

# PHANGS-JWST

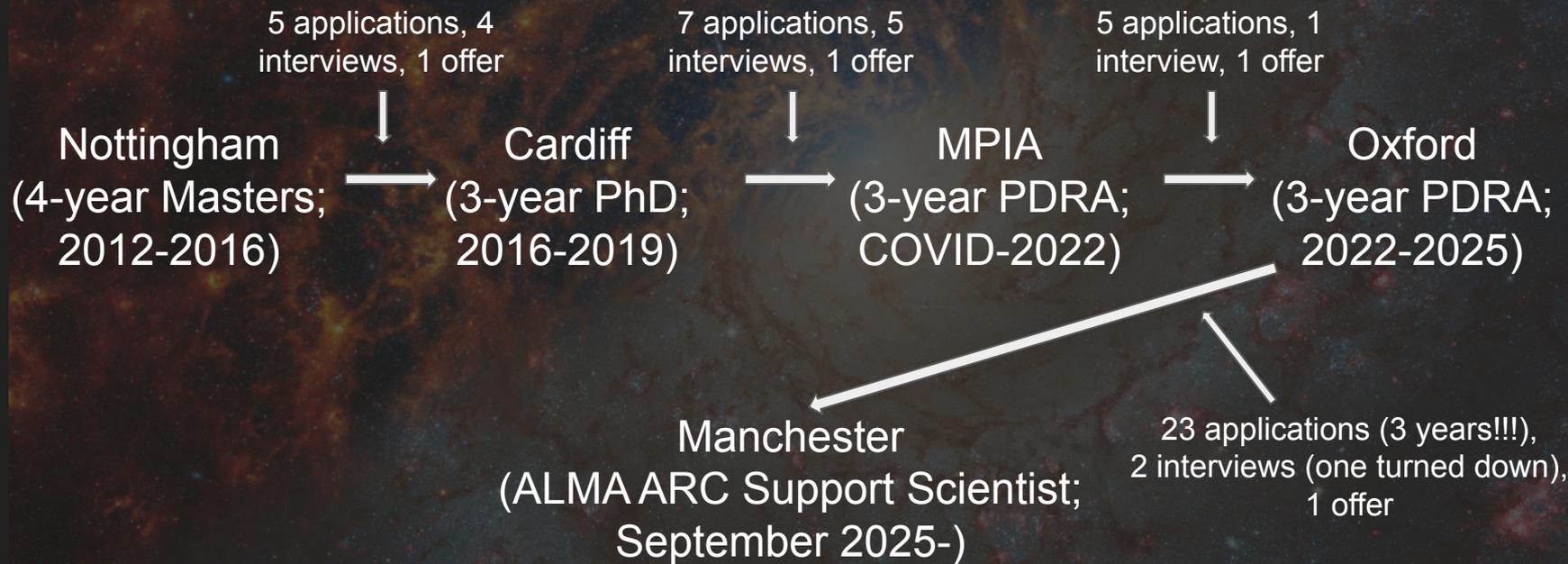
Thomas Williams

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# Outline

- A little bit about me
- Why study nearby galaxies?
- The power of using JWST to observe nearby galaxies
- Introduction to PHANGS
- Overview of (some) recent PHANGS results

# About me



# About me

- I care about how

☆☆☆☆gas turns into stars☆☆☆☆

- I use data from a lot of telescopes across the electromagnetic spectrum
  - e.g. ALMA, MUSE, JWST, JCMT, Arecibo (RIP), VLA, IRAM, SDSS, WISE
- How much do local environment (e.g. spiral arms) and global galaxy properties (e.g. Hubble type) actually matter for the star formation process?

VAR!

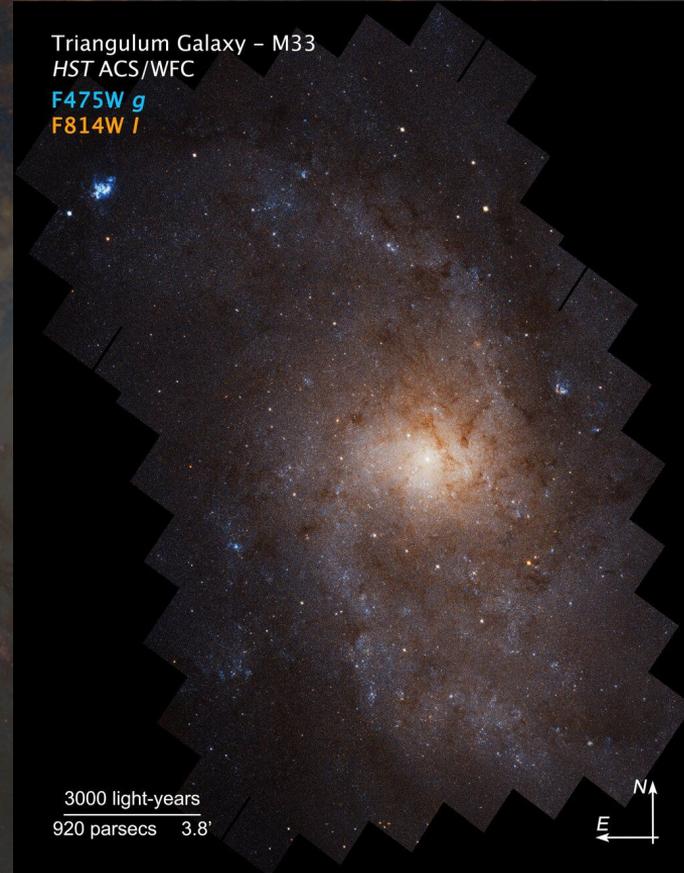
6-Oct  
1913

is done, the resulting values of  $M - m$  are  $-21.8$  and  $-21.9$  for M 31 and M 33 respectively. These must be corrected by half the average ranges of the Cepheids in the two spirals, and the final values are then on the order of  $-22.3$  for both nebulae. The corresponding distance is about 285,000 parsecs\*. The greatest uncertainty is probably in the zero-point of Shapley's curve.

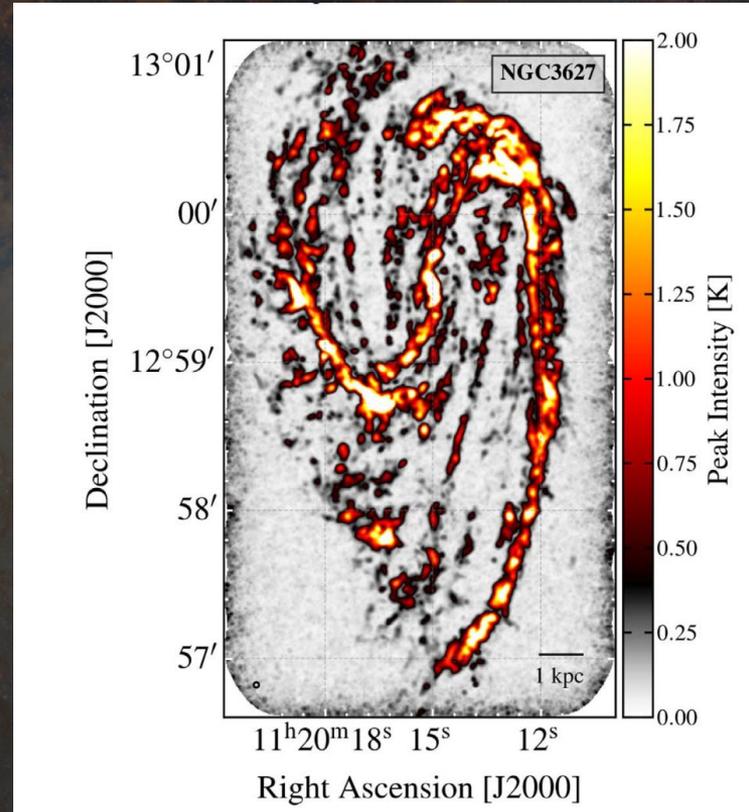


# What makes nearby galaxies so special?

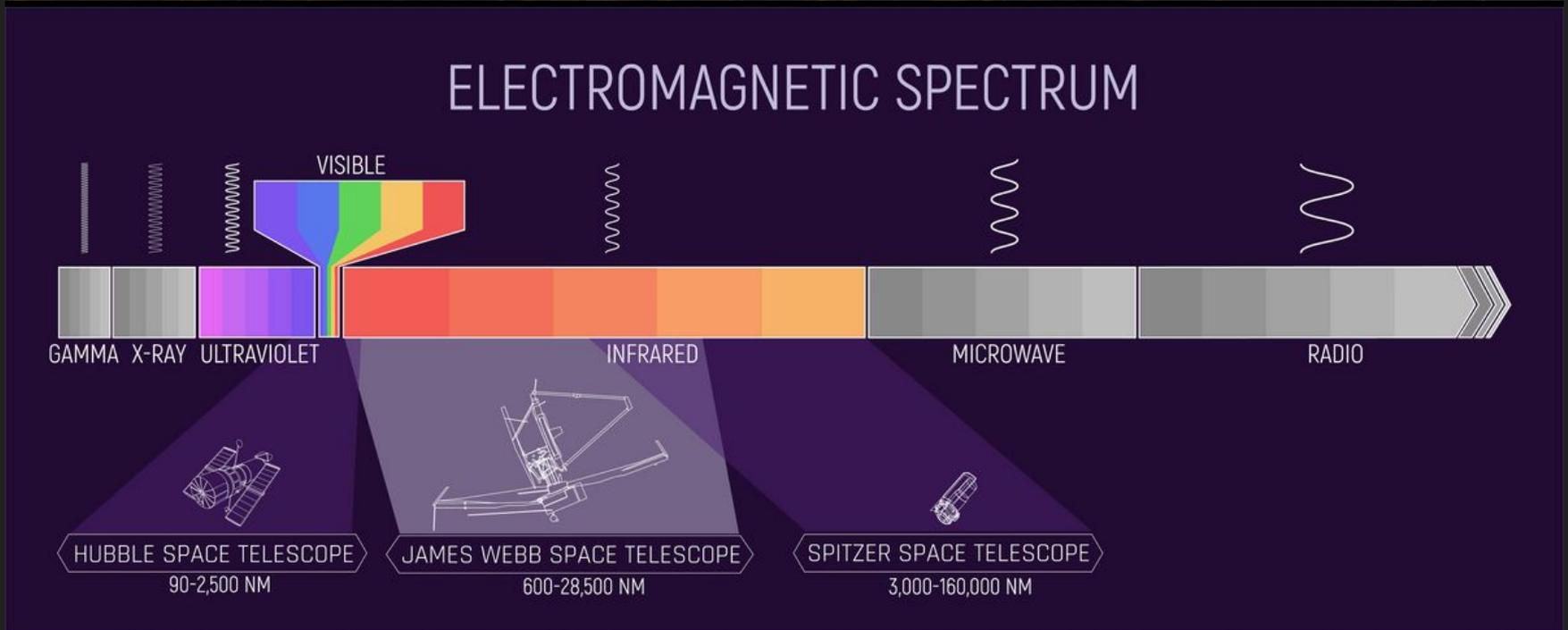
- “Top down” perspective, i.e. we know where things are
  - Not easily possible in the Milky Way
- More nearby = a sharper view
  - 1” resolution is roughly 100pc for a galaxy at 20Mpc



