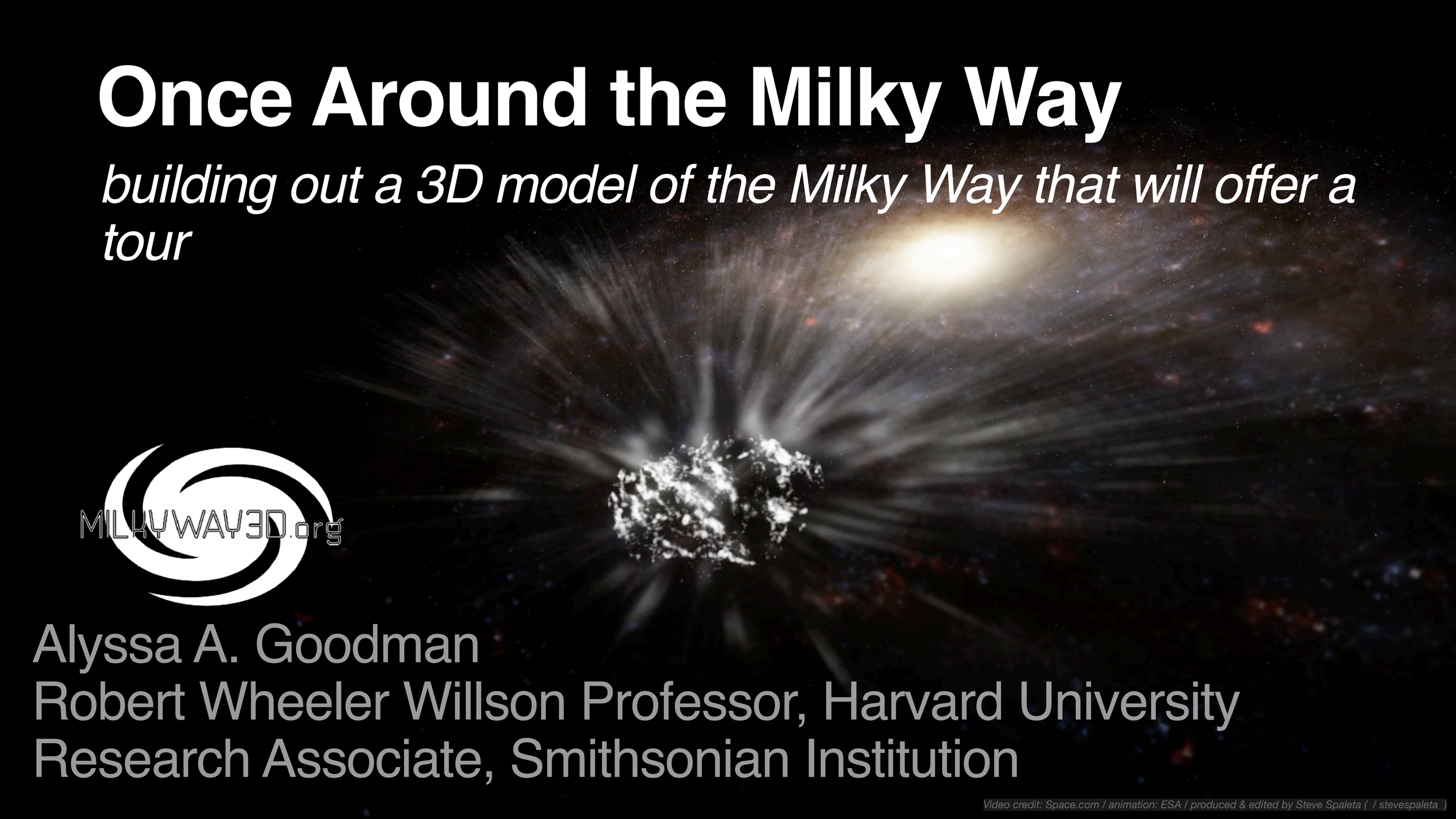
Once Around the Milky Way

building out a 3D model of the Milky Way that will offer a tour



Alyssa A. Goodman
Robert Wheeler Willson Professor, Harvard University
Research Associate, Smithsonian Institution

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

Research

STScI SPACE TELESCOPE SCIENCE INSTITUTE

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I2

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LIVE

glue multidimensional data exploration glueviz.org

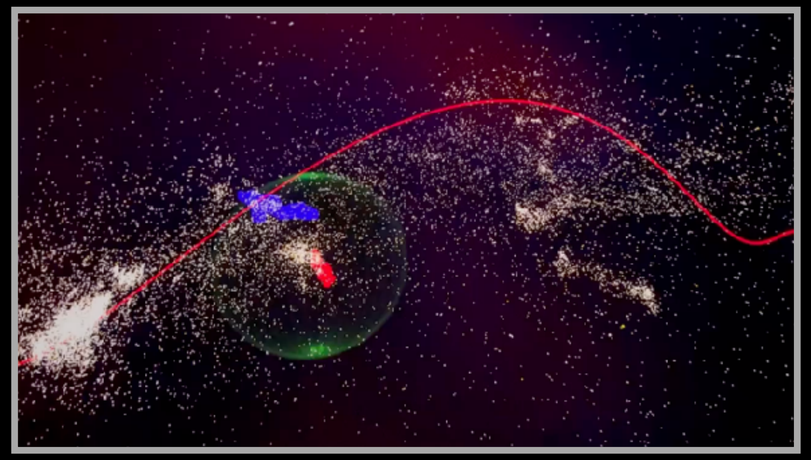
OpenSpace

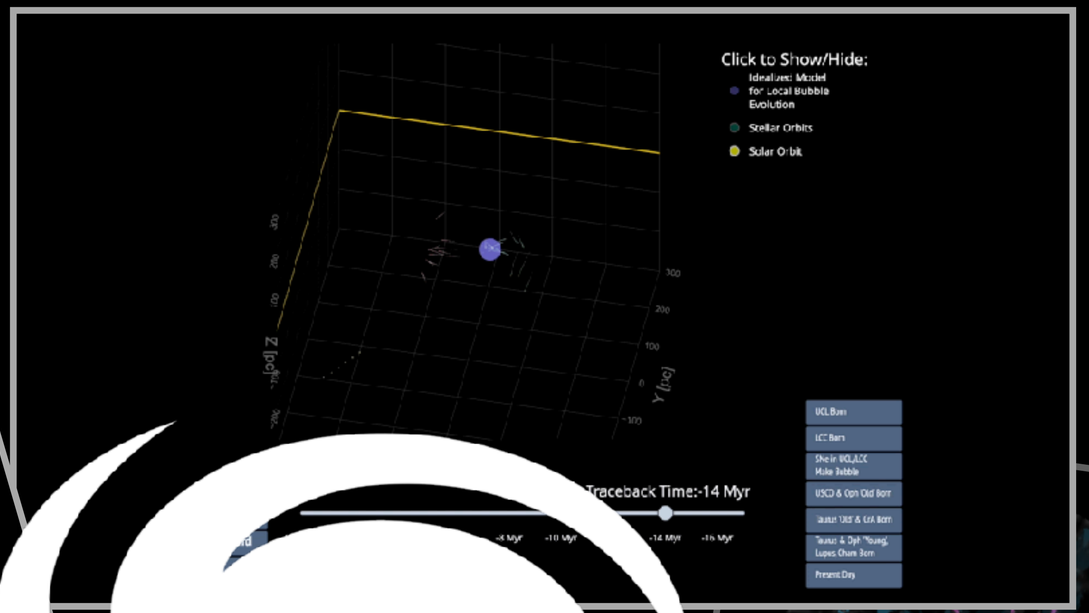
WORLDWIDE TELESCOPE

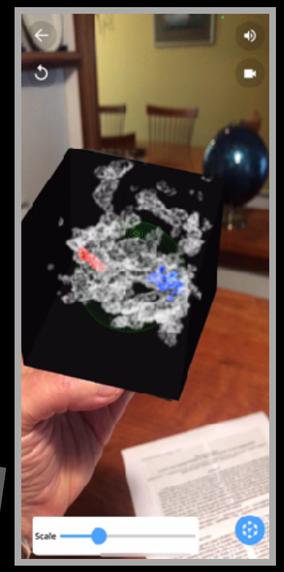
Curated Data Repositories

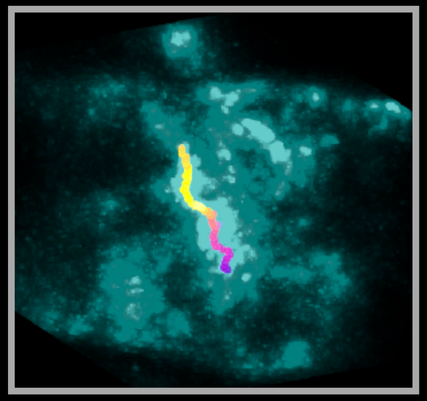
The Dataverse® Project

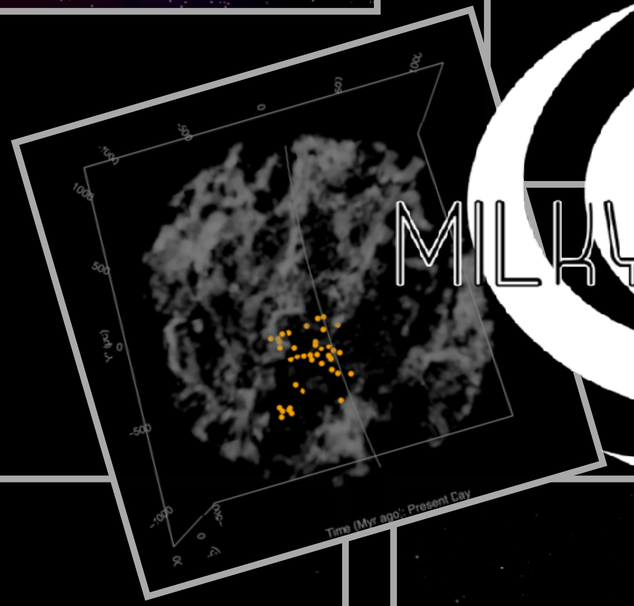
Barbara A. MIKULSKI ARCHIVE FOR SPACE TELESCOPES

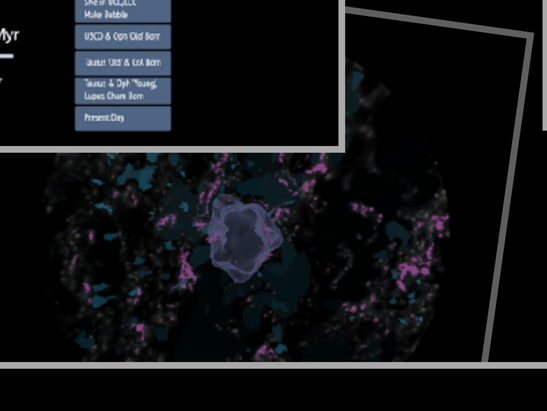




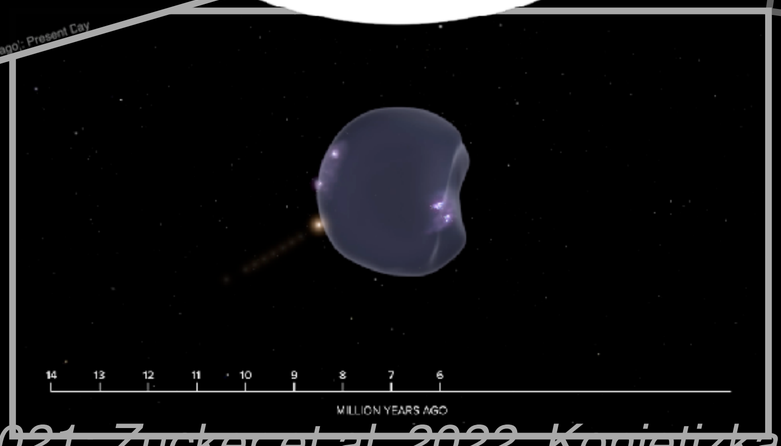


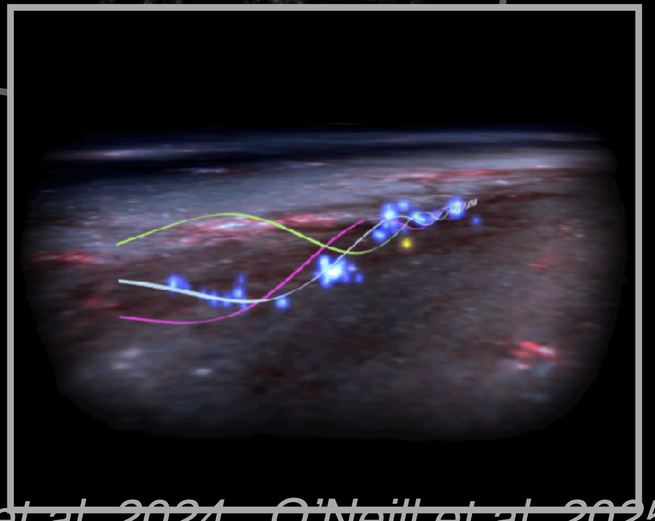






MILKYWAY3D.org





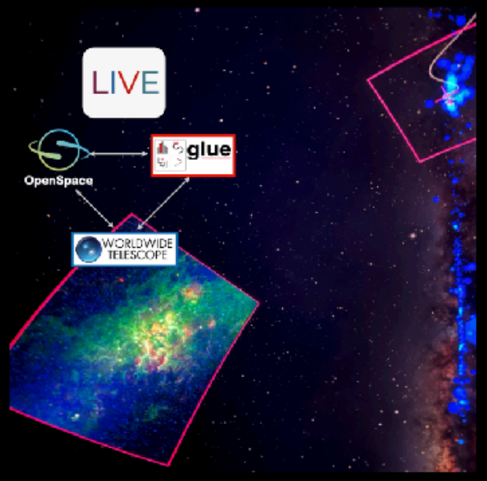
Zucker et al. 2021, Bialy et al. 2021, Zucker et al. 2022, Konietizka et al. 2024, O'Neill et al. 2025, Swiggum 2024

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.

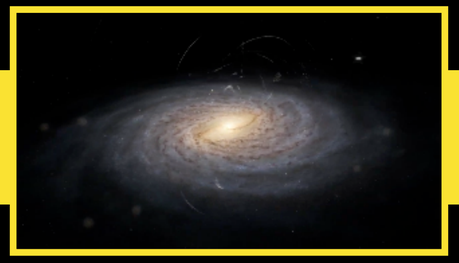
MilkyWay3D's open science premise: Data + Software + People + Computing + Physics = Understanding, Learning, and Discovery

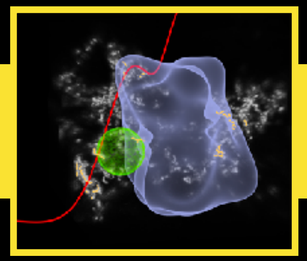
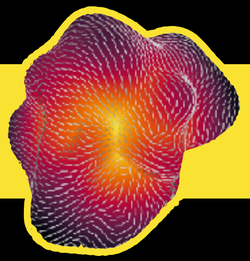
Bringing you the Galaxy as we know it. Updated as we learn more.

But first, some backstory.

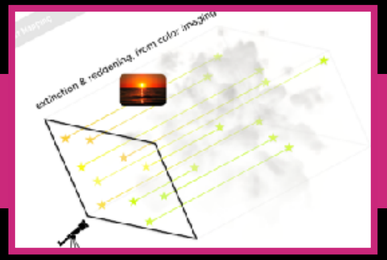
The NEW Milky Way

what it looks like

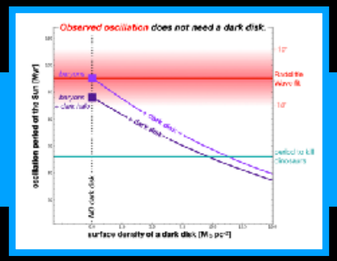


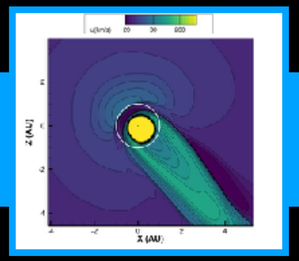



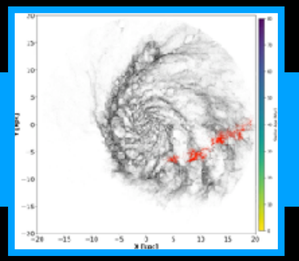
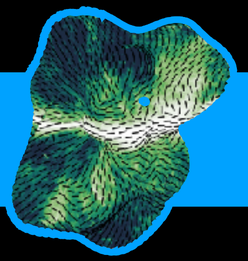
how we know



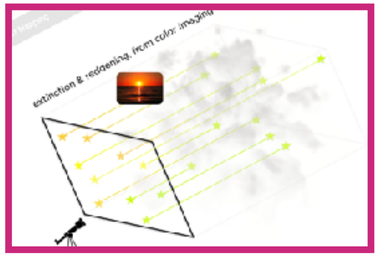
why it matters



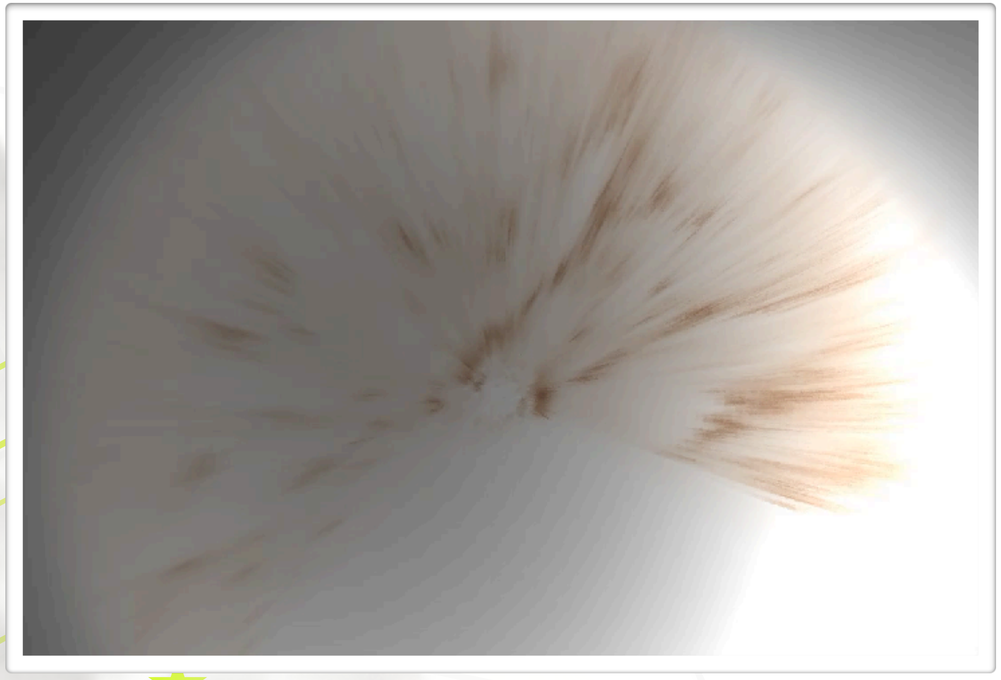


3D dust mapping

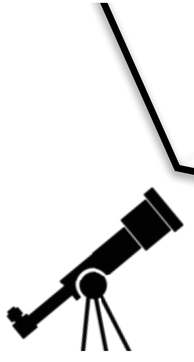


Extinction & Reddening, from Color Imaging



Green et al. 2019

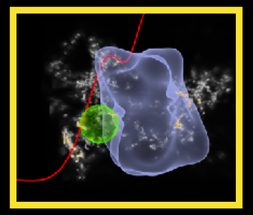
Can infer matter's distance from *dust's* effects on stars.



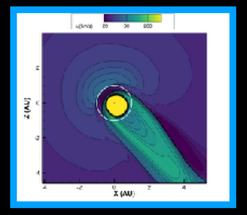
WARNING: schematic diagram, NOT to scale (credit A. Goodman,

Past 5 years….

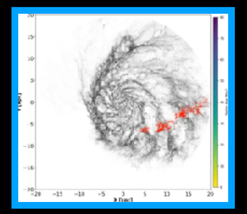
Arms of galaxies (1) look like they "wave," and (2a) they move like that too. (2b) There appears to be almost no dark matter in the Milky Way's disk.)



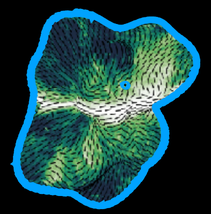
(3a) Feedback from supernovae & winds are as important as theorists said it was 50 years ago, even though observers didn't believe them. (3b) Star forming clouds may largely form at the intersection of feedback bubbles.



