Understanding the Structure of the Milky Way®

[USA edition]

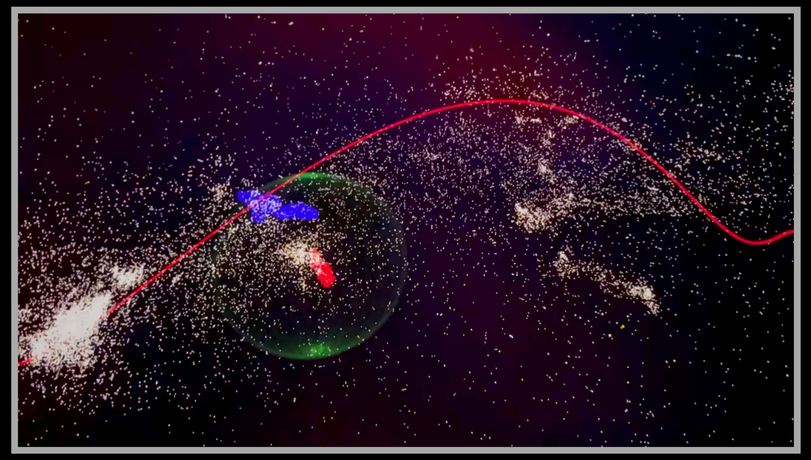
Understanding the Structure of the

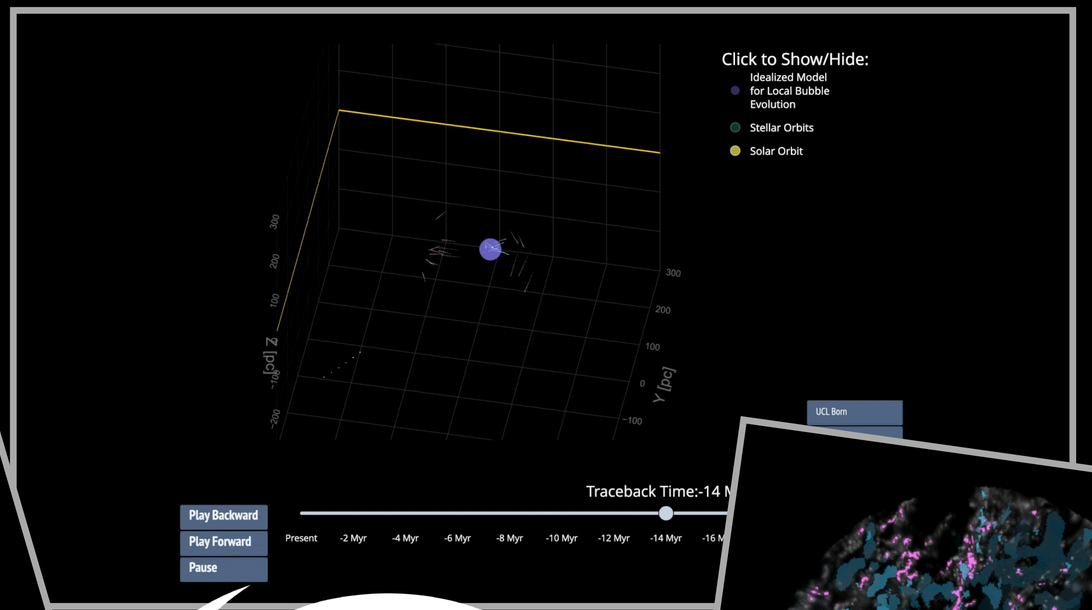
[global edition]

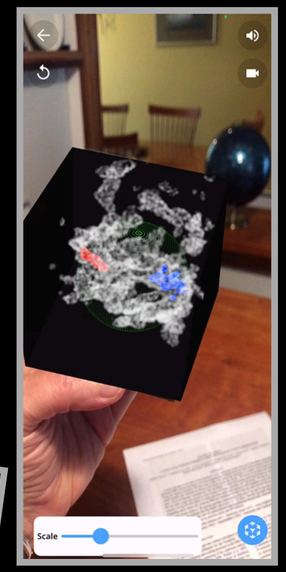
Understanding the Structure of the Milky Way

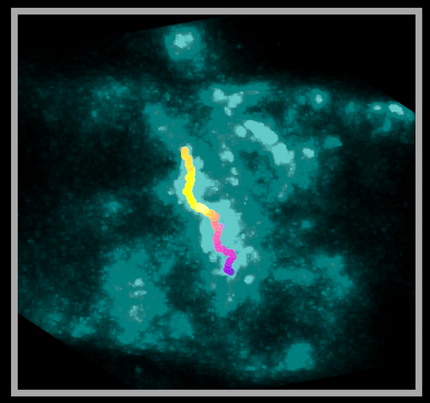
[astronomy edition]

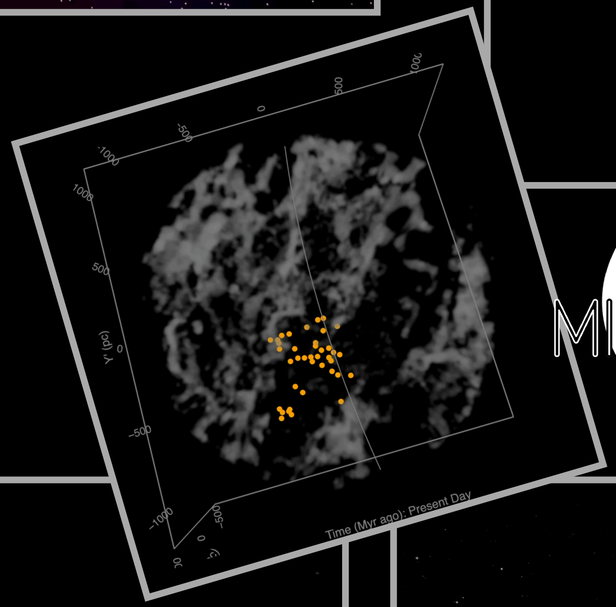
presented by Alyssa Goodman, Harvard University/CfA

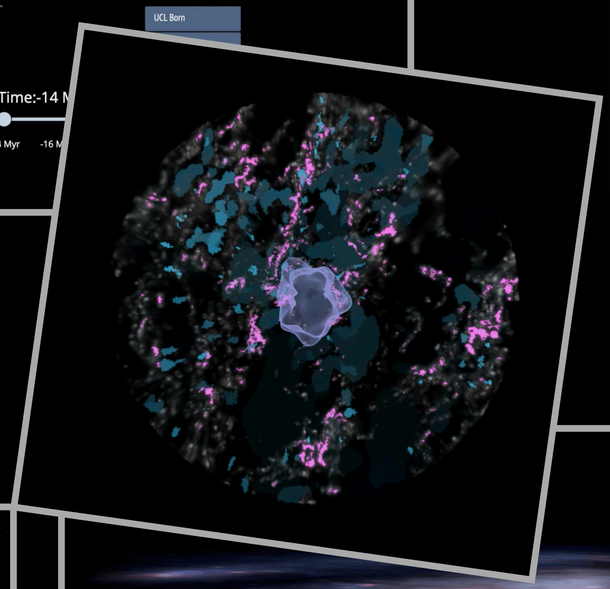




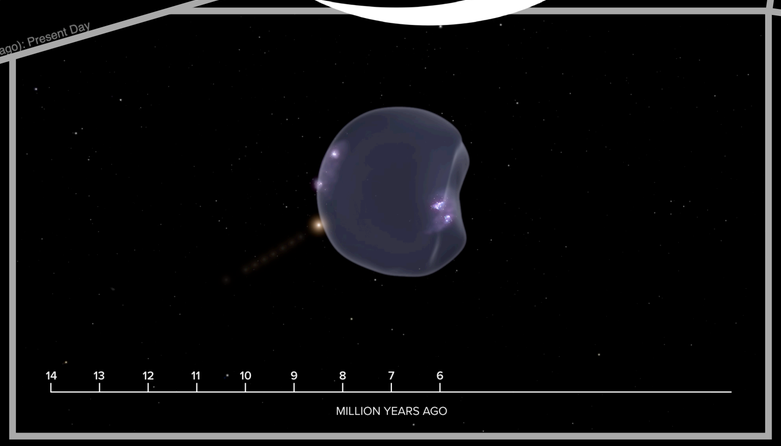


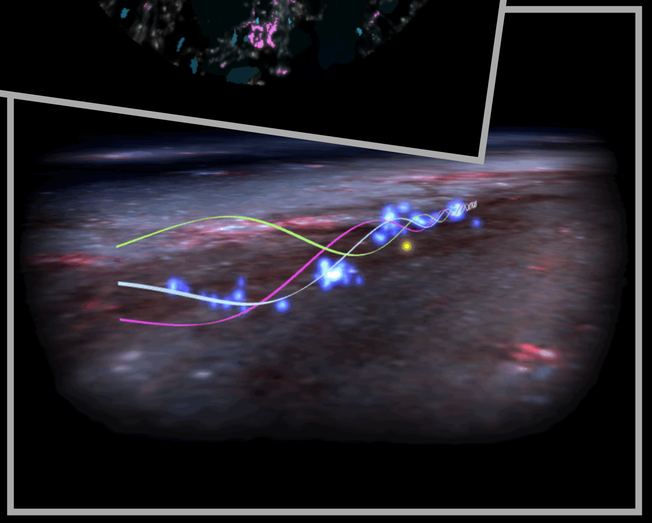






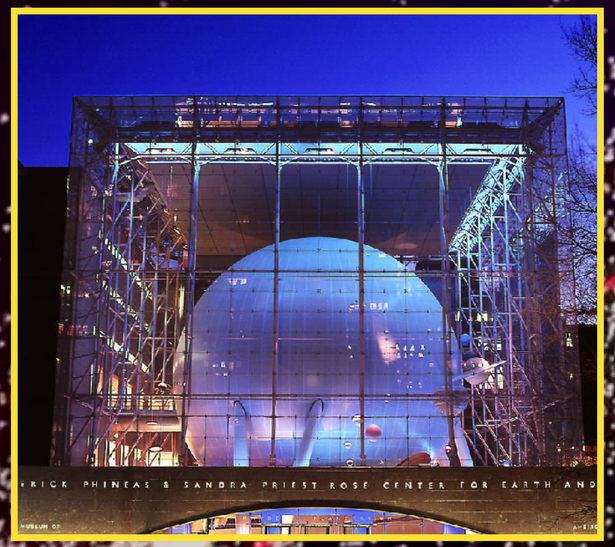
MILKYWAY3D.org





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

a.k.a. “Making a 3D Movie of the Star-Forming Milky Way I never thought I'd see”, with my friends



MILKYWAY3D.org

AG, with 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.

with my friends
CLOSED FOR A PRIVATE EVENT
MILKYWAY3D.org

star-forming nebulae

“Messier” Objects

galaxies

Mes·sier, Charles

| ˈmesiə, mesye, ˌmesēˈā, mesˌyā |

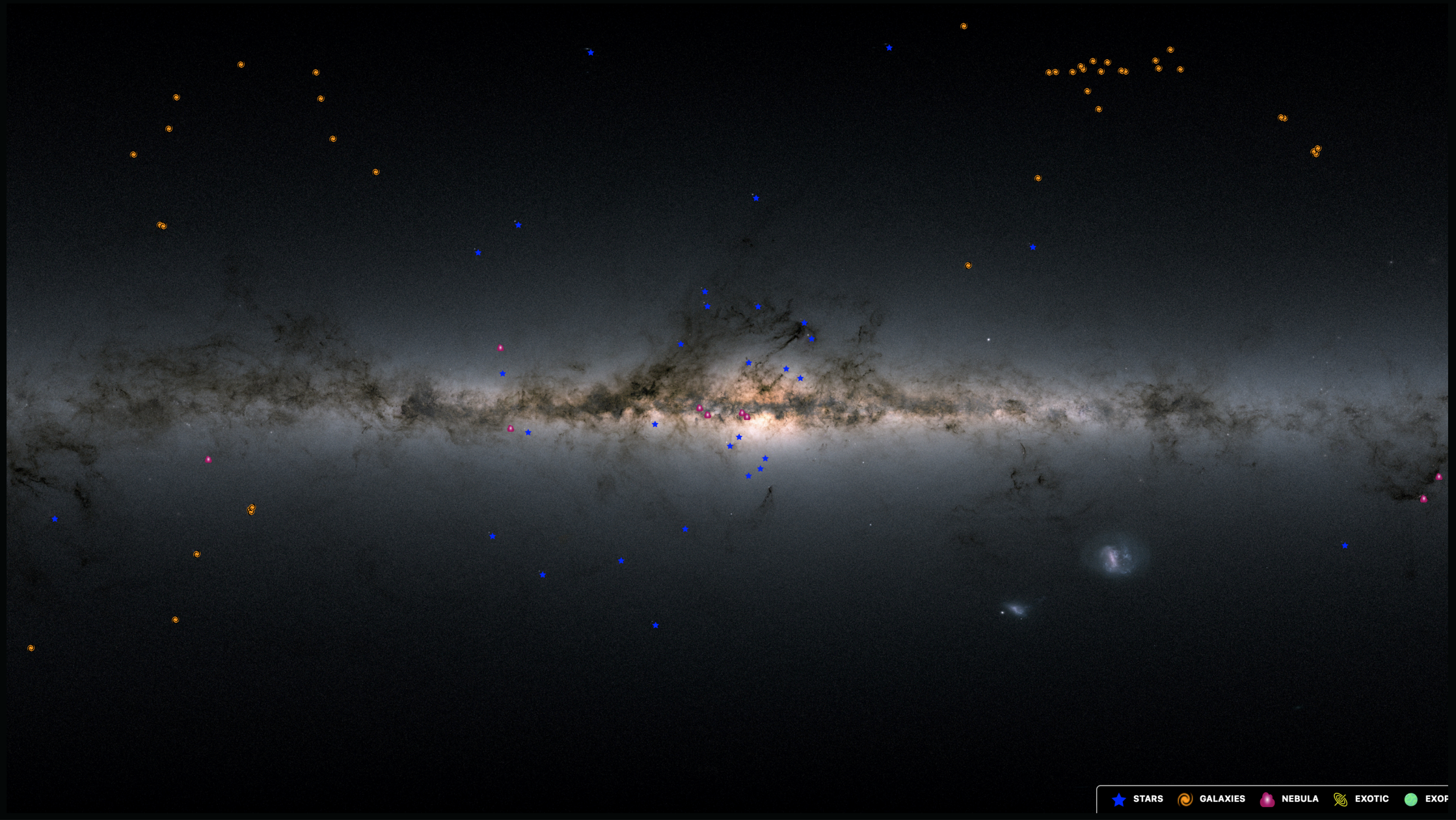
(1730–1817), French astronomer. He discovered a number of nebulae, galaxies, and star clusters, which he designated by M numbers.

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



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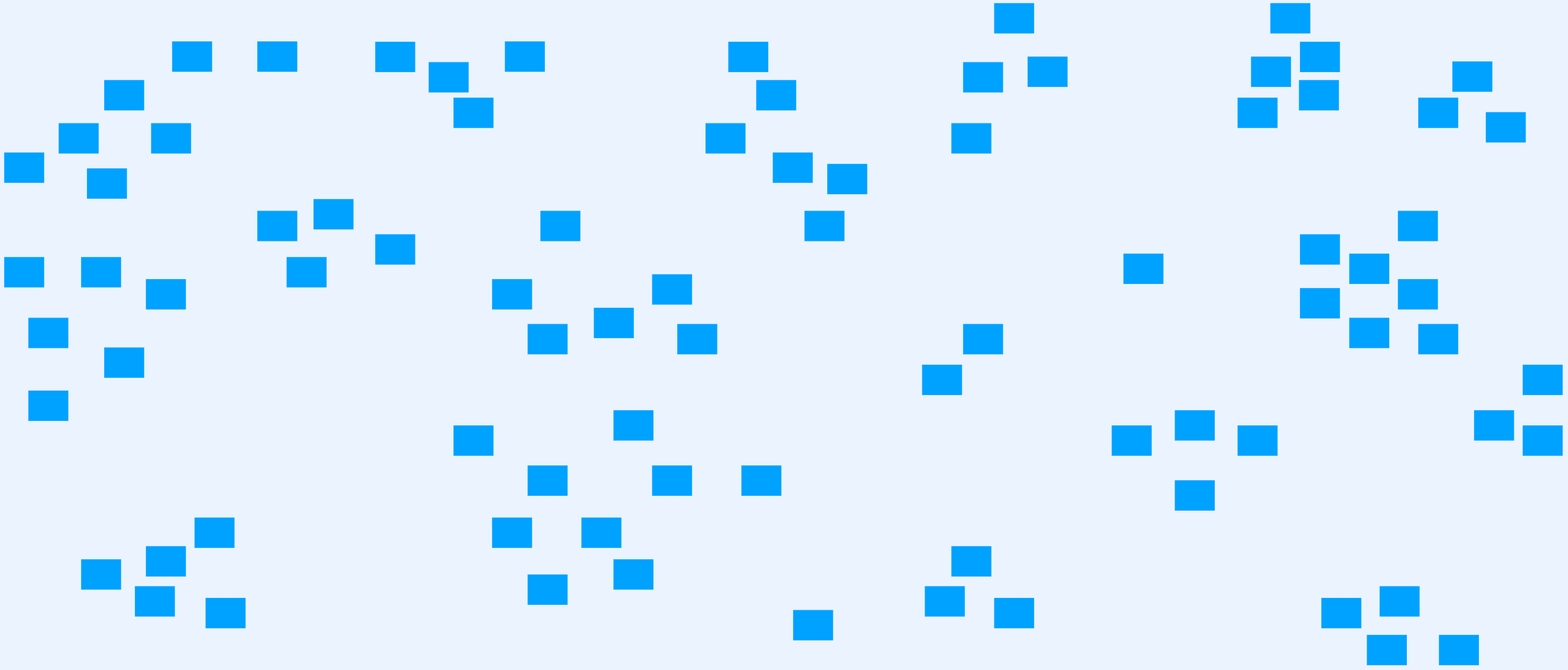
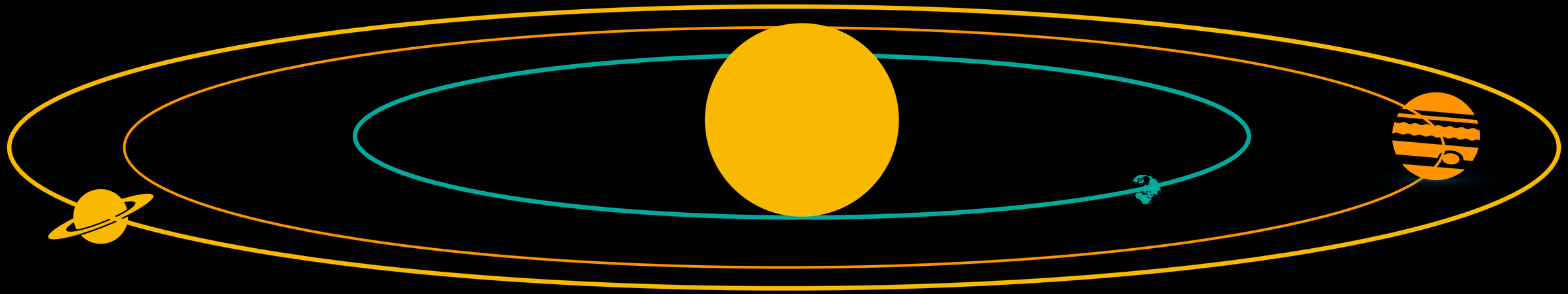
WHERE ARE WE?

