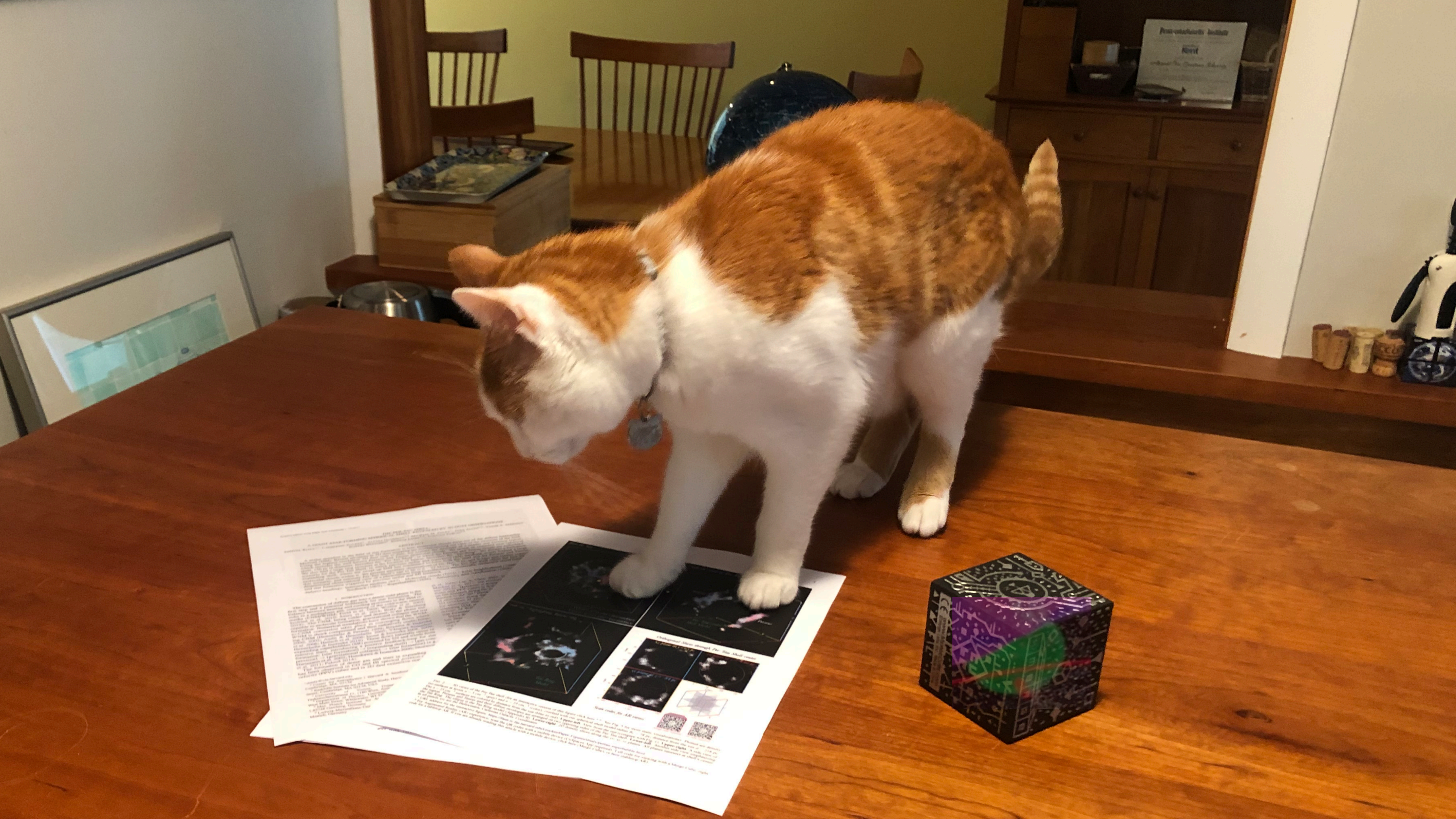


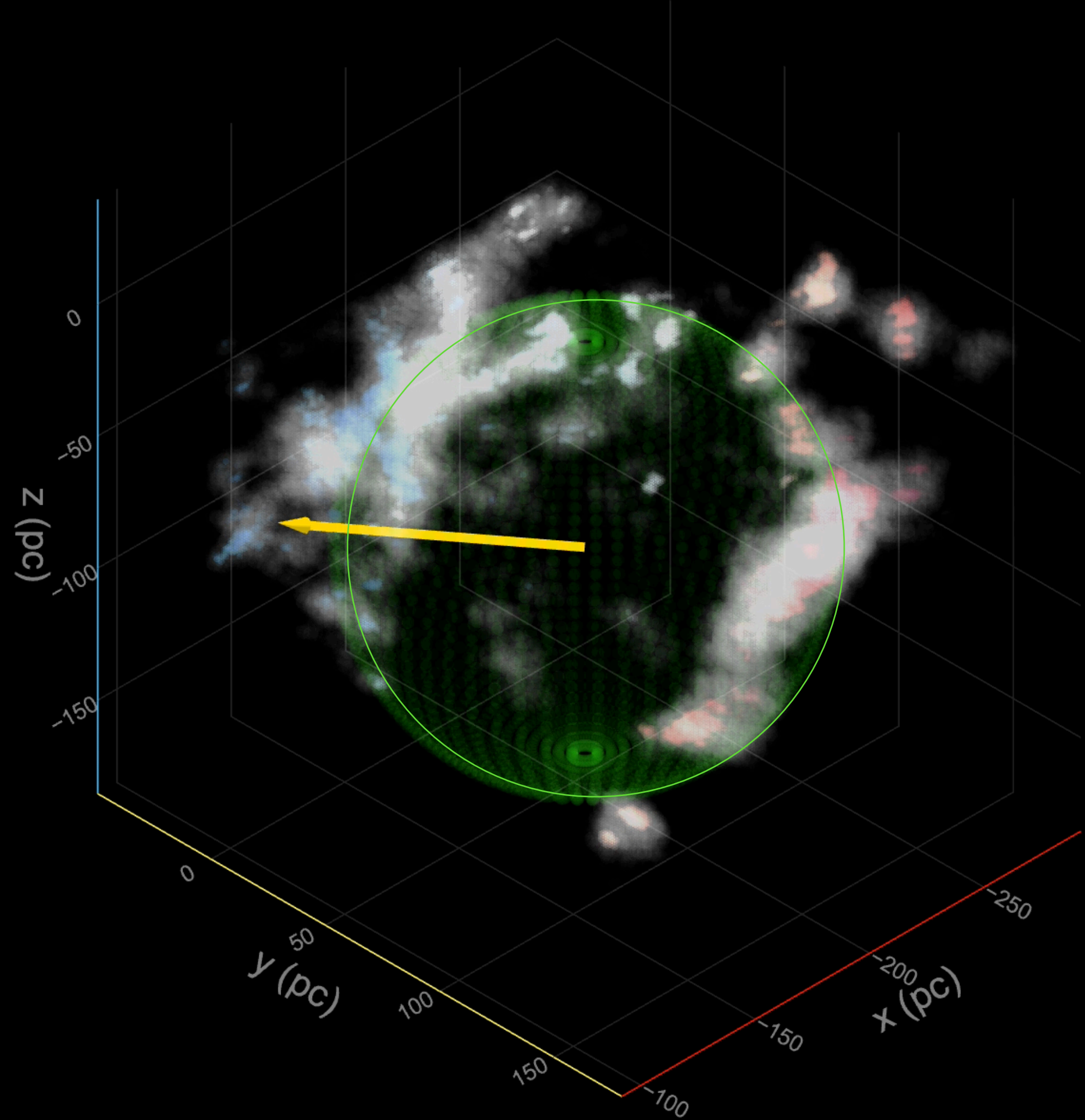


# Mapping the Milky Way Galaxy from the Inside Out

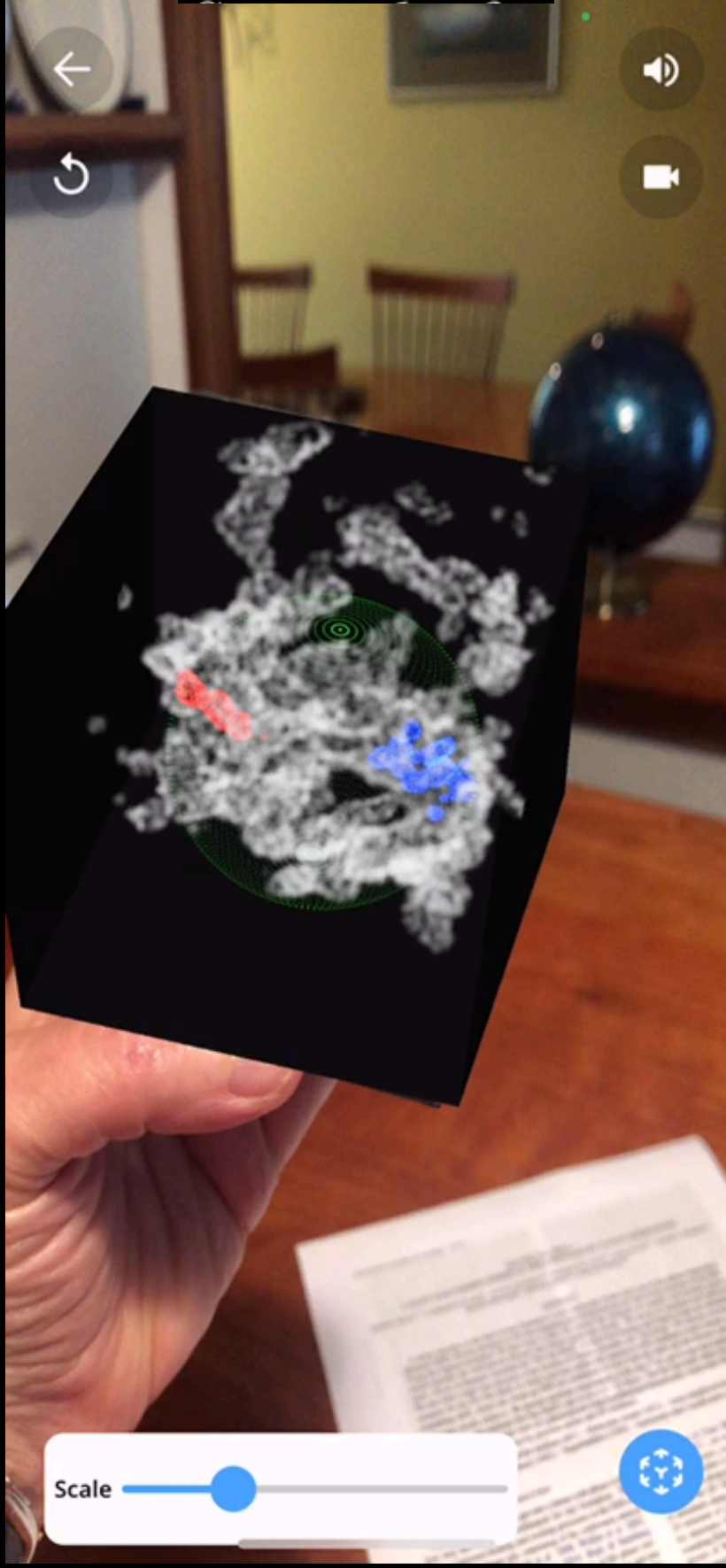
*Prof. Alyssa Goodman, Harvard/CfA, the MilkyWay3D.org team + OpenAI*



# 2021 "PERSEUS-TAURUS SUPERSHELL"



[TINYURL.COM/UNIVERSE-IN-MY-HAND](https://tinyurl.com/universe-in-my-hand)



AUGMENTED REALITY

# MILKYWAY3D.org



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

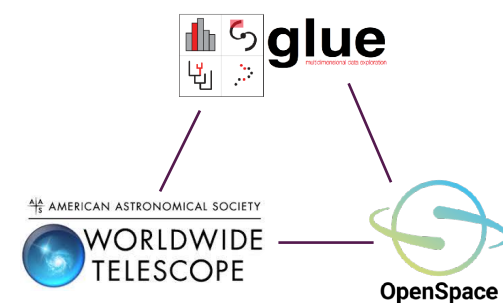
MilkyWay3D.org is an open-data open-source discovery hub, providing data, visualization, and research tools for studying the MilkyWay in 3D.

INFRASTRUCTURE ←

SCIENCE ←

→ EDUCATION & OUTREACH

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



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



making data accessible online for decades

Lead: Alyssa Goodman, CfA

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



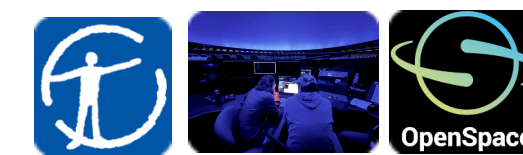
topology, positions & motions of (long) features



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

Lead: Catherine Zucker, CfA

connecting real research data,  
software, and science to learners

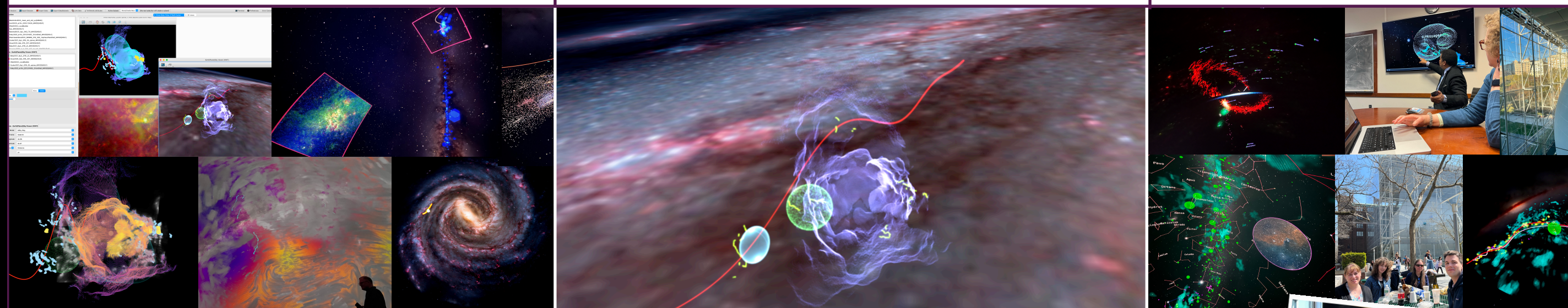


real-time data exploration  
anywhere, including in planetaria



“Cosmic Data Stories”  
teach data science using  
astronomical data & tools

Lead: Jackie Faherty, AMNH



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); Linköping University (Alex Bock); University of Vienna (Joao Alves, Sebastian Rattenböck); 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.

TODAY



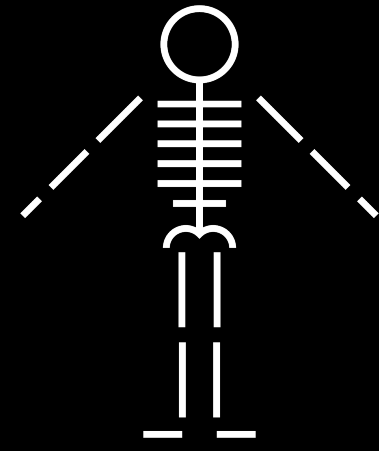
2 MilkyWay3D.org founders wearing the colors (grad student Theo O'Neill & AMNH's Dr. Jackie Faherty, at the Flatiron Institute, NYC, Fall 2023)



2010



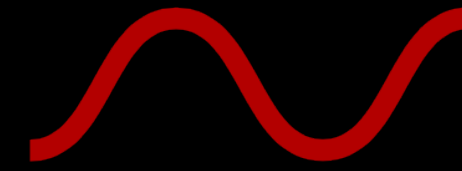
2014



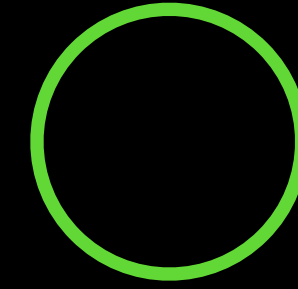
2015



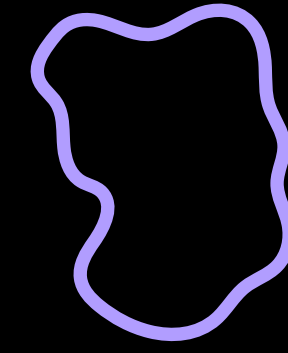
2018



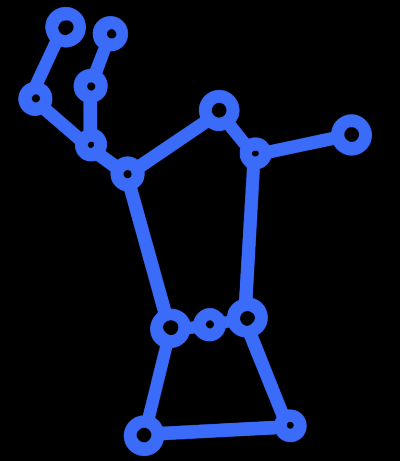
2020  
2024



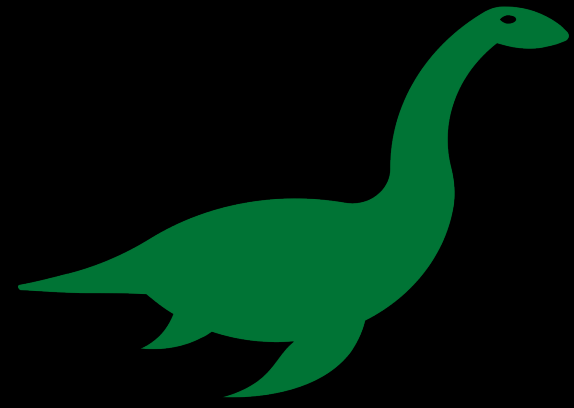
2021



2022  
2024



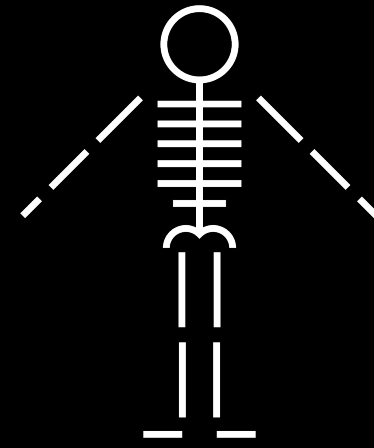
2022



Nessie



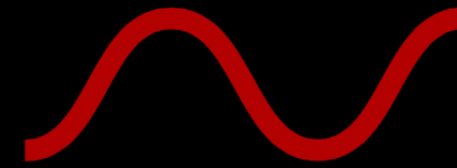
Bones



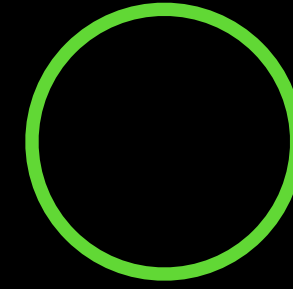
Skeleton



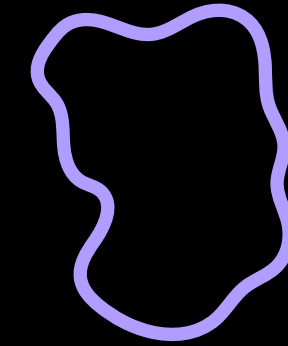
Perseus



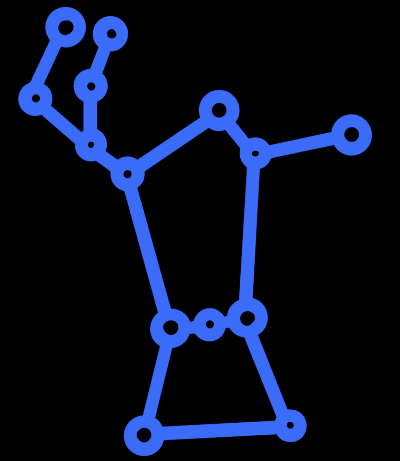
RadWave



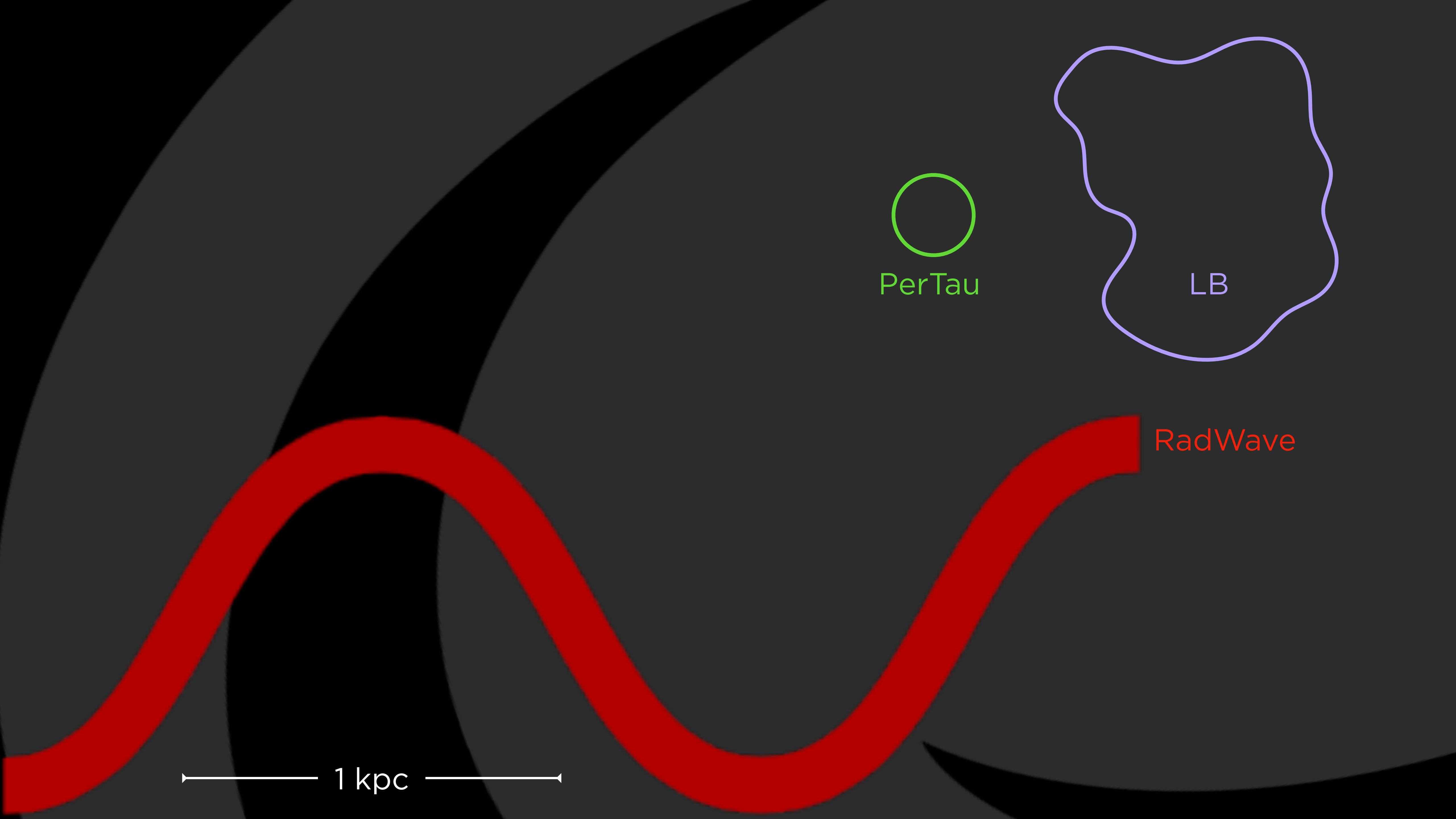
PerTau



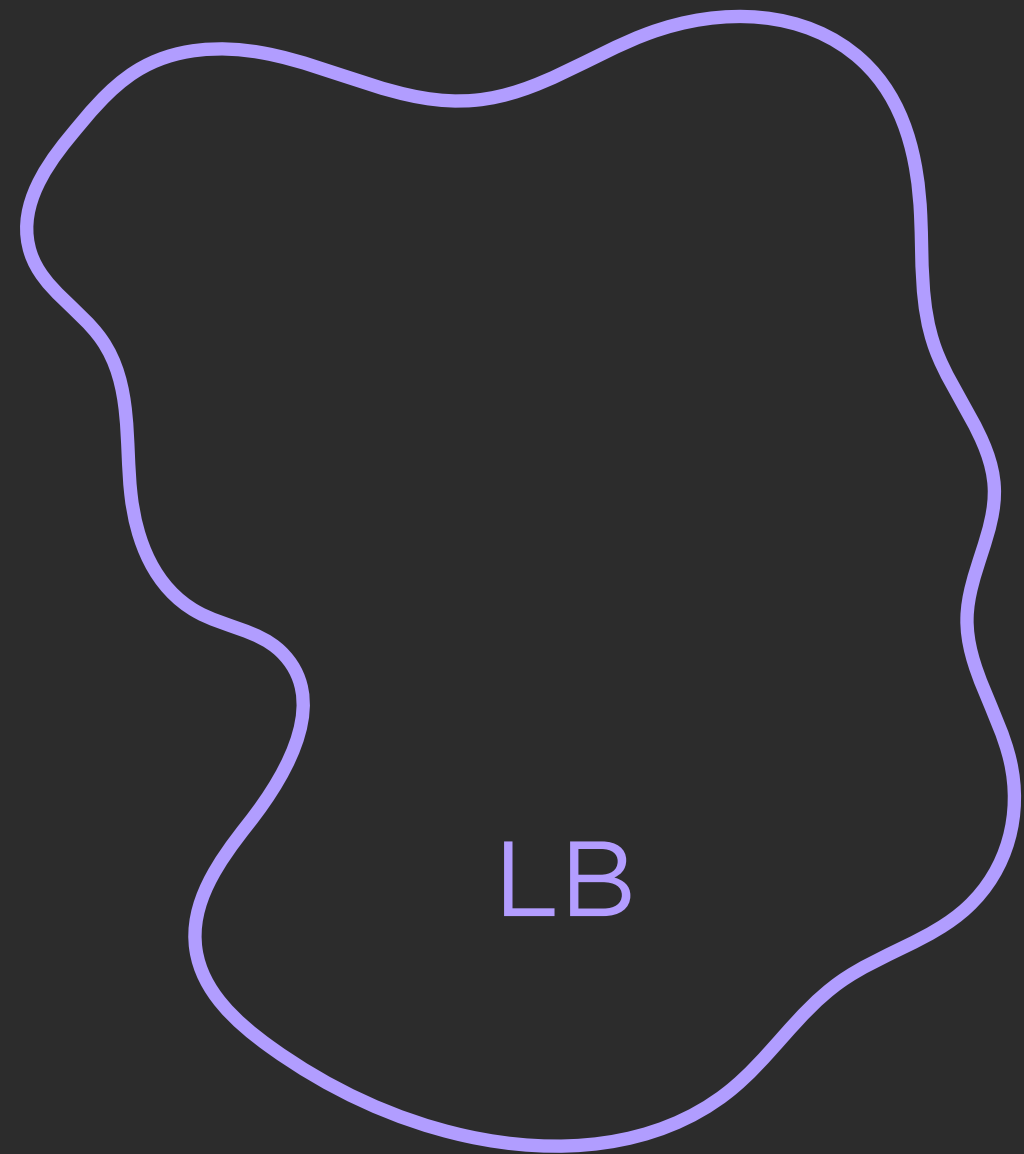
LB



Barnard++



PerTau



LB

RadWave



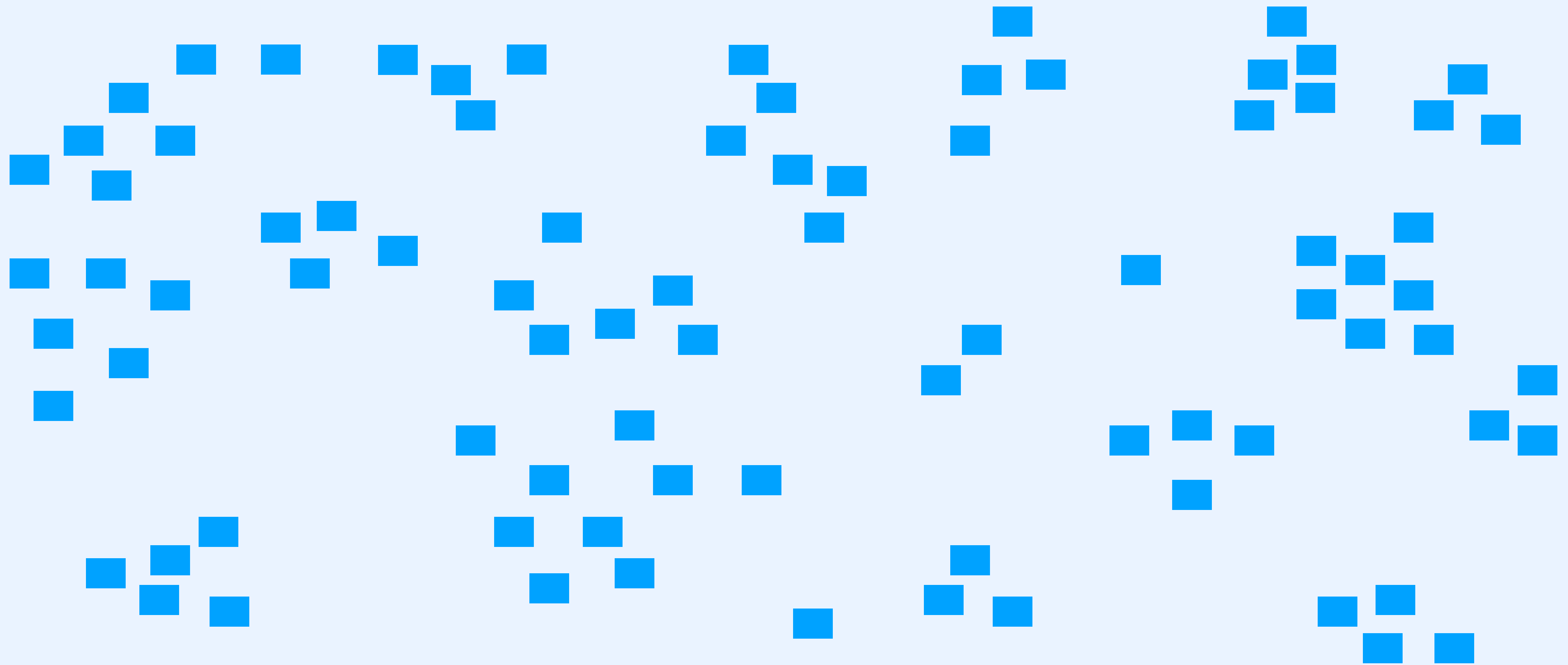
1 kpc

WHERE ARE WE?

