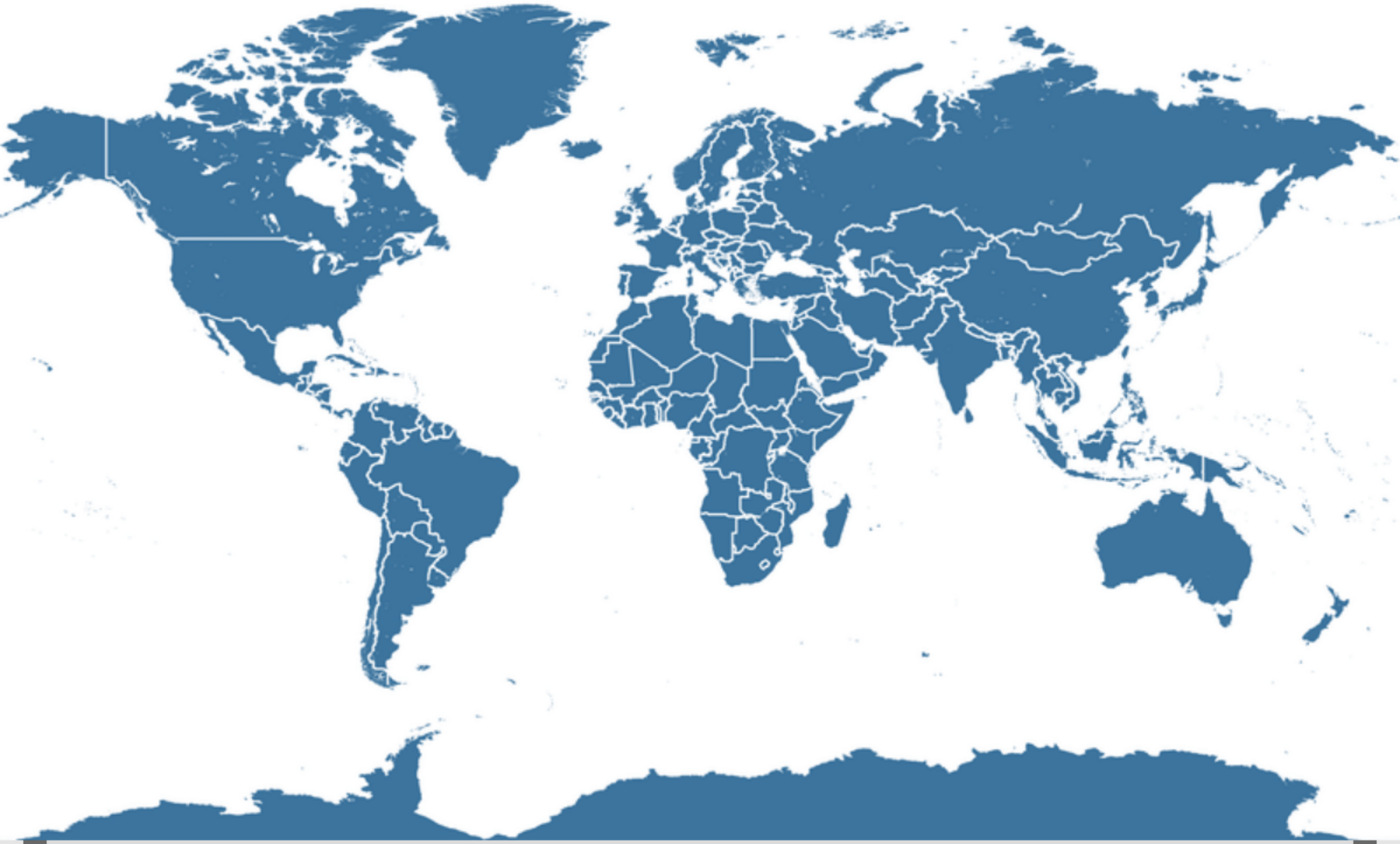
# Knitting Together an Amazing new Multi-Color View of the Milky Way, in 3D

Alyssa A. Goodman
Center for Astrophysics | Harvard & Smithsonian
and Radcliffe Institute for Advanced Study

photo credit: Tom Dame

# Where are you?



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# Who are you?

High-school student

Undergraduate student

Graduate student

Postdoc

Research Staff

Faculty Member

None of the above…just interested!

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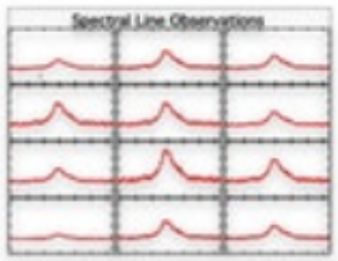
# Do you know about...?

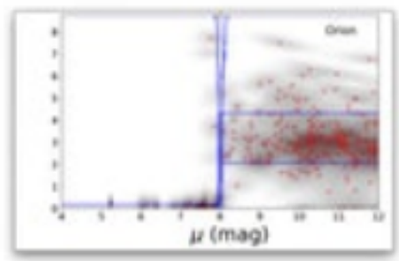
spiral galaxies




spectral-line mapping

numerical simulation

photometric imaging (over time)




statistical reconstruction

The Radcliffe Wave

Knitting

ngvla

Next Generation VLA

Merge Cube

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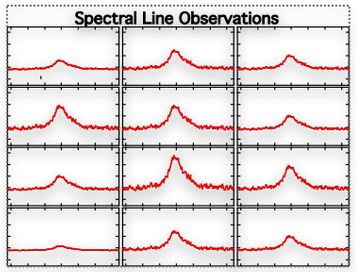
spiral galaxies

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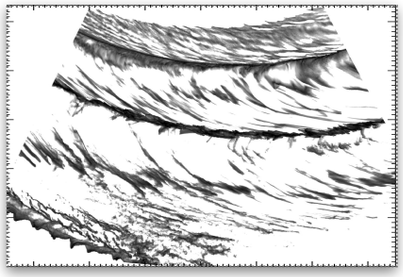

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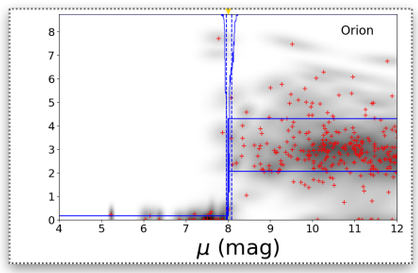


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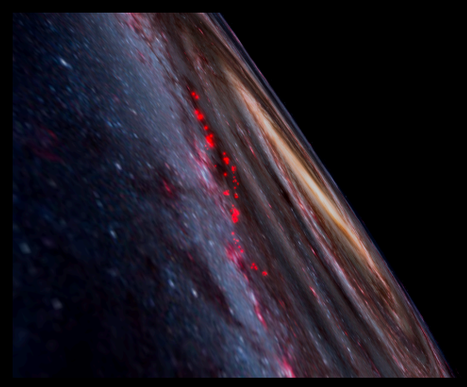

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# The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork

The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm, and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm.

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.

More information can be found at:
http://sings.stsci.edu/

Ellipticals

Unbarred Spirals

Weak Bulge

Strong Bulge

Intermediate Spirals

Irregulars

Barred Spirals

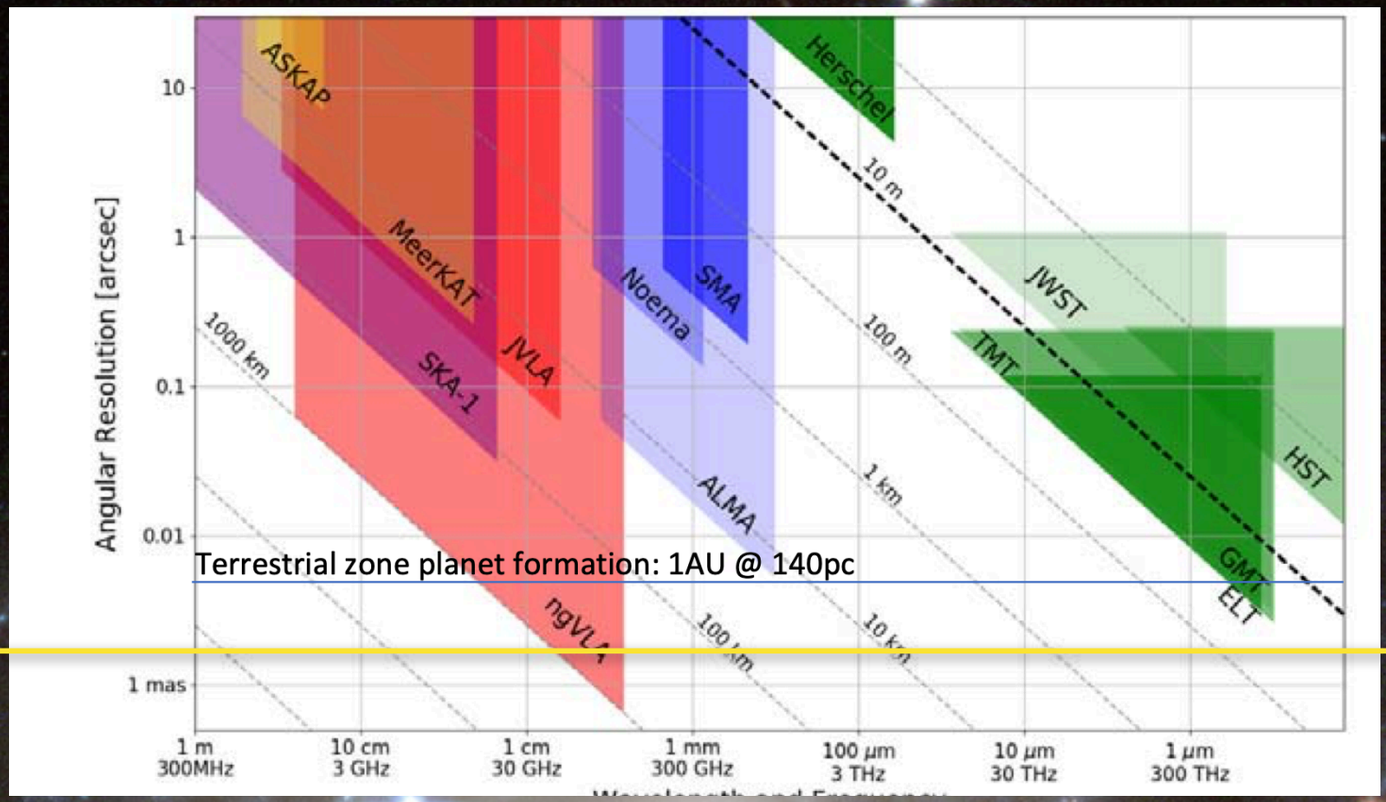
NGC 855 E
NGC 3265 E
NGC 584 E4
NGC 1482 SA0
NGC 3773 SA0
NGC 1404 E
NGC 5866 (M102) S0
NGC 4552 (M89) E0
NGC 4125 E6p
NGC 1377 S0
NGC 1266 SB0
NGC 1316 SAB0
NGC 4569 (M90) SABab
NGC 4579 (M58) SABb
NGC 4725 SABab
NGC 3627 (M66) SABb
NGC 1566 SABbc
NGC 4536 SABbc
NGC 5713 SABbcp
NGC 5194/5 (M51) SABbc/SB0p
NGC 3521 SABbc
NGC 4321 (M100) SABbc
NGC 4559 SABcd
NGC 2403 SABcd
NGC 3184 SABcd
NGC 6946 SABcd
NGC 925 SABd
NGC 4826 (M64) SAab
NGC 3031 (M81) SAab
NGC 4736 (M94) SAab
NGC 4450 SAab
NGC 3938 SAc
NGC 7552 SAc
NGC 2976 SAc
NGC 24 SAc
NGC 5033 SAc
NGC 4254 (M99) SAc
NGC 628 (M74) SAc
NGC 5474 SAcd
NGC 7793 SAd
NGC 3621 SAd
NGC 7331 SAb
NGC 2841 SAb
NGC 5055 (M63) SAbc
NGC 3190 SAap
NGC 4594 (M104) SAa
NGC 2798 SBa
NGC 1291 SBa
NGC 3351 (M95) SBb
NGC 1097 SBb
NGC 3049 SBab
NGC 1512 SBab
NGC 3198 SBc
NGC 337 SBd
NGC 4631 SBd
NGC 5398/Tol 89 SBdm
NGC 4236 SBdm
NGC 4625 SABmp
NGC 3034 (M82) I0
NGC 2915 I0
DDO 154 IBm
NGC 6822 IBm
Mrk 33 Im
Ho IX Im
DDO 165 Im
NGC 5408 IBm
Ho II Im
DDO 053 Im
NGC 1705 Am
IC 4710 SBm
IC 2574 SABm
M81 DwA I?
M81 DwB Im

Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)

SINGS Team
Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou

SPITZER SPACE TELESCOPE

UGC 12158 (Mark Reid's favorite Milky Way analog)




**~40 kpc**

**40 kpc is 0.02 degrees at 120 Mpc, so 1 pc is 1.8 mas**

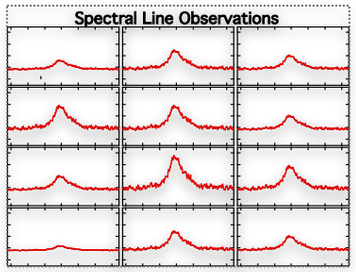
**ngVLA could resolve the 1 pc-scale structure of molecular clouds in UGC 12158**

***and easily see 10-pc-scale vertical structure in edge-on disks…_***

ngvla

UGC 12158 (Mark Reid's favorite Milky Way analog)

spiral galaxies

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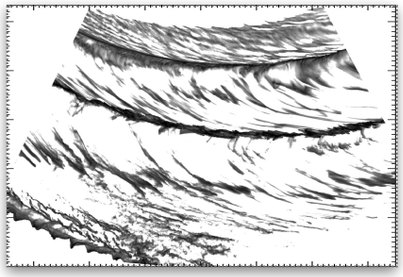

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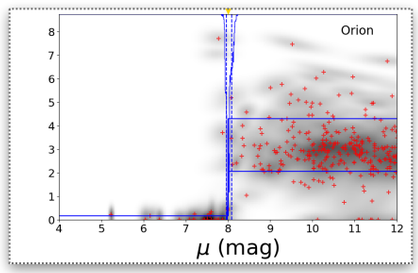
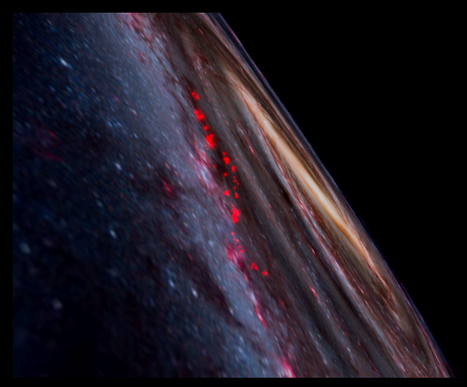



statistical reconstruction



The Radcliffe Wave

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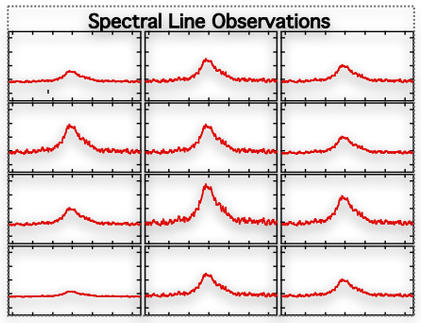
# “Knitting”?

Dust
(density, 3D position)
Gas
(~density, line-of-sight velocity, 2D position)
Stars
(3D velocity, 3D position)

Dr. Catherine Zucker
catherinezucker

Alyssa A. Goodman

"Data"= 3D cubes, 2D images, 1D catalogs, from…

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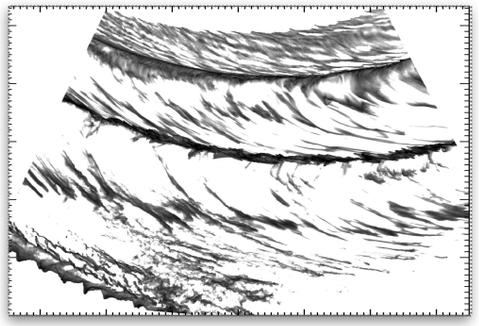

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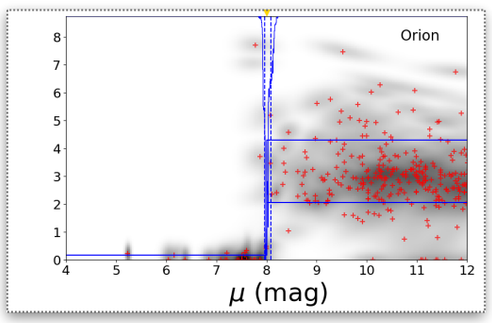
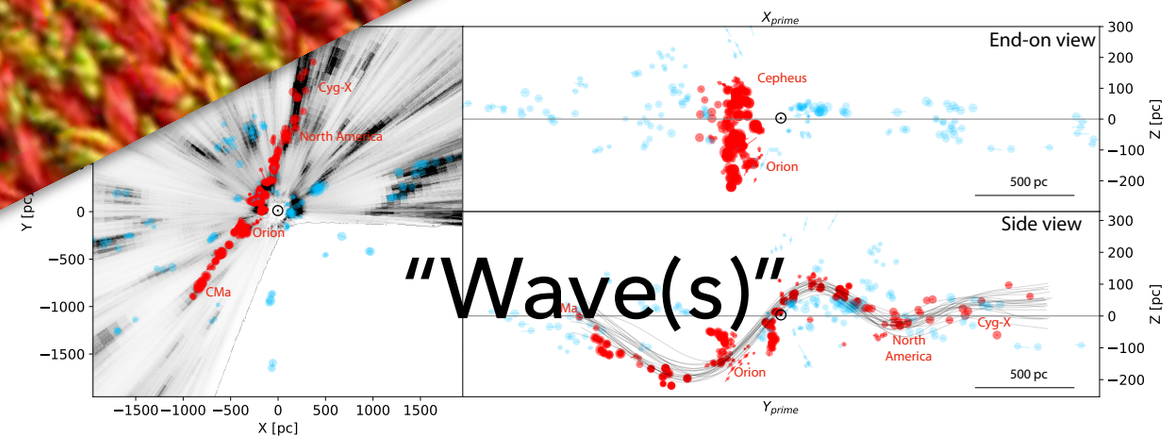



statistical reconstruction

Gas in "3D"
*p-p-*

Dust in 3D
*p-p-p*




"Theory" questions re: magnetic fields, feedback, collisions, oscillations, dark matter…

# "Knitting" Together the Milky Way

**Try tinyurl.com/milkywayknitting to examine and explore these knitting instructions on your own.**

(flow chart from 2020 NASA ADAP proposal by Zucker, Finkbeiner, Goodman, et al.)

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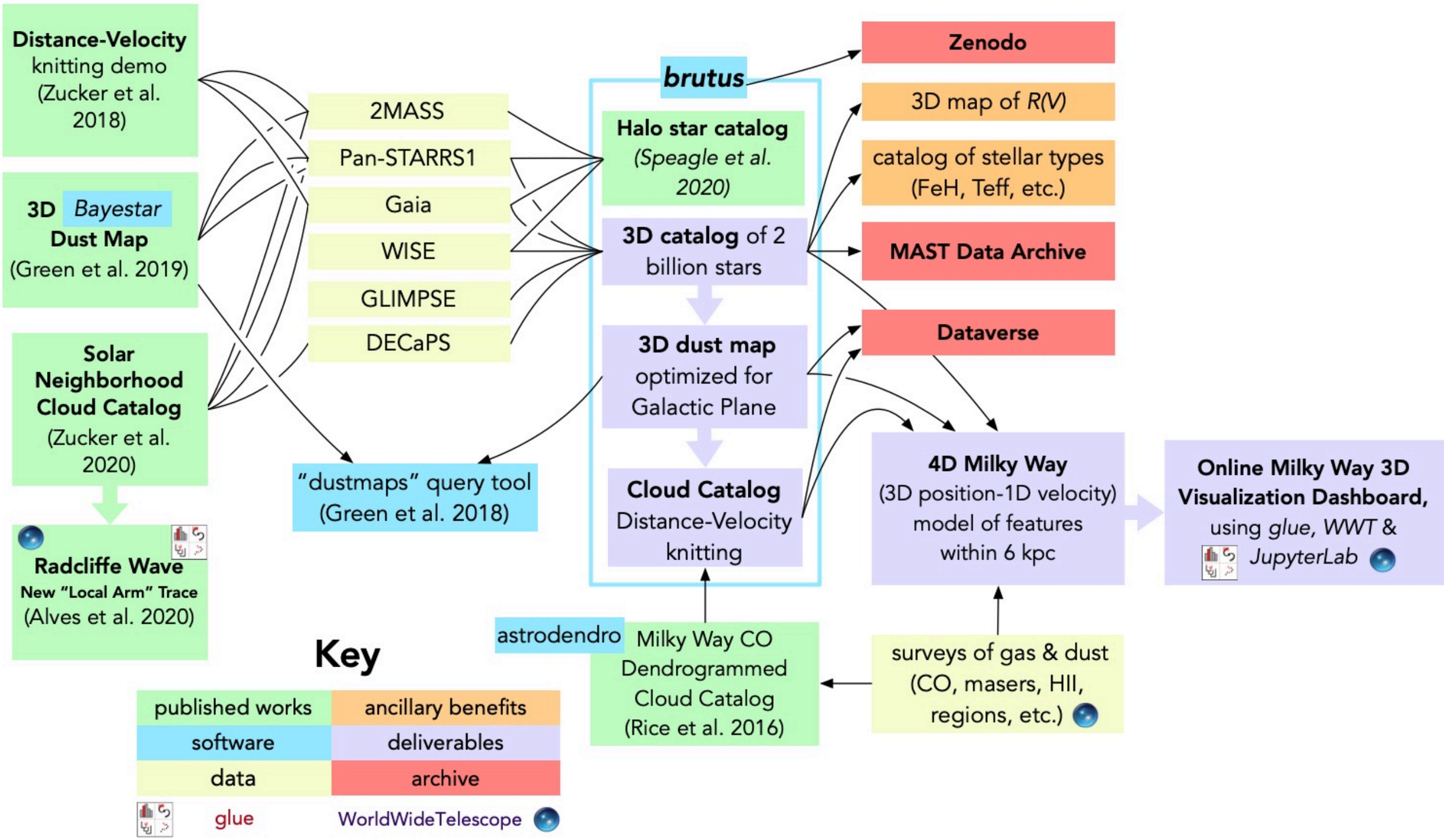


