

Galactic Center Star Formation in the Context of Gas Flows and the Dust Ridge

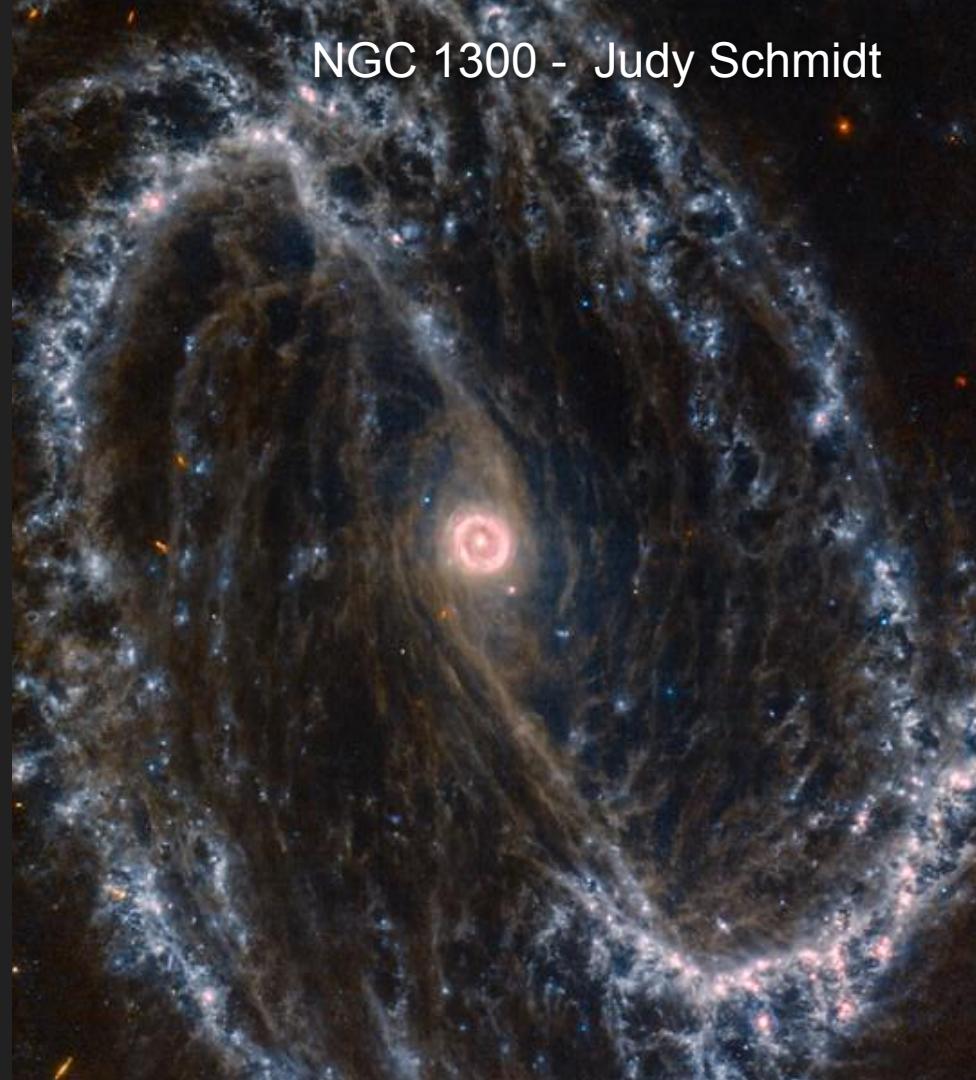
Savannah Gramze

Committee: Adam Ginsburg, Jaehan Bae,
Desika Narayanan, Jorg Peters

The Galactic Center

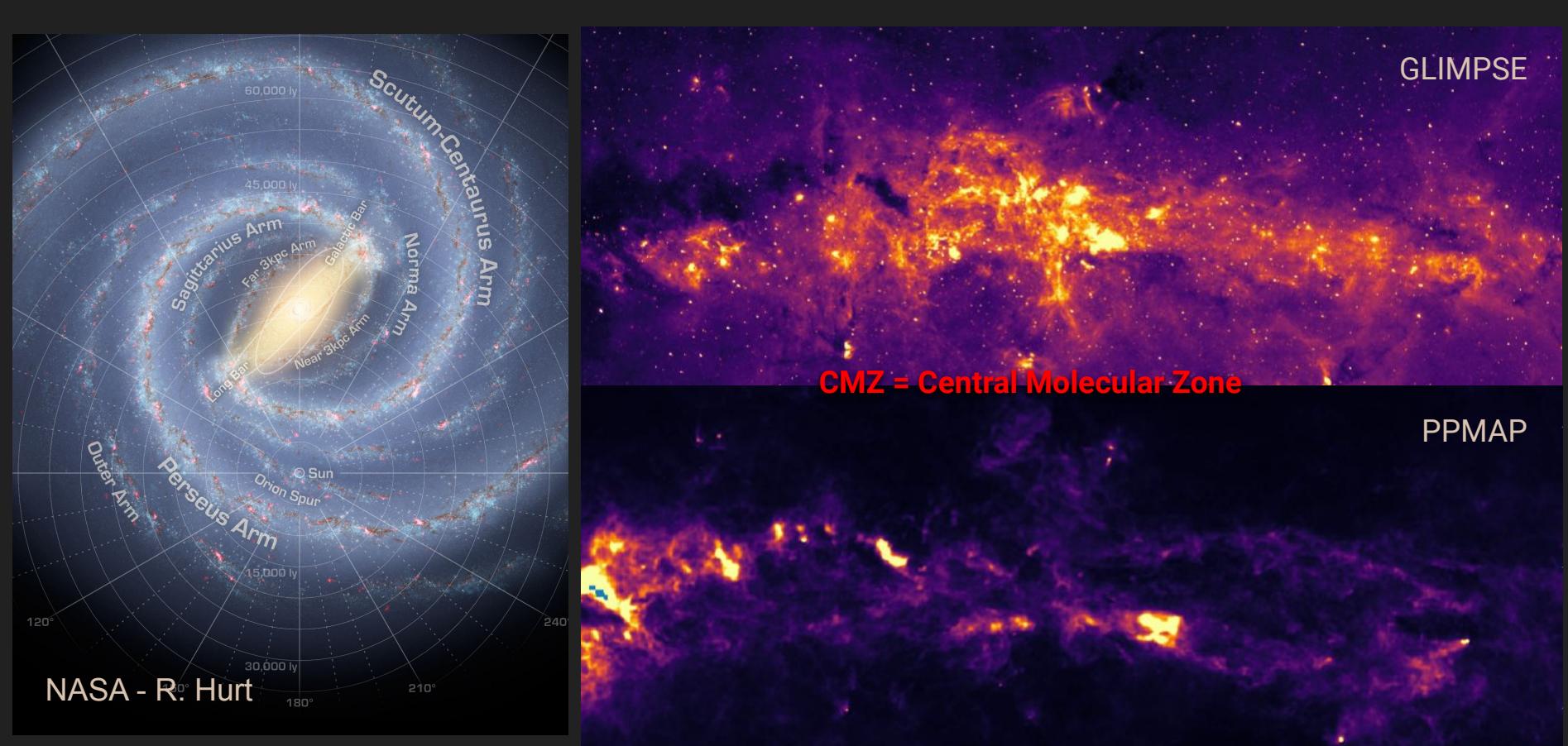
Galactic Center
Structure and Dynamics

NGC 1300 - Judy Schmidt



This image shows a dark, grainy texture representing a star field. Several bright, yellowish-orange stars of varying sizes are scattered across the frame, with one prominent star in the lower-left quadrant and others in the upper-right and center. The background is a deep black.

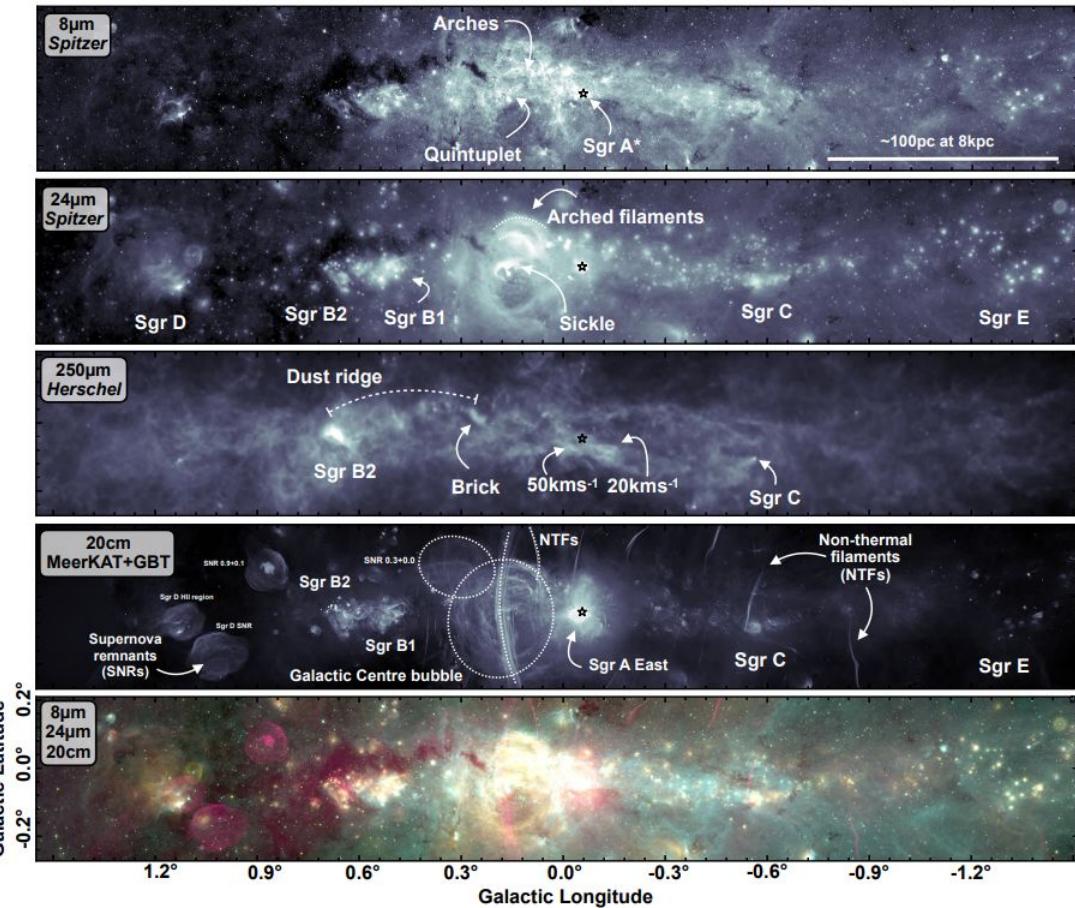
SDSS - Optical



The Galactic Center

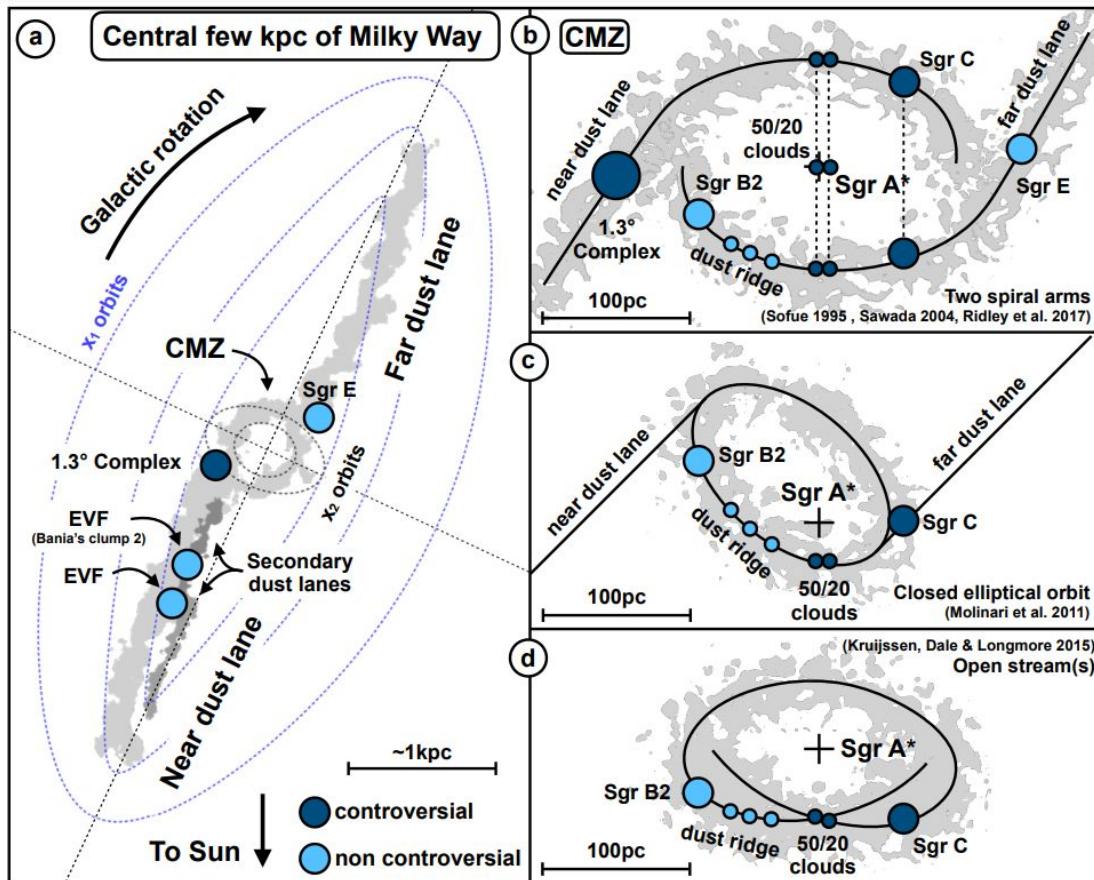
Galactic Center: Notable Features

- Sgr A* at the center
- Dense Star Clusters
- Star Formation Regions
 - Sgr B2
- The Dust Ridge
 - Includes Cloud C!
- Sgr C (different from Cloud C)
- Sgr E
- Lots of gas and dust!
 - Gas is hot and turbulent!
 - 80% of the Galaxy's cold molecular gas

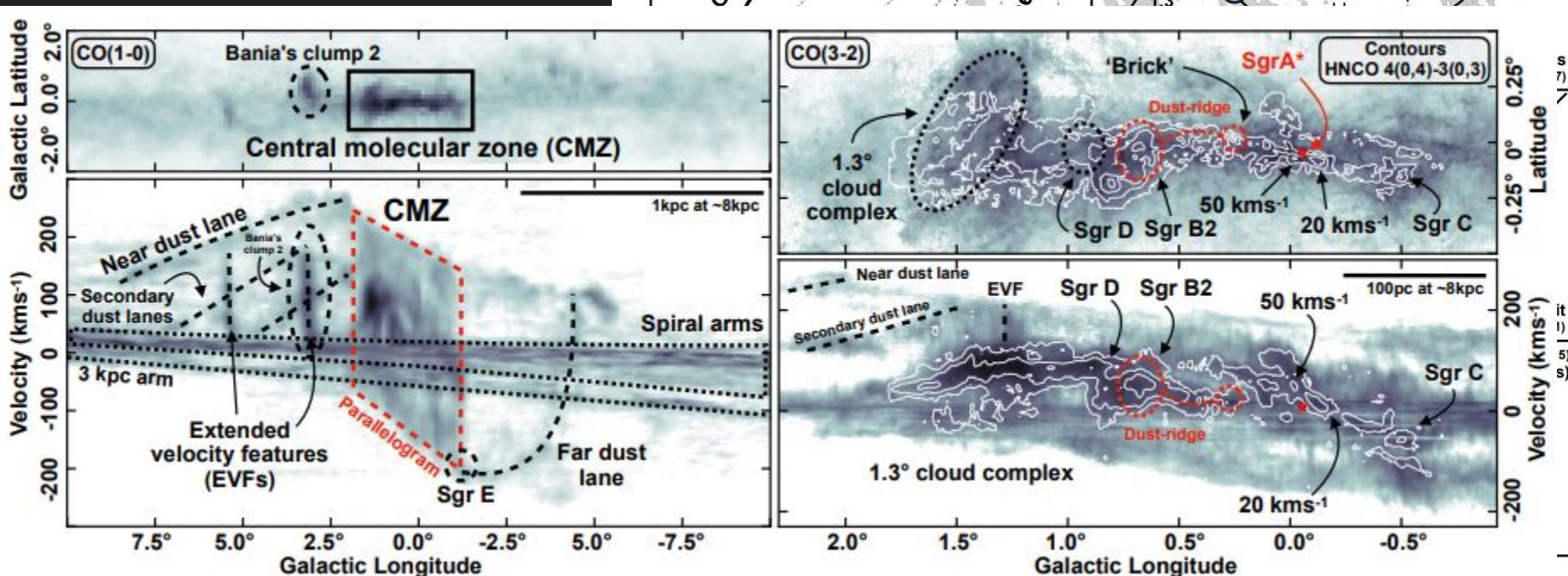


Galactic Center: Structure and Kinematics

- Dust lanes feed material from X1 orbits (long, bar orbits) to X2 orbits (Central Molecular Zone)
- Material orbits around the Galactic Center on X2 orbits, but what does that really look like?
- Three popular models for how molecular gas flows on these orbits.
- Dust ridge clouds silhouetted against the CMZ



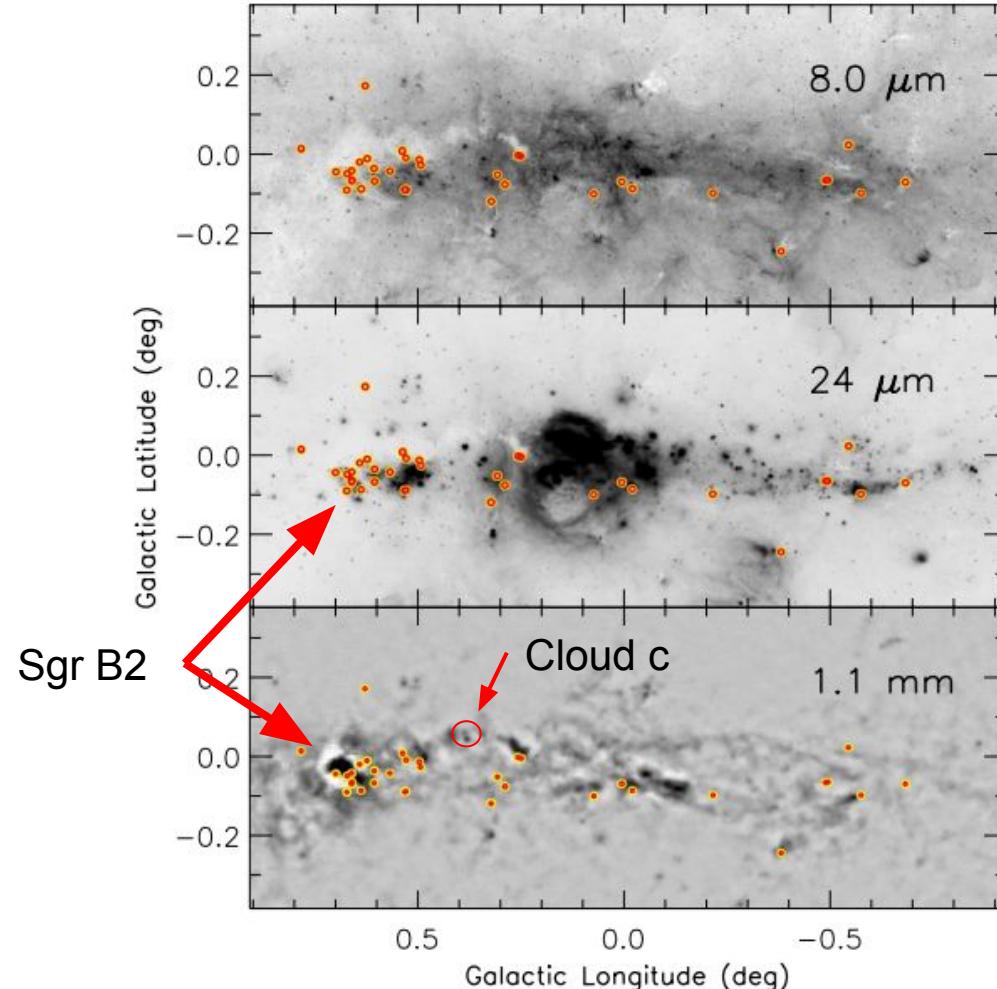
Galactic Center: Structure and Kinematics



Henshaw et al 2022

Galactic Center: Star Formation

- 0.1 Msun / year
- 10% of Galactic star formation rate
- Not proportional to the amount of cold molecular gas available
- Most Galactic Center star formation seems to happen in Sgr B2
- Why is there so little star formation associated with the rest of the molecular gas in the CMZ?
- Where does this gas come from?