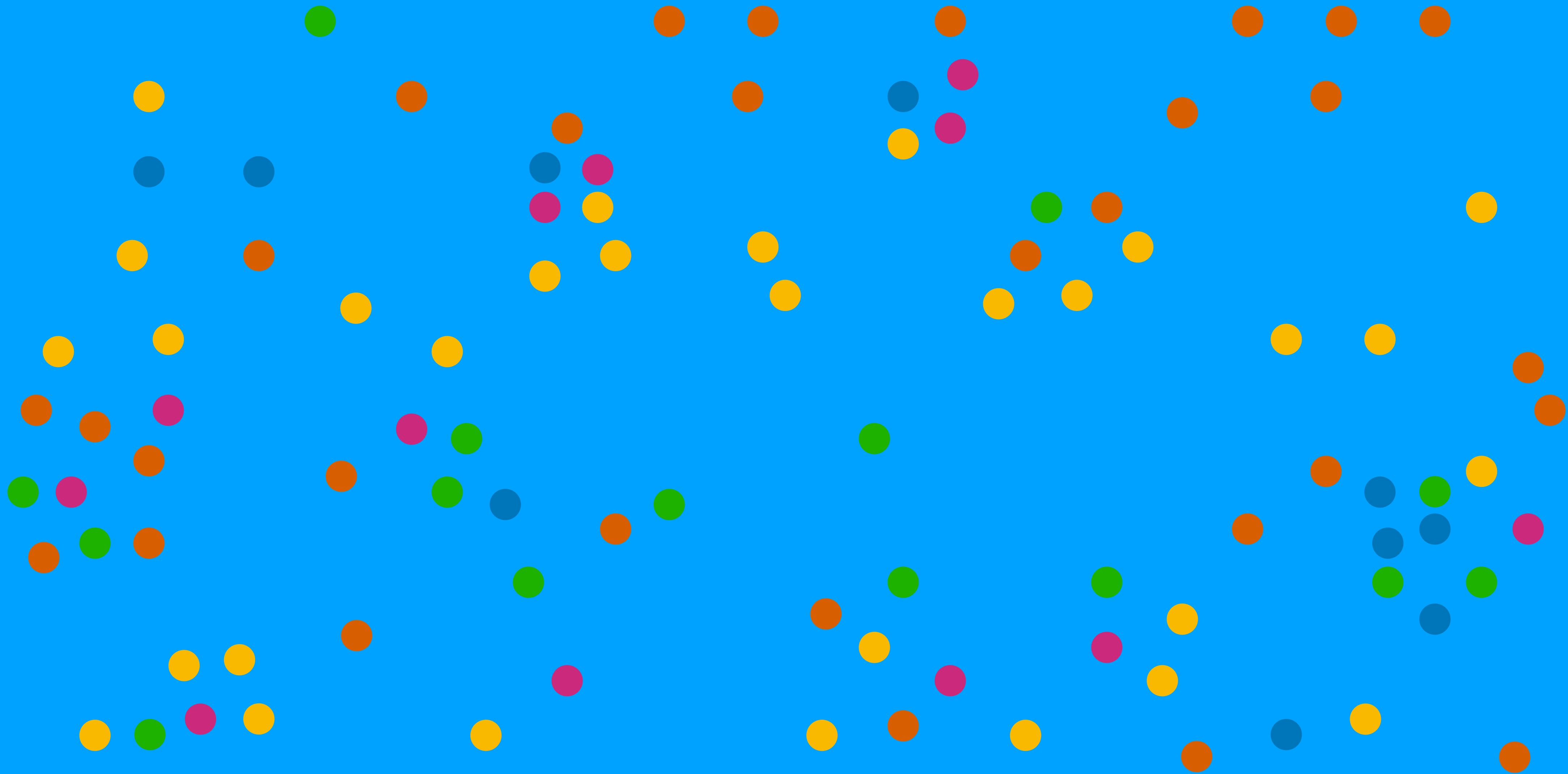


WHERE ARE WE?

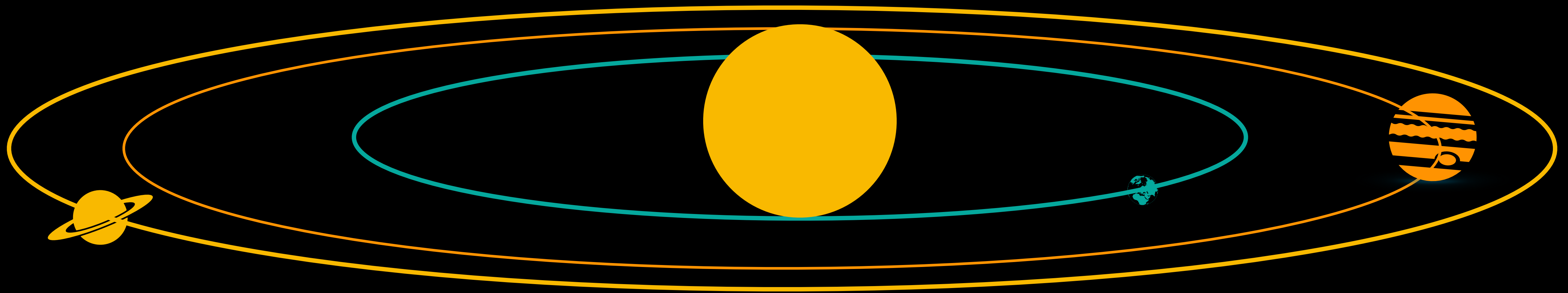
# WHERE ARE WE?



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



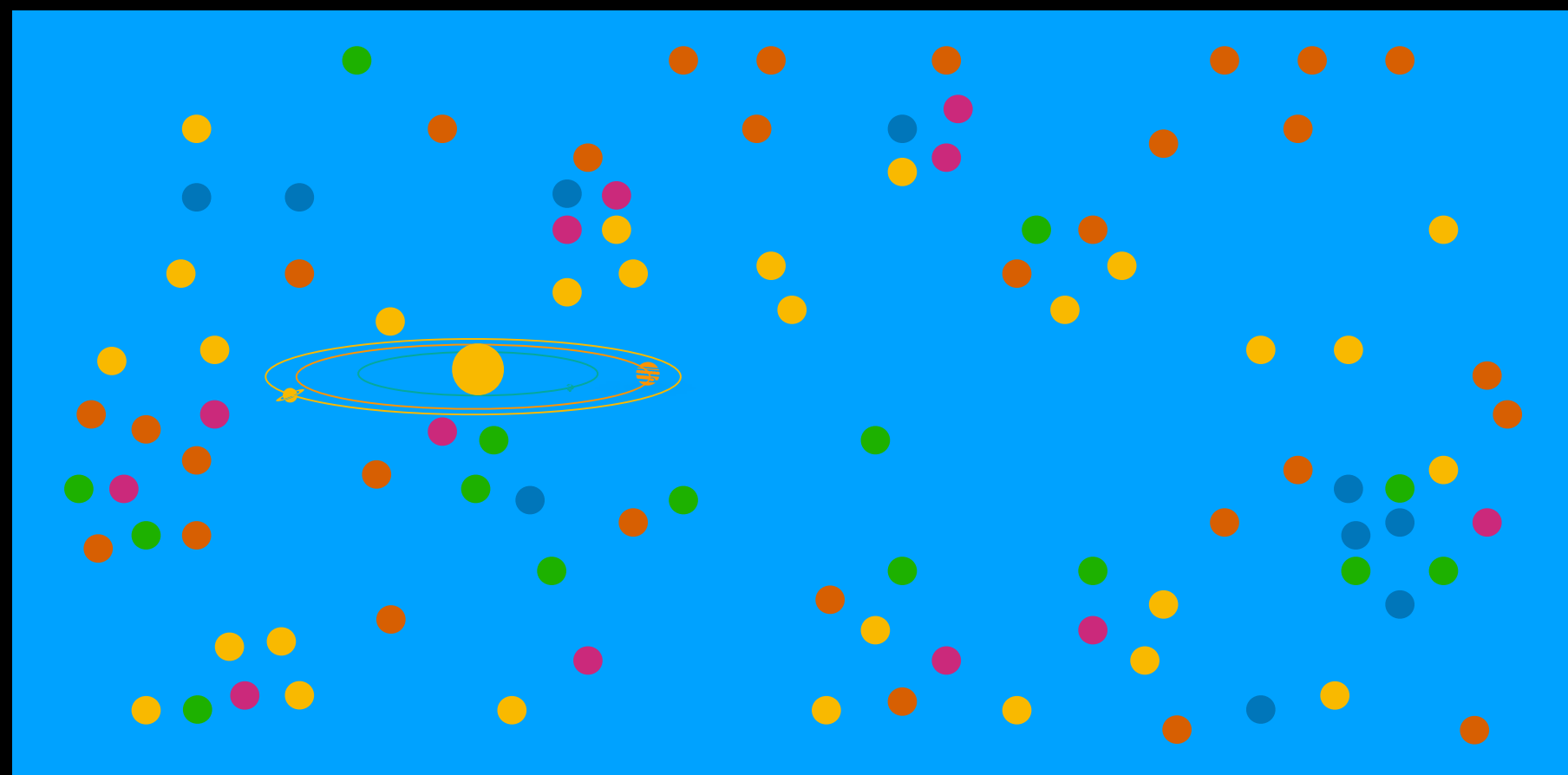
ours is called "The Milky Way" and it contains about 1 hundred billion stars



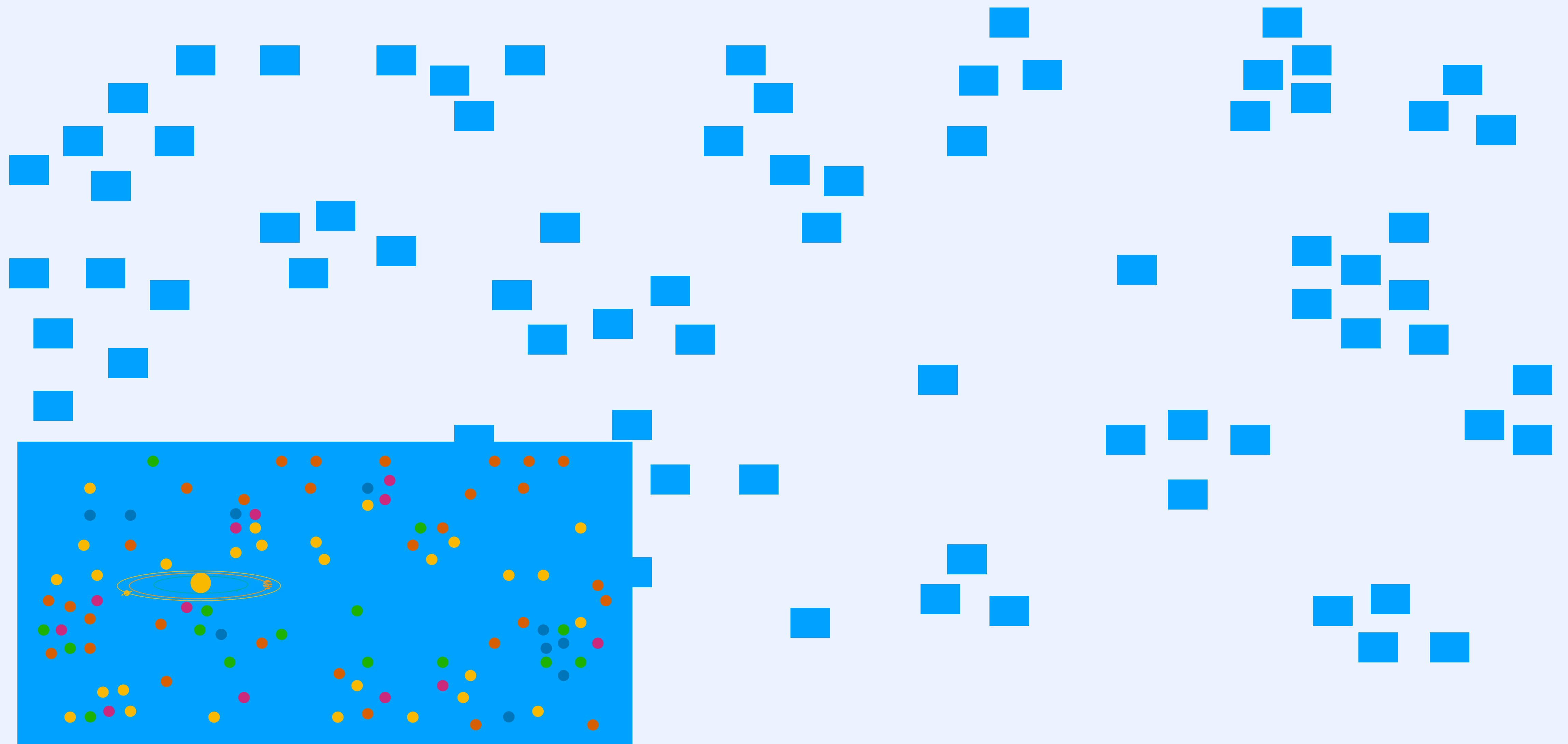
around most of the stars are systems of planets (ours is called "**The Solar System**")



our home planet is **Earth**

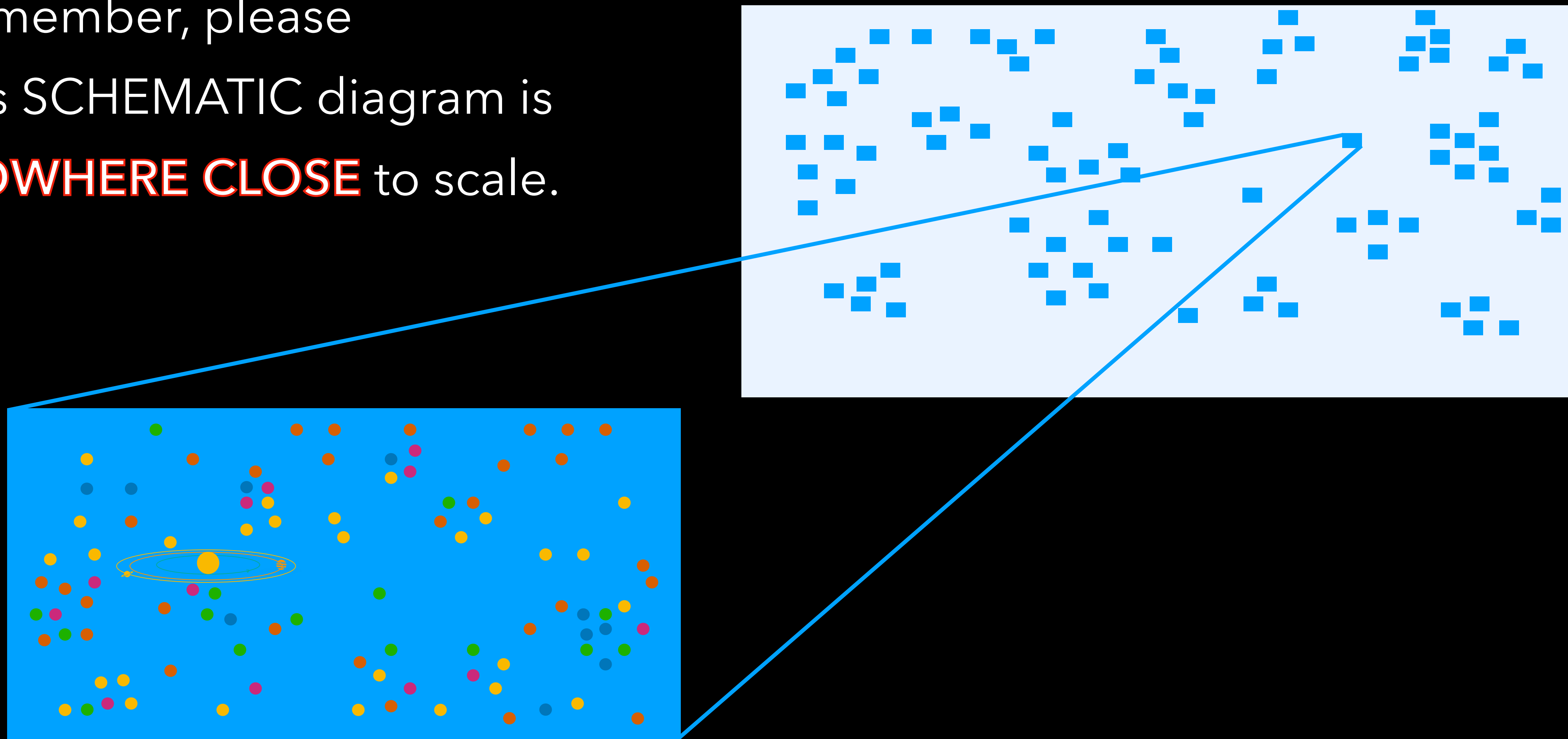


**Earth** resides in the **Solar System**, around the **Sun**, which is one of MANY **stars**,  
**INSIDE** the **Milky Way**,



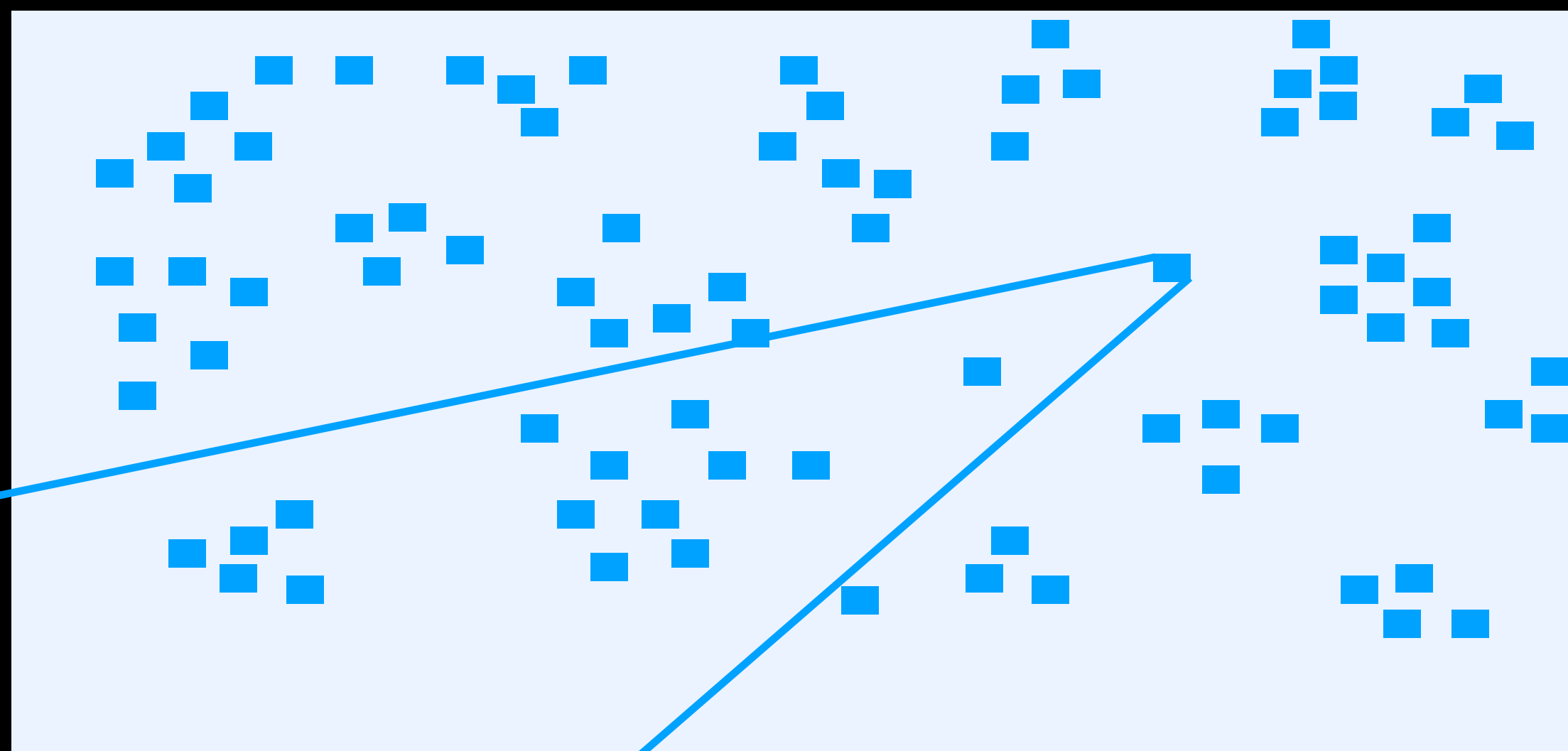
**Earth** resides in the **Solar System**, around the **Sun**, which is one of MANY **stars**,  
INSIDE the **Milky Way**, which is one of MANY **galaxies**, in our **Universe**

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...

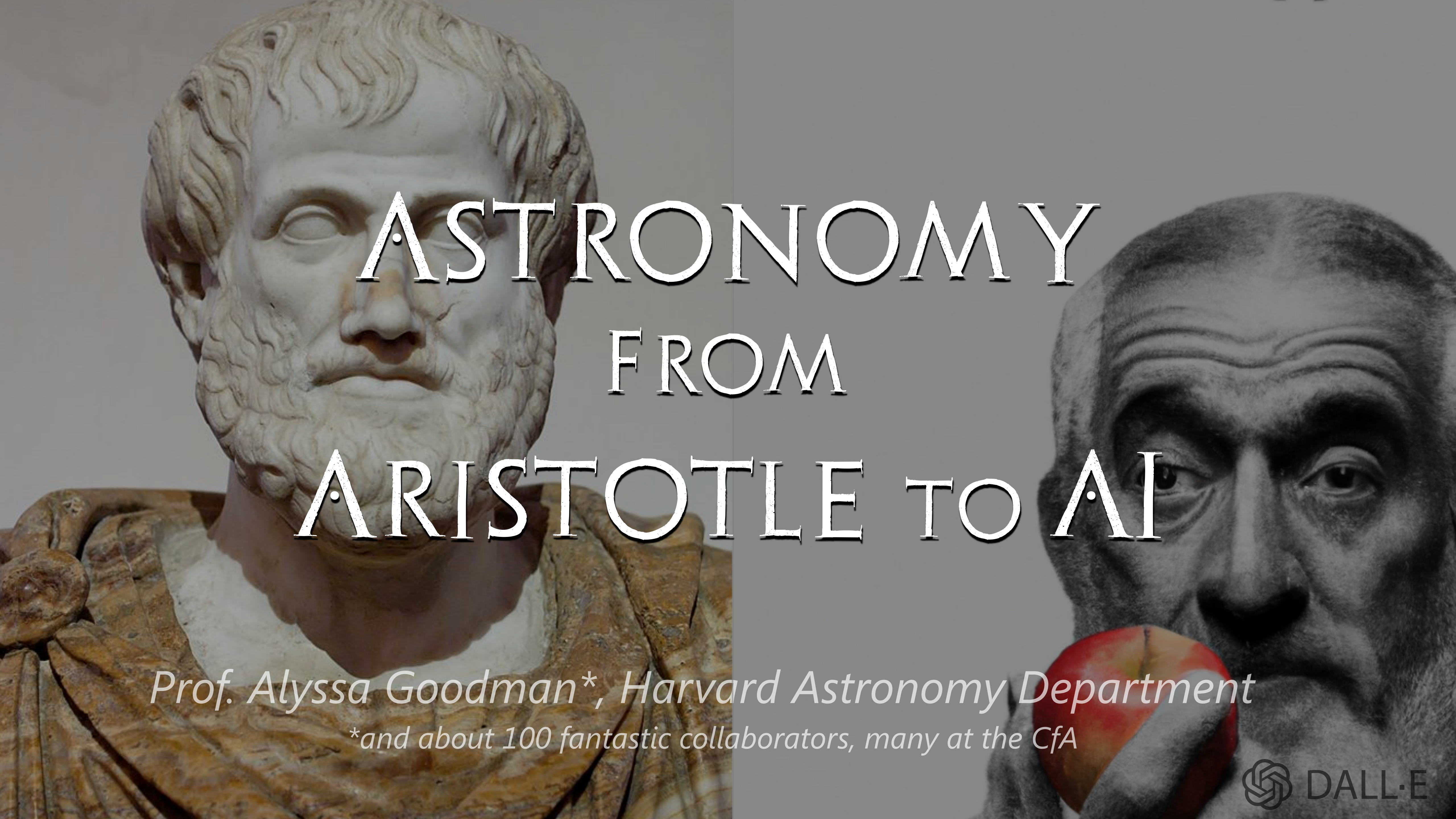


...cartoon!



...and **we** are buried **INSIDE** the Milky Way.

But, how have we come to learn any of that??