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



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



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

Glue (/Users/aagoodman/Library/CloudStorage/GoogleDrive-goodman.alyssa@gmail.com/.shortcut-targets-by-id/1e4RysNCInsaerZT11AaNJ9GKPS9q7vZg/MilkyWay3D.ORG/Sessions/munich_demo.glu)

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

glue multidimensional data exploration glueviz.org

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

- [x] Edenhofer_2023_3D_Dust_XYZ_Revised-2
- [x] Zucker2021_ApJ_919_35_spines_MW3D[HDU1]
- [x] Bialy2021_ApJL_919_L5_MW3D[HDU1]
- [x] Pelgrims2020_A+A_636_A17_lmax10_MW3D[HDU1]
- [x] Alves2020_Nat_578_237_MW3D[HDU1]
- [x] Leike2020_A+A_639_A138_xyz_cube_MW3D

Attribute: PRIMARY

Limits: 5.89626e-08 | 0.00643762

Color:

Plot Options - 3D Volume Rendering

x axis Pixel Axis 2 [x]

min/max: -73.9532 ⇄ 812.953

stretch: 1.00

y axis Pixel Axis 1 [y]

min/max: -73.9532 ⇄ 812.953

stretch: 1.00

z axis Pixel Axis 0 [z]

min/max: -54.101 ⇄ 593.101

stretch: 1.00

reference: Leike2020_A+A_639_A138_xyz_cube_MW3D

resolution: 256

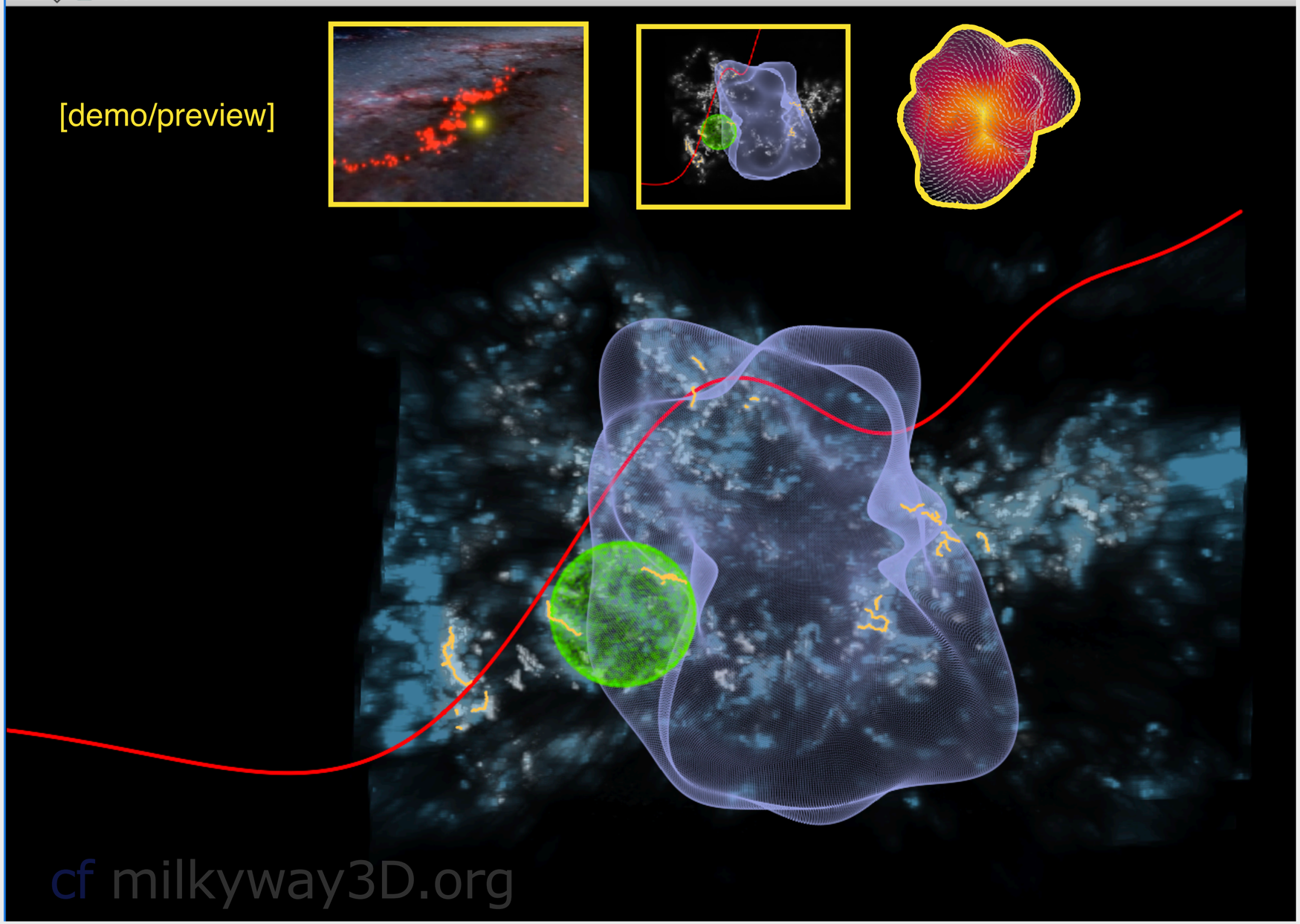
- [x] Native aspect ratio
- [ ] Perspective
- [ ] Downsample when panning

Line Width 1

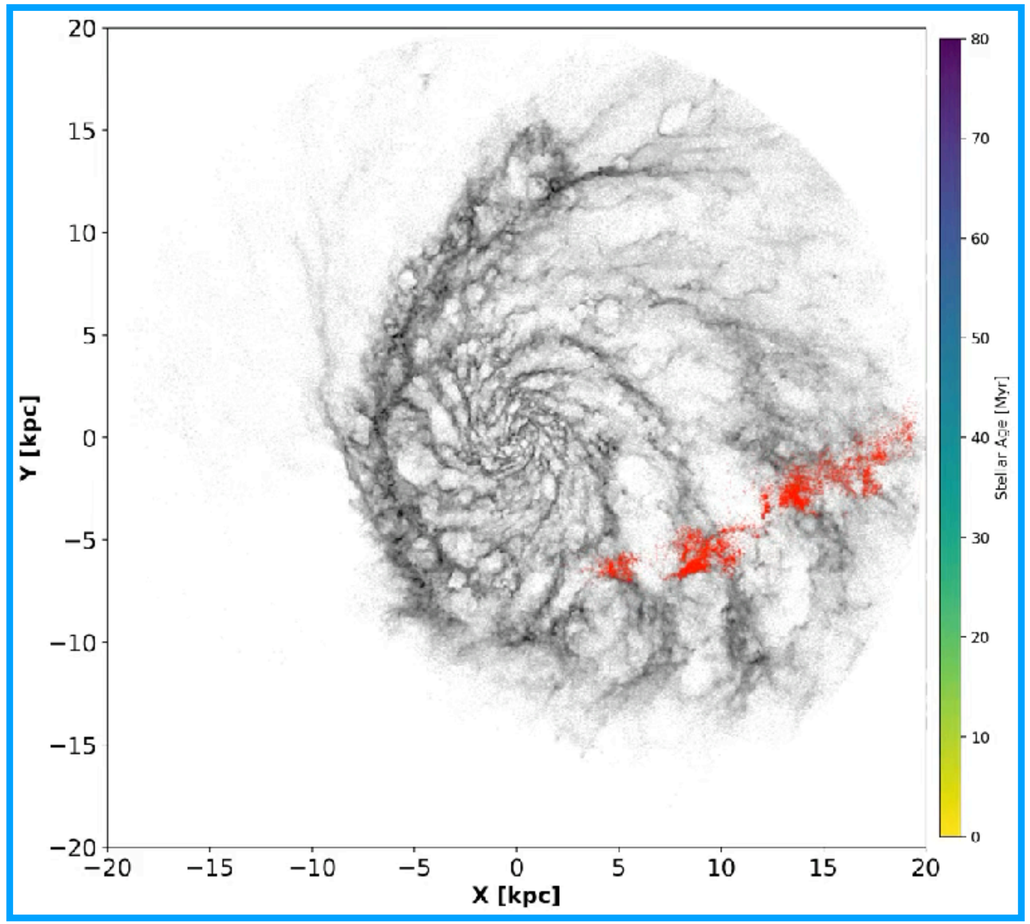
- [ ] Show axes

Tab 1 | Tab 2 | Tab 3

3D Volume Rendering

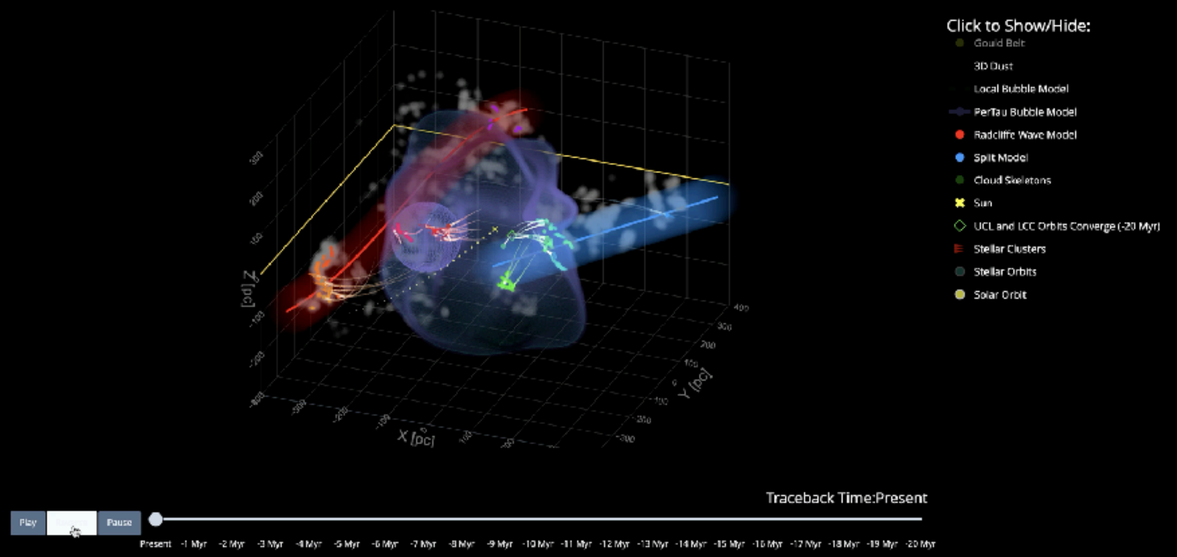


“Snapshots” can be deceiving–
pattern speed is NOT real motion!



Loebman and Zucker et al. will present this SIMULATION

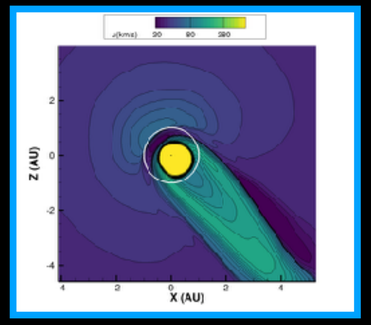
“Crazy” stuff *IS* happening?!



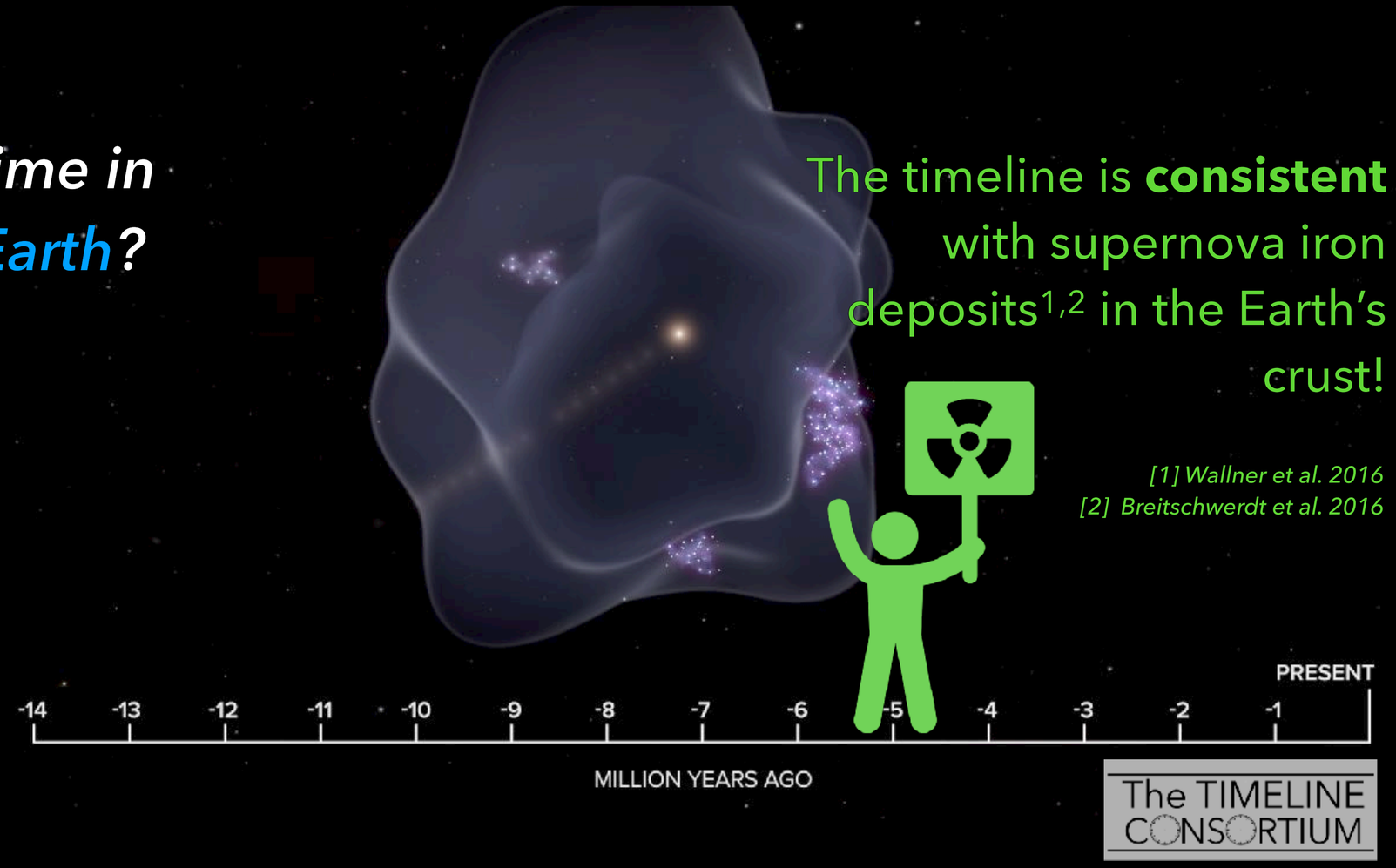
DEMO: https://faun.rc.fas.harvard.edu/czucker/Interactive_Figure3_Alyssa.html,
based on Zucker et al. 2022 (& Konietzka et al. 2024)

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

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



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

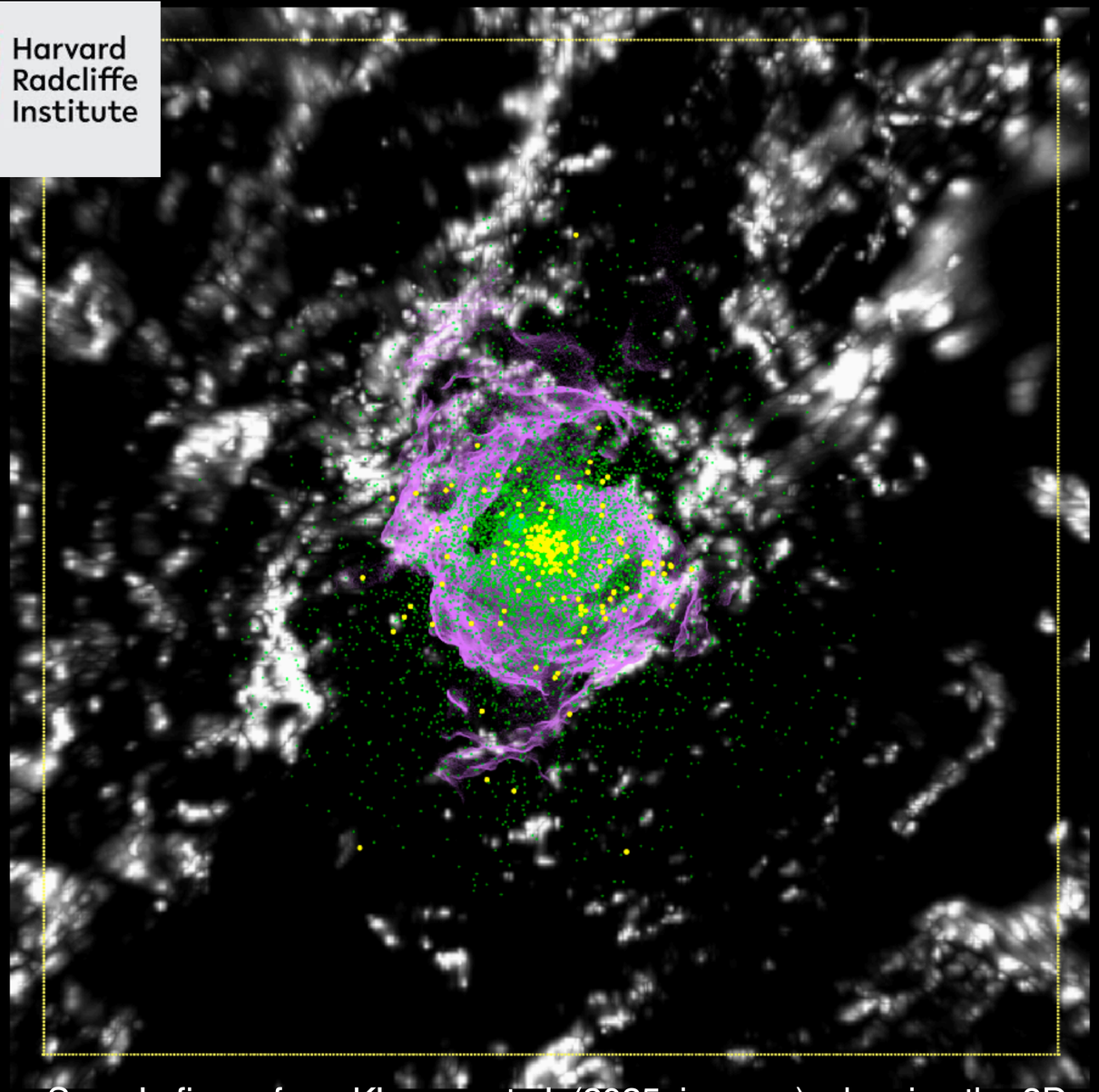


The timeline is **consistent** with supernova iron deposits[1,2] in the Earth's crust!

[1] Wallner et al. 2016
[2] Breitschwerdt et al. 2016

In **2024, while** on sabbatical at Harvard's Radcliffe Institute, Ralf Klessen studied how Earth's Night Sky might change, depending on the Sun's Position relative to the Local Bubble.

Working with Ralf on that made me wonder what a star's Sky "looks like" over a full Galactic orbit, and how "agent-based" modeling might offer new understanding of what João Alves likes to call "galactic



Sample figure from Klessen et al. (2025, in prep.) showing the 3D positions of the brightest stars (yellow, green) visible from the Sun's current position, in the context of the Edenhofer 2023 3D dust map. Local Bubble model from O'Neill et al. 2024 shown in purple.

“galactic weather”

universität wien

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Galactic weather: Solar system encounters with dense gas clouds

Supervisor: João Alves in collaboration with Stefan Meingast (Dept. of Astrophysics), Catherine Zucker and Alyssa Goodman, (Dept. Astronomy, Harvard University)

Funding Situation: potentially via a VISESS PhD fellowship

Project outline: Several studies over the past 40 years have suggested that there is a causal connection between the Sun's crossing of spiral arms and giant molecular clouds and terrestrial mass extinctions or climate change, although this remains a controversial topic. This project will take
System with the Radcliffe Wave and loca
will work with data from the ESA Gaia mi
and will be part of a young, exploration-
ongoing collaboration with Harvard Univ

This PhD project, connected with the pr
the making: the origin and evolution of t
questions:

- What is the origin and motion of G
- How do star-forming regions form
- Has the Solar System interacted w

We are looking for an enthusiastic candi

Contact

University of Vienna
Faculty of Earth Sciences, Geography and Astronomy
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A-1090 Vienna

T. +43-1-4277-53009

A&A, 694, A167 (2025)
https://doi.org/10.1051/0004-6361/202452061
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Astronomy & Astrophysics

The Solar System's passage through the Radcliffe wave during the middle Miocene

E. Maconi[1,*], J. Alves[1], C. Swiggum[1], S. Ratzenböck[1,2], J. Großschedl[1,3,4], P. Köhler[5], N. Miret-Roig[1], S. Meingast[1], R. Konietzka[6], C. Zucker[6], A. Goodman[6], M. Lombardi[7], G. Knorr[5], G. Lohmann[5,8], J. C. Forbes[9], A. Burkert[10], and M. Opher[11,12]

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[2] University of Vienna, Research Network Data Science at Uni Vienna, Kolingasse 14–16, 1090 Vienna, Austria
[3] I. Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany
[4] Astronomical Institute of the Czech Academy of Sciences, Boční II 1401, 141 31 Prague, Czech Republic
[5] Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 27570 Bremerhaven, Germany
[6] Harvard University Dep. of Astronomy and Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA
[7] Università degli Studi di Milano, Dipartimento di Fisica, Via Celoria 16, 20133 Milano, Italy
[8] Department of Environmental Physics and MARUM, University of Bremen, Bremen, Germany
[9] School of Physical and Chemical Sciences, Te Kura Matū, University of Canterbury, Christchurch 8140, New Zealand
[10] University of Munich, Physics Department, Scheinerstrasse 1, 81679 Muenchen, Germany
[11] Radcliffe Institute for Advanced Studies at Harvard University, Cambridge, MA, USA
[12] Astronomy Department, Boston University, Boston, MA 02215, USA

Received 30 August 2024 / Accepted 8 January 2025

ABSTRACT

Context. As the Solar System orbits the Milky Way, it encounters various Galactic environments, including dense regions of the interstellar medium (ISM). These encounters can compress the heliosphere, exposing parts of the Solar System to the ISM, while also increasing the influx of interstellar dust into the Solar System and Earth's atmosphere. The discovery of new Galactic structures, such as the Radcliffe wave, raises the question of whether the Sun has encountered any of them.
Aims. The present study investigates the potential passage of the Solar System through the Radcliffe wave gas structure over the past 30 million years (Myr).
Methods. We used a sample of 56 high-quality, young (≤30 Myr) open clusters associated with a region of interest of the Radcliffe wave to trace its motion back and investigate a potential crossing with the Solar System's past orbit.
Results. We find that the Solar System's trajectory intersected the Radcliffe wave in the Orion region. We have constrained the timing of this event to between 18.2 and 11.5 Myr ago, with the closest approach occurring between 14.8 and 12.4 Myr ago. Notably, this period coincides with the Middle Miocene climate transition on Earth, providing an interdisciplinary link with paleoclimatology. The potential impact of the crossing of the Radcliffe wave on the climate on Earth is estimated. This crossing could also lead to anomalies in radionuclide abundances, which is an important research topic in the field of geology and nuclear astrophysics.