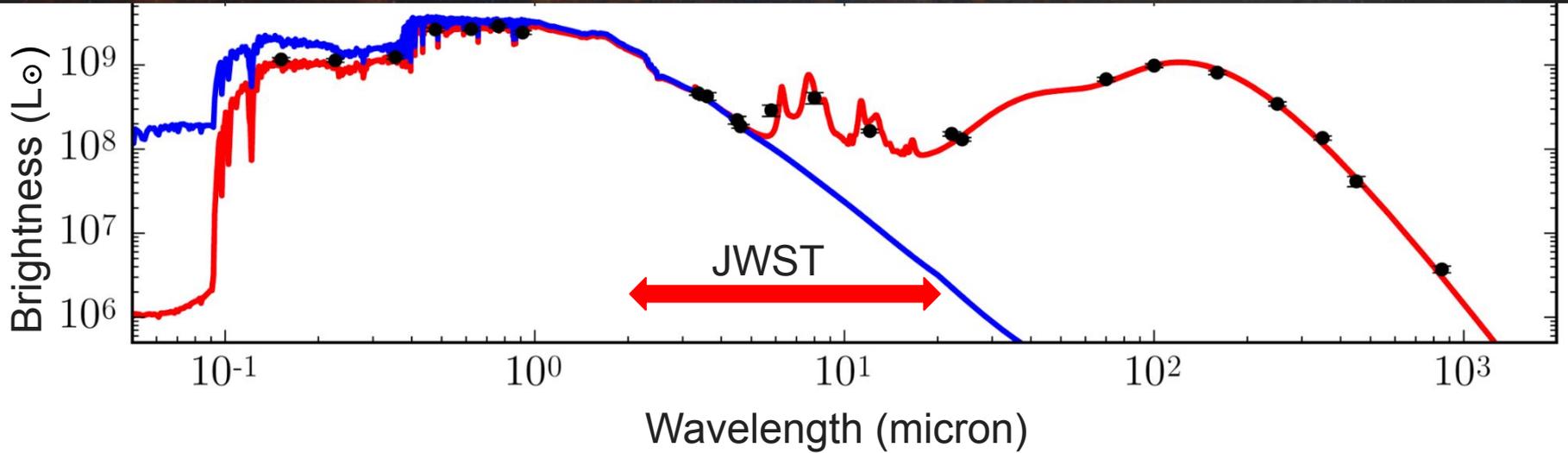
# We need Resolution



# What can JWST look at in nearby galaxies?



# A cool wavelength range to look at



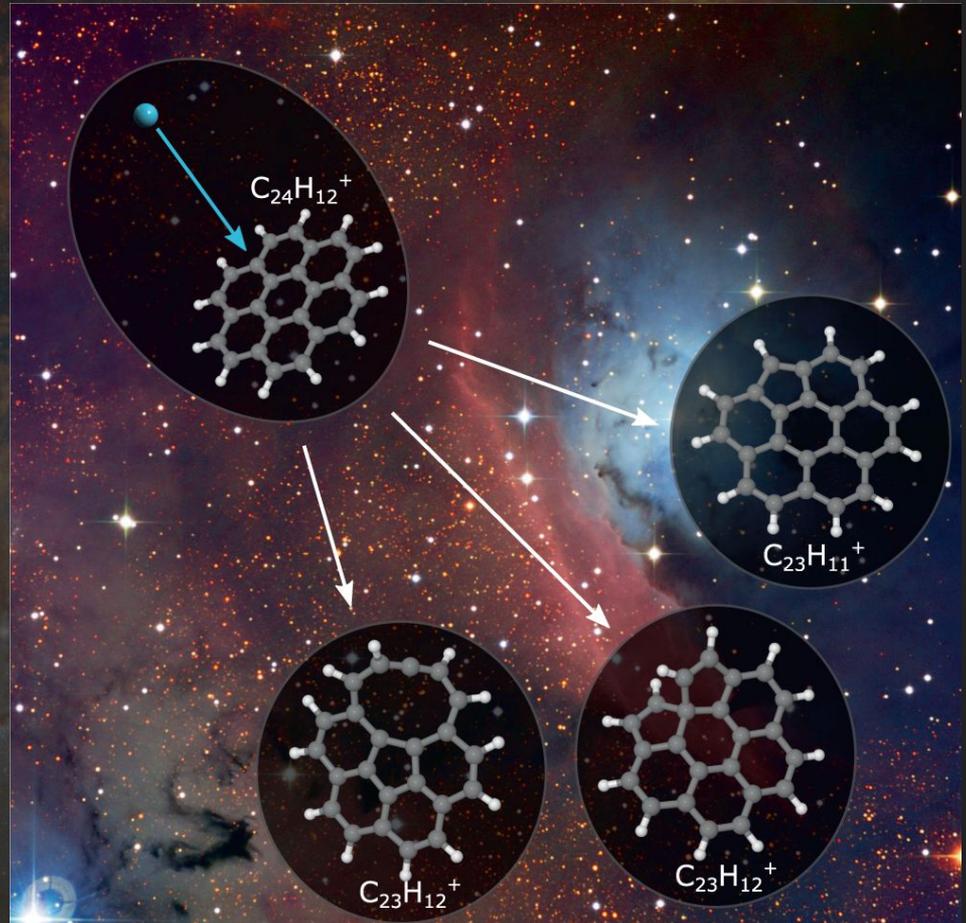
# Young stars

- Peer deep into regions of high dust attenuation
  - See the youngest stars (<10Myr) as they form
- Combine this with e.g. HST for a complete look at the stellar inventory of a galaxy



# Polycyclic Aromatic Hydrocarbons

- Small dust grains, have emission features in N/MIR
- Very important for processing of starlight, but still mysterious



# Polycyclic Aromatic Hydrocarbons

- Still poorly understood, and some may have more complex sub-features we haven't really seen yet

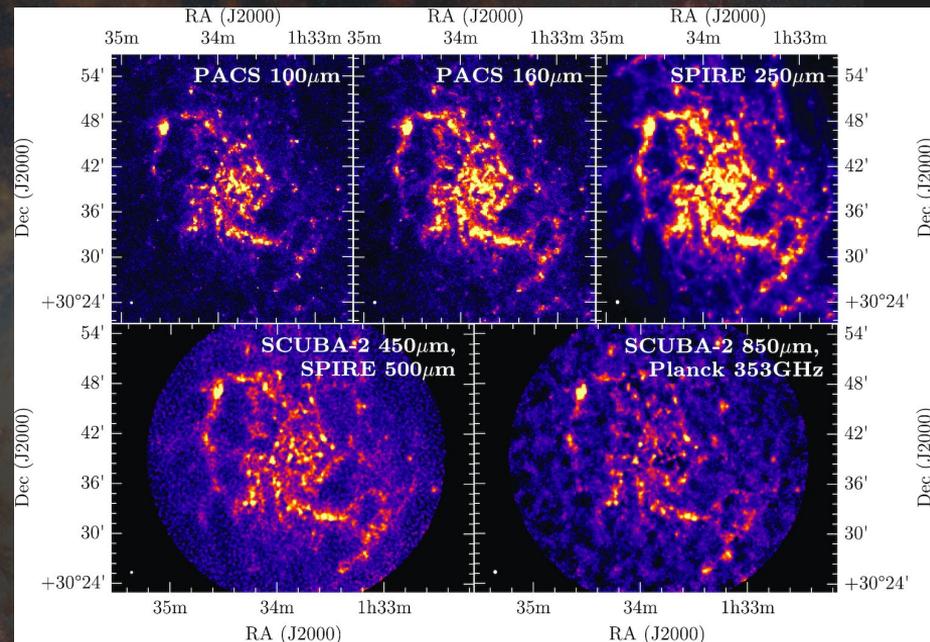
TABLE I  
PAH RESONANCE PARAMETERS

<i>j</i>	$\lambda_j$ ( $\mu\text{m}$ )	$\gamma_j$	$\sigma_{\text{mi},j} \equiv \int \sigma_{\text{abs},j} d\lambda^{-1}$		TENTATIVE IDENTIFICATION
			Neutral ( $10^{-20}$ cm/C)	Ionized ( $10^{-20}$ cm/C)	
1.....	0.0722	0.195	$7.97 \times 10^7$	$7.97 \times 10^7$	$\sigma \rightarrow \sigma^*$ transition in aromatic C
2.....	0.2175	0.217	$1.23 \times 10^7$	$1.23 \times 10^7$	$\pi \rightarrow \pi^*$ transition in aromatic C
3.....	1.050	0.055	0	$2.0 \times 10^4$	Weak electronic transition(s) in PAH cations
4.....	1.260	0.11	0	0.078	Weak electronic transition(s) in PAH cations
5.....	1.905	0.09	0	-146.5	?
6.....	3.300	0.012	394(H/C)	89.4(H/C)	Aromatic C-H stretch
7.....	5.270	0.034	2.5	20	C-H bend + C-H stretch combination mode
8.....	5.700	0.035	4	32	C-H bend + C-H stretch combination mode
9.....	6.220	0.030	29.4	235	Aromatic C-C stretch (in-plane)
10.....	6.690	0.070	7.35	59	?
11.....	7.417	0.126	20.8	181	Aromatic C-C stretch
12.....	7.598	0.044	18.1	163	Aromatic C-C stretch
13.....	7.850	0.053	21.9	197	C-C stretch + C-H bending
14.....	8.330	0.052	6.94(H/C)	48(H/C)	C-C stretch + C-H bending?
15.....	8.610	0.039	27.8(H/C)	194(H/C)	C-H in-plane bending
16.....	10.68	0.020	0.3(H/C)	0.3(H/C)	C-H out-of-plane bending, solo?
17.....	11.23	0.012	18.9(H/C)	17.7(H/C)	C-H out-of-plane bending, solo
18.....	11.33	0.032	52(H/C)	49(H/C)	C-H out-of-plane bending, solo
19.....	11.99	0.045	24.2(H/C)	20.5(H/C)	C-H out-of-plane bending, duo
20.....	12.62	0.042	35(H/C)	31(H/C)	C-H out-of-plane bending, trio
21.....	12.69	0.013	1.3(H/C)	1.3(H/C)	C-H out-of-plane bending, trio
22.....	13.48	0.040	8.0(H/C)	8.0(H/C)	C-H out-of-plane bending, quartet?
23.....	14.19	0.025	0.45	0.45	C-H out-of-plane bending, quartet?
24.....	15.90	0.020	0.04	0.04	?
25.....	16.45	0.014	0.5	0.5	C-C-C bending?
26.....	17.04	0.065	2.22	2.22	C-C-C bending?
27.....	17.375	0.012	0.11	0.11	C-C-C bending?
28.....	17.87	0.016	0.067	0.067	C-C-C bending?
29.....	18.92	0.10	0.10	0.17	C-C-C bending?
30.....	15	0.8	50	50	...

Draine & Li, 2007

# Molecular gas

- Dust grains are critical adsorption sites for the formation of molecular hydrogen
- This potentially means the dust continuum (from larger grains than PAHs) could potentially be a sensitive tracer of molecular gas
- Not in this talk, but there are also molecular hydrogen lines in this wavelength range that trace warm hydrogen (thousands of K)



Williams, Gear, and Smith, 2019

# PHANGS



# PHANGS Overview

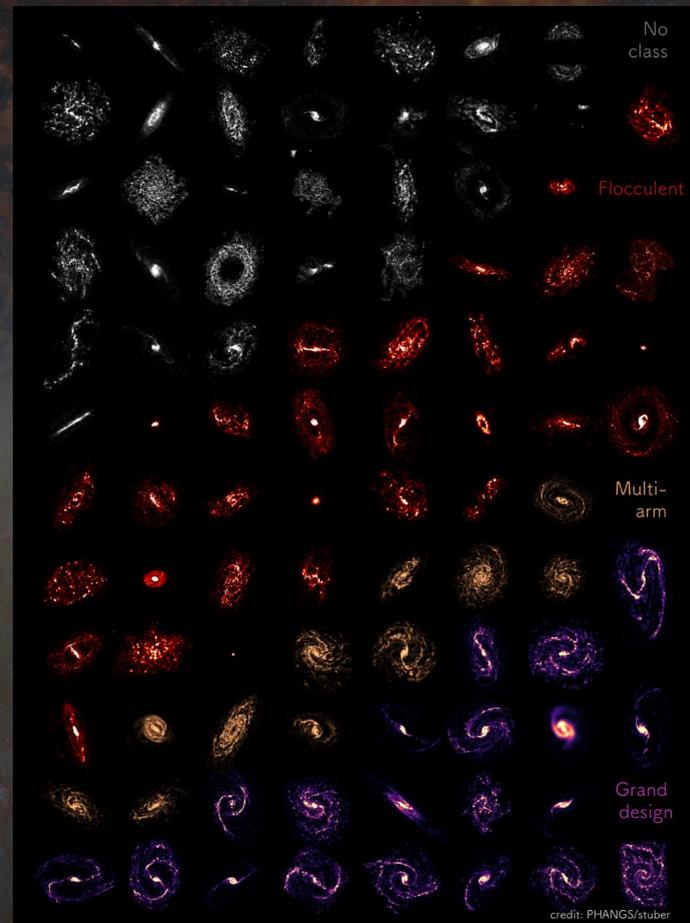
- Physics at High Angular Resolution in Nearby Galaxies
- High resolution observations of ~100 galaxies
- Several large programs, including
  - ALMA
  - VLT-MUSE
  - HST
  - MeerKAT
  - JWST
- ~150 people across six continents

# Why all these telescopes?

Different wavelength ranges probe different phases of galaxies

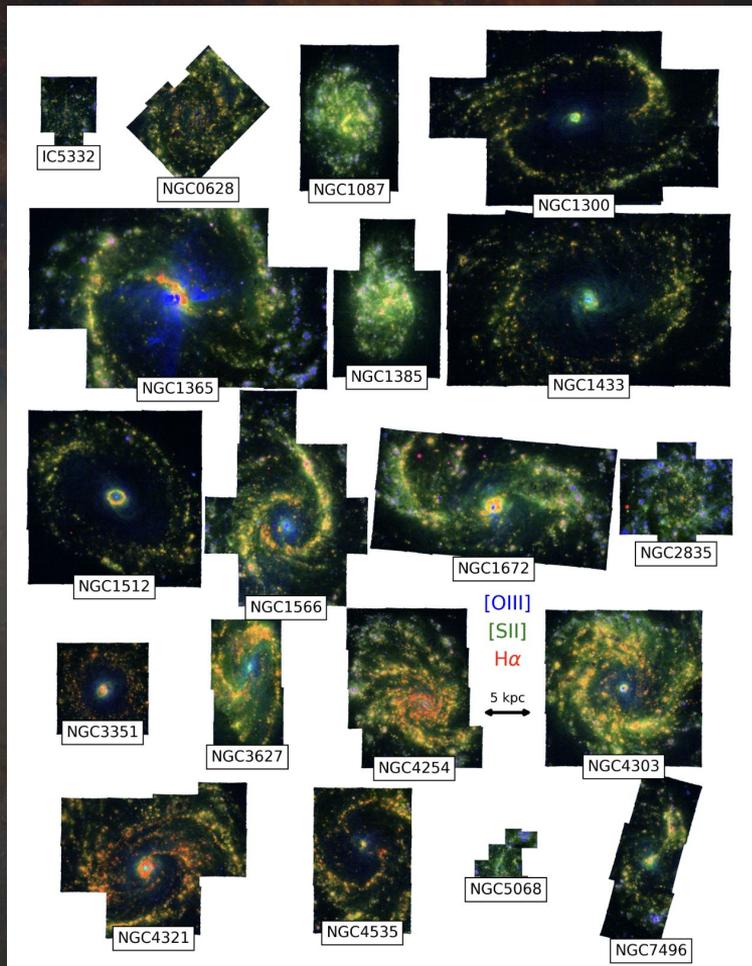
# PHANGS-ALMA

- ~90 galaxies observed with ALMA in the CO(J=2-1) line
  - Traces the bulk molecular gas in a galaxy
- The “original” PHANGS survey, and defined the sample selection for later work
- Despite being “typical” star-forming galaxies, a huge variety in how they look!



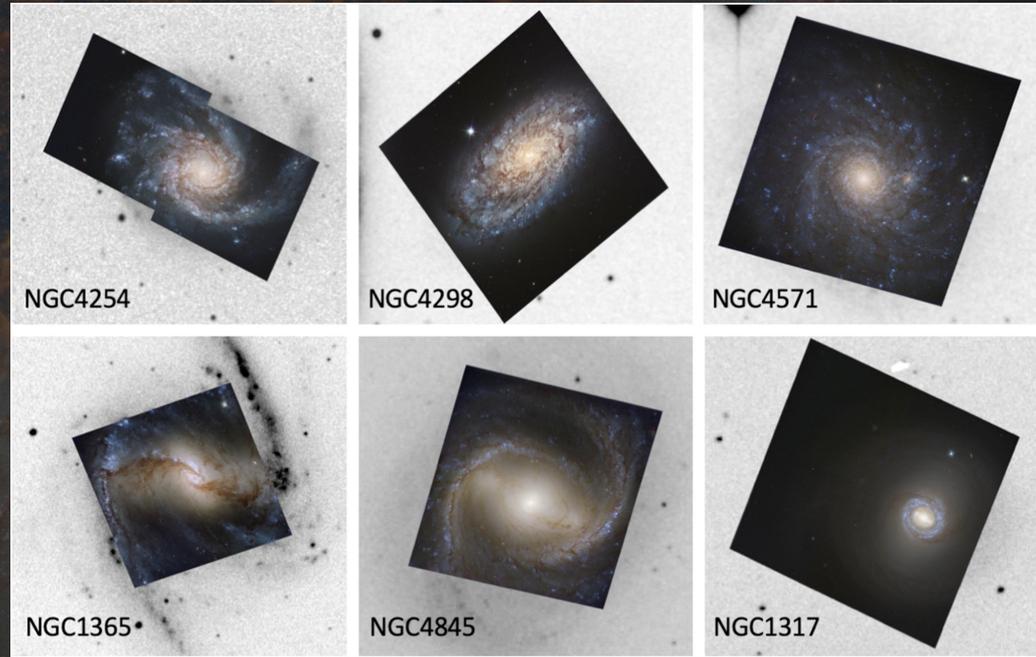
# PHANGS-MUSE

- Subset of 19 of the 90 PHANGS-ALMA galaxies
  - Currently building out an “extended sample”
- VLT-MUSE is an integral field spectrograph
  - A spectrum in every pixel!
- Gets a whole load of interesting emission lines that can trace SFR, dust attenuation, etc.