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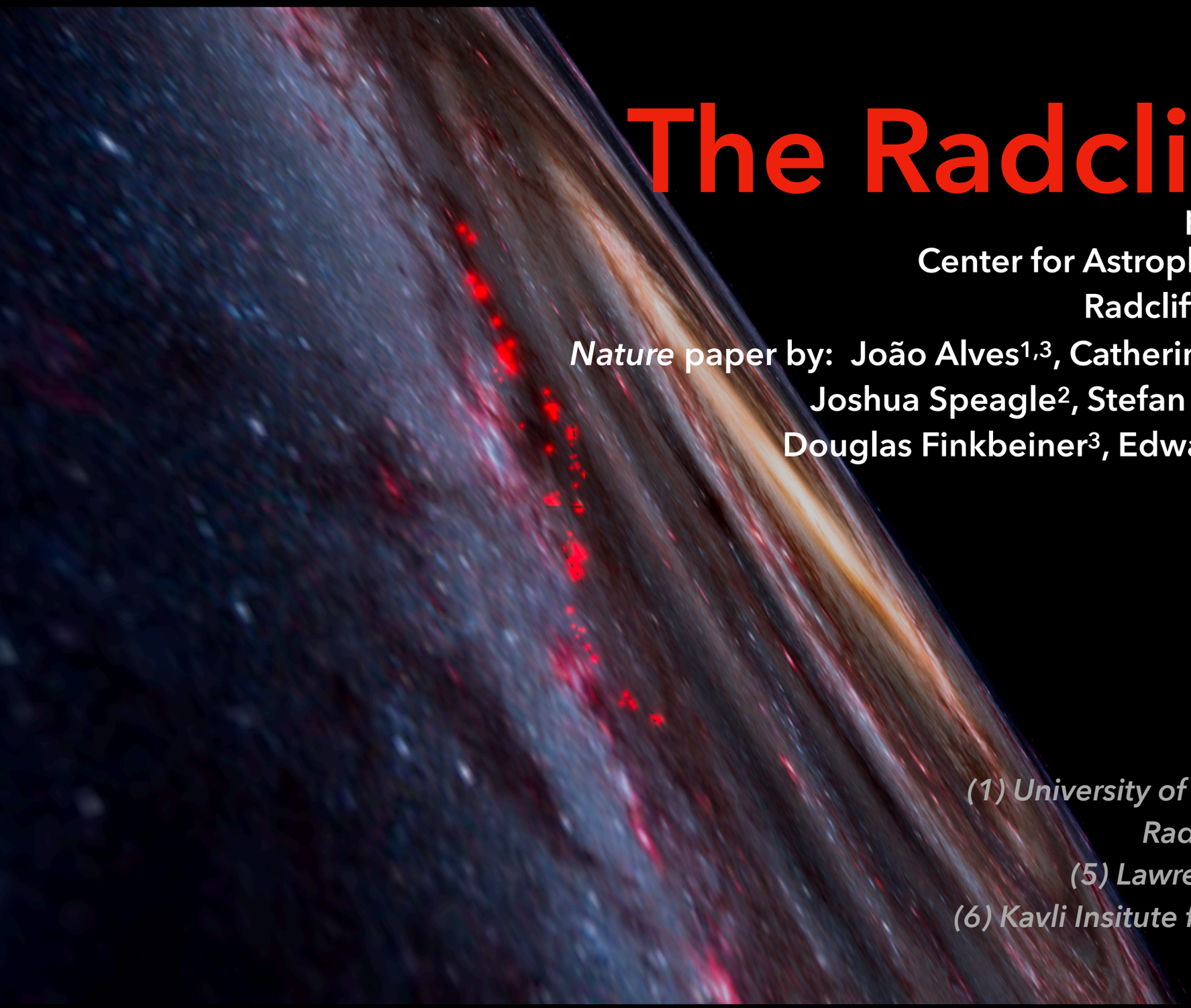


# The Radcliffe Wave


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

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

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

# The Radcliffe Wave

CARTOON*

DATA

*drawn by Dr. Robert Hurt, in collaboration with Milky Way experts based on data; as shown in screenshot from AAS WorldWide Telescope

# The Radcliffe Wave

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

The Radcliffe Wave is **9000 light years long**, and **400 light years wide**, with crest and trough reaching **500 light years** out of the Galactic Plane. Its gas mass is **more than three million times** the mass of the Sun.

*video created by the authors using AAS WorldWide Telescope*
*(includes cartoon Milky Way by Robert Hurt)*

# The Radcliffe Wave

## ACTUALLY 2 IMPORTANT DEVELOPMENTS

DISTANCES!!

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

*Zucker et al. 2019; 2020*

RADWAVE

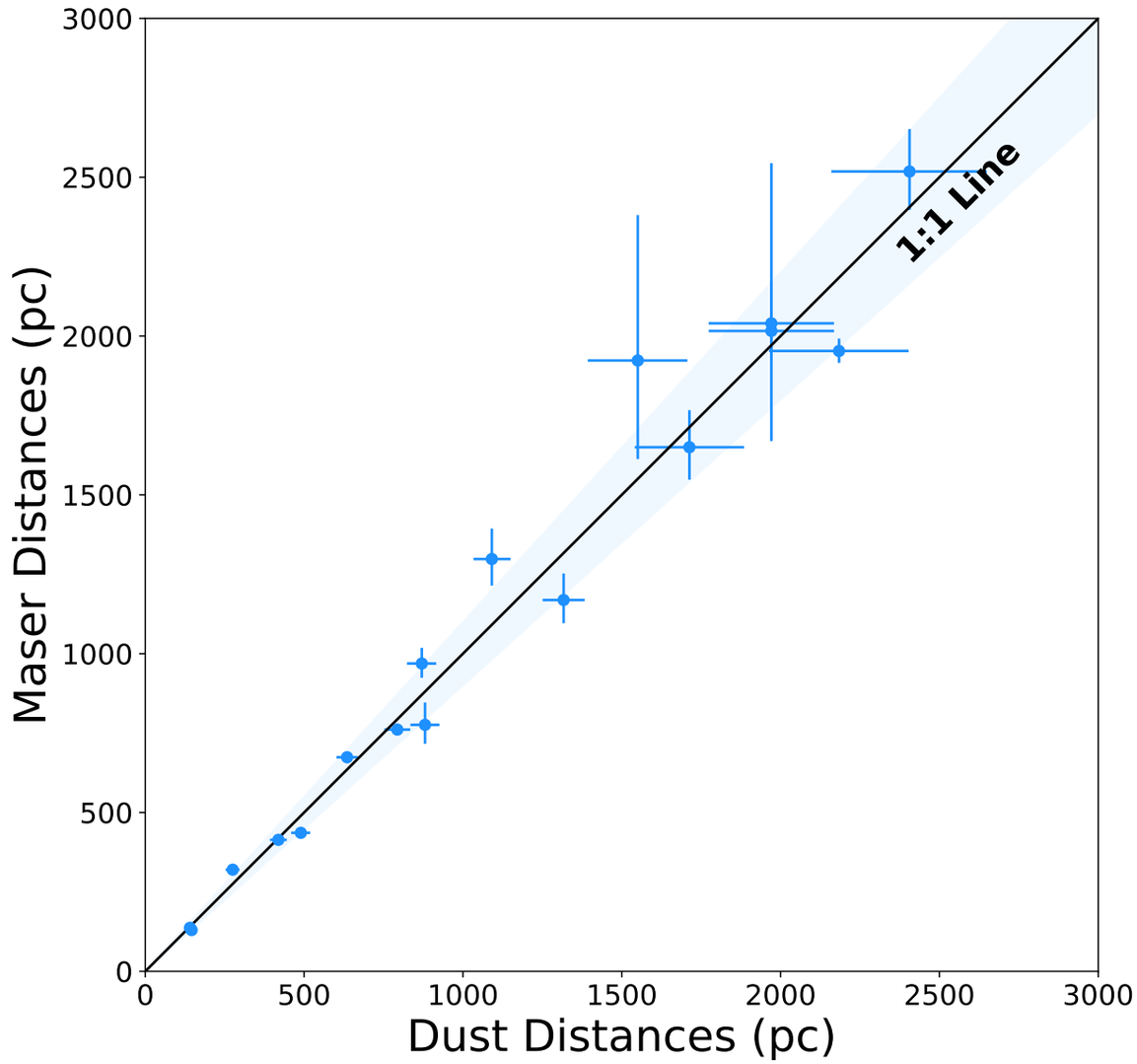
Surprising wave-like arrangement of star-forming gas *is* the "Local Arm" of the Milky Way.

*Alves et al. 2020*

DISTANCES!!

