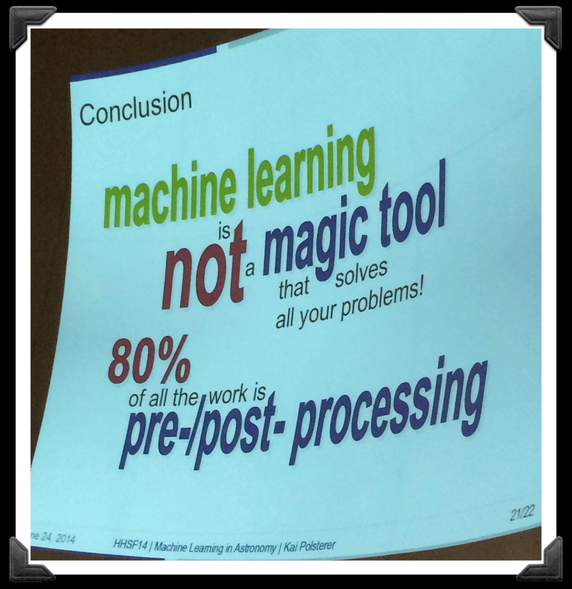
A decade of HHSF 2014-2024, and what's next?

Alyssa Goodman, Harvard

2014

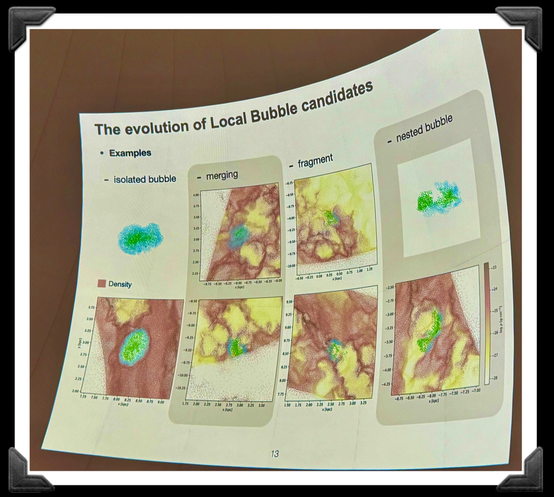
we ❤ filaments

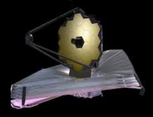


2020

2022

2024

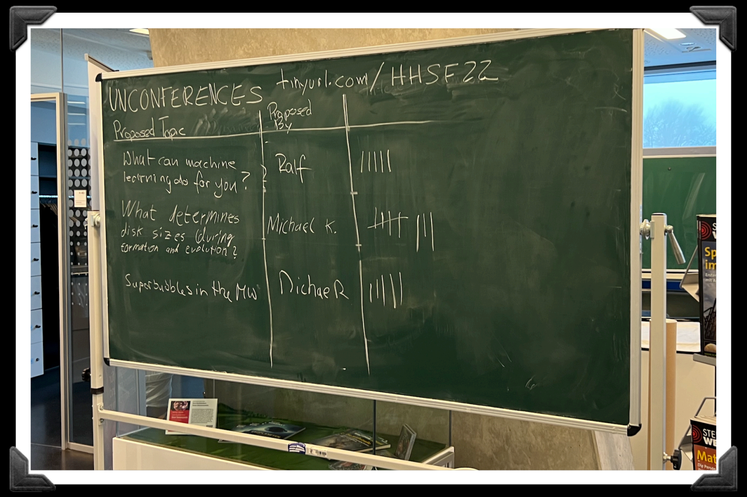


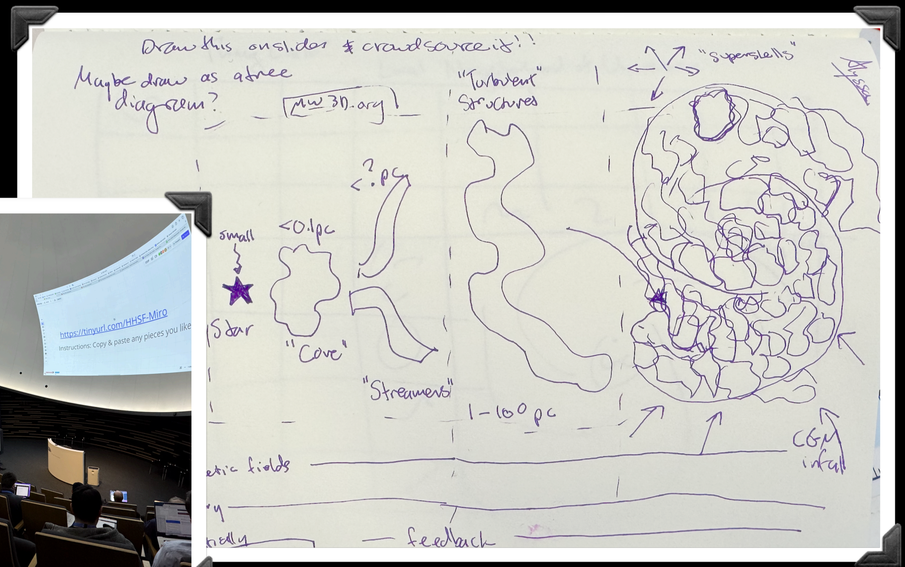


connecting to larger scales

we ❤ bubbles & JWST!

“Everything everywhere all at once?…”





"Everything, Everywhere, All at Once"

from Henrik Beuther in the survey…

>Gyr

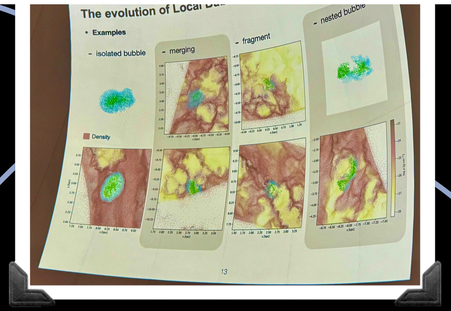
galaxies form

~10 Myr

clouds form

Cut & Paste an Abstract here (optional, see below)

This is not about an individual finding but about the generally derived picture that the entire star formation process is extremely dynamic and gas flows over all scales, from large molecular clouds via filamentary structures to cores, disks and finally the protostars. And then again back via feedback processes like outflows, radiation, HII regions, Supernovae and all kind of bubbles back to the ISM where via converging gas flows new clouds can form.



born & move

galaxies accrete/merge
evolve/change shape

~100 Myr

clouds merge/evolve/
change shape/disappear

~10 to 100 Myr

bubbles
overlap/merge
disappear

~10s of Myr

stars blow
stuff out

~1 to >100 Myr

"Everything, Everywhere, All at Once"