Key words. ISM: kinematics and dynamics – open clusters and associations: general – solar neighborhood

JILA a joint institute of University of Colorado Boulder and NIST

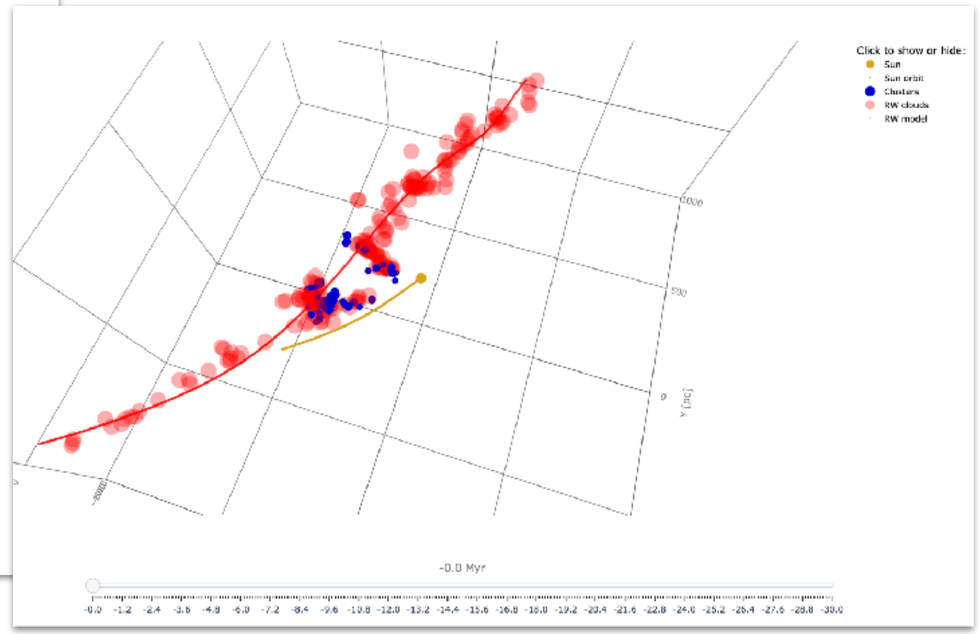
Effects of the Sun's trajectory through the galaxy on Earth's climate over the past 10 million years

Details

Speaker Name/Affiliation: Merav Opher / Boston University
When: Wed, Oct 15 2025, 4 - 5pm
Seminar Type: Physics Department Colloquium
Location (Room): JILA Auditorium
Event Details & Abstracts

Abstract: With the advent of the Gaia space mission, there has been a revolution in astronomers' ability to precisely locate the interstellar structures the Sun may have encountered on its voyage around the galaxy. We now have the spatial resolution to trace the Sun's trajectory back through its interstellar environment up to 60 million years in the past (4000 light-years in distance). This timescale is commensurate with the timescale over which we can reconstruct the paleoclimate of Earth from deep ocean foraminiferas. Today's heliosphere, the cocoon formed by the solar wind as it moves through the galaxy, engulfs all the planets extending in the nose direction to ~ 120 astronomical units (au). The Sun moves with 18pc/Myr and has traversed many different structures in the interstellar medium that affect the heliosphere, at times collapsing it to sub-au scales. These periods of collapse introduce climate and radiation changes in Earth environment.
The frequency of such encounters could be as often as every couple of Myrs, making it a major external disturbance to the development of life on Earth. Stepwise shifts in past global climate, seen in deep sea sediment cores, indicate intervals of more rapid cooling
Mya and 2-3Mya, for which the driving mechanisms are subject to ongoing debate. Such cooling events might be trig
collapse. I will discuss our recent work that show that in two occasions 3 and 7 million years ago (Mya), the Sun enco
shrank the heliosphere —the solar cocoon protecting our solar system— exposing Earth to its interstellar environment
evidence from 60Fe and 244Pu isotopes and discuss the implications for Earth's climate and biodiversity.

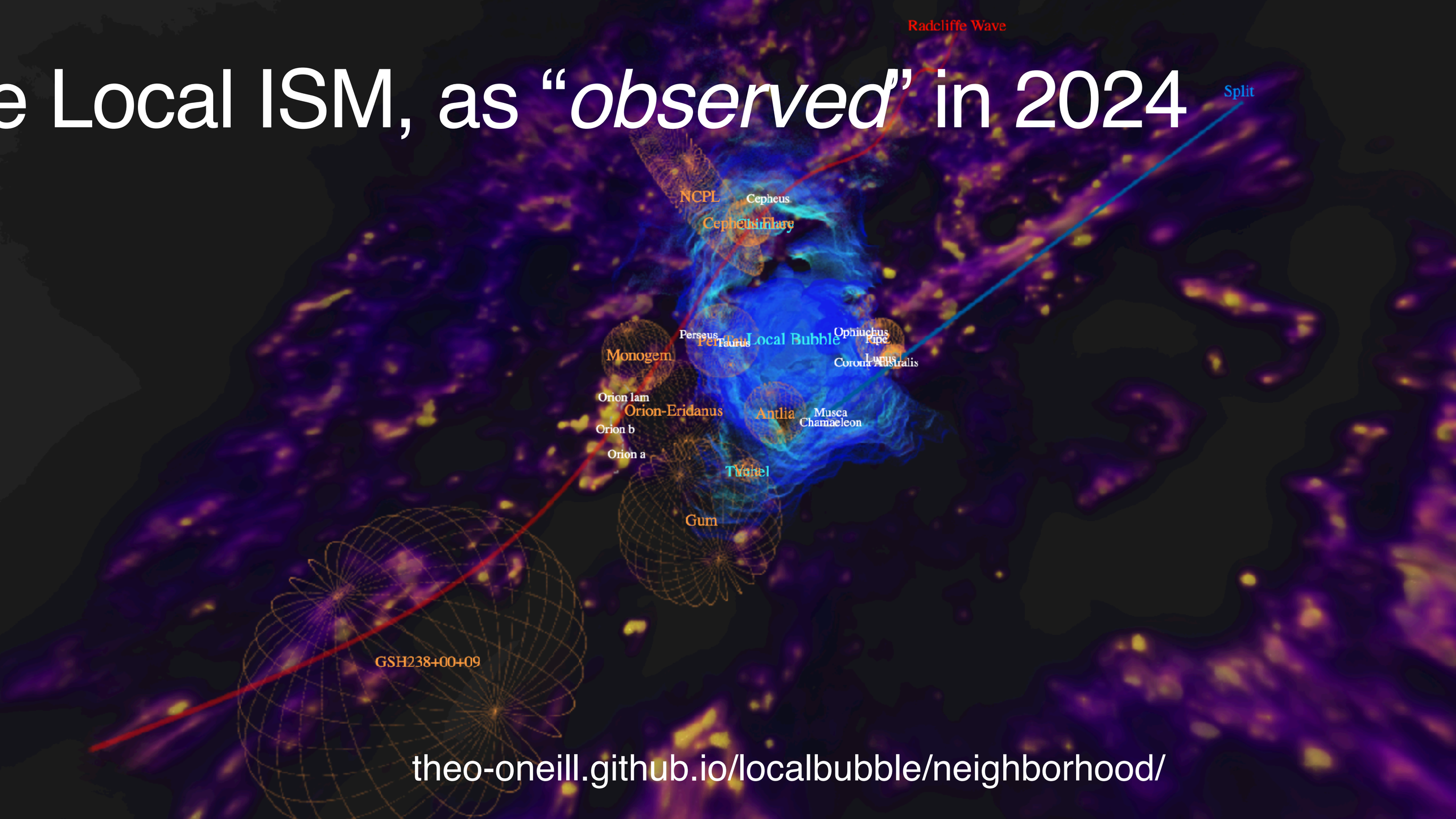
Harvard Radcliffe Institute



Today's Challenge

Can we combine what we learn from analysis of *observations* with *simulations* to understand what a star like the Sun might encounter on a journey once around the Milky Way?

e Local ISM, as "*observed*" in 2024



theo-oneill.github.io/localbubble/neighborhood/

“Milky Ways” as ***Simulated*** in 202

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 532, 1814–1831 (2024) https://doi.org/10.1093/mnras/stae1598
Advance Access publication 2024 June 27

Overview and public data release of the augmented Auriga Project: cosmological simulations of dwarf and Milky Way-mass galaxies

Robert J. J. Grand [1★], Francesca Fragkoudi [2], Facundo A. Gómez [3,4], Adrian Jenkins [2], Federico Marinacci [5], Rüdiger Pakmor [6] and Volker Springel [6]

[1] Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
[2] Department of Physics, Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK
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[5] Department of Physics & Astronomy 'Augusto Righi', University of Bologna, via Gobetti 93/2, I-40129 Bologna, Italy
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Accepted 2024 June 25. Received 2024 June 21; in original form 2024 January 12

ABSTRACT

We present an extended suite of the Auriga cosmological gravo-magnetohydrodynamical 'zoom-in' simulations of 40 Milky Way-mass haloes and 26 dwarf galaxy–mass haloes run with the moving-mesh code AREPO. Auriga adopts the Lambda cold dark matter cosmogony and includes a comprehensive galaxy formation physics model following the coupled cosmic evolution of dark matter, gas, stars, and supermassive black holes which has been shown to produce numerically well-converged galaxy properties for Milky Way-mass systems. We describe the first public data release of this augmented suite of Auriga simulations, which includes raw snapshots, group catalogues, merger trees, initial conditions, and supplementary data, as well as public analysis tools with worked examples of how to use the data. To demonstrate the value and robustness of the simulation predictions, we analyse a series of low-redshift global properties that compare well with many observed scaling relations, such as the Tully–Fisher relation, the star-forming (SF) main sequence, and H I gas fraction/disc thickness. Finally, we show that SF gas discs appear to build rotation and velocity dispersion rapidly for $z \gtrsim 3$ before they 'settle' into ever-increasing rotation-dispersion ratios (V/σ). This evolution appears to be in rough agreement with some kinematic measurements from Hα observations, and demonstrates an application of how to utilize the released data.

Key words: methods:numerical – galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: structure.

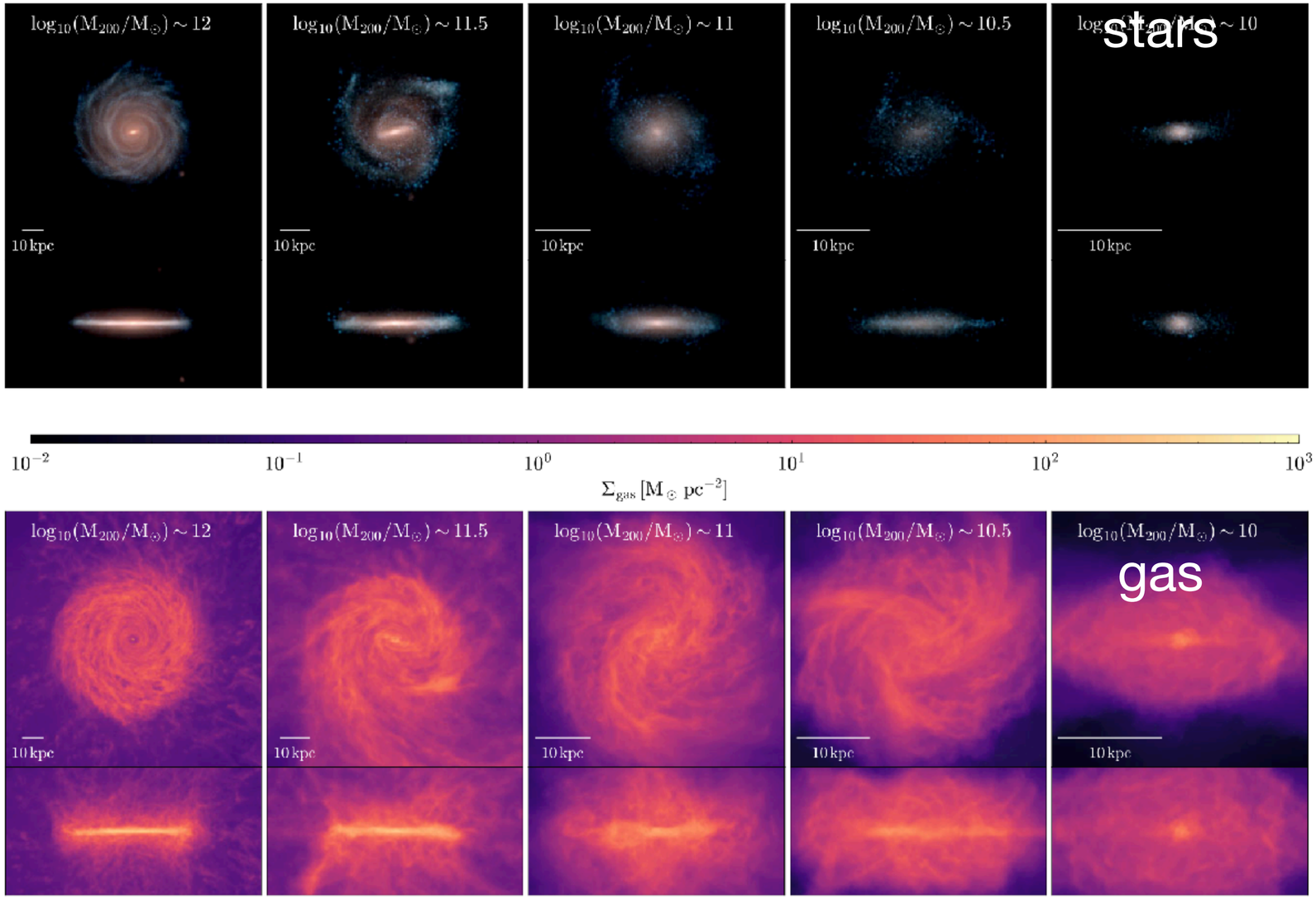


Figure 5. Top panels: face-on and edge-on stellar light projections of a selection of simulated galaxies at redshift $z = 0$. The z-axis is aligned with the eigenvector of the moment of inertia tensor of all star particles within $0.1R_{200}$ that is closest to the spin axis vector of those stars. We show one galaxy per 0.5 dex in halo mass to illustrate the dependence on halo mass. The scale bar is located in the bottom left corner of the face-on images in each case. Bottom panels: as for the top panels but for projections of the gas surface density.

Auriga Project Simulations using **AREPO**

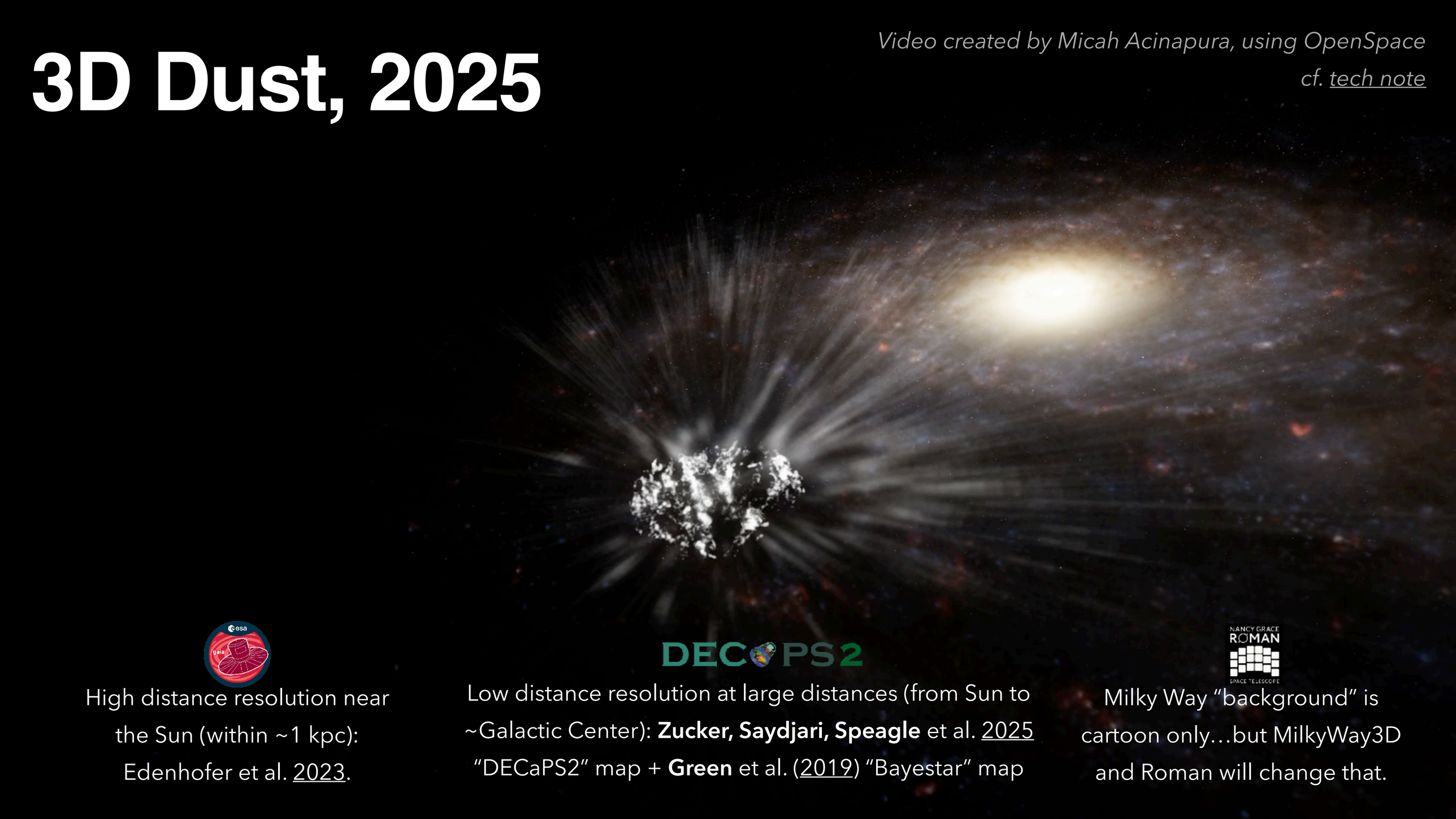
Auriga-like Milky Way(s) will be *wonderful* when **resolution** is ~10 pc & feedback is realistic.

Currently ~100 pc, with sub grid winds.