WHERE ARE WE?



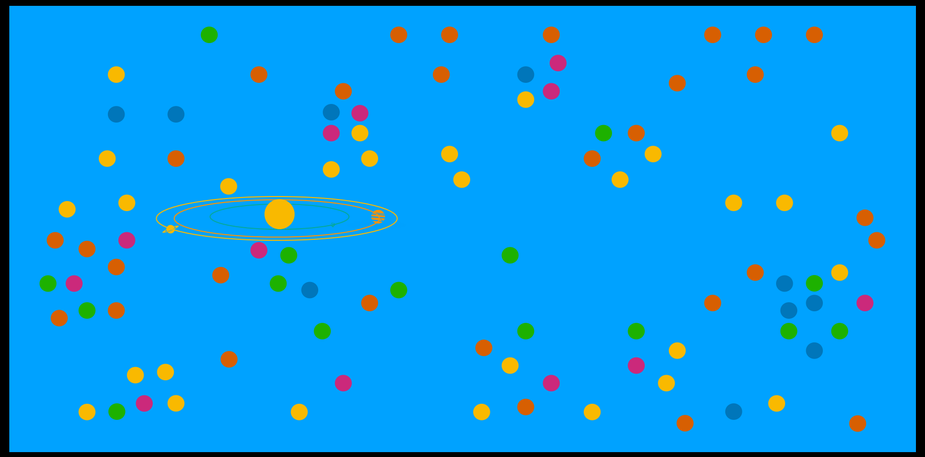
our **Universe** contains MANY billions of **galaxies**

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

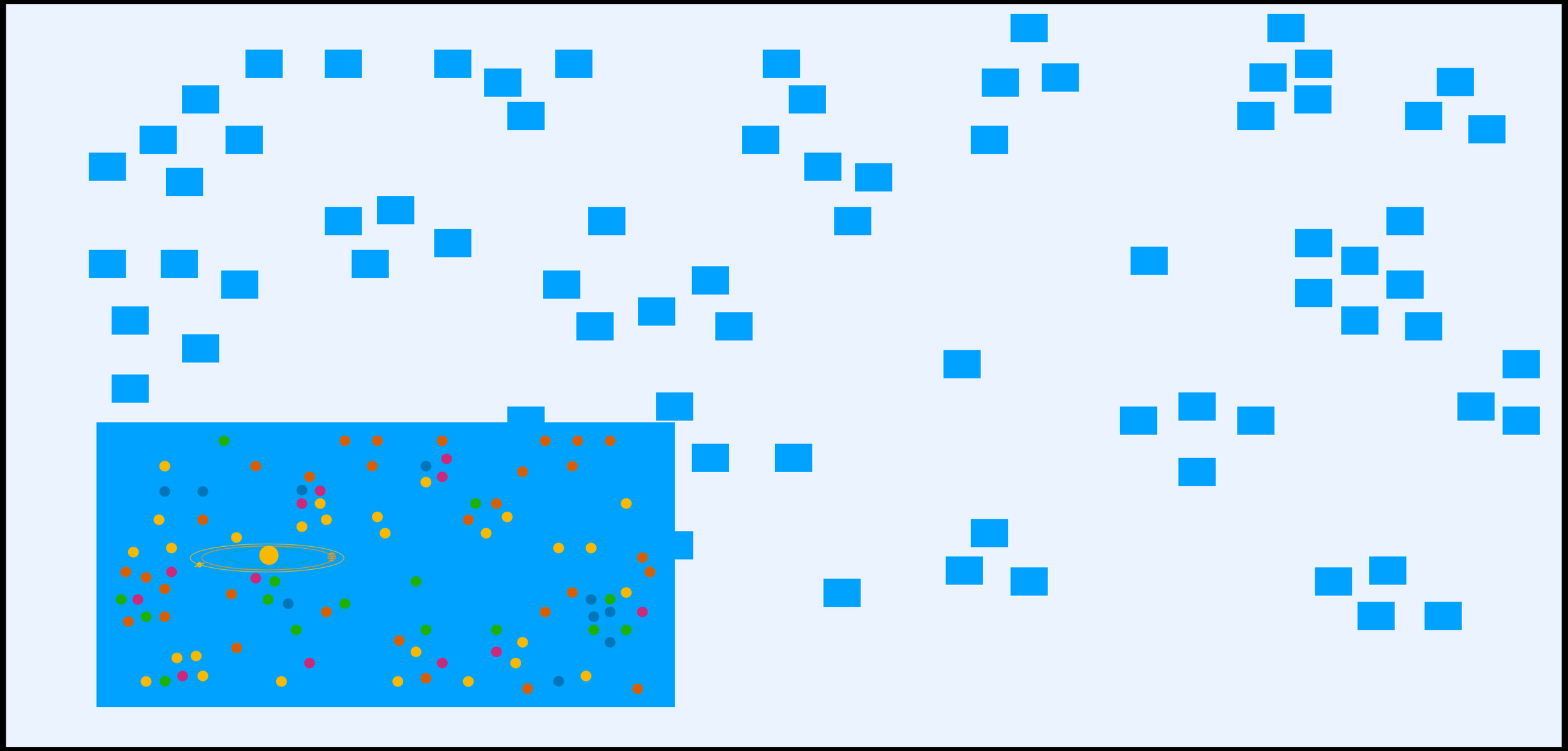


around most of the stars are systems of planets (ours is called “**The Solar System**”)

our home planet is **Earth**



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



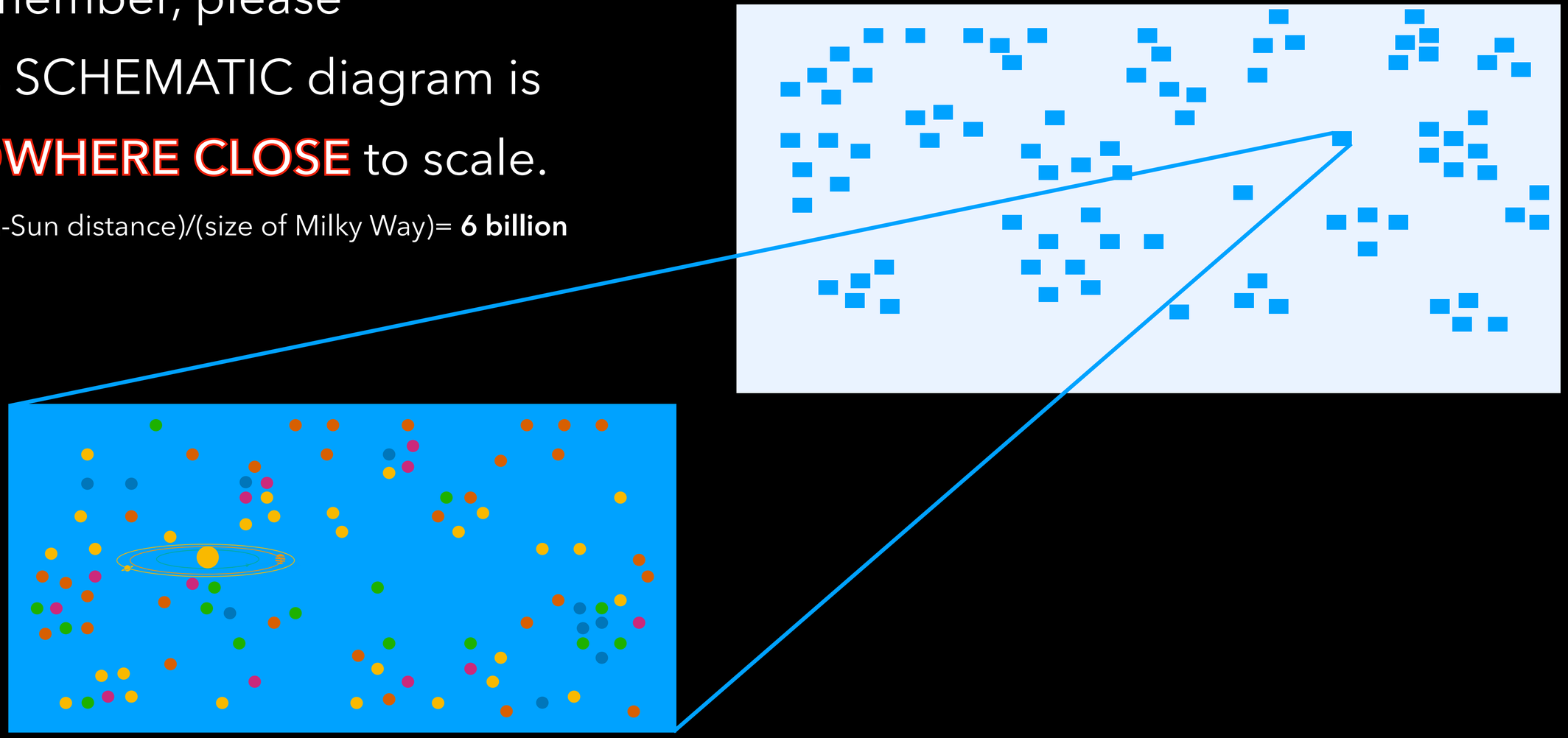
Earth resides in the **Solar System**, around the **Sun**, which is one of MANY **stars**, INSIDE the **Milky Way**, which is one of MANY **galaxies**, in our **Universe**

Remember, please

this SCHEMATIC diagram is

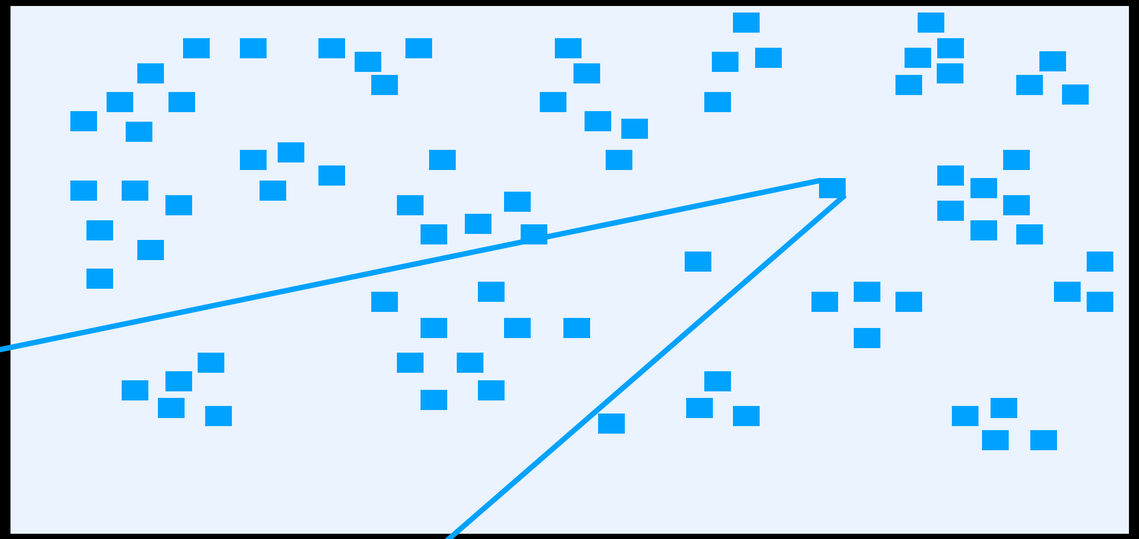
NOWHERE CLOSE to scale.

(Earth-Sun distance)/(size of Milky Way)= **6 billion**



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…



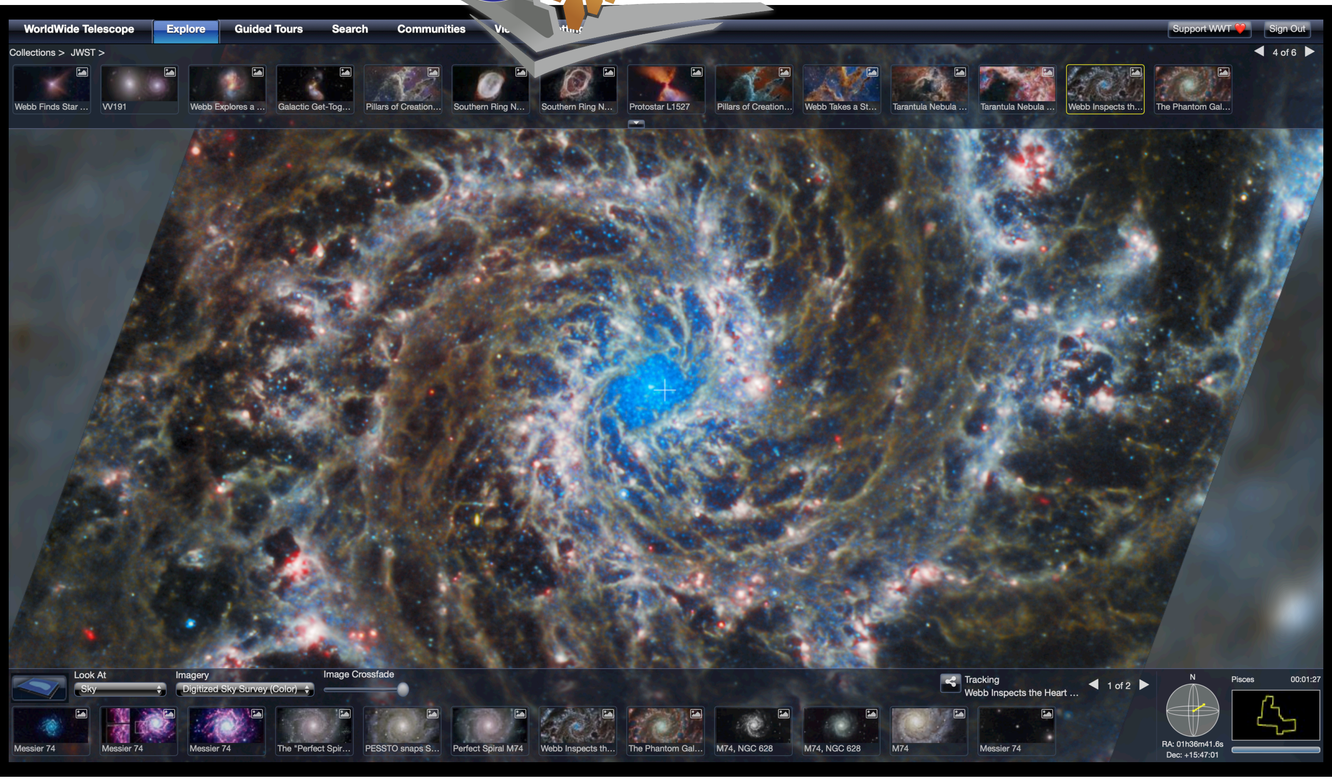
…cartoon!