# ASTRONOMY FROM ARISTOTLE TO AI

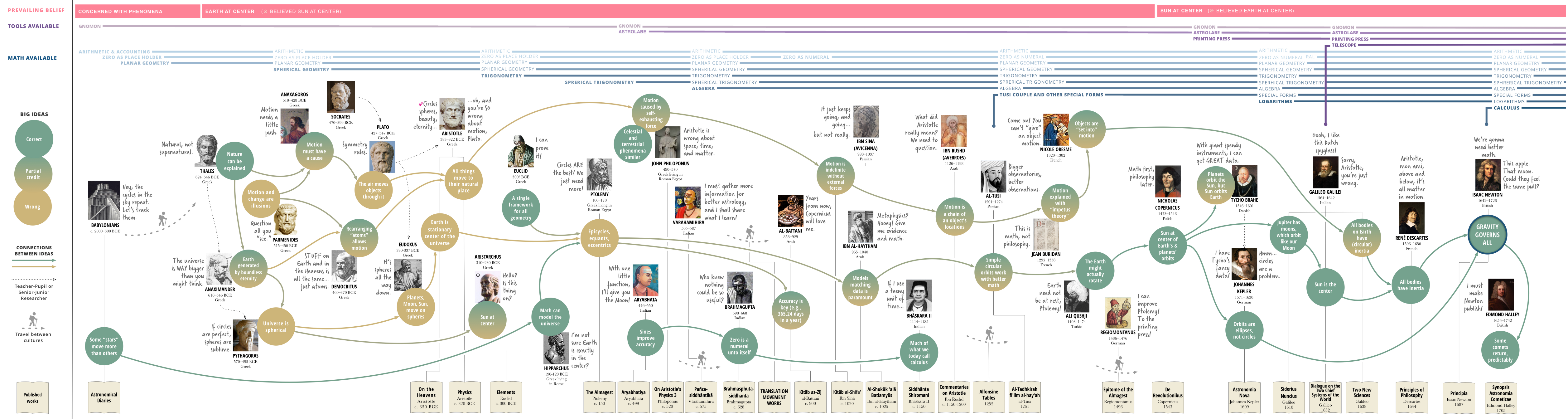
*Prof. Alyssa Goodman\*, Harvard Astronomy Department*

*\*and about 100 fantastic collaborators, many at the CfA*

# The Path to Newton



## The Path to Newton

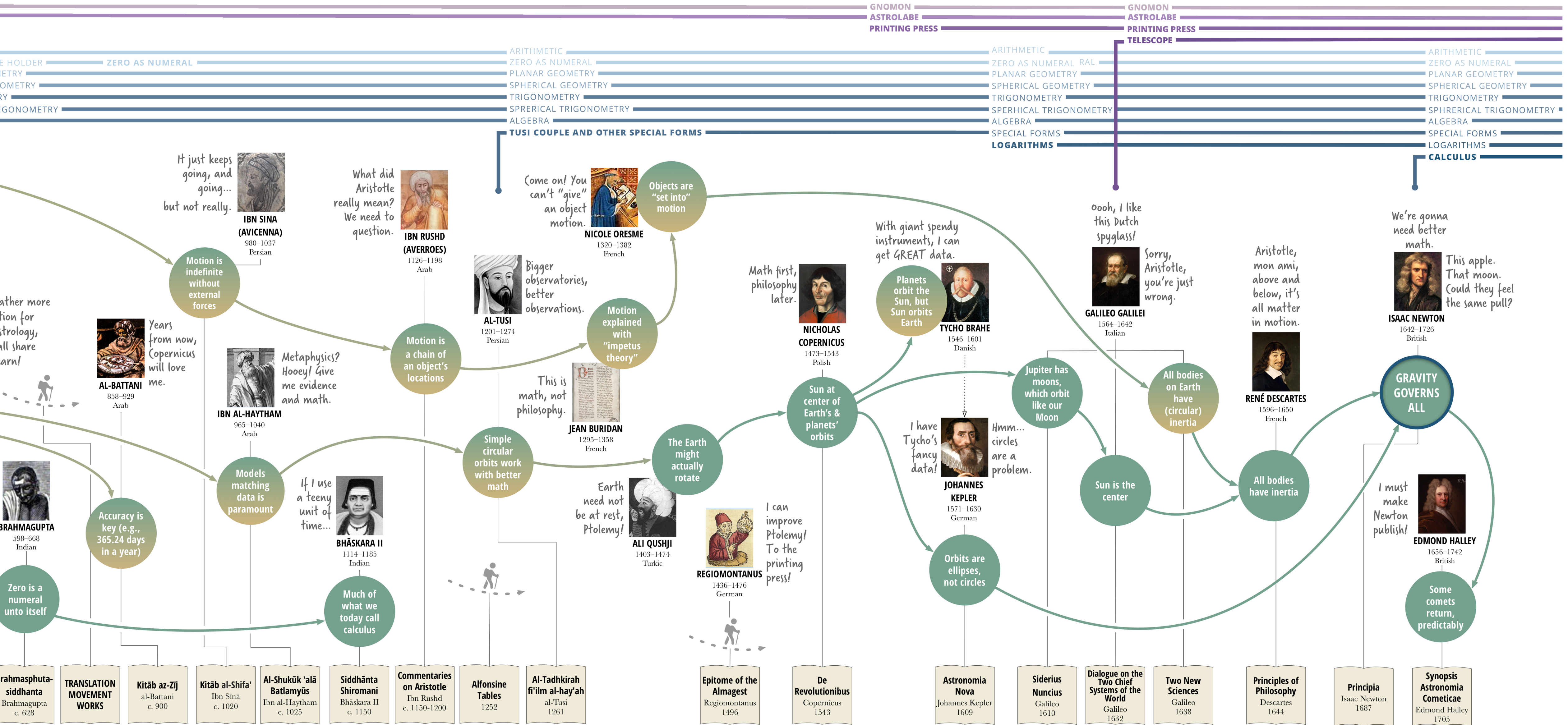


© Harvard University, created by Alyssa Goodman, Jais Brohinsky, Drew Lichtenstein & Katie Peek, re-use is allowed, with attribution, version 1, 2019



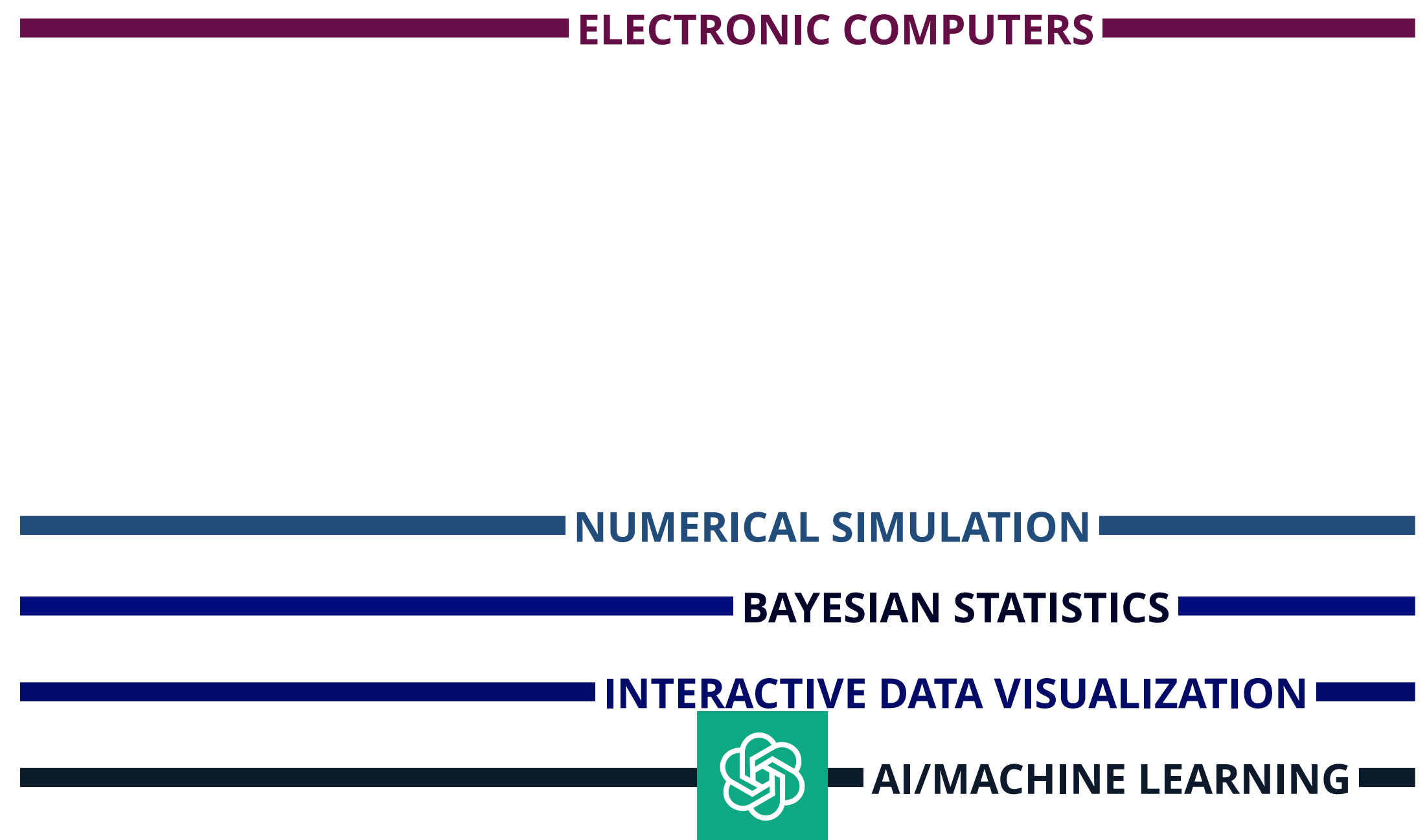
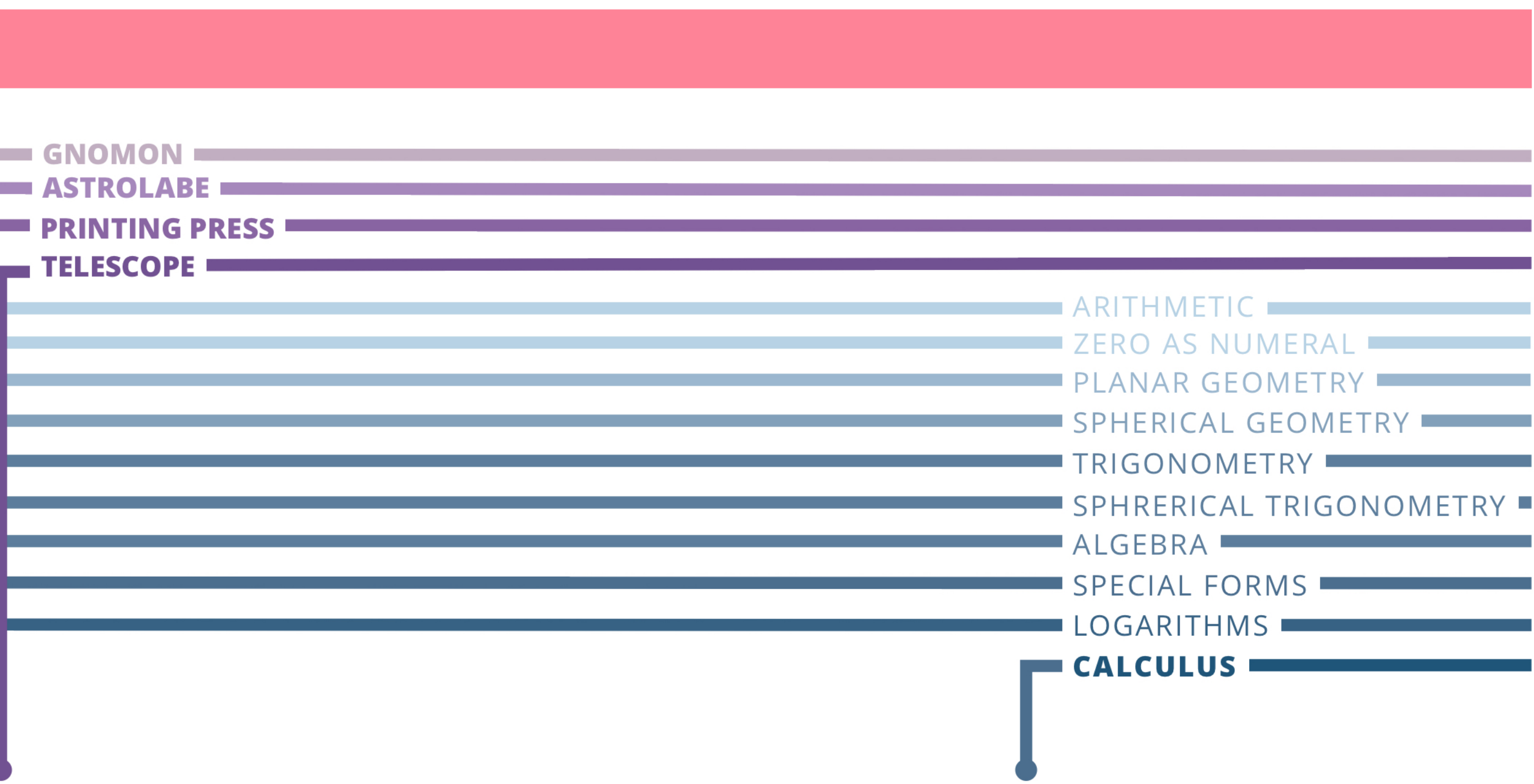


SUN AT CENTER (☉ BELIEVED EARTH AT CENTER)





# “ARE COMPUTERS THE NEW TELESCOPES?”



I like Dutch class!

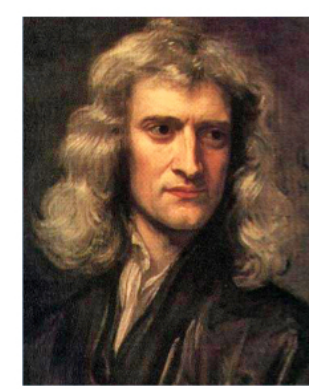


Sorry, Aristotle, you're just wrong.

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?



You

write out a timeline of key events in our understanding of the structure of the Milky Way, suitable for use in a public talk given by a professional astronomer



ChatGPT

Certainly! A timeline of key events in our understanding of the Milky Way's structure would help convey the dramatic evolution of our cosmic perspective, especially in a public talk given by a professional astronomer. Here's a streamlined timeline highlighting significant milestones:

### ### Updated Timeline of Key Events in Understanding the Structure of the Milky Way

#### 1. **Ancient Civilizations** (Various Dates)

Various ancient cultures recognized the Milky Way as a **distinct entity in the night sky**, often weaving it into their mythology.

#### 2. **1610 - Galileo Galilei**

Galileo used the **newly invented telescope** to discover that the Milky Way was composed of countless stars.

#### 3. **1750 - Thomas Wright**

Wright proposed that the Milky Way was a **flat disk of stars and introduced the concept that some nebulae were separate galaxies.** (cf. Charles Messier, 1730-1817).

#### 4. **1785 - William Herschel**

Herschel attempted to map the **shape of the Milky Way using star counts**, concluding it was **disk-shaped (✓) with the Sun near the center (✗).**

#### 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.

#### 6. **1923 - Edwin Hubble**

Hubble identified Cepheid variable stars in the **Andromeda** Nebula, confirming it and others as **separate galaxies outside the Milky Way.** (cf. Henrietta Leavitt!)

#### 7. **1950s - Radio Astronomy**

The advent of radio astronomy revealed the **Milky Way's spiral structure (maybe?!)** through the radio emissions of **hydrogen gas.**

#### 8. **1970s - Infrared Astronomy**

Infrared observations **penetrated cosmic dust**, allowing closer study of the galactic center and supporting evidence of a spiral structure.

#### 9. **1990s - The Hubble Space Telescope**

**High-resolution** imaging provided **deeper insights into the structure** and composition of the Milky Way and other celestial phenomena.

#### 10. **2013 - Gaia Mission Launched**

The European Space Agency's Gaia spacecraft began **mapping billions of stars in the Milky Way** in unprecedented detail, helping to refine our understanding of the galaxy's **structure and dynamics.**

#### 11. **2010s Onwards - 3D Dust Mapping**

Advances in technology have enabled astronomers to create detailed 3D maps of dust in the Milky Way, crucial for understanding the distribution of stars and the structure of the galaxy. Projects like the Pan-STARRS1 surveys and data from Gaia have been instrumental in **mapping interstellar dust in three dimensions.**

#### 12. **2019 and Beyond - Gaia's Data Releases**

Gaia's second data release in 2018 provided positions, distance indicators, and motions for nearly 1.7 billion stars. Subsequent data releases have **enhanced models of the Milky Way's kinematics and structural components, including stellar streams, the galactic bar, and spiral arms.** Gaia's data has also been **pivotal in improving 3D dust mapping techniques** by providing essential calibration stars to map dust absorption and re-emission across the galaxy.

**These updates show the dynamic and rapidly advancing field of astronomy, emphasizing how contemporary missions like Gaia and techniques like 3D dust mapping are reshaping our understanding of the Milky Way.** This detailed timeline would be **quite engaging for a professional astronomer's public talk**, highlighting both historical context and modern scientific achievements.

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

For Release to Afternoon Papers,  
Monday, April 26

or  
files

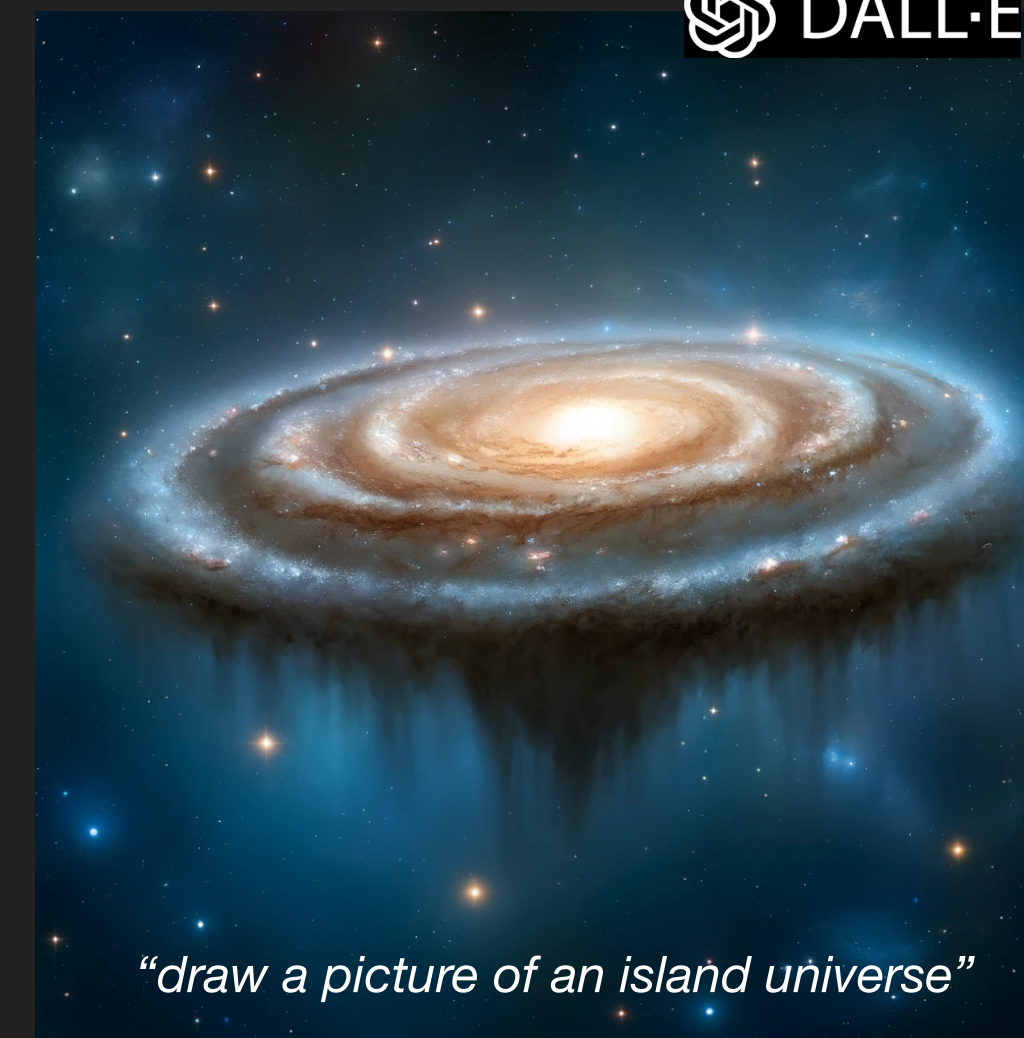
HOW MANY UNIVERSES ARE THERE?

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.

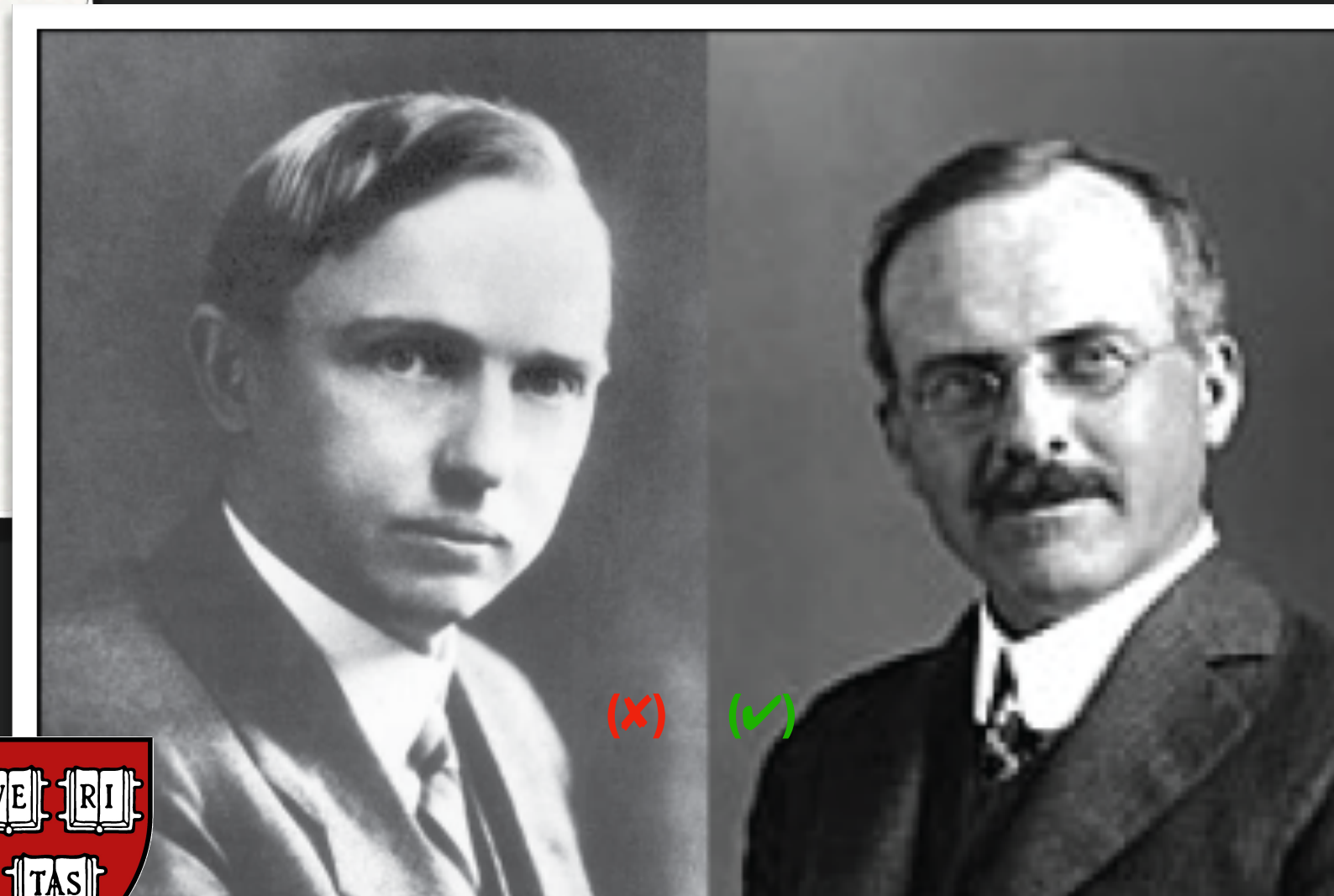
Doctor Shapley's views will be followed by the discussion of Doctor Heber D. Curtis of the Lick Observatory, who will defend the older view that our Milky Way is approximately of the dimensions suggested by Newcomb, about 30,000 light-years in diameter, with the spiral nebulae regarded as very probably 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.

DALL-E



5. \*\*1920 - The Great Debate\*\*

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



The Shapley-Curtis Debate at the  
Smithsonian Natural History Museum, 1920

star-forming nebulae

# "Messier" Objects (images, *not* cartoons or AI)

galaxies

## Mes·sier, Charles

| 'mesiə, mesye, ,mesē'ā, mes,yā |  
(1730–1817), French astronomer. He discovered a number of nebulae, galaxies, and star clusters, which he designated by M numbers.

mess·y | 'mesē | adjective (**messier** | 'mesēər |, **messiest** | 'mesēɪst |)

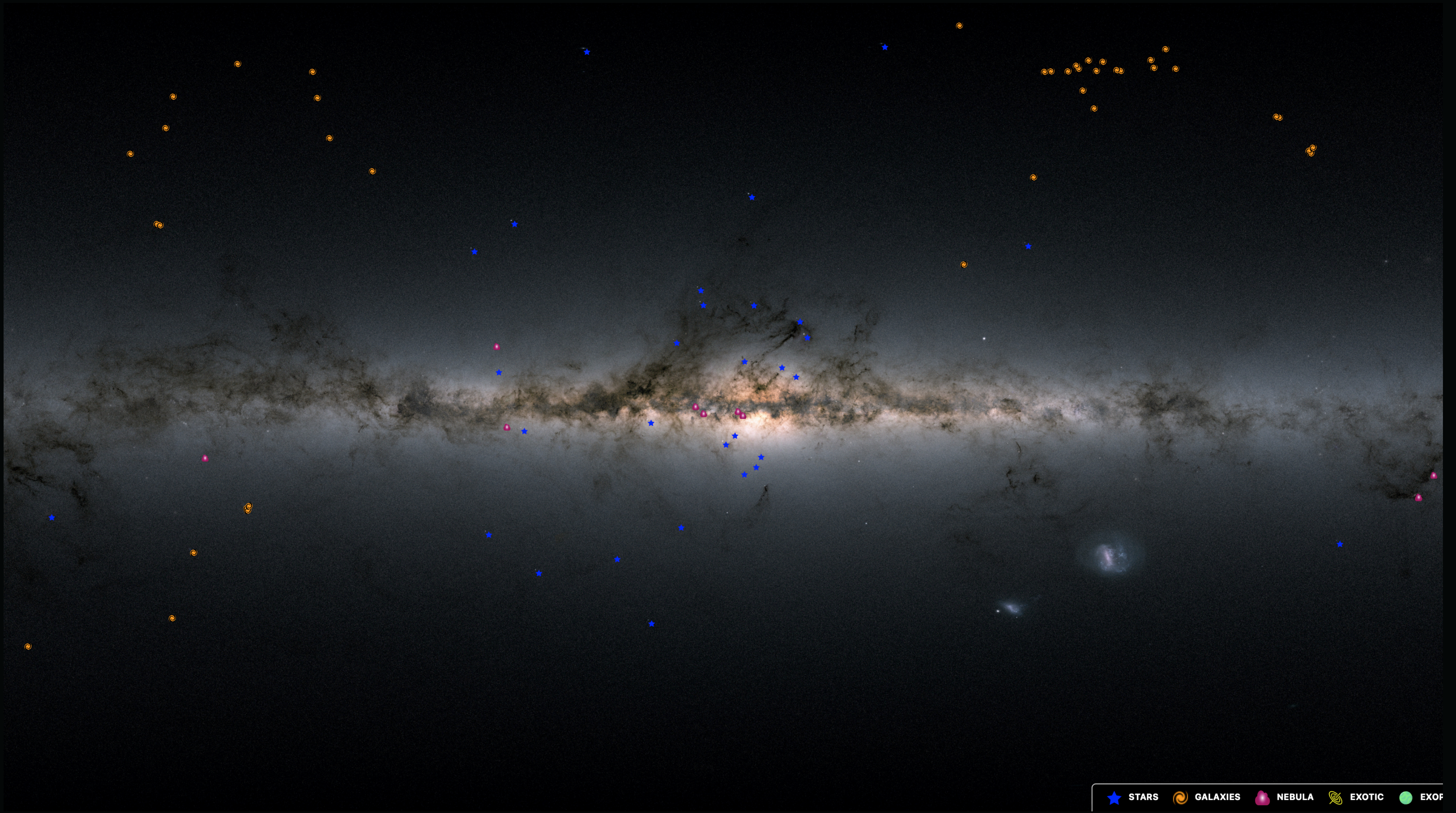
1 untidy or dirty: *his messy hair*.

- generating or involving mess or untidiness: *stripping wallpaper can be a more*



### 3. \*\*1750 - Thomas Wright\*\*

Wright proposed that the Milky Way was a flat disk of stars and introduced the concept that some nebulae were separate galaxies. (cf. Charles Messier, 1730-1817).



