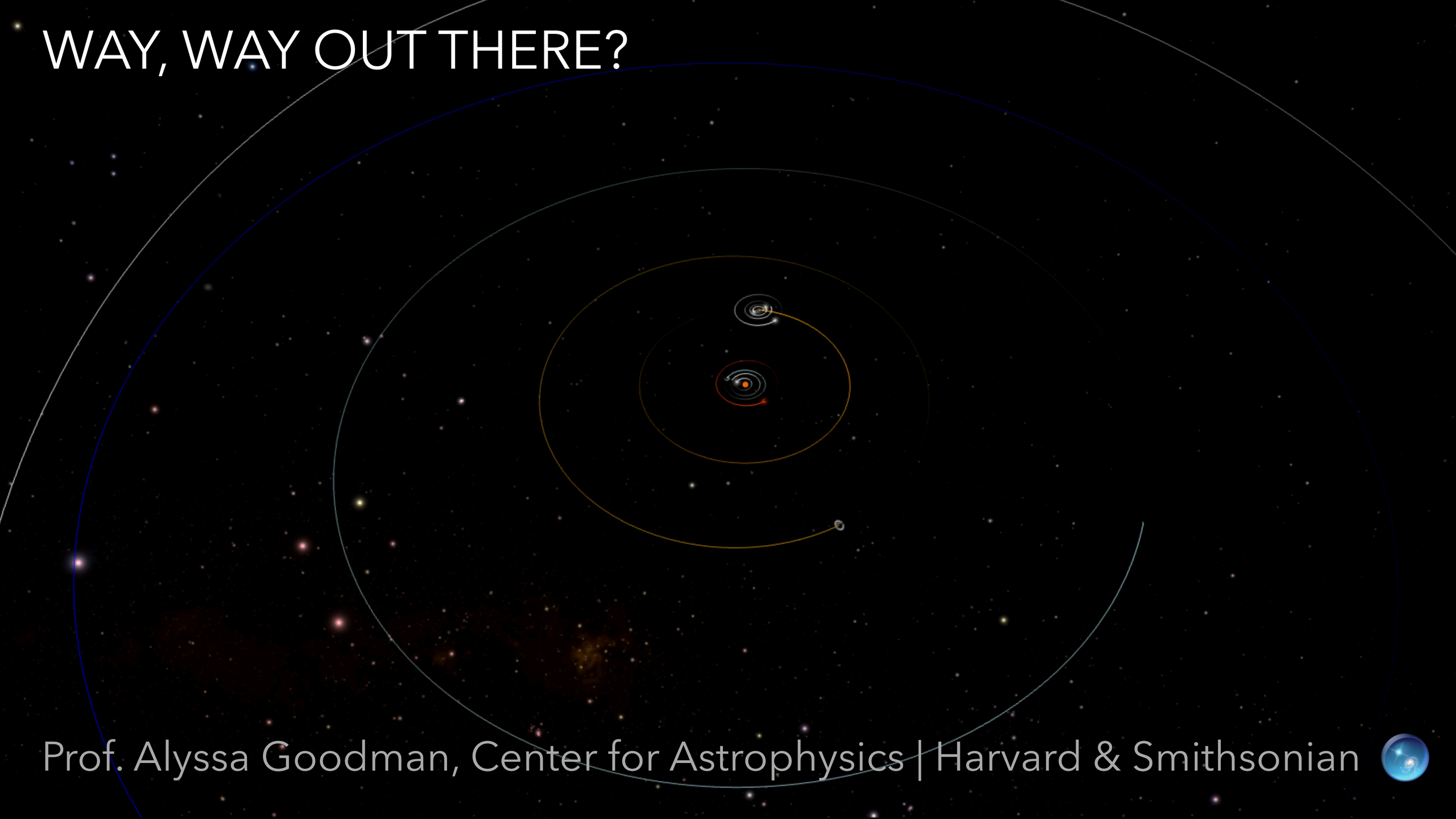
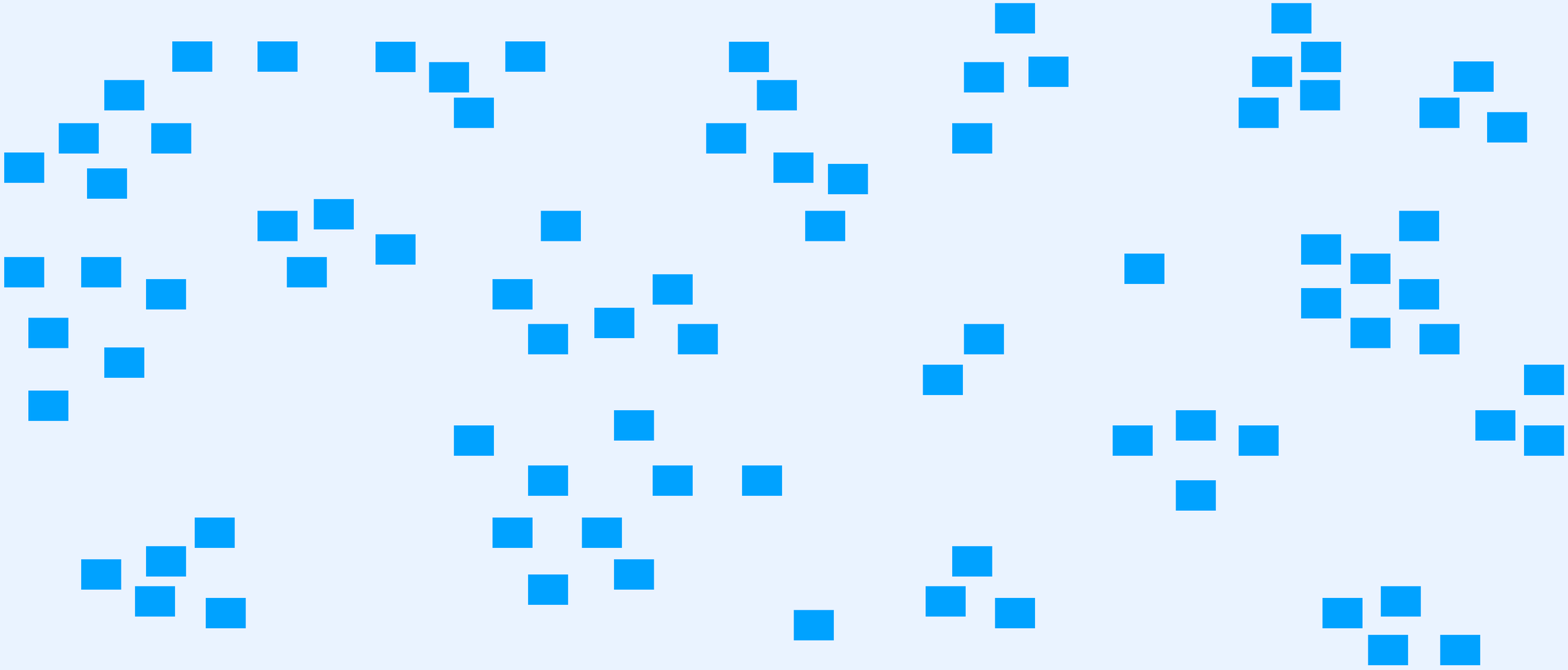
WAY, WAY OUT THERE?



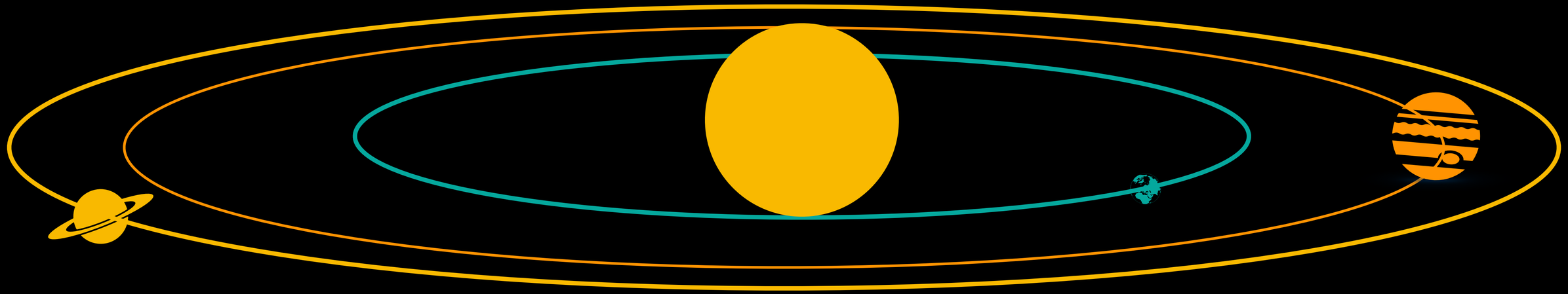
Prof. Alyssa Goodman, Center for Astrophysics | Harvard & Smithsonian

WAY, WAY OUT THERE?



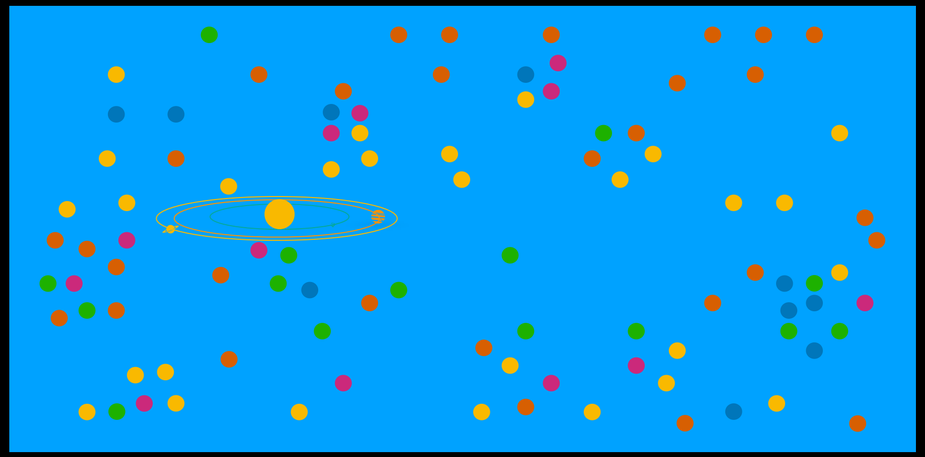
our **Universe** contains MANY billions of **galaxies**

ours is called “The Milky Way” and it contains about 2 hundred billion stars

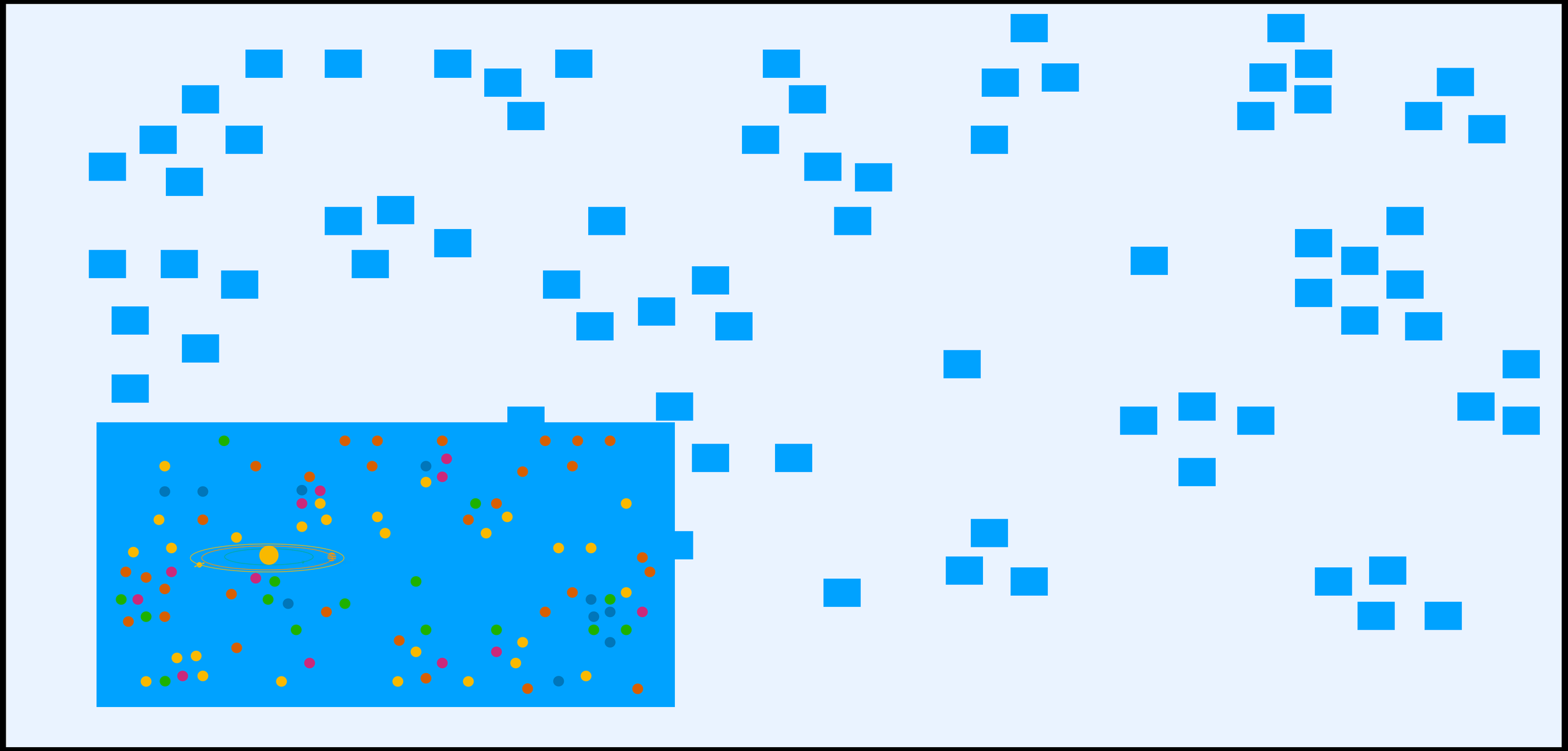


around most of the stars are systems of planets (ours is called “**The Solar System**”)

our home planet is **Earth**



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



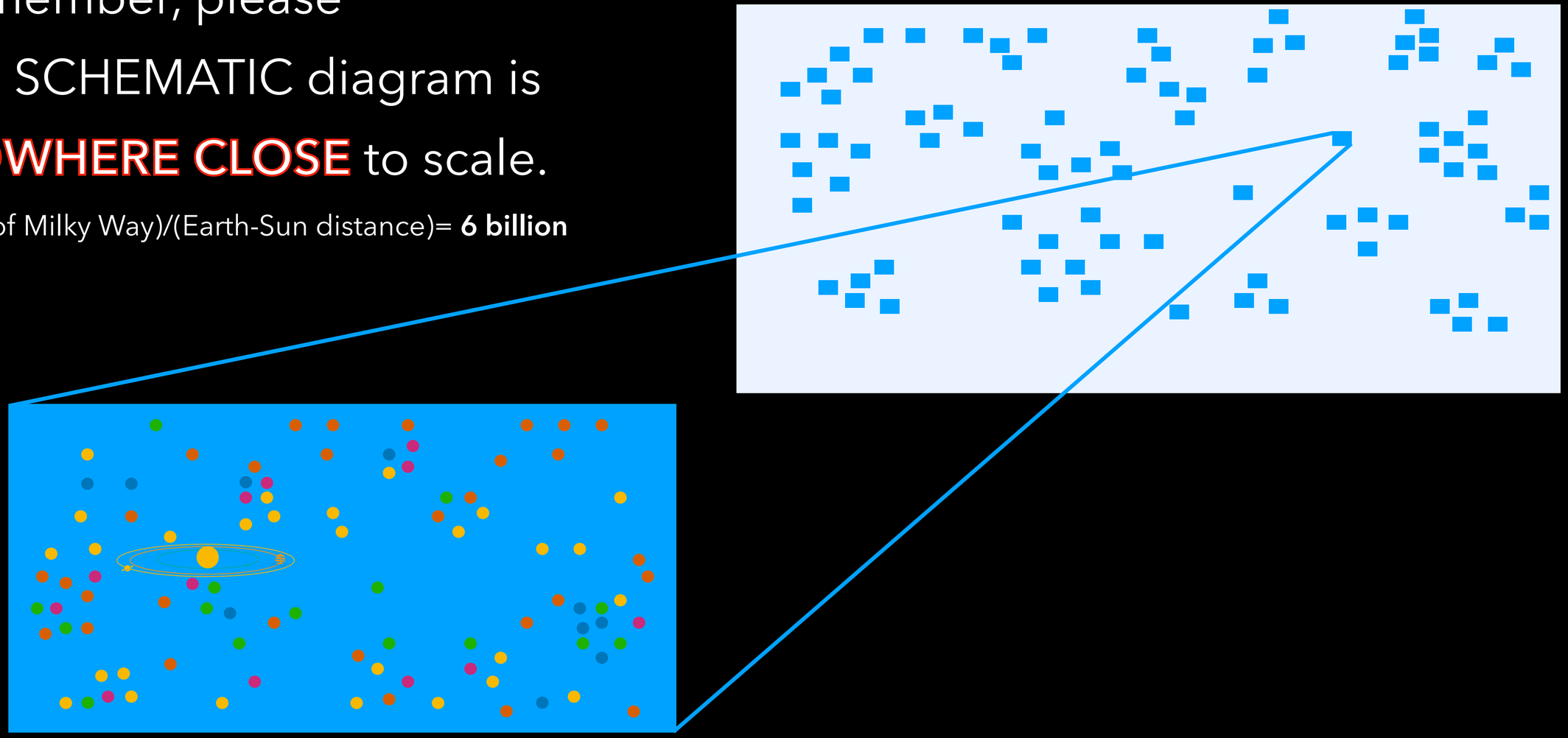
Earth resides in the **Solar System**, around the **Sun**, which is one of MANY **stars**, INSIDE the **Milky Way**, which is one of MANY **galaxies**, in our **Universe**

Remember, please

this SCHEMATIC diagram is

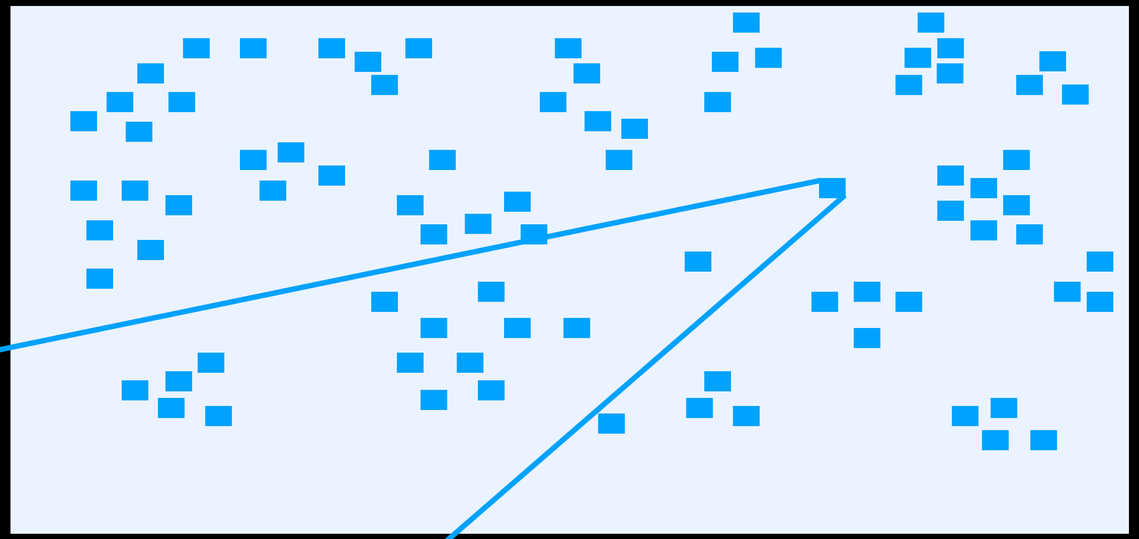
NOWHERE CLOSE to scale.