3D Dust, 2025

Video created by Micah Acinapura, using OpenSpace

cf. tech note

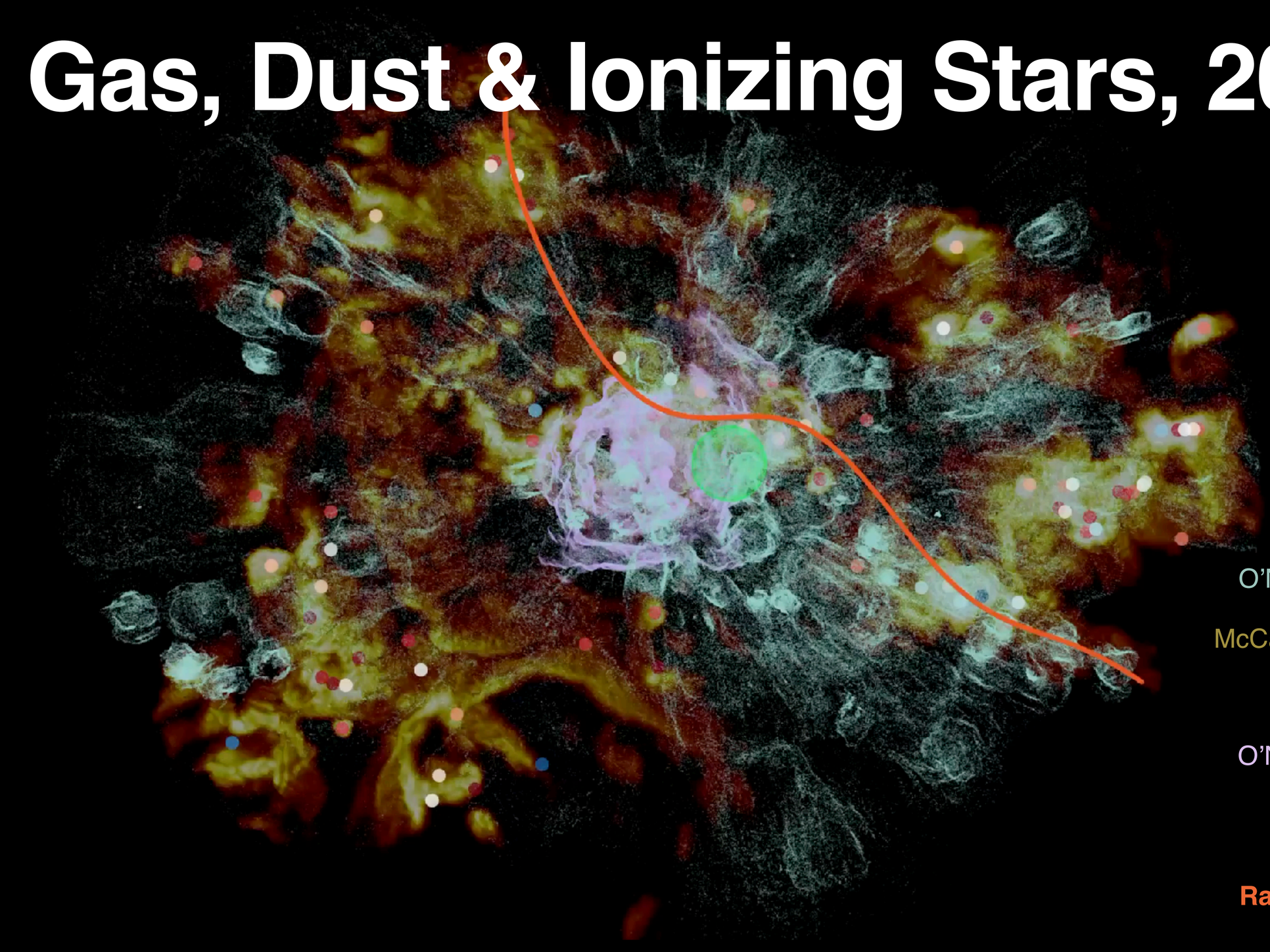


High distance resolution near the Sun (within ~1 kpc): Edenhofer et al. 2023.

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.

Gas, Dust & Ionizing Stars, 2025



glue
multidimensional data exploration
glueviz.org

MILKYWAY3D.org

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)

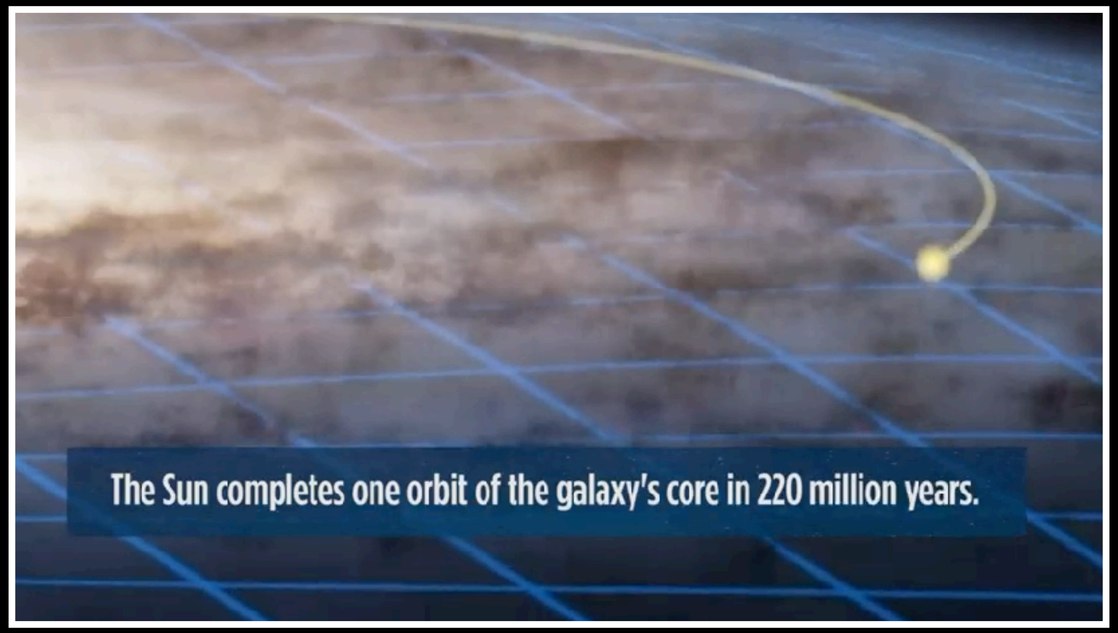
Today's Challenge

Can we combine what we learn from analysis of *observations* with *simulations* to understand what a star like the Sun might encounter on a journey once around the Milky Way?

A “Milky Way Like” Galaxy from JWST (NGC 628)

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

What's wrong in this view?



The Sun's environment is unchanging.

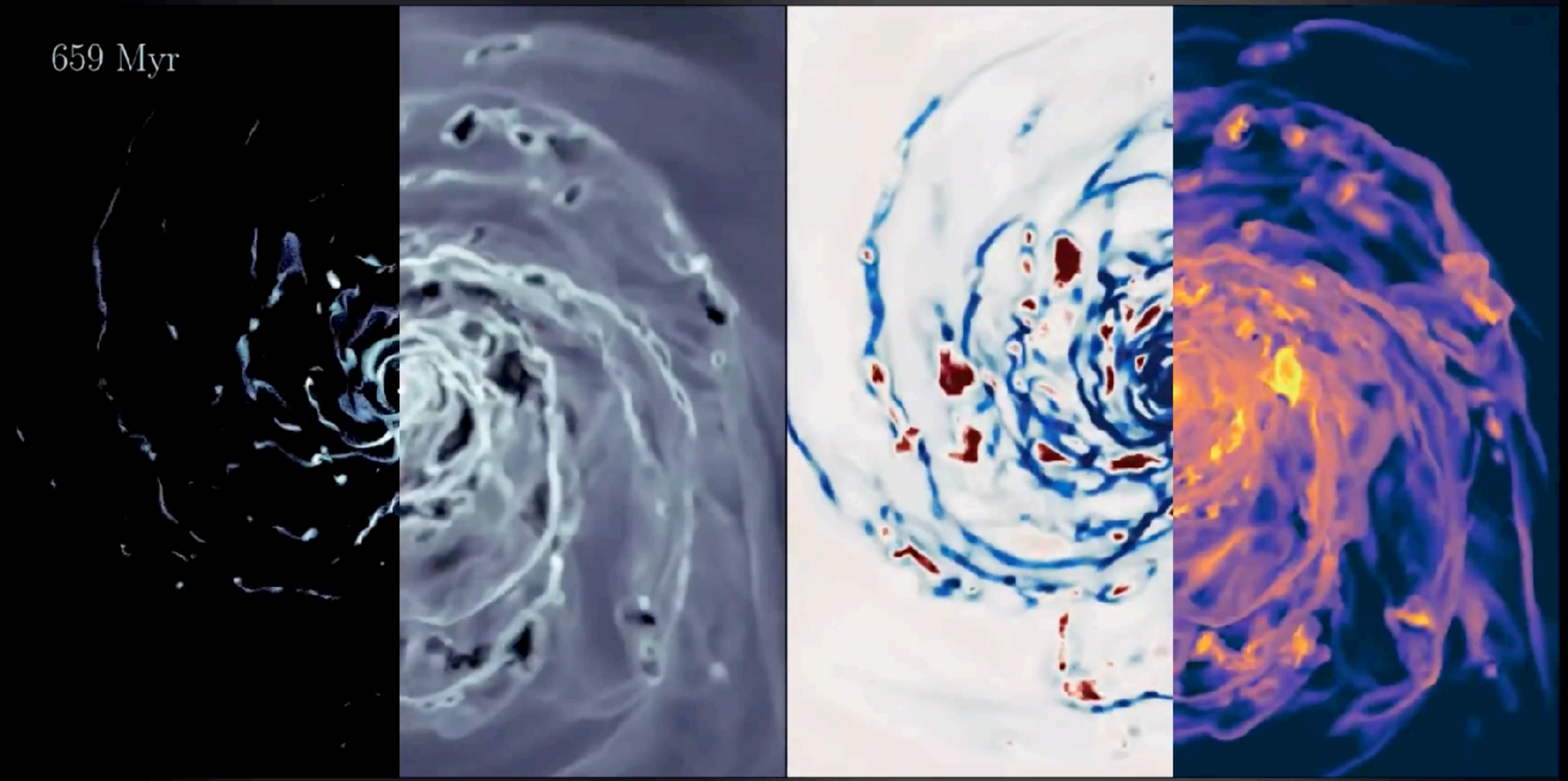
More realistic (?) view of just 1.5 Solar orbital periods

recently formed **stars**

gas density
brighter color = higher density

gas temperature
blue is cold (less than 1000 K)
red is hot (higher than 100000 K)

turbulent velocity
blue = few km/s
orange-yellow=more than 10 km/s



stars

gas

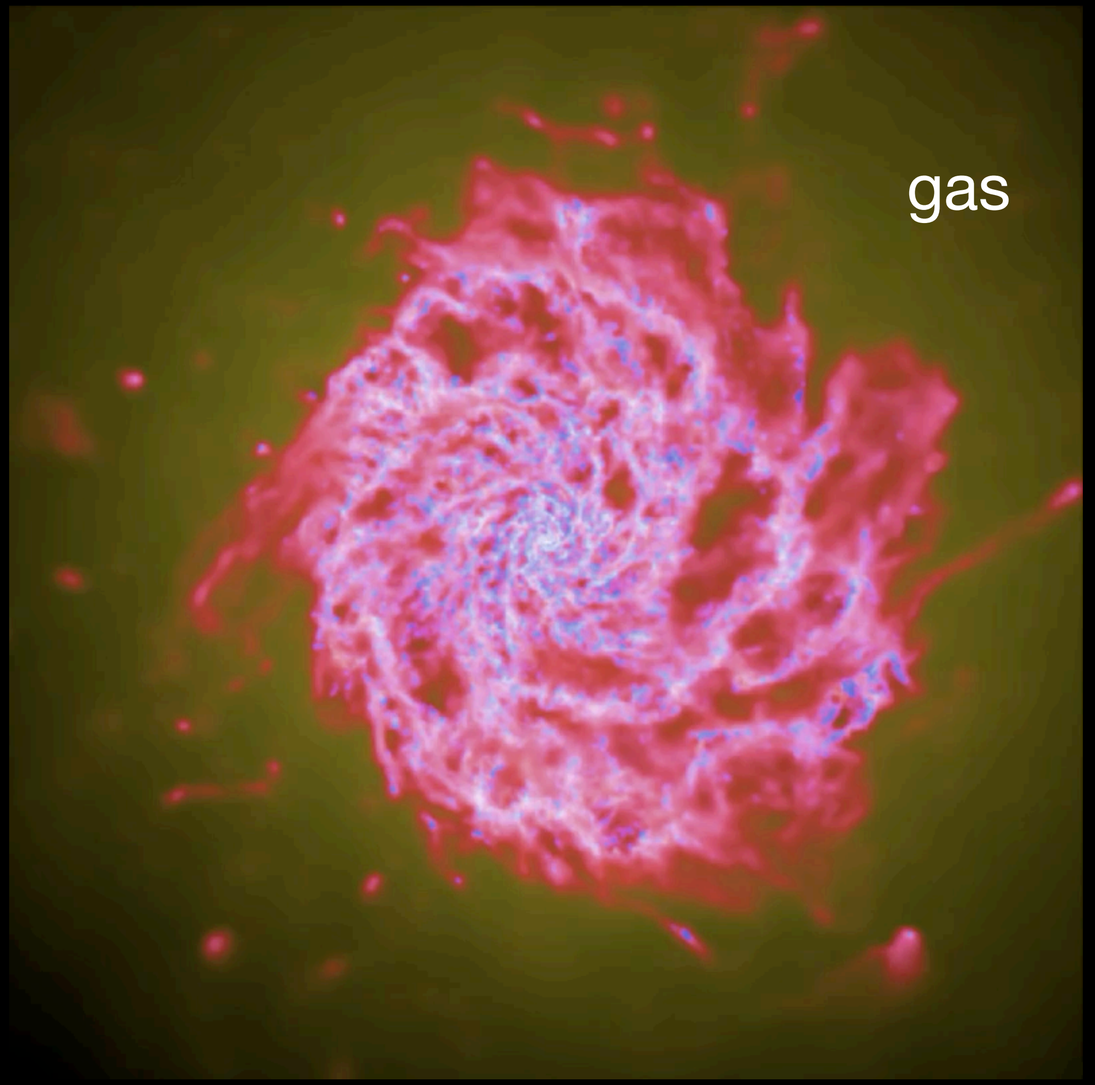
Milky Way-like Galaxy, by Vadim Semenov, 25 views Aug 31, 2021

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

Realistic

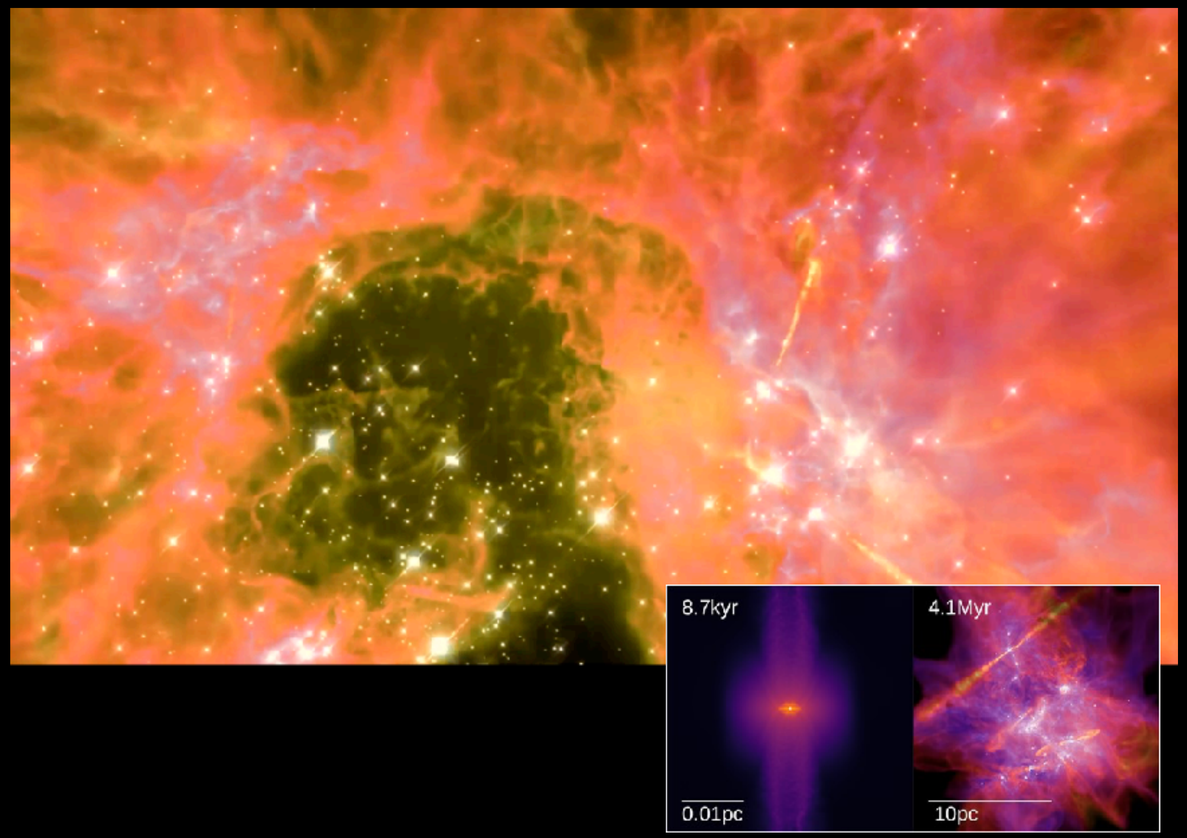
stars

gas



Inside a Milky Way…

STARFORGE
(<1 to ~100 pc, Myrs)



TIGRESS
(several kpc high, Gyrs)

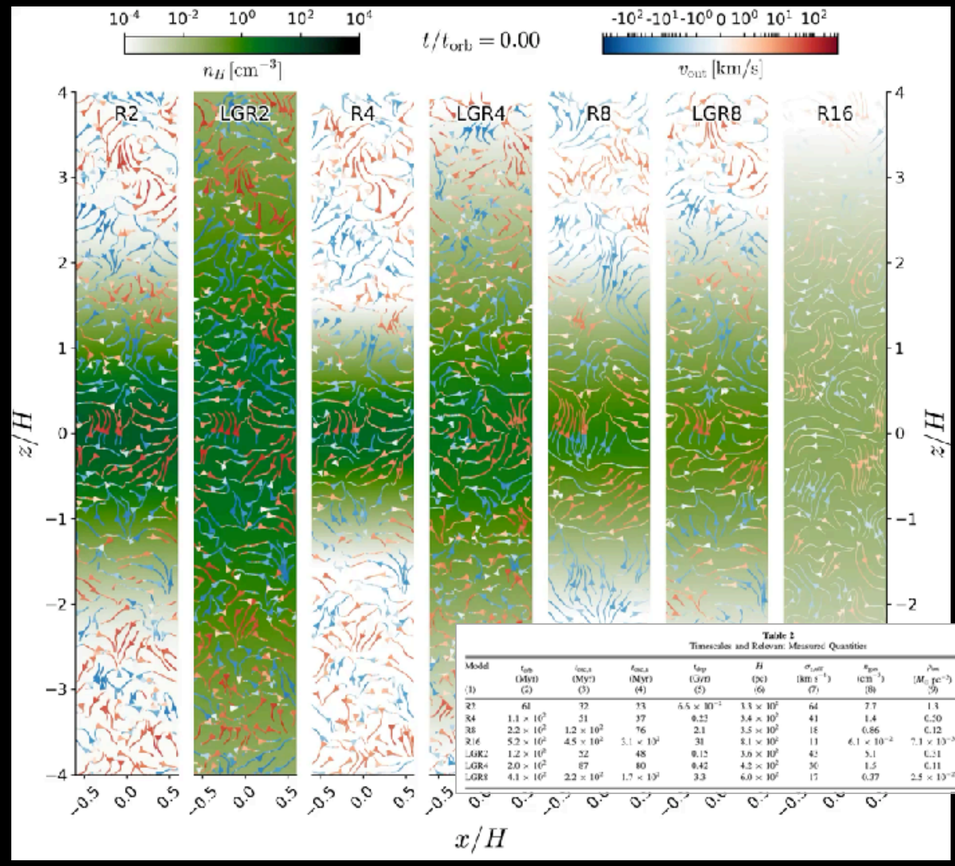


Table 2
Timescales and Relevant Measured Quantities

Model	$t_{\rm orb}$ (Myr)	$t_{\rm max,2}$ (Myr)	$t_{\rm max,4}$ (Myr)	$t_{\rm sfr}$ (Gyr)	H (pc)	$\sigma_{z,\rm eff}$ (km s^{-1})	$n_{\rm gas}$ (cm^{-3})	$\rho_{\rm sfr}$ ($M_\odot$ pc^{-3})	$\Sigma_{\rm gas}$ ($M_\odot$ pc^{-2})	$\Sigma_{\rm sfr}$ ($M_\odot$ kpc^{-2} yr^{-1})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
R2	61	72	73	6.5×10^{-1}	3.3×10^2	64	7.7	1.3	74	1.1
R4	1.1×10^2	51	37	0.23	3.4×10^2	41	1.4	0.50	30	0.13
R8	2.2×10^2	1.2×10^2	76	2.1	3.5×10^2	18	0.86	0.12	11	5.1×10^{-3}
R16	5.2×10^2	4.5×10^2	3.1×10^2	31	8.1×10^2	11	6.1×10^{-2}	7.1×10^{-3}	2.5	7.9×10^{-5}
LGR2	1.2×10^2	52	48	0.12	3.6×10^2	42	5.1	0.21	75	0.49
LGR4	2.0×10^2	87	80	0.42	4.2×10^2	36	1.5	0.11	38	9.0×10^{-2}
LGR8	4.1×10^2	2.2×10^2	1.7×10^2	3.3	6.0×10^2	17	0.37	2.5×10^{-2}	10	3.2×10^{-3}

Grudić, M. Y., Guszejnov, D., Hopkins, P. F., Offner, S. S. R., & Faucher-Giguère, C.-A. (2020). STARFORGE: Toward a comprehensive numerical model of star cluster formation and feedback. In *arXiv [astro-ph.IM]* (Issue 2, pp. 2199–2231). arXiv. https://doi.org/10.1093/mnras/stab1347, and many papers since

