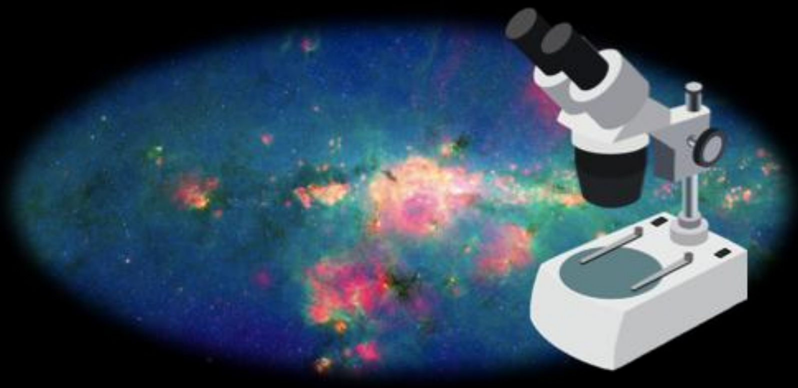


The Milky Way Laboratory

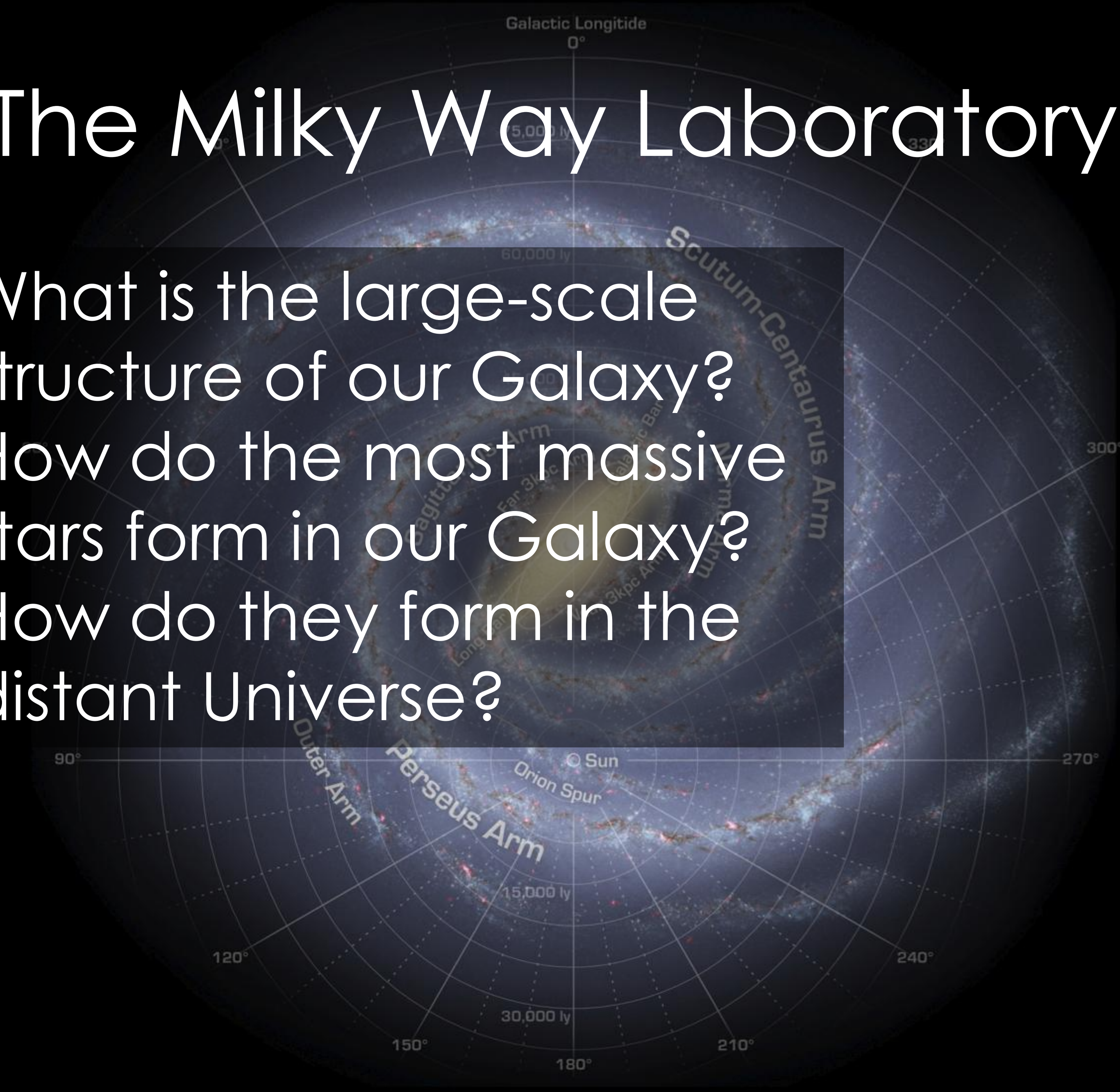
Cara Battersby
Harvard-Smithsonian Center for Astrophysics

The Milky Way Laboratory

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

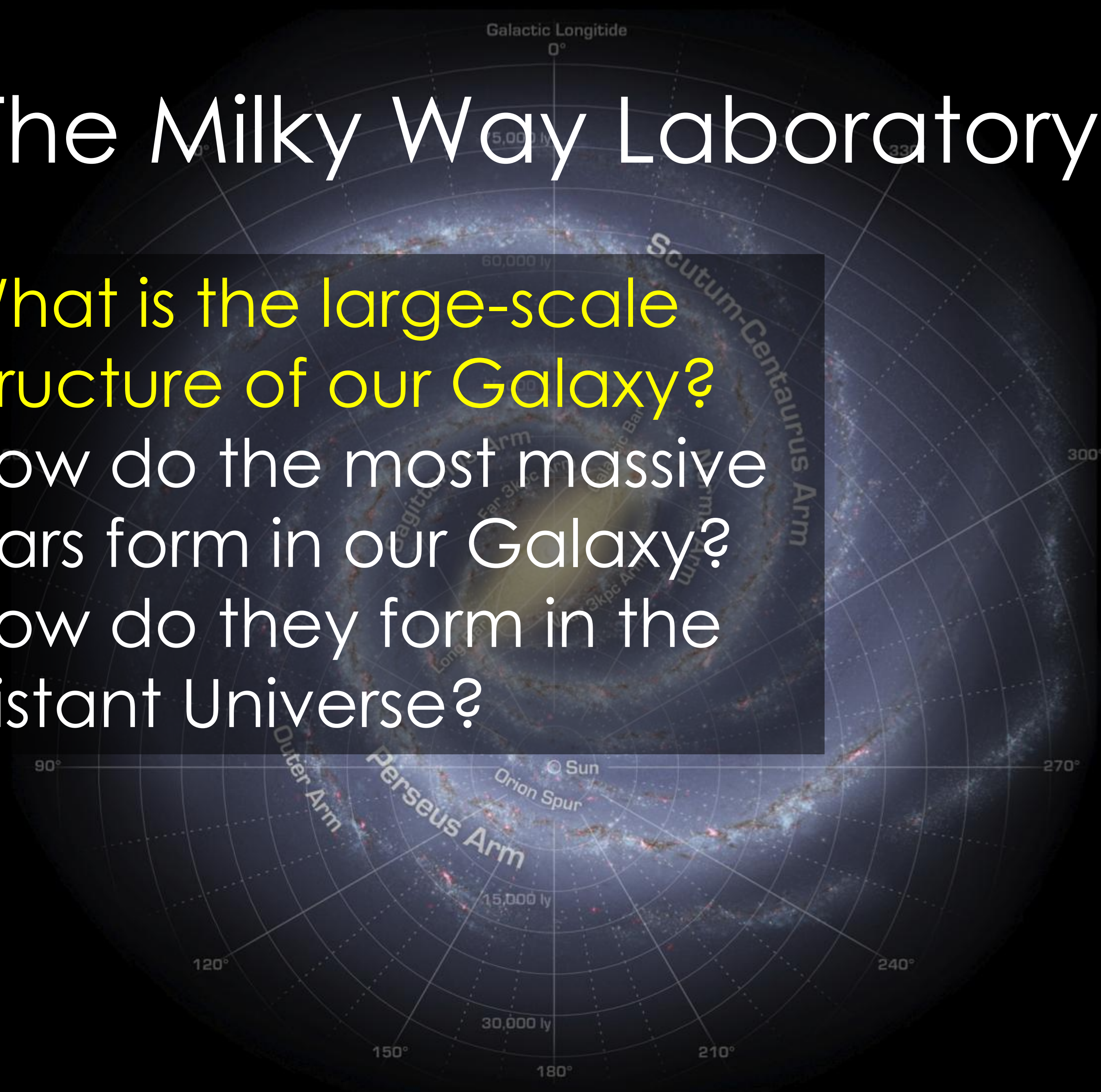
The Milky Way Laboratory

1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?



The Milky Way Laboratory

1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?



The Milky Way Laboratory

Stop 1: The Skeleton of the Milky Way

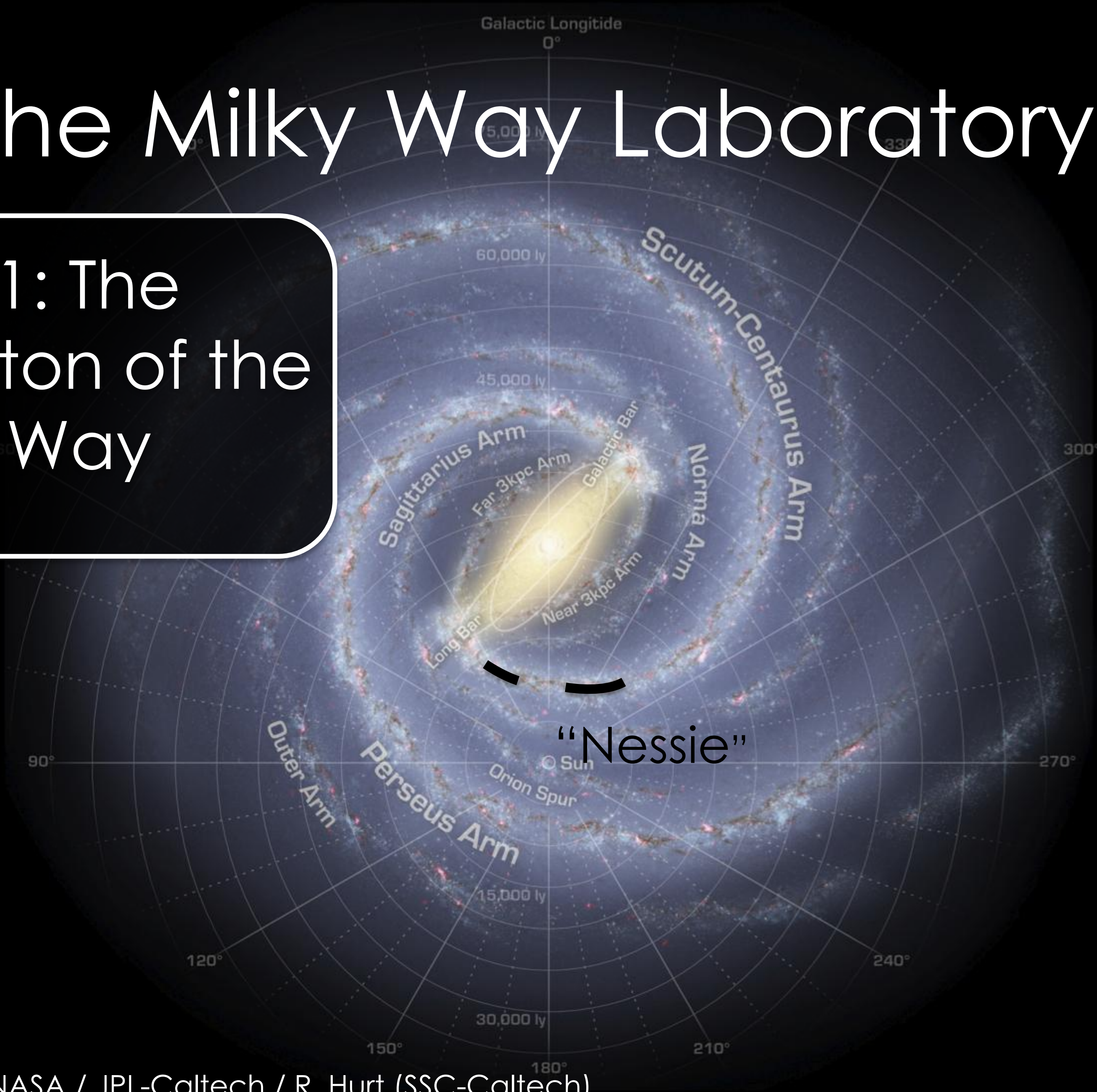
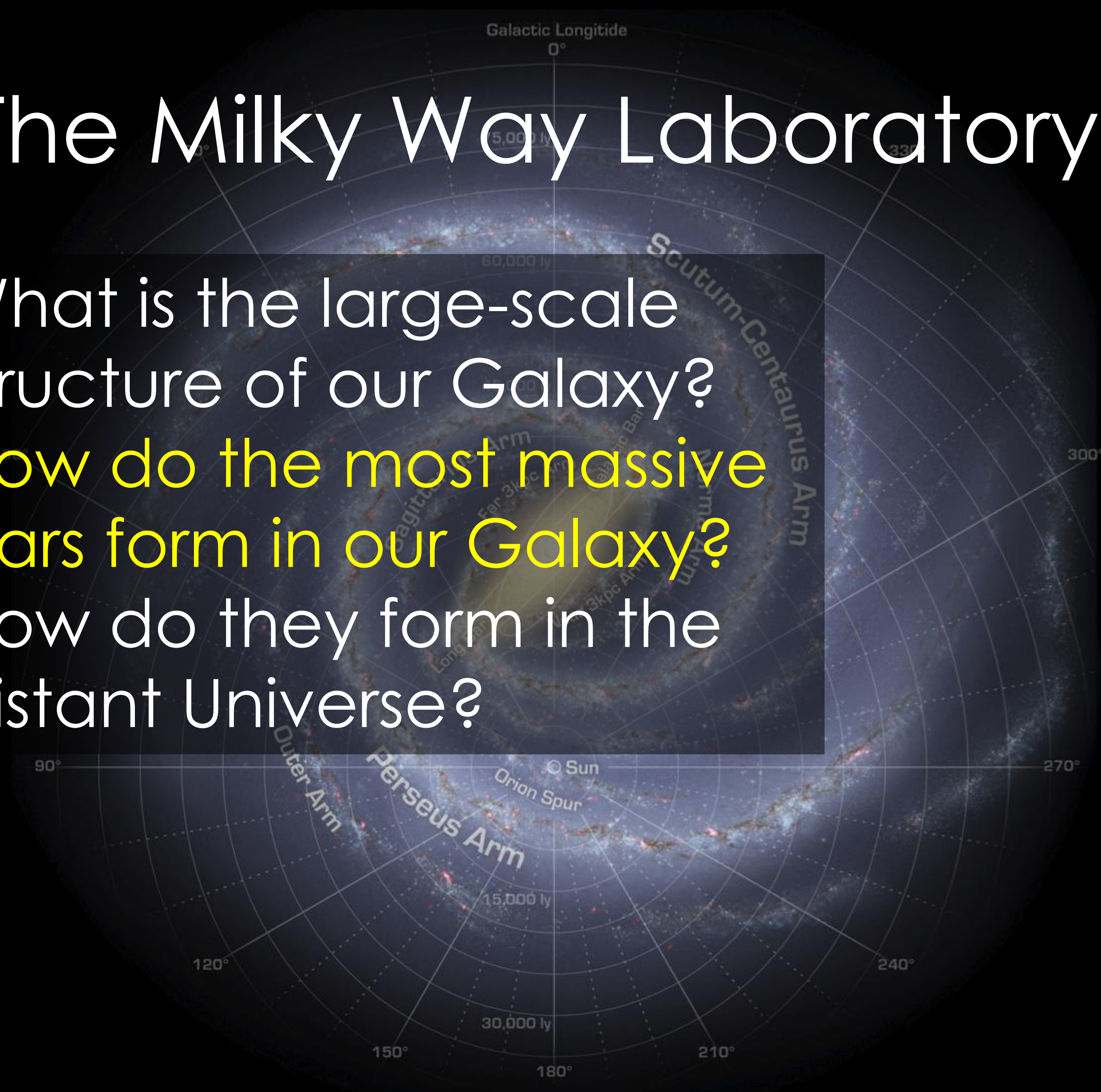


Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

The Milky Way Laboratory

1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?



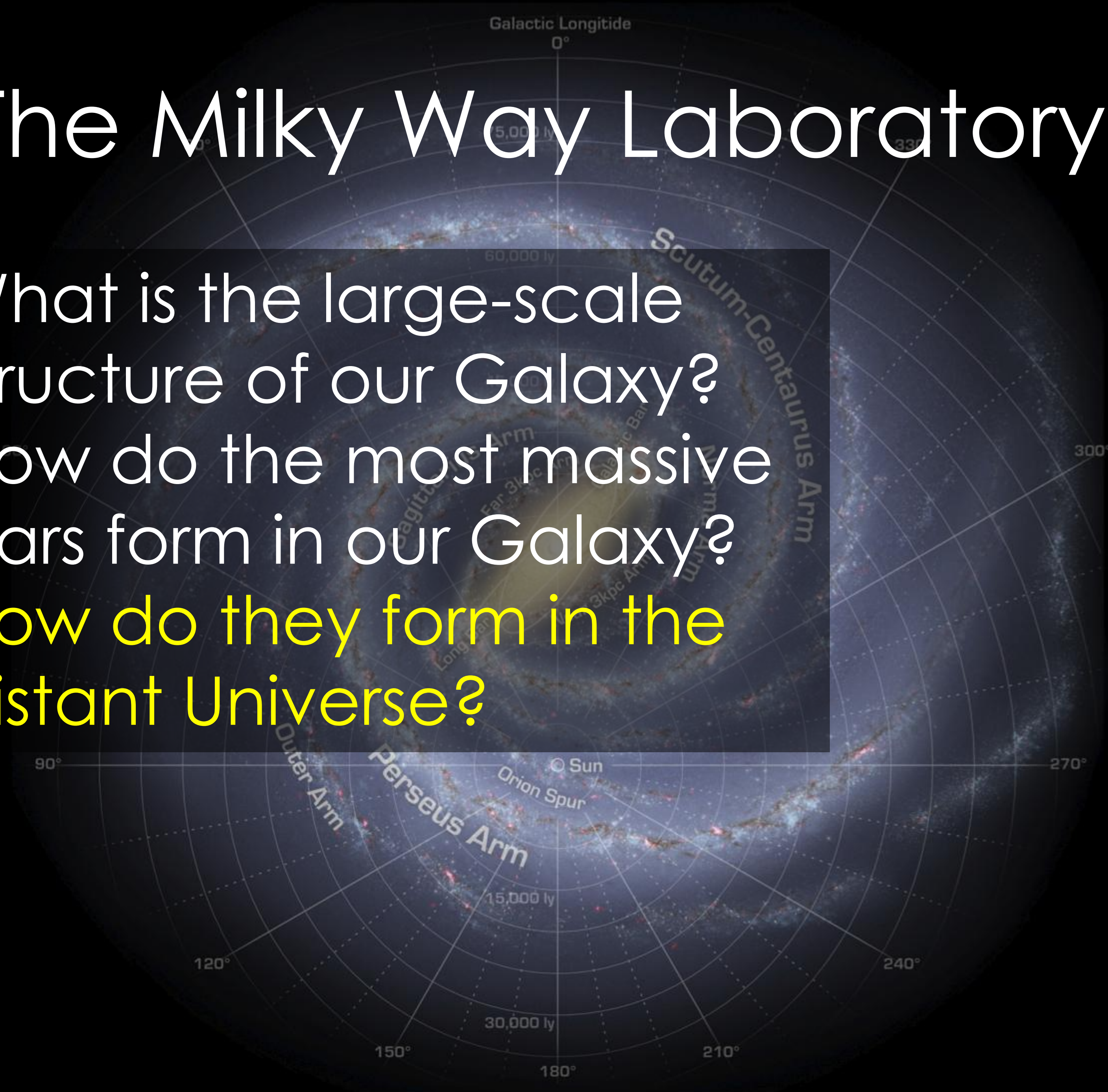
The Milky Way Laboratory

Stop 2: Massive star and cluster formation

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

The Milky Way Laboratory

1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?



The Milky Way Laboratory

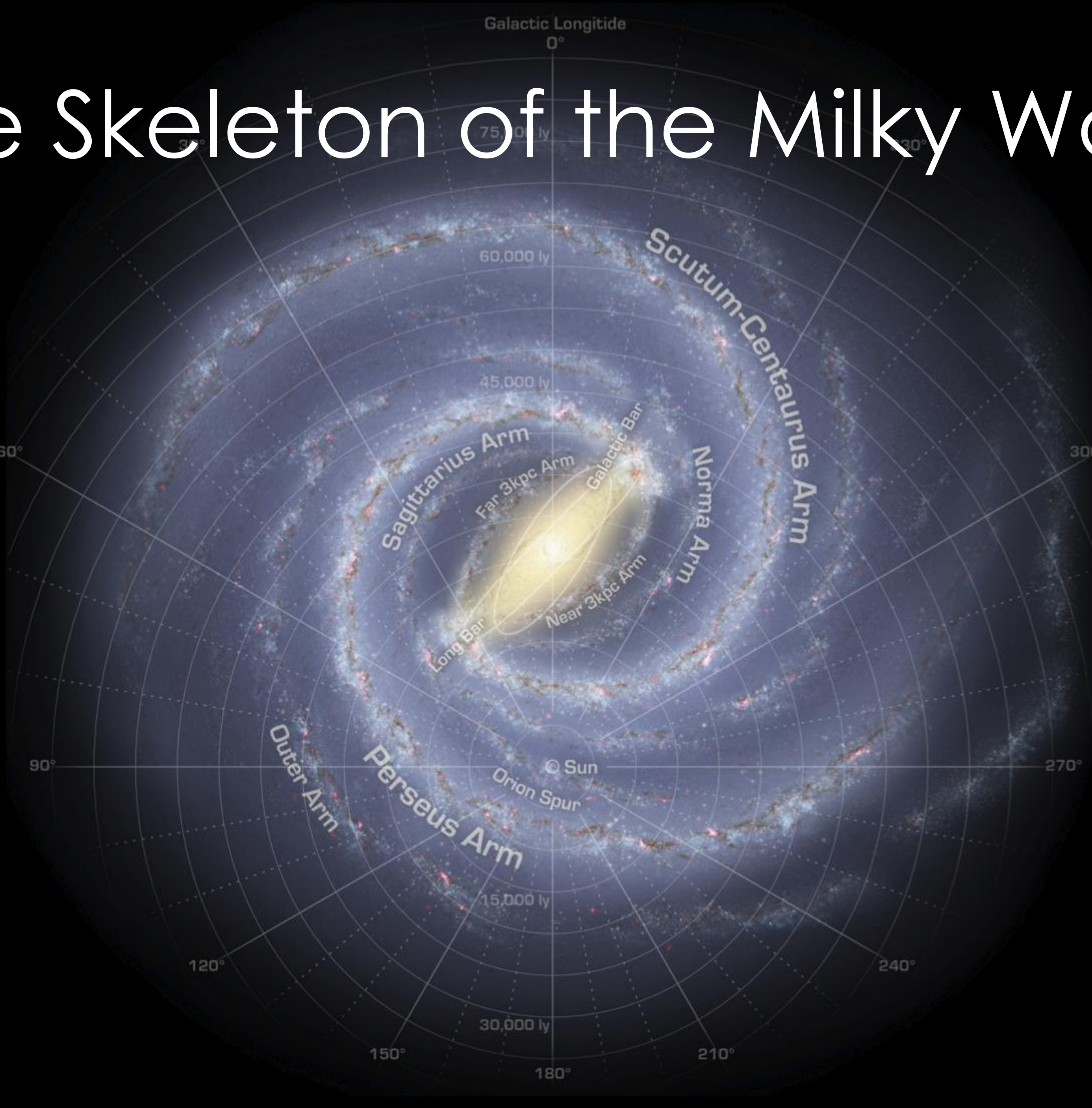
Stop 3:
Extreme SF in our Galactic Center

Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

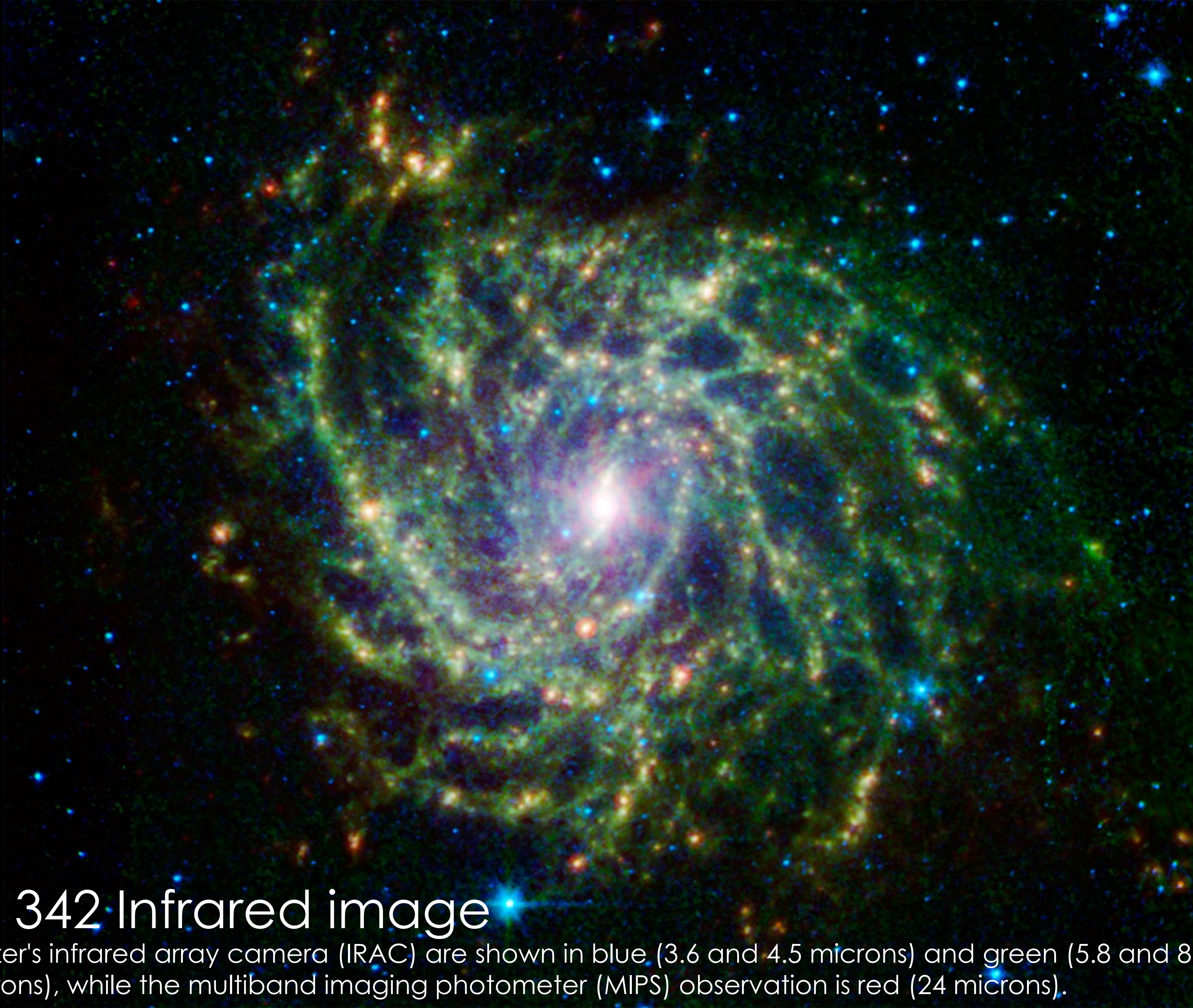
The Milky Way Laboratory

Stop 1: The Skeleton of the Milky Way

The Skeleton of the Milky Way



M51: the Whirlpool Galaxy
From the Hubble Space Telescope. NASA / JPL-Caltech / R. Kennicutt (U. Arizona)

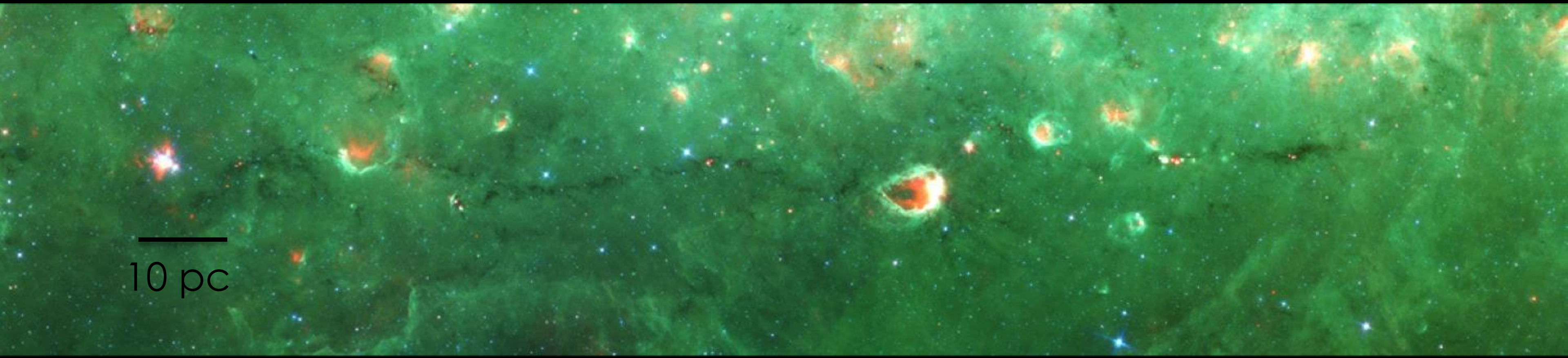


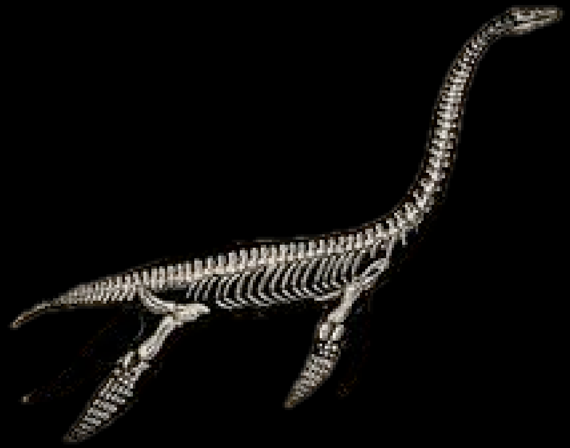
IC 342 Infrared image

Spitzer's infrared array camera (IRAC) are shown in blue (3.6 and 4.5 microns) and green (5.8 and 8.0 microns), while the multiband imaging photometer (MIPS) observation is red (24 microns).

The Milky Way

Nessie – Bone of the Milky Way?

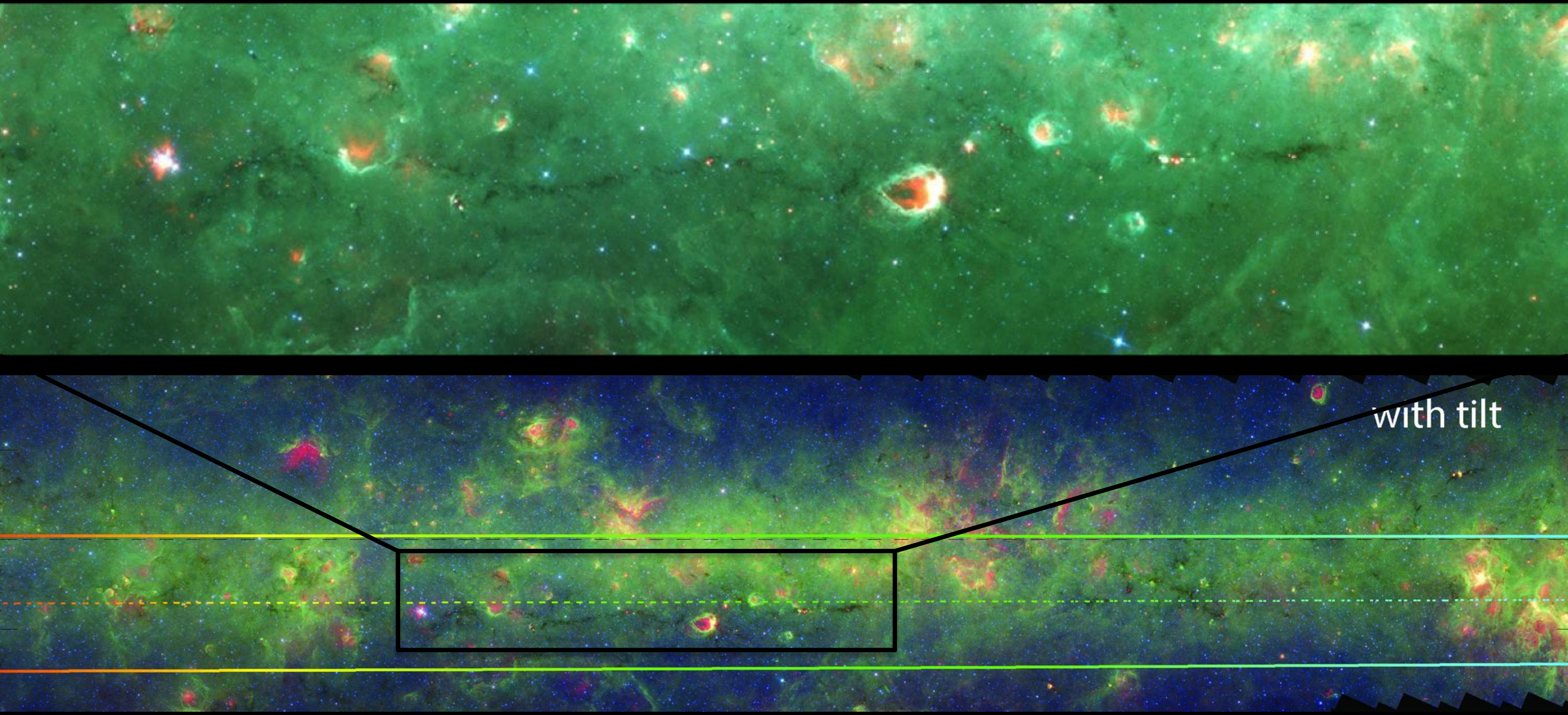




Goodman et al. 2014

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)

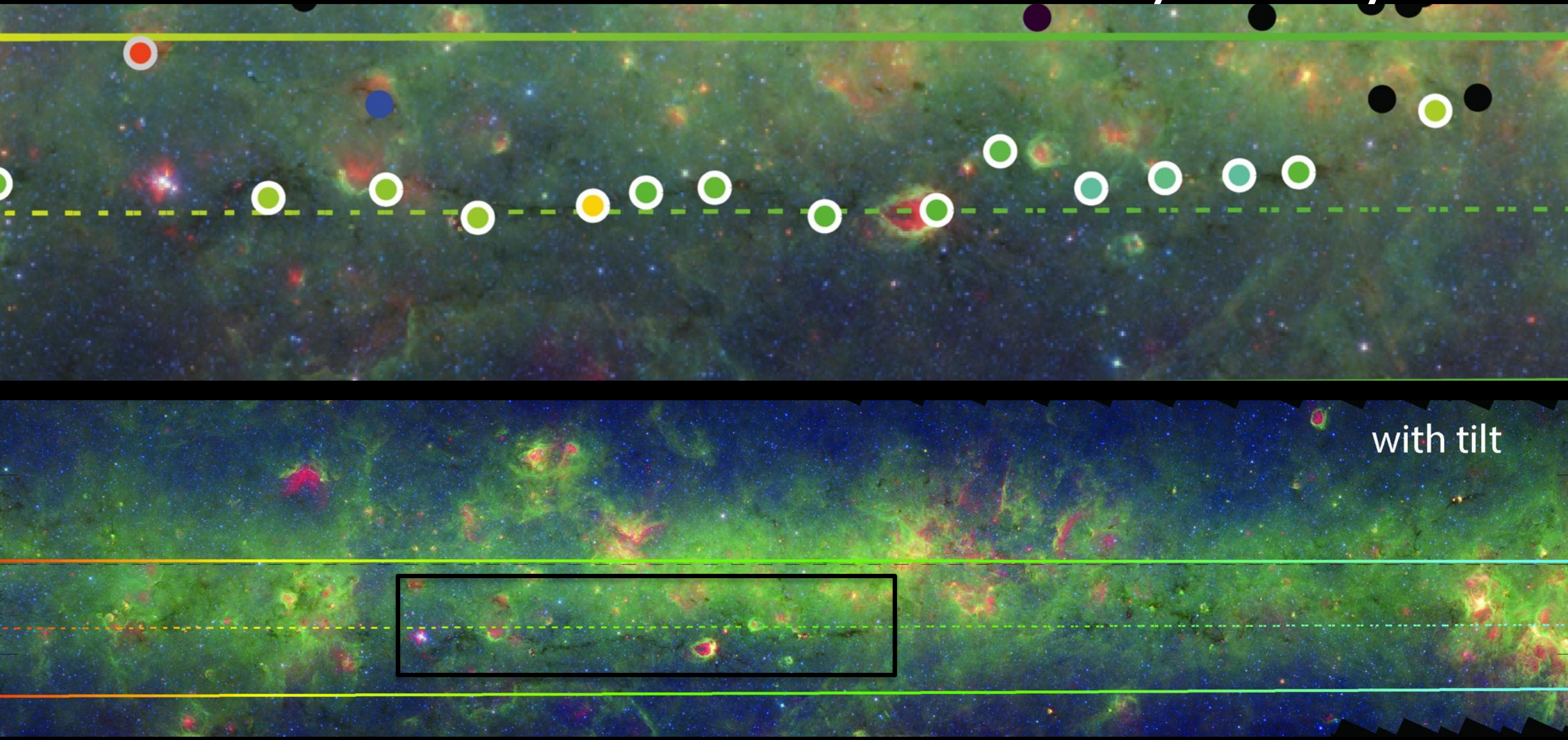
Nessie – Bone of the Milky Way?



Goodman et al. 2014

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)

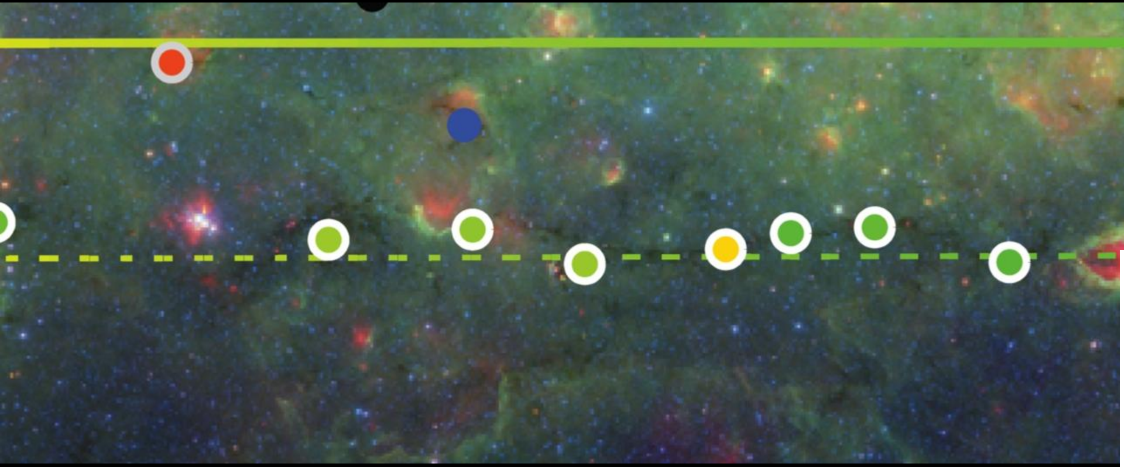
Nessie – Bone of the Milky Way?



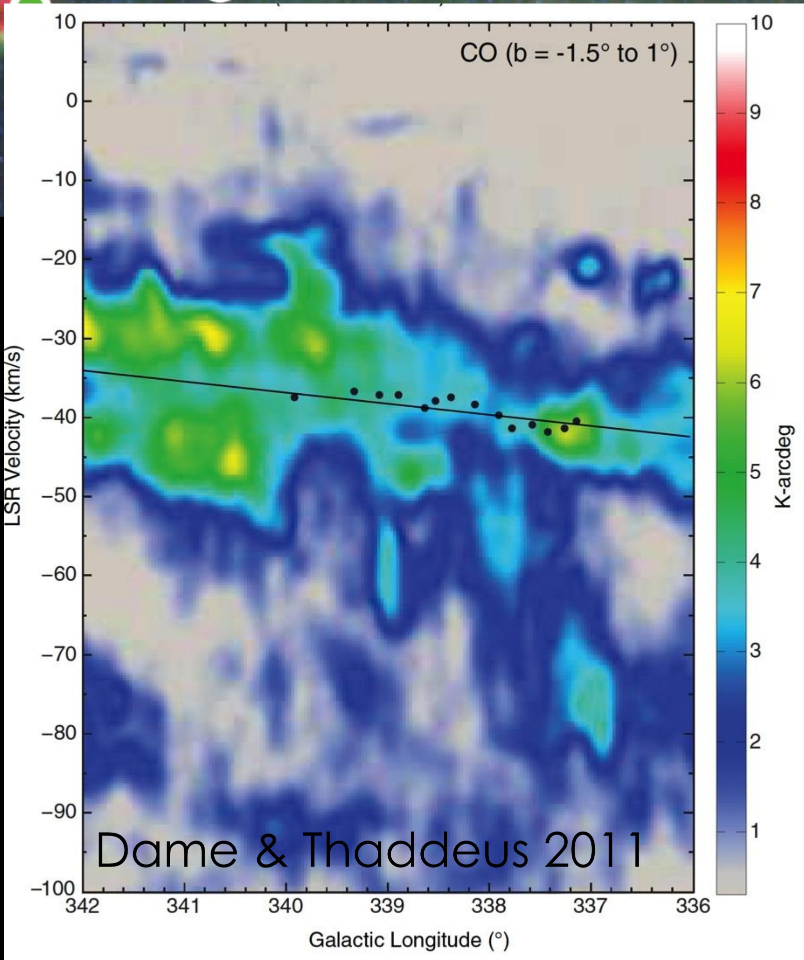
Goodman et al. 2014

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)

Nessie – Bone of the Milky Way?