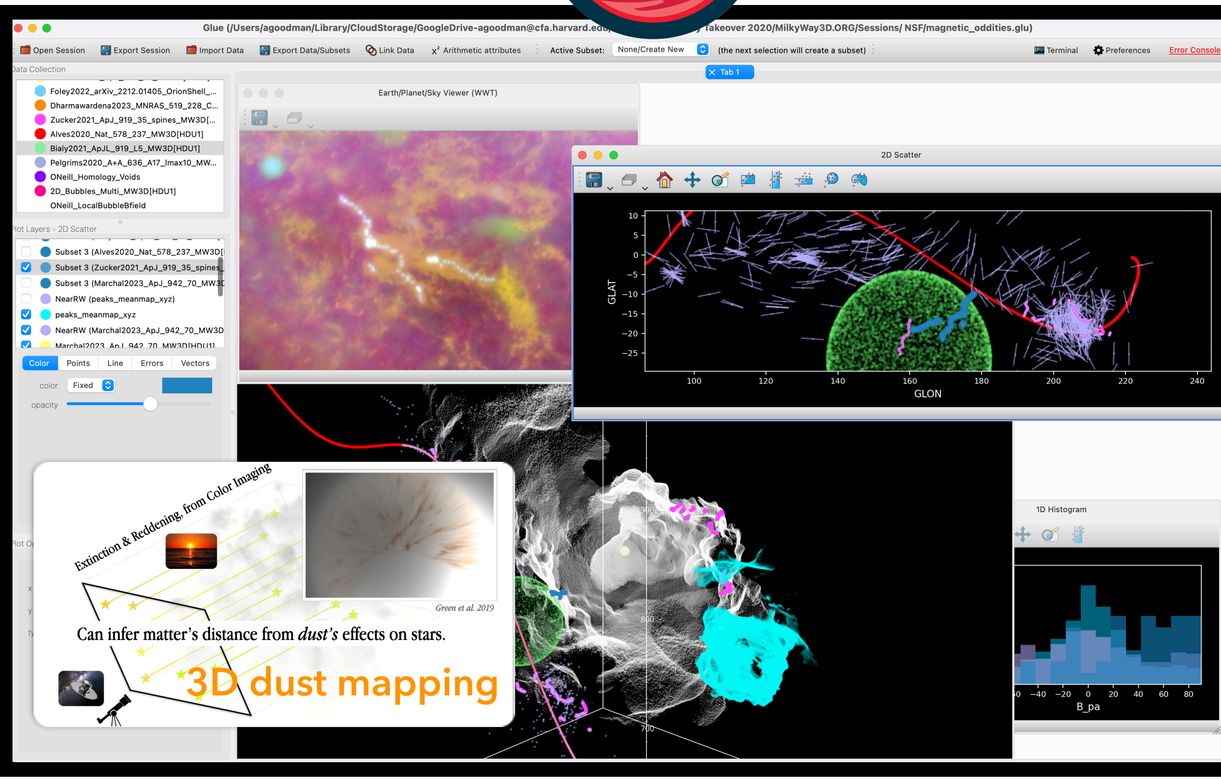
…and we are buried INSIDE the Milky Way.

OK, great, I get where we are.

Why work on
“understanding the structure of the Milky Way”
in 3D *now*?

unprecedented data





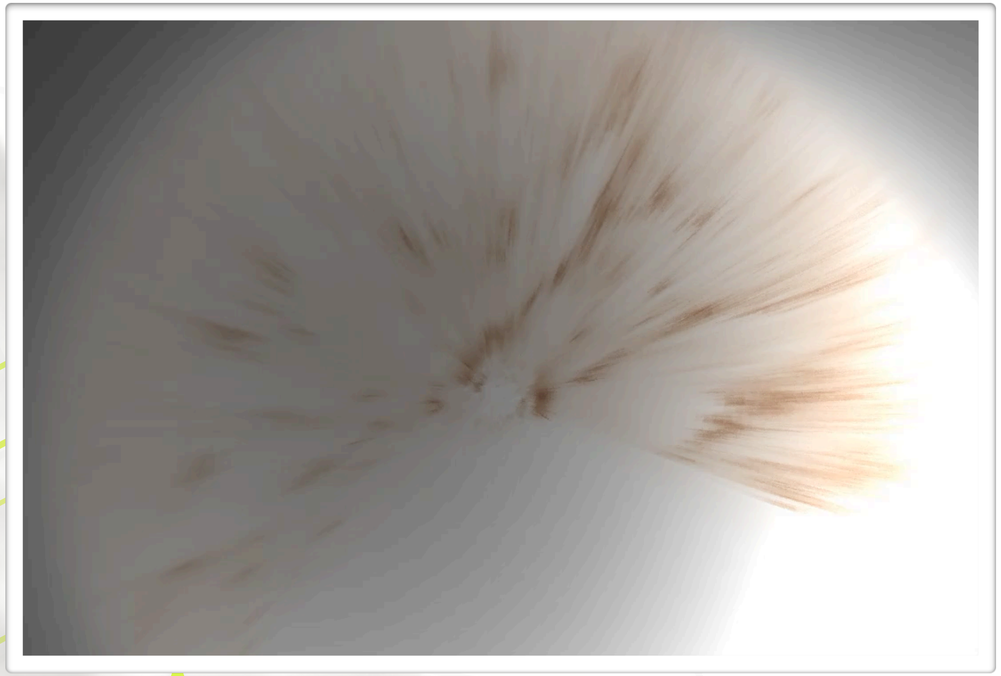
WORLDWIDE TELESCOPE

glue
multidimensional data exploration
glueviz.org

unprecedented software tools

3D dust mapping

Extinction & Reddening, from Color Imaging

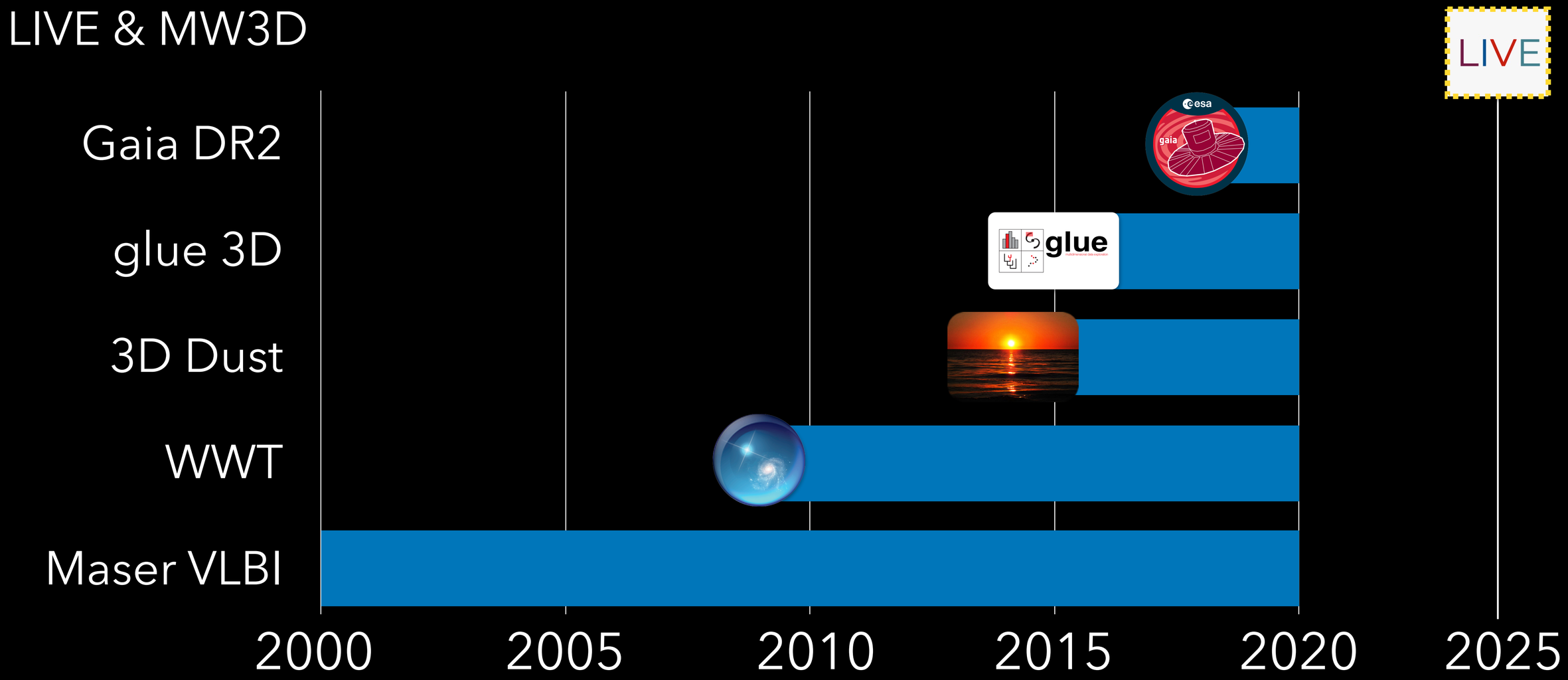


Green et al. 2019

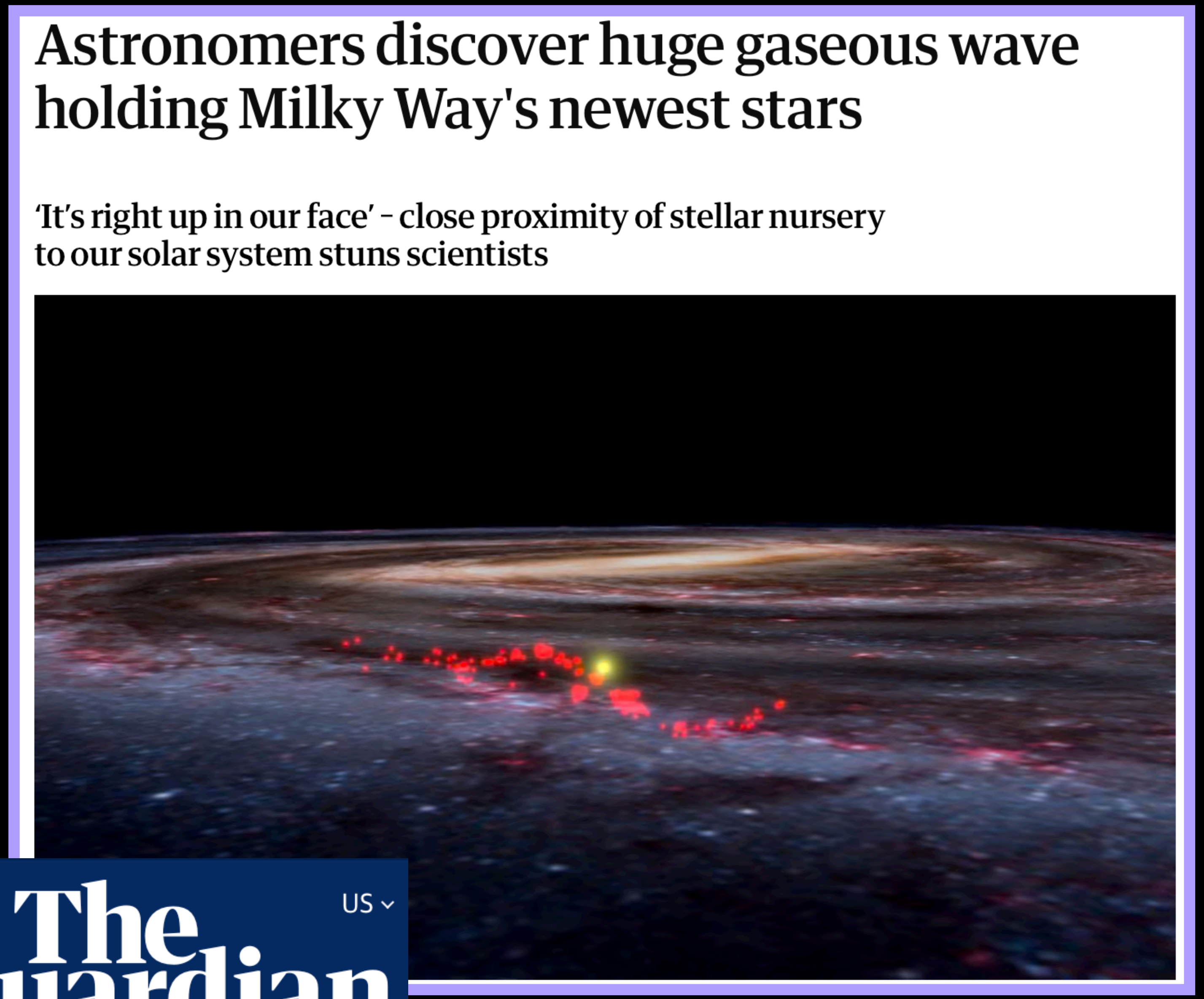
Can infer matter's distance from *dust's* effects on stars.

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

WHY *now*?

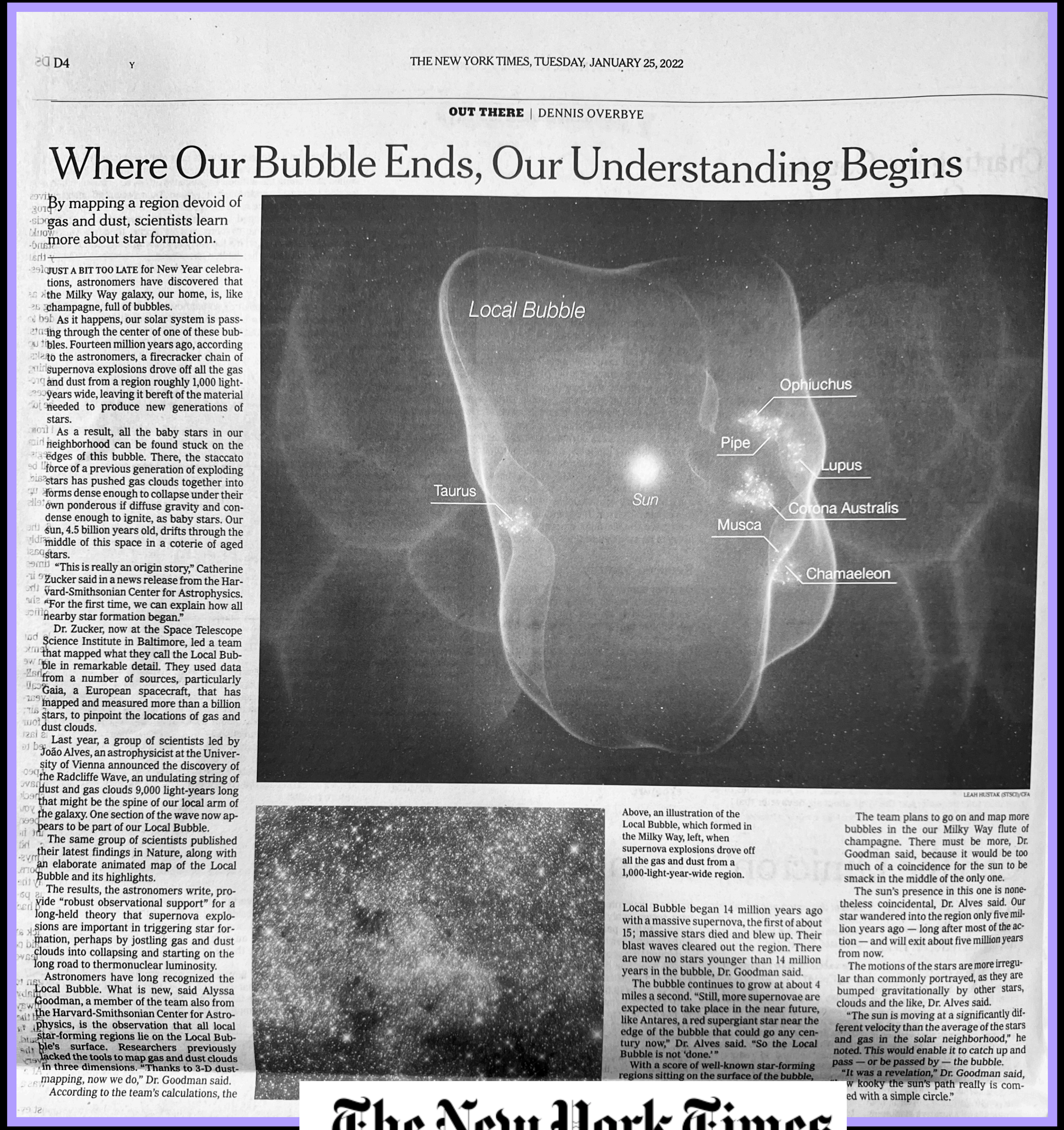

LIVE & MW3D
Gaia DR2
glue 3D
3D Dust
WWT
Maser VLBI
2000
2005
2010
2015
2020
2025
LIVE
esa
gaia
glue

WHY *now*?



2020

Ian Sample, The Guardian



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

OUT THERE | DENNIS OVERBYE

Where Our Bubble Ends, Our Understanding Begins

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

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

LEAH HUSTAK (STSCI)/CFA

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.

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 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.