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

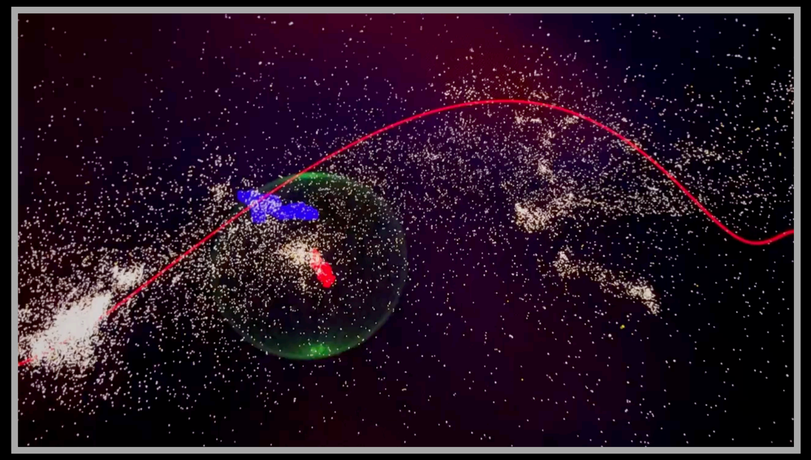
Once Around the Milky Way

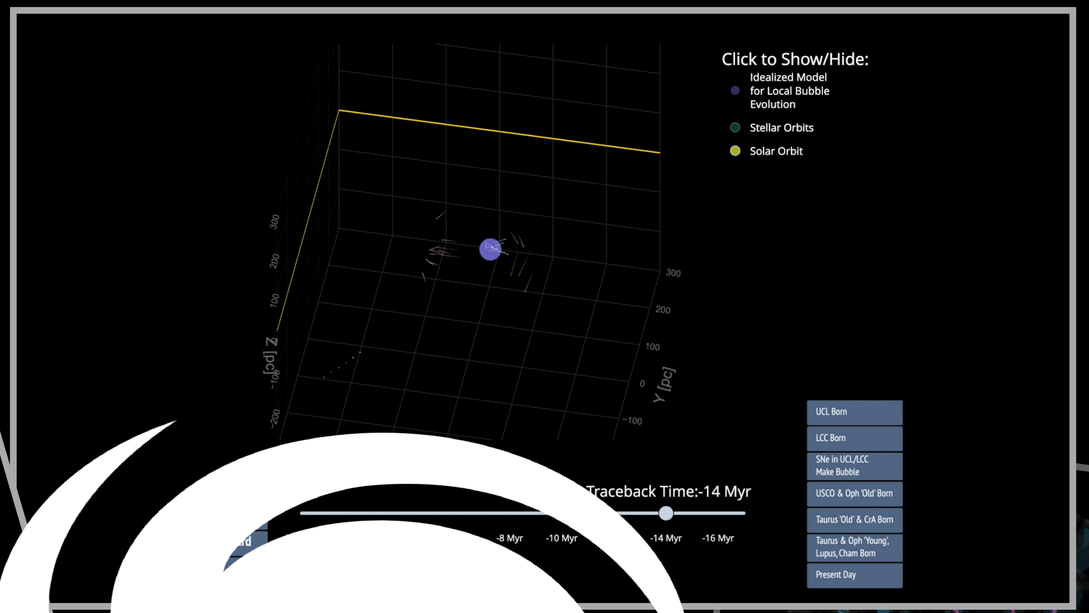
building out a 3D model of the Milky Wa… …ll offer a tour

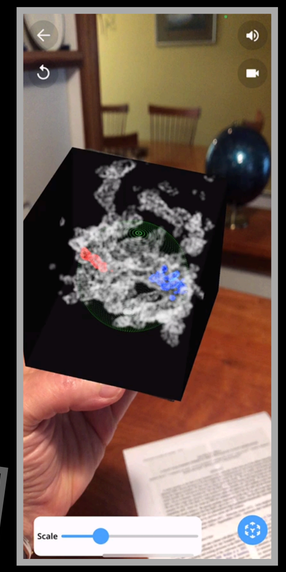
— a few colloquium slides from late 2025 —

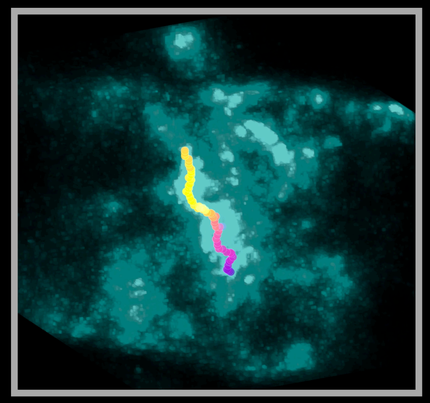
Alyssa A. Goo…
Robert W… Willson Professor, Harvard University
Re… Associate, Smithsonian Institution

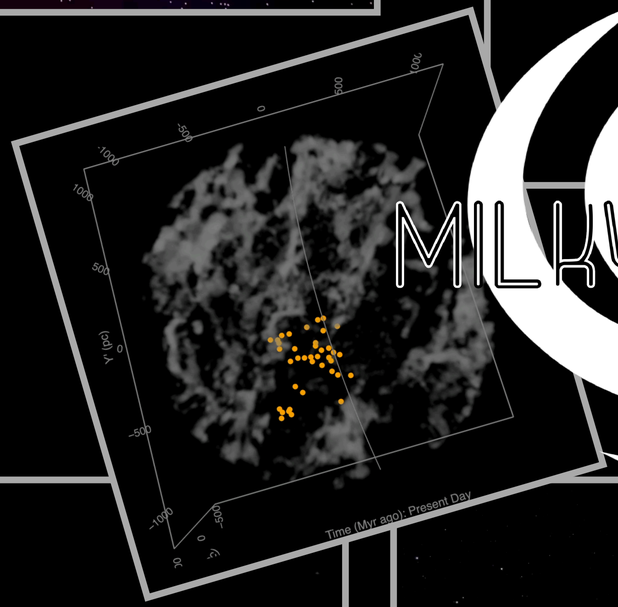
Video credit: Space.com / animation: ESA / produced & edited by Steve Spaleta (/ stevespaleta)

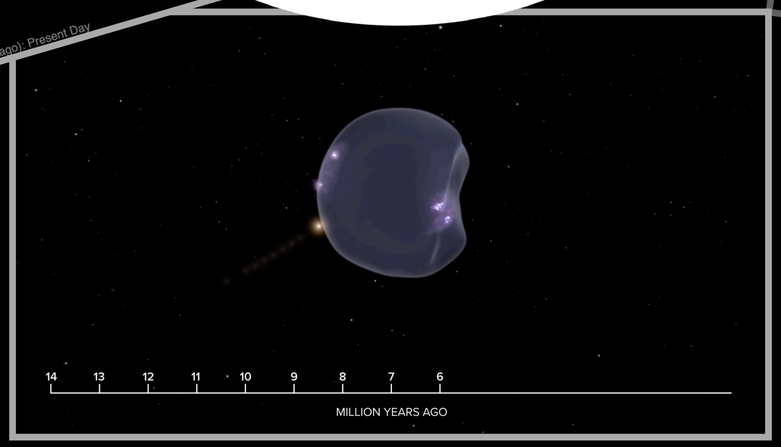


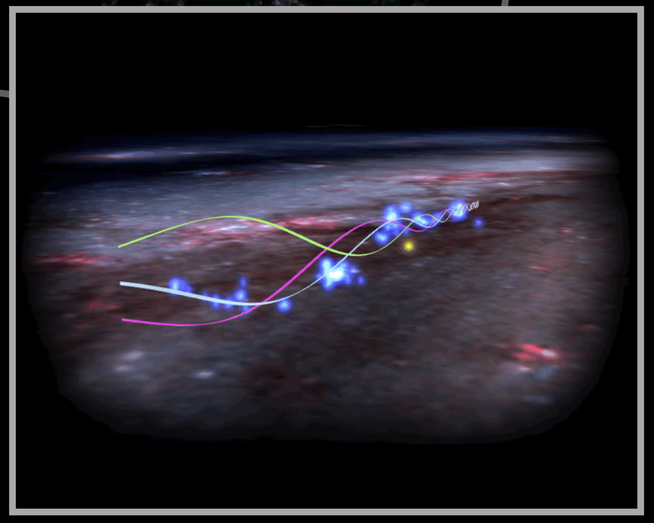










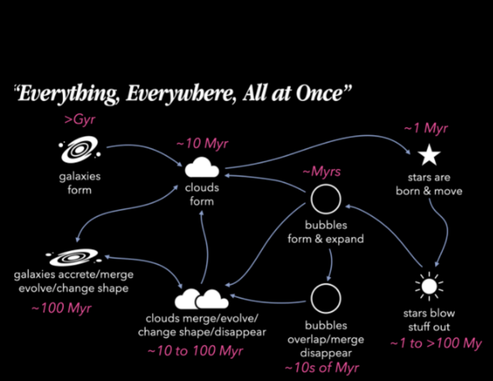


MILKYWAY3D.org

Zucker et al. 2021, Bialy et al. 2021; Zucker et al. 2022, Konietizka et al. 2024, O'Neill et al. 2025, Swiggum et al. 2024

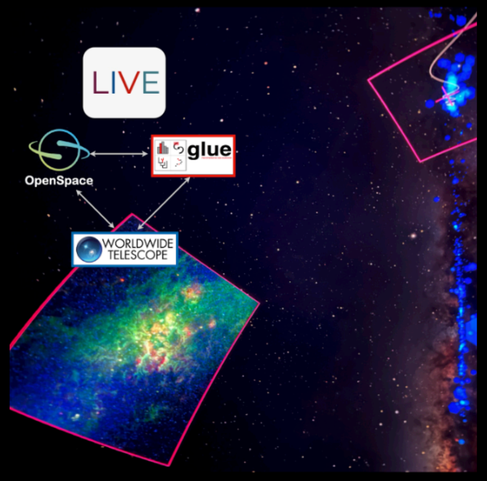
MilkyWay3D.org

Skip directly to: DATA | SOFTWARE | OUTREACH | JOINING IN



Science

Researchers worldwide contribute to, and use, MilkyWay3D resources in order to improve our understanding of the Milky Way's origins, workings, and future.



Data & Software

We combine data and software that can offer myriad views of the Milky Way, as best we know it. The software is built using the LIVE Environments exploratory data analysis tools.

MW3D for Everyone

Using the same data and tools as researchers, educators and learners of all ages can explore and study the Galaxy in which we all live.

MilkyWay3D's open science premise: Data + Software + People + Computing + Physics = Understanding, Learning, and Discovery

Bringing you the Galaxy as we know it. Updated as we learn more.

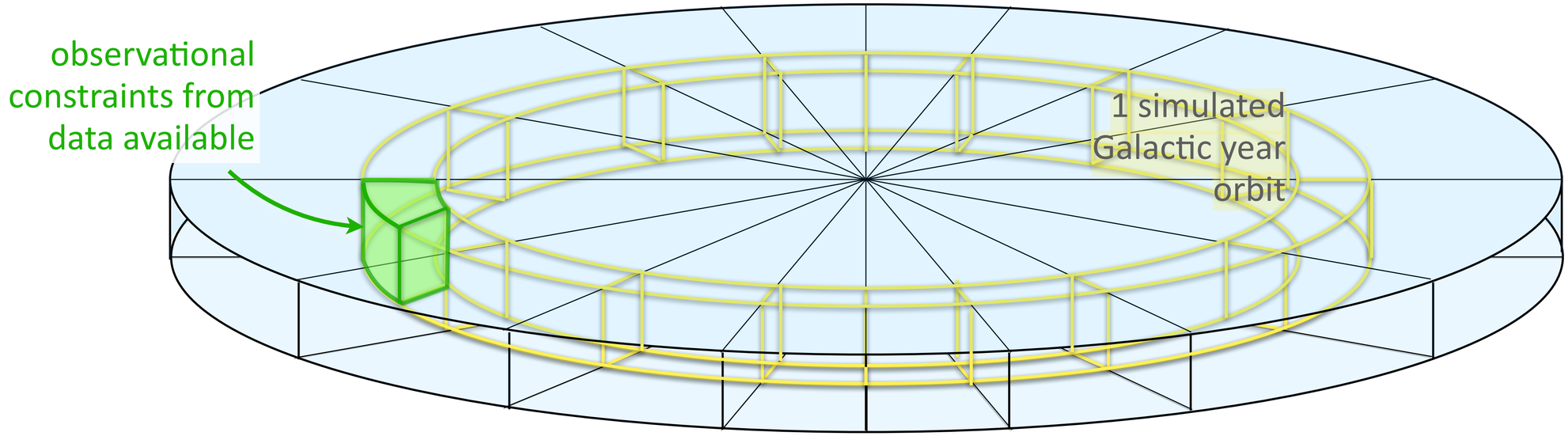
MILKYWAY3D.ORG

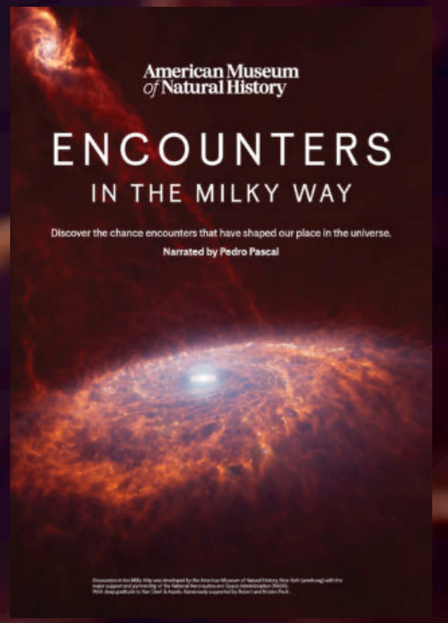
v.2025

Proposal - 286673

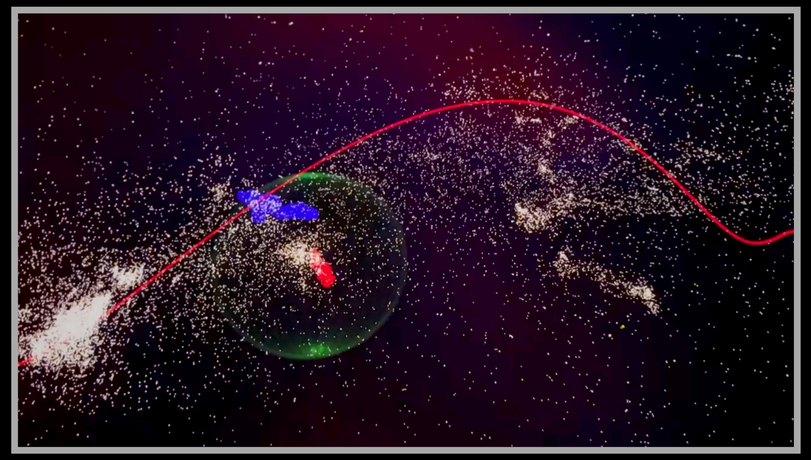
Proposal Title: "Once Around the Milky Way": A Data-Simulation Synthesis enabled by the MW3D Project

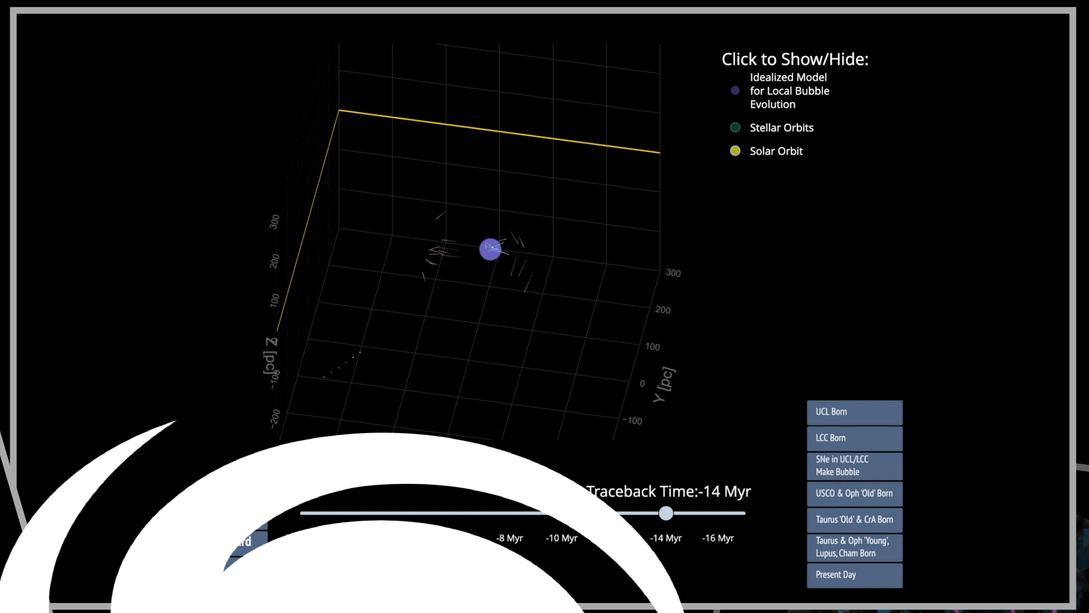
Funding Opportunity: NSF 22-624 - Astronomy and Astrophysics Research Grants

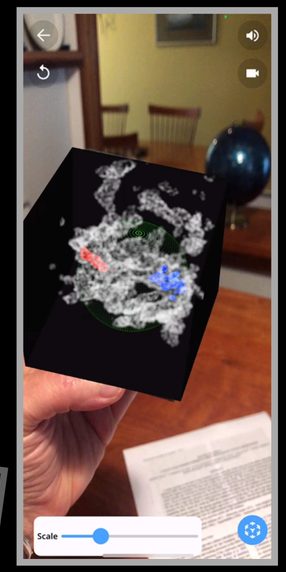


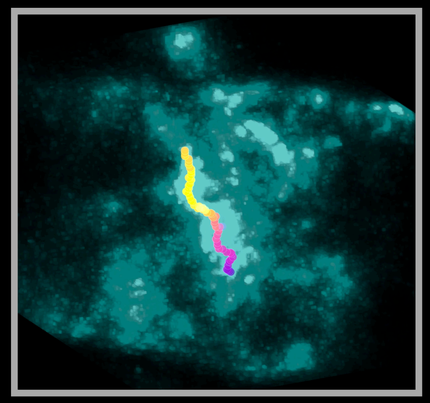


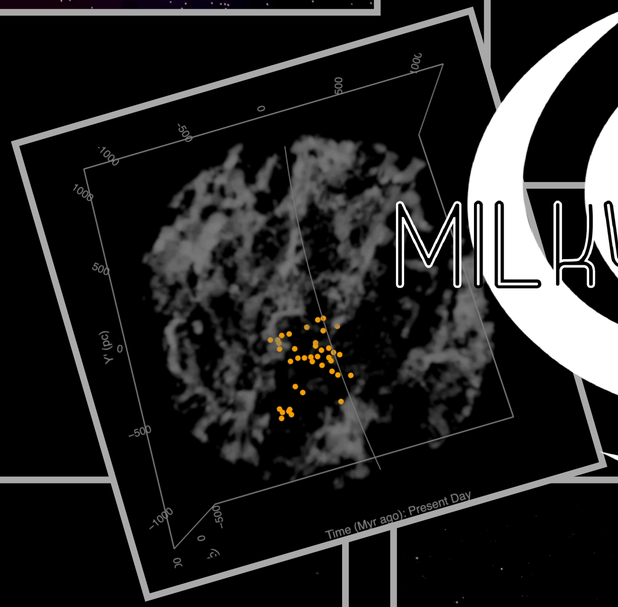
Curator: Jackie Faherty, AMNH, Simulation Jason Hunt, Surrey, plus MW3D collaborators, narrated by Pedro Pascal

