

"6D" Movie
A ~~3D~~ Map of the Star Forming Milky Way, **for Everyone**

Alyssa **Goodman**, Center for Astrophysics | Harvard & Smithsonian; 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 Institute 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; and the Full MilkyWay3D.org Team, please visit "Collaborators" at MilkyWay3D.org.



10:00 AM CT - 10:25 AM CT

MilkyWay3D.org: A 3D Map of the Star Forming Milky Way--for ...

Alyssa Goodman, Center for Astrophysics | Harvard & Smithsonian; Catherine Zucker, Center for Astrophysics | Harvard & S...

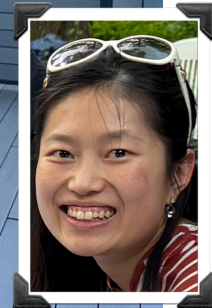


Theo O'Neill

Catherine Zucker



Cameren Swiggum



Annie Gao

11:16 AM CT - 11:29 AM CT

Uncovering three past massive star-forming complexes that sh...

Cameren Swiggum, University of Vienna; João Alves, University of Vienna; Robert Benjamin, University of Wisconsin, White...

11:03 AM CT - 11:16 AM CT

The Geometry of the IRAS Vela Shell: Insights from 3D Dust M...

Bore Gao, Johns Hopkins University.

10:50 AM CT - 11:03 AM CT

Mapping Galactic Bubbles, Shells, and Clouds with Persistent...

Theo O'Neill, Center for Astrophysics | Harvard & Smithsonian; Catherine Zucker, Center for Astrophysics | Harvard & Smi...

10:25 AM CT - 10:50 AM CT

3D Dust Mapping of Local Diffuse Gas in the Gaia Era: Progre...

Catherine Zucker, Center for Astrophysics | Harvard & Smithsonian.

A 3D Map of the Star Forming Milky Way, for Everyone

Thanks to the ongoing revolution in our ability to understand the structure of the Milky Way near the Sun made possible by 3D dust mapping and Gaia, we are in the process of synthesizing not just a 3D image, but a 3D **movie** of how our local Milky Way came to be as it is today. **The goal of MilkyWay3D.org, and the technology enabling it, called "LIVE Astro," is to share the data, software, and results being used to create this new 3D view of our local Milky Way, with researchers, educators, and the general public.**

**MOVIE
GOAL**

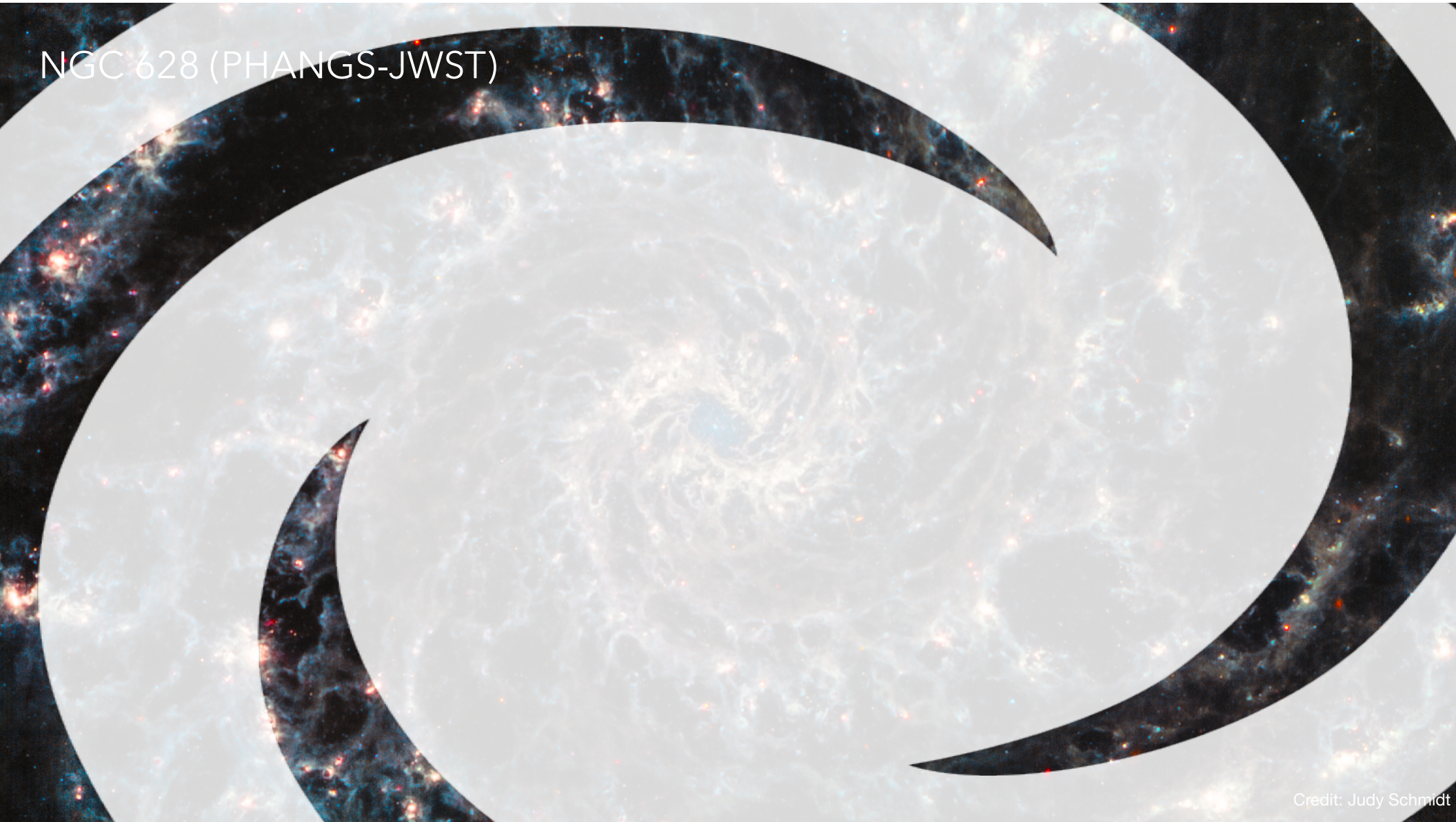
The talk will explain what has been done so far to make data and tools available, by demonstrating and explaining the LIVE-env.org (LIVE-env.org) and MilkyWay3D.org (MilkyWay3D.org) websites. Accomplishments of members of our team already include: several key research findings (e.g about the **Radcliffe Wave, Perseus-Taurus Supershell, Star Formation on the Local Bubble, and Galactic weather**); a variety visualization and software advances (e.g. **glue, interactive and augmented reality figure technologies**); and also work brining our 3D view of the Milky Way to the public via NASA-sponsored educational efforts (e.g. **Cosmic Data Stories, Planetarium Shows** at the AMNH) and the popular press (e.g. via **Sky & Telescope**). A key goal of offering this talk will be to **recruit the meeting-in-a-meeting participants—especially those interested in open science—into this combined research/infrastructure/education community effort.**

**TECH
SO FAR**

YOU

++

NGC 628 (PHANGS-JWST)



Credit: Judy Schmidt

“Everything, Everywhere, All at Once”

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

Nothing stays still. Nothing lasts forever.