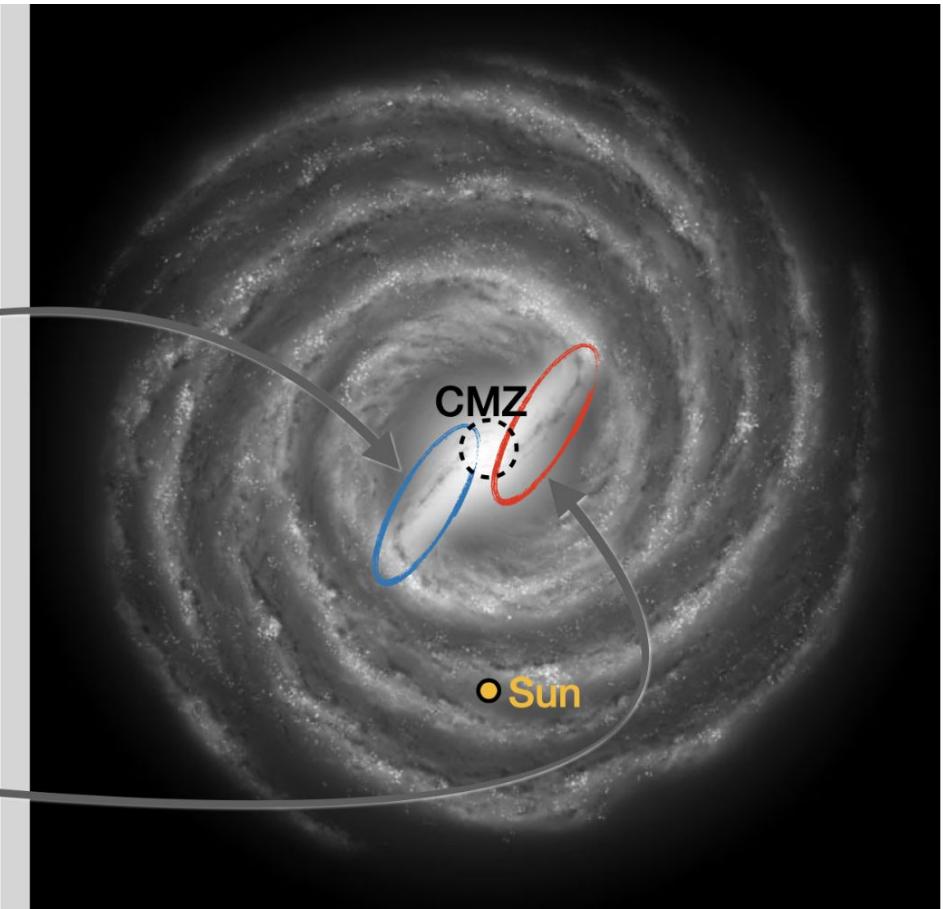
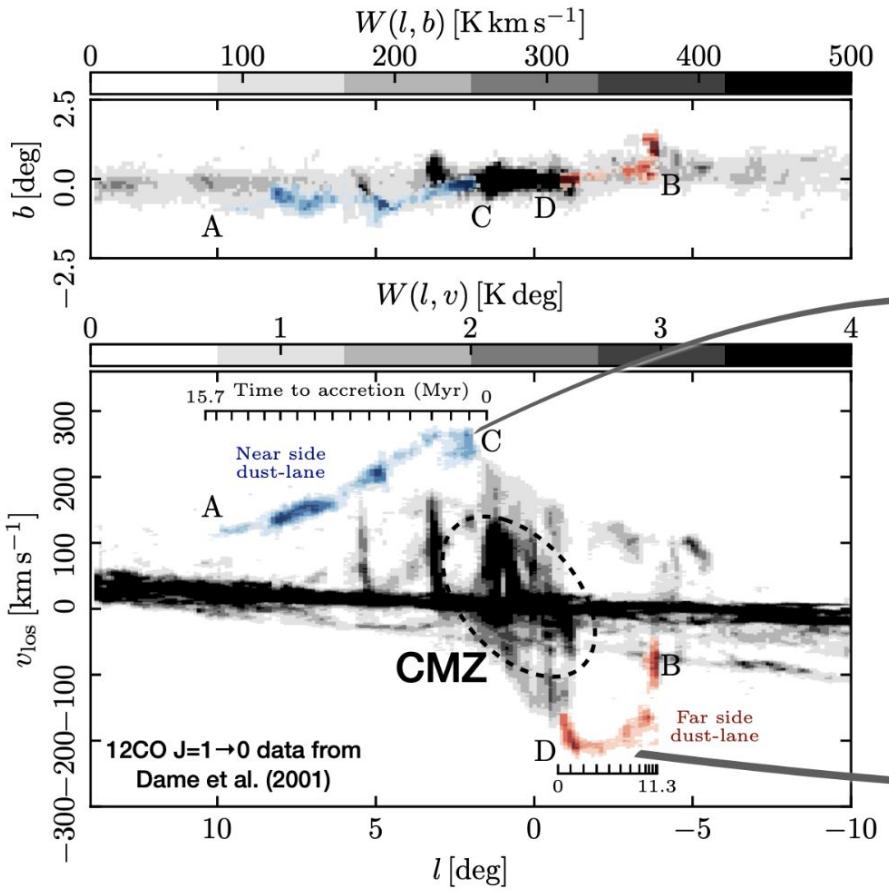


An et al 2011

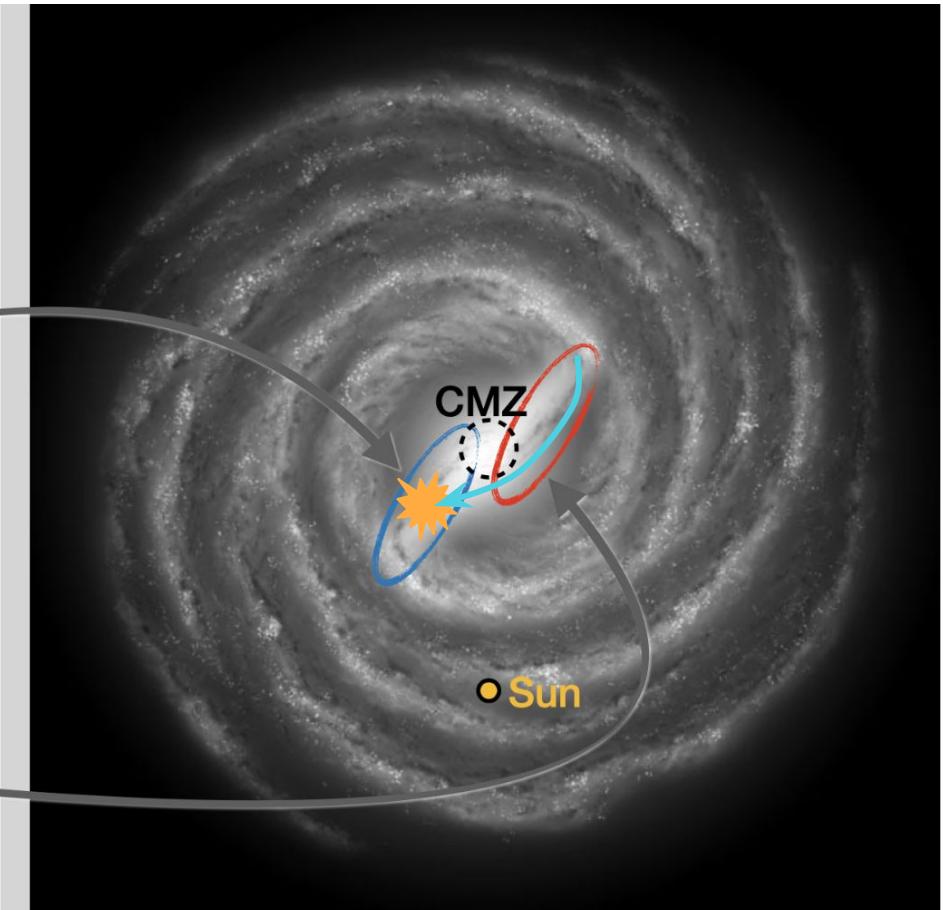
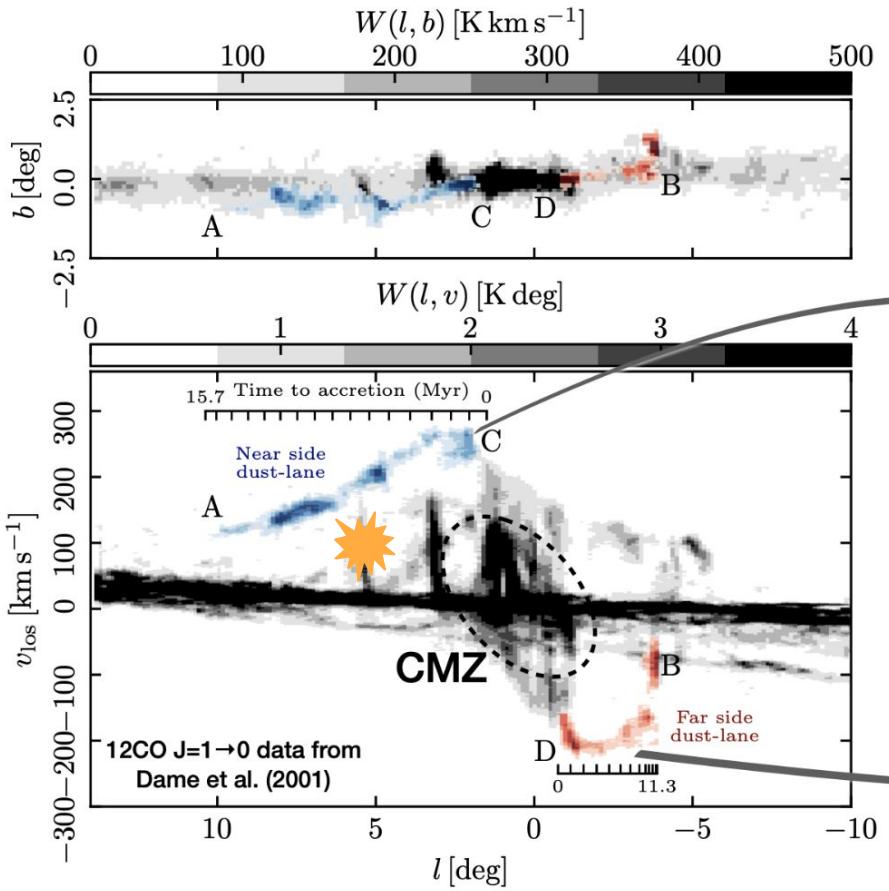
The Bar Lanes

Galactic Center
Structure and Dynamics

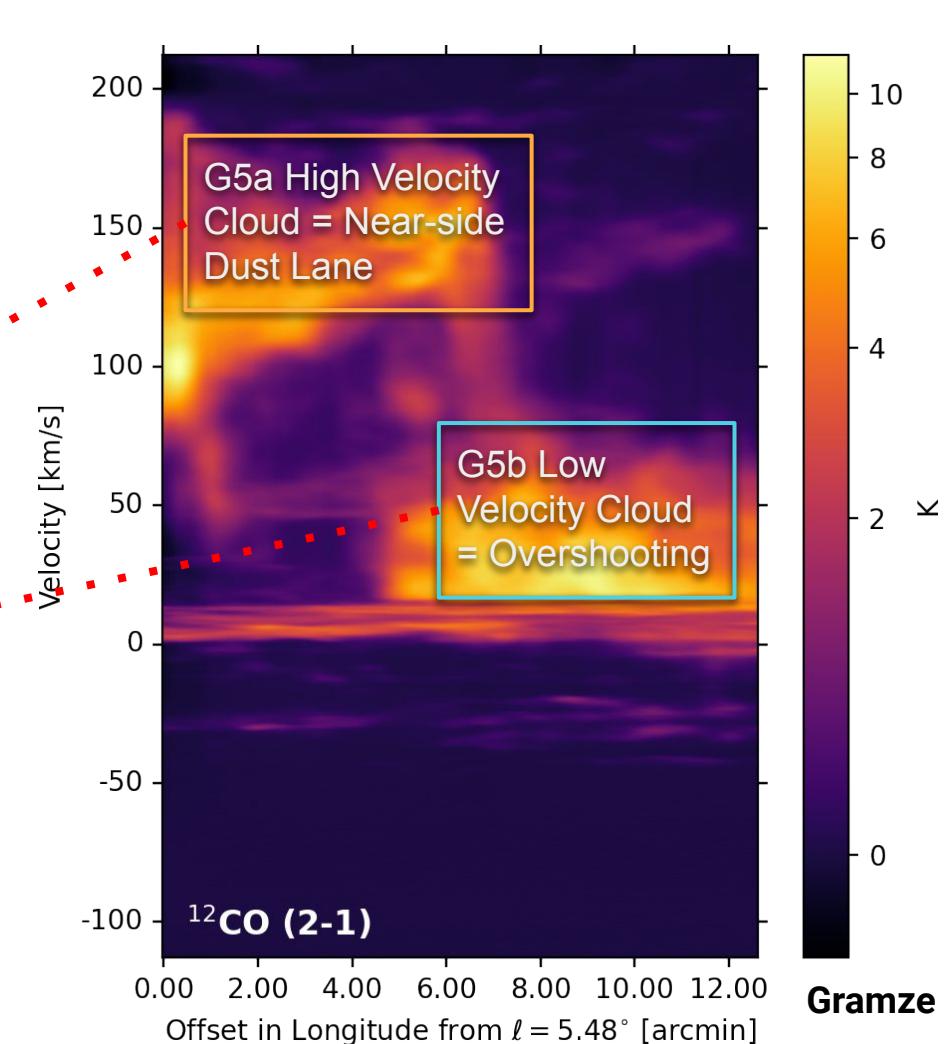
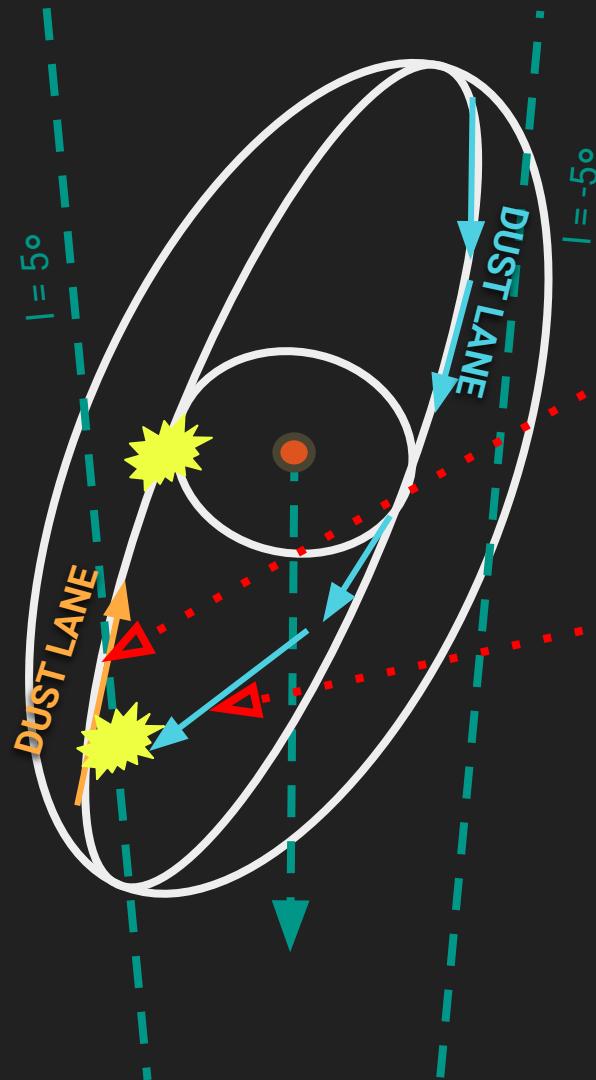
- How does gas get to the Galactic Center?



Sormani et al 2019



Sormani et al 2019

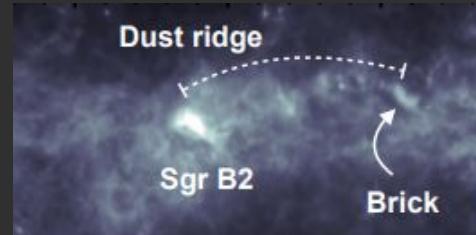


Gramze et al 2023

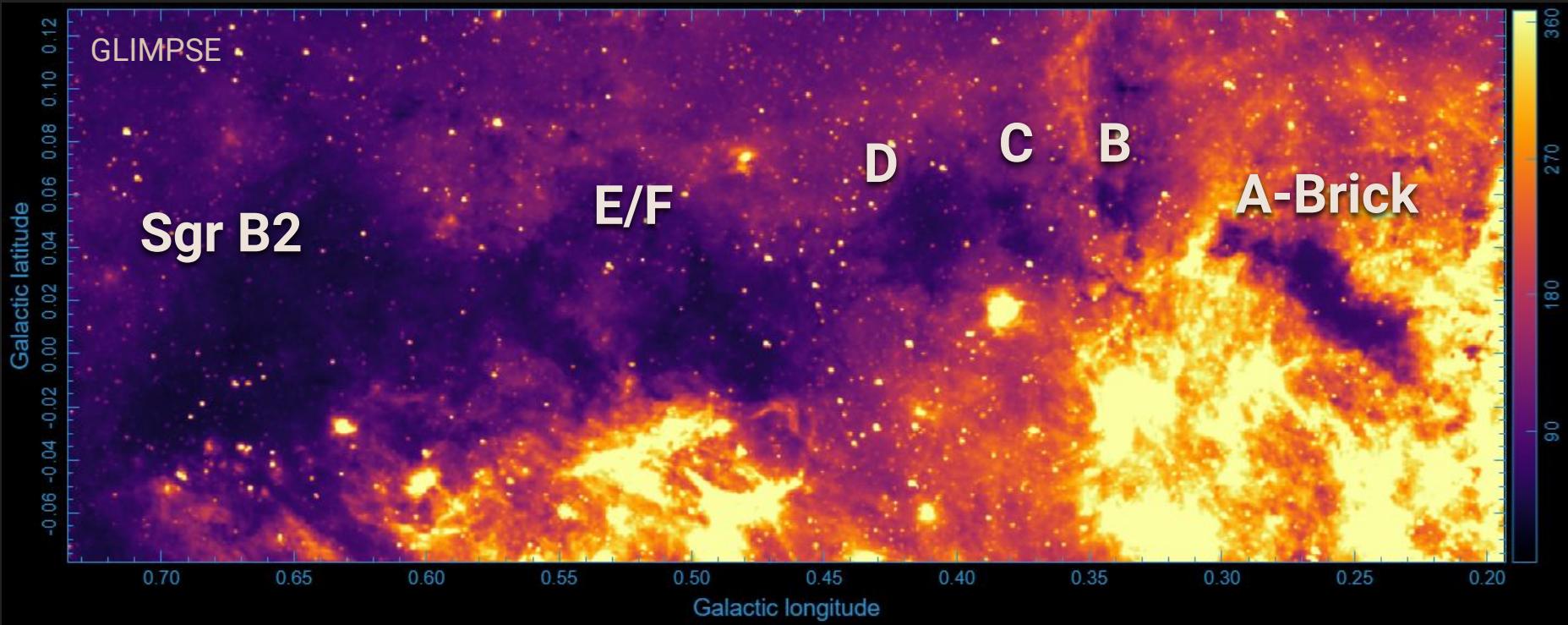
The Dust Ridge

Galactic Center
Structure and Dynamics

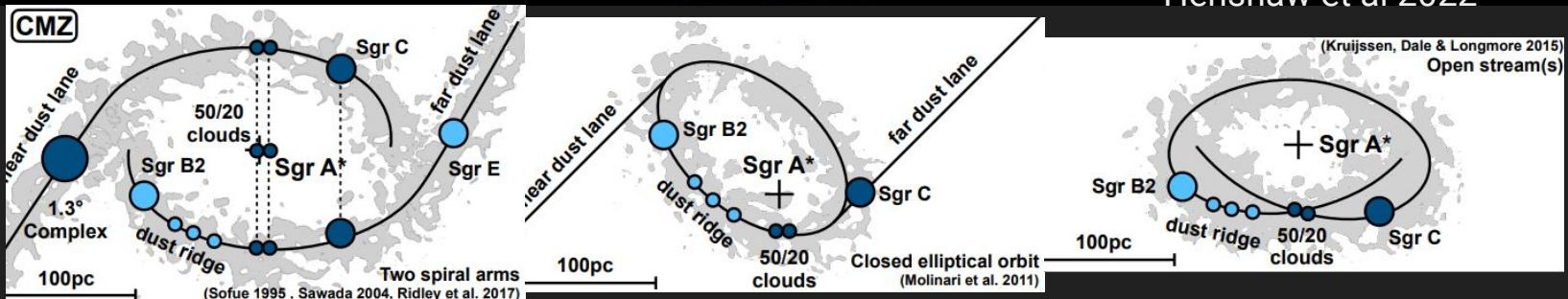
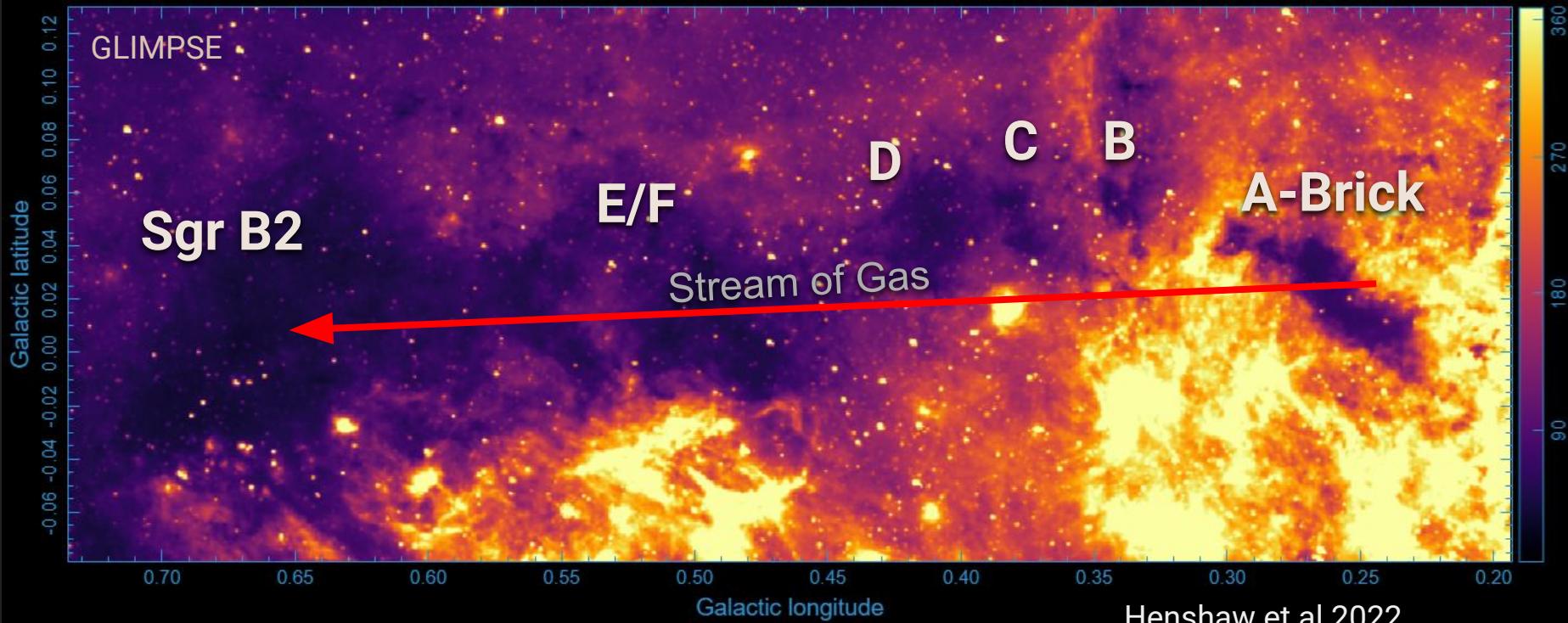
- How does star formation progress along the dust ridge?