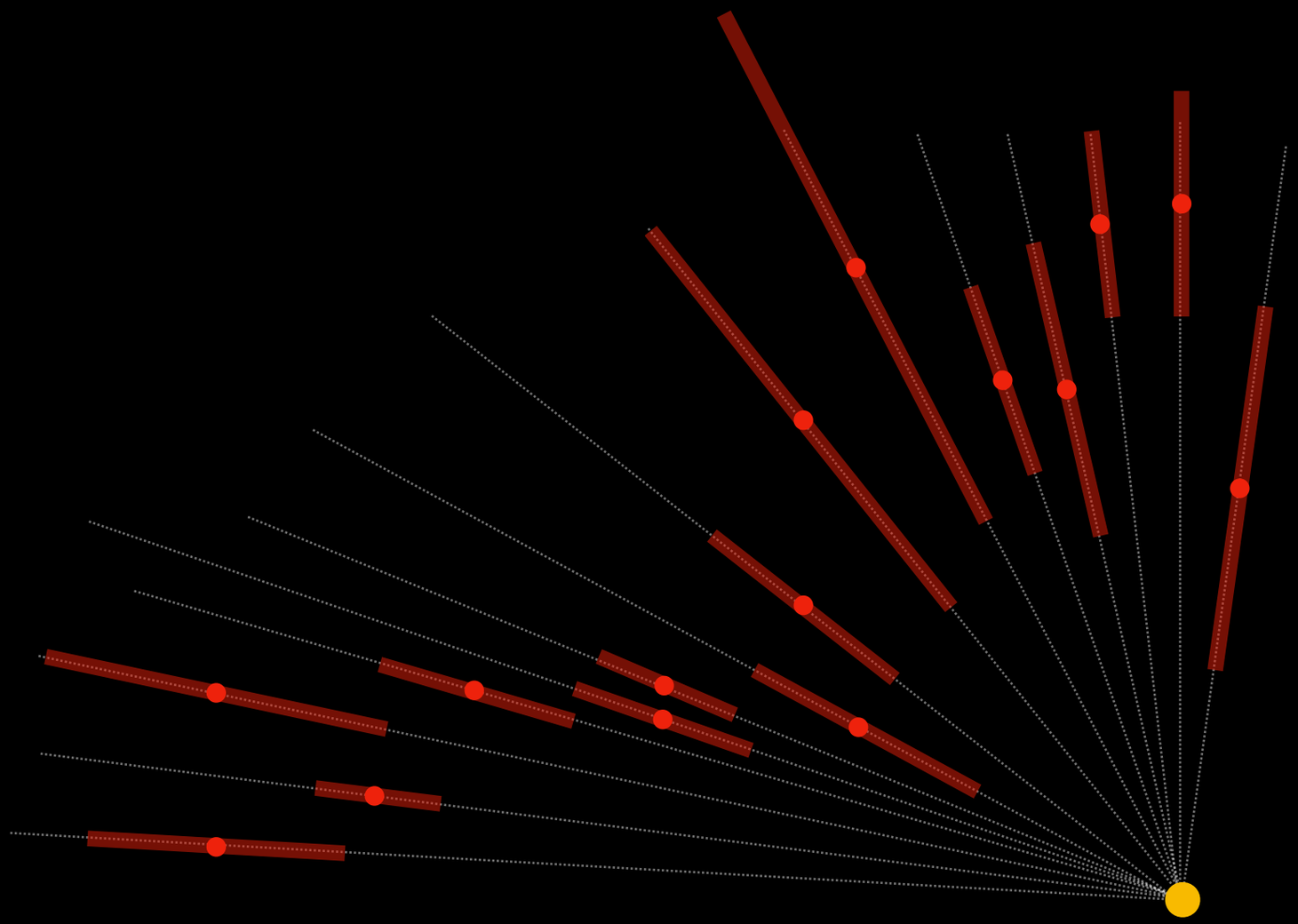
We can now measure distances to gas clouds in our own Milky Way galaxy to ~5% accuracy.

requires **special** regions on the Sky (HII regions with masers)




can be used **anywhere** there's dust & measurable stellar properties

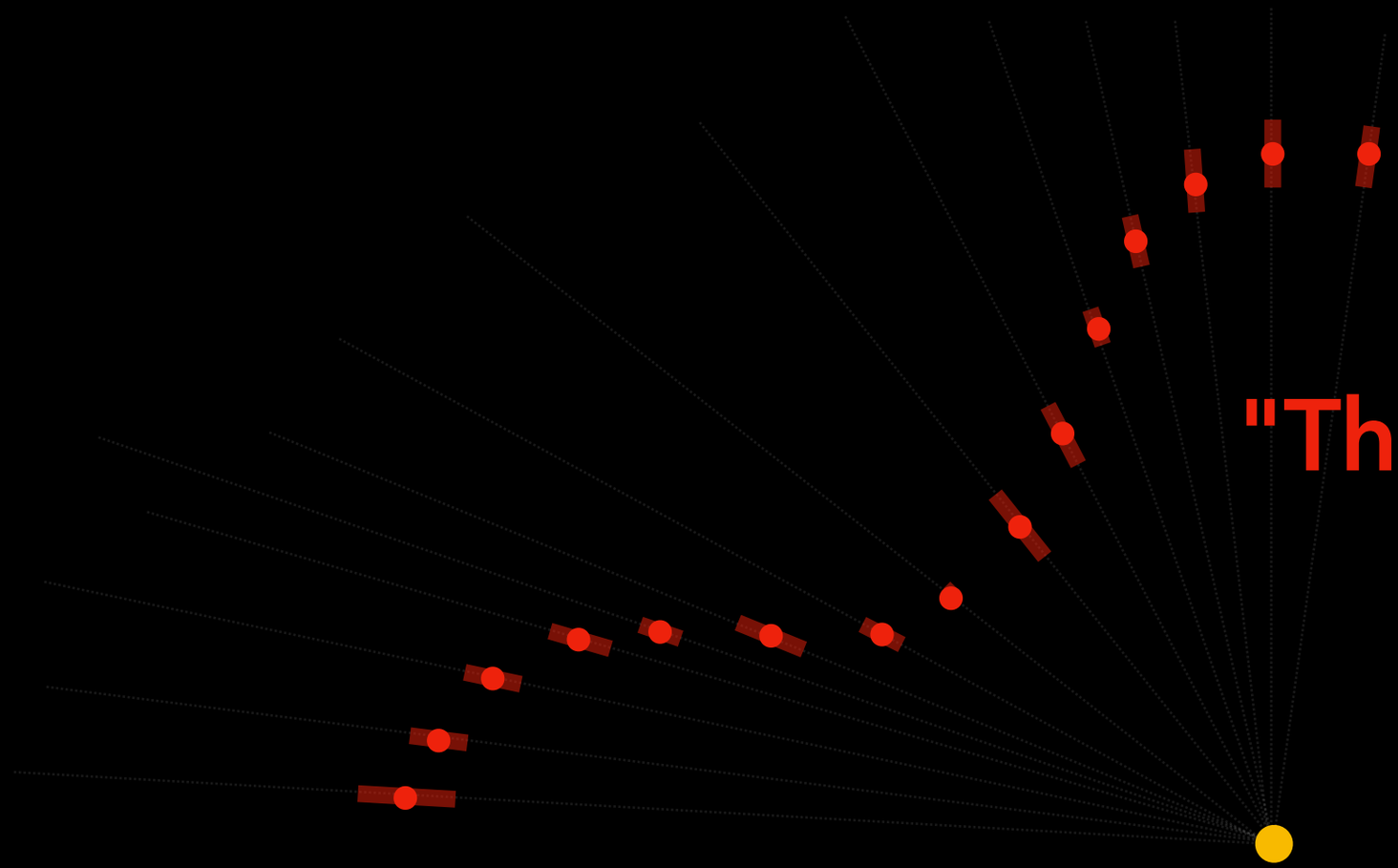
*Zucker et al. 2019*



# Uncertain Distances

SCHEMATIC CARTOON(!)

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



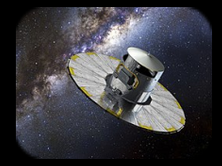
"The Radcliffe Wave"

SCHEMATIC CARTOON(!)

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

HOW= 3D dust mapping*

+ Gaia*

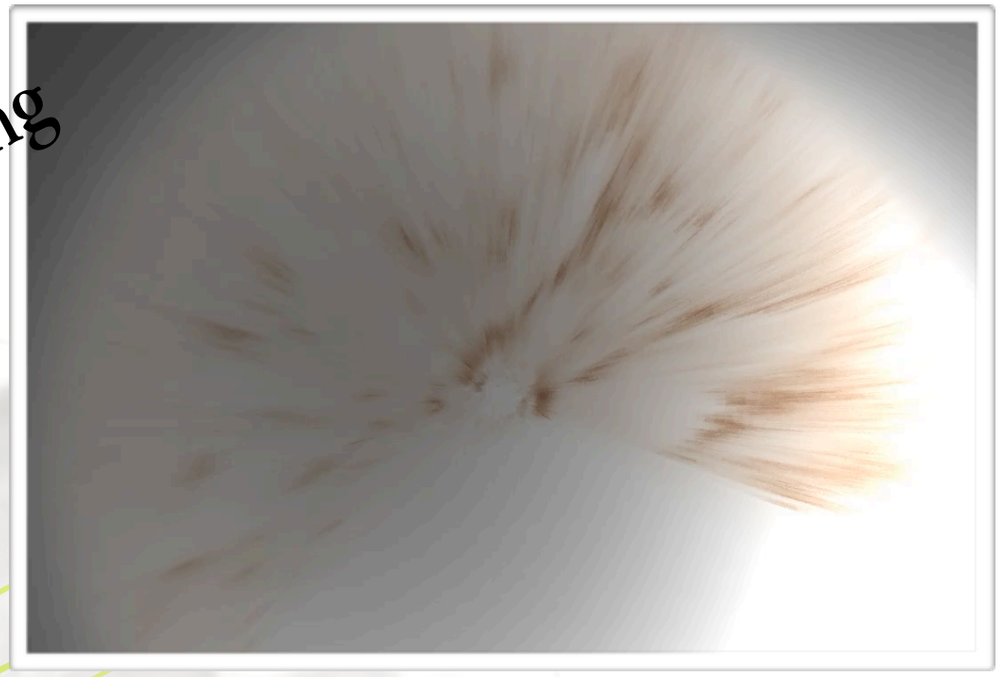


+ glue*

+ WorldWide Telescope

*2 million CPU hours, Harvard *800 million stars, ESA *NASA/JWST, NSF *Microsoft Research, NSF, AAS

