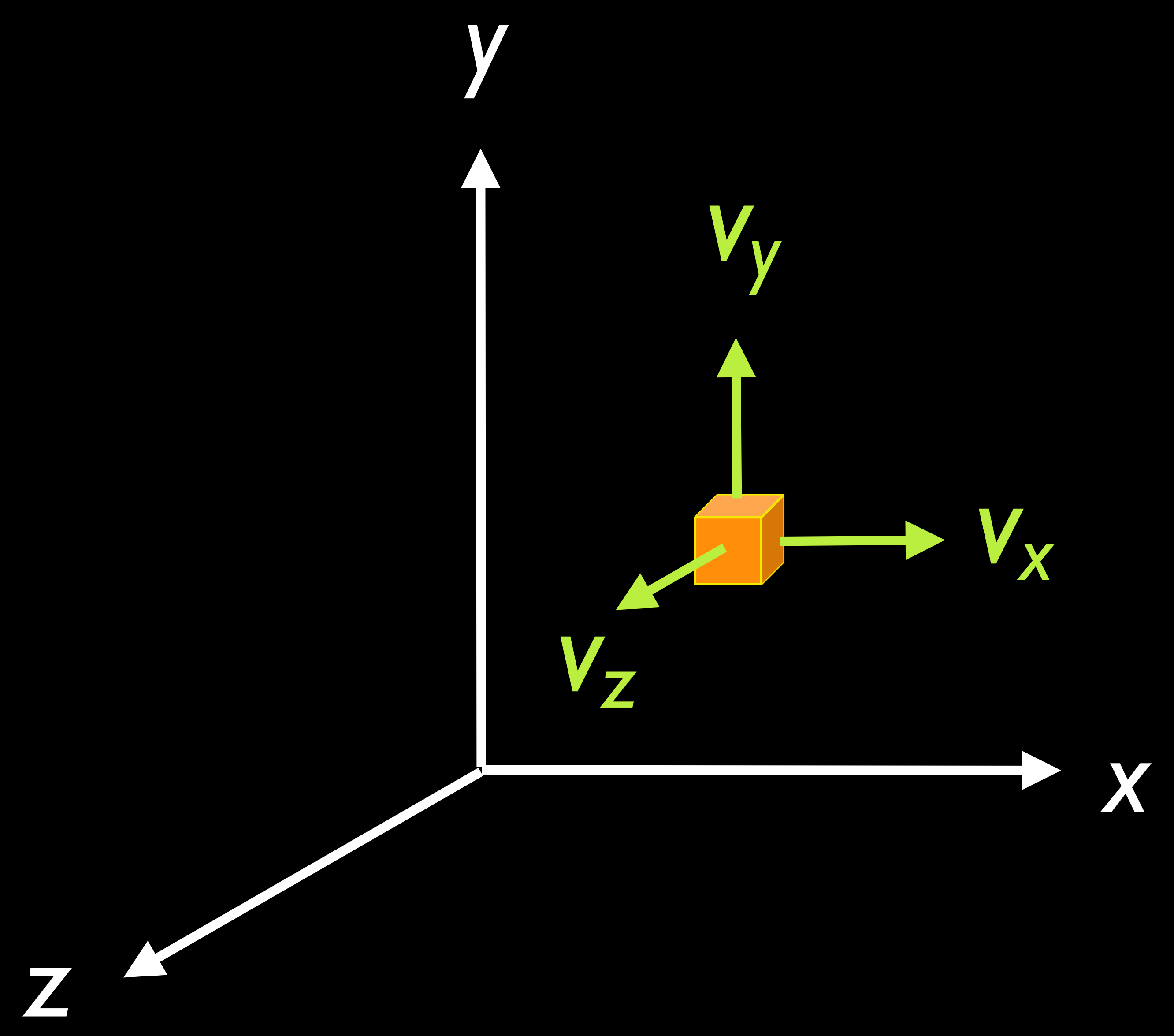
What we could do in 2011…(and what we really wanted)

p-p-v space: Not exactly “3D”

true 3D with velocities (a.k.a. 6D)



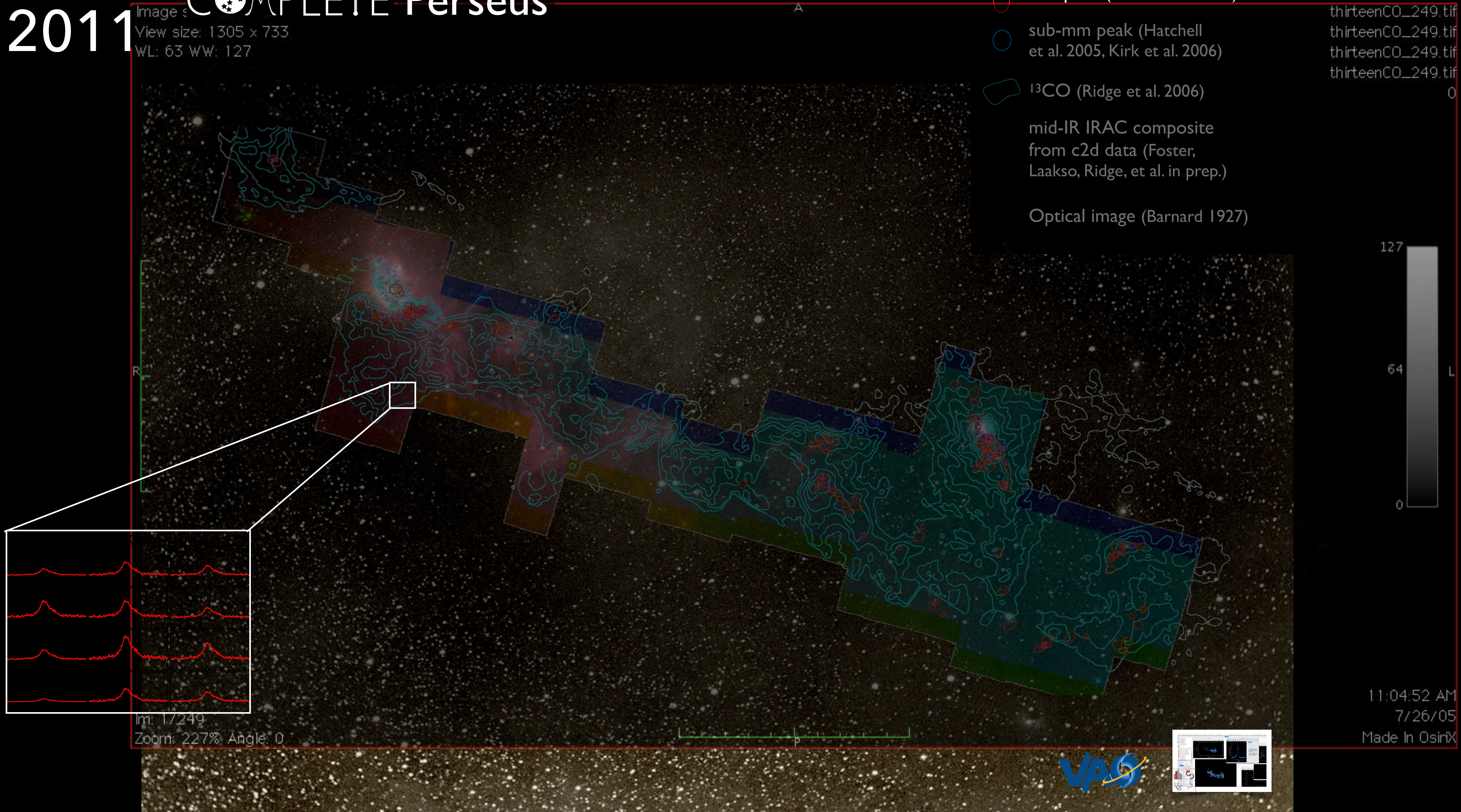




v_z *only* from “spectral-line maps”

“***p-p-v***” *or* “*position-position-velocity*” *space*

2011 COMPLETE Perseus



2011

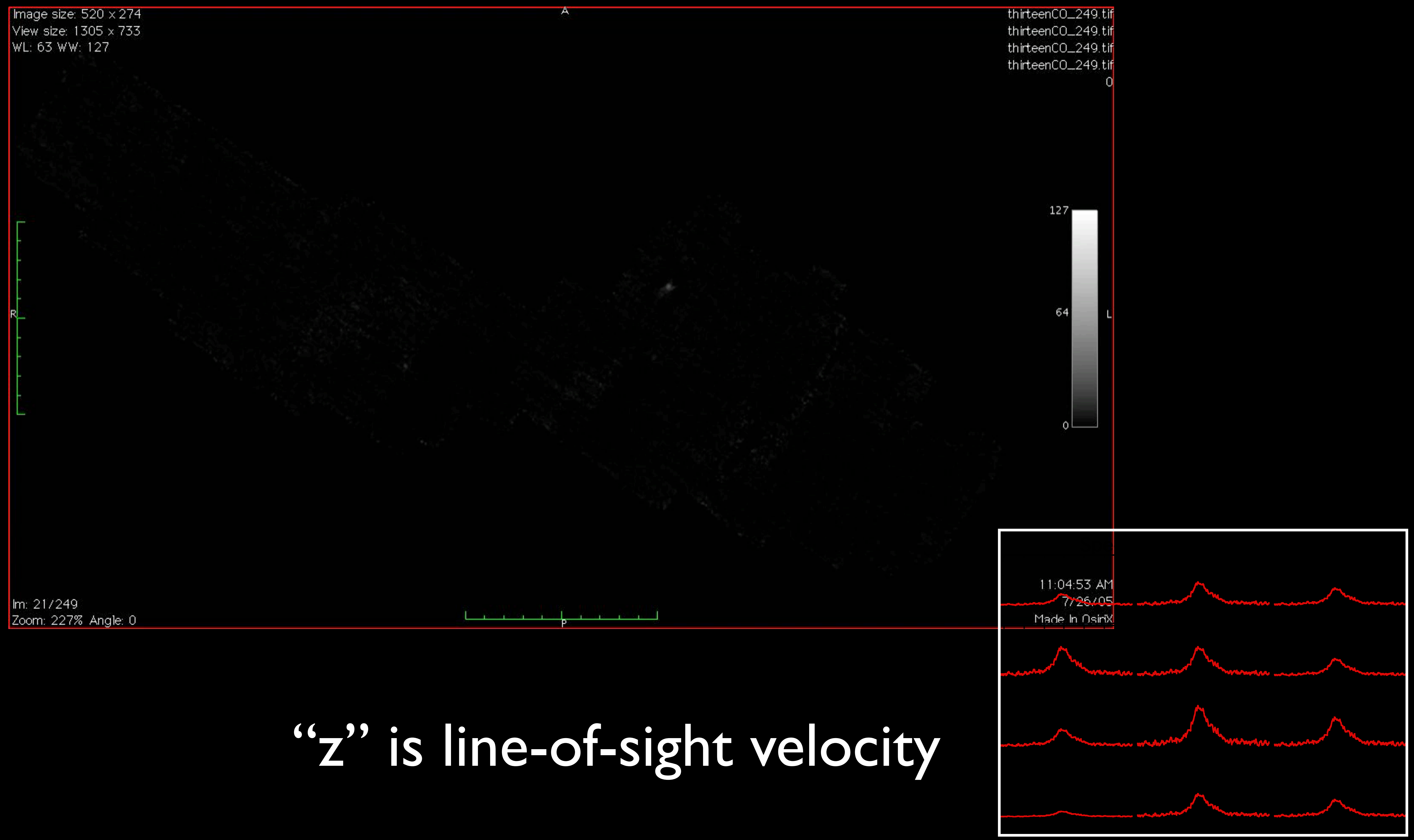
Real 3D

“KEITH”

“z” is depth into head

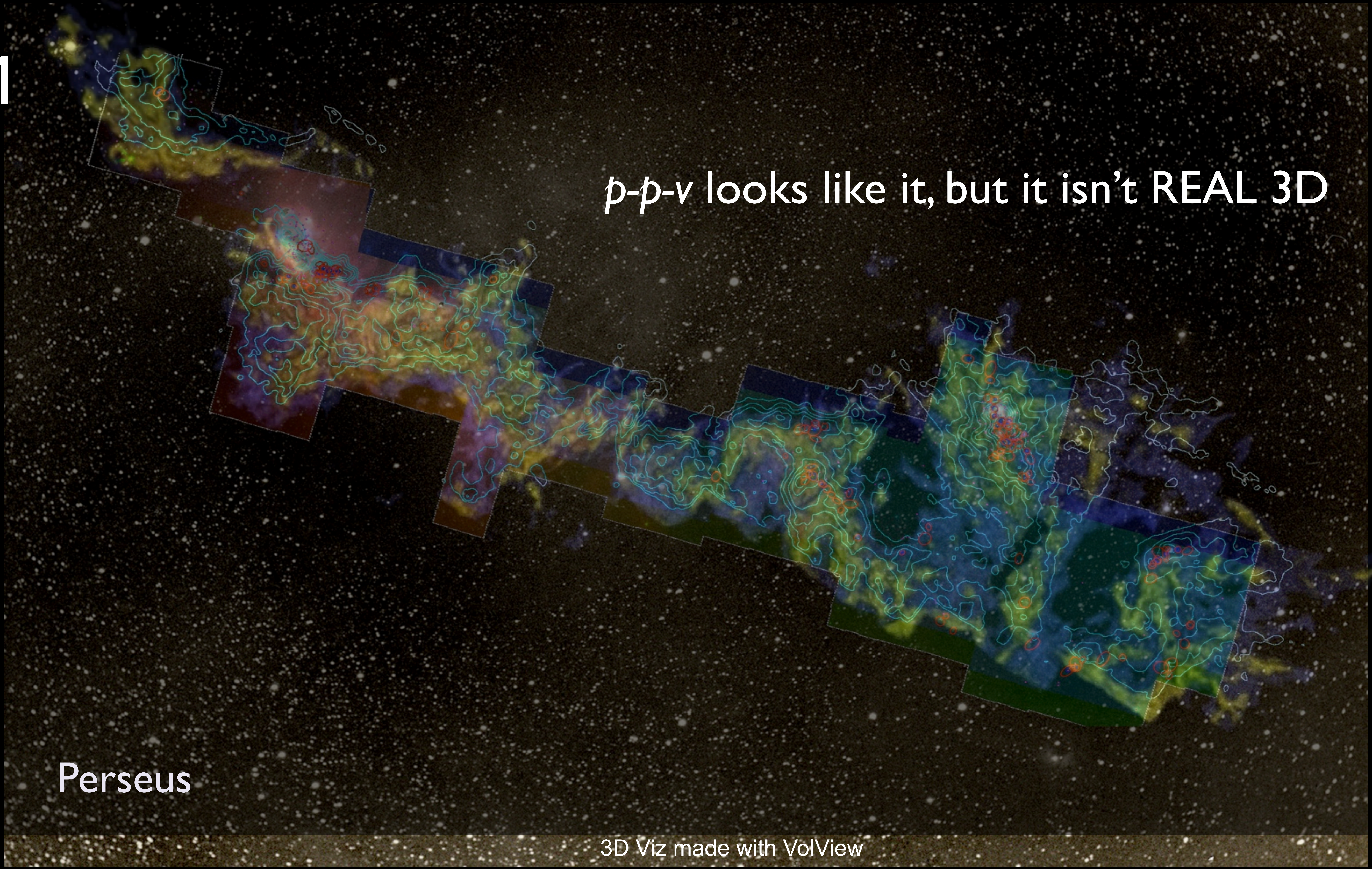
p-p-v looks like it, but it isn’t REAL 3D

“PERSEUS”



“z” is line-of-sight velocity

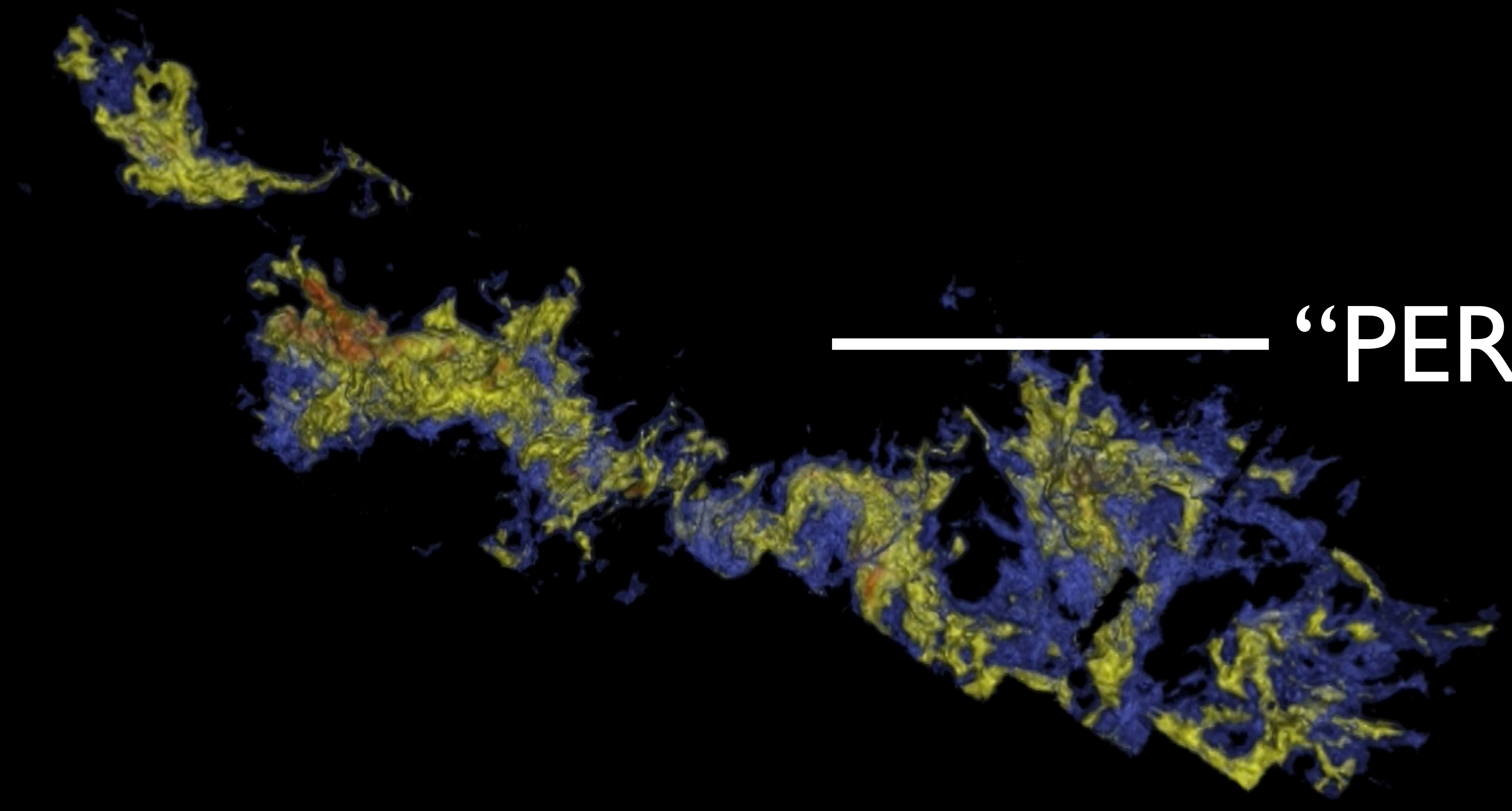
2011


p-p-v looks like it, but it isn't REAL 3D
Perseus
3D Viz made with VolView

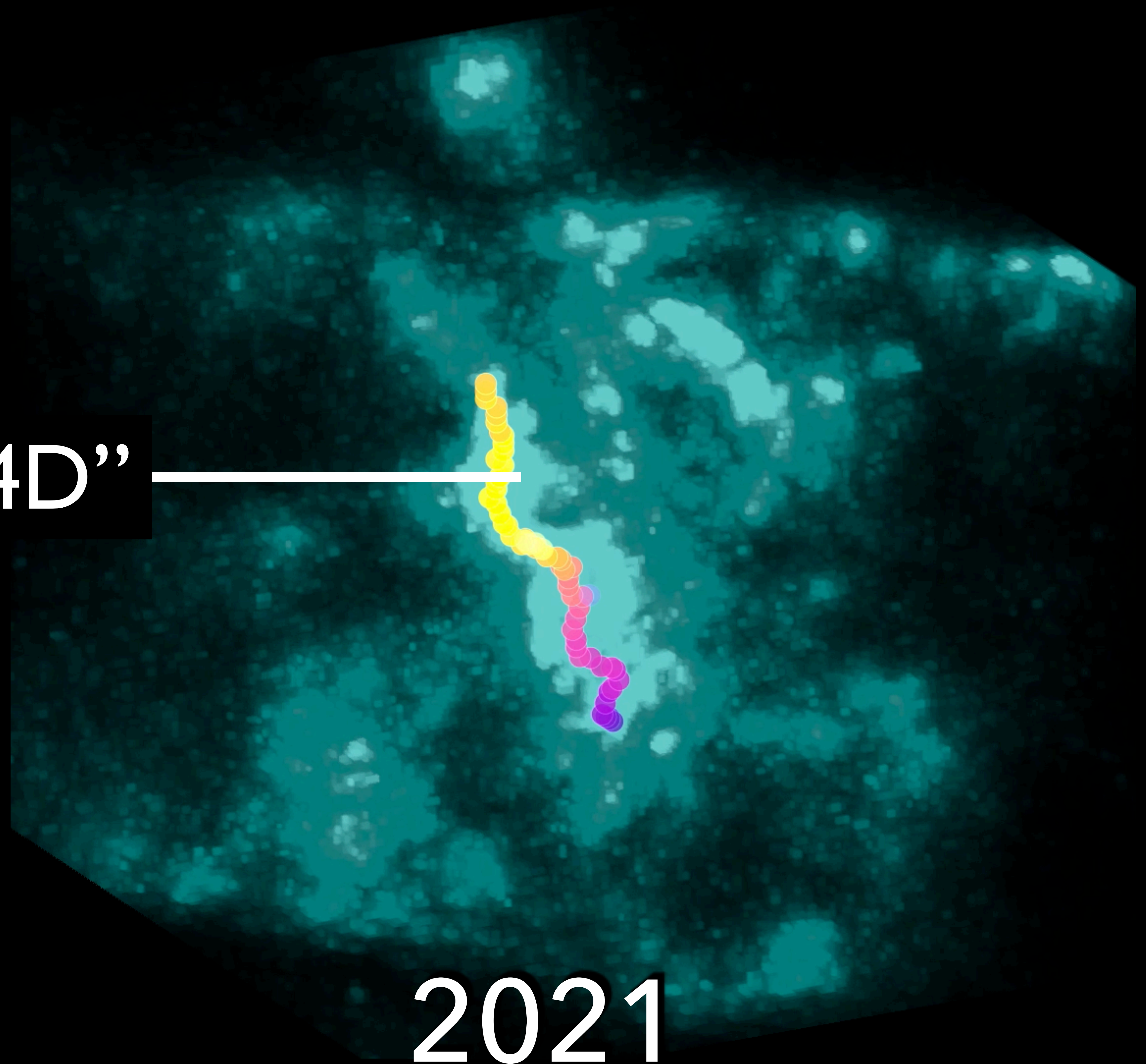
p-p-v space: **not** exactly "3D"