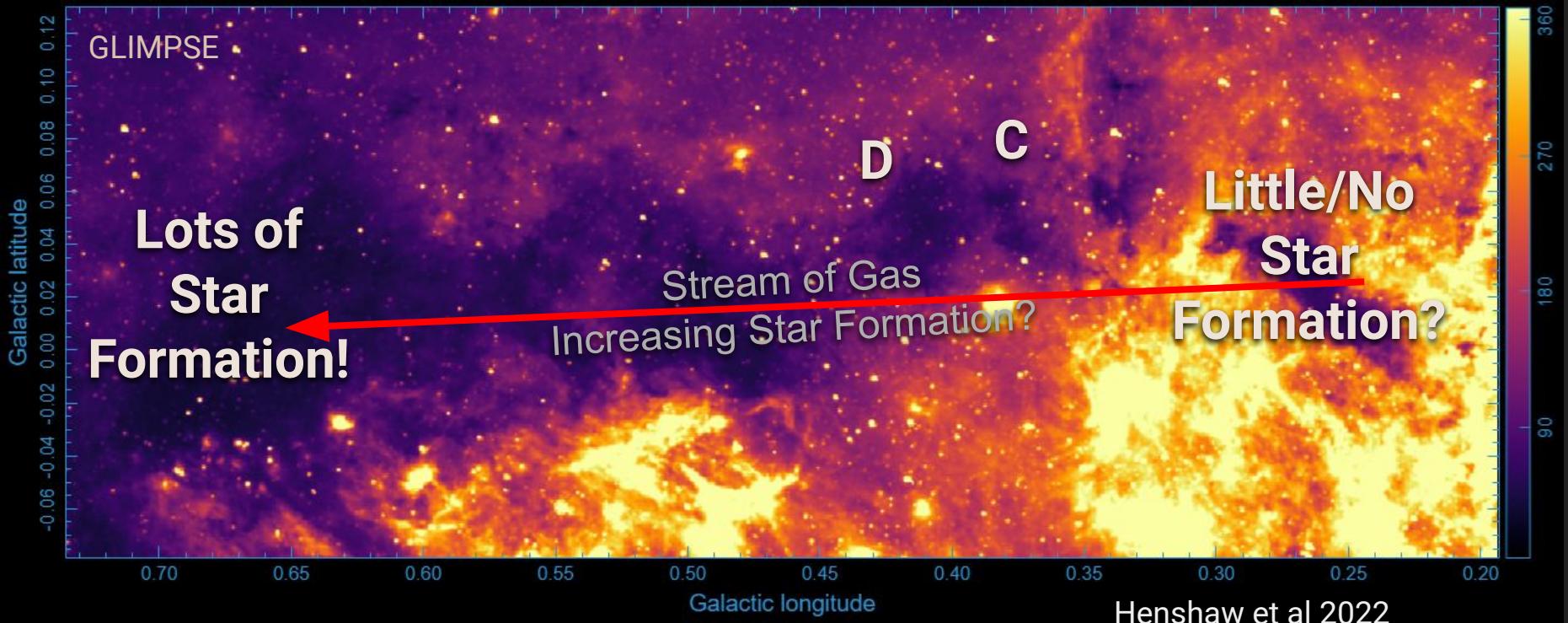


Henshaw et al 2023

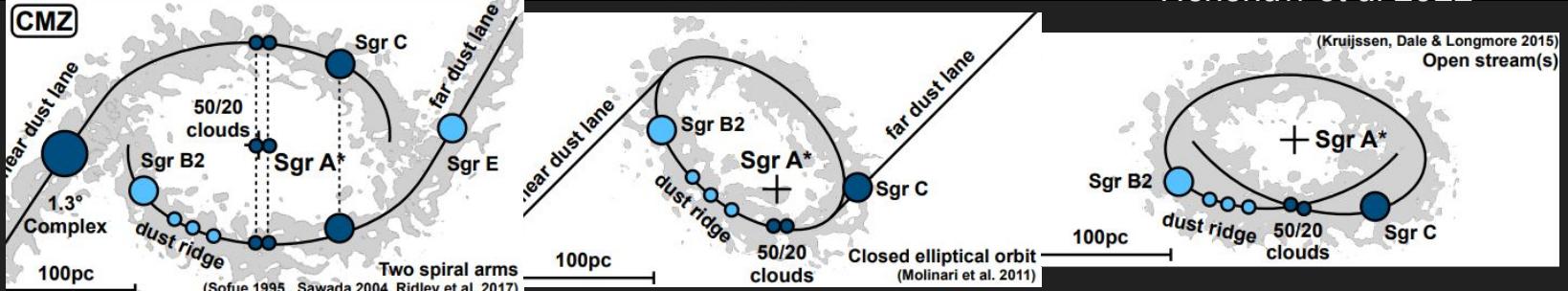


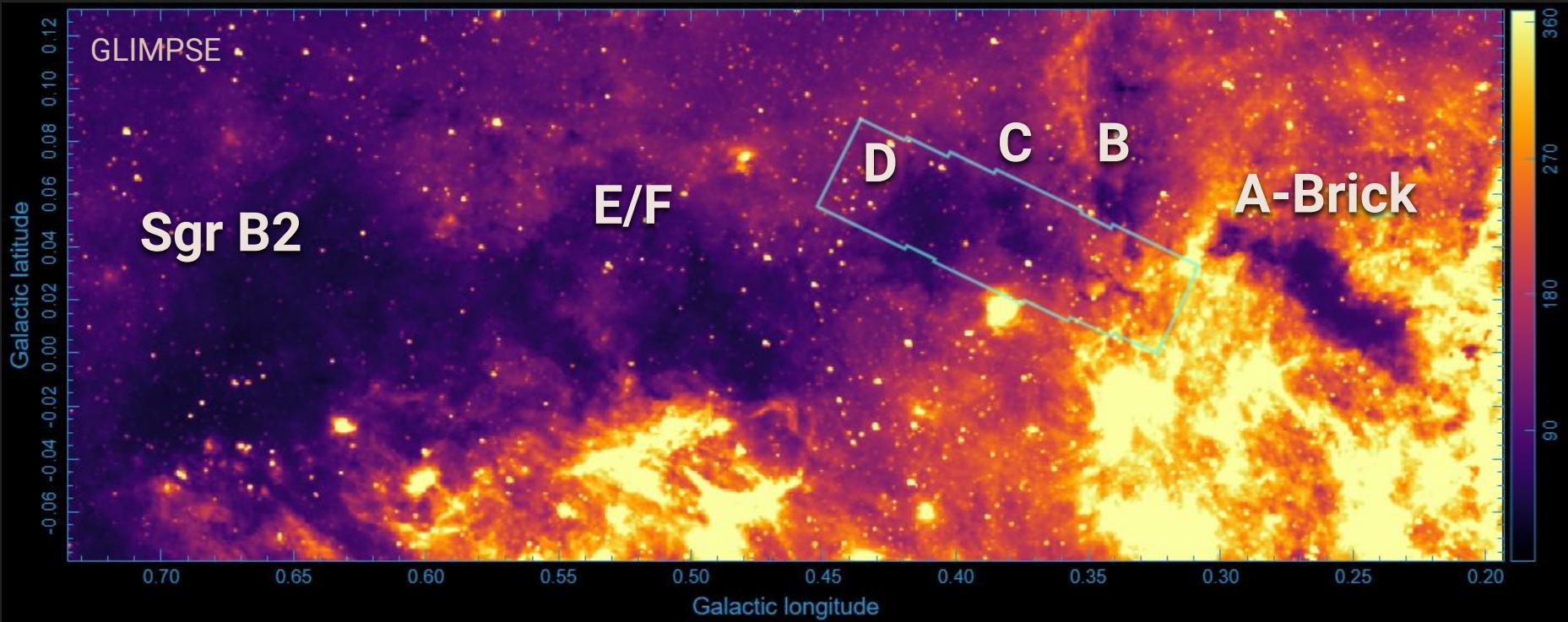
The Dust Ridge



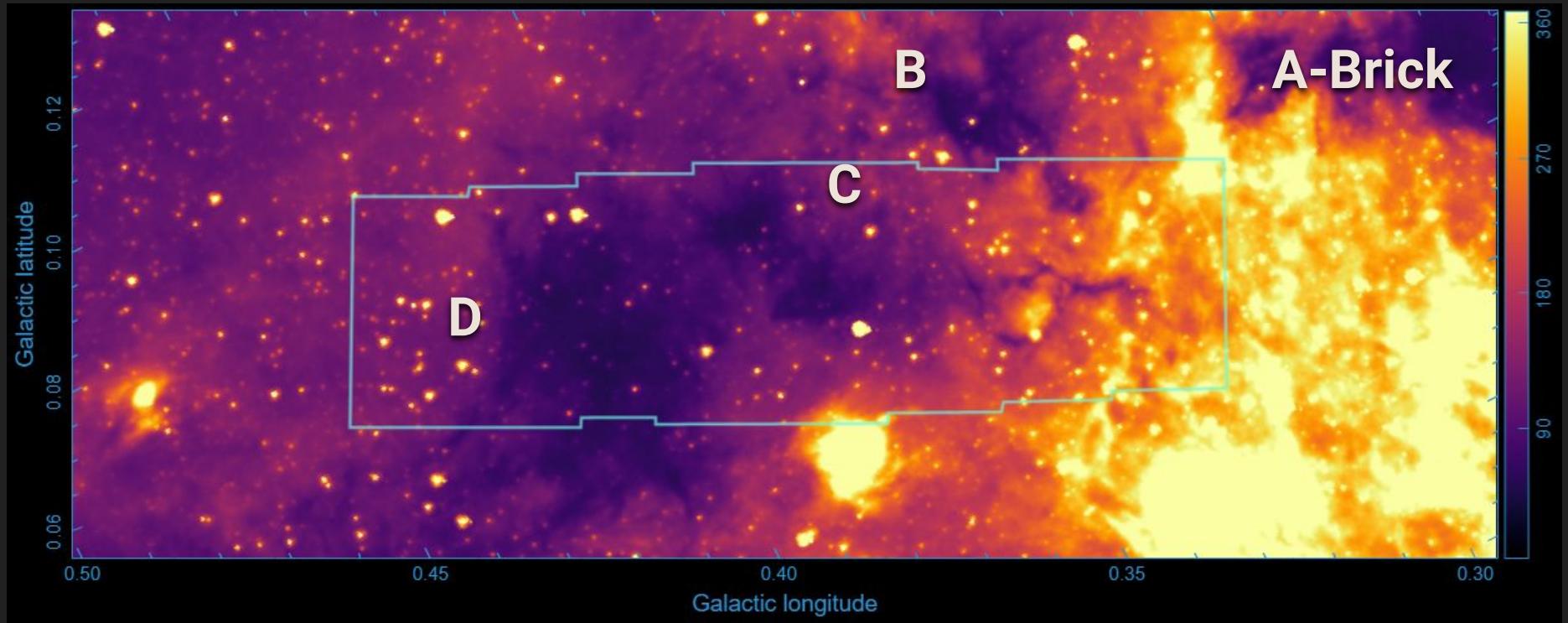


Henshaw et al 2022



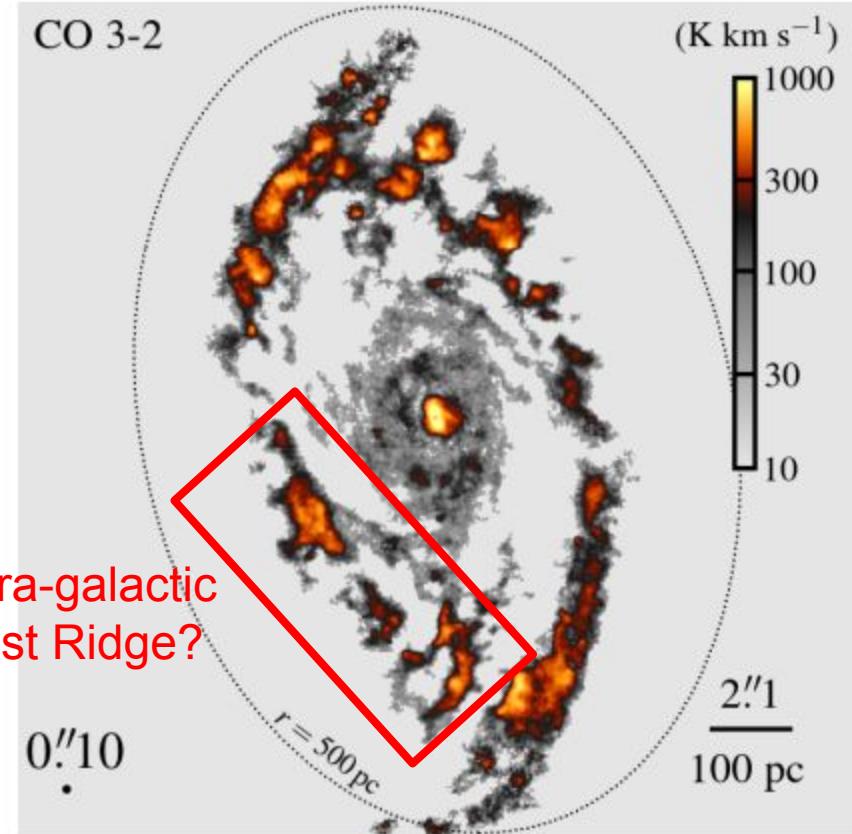


The Dust Ridge - NIRCam field



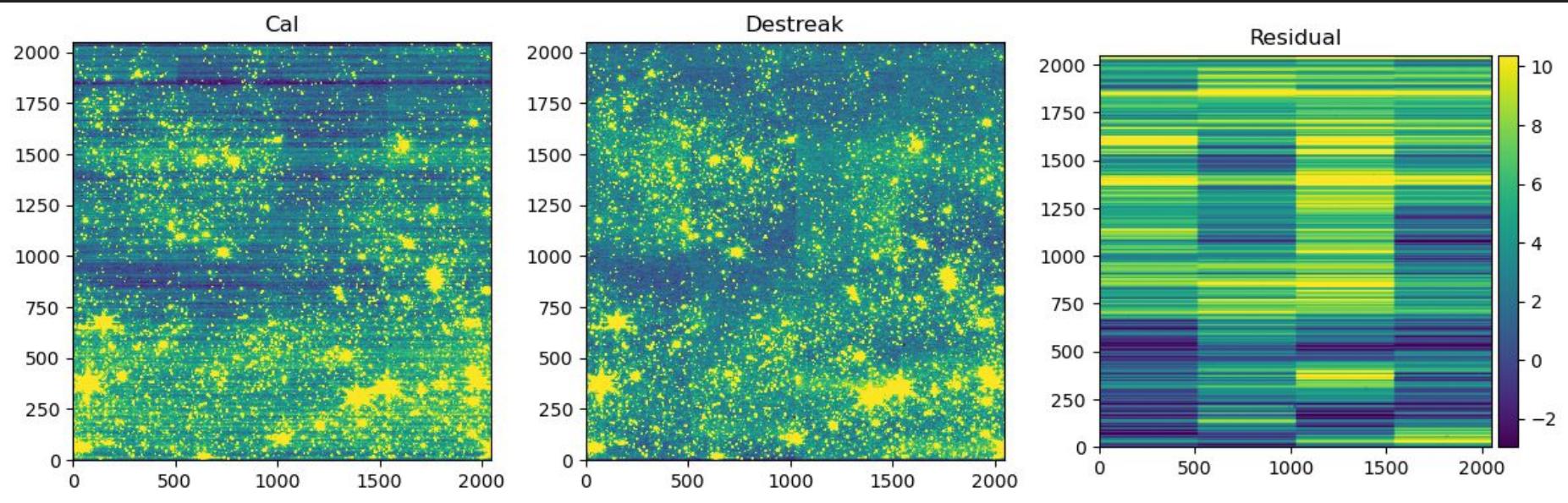
Goals for Studying the Dust Ridge

- Models of gas streams in the CMZ agree that the dust ridge is likely one stream of gas.
- This gas is likely on the same orbital path as Sgr B2. (Sgr B2 = very active SFR)
- Verify that the clouds are part of the dust ridge.
- Learn more about star formation in the CMZ
- How does star formation progress along the dust ridge?

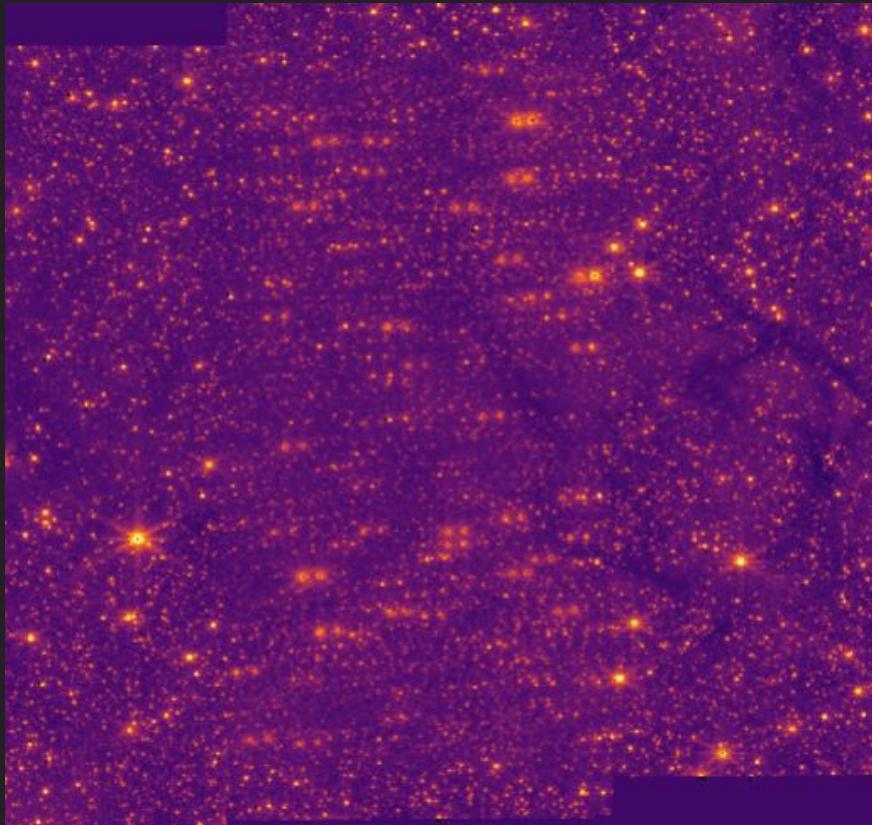
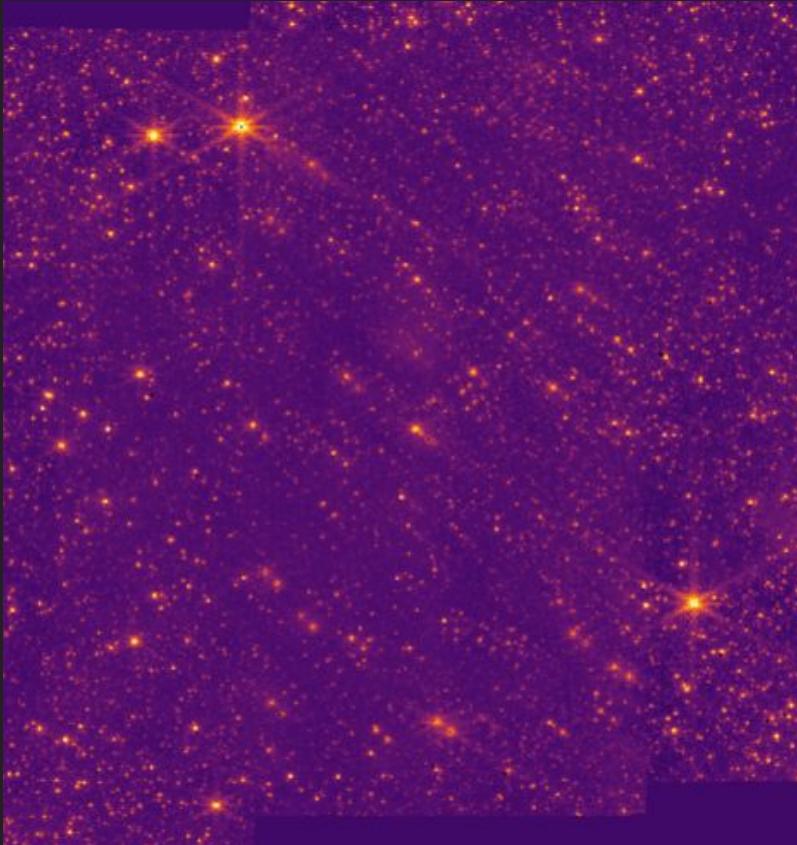