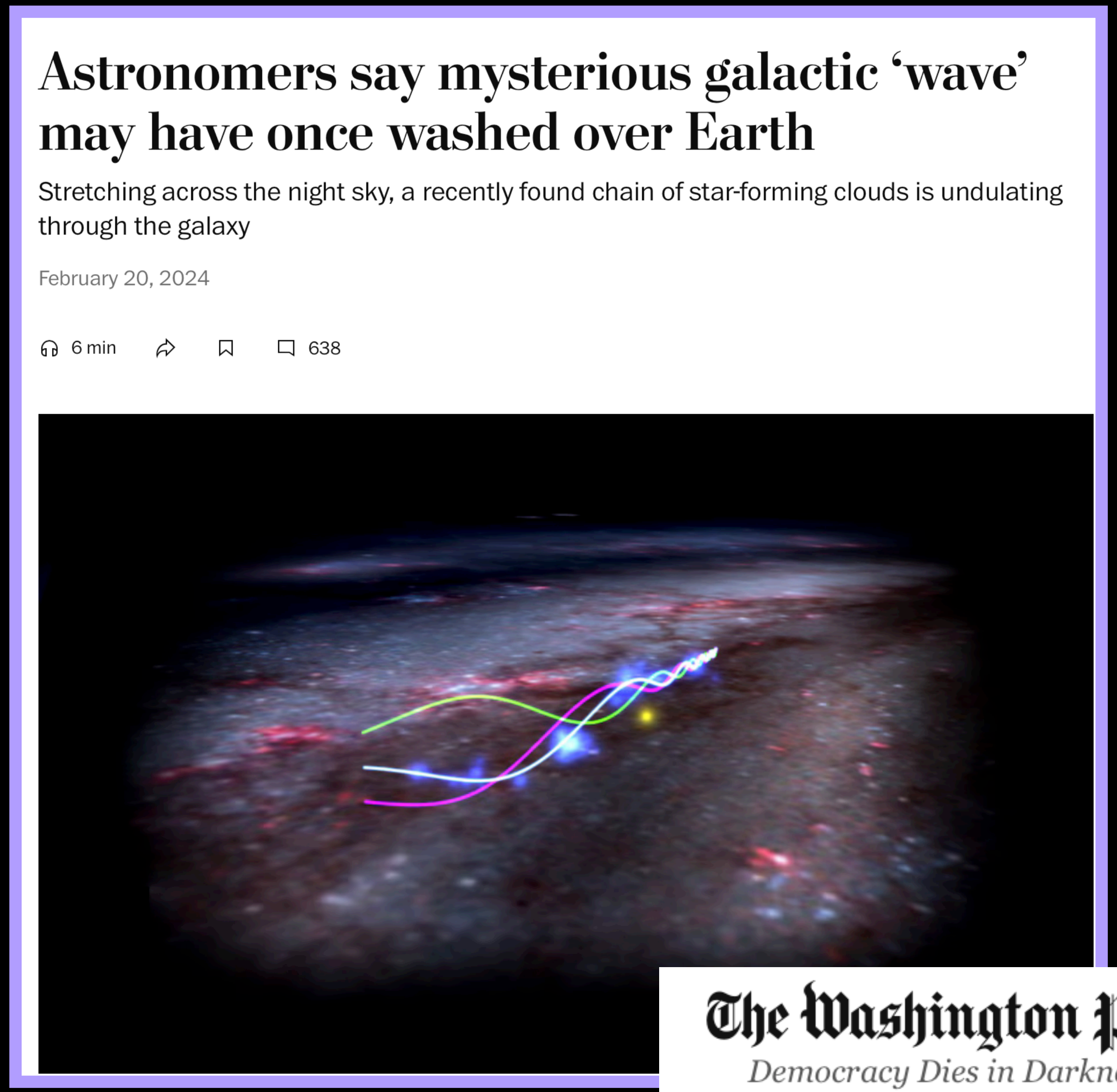
The motions of the stars are more irregular than commonly portrayed, as they are bumped gravitationally by other stars, clouds and the like, Dr. Alves said.

"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, "...w kooky the sun's path really is com...ed with a simple circle."

2022

Dennis Overbye, NY Times

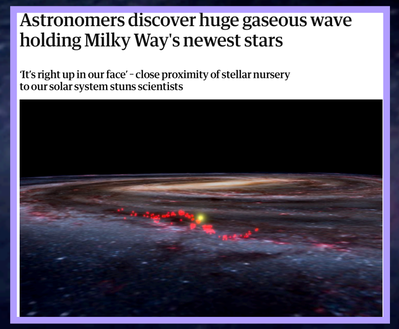


2024

Joel Achenbach, Washington Post

The Radcliffe Wave

Each **red** dot marks a star-forming blob of gas whose distance from us has been accurately measured.


Astronomers discover huge gaseous wave holding Milky Way's newest stars

'It's right up in our face' – close proximity of stellar nursery to our solar system stuns scientists

2020

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)

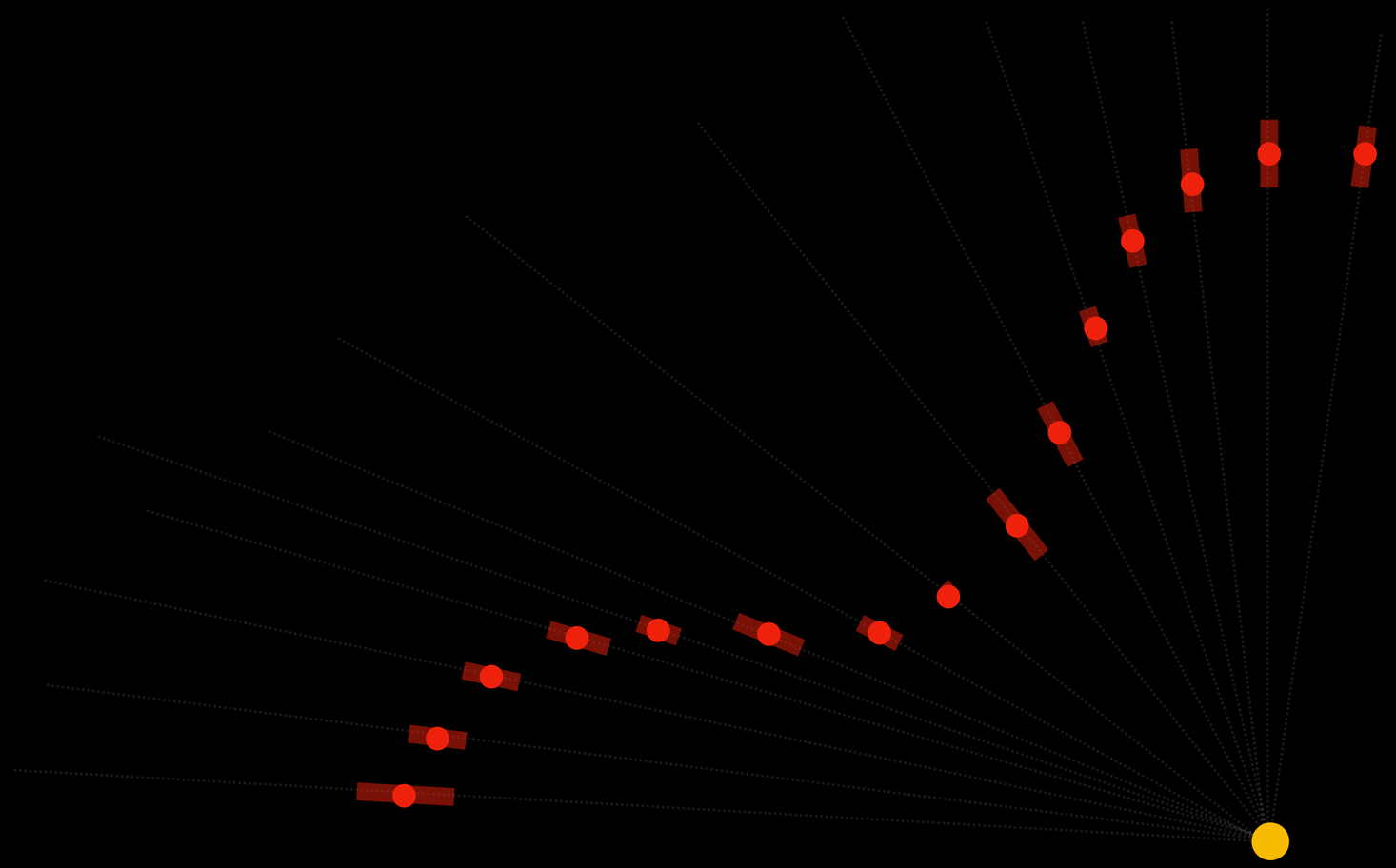
DISTANCES!!

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

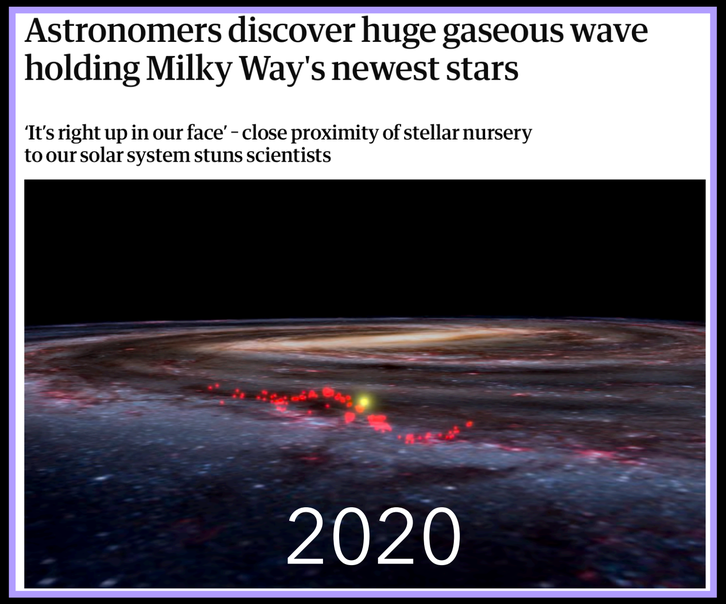
Uncertain Distances

SCHEMATIC CARTOON(!)

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



"The Radcliffe Wave"



SCHEMATIC CARTOON(!)

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

Distances estimates today more like 1%!

2022

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 we live in a bubble. Specifically, in the champagne fizz of bubbles.

As it happens, our solar system is passing through the ribbon of one of these bubbles. Fourteen million years ago, according to the astronomers' calculations, a series of supernova explosions drove off all the gas and dust from a region roughly 1,000 light-years wide, leaving behind a void that later would be invaded by newer generations of stars.

As a result, all the baby stars in our neighborhood can be found stuck on the ridges of this bubble. There, the staccato shock waves from supernovas have caused stars' fiery fuse-ended gas clouds together long enough to collapse under their own gravity, igniting as baby stars. Our sun, 4.5 billion years old, is now sitting in the middle of this space in a cosmic of aged stars.

"This is really an origin story," Catherine Zucker said in a news release from the Harvard-Smithsonian Center for Astrophysics. "It's a new way to understand how all nearby star formation began."

Dr. Zucker, now at the Space Telescope Science Institute in Baltimore, was part of the team that mapped what they call the Local Bubble in remarkable detail. They used data from the Gaia space observatory, particularly from its European Space Agency satellite, to pinpoint the locations of gas and dust clouds.

Separately, a group of scientists led by Julia Kloss, an astrophysicist at the University of Vienna announced the discovery of a ring of gas and dust clouds 3,000 light-years long that might be the spine of our local arm of the Milky Way galaxy. Our solar system appears to be part of our Local Bubble.

The same group of scientists published in Nature, along with an elaborate computer map of the Local Bubble and its neighbors.

The results, the astronomers write, provide "robust observational support" for a theory that supernova explosions and winds are important in triggering star formation, perhaps by jostling gas and dust together in ways that can lead to the long road to thermonuclear luminosity.

Astronomers have long recognized the Local Bubble, but Alyssa Goodman, a member of the team also from the Harvard-Smithsonian Center for Astrophysics, said that mapping the bubble's dust-forming regions for the first time gave the team's surface. Researchers previously had only a two-dimensional picture of the bubble's interior. "We have to do more than mapping, now we do," Dr. Goodman said.

According to the team's calculations, the

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

Local Bubble began 14 million years ago when supernovas blasted away gas and dust. Its balloon-like shape was formed by shock waves created as the stars exploded. The sun and its stars are now no more than 14 million years old.

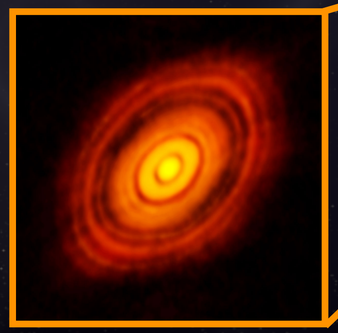
The team plans to go on and map more bubbles in the our Milky Way. Date of champagne. There must be more, Dr. Goodman said, because it would be too much of a coincidence for the sun to be sitting in the middle of just one bubble.

The sun's presence in this one is nevertheless coincidental, Dr. Alves said. Our star probably formed somewhere else, maybe 100 years ago — long after most of the action — and will exit about five million years from now.

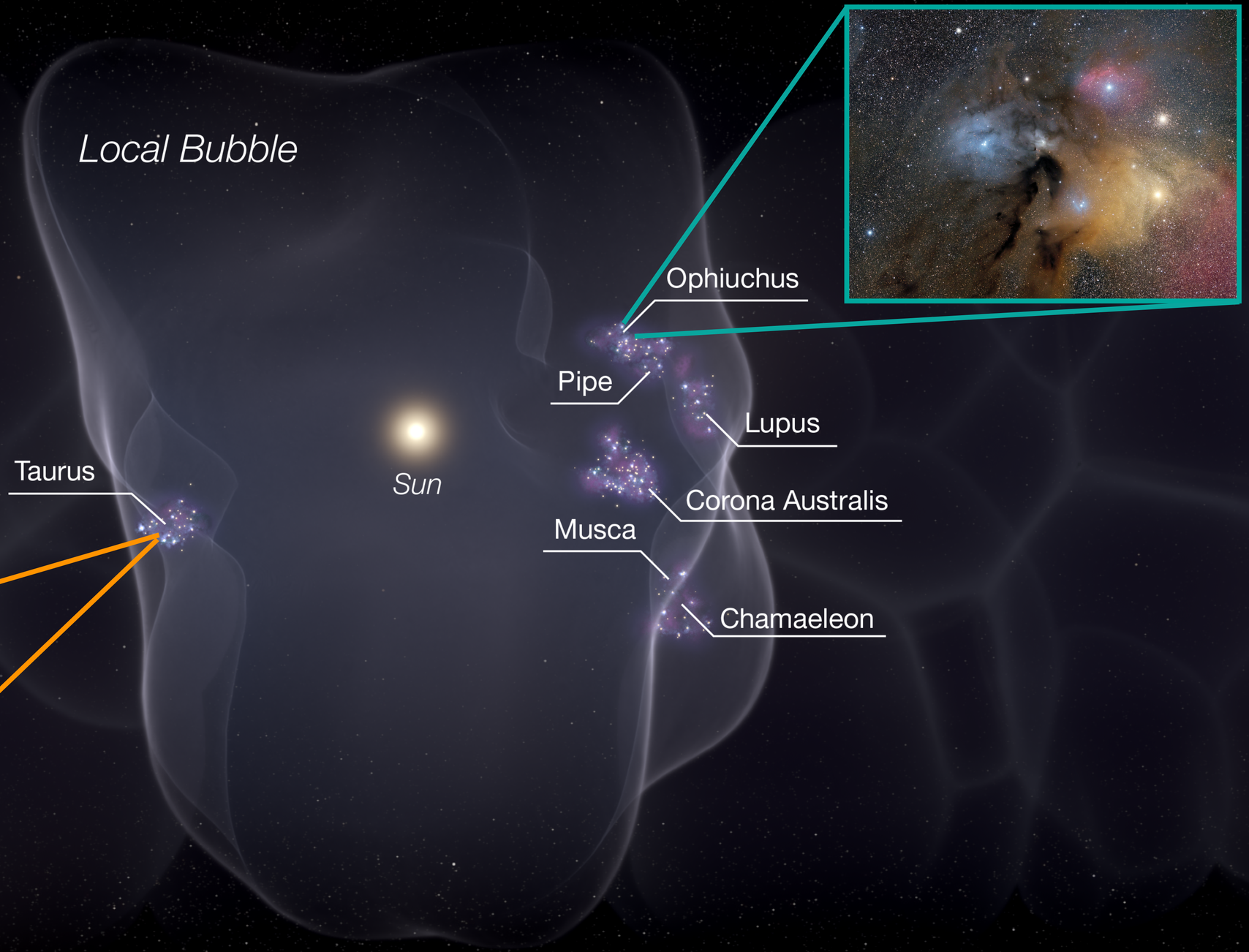
The motions of the stars are more irregular than commonly portrayed, as they are pulled in different directions by the sun's, Orion and the Sea, Dr. Alves said.

"The sun is moving at a significantly different velocity than the average of the stars and gas of the solar neighborhood," he said. "Eventually we'll be left behind as old pals — as the parent has — the bubble."

Dr. Goodman, a science writer, said, "How would the word 'pals' really is compared with a single star."