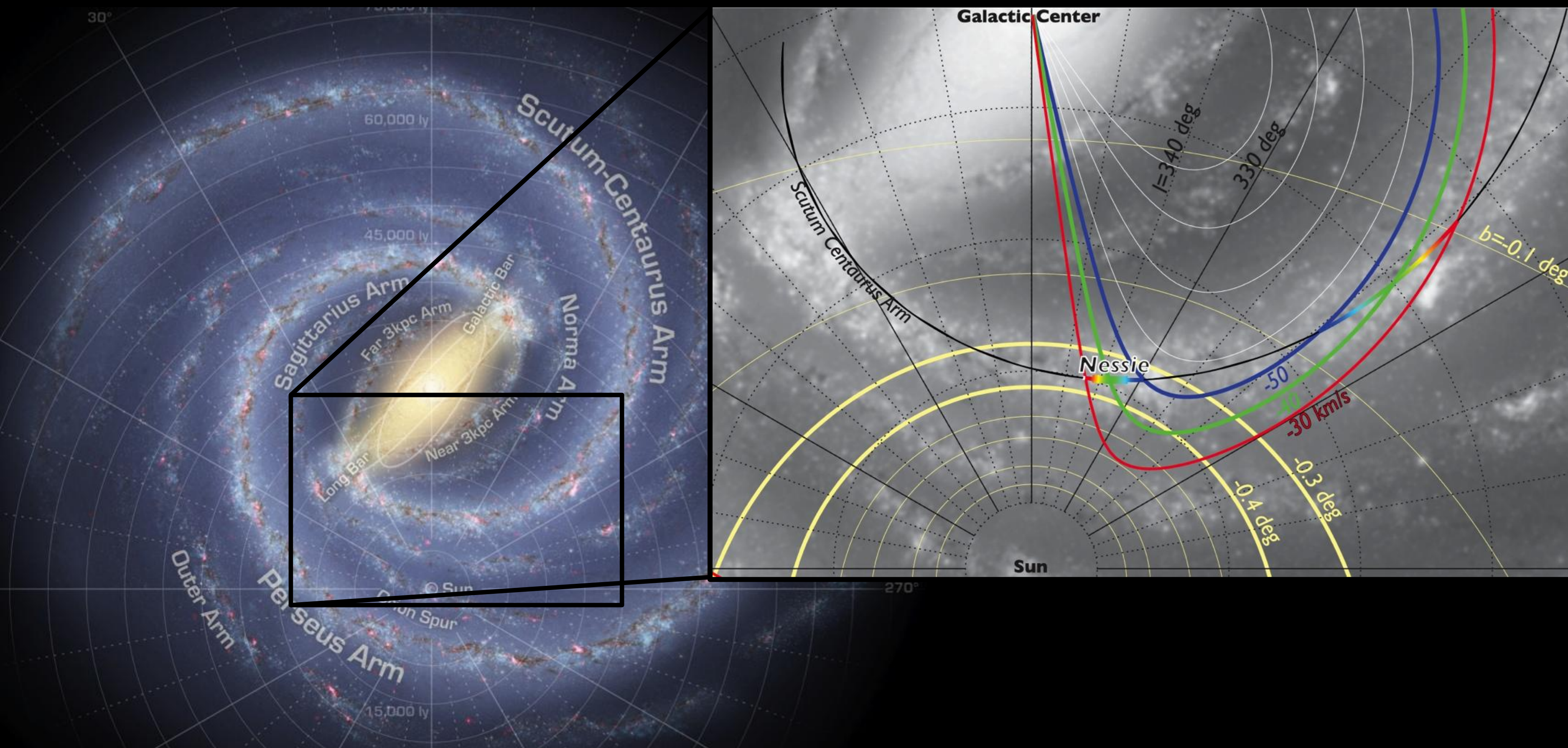


Goodman et al. 2014



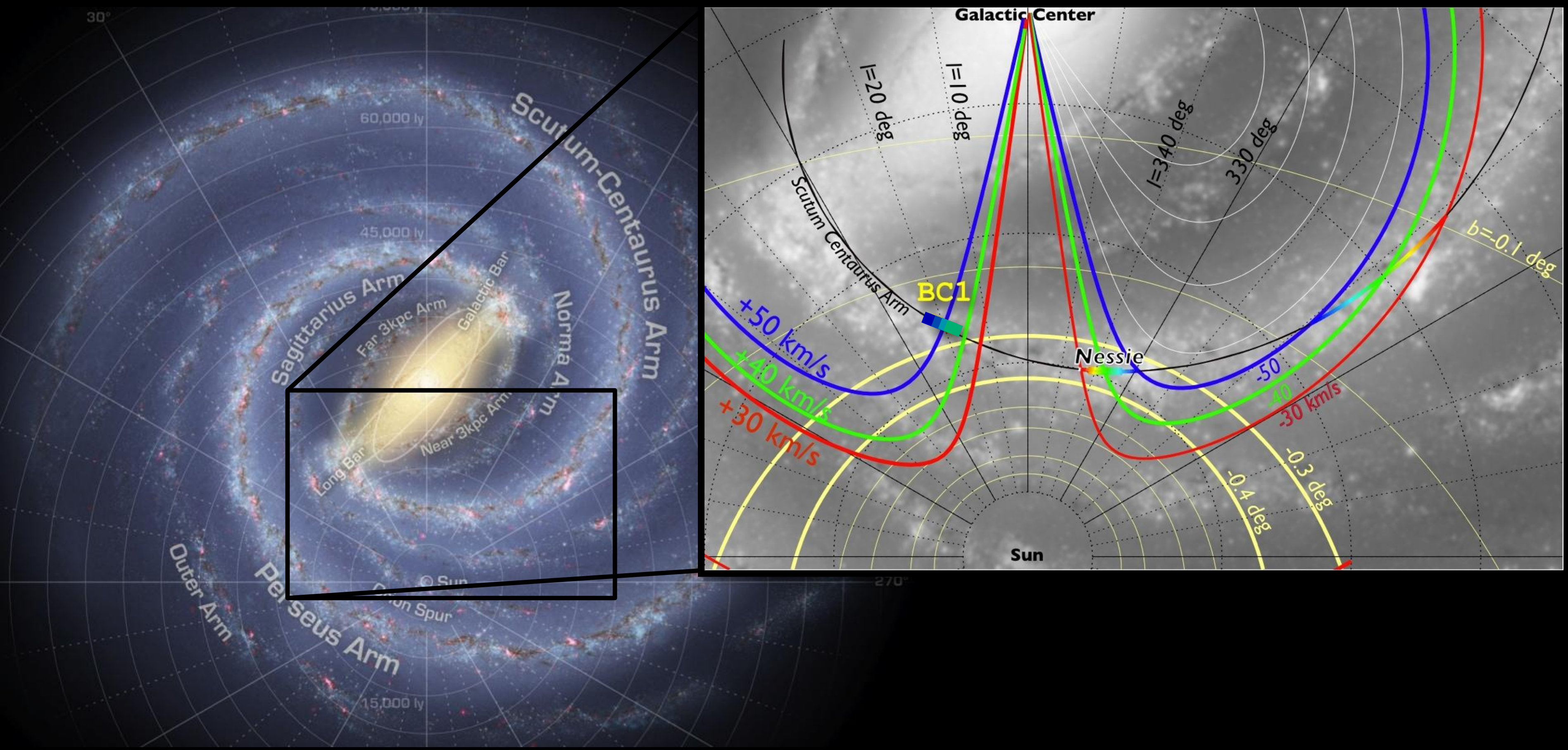
Dame & Thaddeus 2011

Nessie traces out the Scutum-Centaurus Arm. Are there others?

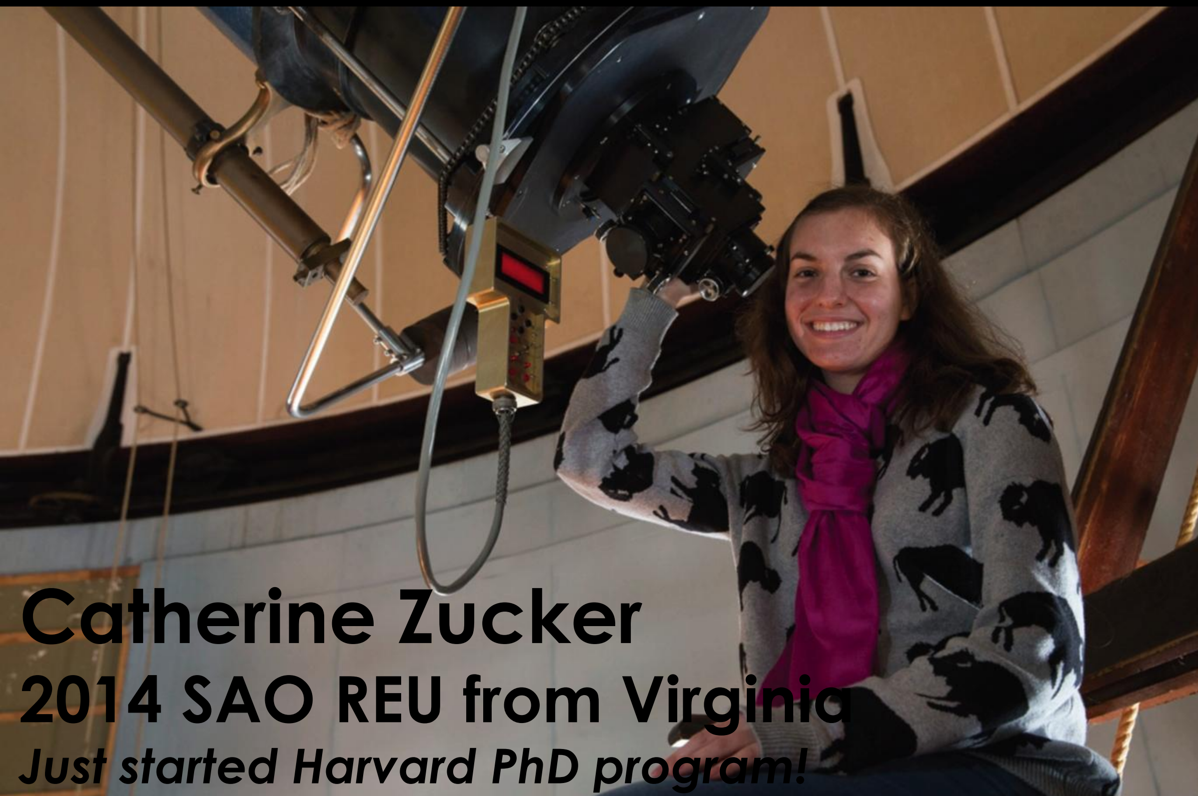


Nessie traces out the Scutum-Centaurus Arm. Are there others?

Yes!



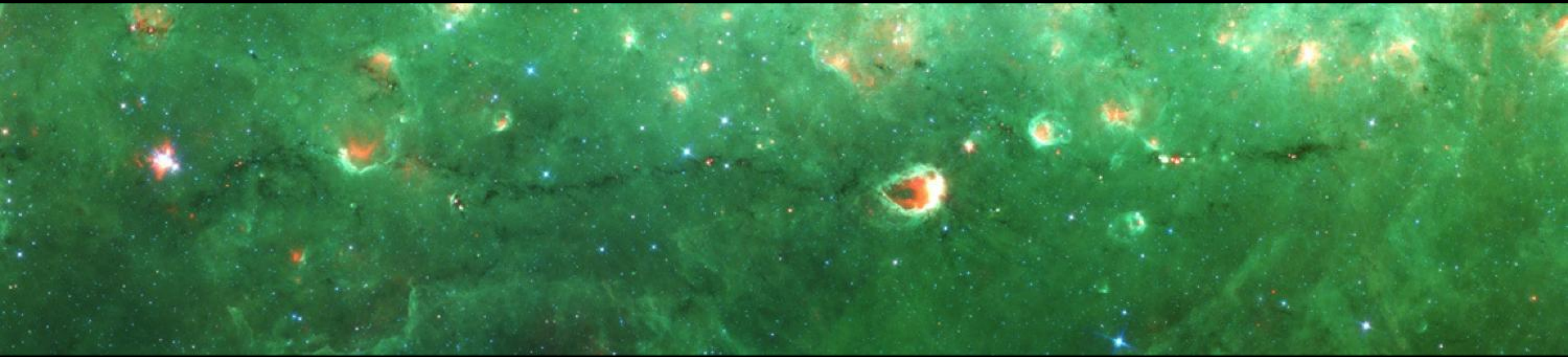
Search for more Bones of the Milky Way



Zucker, Battersby, & Goodman 2015

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)

Search for more Bones of the Milky Way

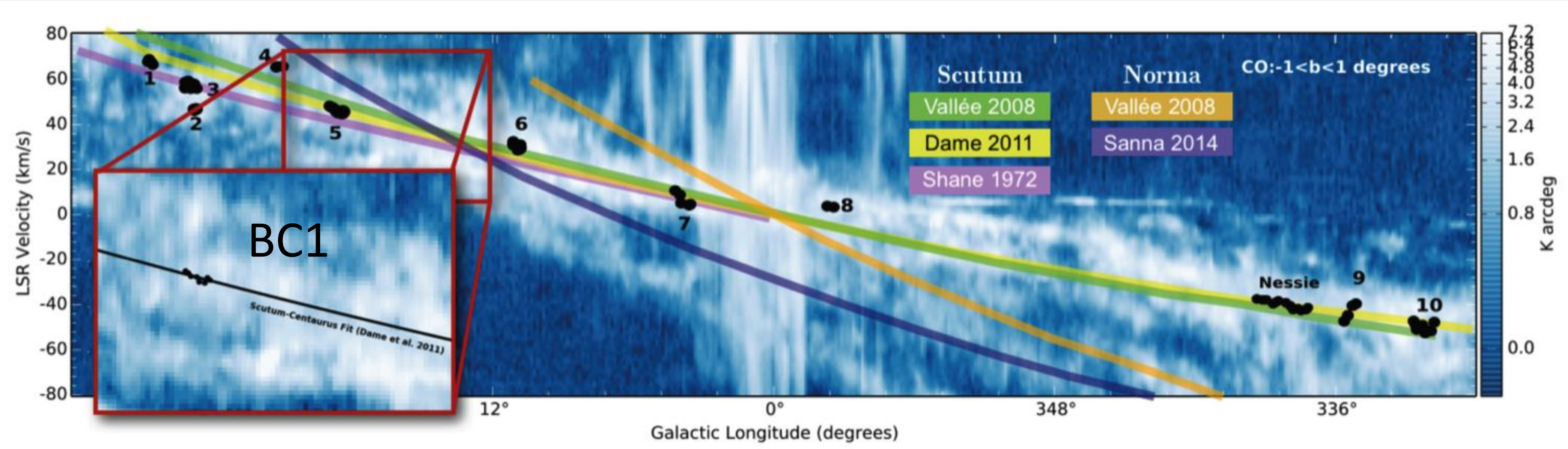


- Mid-infrared extinction feature
- Roughly parallel to the Galactic plane
- Within 20 pc of the physical Galactic mid-plane
- Within 10 km/s of the global-log spiral fit to any MW arm
- Projected aspect ratio greater than or equal to 50:1

Zucker, Battersby, & Goodman 2015

Red: 24 μm, Green: 8 μm, Blue: 4.5 μm, MIPSGAL (Carey et al. 2009) and GLIMPSE (Benjamin et al. 2003)

Search for more Bones of the Milky Way

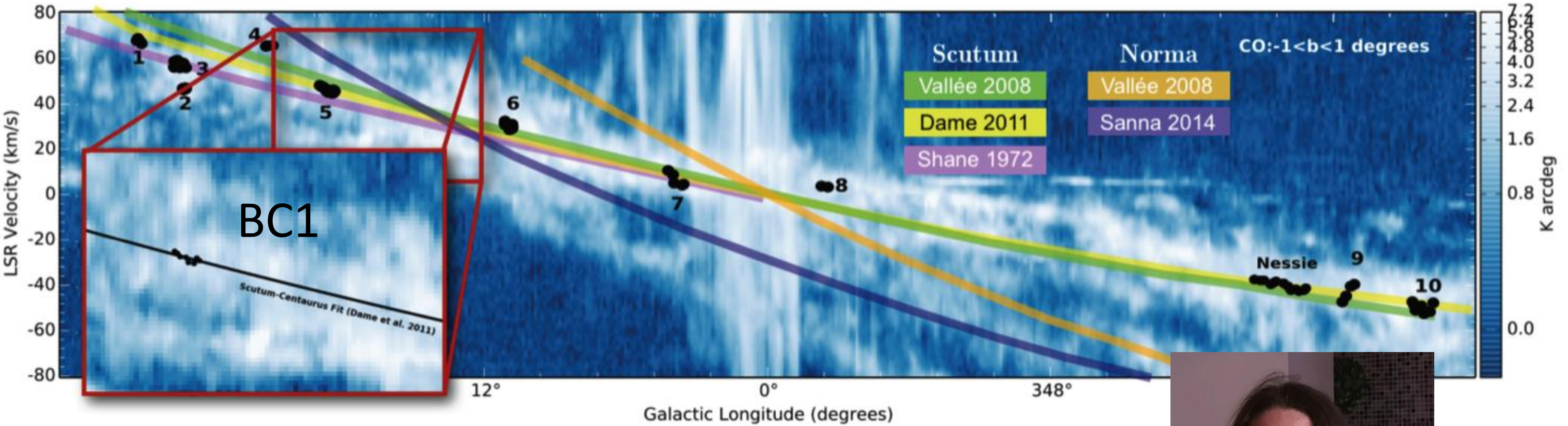


6/10 candidates are excellent tracers of spiral arm in 3-D
(position-position-velocity space)

We are now working to assemble a full 'Skeleton'

Zucker, Battersby, & Goodman 2015

Bones of the Milky Way



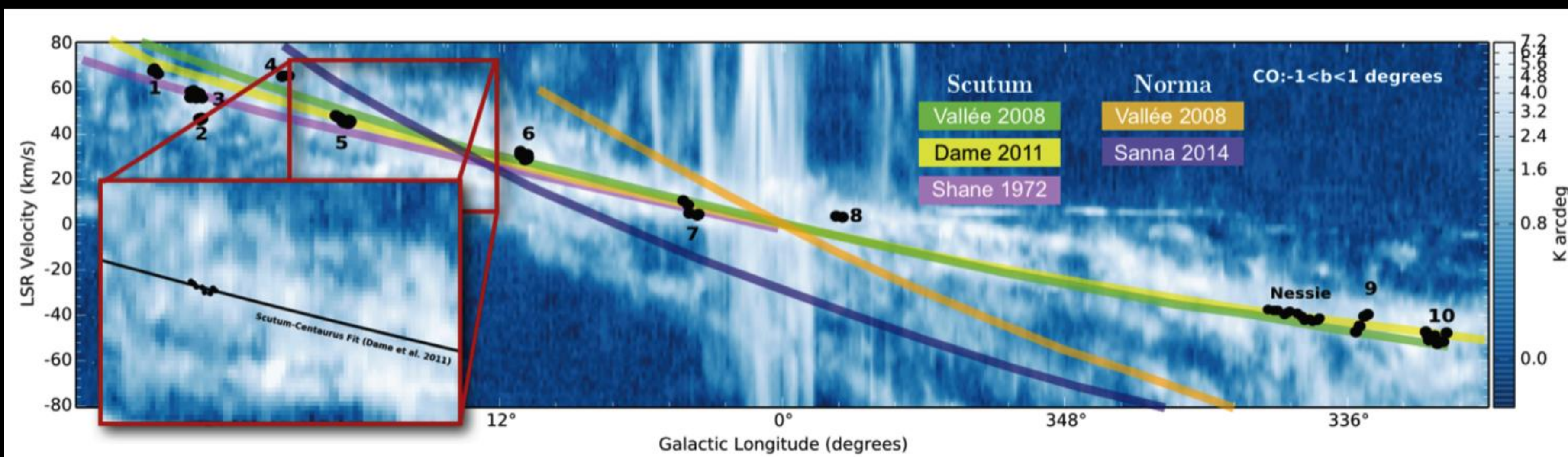
Working to characterize their physical properties and kinematics with Harvard undergraduate, Amy Cohn

Zucker, Battersby, & Goodman 2015

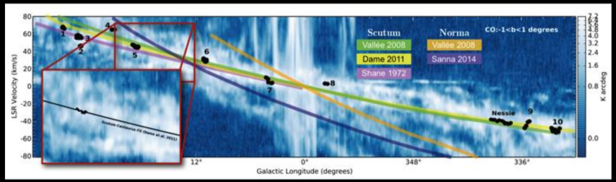
Next Steps: The Skeleton of the Milky Way

Next Steps: The Skeleton of the Milky Way

- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure

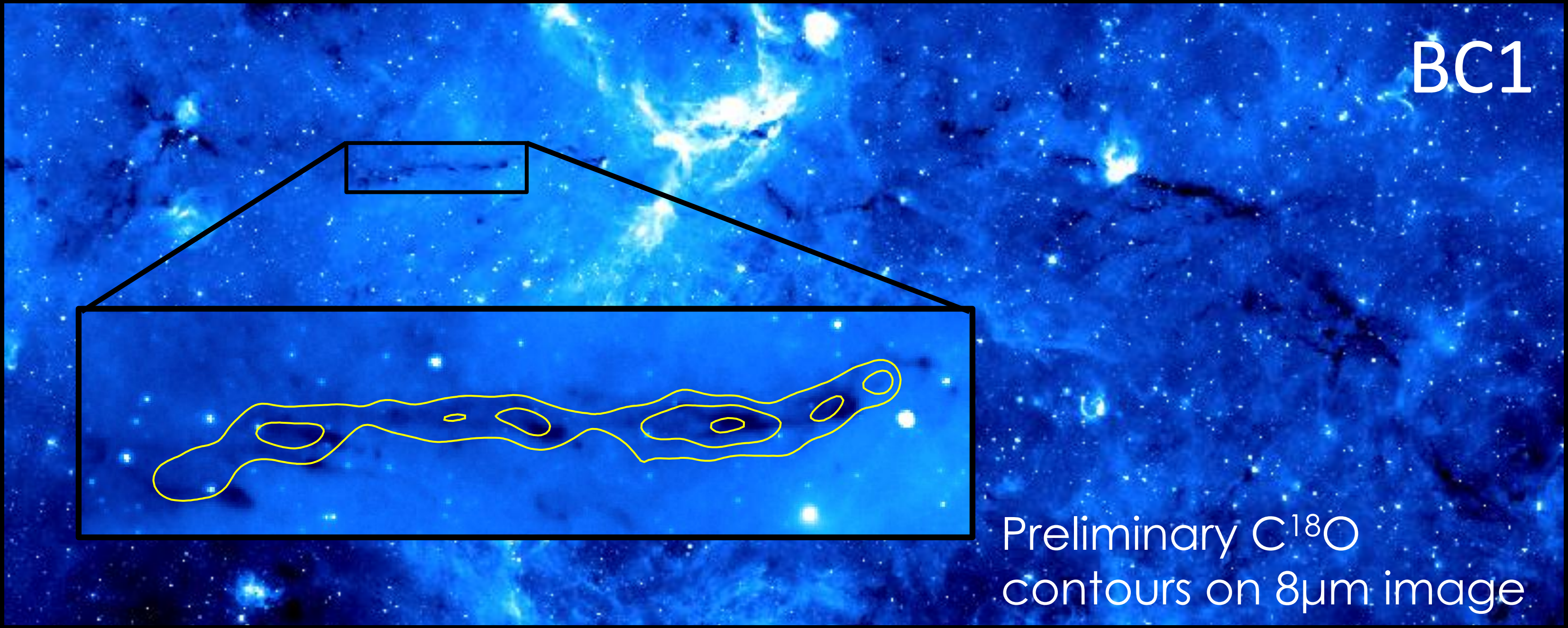


Next Steps: The Skeleton of the Milky Way



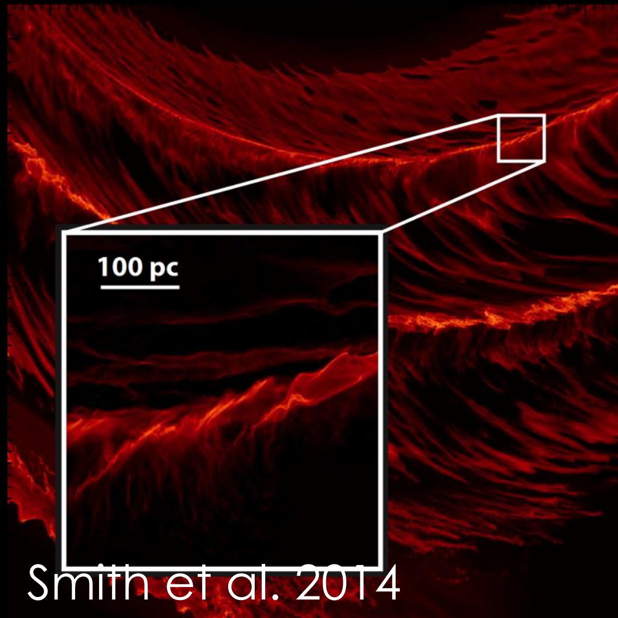
- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure

- Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations

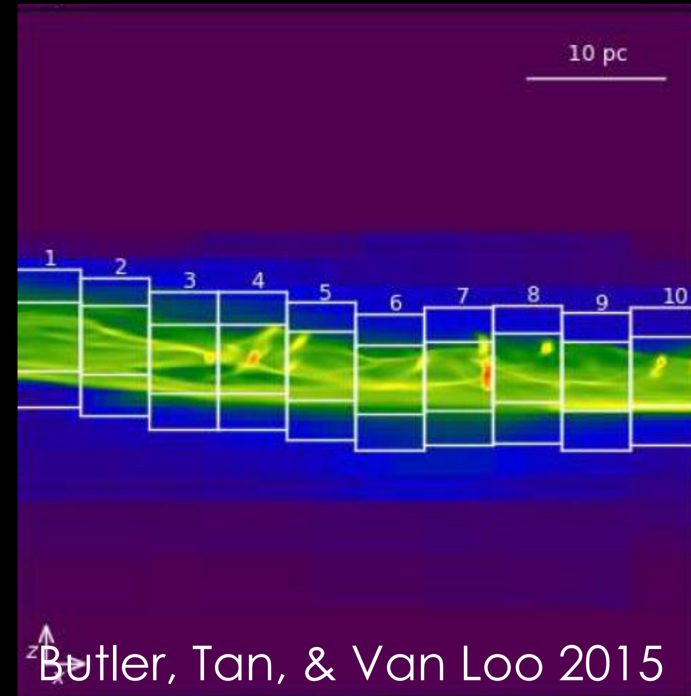


- Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations

60 hour IRAM Project (PI: Battersby) to map our best Northern "Bone candidate"



Smith et al. 2014

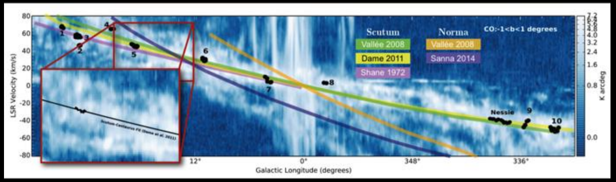


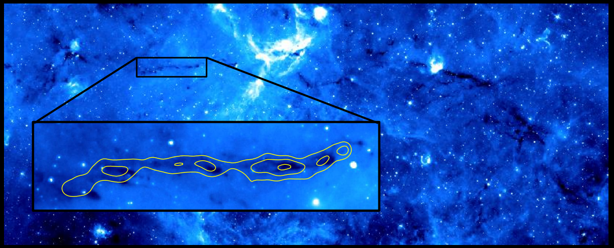
Butler, Tan, & Van Loo 2015

- Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations

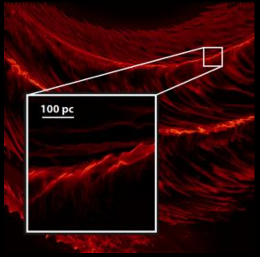
Next Steps: The Skeleton of the Milky Way

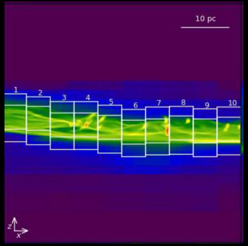
- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure



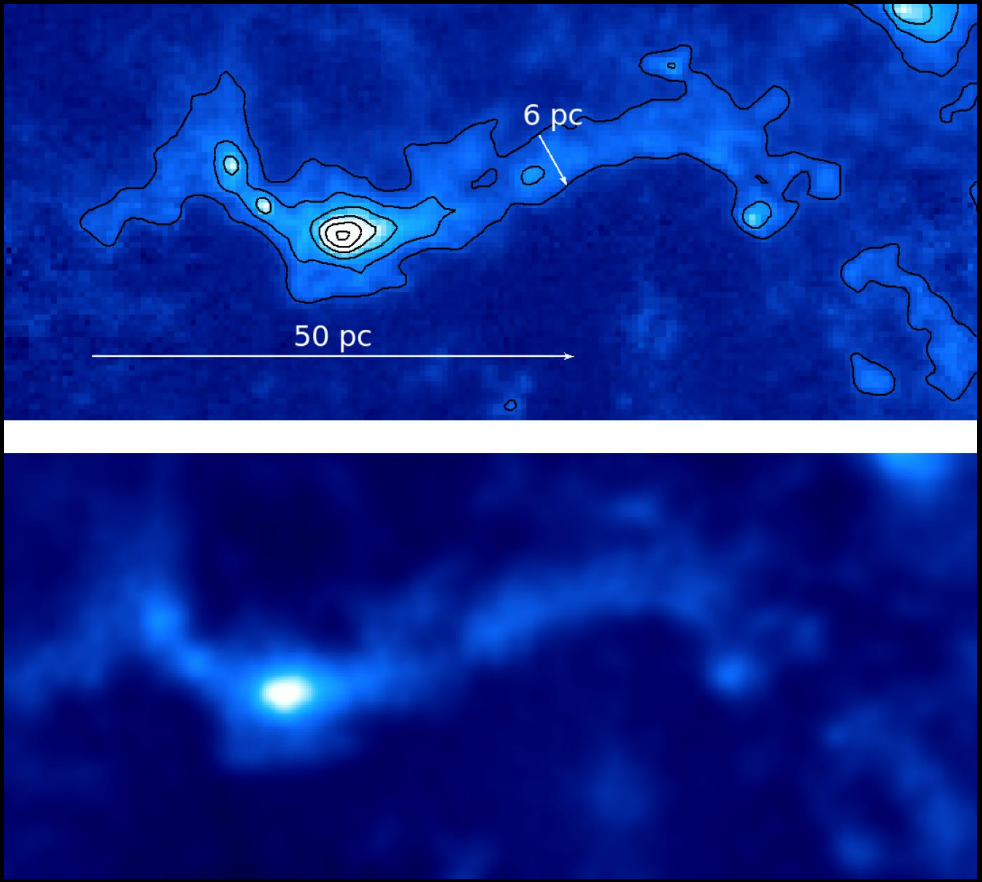


- Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations





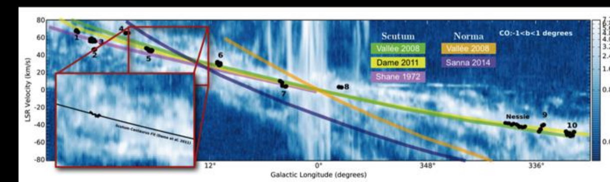
- Detect Bones in nearby face-on spiral galaxies to understand their role in Galactic structure

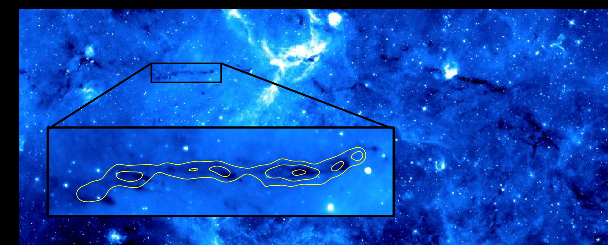


- Detect Bones in nearby face-on spiral galaxies to understand their role in Galactic structure

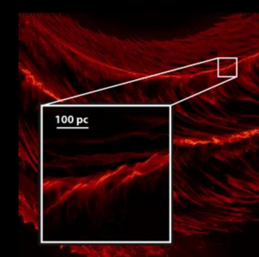
Next Steps: The Skeleton of the Milky Way

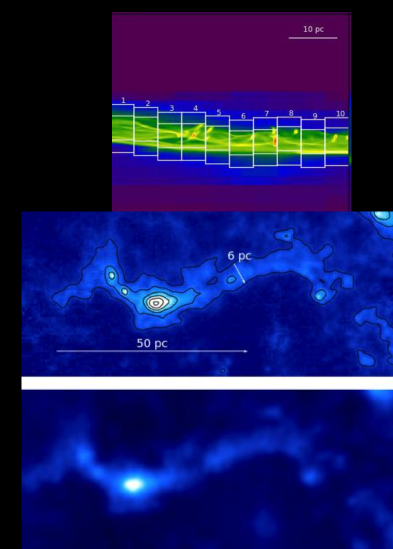
- Identify more Bones of the Milky Way. Combine with other tracers (e.g. CO, HI, dense gas) to develop a model of Galactic structure





- Measure physical properties and kinematics of Bones – compare directly with simulations. Develop improved Galactic-scale simulations

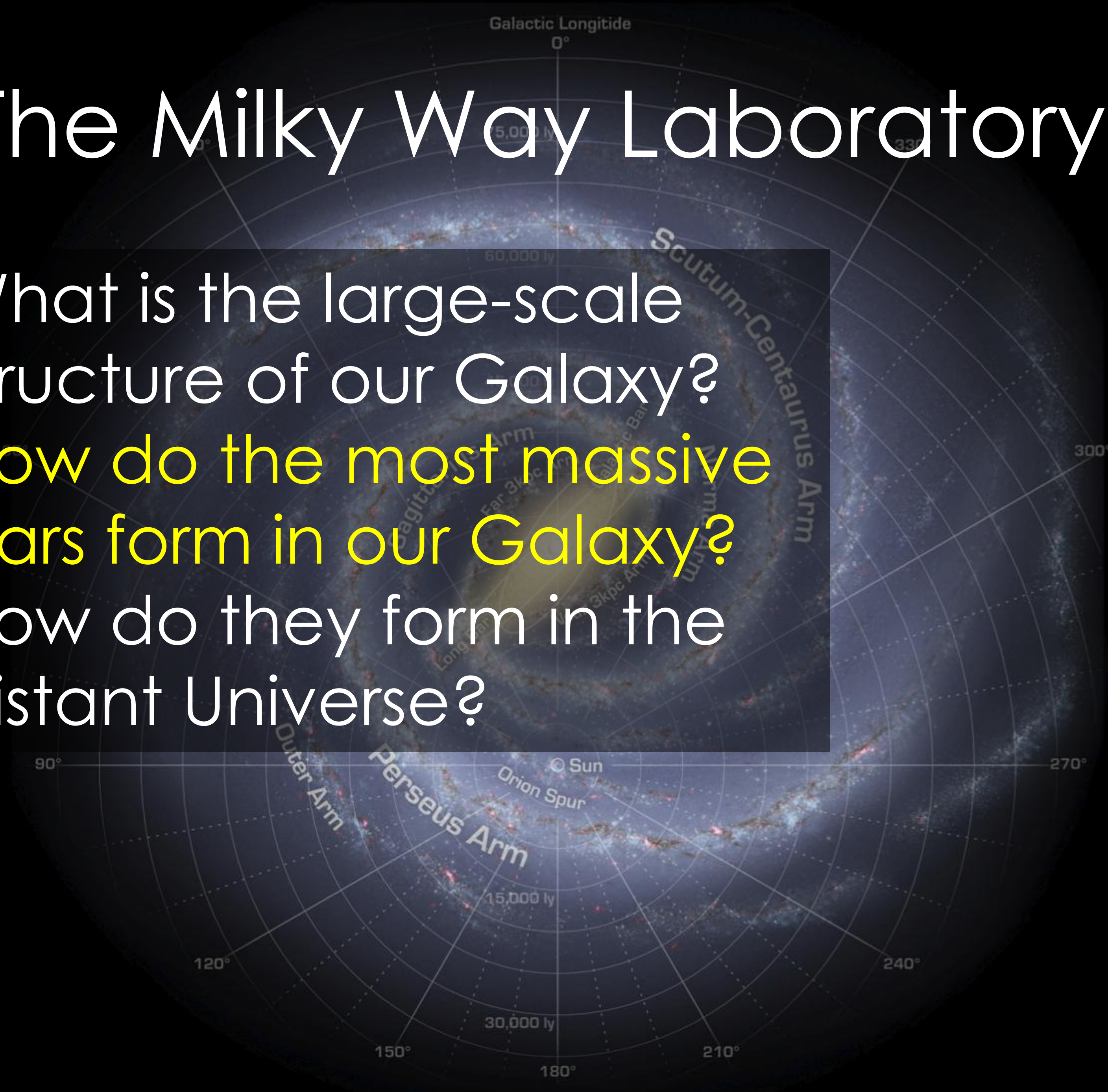




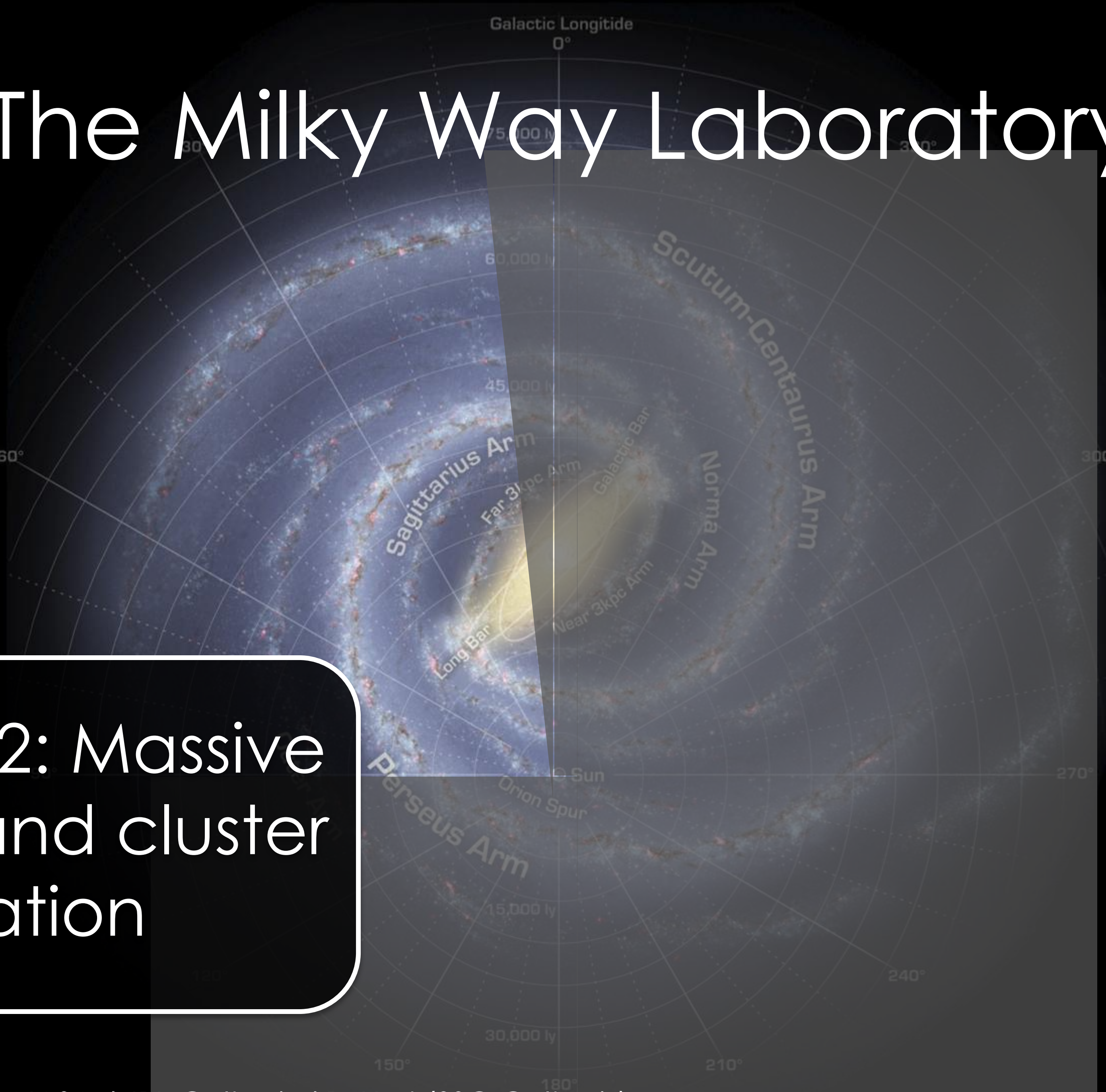
- Detect Bones in nearby face-on spiral galaxies to understand their role in Galactic structure

The Milky Way Laboratory

1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?