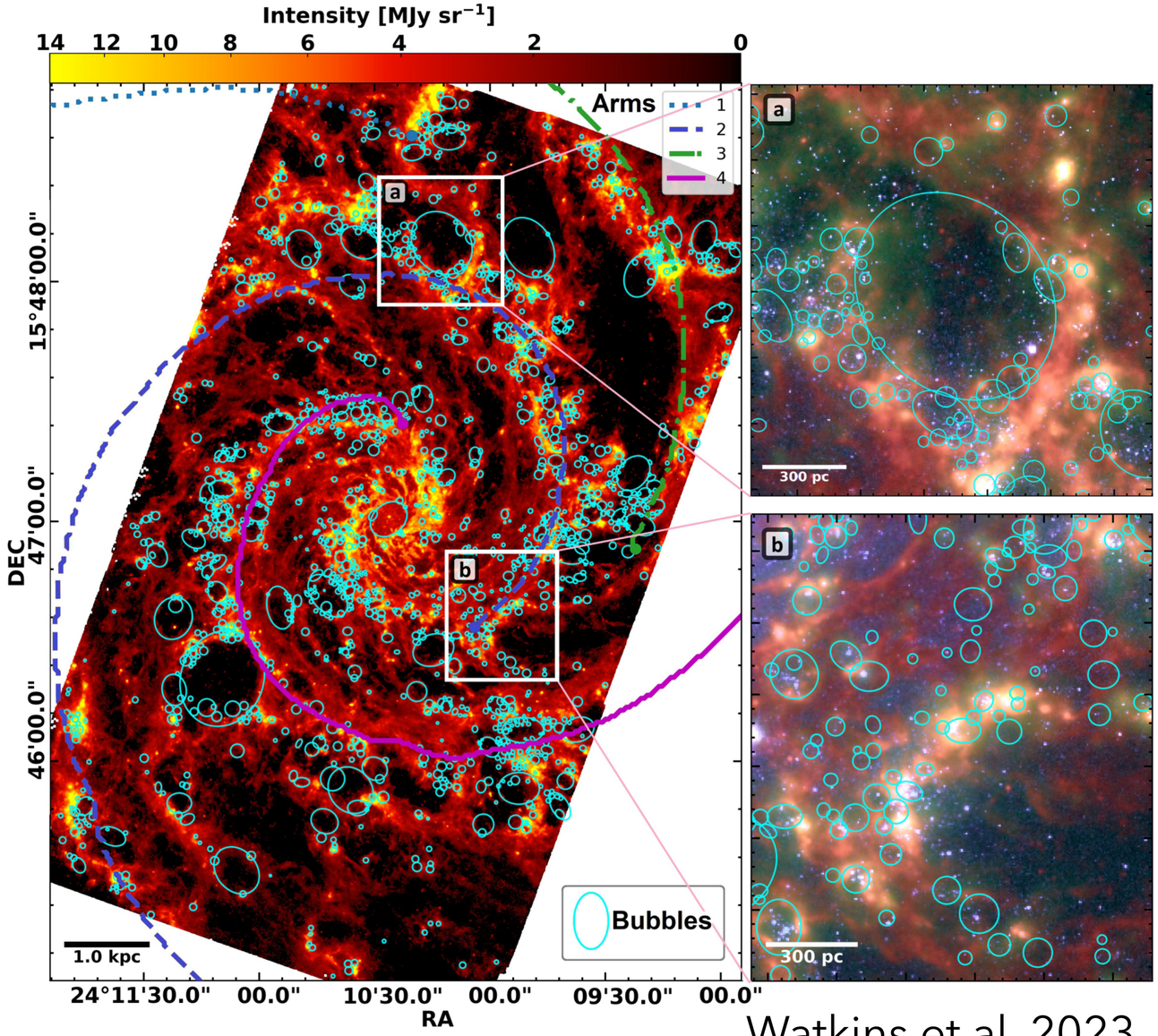
MOVIE

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.