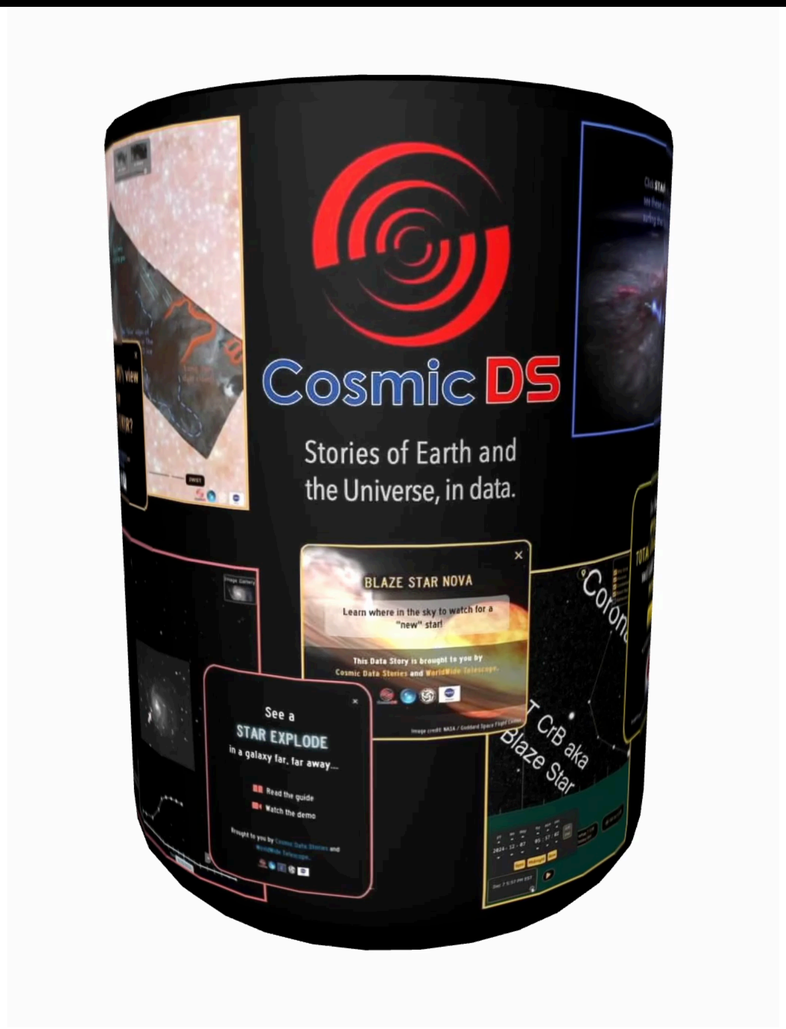
10,000x zoom



[LIVE demo!]

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

TODAY: RESEARCH + EDUCATION + OUTREACH



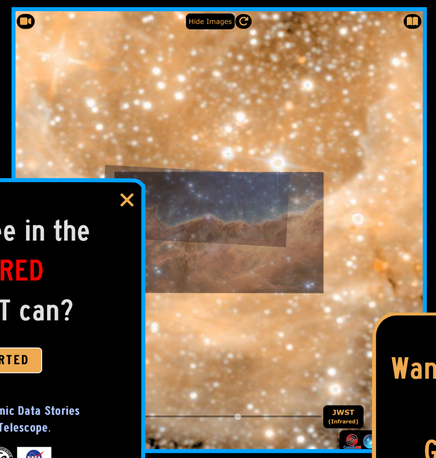
EDUCATION + OUTREACH

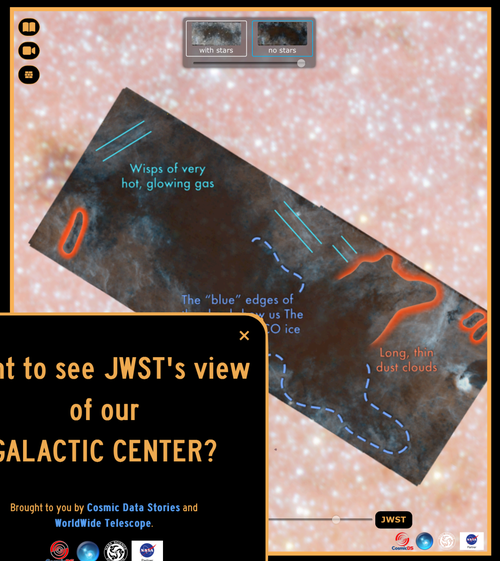
NASA SCIENCE ACTIVATION

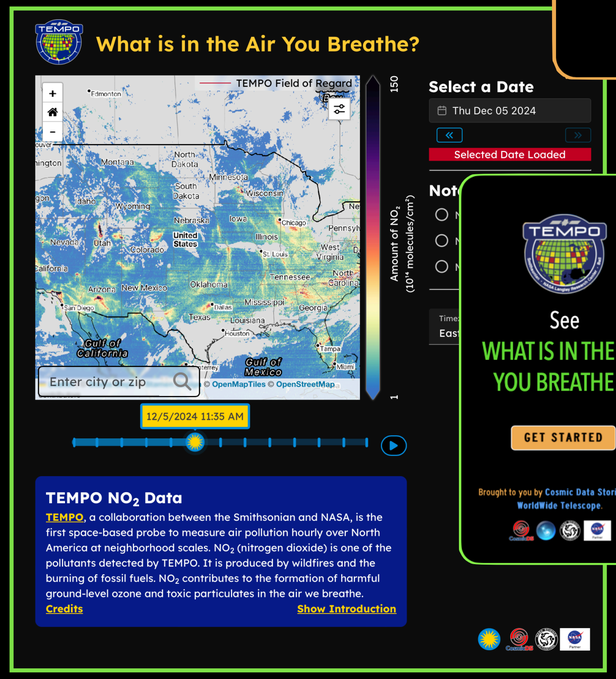
cosmicds.cfa.harvard.edu

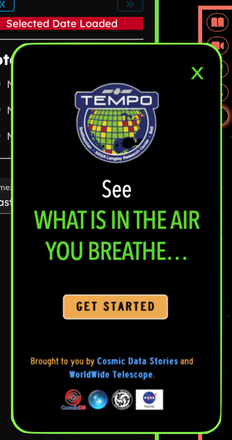
Cosmic DS

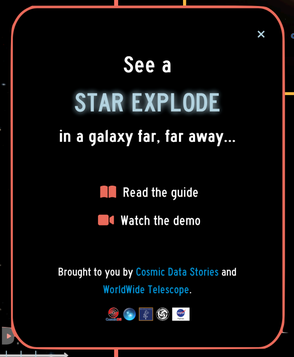
Stories of Earth and the Universe, in data.

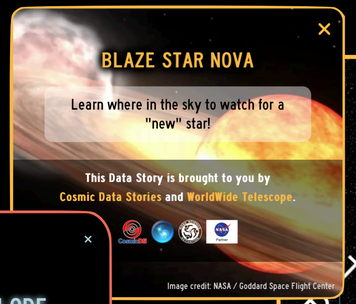


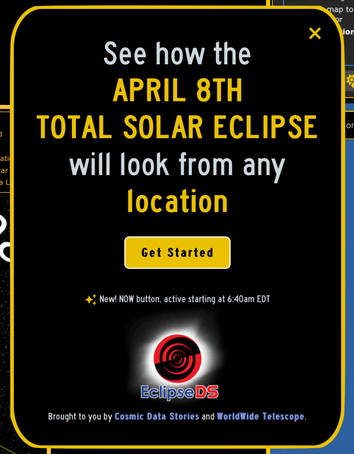


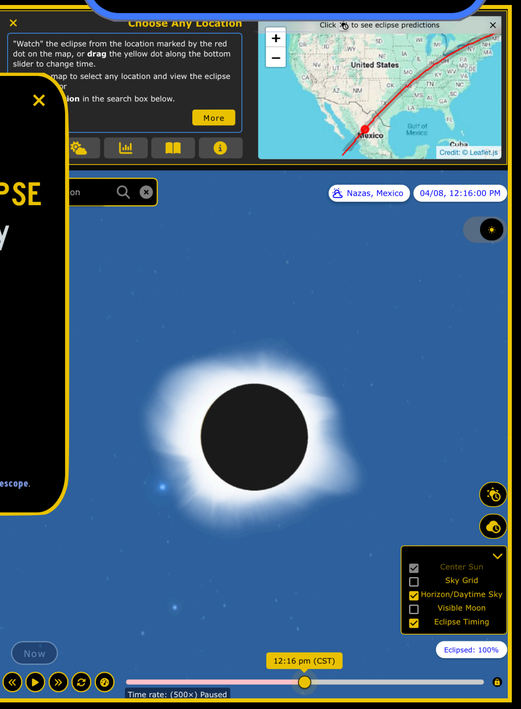




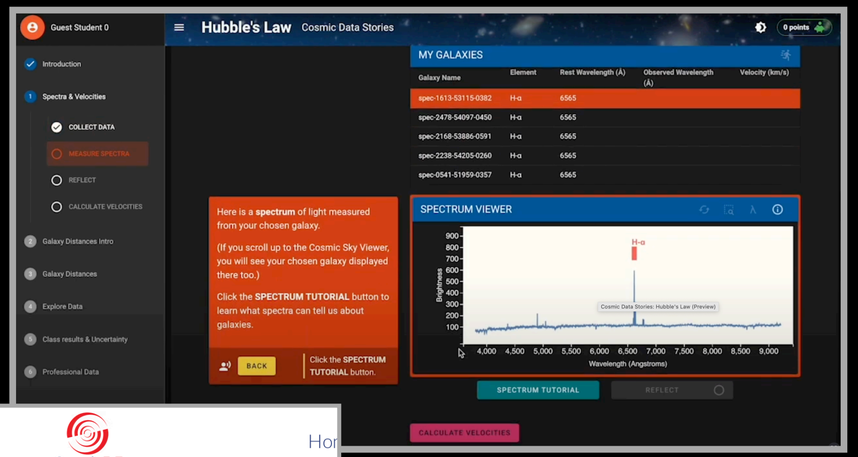


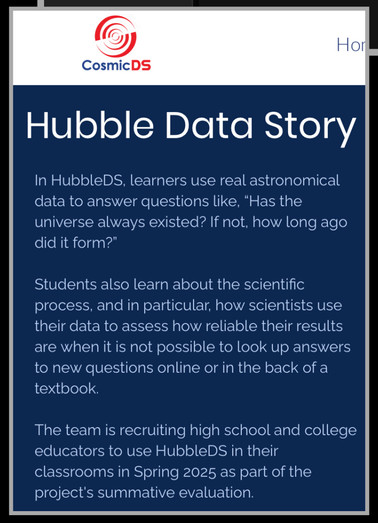


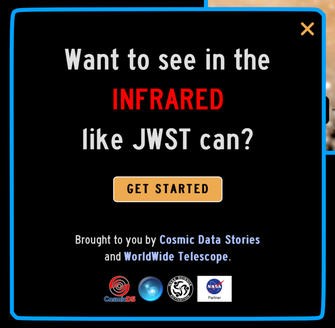


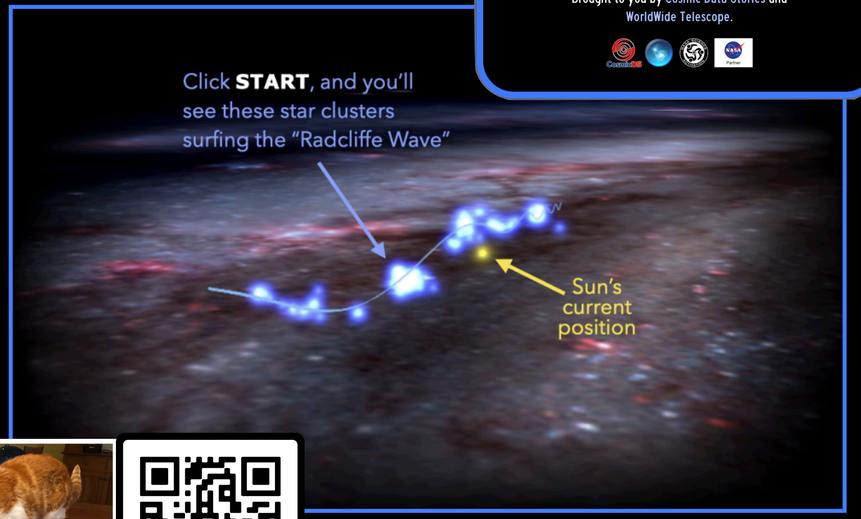


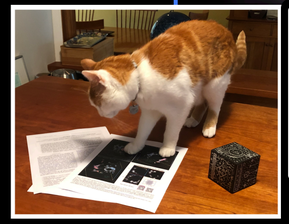
The Great Debate, E.E. Barnard, and my cat











Merge Cube view

CosmicDS

Stories of Earth and the Universe, in data.

cosmicds.cfa.harvard.edu

NASA SCIENCE ACTIVATION

From National Academy of Sciences,
Smithsonian Institution, Washington, D. C.
(Carl H. Butman, Representative).

For Release to Afternoon Papers,
Monday, April 26

for Files

HOW MANY UNIVERSES ARE THERE?

This evening two California astronomers will discuss the Size of the Universe, and present their views as to whether or not there is only one or several universes, before the National Academy of Sciences, which is now in session in Washington.

In this public meeting, Dr. Harlow Shapley of the Mt. Wilson Solar Observatory, will discuss recently secured evidence pointing to the dimensions of our galaxy of stars, known popularly as the Milky Way, which he believes to be ten times greater than is held in the older theories concerning the dimensions and compositions of the Milky Way. In other words, he claims that it takes light about three hundred thousands of years to cross from one side to the other of the space occupied by the 3,000,000,000 stars of which our sun is the nearest one. He holds the spiral nebulae, those clam-shell-like cloudy luminous objects seen by great telescopes, to be inside our system.

Doctor Shapley's views will be followed by the discussion of Doctor Heber D. Curtis of the Lick Observatory, who will defend the older view that our Milky Way is approximately of the dimensions suggested by Newcomb, about 30,000 light-years in diameter, with the spiral nebulae regarded as very probably individual galaxies of "island universes", like ours. Thus there may be a million other universes each having 3,000,000,000 stars. Inhabitants of these numerous universes would see our Milky Way as a spiral nebula. The lectures of these two learned astronomers will be followed by a general discussion open to the auditors present who are interested in the development of this new advance in scientific research.

5. **1920 - The Great Debate**

Harlow **Shapley** (✗) and Heber **Curtis** (✓) debated the **extent of the Milky Way** and the nature of nebulae, setting the stage for modern understanding of galaxies.

The Great Debate, 1920

E. E. Barnard, 1919

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:

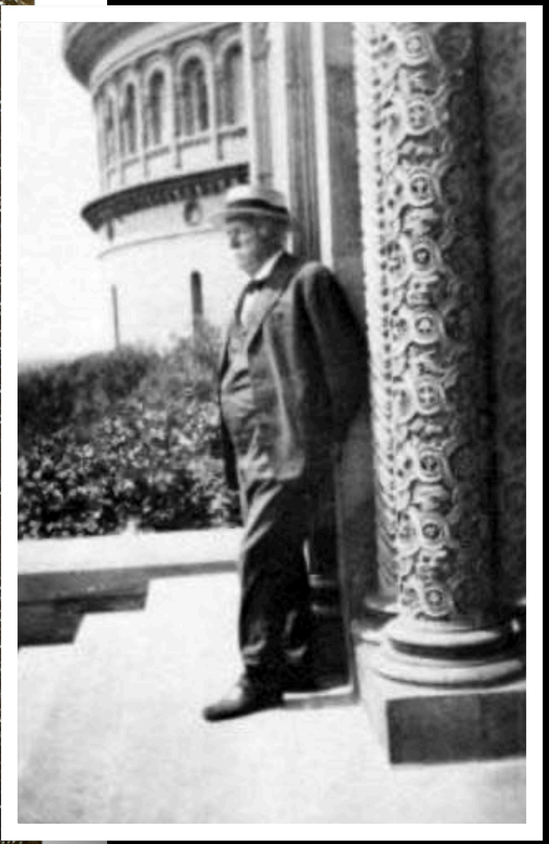
1. The photograph of the nebula about Nu Scorpii[1] which clearly shows partial and complete obscuration by the great wing-like nebula that covers much of the immediate region of Nu Scorpii and extends southward to the great nebula of Rho Ophiuchi.

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 II*a*, facing p. 10.

@Yerkes, 1920



MILKYWAY3D.org

Museum of Science

American Museum of Natural History

Center for Astrophysics Harvard & Smithsonian

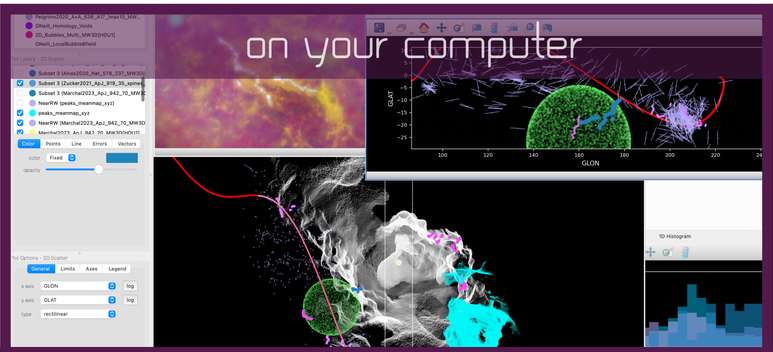
Smithsonian Institution

I2

Universität Heidelberg Zukunft seit 1386

universität wien

STScI Space Telescope Science Institute



Merge Cube view

CosmicDS

LIVE

Explore. Share. Discover. Learn. Your Milky Way. In 3D.