★ STARS    🌀 GALAXIES    🌌 NEBULA    🌀 EXOTIC    🟢 EXOP

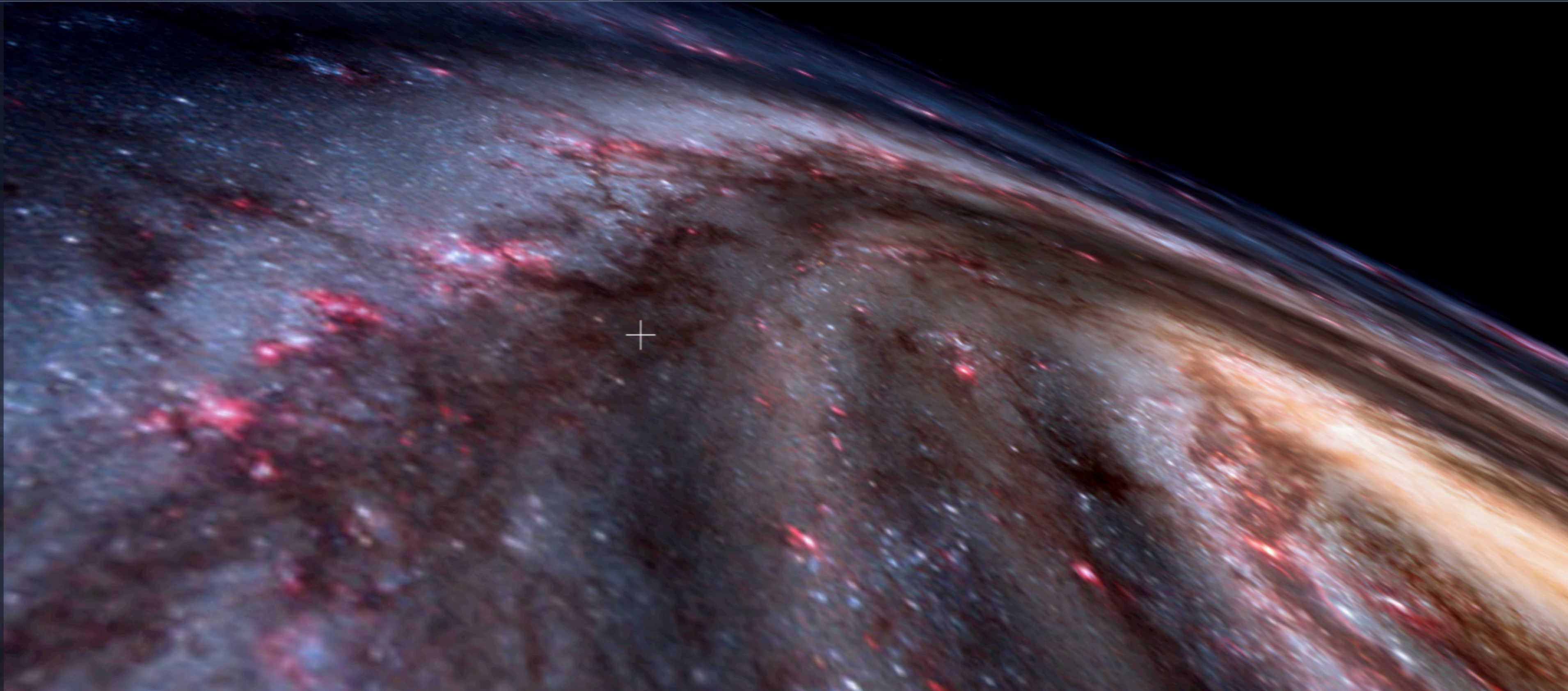
Start the presentation to see live content. Still no live content? Install the app or get help at [PollEv.com/app](https://PollEv.com/app)

Collections > 1 of 2

- Constellations
- Solar System (Sky)
- All-Sky Surveys
- External (HiPS) Sur...
- JWST
- Spitzer Studies
- Chandra Studies
- Hubble Studies
- Astrophotography
- Radio Studies
- NOIRLab Studies
- ESO Studies
- Gemini Studies
- WISE Studies

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



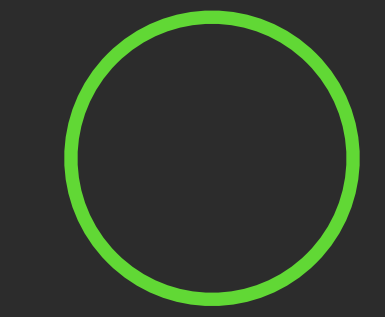
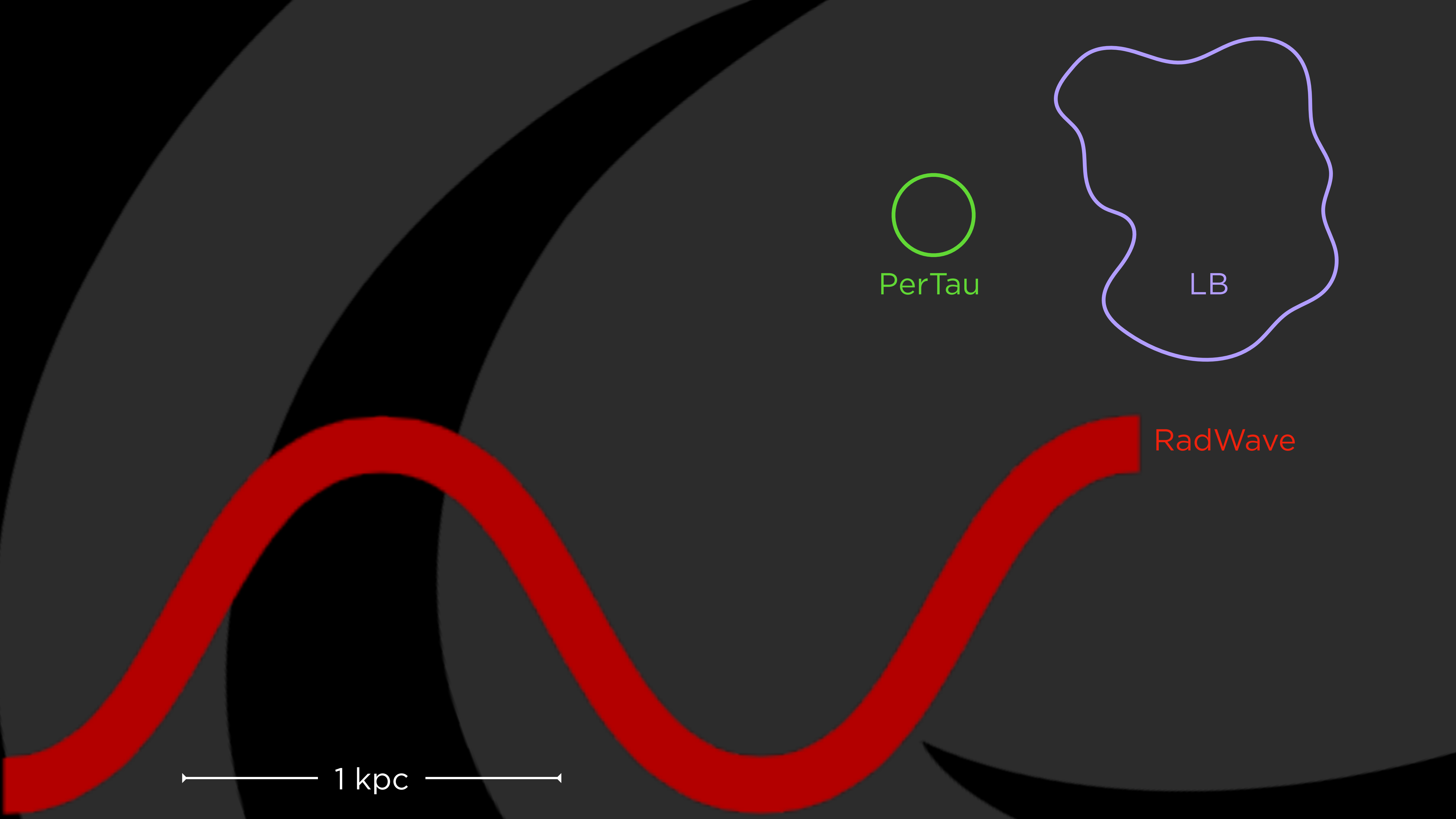
Time Scrubber

Look At: SolarSystem | Imagery: 3D Solar System View

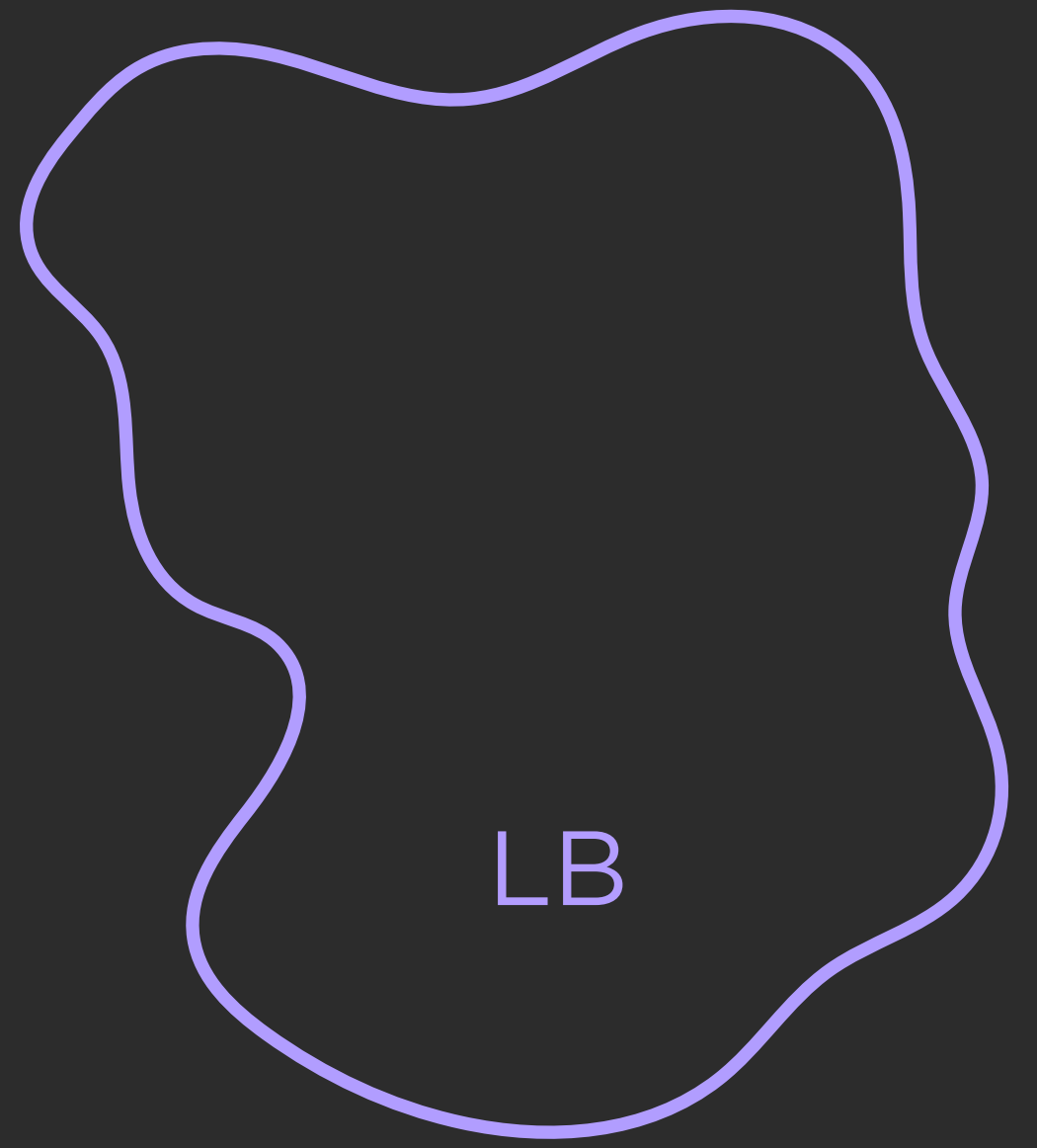
- Sun
- Mercury
- Venus
- Earth
- Mars
- Jupiter
- Saturn
- Uranus
- Neptune
- Pluto
- Moon
- Io

Planet Size: Actual | Large | Pisces 451333778:06:44

Lat: -32:30:29



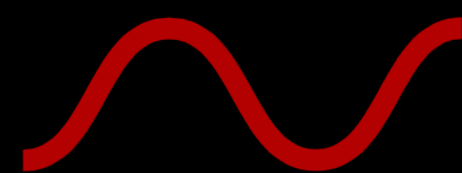
PerTau



LB

RadWave

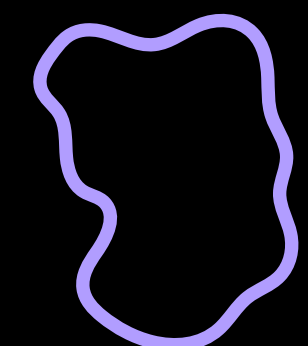
1 kpc



2020  
2024



2021



2022  
2024

**MILKYWAY3D.org**

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**  
linking data, using modern practices (plus glue)  
making data accessible online for decades  
**Lead: Alyssa Goodman, UGA**

**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  
**CosmicDS**  
"Cosmic Data Stories" teach data science using astronomical data & tools  
**Lead: Jackie Faherty, AMNH**

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

TEAM: Harvard/Smithsonian CIA (Jonathan Carrillo, Alyssa Goodman, Ralf Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), AMNH (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty), Linköping University (Alex Bock), University of Vienna (Joao Alves, Sebastian Rätzke), glue solutions, inc./Apatia (Thomas Robitaille), University of Wisconsin, Whitewater (Bob Benjamin), STScI/Johns Hopkins (Josh Peek), Max Planck IIA (Gordian Edenhofer), Northeastern University (Michelle Borkin), and YOHJ

2023 and beyond!



# 2020 The Radcliffe Wave

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

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

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

# The Radcliffe Wave

CARTOON\*

DATA

*\*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.

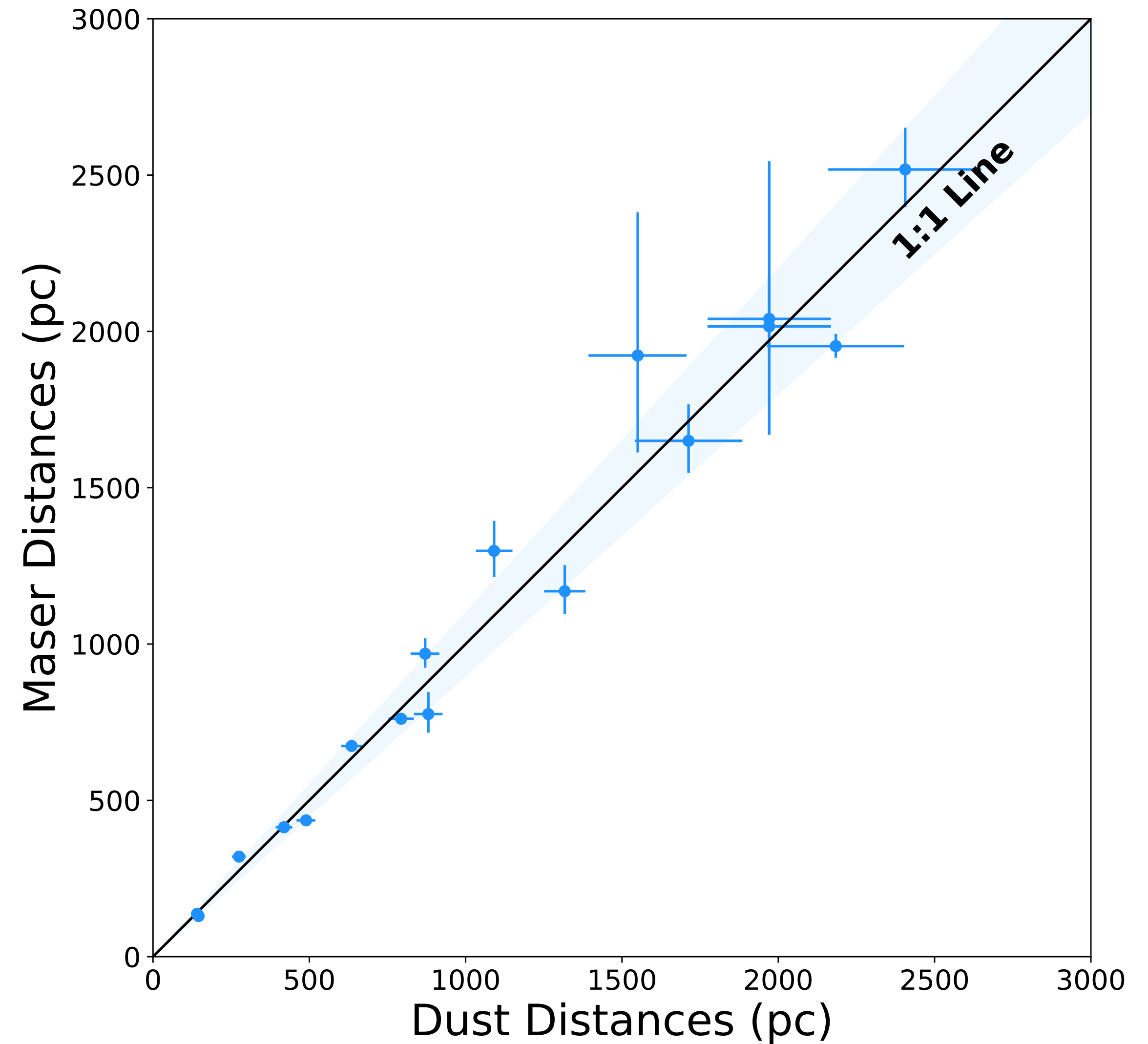
*Alves et al. 2020*

*“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

## DISTANCES!!

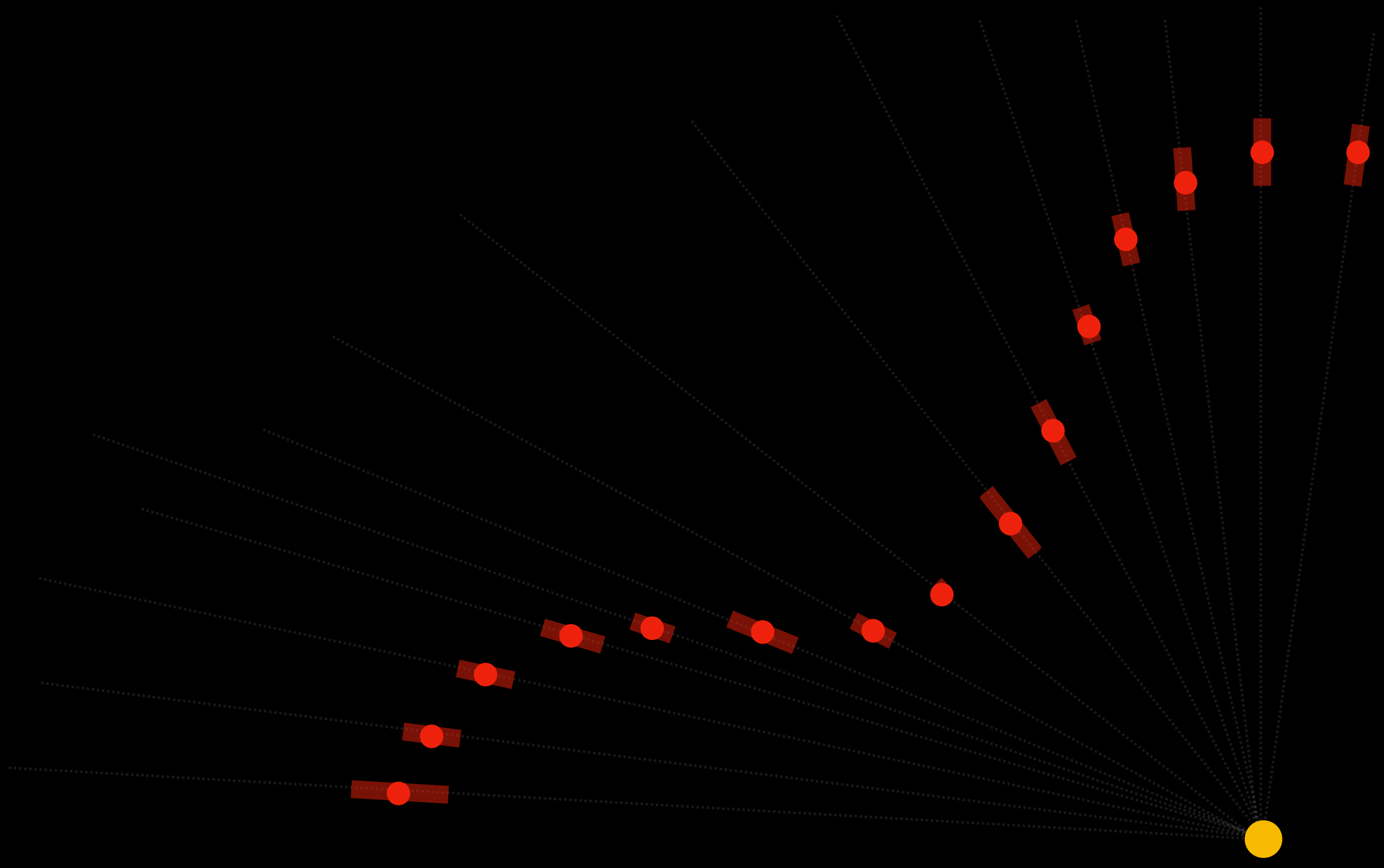
We can now  
measure distances  
to gas clouds in our  
own Milky Way  
galaxy to ~5%  
accuracy.

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%)

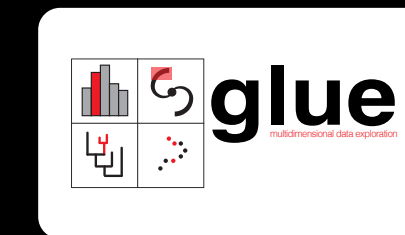
**HOW= 3D dust mapping\***



**+ Gaia\***



**+ glue\***



**+ WorldWide Telescope**



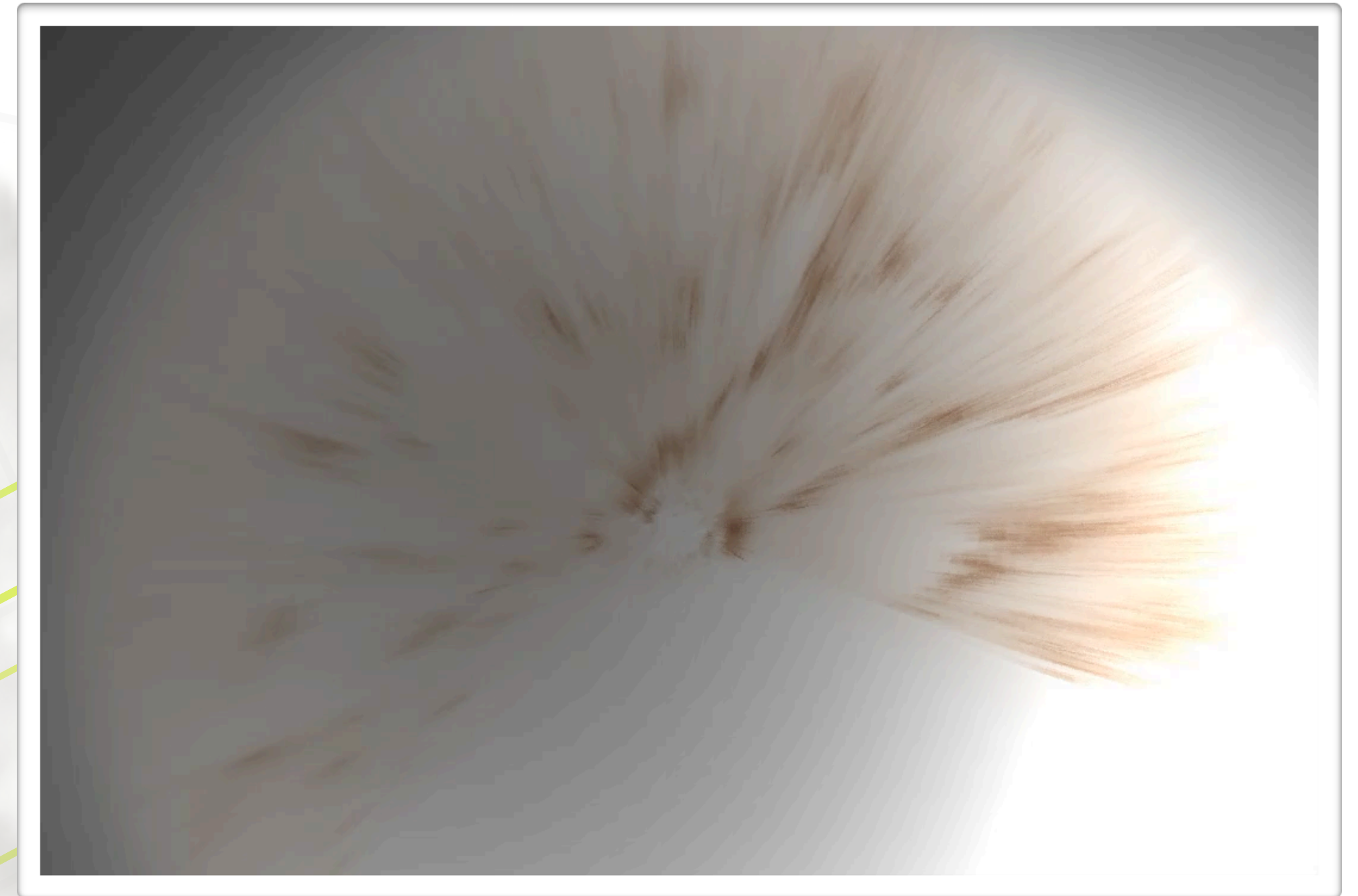
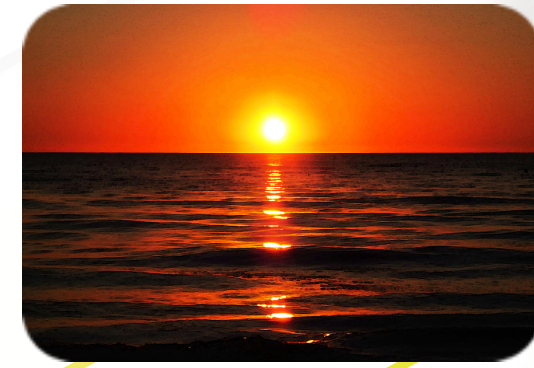
**\*2 million CPU hours, Harvard**

**\*800 million stars, ESA**

**\*NASA/JWST, NSF**

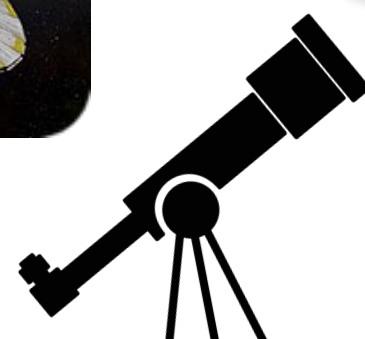
**\*Microsoft Research, NSF, AAS**

# Extinction & Reddening, from Color Imaging



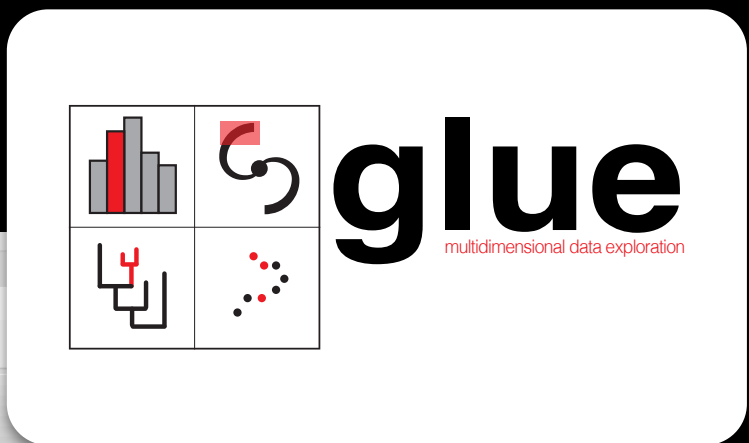
Green et al. 2019

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



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

# "Seeing" The Radcliffe Wave, in 3D



**Data Collection**

- Possible Wave Models
- Best Fit Wave Model
- CO Gas (Local)
- Gould's Belt (Perrot & Grenier 2003)
- Green 2019 3D Dust
- Local Arm Fit (Reid+2016)
- Major Cloud Catalog
- Maser Catalog (Reid+2014,2016)
- Sagittarius Arm Fit (Reid+2016)
- Tenuous Connections
- Sun

**Subsets**

- 

**Plot Layers - 3D Volume Rendering**

- RadWave (Sun)
- Local Arm Masers (Sun)
- Sagittarius Arm Masers (Sun)
- Sun
- RadWave (Major Cloud Catalog)
- Tenuous Connections

Attribute: PRIMARY  
Limits: 1 5  
Color: [Slider]