# PHANGS-HST

- 5-band optical imaging of 38 galaxies
- Primary science goals to study young stellar clusters (given high resolution of HST) and measure stellar population ages
- Can also look at dust via attenuation, but this is a little tricky!



Lee+, 2022

# The PHANGS Mission



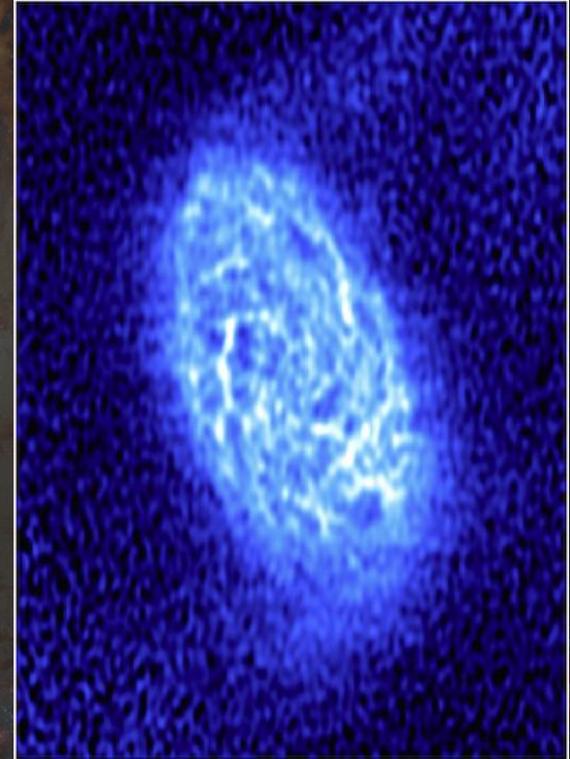
To understand what global and local processes drive the “Baryon Cycle”

# The Baryon Cycle



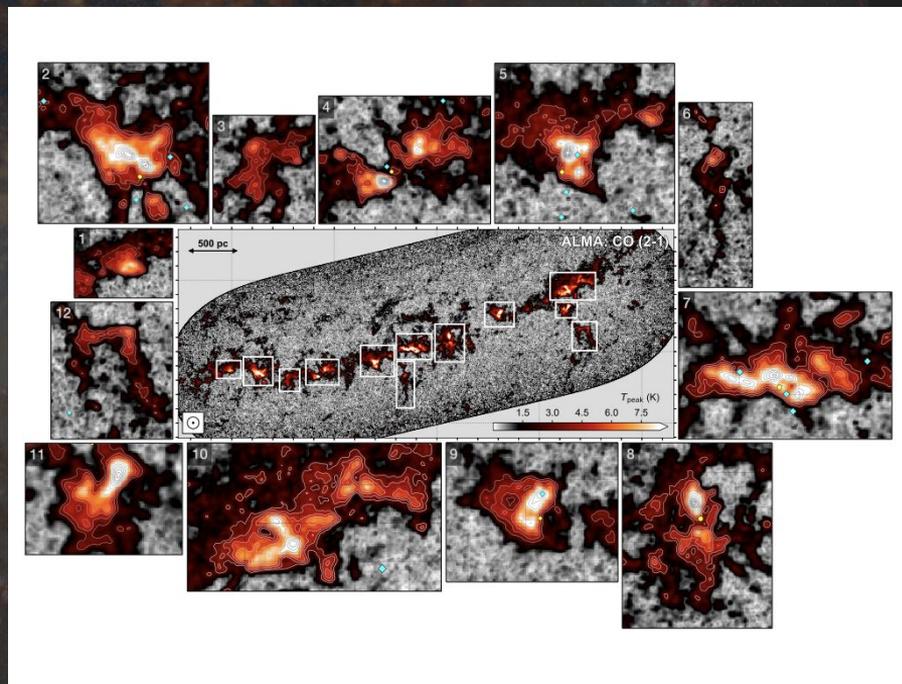
# Atomic Hydrogen

- The raw fuel for star-formation, as at high enough density will form into molecular hydrogen
- Typically traced via the 21cm spin-flip line
- Typically the most extended galaxy component
  - HI rotation curves are a key indicator of Dark Matter



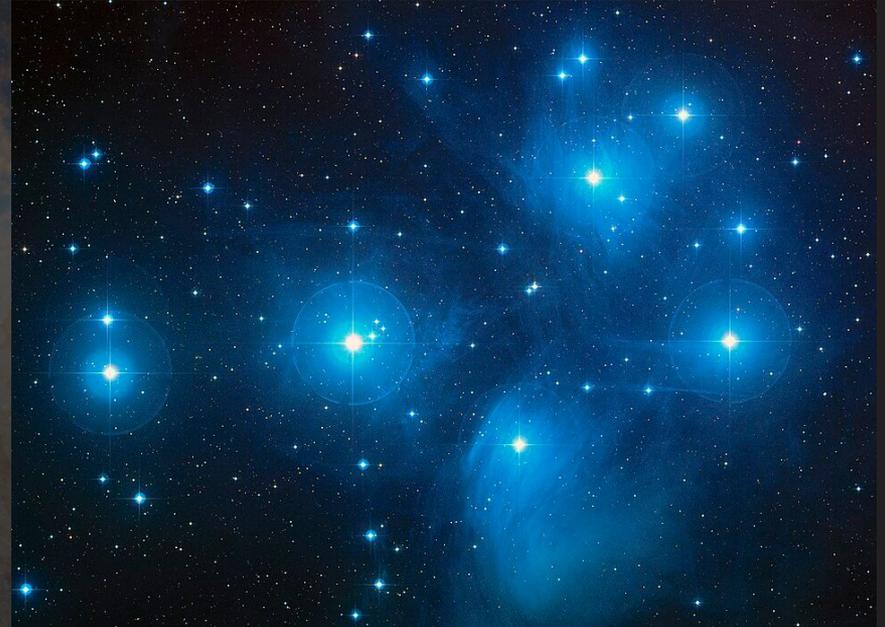
# Molecular hydrogen

- Cold, dense  $\text{H}_2$  will form into stars
- Molecular hydrogen small, no dipole moment so not possible to observe directly
- Normally traced via next most common molecular (CO) plus a conversion factor



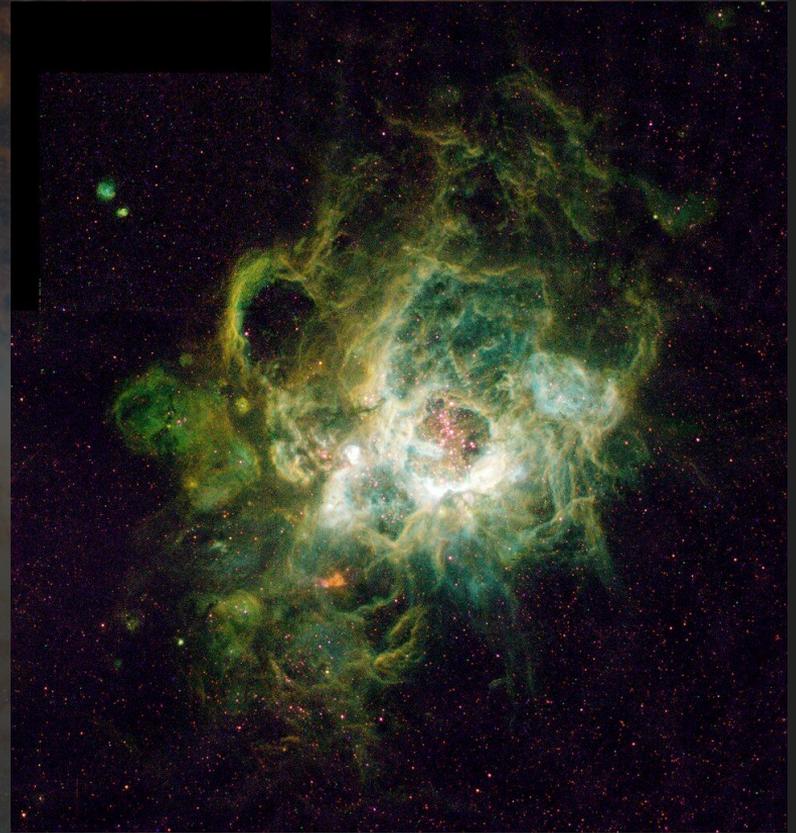
# Star Clusters

- Groups of stars that condensed from the same molecular cloud
- These are where most stars form
- Typically these are quite young, but old (globular) clusters also exist



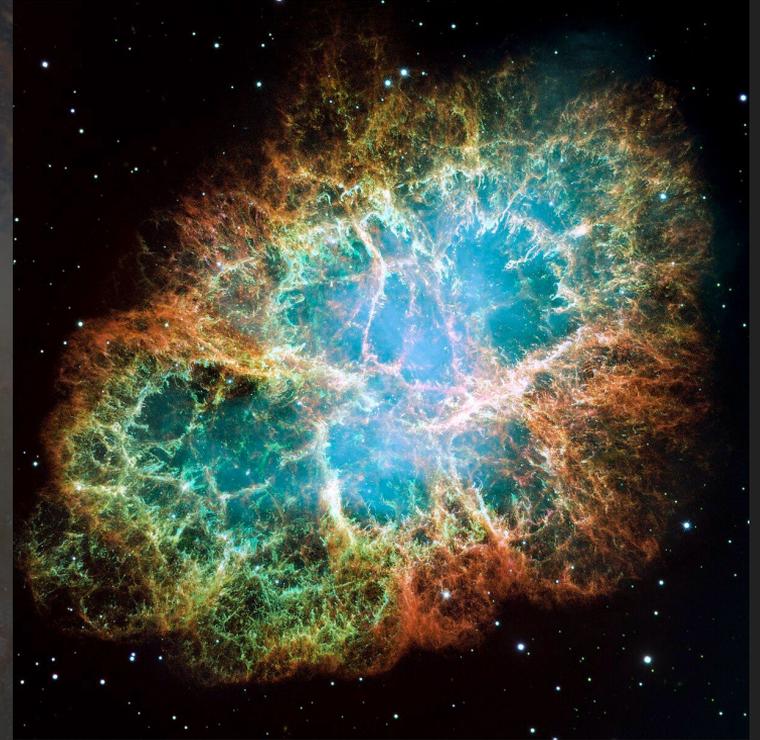
# HII Regions

- This is gas (mostly atomic hydrogen) being ionised by new stars forming
- Show up typically in forbidden ionisation lines in optical wavelengths
- Eventually, this gas will be dispersed by SNe and stellar winds



# SNe

- Massive stars ( $>10M_{\odot}$ ) will end their lives as supernovae
- These explosions throw heavy elements out into the ISM, enriching it for future generations
- This is where most heavy elements in the Universe come from