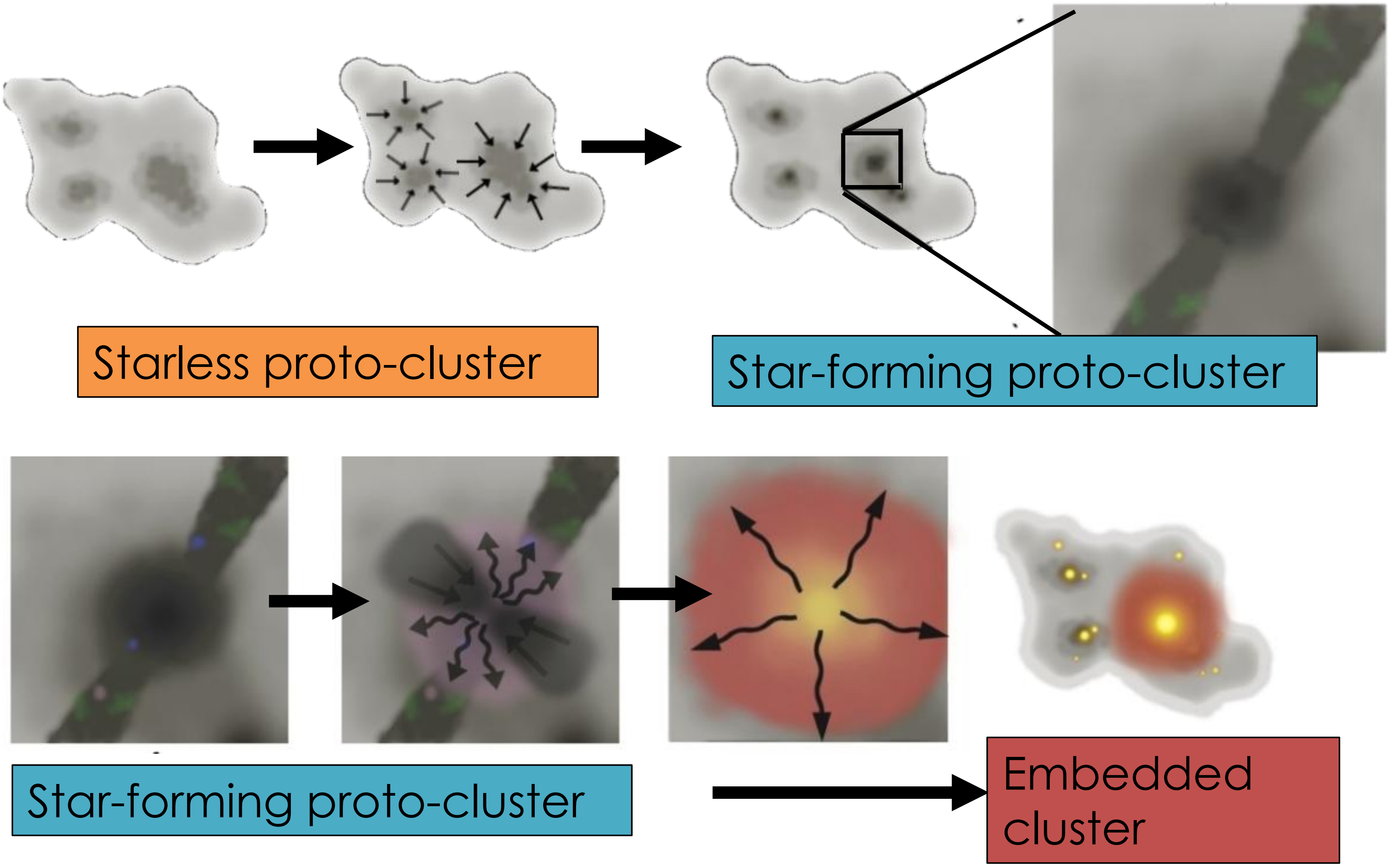
The Milky Way Laboratory



Stop 2: Massive star and cluster formation

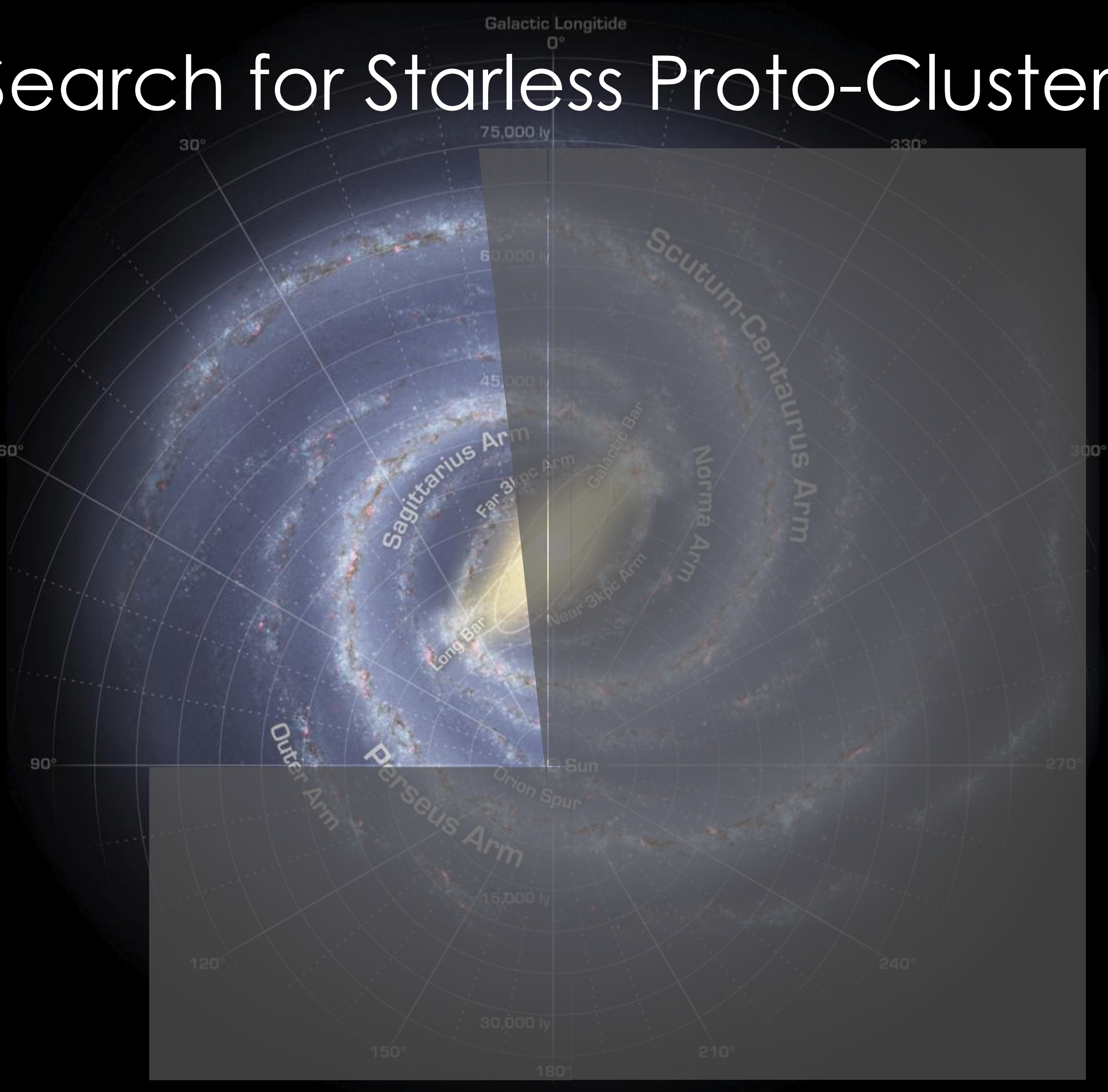
Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

Evolution

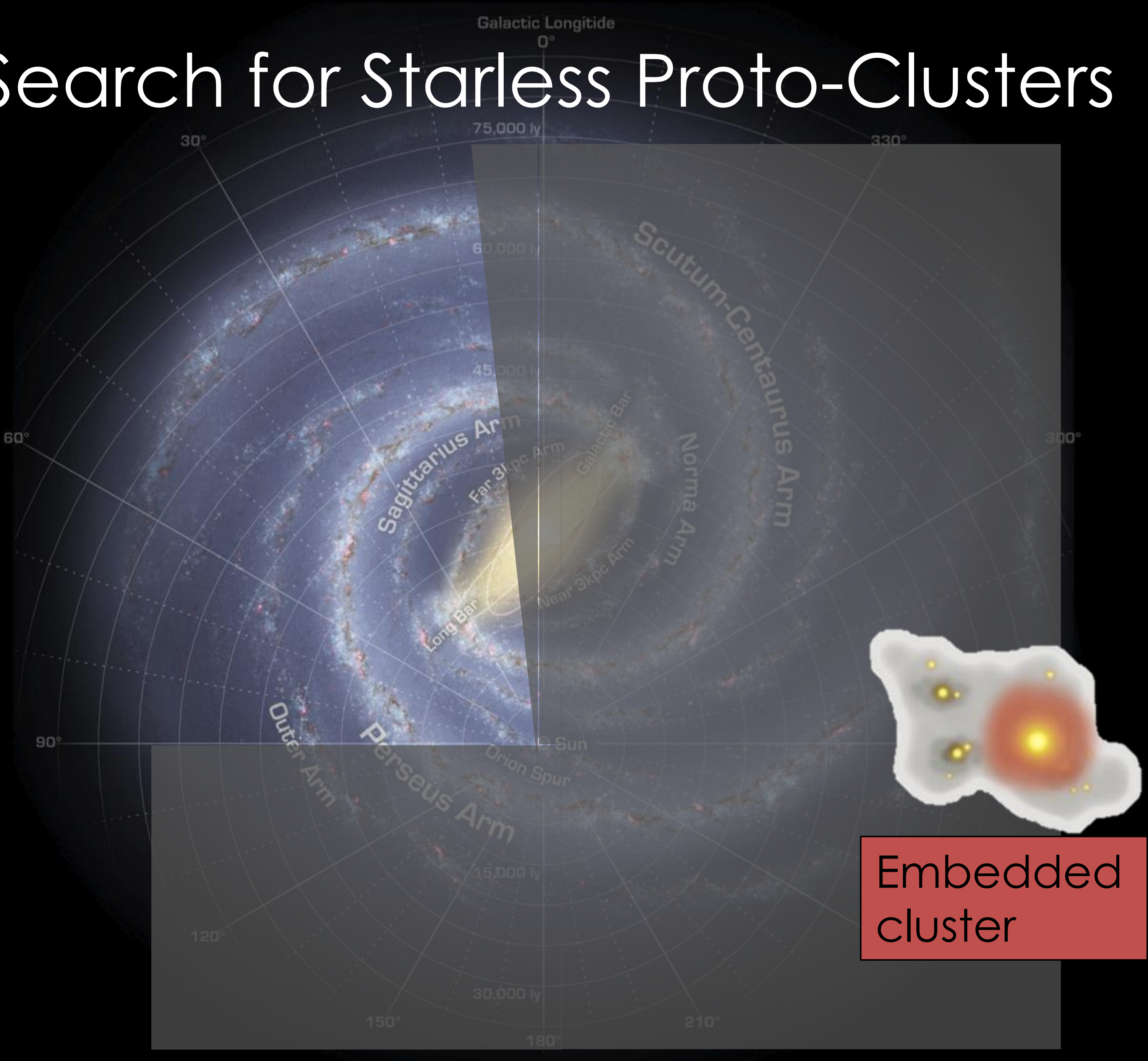


Battersby et al. 2010; 2011

Search for Starless Proto-Clusters



Search for Starless Proto-Clusters

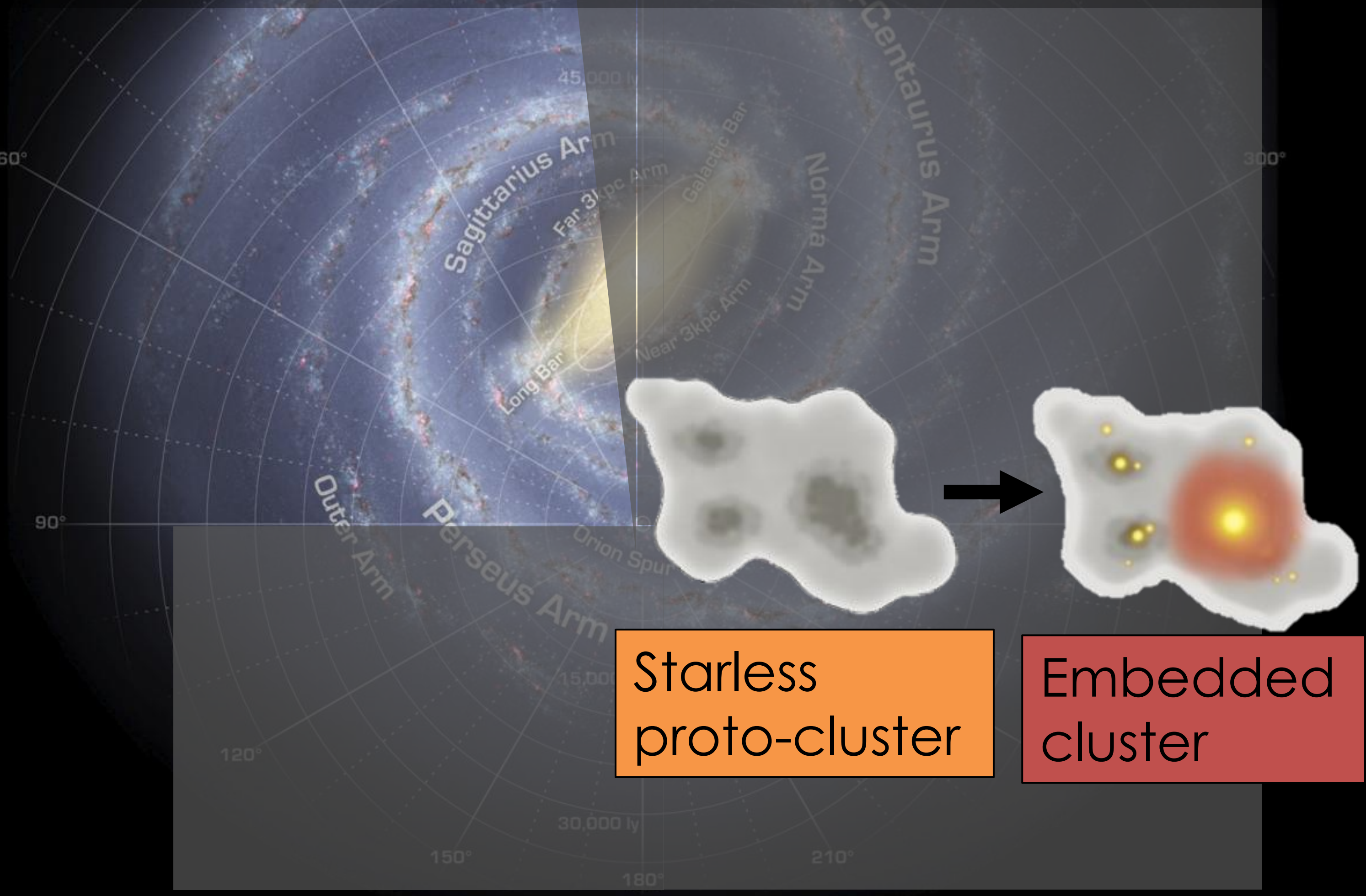


Embedded cluster

Search for Starless Proto-Clusters

First ever complete search for massive, compact starless proto-clusters (BGPS: Ginsburg, Battersby, et al. 2012)

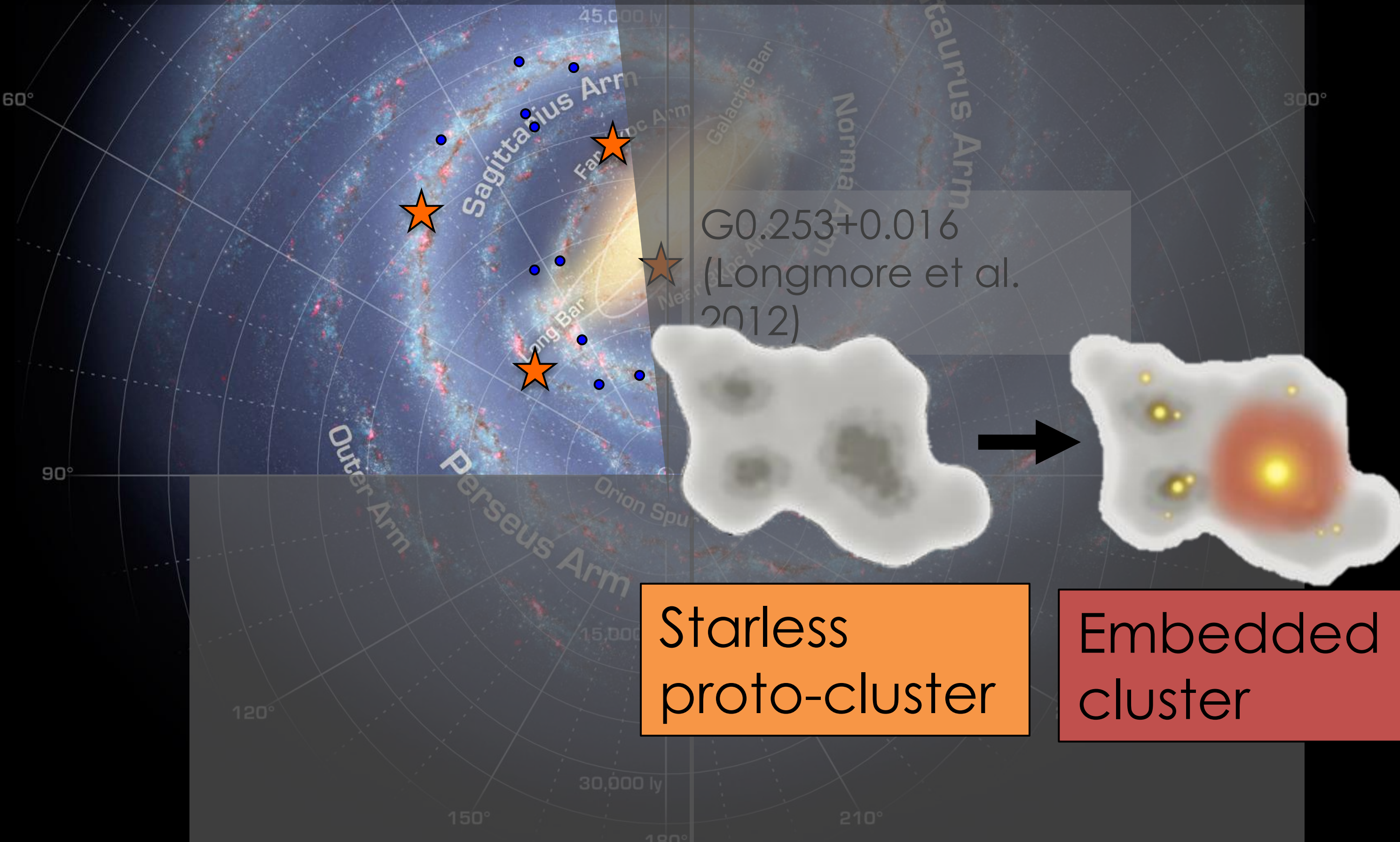
- Massive, Tightly Bound: $3 \times 10^4\ M_\odot$ ($1 \times 10^4\ M_\odot$) $r < 2.5$ pc



Search for Starless Proto-Clusters

First ever complete search for massive, compact starless proto-clusters (BGPS: Ginsburg, Battersby, et al. 2012)

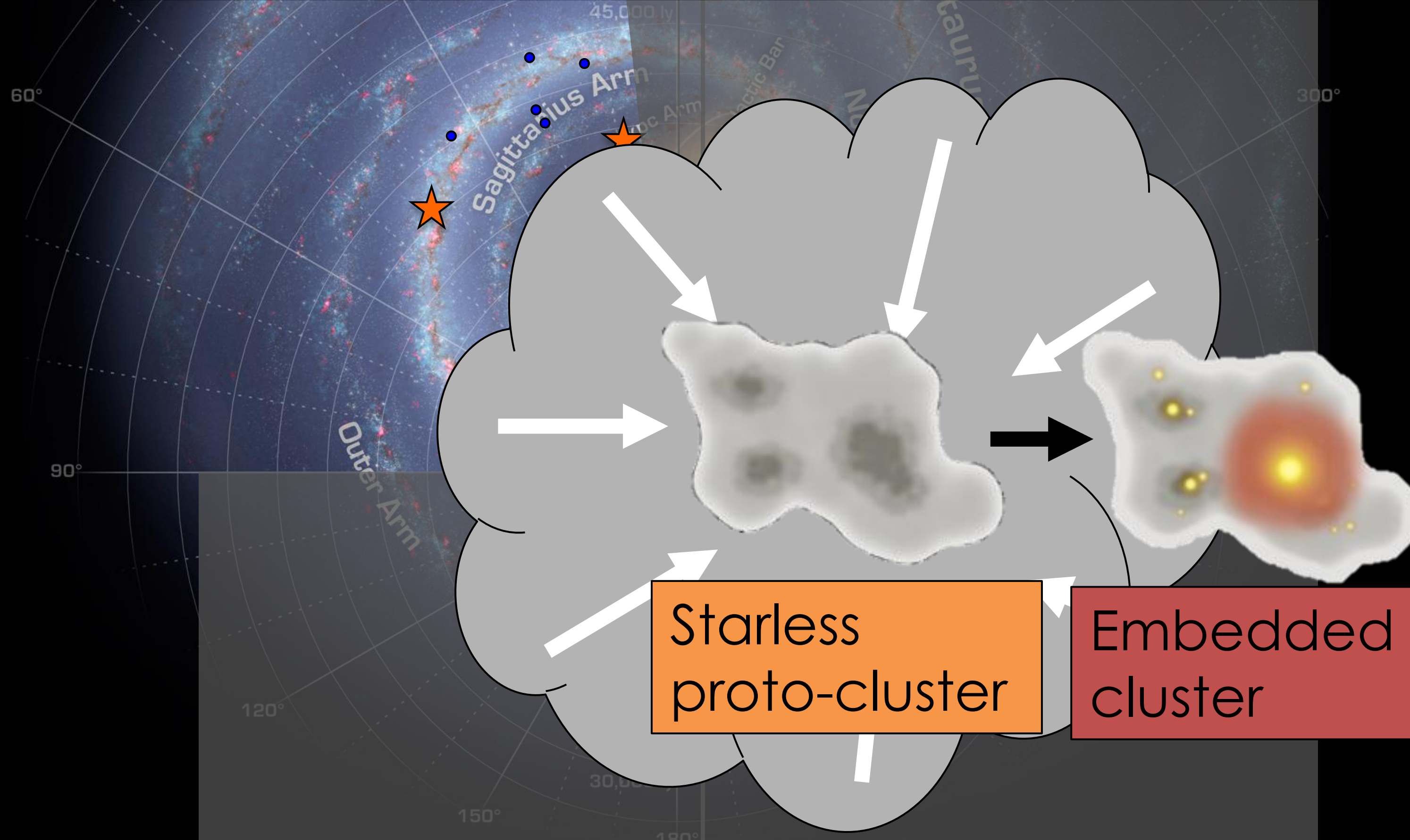
- Massive, Tightly Bound: $3 \times 10^4\ M_\odot$ ($1 \times 10^4\ M_\odot$) $r < 2.5$ pc
- yields 3 (18), none of which are starless



Search for Starless Proto-Clusters

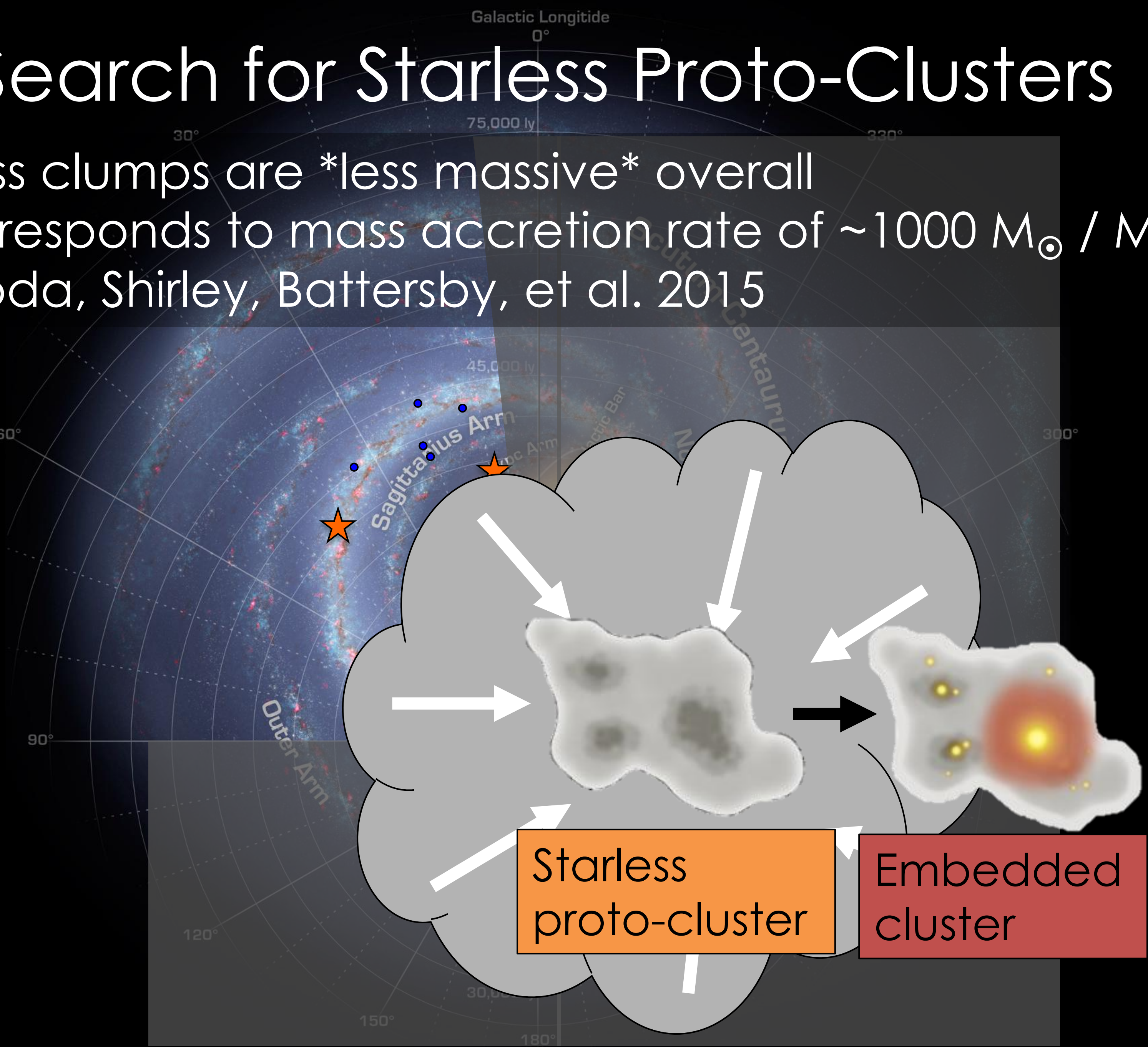
First ever complete search for massive, compact starless proto-clusters (BGPS: Ginsburg, Battersby, et al. 2012)

- Massive, Tightly Bound: $3 \times 10^4\ M_\odot$ ($1 \times 10^4\ M_\odot$) $r < 2.5$ pc
- yields 3 (18), none of which are starless



Search for Starless Proto-Clusters

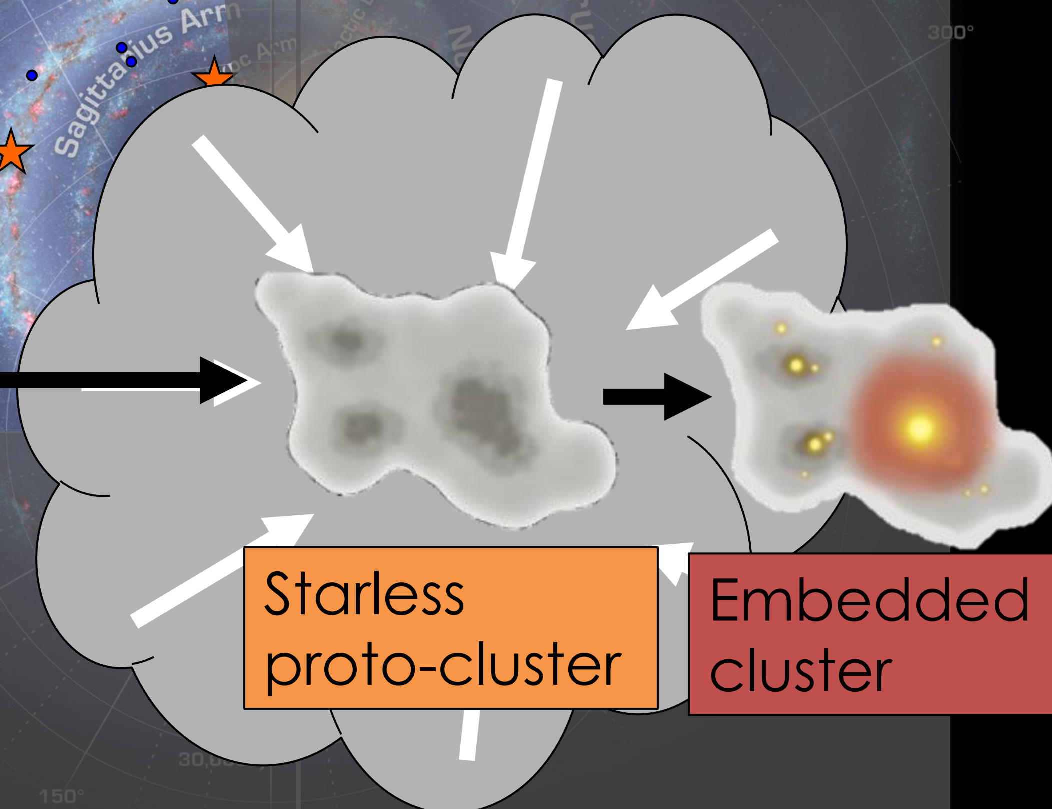
Starless clumps are *less massive* overall
→ corresponds to mass accretion rate of ~1000 $M_\odot$ / Myr
Svoboda, Shirley, Battersby, et al. 2015

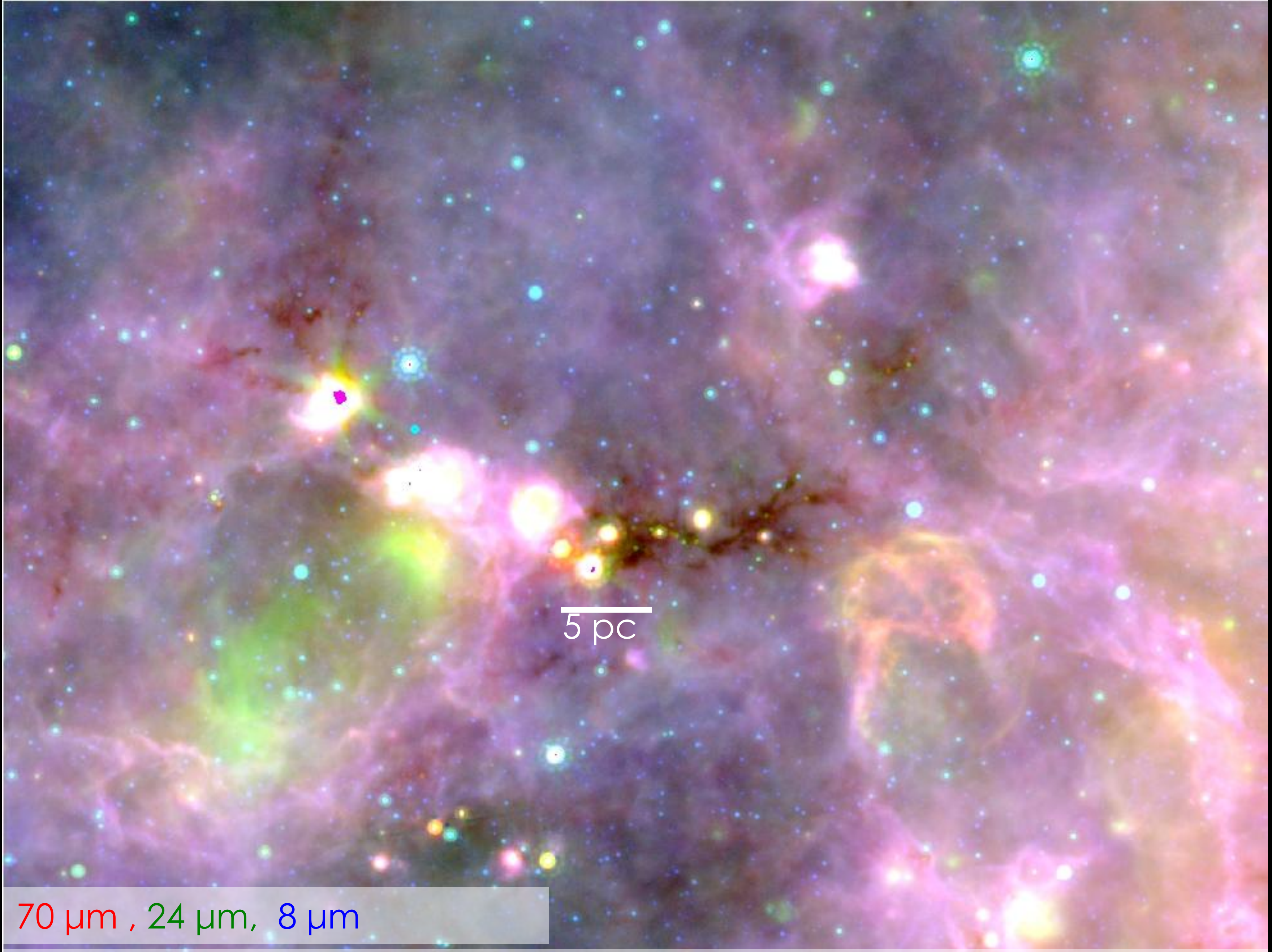


Search for Starless Proto-Clusters

Starless clumps are *less massive* overall
→ corresponds to mass accretion rate of ~1000 $M_\odot$ / Myr
Svoboda, Shirley, Battersby, et al. 2015

Follow-up SMA and ALMA surveys toward most massive starless clumps → initial structure before disruption by stellar feedback

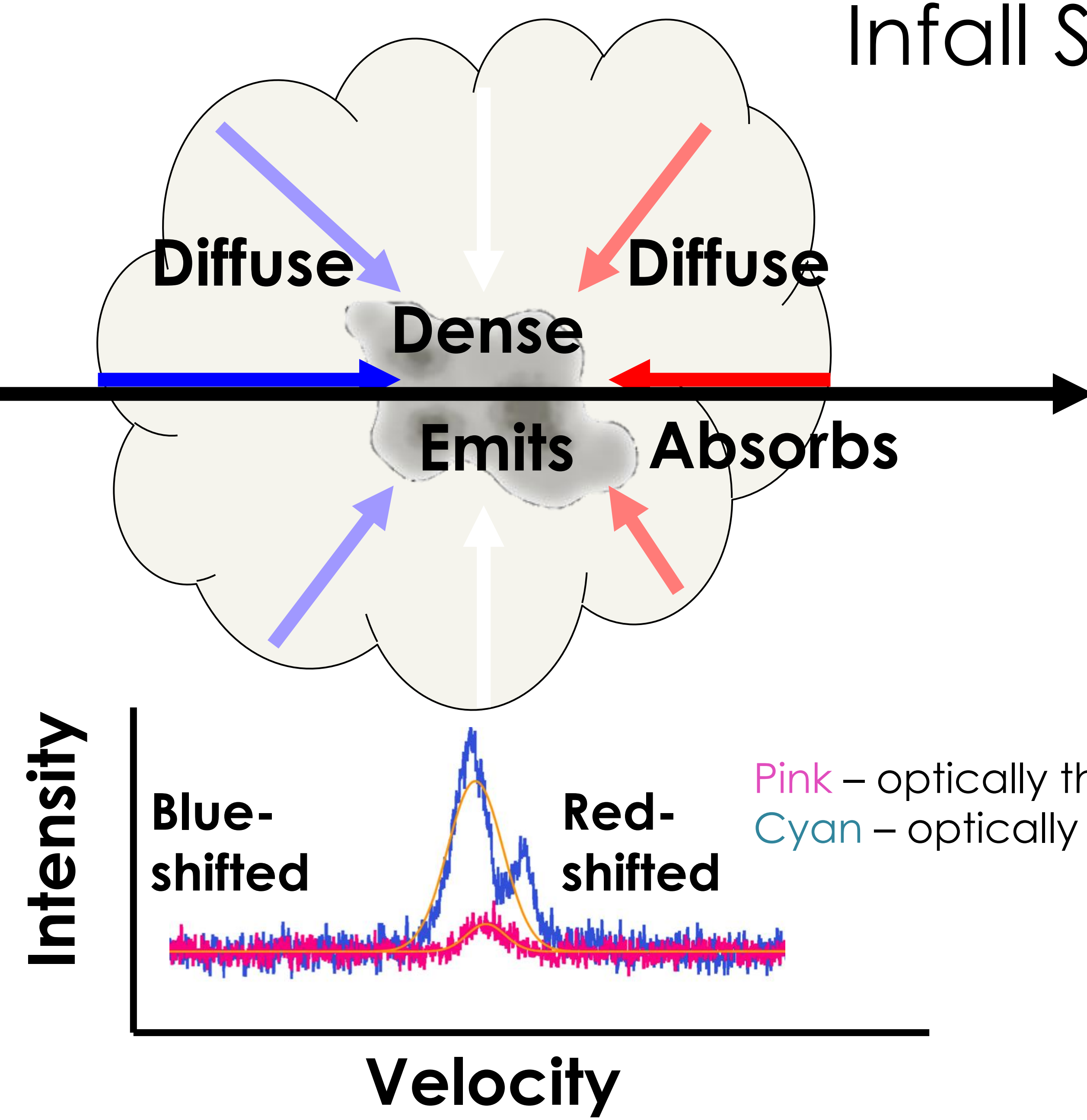




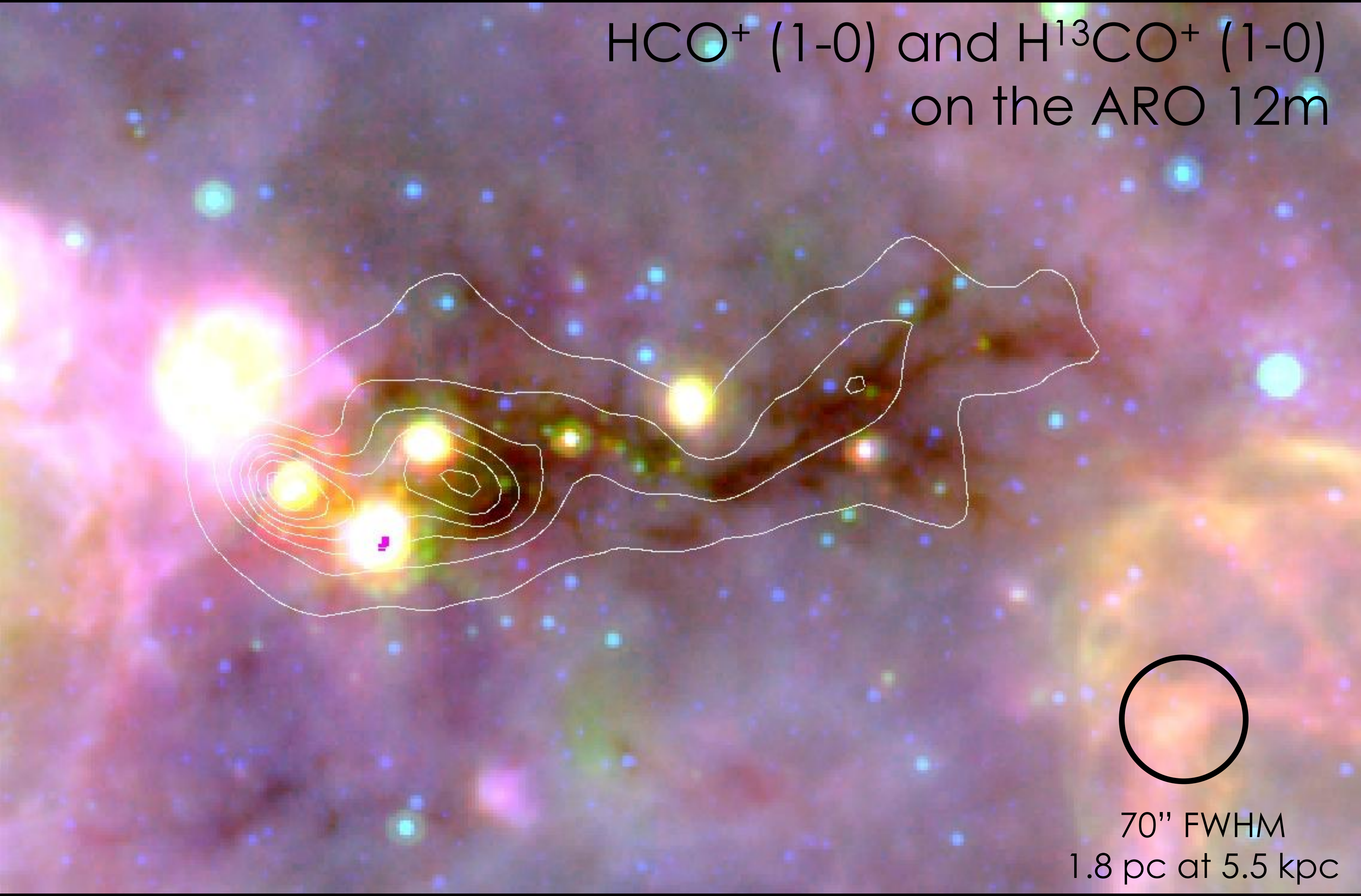
From Battersby et al. 2014b; Hi-GAL: Molinari et al. (2011), MIPSGAL: Carey et al. (2009), GLIMPSE: Benjamin et al. (2003),


→ look for evidence of infall in line asymmetries
70 μm , 24 μm, 8 μm, Herschel N(H2) contours
G32.03+0.05, Battersby+ in prep

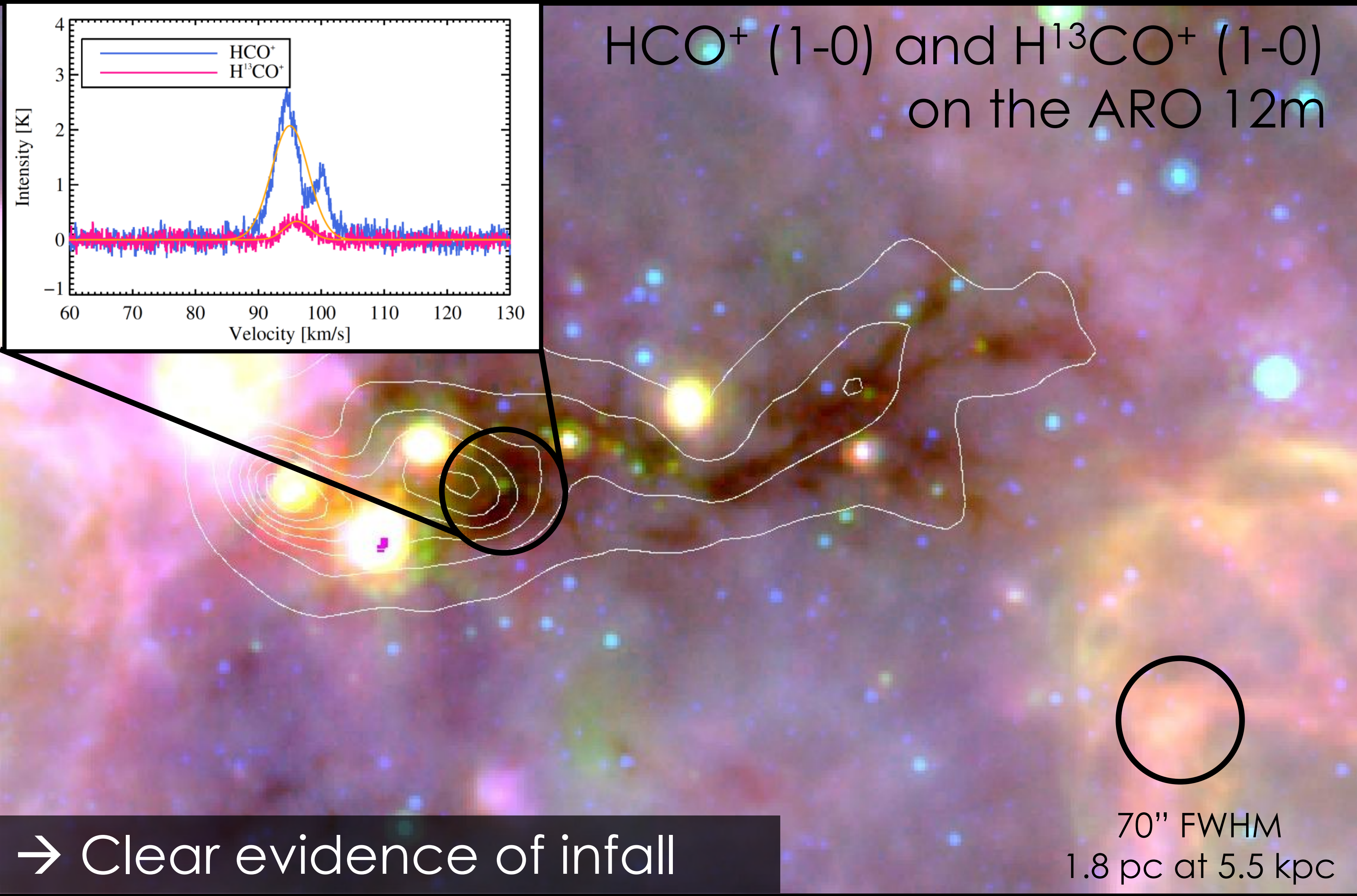
Infall Signature



Pink – optically thin → sees the entire cloud
Cyan – optically thick → only sees envelope

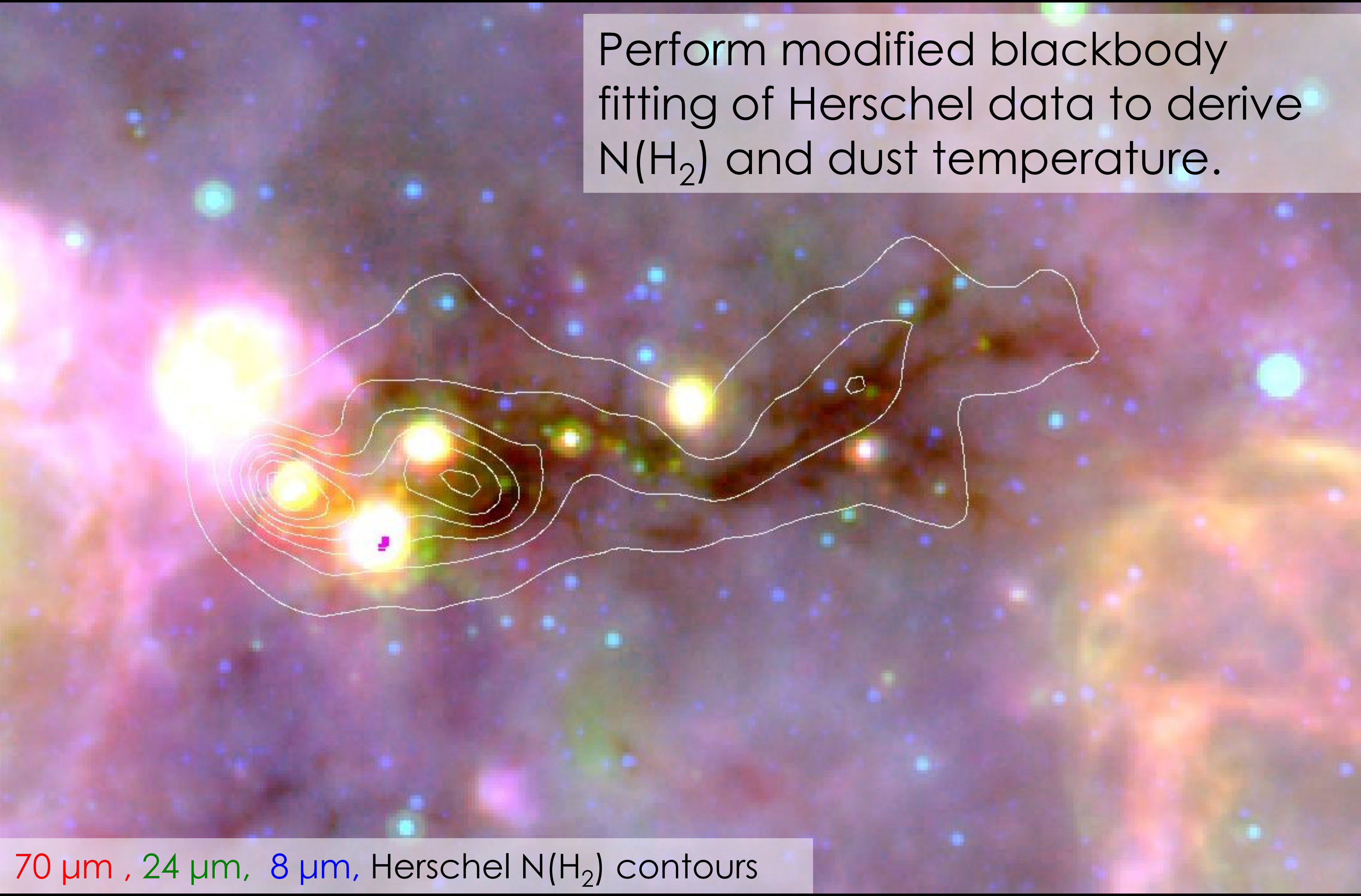


G32.03+0.05, Battersby, Myers, Keto, et al. in prep



G32.03+0.05, Battersby, Myers, Keto, et al. in prep

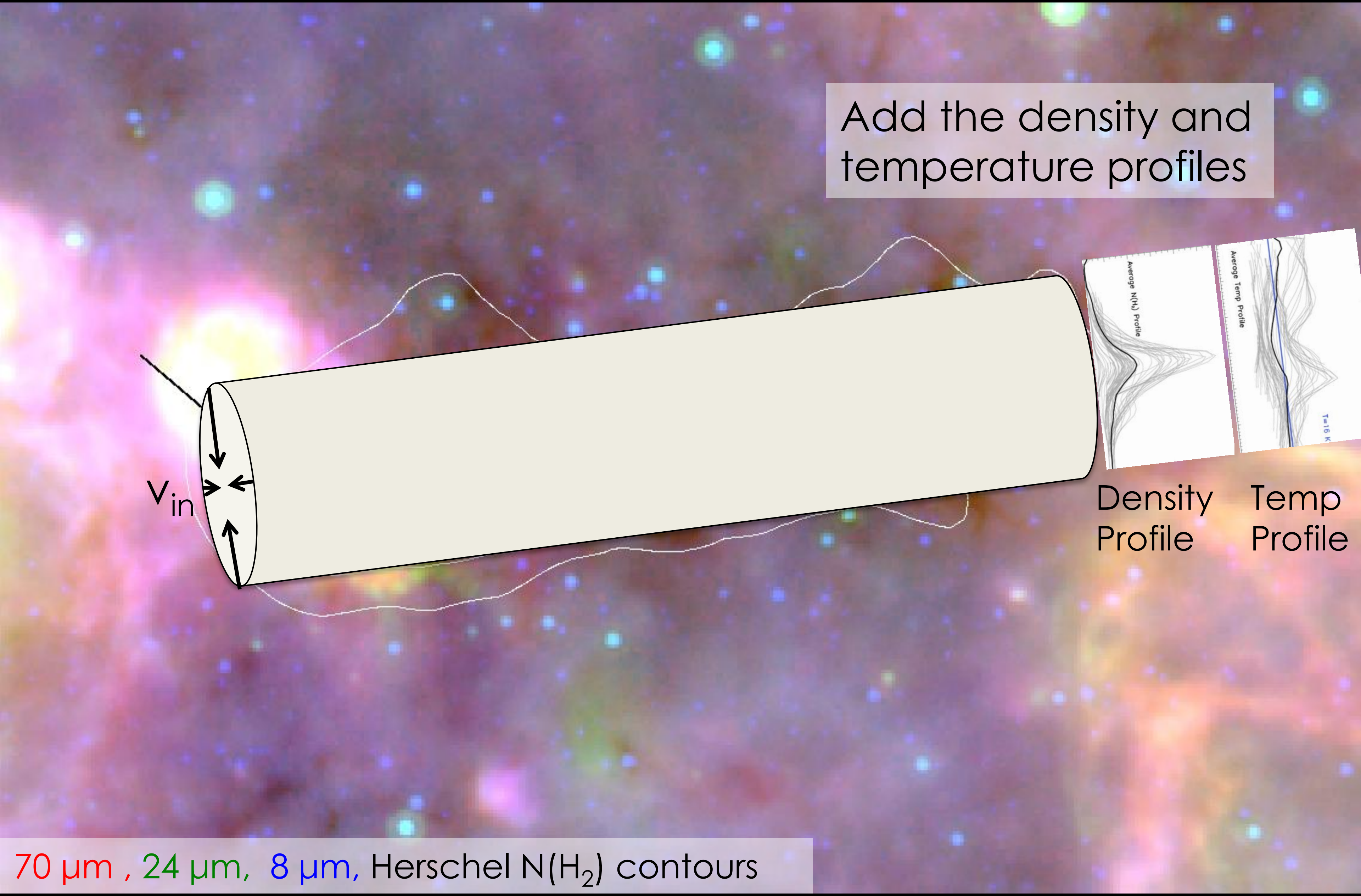
Perform modified blackbody fitting of Herschel data to derive $N(H_2)$ and dust temperature.