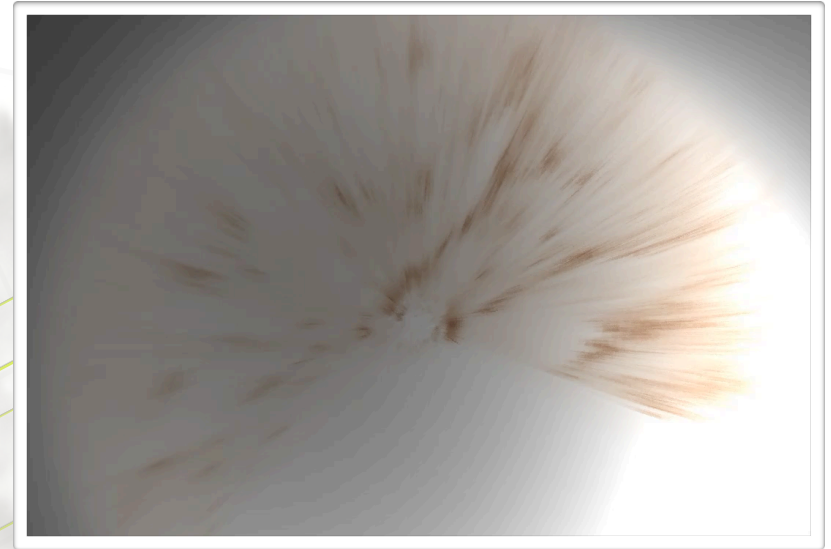
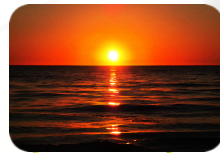




+ *and the ISM perpetually trades material with the IGM*

3D dust mapping in 1 slide

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

MILKYWAY3D.org

GOAL



SCAN ME

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

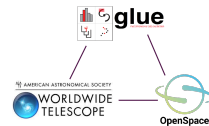
MilkyWay3D.org is an open-data open-source discovery hub, providing data, visualization, and research tools for studying the MilkyWay in 3D.

INFRASTRUCTURE

SCIENCE

EDUCATION & OUTREACH

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



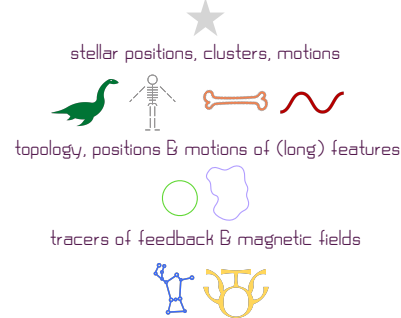
linking position and motion across dimensions,
using the modular architecture enabled by LIVE
(LIVE-Astro elements include glue, WWT, OpenSpace & more)



making data accessible online for decades

Lead: Alyssa Goodman, CFA

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



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

Lead: Catherine Zucker, CFA

connecting real research data,
software, and science to learners



real-time data exploration
anywhere, including in planetaria



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

Lead: Jackie Faherty, AMNH

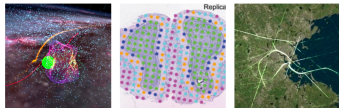
INFRASTRUCTURE

LIVE

Linkable Interactive Visualization Exploration (LIVE) Environments

What is LIVE?

LIVE lets anyone build "Linkable Interactive Visualization and Exploration" Environments. LIVE is free, open-source, and helps with shared data and visualization challenges across astronomy (LIVE Astro), biology (LIVE Bio) and GIS (LIVE GIS). As LIVE's infrastructure is being built, collaborators are ensuring its utility across Astronomy, Biology, and GIS by pursuing LIVE's science demonstration projects.



LIVE Astro

LIVE Bio

LIVE GIS

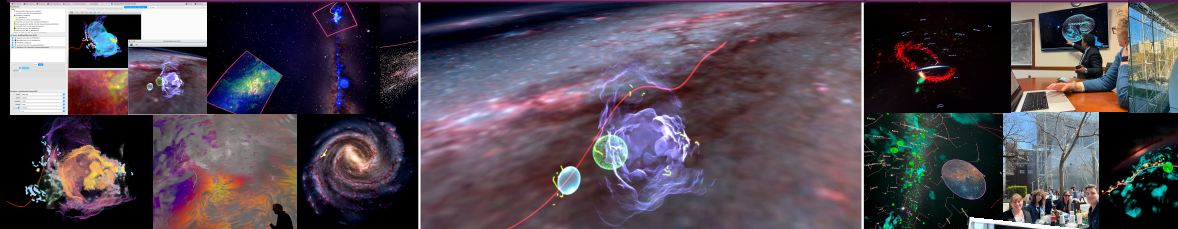
EDUCATION & OUTREACH



RadWave in Motion

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

Learn more about the discovery of the RadWave here!