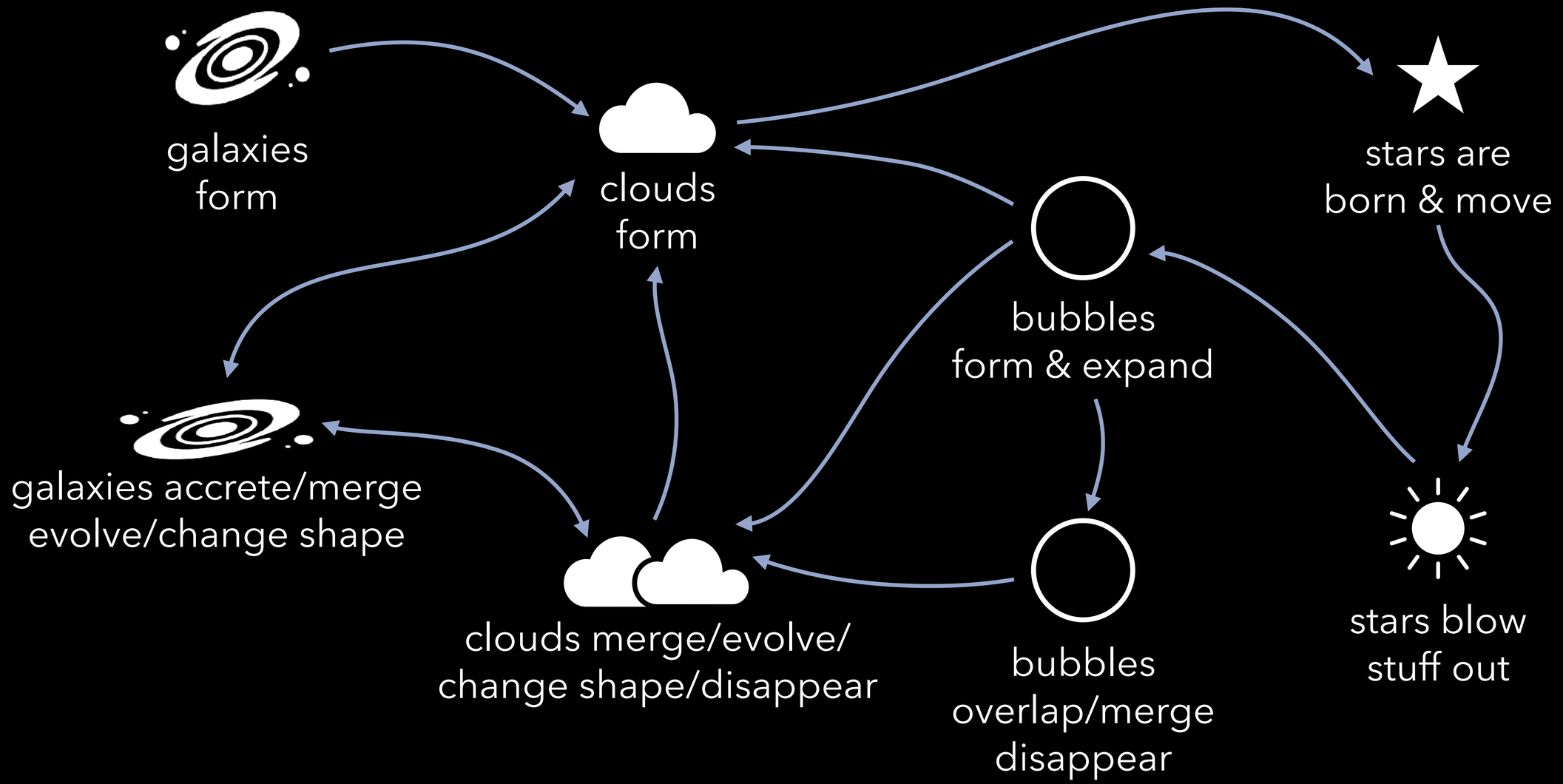
Kim, C.-G., Ostriker, E. C., Somerville, R. S., Bryan, G. L., Fielding, D. B., Forbes, J. C., Hayward, C. C., Hernquist, L., & Pandya, V. (2020). First results from SMAUG: Characterization of multiphase galactic outflows from a suite of local star-forming galactic disk simulations. In *arXiv [astro-ph.GA].* arXiv. https://doi.org/10.3847/1538-4357/aba962 , and many papers since

“Everything, Everywhere, All at Once”

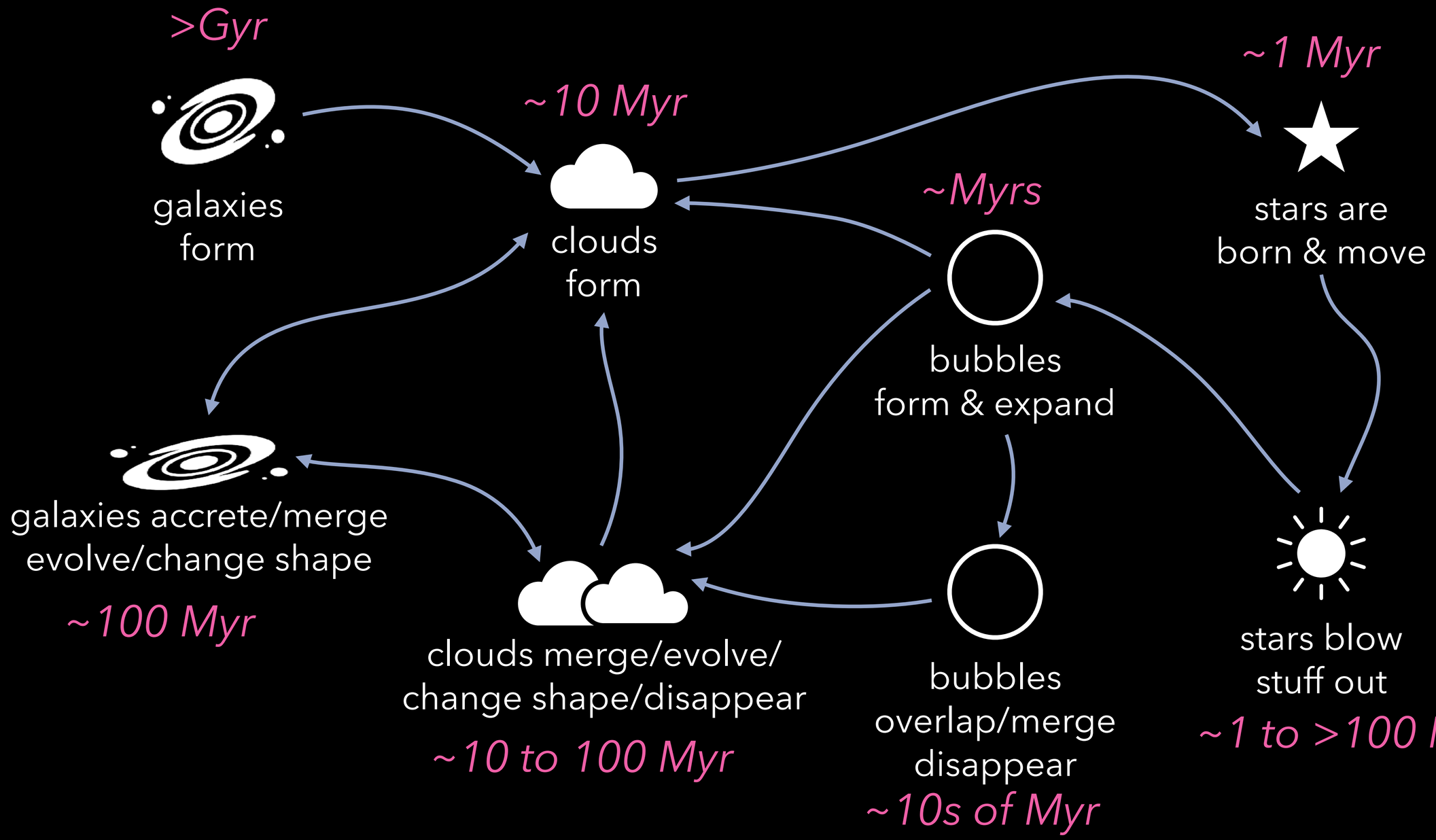
Nothing stays still. Nothing lasts forever.

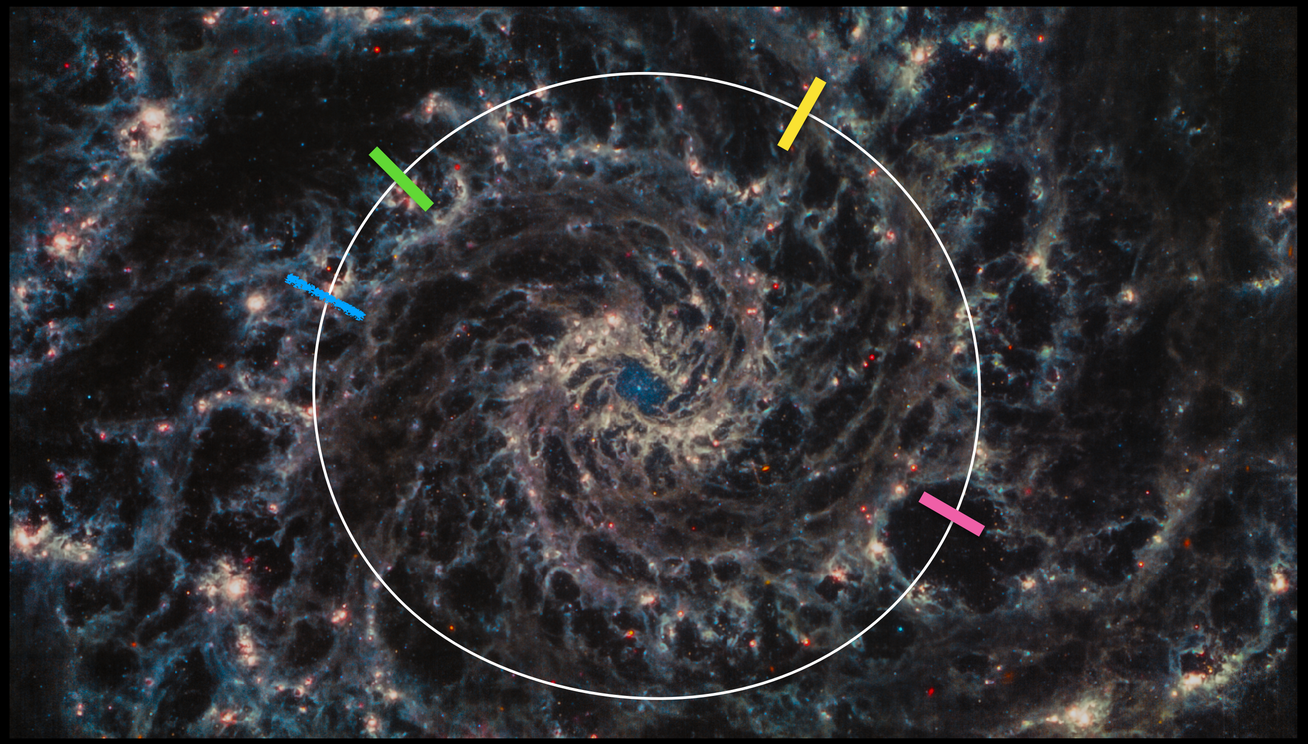
ESA/Webb, NASA & CSA, J. Lee and the PHANGS-JWST Team, Acknowledgement: J. Schmidt

“Everything, Everywhere, All at Once”

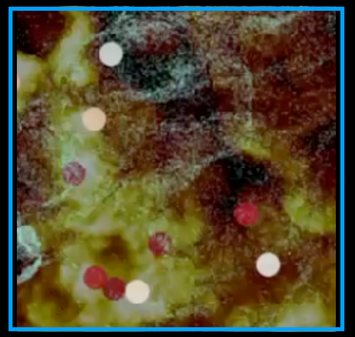


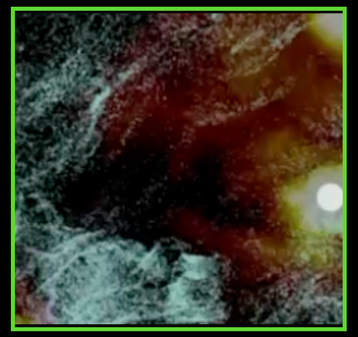
"Everything, Everywhere, All at Once"

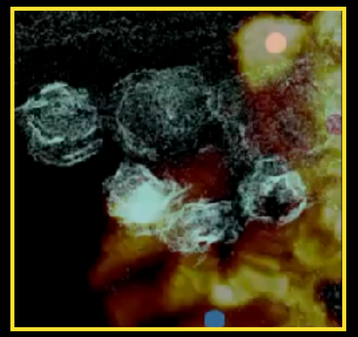


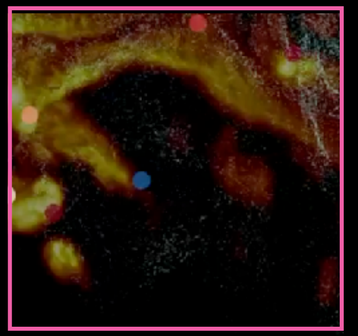


How does the “view” from a star change, as it orbits?

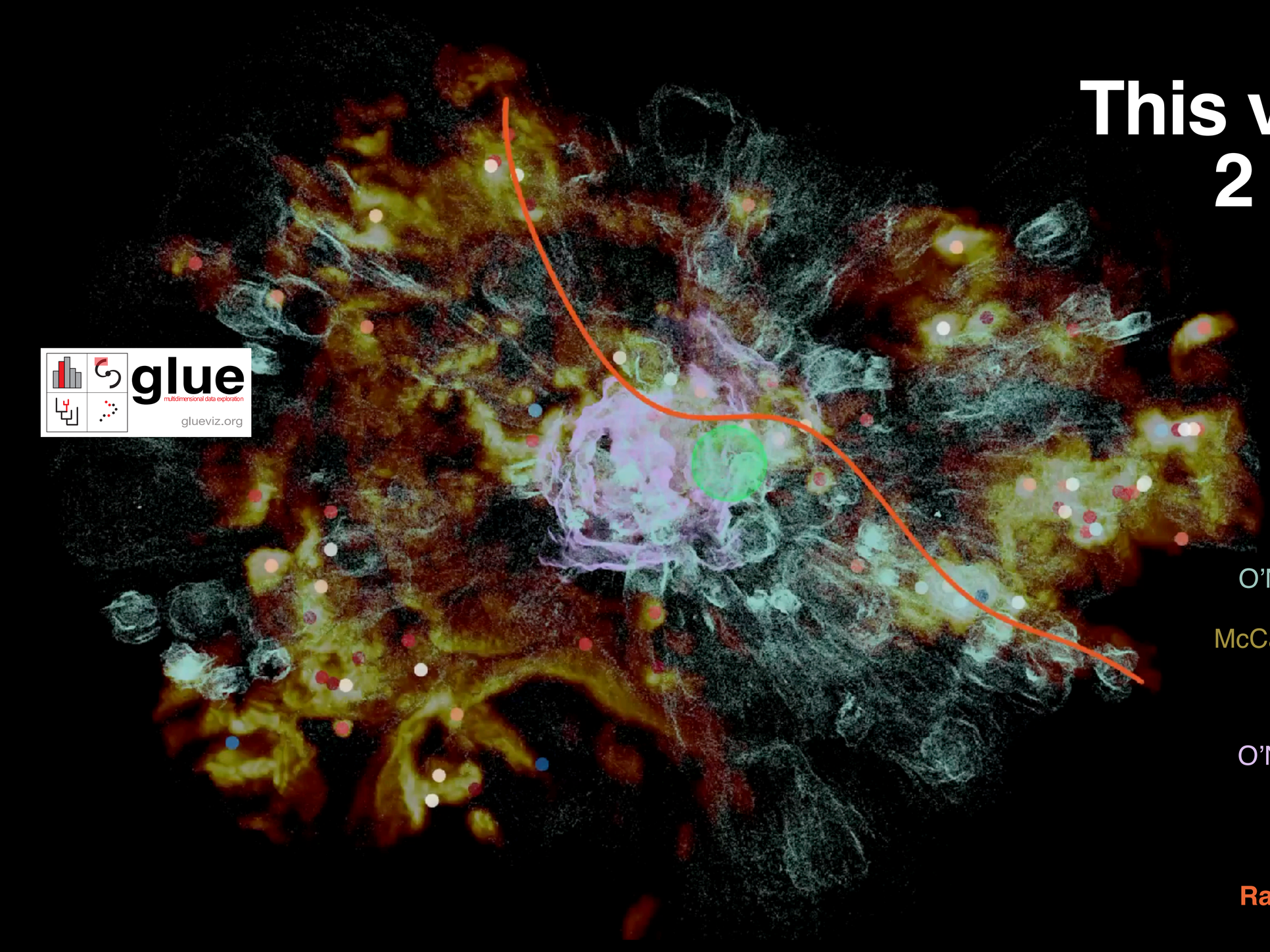








This view is only 2 kpc across



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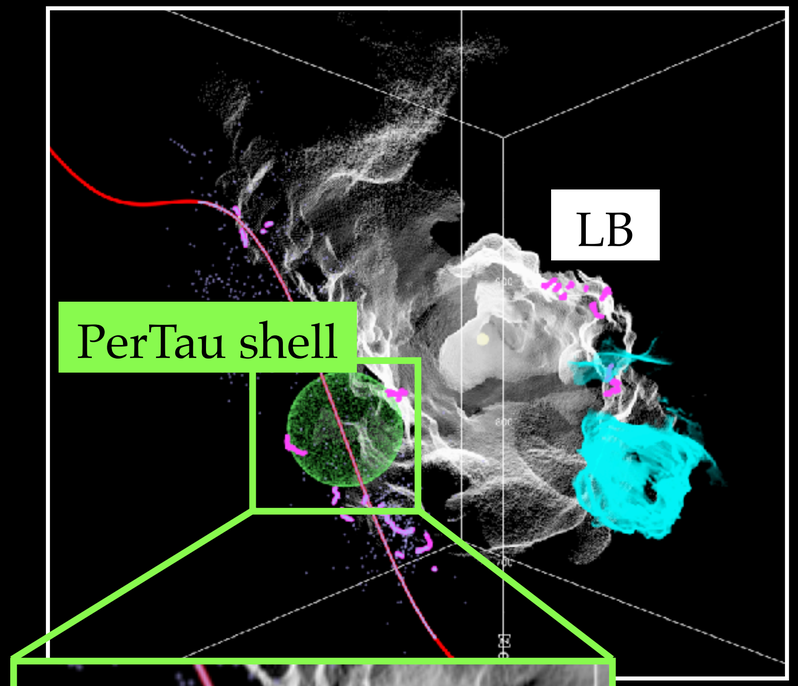
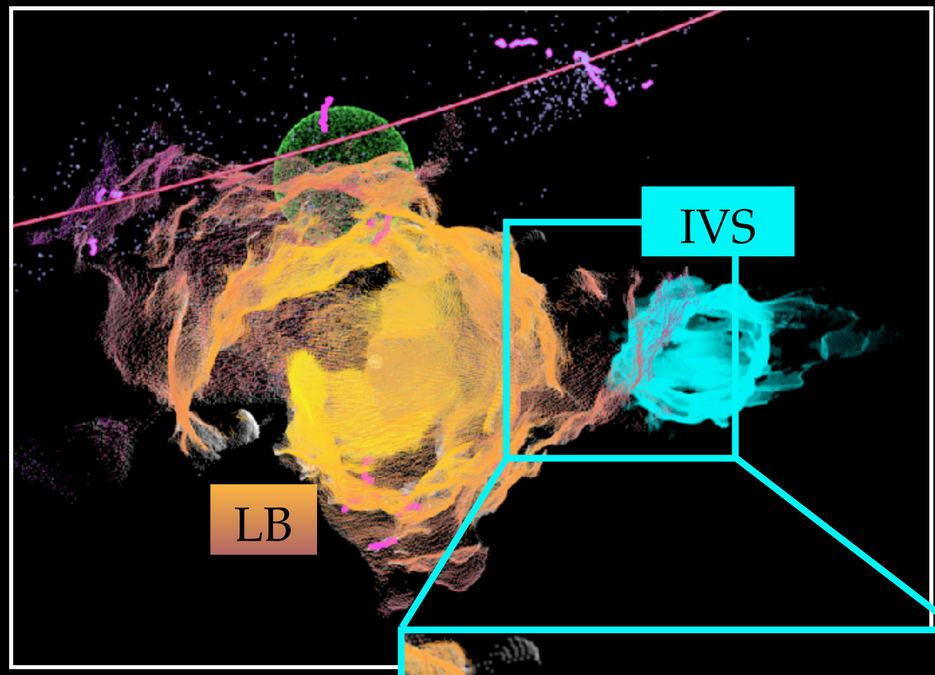
PerTau Shell (Bialy et al. 2021)

Radcliffe Wave (Alves et al. 2020)



But has 0.1 pc resolution



PerTau Shell (Bialy et al. 2021) **Clouds on LB** (Zucker et al. 2022) **LB Model & B-field** (O’Neill et al. 2024, 2025) **IVS** (Gao et al. 2025)

LIVE Environments | About LIVE | Capabilities | Tech | Who are we? | Learn More

Linkable Interactive Visualization Exploration (LIVE) Environments

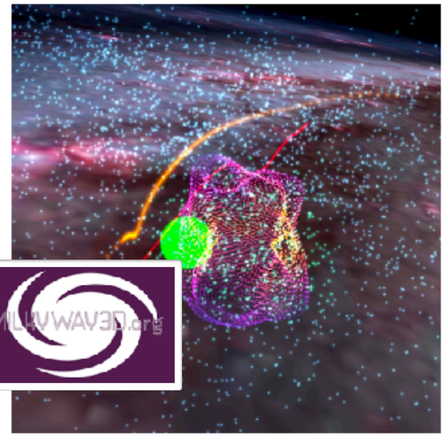
LIVE

What is LIVE?