OpenSpace

glue multidimensional data exploration
glueviz.org

Seamless Sky Harvard College Observatory

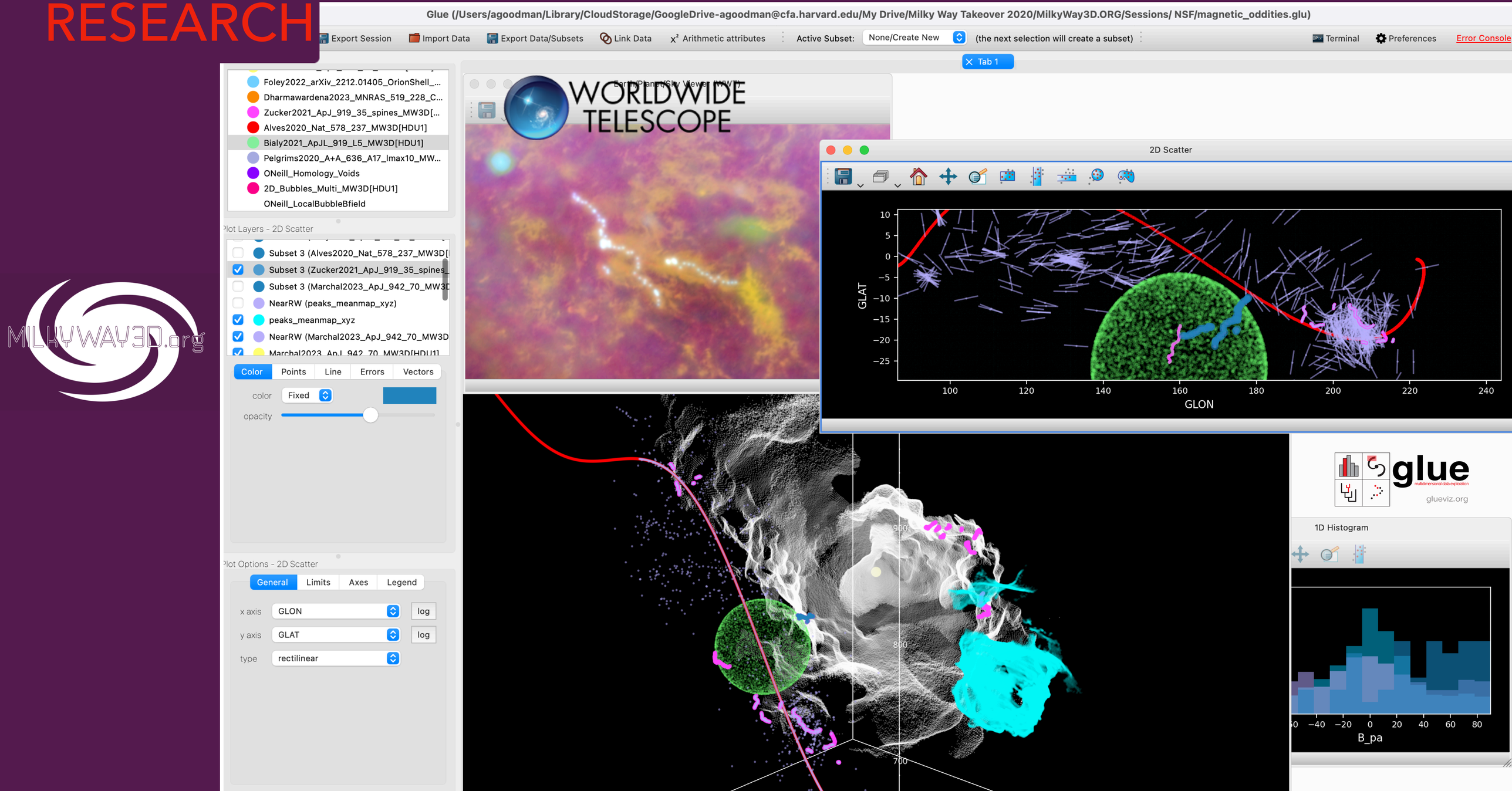
The Dataverse Project

Barbara A. Mikulski Archive for Space Telescopes

Digital Universe

WorldWide Telescope

RESEARCH


Glue (/Users/agoodman/Library/CloudStorage/GoogleDrive-agoodman@cfa.harvard.edu/My Drive/Milky Way Takeover 2020/MilkyWay3D.ORG/Sessions/ NSF/magnetic_oddities.glu)
Export Session
Import Data
Export Data/Subsets
Link Data
Arithmetic attributes
Active Subset:
None/Create New
(the next selection will create a subset)
Terminal
Preferences
Error Console
Tab 1
Foley2022_arXiv_2212.01405_OrionShell_...
Dharmawardena2023_MNRAS_519_228_C...
Zucker2021_ApJ_919_35_spines_MW3D[...
Alves2020_Nat_578_237_MW3D[HDU1]
Bialy2021_ApJL_919_L5_MW3D[HDU1]
Pelgrims2020_A+A_636_A17_lmax10_MW...
ONeill_Homology_Voids
2D_Bubbles_Multi_MW3D[HDU1]
ONeill_LocalBubbleBfield
Plot Layers - 2D Scatter
Subset 3 (Alves2020_Nat_578_237_MW3D[
Subset 3 (Zucker2021_ApJ_919_35_spines_
Subset 3 (Marchal2023_ApJ_942_70_MW3D
NearRW (peaks_meanmap_xyz)
peaks_meanmap_xyz
NearRW (Marchal2023_ApJ_942_70_MW3D
Color
Points
Line
Errors
Vectors
color
Fixed
opacity
Plot Options - 2D Scatter
General
Limits
Axes
Legend
x axis
GLON
log
y axis
GLAT
log
type
rectilinear
WORLDWIDE TELESCOPE
2D Scatter
GLAT
GLON
glue
multidimensional data exploration
glueviz.org
1D Histogram
B_pa

RESEARCH

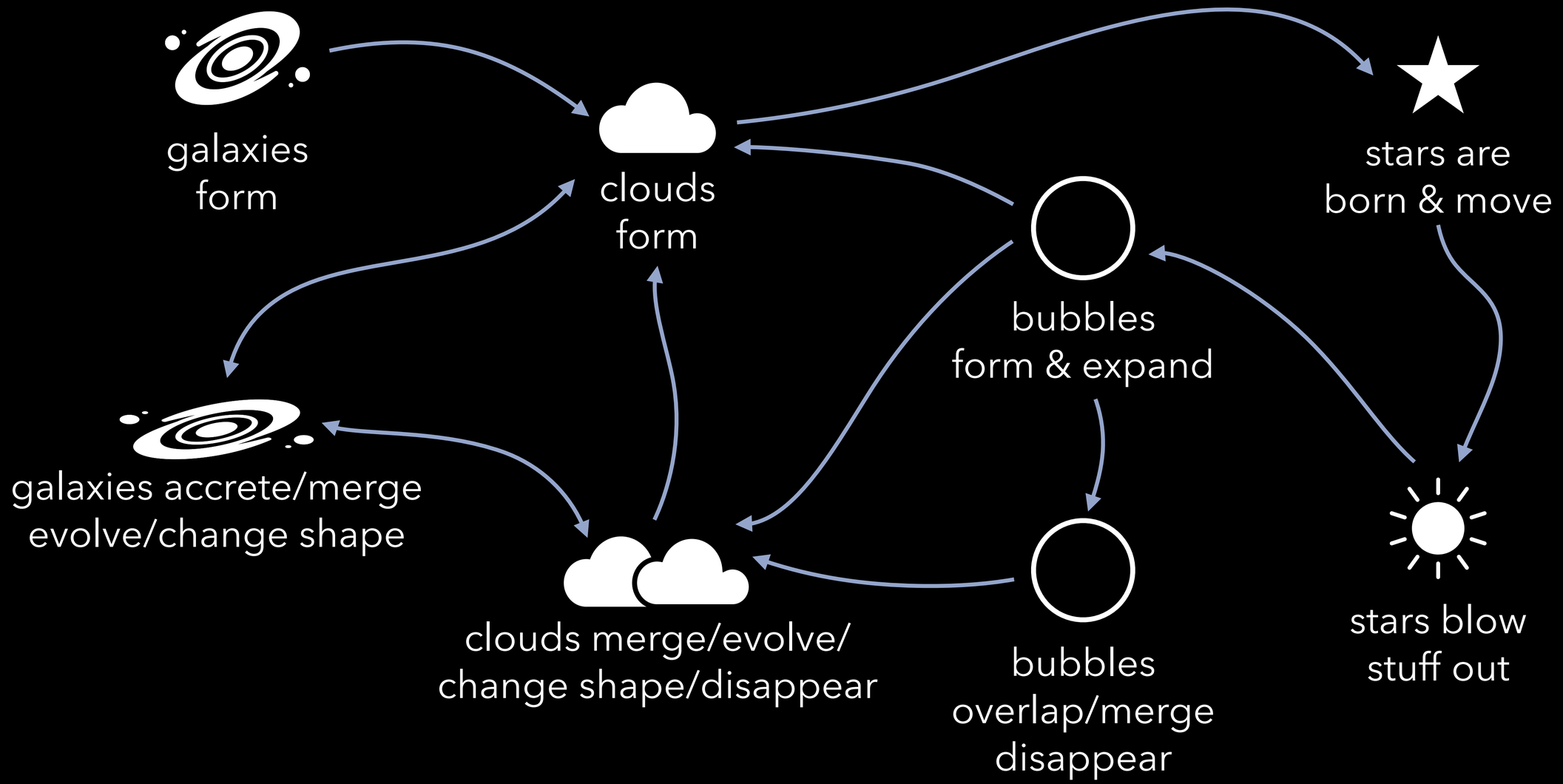
"Everything, Everywhere, All at Once"

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!)

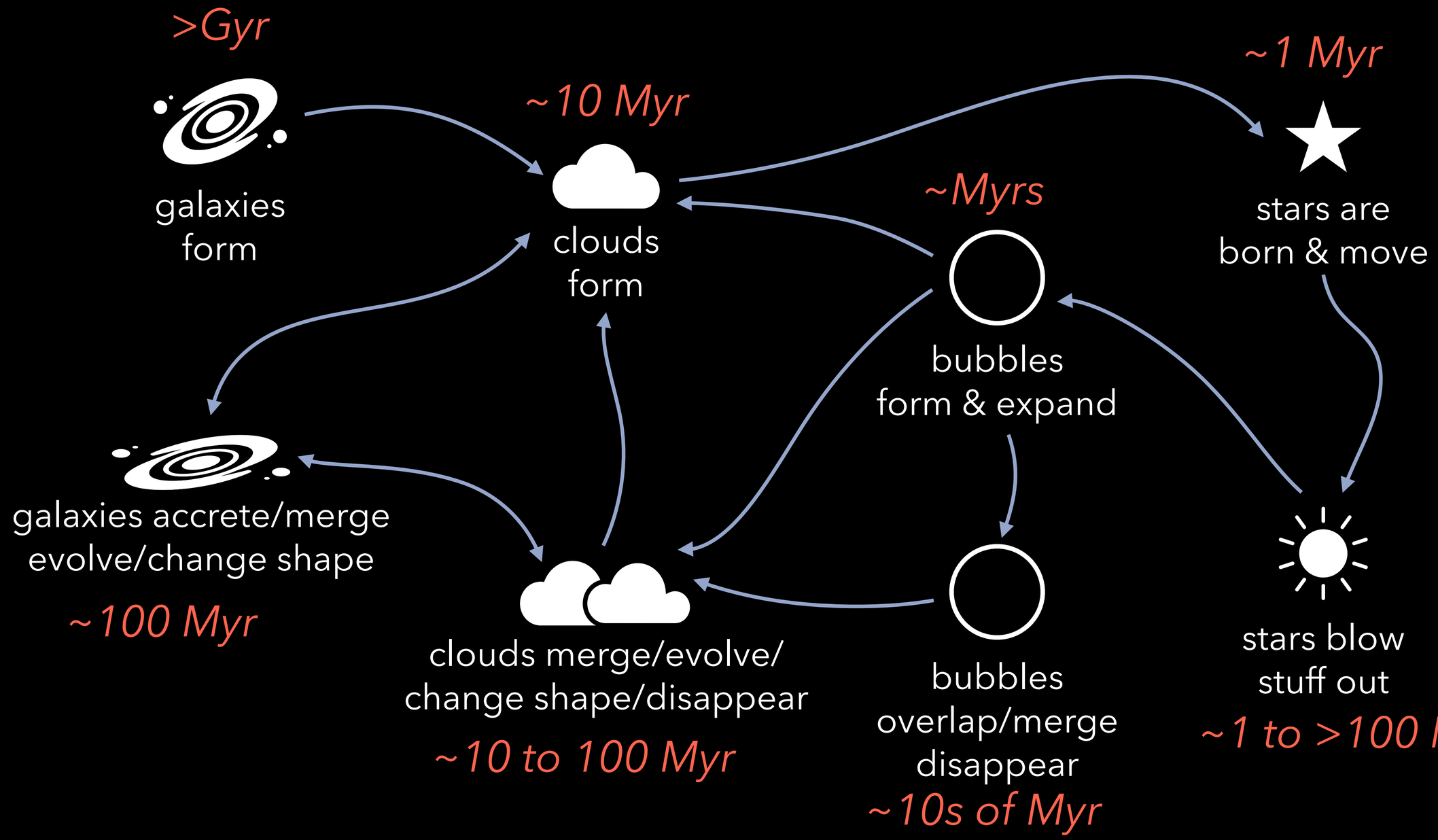
MOVIE

Nothing stays still. Nothing lasts forever.

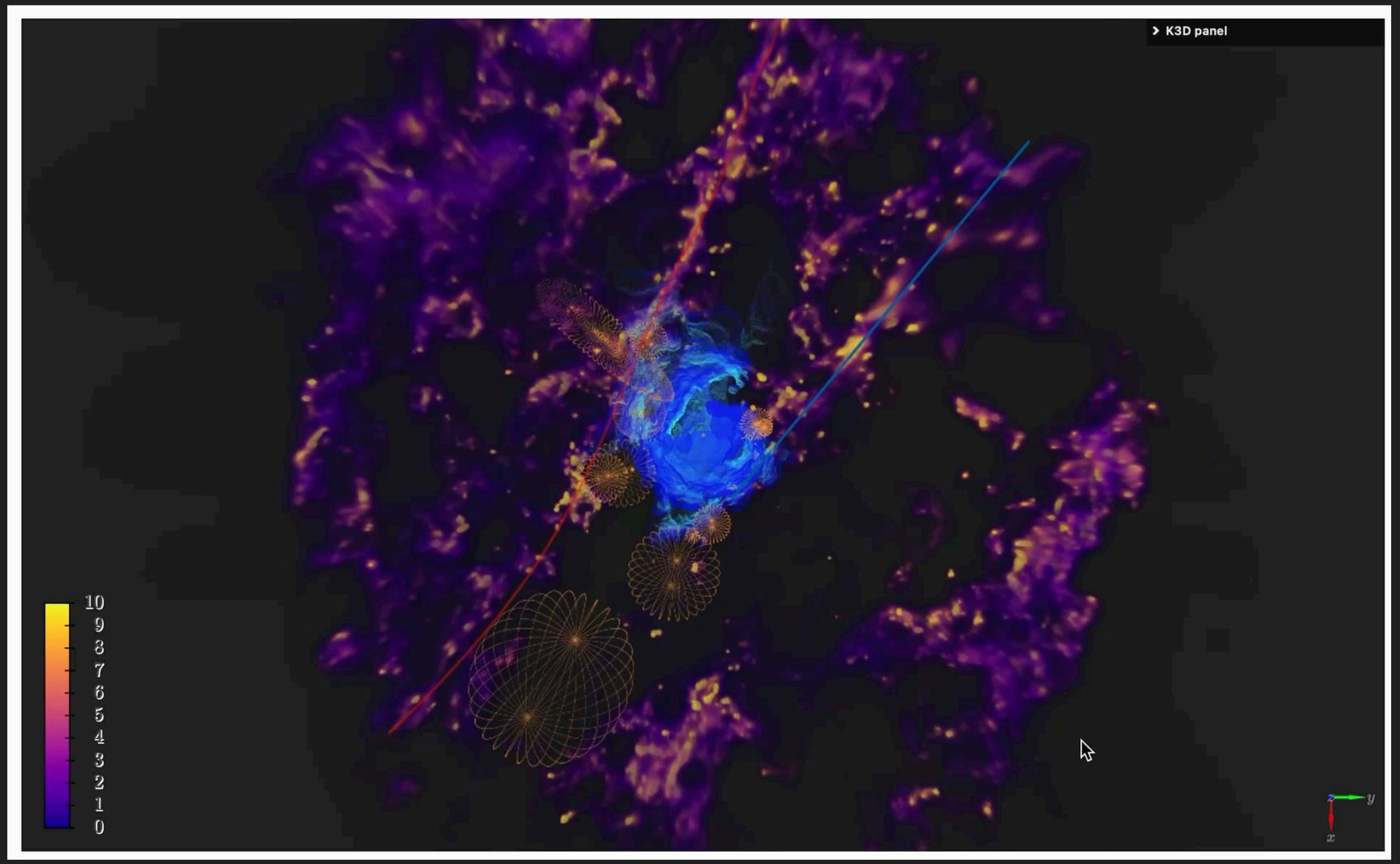
"Everything, Everywhere, All at Once"