TRUE 3D

"I never thought I'd see"



"PERSEUS in 4D"



2011

2021

Ridge et al. 2006

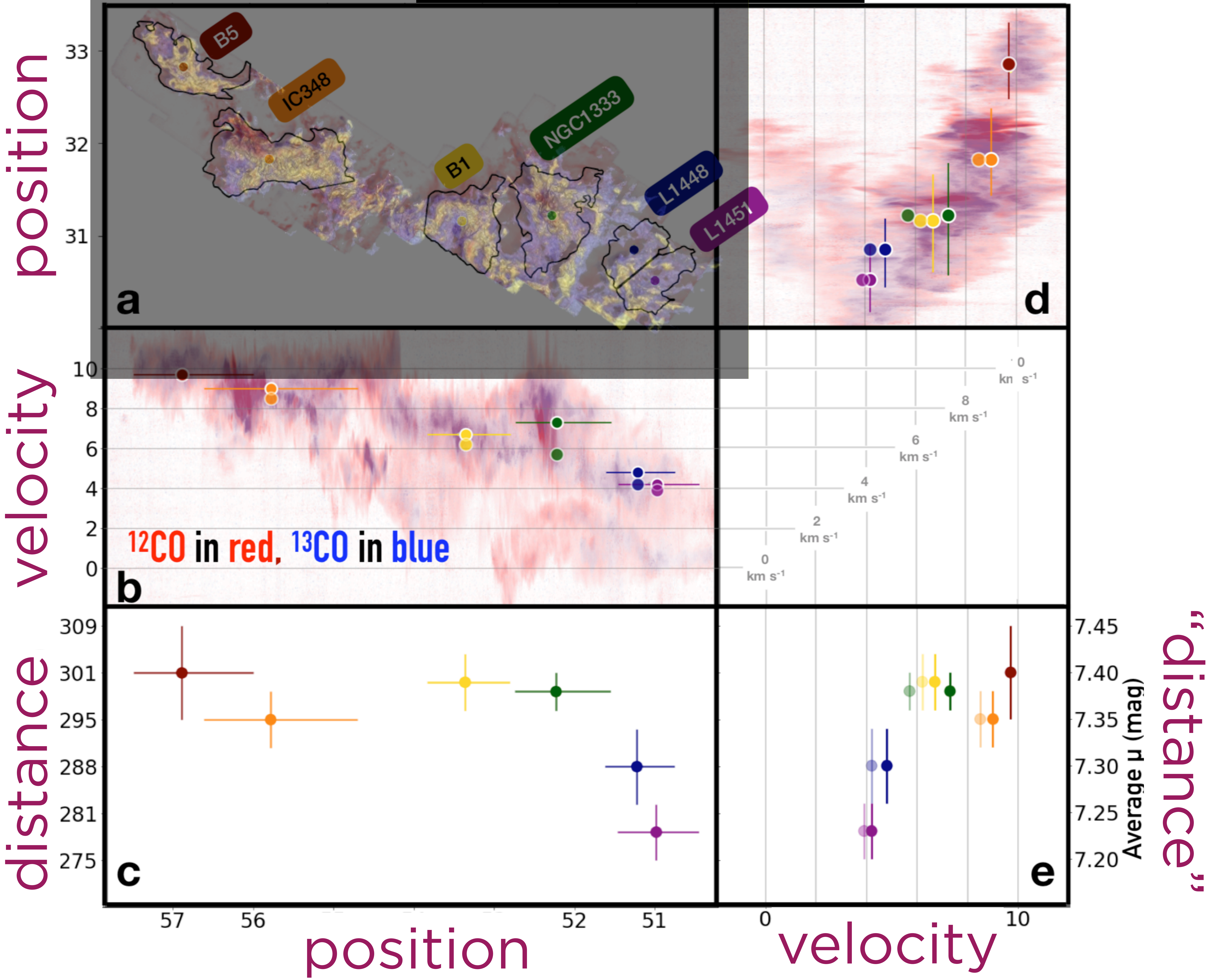
Zucker et al. 2021

The magic began in 2018, with Perseus

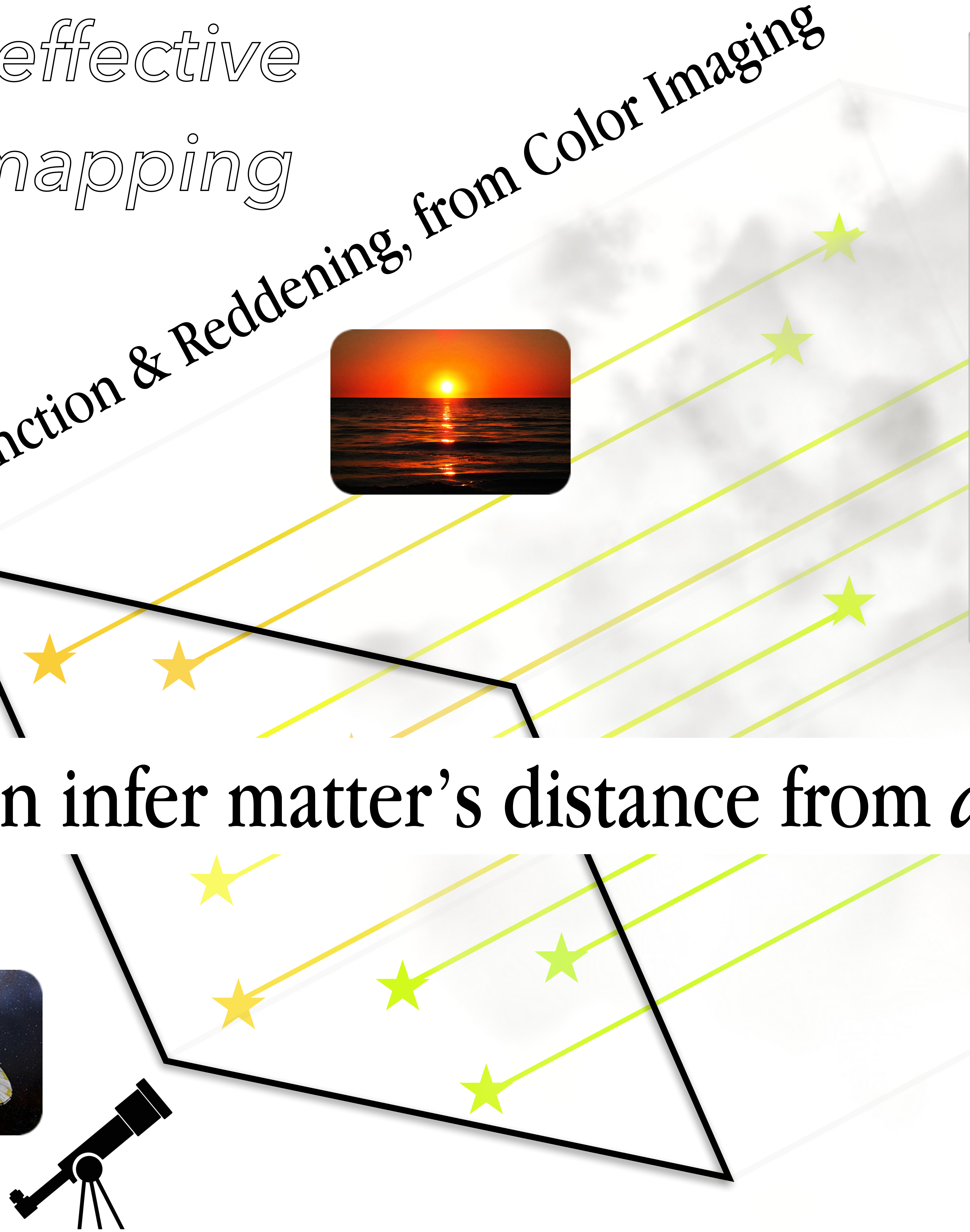
“magic”=effective 3D dust mapping

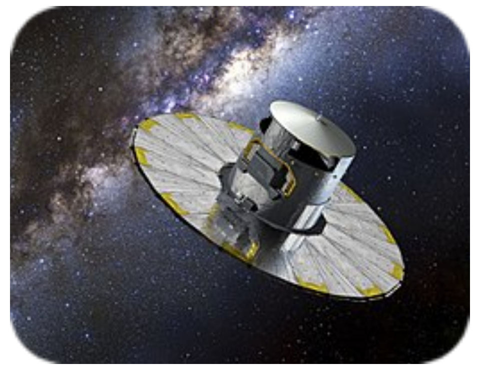
Movie shows COMPLETE CO p-p-v map of Perseus from Ridge et al. 2006;
Knitting to 3D dust & graphic from Zucker et al. 2018

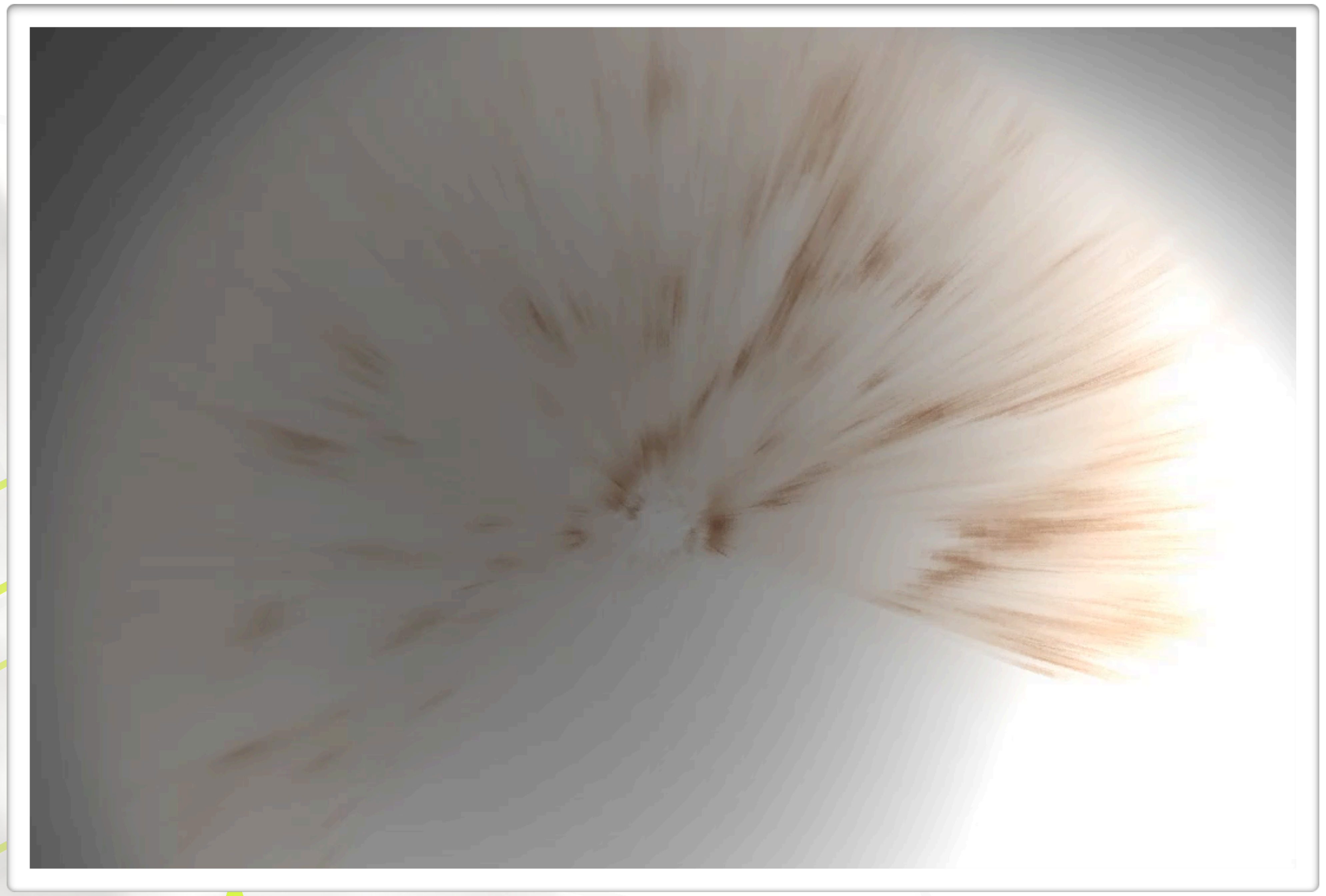
“PERSEUS in 4D”



"magic"=effective 3D dust mapping







Green et al. 2019

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

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

2010

2014

2015

2018

2020
2024

2021

2022
2024

2022

MILKYWAY3D.org

SCAN ME

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

MilkyWay3D.org is an open-data open-source discovery hub, providing data, visualization, and research tools for studying the MilkyWay in 3D.

INFRASTRUCTURE ⟷ SCIENCE ⟷ EDUCATION & OUTREACH

INFRASTRUCTURE

assembling data as a community, using modern, open-source practices

glue

AMERICAN ASTRONOMICAL SOCIETY WORLDWIDE TELESCOPE

OpenSpace

linking position and motion across dimensions, using the plug-in architecture enabled by glue
(plug-ins include WorldWide Telescope, OpenSpace & more)

MAST — The Dataverse Project — Digital Universe

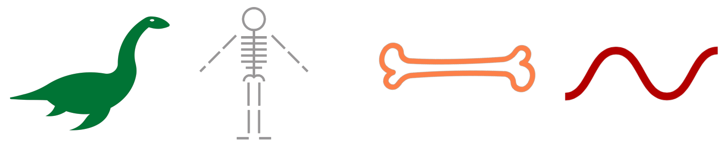
making data accessible online for decades

Lead: Alyssa Goodman, CfA

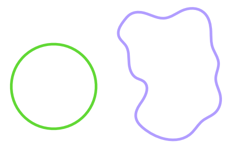
SCIENCE

enabling studies of how galaxies turn gas into stars, using...

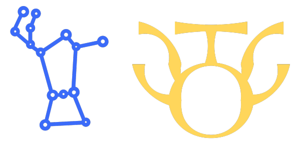
stellar positions, clusters, motions



topology, positions & motions of (long) features



tracers of feedback & magnetic fields



details on star-forming regions...and more!

Lead: Catherine Zucker, CfA

EDUCATION & OUTREACH

connecting real research data, software, and science to learners

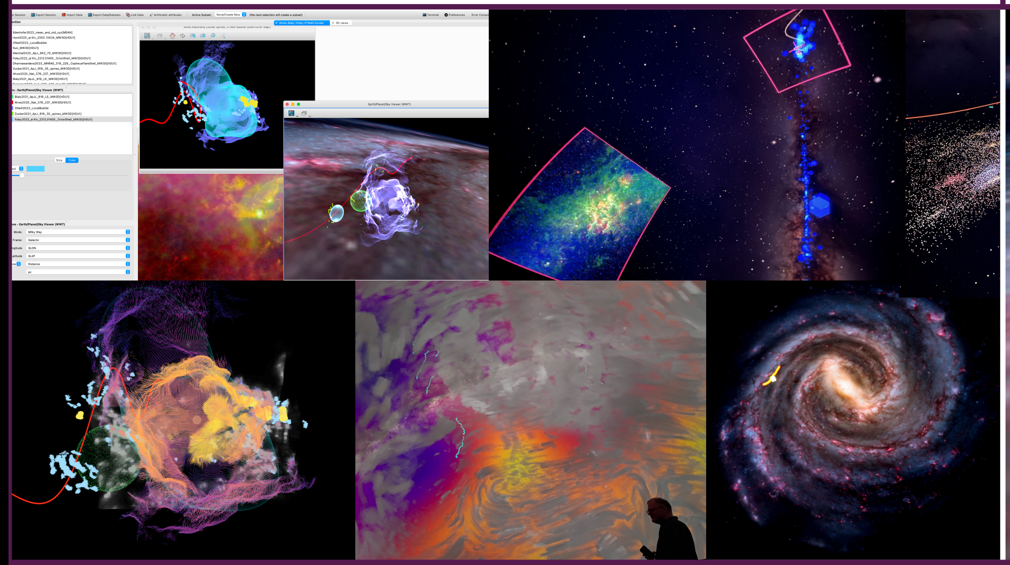
OpenSpace

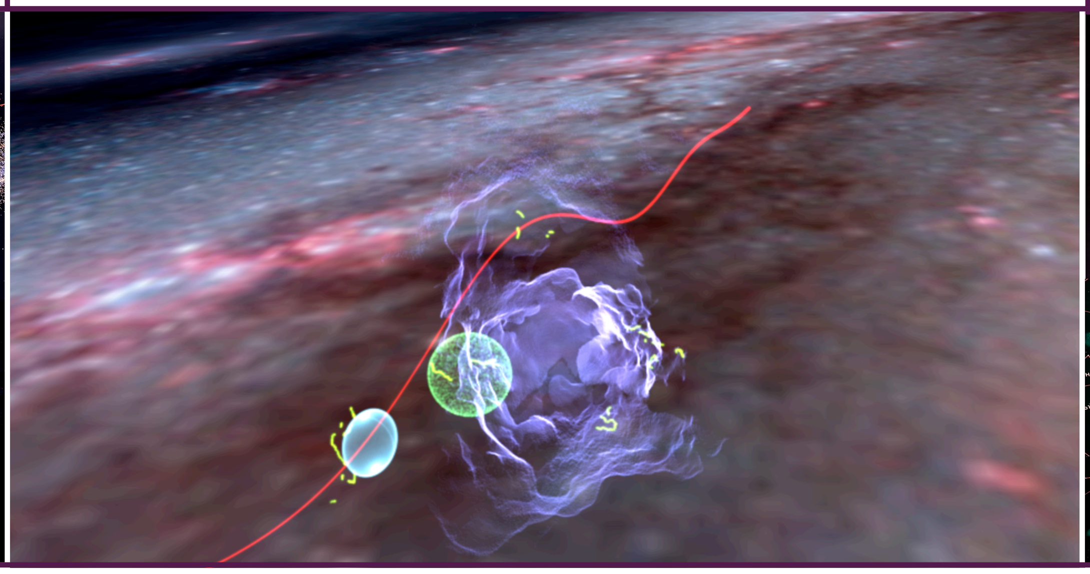
real-time data exploration anywhere, including in planetaria

CosmicDS

"Cosmic Data Stories" teach data science using astronomical data & tools

Lead: Jackie Faherty, AMNH





TEAM: Harvard/Smithsonian CfA (Jonathan Carifio, Alyssa Goodman, Ralf Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), **AMNH** (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty); **Linkoping University** (Alex Bock) ; **University of Vienna** (Joao Alves, Sebastian Ratzenbock); **glue solutions, inc./Aperio** (Thomas Robitaille); **University of Wisconsin, Whitewater** (Bob Benjamin), **STScI/Johns Hopkins** (Josh Peek), **Max Planck IfA** (Gordian Edenhofer); **Northeastern University** (Michelle Borkin); and YOU?!