tinyurl.com/HHSF24-survey-results

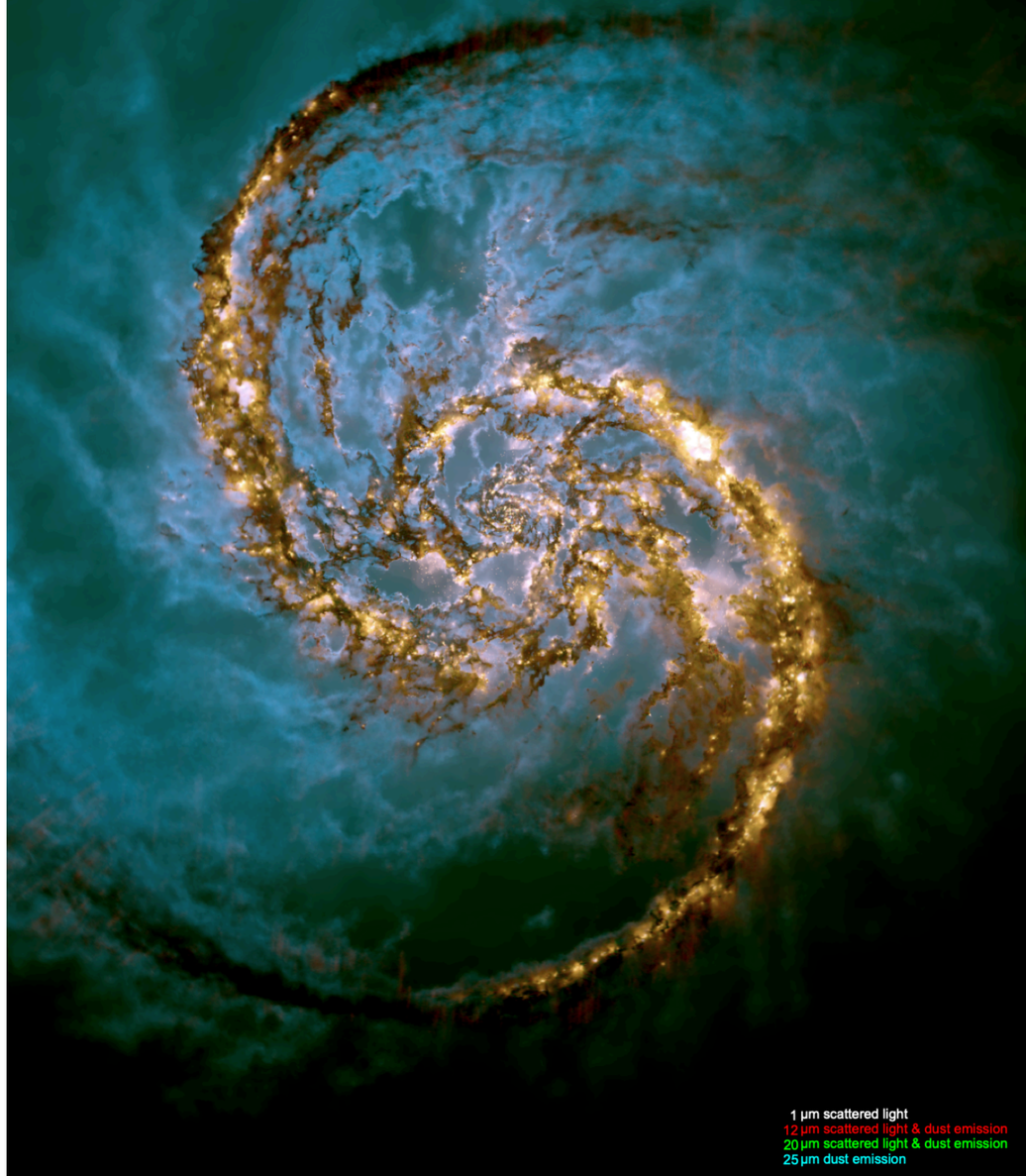
NGC 628 from JWST



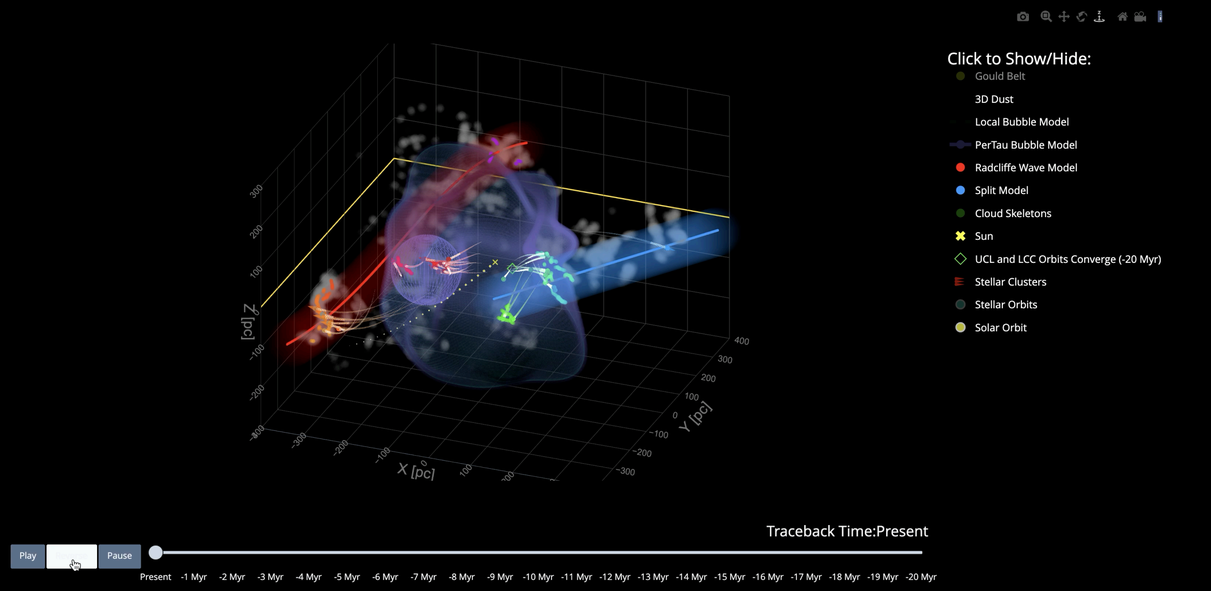
Watkins et al. 2023

The Whirlpool-Galaxy M51
modelled on a Computer

Stefan Reißl & Robin Treß

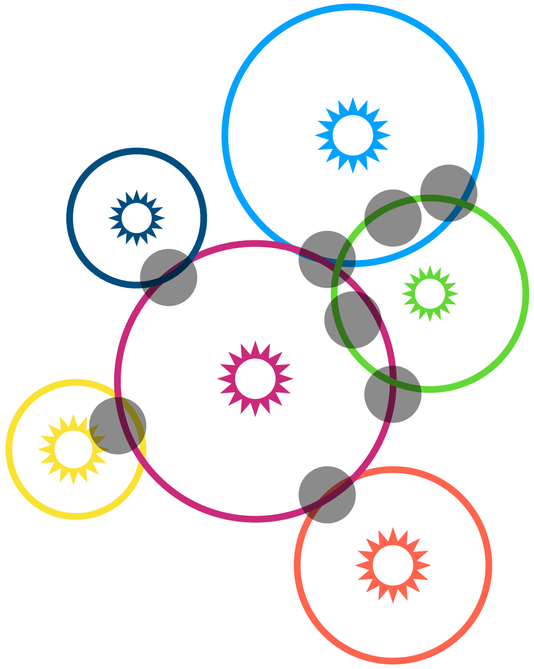


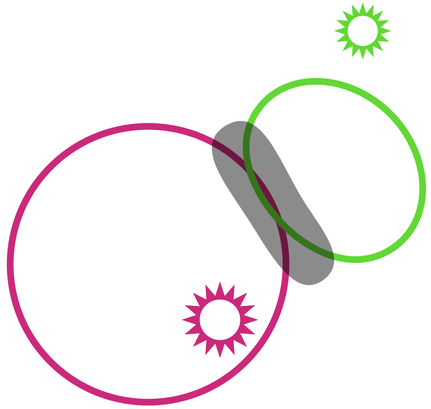
Do filament “collisions” cause bubbles?

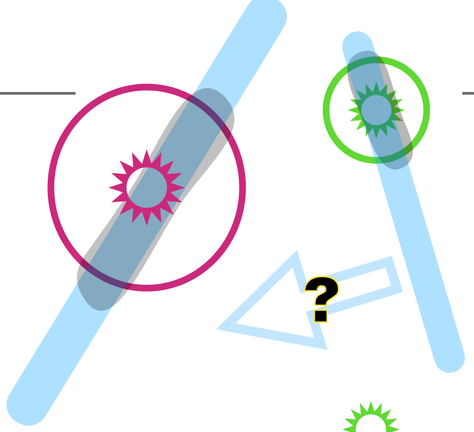


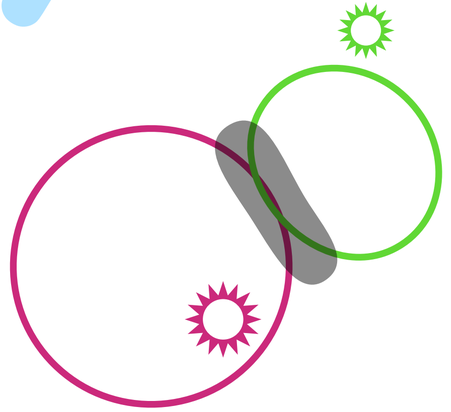
https://faun.rc.fas.harvard.edu/czucker/Interactive_Figure3_Alyssa.html,
based on Zucker et al. 2022

Thought Experiments on the Relationship between Feedback and Dense Star-Forming Gas









Panel 1: Idealized situation (unrealistic).
All cavities are circles. Progenitor star or cluster centered and still present, and all feedback events were roughly simultaneous, and of only slightly different energy. "Spherical" dense clouds form at bubble overlaps.