"Everything, Everywhere, All at Once"

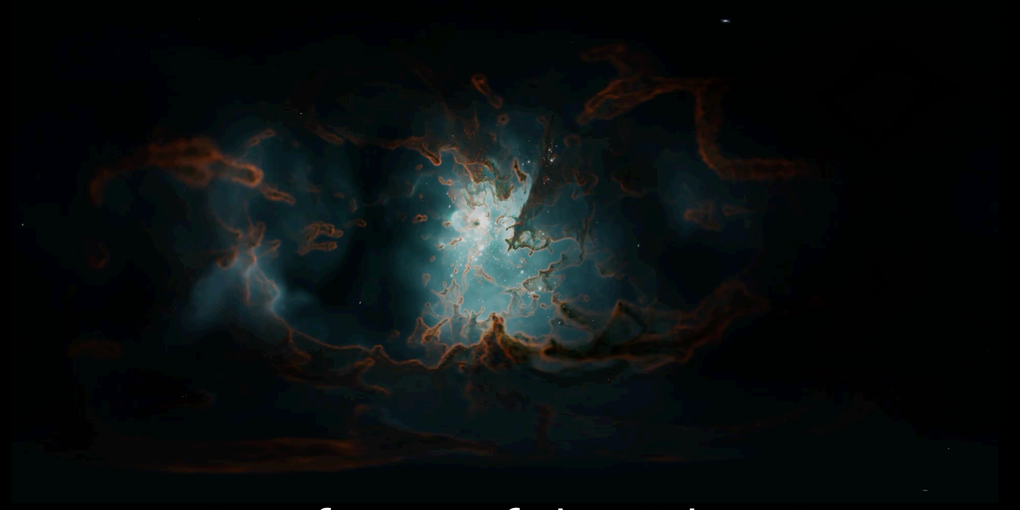


“Everything, Everywhere, All at Once”



from O’Neill et al. 2024 “The Local Bubble is a Local Chimney"

Starforge (theory-world)



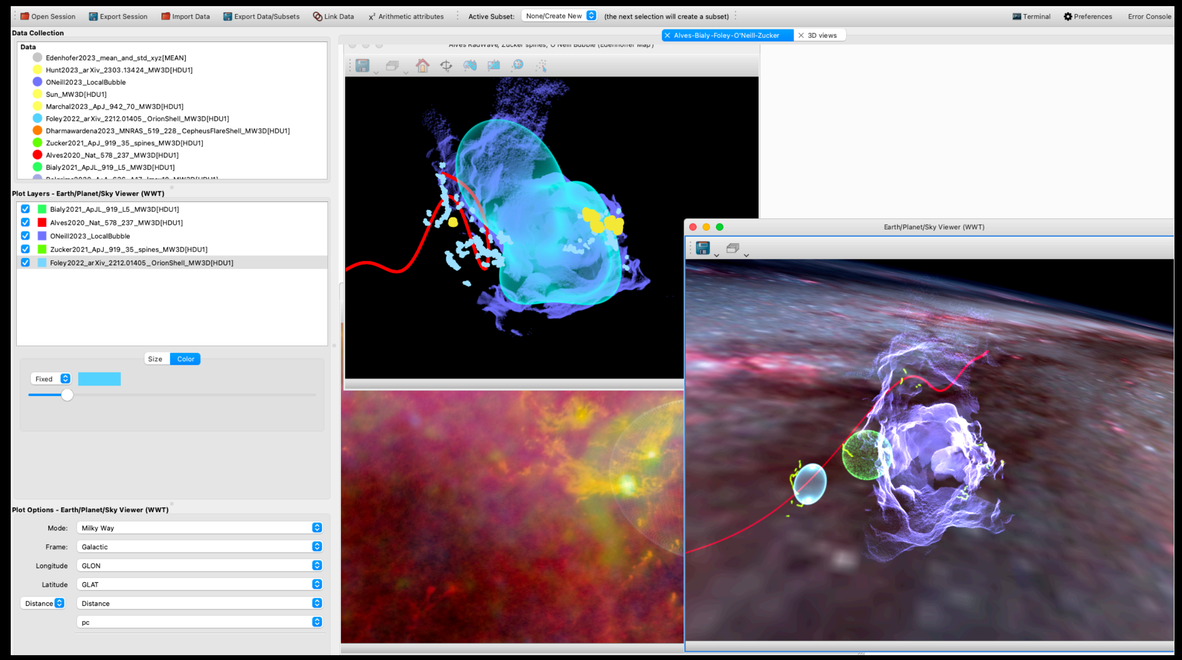
Starforge, fake “data”

RESEARCH

Deducing a 3D movie of

“Everything, Everywhere, All at Once,”

from snapshot measurements of the star-forming Milky Way, using physical simulations to guide us.



glue-ing together the story (real data)

RESEARCH

on your computer

Glue (/Users/agoodman/Library/CloudStorage/GoogleDrive-agoodman@cfa.harvard.edu/My Drive/Milky Way Takeover 2020/MilkyWay3D.ORG/Sessions/ NSF/magnetic_oddities.glu)

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

Tab 1

Foley2022_arXiv_2212.01405_OrionShell_...
Dharmawardena2023_MNRAS_519_228_C...
Zucker2021_ApJ_919_35_spines_MW3D[...
Alves2020_Nat_578_237_MW3D[HDU1]
Bialy2021_ApJL_919_L5_MW3D[HDU1]
Pelgrims2020_A+A_636_A17_lmax10_MW...
ONeill_Homology_Voids
2D_Bubbles_Multi_MW3D[HDU1]
ONeill_LocalBubbleBfield

Plot Layers - 2D Scatter

Subset 3 (Alves2020_Nat_578_237_MW3D[
Subset 3 (Zucker2021_ApJ_919_35_spines_
Subset 3 (Marchal2023_ApJ_942_70_MW3D
NearRW (peaks_meanmap_xyz)
peaks_meanmap_xyz
NearRW (Marchal2023_ApJ_942_70_MW3D
Marchal2023_ApJ_942_70_MW3D[HDU1]

Color | Points | Line | Errors | Vectors

color: Fixed

opacity

Plot Options - 2D Scatter

General | Limits | Axes | Legend

x axis: GLON log

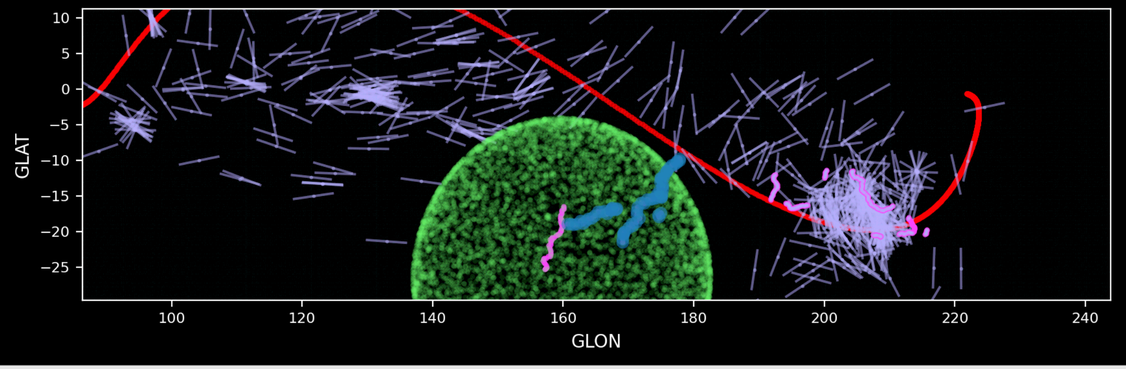
y axis: GLAT log

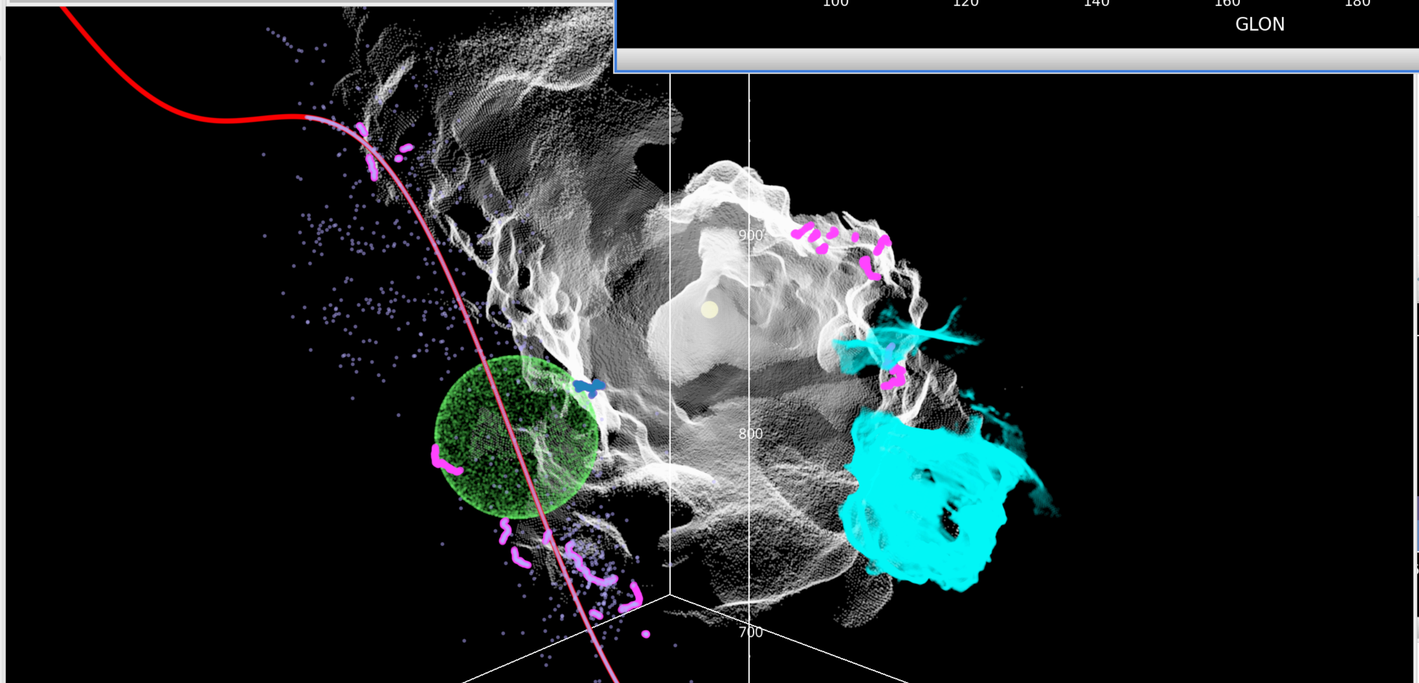
type: rectilinear

Earth/Planet/Sky Viewer (WWT)

WORLDWIDE TELESCOPE

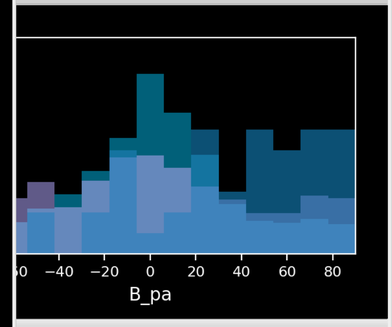
2D Scatter





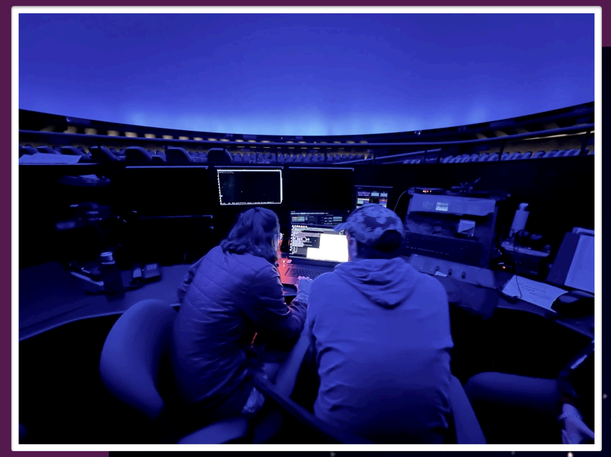
glue
multidimensional data exploration
glueviz.org

1D Histogram



in a planetarium

RESEARCH
+EDUCATION
+OUTREACH

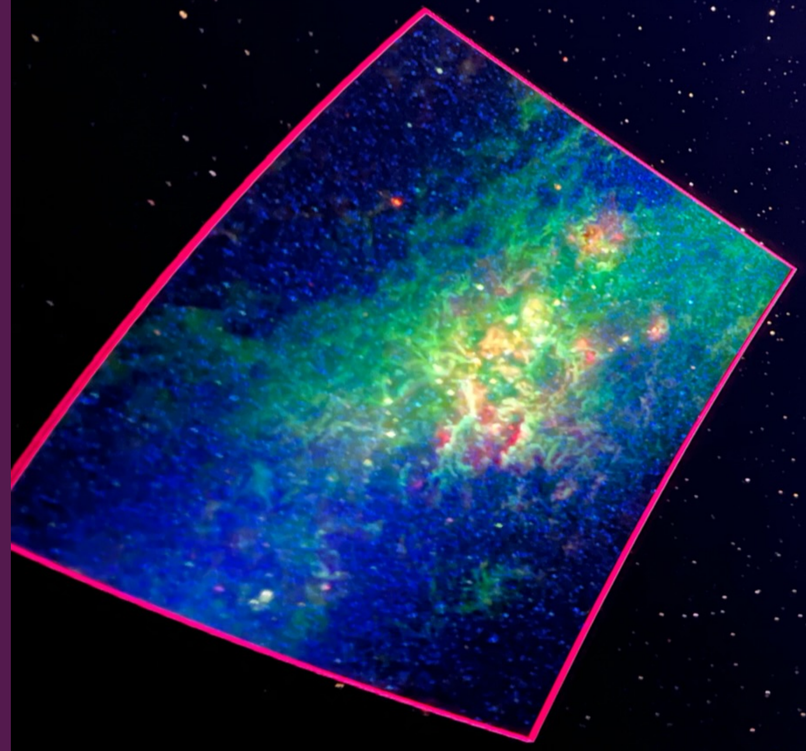


MILKYWAY3D.org

OpenSpace

glue
multidimensional data exploration

WORLDWIDE TELESCOPE



in a augmented reality, on your phone...