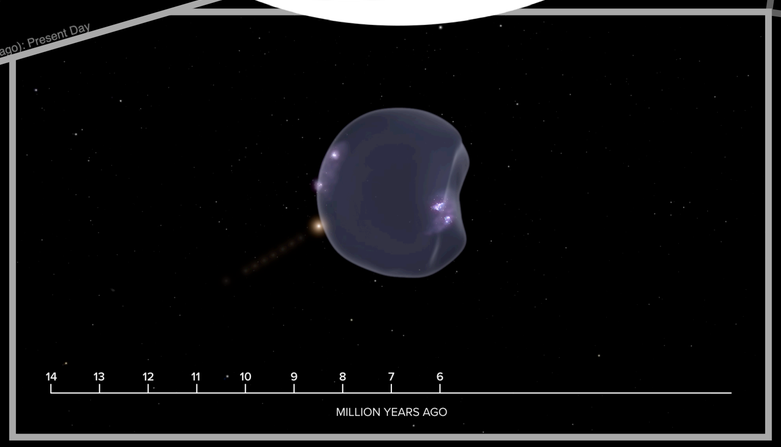


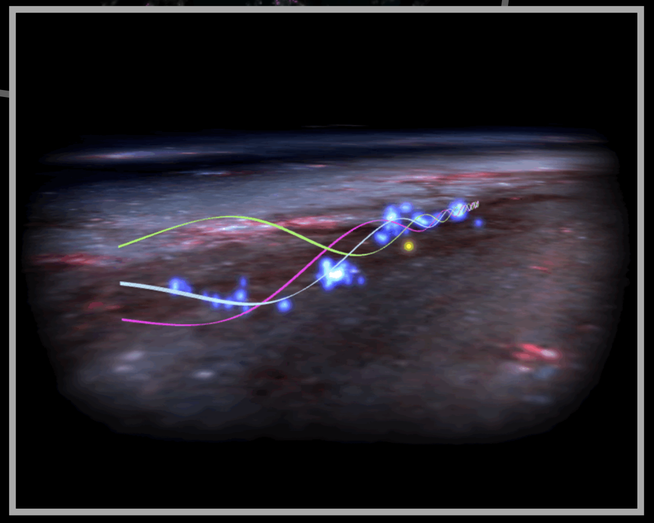












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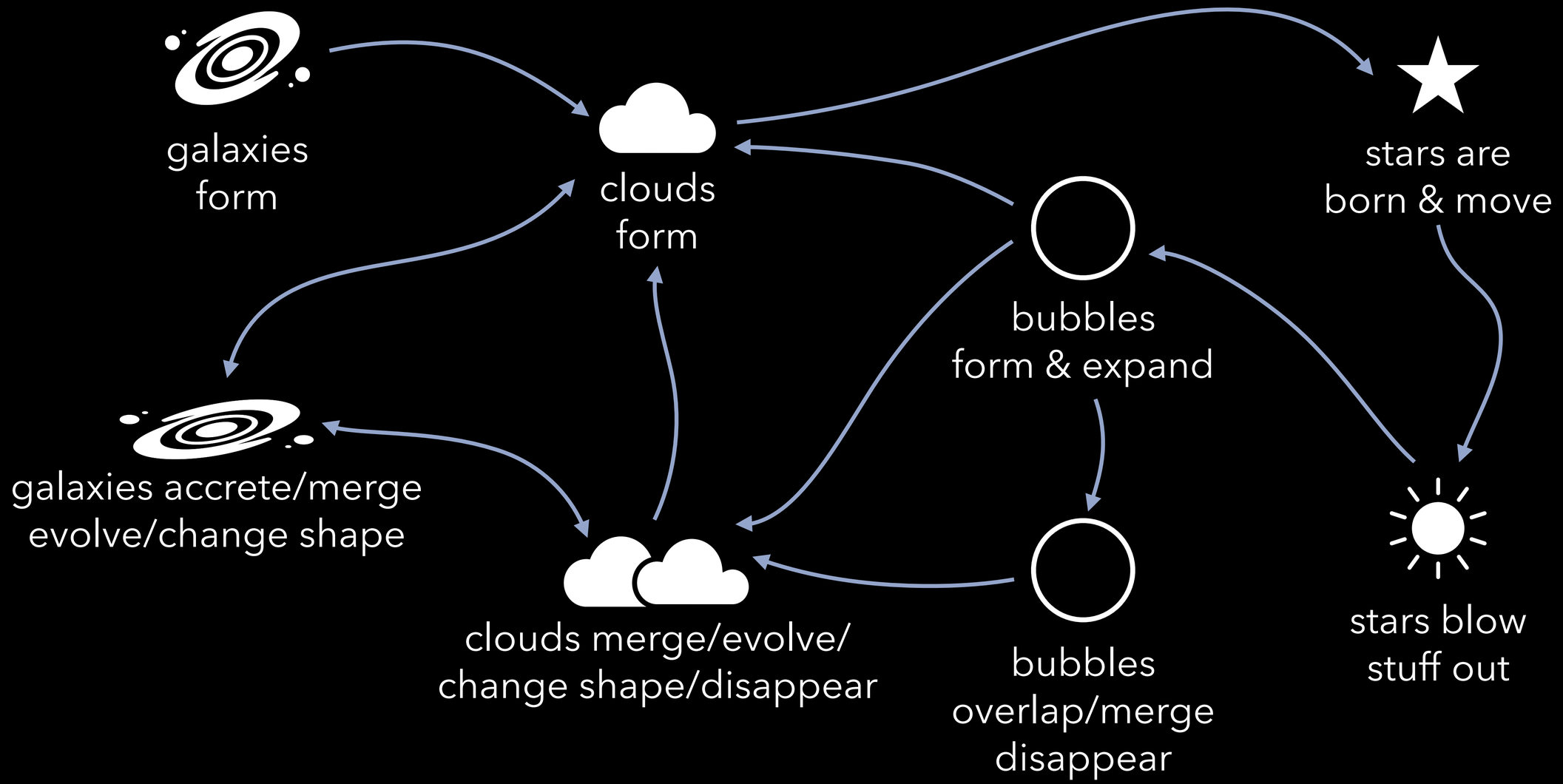
Zucker et al. 2021, Bialy et al. 2021; Zucker et al. 2022, Konietizka et al. 2024, O'Neill et al. 2025, Swiggum et al. 2024

“Everything, Everywhere, All at Once”

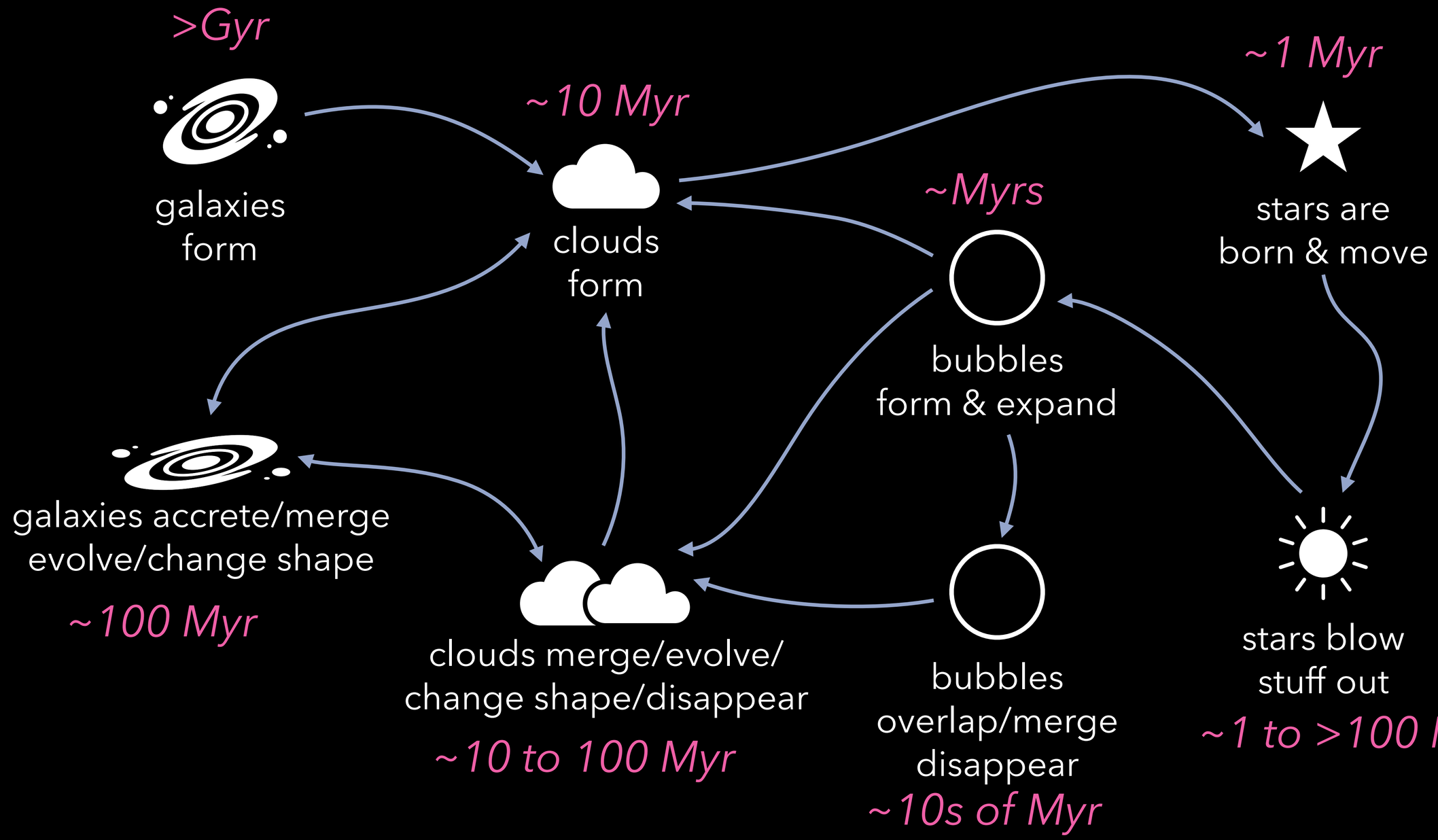
Nothing stays still. Nothing lasts forever.

ESA/Webb, NASA & CSA, J. Lee and the PHANGS-JWST Team, Acknowledgement: J. Schmidt

"Everything, Everywhere, All at Once"



"Everything, Everywhere, All at Once"



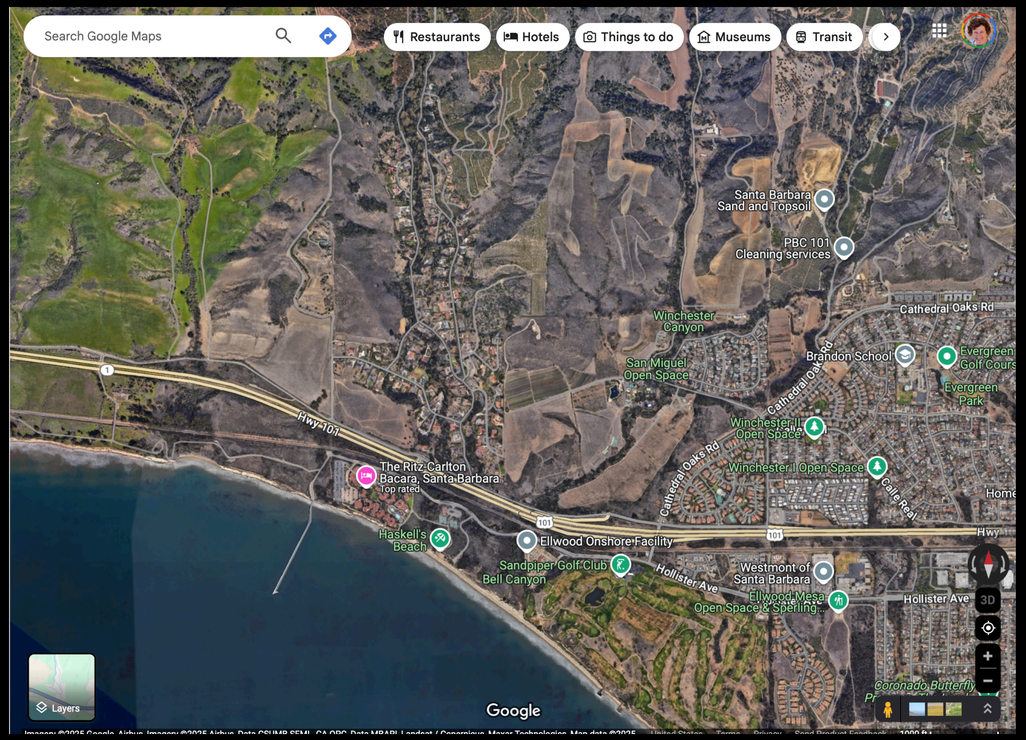
Simulating *"Everything, Everywhere, All at Once"?*

SimCity 2000, re:decades

Starforge Simulations, re:>100 Myr

SimCity 2000

Satellite Image



Open Session | Export Session | Import Data | Export Data/Subsets | Link Data | x^2 Arithmetic attributes | Active Subset: Perseus Only | Mode: | Terminal | Preferences

Data Collection

- 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
- Lallement2019_A+A_625_A135_solar_nei...
- ONeill_LocalBubble_lmax6
- Cahlon2023_Clouds[HDU1]

Subsets

- Perseus Only

Plot Layers

Alves-Bialy-Foley-O'Neill-Zucker | 3D views

3D view, note *selection*

2D (Sky) WWT

glue
multidimensional data exploration
glueviz.org

The 3D visualizations are just part of a much richer environment...

Linkable Interactive Visualization Exploration (LIVE) Environments

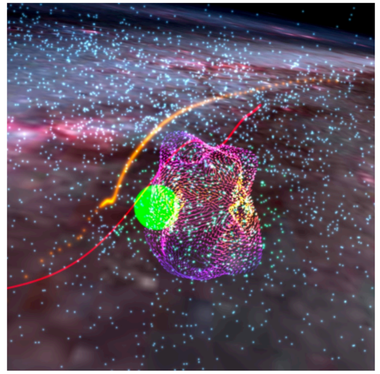
LIVE

What is LIVE?

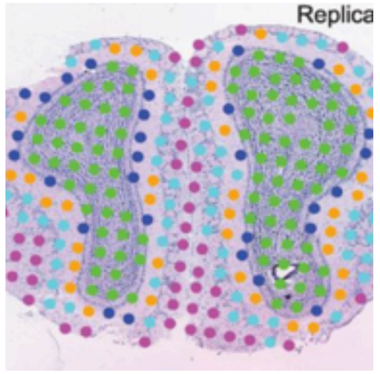
LIVE lets anyone build
"Linkable Interactive Visualization and Exploration" Environments.

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

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



LIVE Astro



LIVE Bio

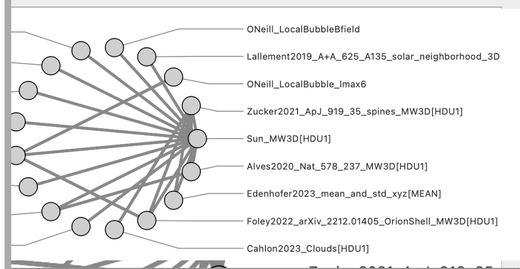
LIVE GIS

command-line terminal

ou can type any valid Python code here, and you
fined variables:

Link Editor

an existing connection to edit links. Selected datasets are shown
rs show directly and indirectly linked (blue) and inaccessible

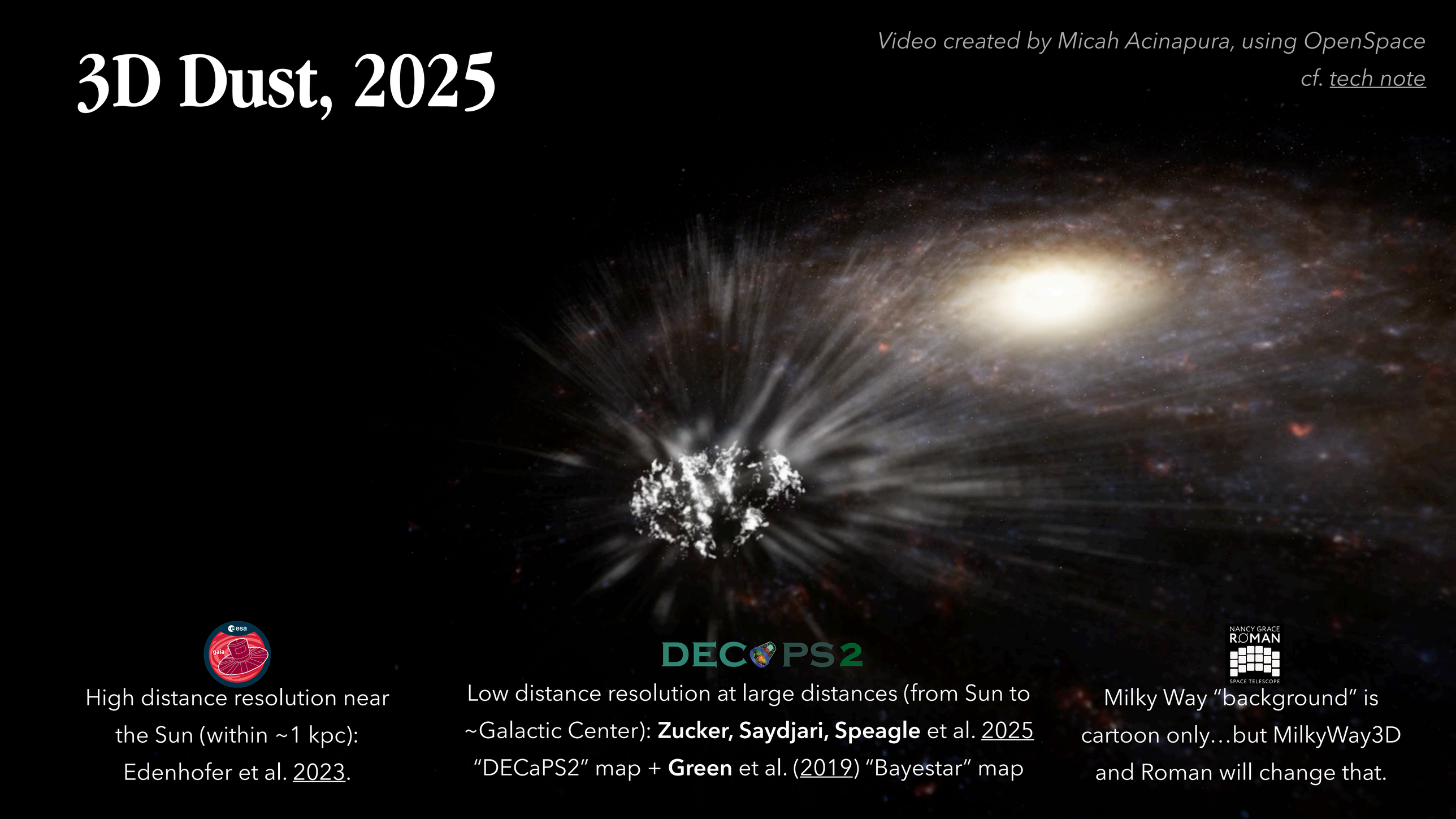


GUI data set link editor

3D Dust, 2025

Video created by Micah Acinapura, using OpenSpace

cf. tech note



High distance resolution near the Sun (within ~1 kpc): Edenhofer et al. 2023.