Panel 2: Slightly less idealized situation, shown for just two cavities, for simplicity.
Cavities distorted by asymmetries, especially in ambient medium, some progenitor stars or clusters can still be identified, and the two feedback events are assumed have overlapped in time enough to form dense, non-spherical, clouds at bubble overlaps.

Panel 3: Imagining the past and dense clouds' origins. When one considers the origins of feedback progenitors' dense-cloud homes, things get complicated, due to the limited lifetimes of large star-forming clouds, and, in more realistic scenarios than drawn, mixing of structures with each other over time.

Notes: This is a 2-D cartoon of a 3D process. In all panels, circles or ellipses represent *expanding* cavities of low-density, caused by feedback events, typically explosions of one or more supernovae, originating in a stellar cluster represented by a ☼ symbol. Semi-transparent shapes are meant to represent highly-idealized "molecular clouds" or pieces of larger-scale Galactic structures.

HHSF24 Participants' Favorite Findings and Codes, 2014-2024

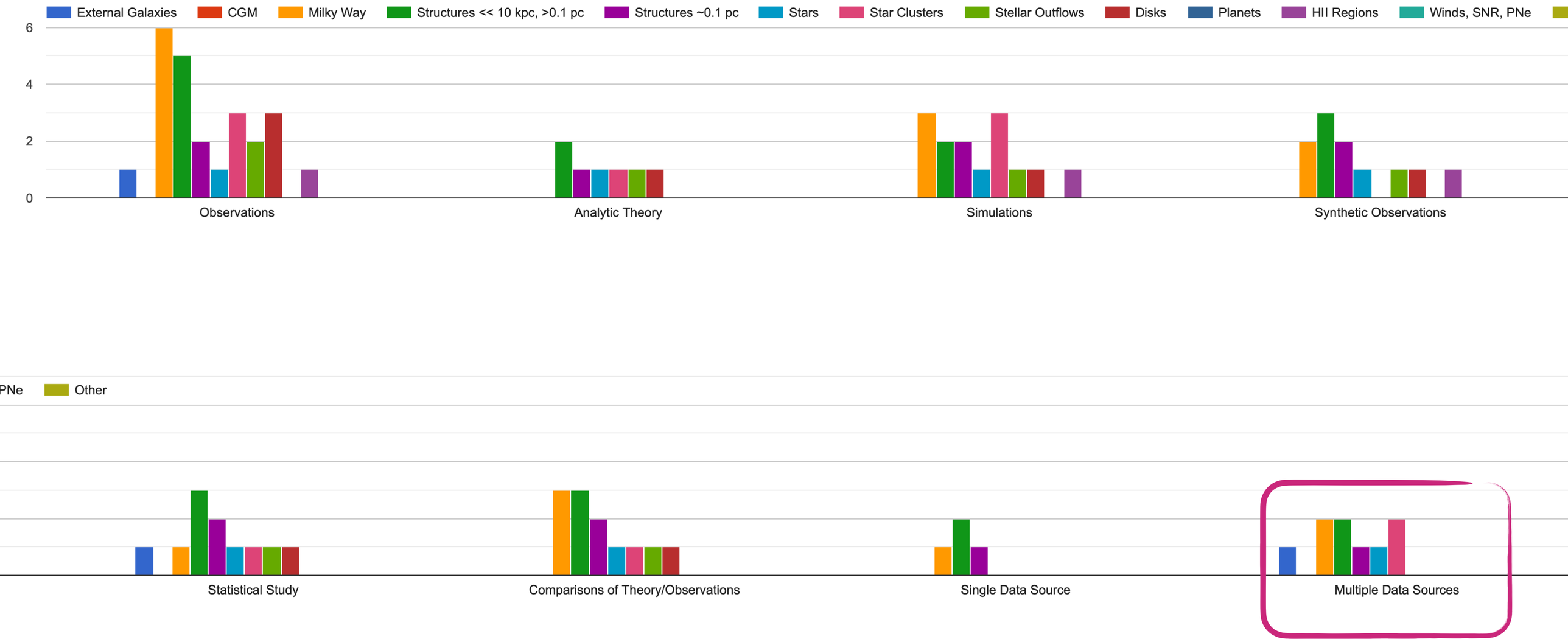
Use this form at least **once**, and up to five times, to let everyone know about your favorite **finding** or useful **code** from the time period 2014-2024.

- A "**finding**" can be based on observations, simulations, or statistical or analytic calculations.
- A "**code**" refers to any kind of new or improved software, web technology, or tool, e.g. for simulation, segmentation, data analysis, data visualization, data hosting, AI, etc.

It is fine to submit work in which you were involved--but that is not required, especially if you make multiple entires.

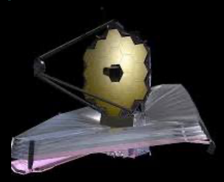
tinyurl.com/HHSF24-survey-results

Part 1: Theory, Observation, Stats



tinyurl.com/HHSF24-survey-results

JWST image of Fomalhaut [Gaspar 2023 @25.5um] -- multi-eccentric ring disk. Relic of protoplanetary disk or planet-driven asymmetries?