# Extinction & Reddening, from Color Imaging

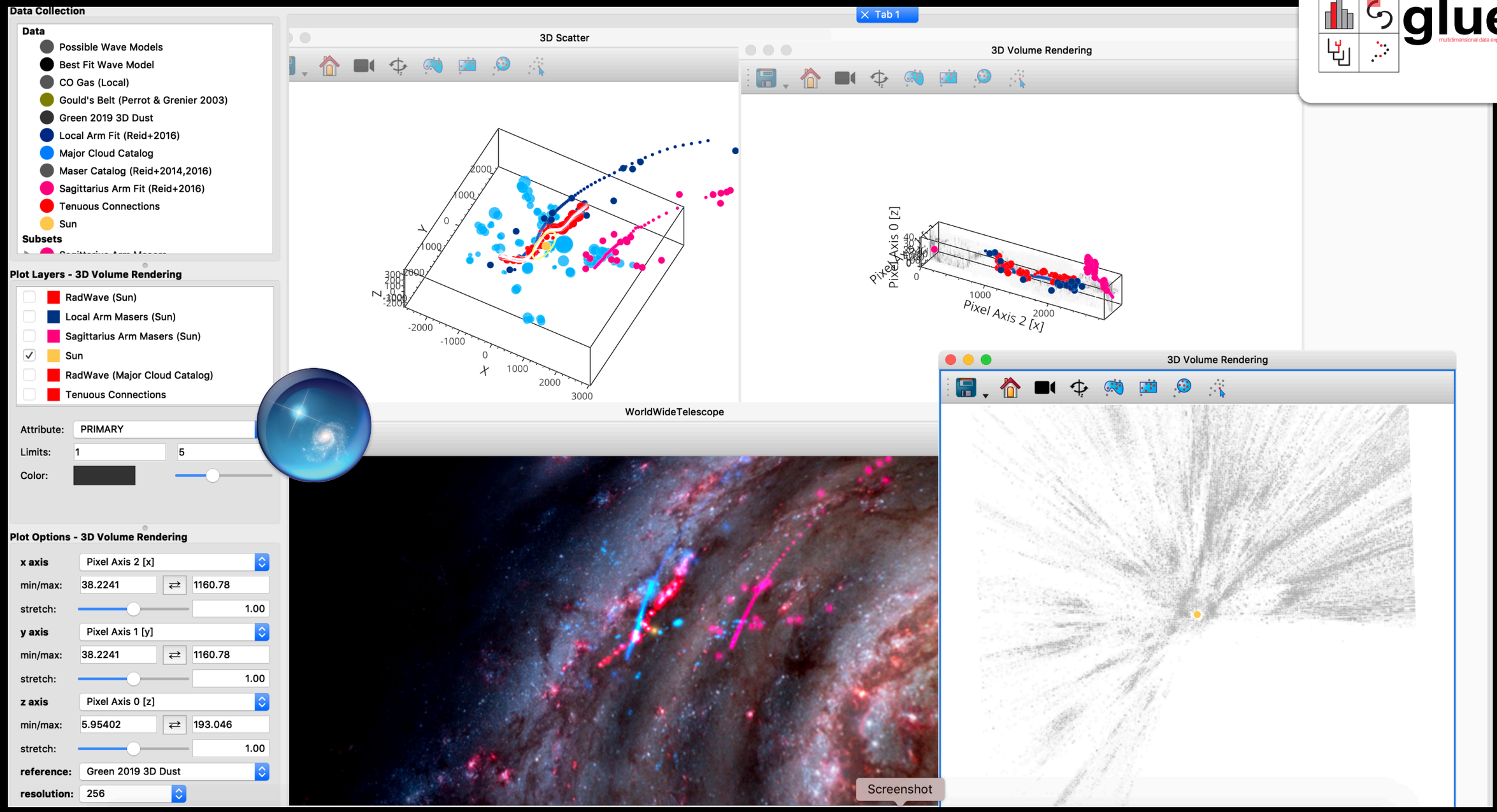


*Green et al. 2019*

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

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

# "Seeing" The Radcliffe Wave, in 3D

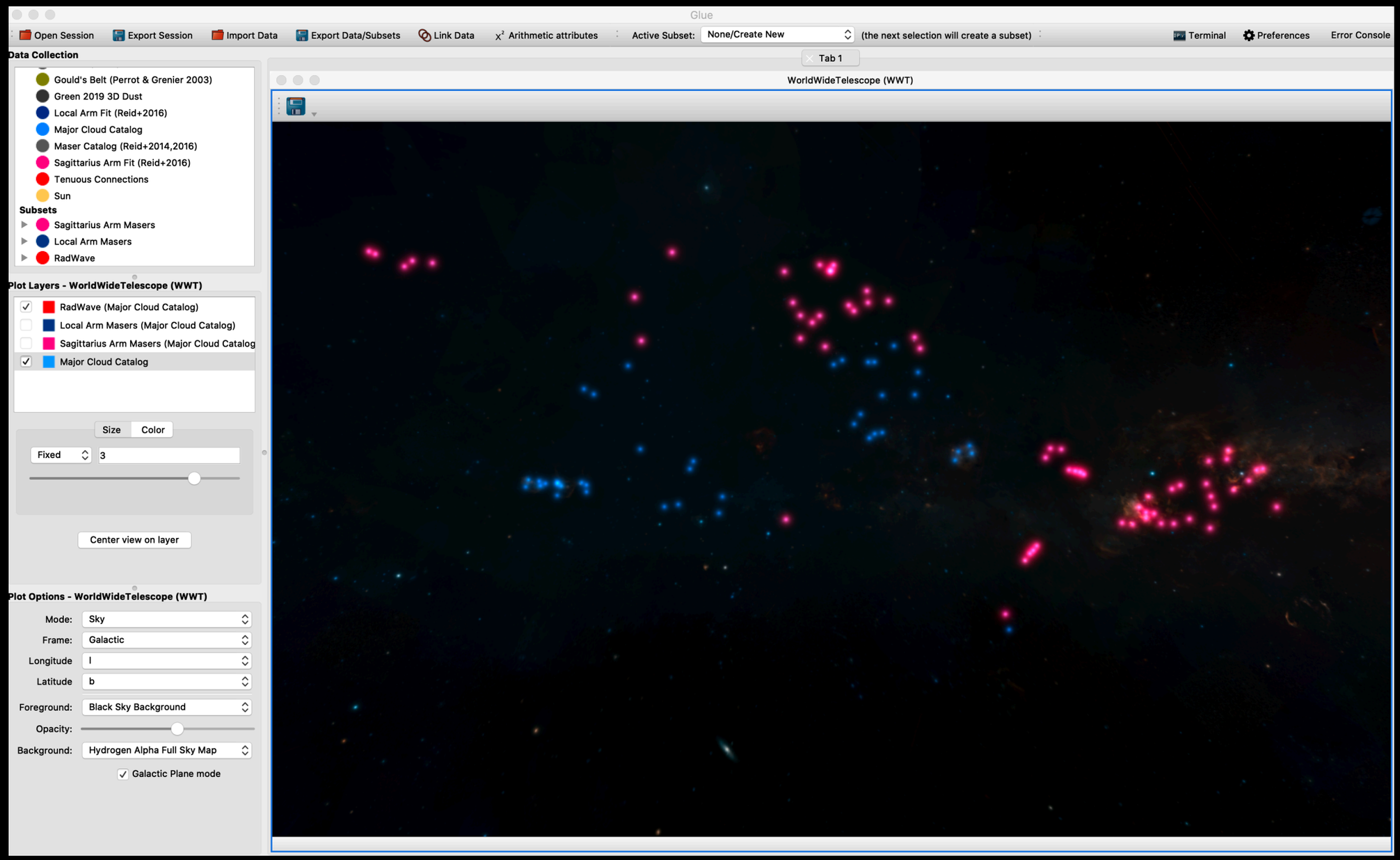



AAS WorldWide Telescope: worldwidetelescope.org

glue: glueviz.org

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

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

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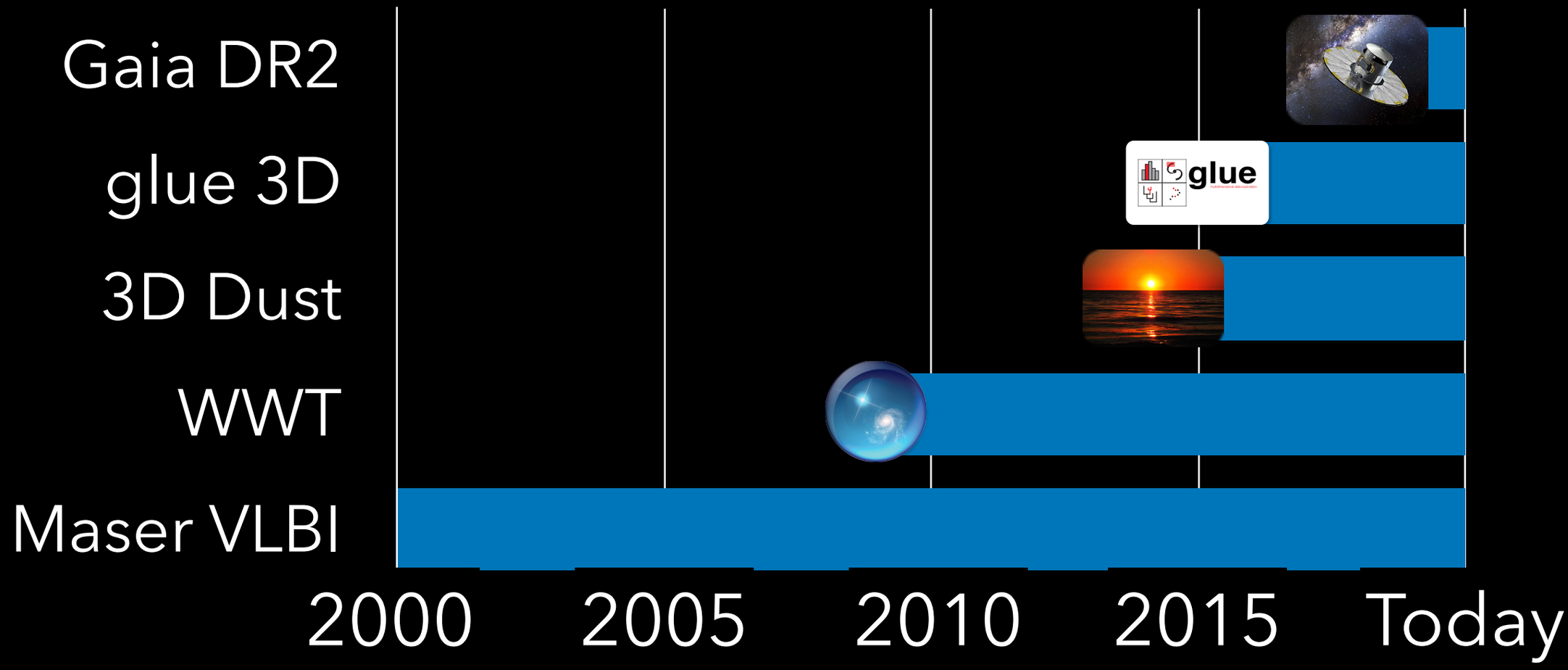
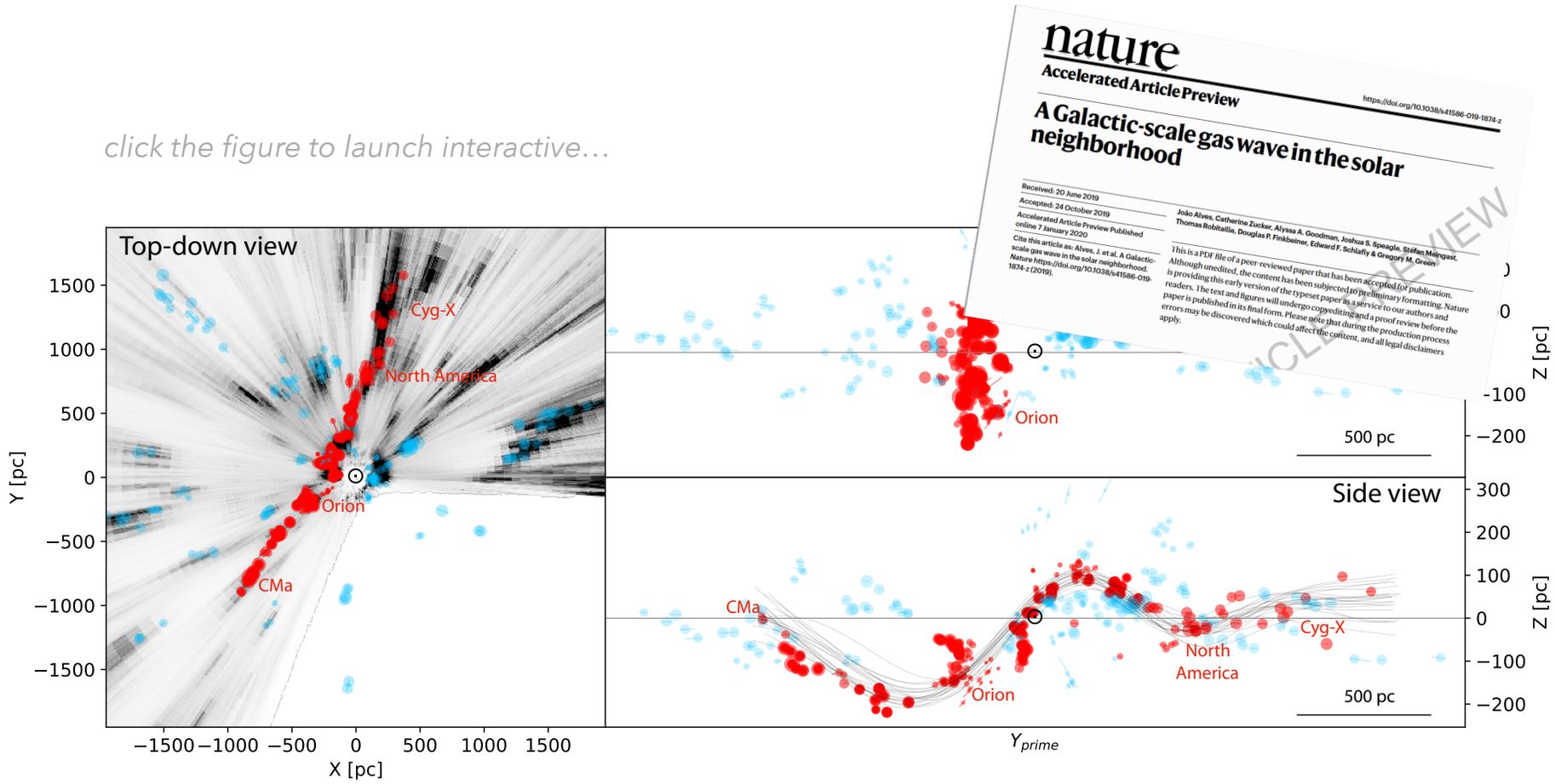