Join us, contribute, and yes, you get a T-Shirt.

2 MilkyWay3D.org founders wearing the colors (grad student Theo O'Neill & AMNH's Dr. Jackie Faherty, at the Flatiron Insitute, NYC, Fall 2023

2010
2014
2015
2018
2020
2024
2021
2022
2024
2022

Nessie Bones Skeleton Perseus RadWave PerTau LB Barnard++


PerTau
LB
RadWave
1 kpc

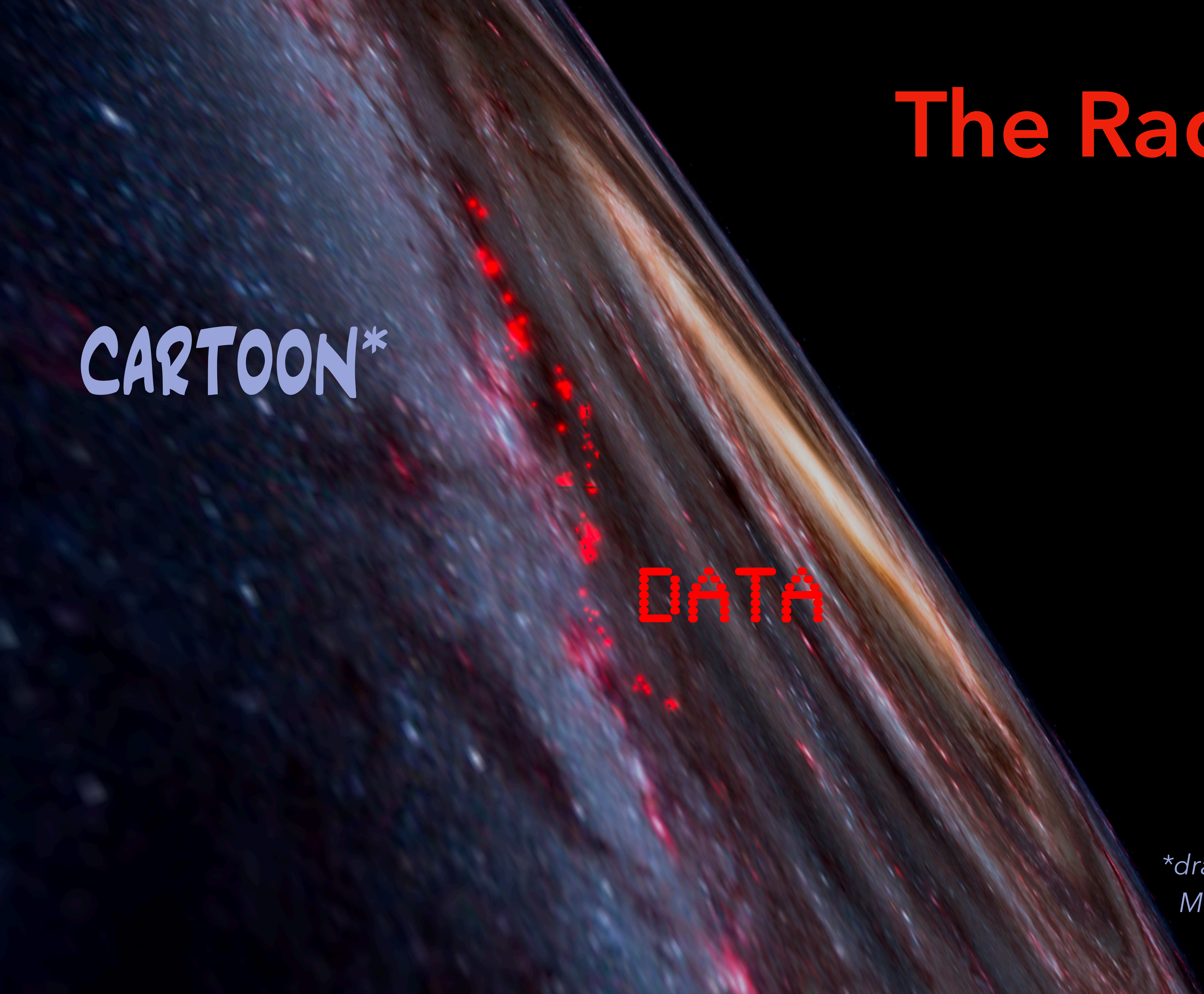
2020 **The Radcliffe Wave**

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

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

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

The Radcliffe Wave



*drawn by Dr. Robert Hurt, in collaboration with Milky Way experts based on data; as shown in screenshot from AAS WorldWide Telescope

The Radcliffe Wave
Each red dot marks a star-forming blob of gas whose distance from us has been accurately measured.
The Radcliffe Wave is 9000 light years long, and 400 light years wide, with crest and trough reaching 500 light years out of the Galactic Plane. Its gas mass is more than three million times the mass of the Sun.
video created by the authors using AAS WorldWide Telescope
(includes cartoon Milky Way by Robert Hurt)

The Radcliffe Wave

ACTUALLY 2 IMPORTANT DEVELOPMENTS

DISTANCES!!

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

Zucker et al. 2019; 2020

RADWAVE

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

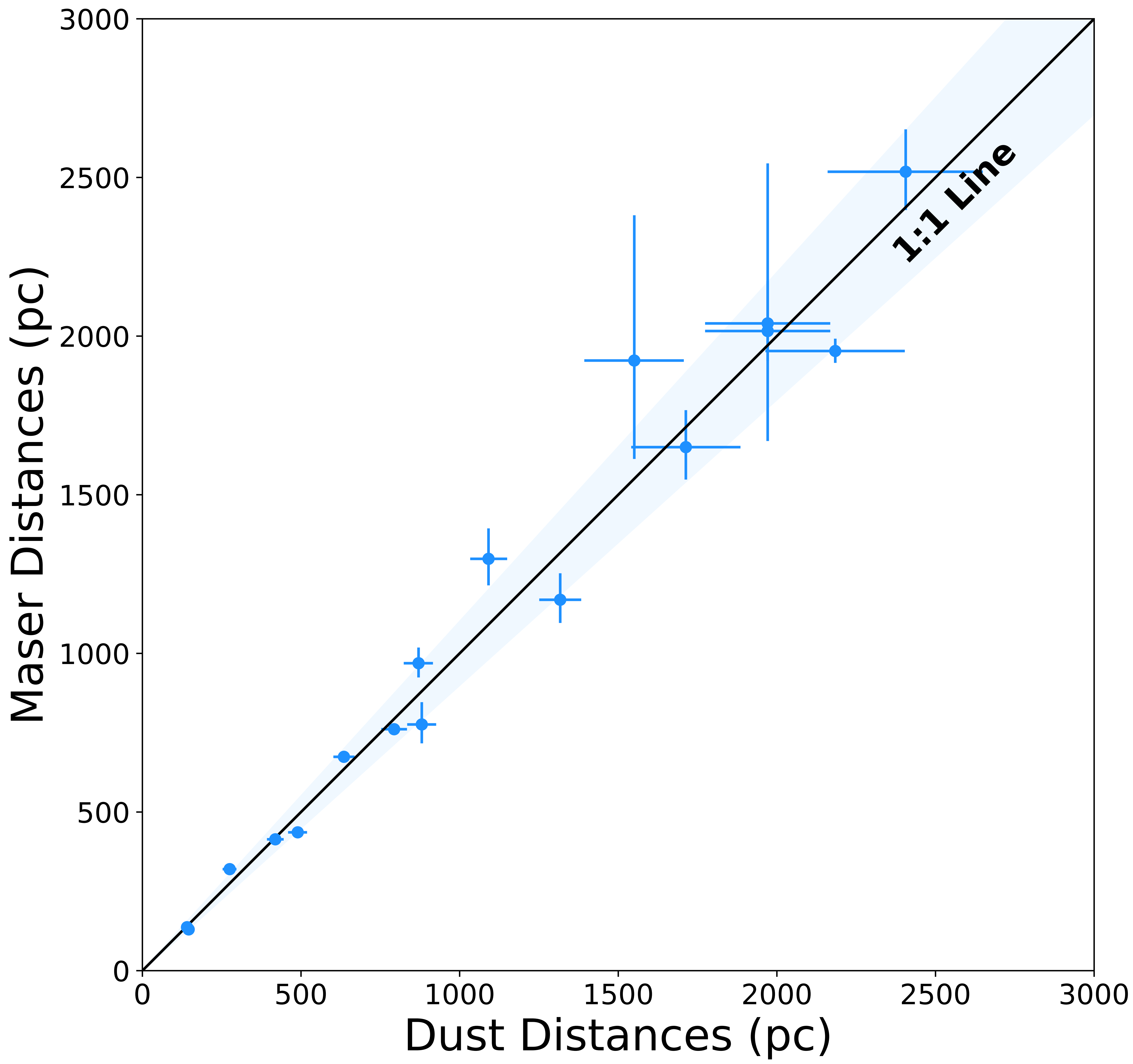
Alves et al. 2020

"Why should I believe all this?"

DISTANCES!!

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

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



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

Zucker et al. 2019

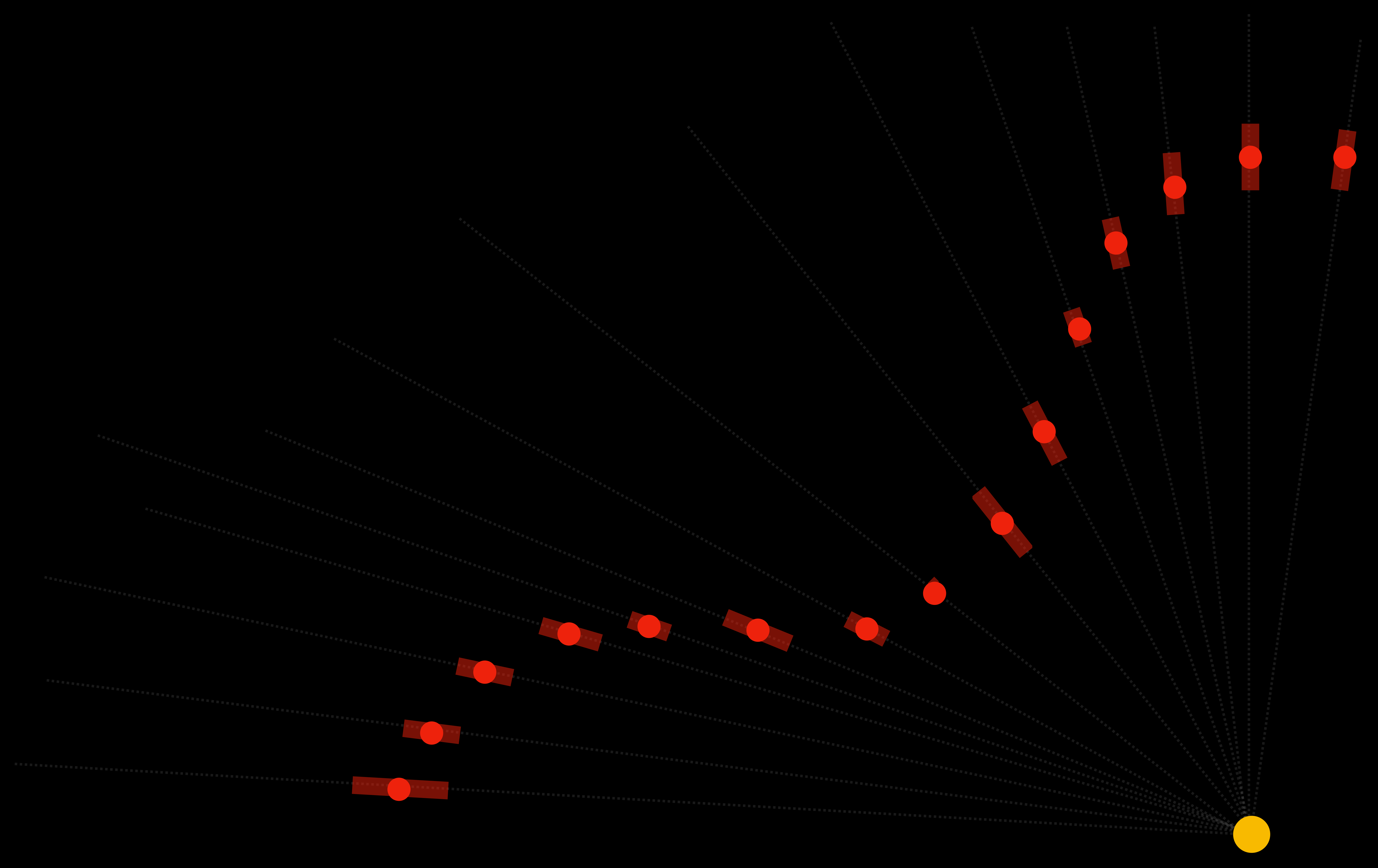
DISTANCES!!

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%)



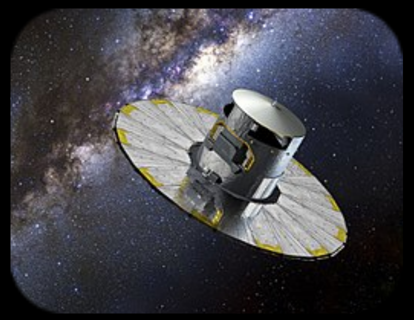
"The Radcliffe Wave"

SCHEMATIC CARTOON(!)