# The Baryon Cycle

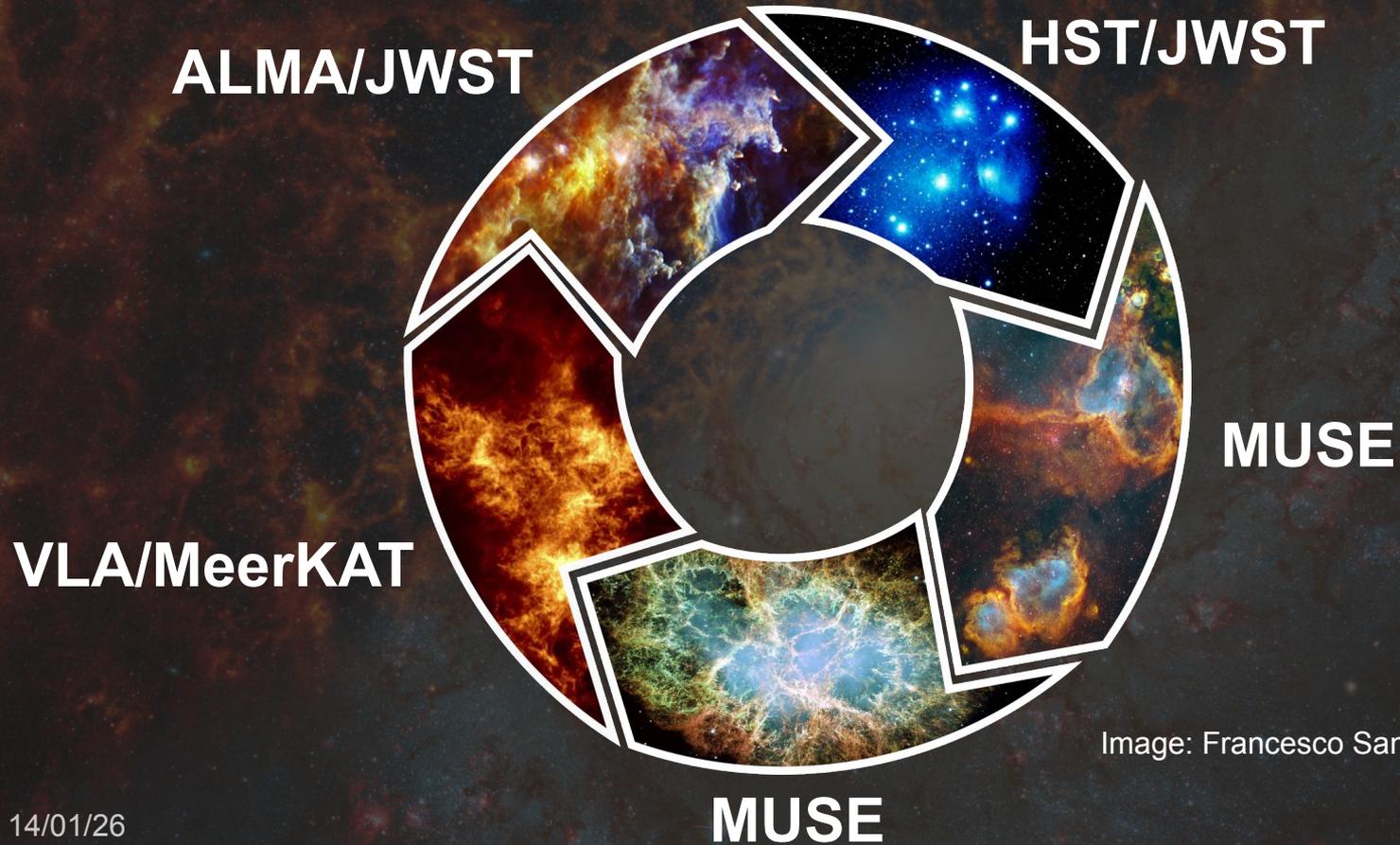


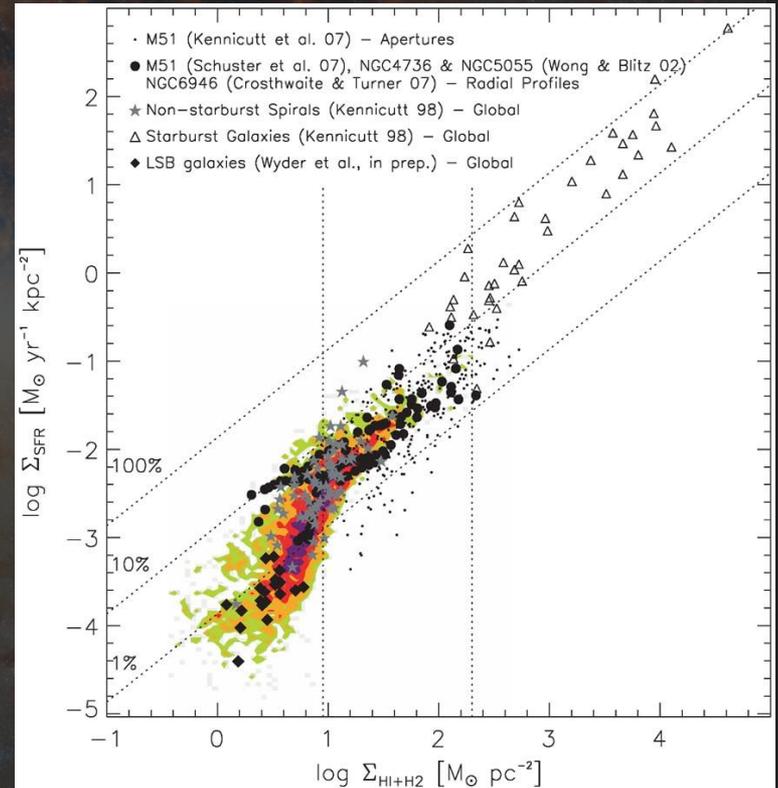
Image: Francesco Santoro

# But why do we actually care?

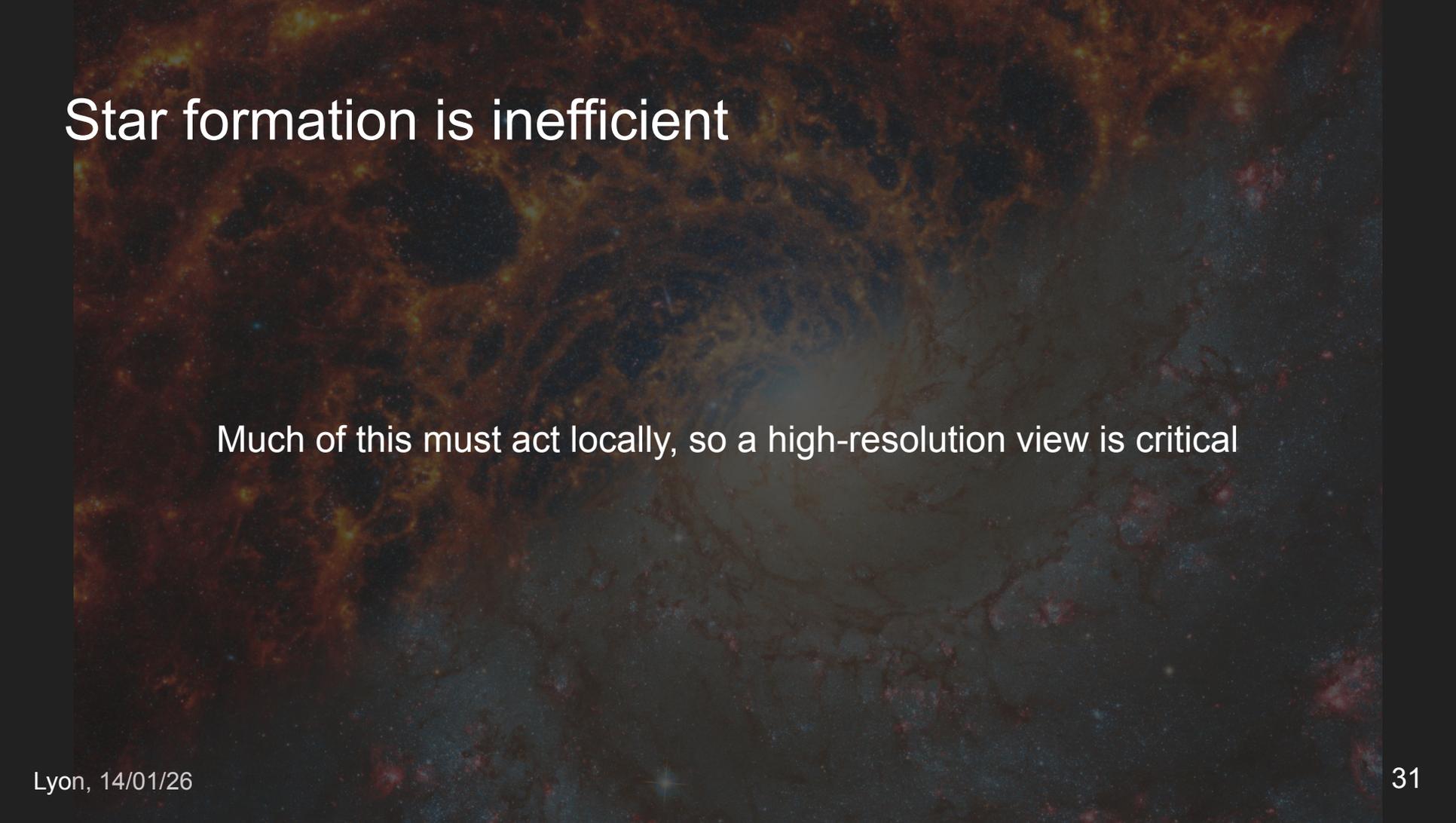
- 1) Star formation is inherently inefficient
- 2) The efficiency of star formation is different in different places

# Star formation is inefficient

- Just taking masses of molecular clouds and assuming pure gravitational collapse leads to very short cloud lifetimes ( $\sim 1\text{Myr}$ ), much shorter than the  $\sim 10\text{Myr}$  they actually survive for (e.g. Federrath+2015; Kim+22)
- Things like feedback, pressure, magnetic fields must act to slow down collapse



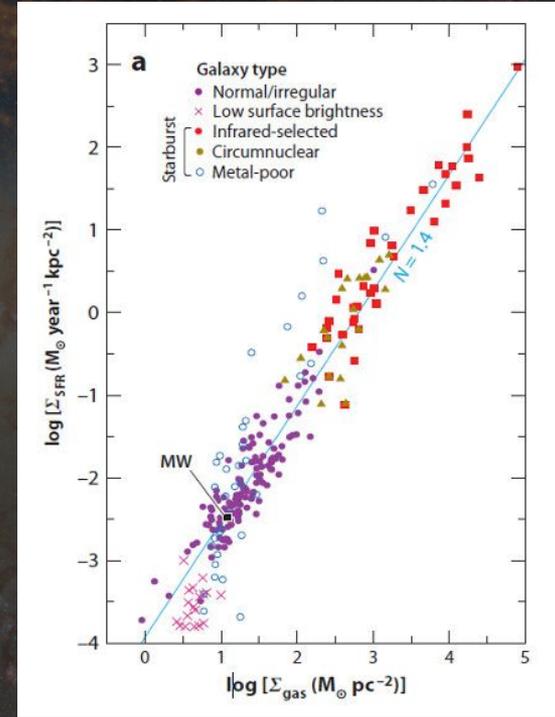
# Star formation is inefficient



Much of this must act locally, so a high-resolution view is critical

# Star formation efficiency varies

- Star formation efficiency can vary by at least a factor of a few between galaxies types (quiescent, normal spiral, starburst)
- Is this localised (e.g. maybe the central region has very efficient star formation, the rest of the galaxy is normal) or constant across a galaxy?



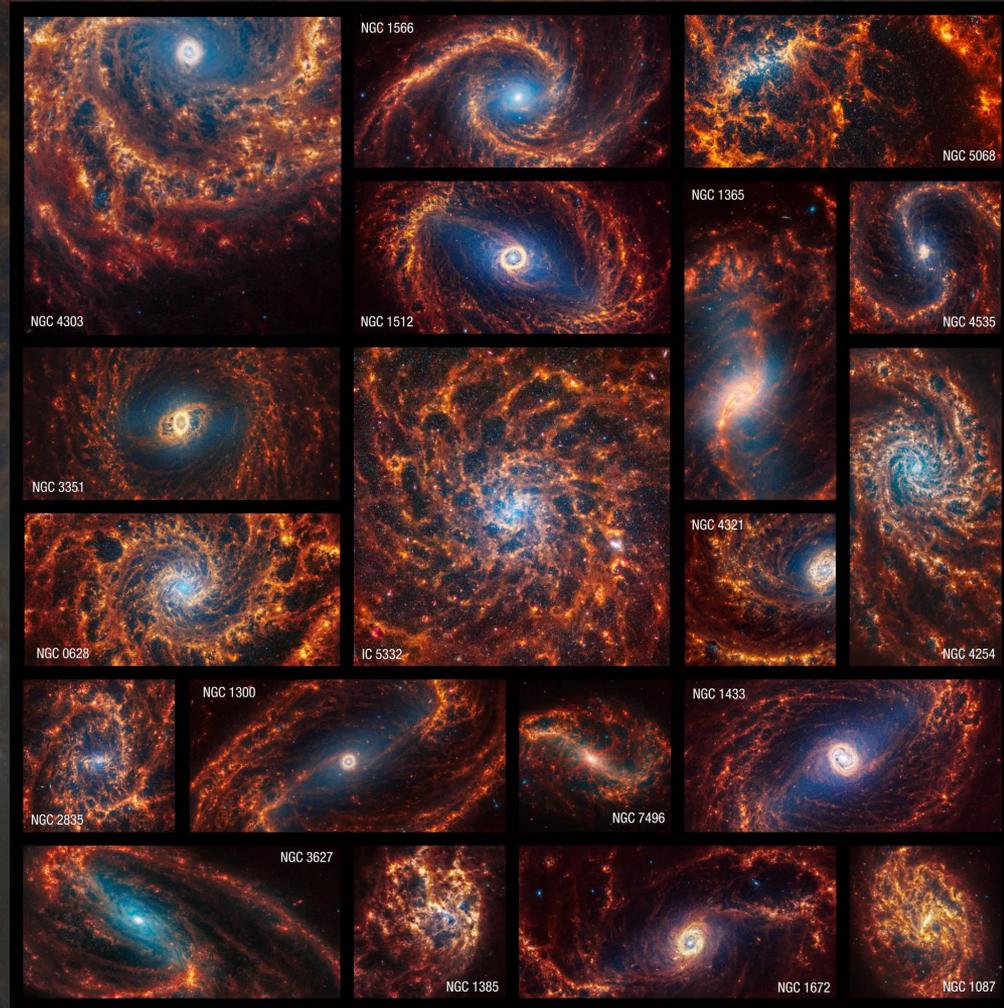
# Star formation efficiency varies

Seeing where star formation efficiency is different requires resolving galaxies

# PHANGS-JWST

- Cycle 1 Treasury Programme
- Looked at 19 galaxies in 8 different filters
- All of these images are public - go have fun with them!