**Plot Options - 3D Volume Rendering**

x axis: Pixel Axis 2 [x]  
min/max: 38.2241 ⇌ 1160.78  
stretch: [Slider] 1.00

y axis: Pixel Axis 1 [y]  
min/max: 38.2241 ⇌ 1160.78  
stretch: [Slider] 1.00

z axis: Pixel Axis 0 [z]  
min/max: 5.95402 ⇌ 193.046  
stretch: [Slider] 1.00

reference: Green 2019 3D Dust  
resolution: 256

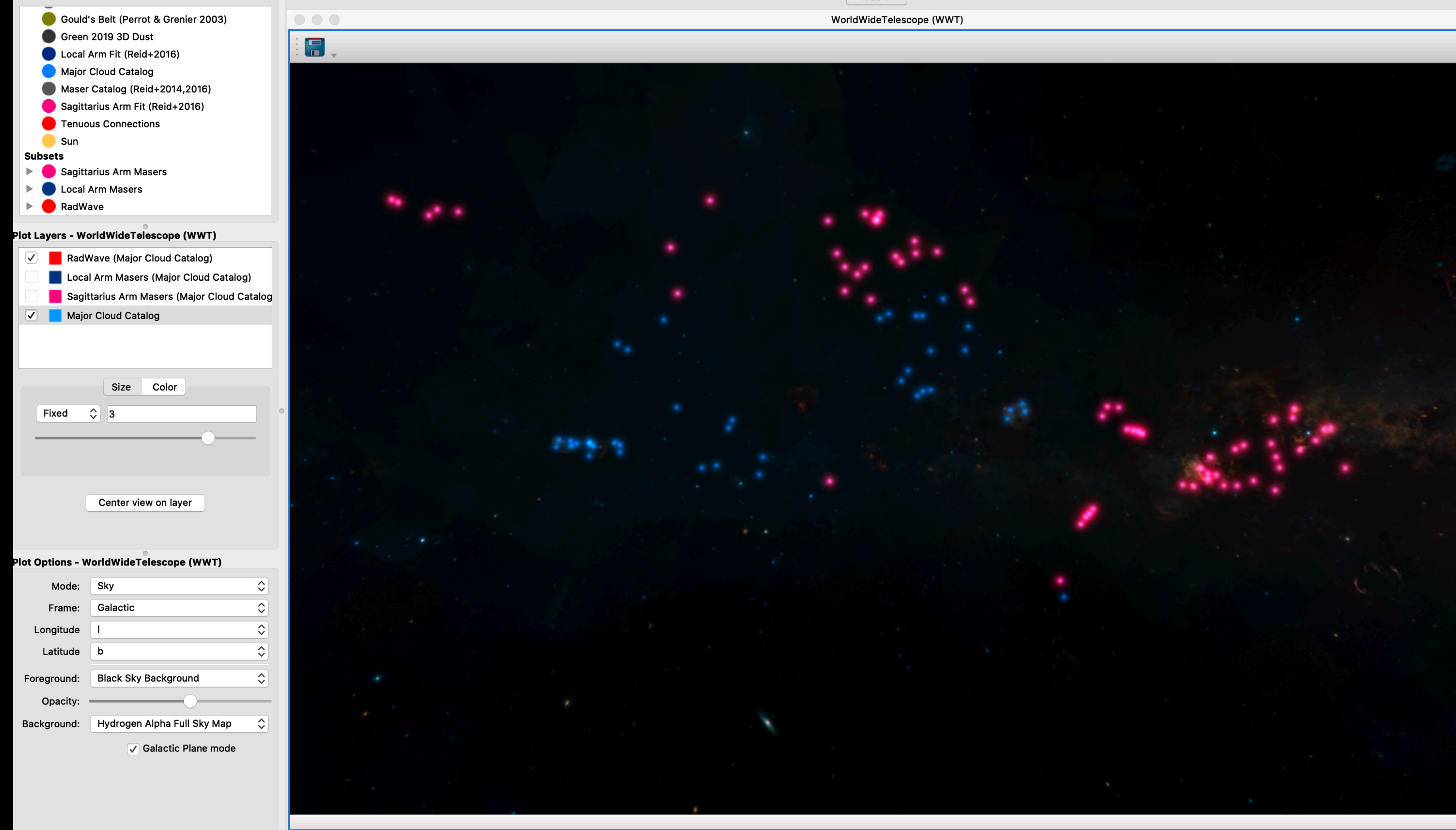
**3D Scatter**  
WorldWideTelescope

**3D Volume Rendering**  
Pixel Axis 0 [z]  
Pixel Axis 2 [x]

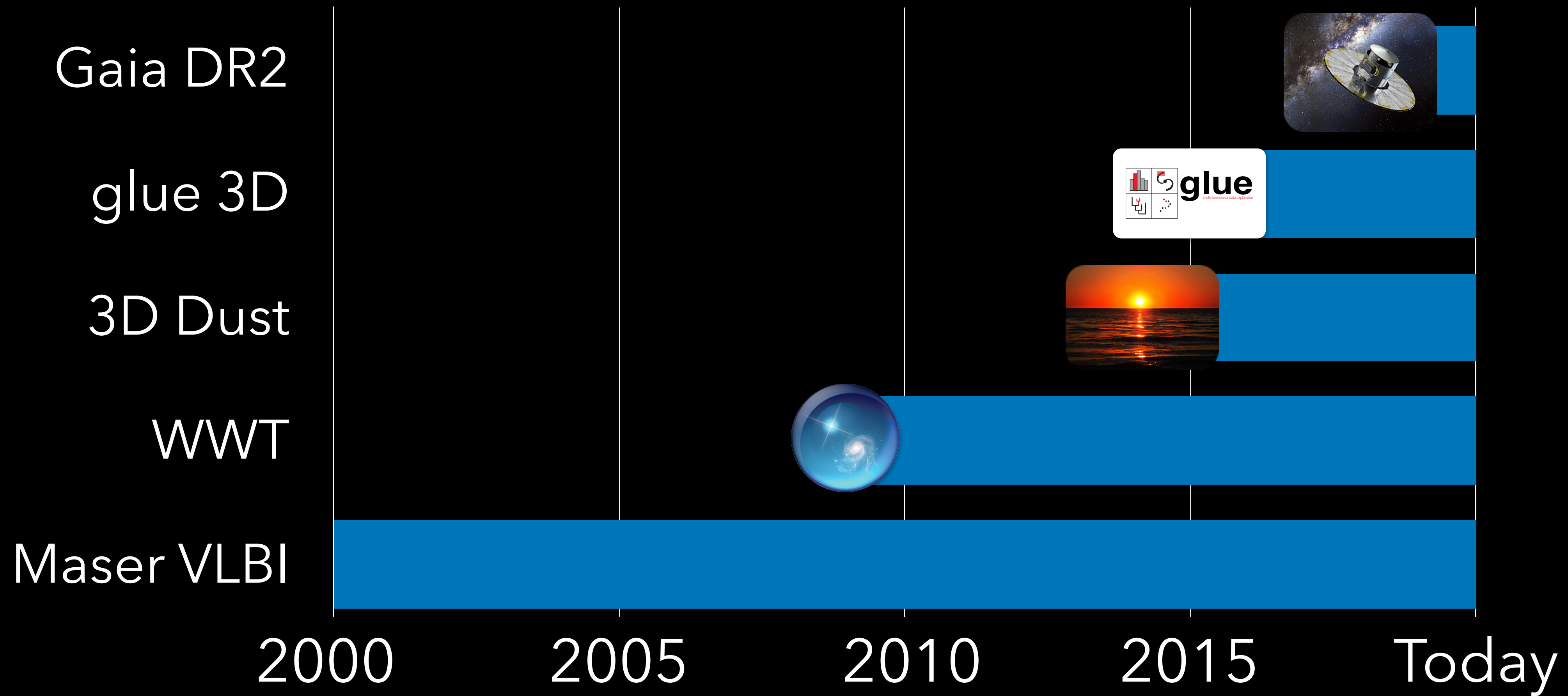
**3D Volume Rendering**  
Screenshot

# WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?

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



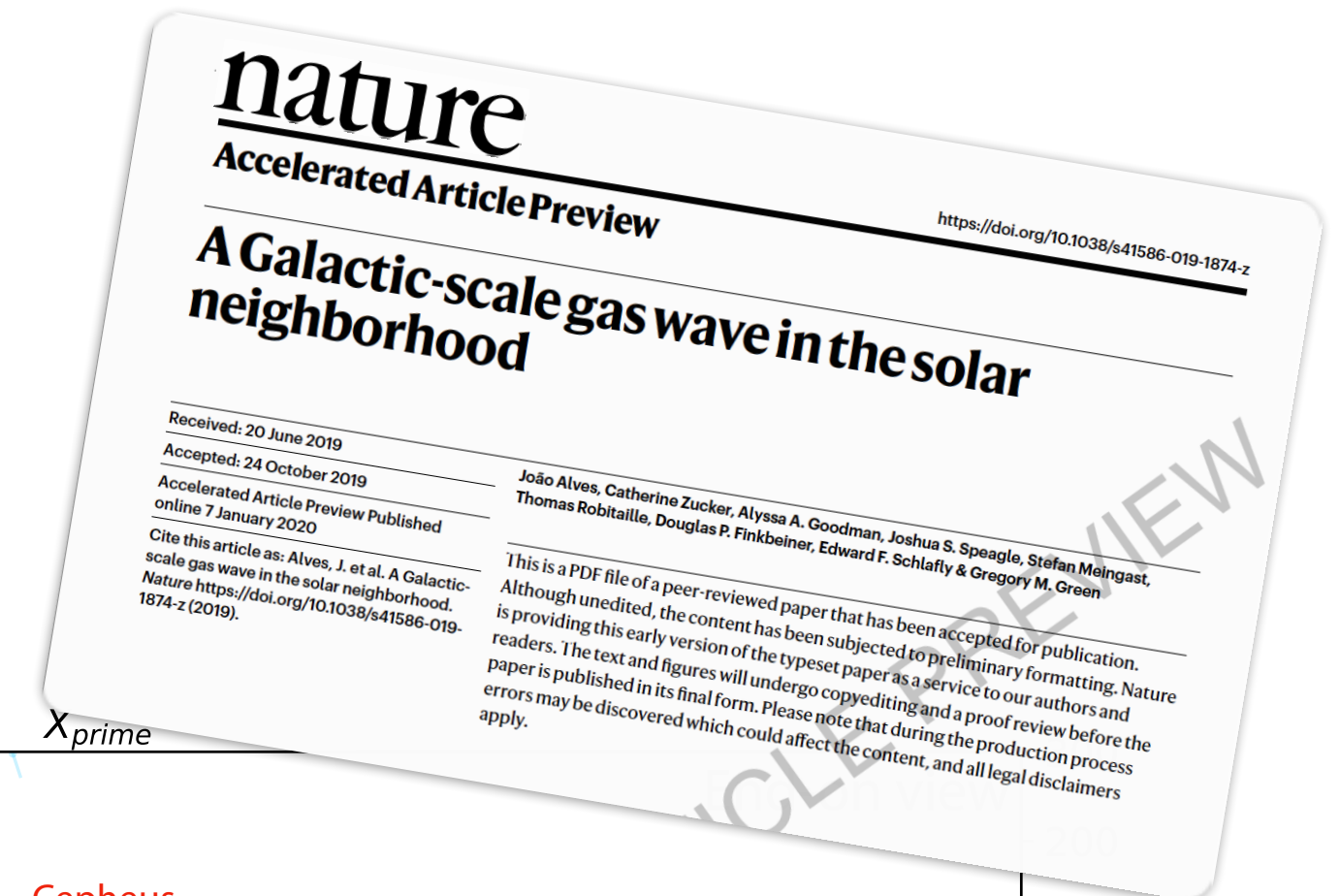
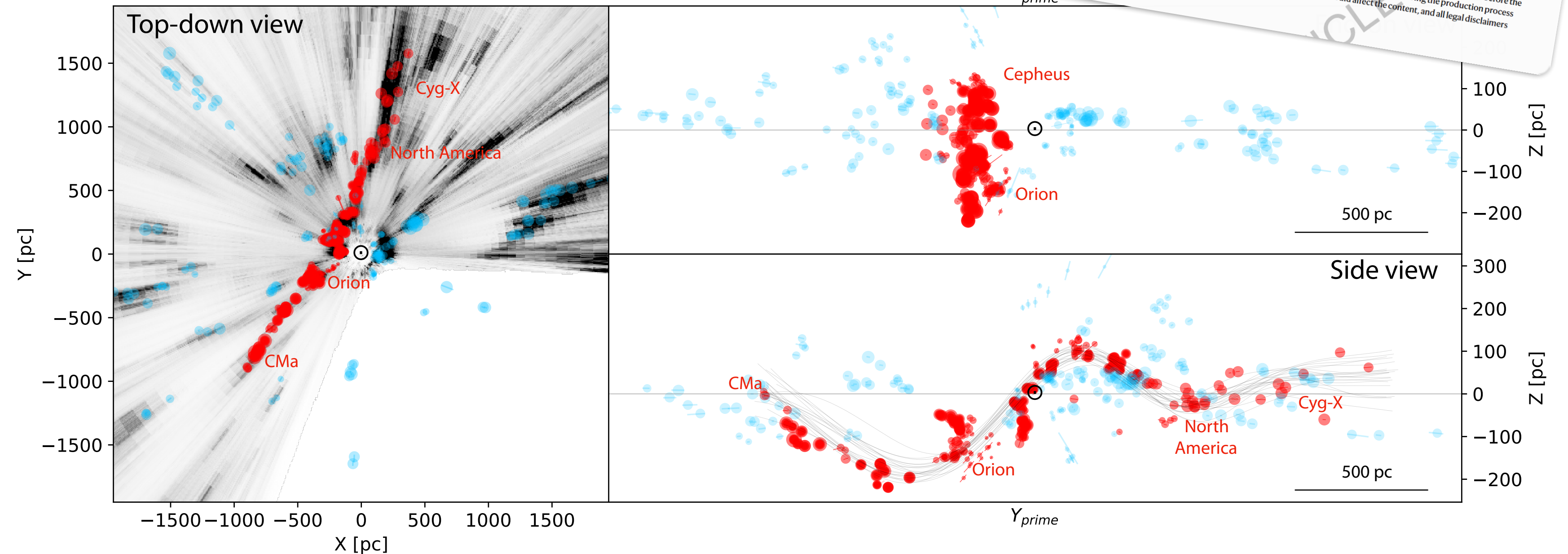
# WHY DIDN'T WE FIND THE RADCLIFFE WAVE SOONER?



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

# The Radcliffe Wave

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](https://plot.ly) & [bokeh](https://bokeh.org)), and deep links to data (on [Dataverse](https://dataverse.org)) and code (on [GitHub](https://github.com)) 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

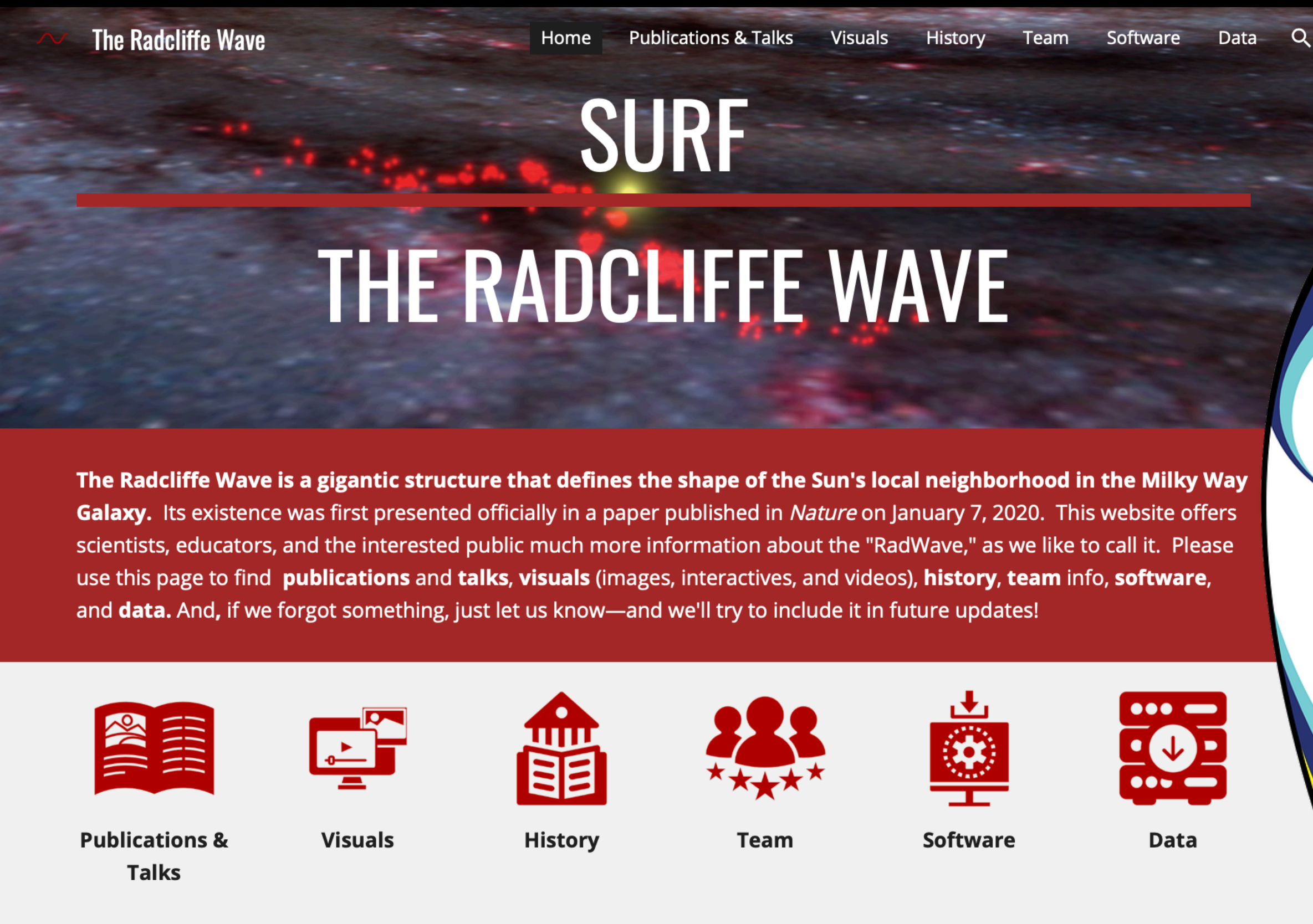
What is the **ORIGIN** of the Radcliffe Wave? Collision?

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



The Radcliffe Wave

Home Publications & Talks Visuals History Team Software Data

## SURF

### THE RADCLIFFE WAVE

The Radcliffe Wave is a gigantic structure that defines the shape of the Sun's local neighborhood in the Milky Way Galaxy. Its existence was first presented officially in a paper published in *Nature* on January 7, 2020. This website offers scientists, educators, and the interested public much more information about the "RadWave," as we like to call it. Please use this page to find **publications** and **talks**, **visuals** (images, interactives, and videos), **history**, **team** info, **software**, and **data**. And, if we forgot something, just let us know—and we'll try to include it in future updates!

Publications & Talks Visuals History Team Software Data

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](https://tinyurl.com/RadWave)

# The Radcliffe Wave



RADCLIFFE INSTITUTE  
FOR ADVANCED STUDY  
HARVARD UNIVERSITY



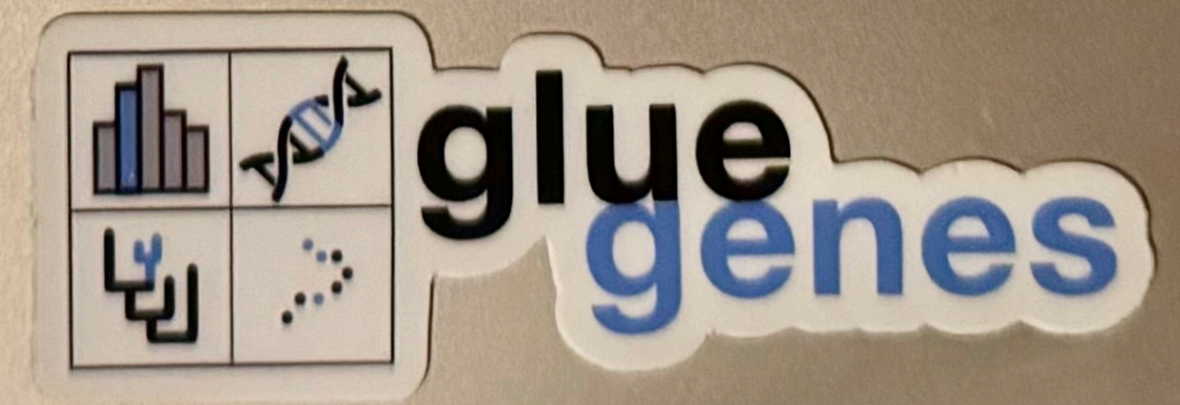
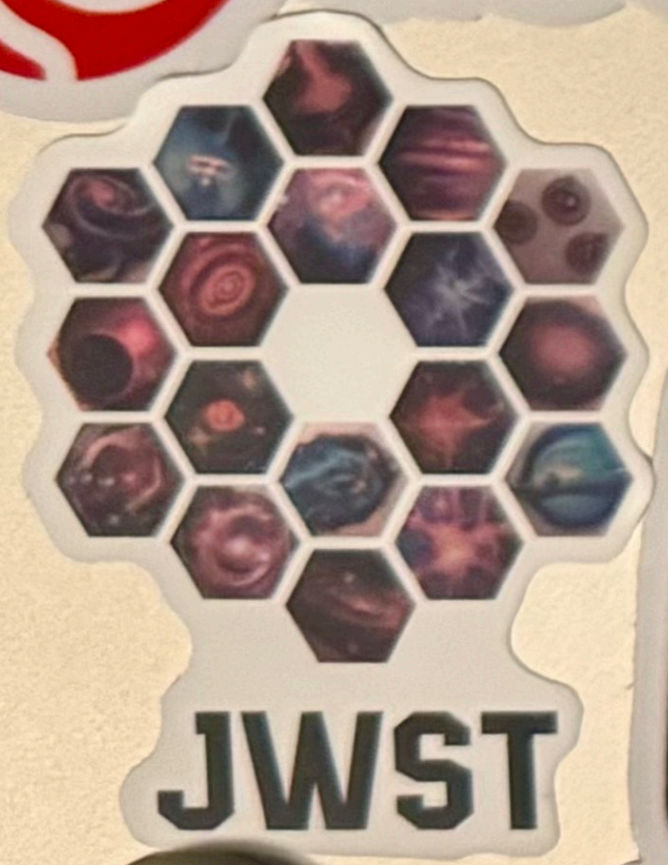
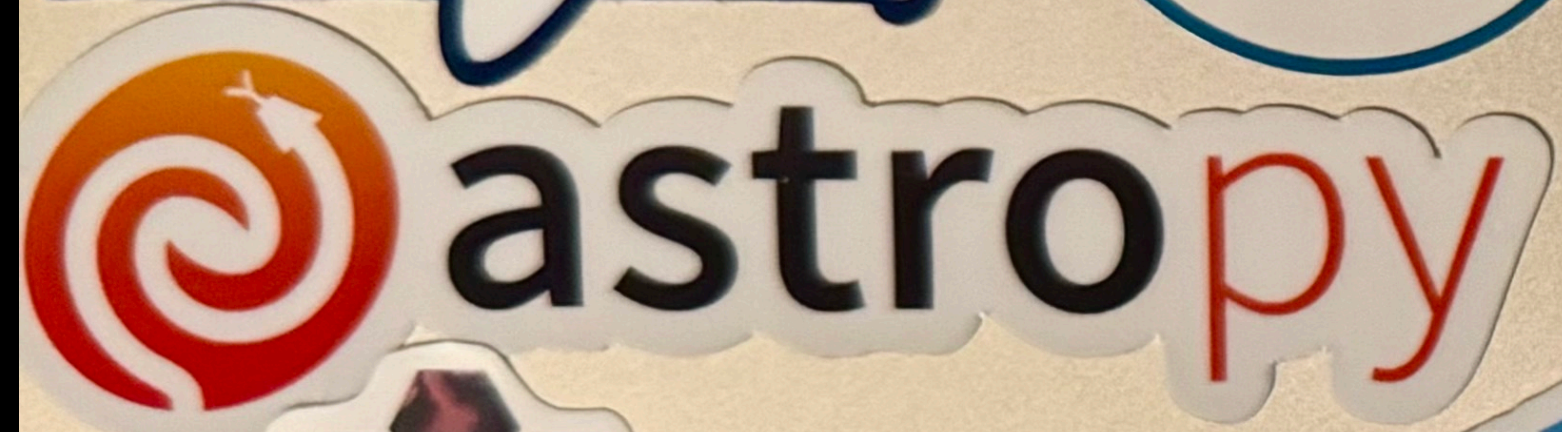
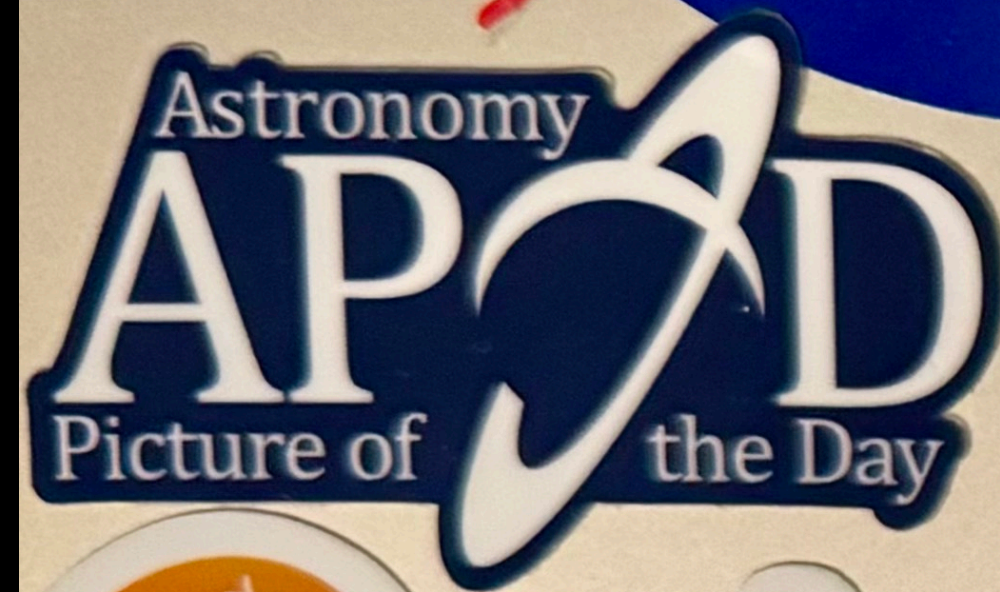
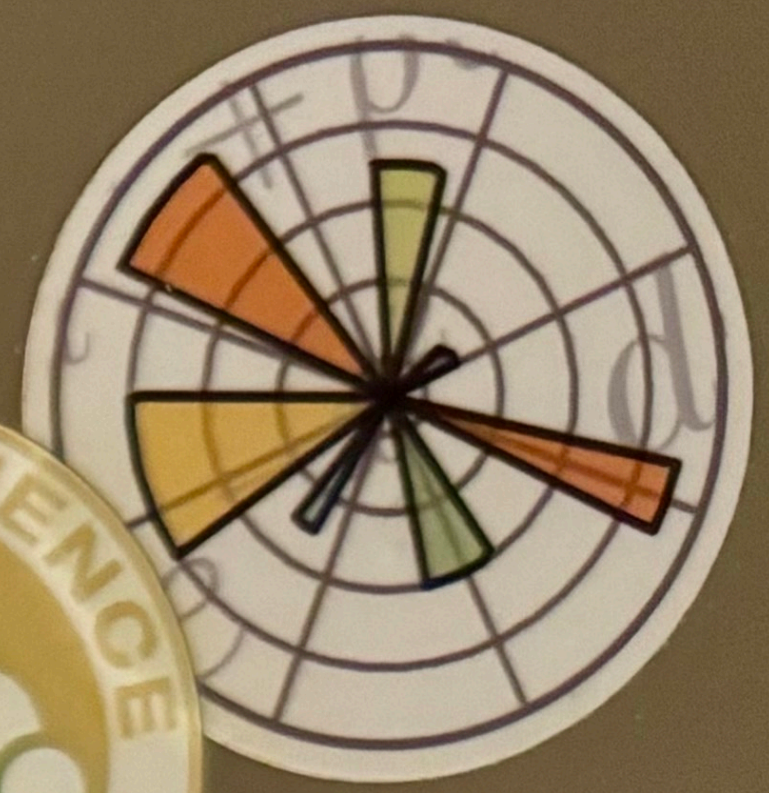
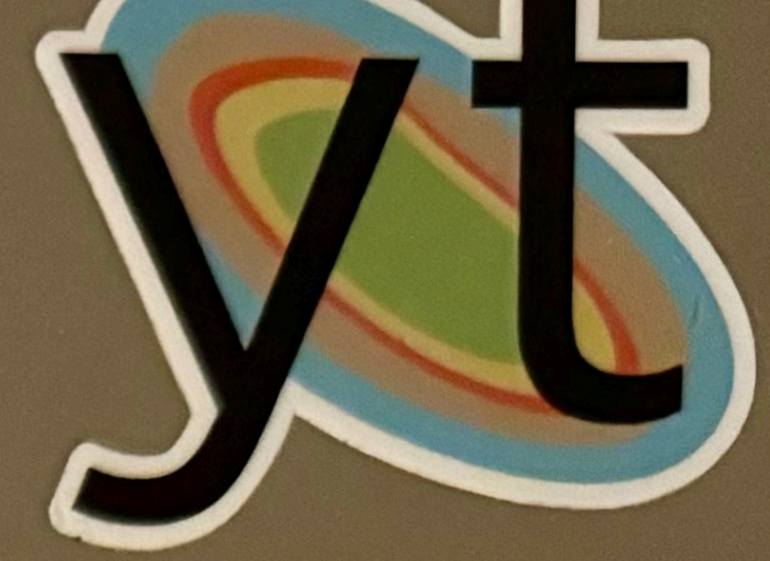
RADCLIFFE INSTITUTE  
FOR ADVANCED STUDY  
HARVARD UNIVERSITY

Catherine  
Zucker

João  
Alves

Alyssa  
Goodman

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



# TECH interlude

Using the **LIVE-env.org** website, let's ask:

What is **glue**?

What is it\* used for in **Astronomy, Biology, GIS**?

Why will LIVE be even better?

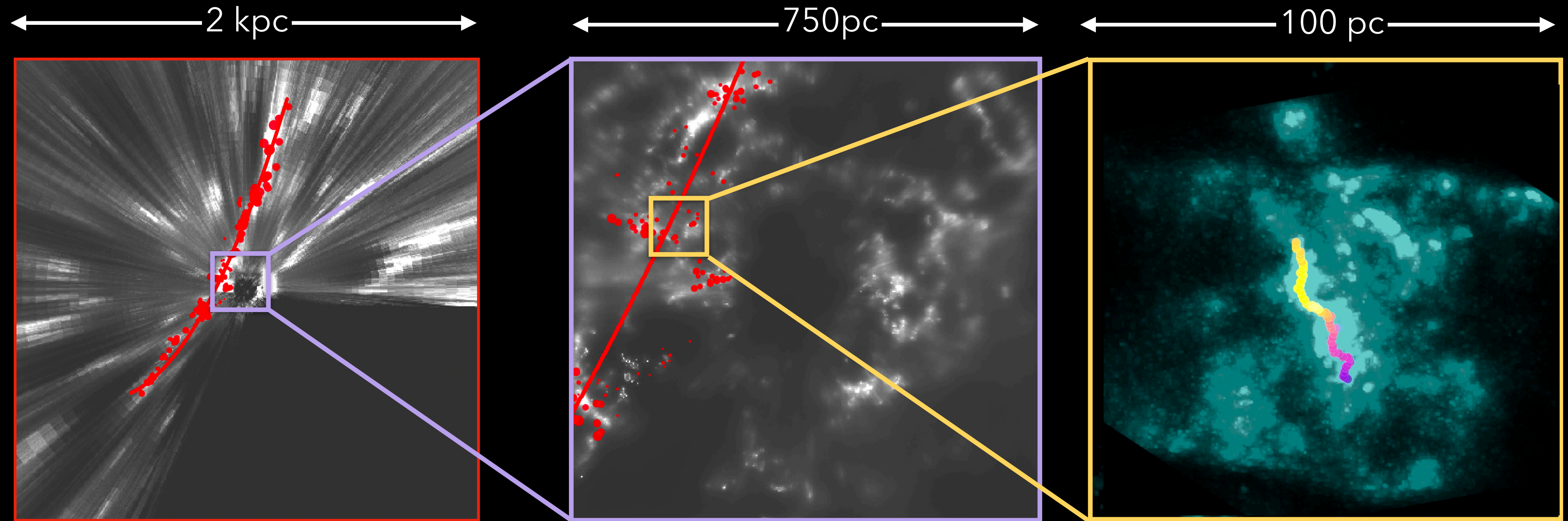
**browser**-based, more **tools**, more **customizable**, **AI**, more **AR**

How does LIVE-Astro **relate** to **MilkyWay3D.org**?

Who is **paying** for this?