Sun et al 2024

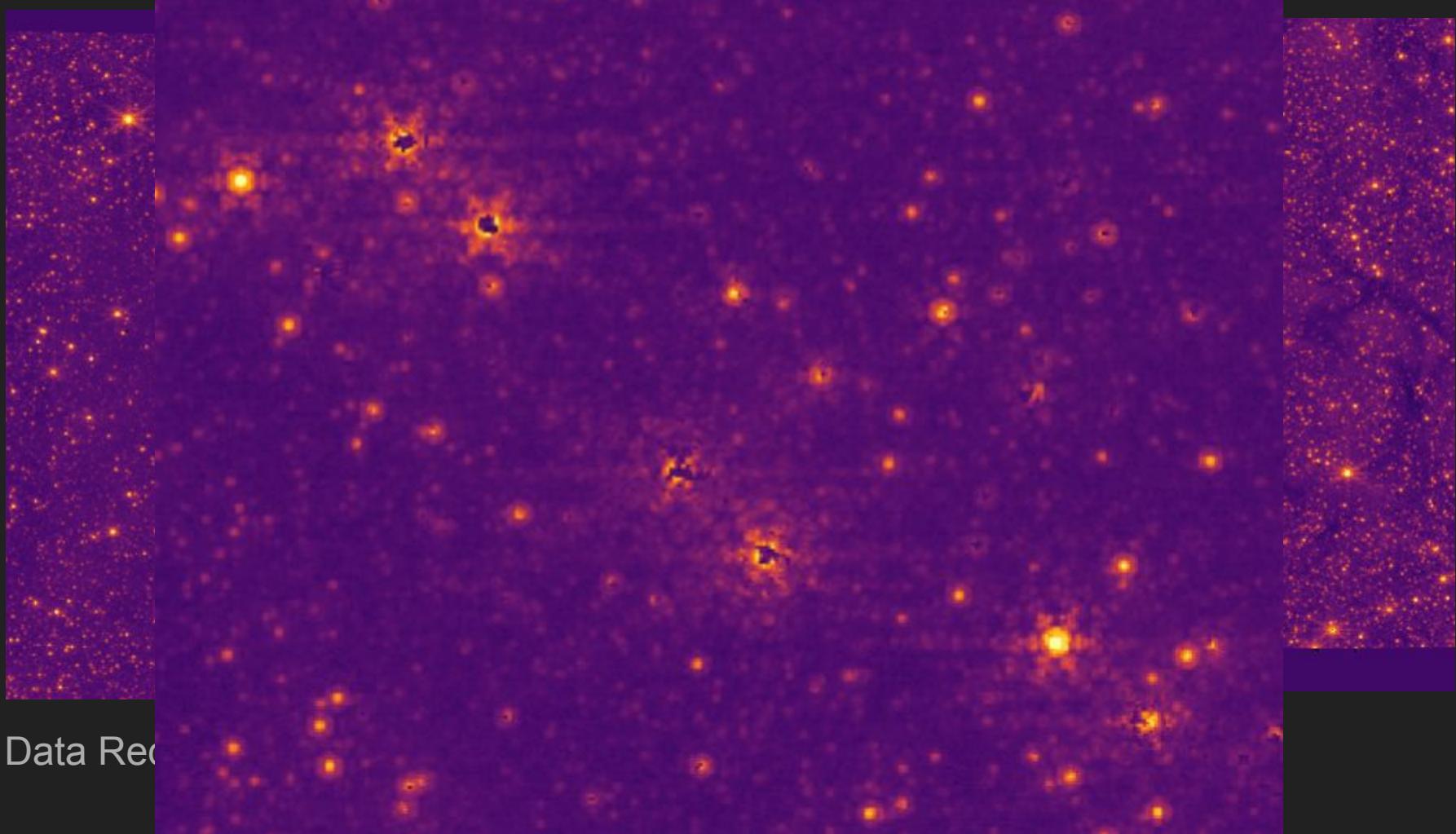
Data Reduction



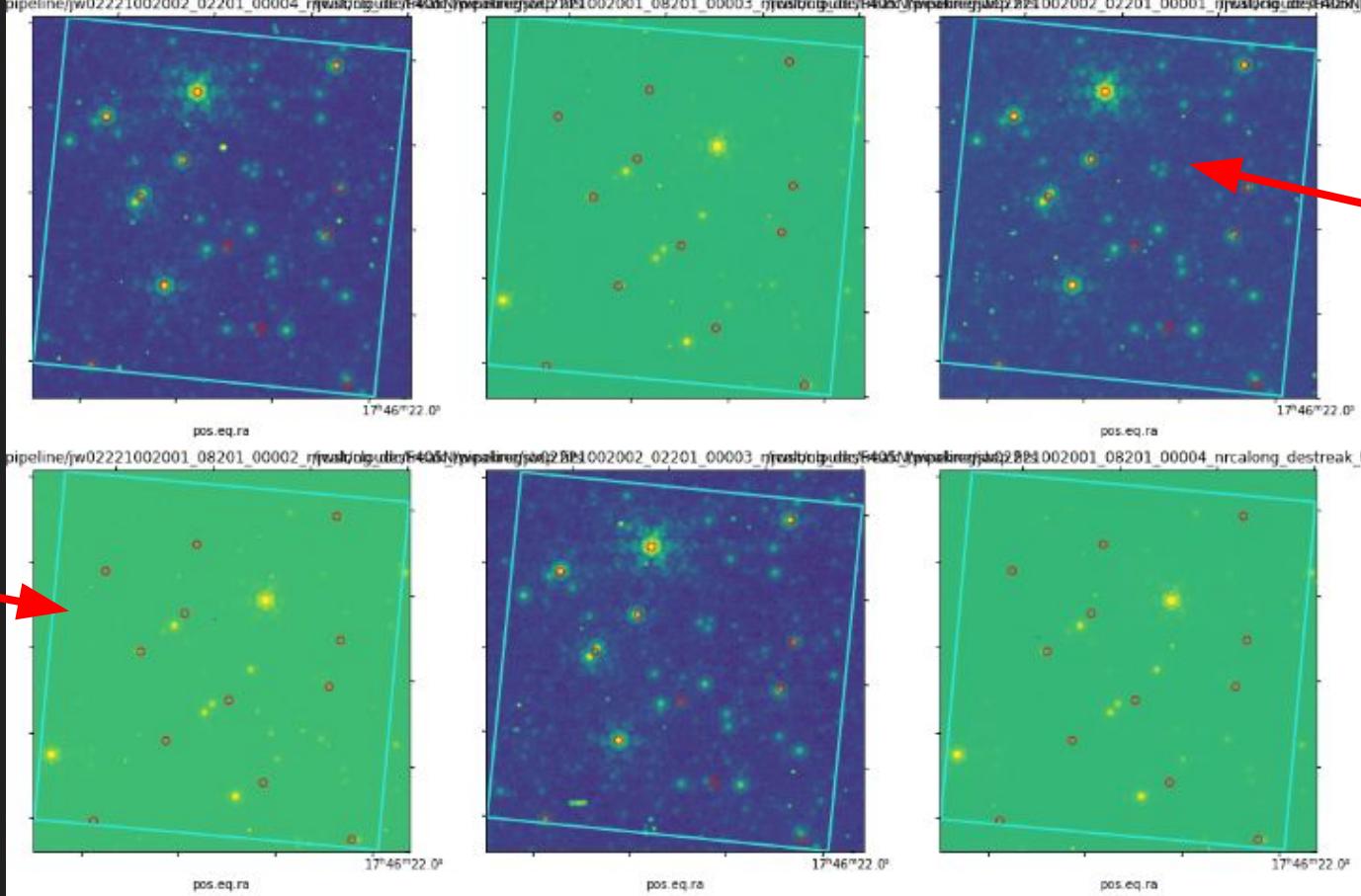
Data Reduction - Destreak - F212N



Data Reduction - The Offset Problem: Double Stars

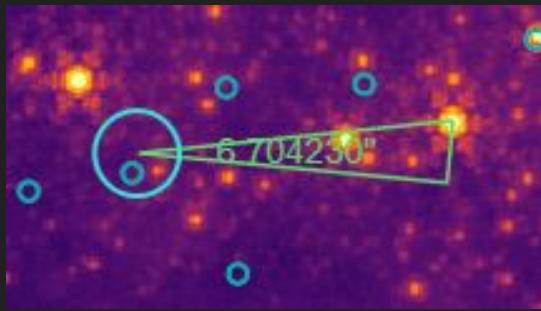


Data Rec

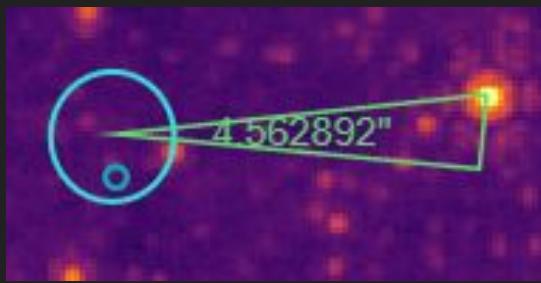


The Cause: Tweakreg failed to align all frames

Visit 001

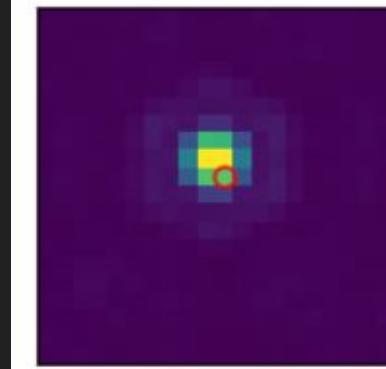


Visit 002

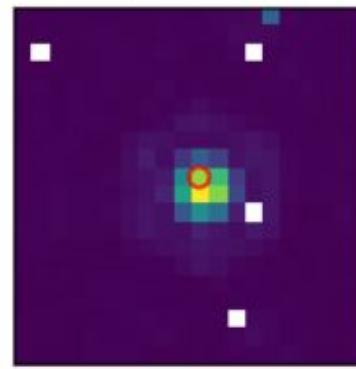


Refining Offset Correction

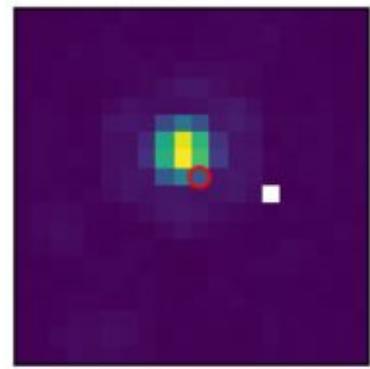
Star 1



Star 2

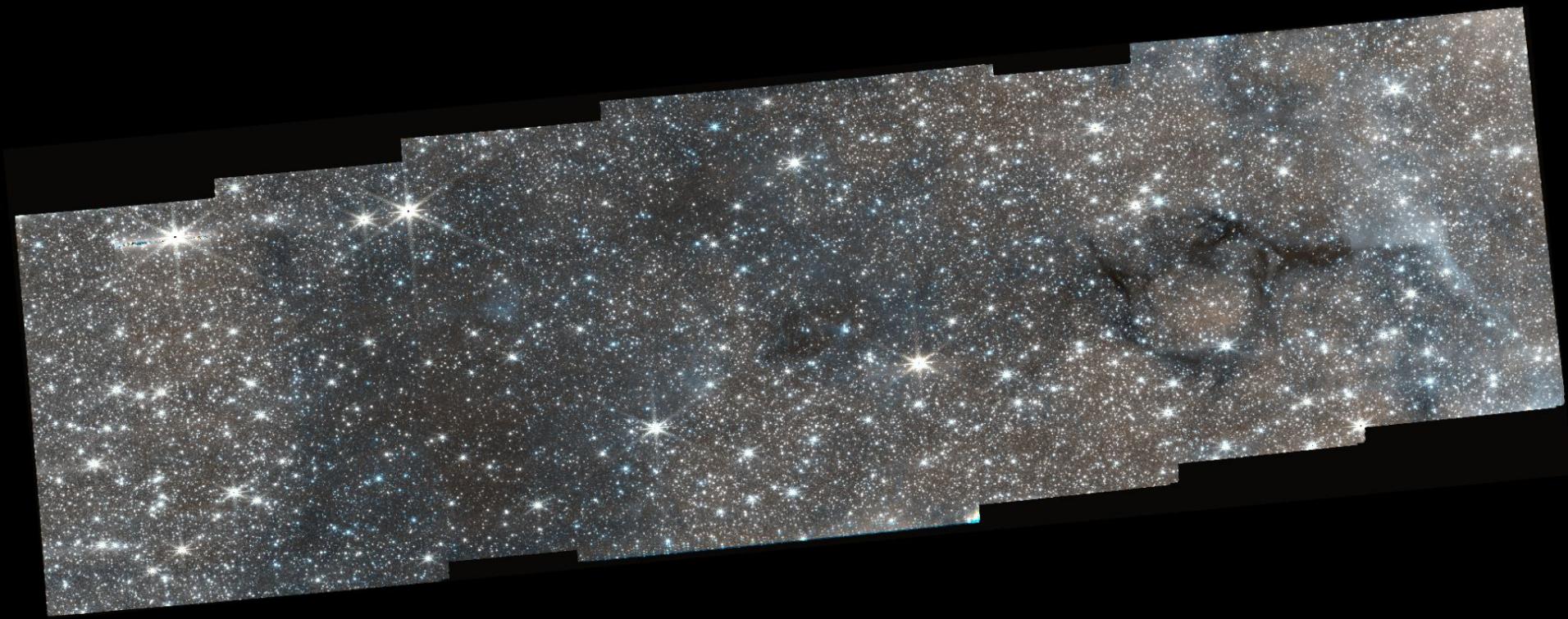


Star 3

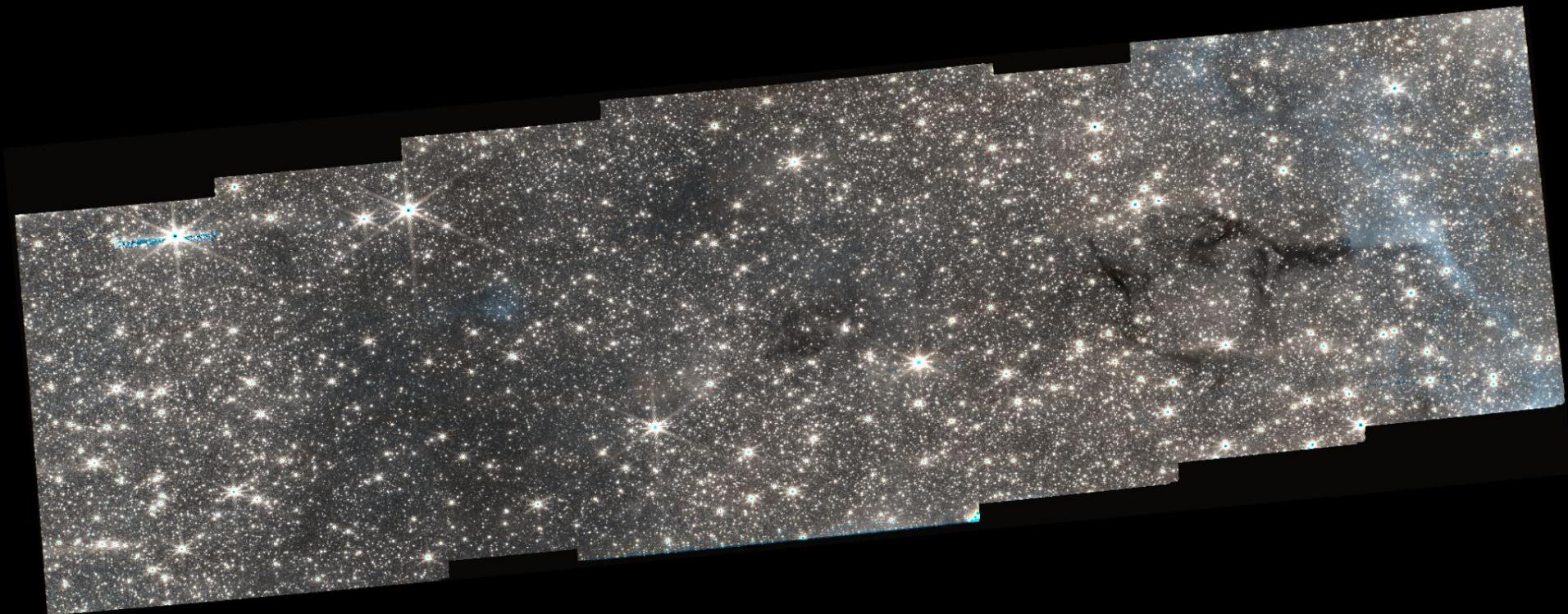


The Solution: Measure Offsets, Apply Before Tweakreg

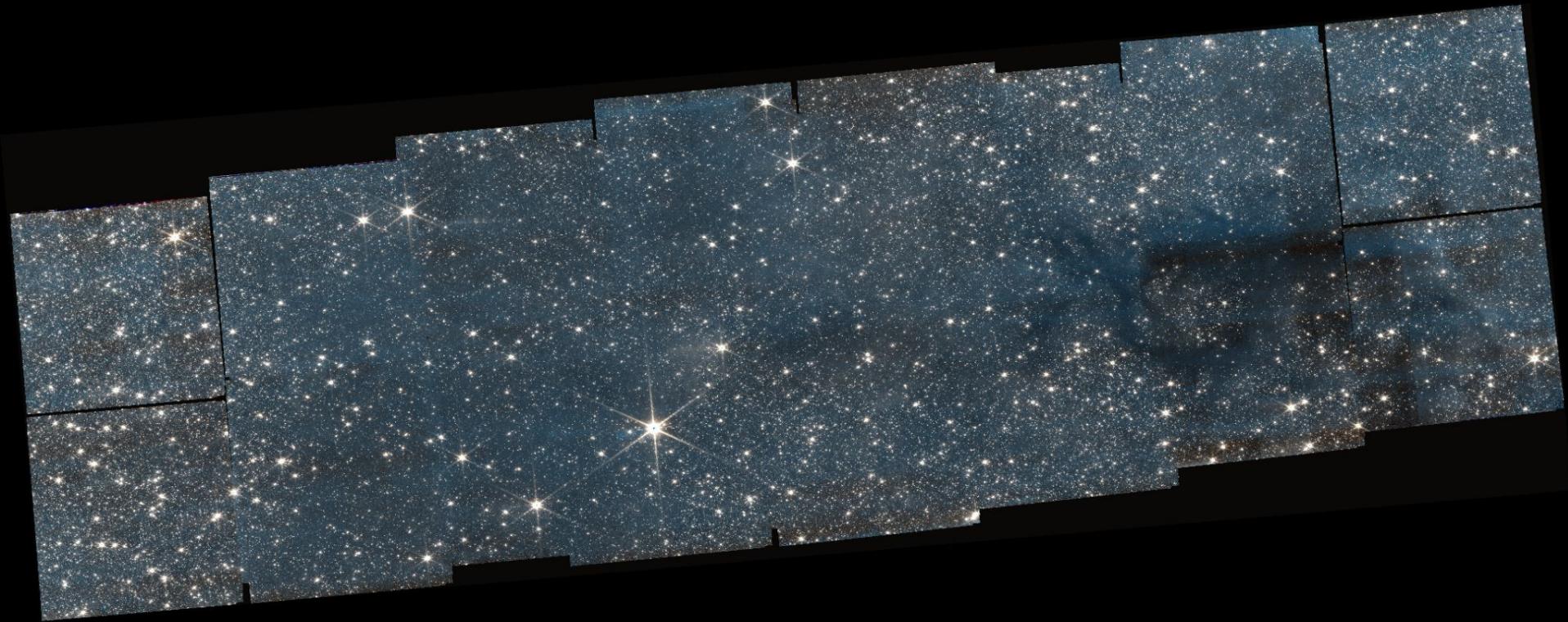




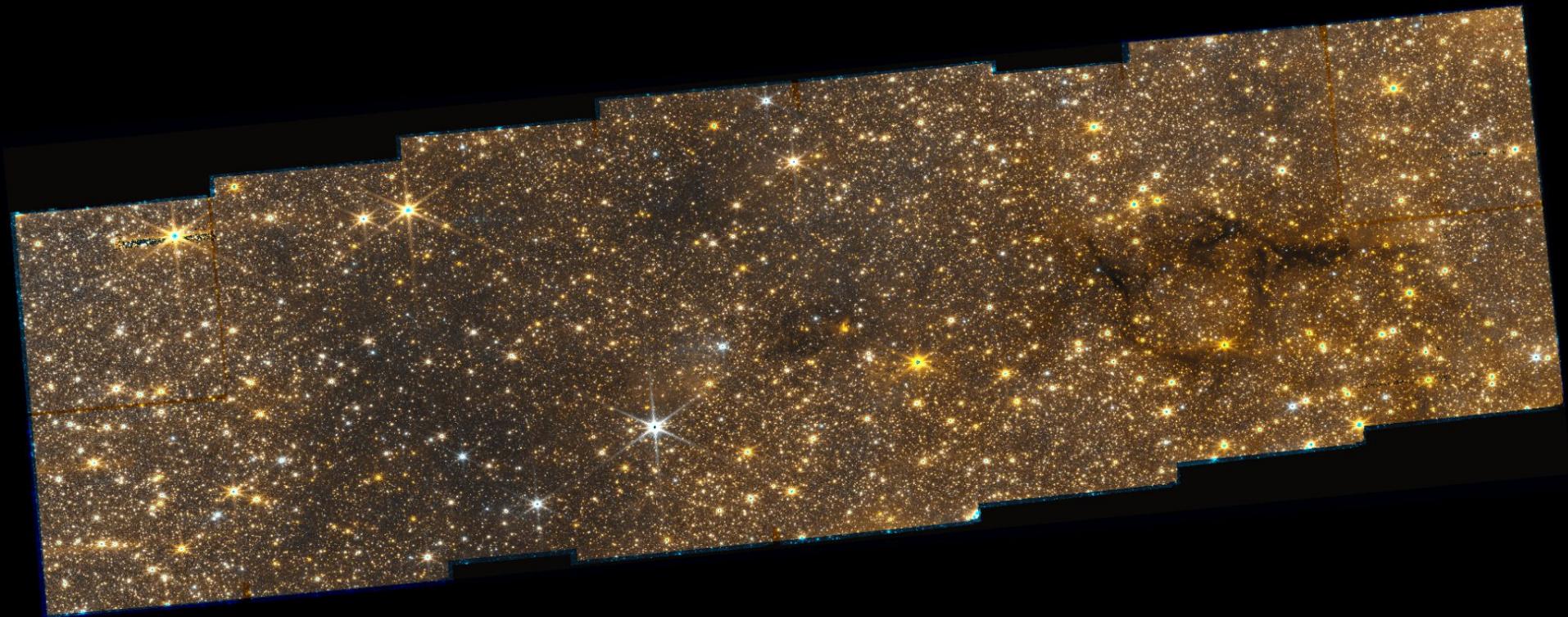
F466N (CO Ice) and F405N (Br-alpha)



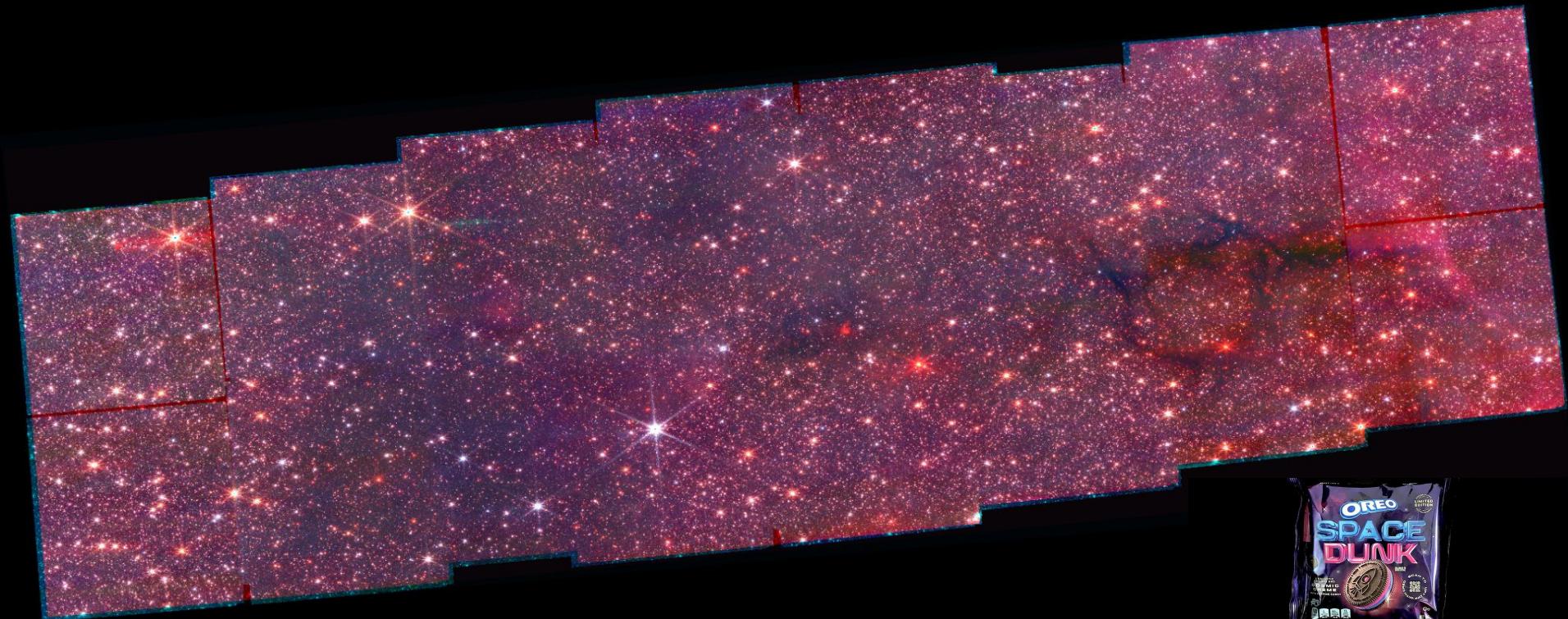
F410M and F405N (Br-alpha)