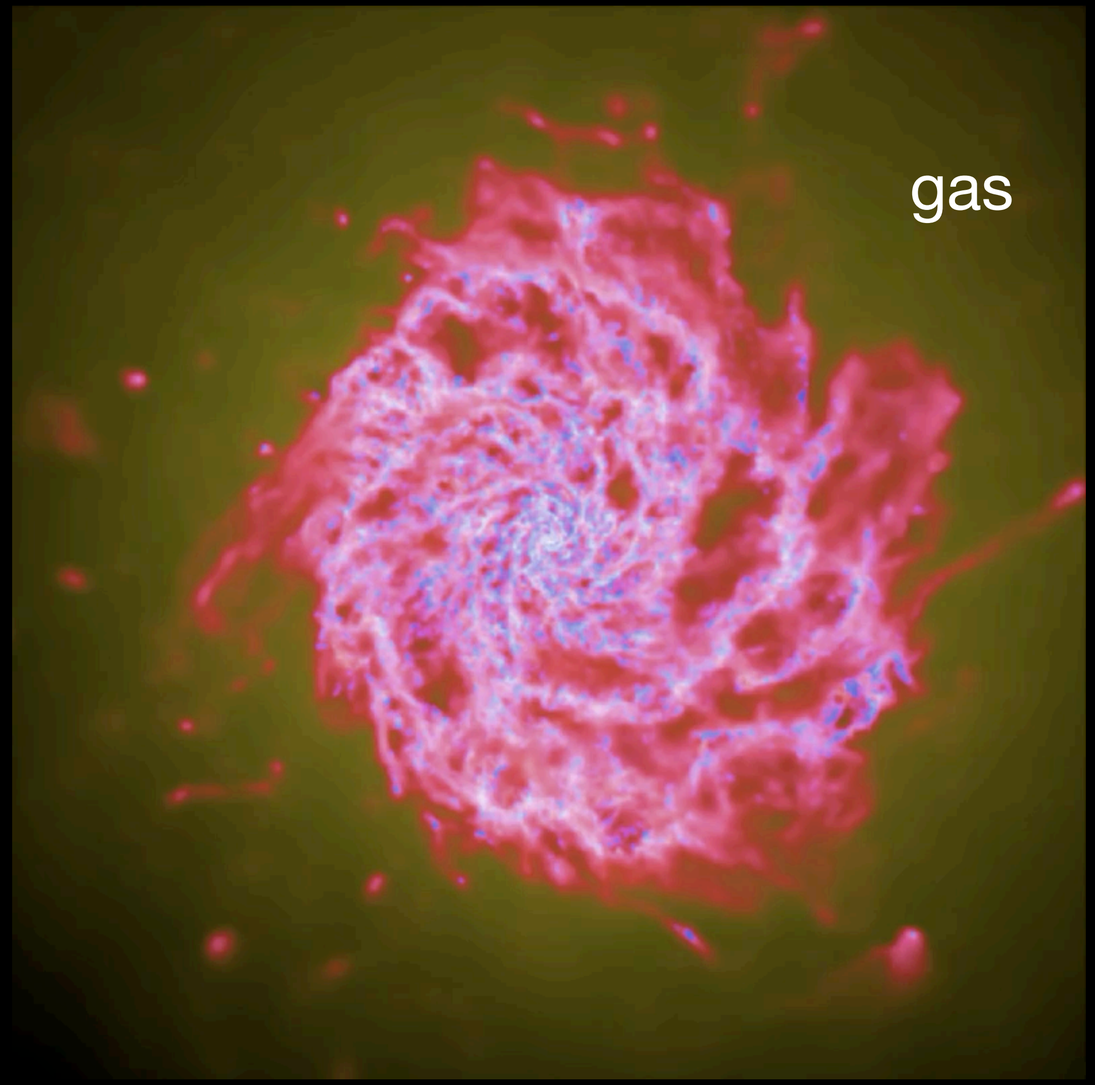
Low distance resolution at large distances (from Sun to ~Galactic Center): **Zucker, Saydjari, Speagle** et al. 2025 "DECaPS2" map + **Green** et al. (2019) "Bayestar" map

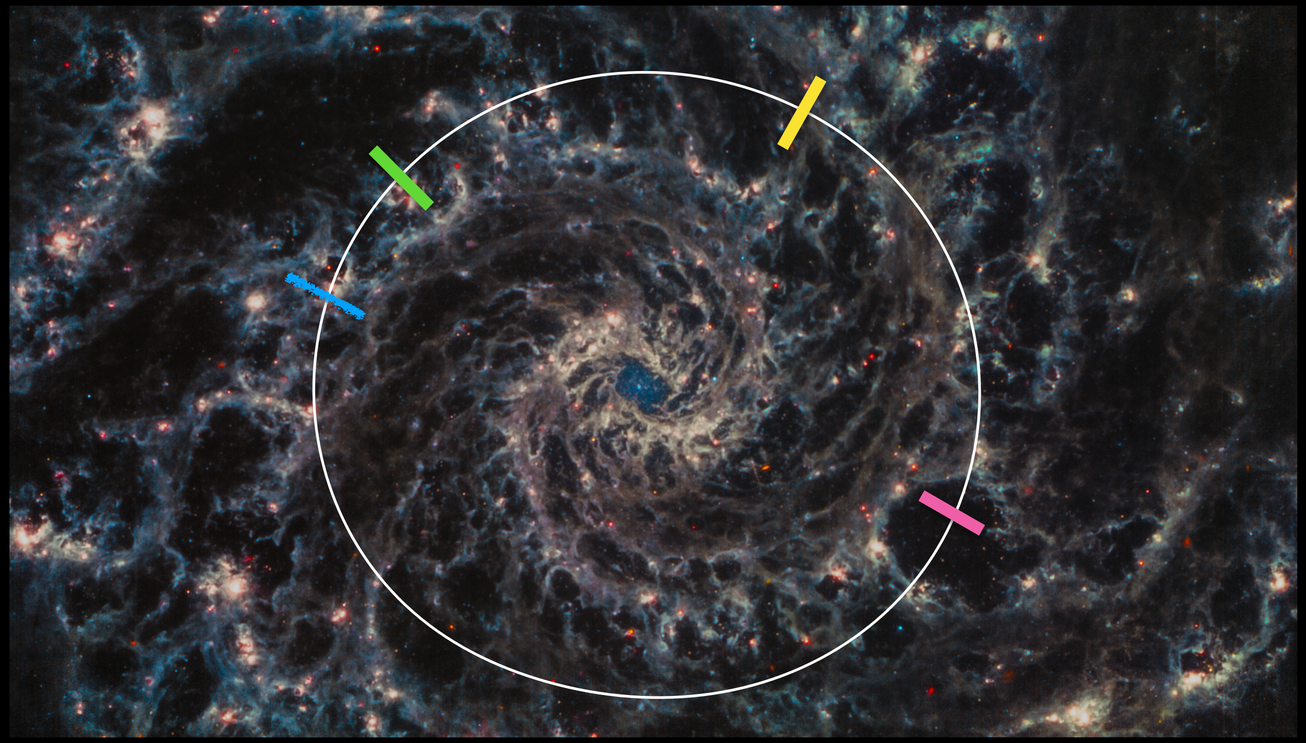
Milky Way "background" is cartoon only…but MilkyWay3D and Roman will change that.

A “Milky Way” from **FIRE** (Feedback In Realistic Environments)

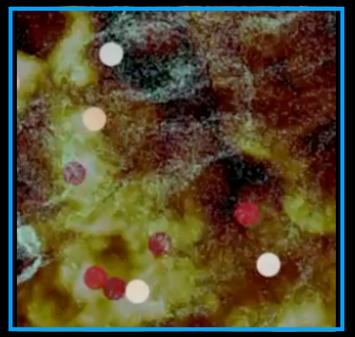
stars

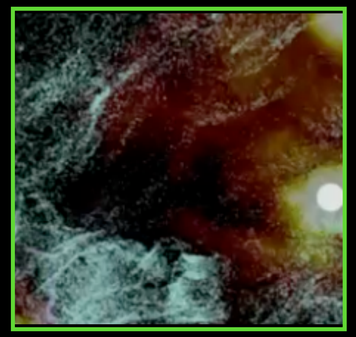
gas

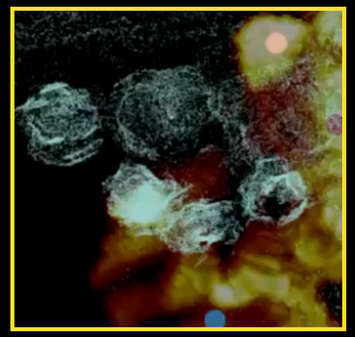


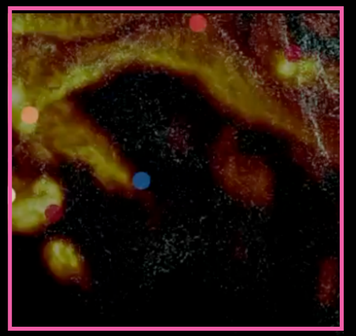


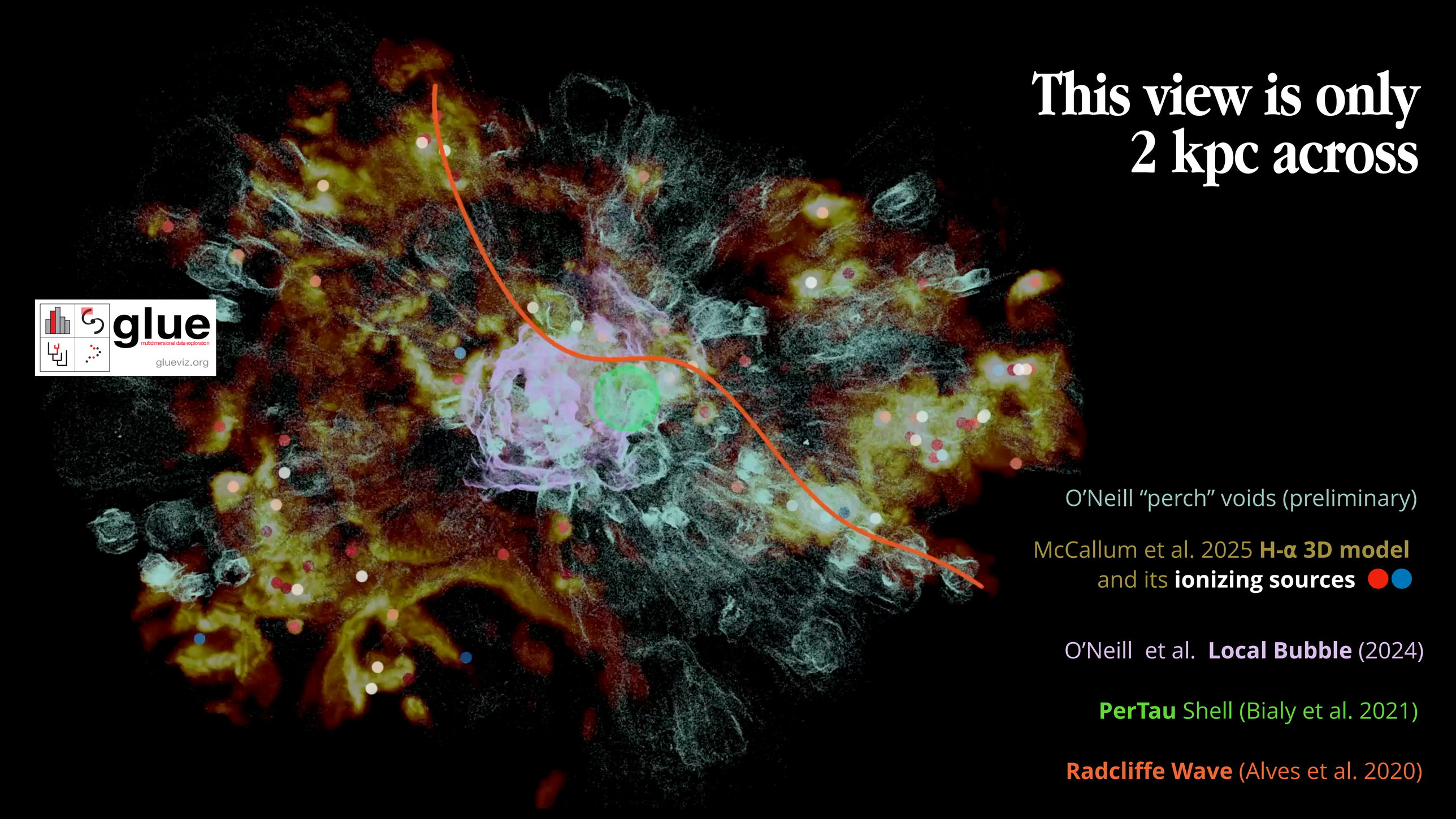
How does the “view” from a star change, as it orbits?











This view is only 2 kpc across

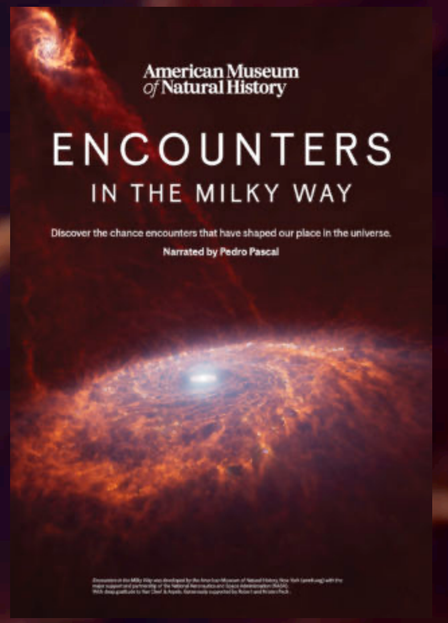
O'Neill "perch" voids (preliminary)

McCallum et al. 2025 **H-α 3D model** and its **ionizing sources**

O'Neill et al. **Local Bubble** (2024)

PerTau Shell (Bialy et al. 2021)

Radcliffe Wave (Alves et al. 2020)

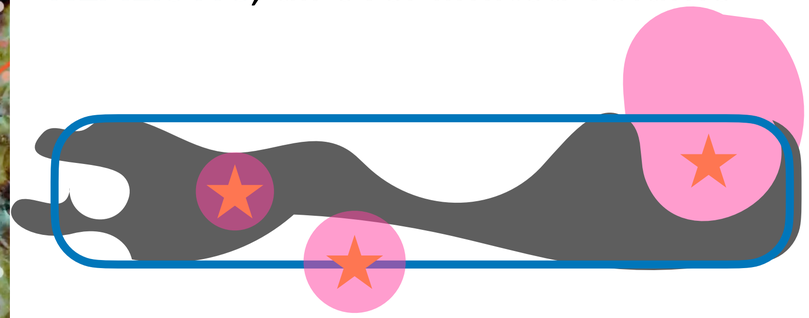


Curator: Jackie Faherty, AMNH, Simulation Jason Hunt, Surrey, plus MW3D collaborators

A sim+obs painting "plan"

OBSERVATIONS

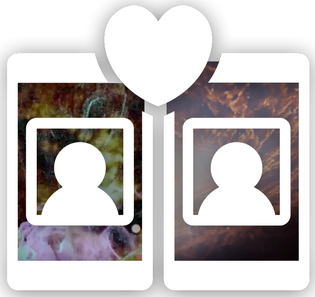
DETAILED 3D structure, almost
STATIC in time, feedback view
REALISTIC, all over *limited* volume



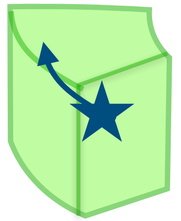
SIMULATIONS

COARSE 3D structure over full Galaxy,
EVOLVING in time for ~Galactic year,
feedback **UNREALISTIC** on small
scales→sub-grid prescriptions

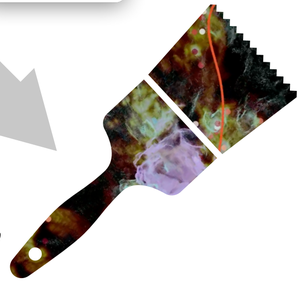
"**match**" SIM snapshots to blurred OBS



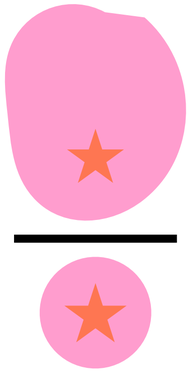
create "**agent-based**" views seen by orbiting stars



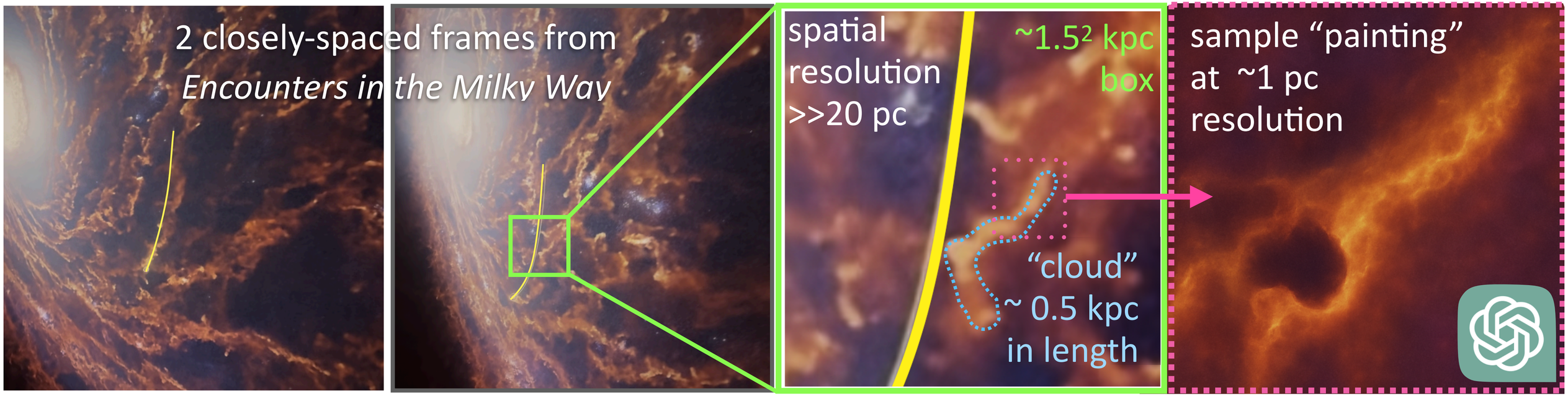
"**paint**" high-spatial-frequency info from OBS onto SIMS



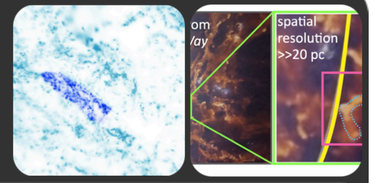
evaluate **changes** in **feedback** interactions



Orange stars represent the position of *observed* stars or clusters massive enough to produce the pink *observed* winds, HII regions, and/or SNe energetic enough to re-distribute material in the surrounding ISM enough to matter for future generations of star formation. The blue rounded rectangle in both panels is meant to show an elongated ISM "cloud" at the ~20 pc resolution of a MW-wide simulation. The density within the blue rectangle would be constant in the simulation, at a level equal to the average of the dense and empty regions in the observations. The simulations on their own cannot capture the re-shaping of the cloud by feedback, apparent in the observations.


2 closely-spaced frames from
Encounters in the Milky Way
spatial resolution >>20 pc
~1.5² kpc box
"cloud" ~ 0.5 kpc in length
sample "painting" at ~1 pc resolution

AI's MANY failures…with some success.



using the first image as a guide (especially perhaps the darker blue area), simulate higher spatial resolution within the dotted outline region of the second image, using the perceived statistical properties of the first. Make the square image that would go in the pink box in the figure, using the same gold-ish coloring as the pink-boxed region in the third panel from the left. State your methods if possible.

ChatGPT's code-based (concise "recipe")

Estimate the small-scale texture statistics from the blue reference image

Convert to grayscale, crop centrally to avoid edges.

Compute the isotropic radial power spectrum (FFT → $|F|^2$ → radial average).

This captures the "how much structure at each spatial frequency" of the high-res data.

Synthesize a new Gaussian random field with the same spectrum

Create a random complex field with the measured magnitude (√PSD as a function of radius) and random phases.

Inverse FFT → a new field whose spatial frequency content matches the reference.

Normalize and lightly band-pass filter to emphasize filamentary scales (e.g., subtract a σ≈5–6 px blur to bring out "wisps").

Imprint a long, squiggly overdensity to mimic the dotted "cloud"

Lay down a spline-like path through the image (length/curvature like the outline).

Add an anisotropic Gaussian tube along that path with a slowly varying width (to resemble clumpy substructure).

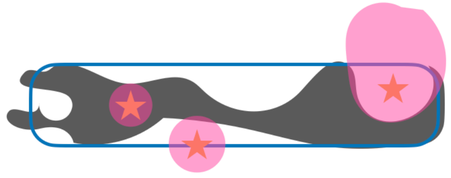
Modulate that tube by the high-frequency component of the synthesized field so it inherits realistic speckle/porosity.