Williams+, 2024



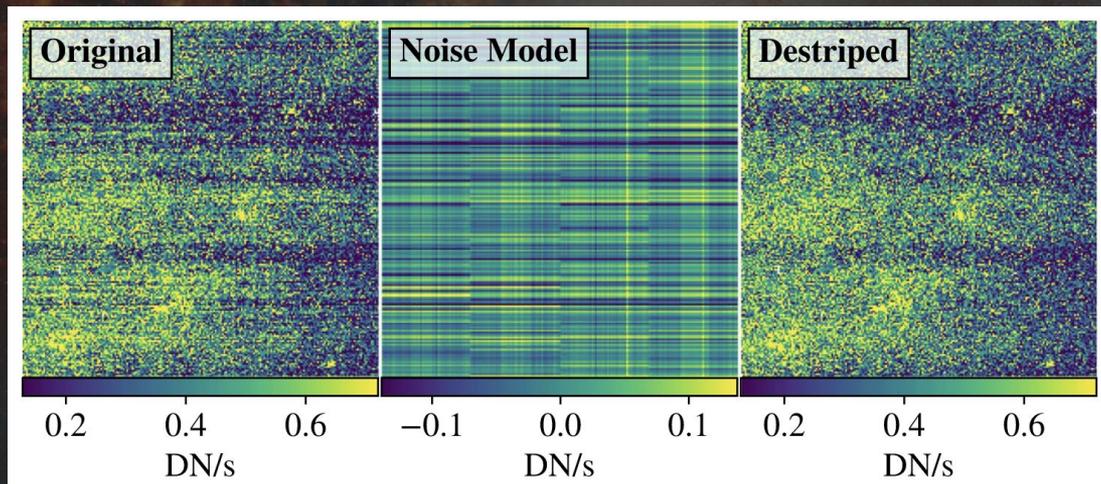
# Brief aside

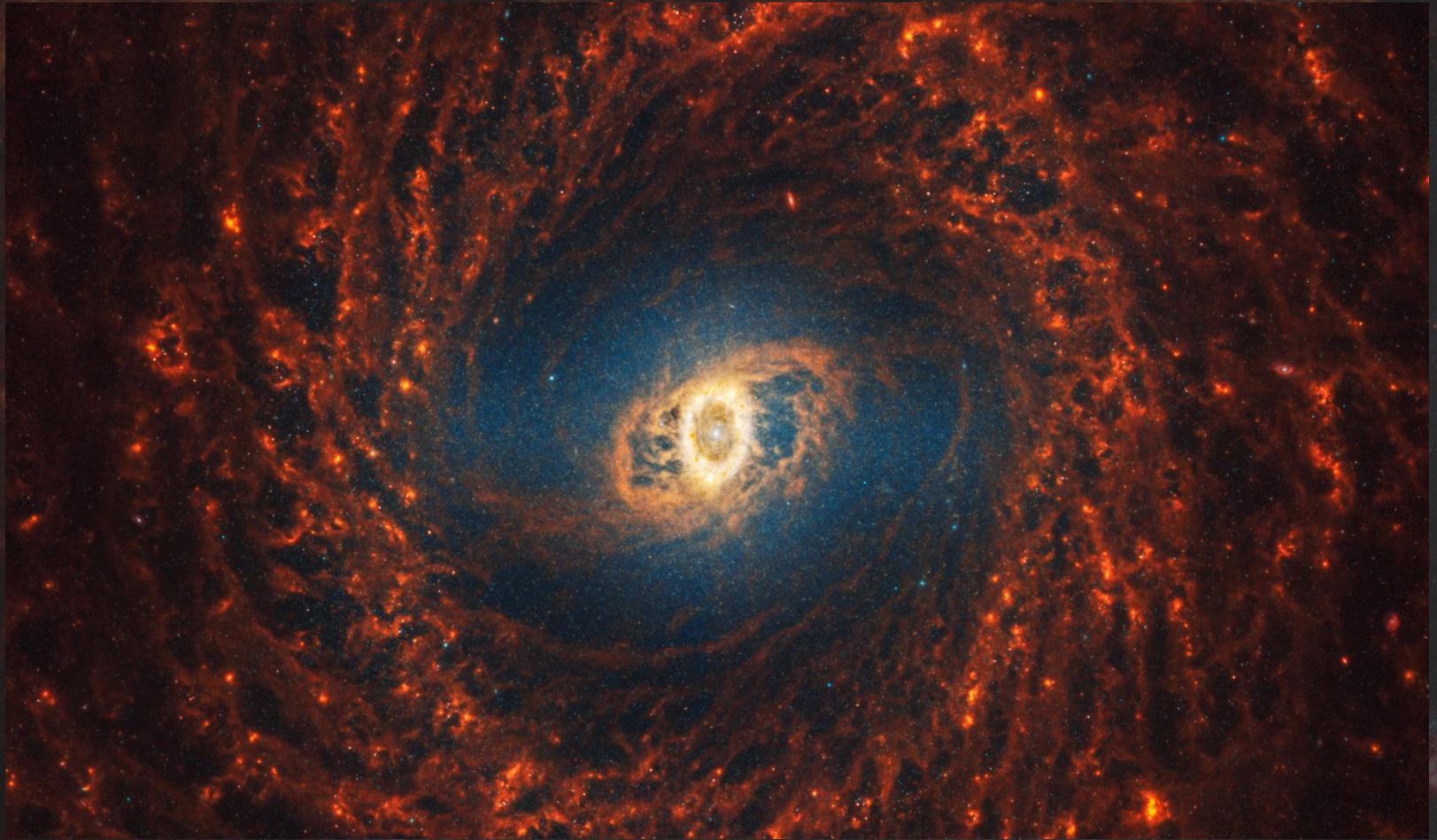
- We got some of the first data taken, so as soon as anything was public so were our first few observations



# Data processing is difficult

- Lots of work involved here, particularly NIRCam which is full of  $1/f$  noise
- Getting the pretty pictures took a village!





Lyon, 14/01/26



# Potted PHANGS-JWST Highlights

# PHANGS-JWST Early Results

[https://iopscience.iop.org/collections/2041-8205\\_PHANGS-JWST-First-Results](https://iopscience.iop.org/collections/2041-8205_PHANGS-JWST-First-Results)

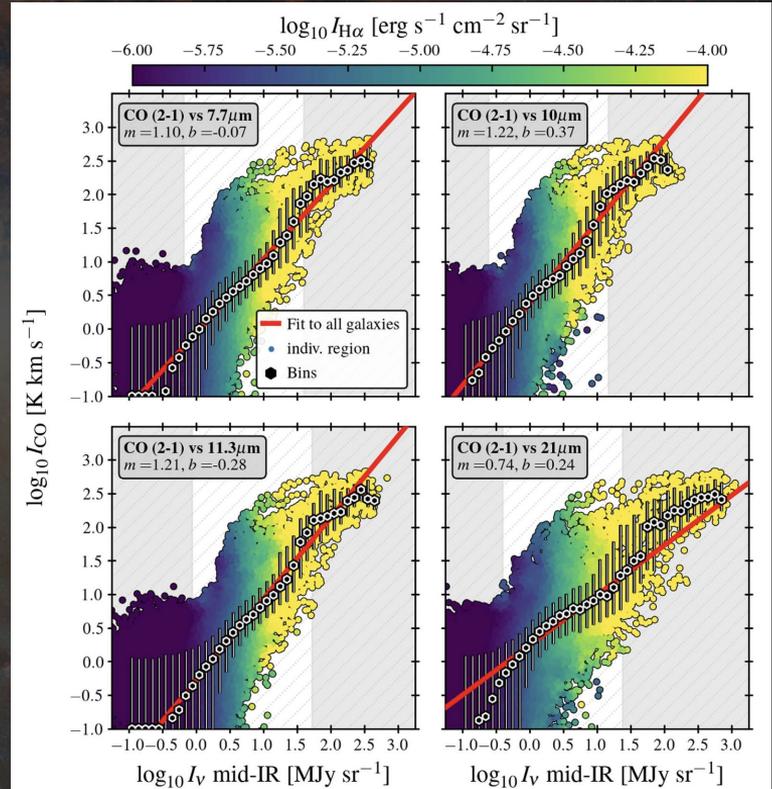
# Using JWST to trace Molecular Gas

- CO (the most common molecular gas tracer) has issues
  - Traces bulk gas, which might not be associated with star-formation
  - Doesn't work well at low metallicity
  - The mysterious “CO dark” gas can be important
- JWST for the same amount of observing time is much (much) more sensitive
- Can we swap out ALMA for JWST?

# Using JWST to trace Molecular Gas

- Yes! Kind of
- The MIR emission correlates well with CO intensity
- However, it also correlates with H $\alpha$  intensity
- It's almost exactly half-and-half

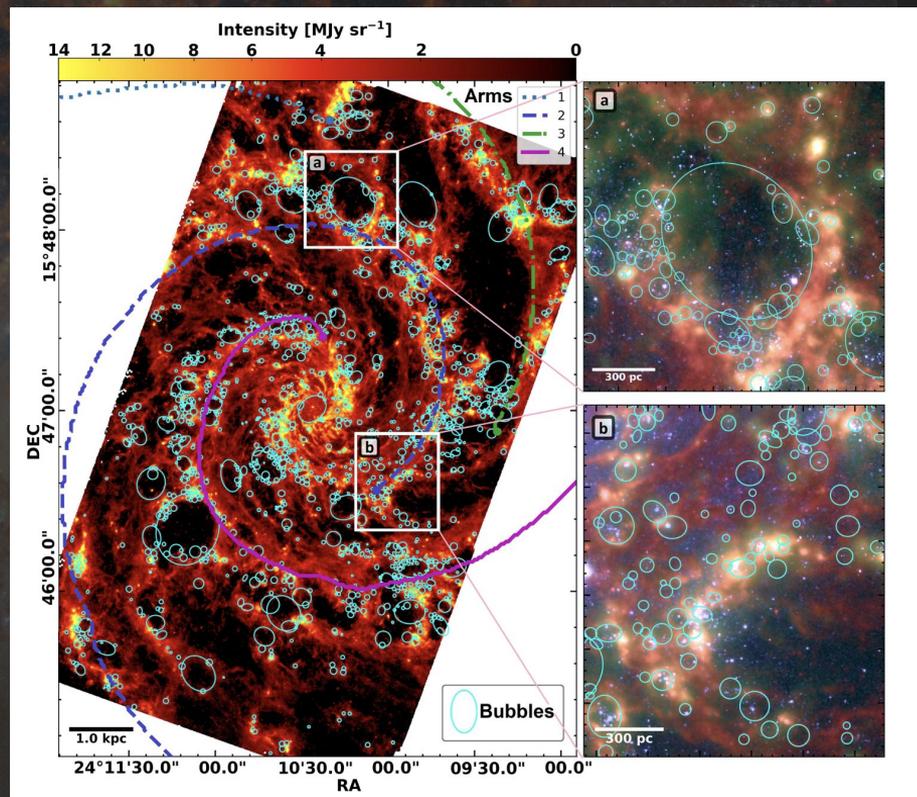
Leroy+, 2023



# Superbubbles

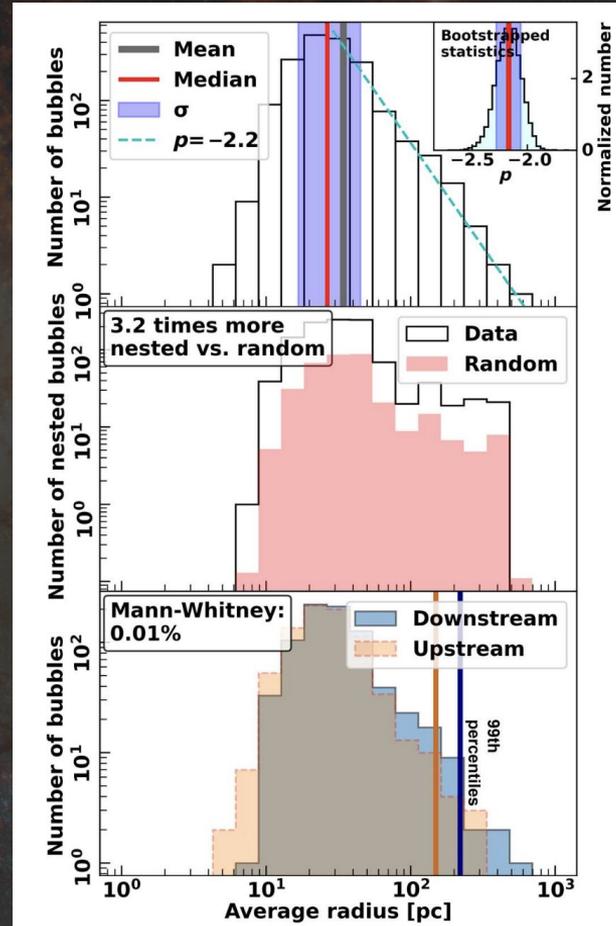
Watkins+, 2023

- JWST has shown that feedback-driven bubbles are ubiquitous in spiral galaxies
- The size distribution is sensitive to the balance of feedback
- The shapes of bubbles are affected by dynamical processes



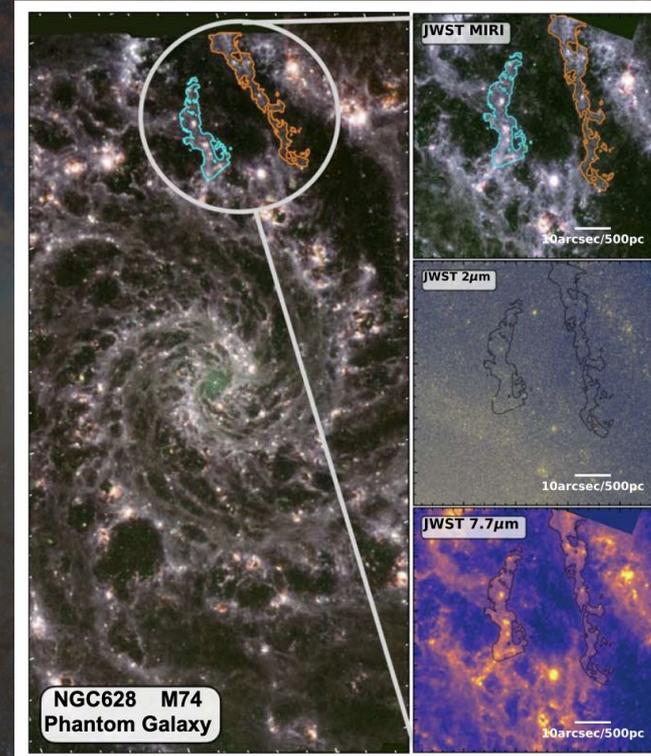
# Superbubbles

- Size distribution shallower than expected
  - Likely due to bubble merging
- Lots of bubbles are nested
  - The compression of bubble expansion drives next generation of supernova, etc.
- More large bubbles on the spiral arm downstream
  - Bubble formation likely set off by spiral arm passage



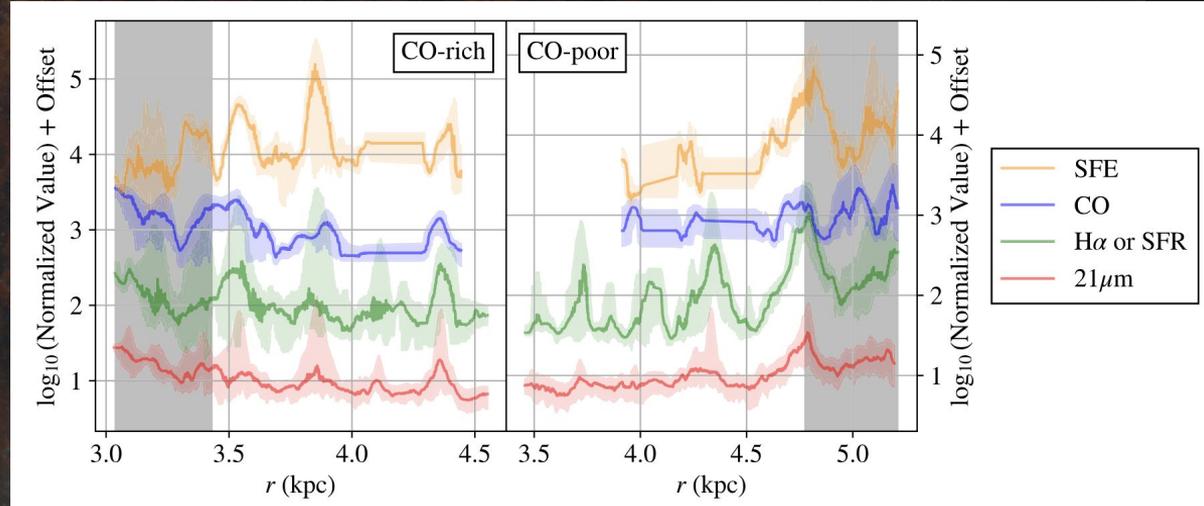
# Star Formation Outside Spiral Arms

- JWST has also shown that “spurs” are ubiquitous features of spiral galaxies
- These have gas, star-formation
- Do stars form here, or just in spiral arms?