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

HOW= 3D dust mapping*

+ Gaia*

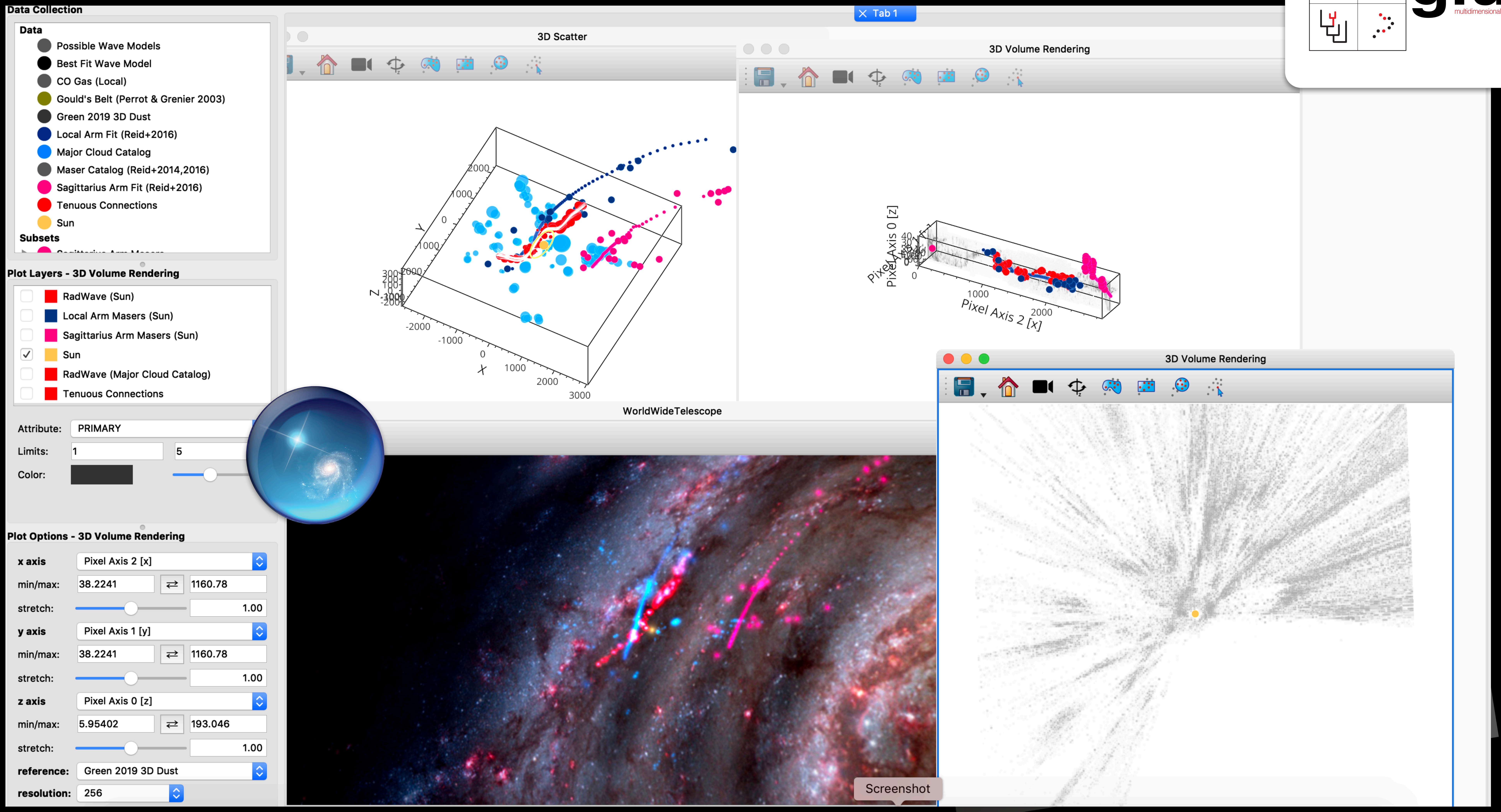


+ glue*

+ WorldWide Telescope

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

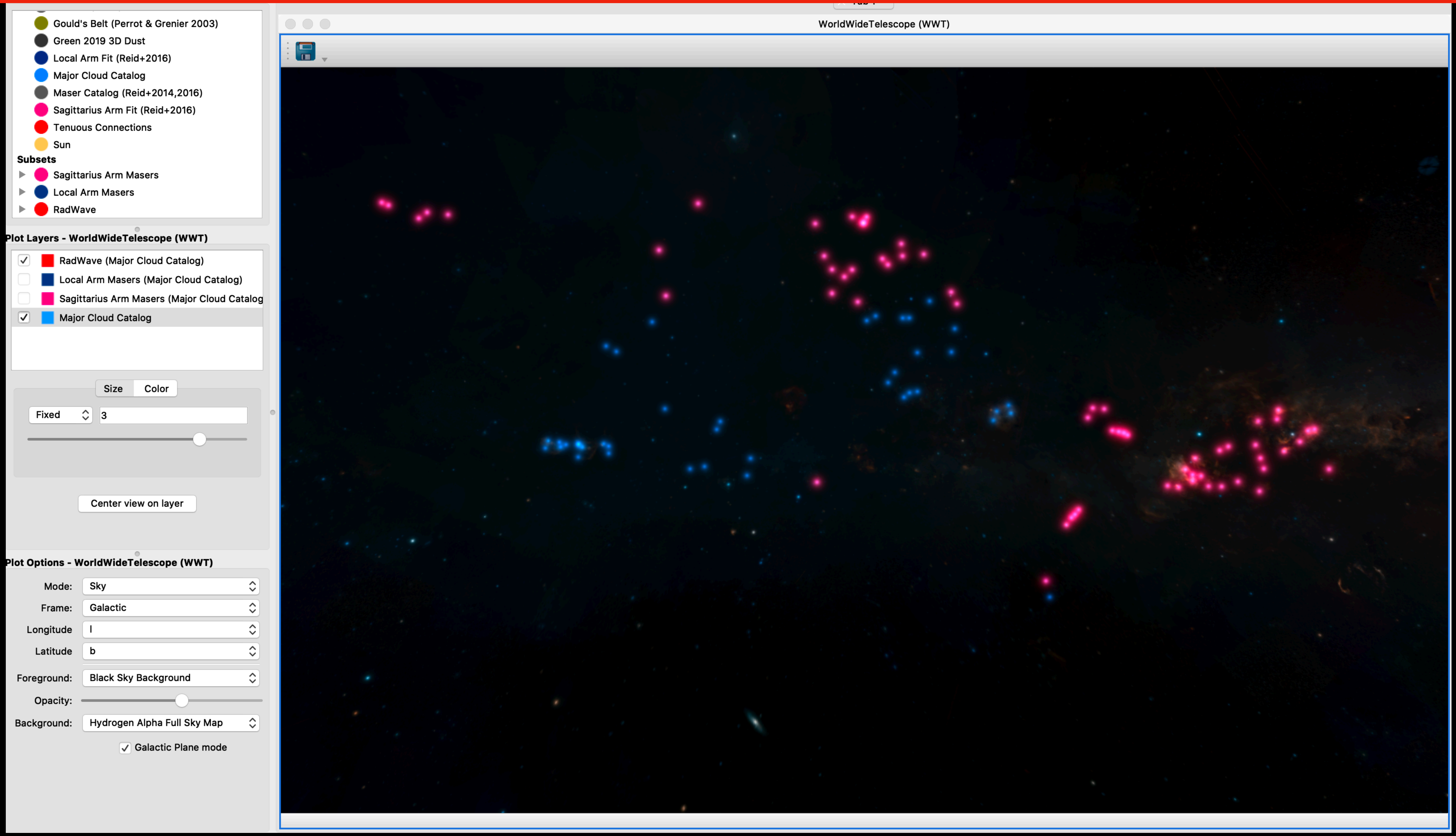
"Seeing" The Radcliffe Wave, in 3D



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

WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

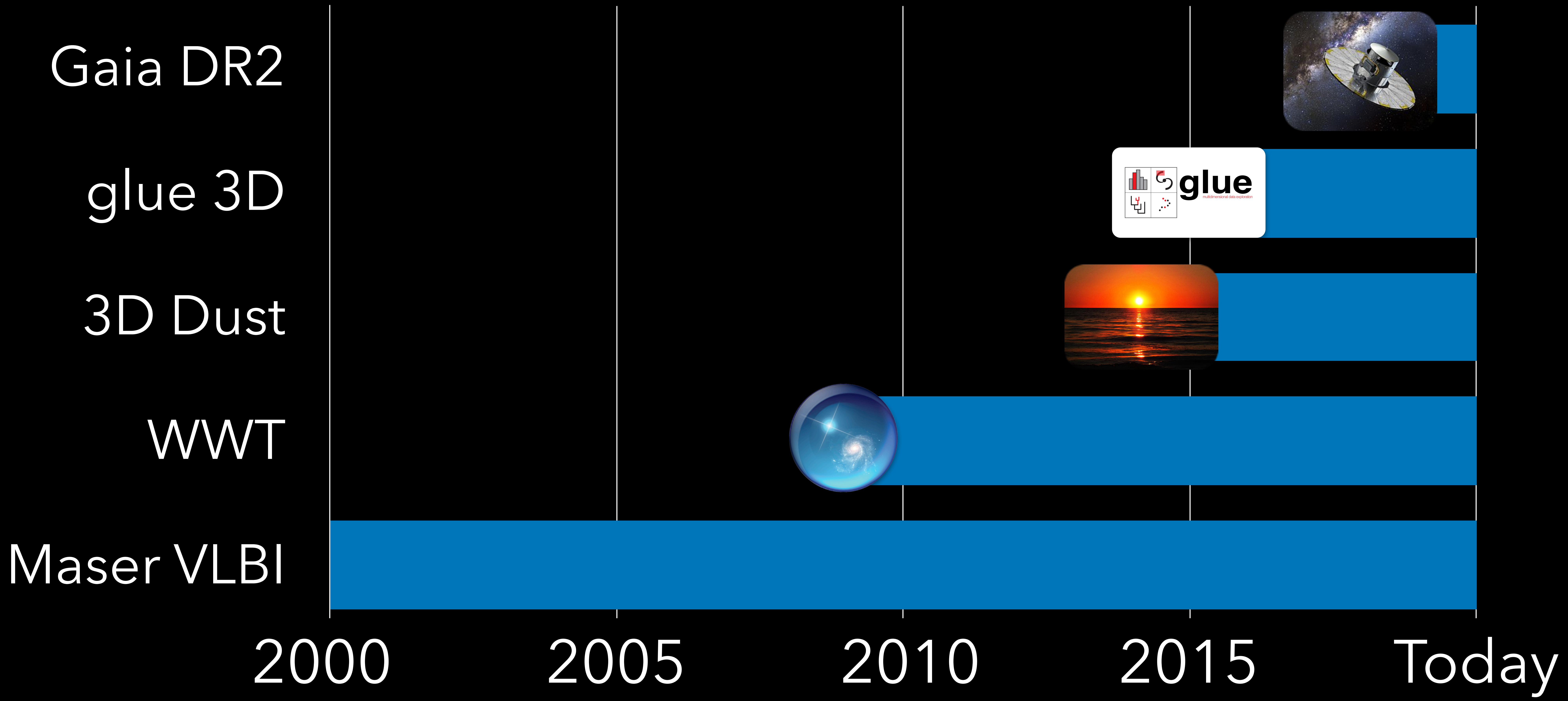
It's not apparent in 2D on the Sky.



AAS WorldWide Telescope: worldwidetelescope.org

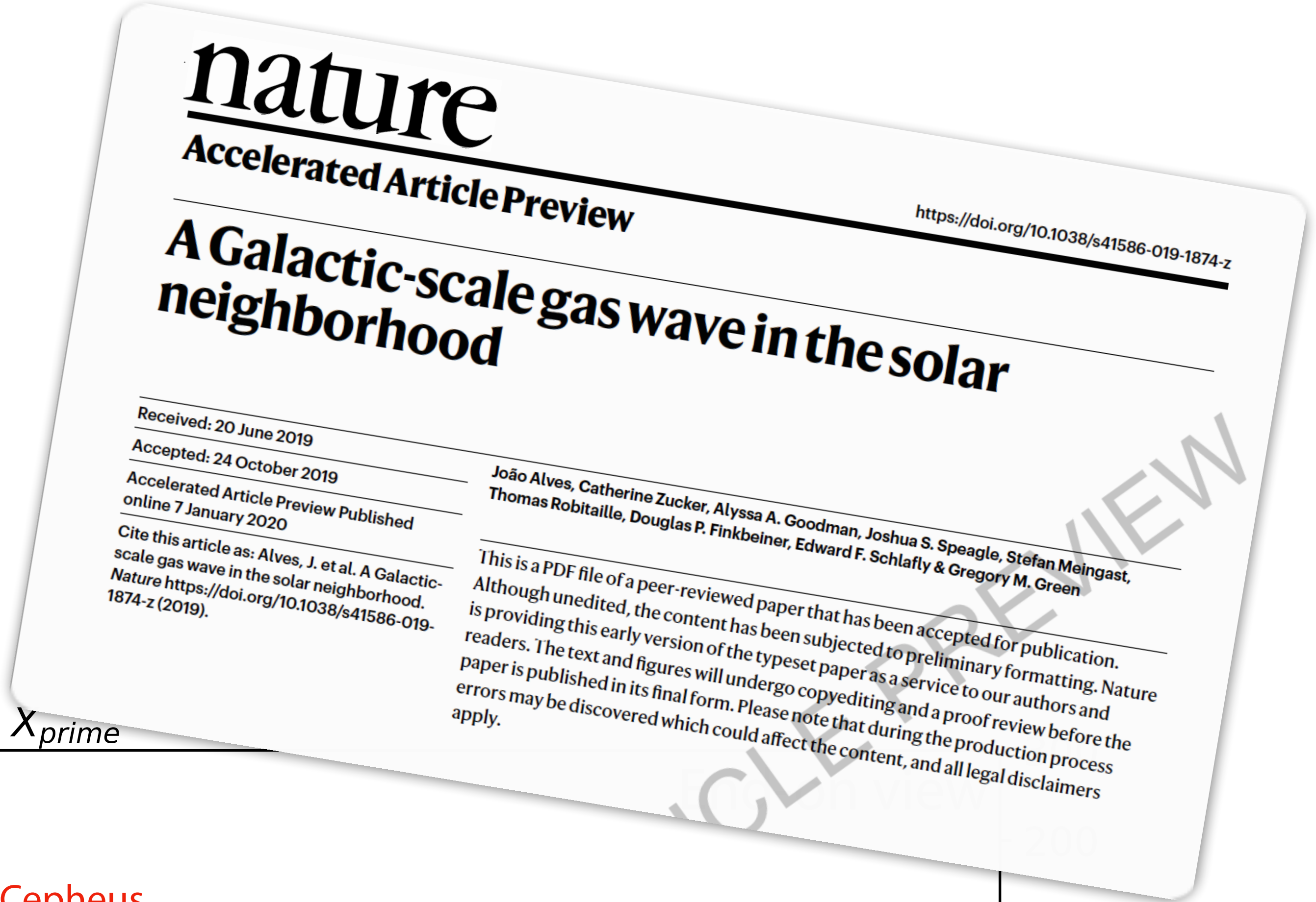
glue: glueviz.org

WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?



The Radcliffe Wave

click the figure to launch interactive…



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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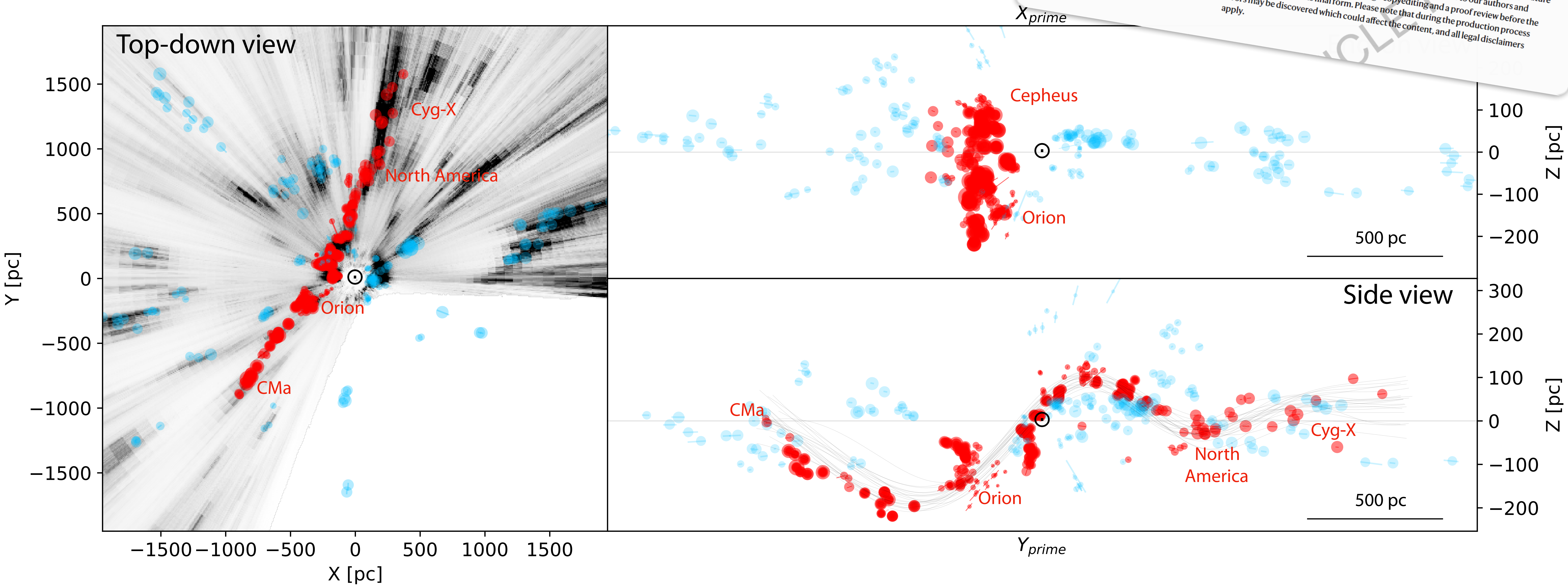
ACCELERATED ARTICLE PREVIEW



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)

RADWAVE

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

"So What," for Astronomers?

demise of "Gould's Belt"

end to 100-year-old paradigm

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

arm is "straight" from top-down

big wave in "arm" never previously observed

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

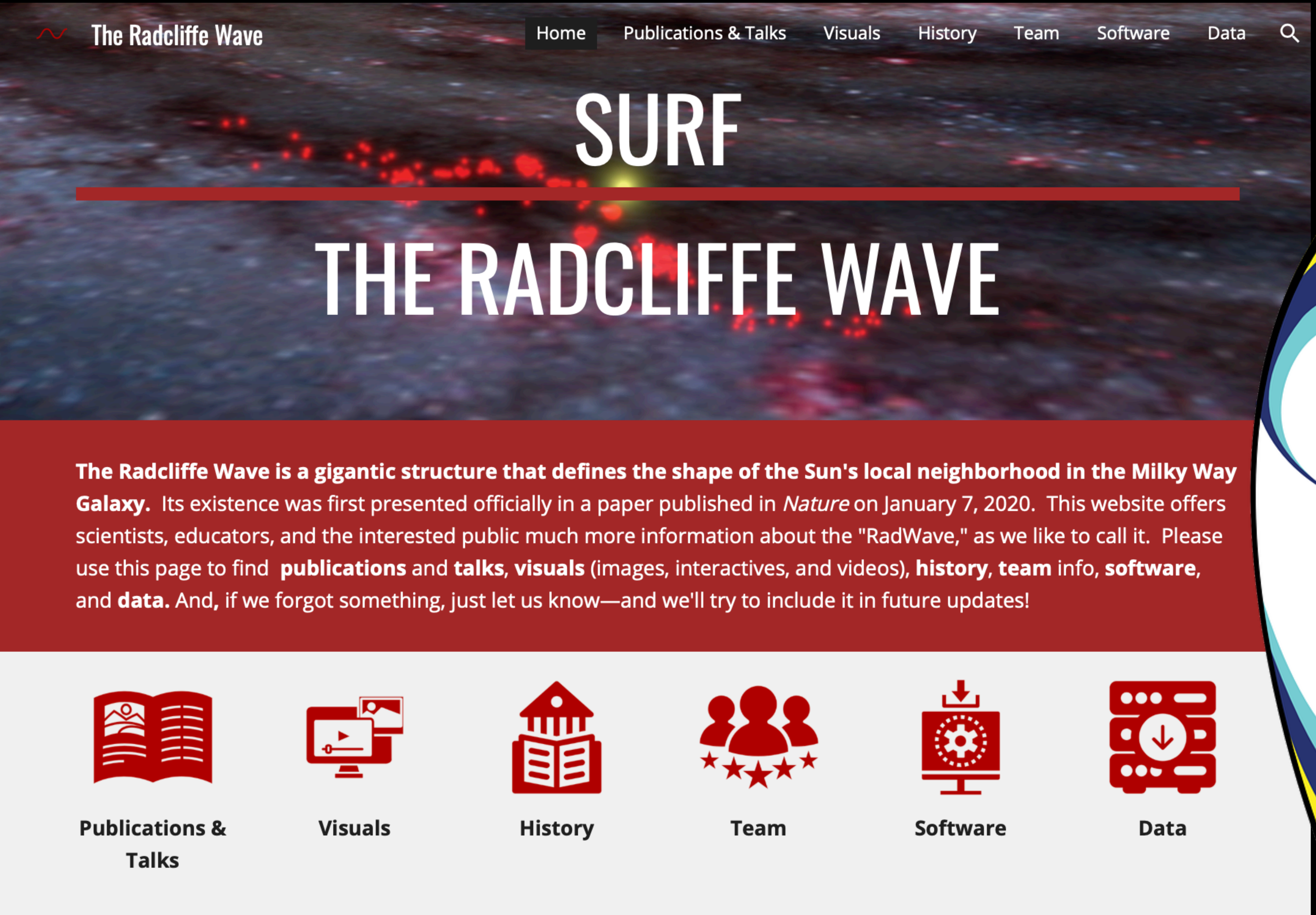
Open Questions

What is the ORIGIN of the Radcliffe Wave? Collision?

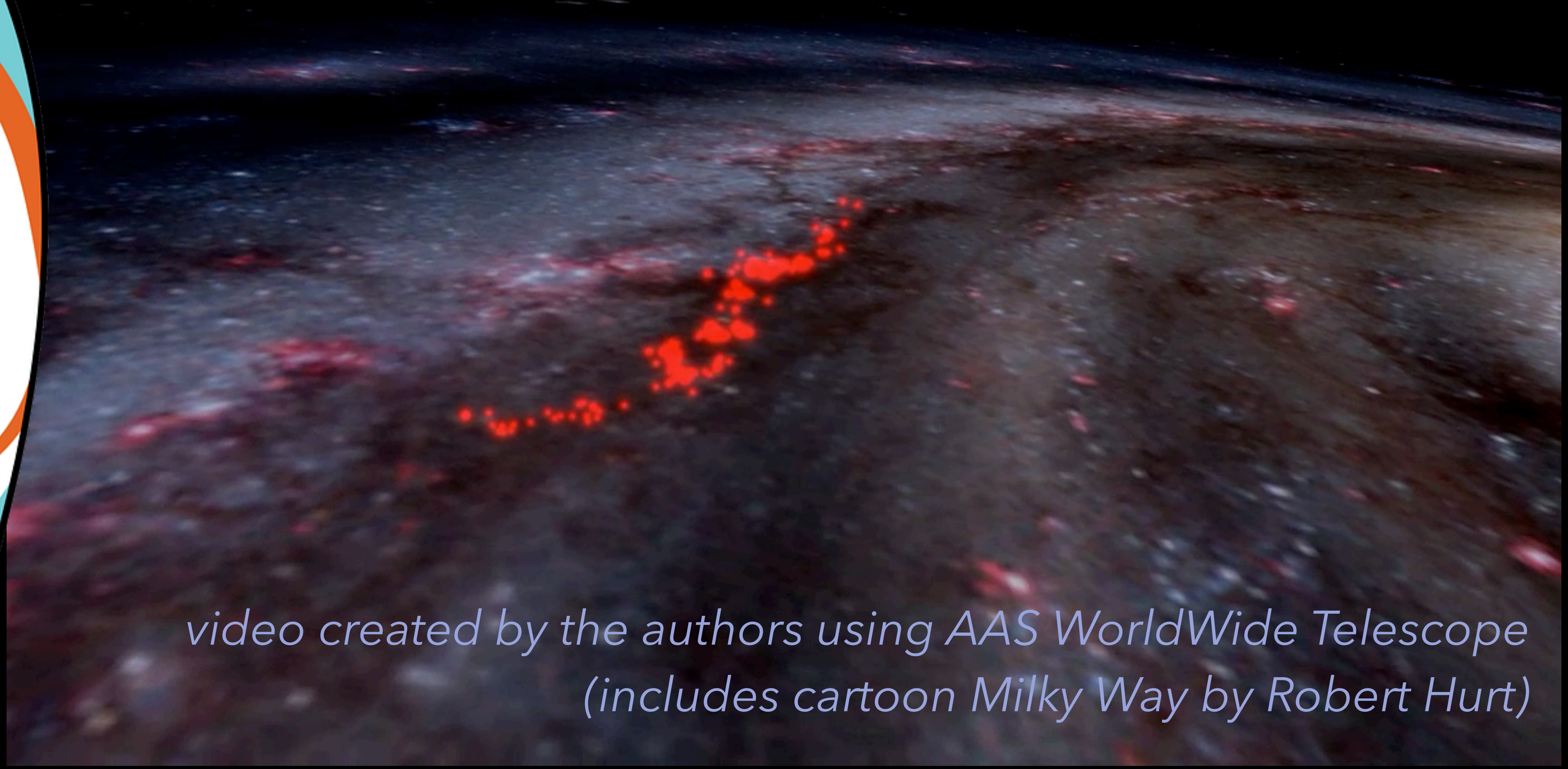
Do other parts of the Milky Way show this wavy structure? How about other galaxies? How can we SEARCH?