JWST image of HH211

Filament/superbubble structure in surveys, JWST observations, and in galactic multiscale simulations

bubbles, bubbles in JWST images of nearby galaxies

Most nearby young star clusters formed in three massive complexes

Discovery of the Radcliffe Wave

cluster census with Gaia

bubbles, the Local Bubble

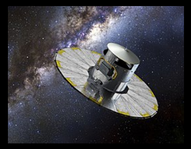


Image matching with astroHOG

Cosmic rays in Arepo

glue

POLARIS

Torch framework for hybrid MHD and N-body simulations

FilFinder

ALMA image of star-forming regions

Kinematic Planetary Signatures (KPS or Kinks)

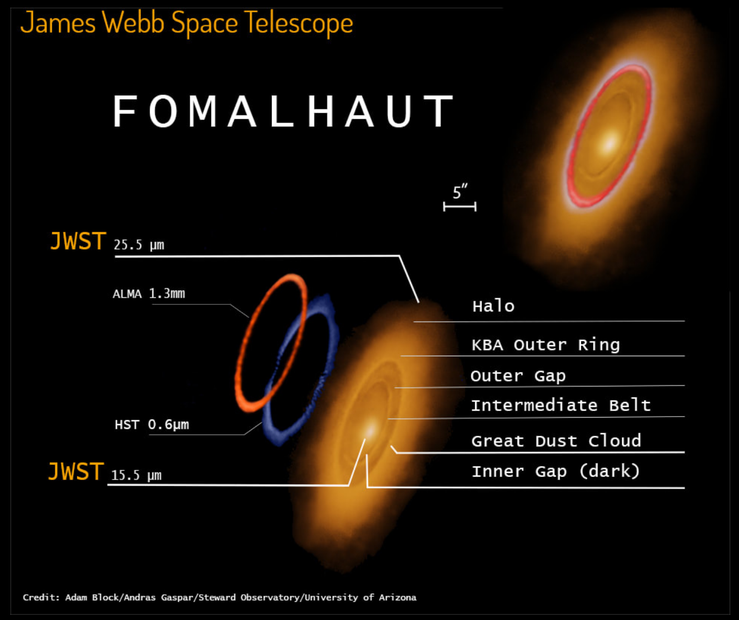
SMA & Pan-STARRS image of IRAS23077+6707

Everything flows

The archaeological record of the Milky Way written in neutral atomic hydrogen (HI)

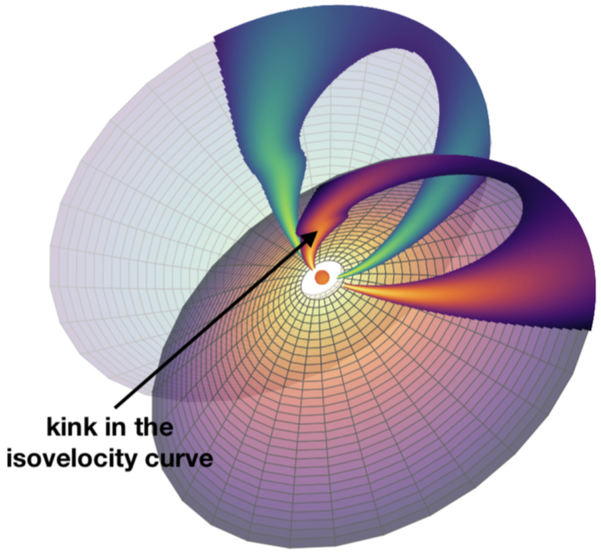
tinyurl.com/HHSF24-survey-results

JWST image of Fomalhaut -- multi-eccentric ring disk.
Relic of protoplanetary disk or planet-driven asymmetries?



cf. Gaspar 2023 @25.5um

Kinematic Planetary Signatures (KPS or Kinks)



Pinte et al 2023

SMA & Pan-STARRS image of IRAS23077+6707

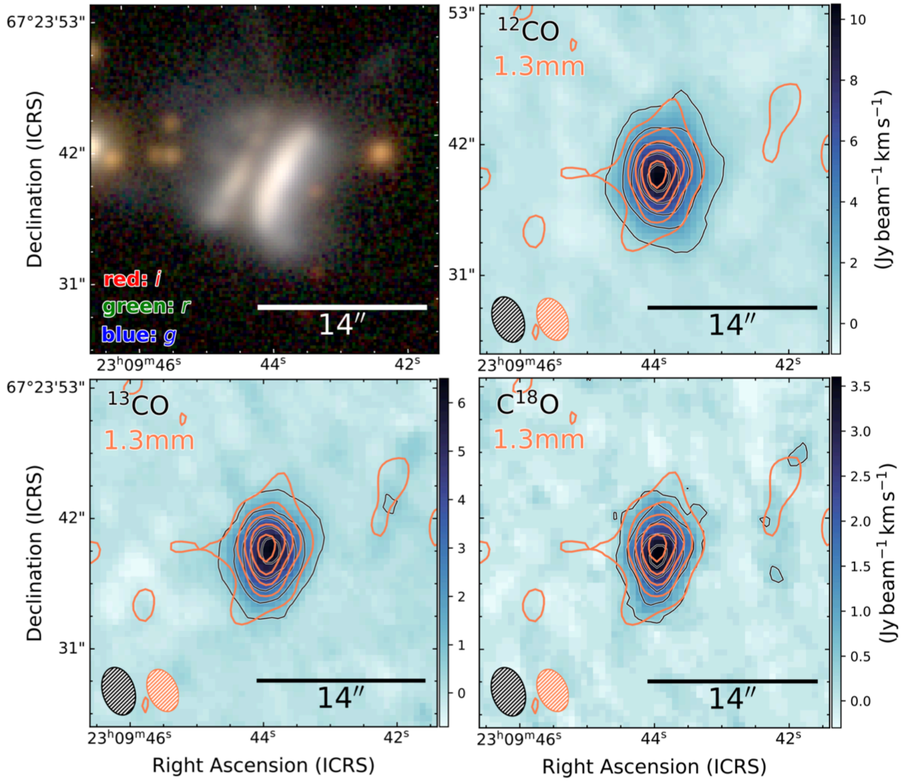
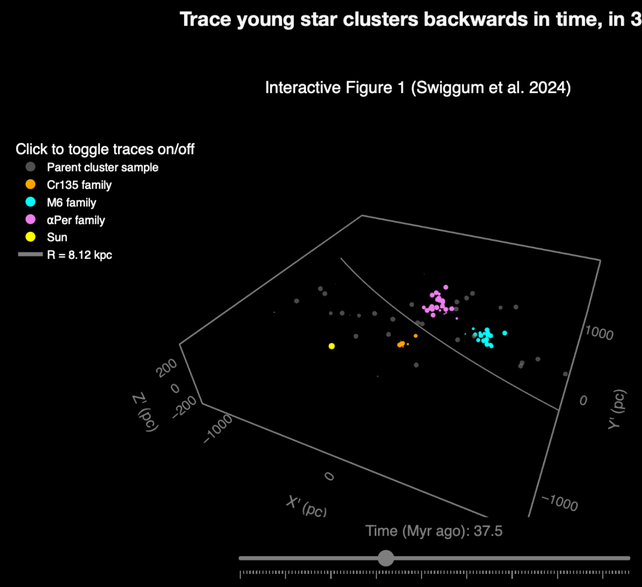


Figure 1. Comparison of optical scattered light and (sub-)mm emission of IRAS 23077+6707. *Top left*: PS1 *irg*-composi image, showing the optical scattered light emission at $\lambda_{\rm mean}$ = 7545, 6215 and 4866 Å, respectively. *Top right*: SMA ^{12}C integrated intensity (or 'moment 0') map, overlaid with its respective contours, as well as the 1.3 mm continuum contours, draw at the 10 %, 30 %, 50 %, 70 % and 90 % levels of their corresponding maximum emission. *Bottom left*: Same for ^{13}CO. *Botto right*: Same for C^{18}O. In the lower right of each panel, we show 14″ scale bars, and the effective CO (black) and continuu (orange) beams in the lower left of the SMA image.