# Star Formation Outside Spiral Arms

- They do form in spurs!
- And with ~the same efficiency as in the arms
- Arms just gather gas up, rather than enhance SFE

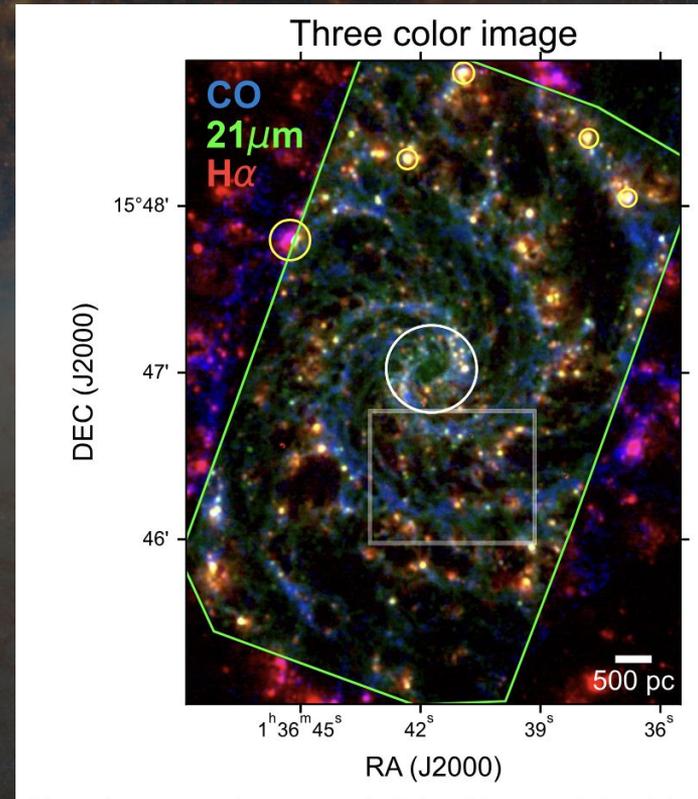


Williams+, 2023

# The Embedded Phase of Star Formation

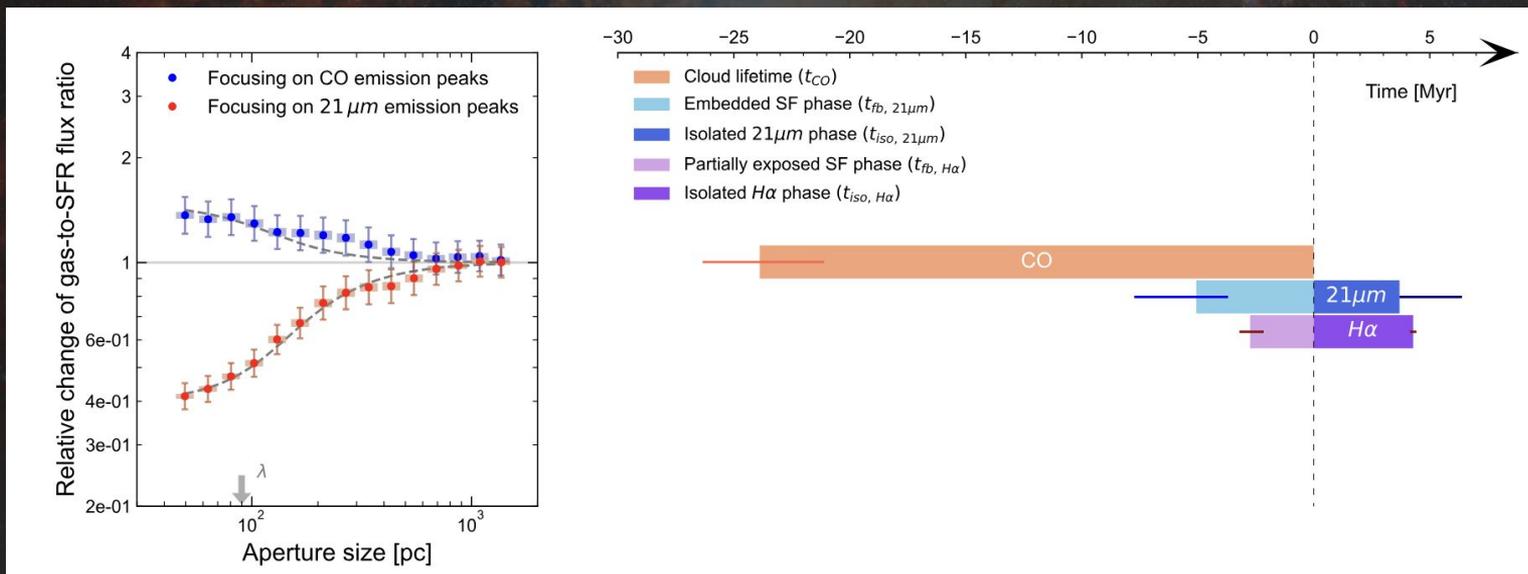
- How long stars stay embedded within their birth clouds is not well-known
- Understanding this is critical, since it sets how long feedback can act on clouds
- JWST lets us peer into the deeply embedded stars and measure this

Kim+, 2023



# The Embedded Phase of Star Formation

- Stars spend ~20% of the cloud lifetime in an embedded phase
- ~half of this is deeply embedded (invisible in the optical)

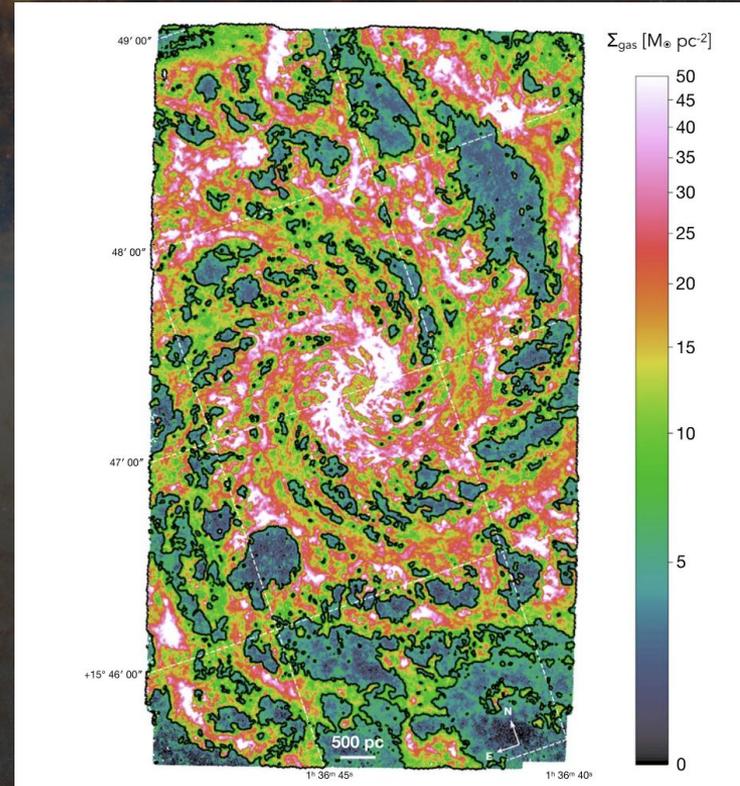


Kim+, 2023

# Swiss Cheese and Meatballs

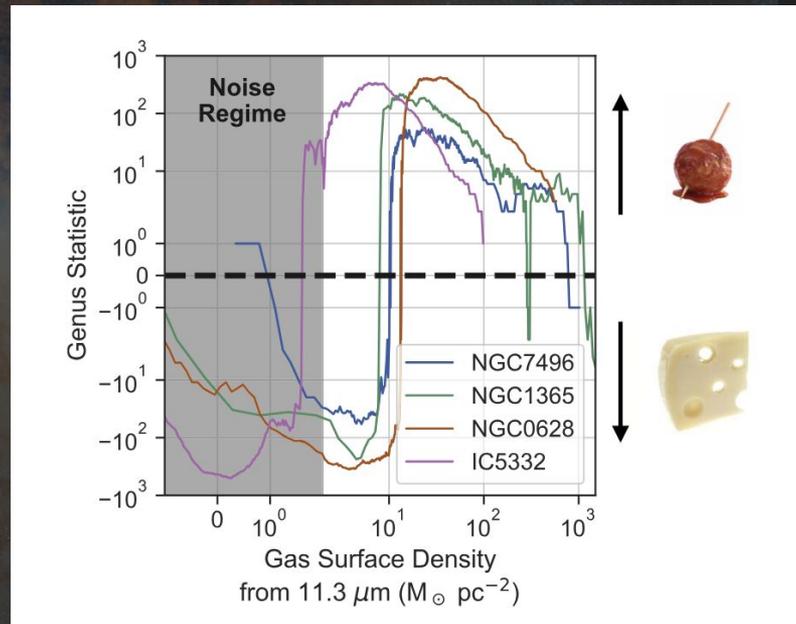
- The ISM broadly looks like peaks of emission (clouds, meatballs) and holes (bubbles, voids, Swiss cheese)
- The topology is very sensitive to the balance of different feedback types, so measuring this in some way informs models

Sandstrom, Koch+, 2023



# Swiss Cheese and Meatballs

- Can be quantified through the Genus statistic
  - Difference between number of connected regions above and below a certain threshold
- The point at which it crosses 0 is where you go from cheesy to meatbally
- This occurs at  $\sim$ where we expect the ISM to transition from primarily atomic to primarily molecular

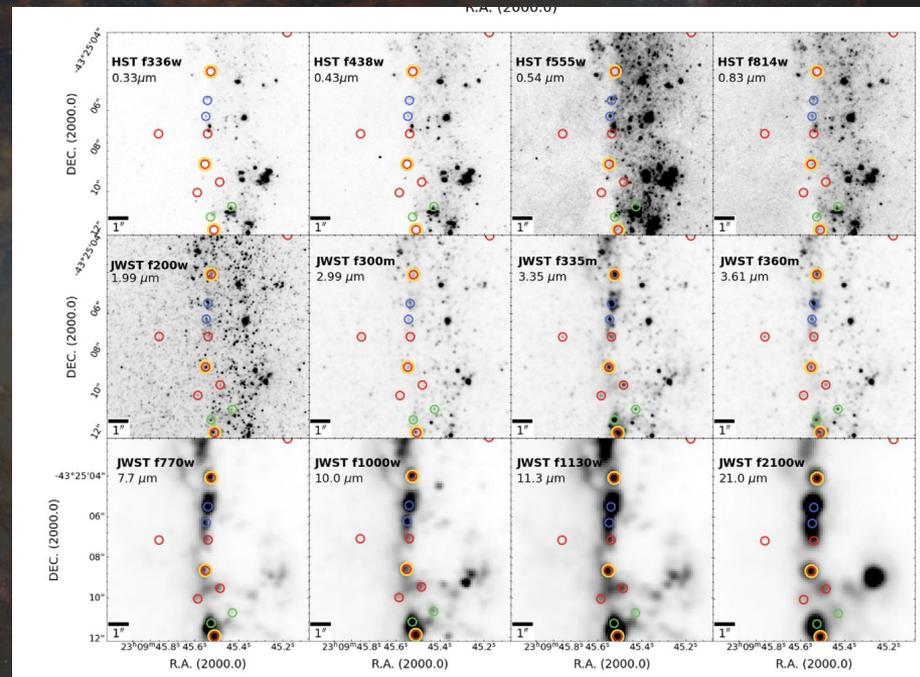


# Embedded Stellar Clusters

- The youngest phases of star formation are hidden in the optical, but seen in the infra-red
- Beyond this, with just HST it's impossible to tell young, embedded stars from old, exposed stars
- JWST should help break this degeneracy!