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

SURF the Radcliffe Wave



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



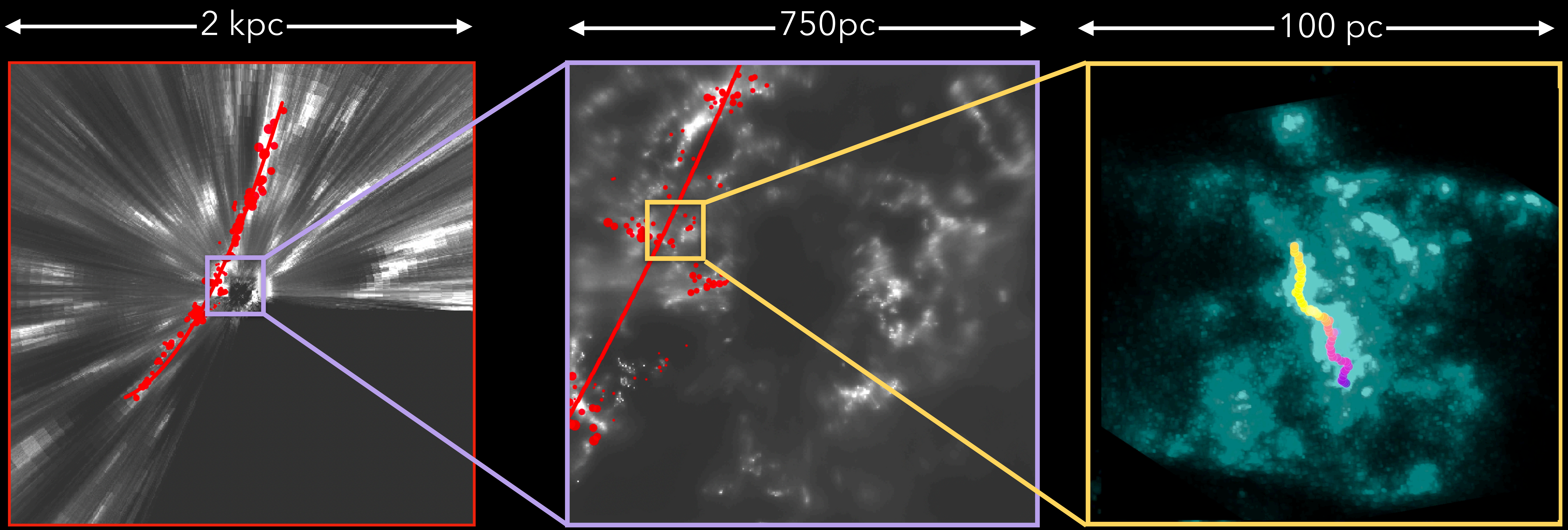
video created by the authors using AAS WorldWide Telescope (includes cartoon Milky Way by Robert Hurt)

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

The Radcliffe Wave

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

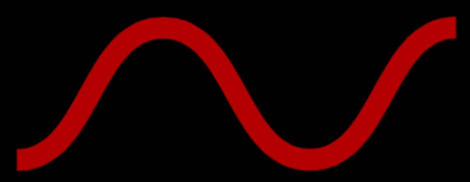
2019 to 2021: from distances to shapes



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



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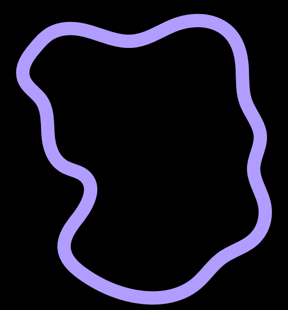
2021

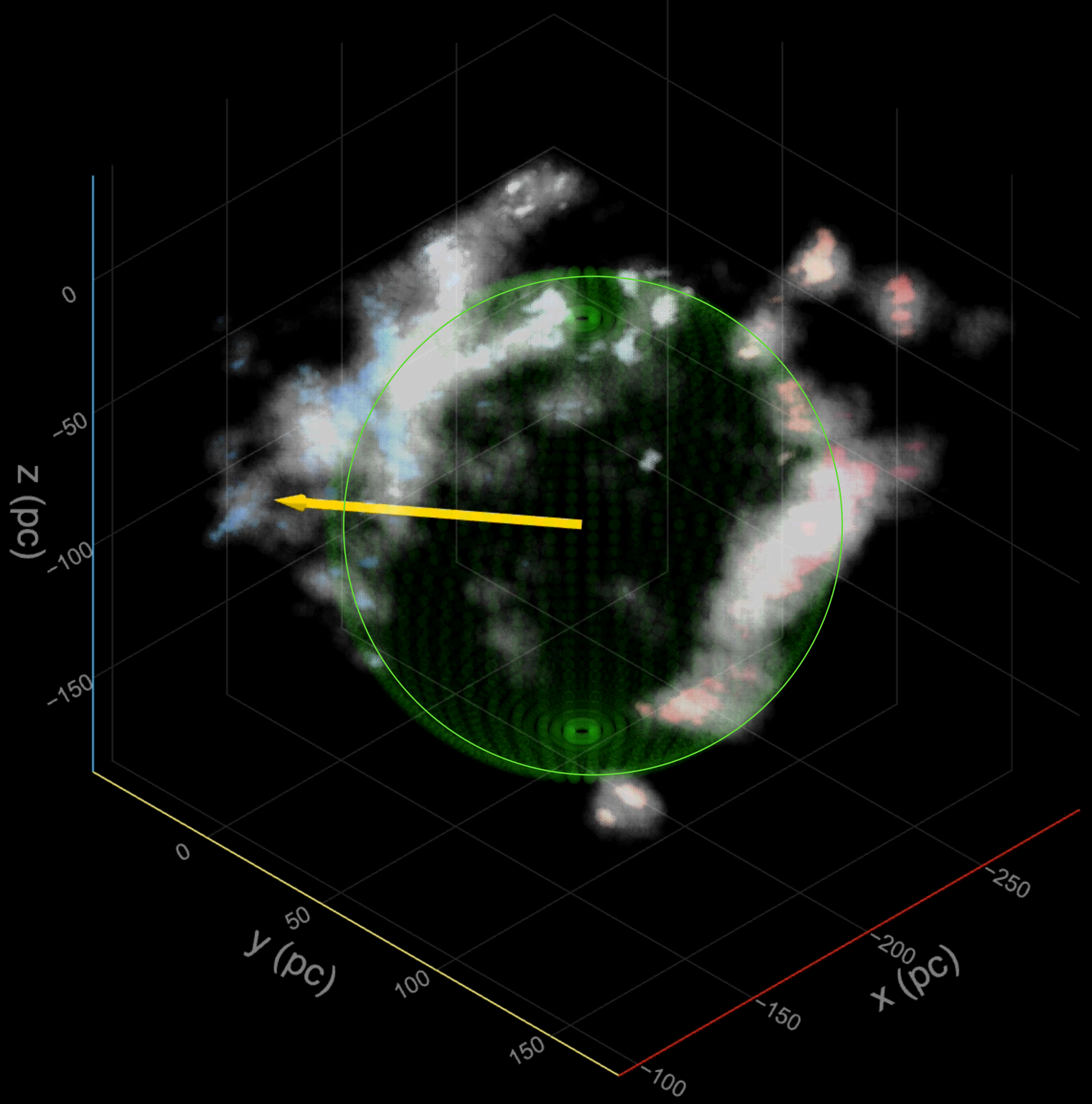


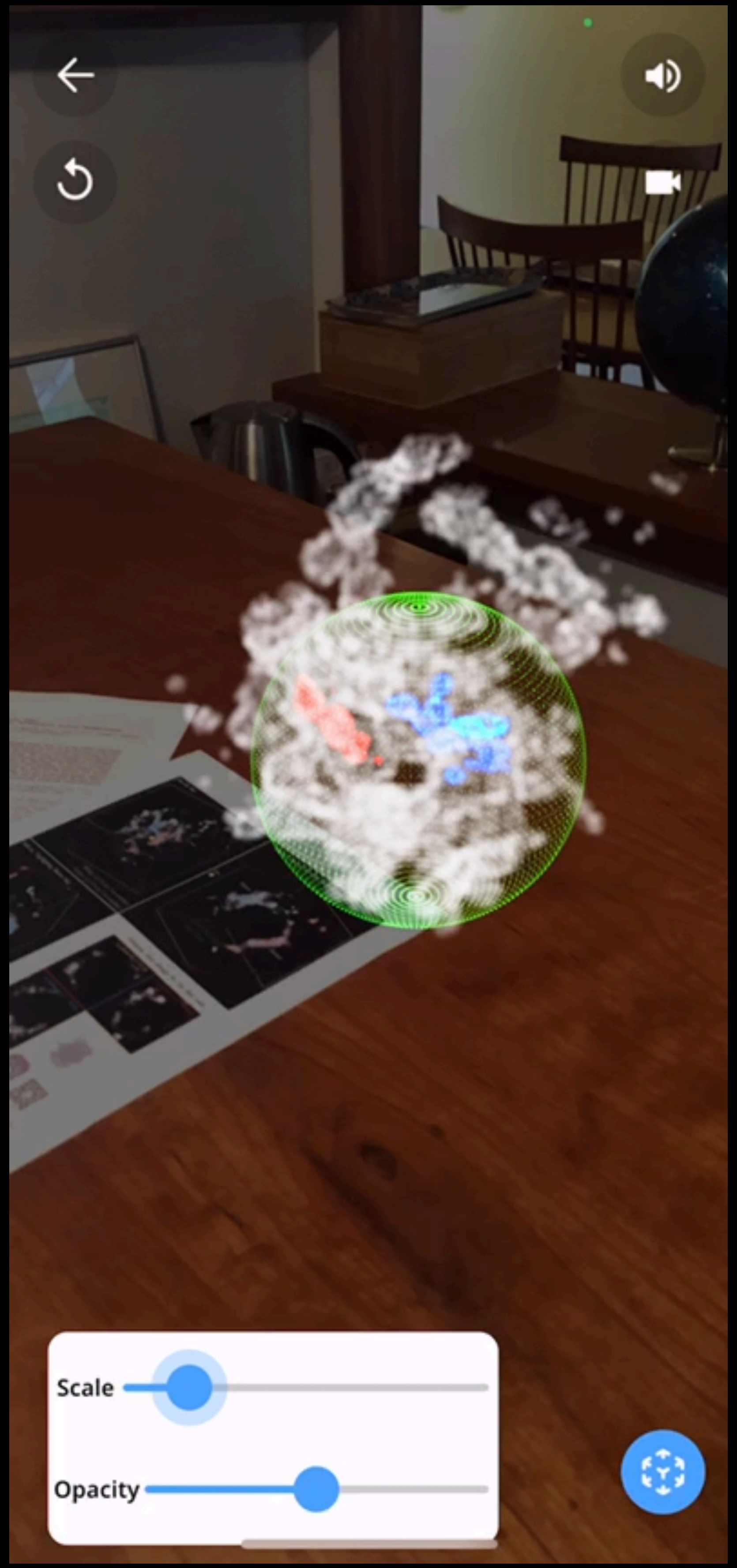
2022
2024

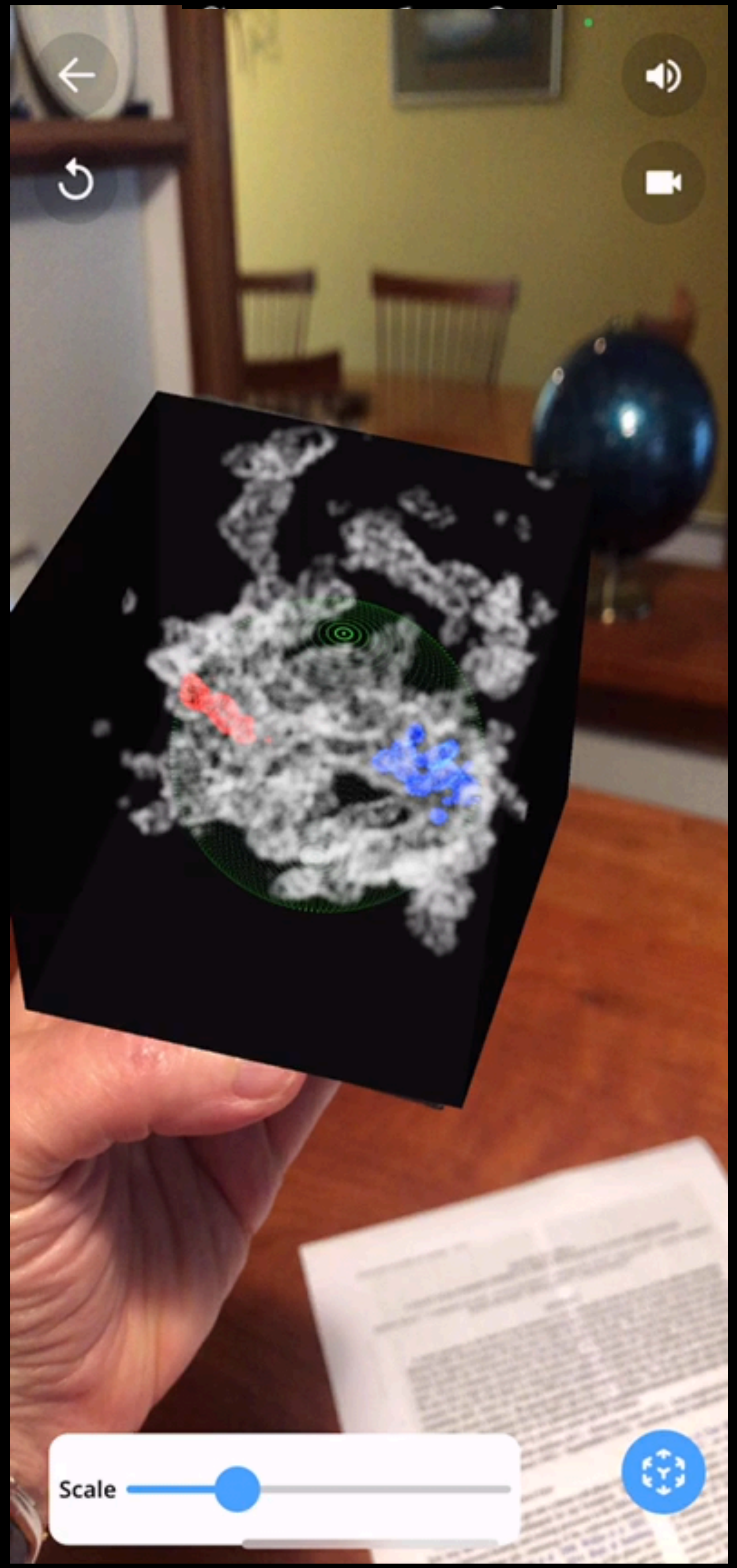
2023 and beyond!


2021
TAURUS
PERSEUS

2021 "PERSEUS-TAURUS SUPERSHELL"

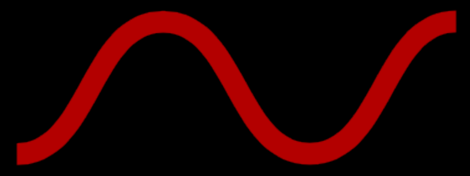






TINYURL.COM/UNIVERSE-IN-MY-HAND

AUGMENTED REALITY



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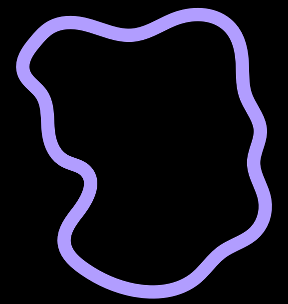
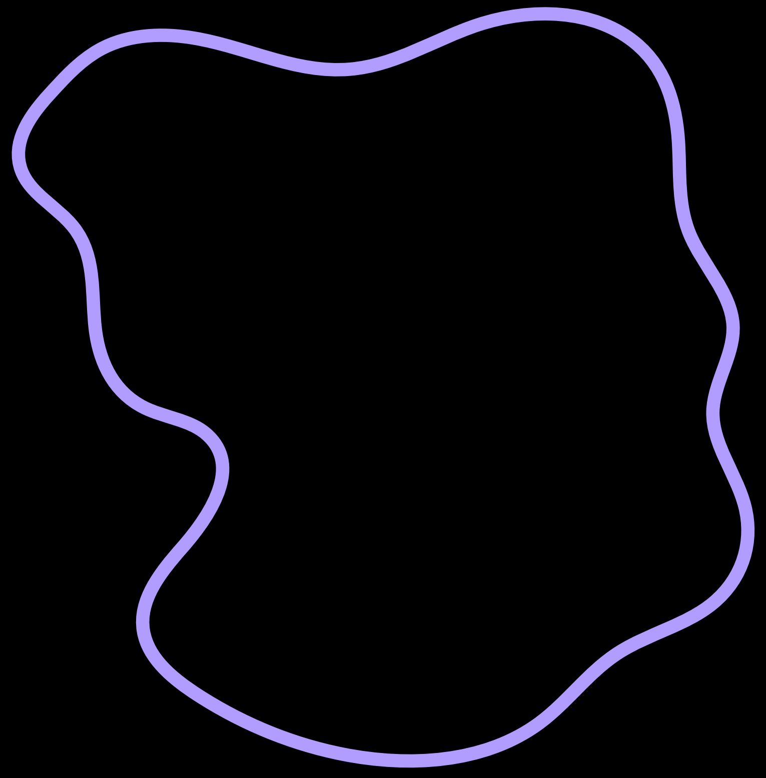


2022
2024

2023 and beyond!



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.

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.

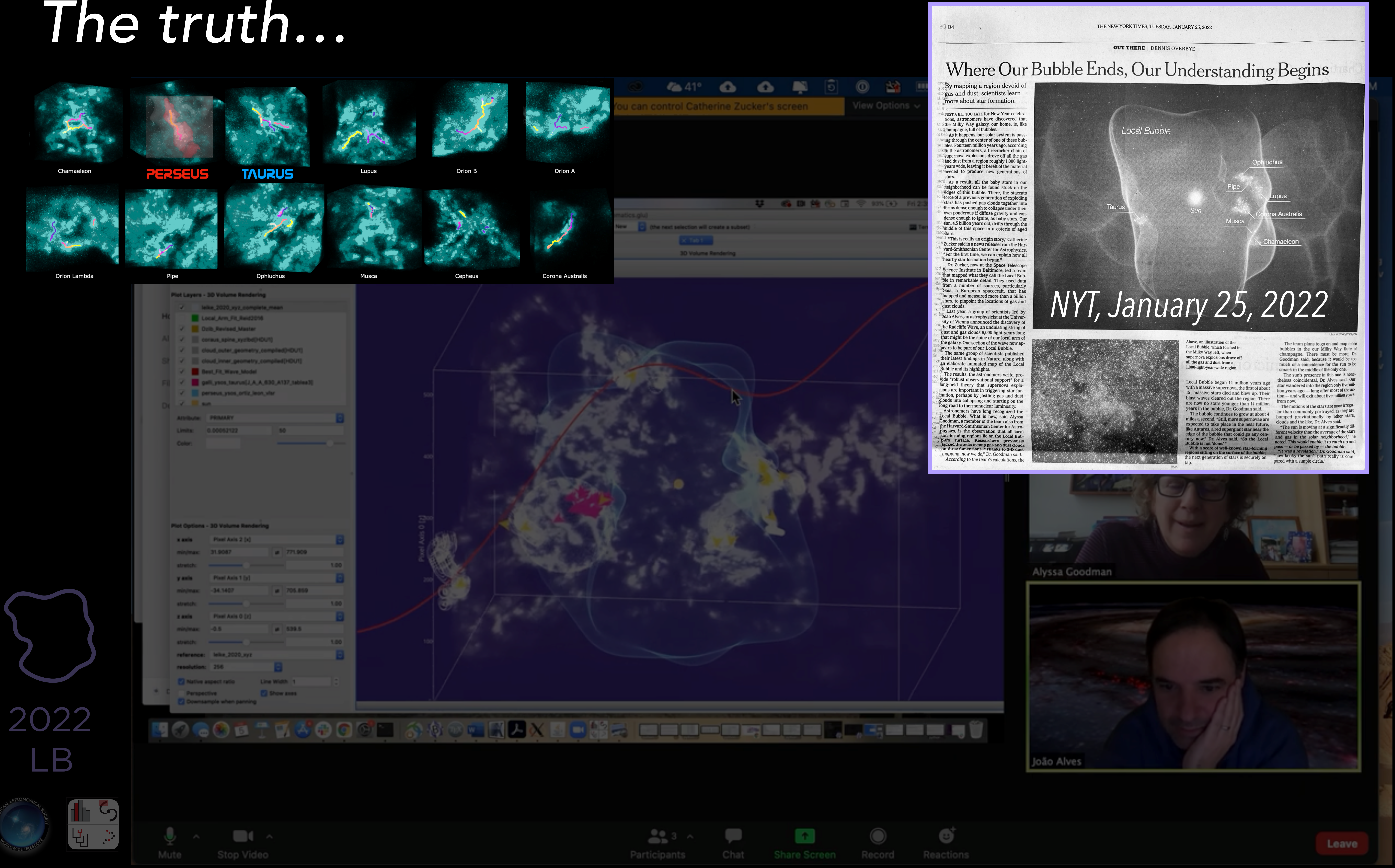
"It was a revelation," Dr. Goodman said, "how kooky the sun's path really is compared with a simple circle."