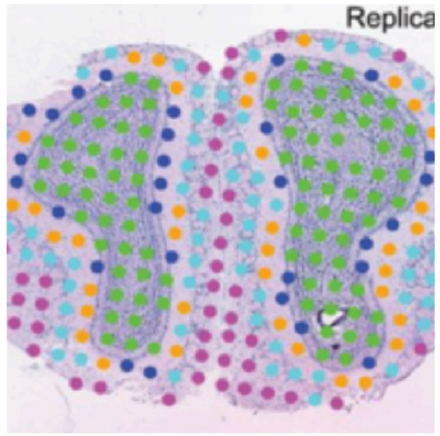
LIVE lets anyone build
"Linkable Interactive Visualization and Exploration" Environments.

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

Creating a LIVE Environment is flexible and easy

1. choose a FRAMEWORK, using a TEMPLATE if you like
2. add visualization TOOLS (as-needed)
3. access/add DATA
4. LINK your data together
5. EXPLORE using linked visualizations
6. SHARE your interactive environment

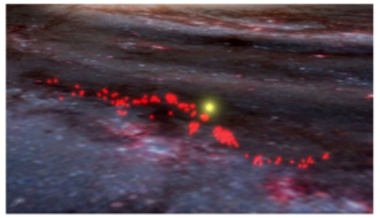
LIVE-env.org

MILKYWAY3D.ORG

v.2024

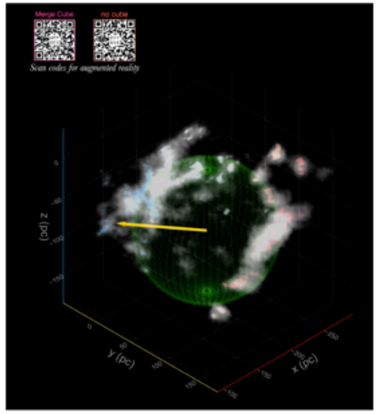
Between 2020 and 2024, a suite of discoveries based on new 3D dust mapping techniques, enhanced using data from Gaia, revealed a completely unanticipated phenomenon in the Milky Way near the Sun. These, and *much* related work since and today, inspire the global sharing effort that is MilkyWay3D.org.

The Radcliffe Wave (2020-)



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* (by Alves et al.) on January 7, 2020. Its website offers scientists, educators, and the interested public much more information about the "RadWave," as we like to call it. At that RadWave site, you can find **publications** and **talks**, **visuals** (images, interactives, and videos), **history**, **team** info, software, and **data**.

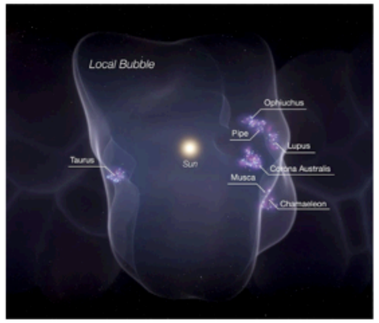
The Perseus-Taurus Supershell (2021)



The sphere-shaped void named the "Perseus Taurus Supershell,) described in the *Astrophysical Journal Letters* (by Bialy et al), spans about 150 parsecs — nearly 500 light years — and is located on the sky among the constellations Perseus and Taurus. It's likely that the cavity was formed by ancient supernovae that went off some 10 million years ago.

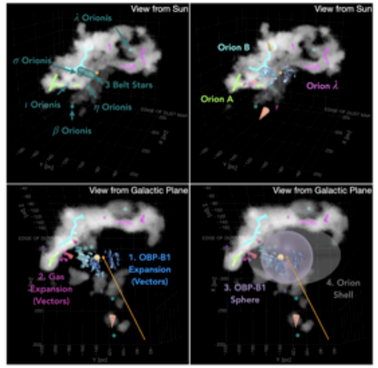
The publication of this result contains the first-ever augmented reality figure in an AAS Journal. Click here to enlarge the interactive figure above, and try the AR by scanning the QR codes.

The Local Bubble (2022-)



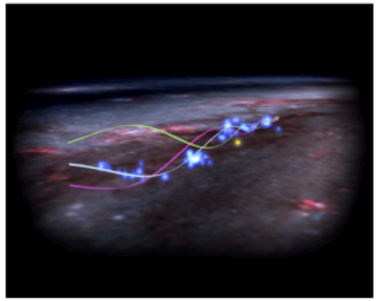
The discovery that the 1000-light-year-wide "Local Bubble" surrounding the Sun and Earth is responsible for the formation of all nearby, young stars was first presented in a paper published in *Nature* (by Zucker et al.) on January 12, 2022. Please use this page to find **news, publications** and **talks**, **visuals**(images, interactives, and videos), **team** info, and **data.**

Orion's Origins (2023)



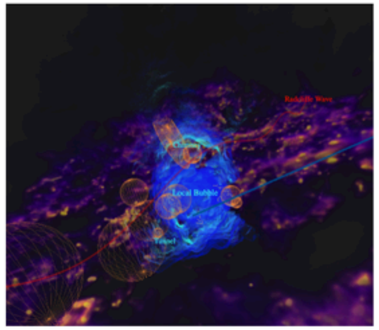
Analysis of 3D dust maps and star cluster dynamics points to supernovae as having created the conditions that formed the star-factories we now know as the "Orion Molecular Clouds." You can read more about these findings in the publication by Foley et al. 2023--and do try its interactive figure too.

Oscillation of the Radcliffe Wave (2024)

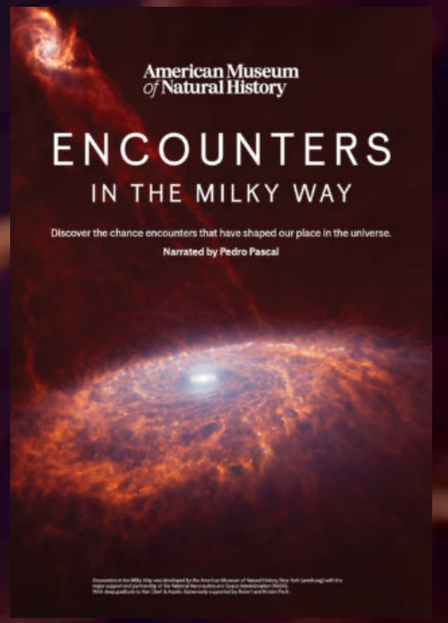


The Radcliffe Wave was called a "wave" in 2020, but it took 4 more years, to use new stellar clustering approaches and analyses of gas dynamics, to show that it really does *wave*. Read more about this in Konietzka et al. 2024's *Nature* paper, and at the RadWave website, where you can find **publications** and **talks**, **visuals** (images, interactives, and videos), **history**, **team** info, software, **data**--and the **first** **animated augmented reality view** of the RadWave that you can see on your phone!

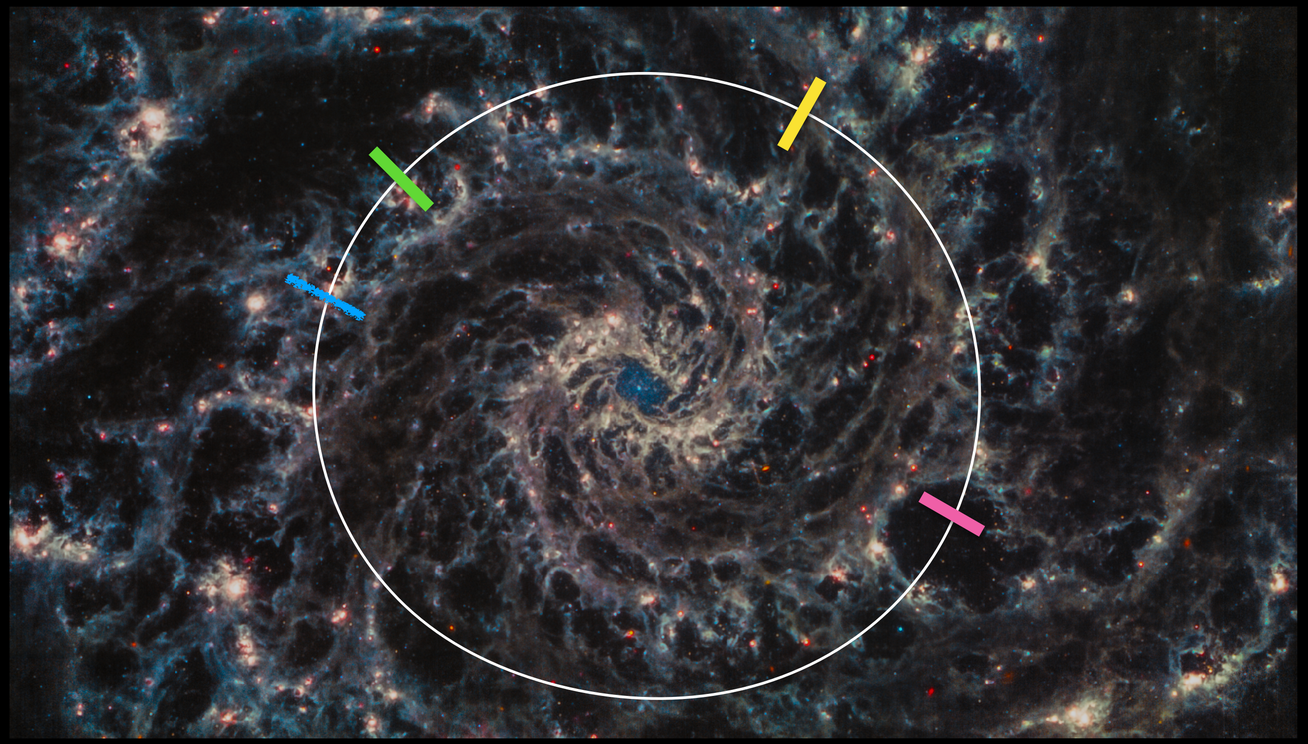
The Local Bubble is a Local Chimney (2024)



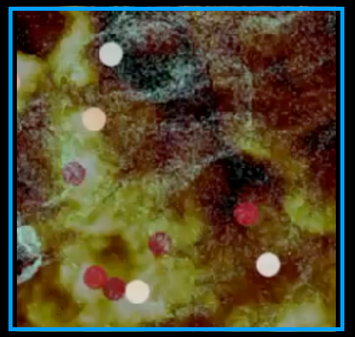
Once thought to be an enclosed shell of hot interstellar gas around the Sun, the 2024 paper by O'Neill et al. offers new models of the 3D dust structures at the "walls" of the Local Bubble that suggest its blown it's "top" off, and is actually a Local Chimney. The paper also offers many interactive figures highlighting the Local Bubble's relationship to other structures being studied as part of MilkyWay3D.org.

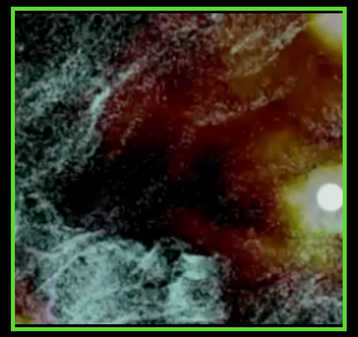


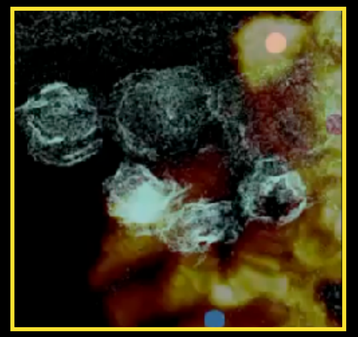
Curator: Jackie Faherty, AMNH, Simulation Jason Hunt, Surrey, plus MW3D collaborators

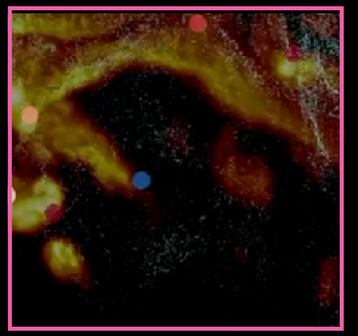


How does the “view” from a star change, as it orbits?









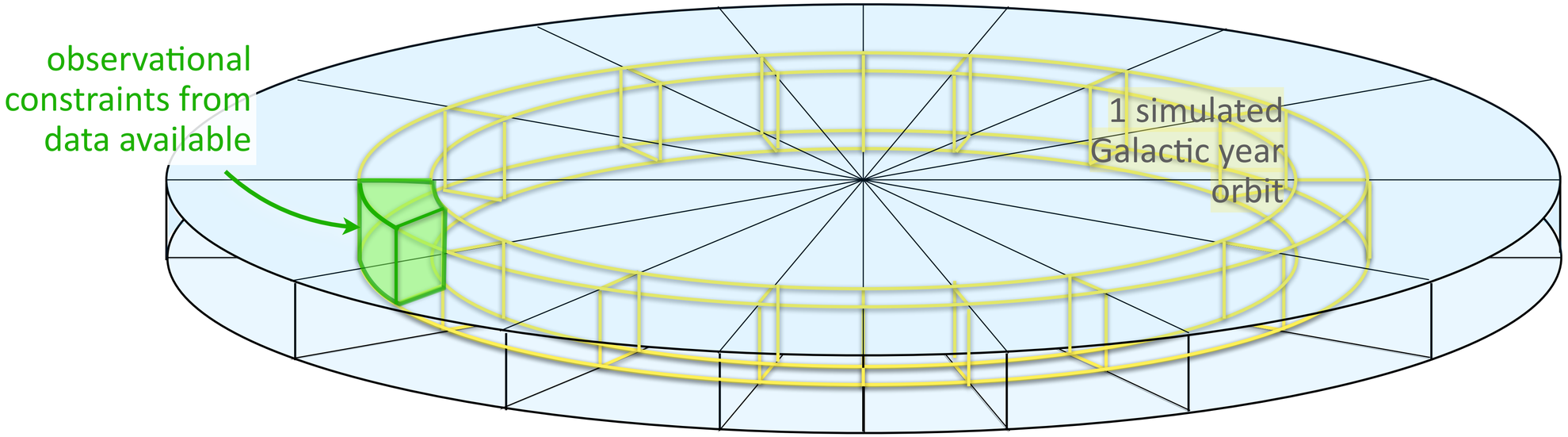
MILKYWAY3D.ORG

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



Yes, 1-pc-scale topology matters to feedback, very much.

JOURNAL ARTICLE

A three-dimensional, multiwavelength view and time-dependent analysis of the Milky Way's local ionized gas

Lewis McCallum ✉, Kenneth Wood, Robert Benjamin, Dhanesh Krishnarao, Anna F McLeod

Monthly Notices of the Royal Astronomical Society, Volume 541, Issue 3, August 2025, Pages 2324–2340, https://doi-org.ezp-prod1.hul.harvard.edu/10.1093/mnras/staf1022

Published: 21 June 2025 **Article history** ▾

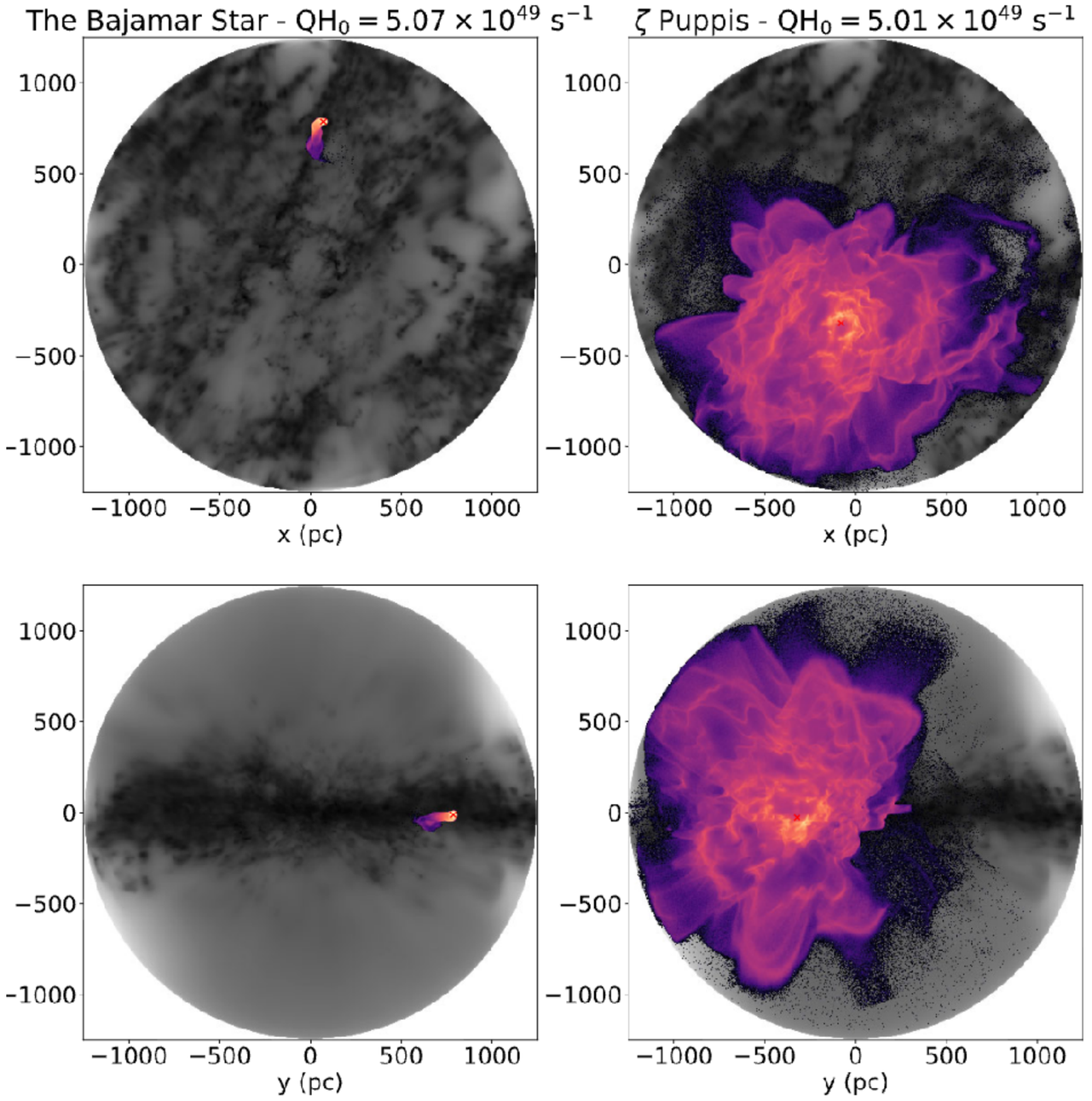
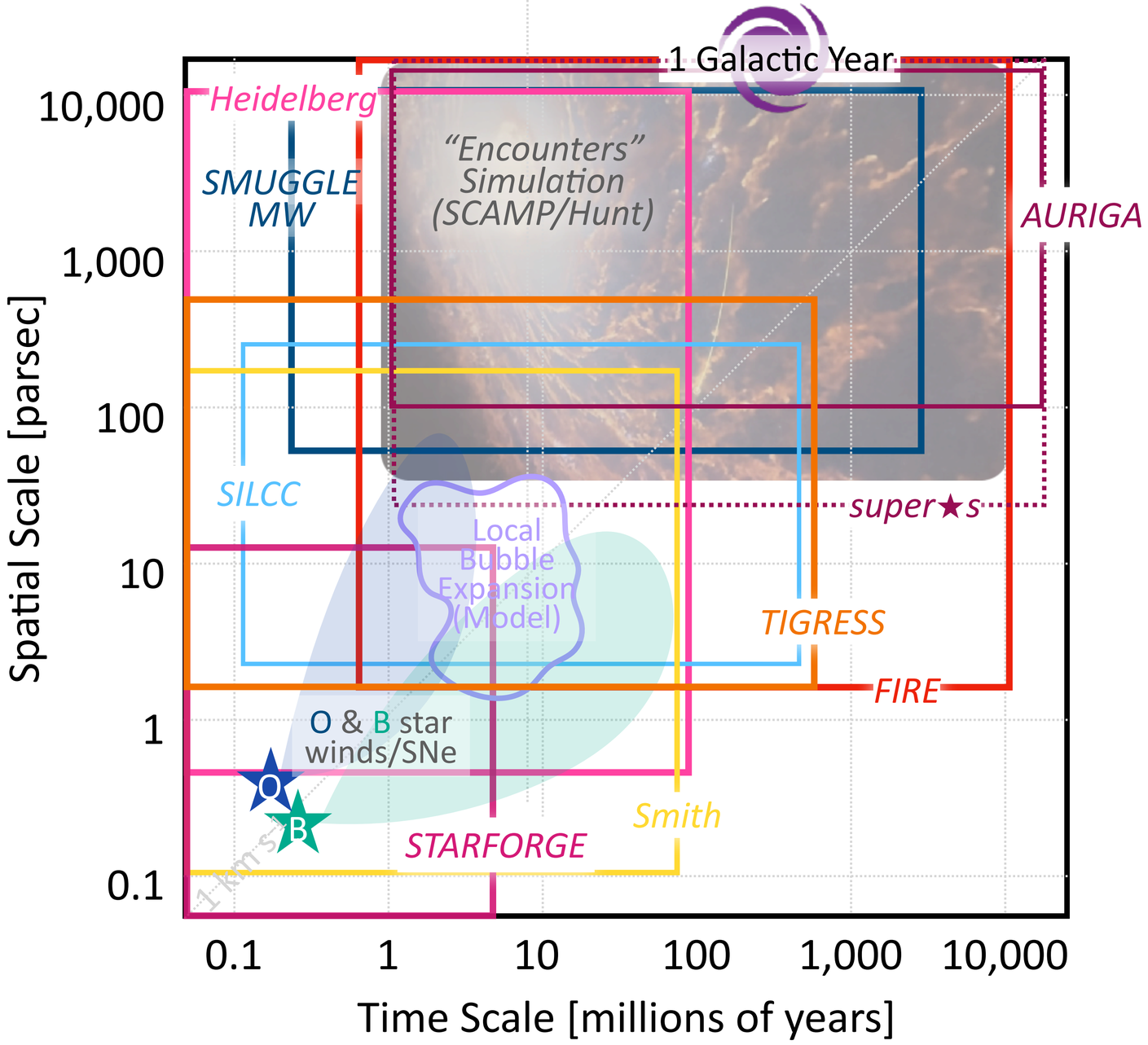