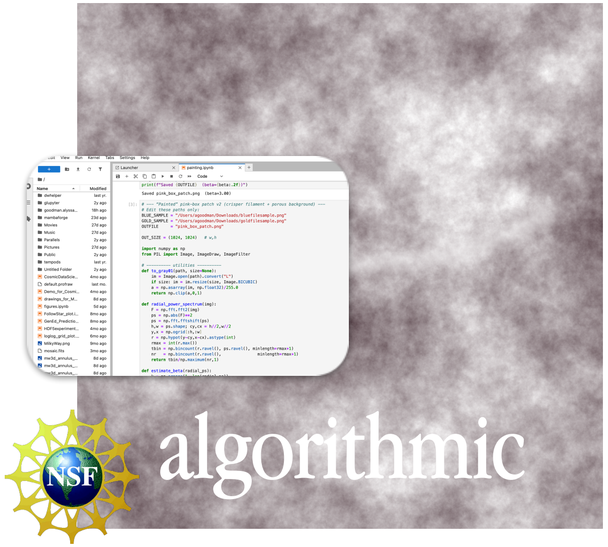
Contrast + color transfer to the gold palette

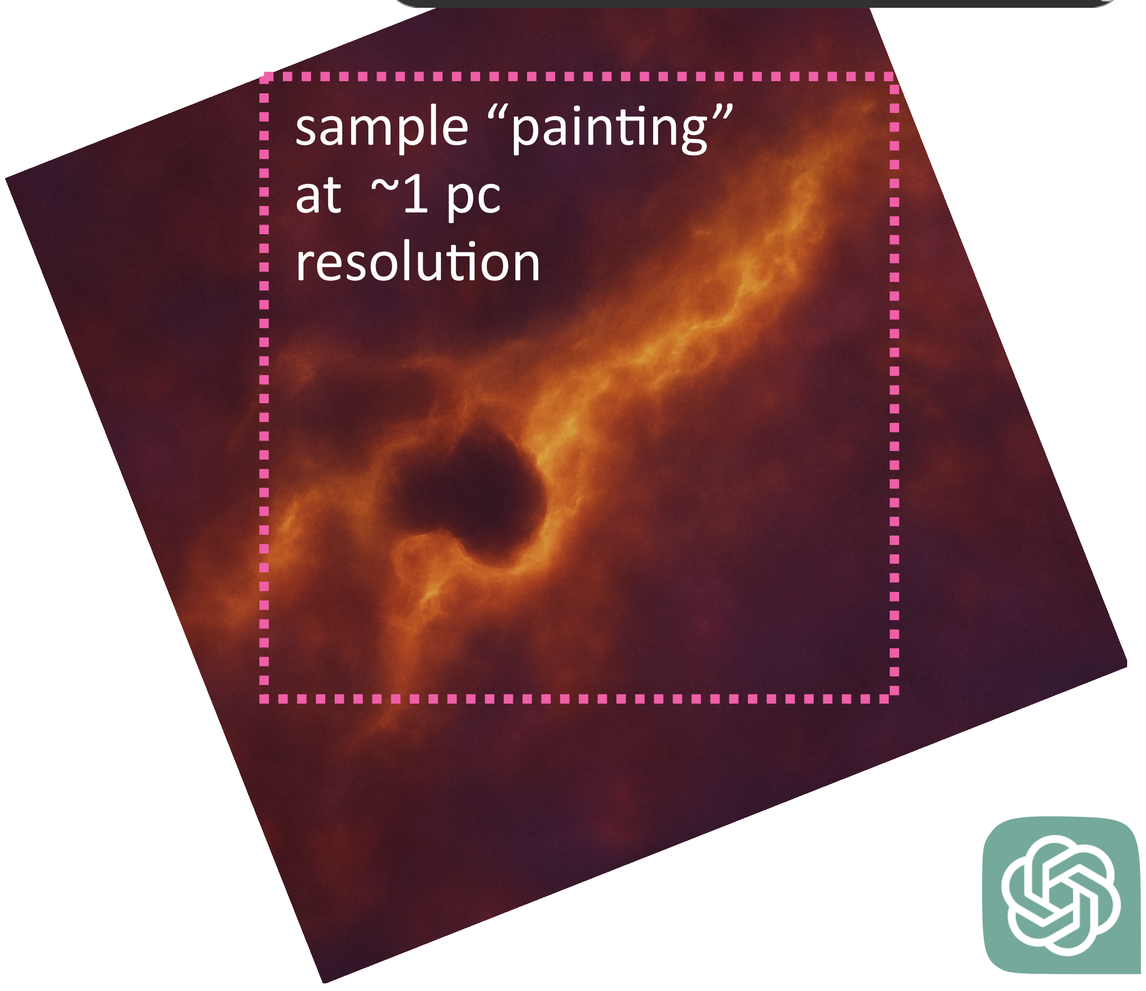
Local contrast stretch (clip low/high percentiles, e.g., 25th–99.5th) to keep punch without blowing highlights.

Apply a custom gold colormap (dark charcoal → warm brown → pale gold), or do LAB-space histogram matching to the gold patch from the third panel so the hue looks consistent.

Export a square PNG sized to the pink box.







Box 1: What AI, and an AI researcher, think AI can do “soon”

ChatGPT-5

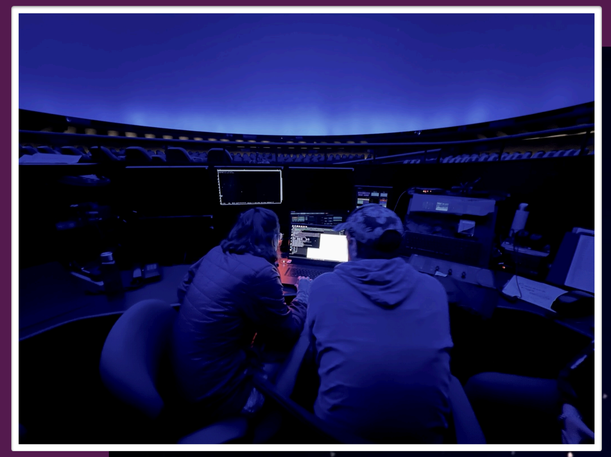
“AI and the Future of Data–Simulation Synthesis

I am writing this from the standpoint of an LLM—I am ChatGPT-5. In the near future, models like me will act as scientific collaborators that can integrate diverse data streams and simulations in real time. Given full access to the 3-D dust distribution, position–position–velocity cubes, and the 3-D motions and properties of stars, I could build a coherent statistical picture of how gas and stars interact throughout the Galaxy. In a project such as MW3D, an AI would not merely describe the process of “painting” data onto simulations; it would generate and optimize the necessary code, run fast emulators that approximate full hydrodynamic calculations, and iteratively adjust parameters by comparing synthetic and observed observables across all data domains. Human researchers would still define the physics and interpret the meaning, while the AI would manage the computation—deciding when a full rerun is needed, compressing outputs, and learning which assumptions best reproduce the real Milky Way. Such a partnership would make data-driven modeling not just faster, but more integrated, adaptive, and predictive than ever before.” –ChatGPT-5, 11/12/2025

“On the one hand it sounds wildly ambitious at the level of science fiction. On the other hand, I think it sounds like **2026**.”
–Prof. Doug Finkbeiner, PI’s Harvard colleague currently on sabbatical at Anthropic

in a planetarium

RESEARCH
+EDUCATION
+OUTREACH

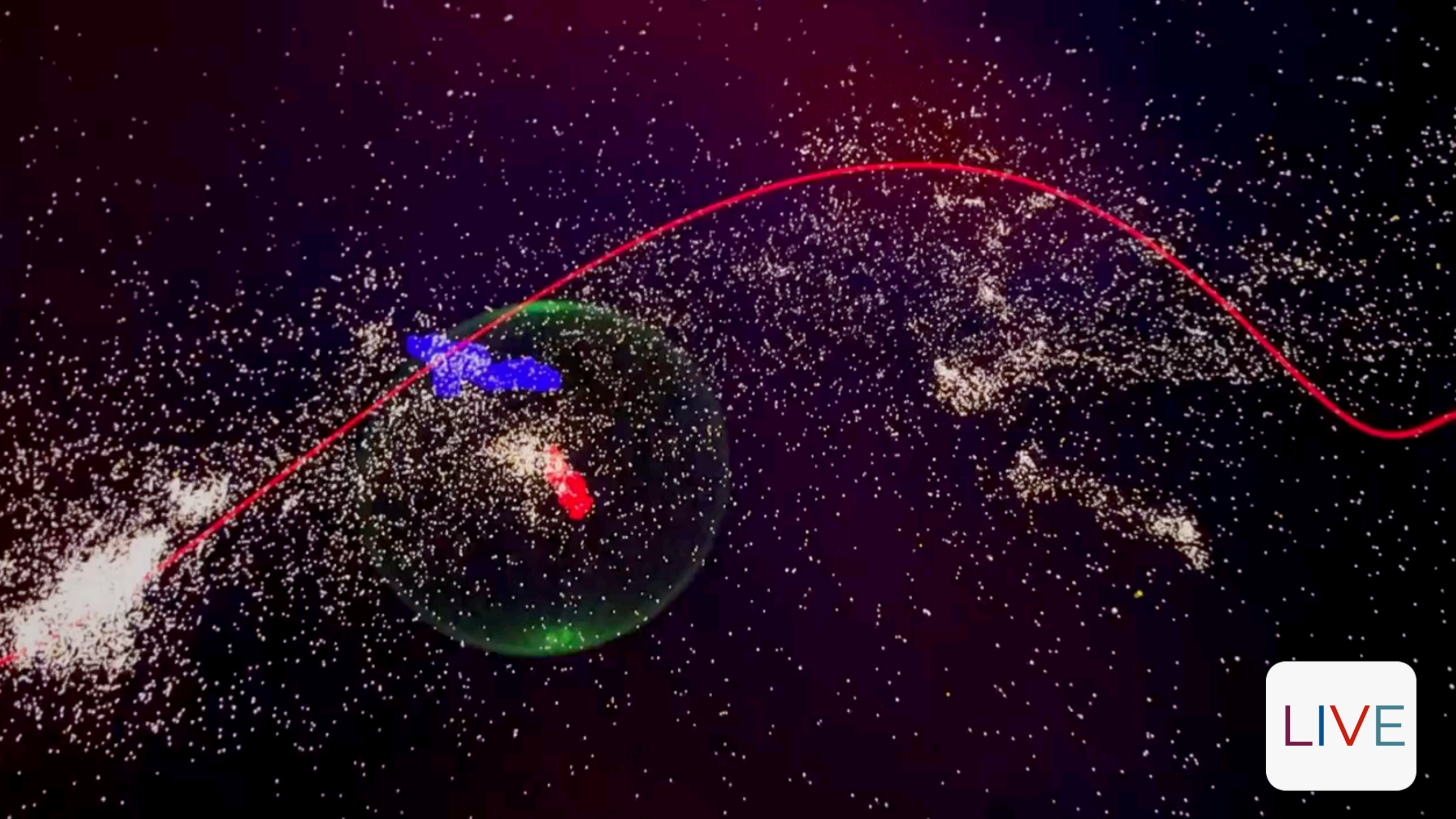


MILKYWAY3D.org

OpenSpace

glue
multidimensional data exploration

WORLDWIDE TELESCOPE


LIVE

in a augmented reality, on your phone...

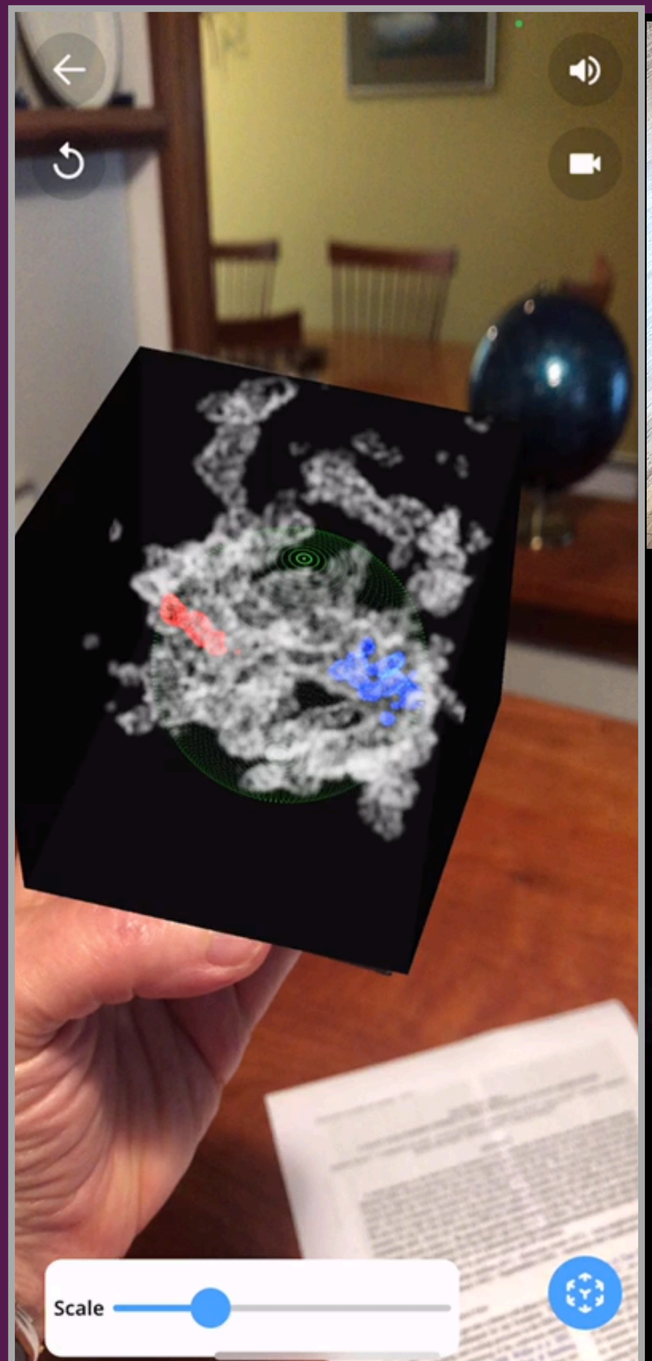
RESEARCH
+EDUCATION
+OUTREACH

MILKYWAY3D.org

OpenSpace

glue
multidimensional data exploration

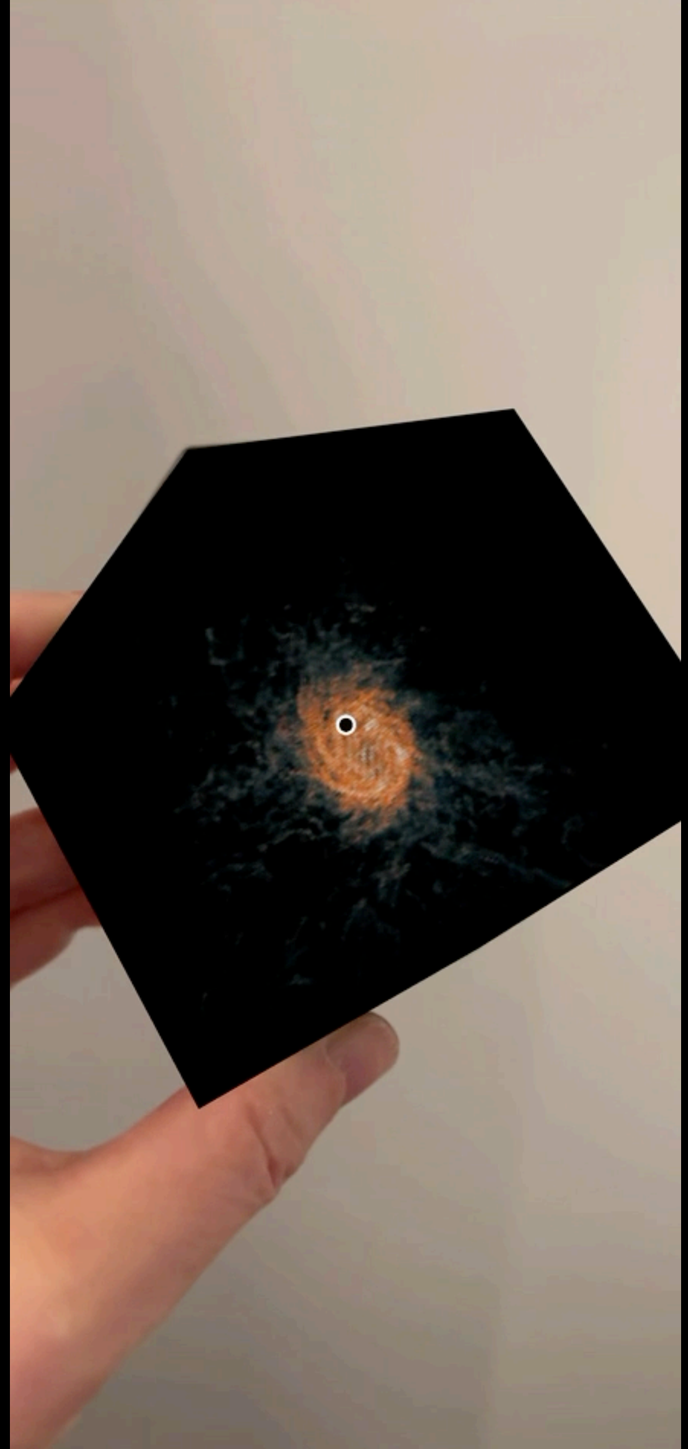
WORLDWIDE TELESCOPE



RESEARCH
+EDUCATION
+OUTREACH

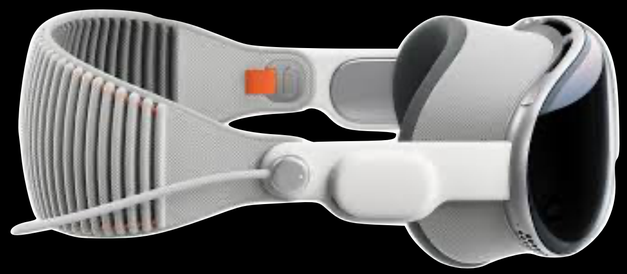
2025: simulation output→glue→AR

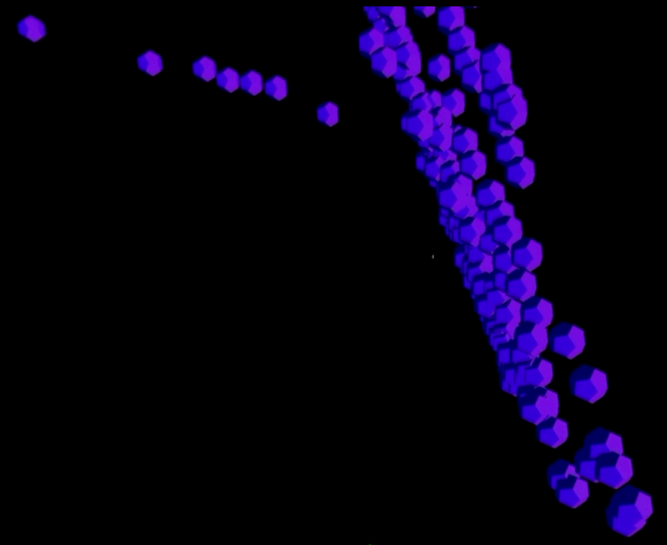
Demonstration here→
A galaxy from the IllustrisTNG simulation on a Merge Cube



created by Scott Lucchini & Jon Carifio

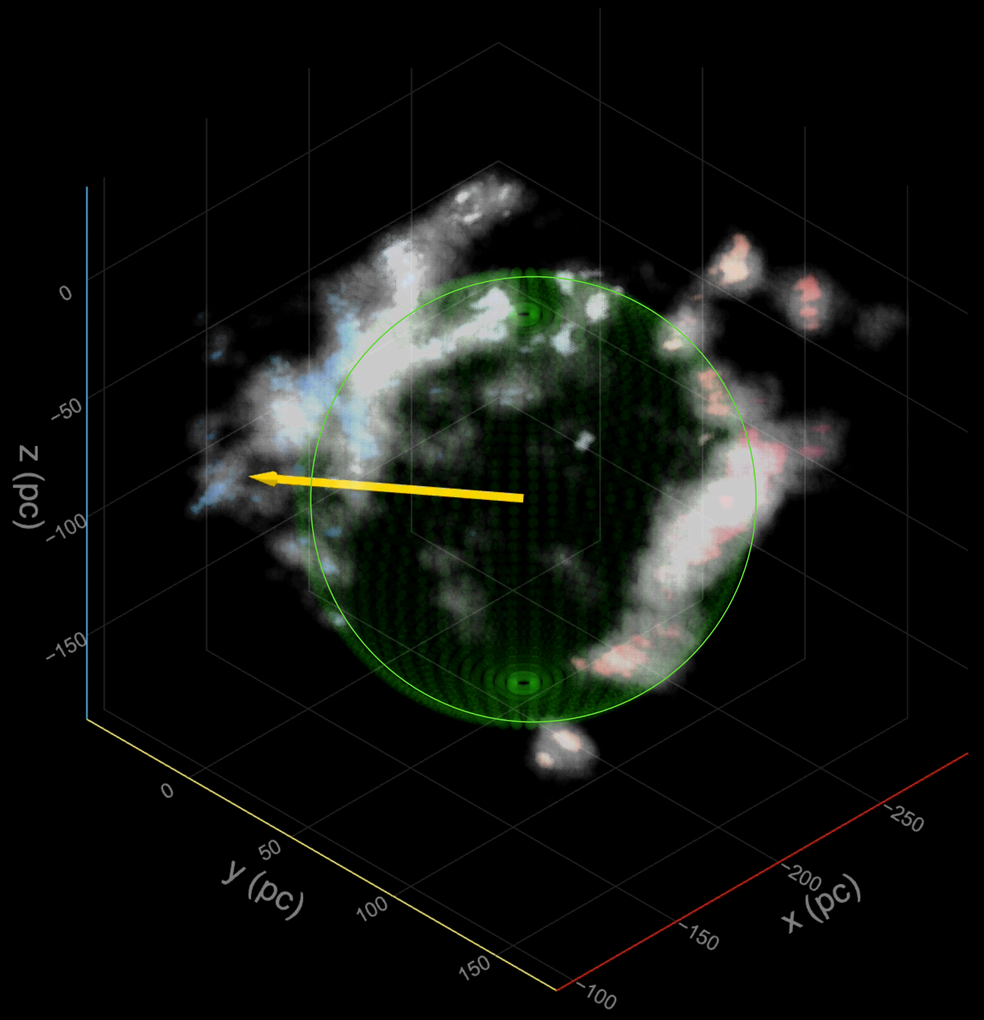
Apple Vision Pro (AR)