LEAH HUSTAK (STSCI)/CFA

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.

The truth…



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

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NASA

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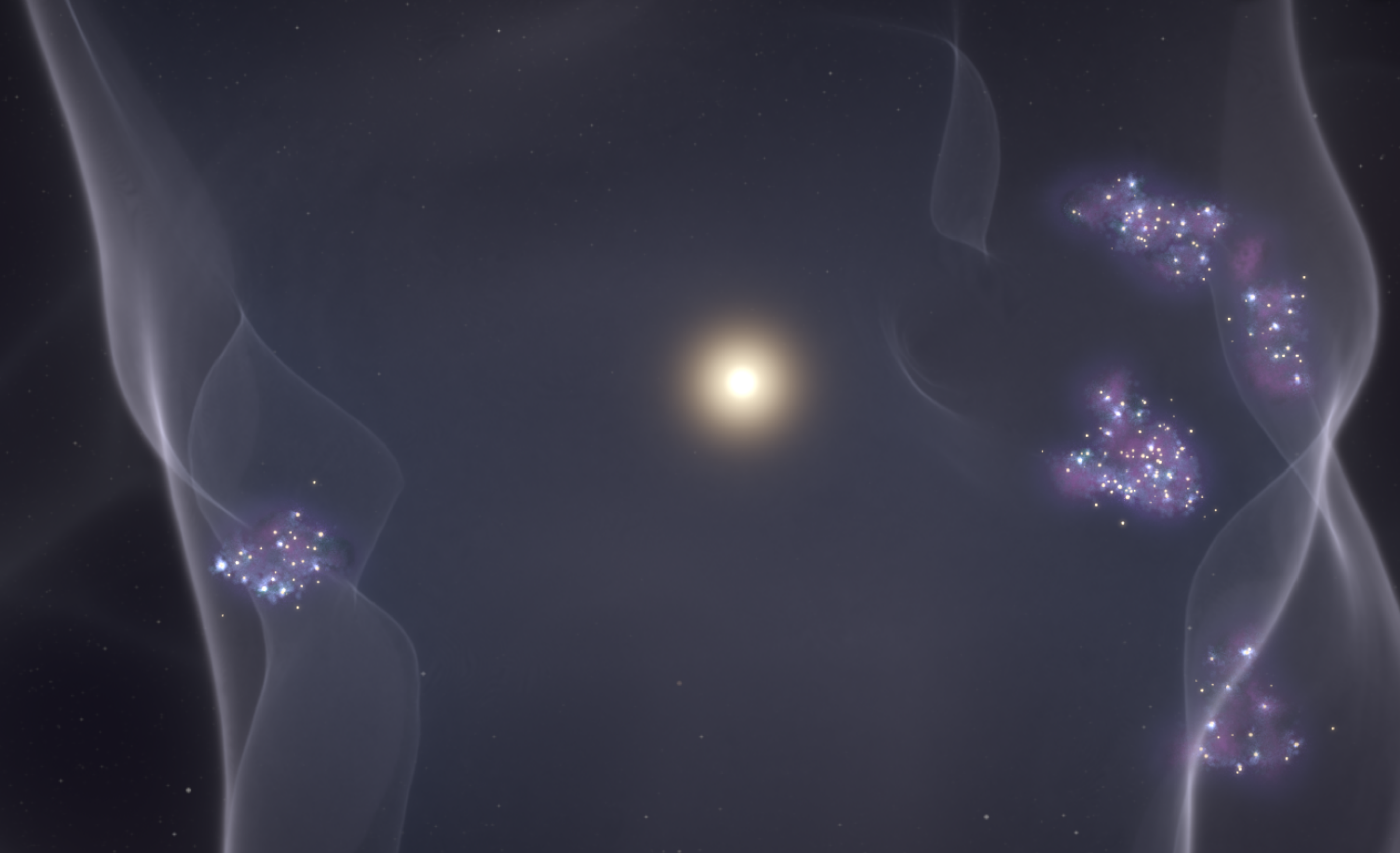
2022
LB

2022

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

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.

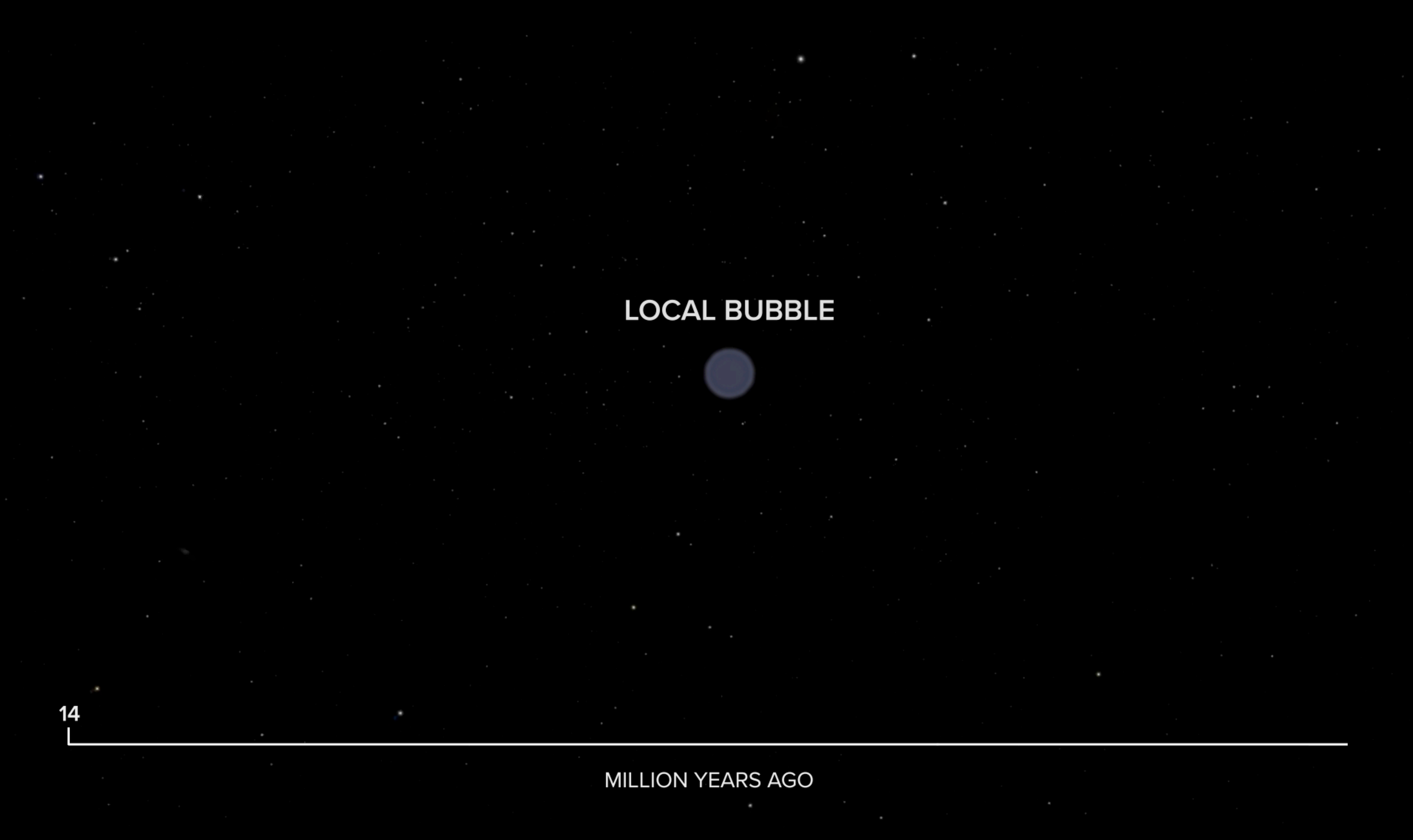
We can reconstruct the evolutionary history of our Galactic neighborhood.

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

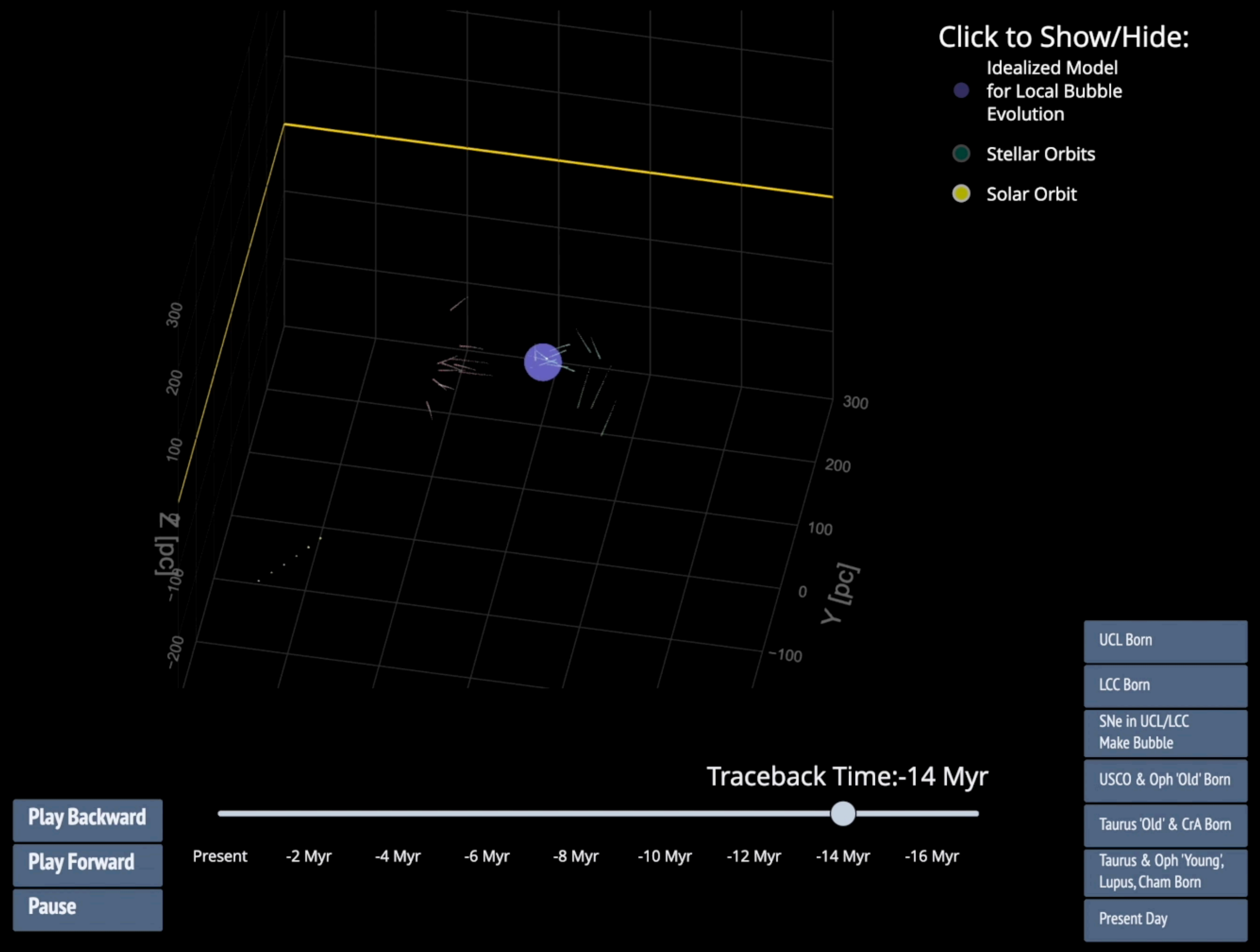
MILLION YEARS AGO

“Cartoon”



“Real Data”

(Zucker et al. 2022, *Nature*)

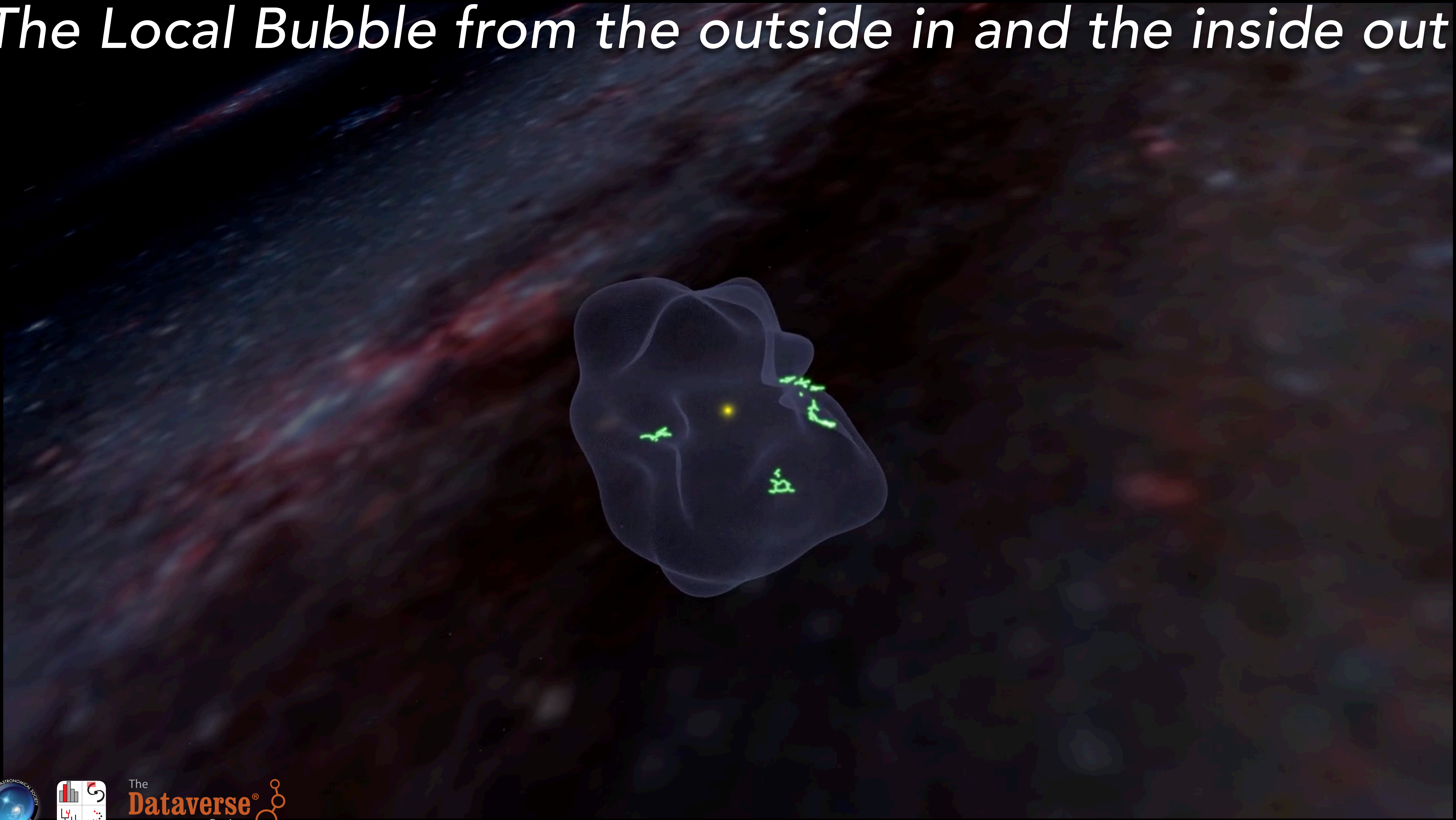


[try the interactive figure]

glue → plotly

The Local Bubble from the outside in and the inside out

The Local Bubble from the outside in and the inside out



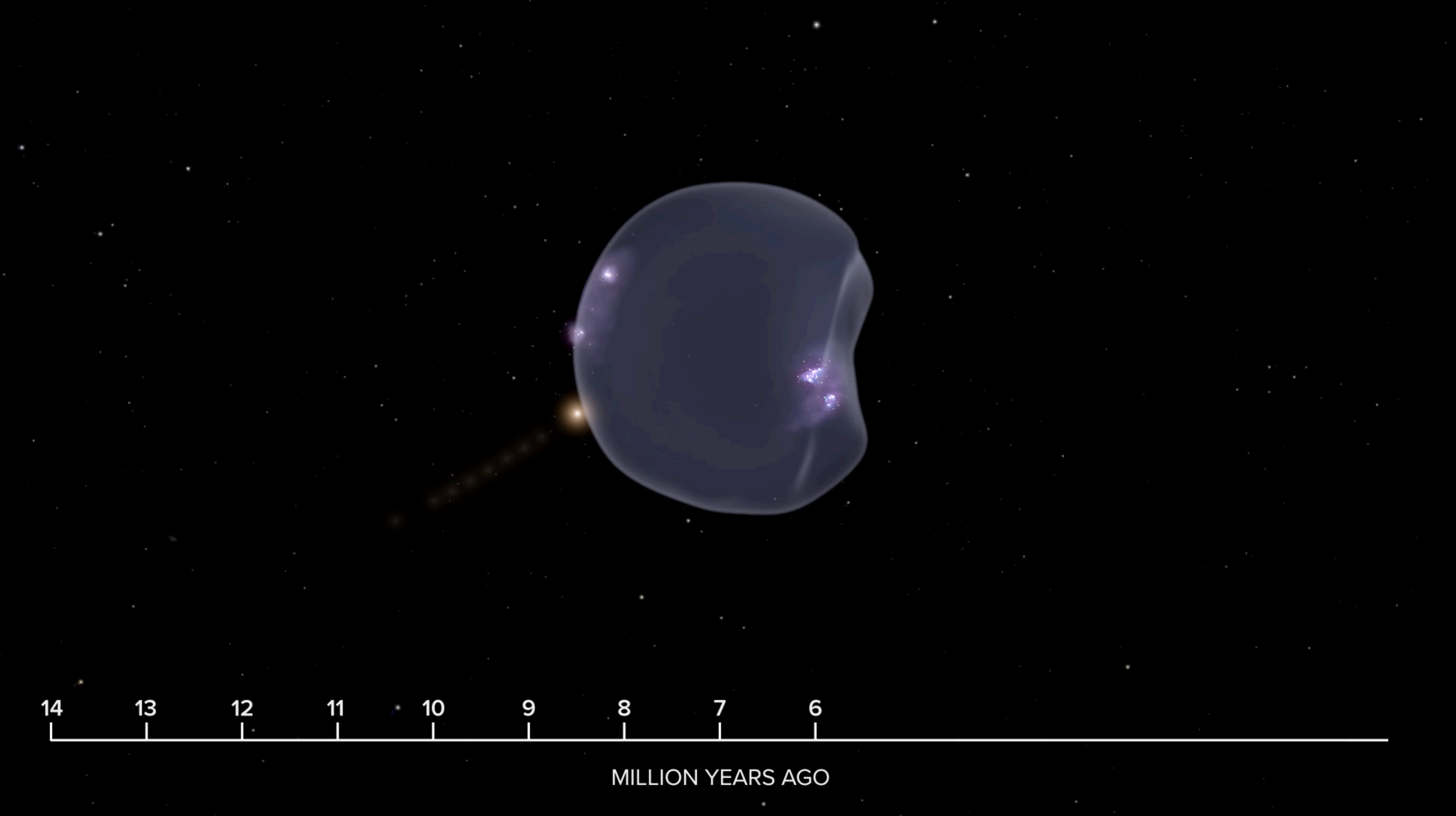
The Dataverse® Project

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.

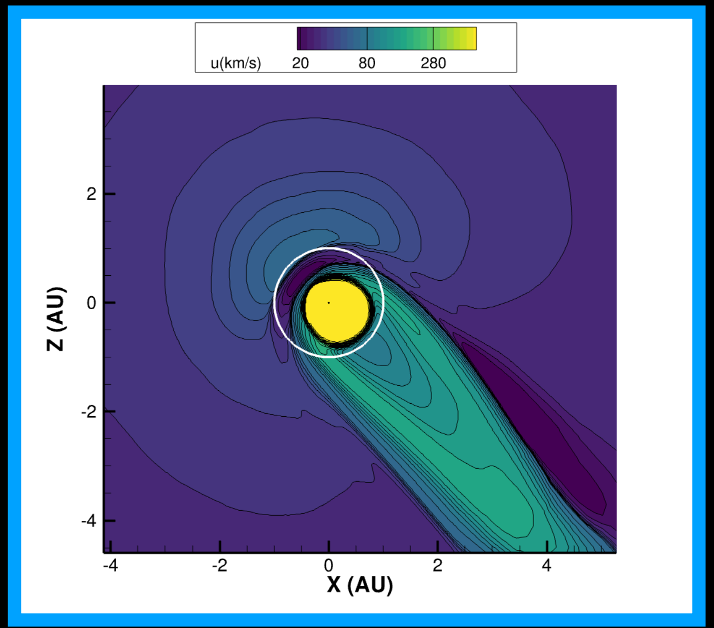
How did the Sun wind up in the bubble? (by accident)

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)

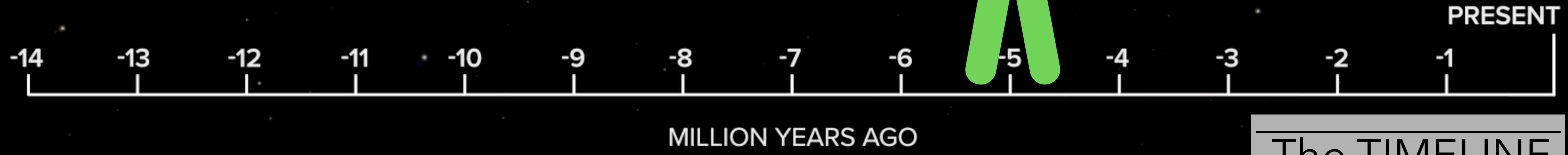
What does the Sun's time in the bubble mean for Earth?