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

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





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

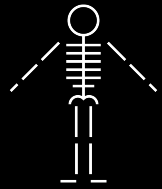
SO FAR



2010



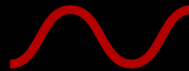
2014



2015



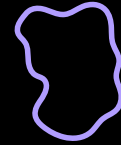
2018



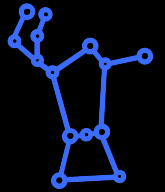
2020
2024



2021



2022
2024



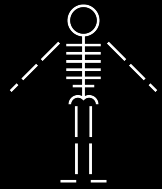
2022
2024



Nessie



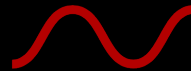
Bones



Skeleton



Perseus



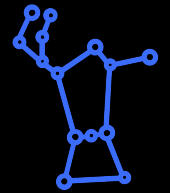
RadWave



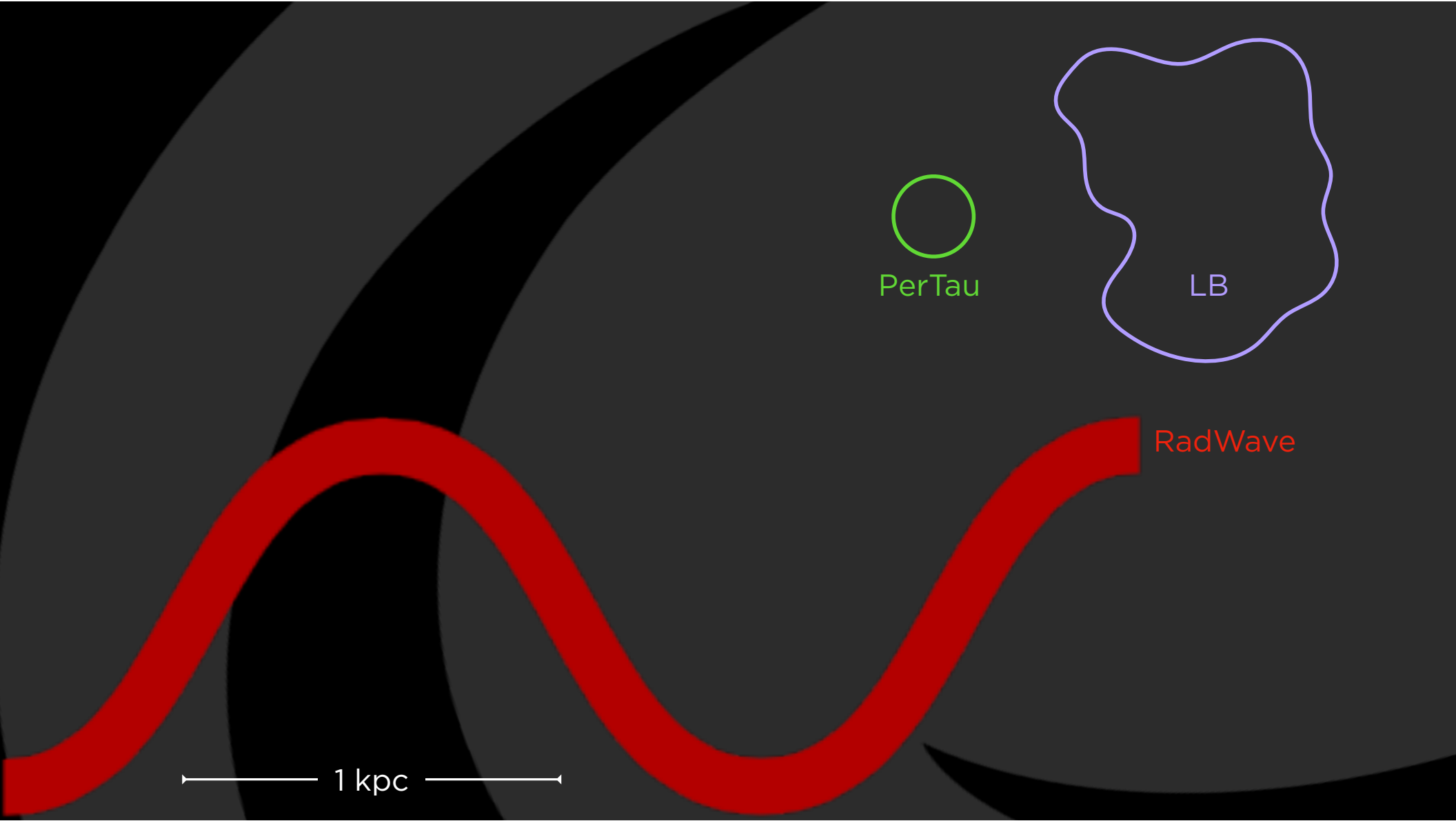
PerTau



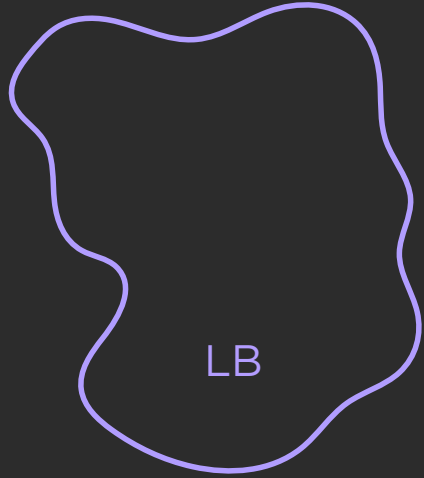
LB



Barnard++



PerTau



LB

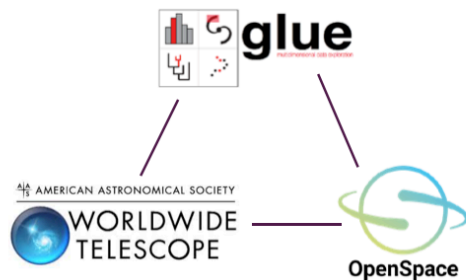
RadWave

1 kpc

INFRASTRUCTURE

LIVE

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



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



The **Dataverse**
Project



making data accessible online for decades

Lead: Alyssa Goodman, CfA



SCIENCE

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



stellar positions, clusters, motions



topology, positions & motions of (long) features



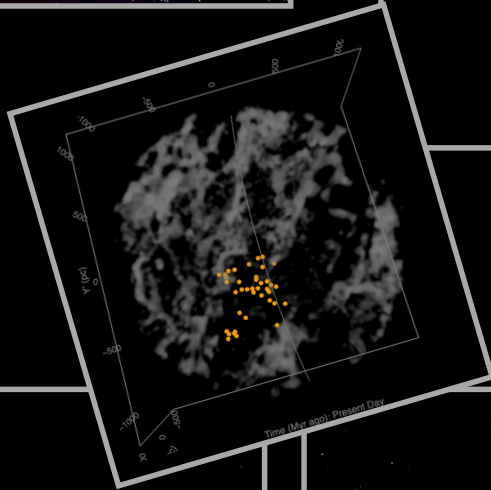