RESEARCH

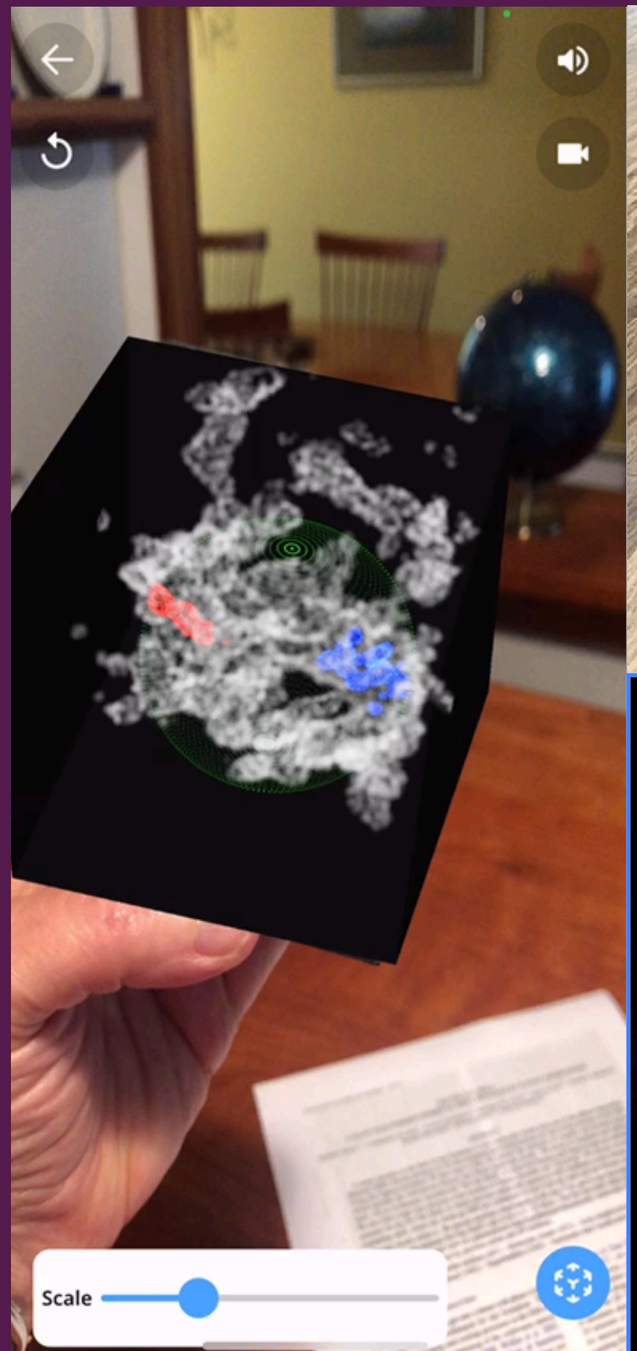
+OUTREACH

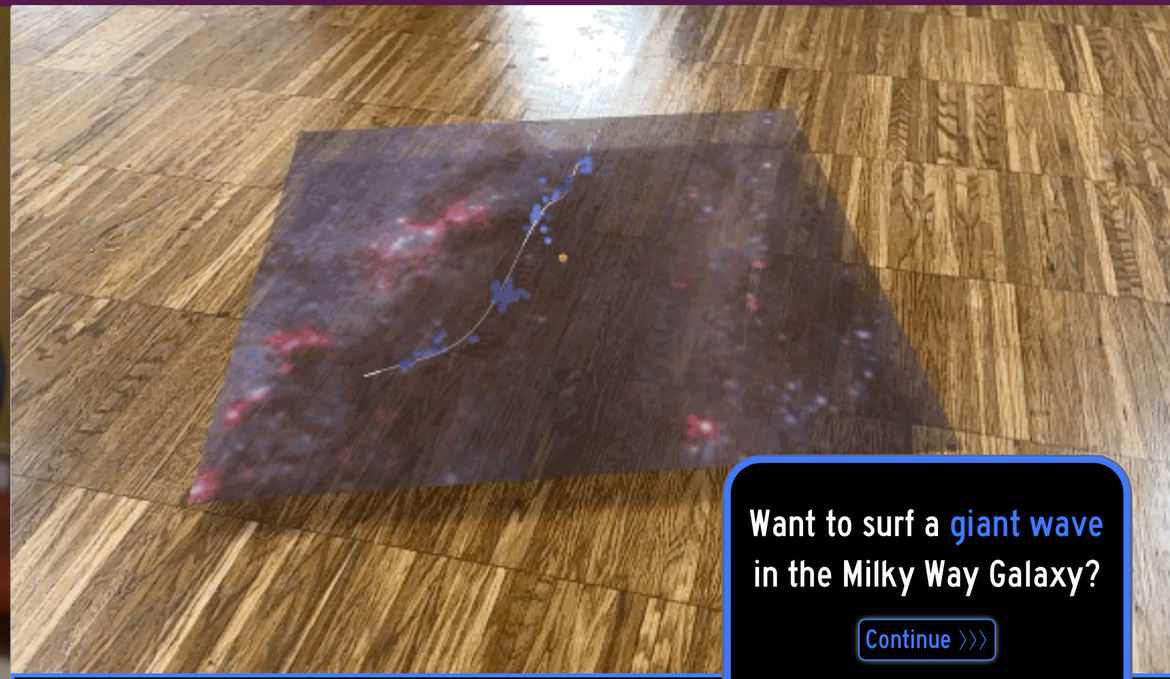
MILKYWAY3D.org

OpenSpace

glue
multidimensional data exploration

WORLDWIDE TELESCOPE

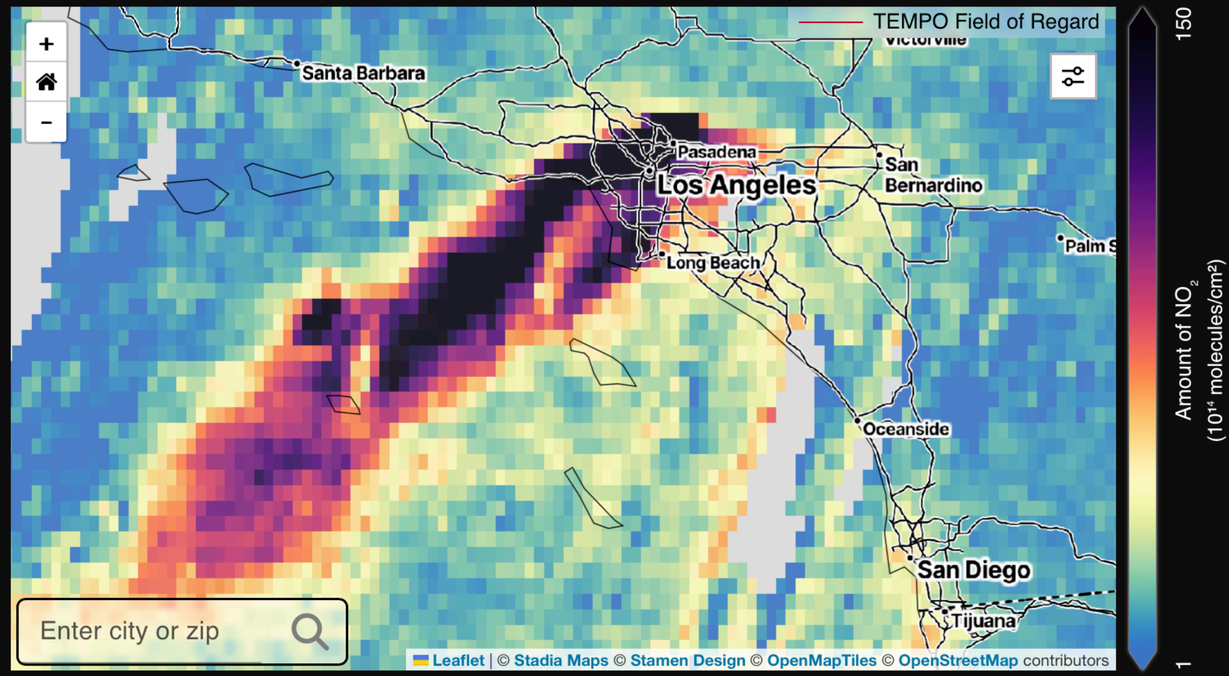




cosmicds.cfa.harvard.edu

Cosmic DS

What is in the Air You Breathe?



1/8/2025 2:51 PM

Select a Date

Wed Jan 08 2025

Data Loaded

Notable Dates

- LA Wildfires (Jan 8, 2025)
- March 28, 2024
- November 3, 2023
- November 1, 2023

Featured Events for Jan 8

- Los Angeles Wildfires

Timezone
Eastern Standard

TEMPO NO_2 Data

TEMPO, a collaboration between the Smithsonian and NASA, is the first space-based probe to measure air pollution hourly over North America at neighborhood scales. NO_2 (nitrogen dioxide) is one of the pollutants detected by TEMPO. It is produced by wildfires and the burning of fossil fuels. NO_2 contributes to the formation of harmful ground-level ozone and toxic particulates in the air we breathe.

MMMM, SORRY

DELICIOUSLY DISTRACTING

EXPLORE

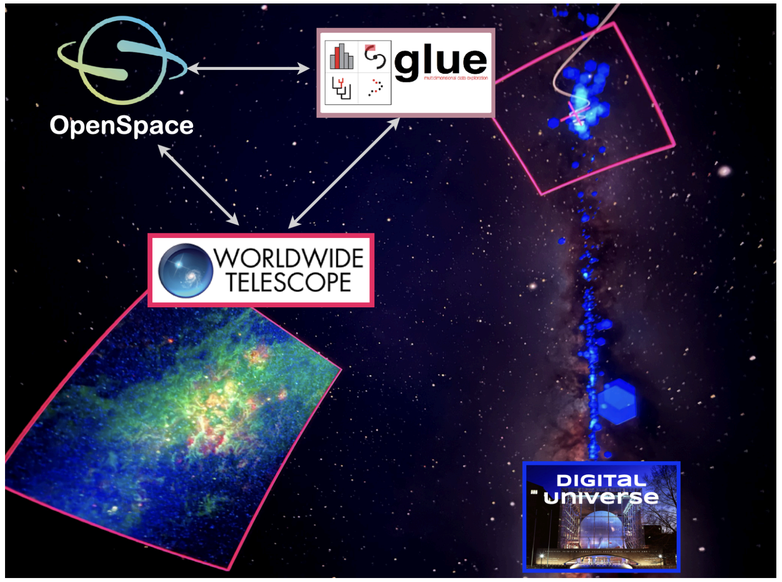
—extra slides—

Planetarium DataViz: OpenSpace, glue and WWT working together

handout, 2/4/2025, Boston Museum of Science: online tinyurl.com/mos-2-25-handout

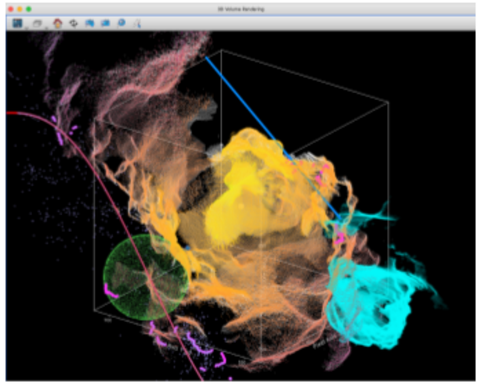
Handout++

Tonight, we will demonstrate how **OpenSpace**, **WorldWide Telescope**, and **glue**, work together to **enhance the visualization of complex data sets**. The integration of these three software packages offers an exceptionally broad range of visualization, discovery, and educational opportunities. In education, Cosmic Data Stories uses glue and WWT together in browser-based environments to teach data science using Astronomy and Earth Science data. The MilkyWay3D.org project, excerpts from which you will see tonight, is a community-based effort to share everything we know and learn about the local Milky Way, to facilitate research, visualization, and outreach efforts simultaneously.

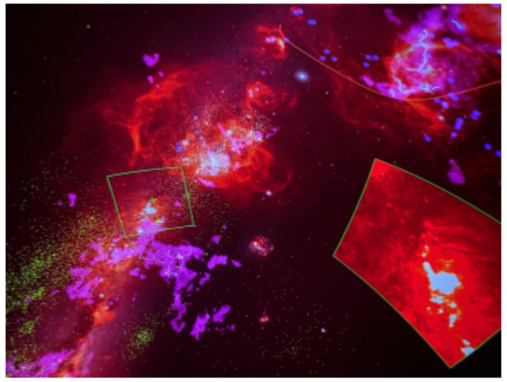


An example from MilkyWay3.org: In the image above, an inset WorldWide Telescope (WWT) view (framed in pink) shows a Spitzer image of the region marked by the pink cross in the center of the frame to the upper right. At right, extending vertically, one can see the Galactic plane, projected on the AMNH Hayden Planetarium dome, with blue hexagons displaying a catalog of HII regions available in OpenSpace thanks to Digital Universe. The model for the Radcliffe Wave is shown as a light pink wavy line at upper right is coming from the glue plug-in to OpenSpace. (Note that WWT 2D views like the one shown are only relevant when the Universe is viewed in OpenSpace in "3D" from near Earth.)

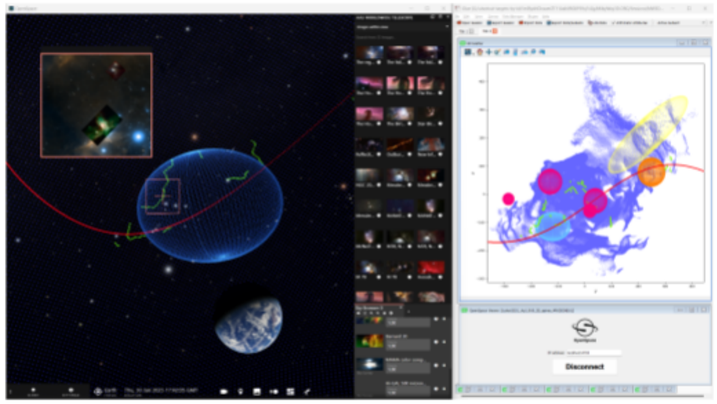
For more information on integrated visualization tools, visit LIVE-Astro.org



glue viewer with multiple datasets from the MilkyWay3D, ready to be viewed in OpenSpace



OpenSpace in the AMNH Hayden Planetarium showing young stars, molecular clouds, with a WorldWide Telescope view of the green-boxed area



A "console" view on a laptop, controlling OpenSpace, glue, and WWT simultaneously. Only visible to the planetarium operator.

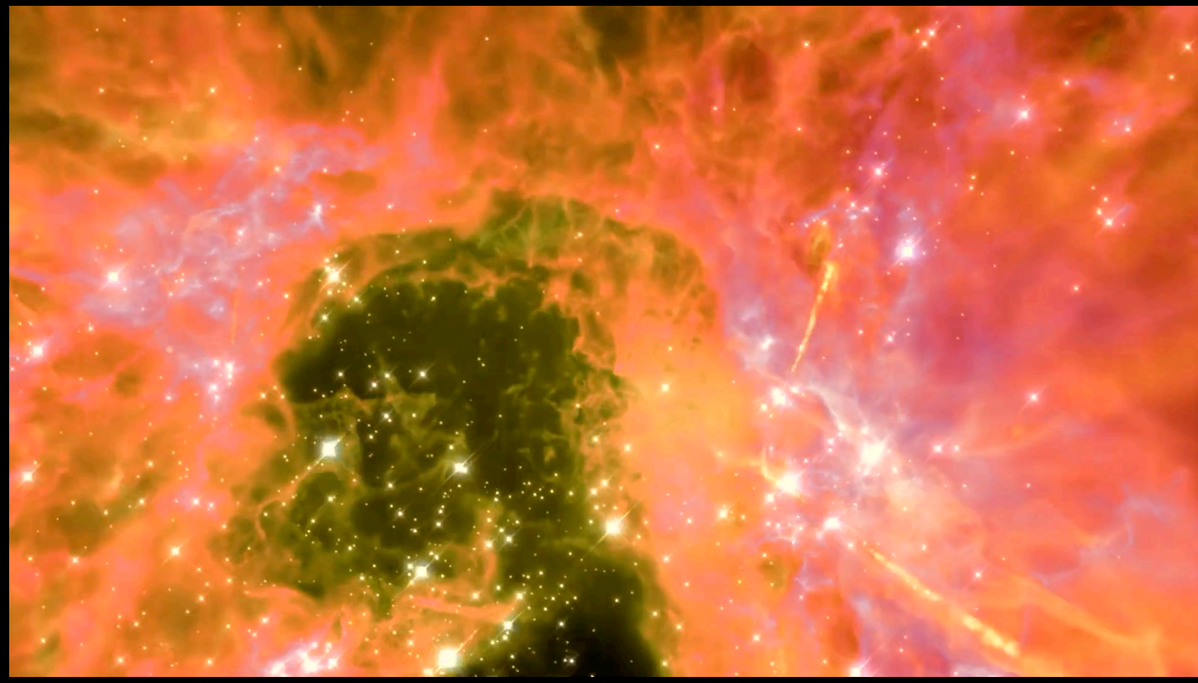
glue glueviz.org · WORLDWIDE TELESCOPE · OpenSpace · LIVE · CosmicDS · SEAMLESS ASTRONOMY

Museum of Science · CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN · AMERICAN MUSEUM OF NATURAL HISTORY · NASA · NSF

For more information on integrated visualization tools, visit LIVE-Astro.org

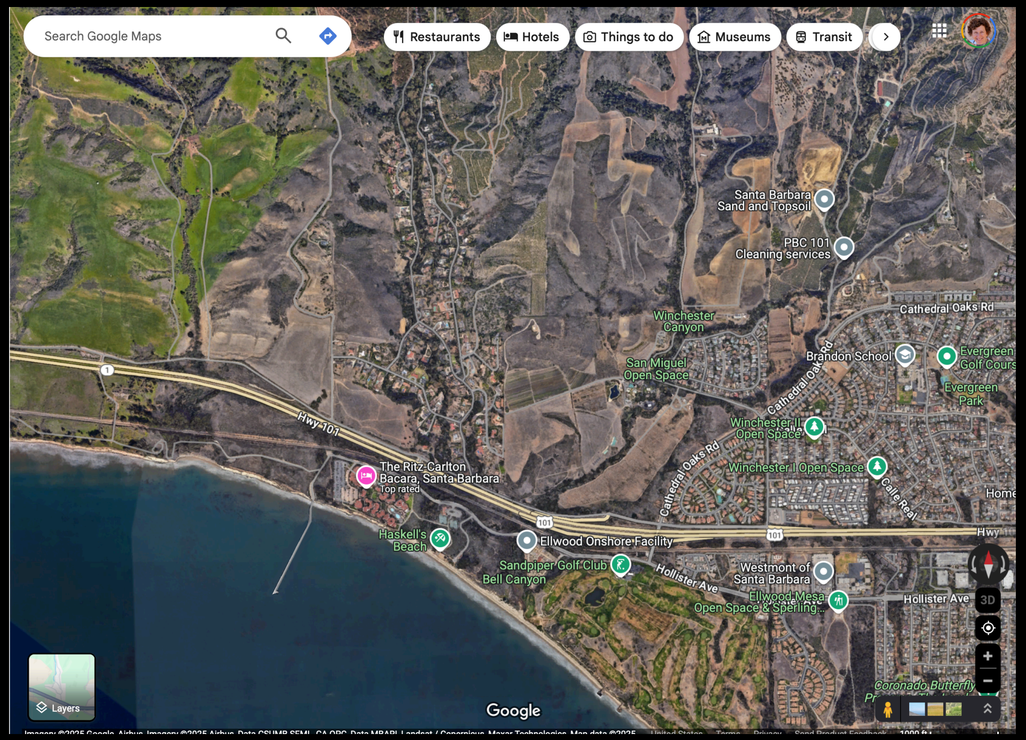
Nessie Bones Skeleton Perseus RadWave PerTau LB Barnard++

Simulating *"Everything, Everywhere, All at Once"?*



SimCity 2000, re:decades

Starforge Simulations, re:>100 Myr

SimCity 2000

Satellite Image