*\*"it" is glue → LIVE, and importantly, LIVE is a new **collaboration** with Jupyter leaders and many, many, others*

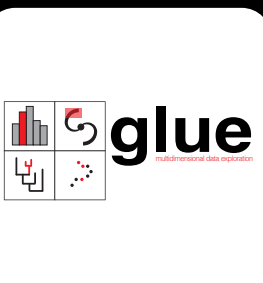
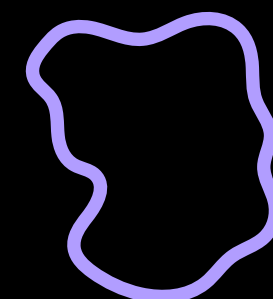
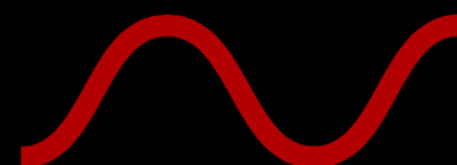
# 2019 to 2021: from distances to shapes

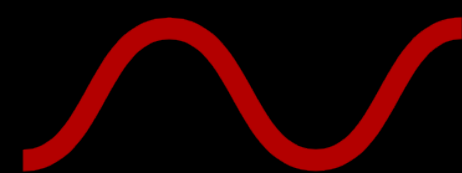


Zucker et al. 2020; Zucker & Speagle et al. 2019; Alves et al. 2020; Green et al. **2019**

Leike, Glatzle, & Enßlin **2020**

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

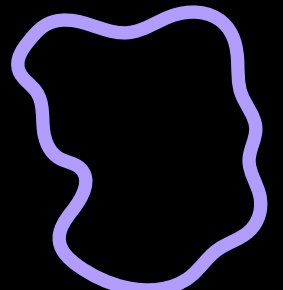




2020  
2024



2021



2022  
2024

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INFRASTRUCTURE ← SCIENCE → EDUCATION & OUTREACH

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

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

connecting real research data, software, and science to learners

glue

LIVE

stellar positions, clusters, motions

topology, positions & motions of (long) features

tracers of feedback & magnetic fields

real-time data exploration anywhere, including in planetaria

“Cosmic Data Stories” teach data science using astronomical data & tools

making data accessible online for decades

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

Lead: Alyssa Goodman, UTA

Lead: Catherine Zucker, CFA

Lead: Jackie Faherty, AMNH

TEAM: Harvard/Smithsonian CIA (Jonathan Carrillo, Alyssa Goodman, Ralf Kowitzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), AMNH (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty), Linköping University (Alex Bock), University of Vienna (Joao Alves, Sebastian Ritzko), glue solutions, inc./Apatia (Thomas Robitaille), University of Wisconsin, Whitewater (Bob Benjamin), STScI/Johns Hopkins (Josh Peek), Max Planck IIA (Gordian Edenhofer), Northeastern University (Michelle Borkin), and YOHJ

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

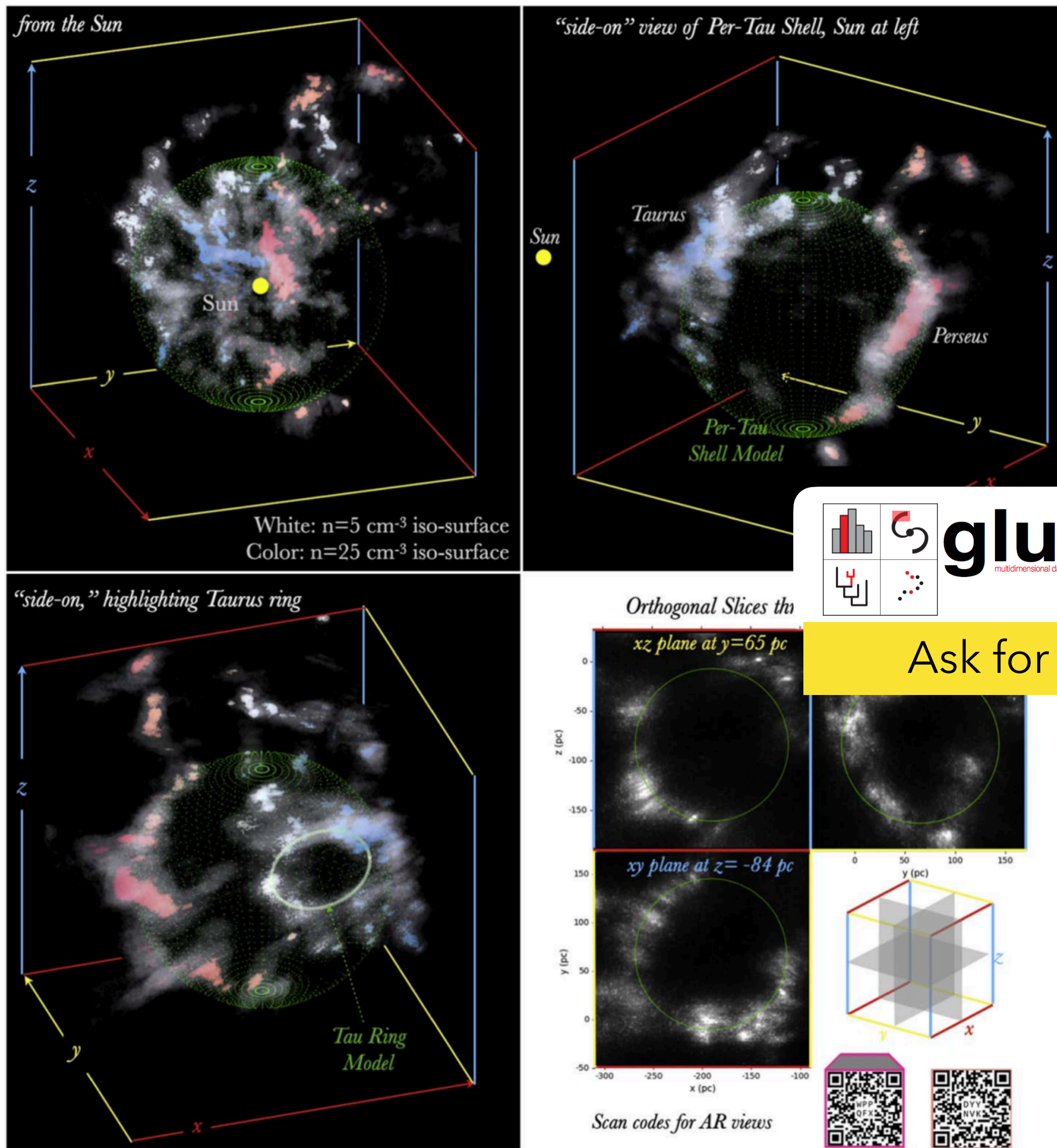
2023 and beyond!

2021

TAURUS

PERSEUS

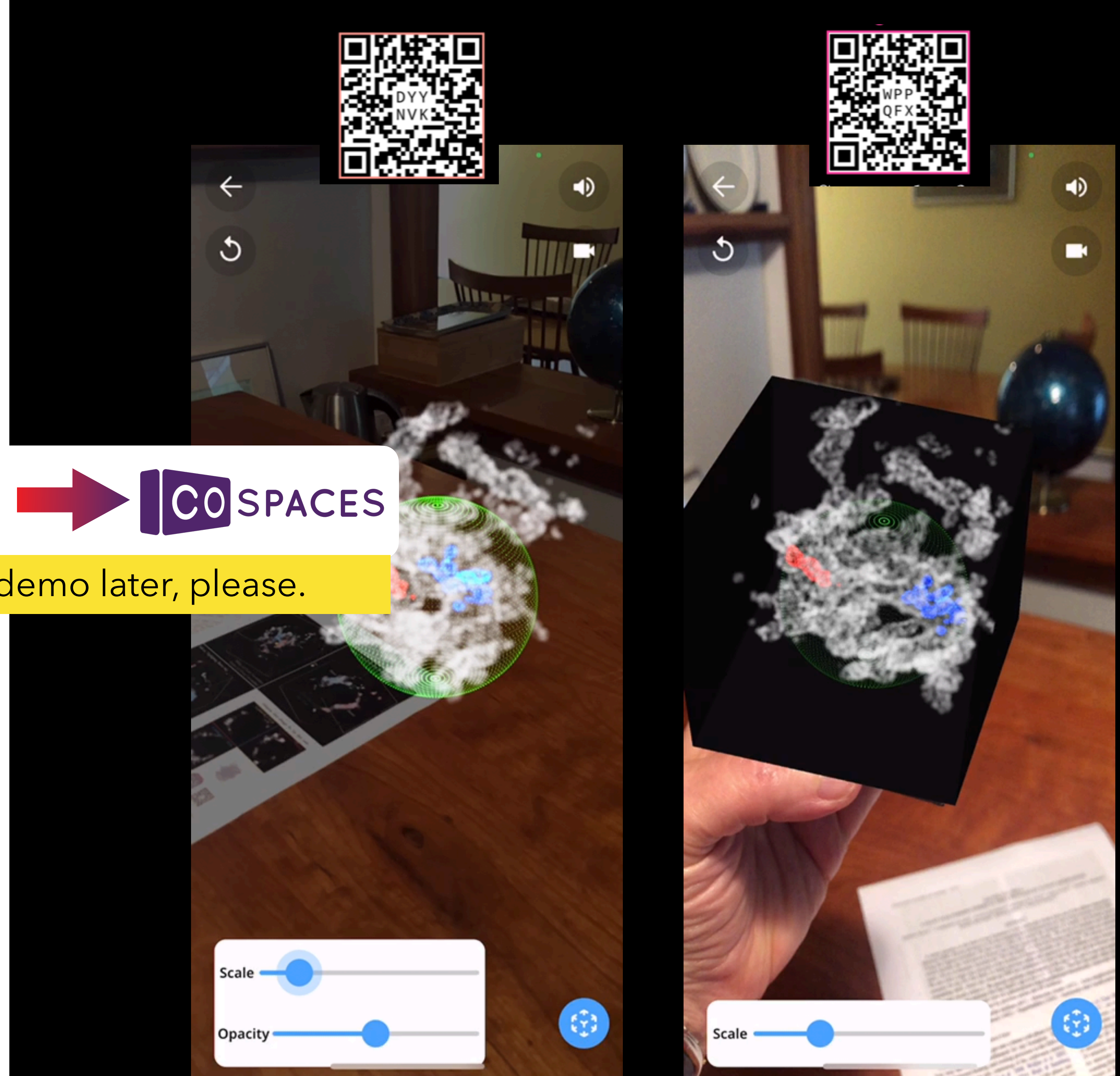


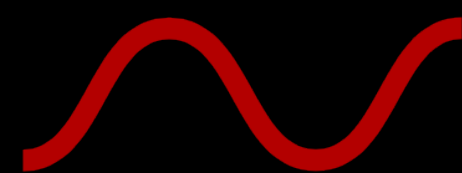


**Figure 2.** 3D views of the Per-Tau shell (for an interactive version<sup>8</sup> of this figure click [here](#)<sup>9</sup>; see Figure 5 for more static visualizations). Plotted are density iso-surfaces at levels  $n = 5 \text{ cm}^{-3}$  (gray) and  $n = 25 \text{ cm}^{-3}$  (color), overlaid with our spherical-shell model, radius  $R_s = 78 \text{ pc}$ , distance from the Sun  $d = 218 \text{ pc}$ . The  $n = 25 \text{ cm}^{-3}$  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  $d \approx 150 \text{ pc}$ , whereas the farthest part extends to  $d \approx 220 \text{ pc}$ .

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

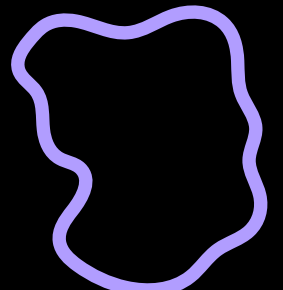




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2021



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2023 and beyond!

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.

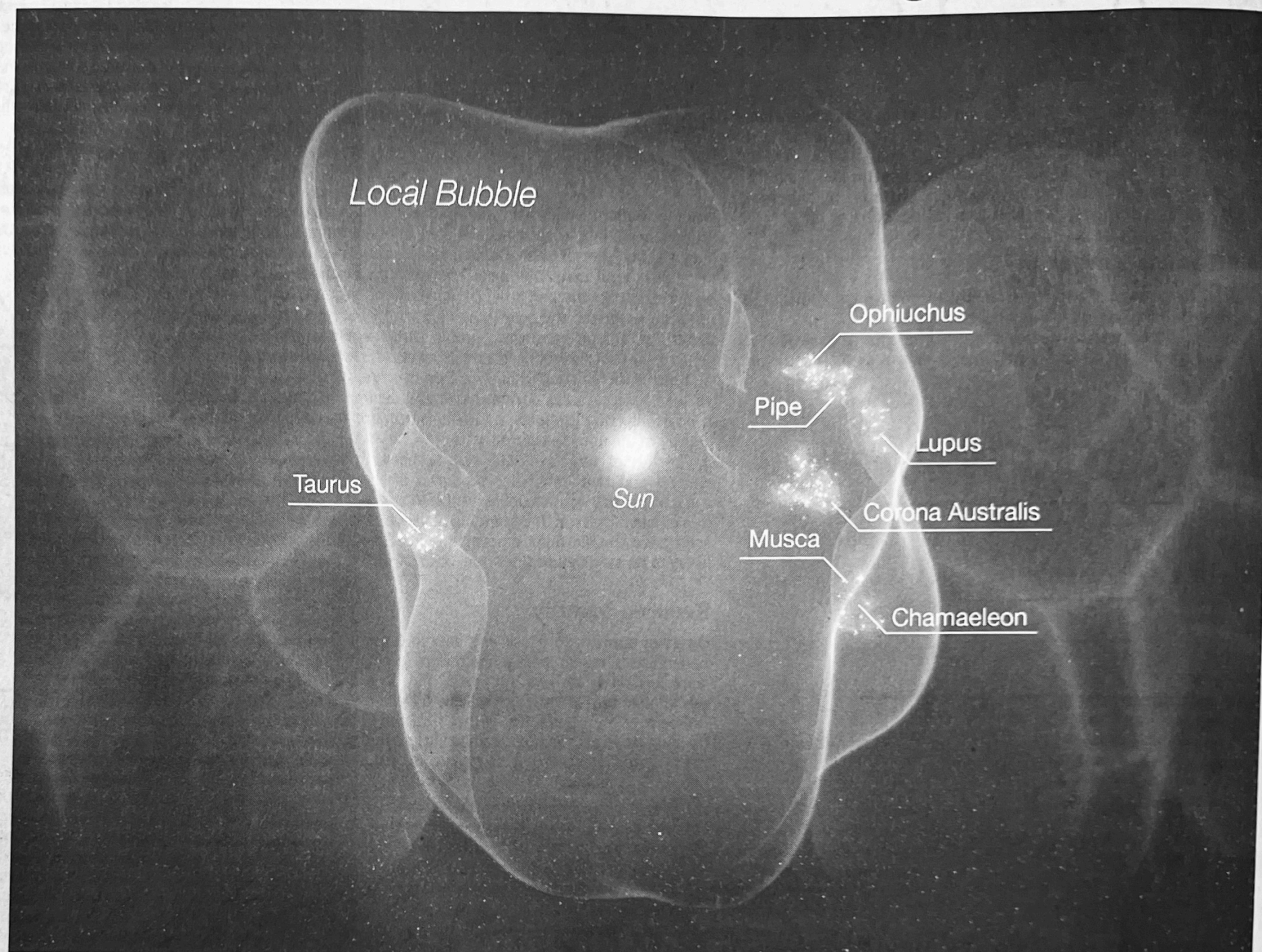
Last year, a group of scientists led by João Alves, an astrophysicist at the University of Vienna announced the discovery of the Radcliffe Wave, an undulating string of dust and gas clouds 9,000 light-years long that might be the spine of our local arm of the galaxy. One section of the wave now appears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

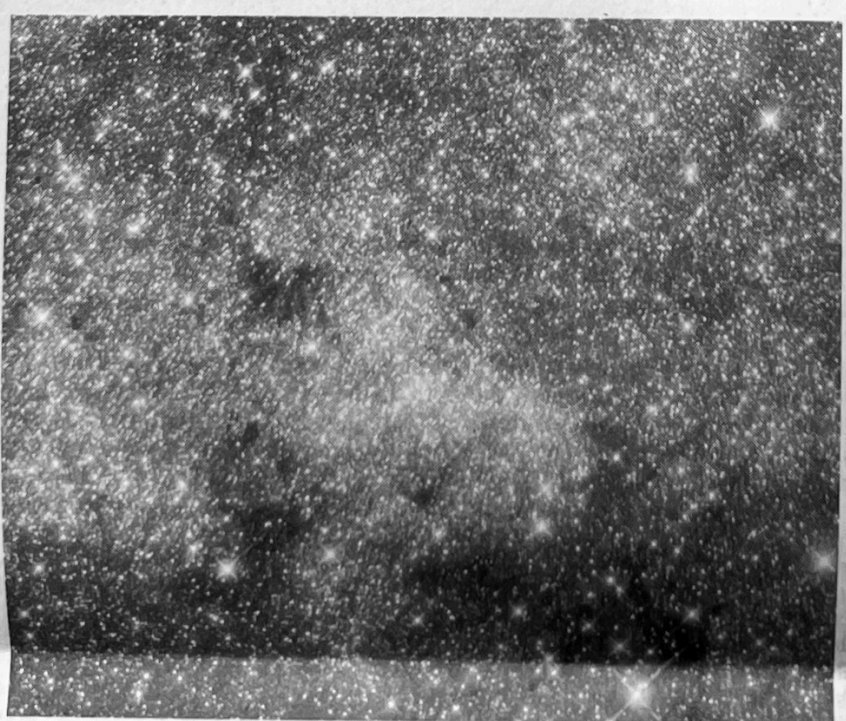
The results, the astronomers write, provide "robust observational support" for a long-held theory that supernova explosions are important in triggering star formation, perhaps by jostling gas and dust clouds into collapsing and starting on the long road to thermonuclear luminosity.

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 (STSC)/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 next generation of stars is securely on tap.

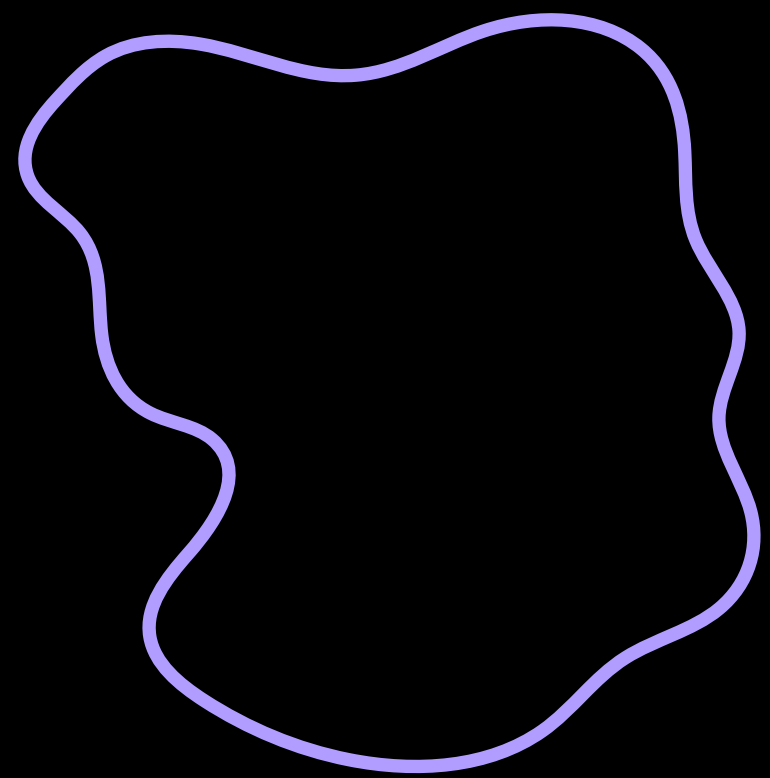
The team plans to go on and map more bubbles in the our Milky Way flute of champagne. There must be more, Dr. Goodman said, because it would be too much of a coincidence for the sun to be smack in the middle of the only one.

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.

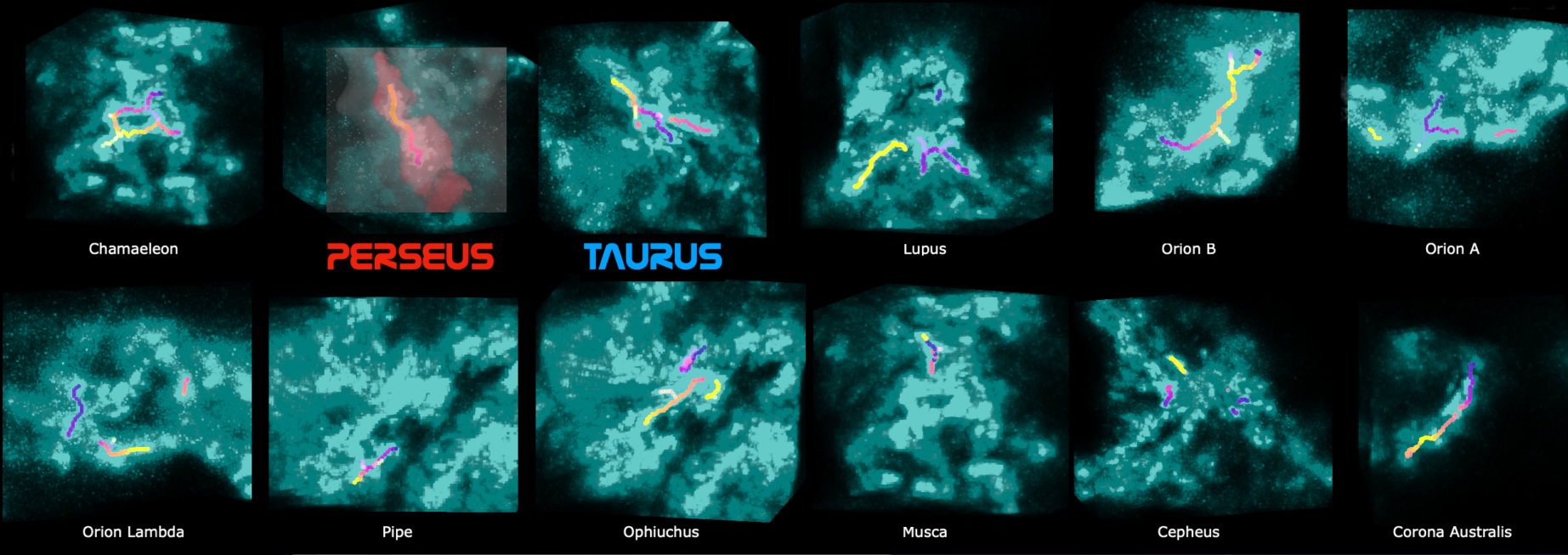
"The sun is moving at a significantly different velocity than the average of the stars and gas in the solar neighborhood," he noted. This would enable it to catch up and pass — or be passed by — the bubble.

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



2022

# The truth...



Plot Layers - 3D Volume Rendering

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- Orion\_B\_Rev2016
- corvus\_spine\_rev2016[HDU1]
- cloud\_outer\_geometry\_compiled[HDU1]
- cloud\_inner\_geometry\_compiled[HDU1]
- Best\_Fit\_Wave\_Model
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Plot Options - 3D Volume Rendering

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min/max: -0.5 at 538.5

stretch: [Slider] 1.00

reference: lha\_2020\_3yr

resolution: 256

Native aspect ratio    Line Width: 1

Perspective     Show axes

Downsample when panning



THE NEW YORK TIMES, TUESDAY, JANUARY 25, 2022

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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 lanky the sun's path really is compared with a simple circle."

NYT, January 25, 2022



2022 LB



Mute   Stop Video   Participants   Chat   Share Screen   Record   Reactions   Leave

2022

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



*Nature* paper by

Catherine **Zucker**<sup>1,6</sup>, Alyssa **Goodman**<sup>1</sup>, João **Alves**<sup>2</sup>,  
Shmuel **Bialy**<sup>1,3</sup>, Michael **Foley**<sup>1</sup>, Joshua **Speagle**<sup>4</sup>,  
Josefa **Grossschedl**<sup>2</sup>, Douglas **Finkbeiner**<sup>1</sup>,  
Andreas **Burkert**<sup>5</sup>, Diana **Khimey**<sup>1</sup> & Cameren **Swiggum**<sup>2</sup>

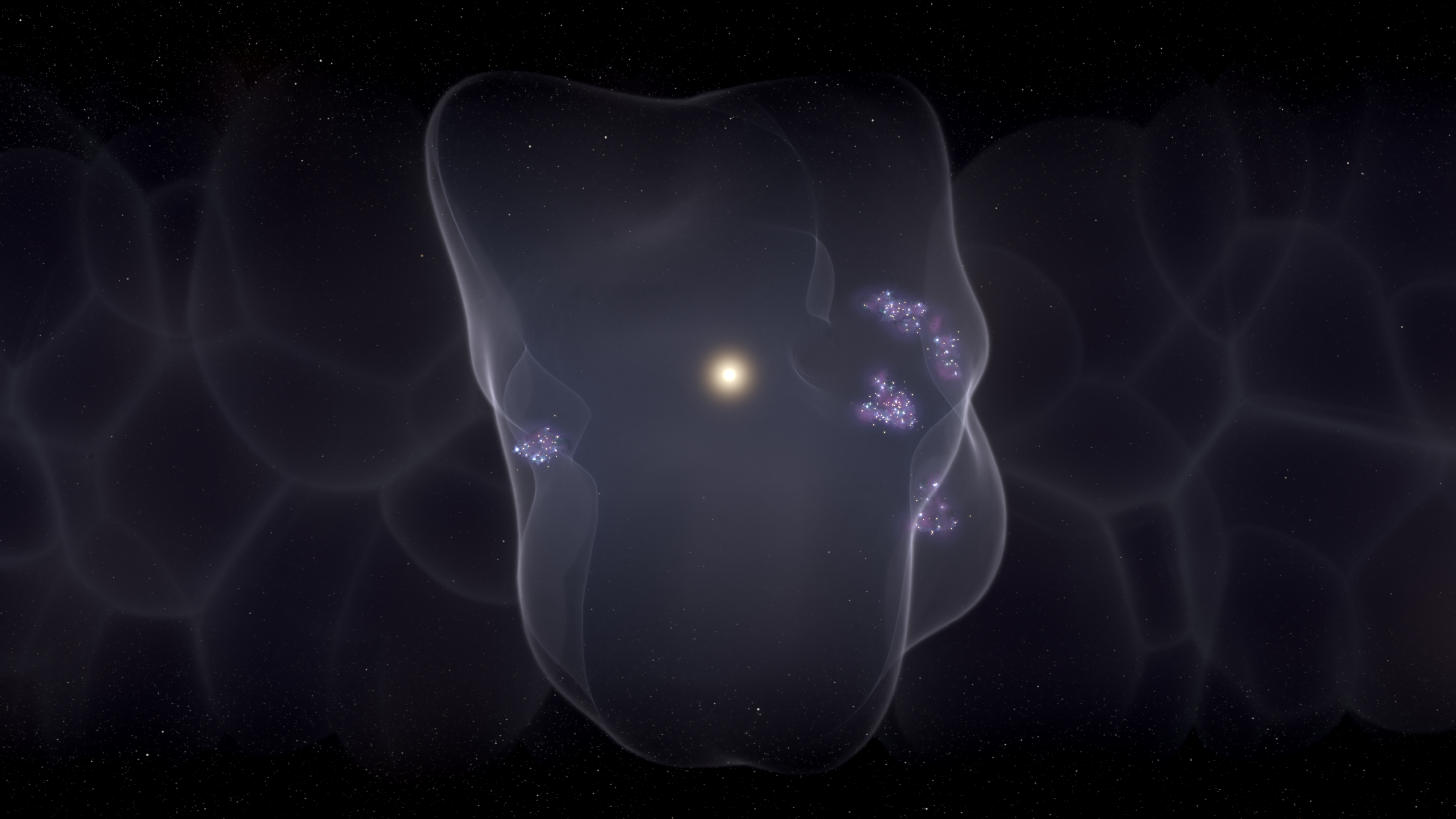
(1) CfA | Harvard & Smithsonian; (2) Univ. Of Vienna;  
(3) University of Maryland; (4) University of Toronto;  
(5) LMU Munich (6) Space Telescope Science Institute

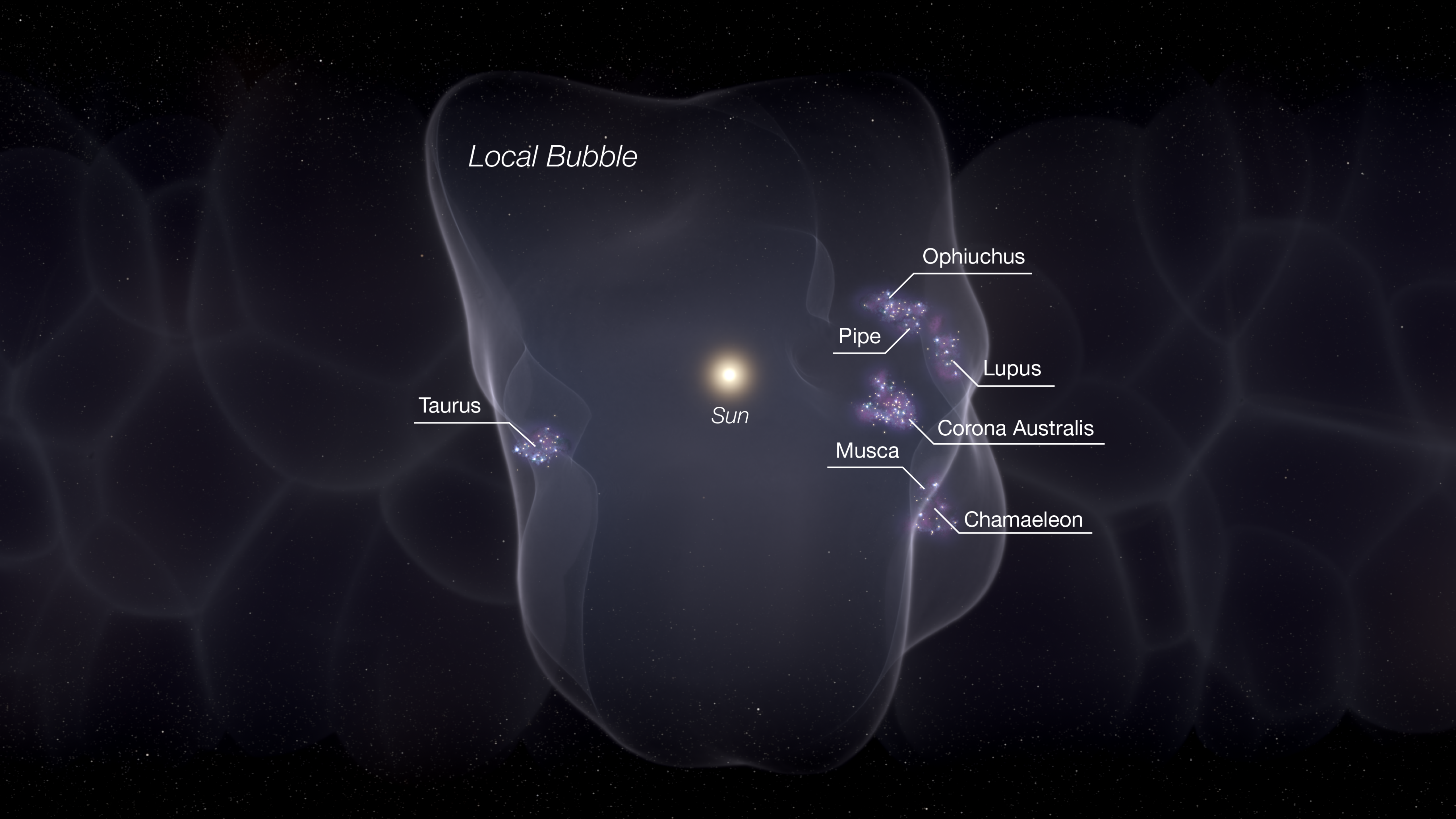
presented by Catherine **Zucker**  
Hubble Fellow, *Space Telescope Science Institute*  
Research Associate, *Center for Astrophysics | Harvard & Smithsonian*