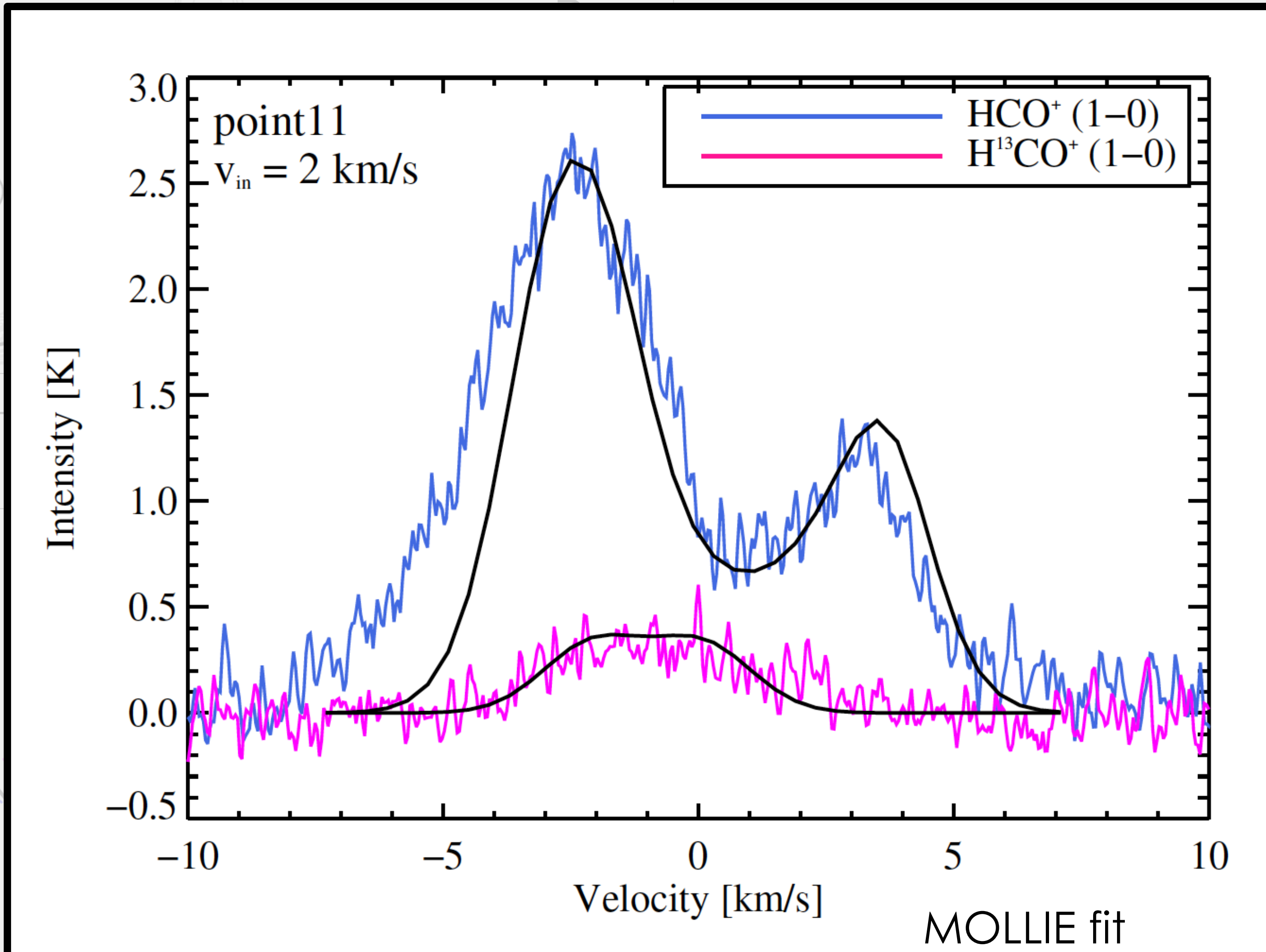
70 µm , 24 µm, 8 µm, Herschel $N(H_2)$ contours

G32.03+0.05, Battersby, Myers, Keto, et al. in prep

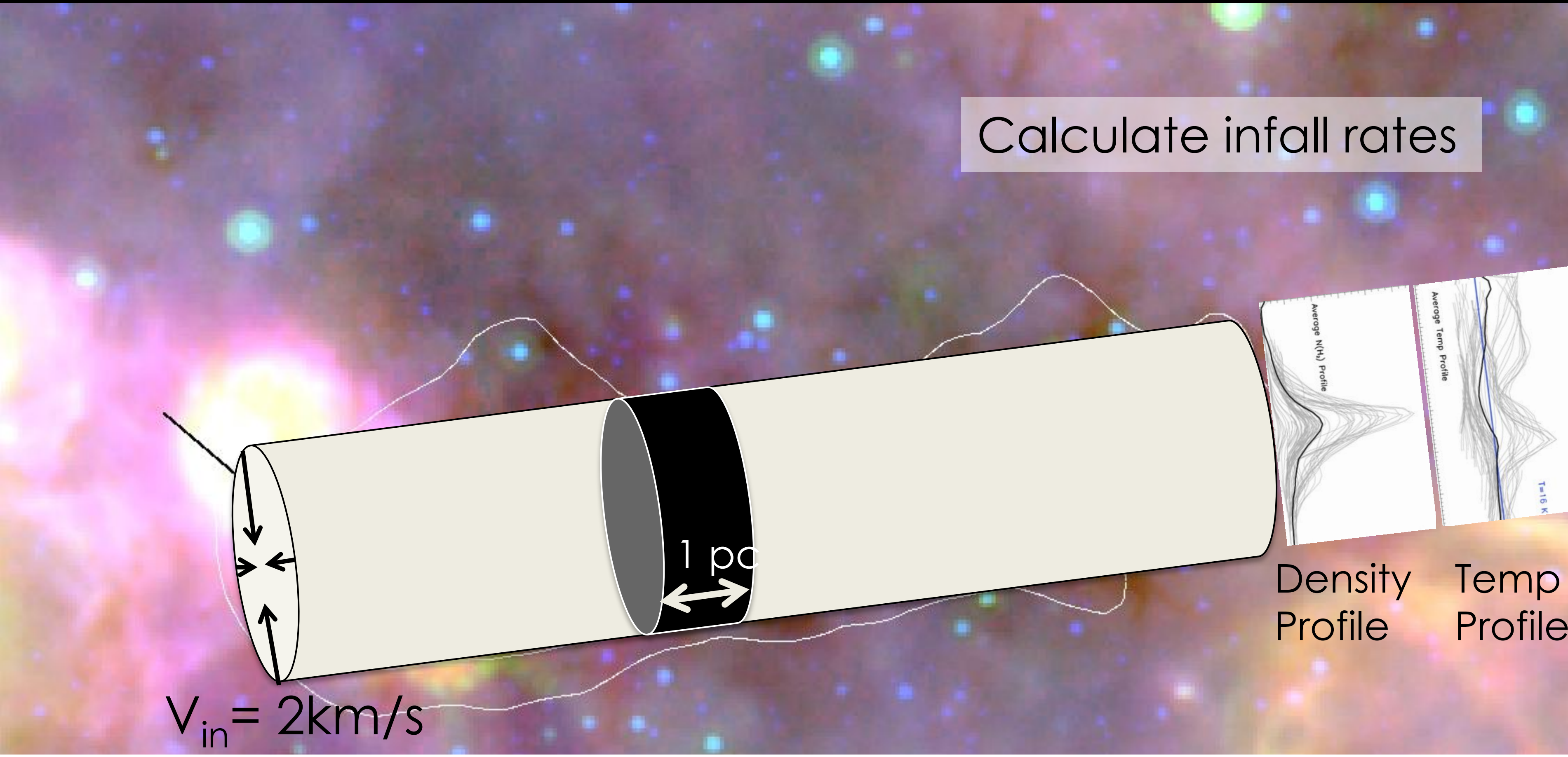
Add the density and temperature profiles



70 µm , 24 µm, 8 µm, Herschel $N(H_2)$ contours



Battersby, Myers, Keto, et al. in prep

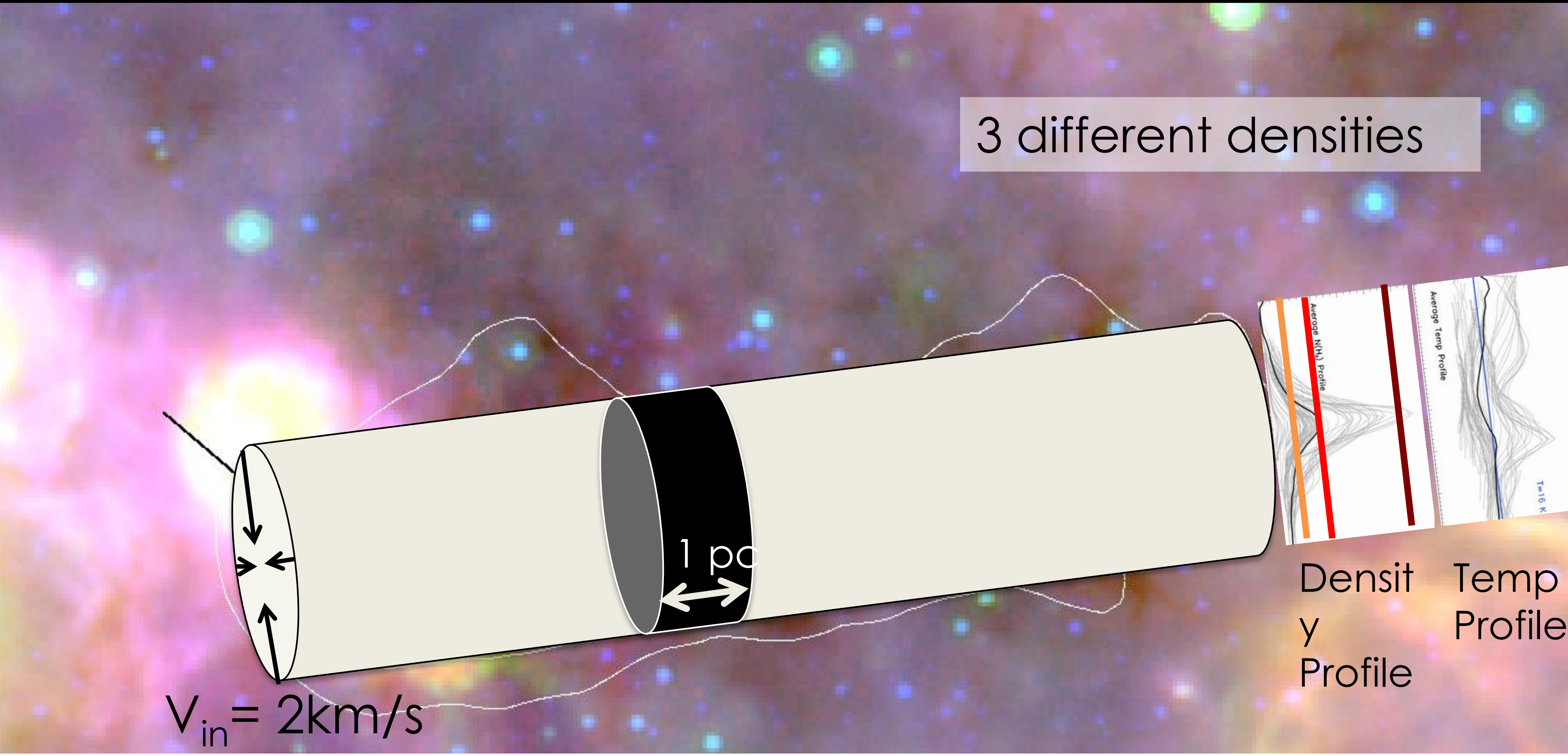


$$\dot{\mathrm{M}} = \rho\sigma\mathrm{v} = \left[\frac{\mathrm{n}}{10^4\ \mathrm{cm}^{-3}}\right]\left[\frac{\sigma}{\mathrm{pc}^2}\right]\left[\frac{\mathrm{v}}{\mathrm{kms}^{-1}}\right] 700\ \mathrm{M}_\odot/\mathrm{Myr}$$

Density from Plummer fit

Surface area of cylinder

HCO^+ line profile fit



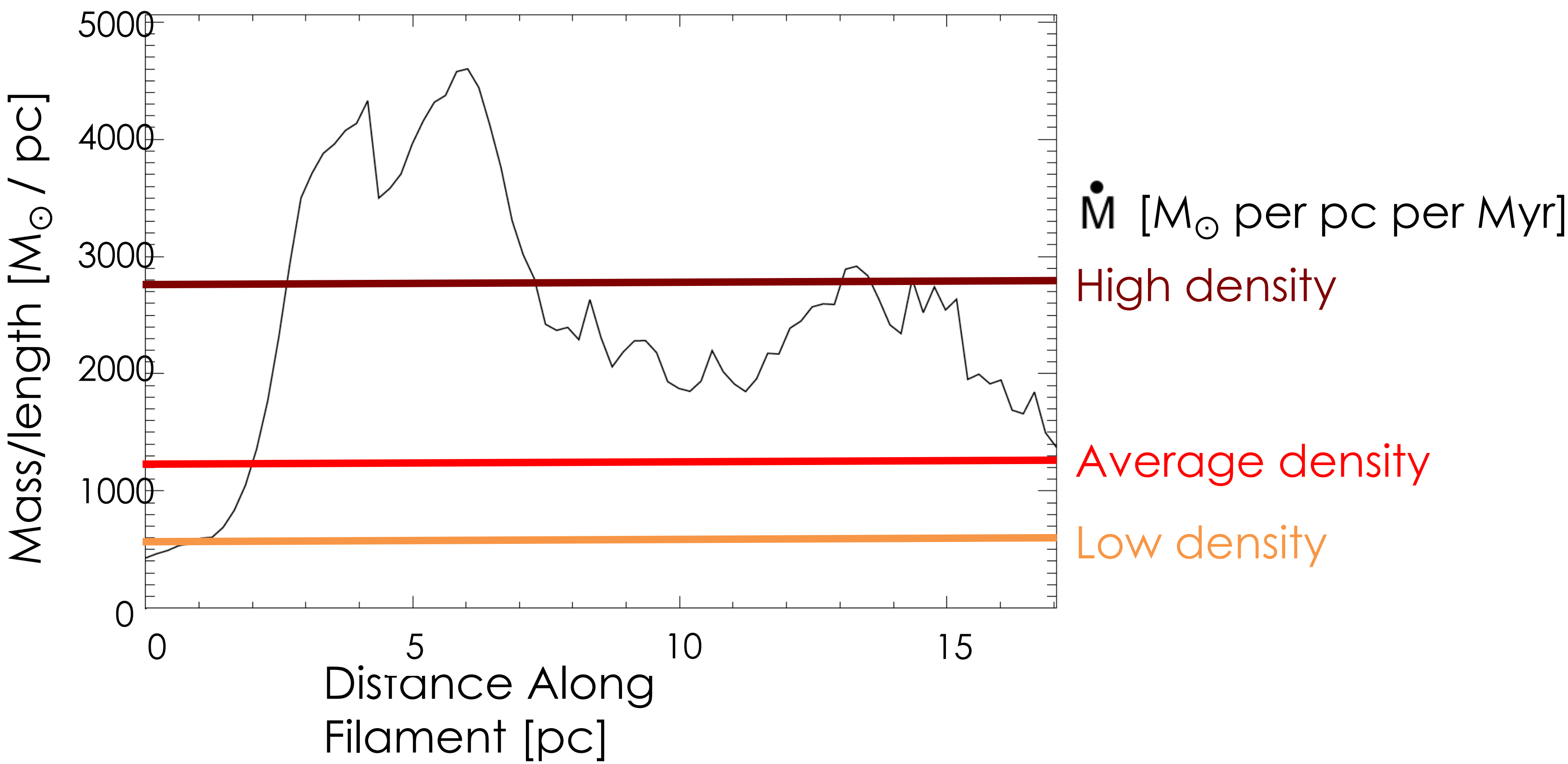
$$\dot{\mathrm{M}} = \rho\sigma\mathrm{v} = \left[\frac{\mathrm{n}}{10^4\ \mathrm{cm}^{-3}}\right]\left[\frac{\sigma}{\mathrm{pc}^2}\right]\left[\frac{\mathrm{v}}{\mathrm{kms}^{-1}}\right] 700\ \mathrm{M}_\odot/\mathrm{Myr}$$

Density from Plummer fit

Surface area of cylinder

HCO^+ line profile fit

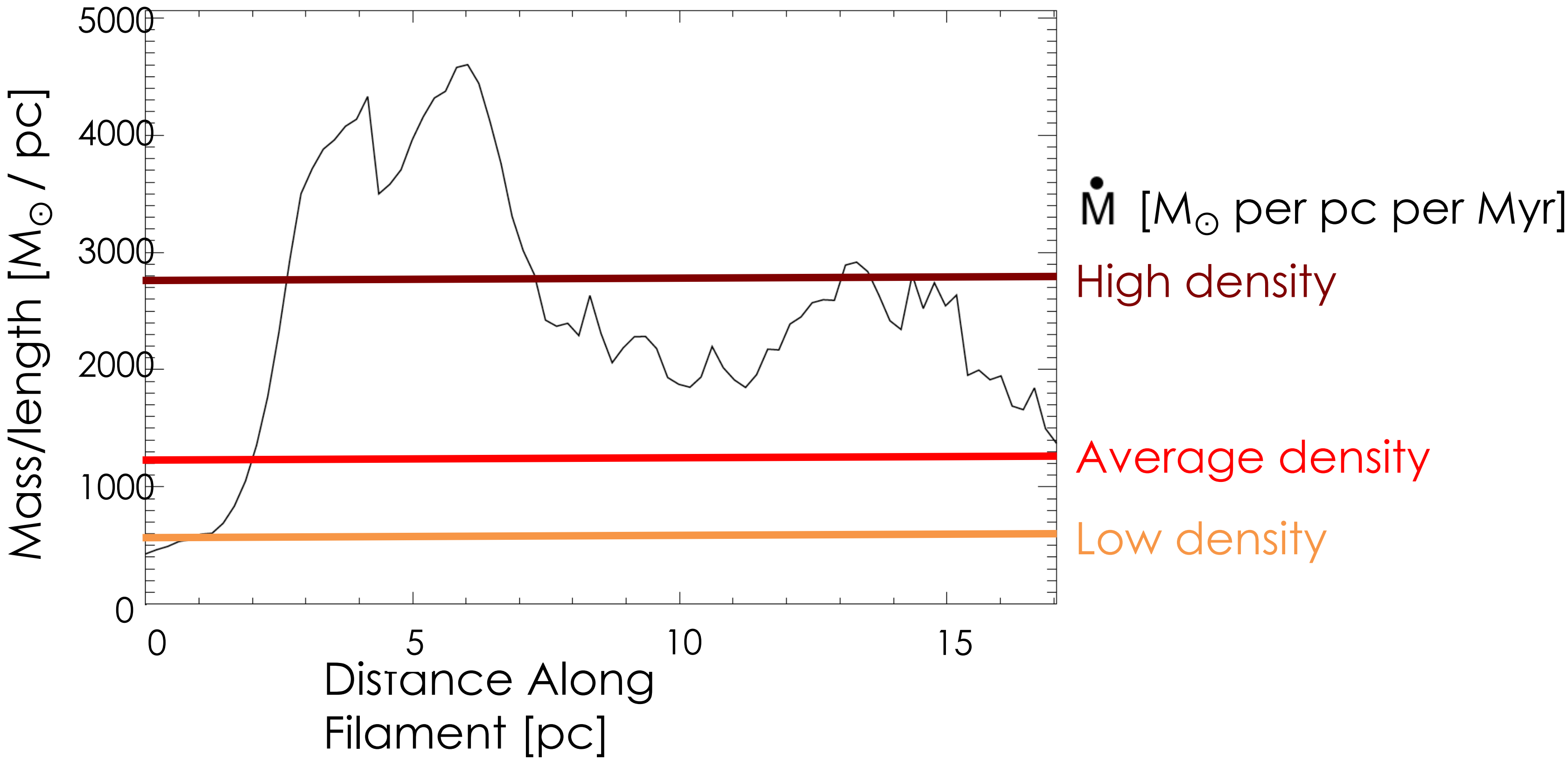
Infall Rates



Battersby et al., in prep. See also Peretto et al. (2013), SDC335 Mass infall rate of 700 $M_\odot$ / Myr.

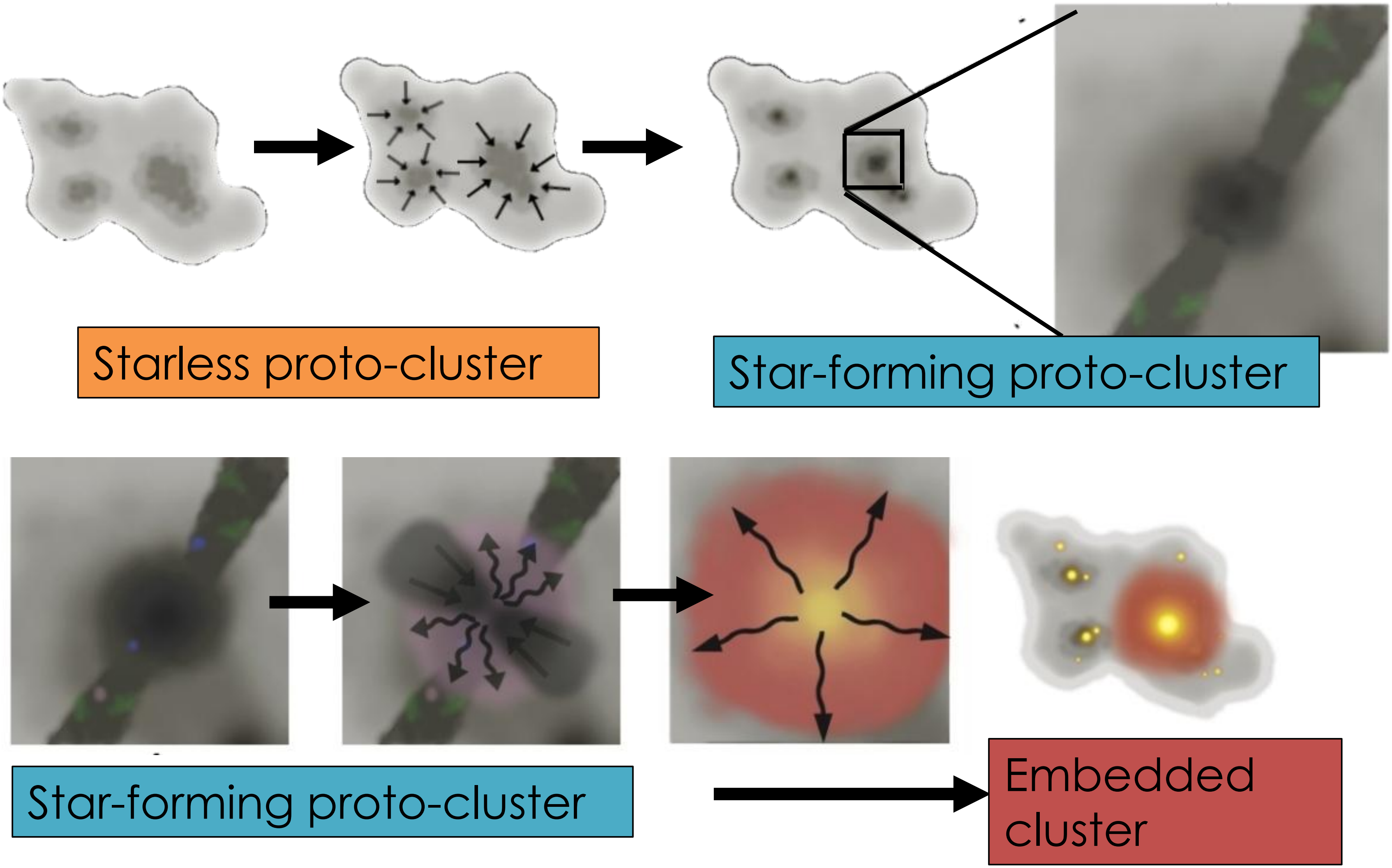
Infall Rates

Region can double its mass in a Myr!

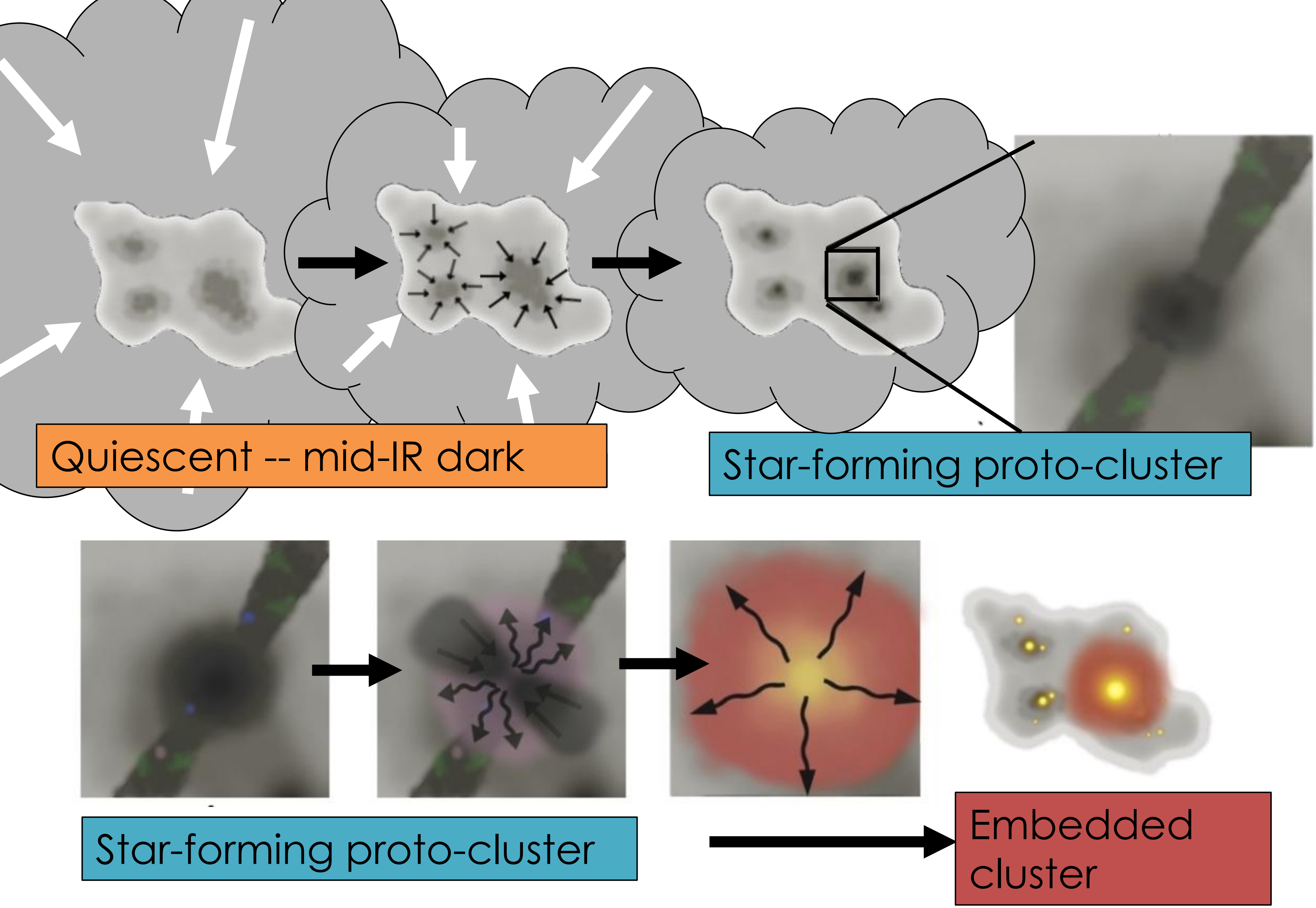


Battersby et al., in prep. See also Peretto et al. (2013), SDC335 Mass infall rate of 700 $M_\odot$ / Myr.

Evolution



Battersby et al. 2010; 2011

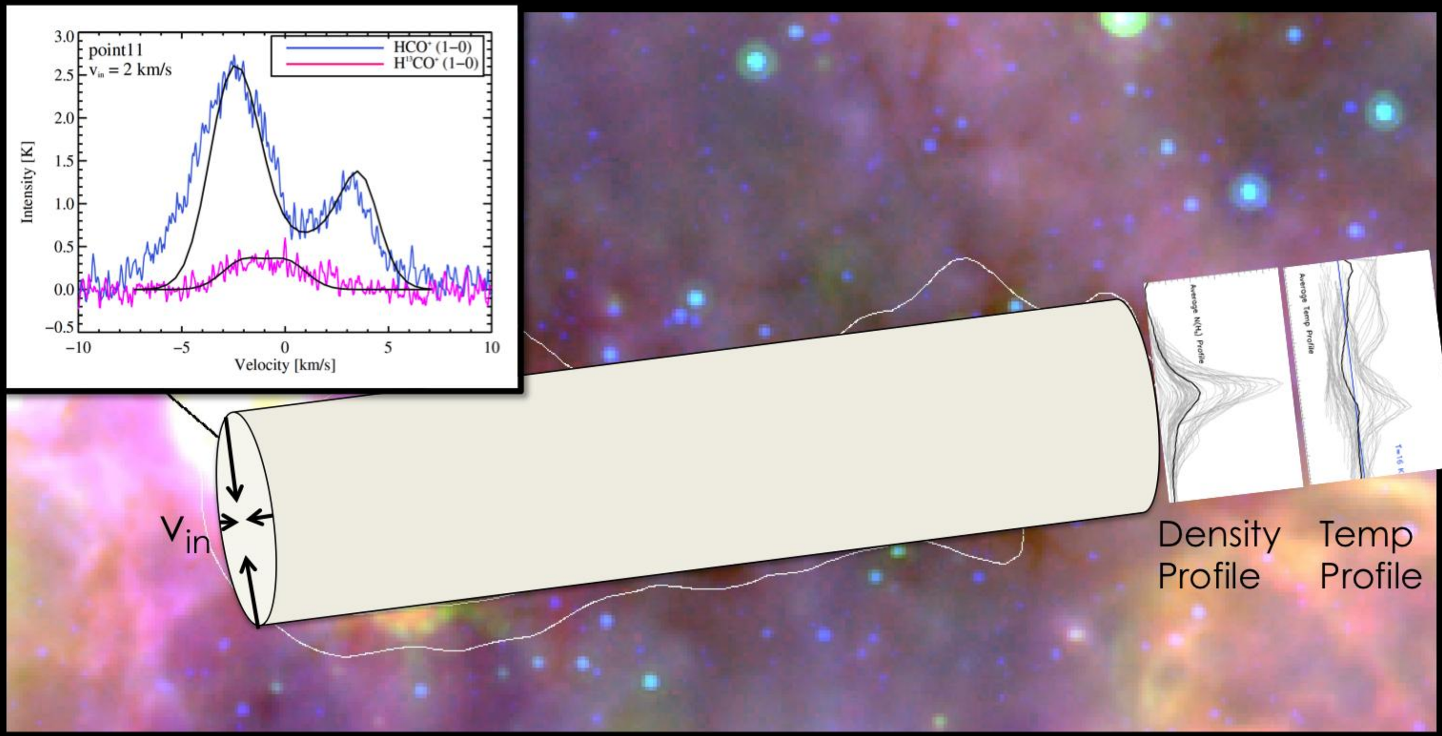


(e.g. Battersby et al. in prep., Longmore et al. (2011); Schneider et al. 2010; Barnes et al. 2010; Galván-Madrid et al. 2010; Liu et al. 2012)

Next Steps: Massive Star and Cluster Formation

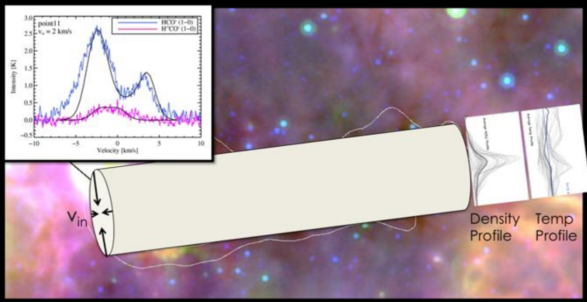
Next Steps: Massive Star and Cluster Formation

- Add more species and improve radiative transfer modeling (JCMT, PI: Kirk).

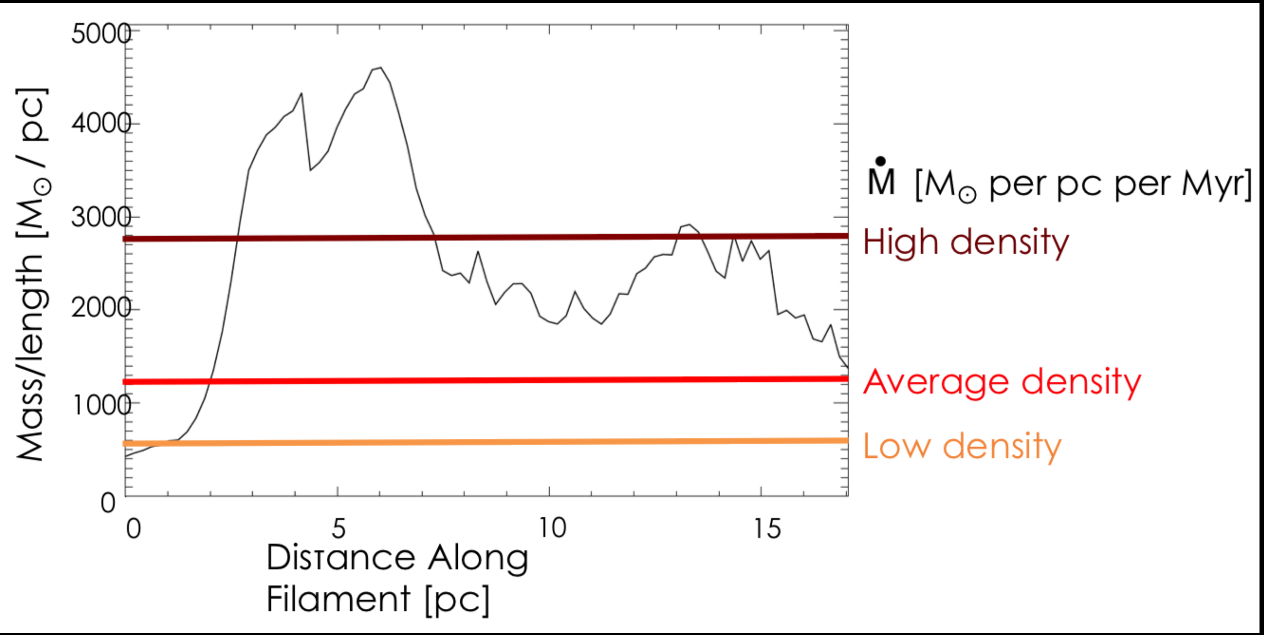


Next Steps: Massive Star and Cluster Formation

- Add more species and improve radiative transfer modeling (JCMT, PI: Kirk).



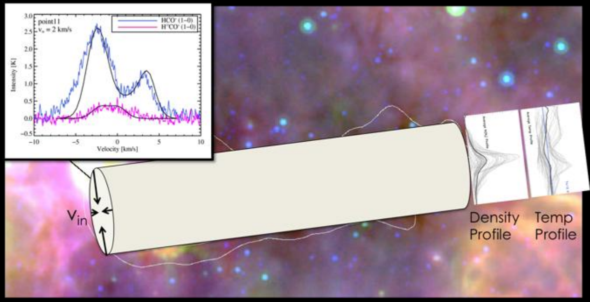
- Measure infall rates toward many more regions. Does it correlate with mass or evolutionary stage? What determines the final mass of a cluster?



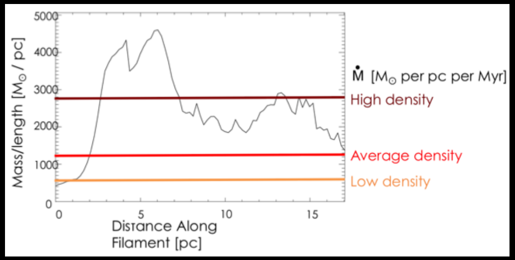
- Measure infall rates toward many more regions. Does it correlate with mass or evolutionary stage? What determines the final mass of a cluster?

Next Steps: Massive Star and Cluster Formation

- Add more species and improve radiative transfer modeling (JCMT, PI: Kirk).



- Measure infall rates toward many more regions. Does it correlate with mass or evolutionary stage? What determines the final mass of a cluster?



The Milky Way Laboratory

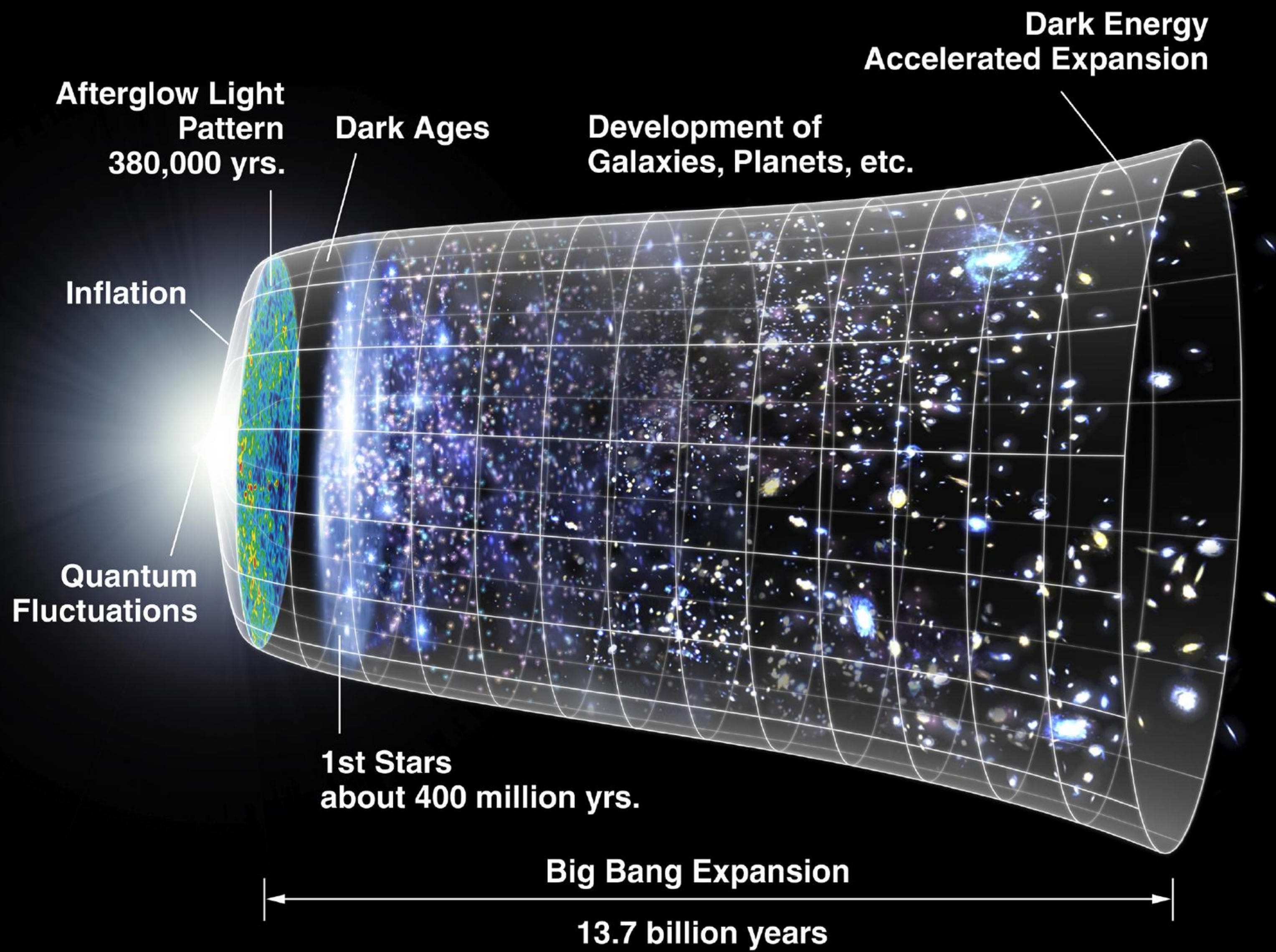
1. What is the large-scale structure of our Galaxy?
2. How do the most massive stars form in our Galaxy?
3. How do they form in the distant Universe?