F182M and F187N (Pa-alpha)

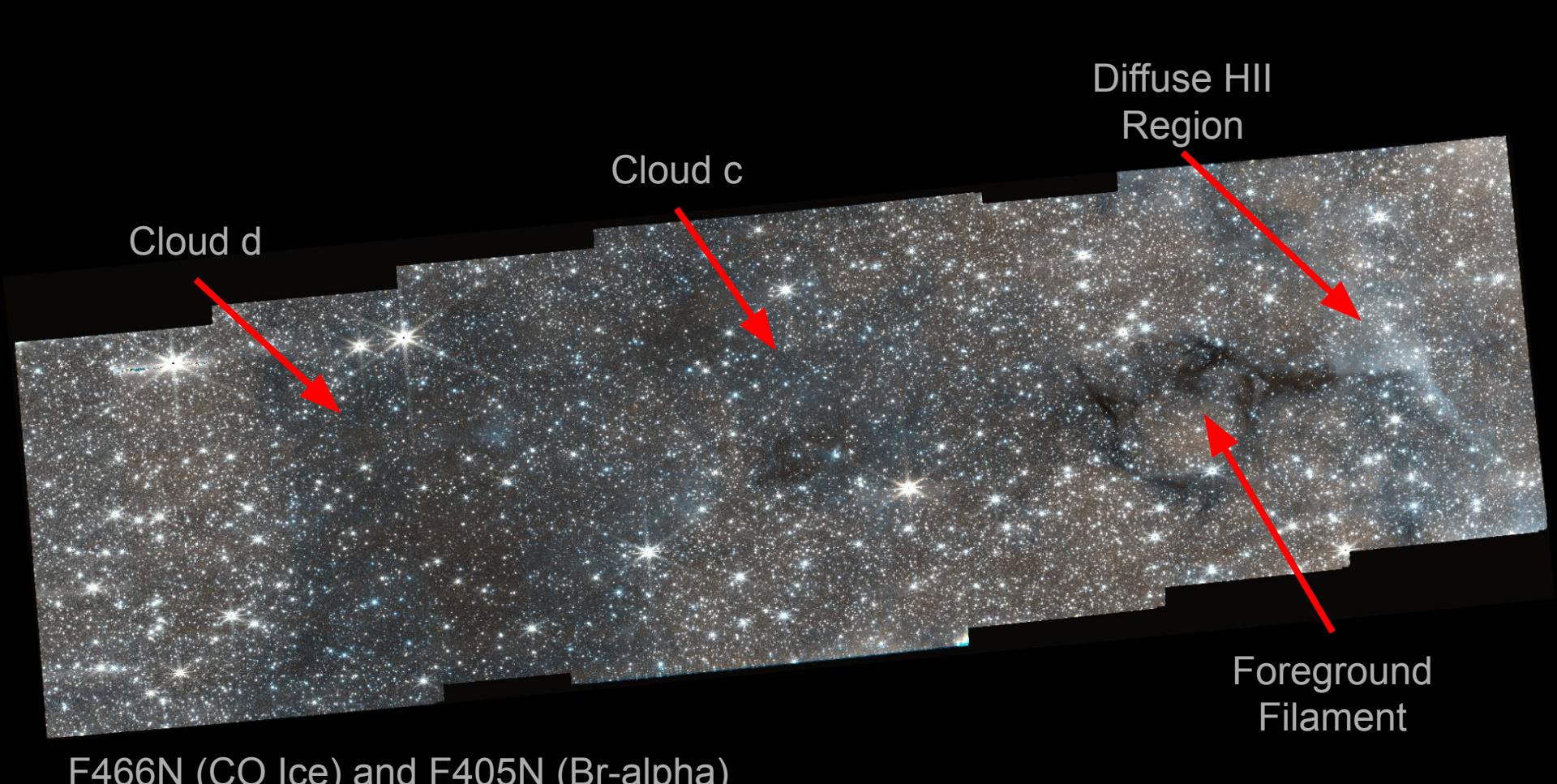


F410M and F182M



F405N and F212N and F187N





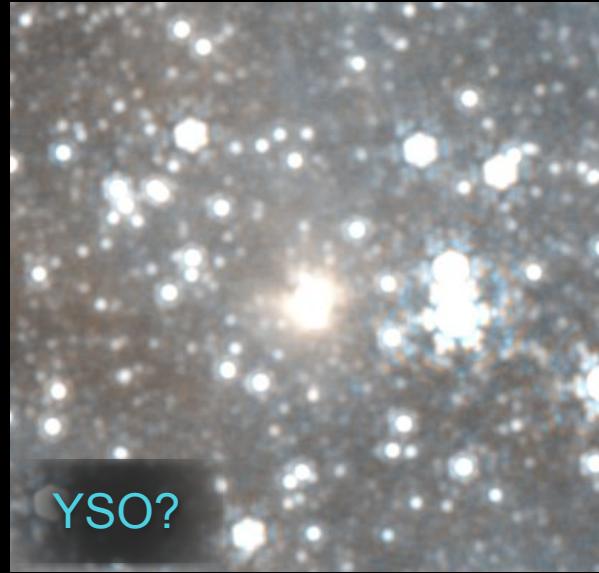
Embedded High-Mass Star Formation Region



Lots
of
Features!



Dark Filament



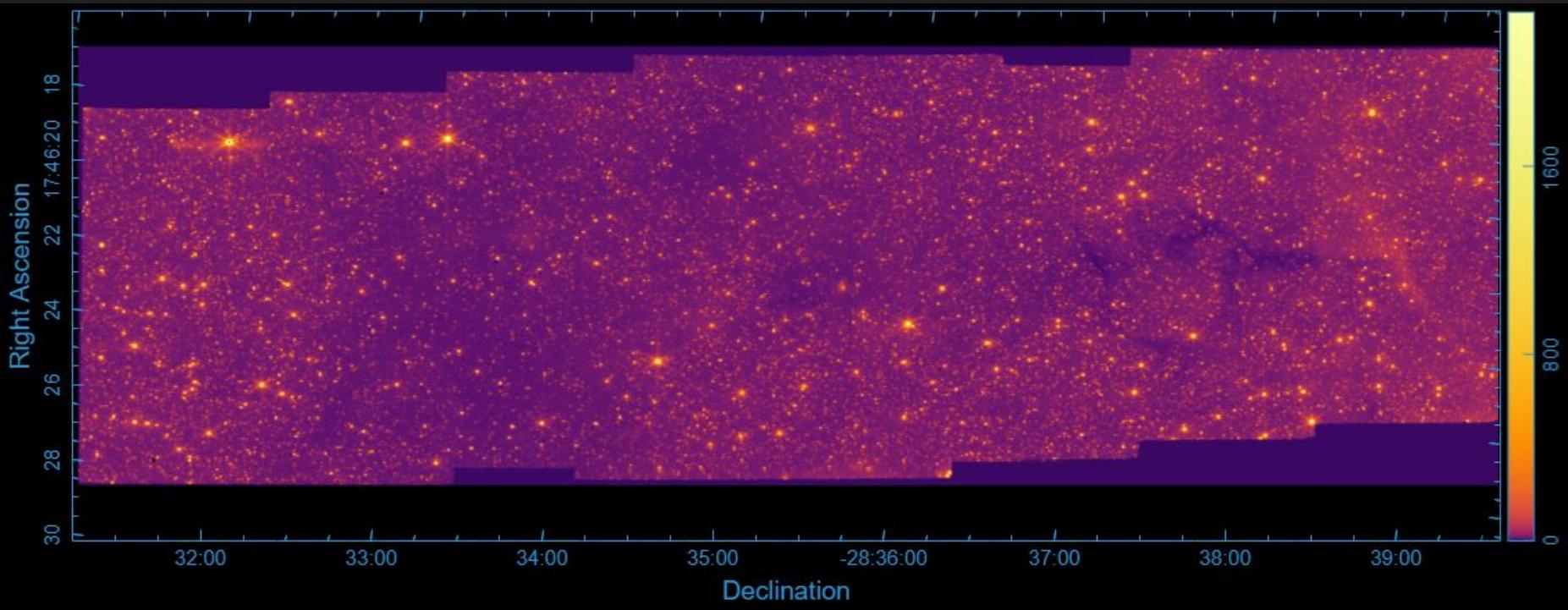
YSO?



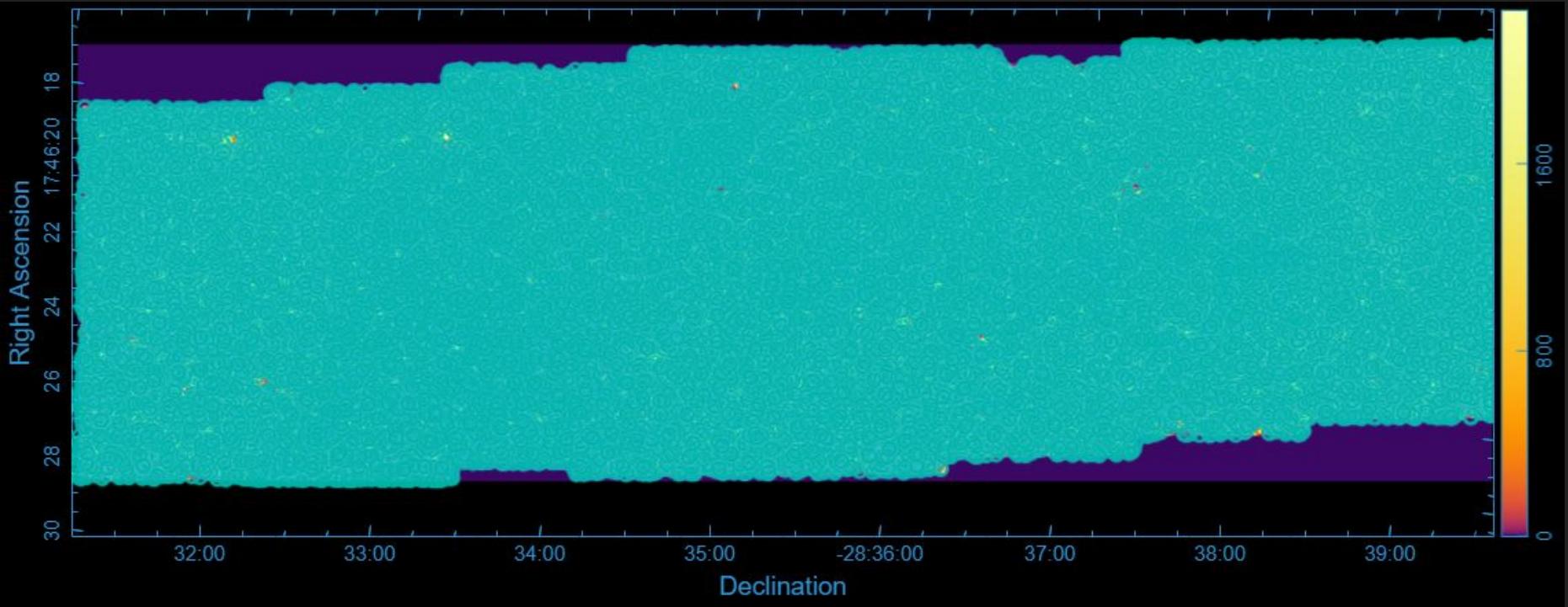
YSO?

Another, Smaller
Diffuse HII Region



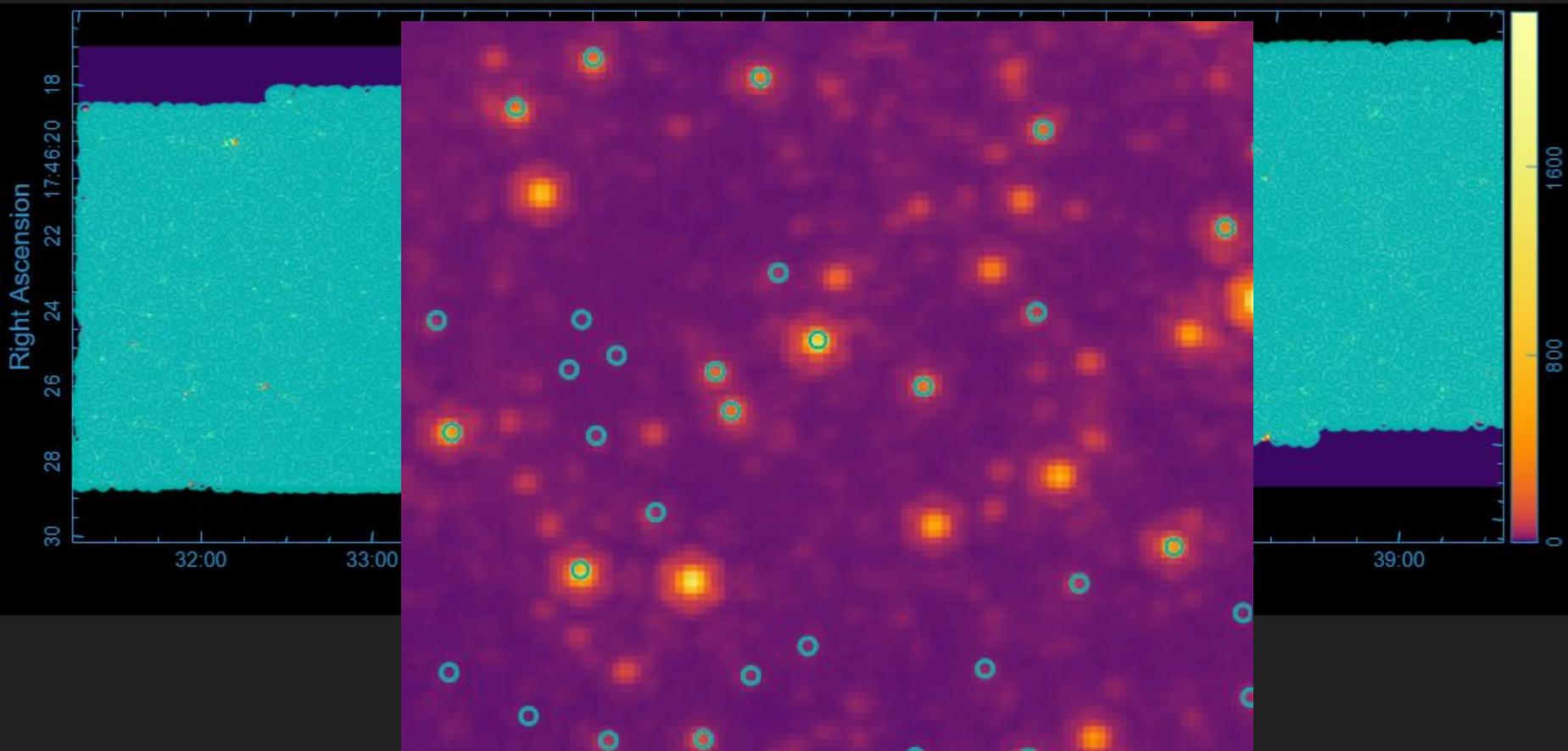


Cataloguing Stars



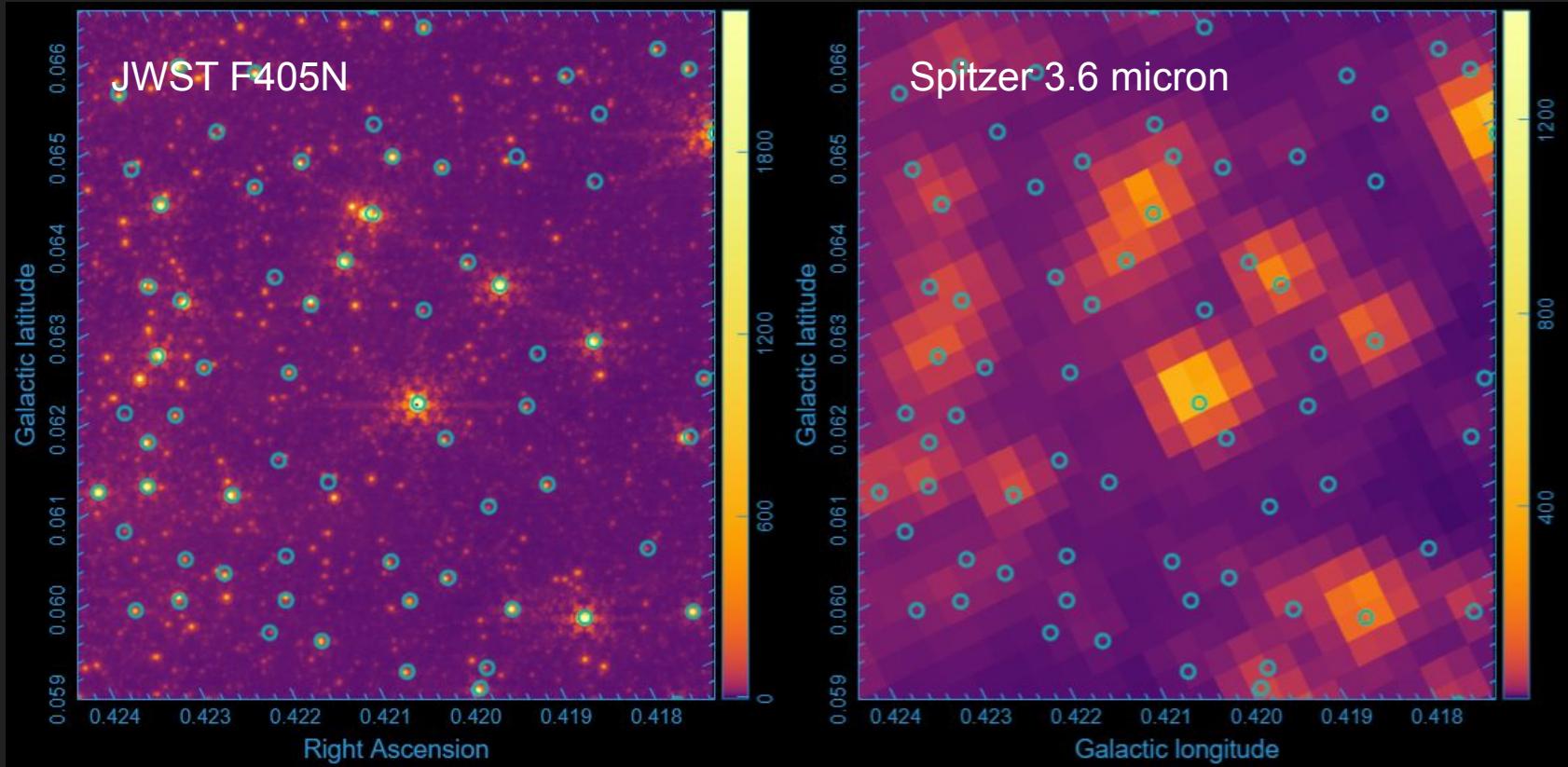
Cataloguing Stars

○ F405N reference catalog



Cataloguing Stars

○ F405N reference catalog



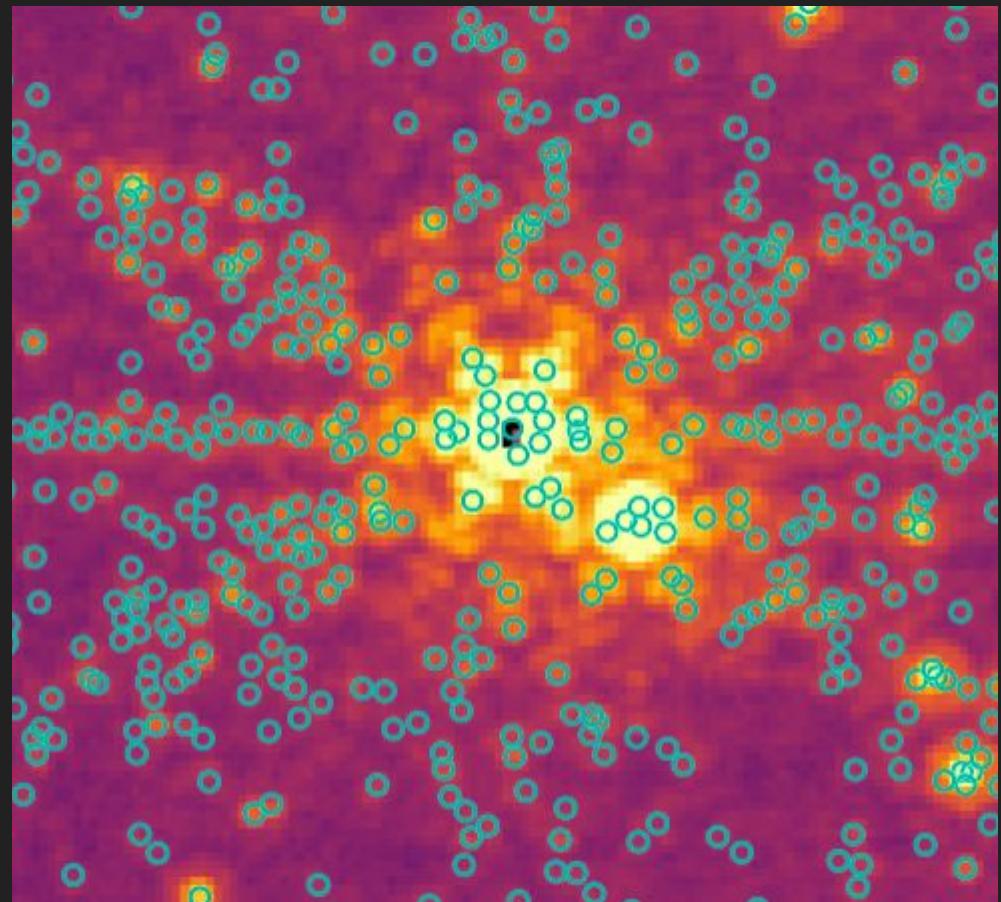
Cataloguing Stars



Vista Variables in the Via Lactea (VVV)
Catalog

Crowded Field Photometry

- In crowded fields, the Point Spread Functions (PSFs) of stars overlap.
- Confusion over the number of stars and the flux contributed by a star in the image.
- Crowded field photometry is a decades old field, the techniques just need to be updated for JWST
- Issues with WebbPSF
- Right: Crowdsource
- Soon: DOLPHOT