Monsch et al. 2024

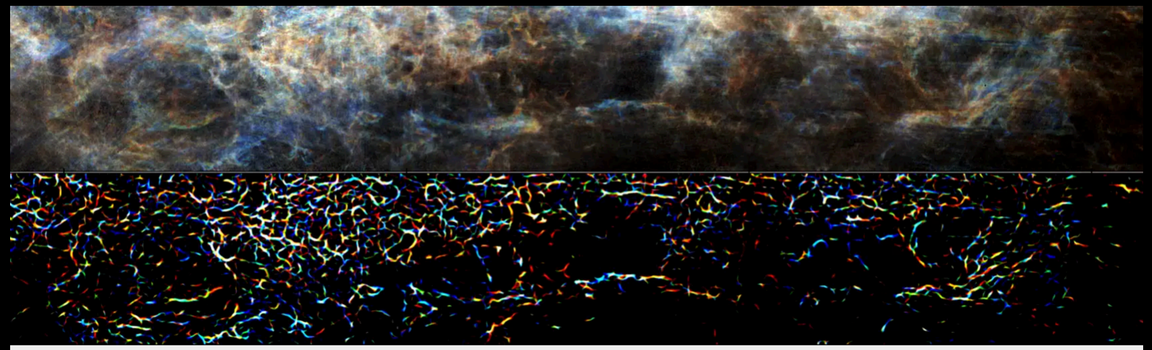
tinyurl.com/HHSF24-survey-results

Most nearby young star clusters formed in three massive complexes



Swiggum et al. 2024

The archaeological record of the Milky Way written in neutral atomic hydrogen (HI)



Atomic hydrogen emission from an excerpt from the THOR survey (top) and associated filamentary structures around the… [more]
Image: J. Soler et al. 2020

Soler et al. 2020

Next...

MILKYWAY3D.org

SCAN ME

INFRASTRUCTURE ⟷ SCIENCE ⟷ EDUCATION & OUTREACH

INFRASTRUCTURE

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

glue

AMERICAN ASTRONOMICAL SOCIETY WORLDWIDE TELESCOPE — OpenSpace

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

MAST Barbara A. Mikulski Archive for Space Telescopes — The Dataverse Project — DIGITAL universe

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

EDUCATION & OUTREACH

connecting real research data,
software, and science to learners

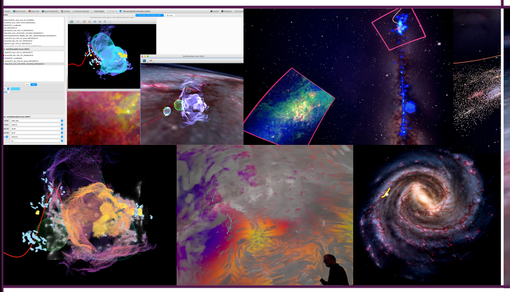
OpenSpace

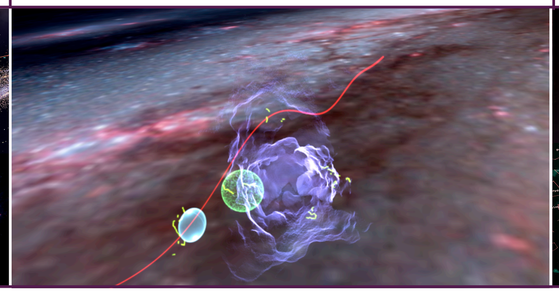
real-time data exploration
anywhere, including in planetaria

CosmicDS

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

Lead: Jackie Faherty, AMNH





TEAM: Harvard/Smithsonian CfA (Jonathan Carifio, Alyssa Goodman, Ralf Konietzka, Theo O'Neill, Patricia Udomprasert, Catherine Zucker), **AMNH** (Brian Abbott, Micah Acinapura, Carter Emmart, Jackie Faherty); **Linkoping 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 get a T-Shirt.