The Milky Way Laboratory

Stop 3: Extreme SF in our Galactic Center

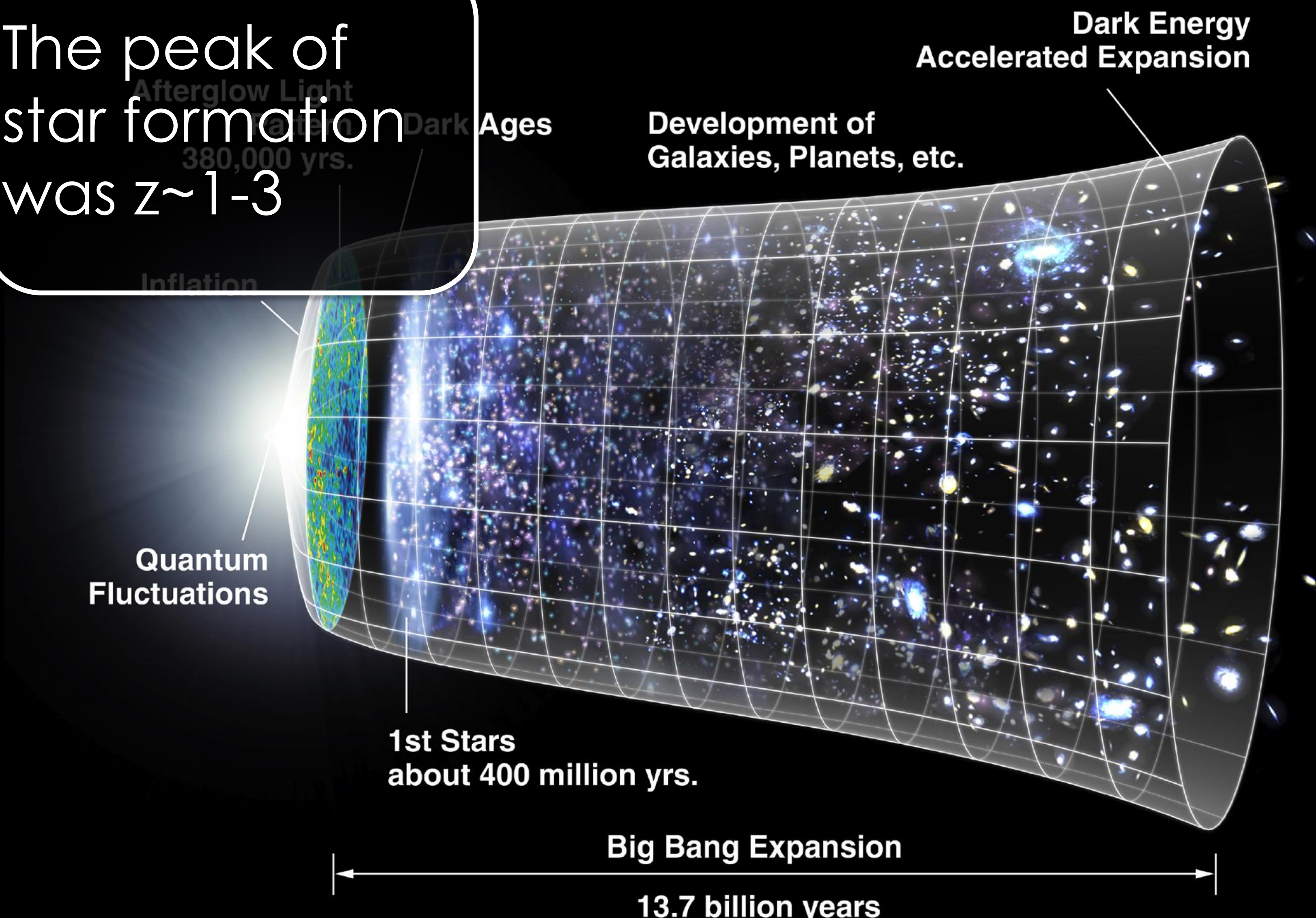
Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

Star Formation over cosmic time



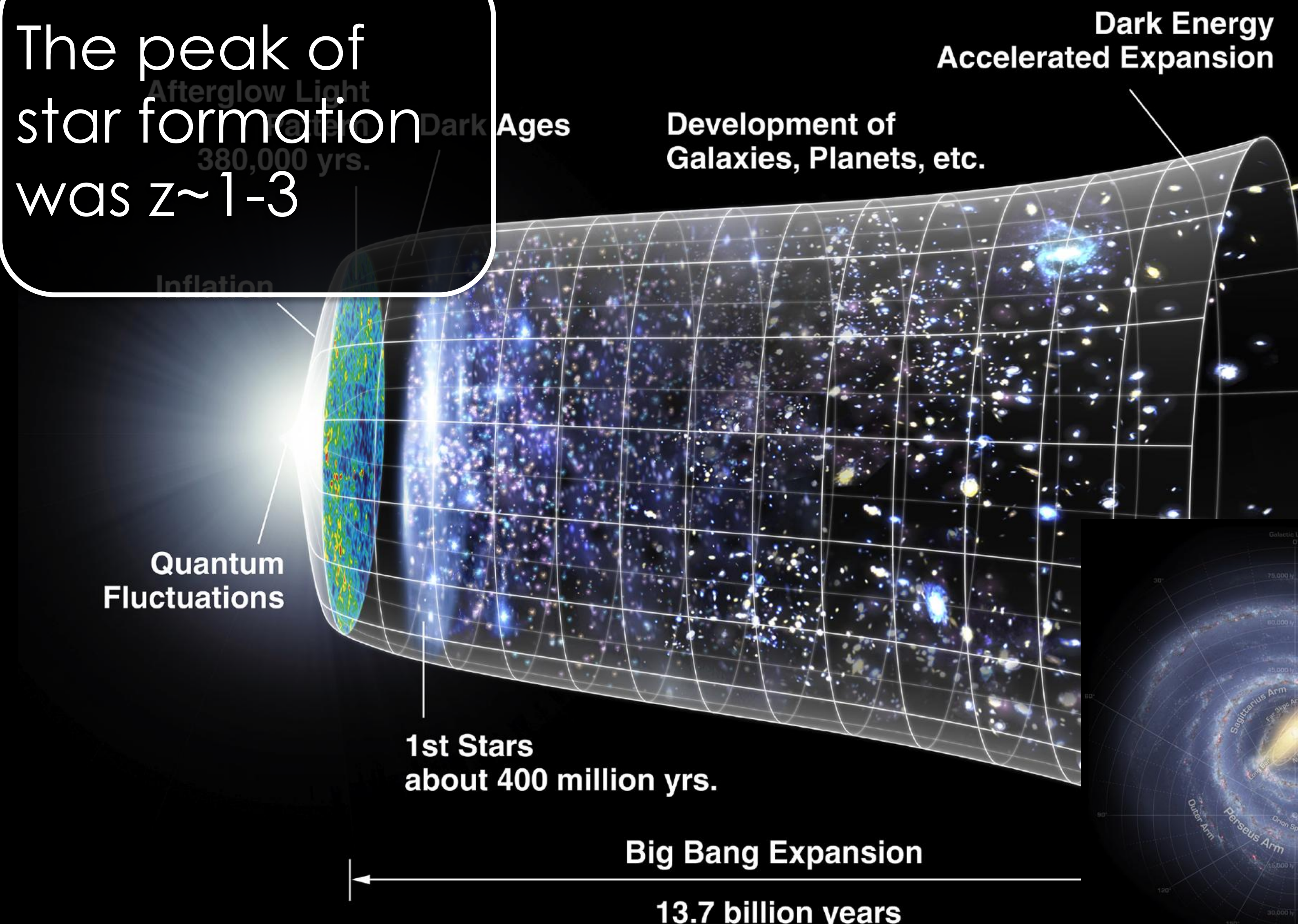
Star Formation over cosmic time

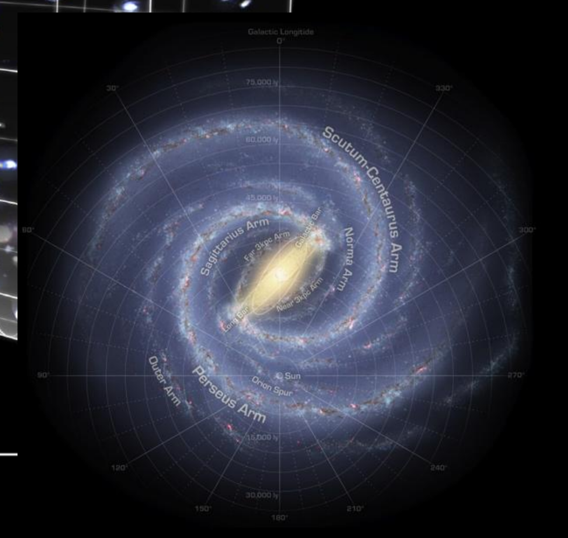
The peak of
star formation
was z~1-3



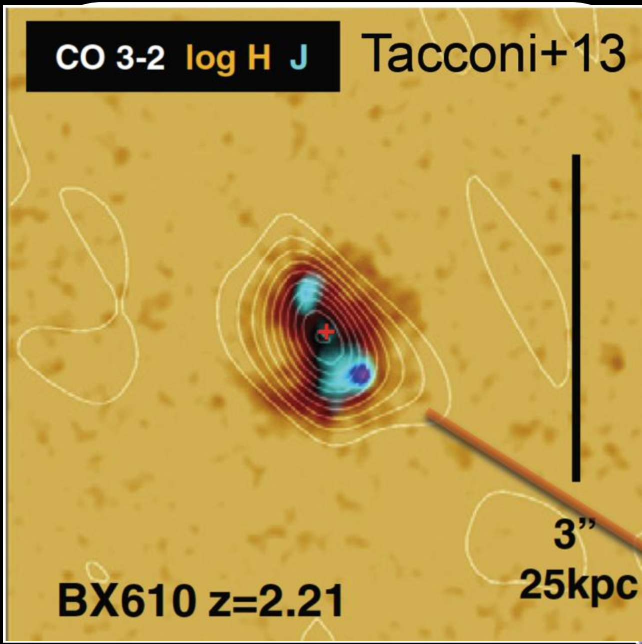
Star Formation over cosmic time

The peak of star formation was z~1-3

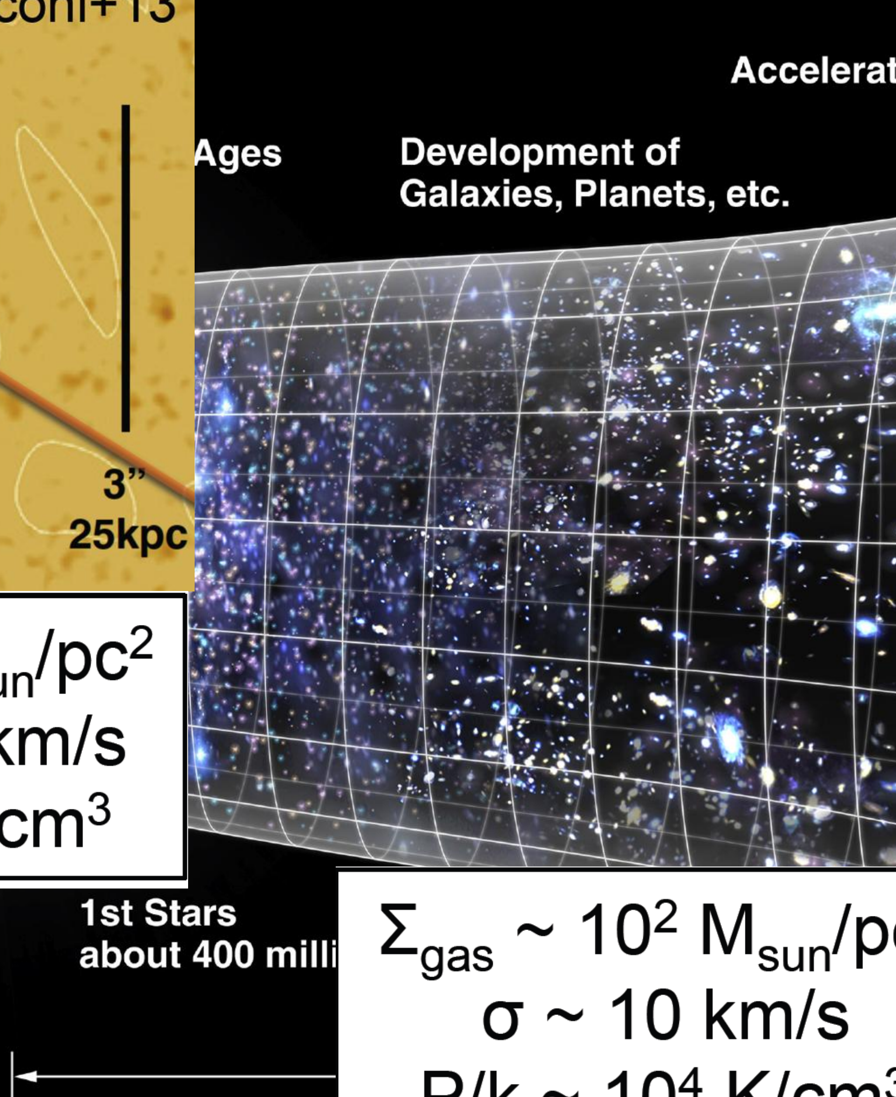


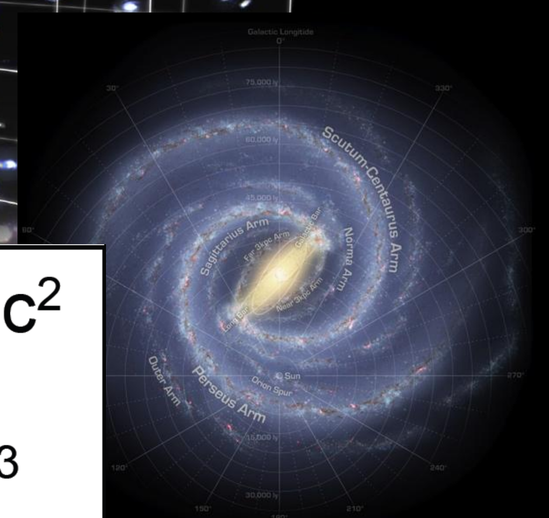


Star Formation over cosmic time



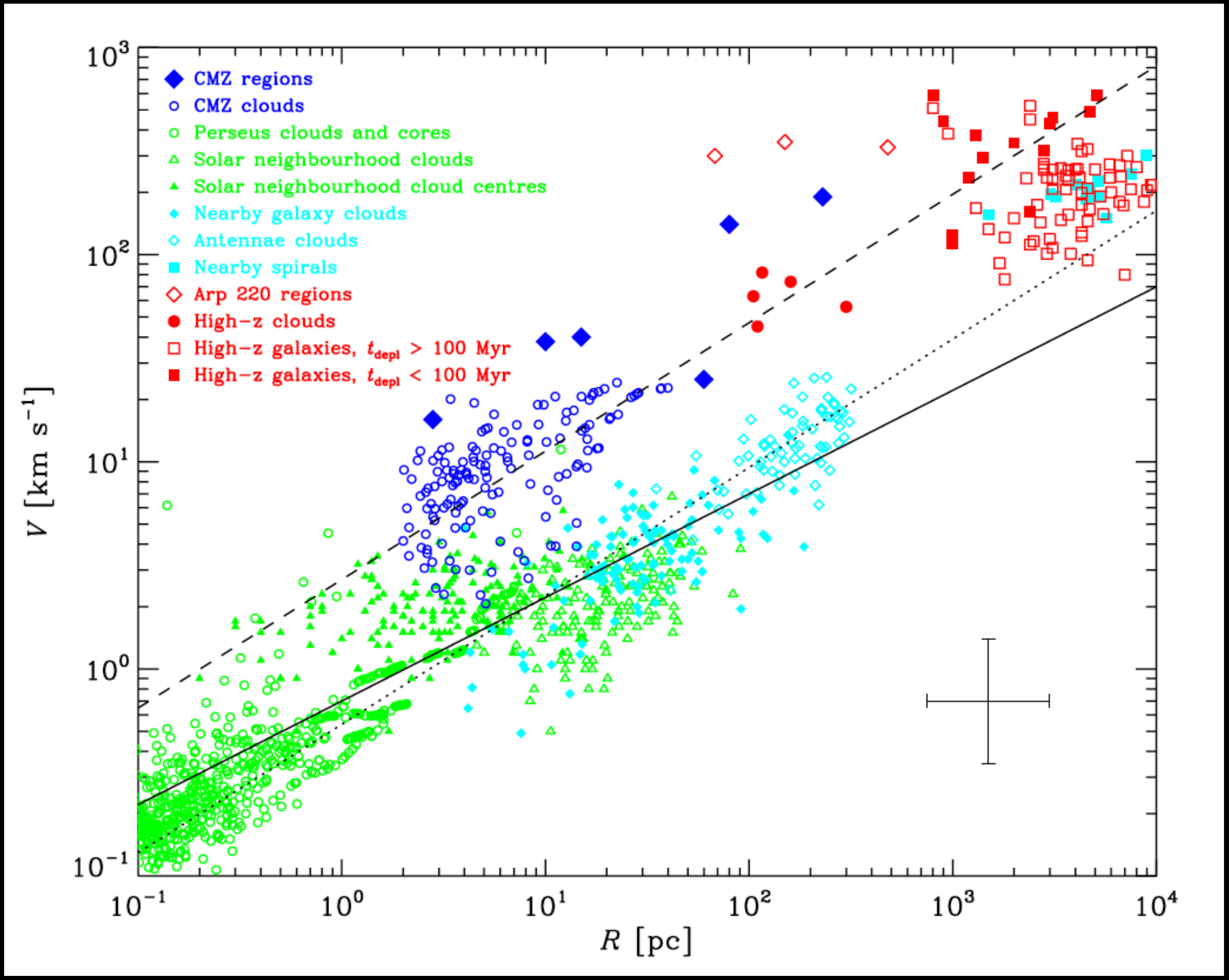
$\Sigma_{gas} \sim 10^3\ M_{sun}/pc^2$
$\sigma \sim 20 – 50$ km/s
$P/k \sim 10^7$ K/cm^3





$\Sigma_{gas} \sim 10^2\ M_{sun}/pc^2$
$\sigma \sim 10$ km/s
$P/k \sim 10^4$ K/cm^3

Star Formation over cosmic time



Kruijssen & Longmore 2013

The Milky Way Laboratory

Stop 3: Extreme SF in our Galactic Center

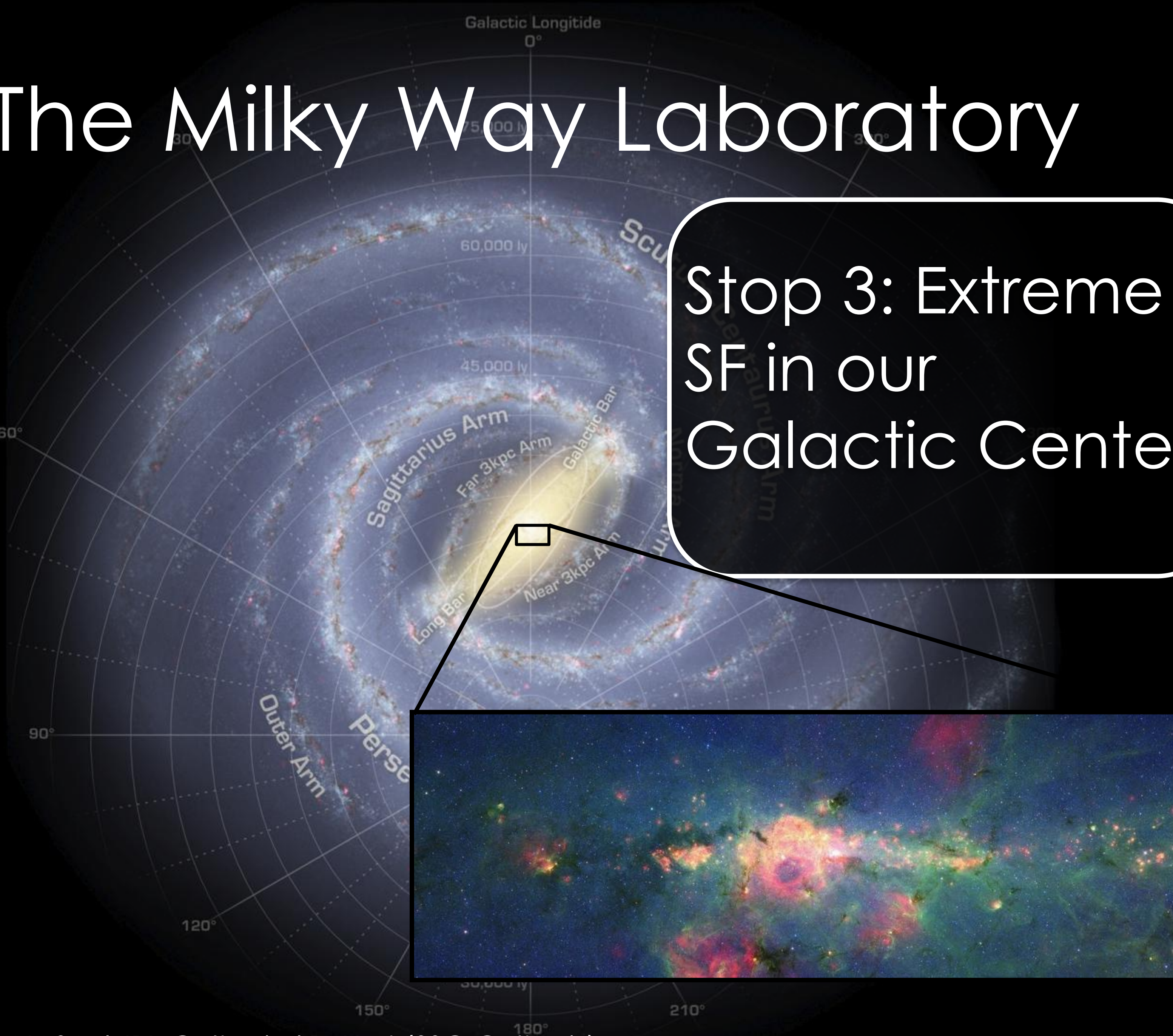


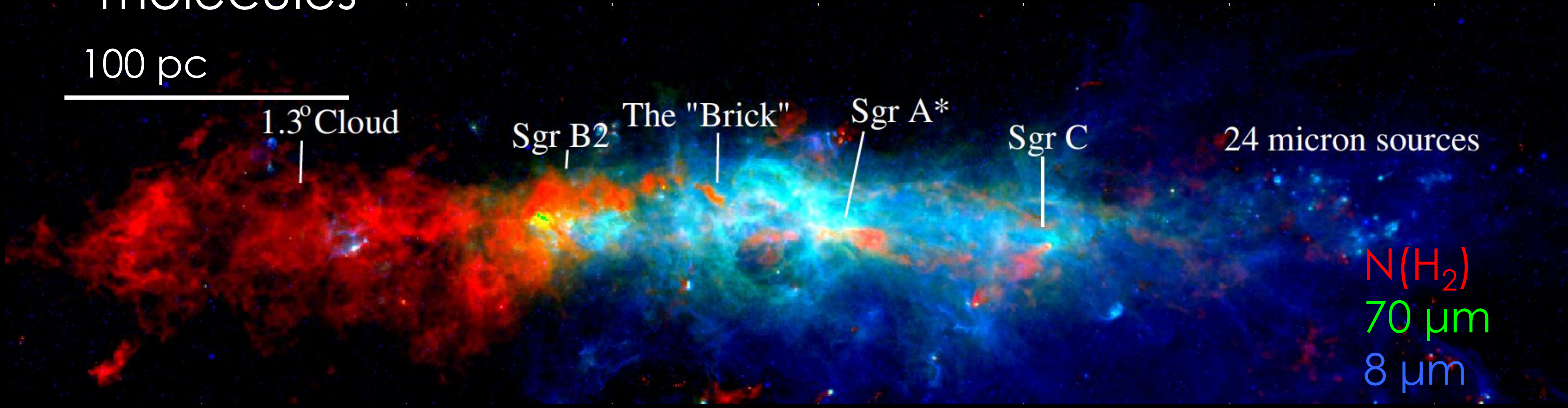
Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

Extreme Star Formation

24 μm
8 μm
4.5 μm

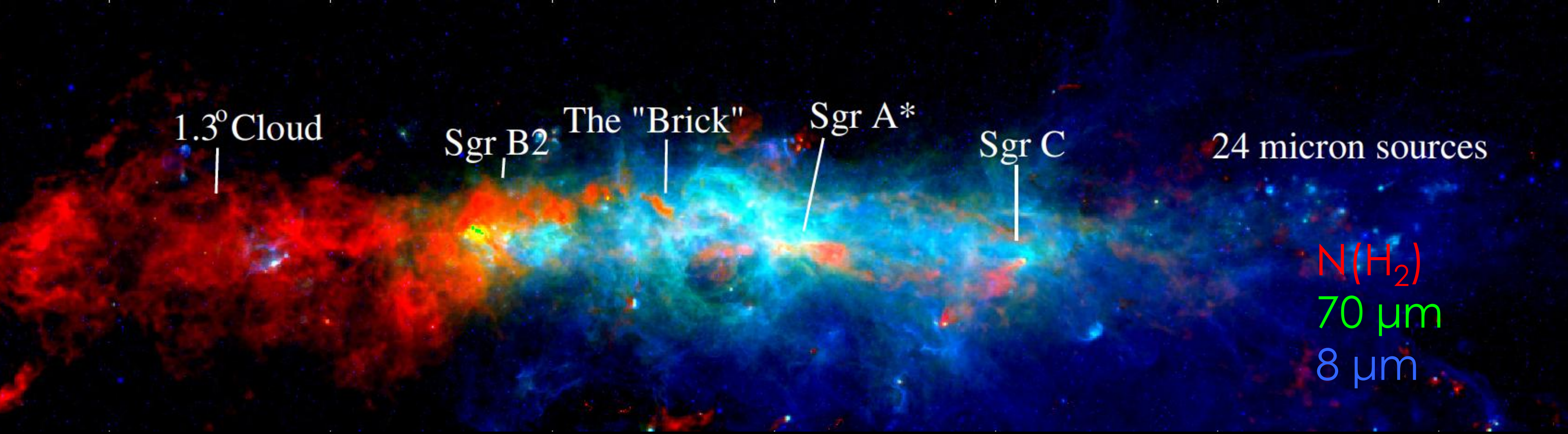
Extreme Star Formation

- Δv ~ 10x higher
- n ~ 10-100x higher
- High temperatures, ubiquitous exotic molecules



The Central Molecular Zone: CMZ

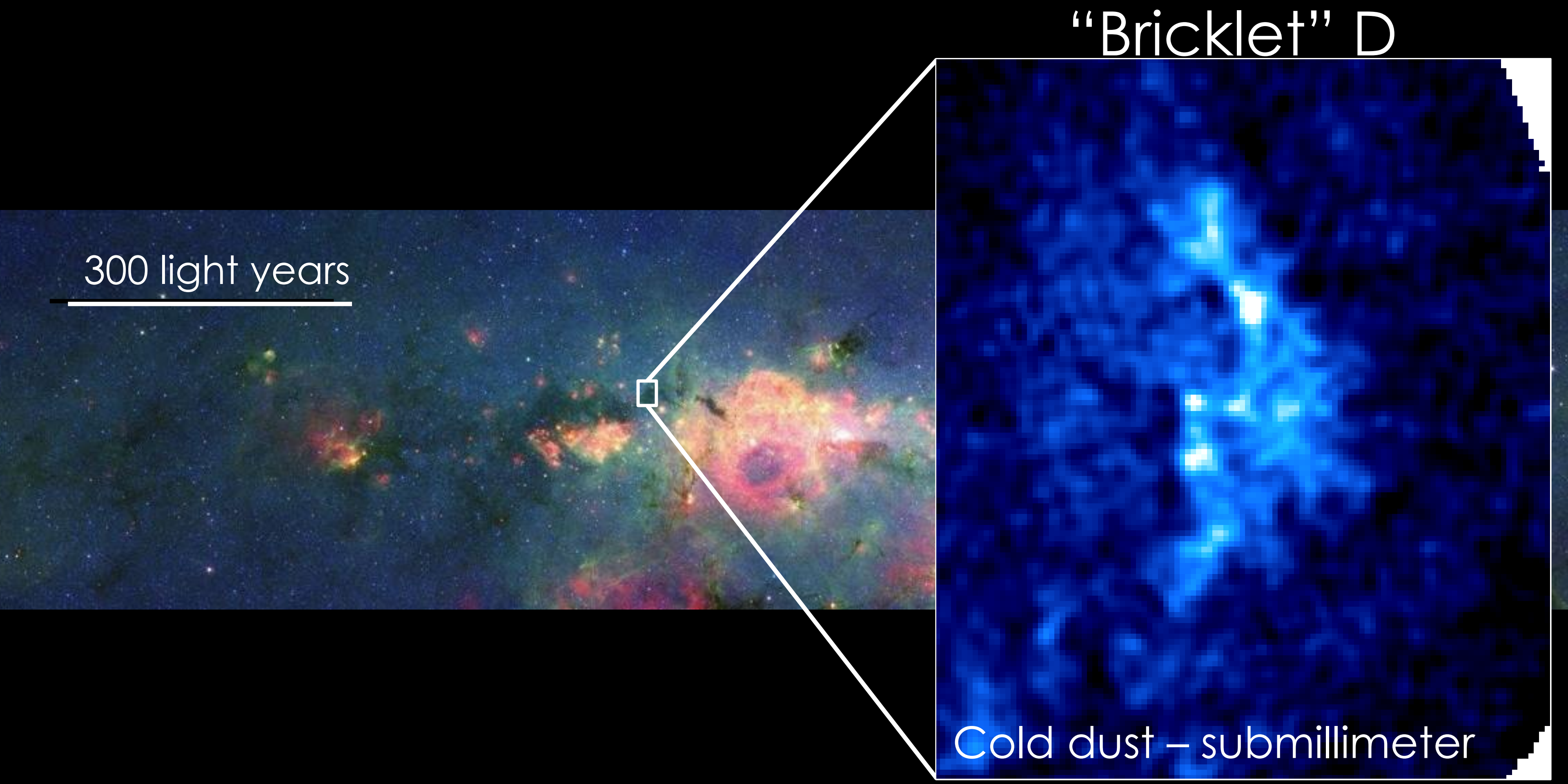
$N(H_2)$ from HiGAL Battersby+, in prep., 70 µm from HiGAL, Molinari+ 2011, 8 µm from GLIMPSE (Benjamin+ 2003)



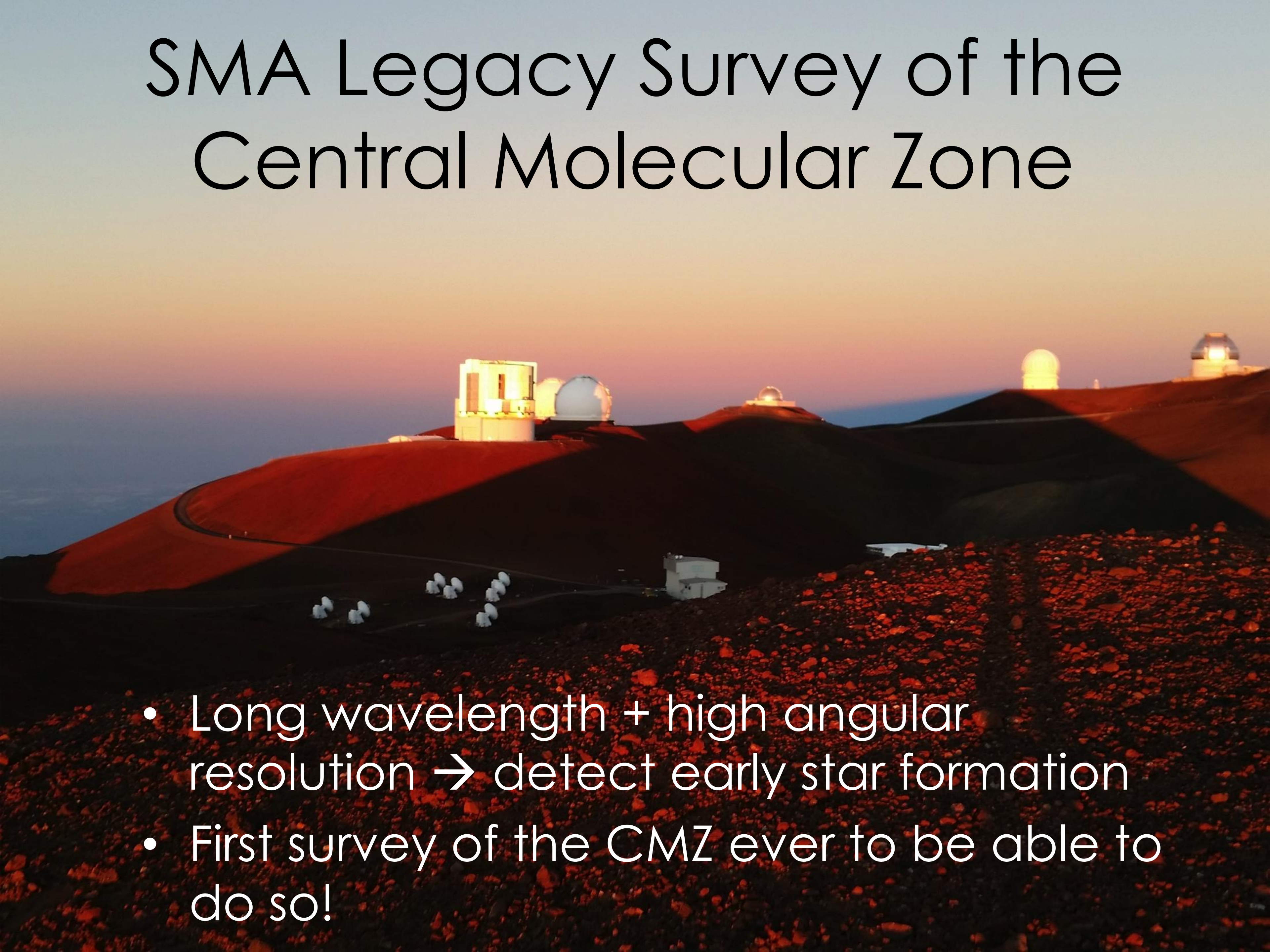
Basic Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?
2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?
3) Is SF induced by tidal compression by SgrA*?
4) Can we find precursors to the most massive stars in the Galaxy?

Central Molecular Zone



SMA Legacy Survey of the Central Molecular Zone

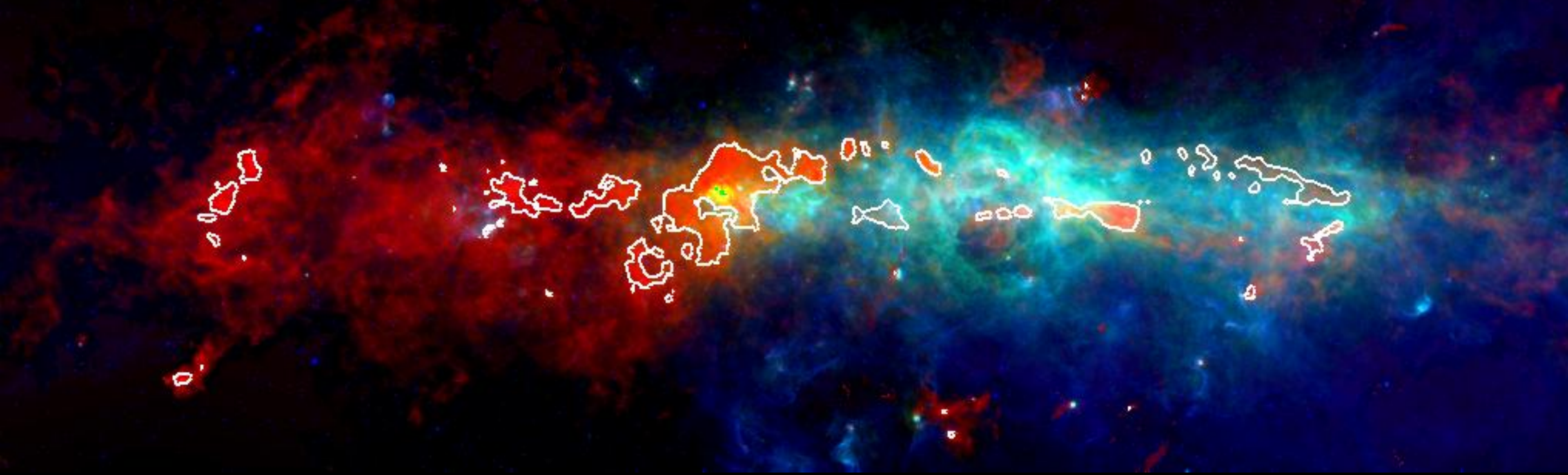


- Long wavelength + high angular resolution → detect early star formation
- First survey of the CMZ ever to be able to do so!

SMA Legacy Survey of the Central Molecular Zone

- Long wavelength + high angular resolution → detect early star formation
- First survey of the CMZ ever to be able to do so!

CMZoom



- 230 GHz (1.3 mm)
- 240 arcmin^2 (above $N(H_2) = 10^{23}$ cm^{-2} or 3×10^{22} cm^{-2})
- 4'' (0.2 pc) resolution, $\Delta v \sim 1.1$ km/s
- dust continuum + spectral lines (H_2CO, ^{12}CO, ^{13}CO, $C^{18}O$, SiO, CH_3OH, CH_3CN, etc.): 8 GHz bandwidth
- 3 mJy RMS continuum, 0.4 K
- 500 hours (50 subcompact, 450 compact/custom)
- Complement with single-dish (APEX, CSO) observations

CMZoom

- 230 GHz (1.3 mm)
- 240 arcmin^2 (above $N(H_2) = 10^{23}$ cm^{-2} or 3×10^{22} cm^{-2})
- 4'' (0.2 pc) resolution, $\Delta v \sim 1.1$ km/s
- dust continuum + spectral lines (H_2CO, ^{12}CO, ^{13}CO, $C^{18}O$, SiO, CH_3OH, CH_3CN, etc.): 8 GHz bandwidth
- 3 mJy RMS continuum, 0.4 K
- 500 hours (50 subcompact, 450 compact/custom)
- Complement with single-dish (APEX, CSO) observations

CMZoom

Team:

CfA: Cara Battersby, Eric Keto, Qizhou Zhang, Xing 'Walker' Lu, Mark Graham (Southampton), Nimesh Patel, Volker Tolls, Dennis Lee, Jimmy Castaño, Liz Gehret

Bonn: Jens Kauffmann, Thushara Pillai

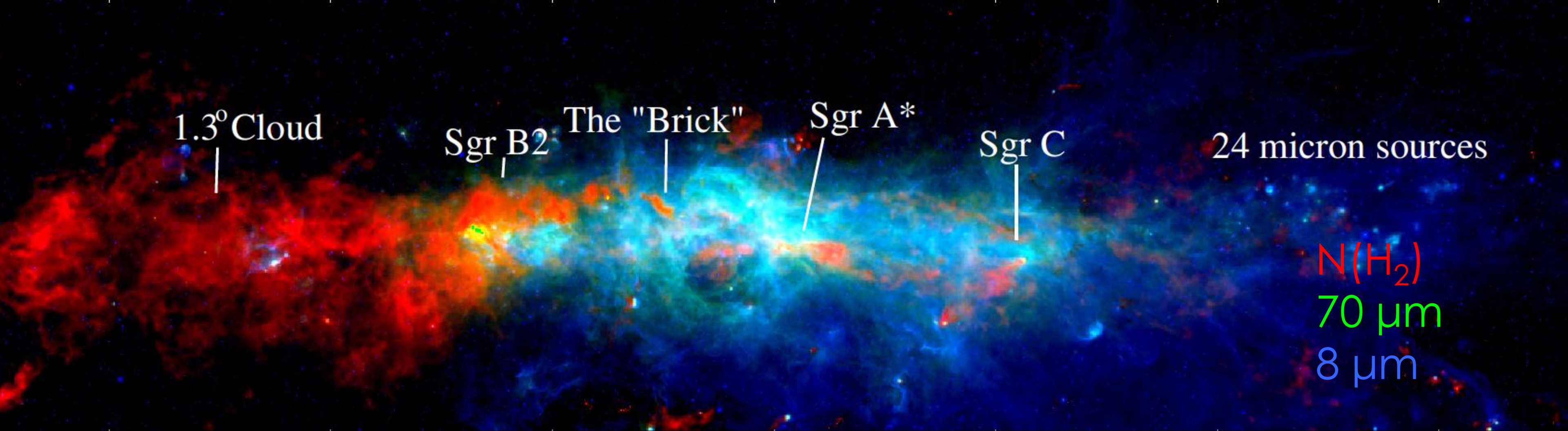
University of Colorado, Boulder: John Bally

Liverpool: Steve Longmore, Daniel Walker, Jonny Henshaw

MPA: Diederik Kruijssen

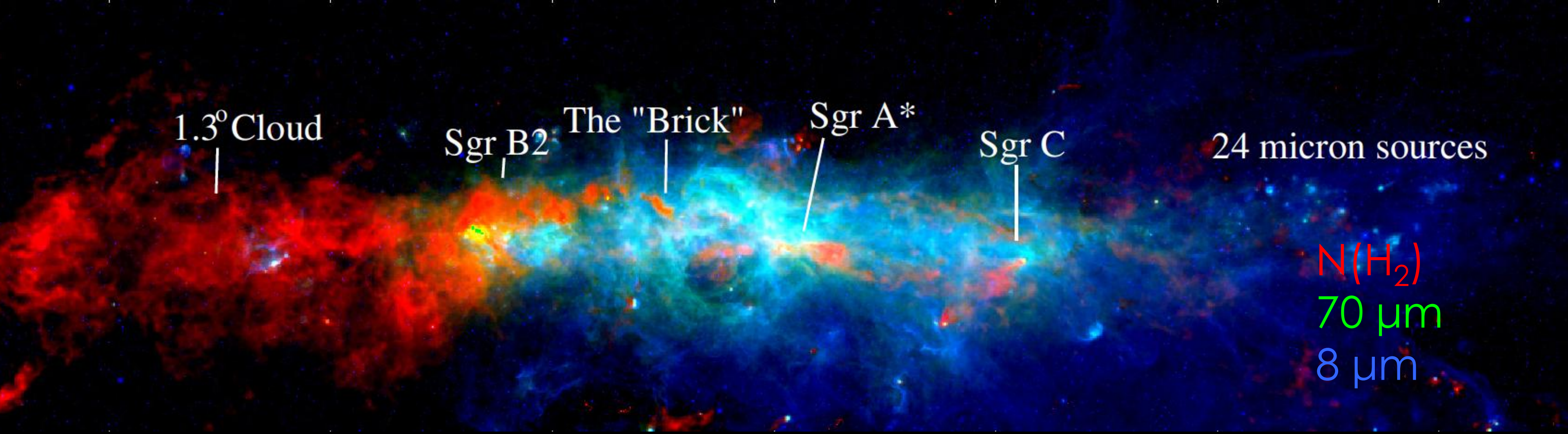
ESO: Adam Ginsburg, Katharina Immer

Peking University: Luis C. Ho, NRAO: Betsy Mills



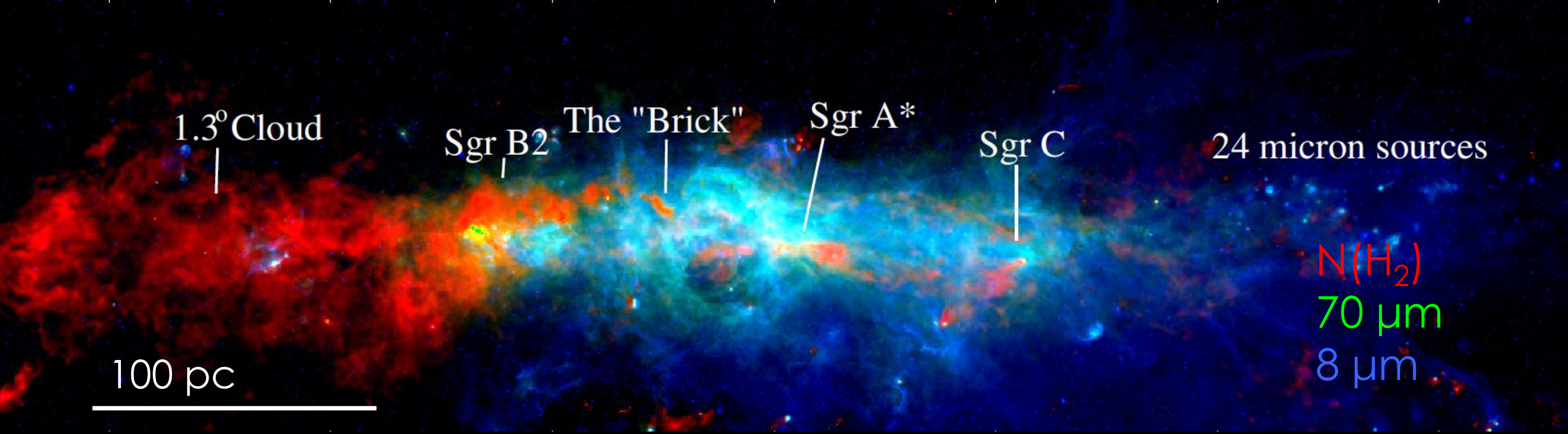
Basic Science Questions:

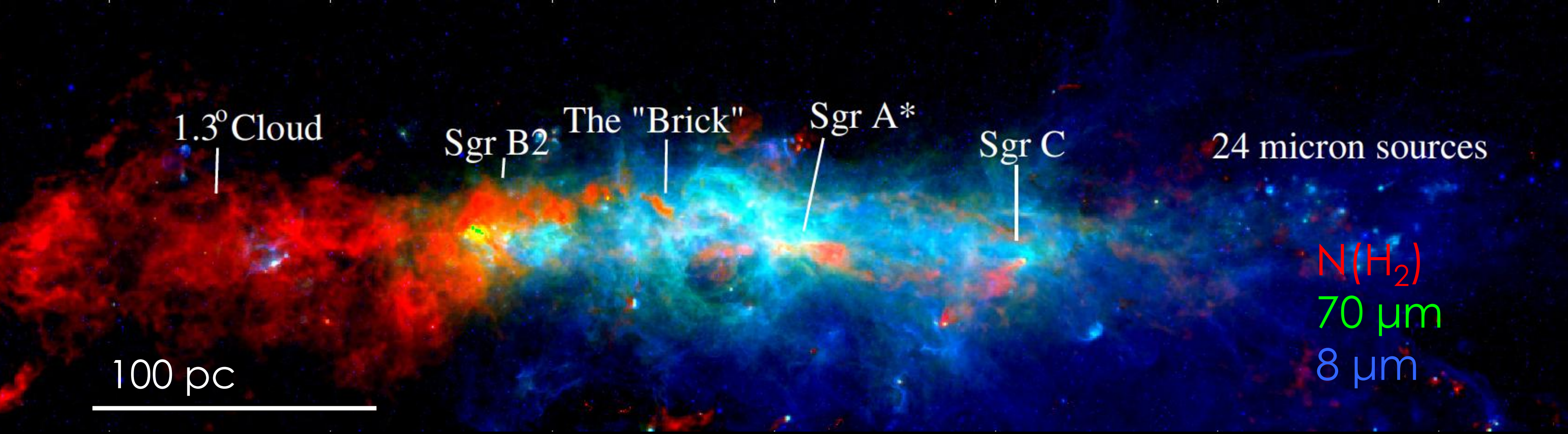
1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?
2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?
3) Is SF induced by tidal compression by SgrA*?
4) Can we find precursors to the most massive stars in the Galaxy?