See Opher et al. 2024 (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

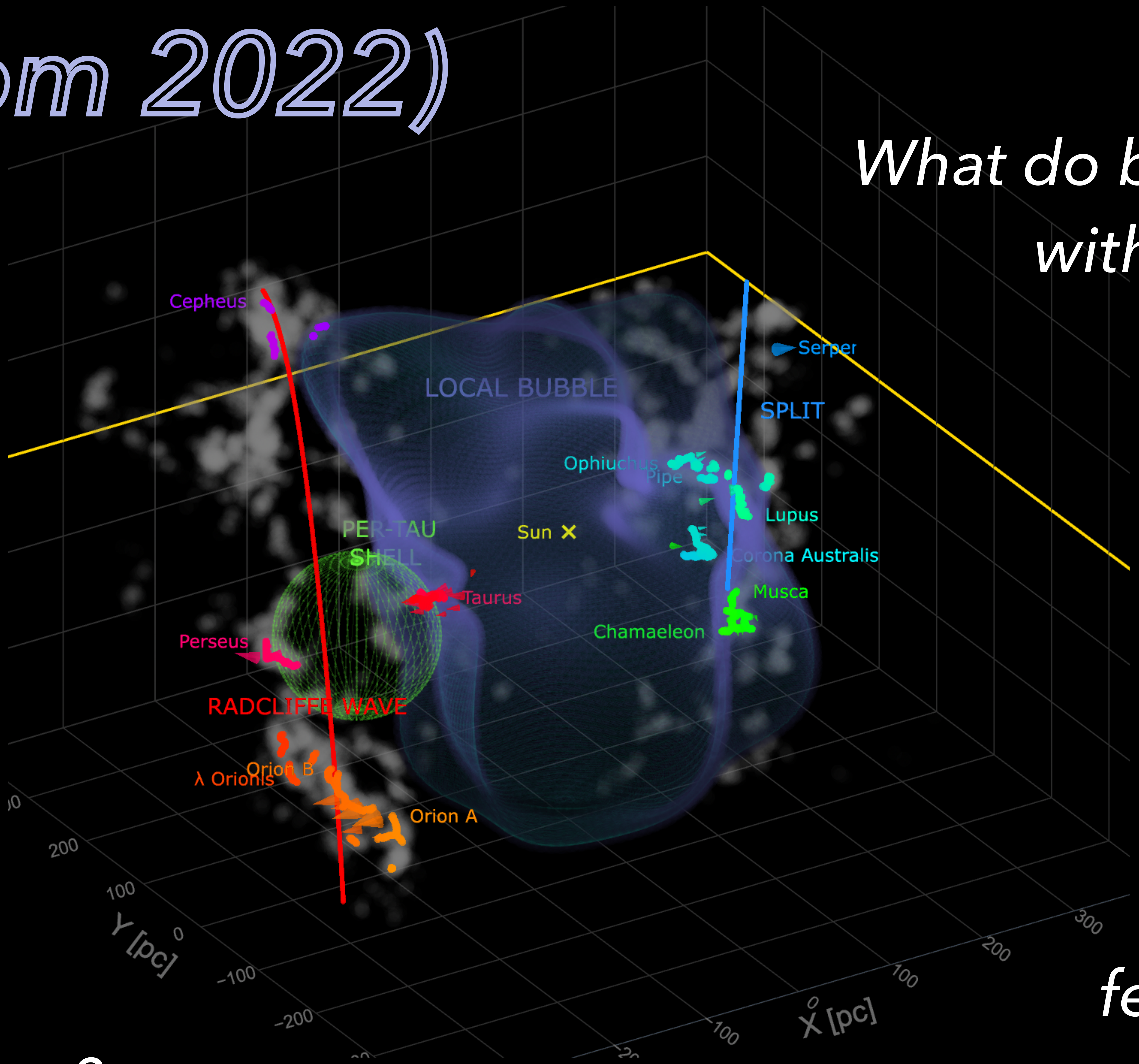
We can now explain how all nearby star formation began

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

“Next” *(from 2022)*

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



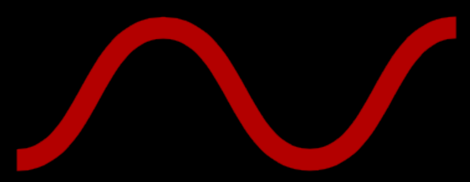
How do we SEARCH for other bubbles?

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]



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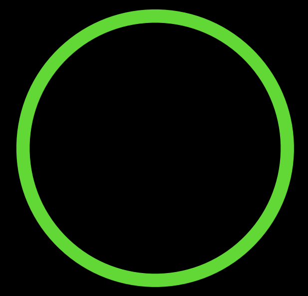
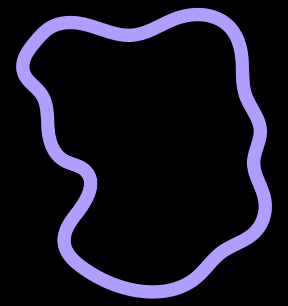
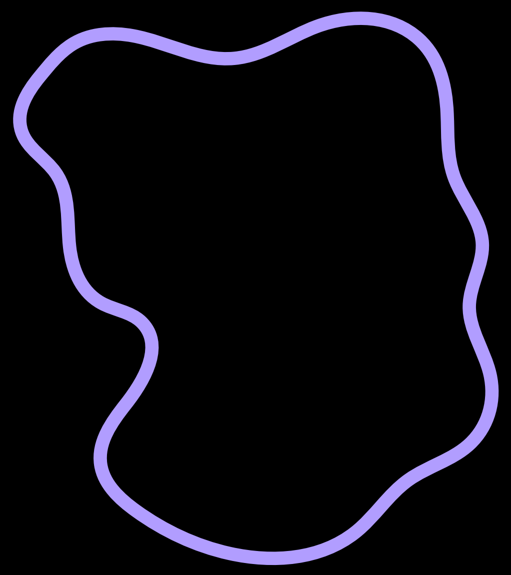


2021



2022
2024

2023 and beyond!

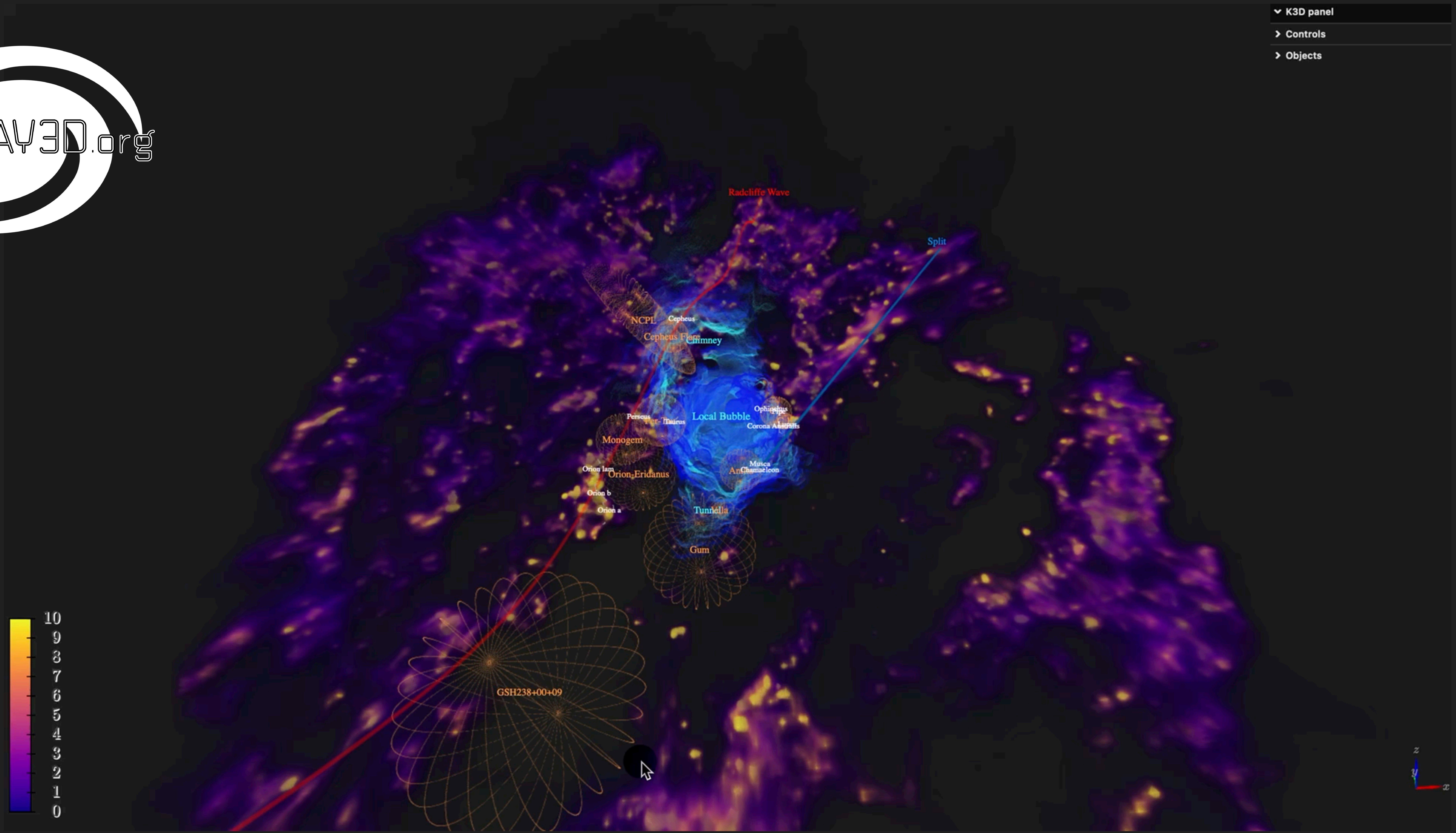


We now think the LOCAL BUBLE is actually a LOCAL CHIMNEY

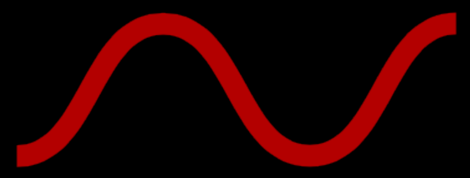
Thanks to O'Neill et al.

2024

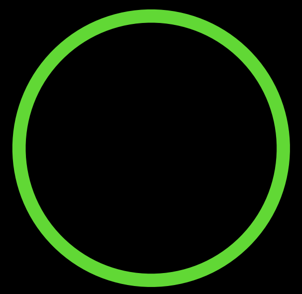
MILKYWAY3D.org



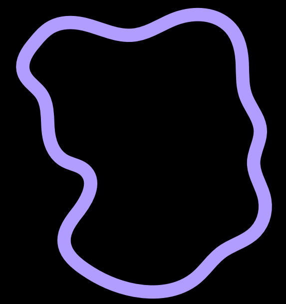
O’Neill et al. 2024



2020
2024



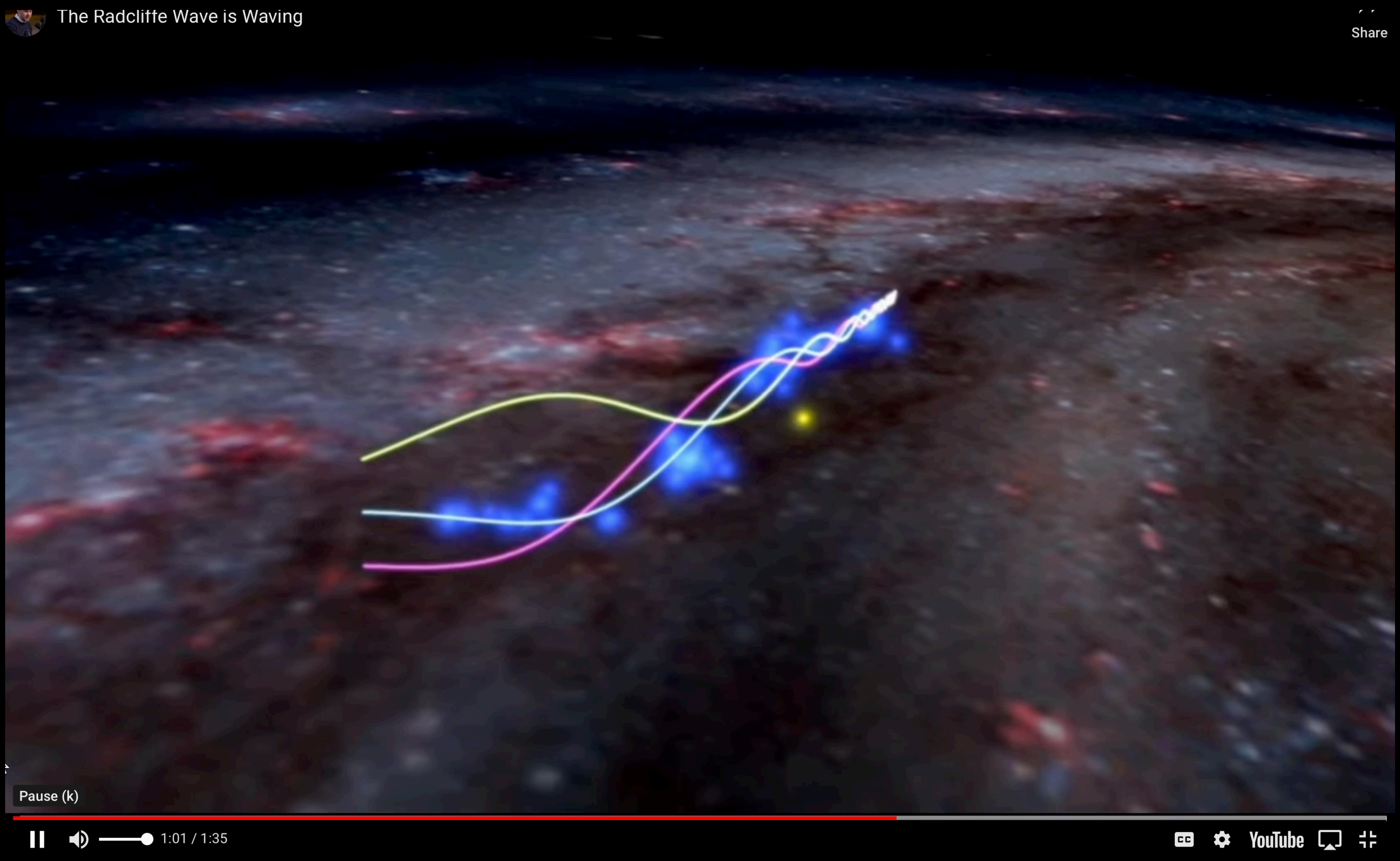
2021



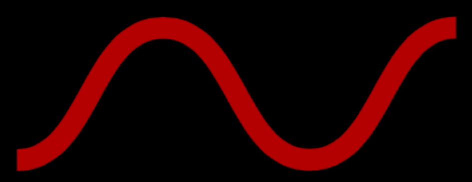
2022
2024

2023 and beyond!

We now know the RADCLIFFE WAVE is actually WAVING.
Thanks to Konietzka et al.
2024

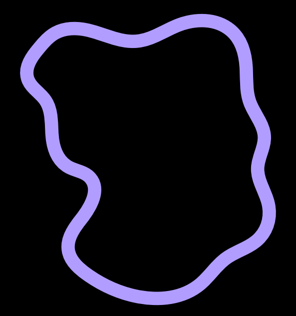


Konietzka et al. 2024



2020
2024

2021



2022
2024

2023 and beyond!

MILKYWAY3D.org

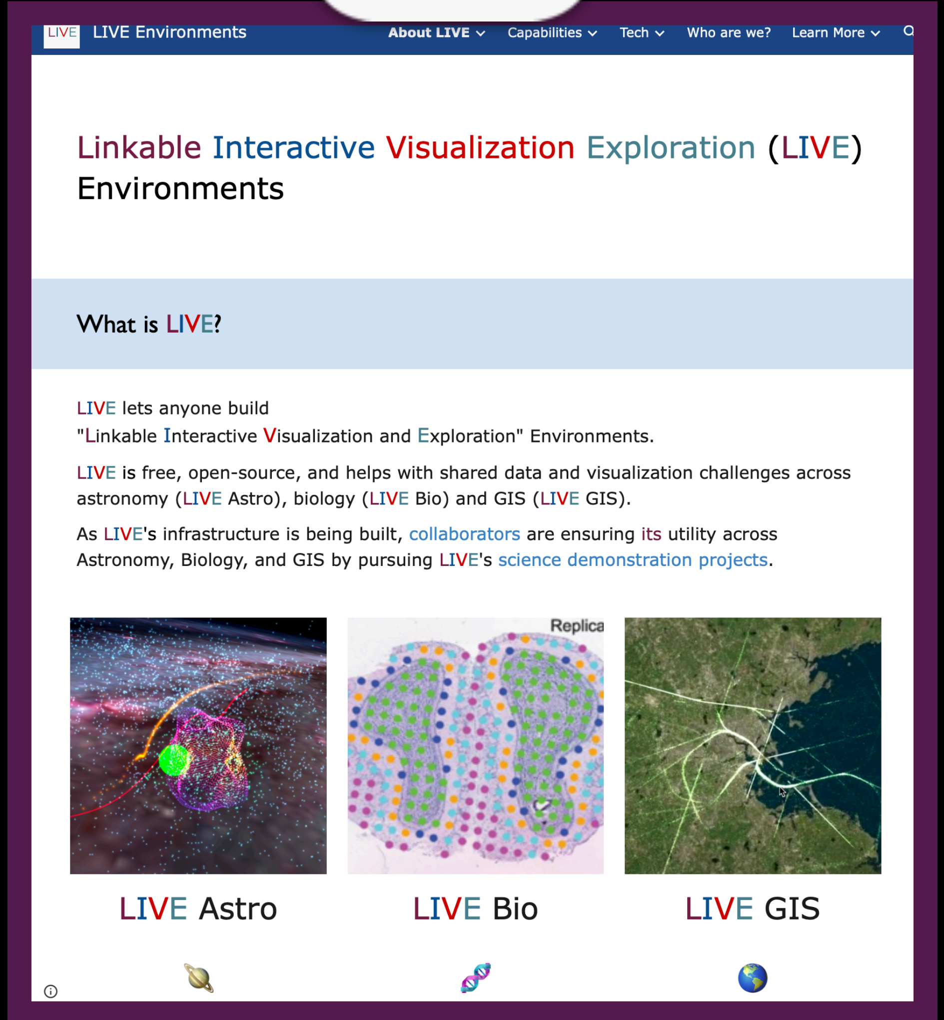
SCAN ME

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

MilkyWay3D.org is an open-data open-source discovery hub, providing data, visualization, and research tools for studying the MilkyWay in 3D.

INFRASTRUCTURE ⟷ SCIENCE ⟷ EDUCATION & OUTREACH

INFRASTRUCTURE


Linkable Interactive Visualization Exploration (LIVE) Environments

What is LIVE?

LIVE lets anyone build
"Linkable Interactive Visualization and Exploration" Environments.

LIVE is free, open-source, and helps with shared data and visualization challenges across astronomy (LIVE Astro), biology (LIVE Bio) and GIS (LIVE GIS).

As LIVE's infrastructure is being built, collaborators are ensuring its utility across Astronomy, Biology, and GIS by pursuing LIVE's science demonstration projects.