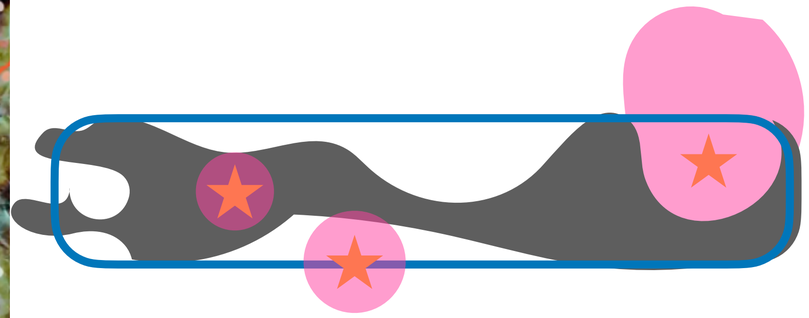
Figure 7.*A projection showing the column density plot of where the LyC photons from individual sources are terminated. Underlying the coloured volume of each zone of influence is the column density of the total mass in the simulation. The top row shows face-on projections of the x–y plane, and the bottom row shows edge-on projections of the y–z plane. The left column shows the region of influence of Ophiuchi, the middle column shows the Bajamar star, and the right column shows Puppis in the Gum Nebula. A red cross shows the location of each source, but has been omitted on the Ophiuchi column to avoid obscuring the region.* ***Despite having near equivalent ionizing luminosities, the difference in the volume influence of Puppis and the Bajamar star is a factor of 827.***


1 Galactic Year
Heidelberg
SMUGGLE MW
"Encounters" Simulation (SCAMP/Hunt)
AURIGA
SILCC
super★s
Local Bubble Expansion (Model)
TIGRESS
FIRE
O & B star winds/SNe
O
B
Smith
STARFORGE
1 km s⁻¹
10,000
1,000
100
10
1
0.1
Spatial Scale [parsec]
0.1
1
10
100
1,000
10,000
Time Scale [millions of years]

The whole “plan”

OBSERVATIONS

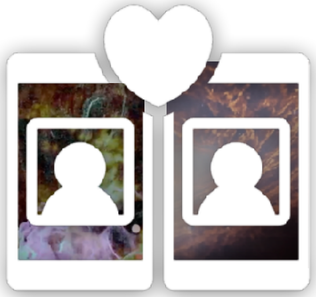
DETAILED 3D structure, almost
STATIC in time, feedback view
REALISTIC, all over *limited* volume

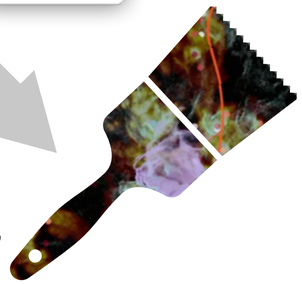


SIMULATIONS

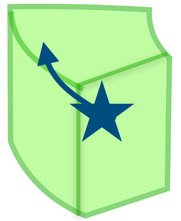
COARSE 3D structure over full Galaxy,
EVOLVING in time for ~Galactic year,
feedback **UNREALISTIC** on small
scales→sub-grid prescriptions

“**match**” SIM snapshots to blurred OBS

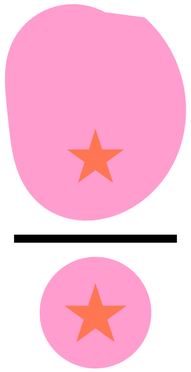




“**paint**” high-spatial-frequency info from OBS onto SIMS

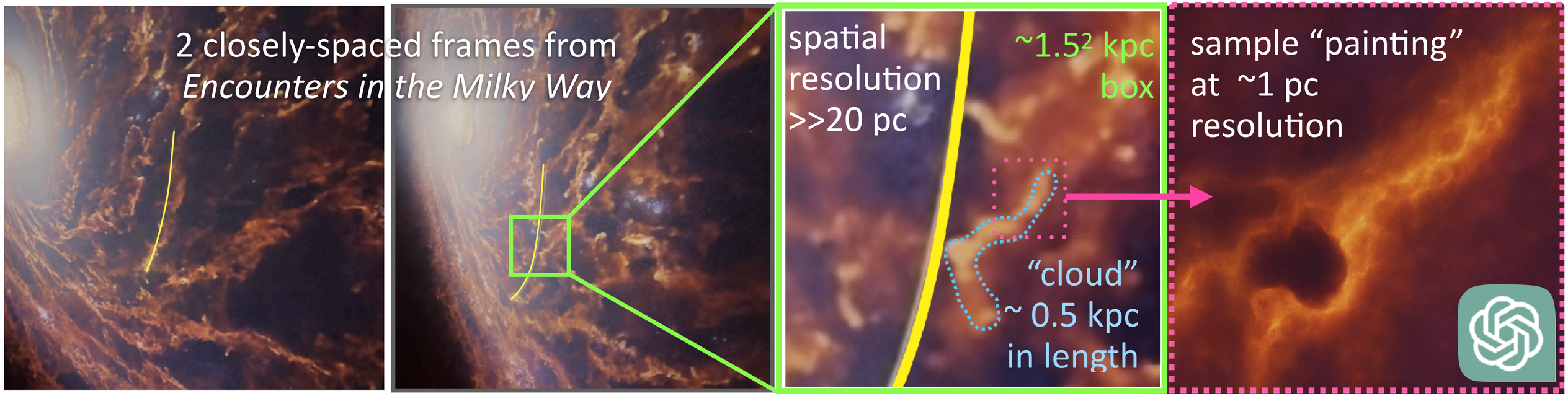


create “**agent-based**” views seen by orbiting stars

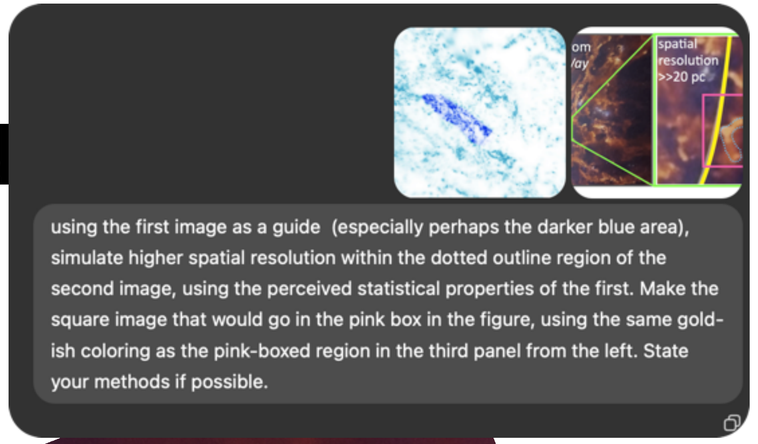


evaluate **changes** in **feedback** interactions

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 su



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”).*

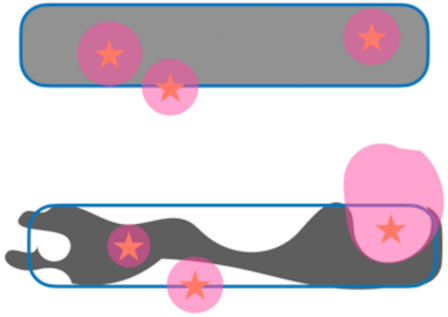
Imprint a long, squiggly overdensity to mimic the dotted “cloud”

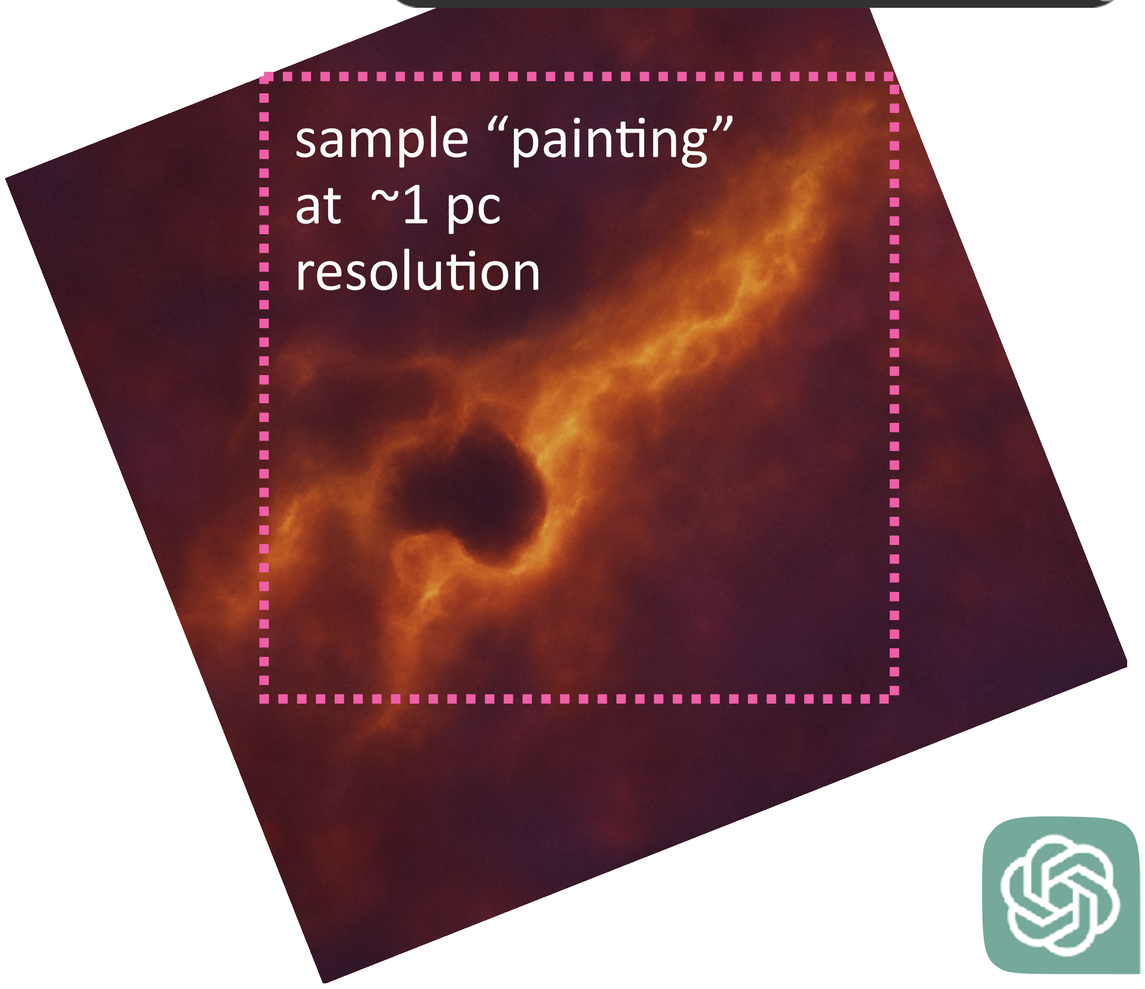
- Lay down a spline-like path through the image (length/curvature like the outline).
- Add an anisotropic Gaussian tube along that path with a slowly varying width (to resemble clumpy substructure).
- *Modulate that tube by the high-frequency component of the synthesized field so it inherits realistic speckle/porosity.*

Contrast + color transfer to the gold palette

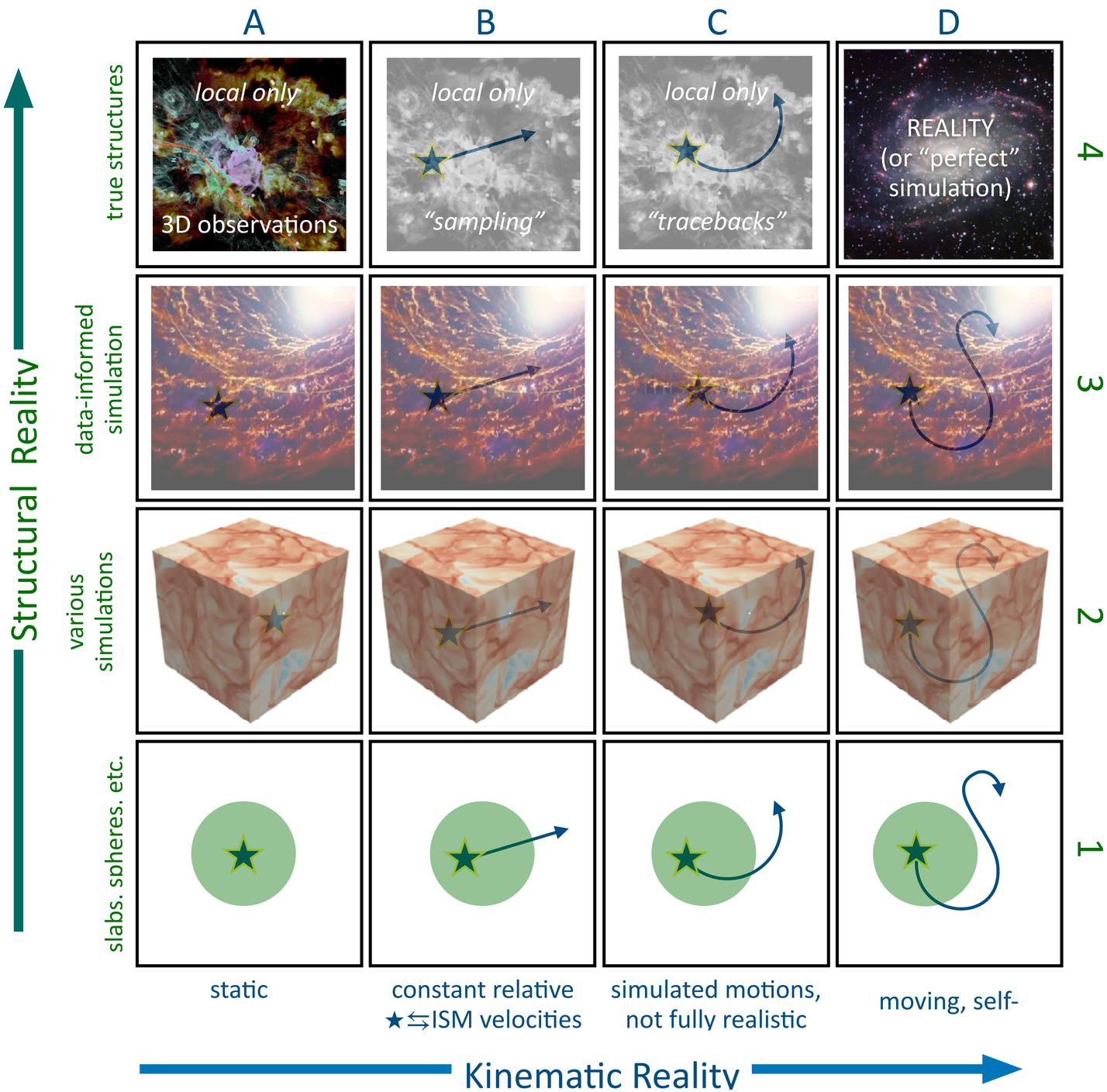
- Local contrast stretch (clip low/high percentiles, e.g., 25th–99.5th) to keep punch without blowing highlights.
- Apply a custom gold colormap (dark charcoal → warm brown → pale gold), or do LAB-space histogram matching to the gold patch from the third panel so the hue looks consistent.

Export a square PNG sized to the pink box.





How close to reality can we get?



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

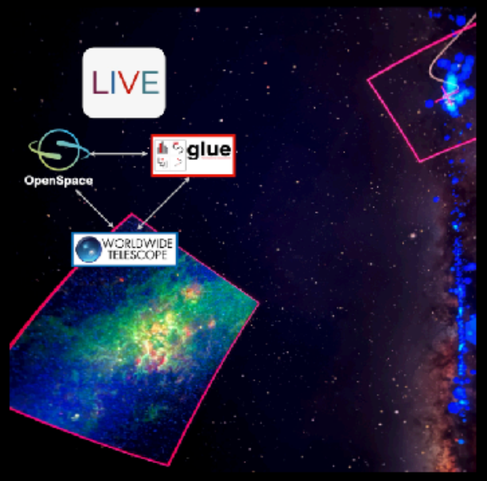
“On the one hand it sounds wildly ambitious at the level of science fiction. On the other hand, I think it sounds like **2026**.” –Prof. Doug Finkbeiner, PI’s Harvard colleague currently on sabbatical at Anthropic

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

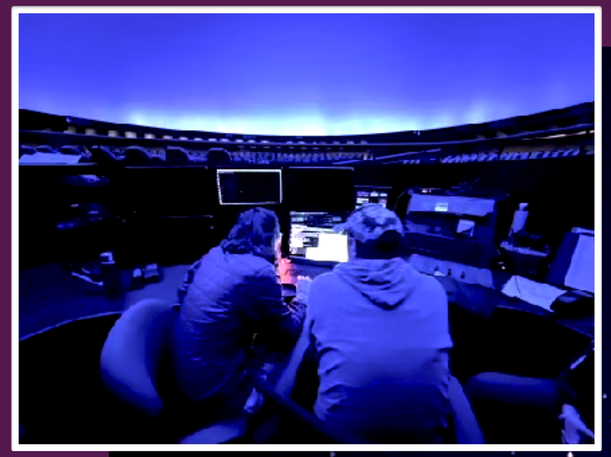
Using the same data and tools as researchers, educators and learners of all ages can explore and study the Galaxy in which we all live.