# Embedded Stellar Clusters

- Can select more cleanly based on 3.3micron emission
- Most younger than 2Myr
- JWST+HST provides promise for finding many more of these in the future

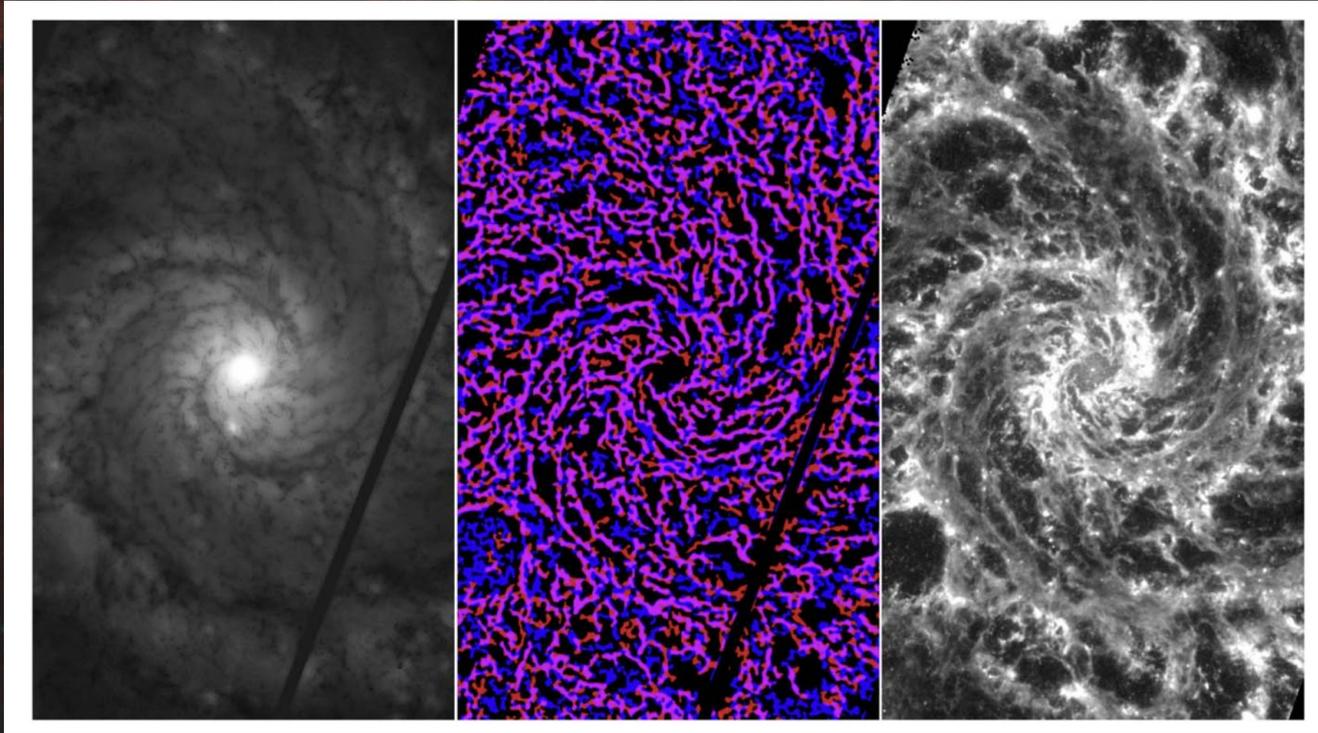


Rodriguez+, 2023

# Dust Filament Networks

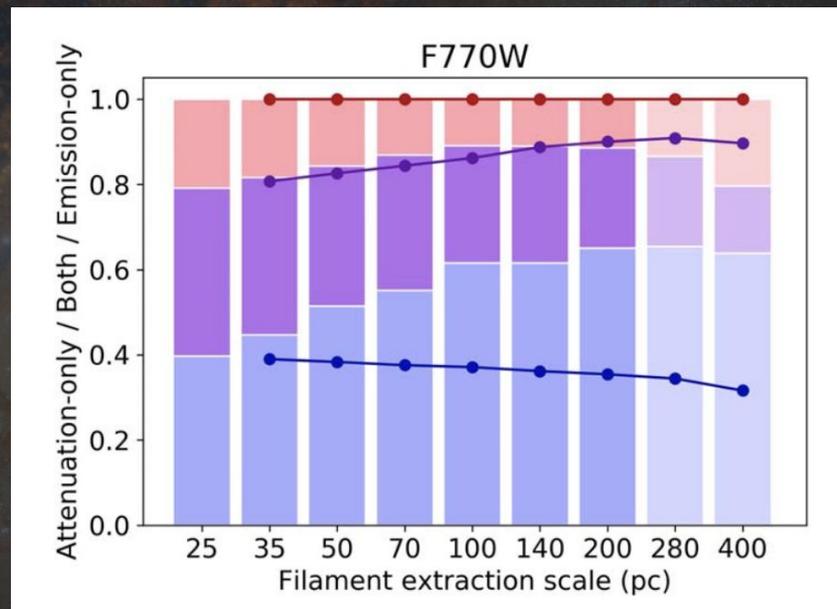
- Dust is pervasive and filamentary across galaxies
- Comparing dust seen in emission (JWST) and in attenuation (HST) may give us some way to map dust if we only have one
- The comparison should also tell us something about dust/star geometry

# Dust Filament Networks



# Dust Filament Networks

- Correspondence is fairly good, about 40% of filaments overlap at small scales
- The emission-only filaments are likely the back of the disk
- The attenuation-only filaments are more mysterious, and not well-understood



Thilker+, 2023

A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are highlighted in shades of orange and red, while the background is a deep, dark blue. The overall structure is intricate and interconnected, representing the large-scale structure of the universe.

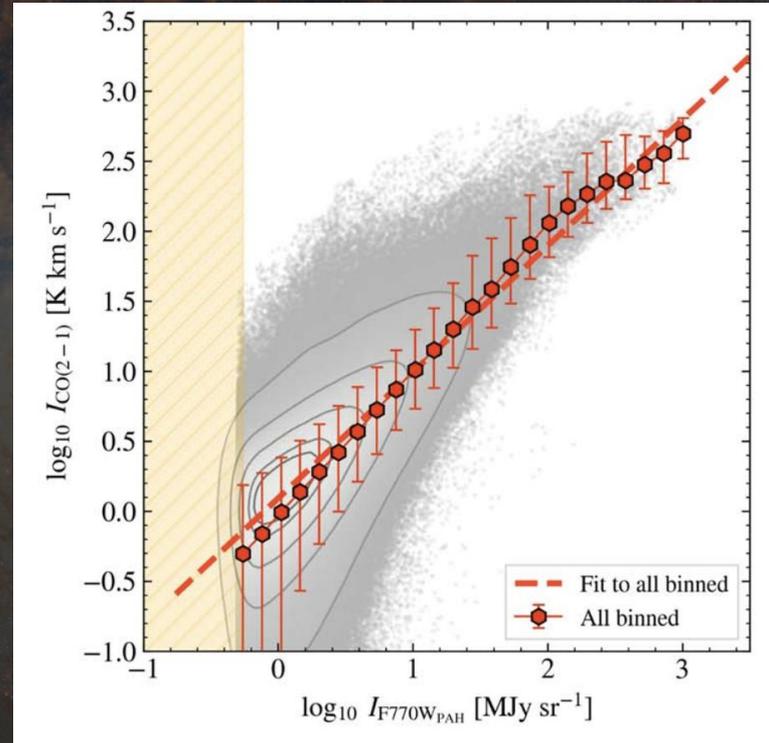
# What now for nearby galaxies?

# Always more data

- In Cycle 2, we had **another** Treasury programme to observe the rest of the 90 PHANGS galaxies with JWST
- This is now complete, data processing is still ongoing but should be done first half of this year
- Most importantly, this is more representative, and probes lower mass

# The CO/PAH Correlation in Local Galaxies

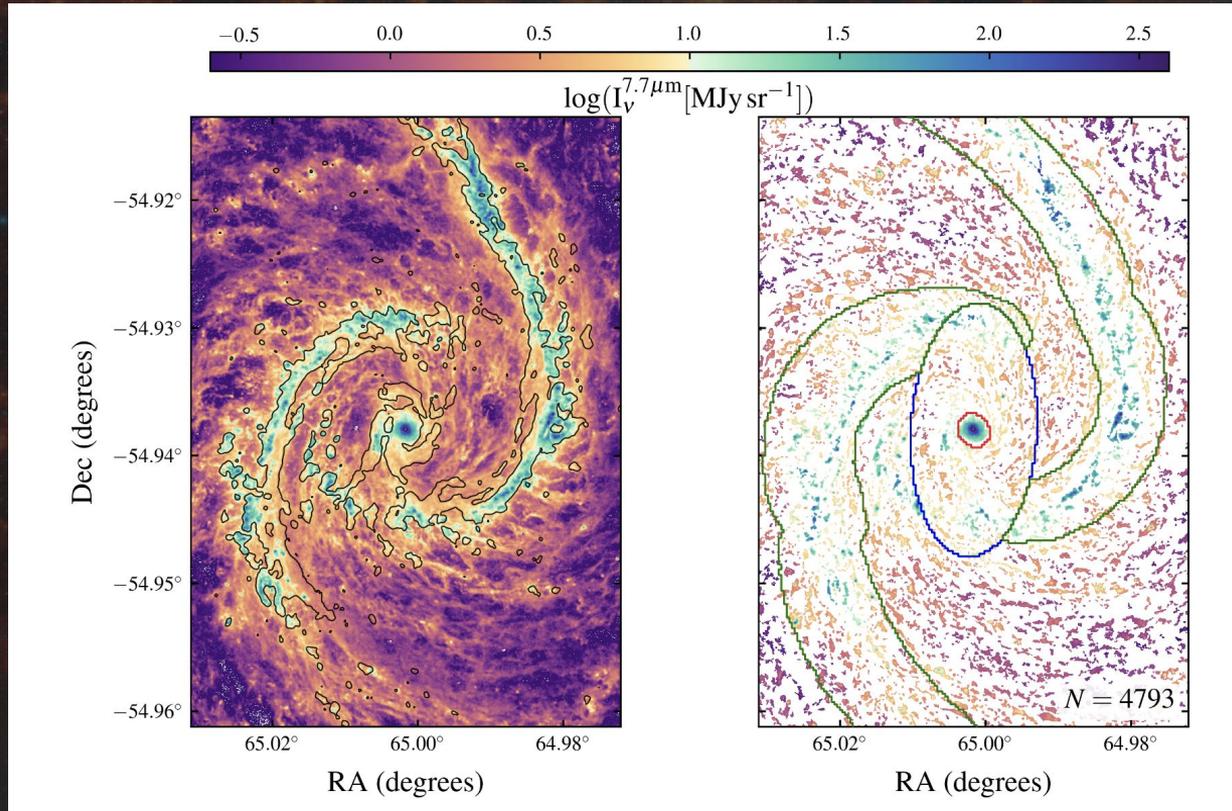
- Extending our earlier work to the full(ish) sample
- Trends still hold!
  - Across mass, HII regions vs diffuse, centres vs disks, etc.



# 100,000 Molecular Clouds

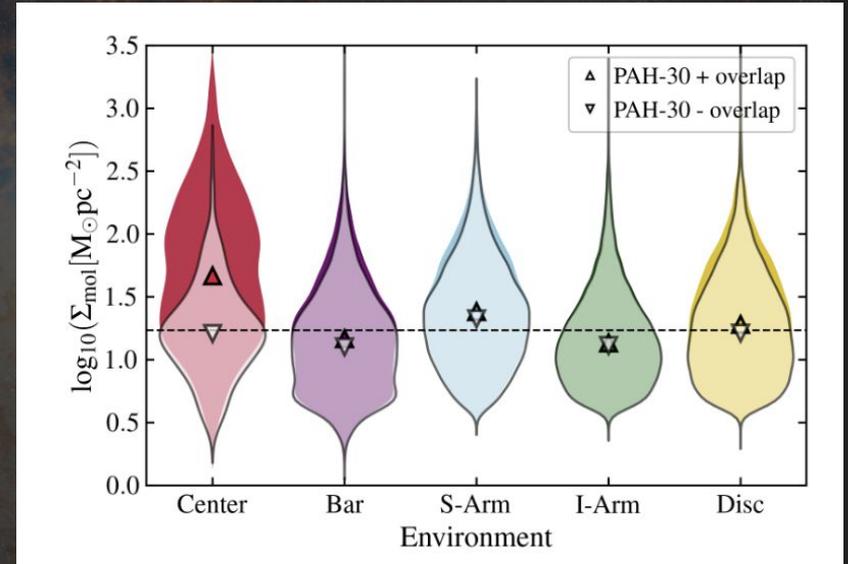
- Since we can use JWST to trace molecular gas, we can also use it to find molecular clouds
- ALMA resolution is great but many “clouds” will in reality be cloud complexes
- JWST improves on this drastically

# 100,000 Molecular Clouds



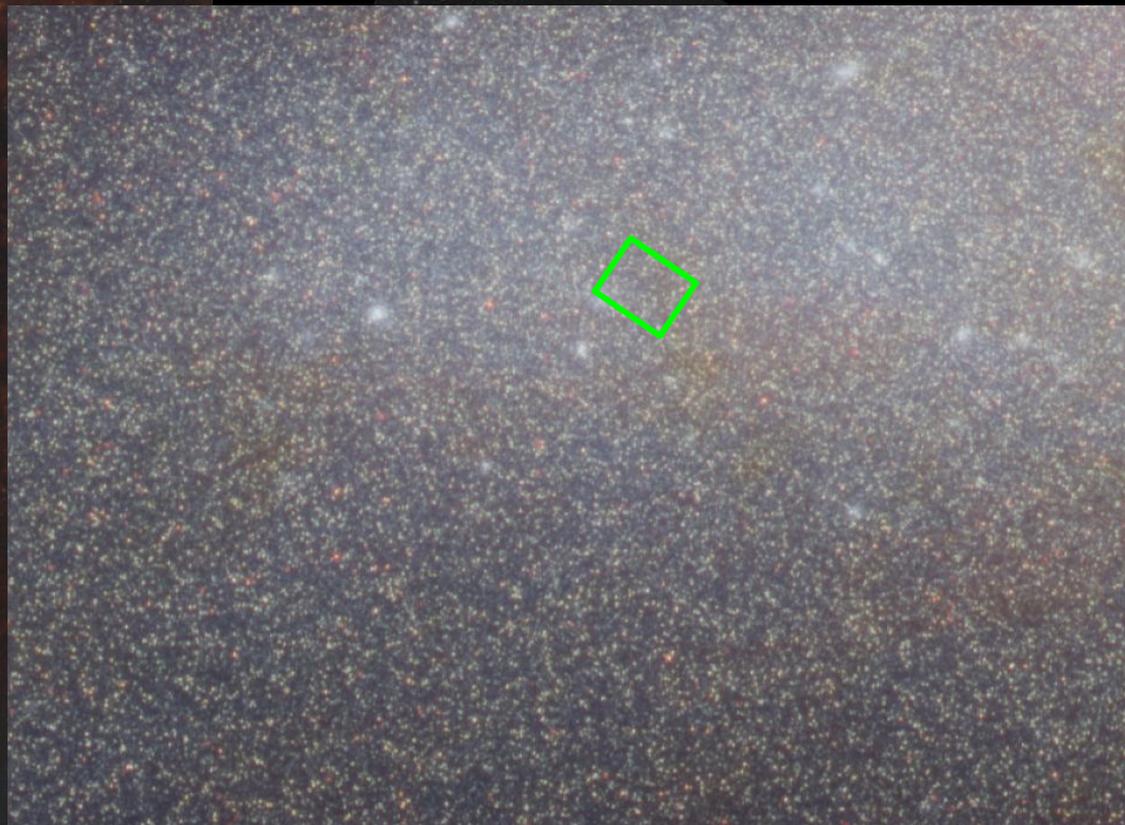
# 100,000 Molecular Clouds

- We can probe to lower intensity and better resolution with JWST than with ALMA
- Centres are complicated, with clouds overlapping along the line-of-sight
  - Spectroscopic information needed here
- Spiral arms have somewhat more massive clouds, on average