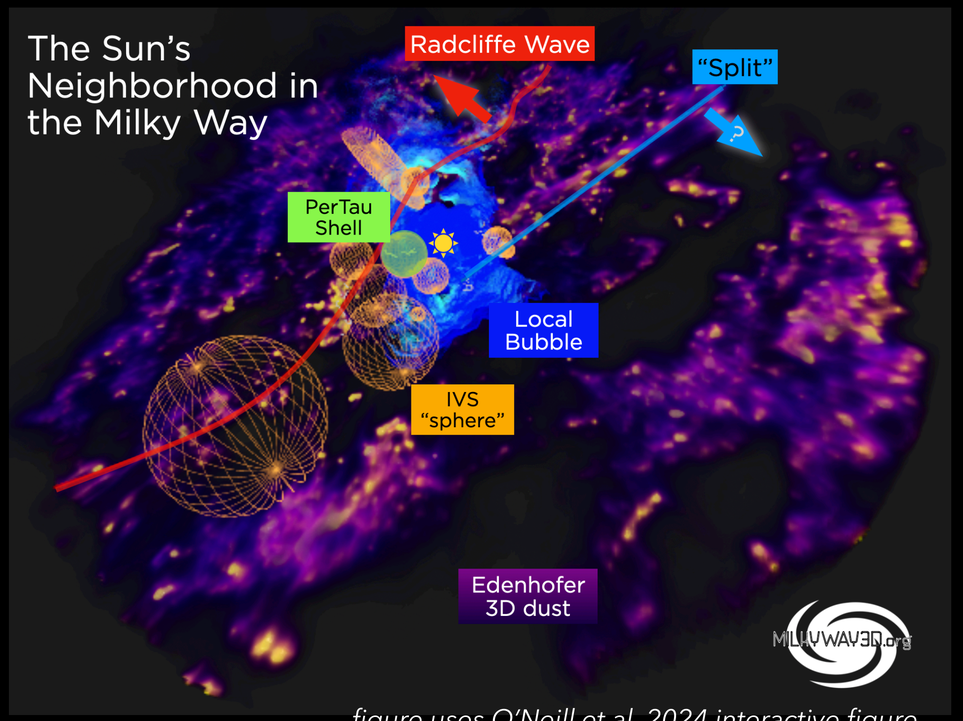
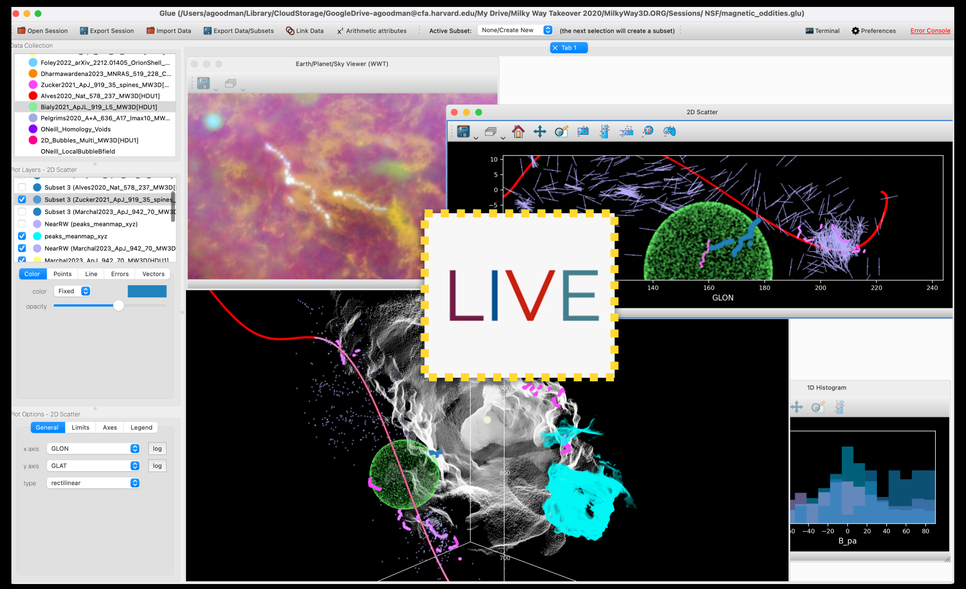
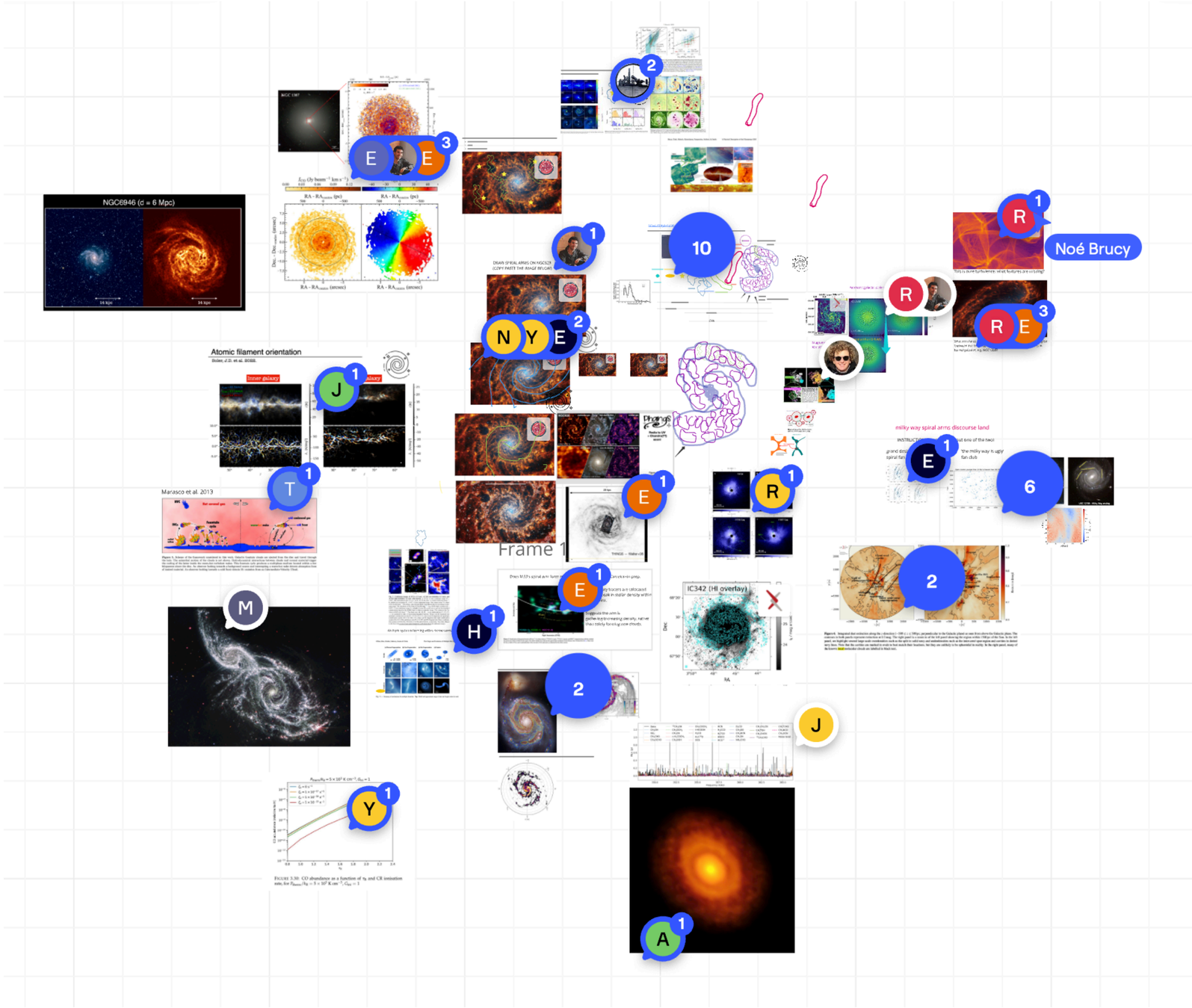