# The Radcliffe Wave

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

*click the figure to launch interactive…*





nature
Accelerated Article Preview
https://doi.org/10.1038/s41586-019-1874-z
A Galactic-scale gas wave in the solar neighborhood
Received: 20 June 2019
Accepted: 24 October 2019
Accelerated Article Preview Published online 7 January 2020
Cite this article as: Alves, J. et al. A Galactic-scale gas wave in the solar neighborhood. Nature https://doi.org/10.1038/s41586-019-1874-z (2019).
João Alves, Catherine Zucker, Alyssa A. Goodman, Joshua S. Speagle, Stefan Meingast, Thomas Robitaille, Douglas P. Finkbeiner, Edward F. Schlafly & Gregory M. Green
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ARTICLE PREVIEW

João Alves, Catherine Zucker, Alyssa Goodman, Joshua Speagle, Stefan Meingast, Thomas Robitaille, Douglas Finkbeiner, Edward F. Schlafly, and Gregory Green 2020, *Nature* (7 January 2020)

Alves et al. *Nature* paper & two distance catalog papers by Zucker et al. (2019, 2020) include several interactive figures (via plot.ly & bokeh), and deep links to data (on Dataverse) and code (on GitHub) inspired by AAS "Paper of the Future" (Goodman et al. 2015)

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

# “So What,” for Astronomers?

**demise of “Gould's Belt”**

*end to 100-year-old paradigm*

**“Local Arm" not shaped as we thought it was, locally**

arm is “straight" from top-down

**big wave in “arm” never previously observed**

wave’s origin unknown (collision? dark matter? accretion?)

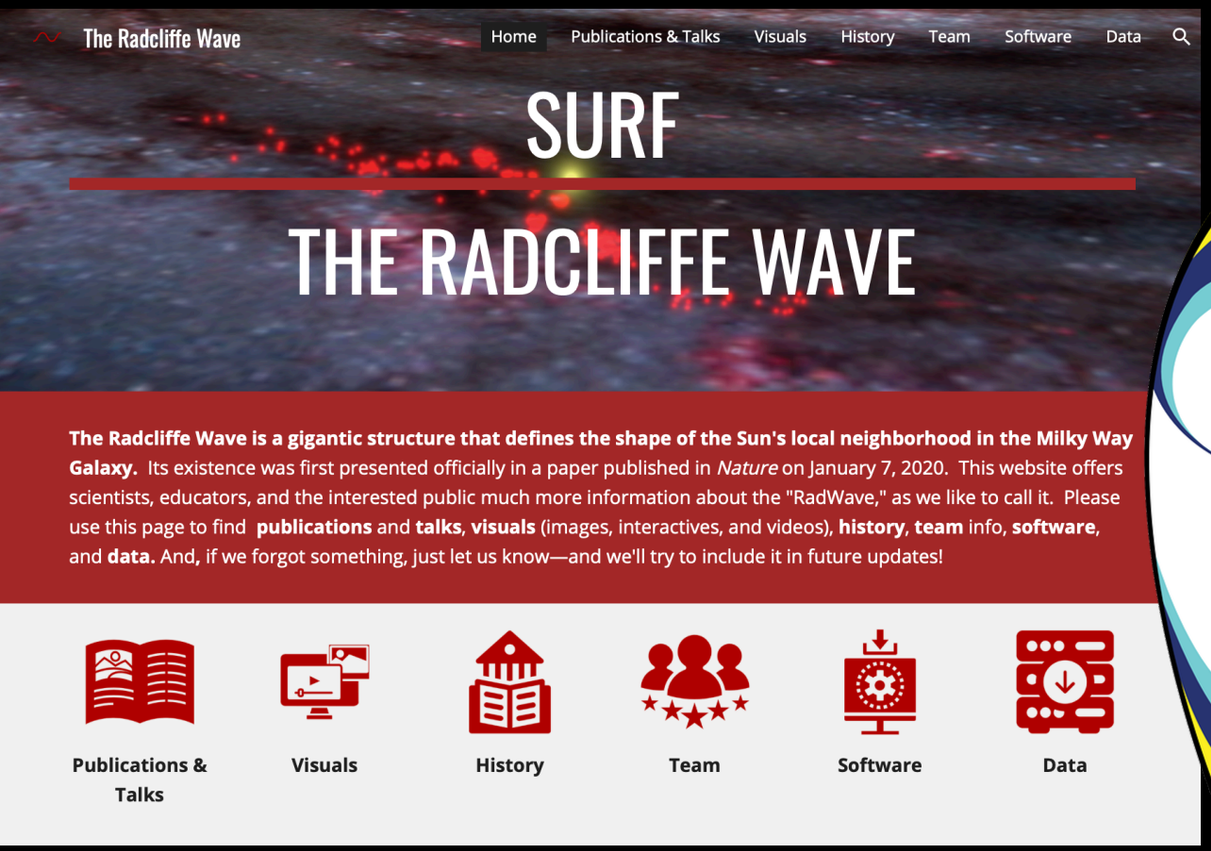
# Open Questions

What is the ORIGIN of the Radcliffe Wave? Collision?

Do other parts of the Milky Way show this wavy structure? How about other galaxies? How can we SEARCH?

What do “waves “ mean for the STAR-FORMING HISTORIES of galaxies?

# SURF the Radcliffe Wave



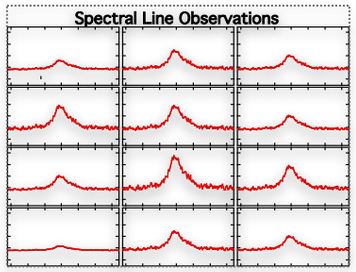

It appears that the Sun, on its galactic orbit, crossed the Radcliffe Wave 13 million years ago, and may cross it again in the future.

*video created by the authors using AAS WorldWide Telescope (includes cartoon Milky Way by Robert Hurt)*

Find slides, papers, videos, WWT Tours, and much more at:

tinyurl.com/RadWave

spiral galaxies

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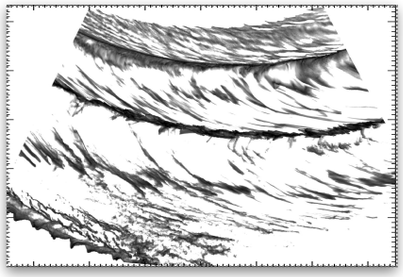

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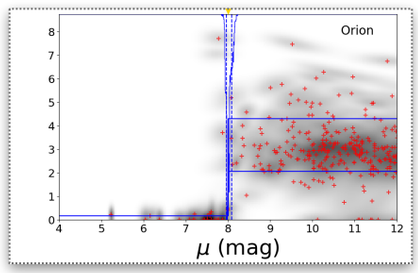


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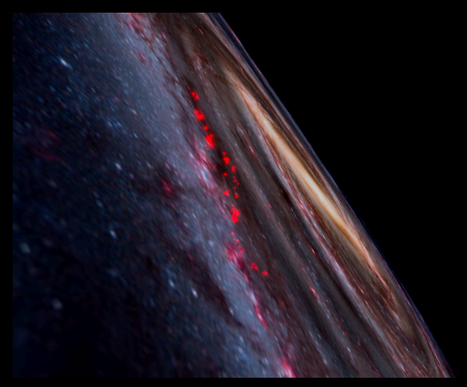

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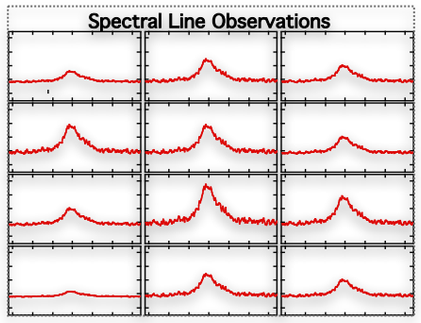
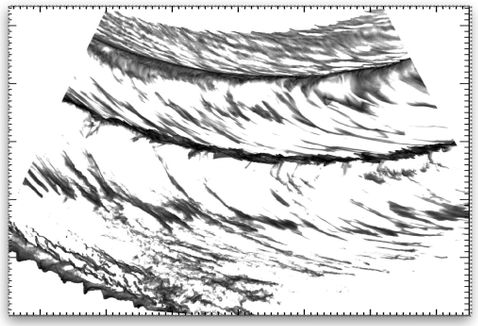
Merge Cube