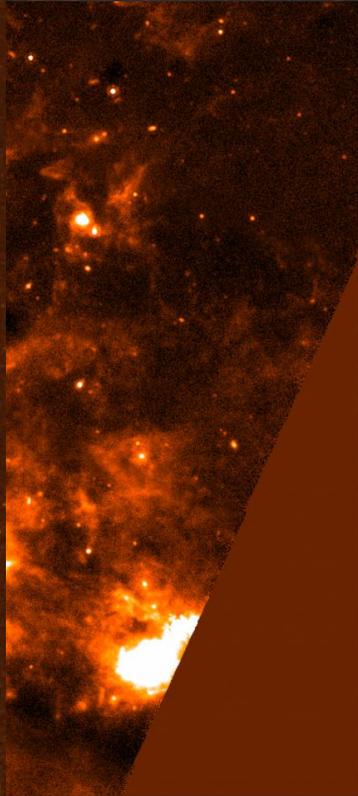
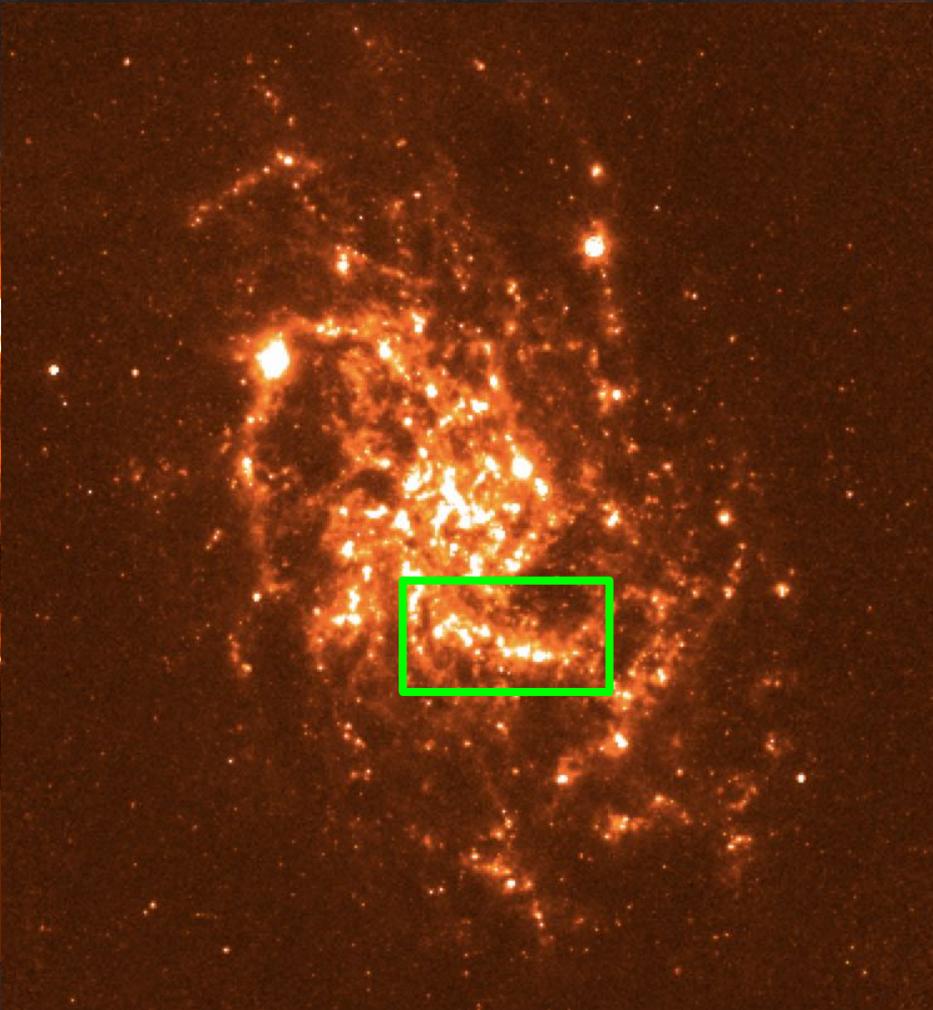
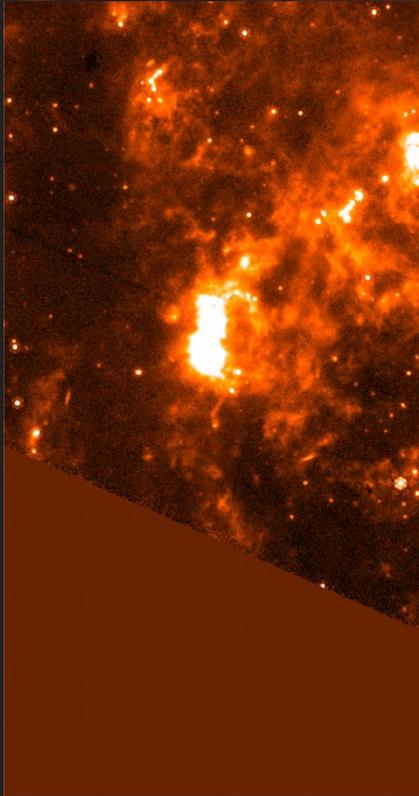


Bazzi+, 2025

Where next?



Where next?

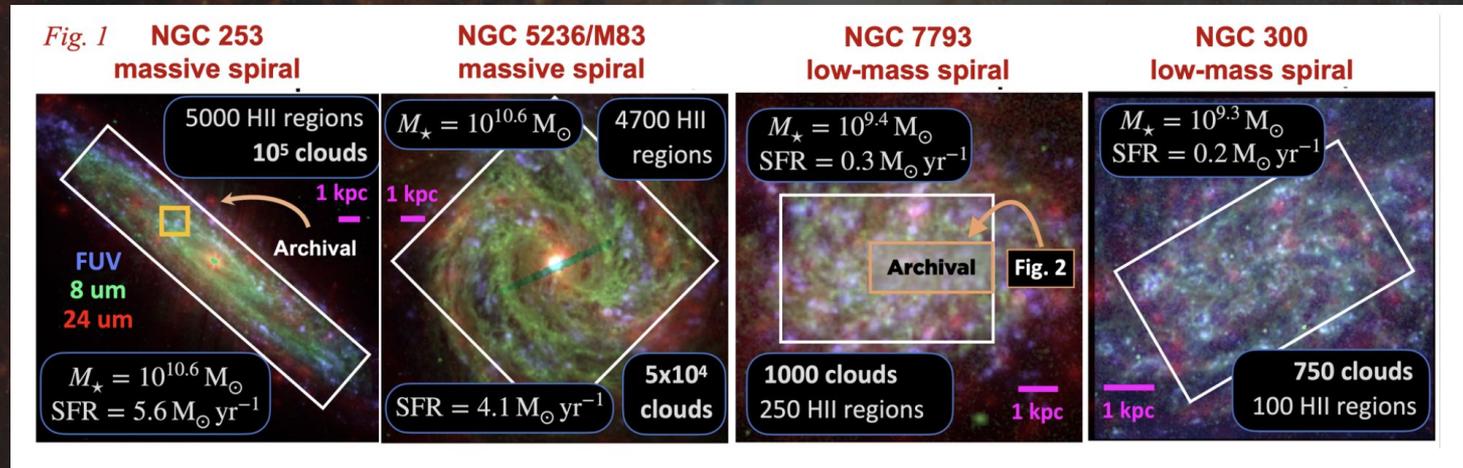


# Moving closer

- JWST is great, but not for:
  - Mapping huge areas of the sky
  - Getting spectroscopic information
- ALMA will remain relevant
  - This is useful because it's what I'm paid to do
- An important next step is to move closer in, and try and resolve clouds

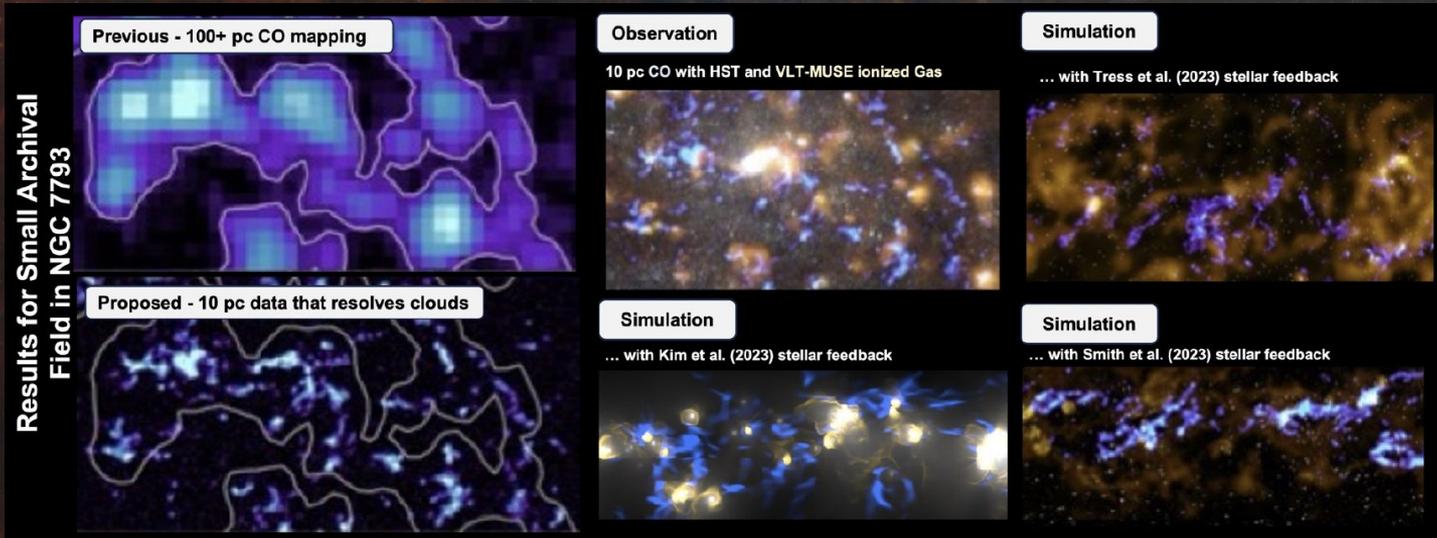
# The ALMA LV-LP

- This is ~800 hours of ALMA time to observe CO in 4 nearby galaxies
- These have distances <5Mpc, so the physical resolution is <25pc
- ~500 hours already observed!
  - It chugs on my computer all day, every day



# Key Science with the LV-LP

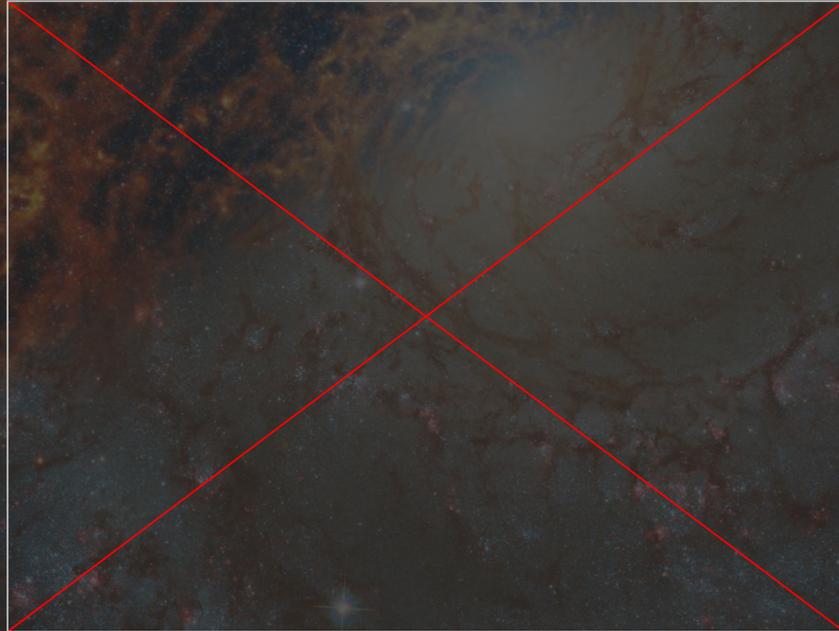
- Comparisons with “realistic” feedback models in simulations



# Key Science with the LV-LP

- The complicated velocity structure of galaxies
  - This is impossible with JWST

Williams+LGLBS in prep.



# Key Science with the LV-LP

## Theoretical sequence of early stellar feedback



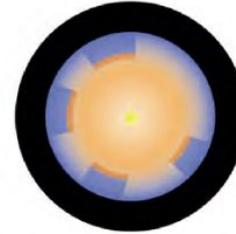
ultra-compact HII region  
size  $\approx 0.1$  pc



(compact) HII region  
size  $\sim 1$  pc



expanded HII region  
size  $\sim 10$  pc



dissolving HII region  
size  $> 10$  pc

Individual regions in different states of evolution form a statistical “movie”

Cold gas mass, kinematics, morphology from CO

Feedback strength and stellar content from VLT-MUSE and *Hubble*



# A final note on my biases

- PHANGS is the first large project I've been involved with, but stands on the shoulders of other giants
  - See PAWS, MaNGA, CALIFA, HERACLES, SINGS, etc.
- Other, similar efforts exist!
  - See ALMAQUeST, VERTICO, KILOGAS, MAUVE, GECKOS, FEAST, etc.
- Other galaxies also exist!
  - There's a whole northern hemisphere that ALMA can't see much of, that contains e.g. M33, M31, and other fun galaxies

# Take-home messages

- JWST is *very cool* for looking at nearby galaxies
- There's a lot we don't understand!
  - Dust physics
  - The youngest stars
  - The overall morphology of the ISM
- JWST + other observatories offer a key way forward to understanding this
  - Inform subgrid models for future generations of simulations
  - Put unresolved, high-redshift observations into context