figure uses O'Neill et al. 2024 interactive figure



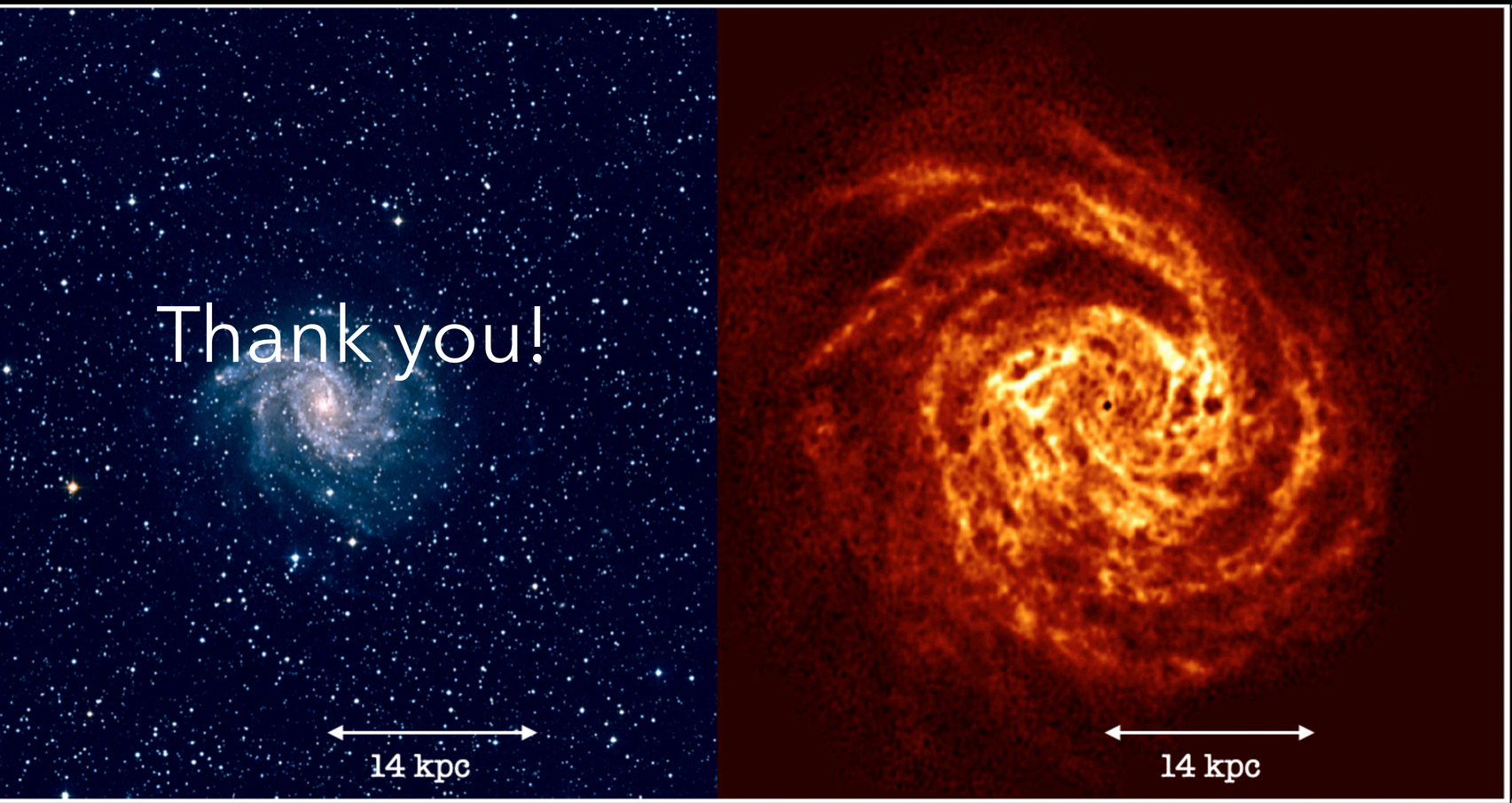
Thank you!

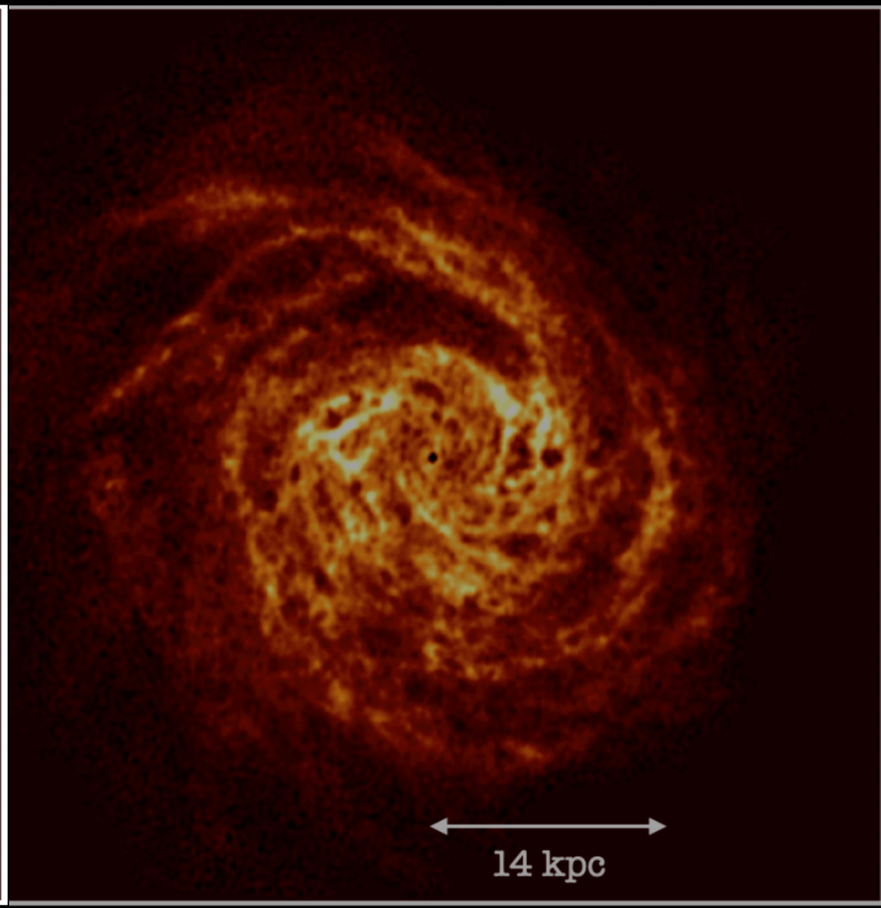
tinyurl.com/HHSF-Miro



NGC6946 (d = 6 Mpc)

= 6 Mpc)

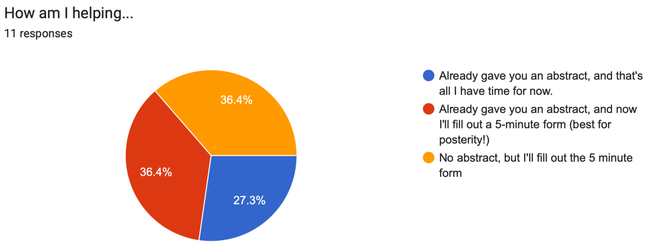




Thank you!

SOC & LOC

Henrik Beuther (chair!!!)
Catharina Fairchild
Annie Gao
Philipp Girichidis
Christelle Hiemstra
Ralf Klessen
Eric Koch
Shanghuo Li
Theo O'Neill
Simon Reyes
Molly Wells
Daniel Ziegler

and to
Thomas Henning
who really
"invented" HHSF!

and to **YOU**