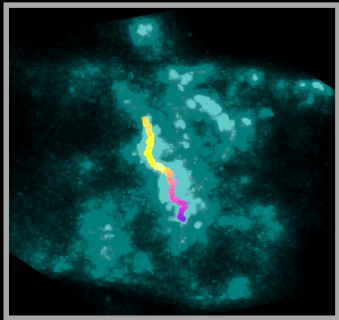
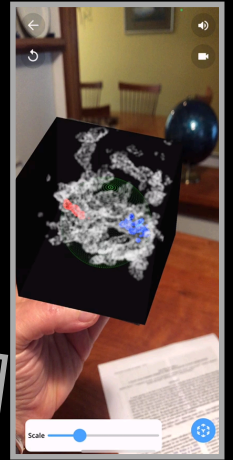
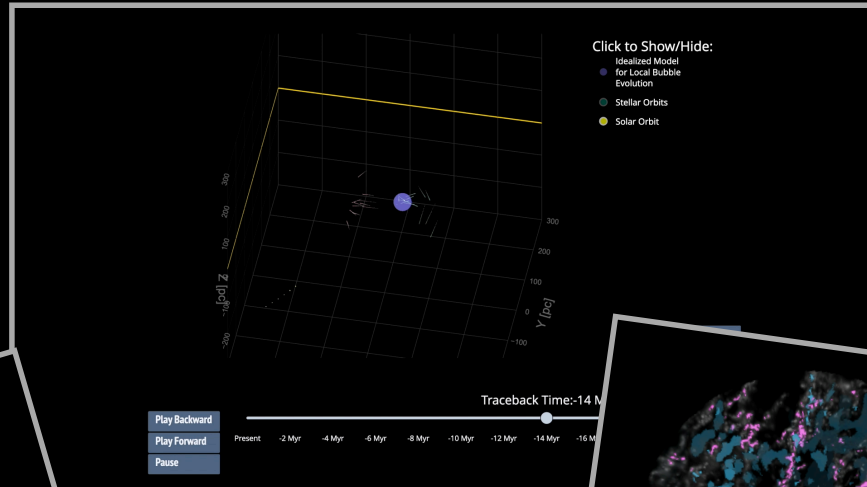
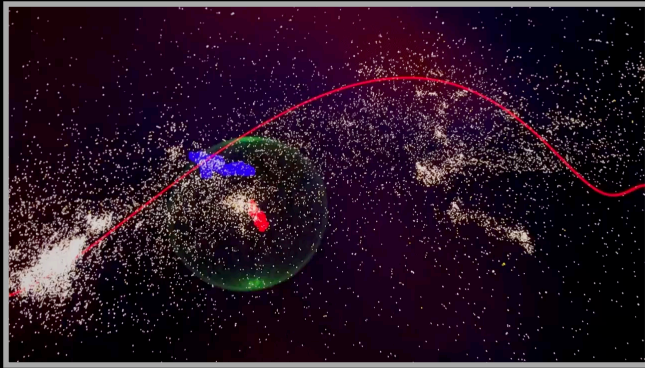
tracers of feedback & magnetic fields



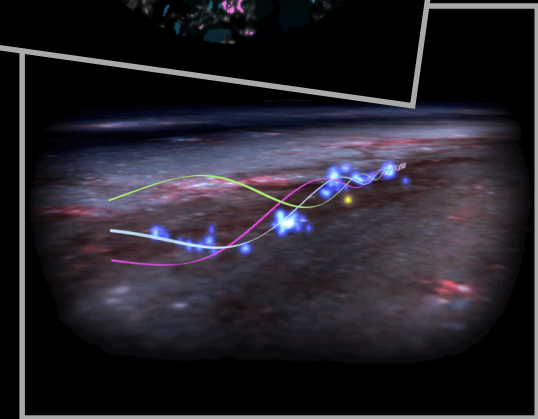
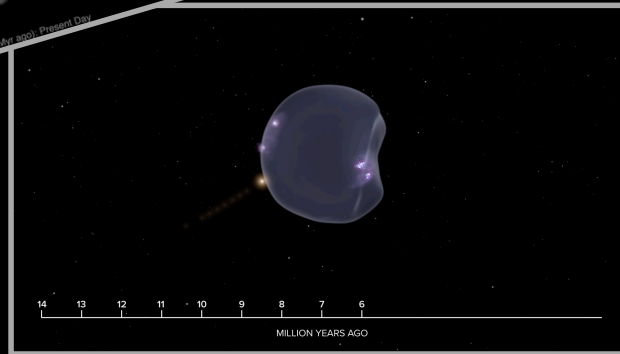
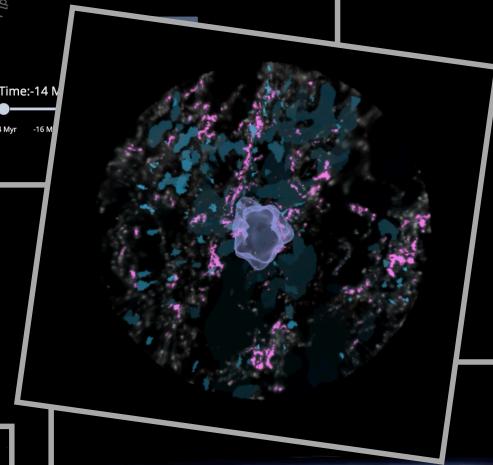
details on star-forming regions...and more!



Lead: Catherine Zucker, CfA



SO FAR




Zucker et al. 2021, Bialy et al. 2021; Zucker et al. 2022, Konietzka et al. 2024, O'Neill et al. 2024, Swiggum et al. 2024*. *embargoed

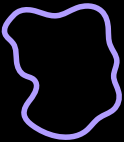
5 years ago, no one knew that...




5 years ago, no one knew that...



There is a giant (2.7 kpc-long) “wave” of star-forming regions (Alves et al. 2020, named “**The Radcliffe Wave**”) waving up & down ($P=90$ Myr; Konietzka et al. 2024) along the “Local Arm” of the Milky Way, the Sun passed through it ~ 13 Myr ago (Maconi et al. 2024*); and a magnetic field runs along it (Panopolou 2024*).



Nearly all star forming regions within 250 pc of the Sun lie on the “surface” of the Local Bubble (Zucker et al. 2022), which is actually a Local Chimney (O’Neill et al. 2024*), and we can estimate what its B-field looks like, in 3D (O’Neill et al. 2024*).