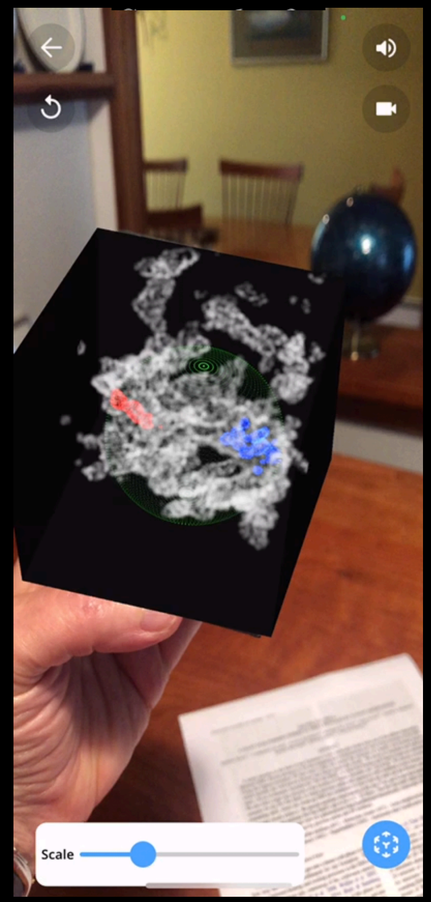


Try it with YOUR data, at glueviz.org/glue-ar/

2021 “PERSEUS-TAURUS SUPERSHELL”

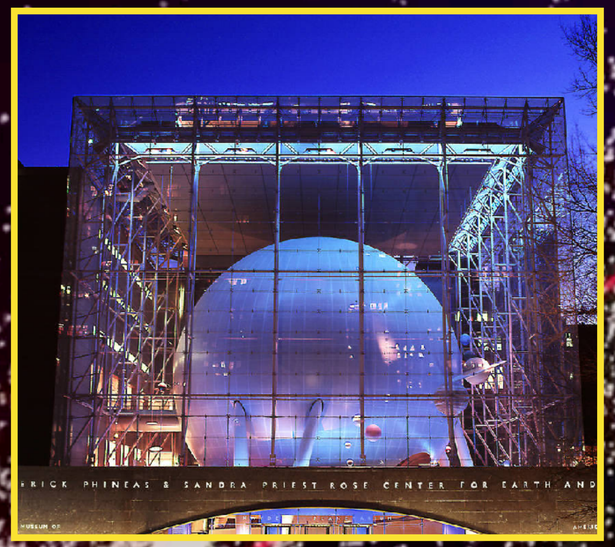


TINYURL.COM/UNIVERSE-IN-MY-HAND



AUGMENTED REALITY

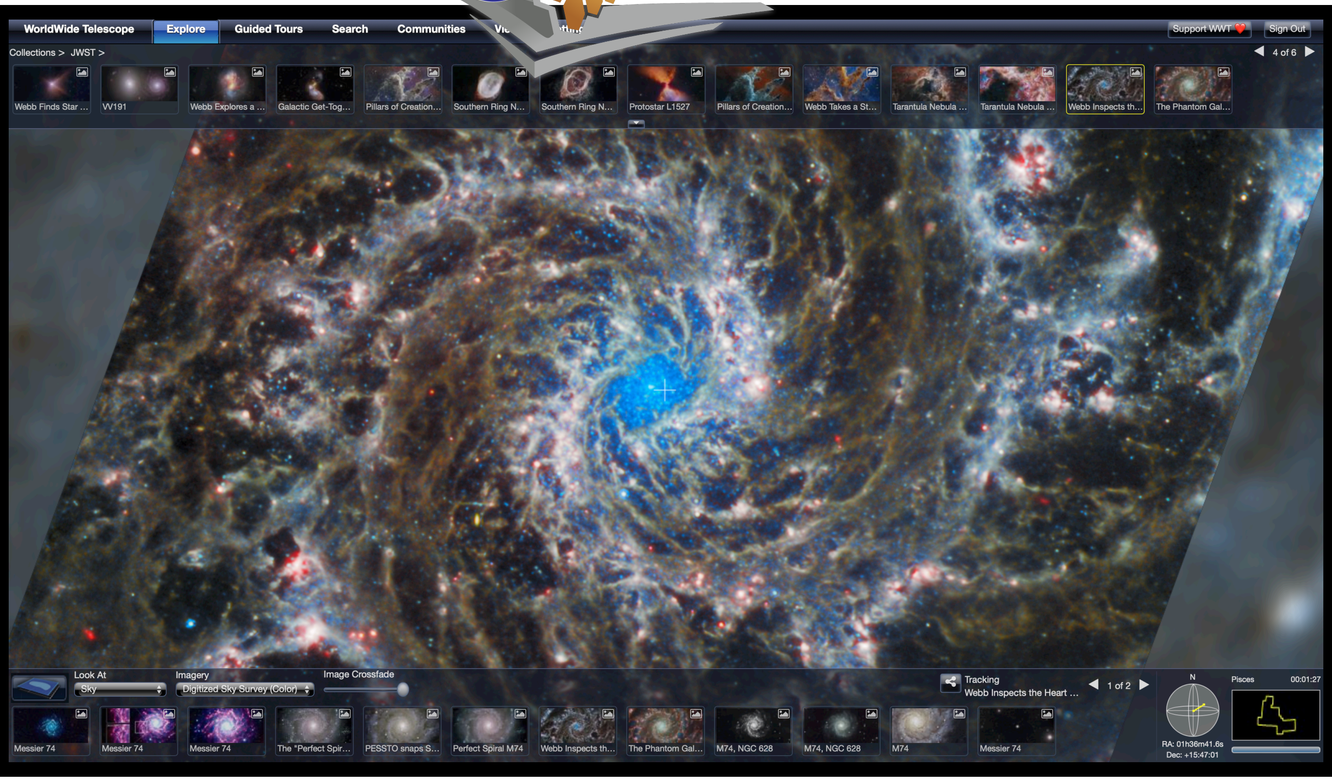
“Making a 3D Movie of the Star-Forming Milky Way I never thought I'd see” , with my friends

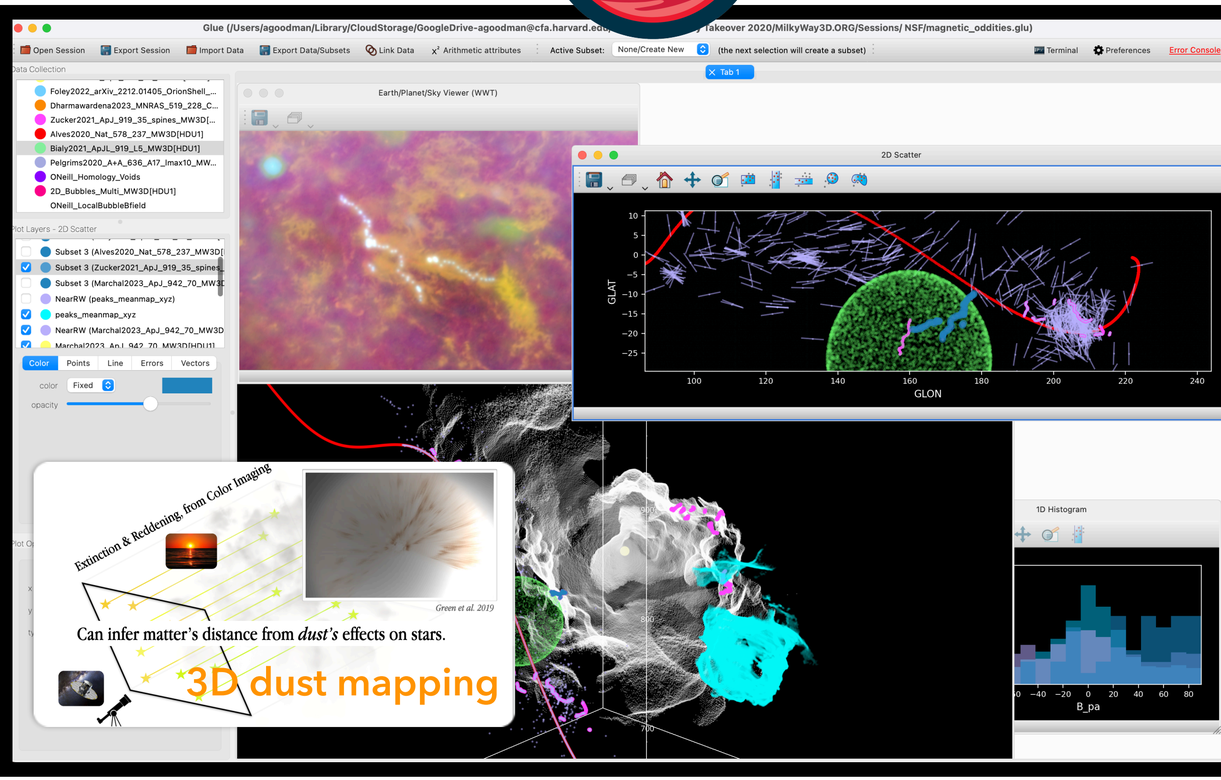


MILKYWAY3D.org

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.

unprecedented data





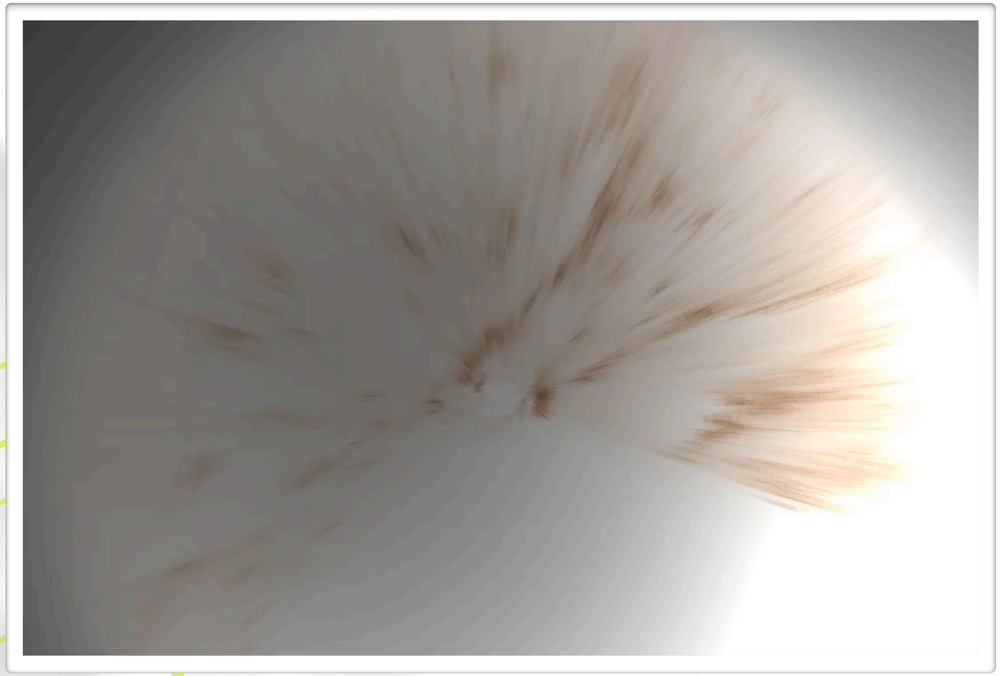
WORLDWIDE TELESCOPE

glue
multidimensional data exploration
glueviz.org

unprecedented software tools

3D dust mapping

Extinction & Reddening, from Color Imaging

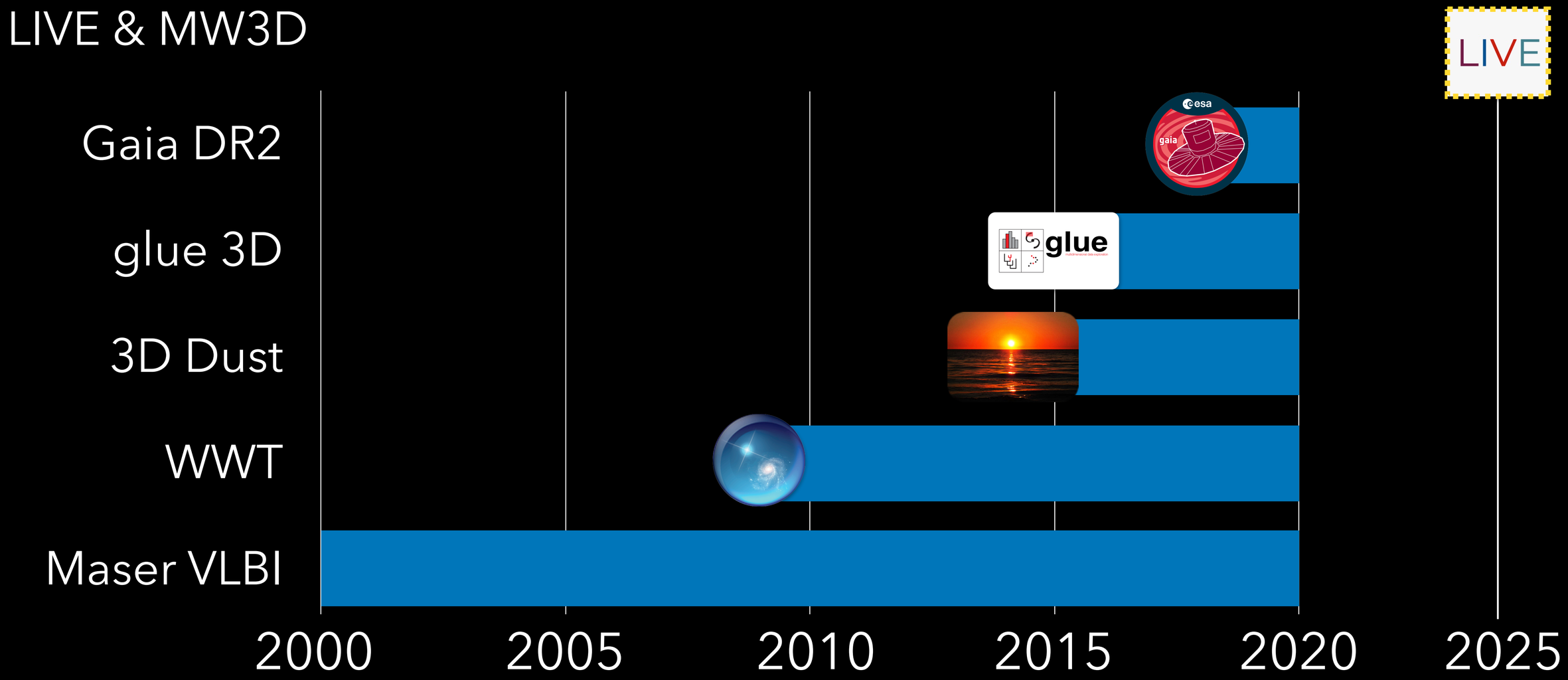


Green et al. 2019

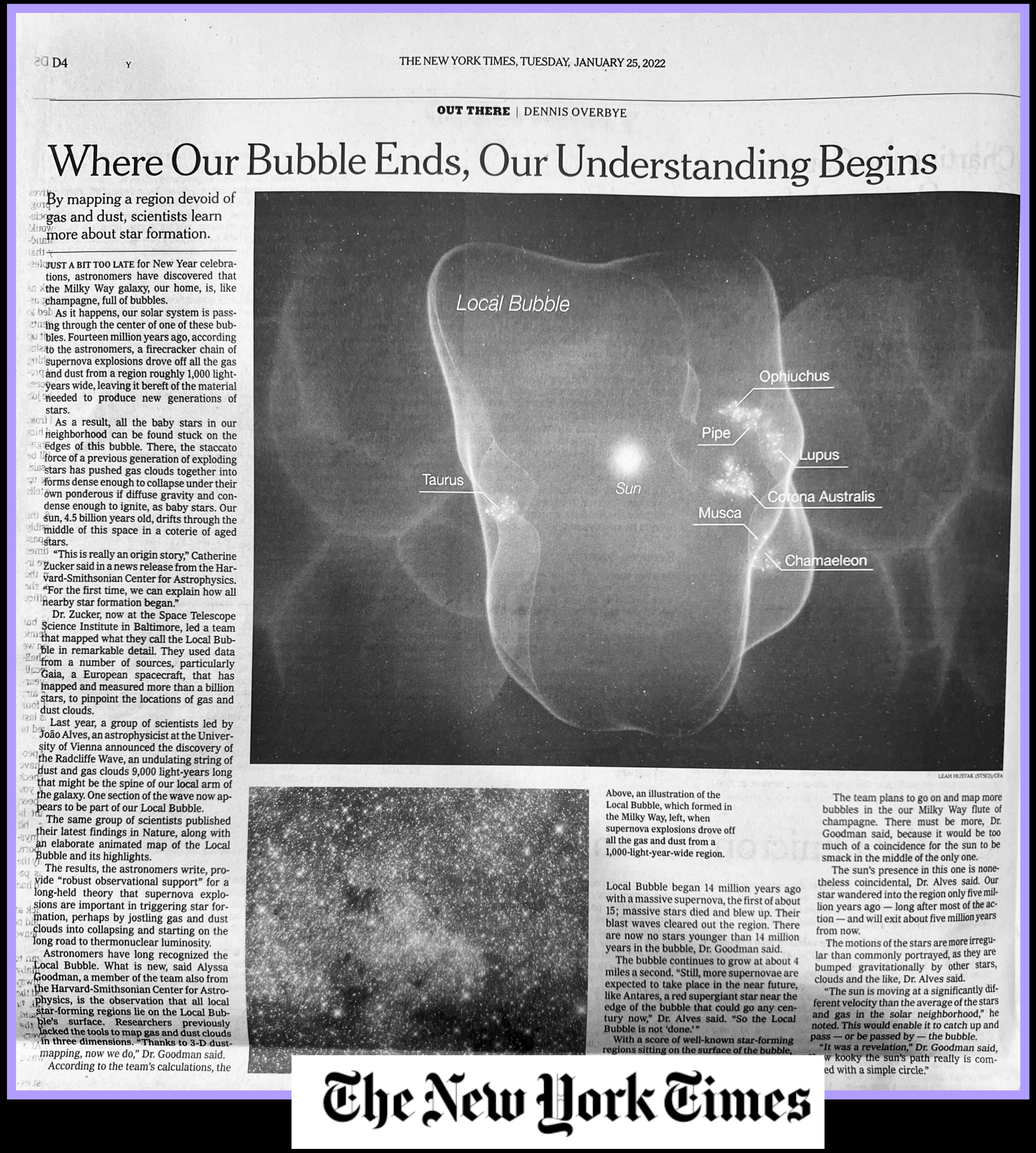
Can infer matter's distance from *dust's* effects on stars.