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.

in a planetarium

RESEARCH
+EDUCATION
+OUTREACH

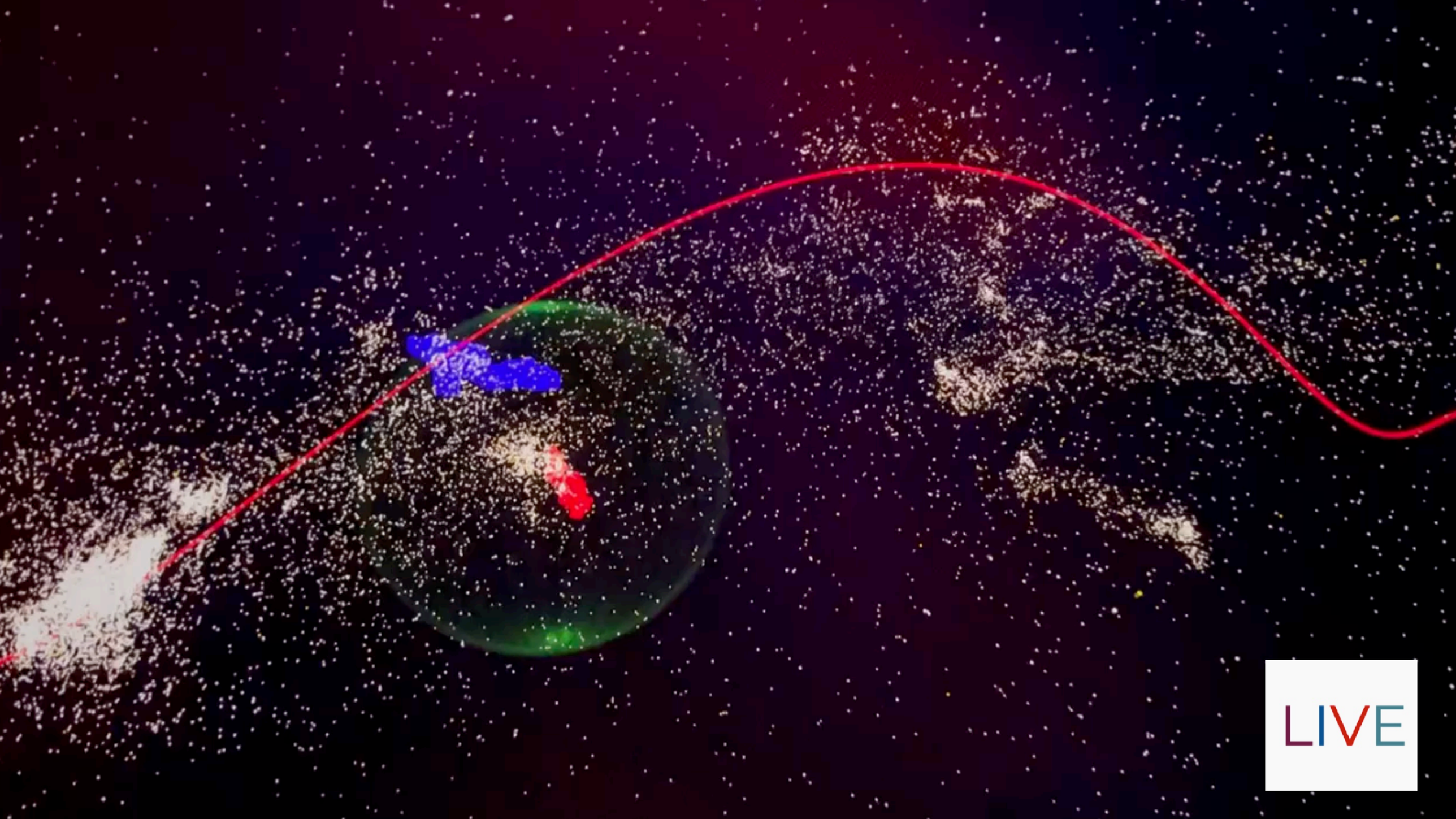


MILKYWAY3D.org

OpenSpace

glue

WORLDWIDE TELESCOPE


LIVE

in a augmented reality, on your phone…

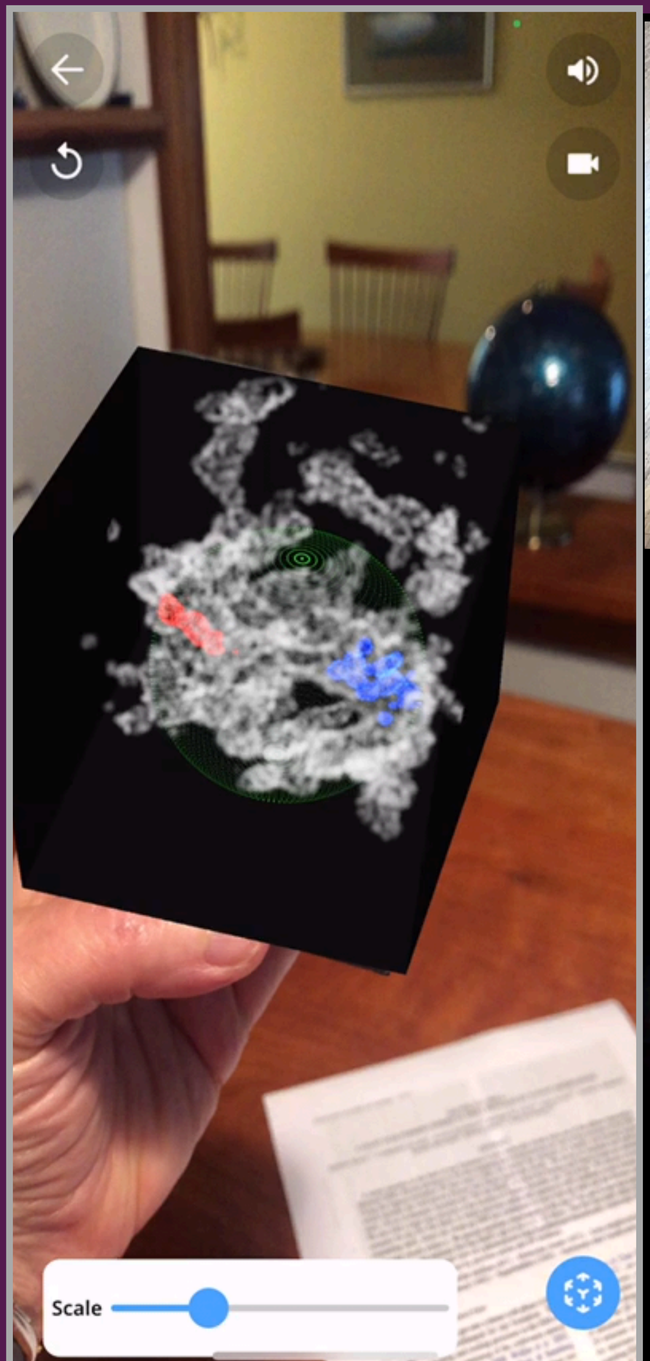
RESEARCH
+EDUCATION
+OUTREACH

MILKYWAY3D.org

OpenSpace

glue

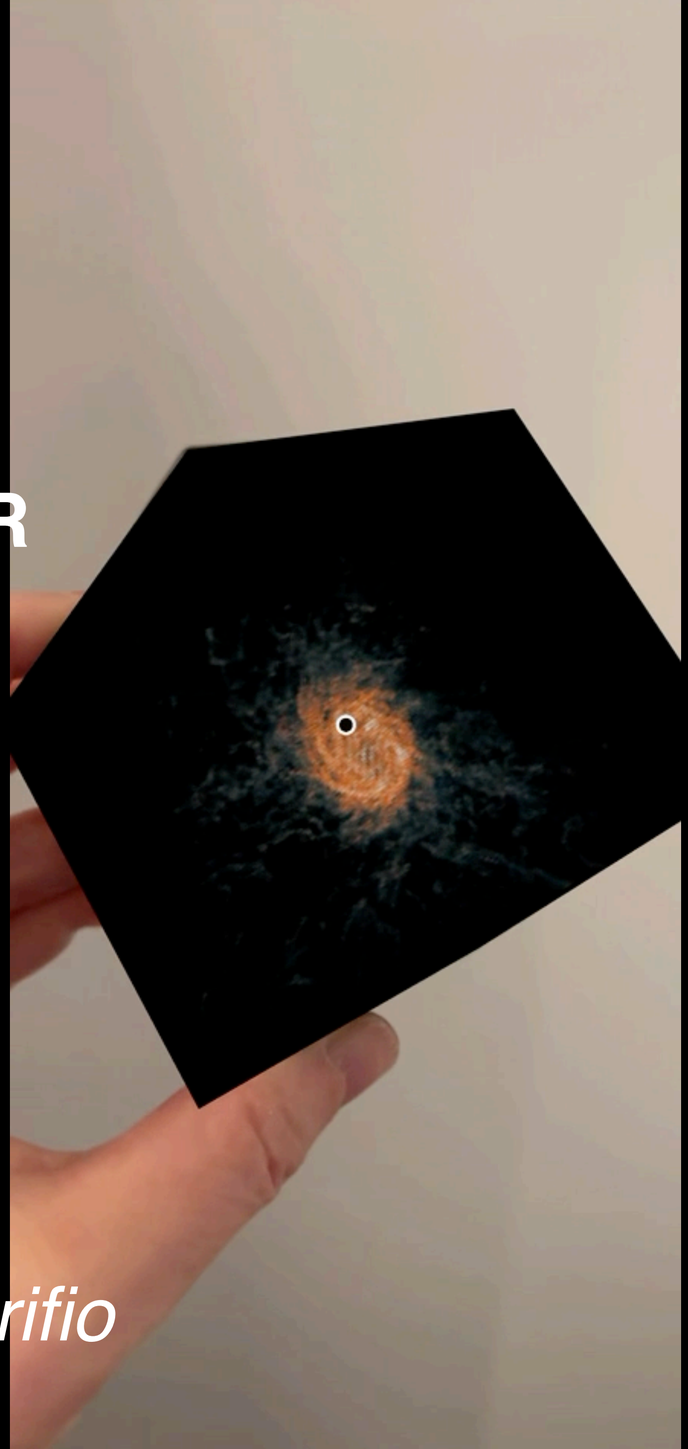
WORLDWIDE TELESCOPE



RESEARCH
+EDUCATION
+OUTREACH

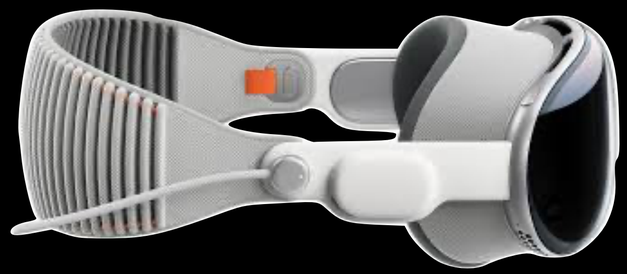
2025: simulation output→glue→AR

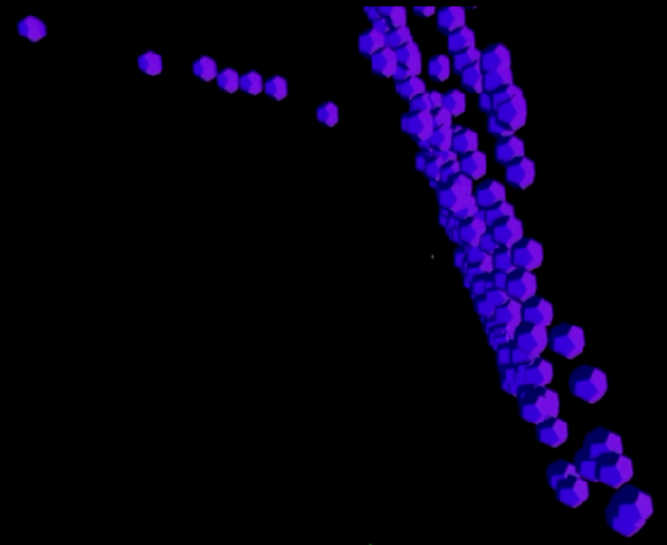
Demonstration here→
A galaxy from the
IllustrisTNG simulation on a
Merge Cube



created by Scott Lucchini & Jon Carifio

Apple Vision Pro (AR)





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

Open Session | Export Session | Import Data | Export Data/Subsets | Link Data | x² Arithmetic attributes | Active Subset: Perseus Only | Mode: | Terminal | Preferences

Data Collection

- Alves2020_Nat_678_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

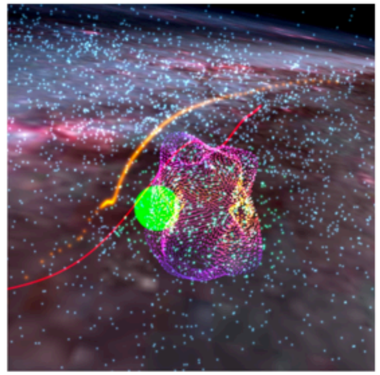
LIVE

What is LIVE?

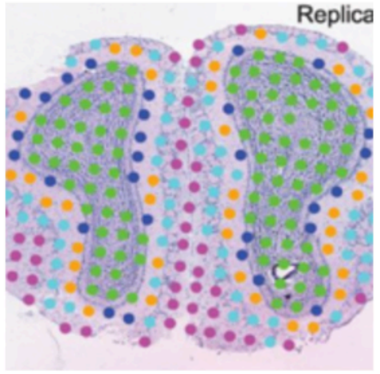
LIVE lets anyone build
"Linkable Interactive Visualization and Exploration" Environments.

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

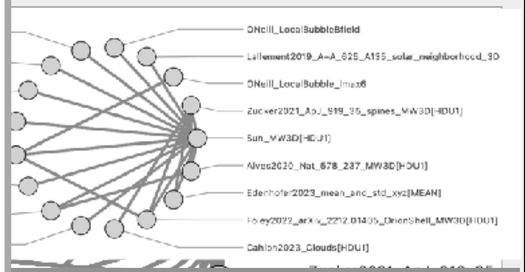
LIVE GIS

command-line terminal

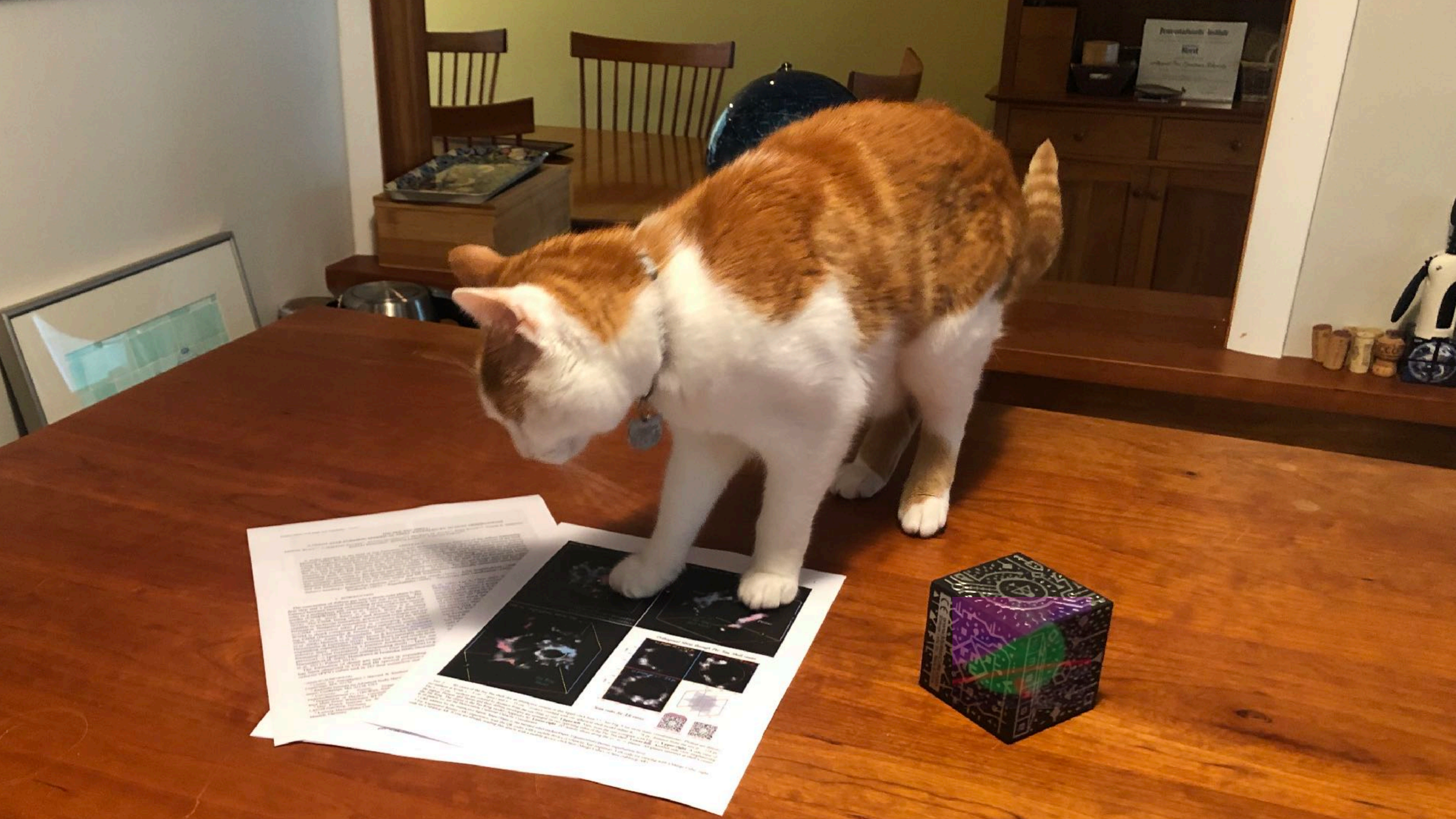
ou can type any valid Python code here, and you
fined variables:

Link Editor

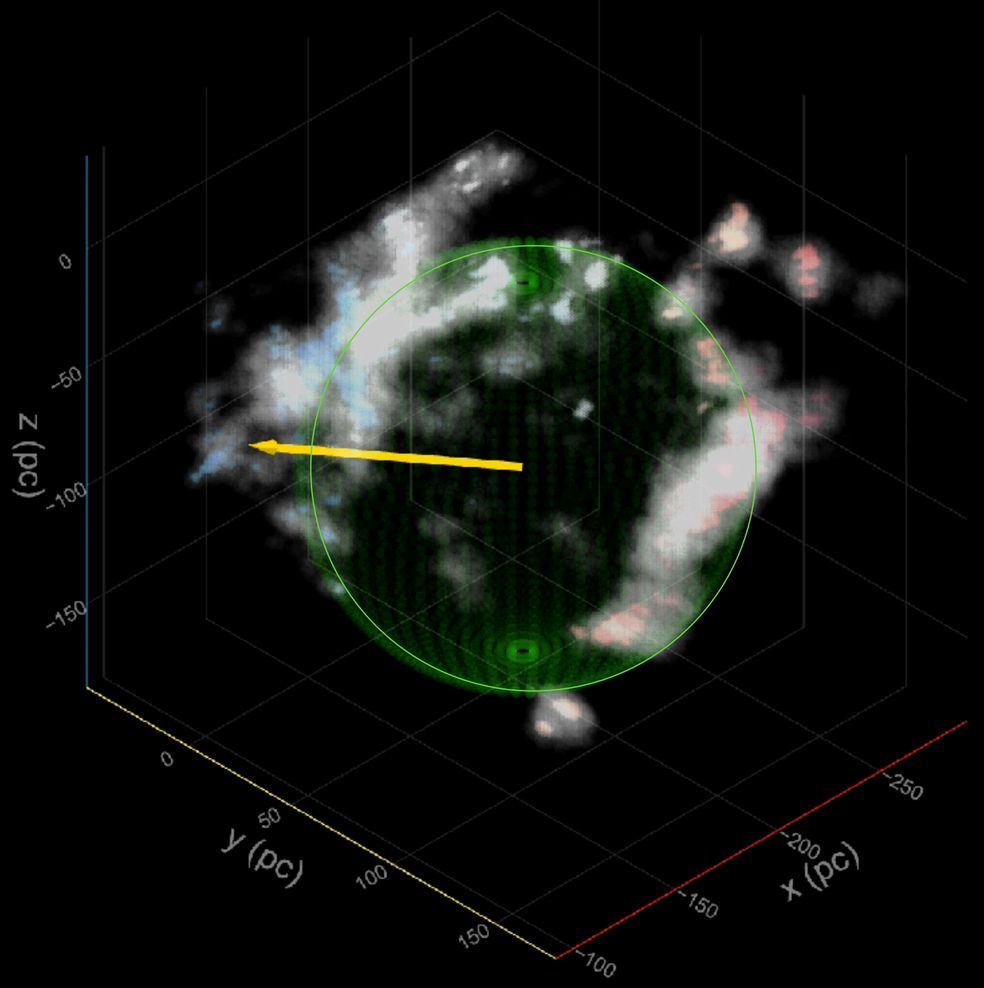
an existing connection to edit links. Selected datasets are shown
rs show directly and indirectly linked (blue) and inaccessible



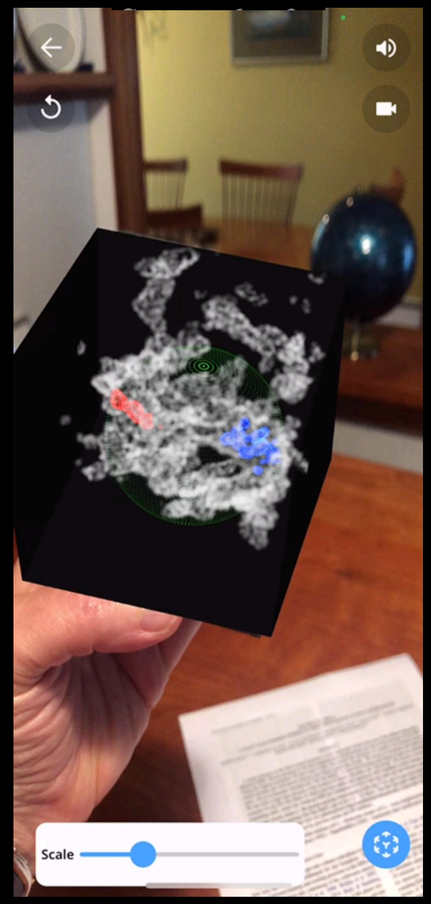
GUI data set link editor



2021 “PERSEUS-TAURUS SUPERSHELL”



TINYURL.COM/UNIVERSE-IN-MY-HAND



AUGMENTED REALITY

“Everything, Everywhere, All at Once”

- What fraction of star-forming **clouds** are or are not candidates for having been **compressed** at bubble surfaces, and/or at **bubble intersections**?
- What fraction of star-forming gas features cannot be clearly associated with structures at least an order-of-magnitude larger than they are? (How much **"free-floating" dense gas** is there in the local ISM?)
- What sources of **feeback** (stellar winds, supernovae, etc.) are most relevant on what **spatial** and **temporal scales**?
- Can we use information about **cluster** populations [illegible] **bulk motions** and expansions of feedback-driven **cavities**?
- **How do "young stars leave home"?** What [illegible] of st[illegible] at what sp[illegible] or do clouds "dissolve" first? How often might young stars drift from [illegible]e star-[illegible]
- Are the **topological characterizations** of [illegible] as (in)**consistent** with any particular **numerical simulation(s)**?
- How well can data, simulations, [illegible] **a** [illegible] given region? Over what time scale? For example, over what spatial [illegible] **a star cluster with** a gas **cavity**?
- Are there clear relationships betwe[illegible] **propert**[illegible] and th[illegible] **sition** or **motion** with respect to significant **Galactic structures**, such [illegible] plane [illegible] feature [illegible] uding spiral arms?
- What are the dominant **mechanisms sha**[illegible] **rmatio**[illegible] **destruction**?
- How are these mechanisms related to clouds’ physical properties and th[illegible] **ger-scale galactic environments**?
- What is the relationship between interstellar **cavities** and the distri[illegible] of **OB associations, supernova remnants,** and **HII regions**?
- Do we observe evidence for **triggered star formation** at the **surfaces** of these **cavities**?
- What role does Galactic structure play in star formation? Are **spiral arm-like structures** in the Milky Way quasi-stationary or **transient** features? Do these arm-like structures **violently** induce shocks or **gently** accumulate gas? If the former, what role do spiral shocks play in star formation?

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