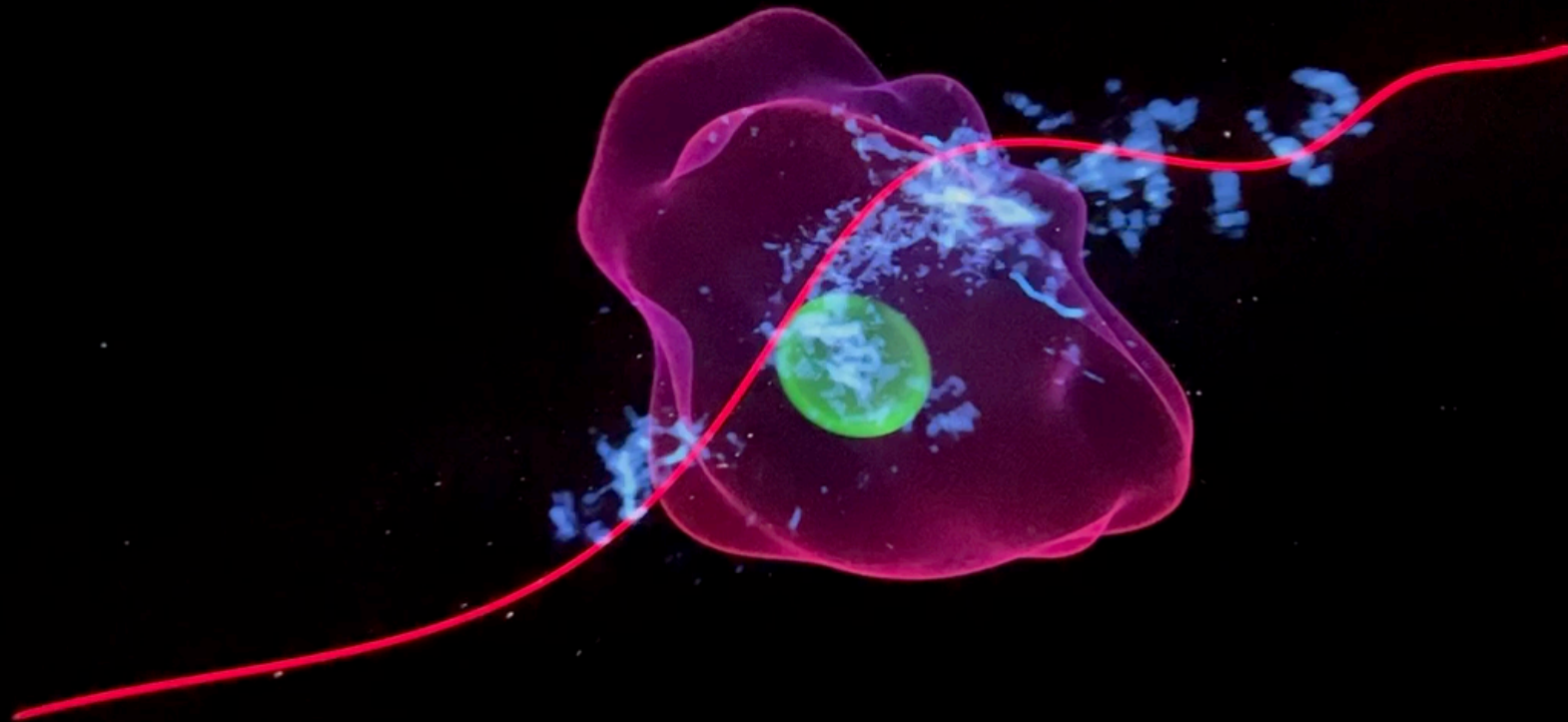


The Perseus and Taurus star-forming regions lie on opposite sides of a “shell,” with Perseus in the Radcliffe Wave, and Taurus smooched between the Local Bubble & the “**Per’Tau Shell**” (Bialy et al. 2021).



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

**submitted, embargoed, or in prep, ask for details*



TECH



glue



OpenSpace

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

Open Session Export Session Import Data Export Data/Subsets Link Data x² Arithmetic attributes Active Subset: None/Create New (the next selection will create a subset)

Data Collection

- Foley2022_arXiv_2212.01405_OrionShell_MW3D[HDU1]
- Reid2019_ApJ_885_131_LocalArmFit_MW3D[HDU1]
- Reid2019_ApJ_885_131_SGNArmFit_MW3D[HDU1]
- Reid2019_ApJ_885_131_MW3D[HDU1]
- Hunt2023_arXiv_2303.13424_MW3D[HDU1]
- Lallement2019_A+A_625_A135_Split_MW3D[HDU1]
- Edenhofer_2023_3D_Dust_XYZ_Revised-2

Subsets

Plot Layers - 3D Volume Rendering

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

Attribute: PRIMARY

Limits: 5.89626e-08 0.00643762

Color:

Plot Options - 3D Volume Rendering

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

Native aspect ratio Line Width 1

Perspective Show axes

Downsample when panning

3D Volume Rendering

[please ask later for demos]

TECH

cf milkyway3d.org


glue
multidimensional data exploration



TECH, demo

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

Linkable Interactive Visualization Exploration (LIVE) Environments

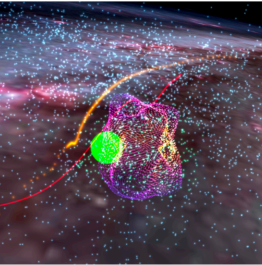


What is LIVE?


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

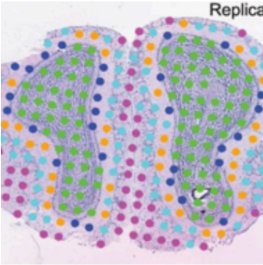
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As LIVE's infrastructure is being built, collaborators are ensuring its utility across Astronomy, Biology, and GIS by pursuing LIVE's science demonstration projects.




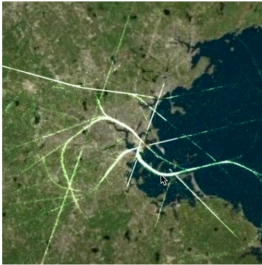
LIVE Astro






LIVE Bio





LIVE GIS





MilkyWay3D.org Home Data Software Science Gallery Events Collaborators Vienna Site (Private)

THE MILKY WAY IN 3D (VI - THE SUN'S NEIGHBORHOOD)

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

With community input, milkyway3d.org will serve as a hub for the interconnected set of outreach, education, and research resources that allow astronomers to map out and understand the three-dimensional structure of the Milky Way (especially near the Sun).

The project includes new software development, approaches to data sharing, and scientific research questions propelling our collaboration forward. In fact, MilkyWay3D's tech is so innovative, that it's the "demonstration project" for LIVE-Astro, the astronomy portion of the "Linkable, Interactive, Visualization, & Exploration" or "LIVE" Environments project.

All data sets and software collected, connected, and created will be available to all--including educators and learners!

Debut in Pasadena

The first time the MilkyWay3D.org was presented to the astronomy research community was at the *Surveying the Milky Way: The Universe in Our Own Backyard*, in the poster shown here, and in talks by Science PI Catherine Zucker and Harvard graduate student Theo O'Neill.