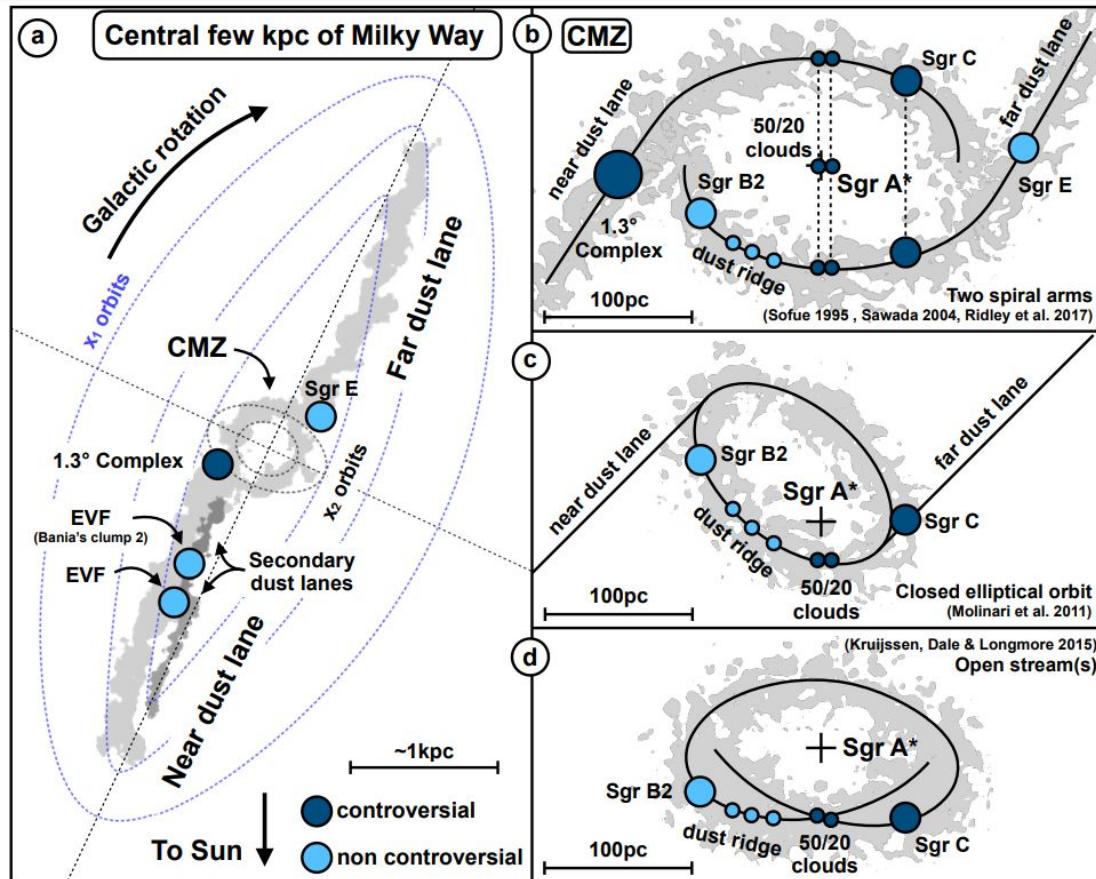


Project #1

Extinction Mapping and Cloud Distances

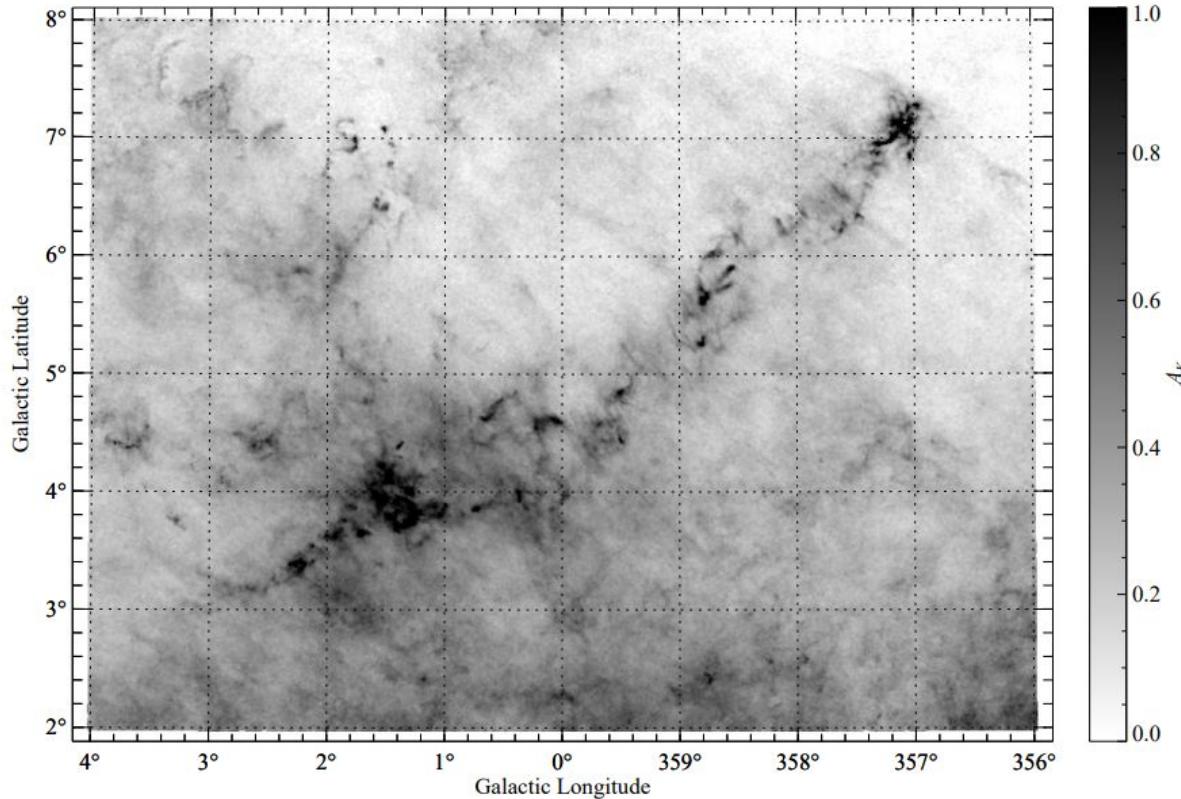
Motivation

- Once gas enters the CMZ, what happens to it?
- What orbital path does it take, is it on the same stream as Sgr B2?
- Confirm that the dust ridge is in front of the CMZ
- Confirm the line of sight velocity of dust ridge clouds
- Confirm the mass of the dust ridge
- Find the positions of the clouds in these models



What is Extinction Mapping?

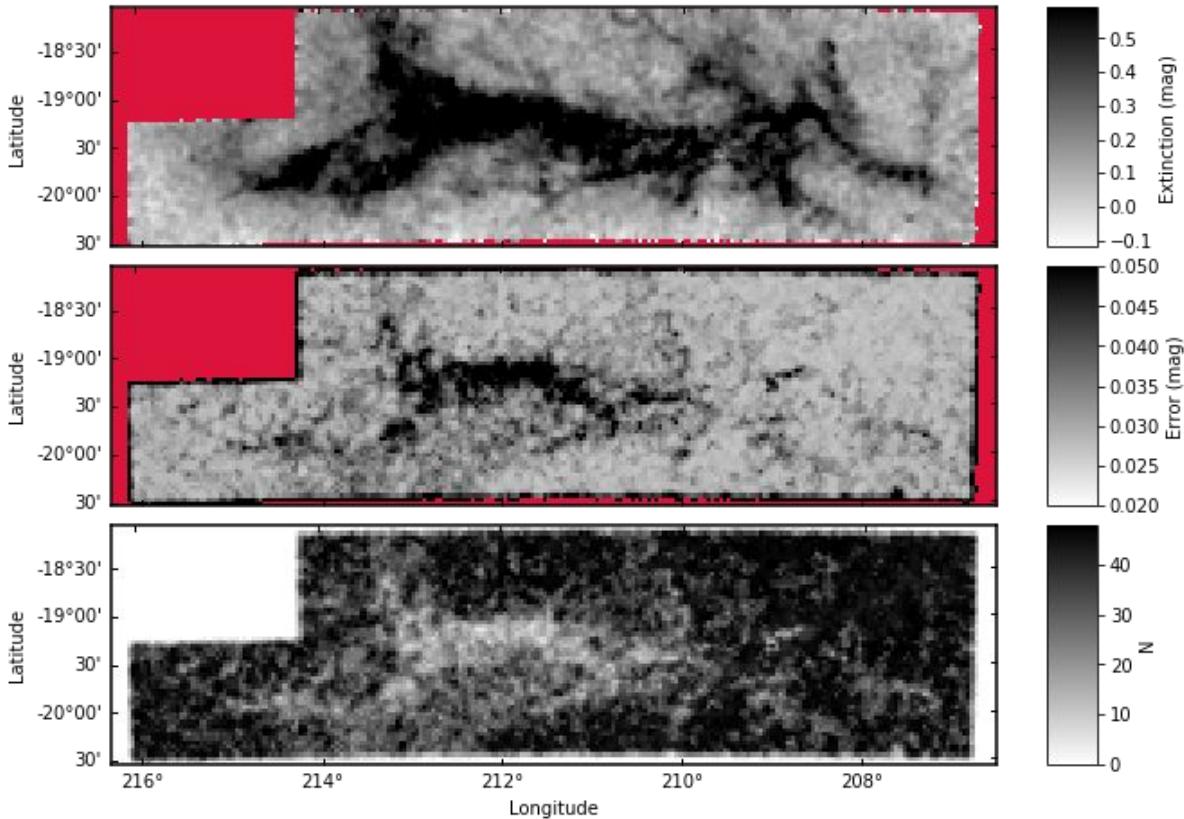
- Extinction Mapping uses the brightness, color, and number density of stars to estimate the extinction along the line of sight.
- Extinction Mapping Techniques: NICE, NICER, PNICER, NICEST
- Uses for Extinction Mapping: Cloud mass estimate, de-reddening, distance measurement, YSO identification, etc.



Lombardi 2009

PNICER

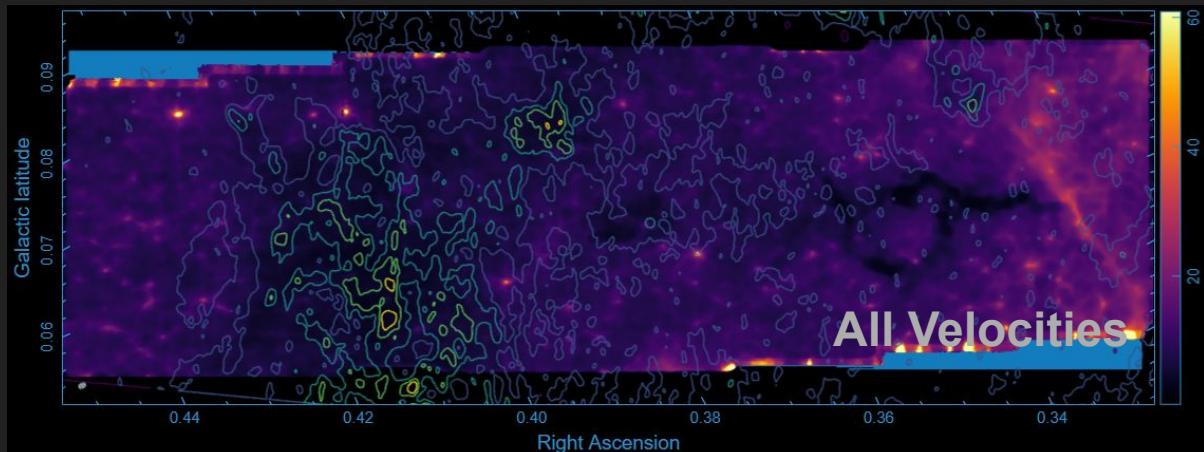
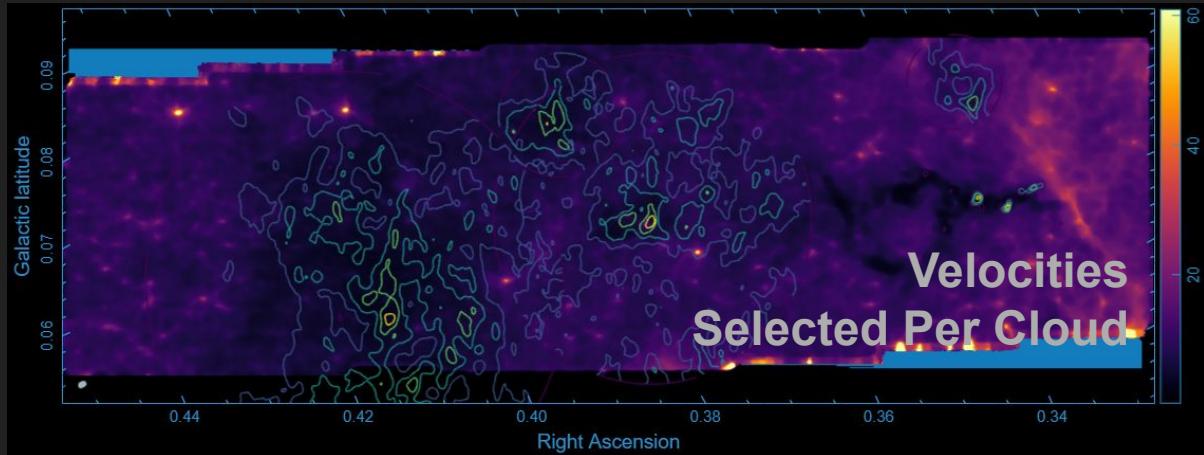
- Open source software for extinction mapping
- Uses unsupervised machine learning
- Includes implementation of NICEST
 - Handles extinction maps to more distant clouds
 - Those with many foreground stars
- Requires magnitudes, errors, and extinction laws for each band used.



Meingast - PNICER

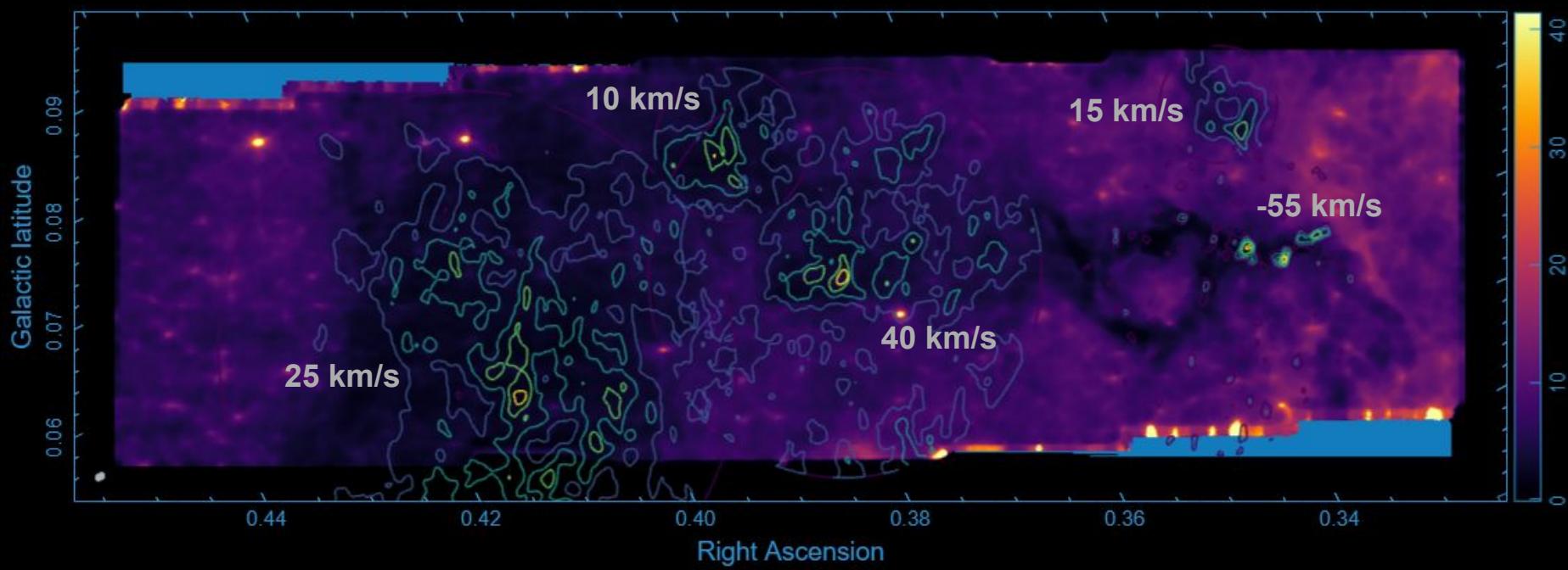
ACES Contours

- Compare the extent of the clouds in extinction maps with their extent in cloud-scale spectral line emission.
- Match extinction features with velocity features
- Associate extinction distances with velocity features
- Find where these clouds are in models of the CMZ
- Compare gas mass estimate with gas mass estimate from extinction map.