# “Data”= 3D cubes, 2D images, 1D catalogs, from…

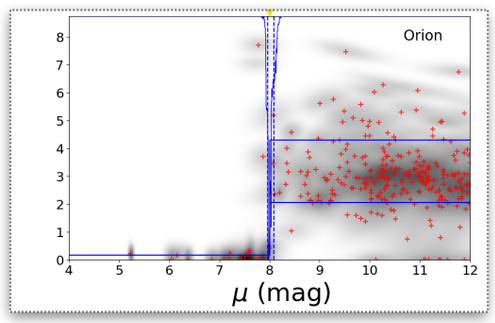



spectral-line mapping



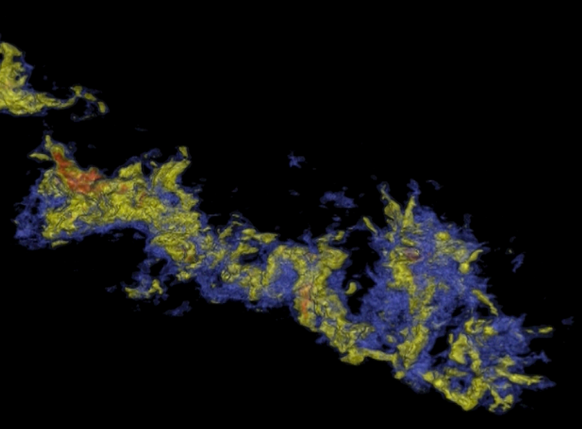
numerical simulation

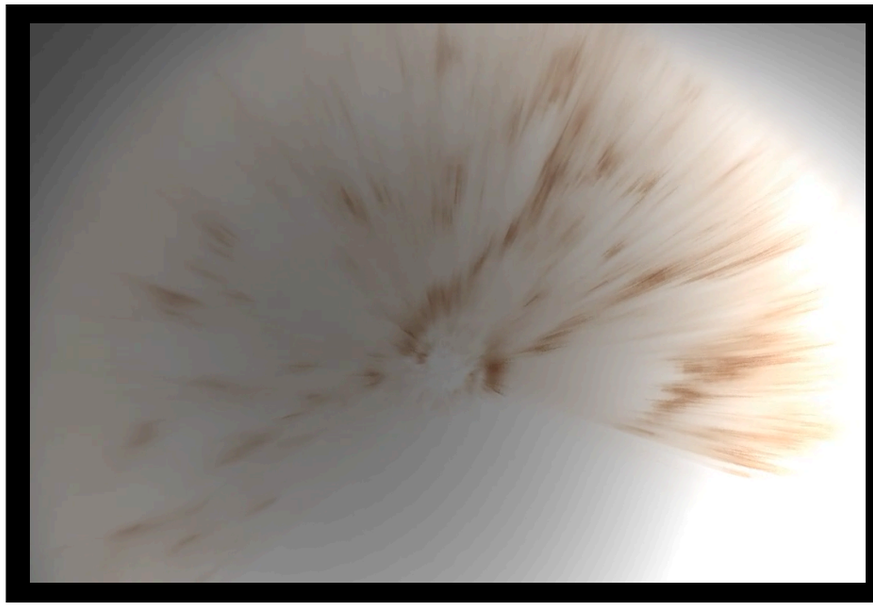
photometric imaging (over time)




statistical reconstruction

Gas in “3D"
*p-p-v*

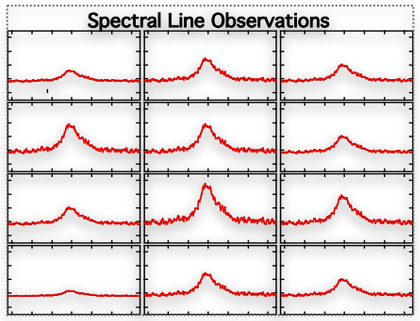




Dust in 3D
*p-p-p*

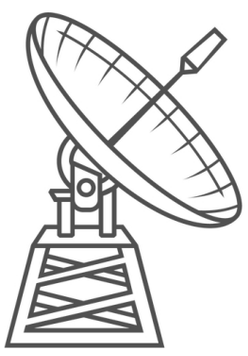
What about 4D??

(*p-p-p-*$v_z$)



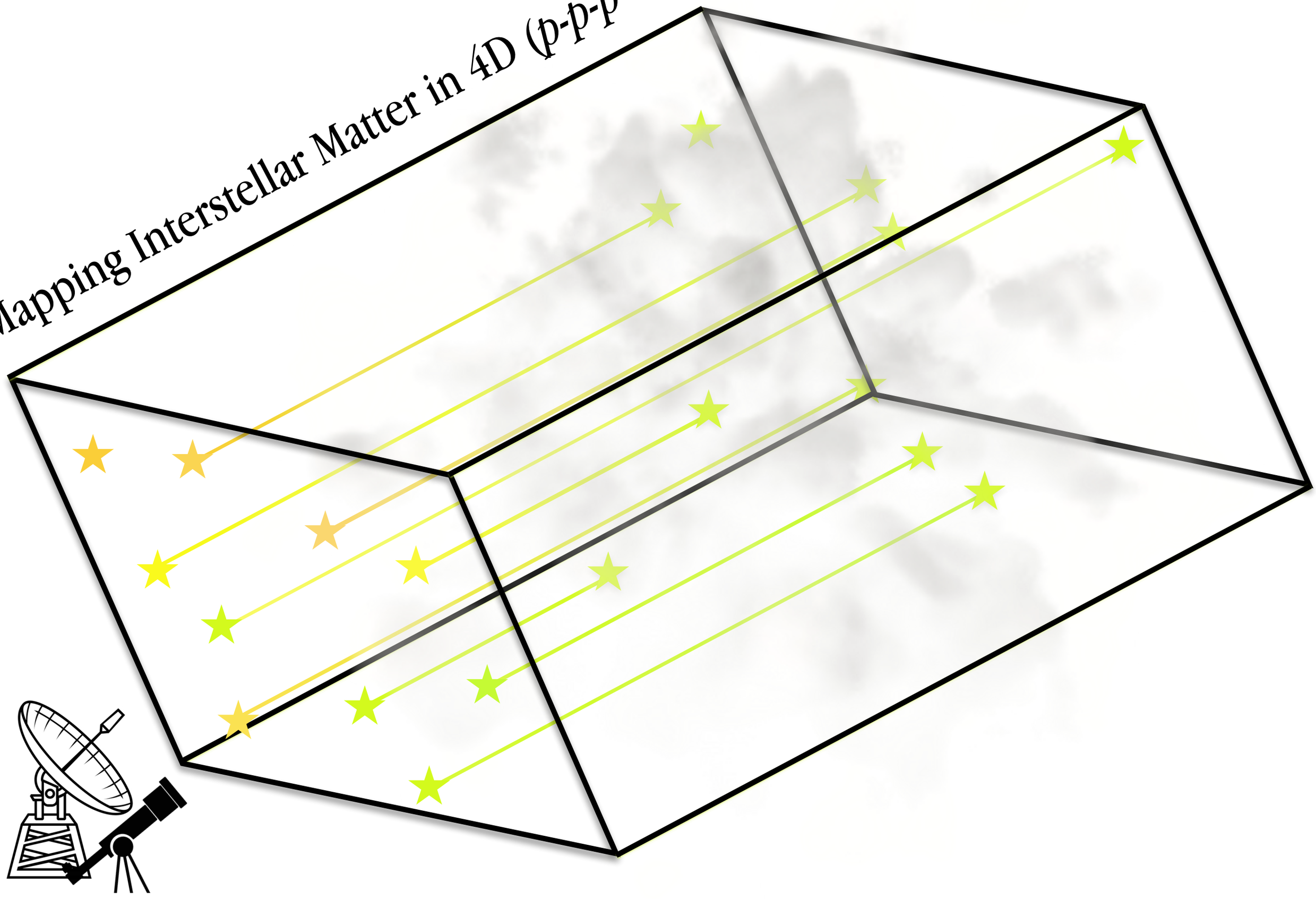

Mapping Interstellar Matter in *p-p-v*

# Spectral-Line Data Cubes give line-of-sight gas velocity



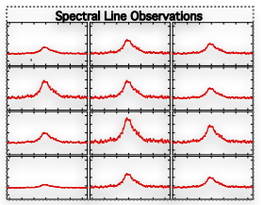
*WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)*

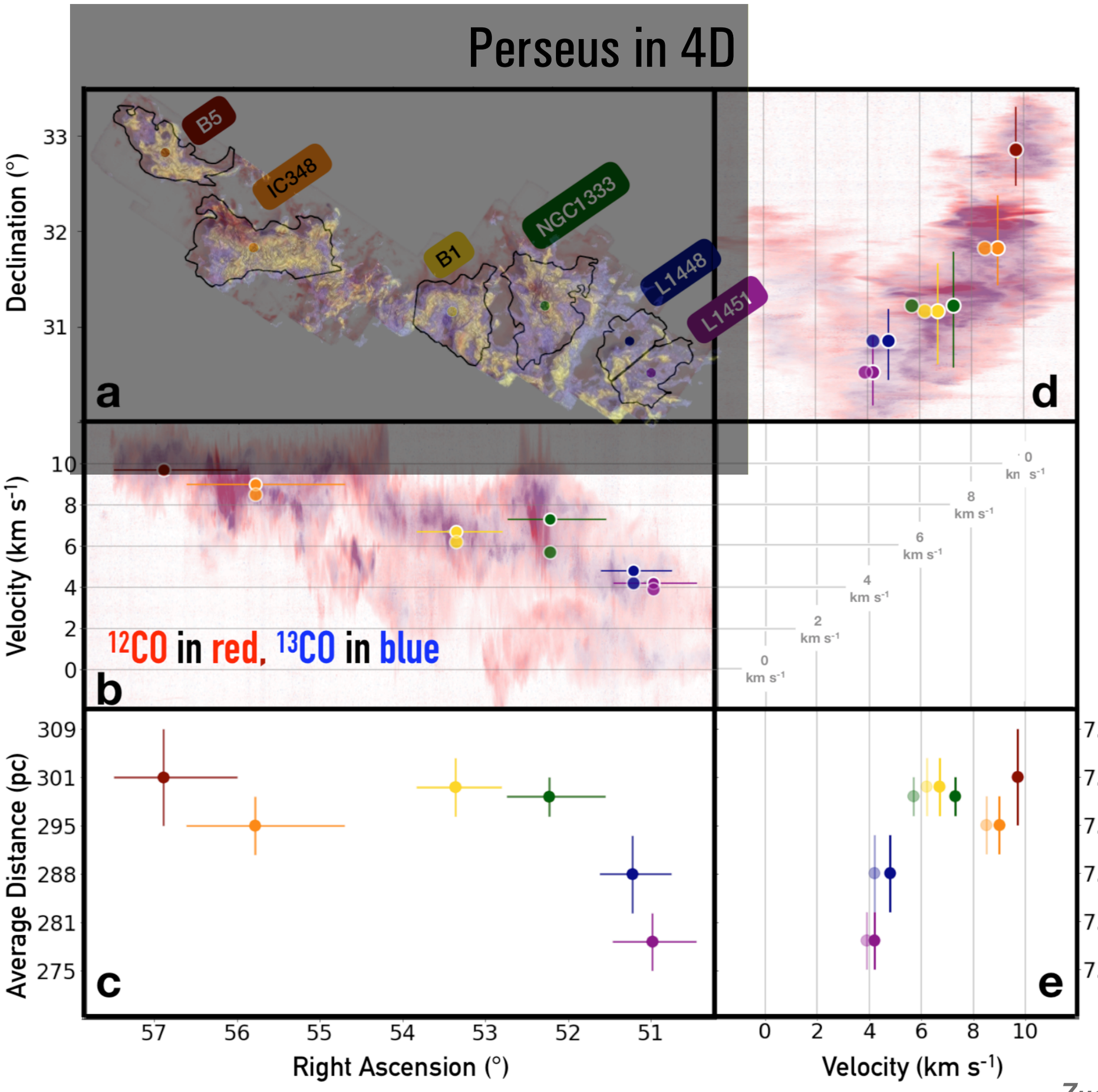
# Mapping Interstellar Matter in 4D ($p$-$p$-$p$-$v_z$)