MILKYWAY3D.org



SCAN ME

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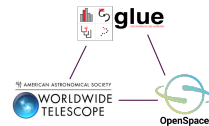
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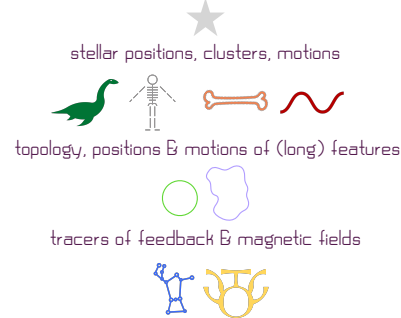
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making data accessible online for decades

Lead: Alyssa Goodman, CFA

enabling studies of how galaxies turn
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anywhere, including in planetaria



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

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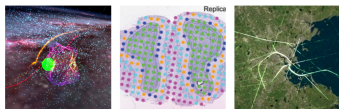
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LIVE Astro

LIVE Bio

LIVE GIS

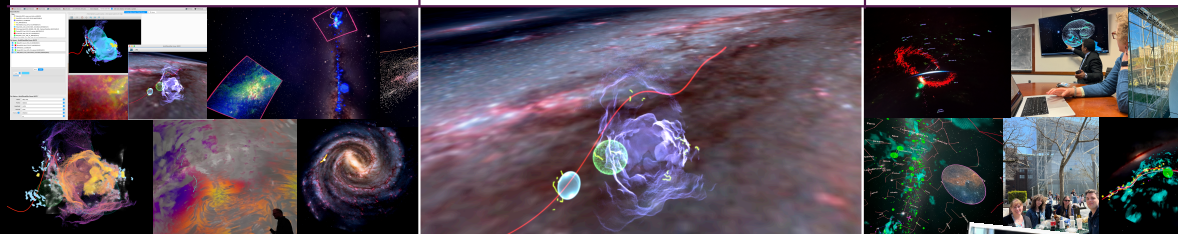
EDUCATION & OUTREACH



RadWave in Motion

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

Learn more about the discovery of the RadWave here!



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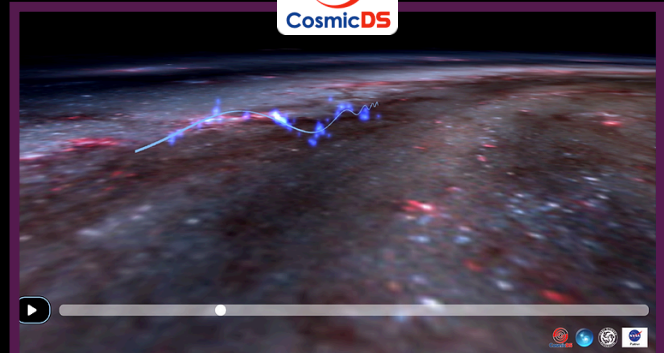
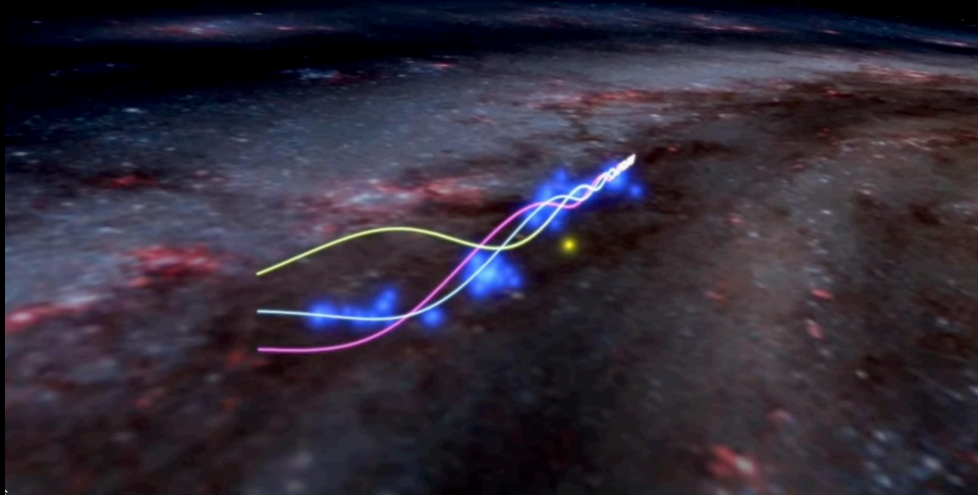
Join us, contribute, and yes, you can get a T-Shirt.



EDUCATION & OUTREACH

The Radcliffe Wave is Waving

Share



RadWave in Motion

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MilkyWay3D.org in NYC (AMNH/Hayden Planetarium)