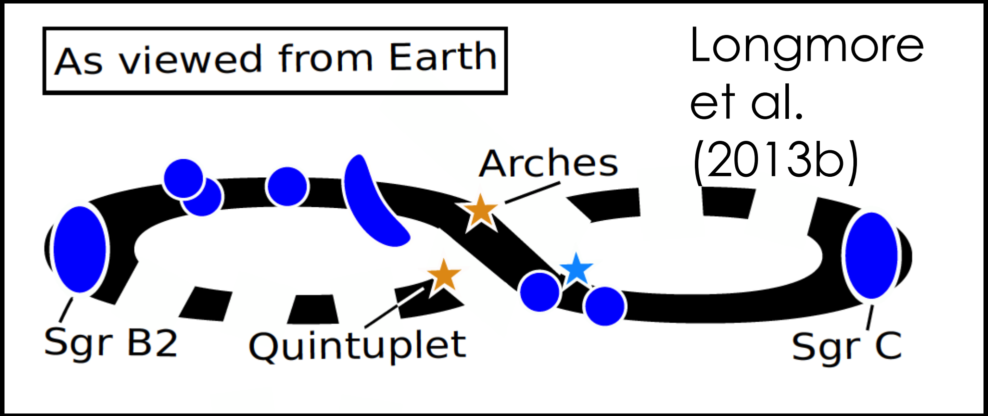


Basic Science Questions:

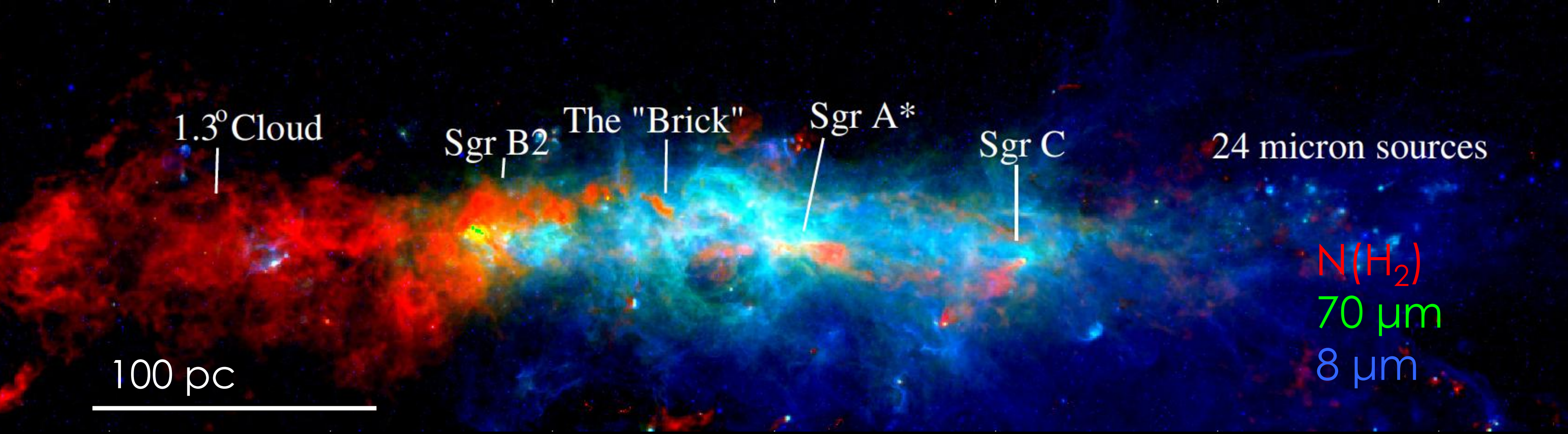
1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?
2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?
3) Is SF induced by tidal compression by SgrA*?
4) Can we find precursors to the most massive stars in the Galaxy?


1.3° Cloud
Sgr B2
The "Brick"
Sgr A*
Sgr C
24 micron sources
100 pc
N(H2)
70 µm
8 µm

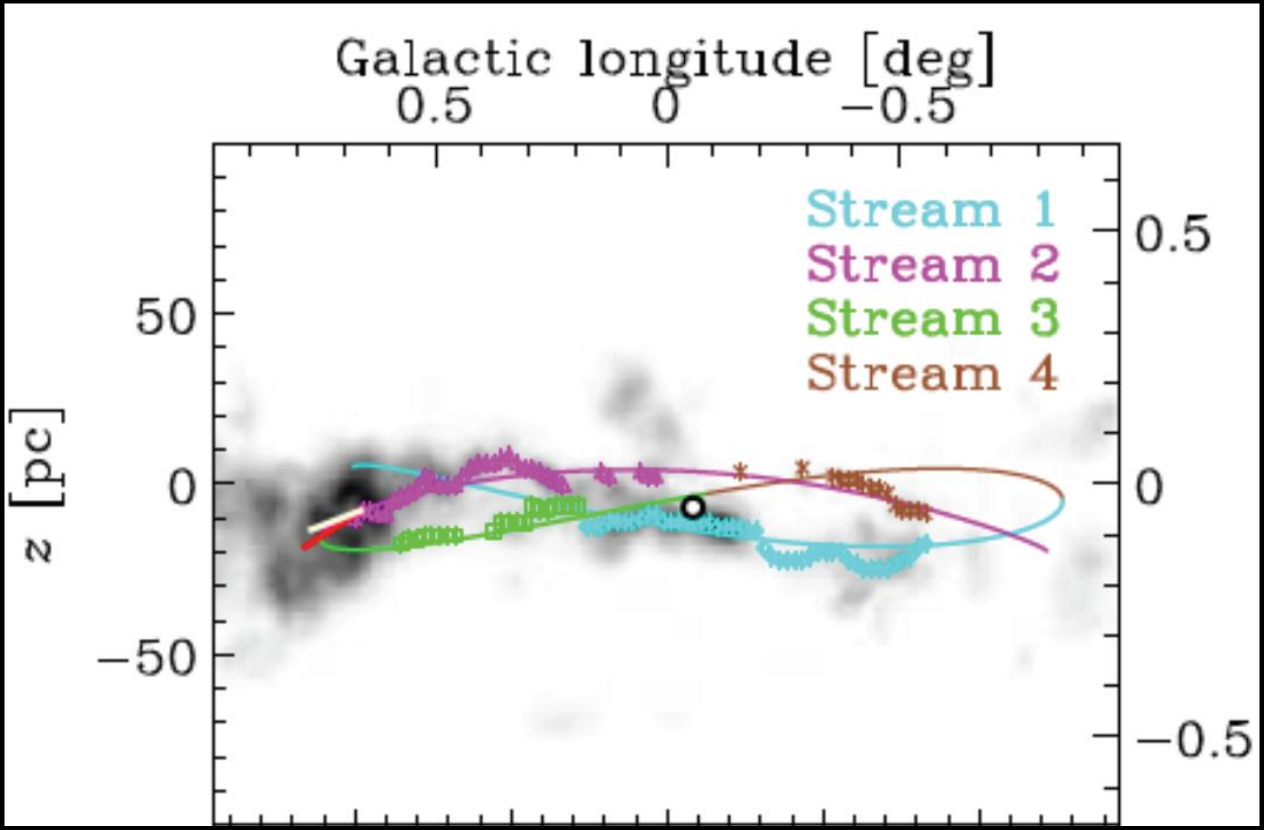


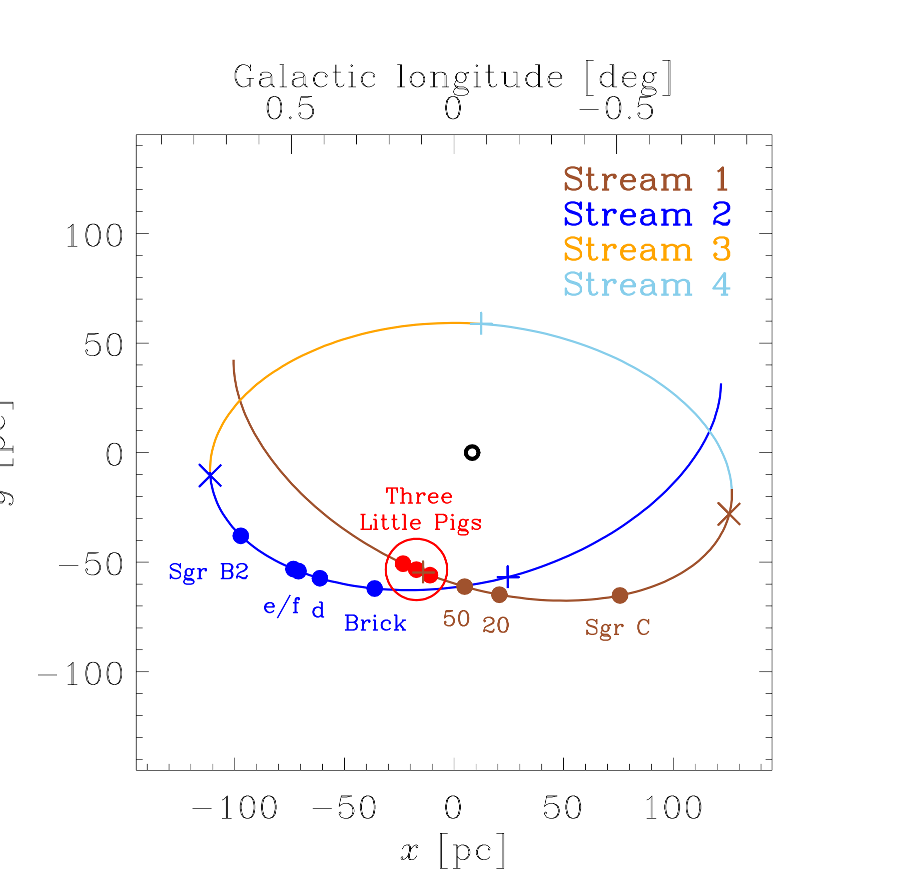


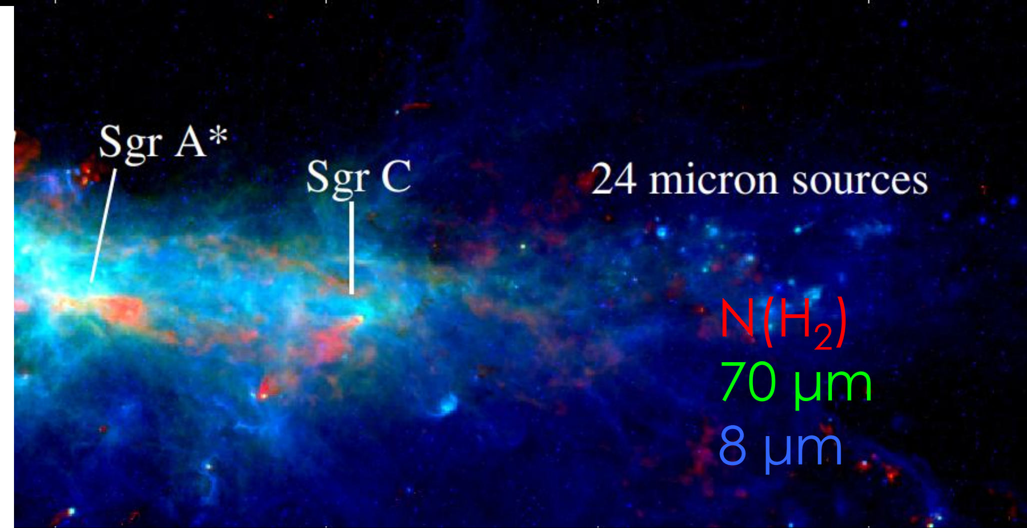
The “Molinari Ring” (Molinari+2011)



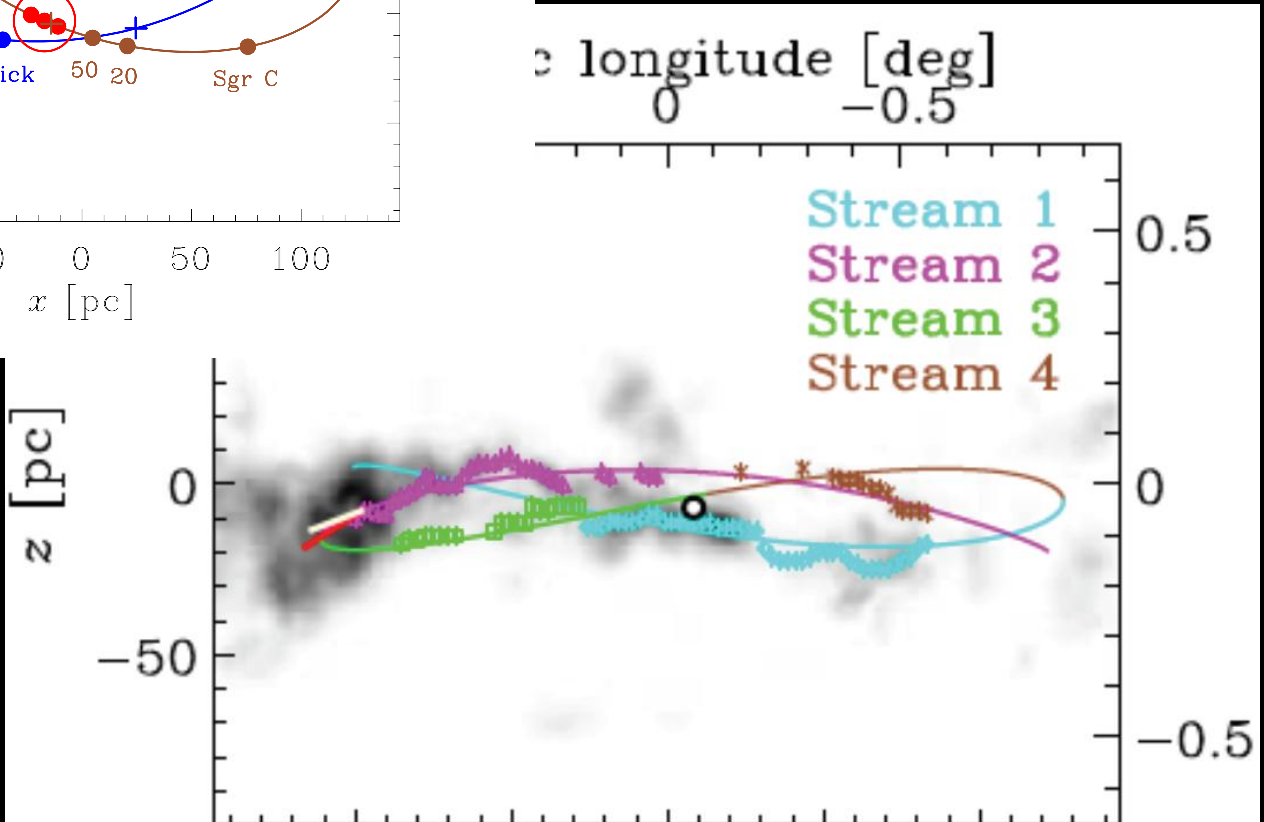
New orbital models (Kruijssen, Dale, & Longmore 2015)







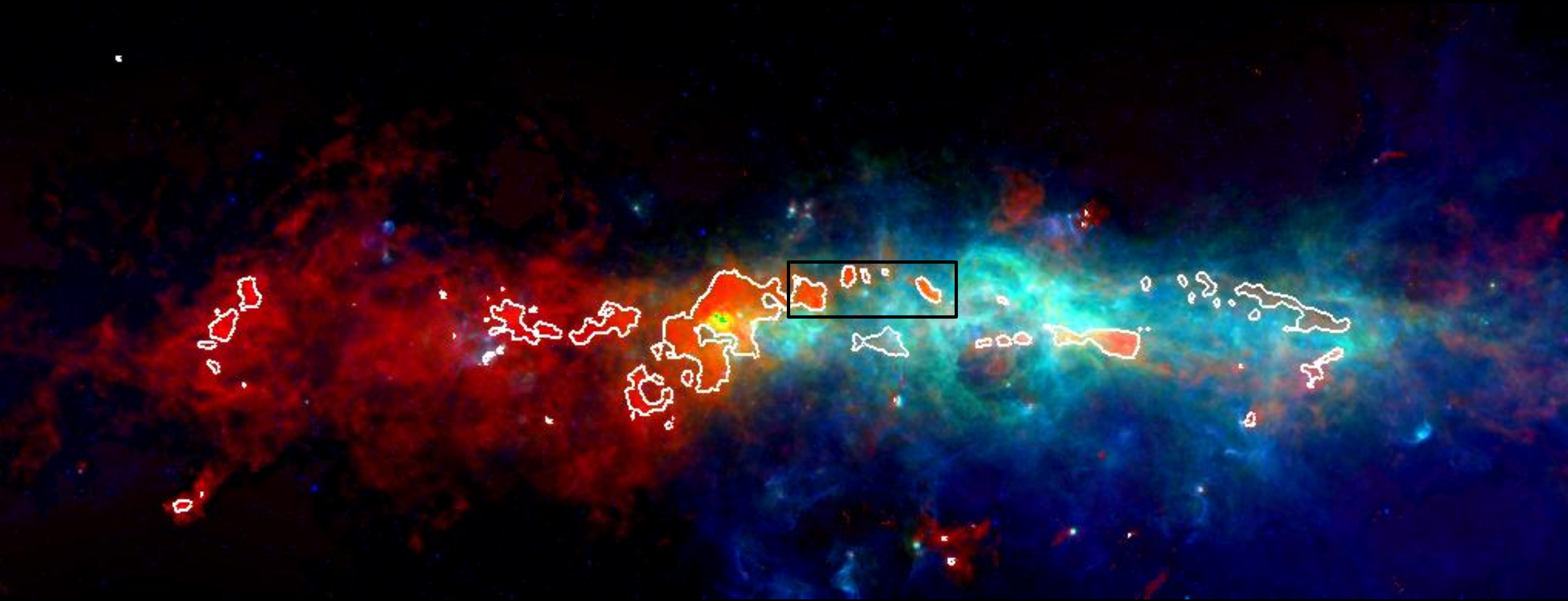
New orbital models (Kruijssen, Dale, & Longmore 2015)



Tidal compression of clouds

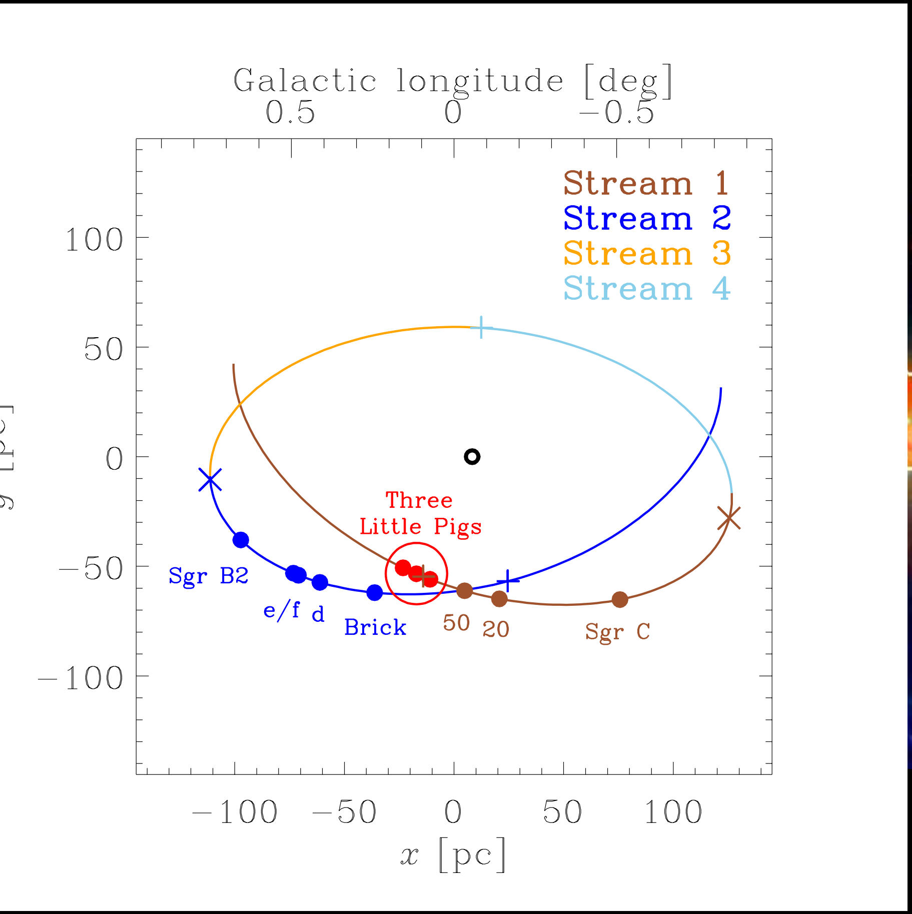
N(H_2) from HiGAL Battersby+, in prep., 70 µm from HiGAL, Molinari+ 2011, 8 µm from GLIMPSE (Benjamin+ 2003)

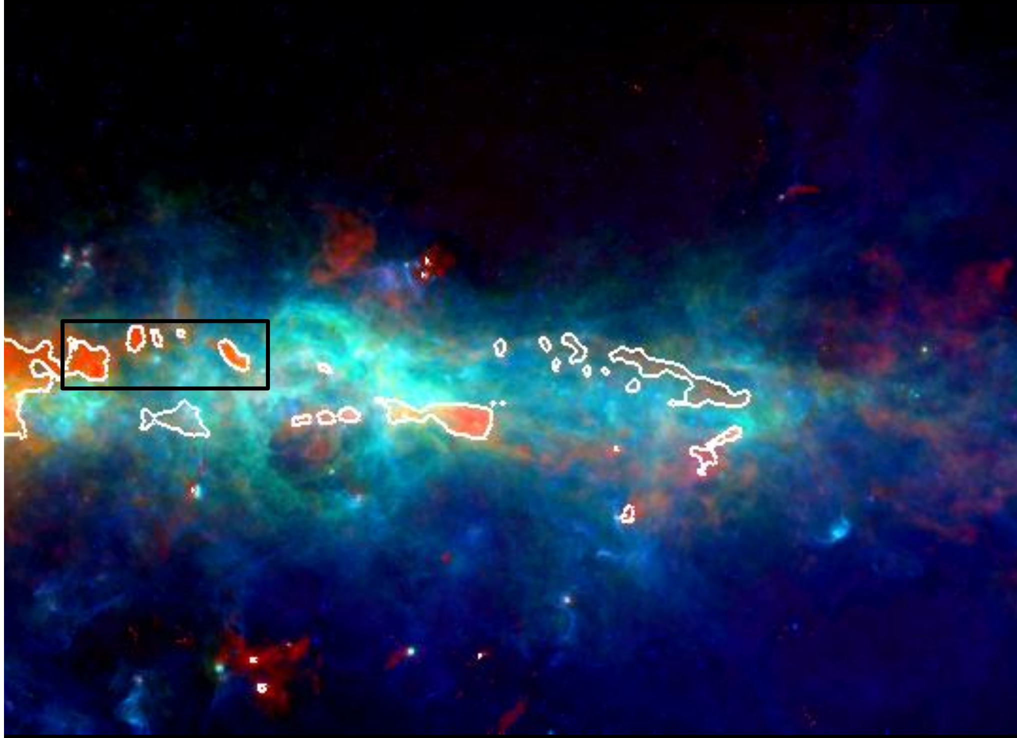
Tidal compression of clouds



N(H_2) from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)

Tidal compression of clouds

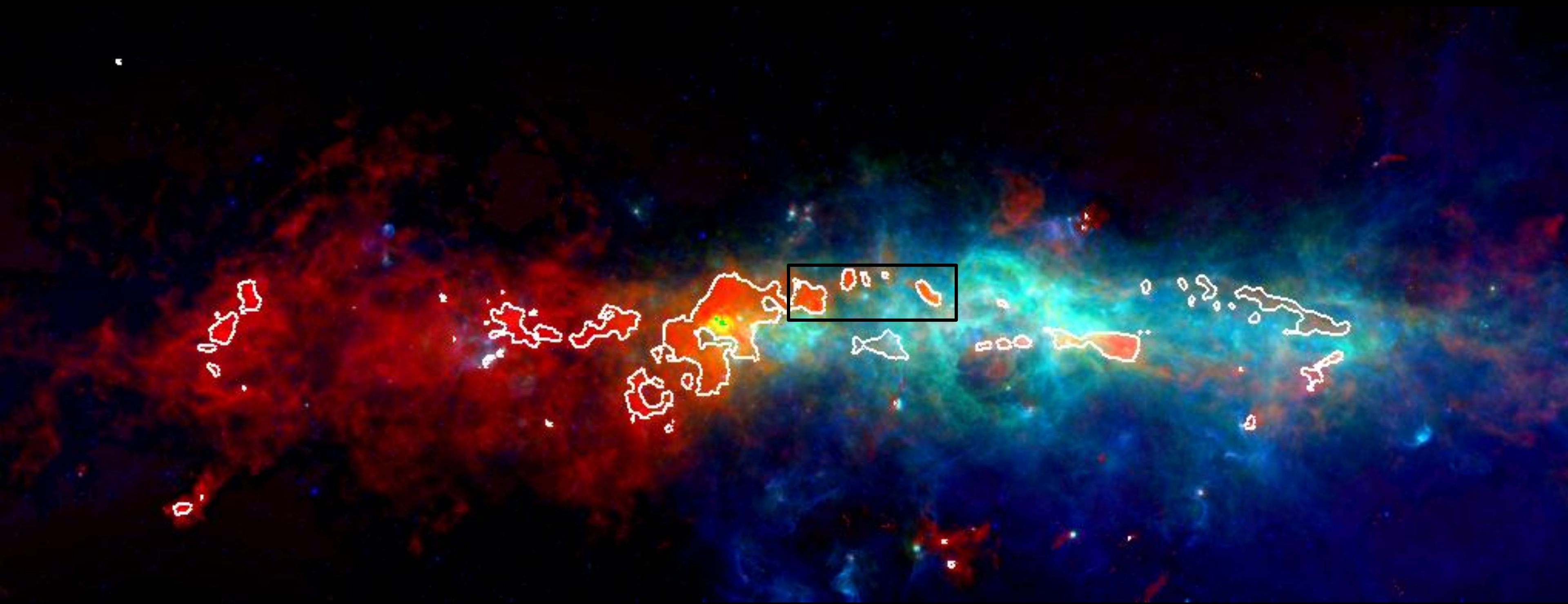




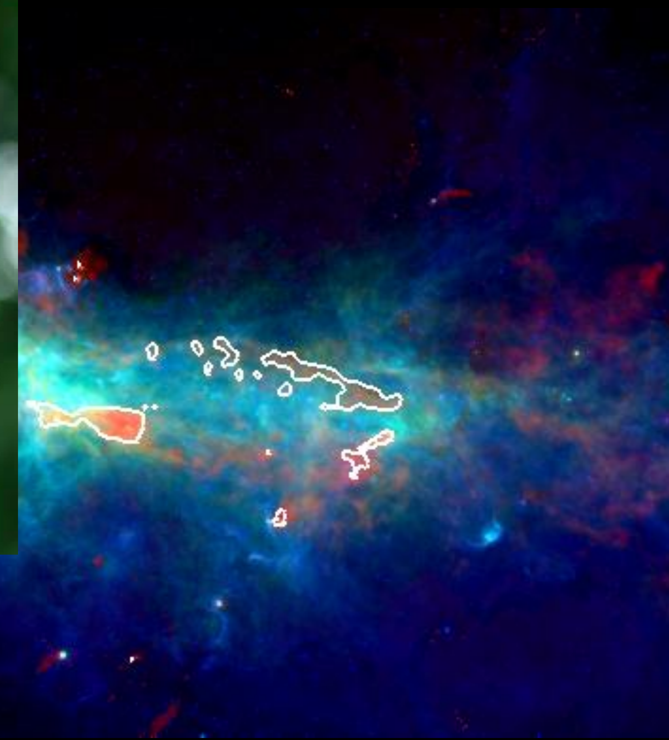
Kruijssen, Dale, Longmore 2015

$N(H_2)$ from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)

Tidal compression of clouds



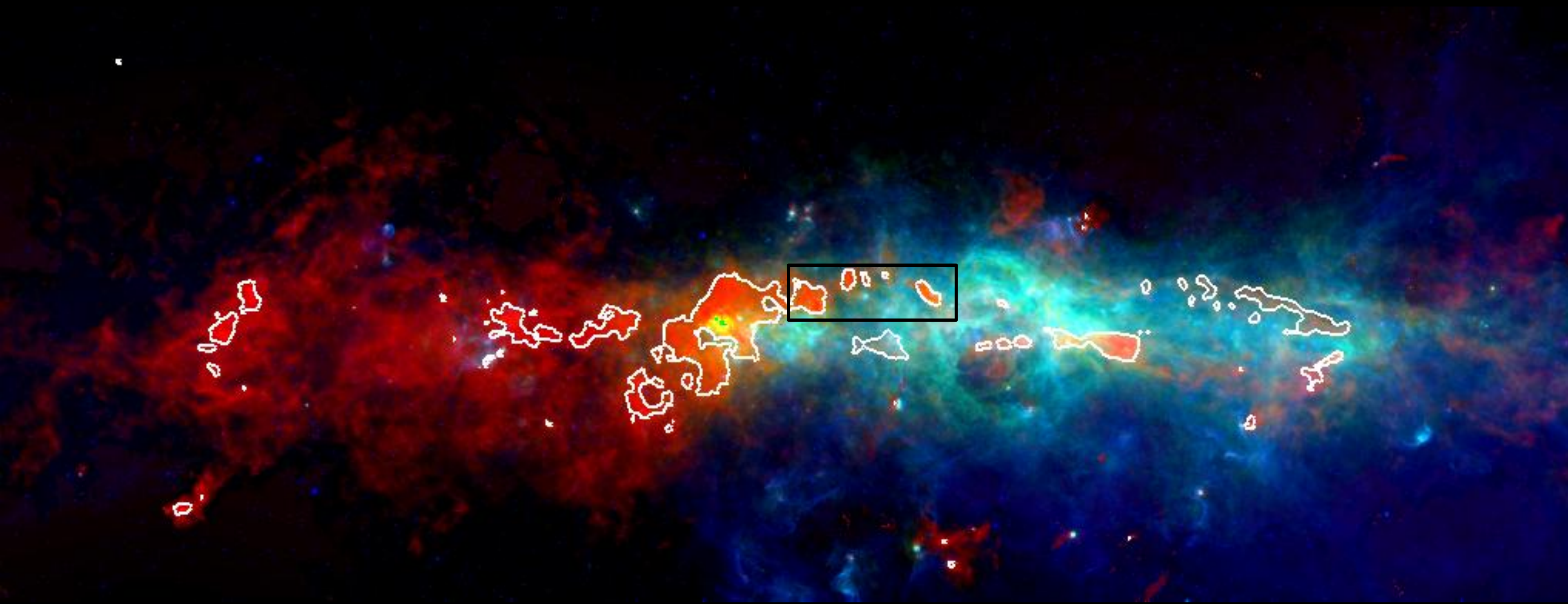
N(H_2) from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)



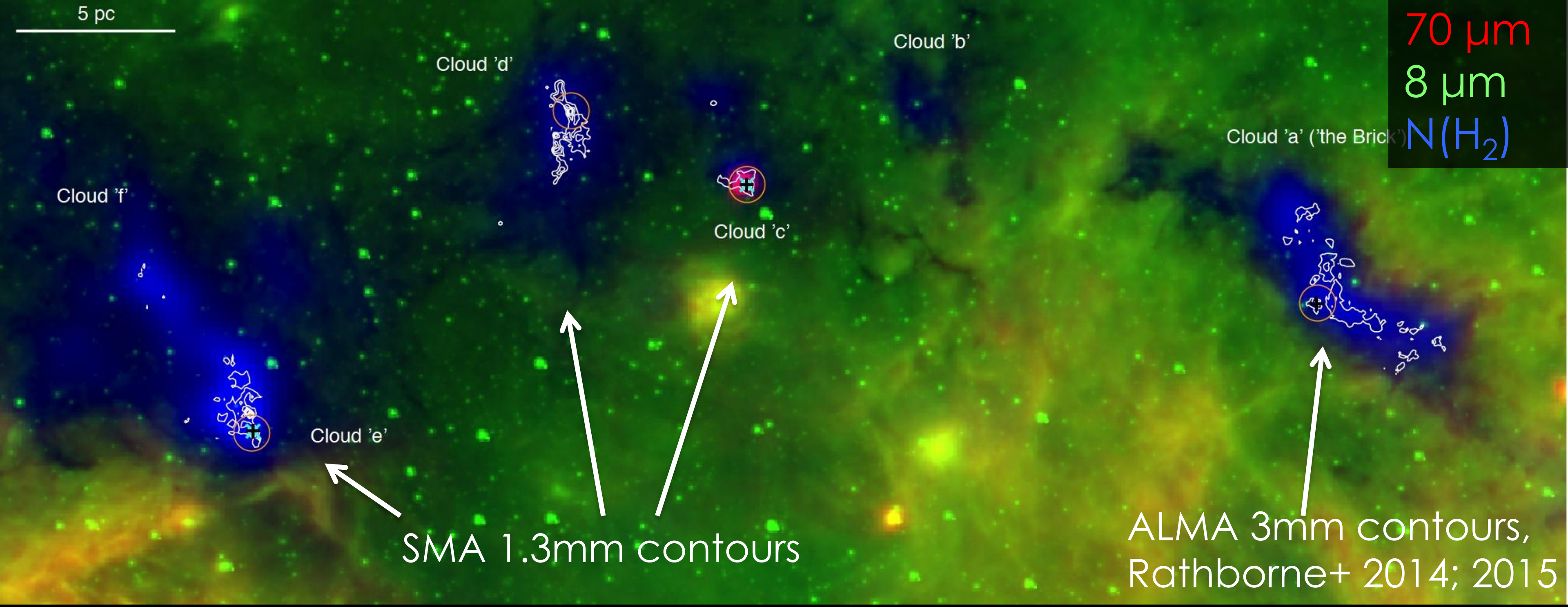
Dan Walker – PhD student in Liverpool
SAO Pre-doc

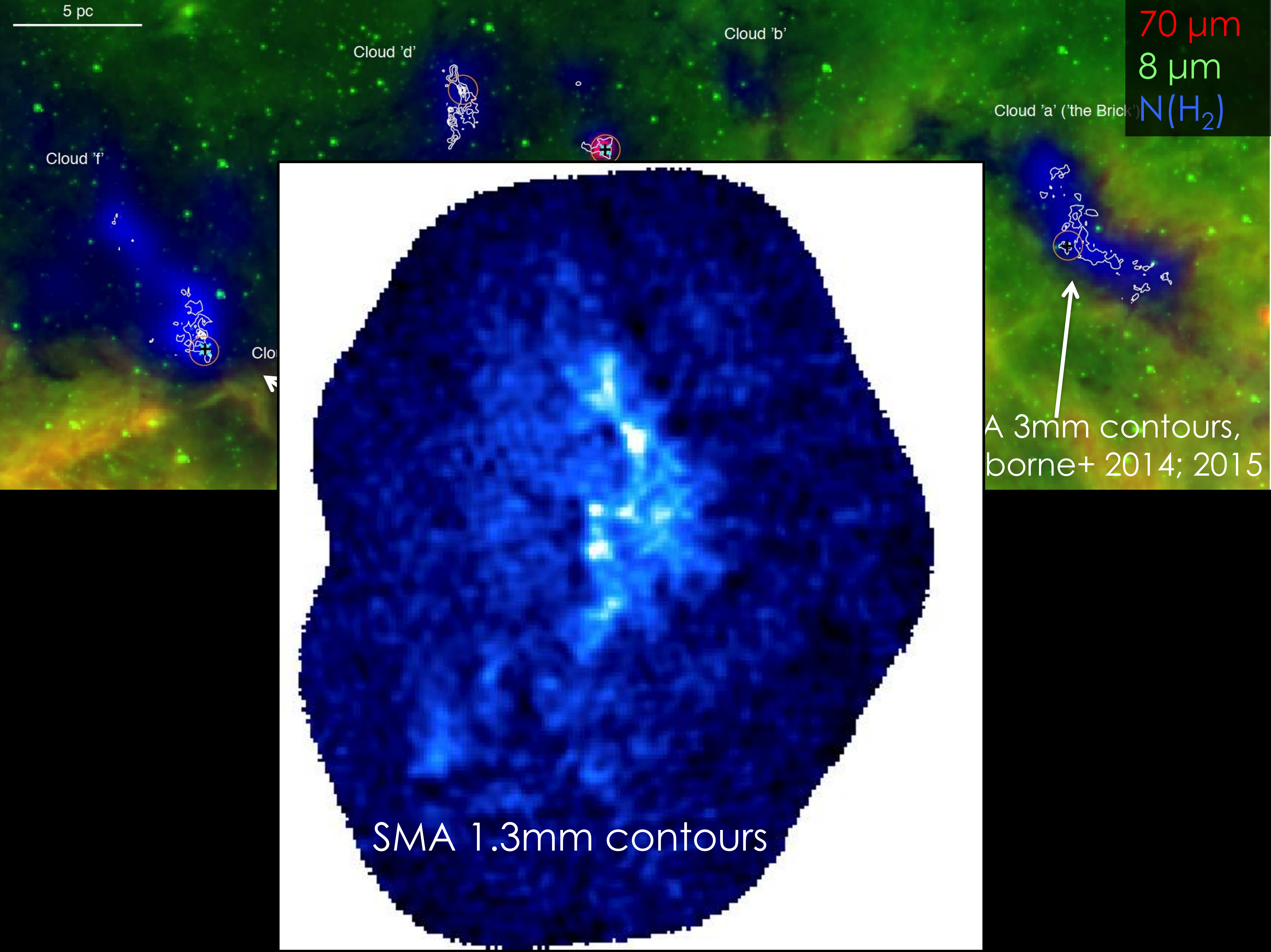
N(H_2) from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)

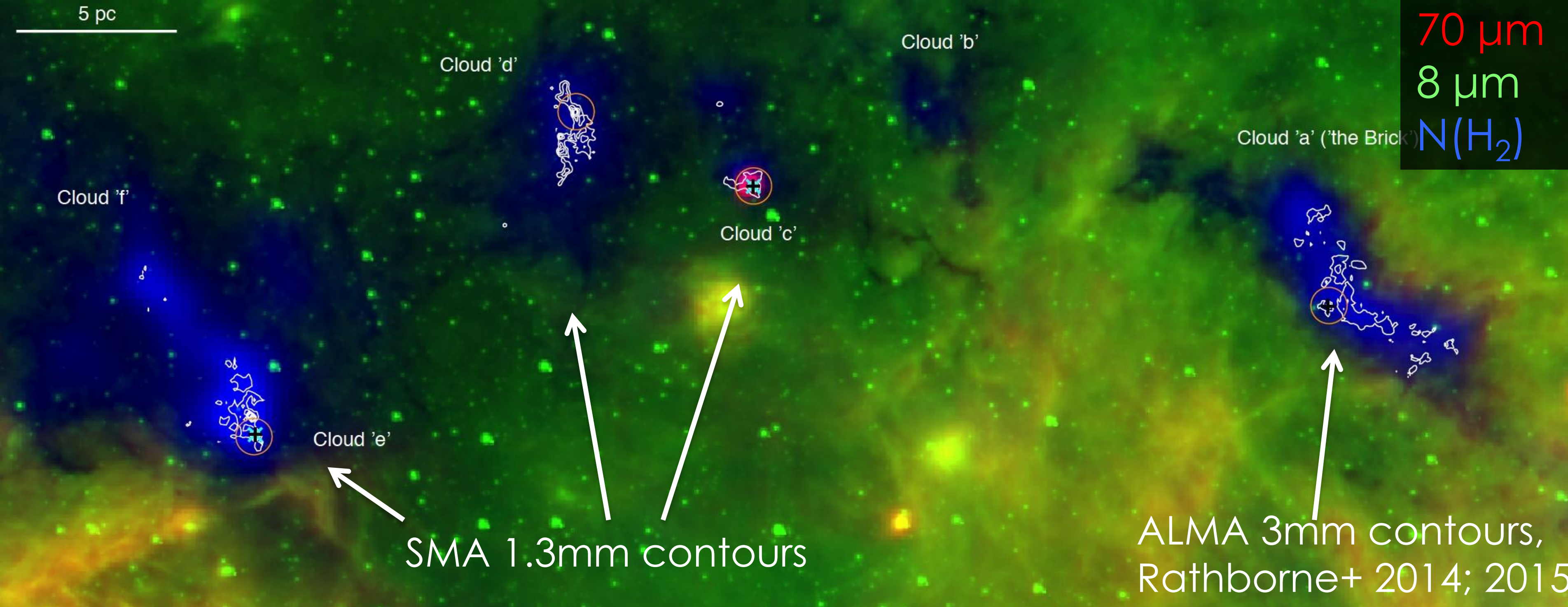
Tidal compression of clouds

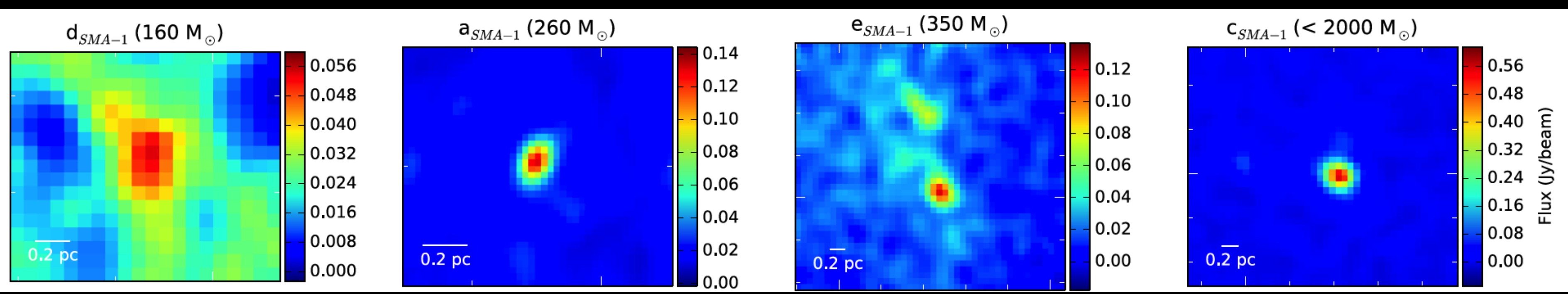


N(H_2) from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)