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*?


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

Local Bubble
Sun
Taurus
Ophiuchus
Pipe
Lupus
Corona Australis
Musca
Chamaeleon

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,

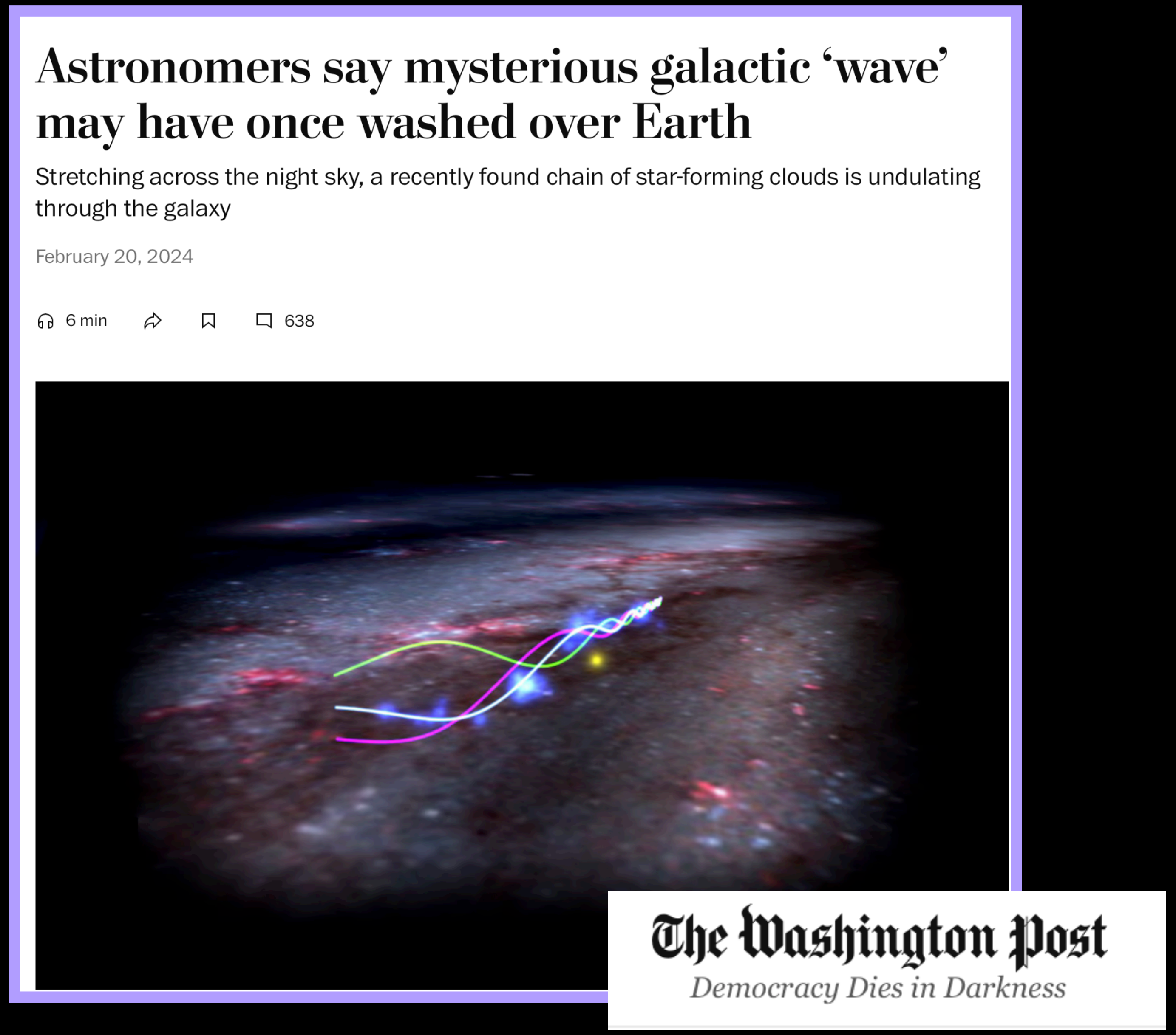
The team plans to go on and map more bubbles in the our Milky Way flute of champagne. There must be more, Dr. Goodman said, because it would be too much of a coincidence for the sun to be smack in the middle of the only one.

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."



2020

Ian Sample, The Guardian

2022

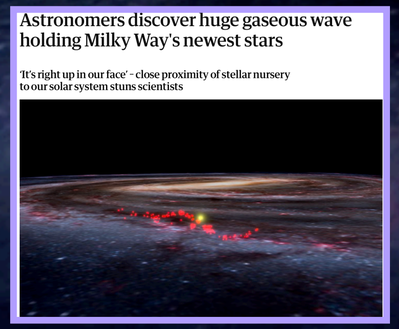
Dennis Overbye, NY Times

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)

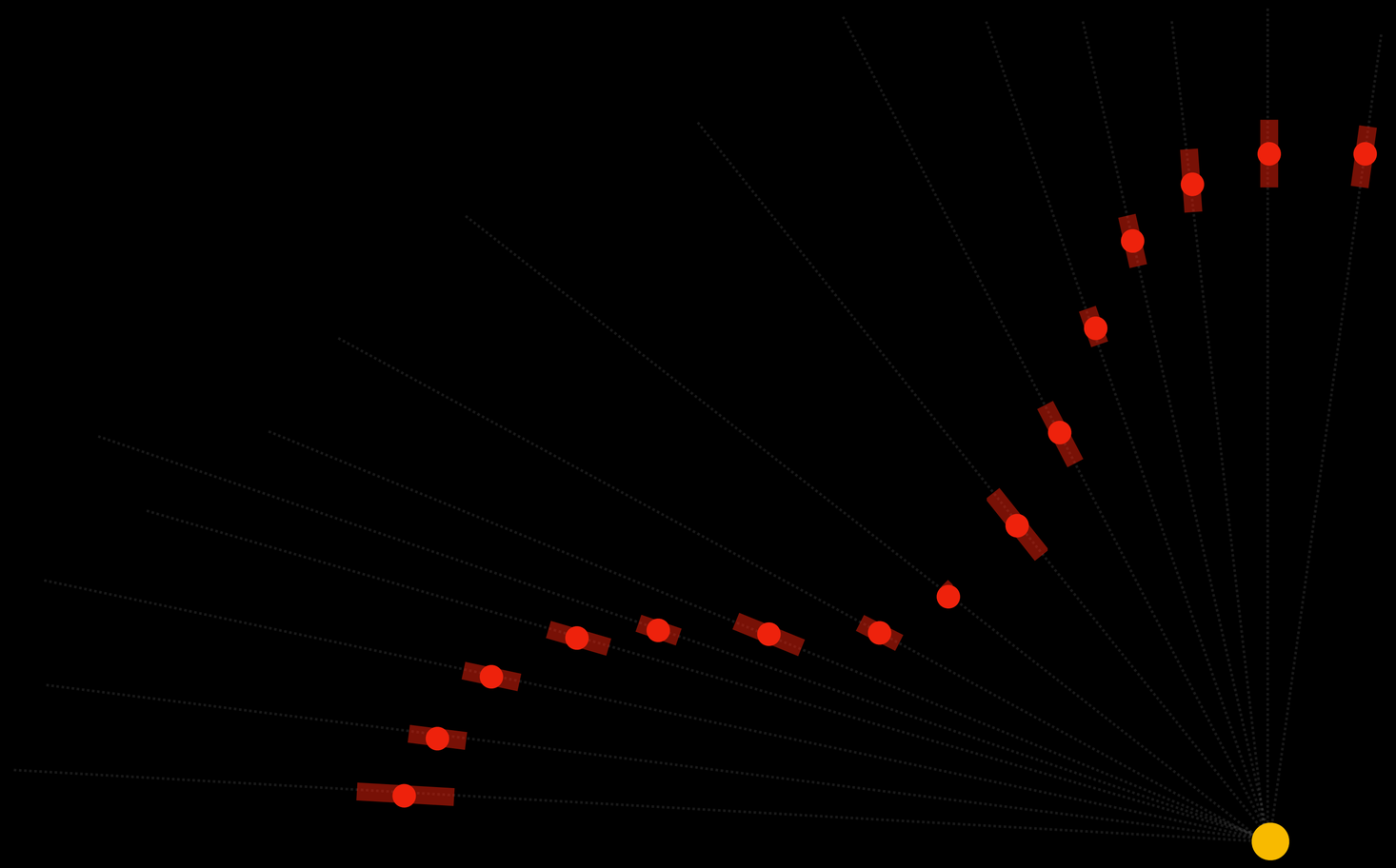
DISTANCES!!

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

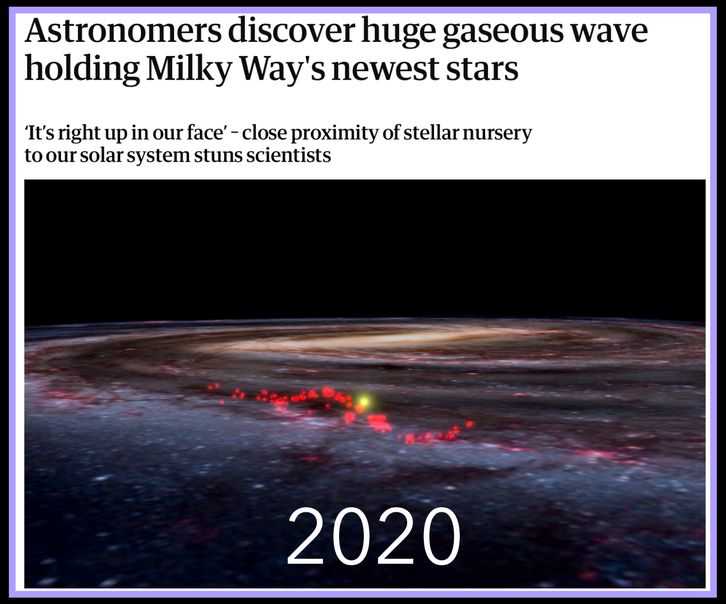
Uncertain Distances

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.

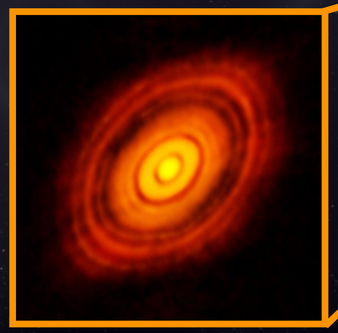
The team plans to go on and map more bubbles in the our Milky Way. Date of champagne. There must be more, Dr. Goodman said, because it would be too much of a coincidence for the sun to be sitting in the middle of just one bubble.

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.

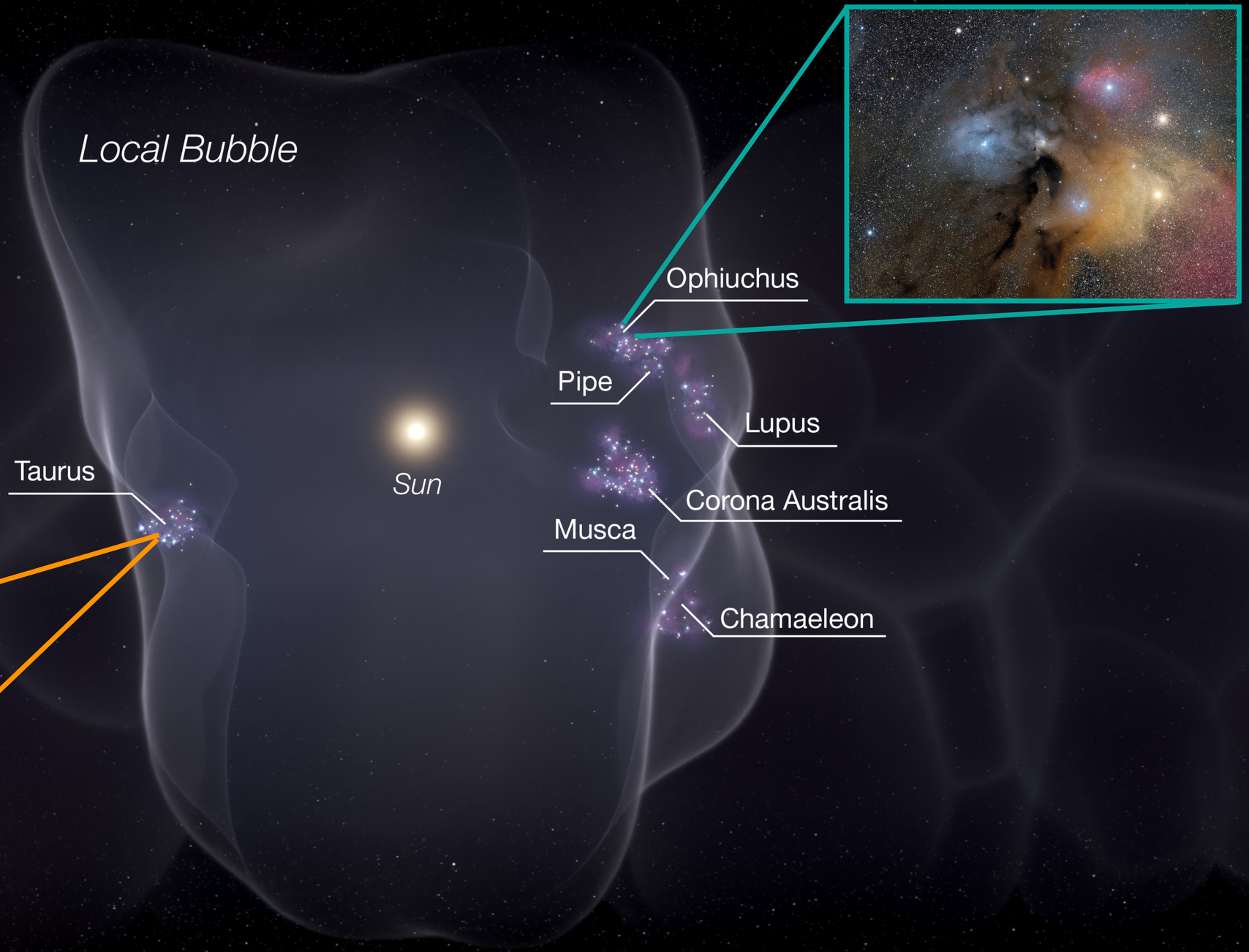
The motions of the stars are more irregular than commonly portrayed, as they are pulled in different directions by the sun's, Orion and the Sea, Dr. Alves said.

"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."



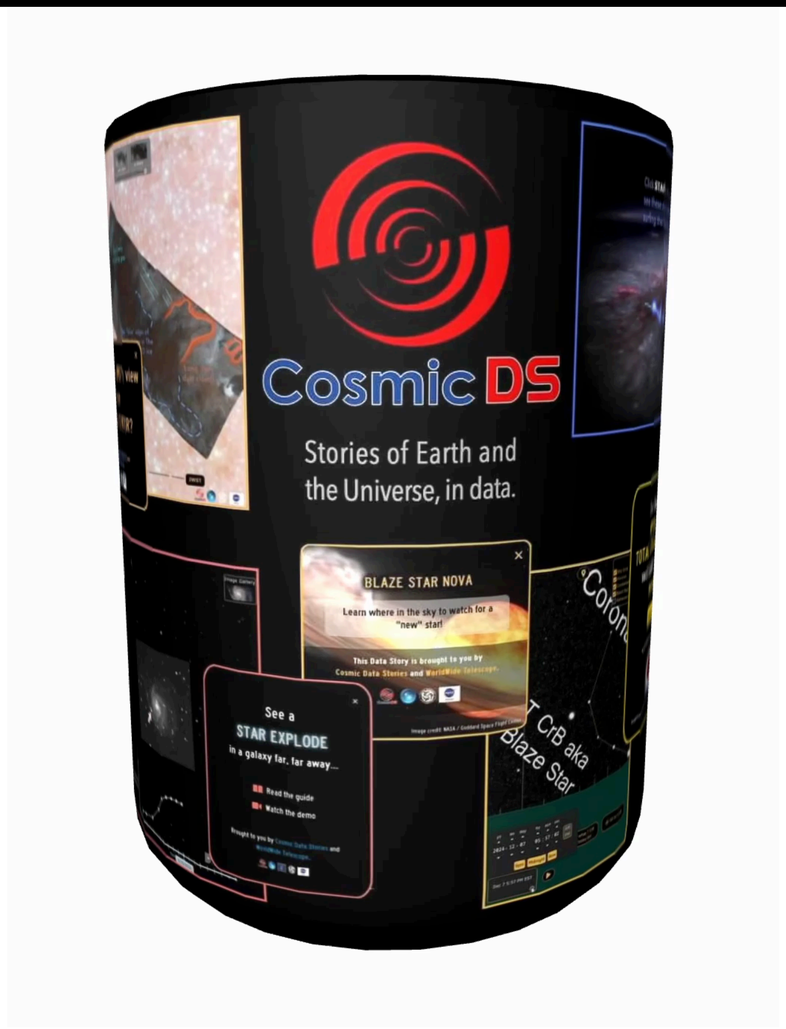
10,000x zoom



[LIVE demo!]

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

TODAY: RESEARCH + EDUCATION + OUTREACH



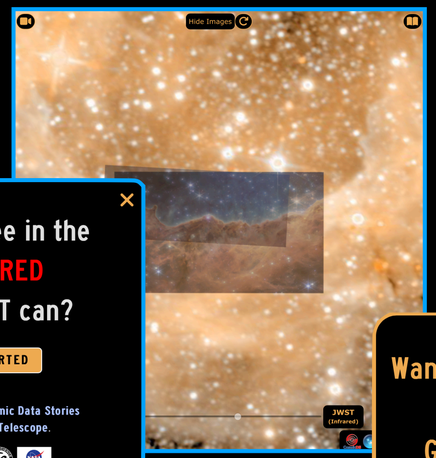
EDUCATION + OUTREACH

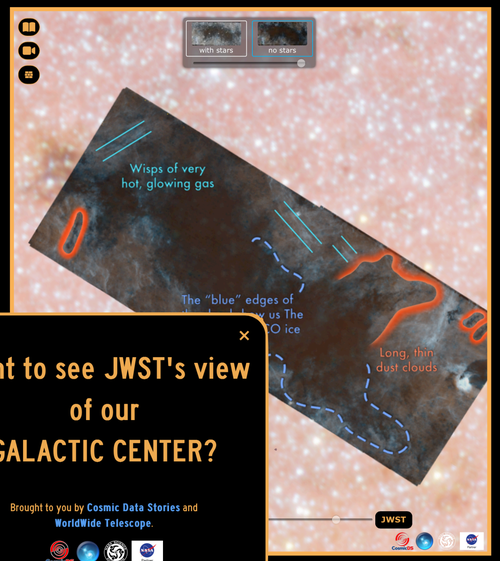
NASA SCIENCE ACTIVATION

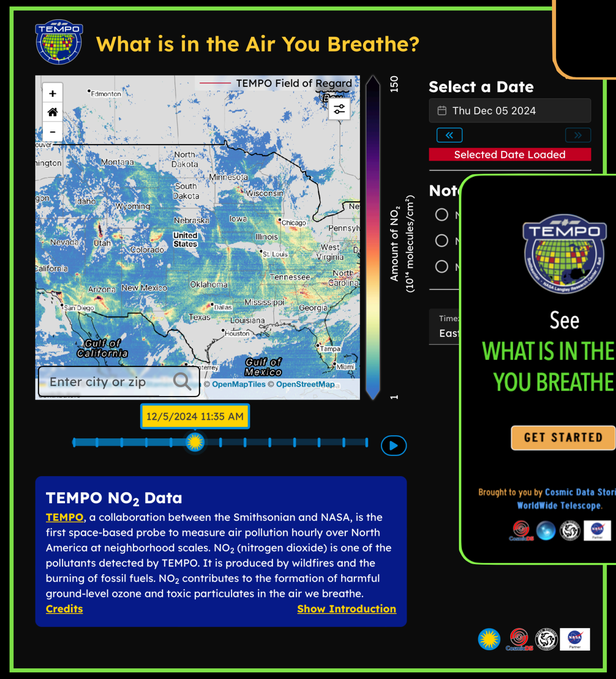
cosmicds.cfa.harvard.edu

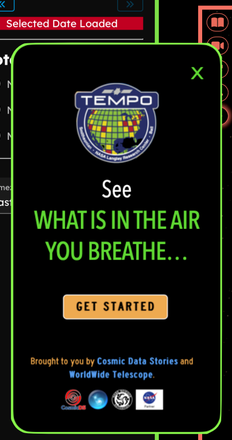
Cosmic DS

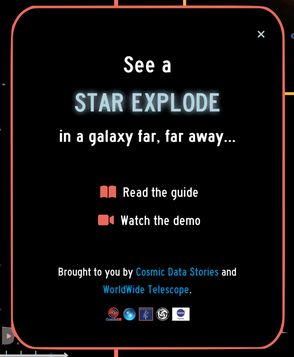
Stories of Earth and the Universe, in data.