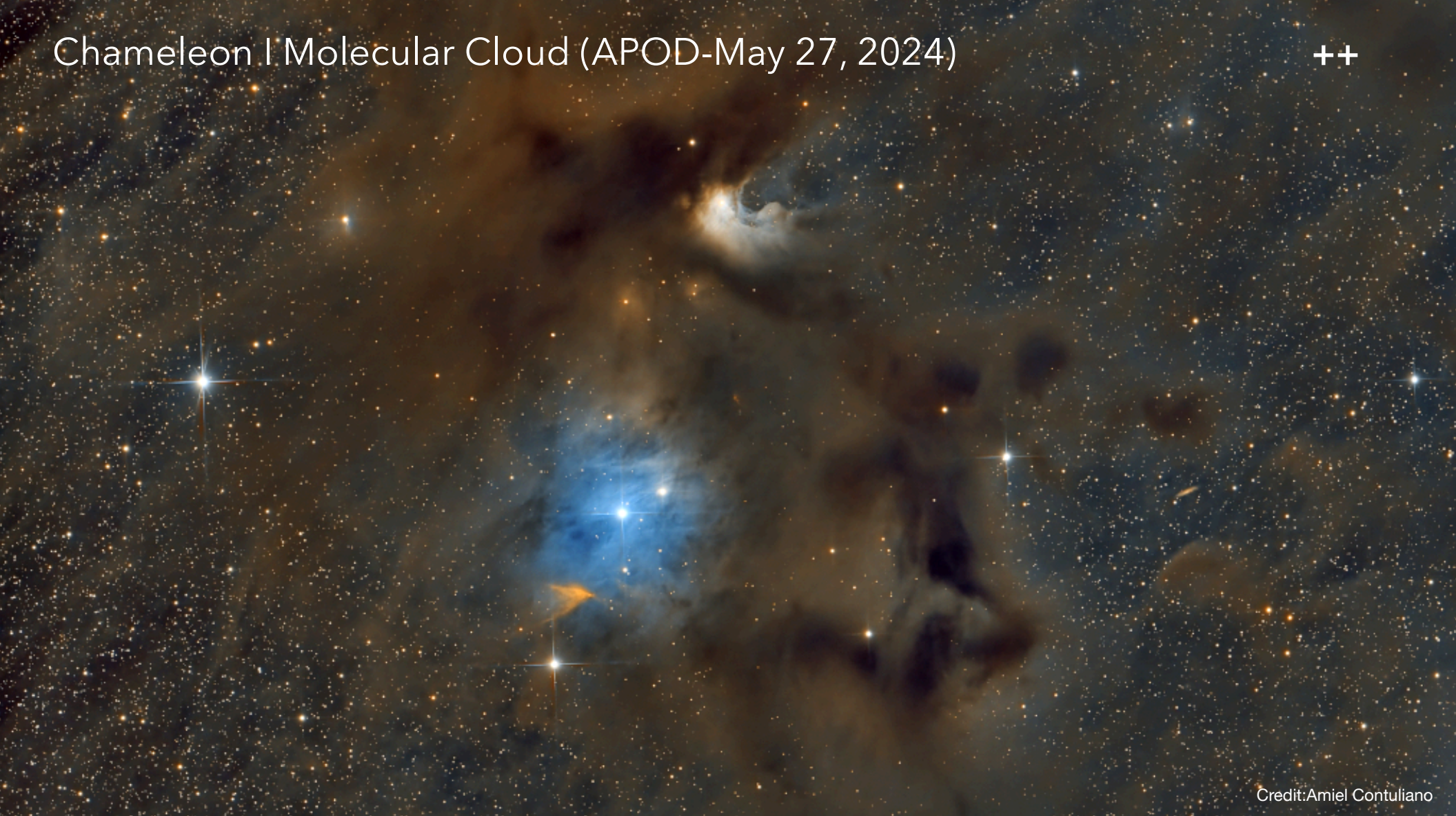


Why?

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Chameleon I Molecular Cloud (APOD-May 27, 2024)

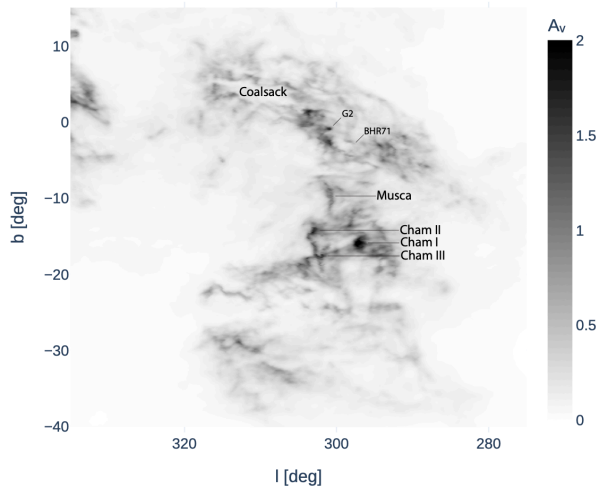
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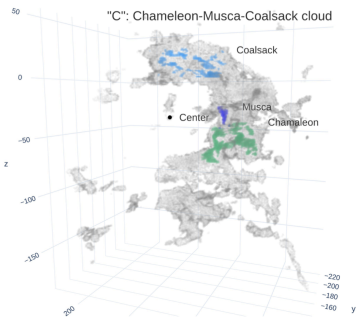
Credit:Amiel Contuliano

Bubbles all the way down (e.g. Chameleon)

(a)



Edenhofer et al. 2024



factor of ~1000 zoom in these panels

1 deg at 200 pc = 3.5 pc
1 arcmin is 0.06 pc

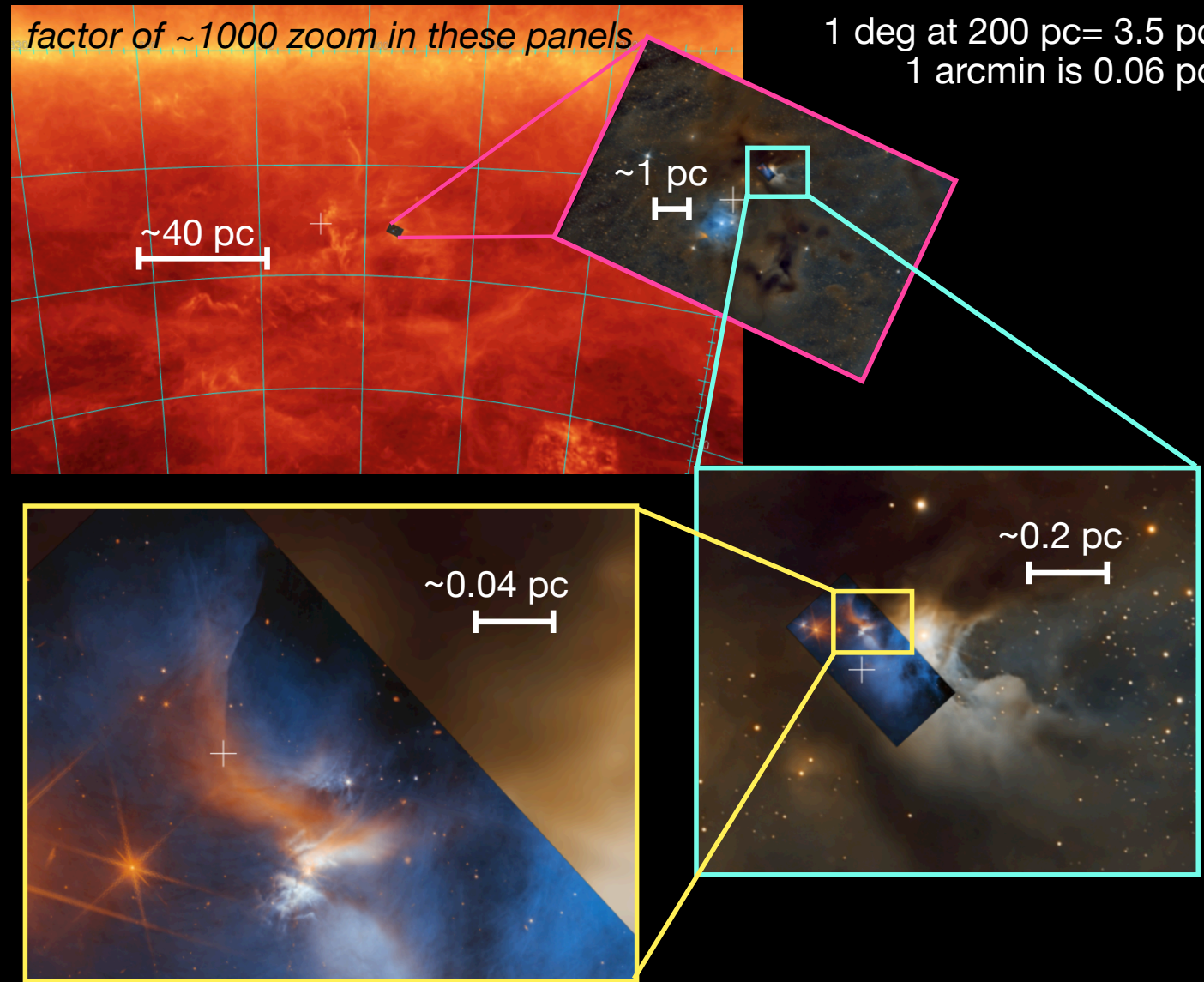
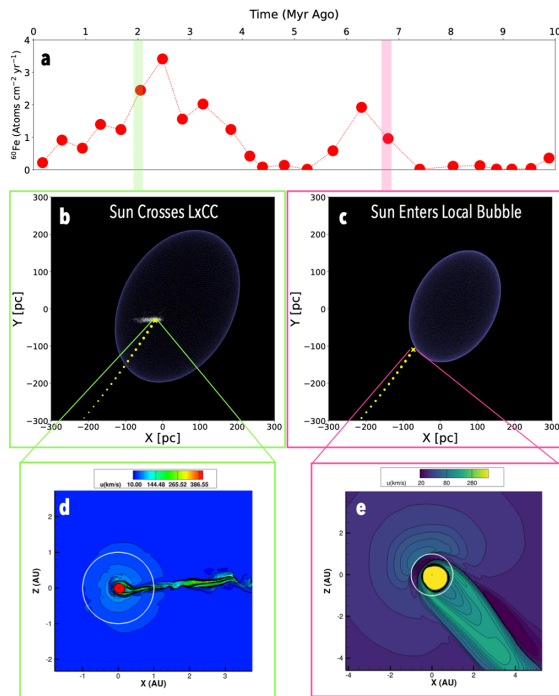