CENTER FOR **ASTROPHYSICS**  
HARVARD & SMITHSONIAN

 **STScI** | SPACE TELESCOPE  
SCIENCE INSTITUTE

*Illustration Credit: Leah Hustak (STScI)*





*Local Bubble*

Taurus

Sun

Ophiuchus

Pipe

Lupus

Corona Australis

Musca

Chamaeleon

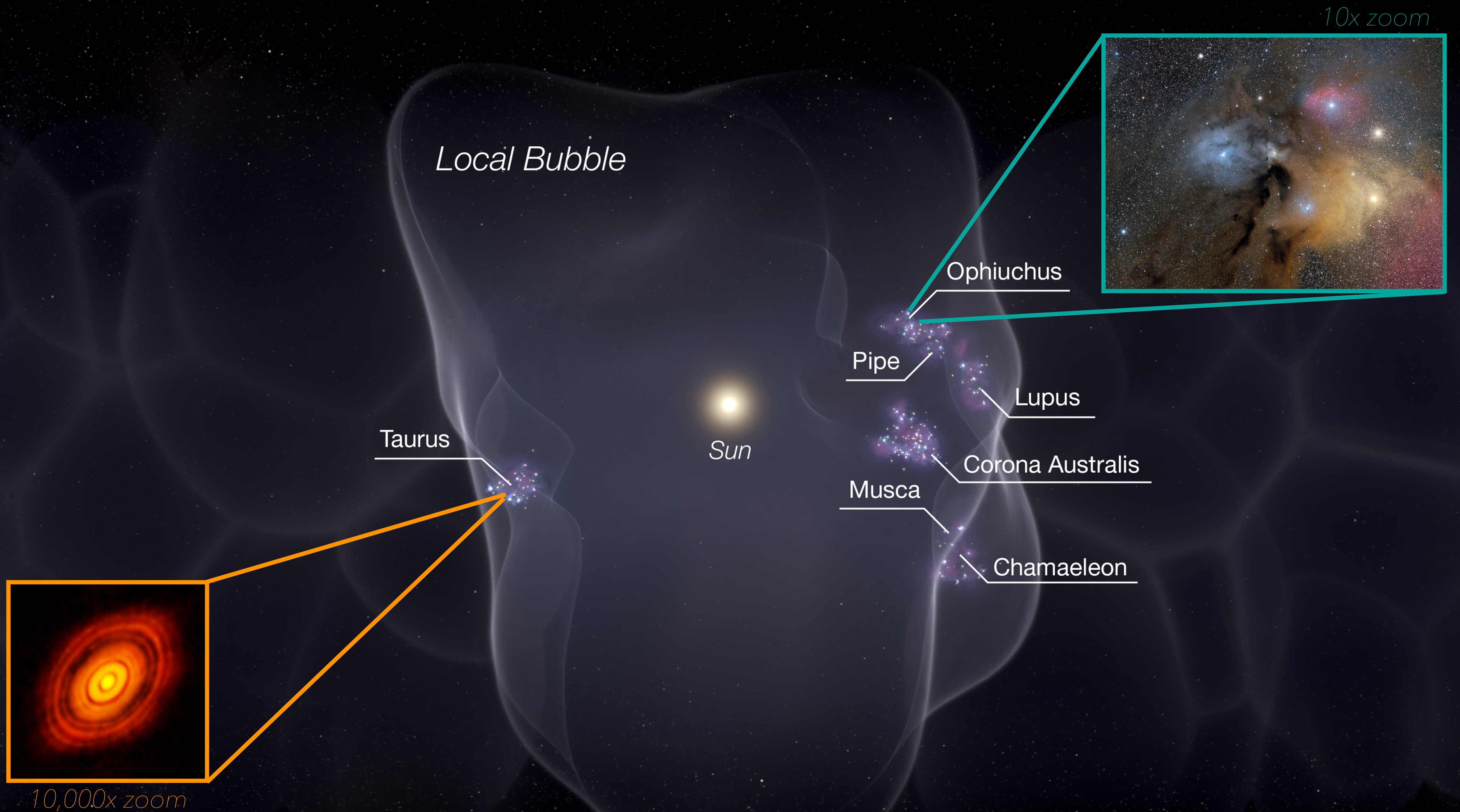
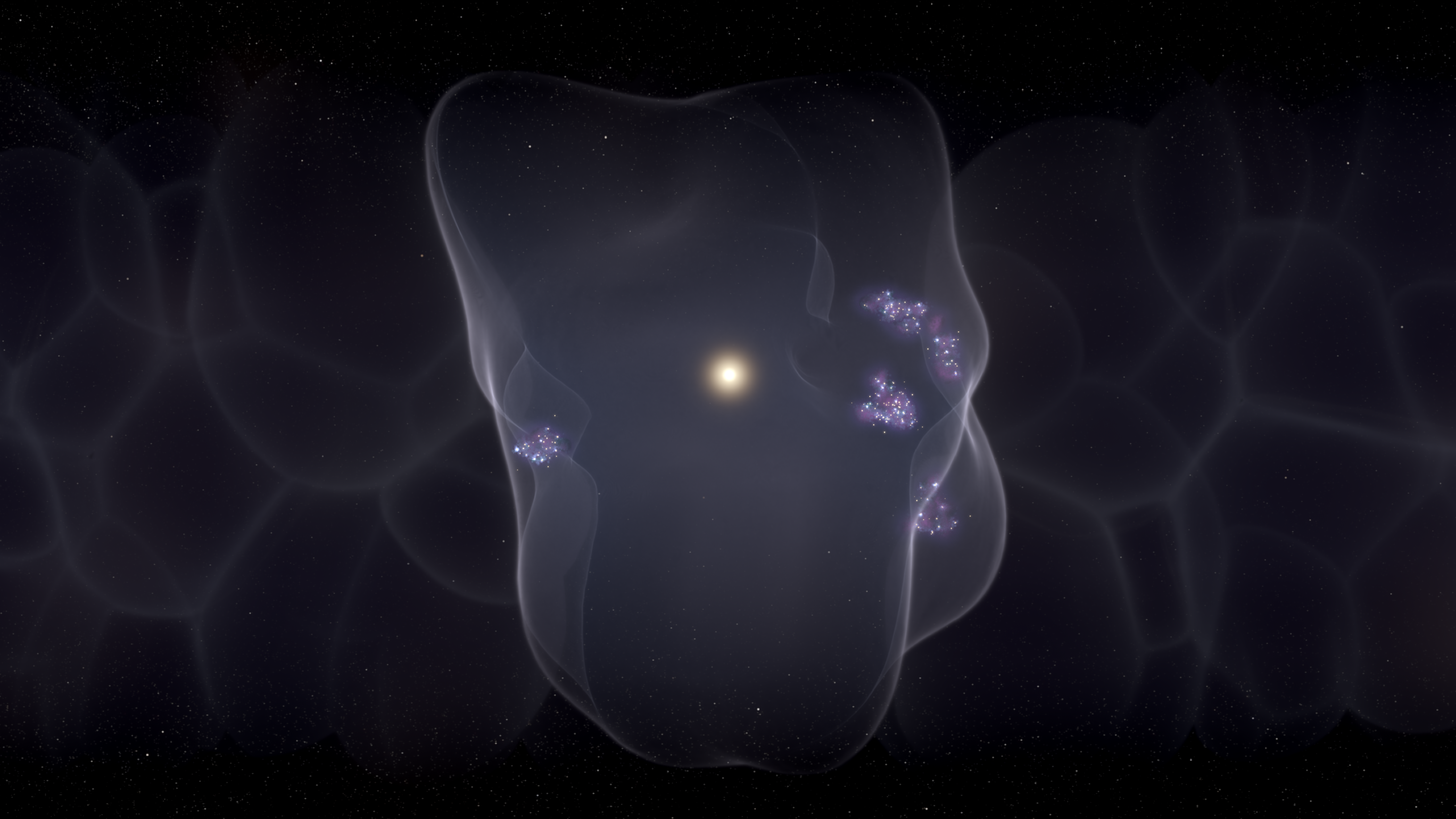
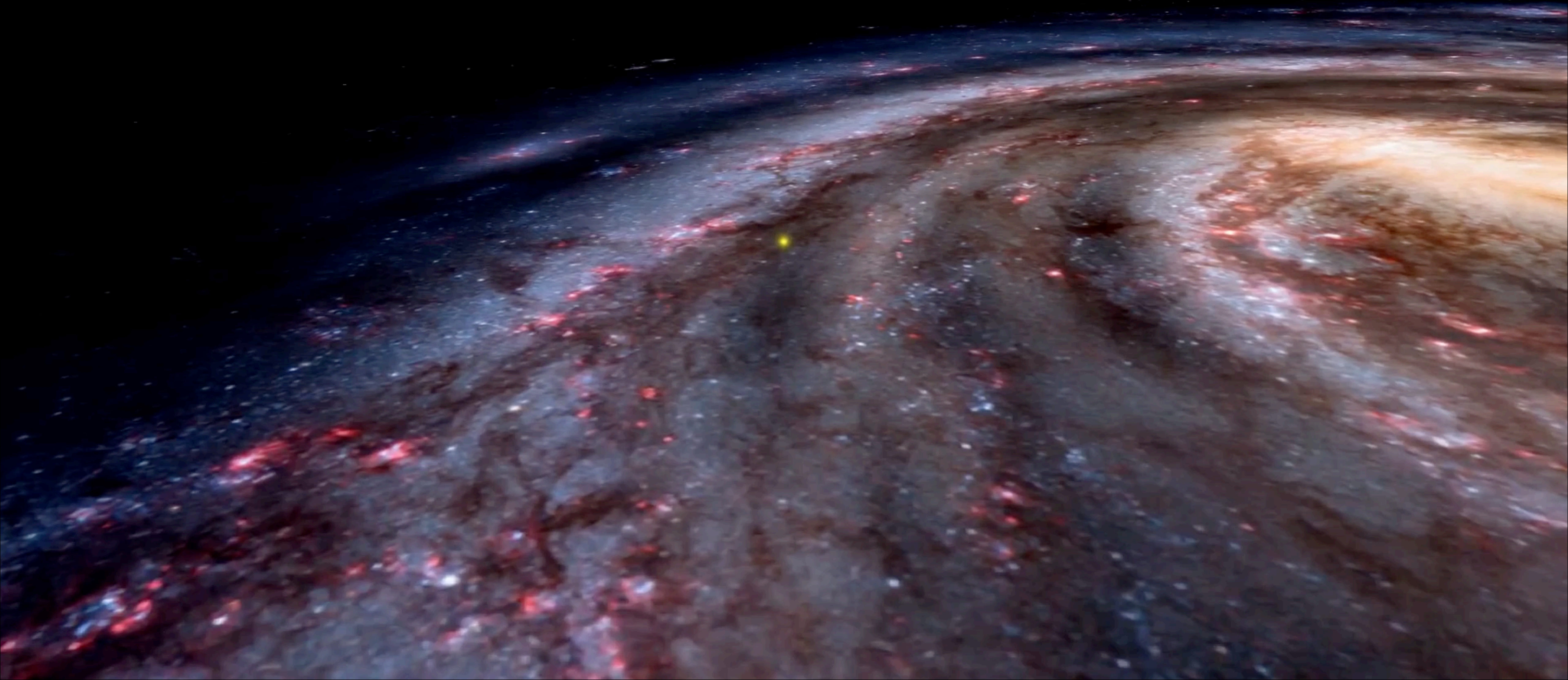


Image credits: Cartoon: Leah Hustak; *HL Tau* disk: ALMA (ESO/NAOJ/NRAO); *Ophiuchus* nebula: Giuseppe Donatiello



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

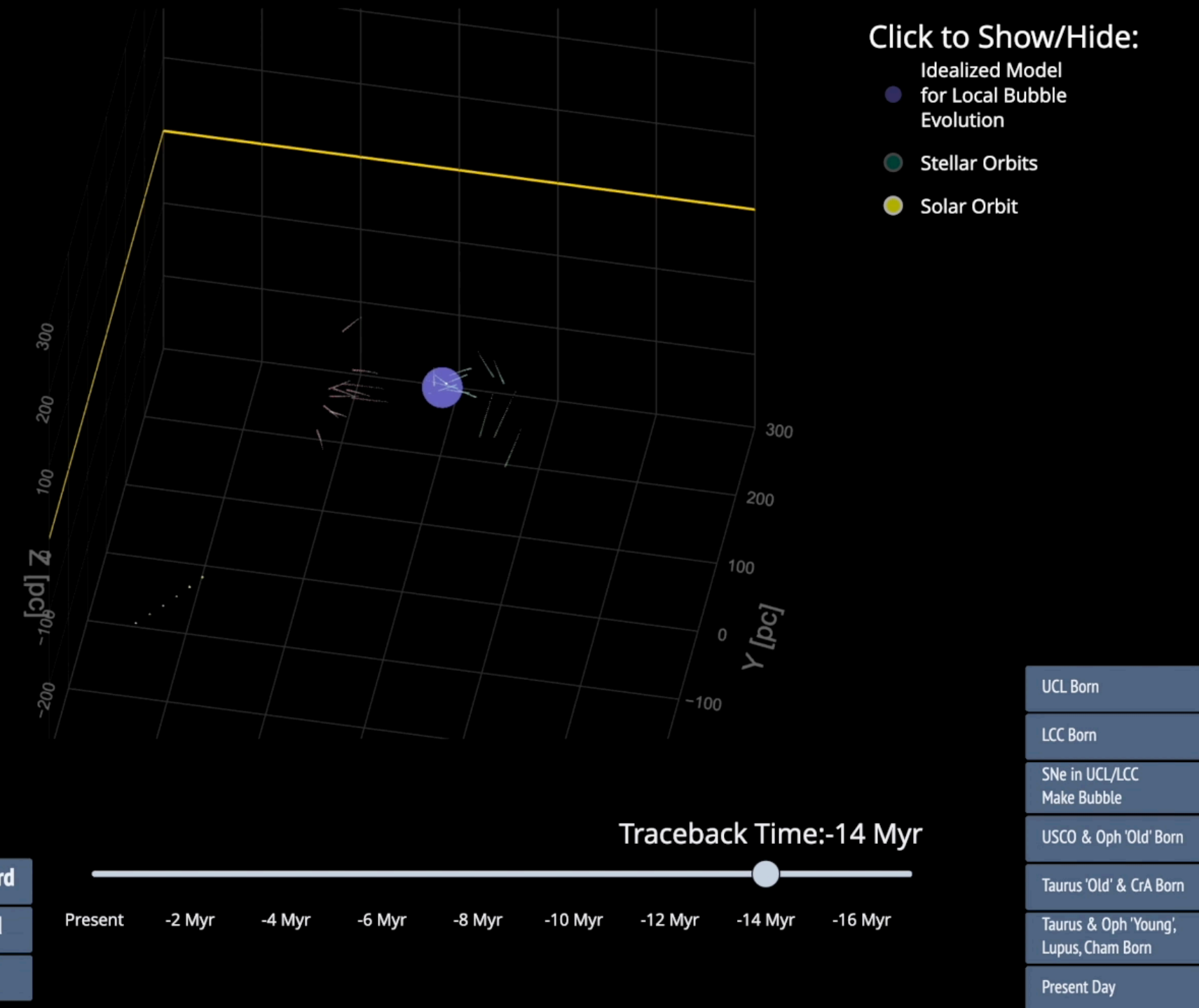
MILLION YEARS AGO

# "Cartoon"

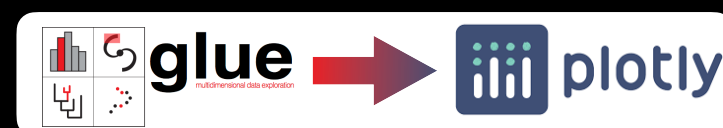


# "Real Data"

(Zucker et al. 2022, *Nature*)



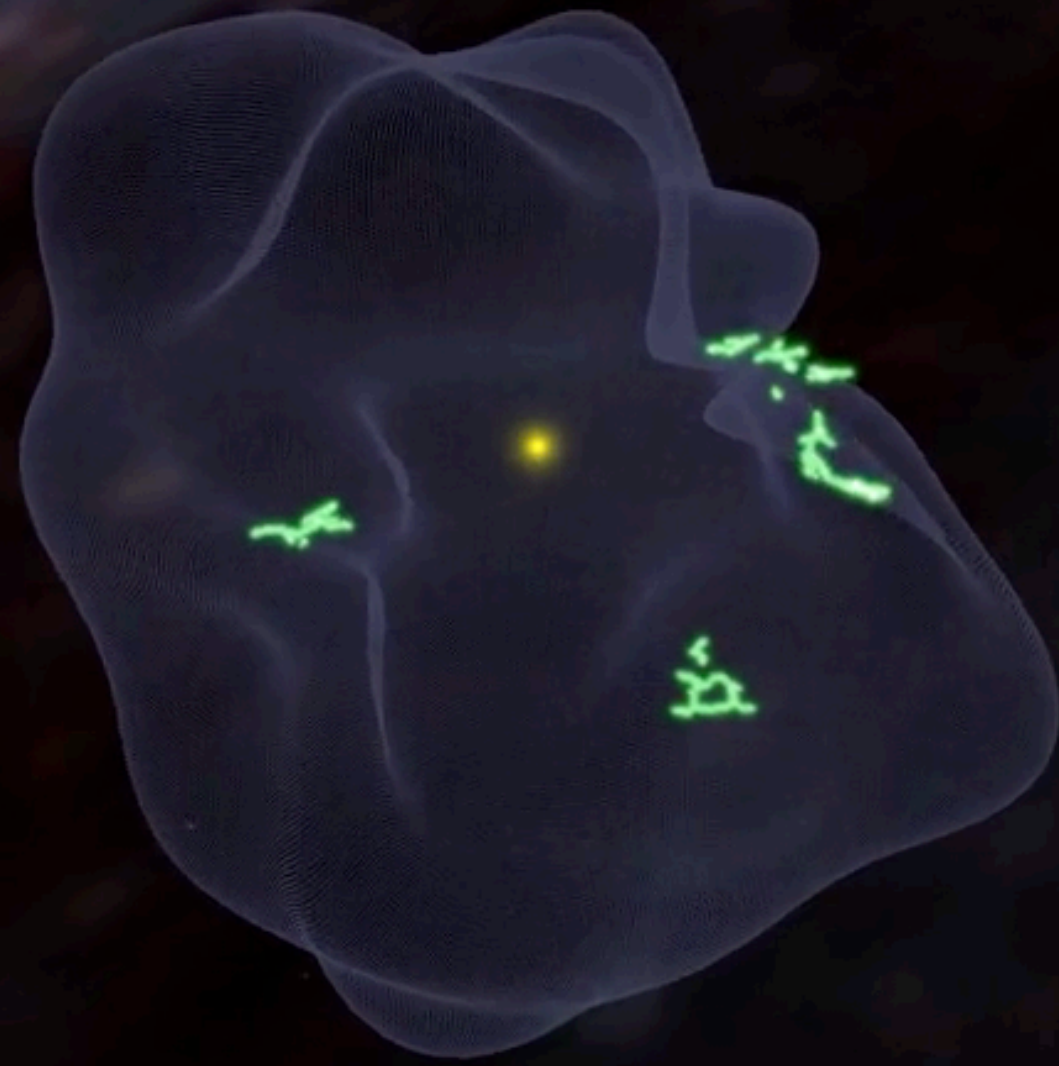
[try the interactive figure]



# *The Local Bubble from the outside in and the inside out*



# *The Local Bubble from the outside in and the inside out*



# 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.

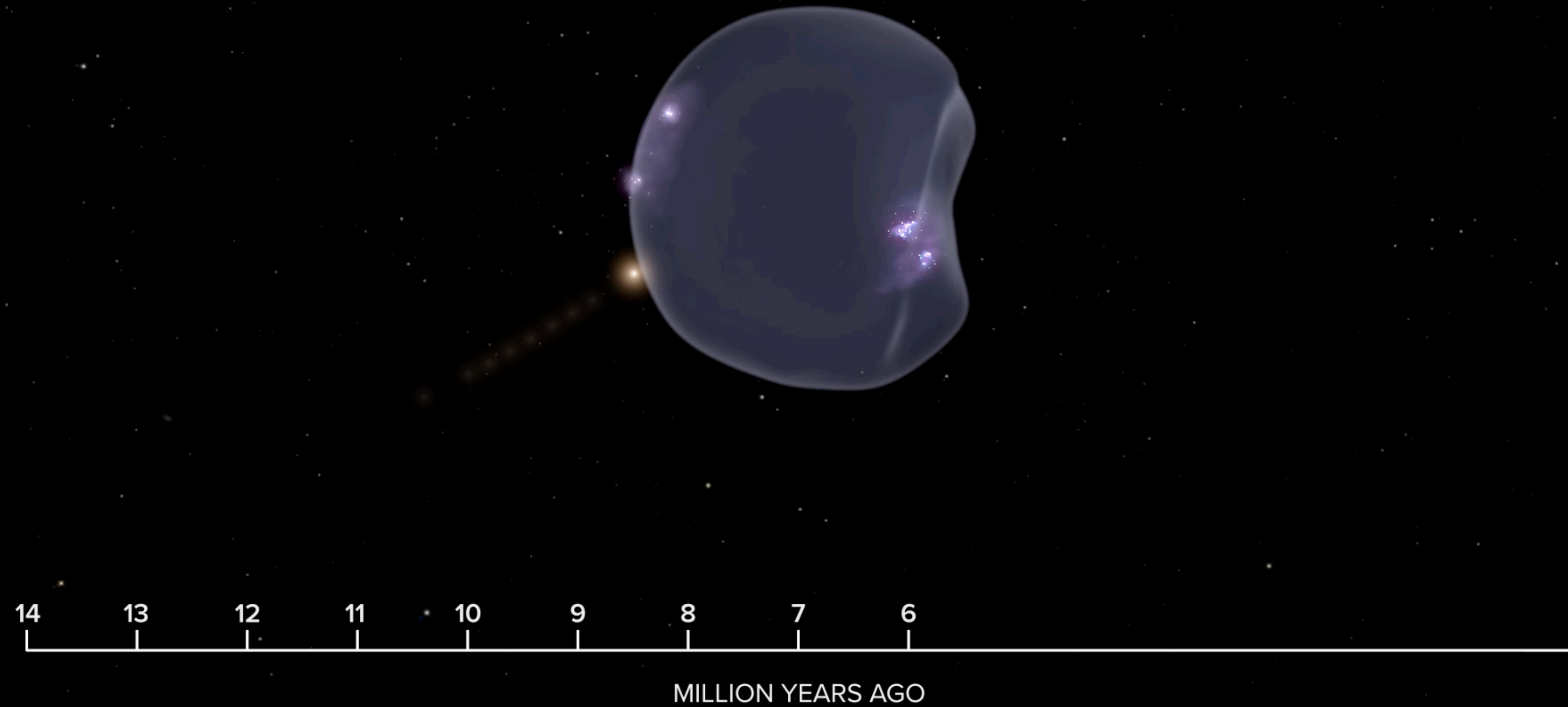
14

MILLION YEARS AGO



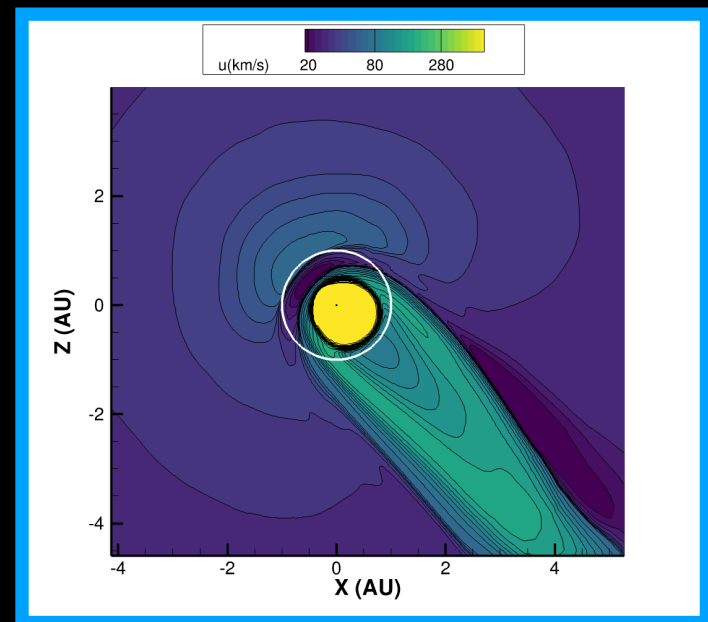
# How did the **Sun** wind up in the bubble? (by accident)

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

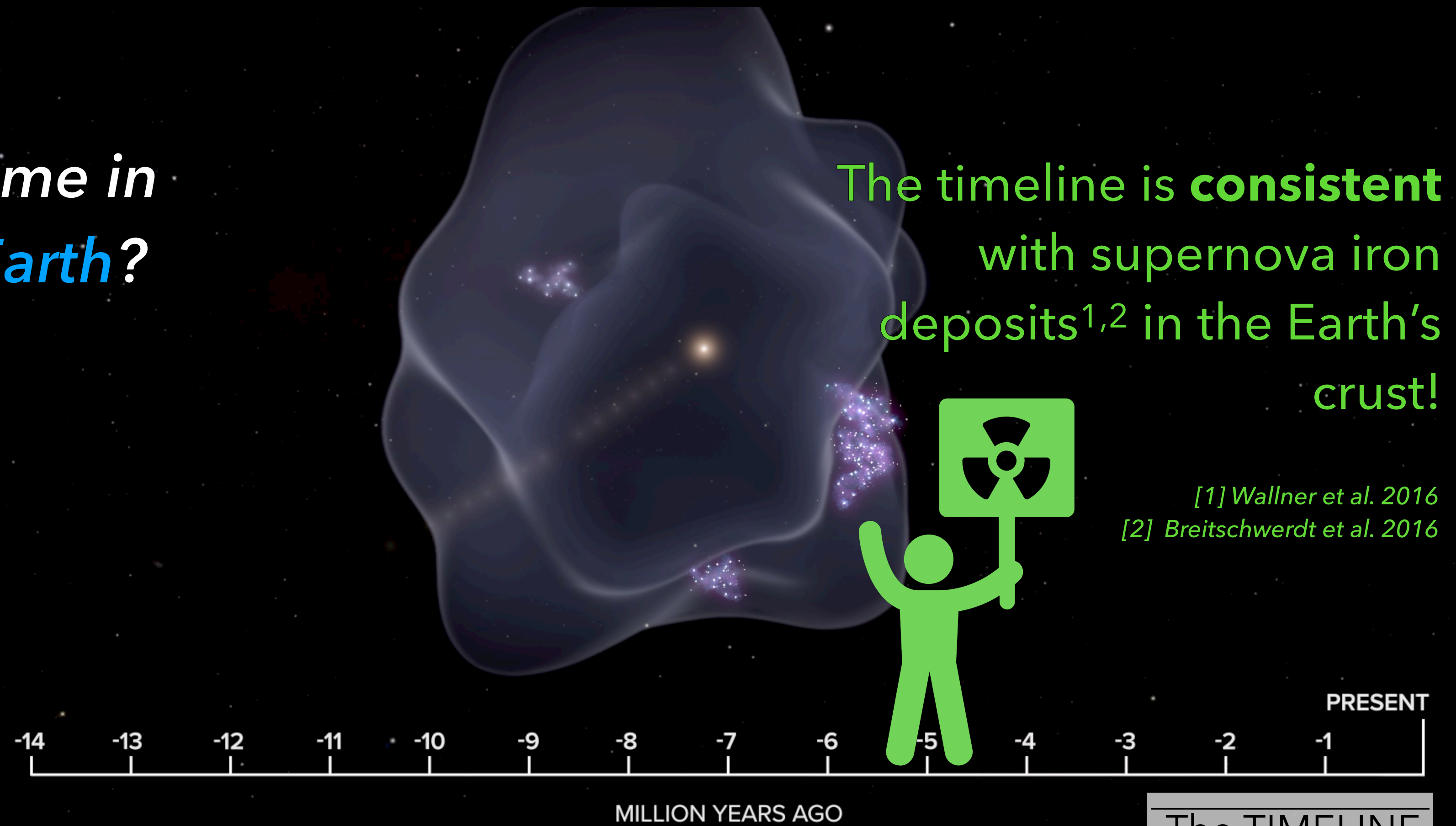


# How did the **Sun** wind up in the bubble? (by accident)

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!)