LIVE Astro | LIVE Bio | LIVE GIS

assembling data as a community, using modern, open-source practices

linking position and motion across dimensions, using the modular architecture enabled by LIVE (LIVE-Astro elements include glue, WWT, OpenSpace & more)

making data accessible online for decades

Lead: Alyssa Goodman, CfA

SCIENCE

enabling studies of how galaxies turn gas into stars, using...

stellar positions, clusters, motions

topology, positions & motions of (long) features

tracers of feedback & magnetic fields

details on star-forming regions...and more!

Lead: Catherine Zucker, CfA

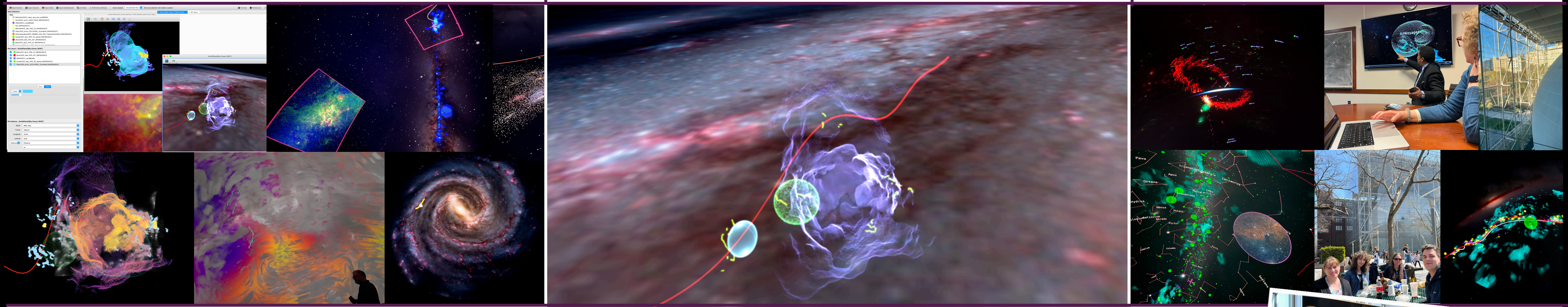
EDUCATION & OUTREACH

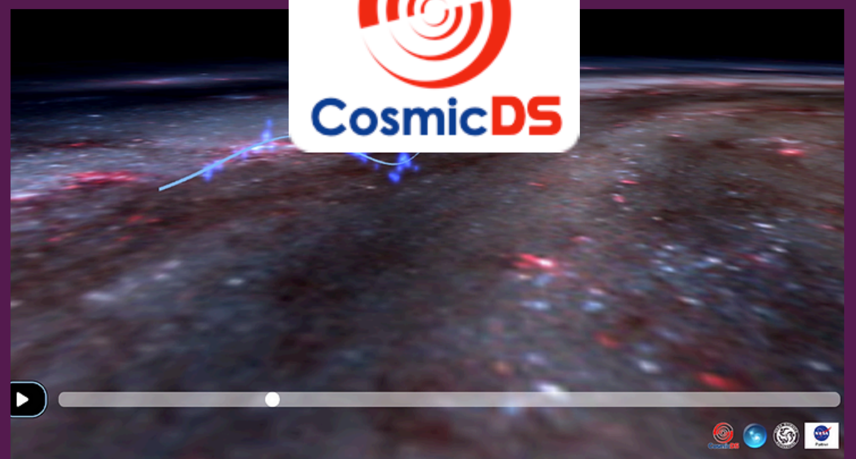
connecting real research data, software, and science to learners

real-time data exploration anywhere, including in planetaria

"Cosmic Data Stories" teach data science using astronomical data & tools

Lead: Jackie Faherty, AMNH





RadWave in Motion

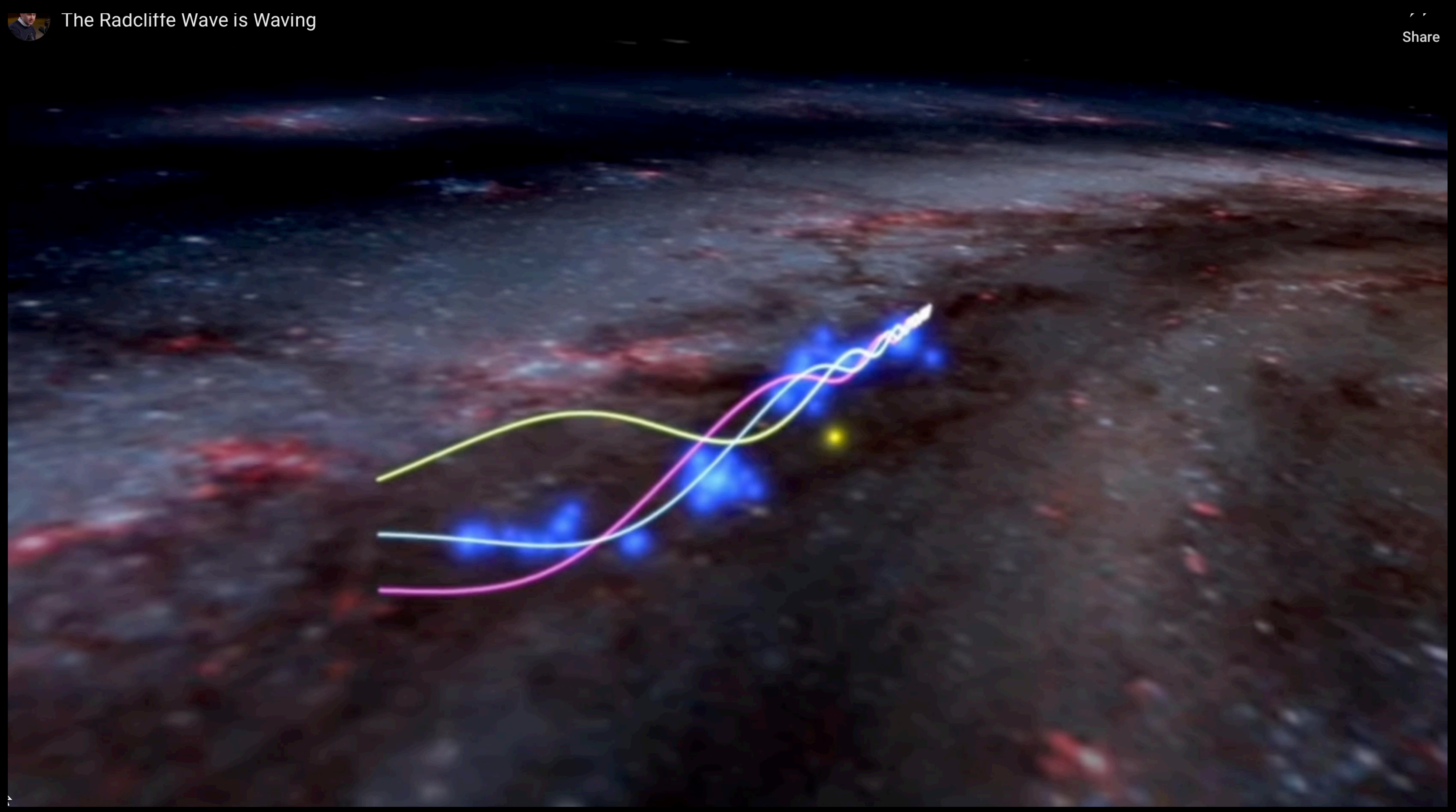
The RadWave is made up of gas, dust, and stars loosely connected in a wave-like shape. It is so huge and so close to us that earlier scientists did not see that these parts were all connected.

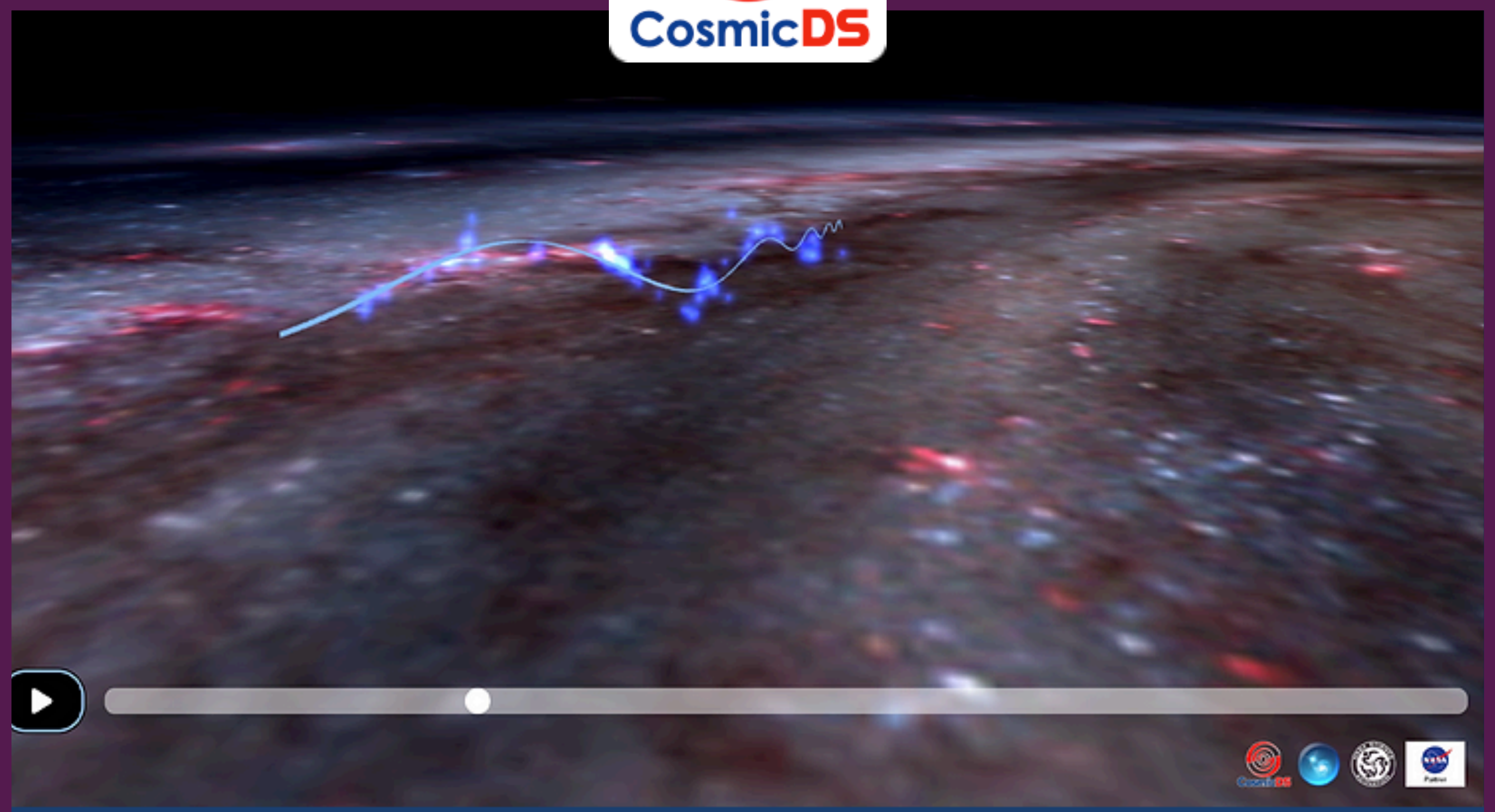
Learn more about the discovery of the RadWave here!

TEAM: Harvard/Smithsonian CfA (Jonathan Carifio, Alyssa Goodman, Ralf Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), **AMNH** (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty); **Linkoping University** (Alex Bock) ; **University of Vienna** (Joao Alves, Sebastian Ratzenbock); **glue solutions, inc./Aperio** (Thomas Robitaille); **University of Wisconsin, Whitewater** (Bob Benjamin), **STScI/Johns Hopkins** (Josh Peek), **Max Planck IfA** (Gordian Edenhofer); **Northeastern University** (Michelle Borkin); and YOU?!

Join us, contribute, and yes, you can get a T-Shirt.

EDUCATION & OUTREACH





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Stay-tuned for more at MilkyWay3D.org
FRICK PHINEAS & SANDRA PRIEST ROSE CENTER FOR EARTH AND
MILKYWAY3D.org
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WORLDWIDE TELESCOPE
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linking position and motion across dimensions, using the plug-in architecture enabled by glue
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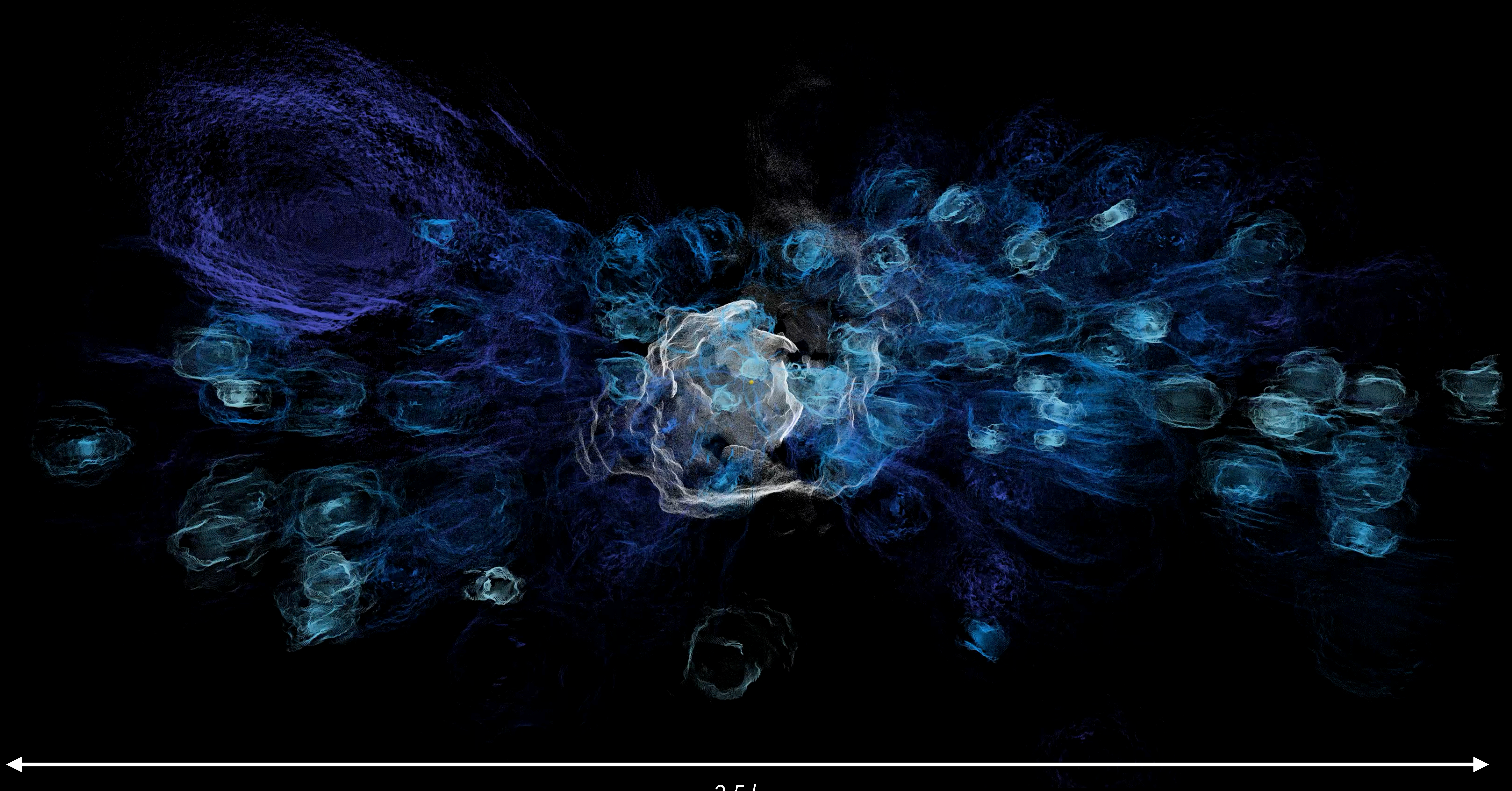
What's next?: MANY MORE BUBBLES



O'Neill et al. 2024b

NGC 628 (PHANGS-JWST)

Credit: Judy Schmidt

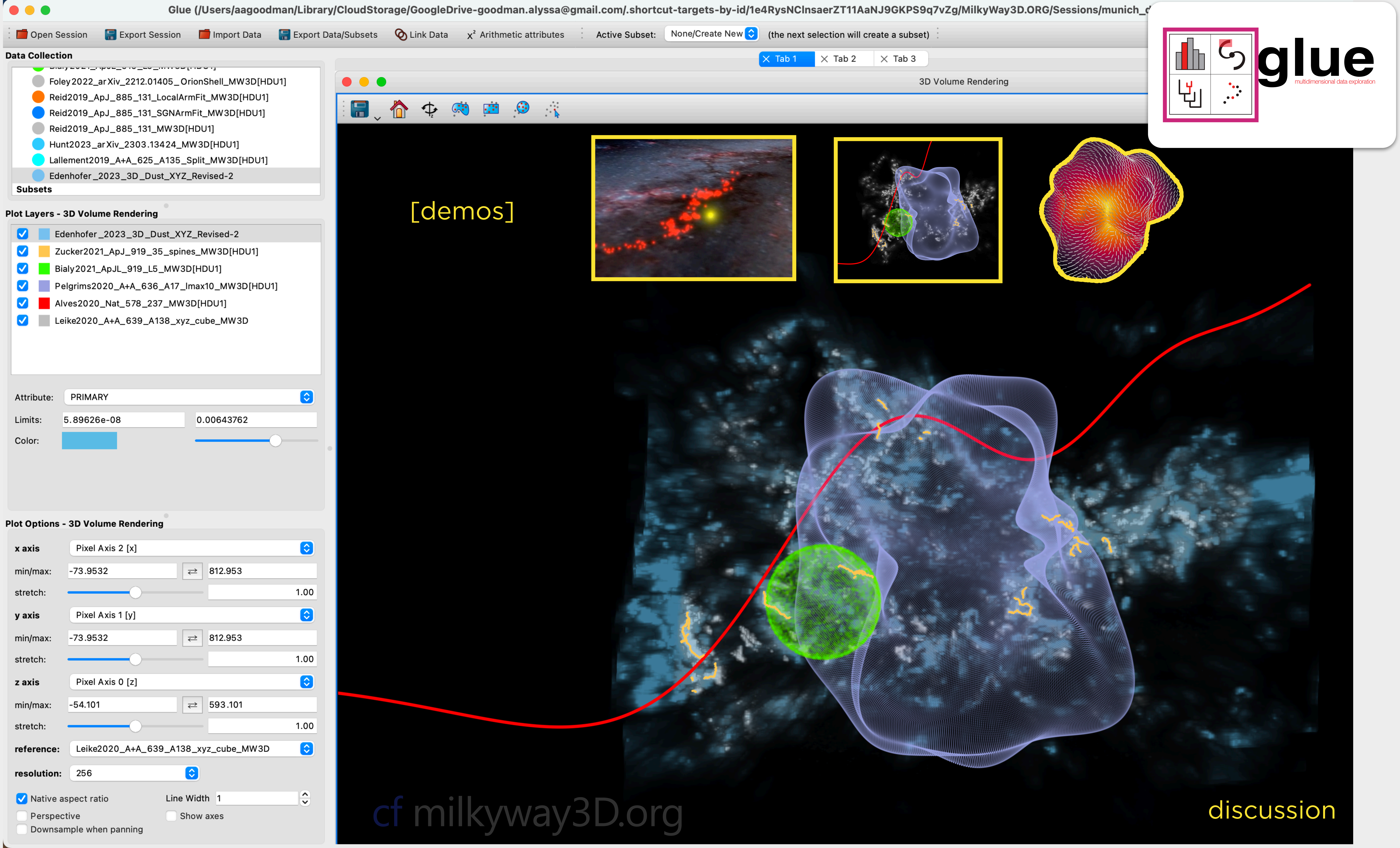
MOVIE

"Everything, Everywhere, All at Once"

1. molecular clouds "*form*"
2. new stars *form* in "molecular clouds"
3. stars *move* while and after they form
4. clouds "*evolve*" (grow, shrink, merge, change shape, change density) over time
5. winds & explosions from stars (called "feedback") *cause* some of the clouds' evolution
6. the most "significant" feedback events can *cause* new molecular clouds to form (see #1!)

Nothing stays still. Nothing lasts forever.

\+ *and the ISM perpetually trades material with the IGM*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Import Data
Export Data/Subsets
Link Data
Arithmetic attributes
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None/Create New
(the next selection will create a subset)
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Tab 2
Tab 3
3D Volume Rendering
[demos]
glue
multidimensional data exploration
cf milkyway3D.org
discussion