HNCO (4-3) - ACES





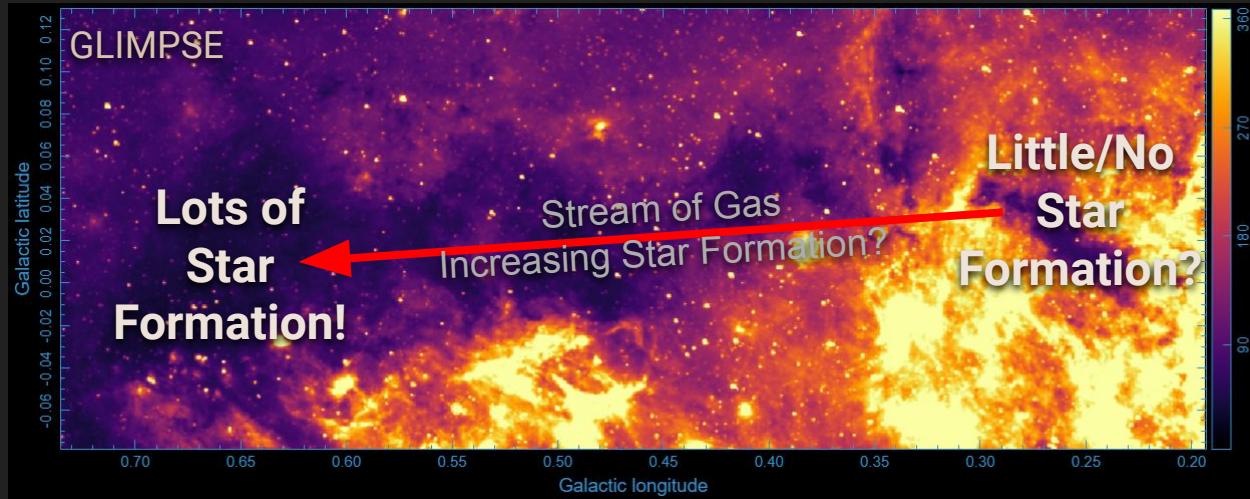
Line-of-Sight Velocities

Project #2

YSO Identification and Cataloguing

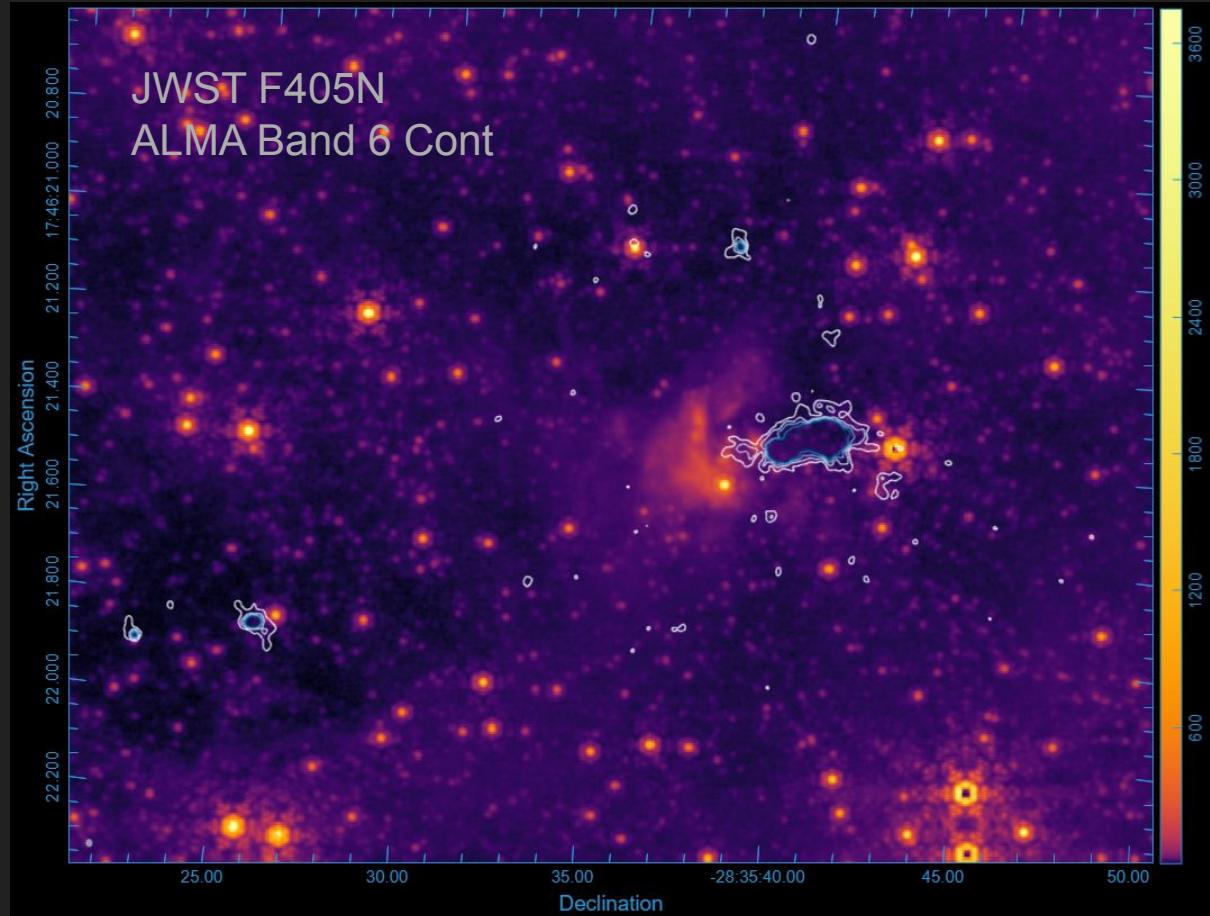
Motivation

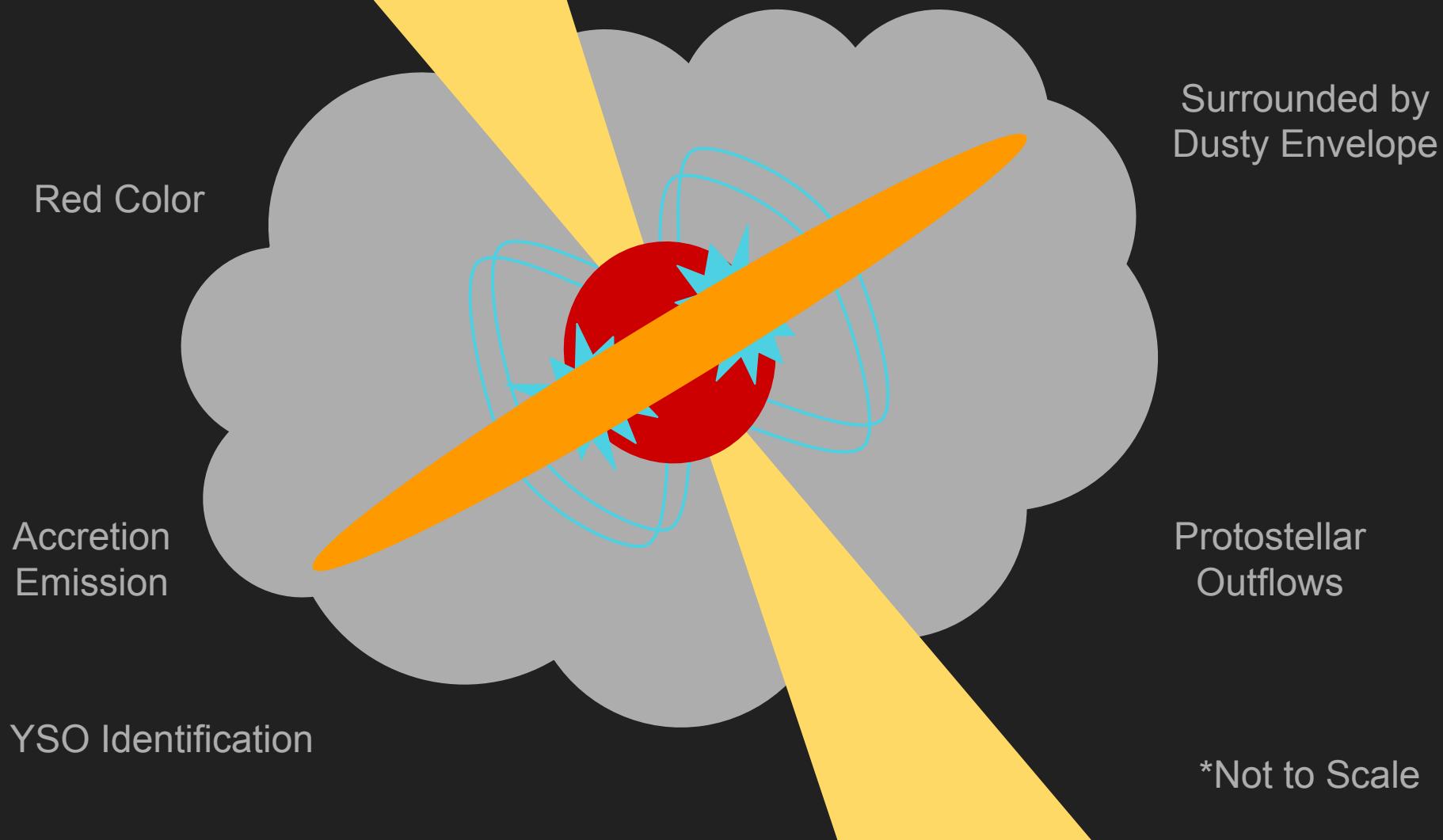
- What happens to gas once it enters the CMZ?
- How does star formation progress along the dust ridge?
- Is CMZ/dust ridge star formation different from disk star formation?
- Is the initial mass function (IMF) different in the dust ridge?



High Mass Star Formation Region

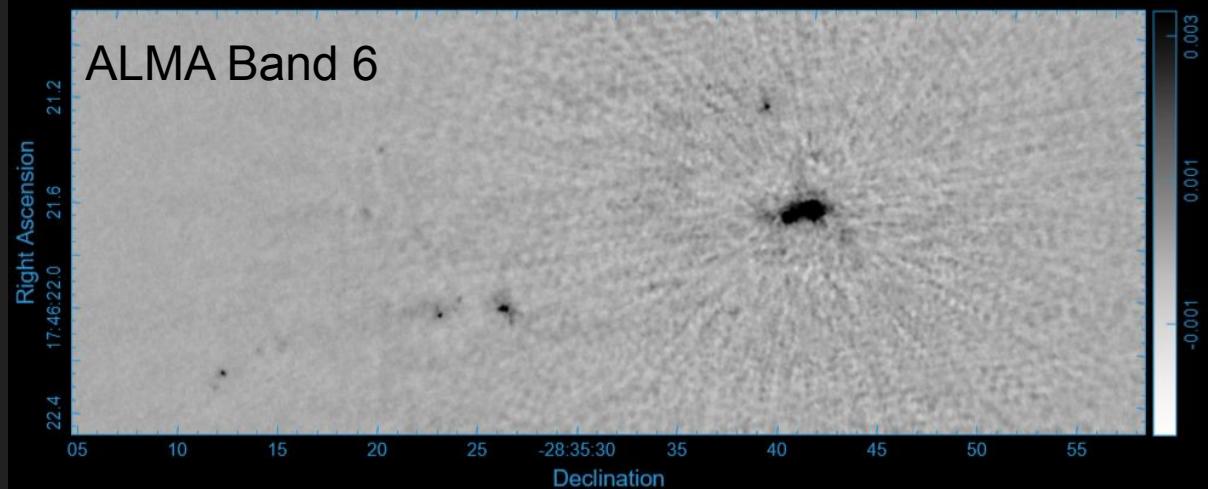
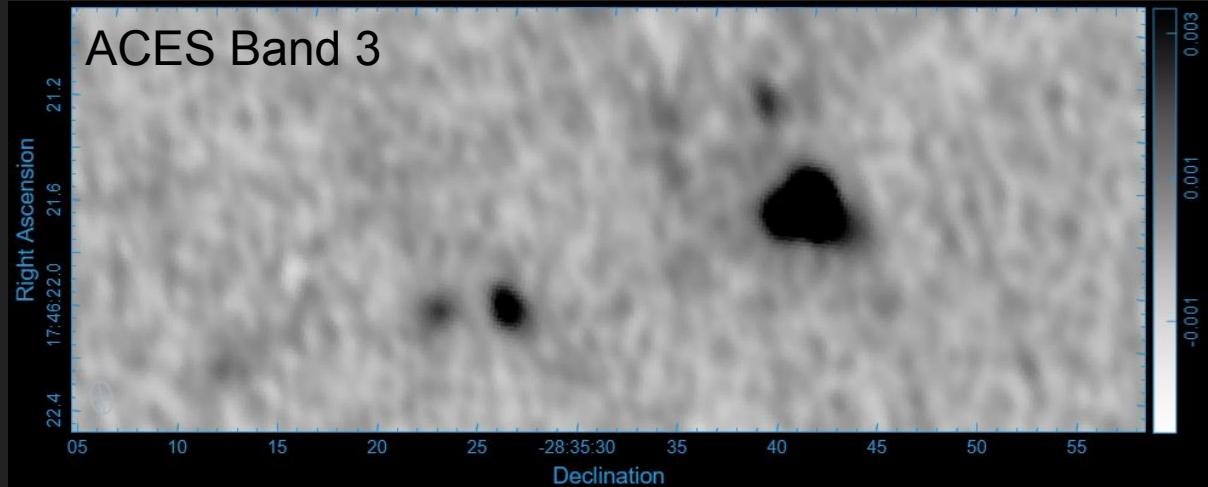
- Dust ridge cloud c has a high mass star formation region (HMSFR)
- There should be many YSOs to identify
- JWST - Class I / II / III YSOs
- ALMA - Class 0 / I YSOs





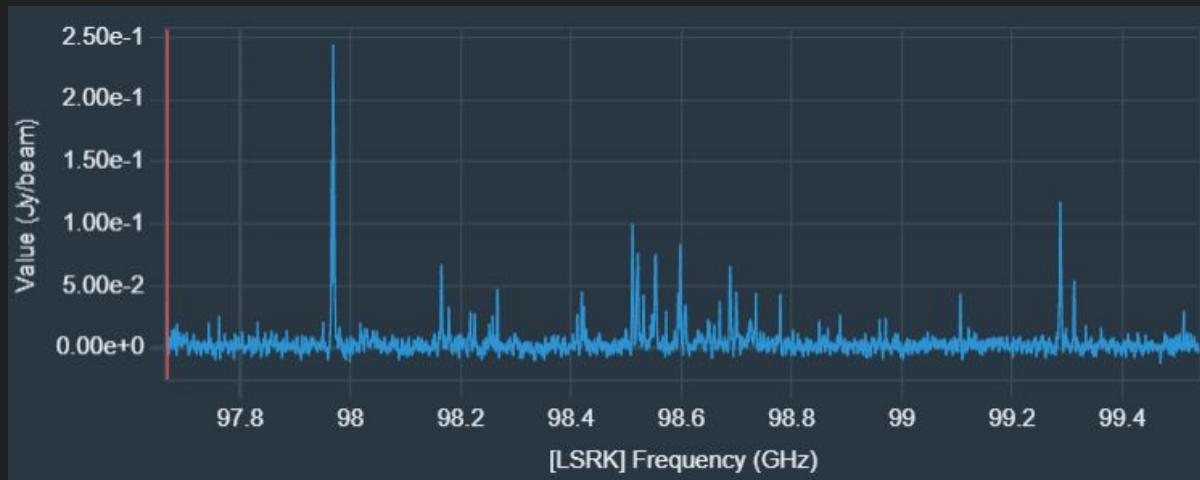
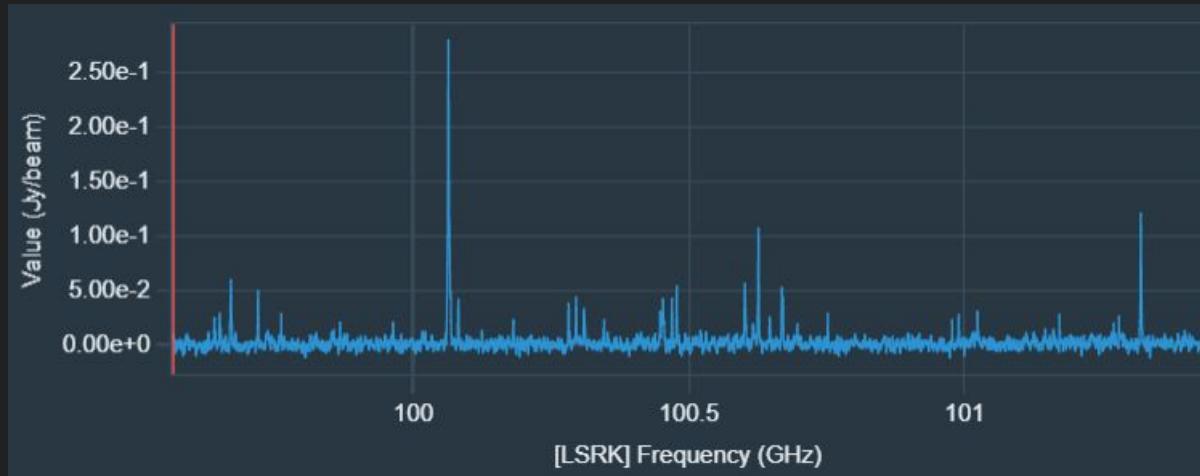
YSO Identification

- Use extinction maps to de-redden stars
- Color-color diagrams
- Color-magnitude diagrams
- 6 JWST filters - try fitting SEDs
- F405N and F187N
 - Br-alpha and Pa-alpha
 - Accretion emission
 - Sets apart from other red objects in the CMZ
- Dusty envelope - Class 0 YSOs
 - Radio continuum
 - Spectral index



YSO Classification

- The HMSFR in cloud c has a hot core
- What is a hot core?
 - Hot $T > 100$ K
 - Dense $\rho > 10^5$ cm $^{-3}$
 - Chemically rich
- High resolution ALMA Band 6 observations of cloud c and ACES Band 3
- Make a catalog of the chemistry of cloud c



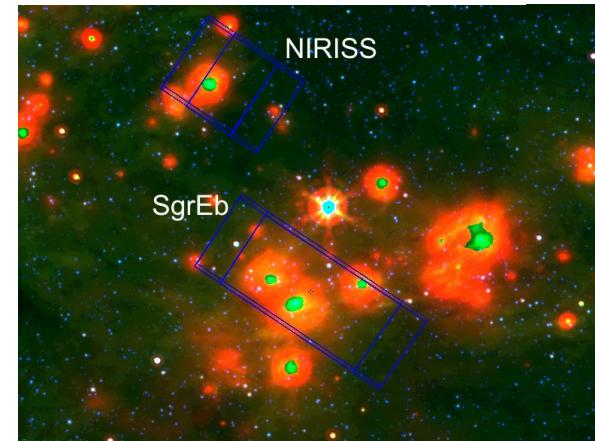
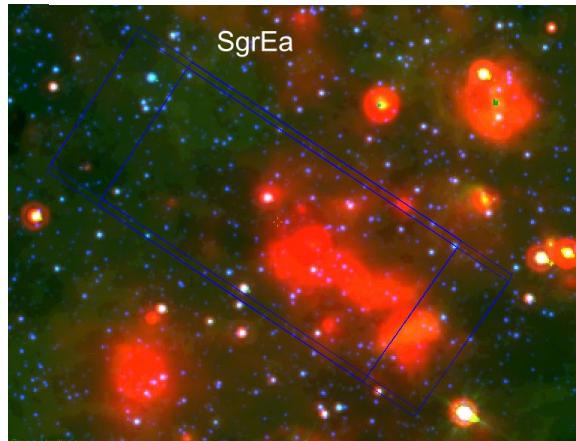
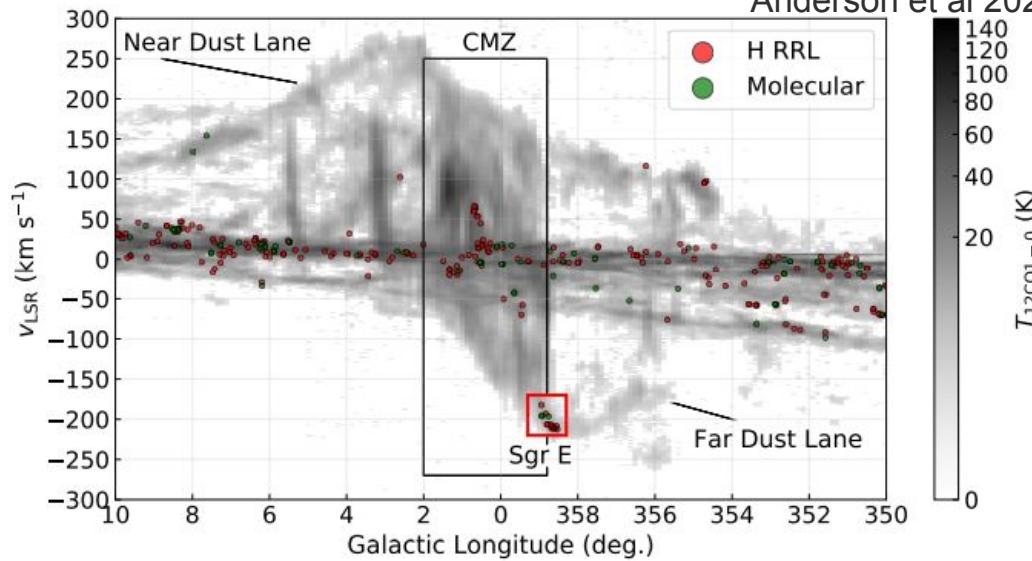
Other Potential Projects

Galactic Center
Structure and Dynamics

- What happens when gas from the bar lanes nears the CMZ?
- Is bar lane star formation different?
- What material from the bar lanes accretes onto the CMZ?
- What happens to gas which accretes onto the CMZ?

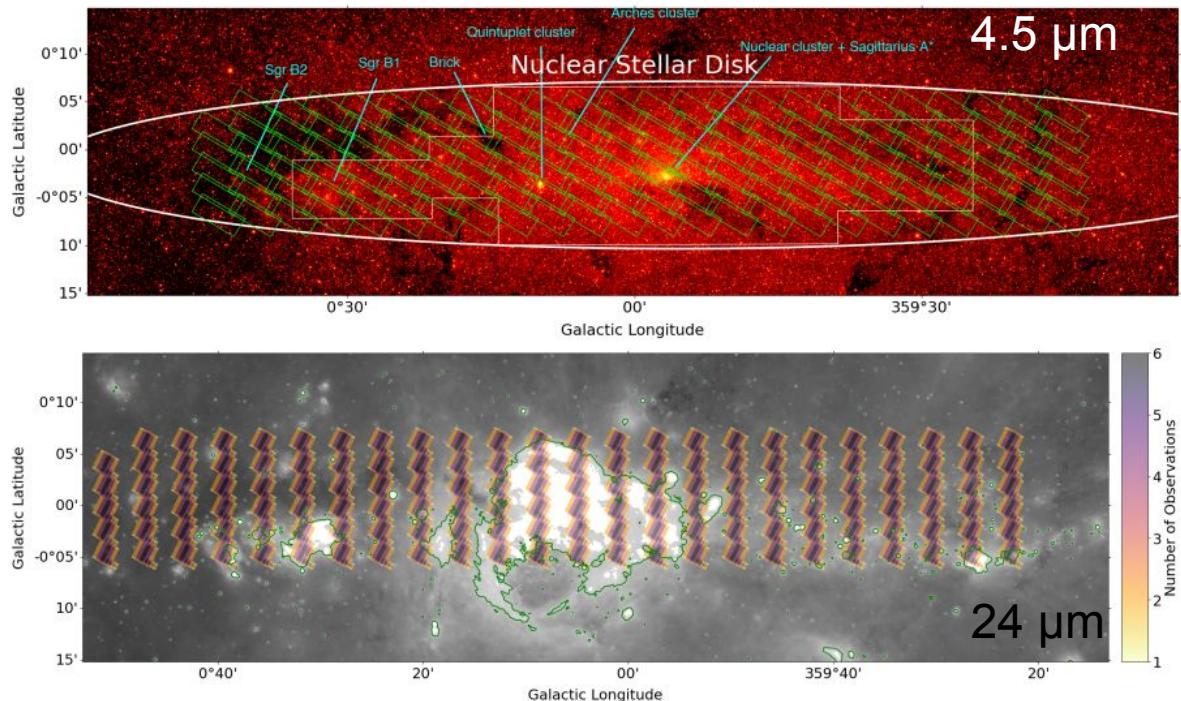
Sgr E

- JWST Proposal submitted for this cycle on Sgr E (PI: Savannah Gramze)
- Sgr E:
 - Molecular Cloud
 - HII region complex
 - Located where the far side bar lane intersects the CMZ
- HII regions with interesting properties
- Star formation event happened 5 Myr ago, probably on bar lanes



JWST Galactic Center Survey

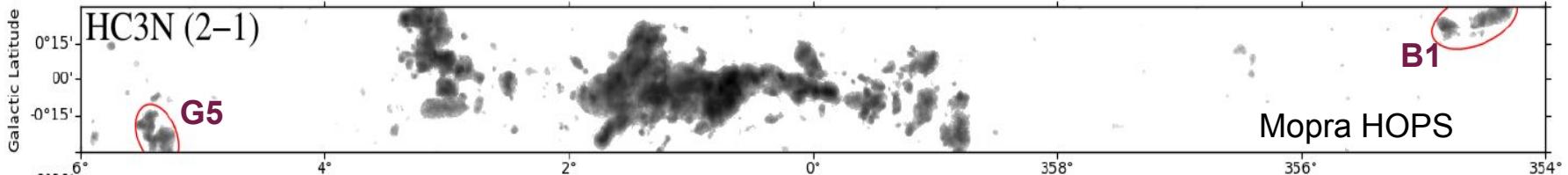
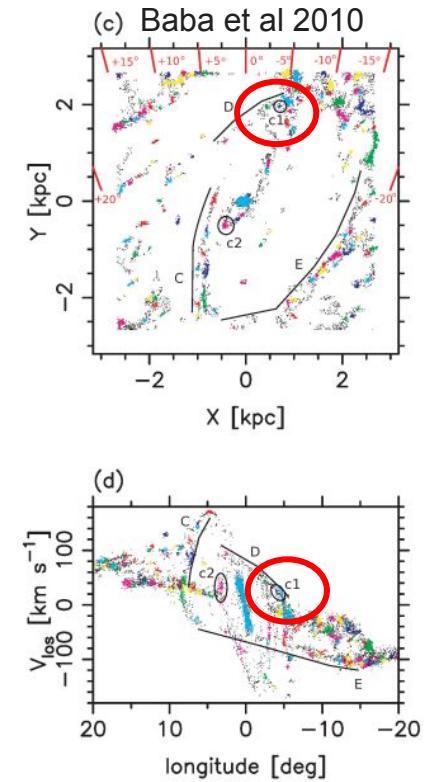
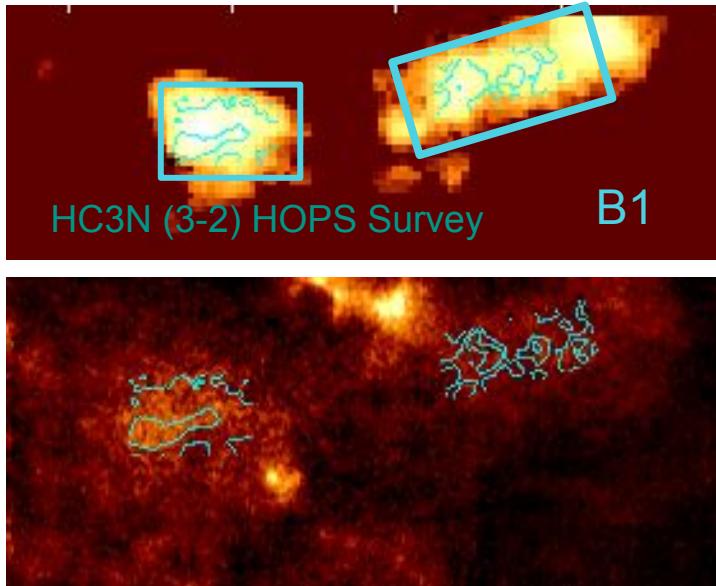
- JWST Large Program proposal submitted this cycle
- Covering much of the CMZ, including the dust ridge
- First epoch of a series of surveys