Fig. 2: 3D view of the isodensity surface of the posterior mean of the 3D dust map of [Edenhofer et al.](#) within the Cartesian selection given in [Table 1](#) showing the "C". An interactive version of this figure is available at https://faun.rc.fas.harvard.edu/gedenhofer/perm/C_C_Chameleon_Musca_Coalsack_cloud.html.

“Galactic Weather”

Sun’s heliosphere shrinking when entering the Local Bubble (Opher et al., under review)



Sun crossing the (clusters of) The Radcliffe Wave (Maconi et al., in prep, do not distribute)

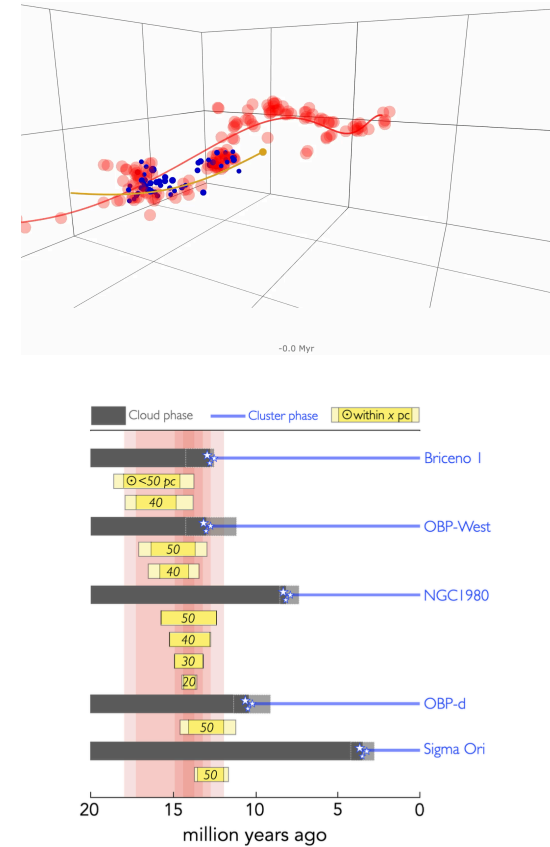


Figure 2: Significant interactions between the Solar System and the clusters of the Radcliffe Wave during their cloud phase in the past 30 Myr, considering various threshold distances ($d_{Sun-cloud}$: 50, 40, 30, and 20 pc). The Radcliffe Wave’s clusters here selected are those that, during their cloud phase, have had a probability greater than 50% of getting closer to the Sun than $d_{Sun-cloud}$, based on our orbits trackbacks. For each cluster, the cloud phase is represented by a horizontal gray band, the moment at which the cluster is formed is highlighted by three small stars, while the blue band indicates the time period during which the cluster is formed. The age range of the cluster, as computed in this work, is indicated by a light-gray band with a dotted edge. The yellow bands highlight the time period during which the Solar System is within a certain distance from the clouds. Light-yellow represents the uncertainty of the interactions. The vertical red stripes summarize the time range during which the Solar System is interacting with the gaseous part of the Radcliffe Wave. The closer the interaction, the redder the vertical stripe. The numerical equivalent of this plot is shown in Table 1.



(Why) we need **YOU**

[Chat GPT example, discussion]

A 3D Map of the Star Forming Milky Way, for Everyone

Thanks to the ongoing revolution in our ability to understand the structure of the Milky Way near the Sun made possible by 3D dust mapping and Gaia, we are in the process of synthesizing not just a 3D image, but a 3D **movie** of how our local Milky Way came to be as it is today. **The goal of MilkyWay3D.org, and the technology enabling it, called "LIVE Astro," is to share the data, software, and results being used to create this new 3D view of our local Milky Way, with researchers, educators, and the general public.**

**MOVIE
GOAL**

The talk will explain what has been done so far to make data and tools available, by demonstrating and explaining the LIVE-env.org (LIVE-env.org) and MilkyWay3D.org (MilkyWay3D.org) websites. Accomplishments of members of our team already include: several key research findings (e.g about the **Radcliffe Wave, Perseus-Taurus Supershell, Star Formation on the Local Bubble, and Galactic weather**); a variety visualization and software advances (e.g. **glue, interactive and augmented reality figure technologies**); and also work brining our 3D view of the Milky Way to the public via NASA-sponsored educational efforts (e.g. **Cosmic Data Stories, Planetarium Shows** at the AMNH) and the popular press (e.g. via **Sky & Telescope**). A key goal of offering this talk will be to **recruit the meeting-in-a-meeting participants—especially those interested in open science—into this combined research/infrastructure/education community effort.**

**TECH
SO FAR**

YOU

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