# So What?

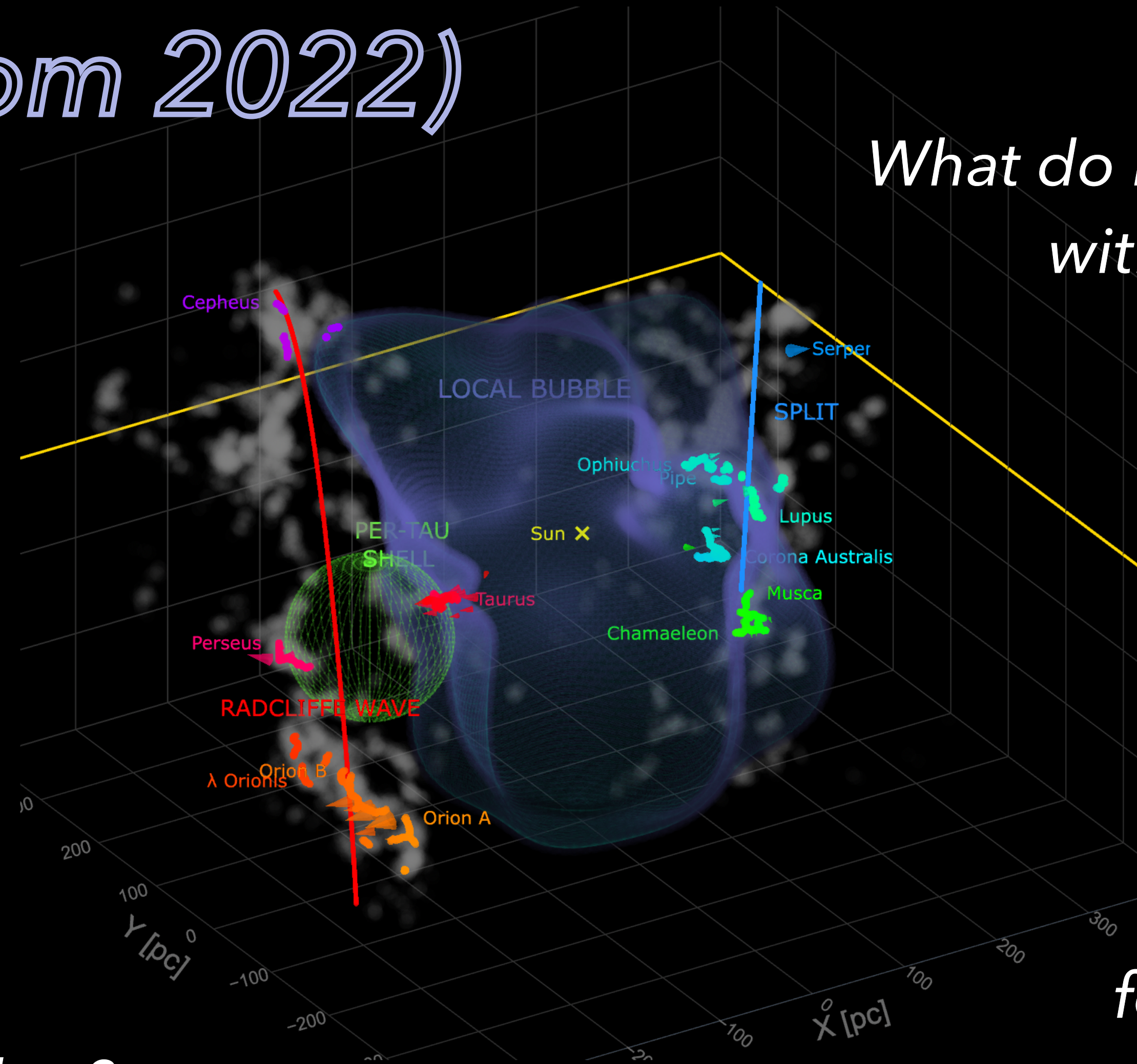
*In the present day, almost every single nearby, young star lies on the surface of the Local Bubble*

*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)



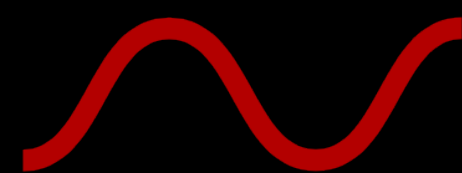
What do bubbles have to do with *SPIRAL* structure? Anything?

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*?

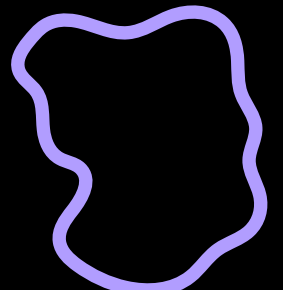
[try the interactive figure]



2020  
2024



2021



2022  
2024

**MILKYWAY3D.org**

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**

assembling data as a community, using modern, open-source practices  
**glue**  
 LIVE  
 making data accessible online for decades  
 Lead: Alyssa Goodman, UTA

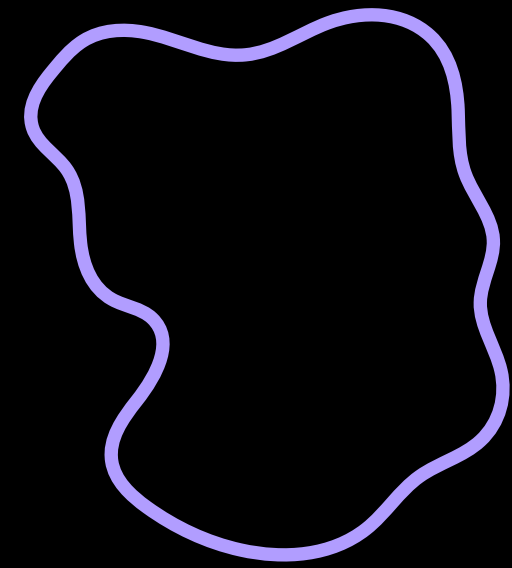
enabling studies of how galaxies turn gas into stars, using...  
 stellar positions, clusters, motions  
 topology, positions & motions of (long) features  
 tracers of feedback & magnetic fields  
 details on star-forming regions...and more!  
 Lead: Catherine Zucker, CFA

connecting real research data, software, and science to learners  
 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 CIA (Jonathan Carrillo, Alyssa Goodman, Ralf Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), AMNH (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty), Linköping University (Alex Bock), University of Vienna (Joao Alves, Sebastian Ritzko), glue solutions, inc./Apatia (Thomas Robitaille), University of Wisconsin, Whitewater (Bob Benjamin), STScI/Johns Hopkins (Josh Peek), Max Planck IIA (Gordian Edenhofer), Northeastern University (Michelle Borkin), and YOHJ

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

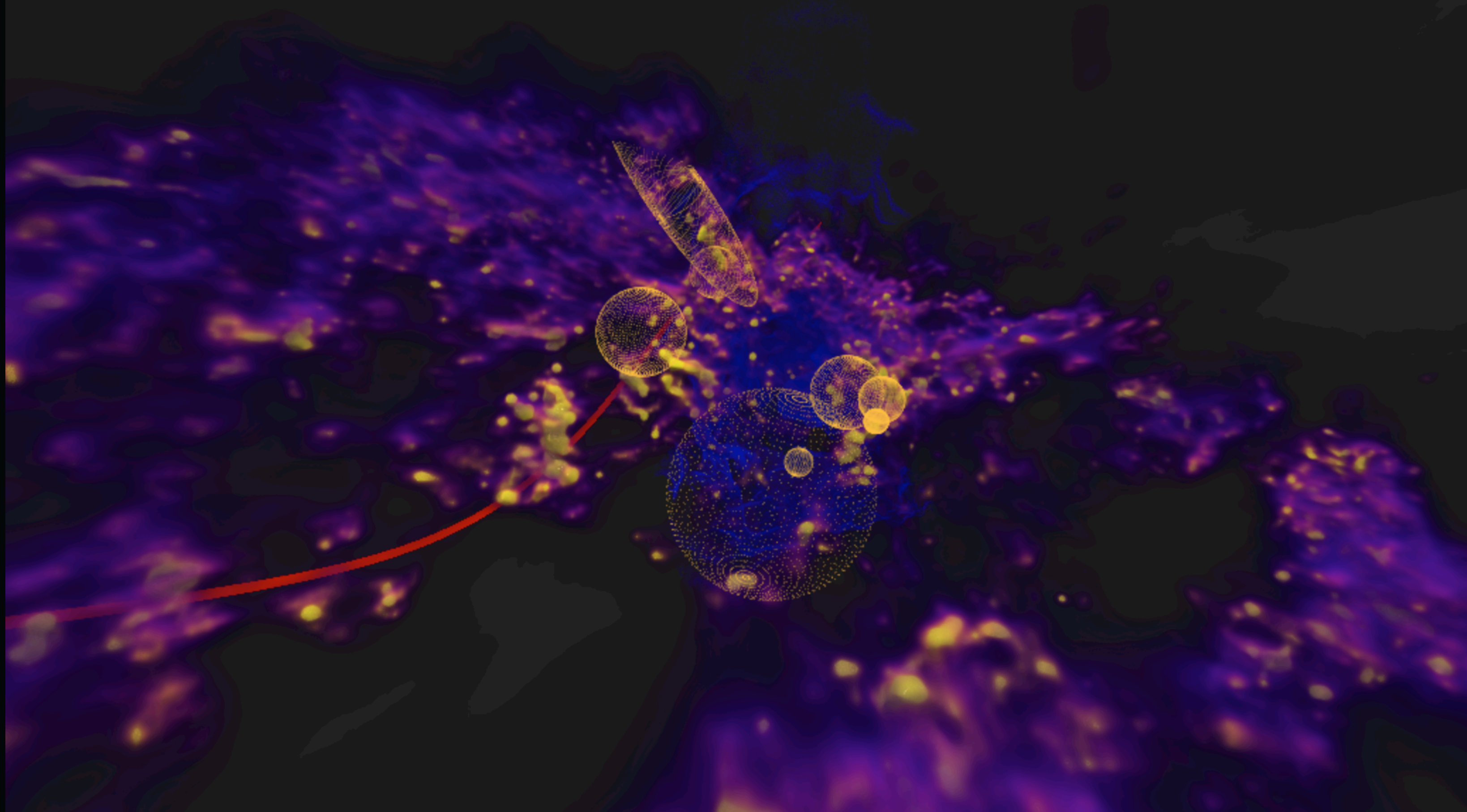
2023 and beyond!



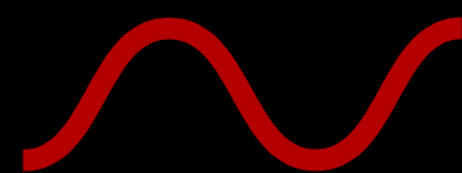
We now think the LOCAL BUBBLE is actually a LOCAL CHIMNEY

Thanks to O'Neill et al.

2024



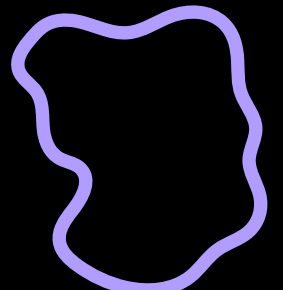
O'Neill et al. Local Chimney 2024 +++



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2024



2021



2022  
2024

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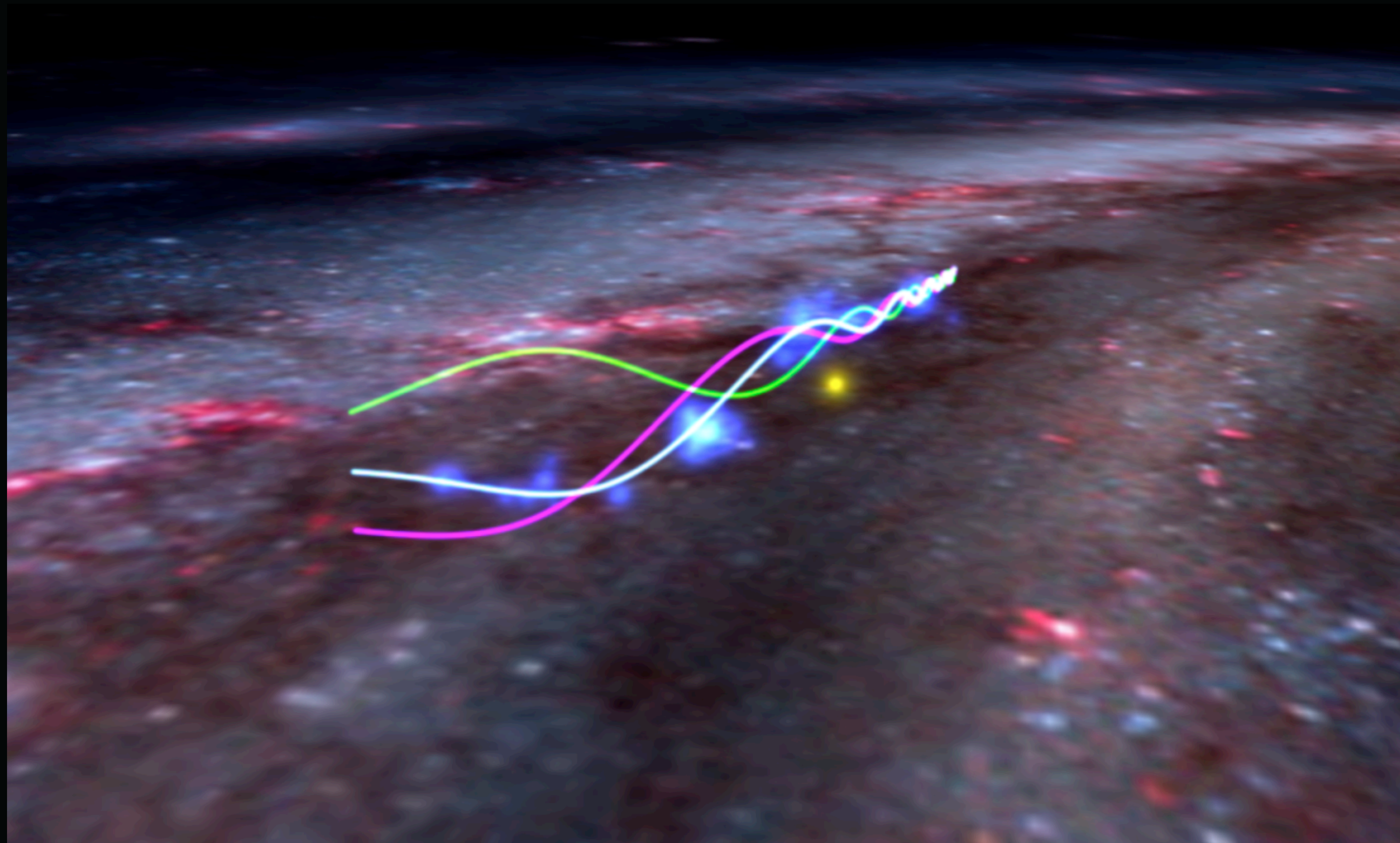
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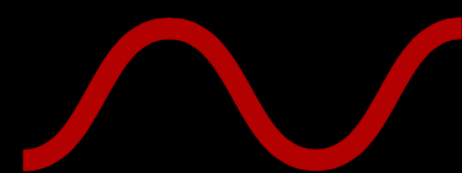
2023 and beyond!





Konietzka et al. — Oscillating RadWave *Nature*, 2024

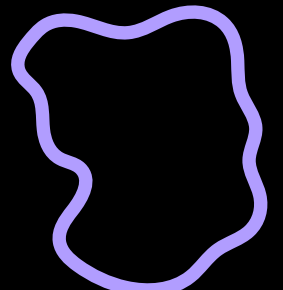




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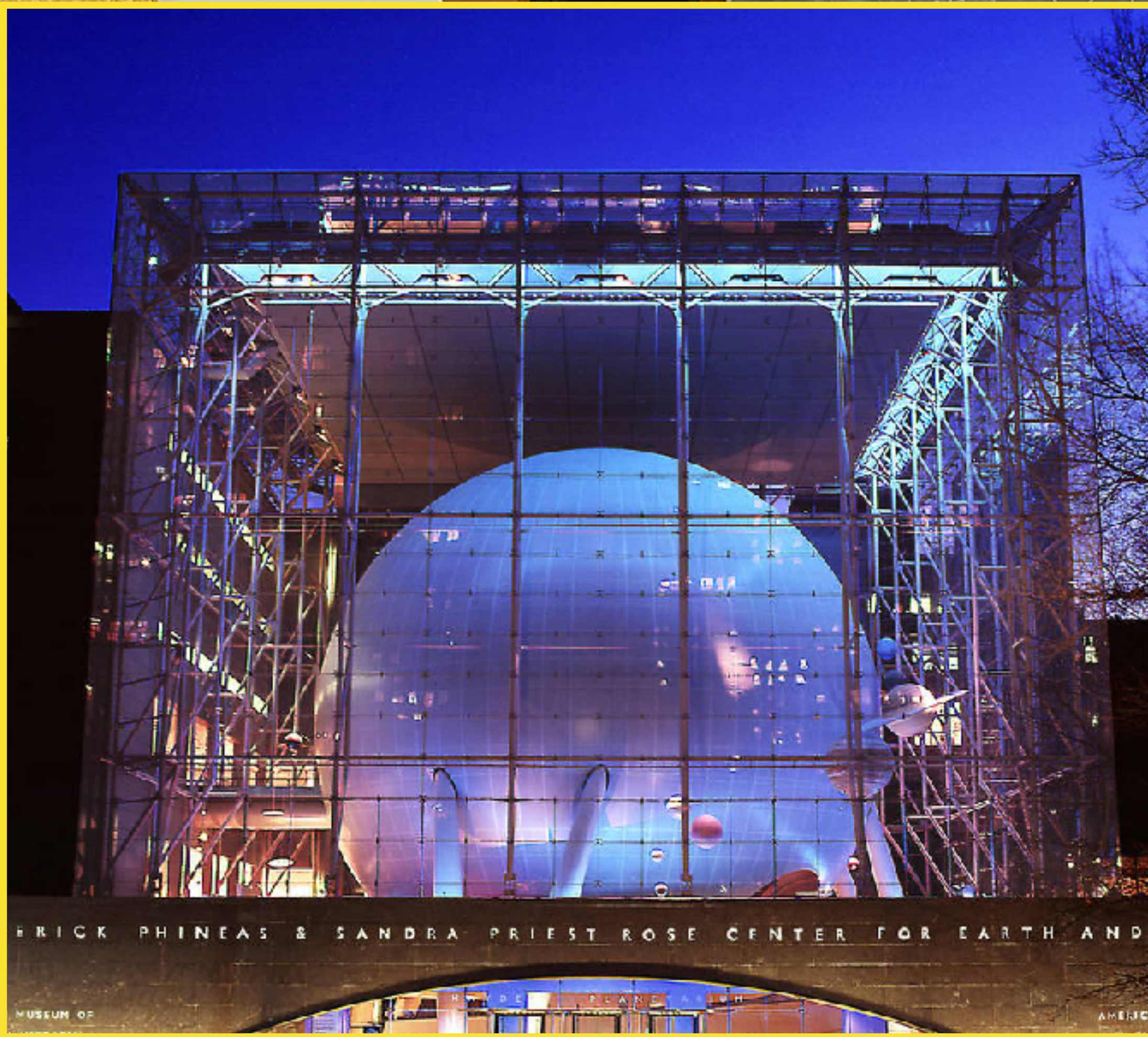
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2023 and beyond!

# Stay-tuned for more at MilkyWay3D.org



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INFRASTRUCTURE	SCIENCE	EDUCATION & OUTREACH
<p>assembling data as a community, using modern, open-source practices</p> <div style="text-align: center;"> </div> <p>linking position and motion across dimensions, using the plug-in architecture enabled by glue (plug-ins include WorldWide Telescope, OpenSpace &amp; more)</p> <div style="text-align: center;"> </div> <p>making data accessible online for decades</p> <p style="text-align: center;"><b>Lead: Alyssa Goodman, CFA</b></p>	<p>enabling studies of how galaxies turn gas into stars, using...</p> <div style="text-align: center;"> </div> <p>stellar positions, clusters, motions</p> <div style="text-align: center;"> </div> <p>topology, positions &amp; motions of (long) features</p> <div style="text-align: center;"> </div> <p>tracers of feedback &amp; magnetic fields</p> <div style="text-align: center;"> </div> <p>details on star-forming regions...and more!</p> <p style="text-align: center;"><b>Lead: Catherine Zucker, CFA</b></p>	<p>connecting real research data, software, and science to learners</p> <div style="text-align: center;"> </div> <p>real-time data exploration anywhere, including in planetaria</p> <div style="text-align: center;"> </div> <p>"Cosmic Data Stories" teach data science using astronomical data &amp; tools</p> <p style="text-align: center;"><b>Lead: Jackie Faherty, AMNH</b></p>
<p>Join us, contribute, and yes, you get a T-Shirt.</p> <div style="text-align: right;"> </div>		

TEAM: Harvard/Smithsonian CFA (Jonathan Carilli, Alyssa Goodman, Rafi Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), AMNH (Brian Abbott, Michal Acinapura, Carter Emmart, Jackie Faherty), Linköping University (Alan Bock), University of Vienna (João Alves, Sebastian Rätzsch), glue solutions, Inc./Aperis (Thomas Robitaille), University of Wisconsin, Whitewater (Bob Benjamin), STScI/Johns Hopkins (Josh Peck), Max Planck IFA (Gordian Edenhofer), Northeastern University (Michelle Borkin), and YOU!



- ### Data Collection
- Foley2022\_arXiv\_2212.01405\_OrionShell\_MW3D[HDU1]
  - 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
- Edenhofer\_2023\_3D\_Dust\_XYZ\_Revised-2
  - Zucker2021\_ApJ\_919\_35\_spines\_MW3D[HDU1]
  - Bialy2021\_ApJL\_919\_L5\_MW3D[HDU1]
  - Pelgrims2020\_A+A\_636\_A17\_lmax10\_MW3D[HDU1]
  - Alves2020\_Nat\_578\_237\_MW3D[HDU1]
  - Leike2020\_A+A\_639\_A138\_xyz\_cube\_MW3D

Attribute: PRIMARY

Limits: 5.89626e-08 0.00643762

Color:

### Plot Options - 3D Volume Rendering

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**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

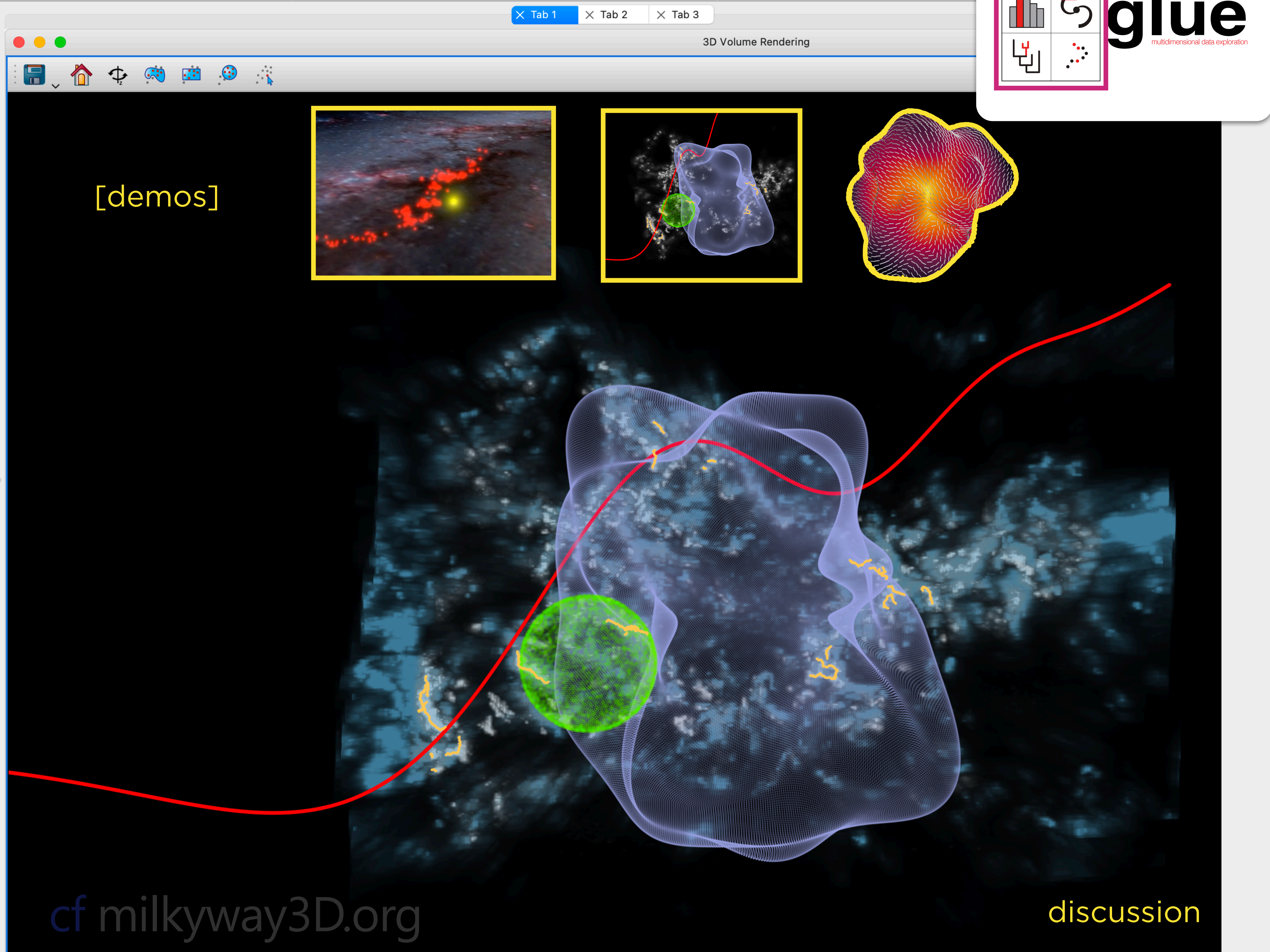
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resolution: 256

Native aspect ratio Line Width 1

Perspective  Show axes

Downsample when panning





## WHAT COMES NEXT IN THIS LIST OF HARVARD COLLEGE OBSERVATORY'S TRADITION OF DATA SHARING?

The history of catalogs and data sharing at the Harvard College Observatory (HCO) is a fascinating story of innovation, collaboration, and significant contributions to the field of astronomy. Here's a concise overview:

### ### Early Beginnings

- **1839**: The Harvard College Observatory was founded, and from its inception, it was at the forefront of astronomical research. Under the leadership of directors like William Cranch **Bond**, the observatory began its tradition of meticulous sky observation and data recording.

### ### Henry Draper Catalog

- **1886-1924**: A major project undertaken by the HCO was the Henry Draper Catalog, initiated by Edward Charles Pickering. This ambitious effort aimed to catalog the spectral types of as many stars as possible, using the photographic plates that the observatory collected. Named after Henry Draper, a pioneer in astrophotography, the catalog eventually listed more than 225,000 stars and was fundamental in establishing the field of spectroscopic astronomy.

### ### Women "Computers"

- **Late 1800s - Early 1900s**: Under Pickering's direction, the observatory employed a group of women known as the "Harvard Computers." These women, including notable astronomers such as Annie Jump Cannon, Henrietta Swan Leavitt, and Williamina Fleming, processed astronomical data and made substantial contributions to star classification and the understanding of stellar and galactic properties. Their work was critical for the success of the Draper Catalog and other publications.

### ### Photographic Plate Collection

- **1885 Onwards**: HCO amassed a vast collection of photographic plates, which remains one of the largest in the world. This collection has been crucial for historical astronomical data and has supported various research projects over the decades.

### ### Data Sharing and Collaboration

- **20th Century**: The HCO has been a leader in data sharing, contributing to and participating in several international projects and collaborations. Its extensive archival collections have been used by researchers worldwide to track changes in star brightness, positions, and other phenomena over time.

### ### DASCH Project

- **2004 Onwards**: The Digital Access to a Sky Century @ Harvard (DASCH) project began with the goal of digitizing the observatory's collection of over 500,000 glass photographic plates. This initiative aims to make a century's worth of astronomical data accessible to the global scientific community, enabling long-term astronomical studies and opening up new possibilities for research in variable stars, galactic structure, and other areas.

### ### Contemporary Contributions

- **21st Century**: Harvard continues to be a hub for astronomical research and data sharing, involving modern telescopes and data analysis technologies. It collaborates with institutions worldwide, contributing to global astronomy projects and furthering the accessibility of astronomical data.

The Harvard College Observatory's commitment to data collection, cataloging, and sharing has made it a cornerstone institution in the history of astronomy. Its contributions have shaped the way astronomical data is gathered, analyzed, and shared, significantly



# Mapping the Milky Way Galaxy from the Inside Out

*Prof. Alyssa Goodman, Harvard/CfA, the MilkyWay3D.org team + OpenAI*

extra slides