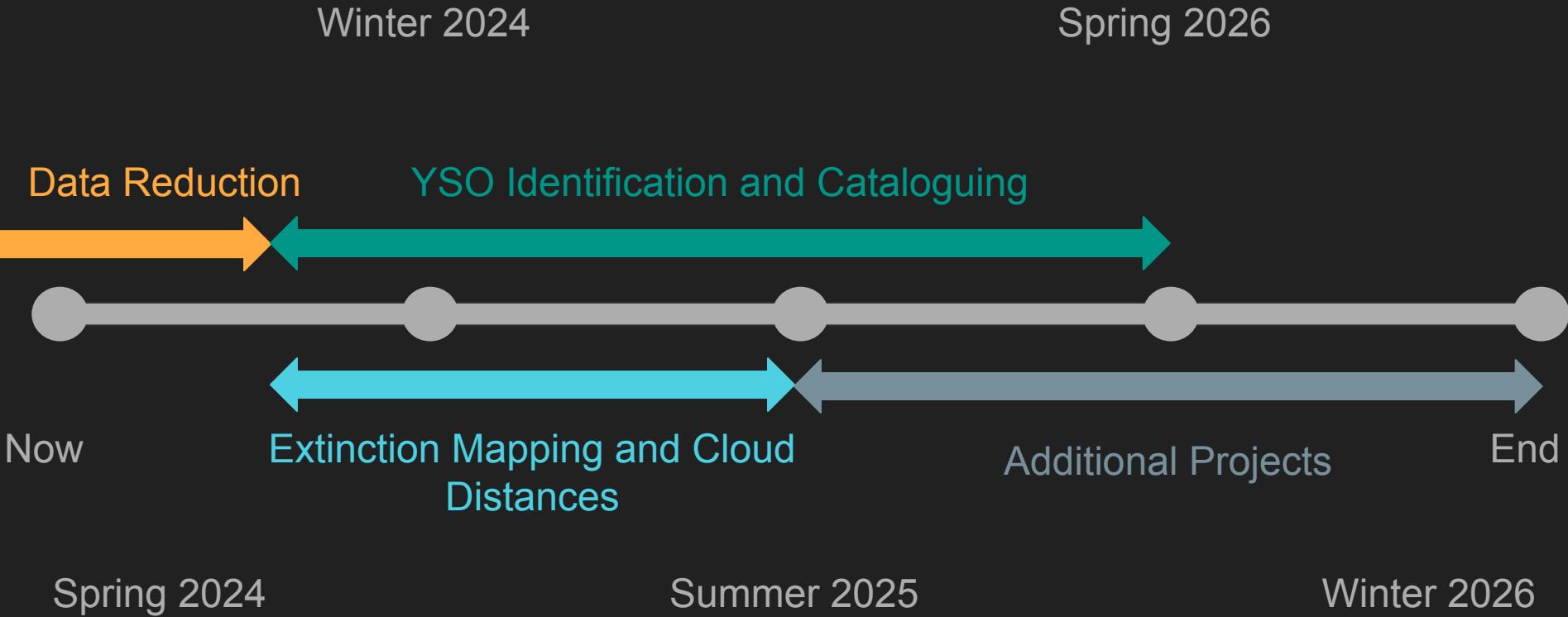
JWST Galactic Center Survey
Schödel et al 2023

Bania's Clump 1

- Data from the same survey that observed G5
 - The cloud-cloud collision on the bar lanes
- B1 originally thought to be G5's counterpart
- But if both are on bar lanes, then B1 is much further out than G5
- B1 at the end of the bar lane?
Overshooting gas on a wider orbit than G5?



PhD Thesis Timeline



PhD Timeline

Sagittarius E

Galactic Center
Structure and Dynamics

- What happens when gas from the bar lanes nears the CMZ?
- Is bar lane star formation different?
- What material from the bar lanes accretes onto the CMZ?

January 2024

Fall 2024

Spring 2026

Data Reduction

YSO Identification and Cataloguing



Now

End

Extinction Mapping and Cloud
Distances

Summer 2024

Spring 2025

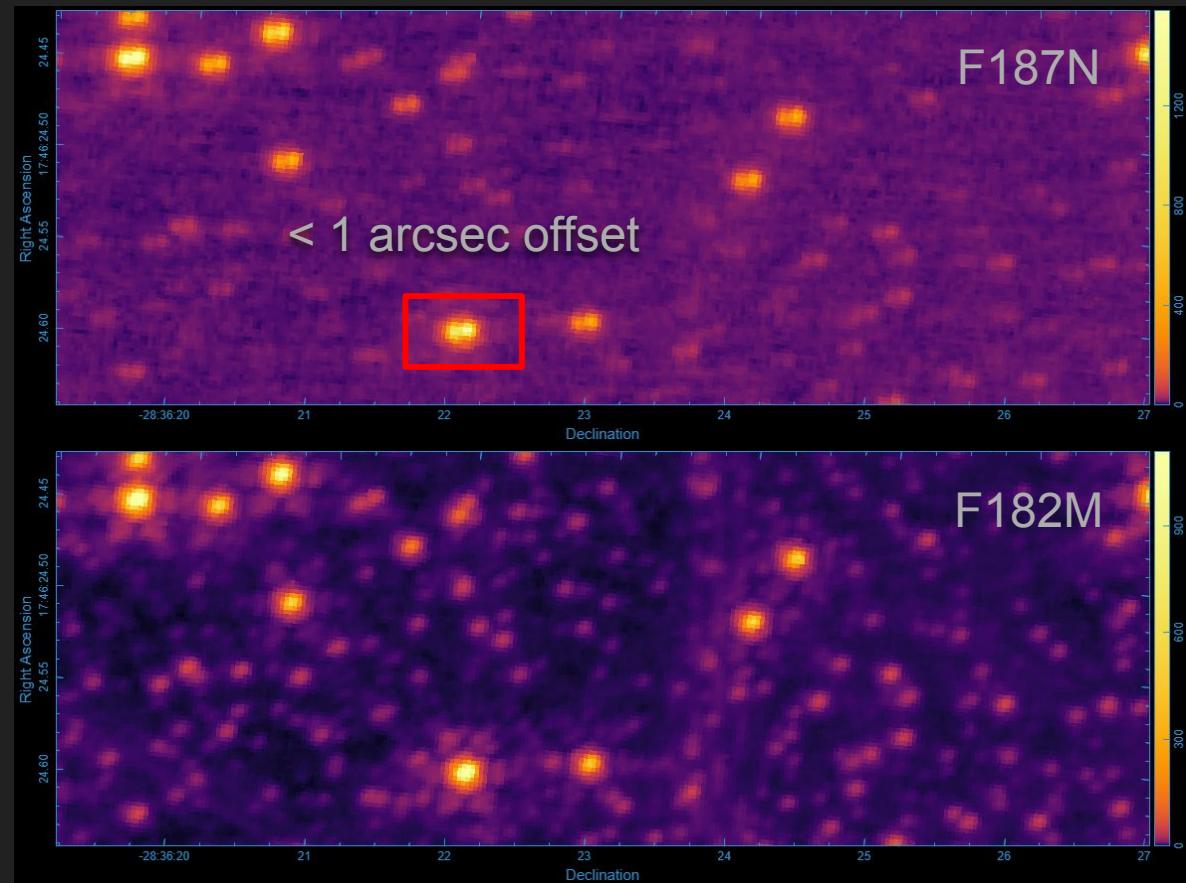
PhD Timeline

Initial Mass Function

- Cold molecular gas in the Galactic Center is hotter and more turbulent than gas in the disk
- It is an extreme environment for star formation
- The IMF in the CMZ might be “top-heavy”
 - Too few low mass stars, or too many massive stars
- Observing star formation regions will help constrain the IMF in the CMZ

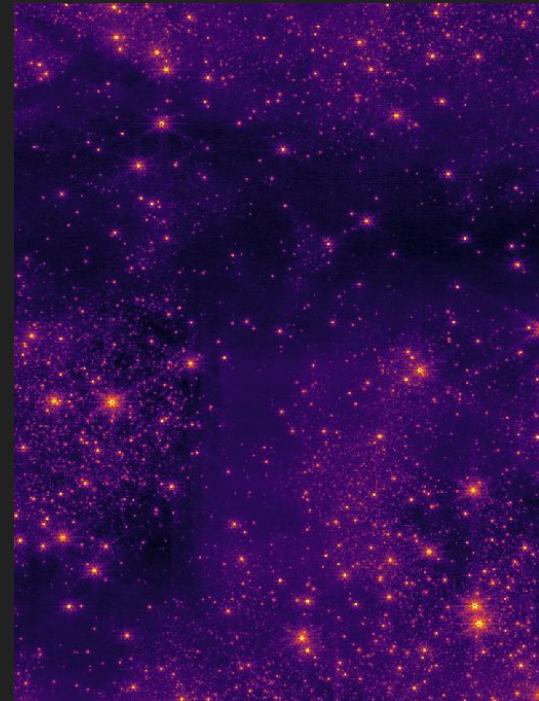
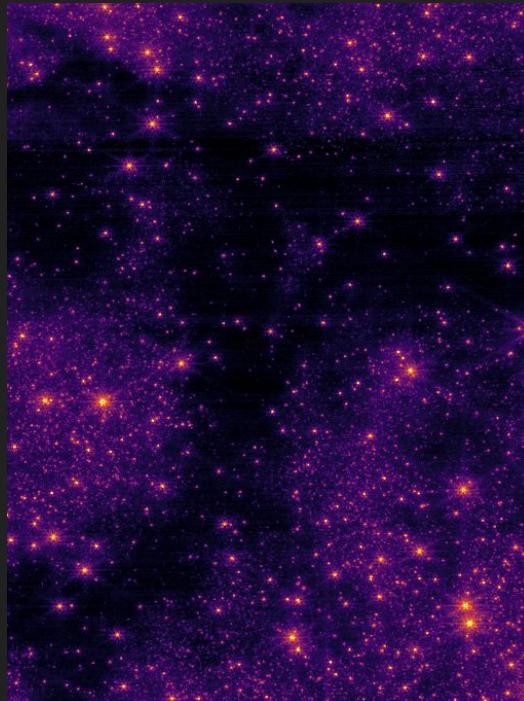
Lingering Offset in Short Wavelength Filters

- Different from the **previous** offset issue
- Offset in module and visit
- To properly align, need to align both modules
- We have a script for that!
 - Image each module individually, then reproject together.
 - But it didn't work for F187N. Why?
- To solve: Measured module offset - more sensitive
- Now the pipeline products have no alignment issues!



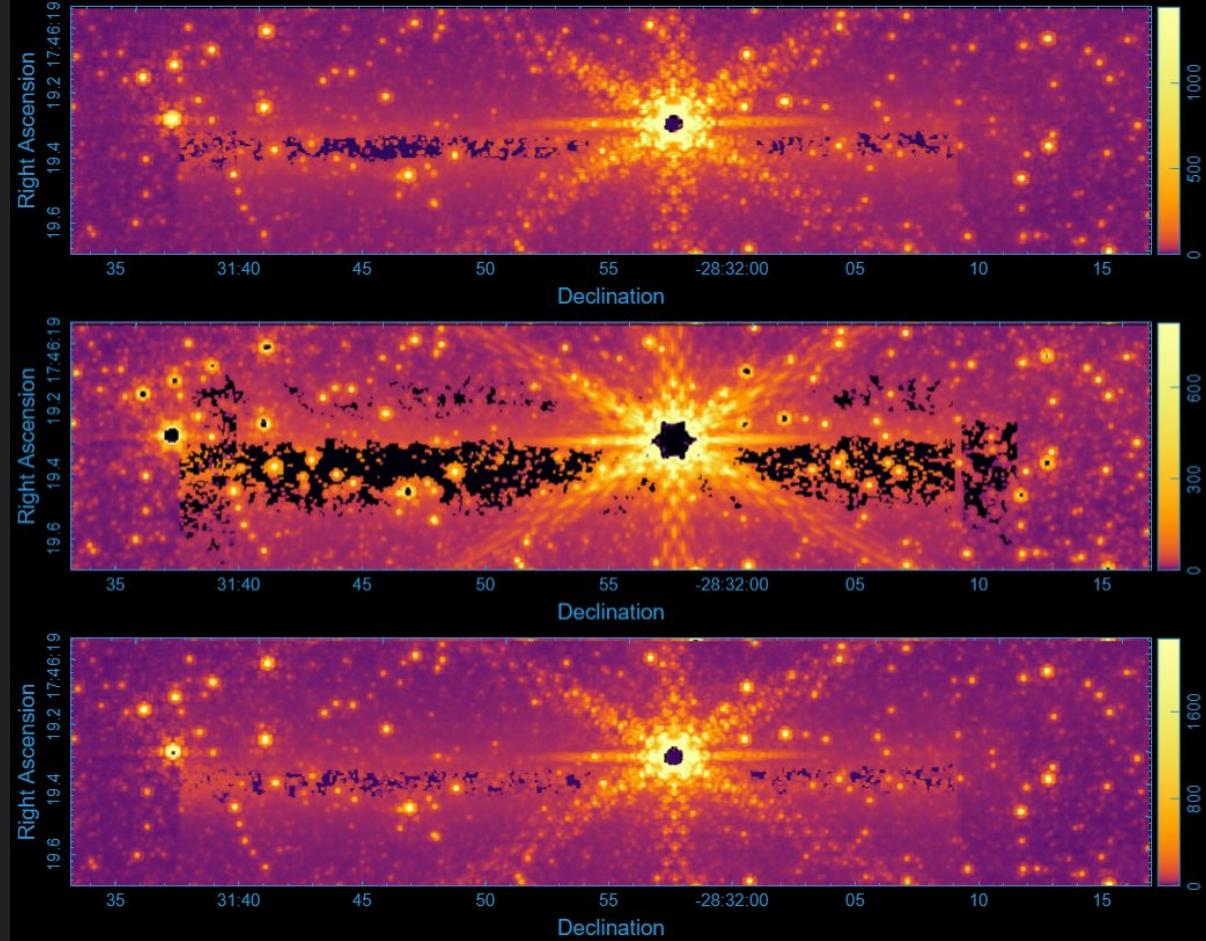
Linger Reduction Issues

- Destreak step doesn't remove all 1/f noise and does not add back all large scale structures



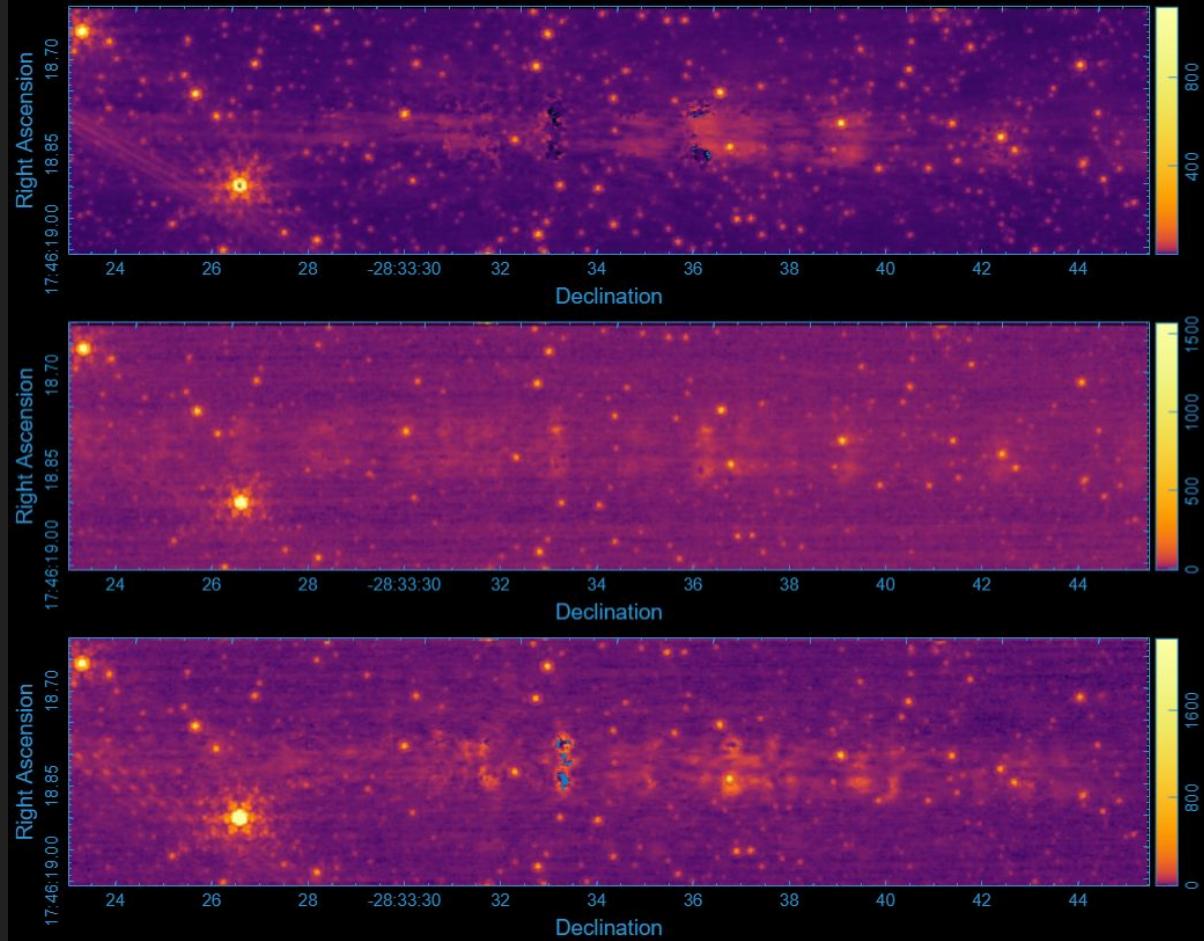
Lingering Reduction Issues

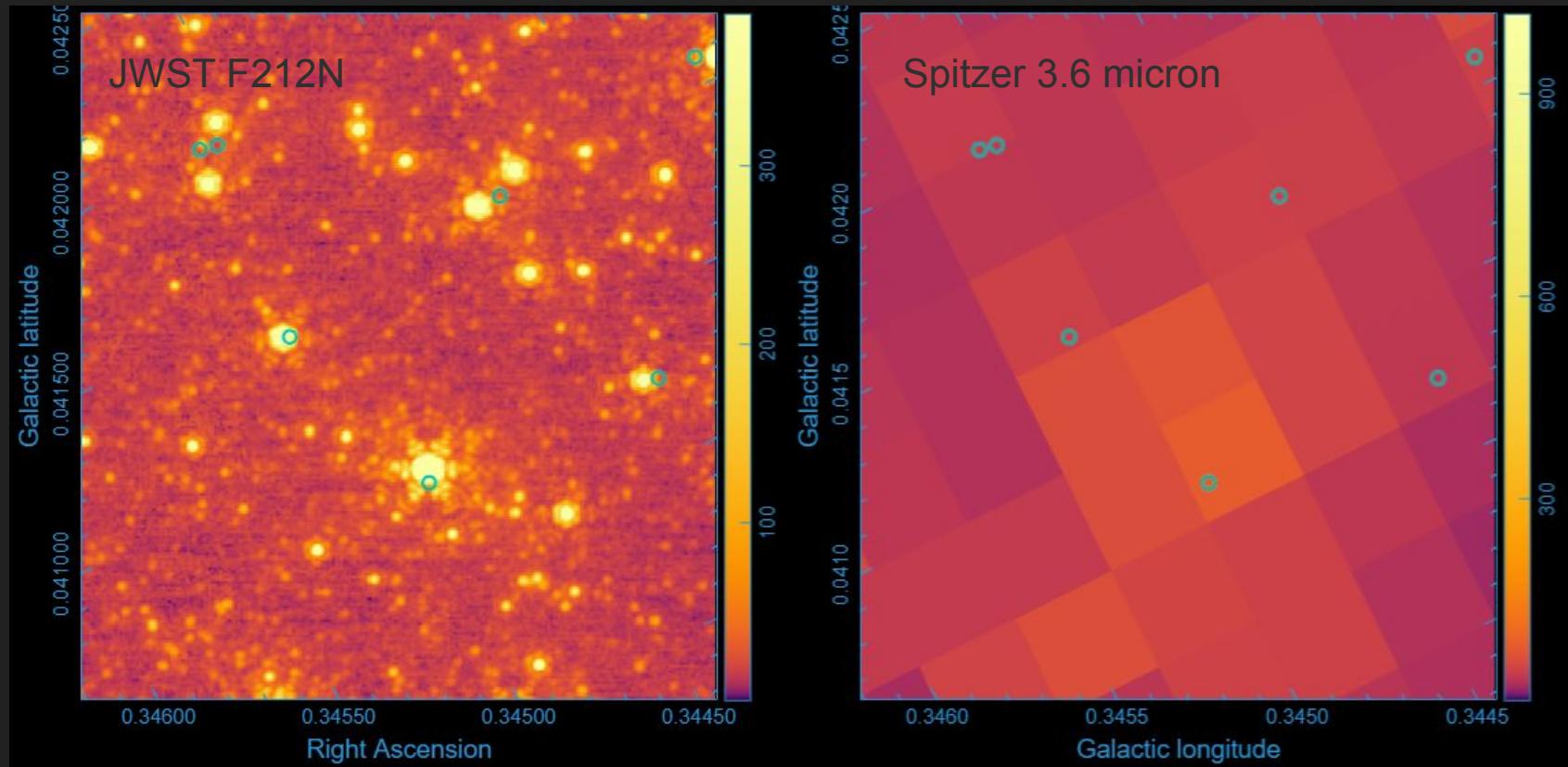
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- Destreaked images behave poorly around especially bright stars in long wavelength data



Linger Reduction Issues

- Destreak step doesn't remove all 1/f noise and does not add back all large scale structures
- Destreaked images behave poorly around especially bright stars in long wavelength data
- Weird imaging artifacts are left in the short wavelength images





Cataloguing Stars



Vista Variables in the Via Lactea (VVV)
Catalog

Dan Walker

YSO Identification

- Use extinction maps to de-redden stars
- Color-color diagrams
- Color-magnitude diagrams
- 6 JWST filters - try fitting SEDs
- F405N and F187N
 - Br-alpha and Pa-alpha
 - Accretion emission
 - Sets apart from other red objects in the CMZ
- Dusty envelope - Class 0 YSOs
 - Radio continuum
 - Spectral index