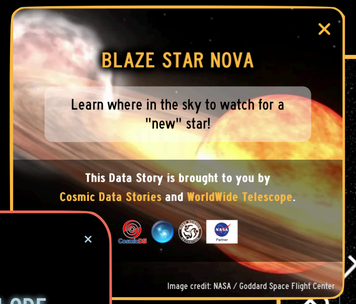


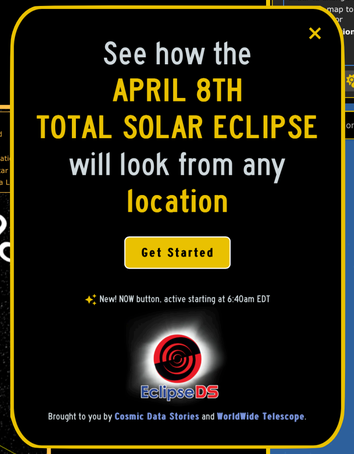


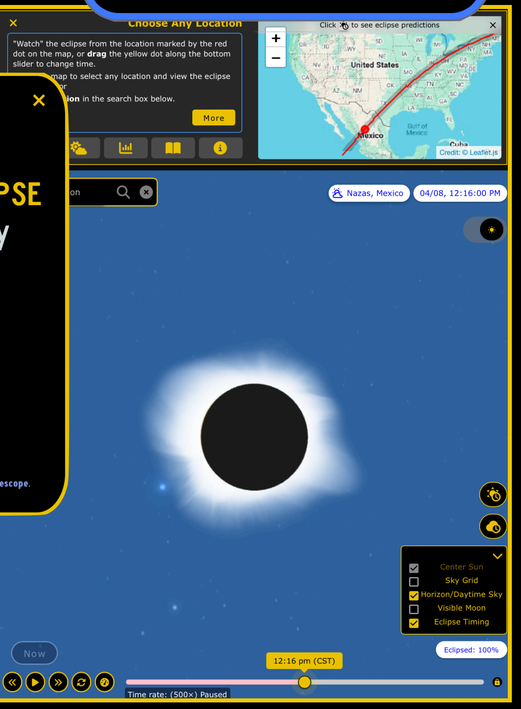












RESEARCH

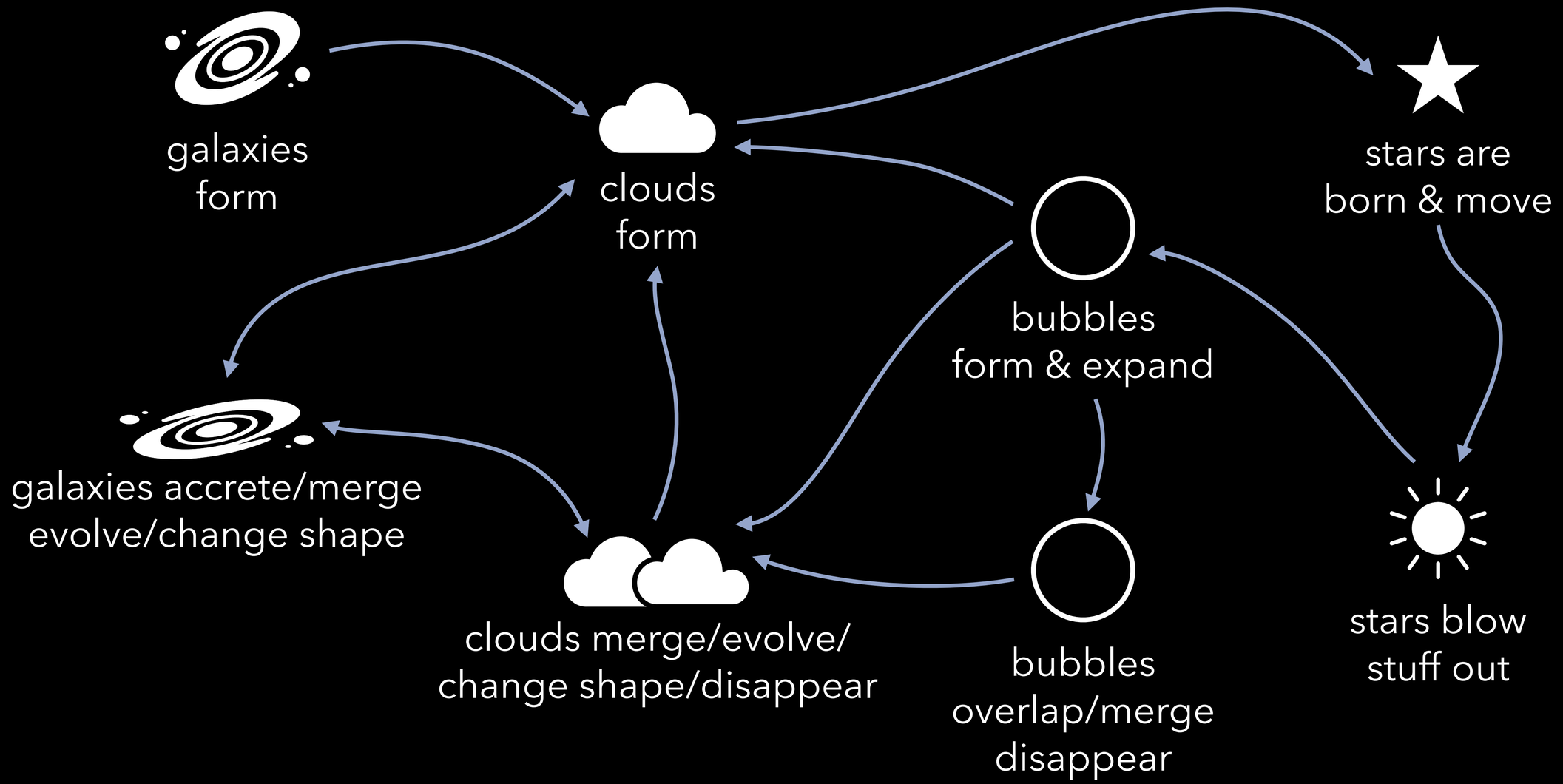
"Everything, Everywhere, All at Once"

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!)

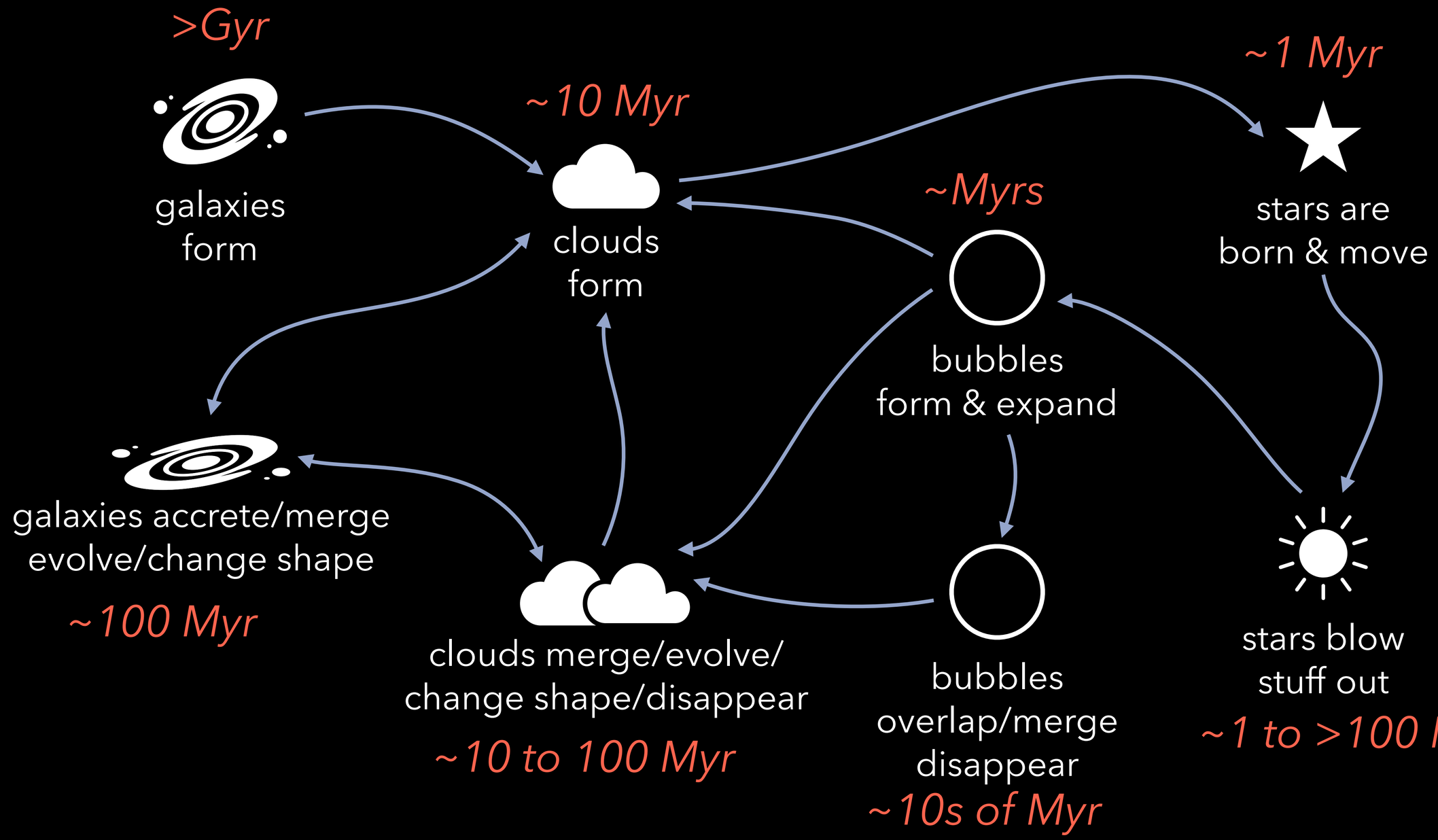
MOVIE

Nothing stays still. Nothing lasts forever.

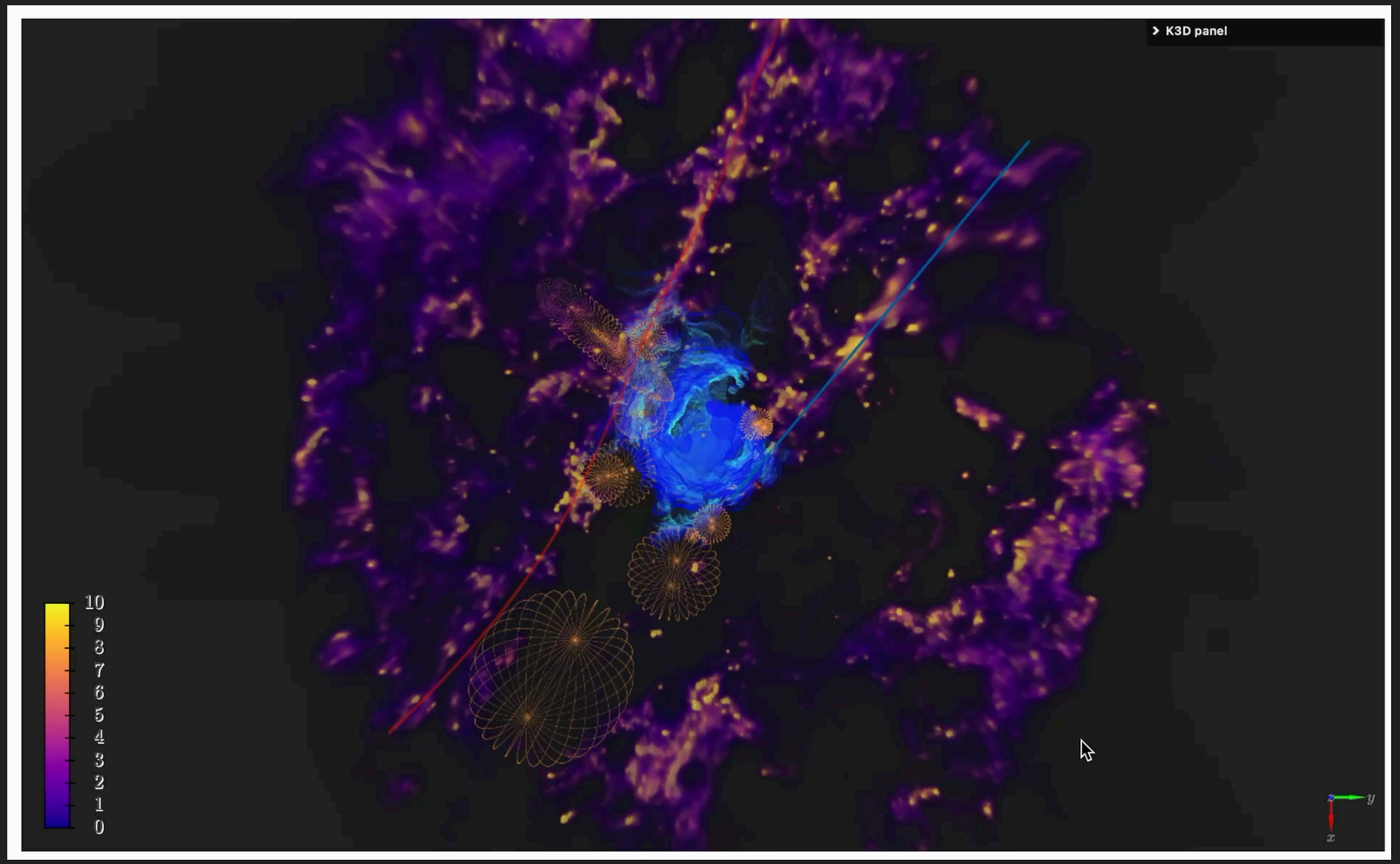
"Everything, Everywhere, All at Once"



"Everything, Everywhere, All at Once"



“Everything, Everywhere, All at Once”



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

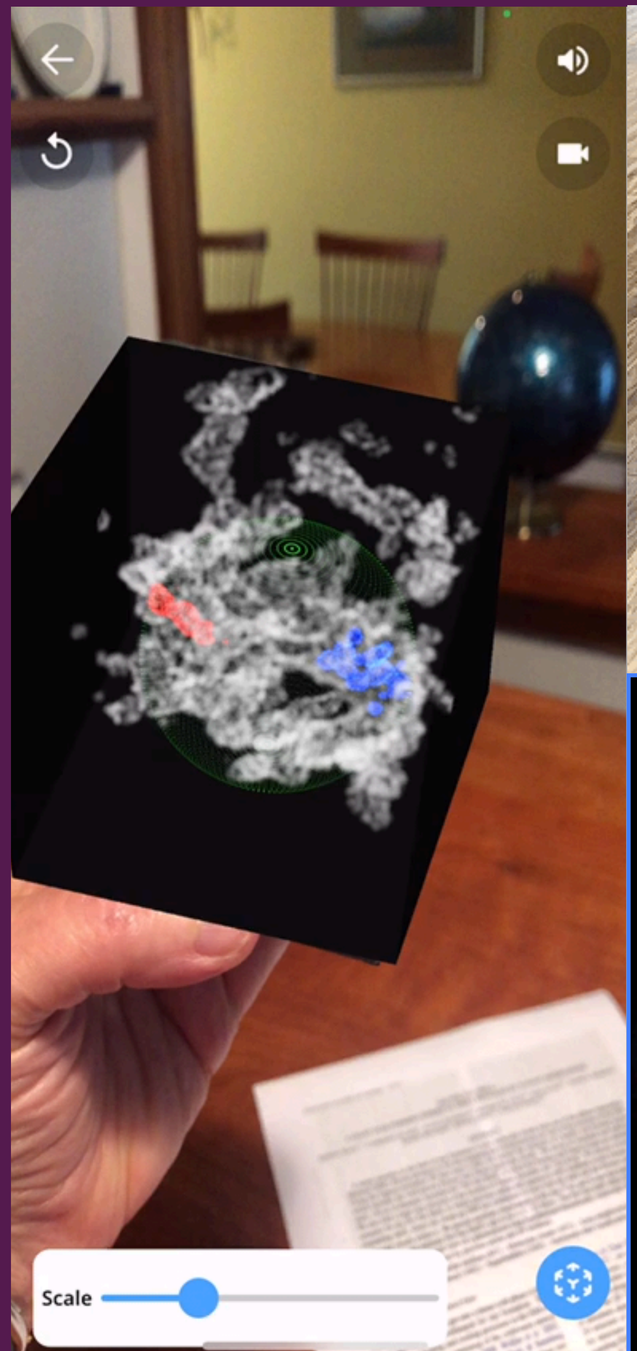
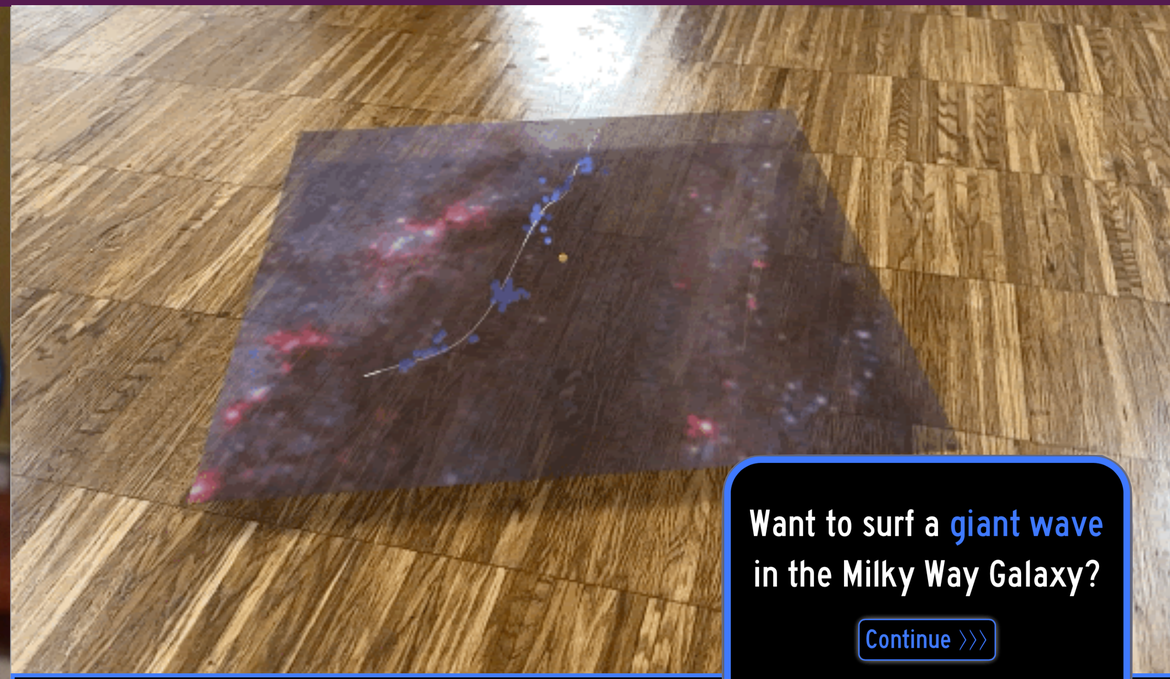
in a augmented reality, on your phone...

RESEARCH

+OUTREACH

MILKYWAY3D.org

OpenSpace

glue
multidimensional data exploration

WORLDWIDE TELESCOPE