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

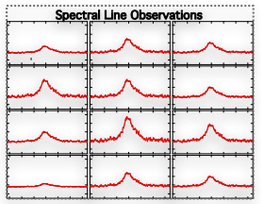
# Perseus in 4D

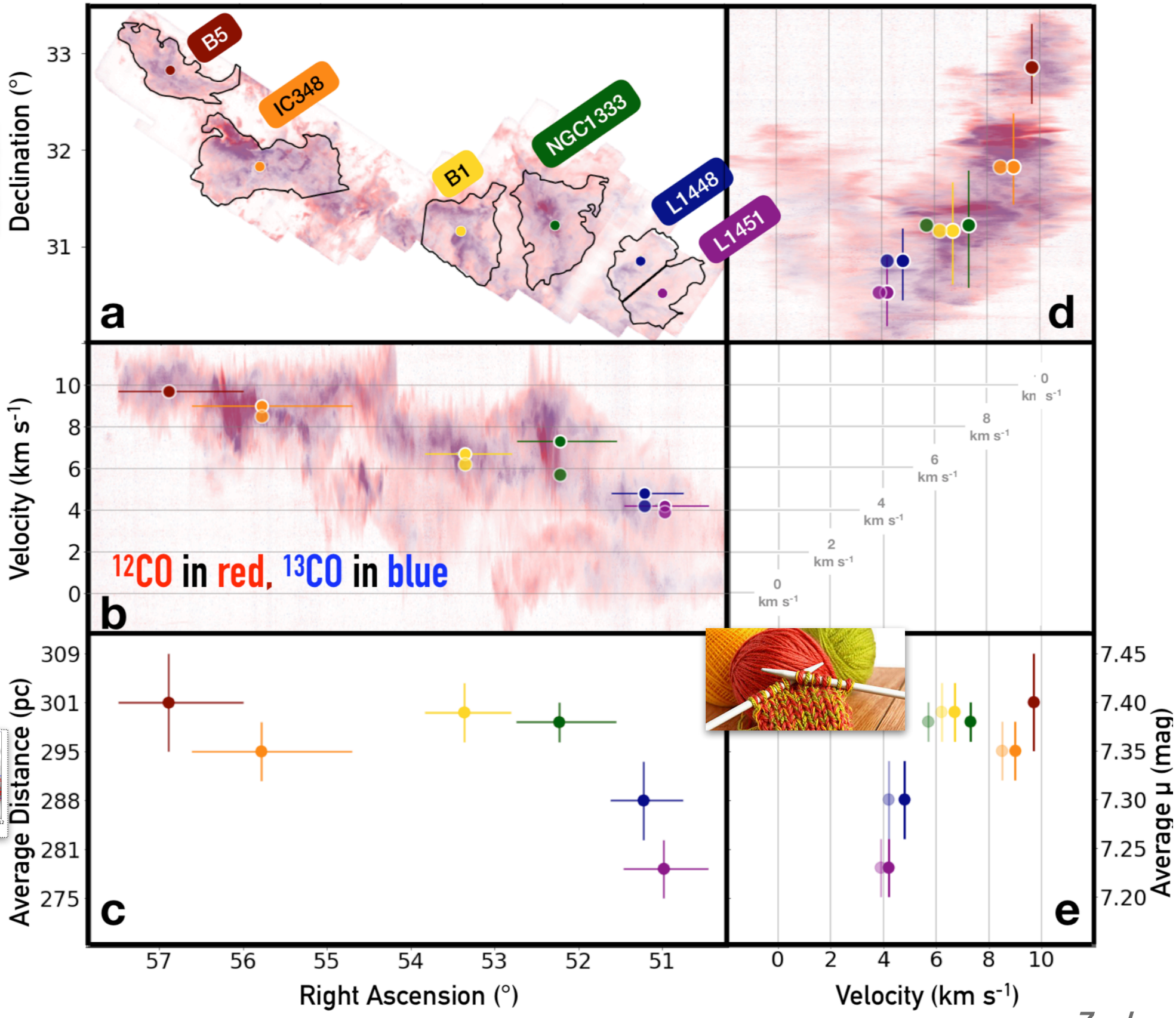


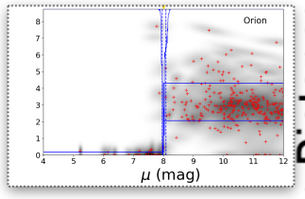




*Zucker et al. 2018*

# Perseus in 4D



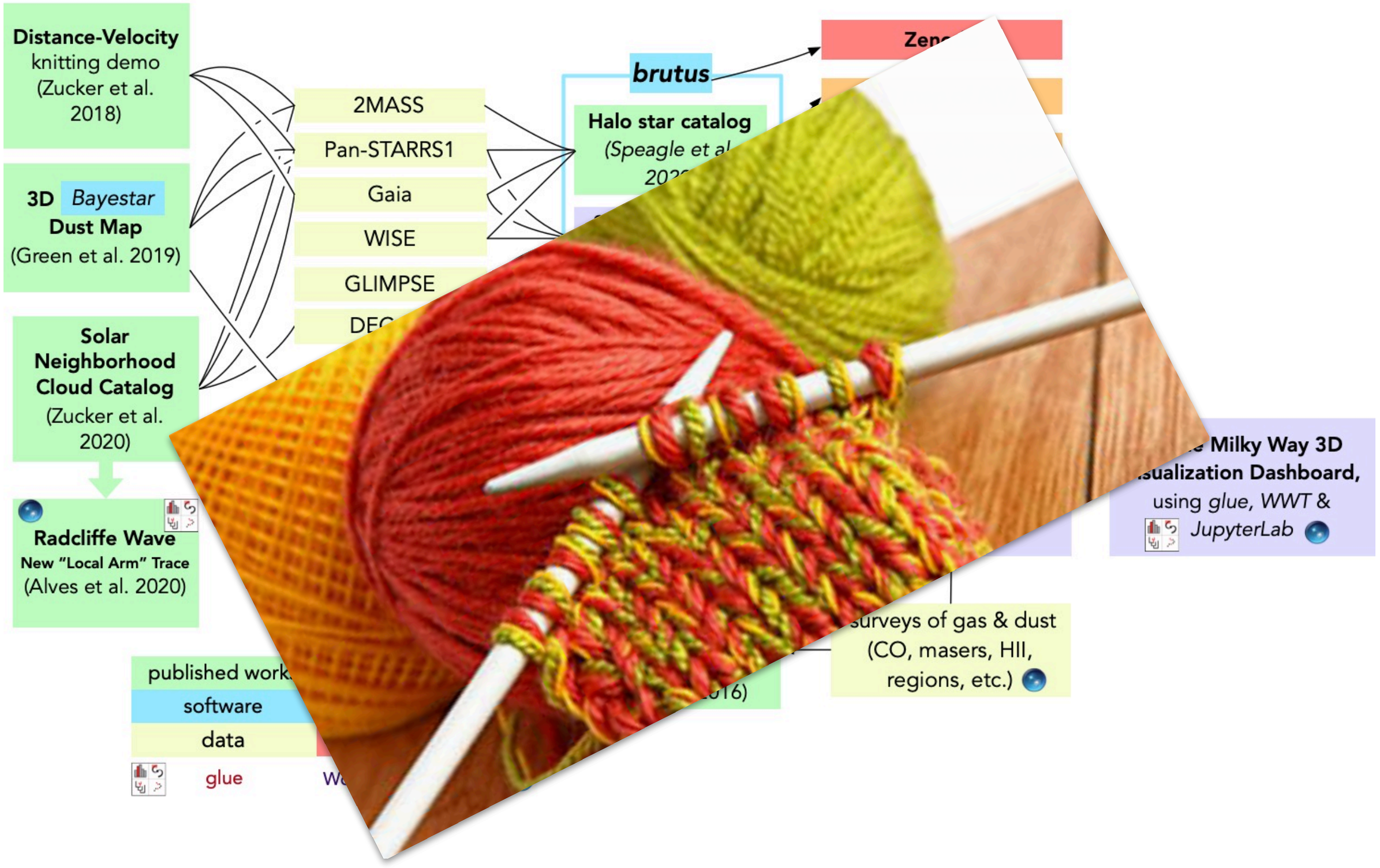






*Zucker et al. 2018*

# "Knitting" Together the Milky Way



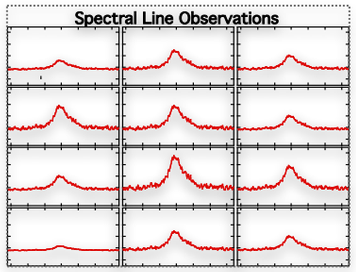

**Try tinyurl.com/milkywayknitting to examine and explore these knitting instructions on your own.**

(flow chart from 2020 NASA ADAP proposal by Zucker, Finkbeiner, Goodman, et al.)

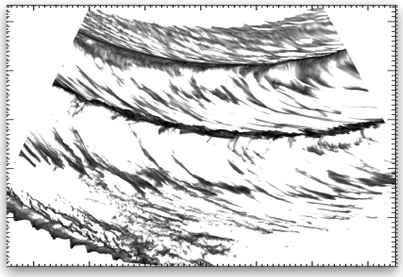
# All DATA soon!

**drawn by Dr. Robert Hurt, in collaboration with Milky Way experts based on data; as shown in screenshot from AAS WorldWide Telescope*

spiral galaxies

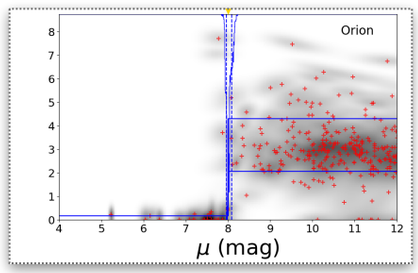



spectral-line mapping

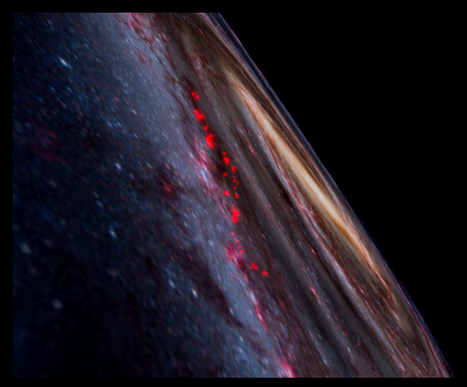


numerical simulation

photometric imaging (over time)




statistical reconstruction



The Radcliffe Wave

Knitting

ngvla

Next Generation VLA

Merge Cube

# Knitting Together an Amazing new Multi-Color View of the Milky Way, in 3D

Alyssa A. Goodman
Center for Astrophysics | Harvard & Smithsonian
and Radcliffe Institute for Advanced Study

photo credit: Tom Dame