5 pc
Cloud 'd'
Cloud 'b'
70 μm
8 μm
N(H2)
Cloud 'a' ('the Brick')
Cloud 'f'
Cloud 'c'
Cloud 'e'
SMA 1.3mm contours
ALMA 3mm contours,
Rathborne+ 2014; 2015


5 pc
Cloud 'd'
Cloud 'b'
70 µm
8 µm
N(H2)
Cloud 'a' ('the Brick')
Cloud 'f'
A 3mm contours,
borne+ 2014; 2015
SMA 1.3mm contours



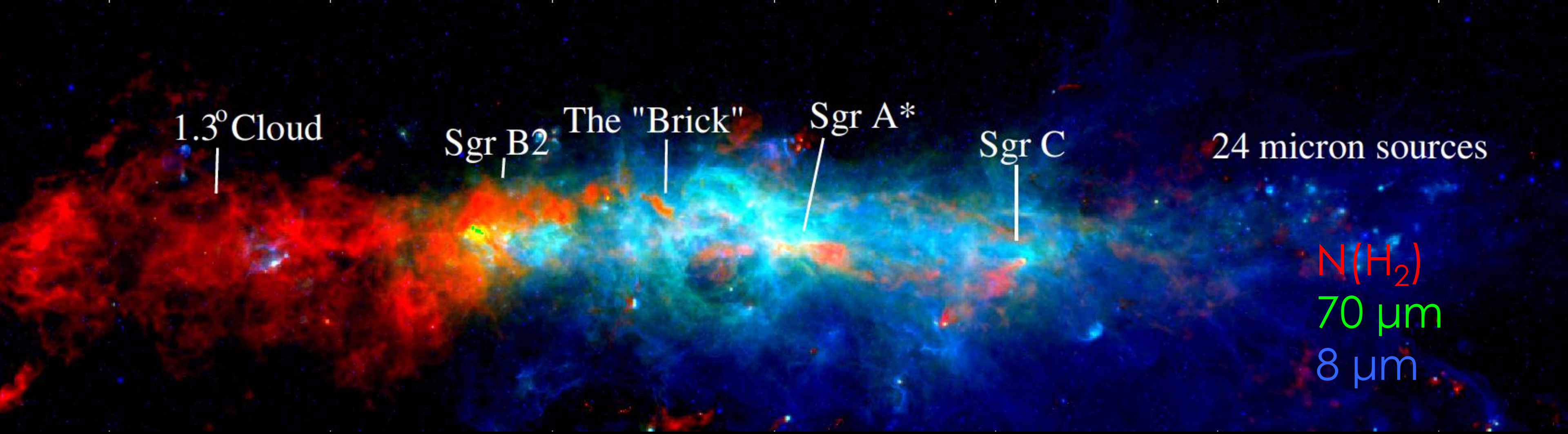


N_{ff} = 0.61
No SF tracers

N_{ff} = 0.65
H_2O maser

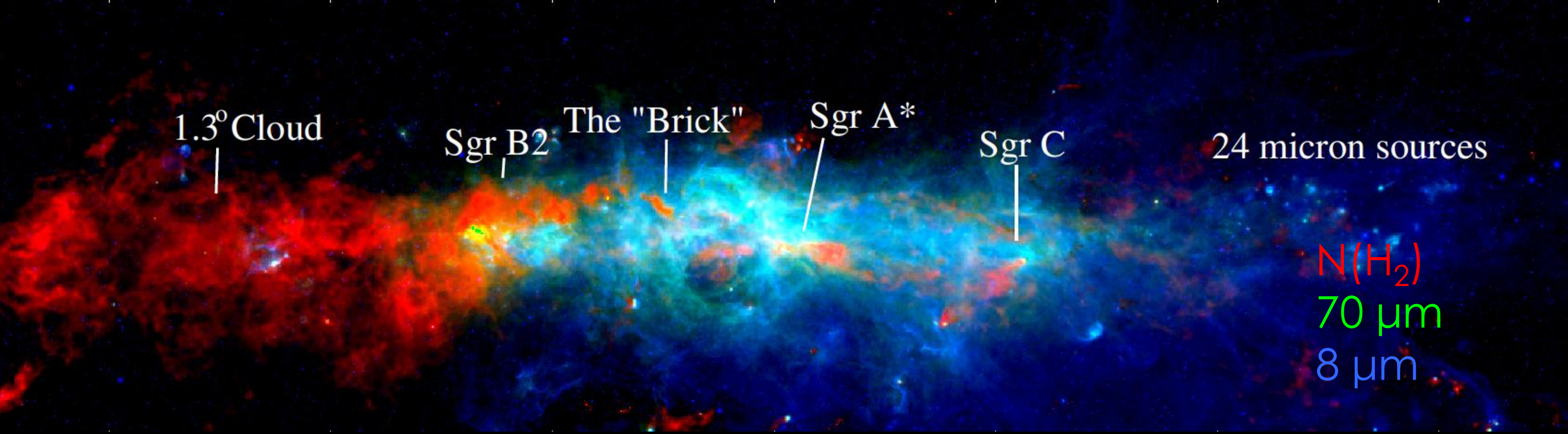
N_{ff} = 1.28
H_2O and CH_3OH masers

N_{ff} = 1.76
H_2O and CH_3OH masers + 70 μm



Basic Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?
2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?
3) Is SF induced by tidal compression by SgrA*?
4) Can we find precursors to the most massive stars in the Galaxy?



Basic Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?
2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?
3) Is SF induced by tidal compression by SgrA*?
4) Can we find precursors to the most massive stars in the Galaxy?

Where is the Galactic Center?

Map of Galaxy in a Star Formation Tracer (water maser)

HOPS: A. Walsh

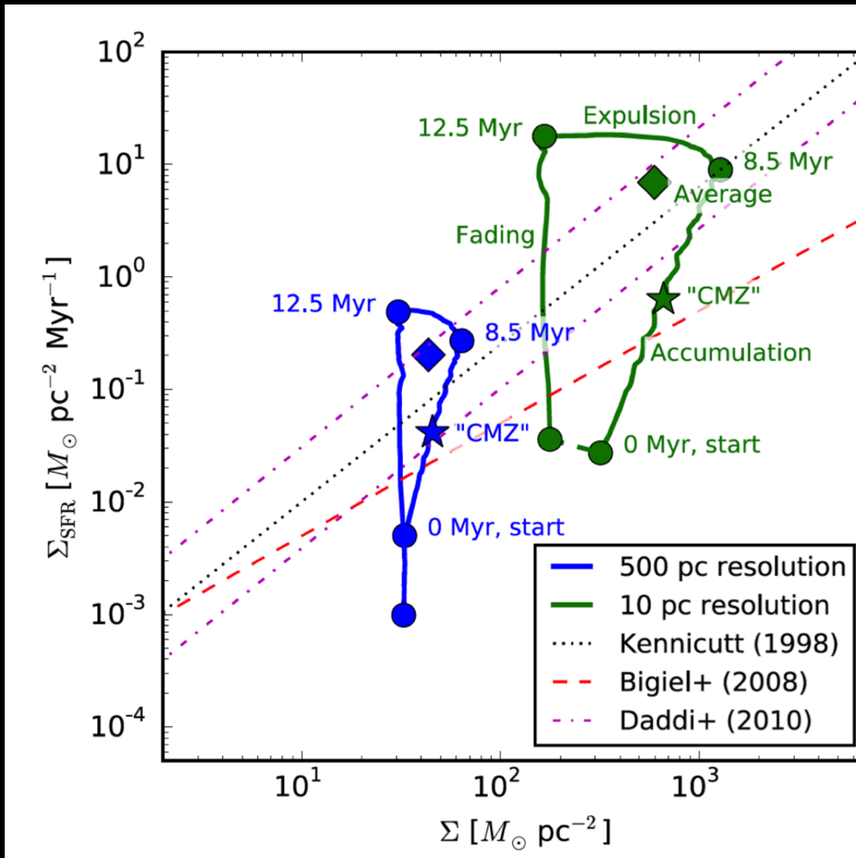
Where is the Galactic Center?

Map of Galaxy in a Star Formation Tracer (water maser)

Map of Galaxy in Dense Gas (HC_3N)

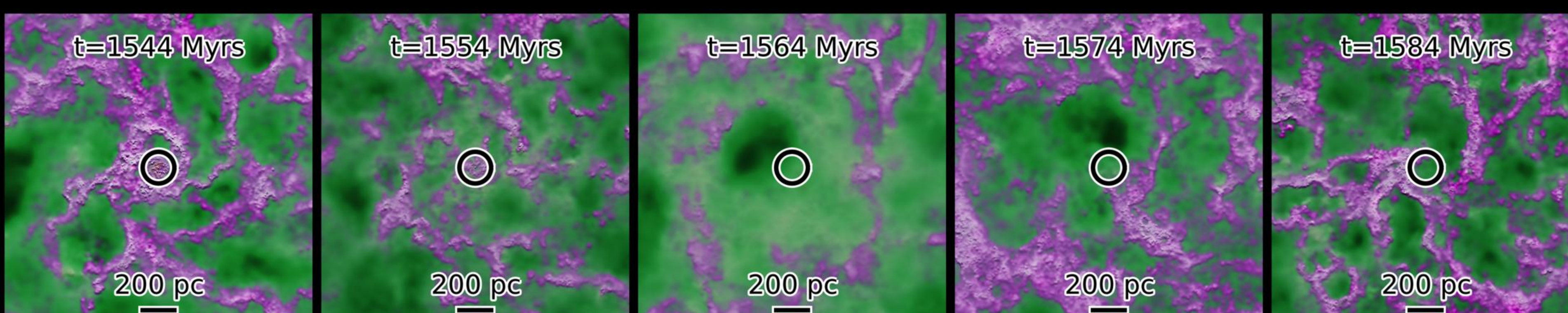
HOPS: A. Walsh

Why is the SFR low in the CMZ?

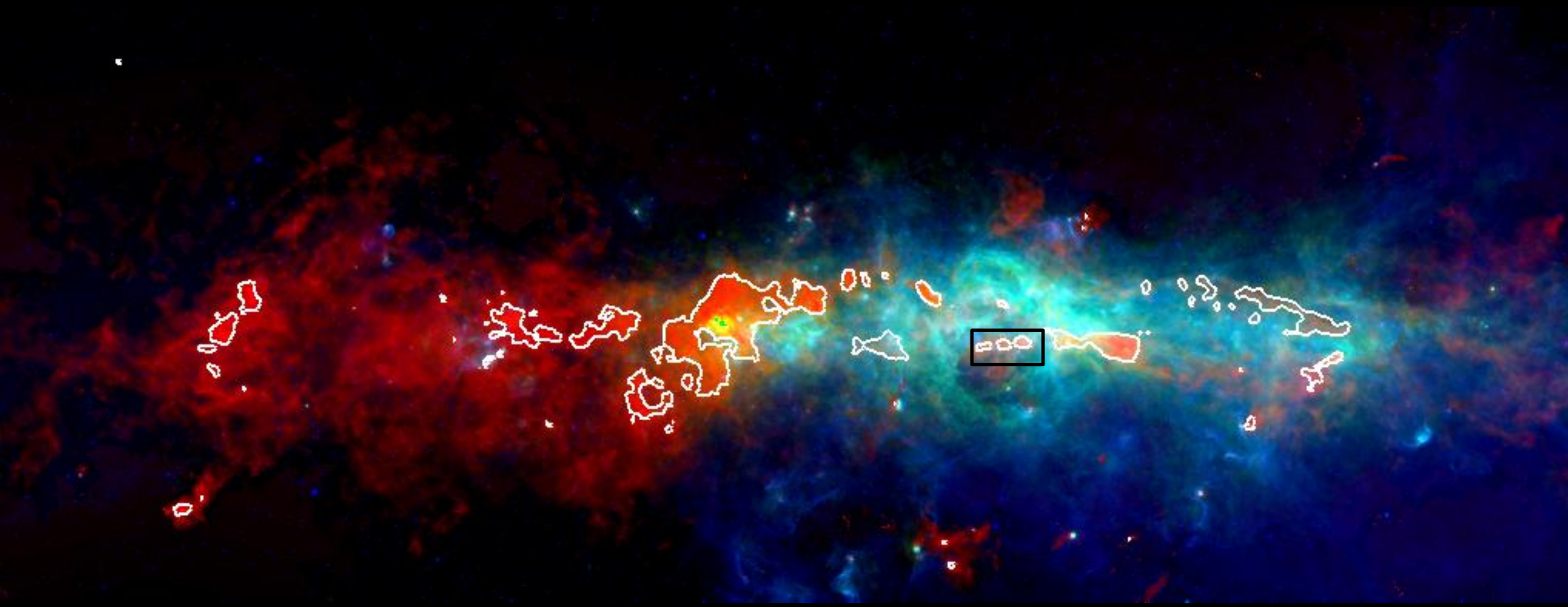


Krumholz & Kruijssen 2015

Torrey et al., submitted

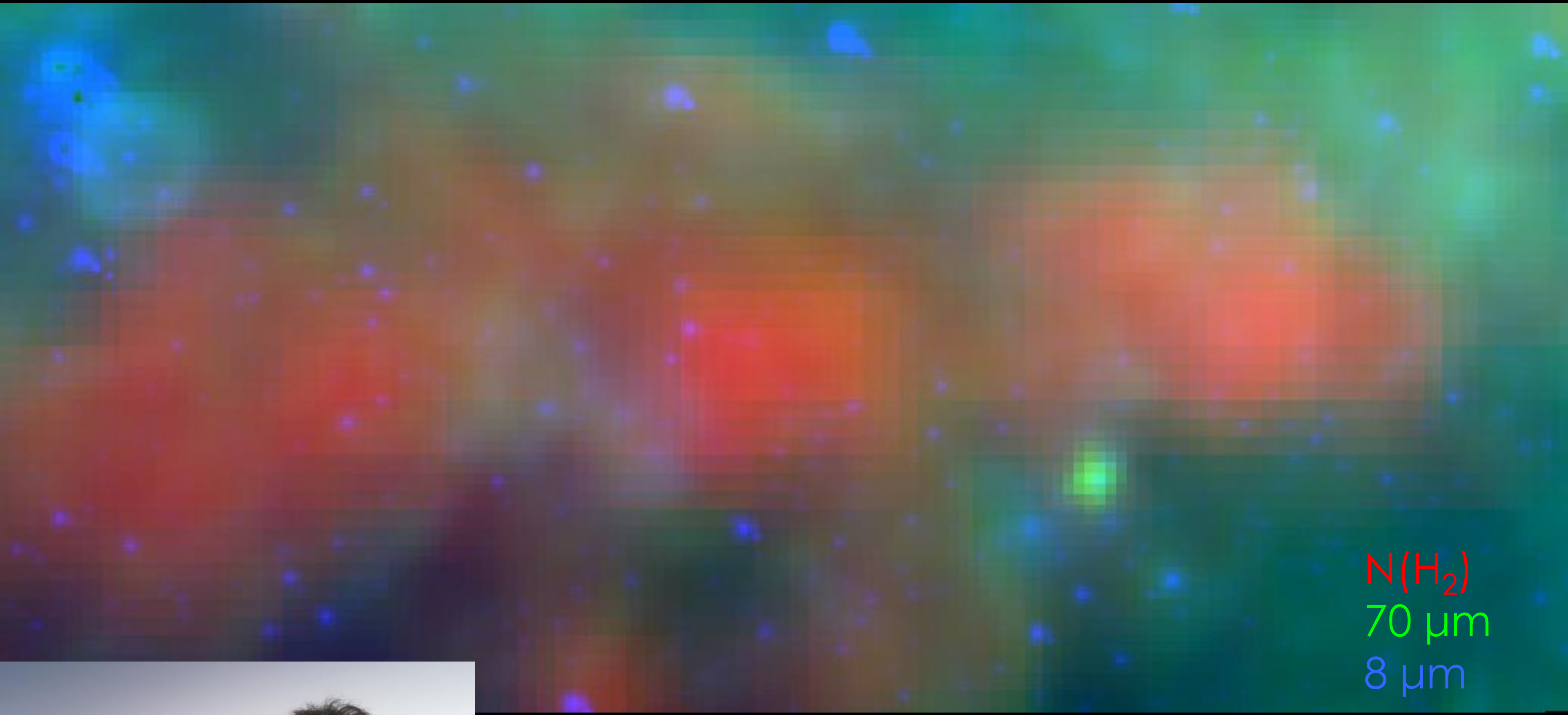


Why is the SFR low in the CMZ?



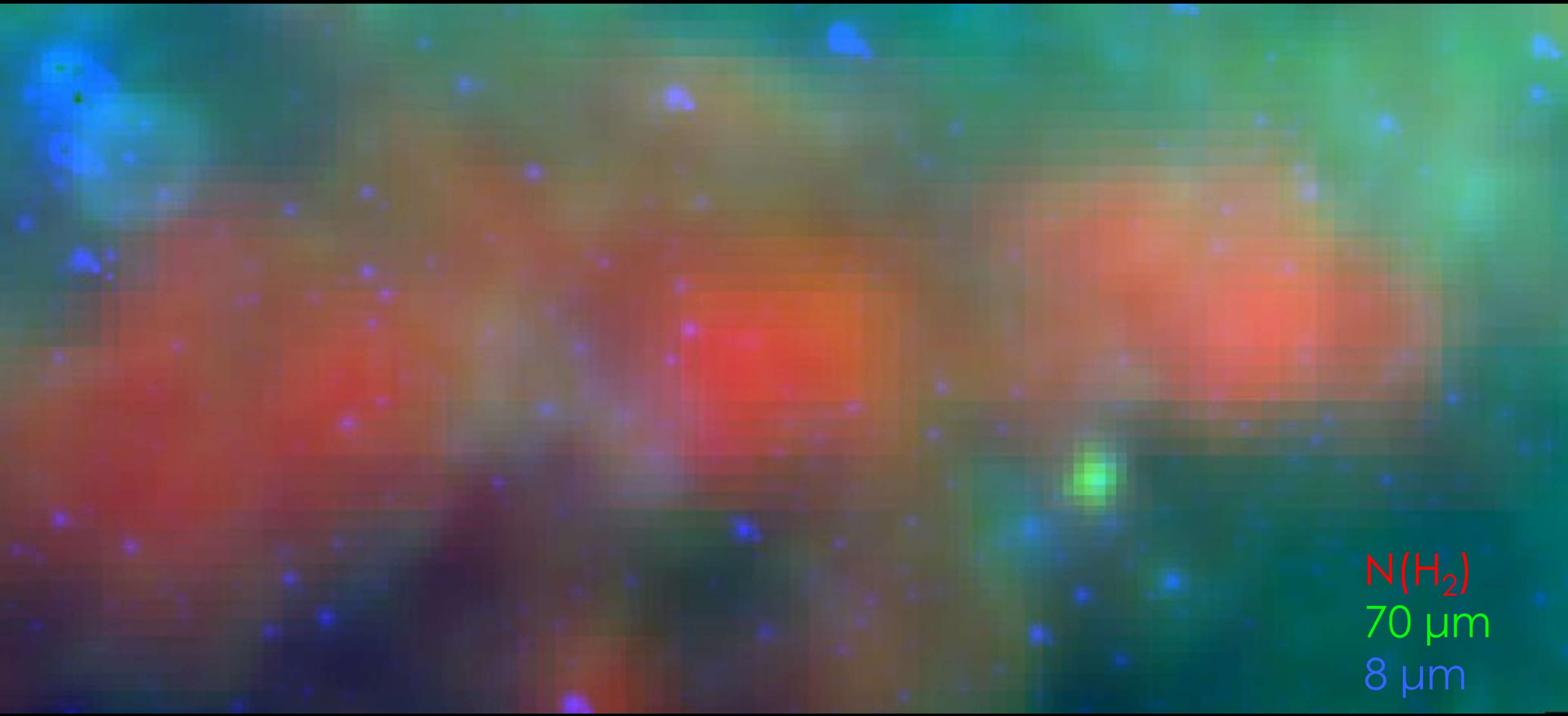
N(H_2) from HiGAL Battersby+, in prep., 70 µm from HiGAL, Molinari+ 2011, 8 µm from GLIMPSE (Benjamin+ 2003)

Why is the SFR low in the CMZ?

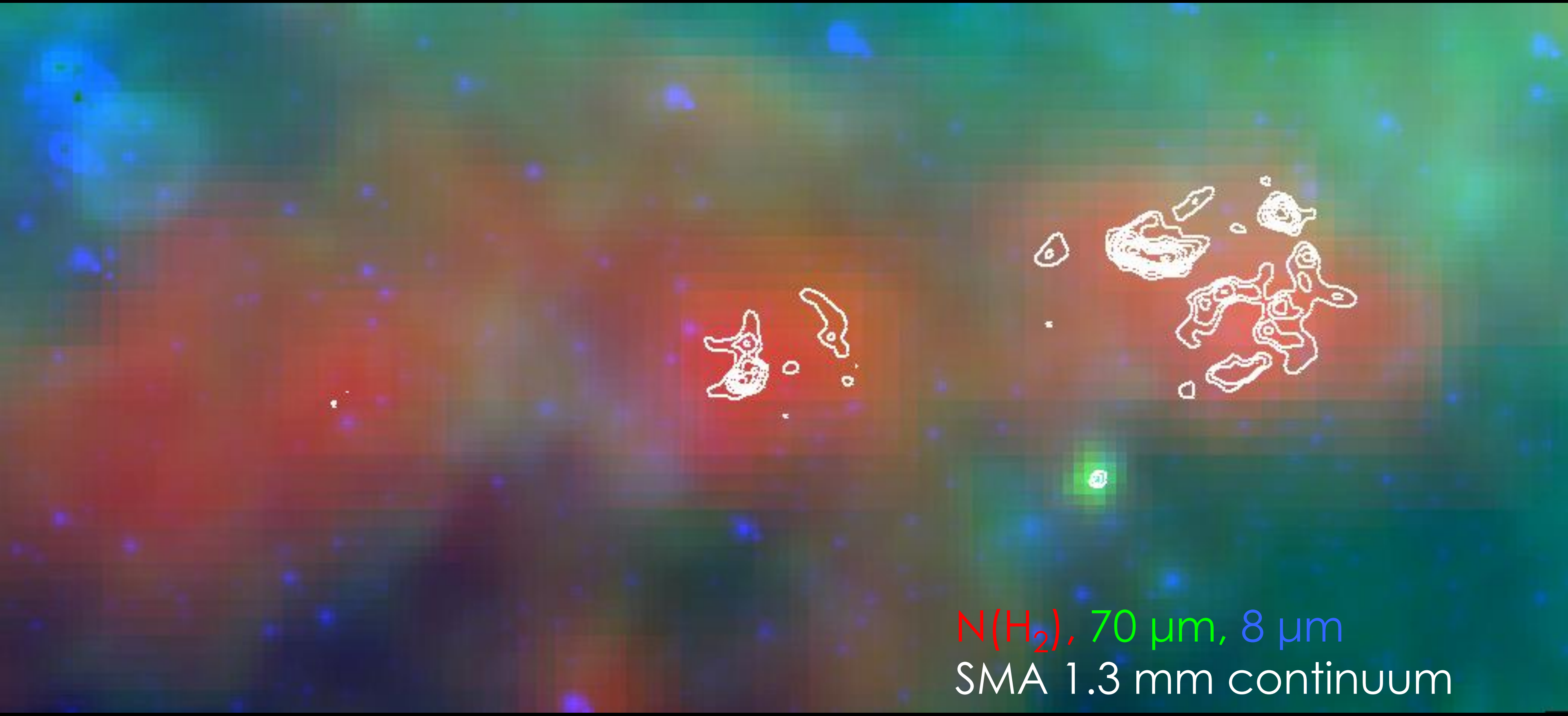


Mark Graham
SAO Pre-doc, now a
PhD student at Oxford

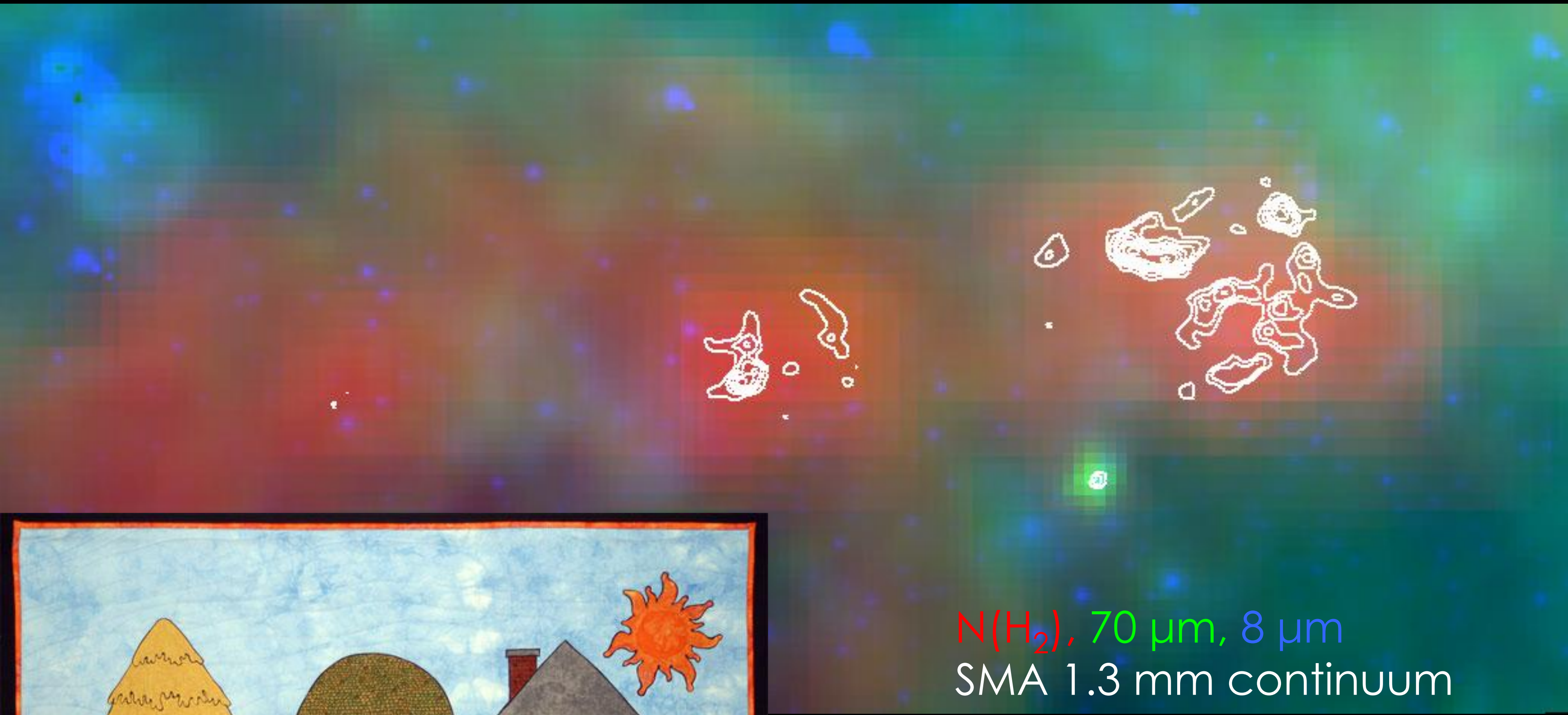
Why is the SFR low in the CMZ?



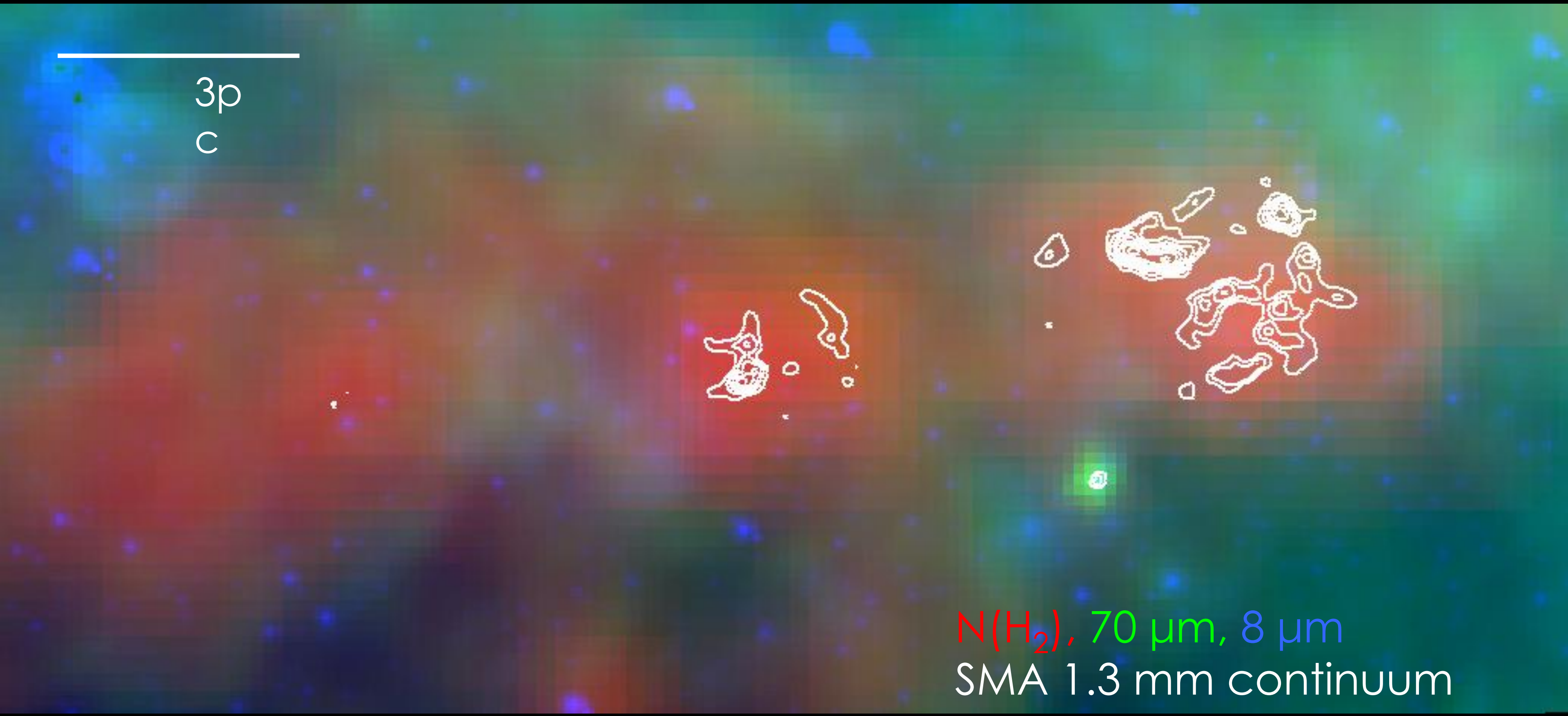
Why is the SFR low in the CMZ?



Why is the SFR low in the CMZ?



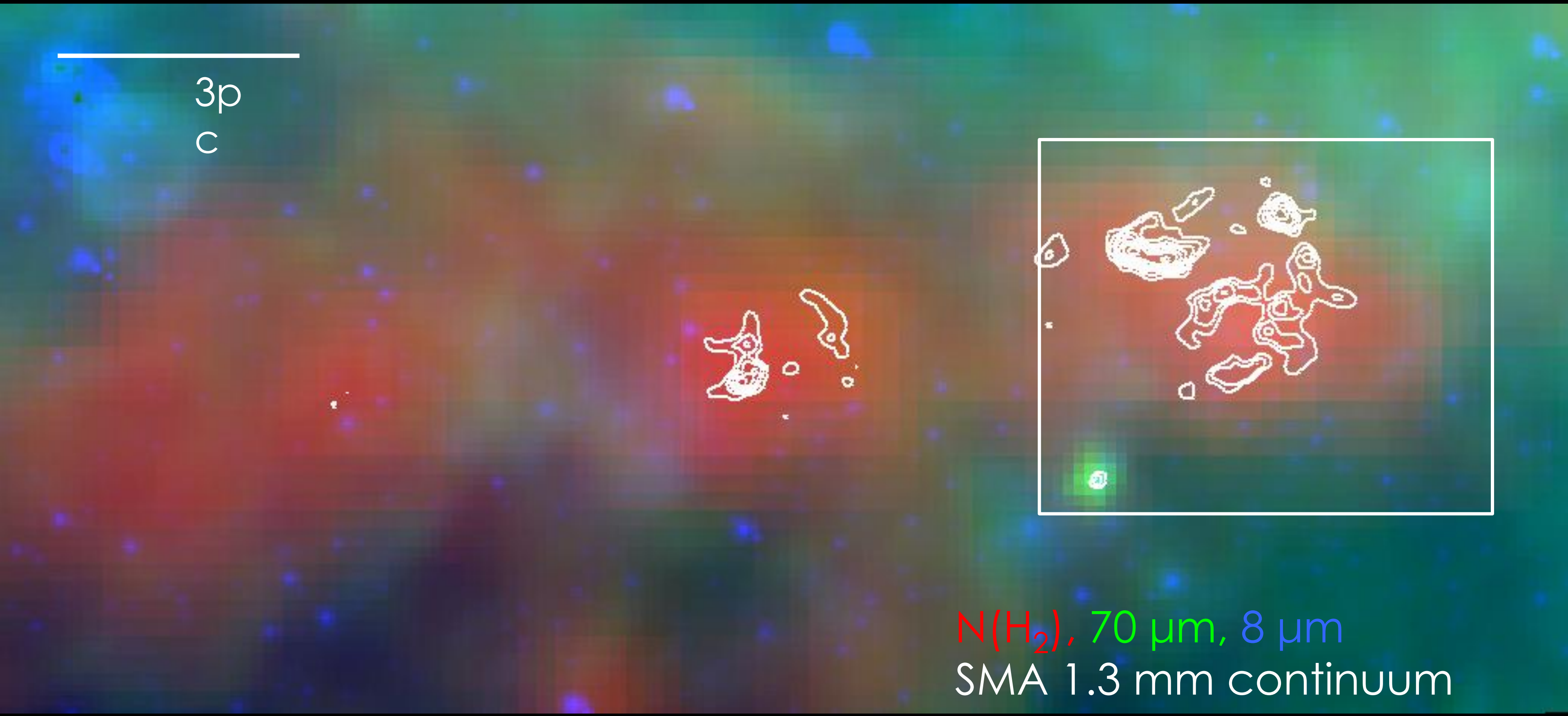
Why is the SFR low in the CMZ?



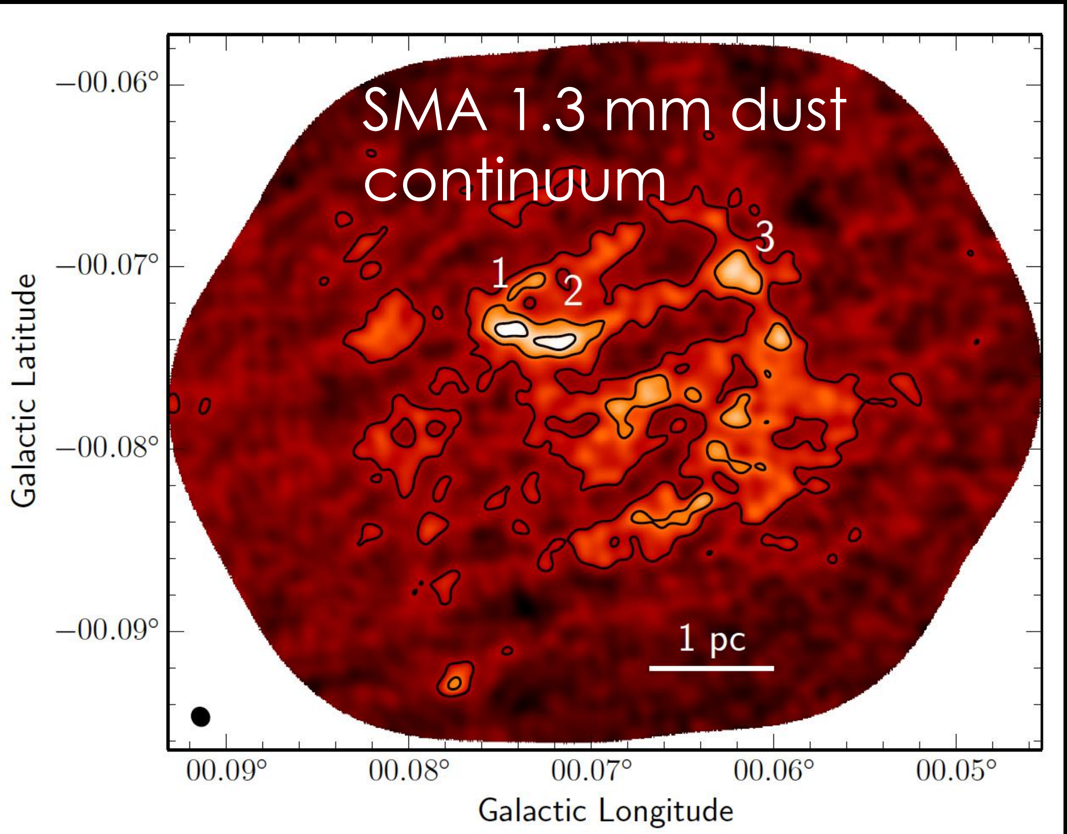
The Three Little Pigs: Very similar global properties but vastly different substructure

Mass ~ 3 x10^4 $M_\odot$
T_{dust} ~20K
$N(H_2)_{peak}$~ 2x10^{23} cm^{-2}
Δv ~ 10 km/s
Battersby, Bally, Longmore, in prep.

Why is the SFR low in the CMZ?



Why is the SFR low in the CMZ?

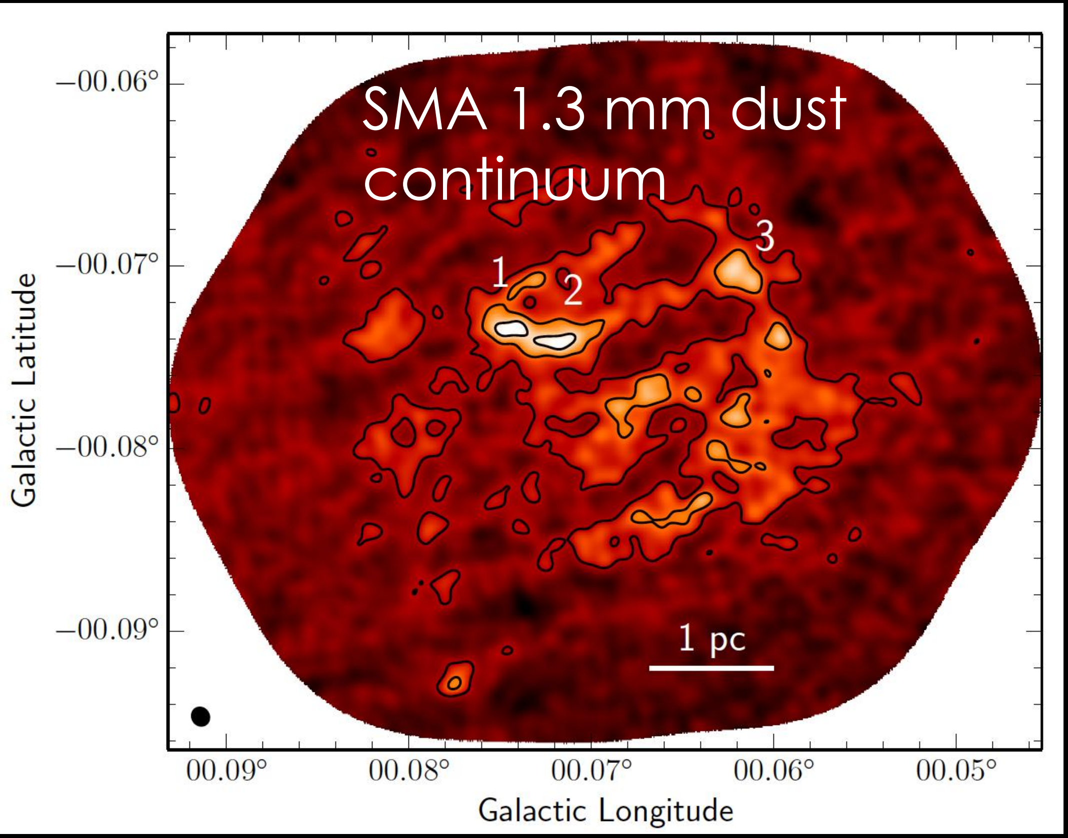


Is it star forming?

- ❑ Dense gas
- ❑ Shocked, highly excited gas
- ❑ Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ❑ Outflow or localized hot-core chemistry

CMZoom

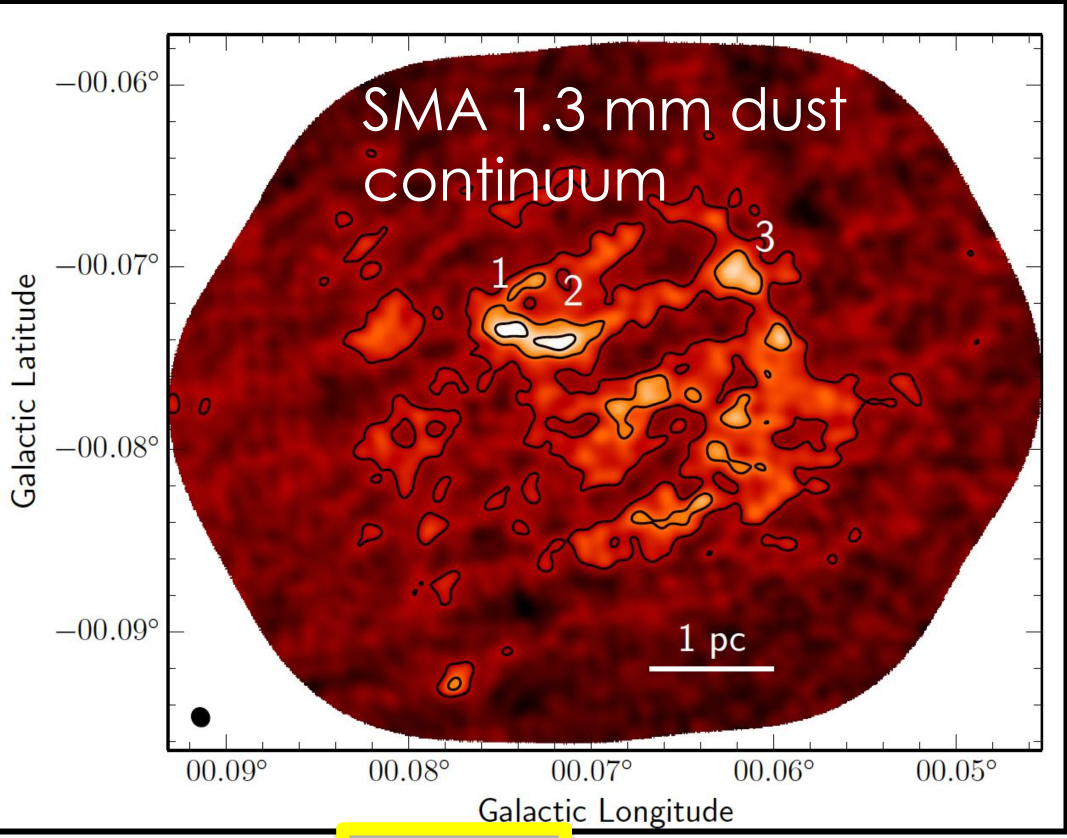
Why is the SFR low in the CMZ?



Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- ❑ Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ❑ Outflow or localized hot-core chemistry

Why is the SFR low in the CMZ?

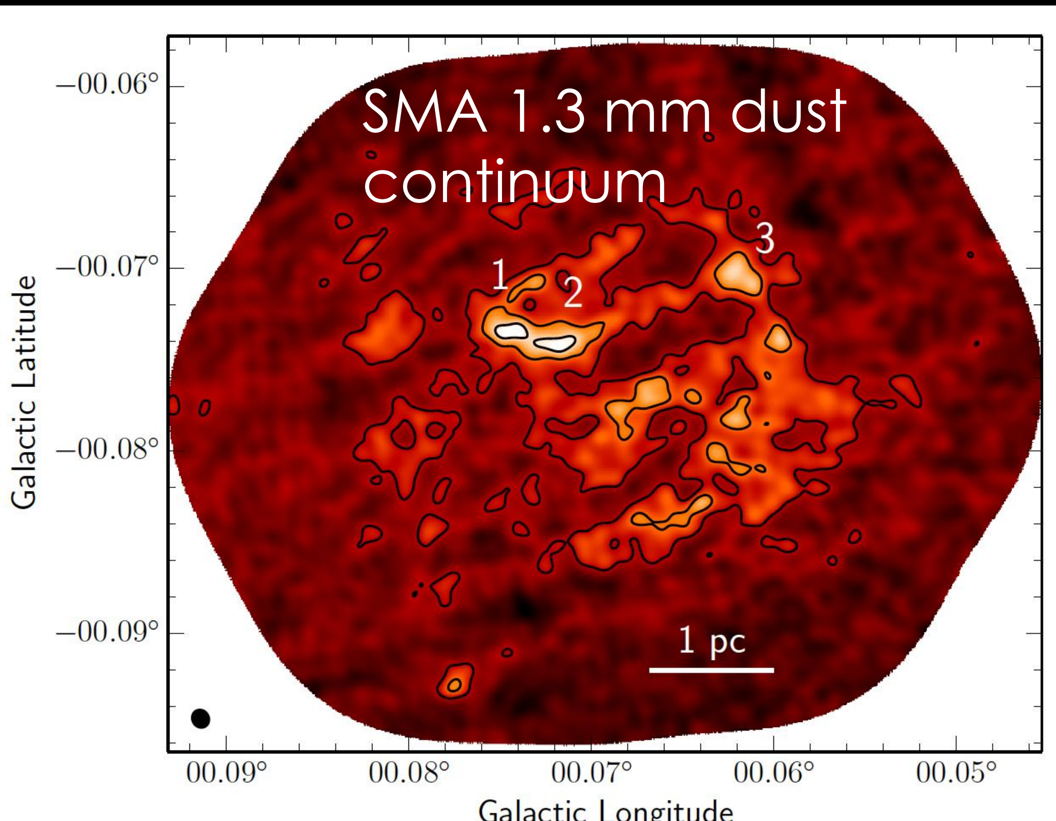


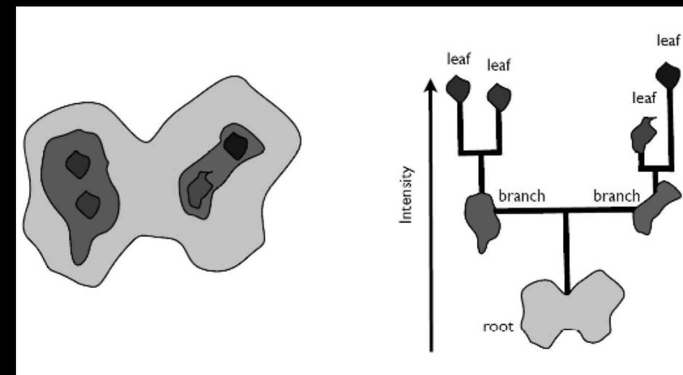
Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- ❑ Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ❑ Outflow or localized hot-core chemistry

Core	Mass ($M_\odot$)	M_{vir}/M	Mean Radius (pc)	Number Density ($\times 10^5$ cm^{-3})	Significance (σ^{-1})	Δv_{H_2CO} (km s^{-1})
1	620	8.8	0.23	1.9	11.7	13.8
2	570	2.2	0.24	1.5	11.4	6.4
3	710	0.7	0.26	1.4	9.7	3.8

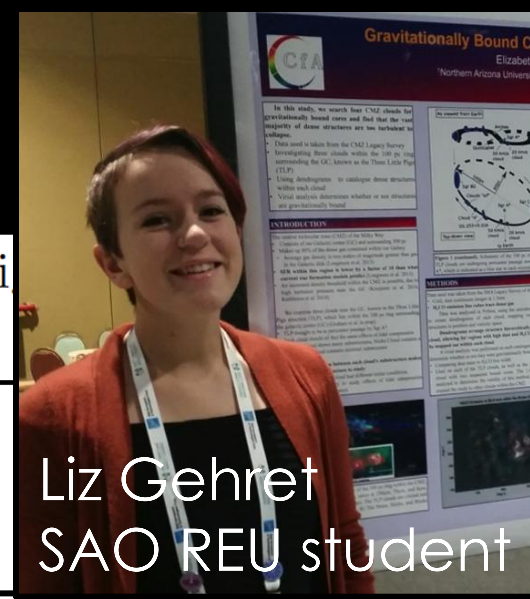
Why is the SFR low in the CMZ?



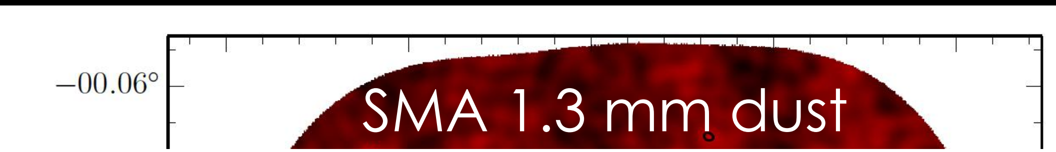


Dendrograms, e.g.
Shetty et al. 2012,
Rosolowsky et al. 2008

Core	Mass ($M_\odot$)	M_{vir}/M	Mean Radius (pc)	Number Density ($\times 10^5$ cm^{-3})	Si
1	620	8.8	0.23	1.9	
2	570	2.2	0.24	1.5	
3	710	0.7	0.26	1.4	

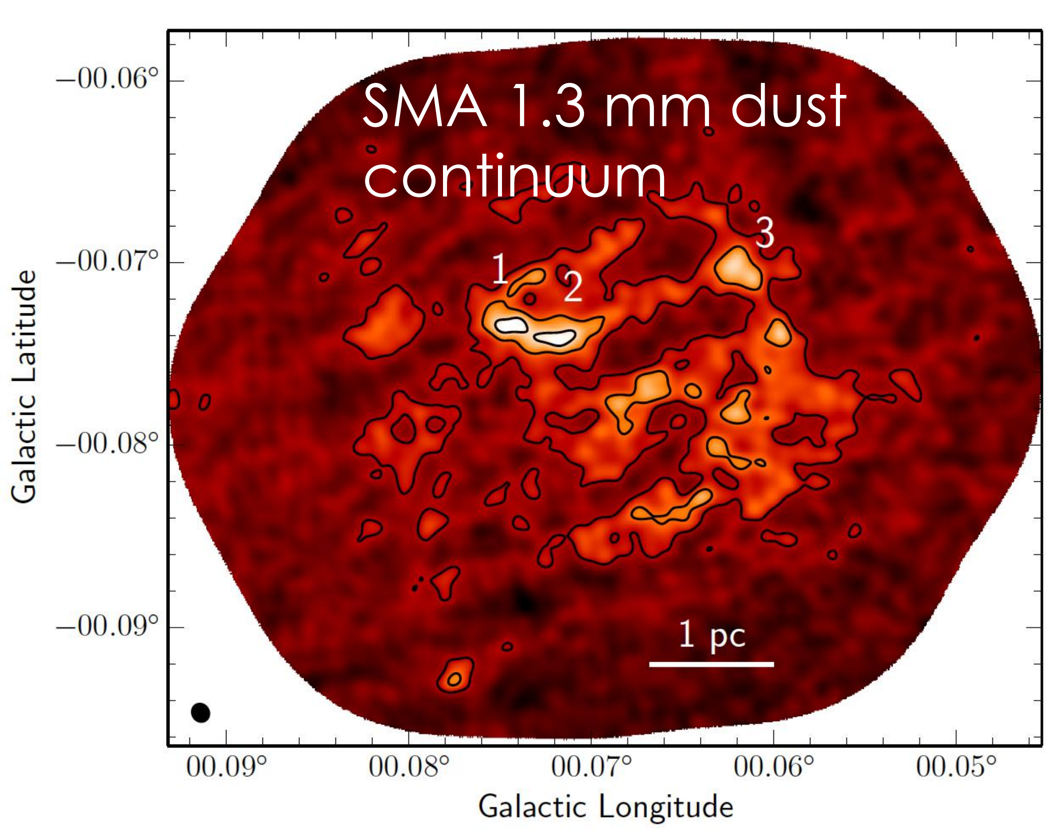


Why is the SFR low in the CMZ?



Structure ID	H_2CO Flux (Jy)	Dust Flux (Jy)	Central Velocity (km/s)	$\Delta\nu_{FWHM}$ (km/s)	M_{dust} ($M_\odot$)	M_{vir} ($M_\odot$)	Virial Ratio (M_{vir}/M_{dust})
0	1.085	4.224	49.66	20.63	7.15E+03	6.22E+04	8.70
1	1.012	4.197	49.34	20.03	7.10E+03	5.85E+04	8.23
2	0.879	3.997	49.36	19.96	6.77E+03	5.70E+04	8.42
3	0.837	3.868	49.54	19.95	6.55E+03	5.59E+04	8.53
4	0.719	3.725	49.43	19.85	6.31E+03	5.41E+04	8.58
5	0.359	1.501	45.46	16.65	2.54E+03	2.36E+04	9.28
6	0.233	0.943	46.03	17.06	1.60E+03	1.90E+04	11.91
7	0.154	0.656	45.17	16.30	1.11E+03	1.46E+04	13.18
8	0.54	2.899	49.28	20.43	4.91E+03	5.03E+04	10.26
9	0.288	1.153	46.09	16.86	1.95E+03	2.11E+04	10.80
10	0.075	0.339	43.52	12.44	5.74E+02	6.05E+03	10.55
11	0.035	0.100	39.86	7.01	1.69E+02	1.27E+03	7.54
12	0.008	0.045	42.00	9.13	7.57E+01	1.11E+03	14.68
13	0.053	0.171	55.23	15.23	2.90E+02	8.20E+03	28.26
14	0.02	0.068	41.35	7.51	1.16E+02	1.20E+03	10.31
15	0.083	0.363	51.82	12.31	6.14E+02	6.64E+03	10.82
16	0.154	0.723	58.80	12.03	1.22E+03	6.94E+03	5.67
17	0.017	0.131	54.87	6.12	2.22E+02	9.80E+02	4.41
18	0.012	0.109	49.58	2.77	1.85E+02	1.85E+02	1.00
19	0.008	0.031	50.85	4.58	5.30E+01	4.37E+02	8.24
20	0.024	0.090	53.91	6.05	1.52E+02	7.76E+02	5.11
21	0.018	0.122	57.90	7.65	2.07E+02	1.87E+03	9.05
22	0.008	0.067	55.09	6.40	1.13E+02	8.48E+02	7.51
23	0.011	0.081	57.67	6.99	1.37E+02	1.13E+03	8.23
24	0.02	0.197	65.77	10.39	3.33E+02	3.16E+03	9.48

Why is the SFR low in the CMZ?

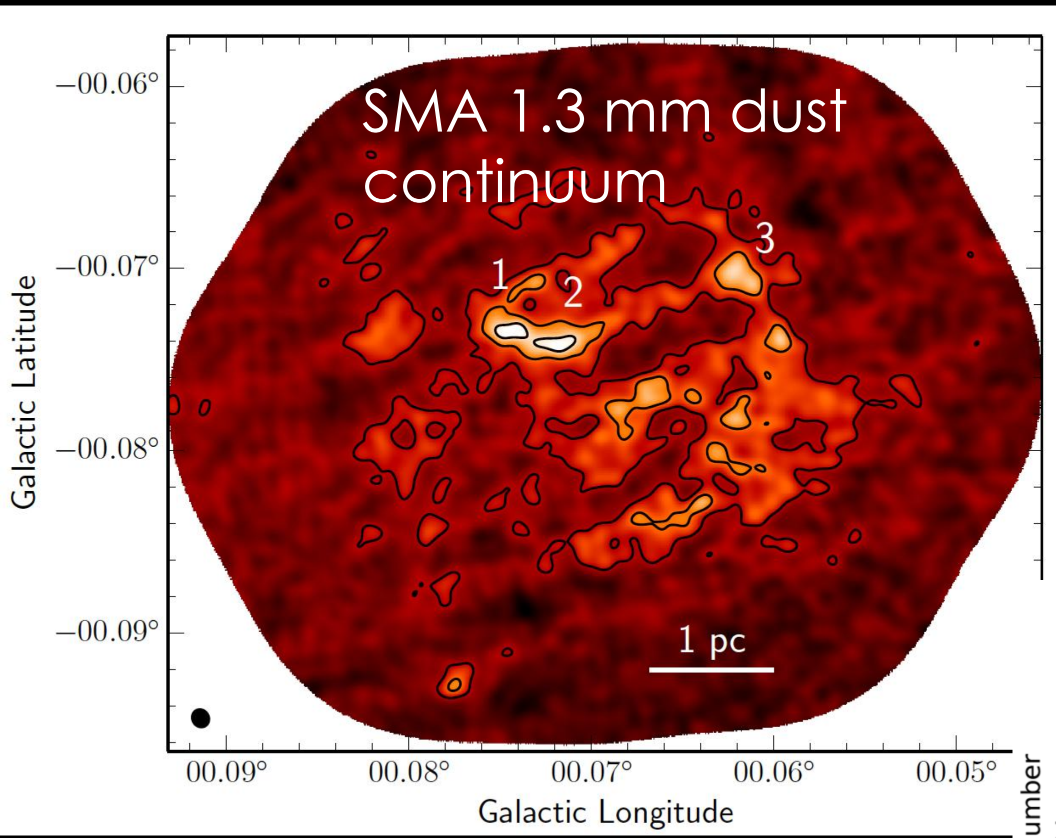


Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- X Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ❑ Outflow or localized hot-core chemistry

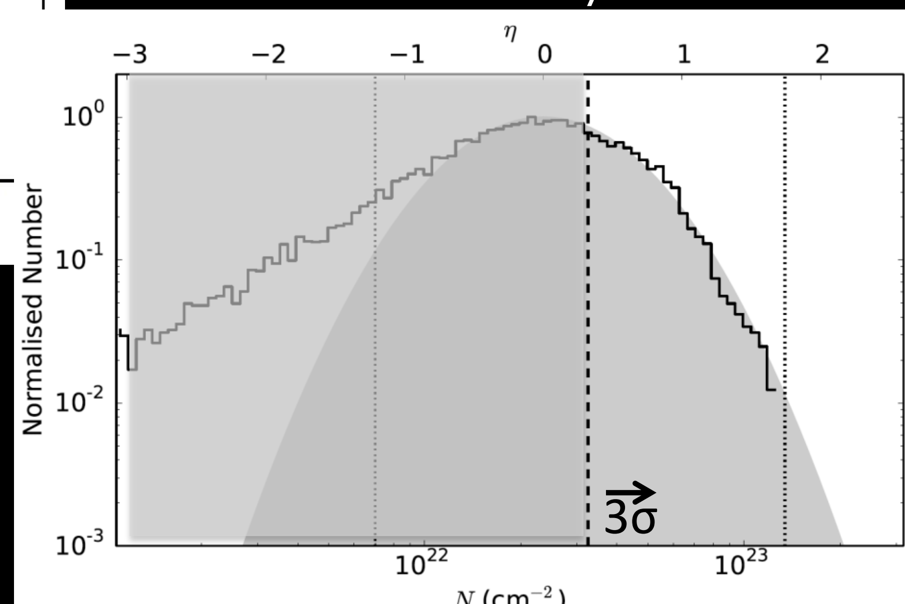
CMZoom

Why is the SFR low in the CMZ?

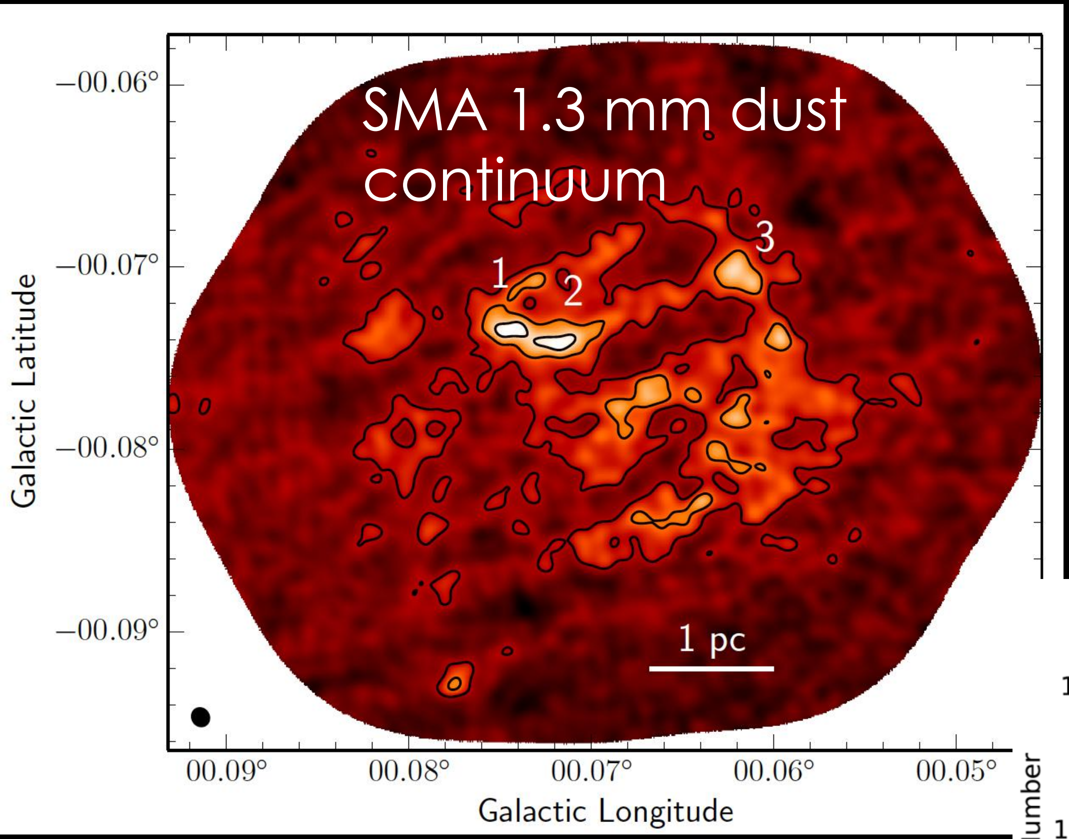


Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- X Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ❑ Outflow or localized hot-core chemistry

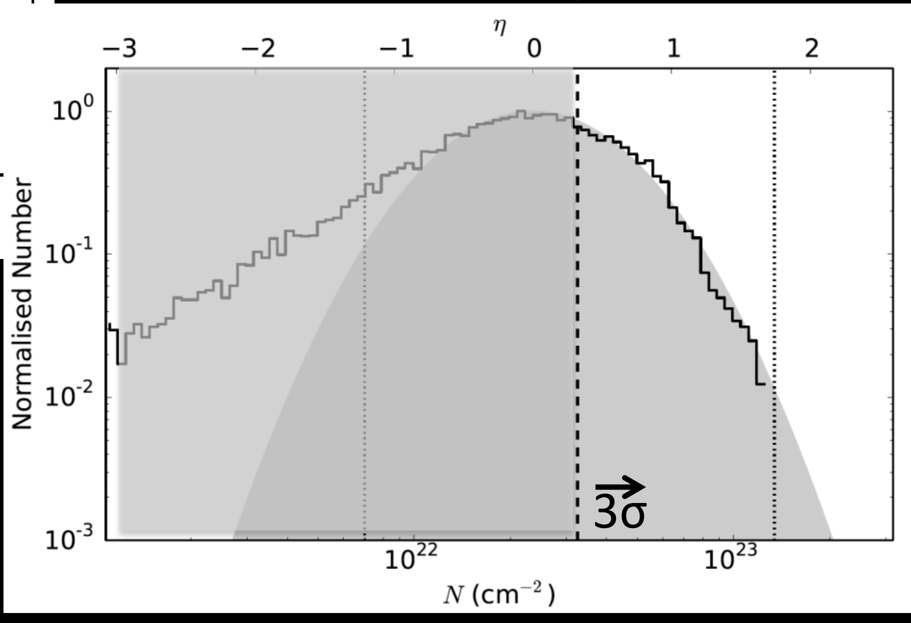


Why is the SFR low in the CMZ?

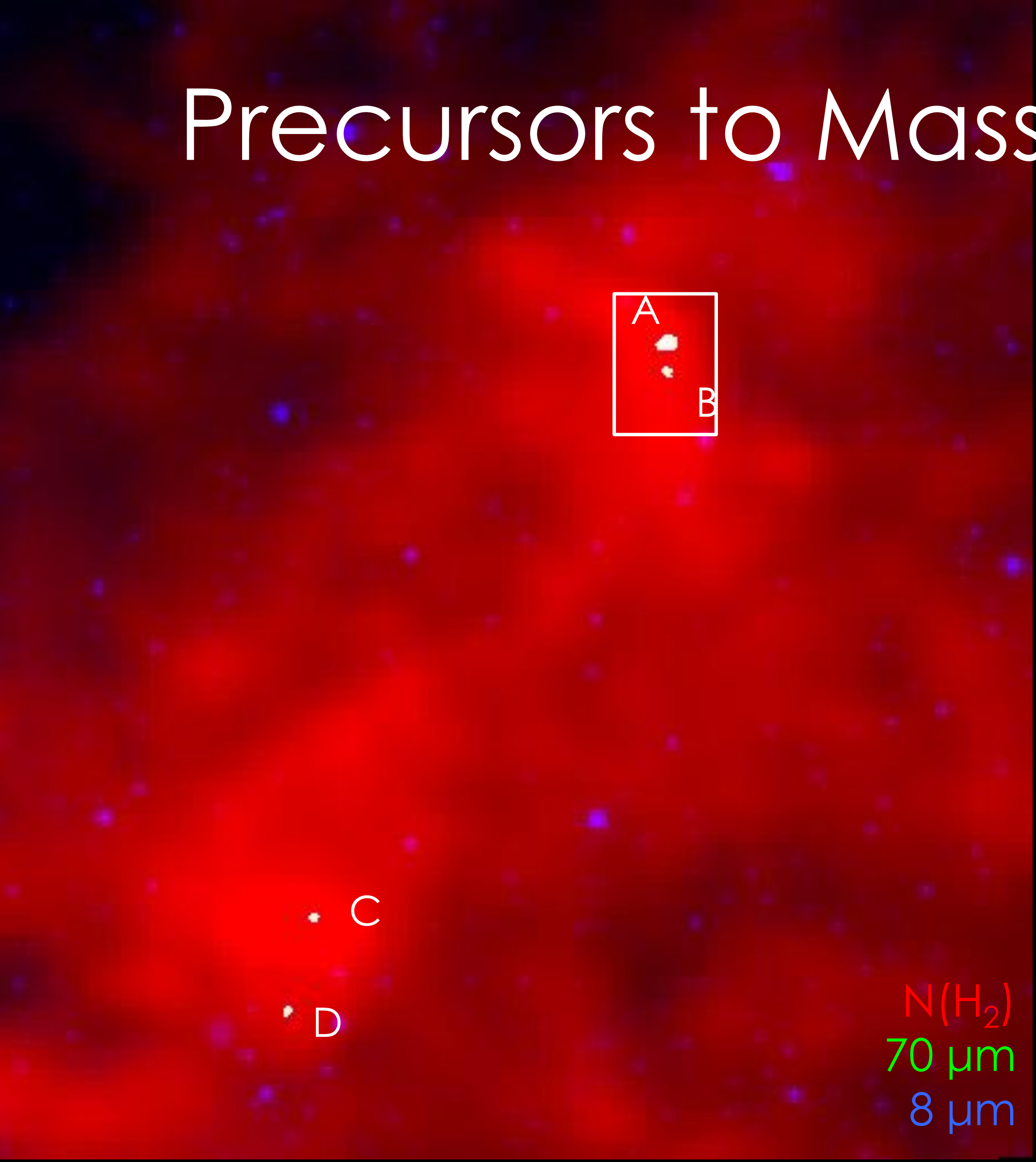


Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- X Virial ratio < 2
- X Power-law tail in N-PDF
- X Outflow or localized hot-core chemistry



Precursors to Massive Stars

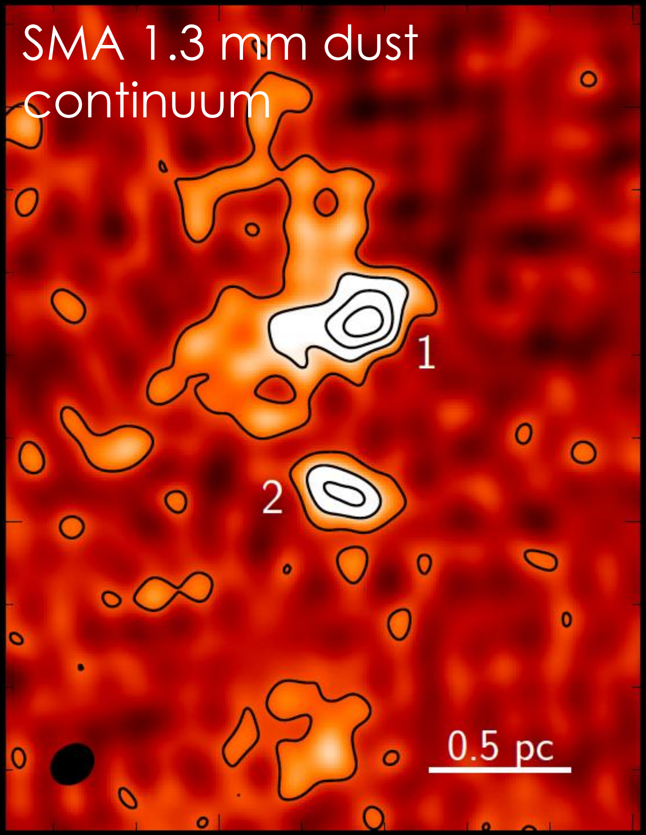


Preliminary Core mass estimates, assuming 20 K

A: 550 $M_\odot$
B: 340 $M_\odot$
C: 140 $M_\odot$
D: 130 $M_\odot$

Battersby, Graham, et al., in prep.

Precursors to Massive Stars

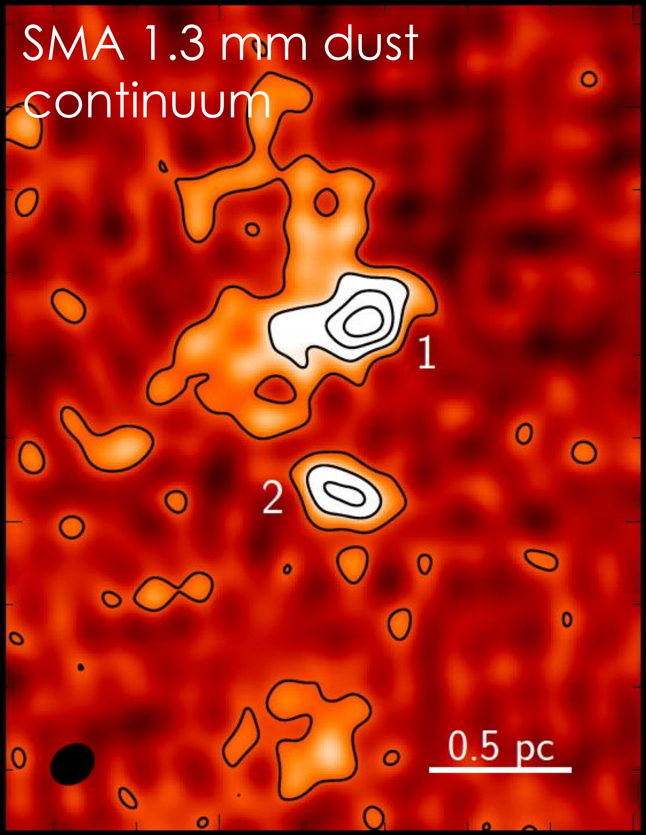


Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- ❑ Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ✓ Outflow or localized hot-core chemistry

Battersby, Graham, et al., in prep.

Precursors to Massive Stars

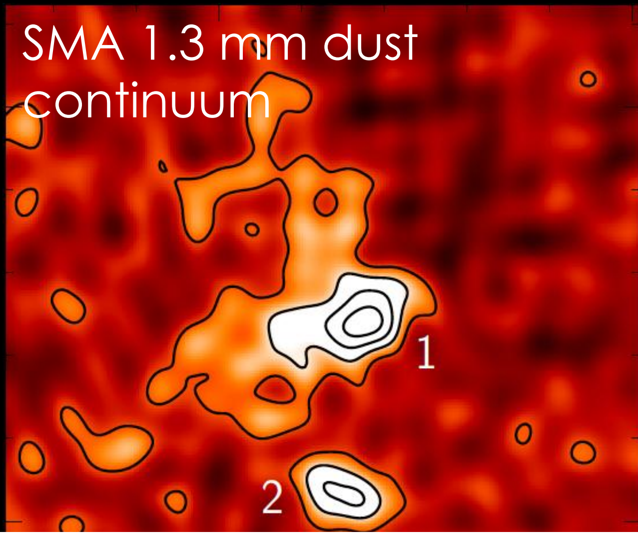


Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- ✓ Virial ratio < 2
- ❑ Power-law tail in N-PDF
- ✓ Outflow or localized hot-core chemistry

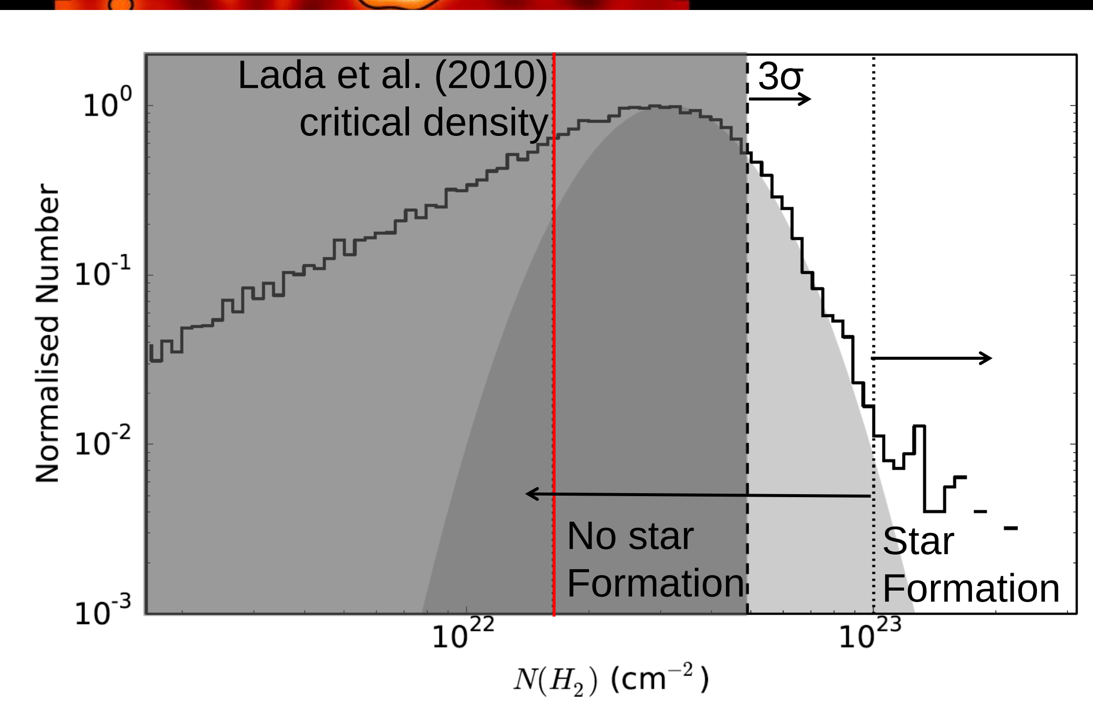
Core	Gas Mass M_{gas} ($M_\odot$)	M_{vir}/M_{gas}	Mean Radius (pc)	Number Density ($\times 10^5$ cm^{-3})	Significance (σ^{-1})	Δv_{H_2CO} (km s^{-1})
1	550	0.9	0.14	7.4	14.5	5.3
2	340	0.4	0.13	5.5	10.5	2.3

Precursors to Massive Stars

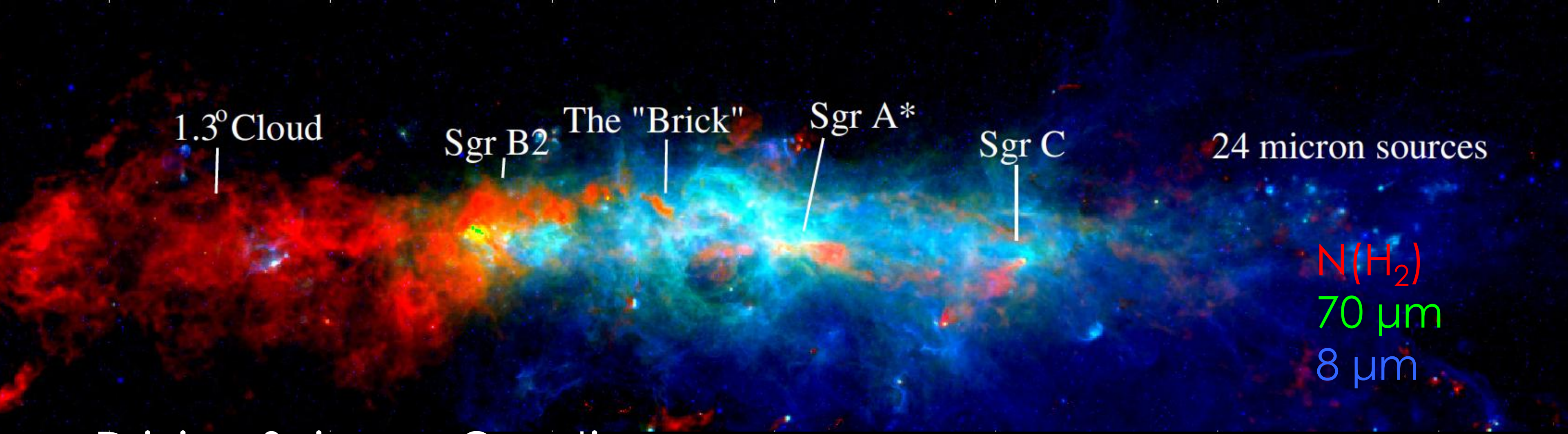


Is it star forming?

- ✓ Dense gas
- ✓ Shocked, highly excited gas
- ✓ Virial ratio < 2
- ✓ Power-law tail in N-PDF
- ✓ Outflow or localized hot-core chemistry



Battersby, Graham, et al., in prep.



Driving Science Questions:

1) What is the cause of the extremely low star formation efficiency (given the reservoir of dense gas) in the CMZ?

   → High levels of turbulence are important

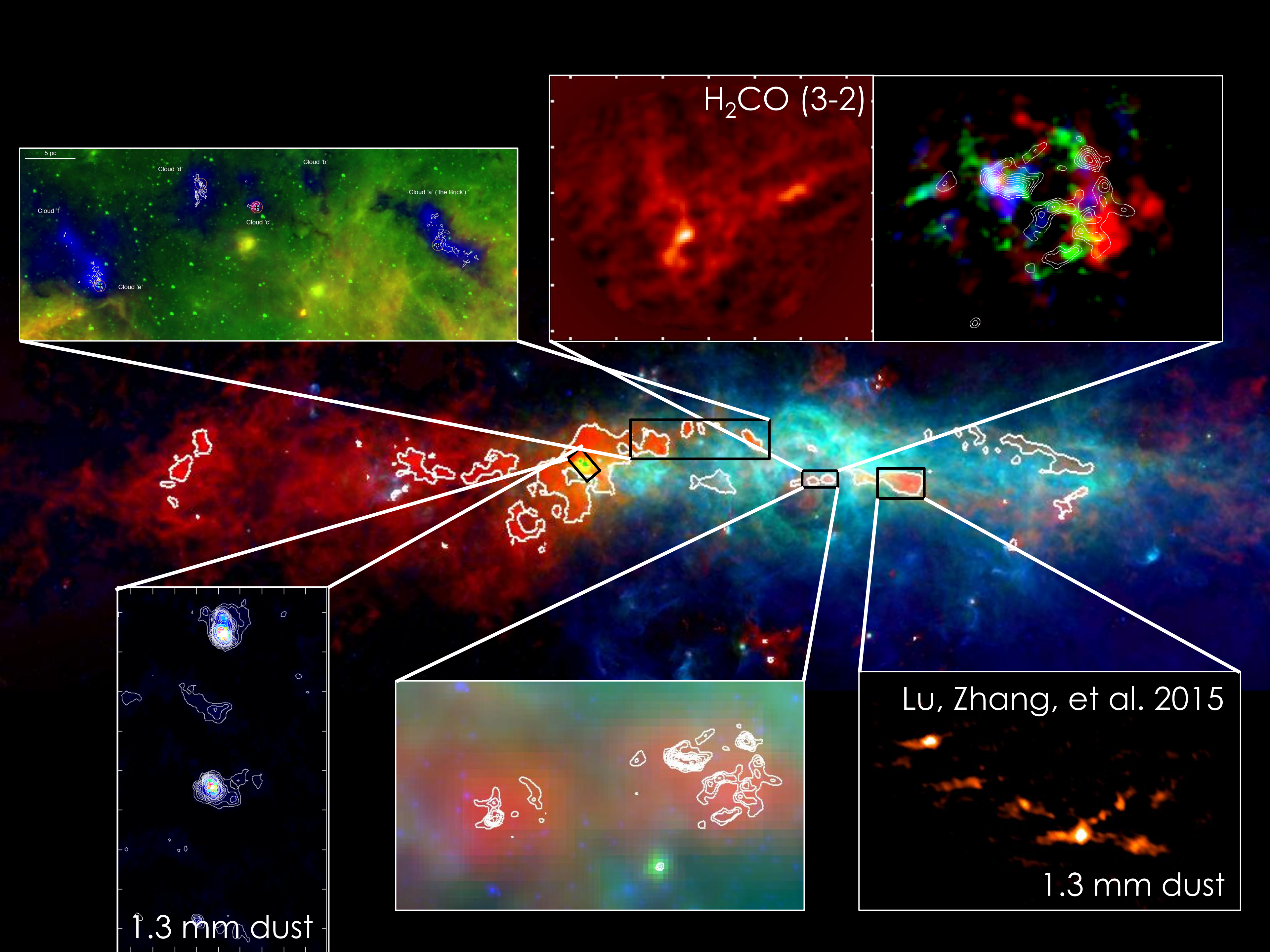
2) Is there an energy and SF cycle in the CMZ? Where does gas enter the CMZ?

3) Is SF induced by tidal compression by SgrA*?

   → Observations are consistent with this scenario

4) Can we find precursors to the most massive stars in the Galaxy?

   → We have some good candidates



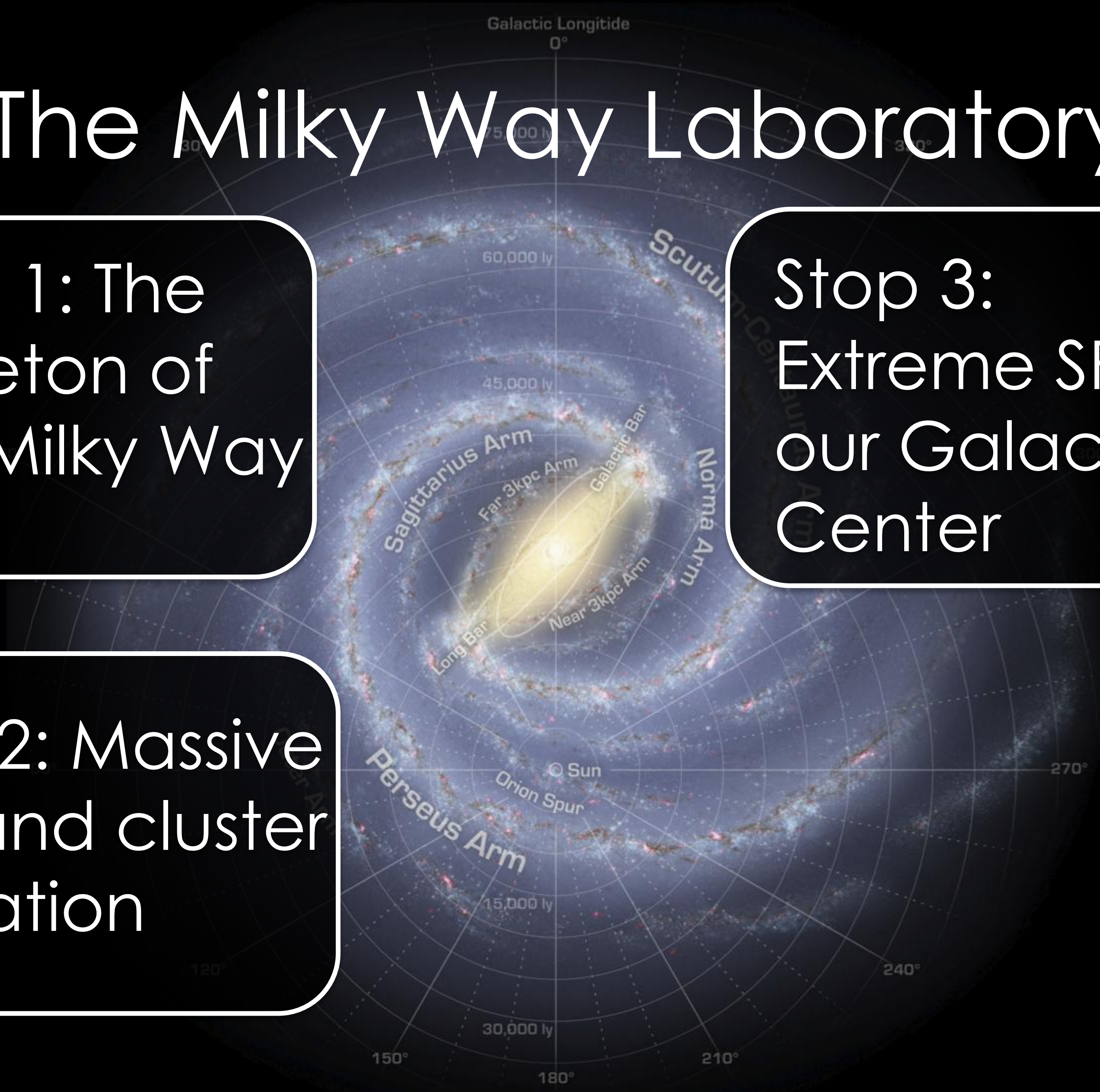
5 pc
Cloud 'd'
Cloud 'b'
Cloud 'a' ('the Brick')
Cloud 'f'
Cloud 'c'
Cloud 'e'
H2CO (3-2)
1.3 mm dust
Lu, Zhang, et al. 2015
1.3 mm dust

The Milky Way Laboratory

Stop 1: The Skeleton of the Milky Way

Stop 3: Extreme SF in our Galactic Center

Stop 2: Massive star and cluster formation



The Milky Way Laboratory

Stop 1: The Skeleton of the Milky Way: We are tracing our Galaxy with long, skinny clouds called the Bones of the Milky Way

Stop 2: Massive star and cluster formation: clusters grow as the stars form!

Stop 3: Extreme SF in our Galactic Center: new, large survey shows turbulence can prevent SF, tidal compression can trigger it, and it can happen where we least expect it.