Star Formation in our Extreme Galactic Center: Results from the CMZoom Survey

Cara Battersby
University of Connecticut

@battersbot
#TracingTheFlow

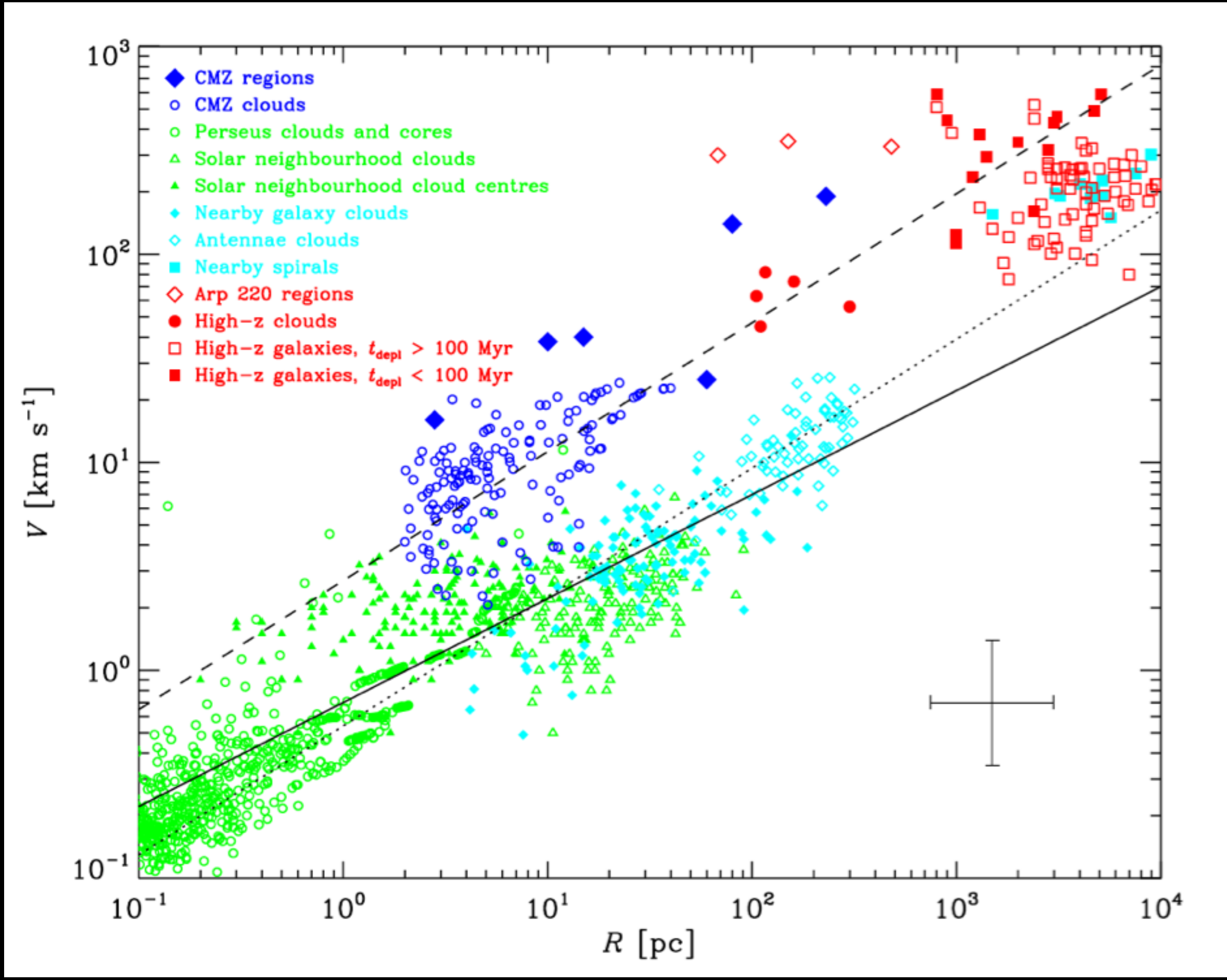
Central Molecular Zone

24 µm (Carey+ 2009.), 8 µm and 4.5 µm (Benjamin+20003)

Central Molecular Zone

$N(H_2)$ (Battersby+ in prep.), 70 μm (Hi-GAL, Molinari+2010,2011), 8 μm (GLIMPSE, Benjamin+20003)

The Central Molecular Zone: A window into the distant universe



Kruijssen & Longmore 2013

Star Formation Rates of the CMZ

Tracer
24 μm IR luminosity
70 μm IR luminosity
Total IR luminosity
YSO counting
free-free emission

About **0.06 - 0.10 M⊙/year**

for a wide variety of methods and tracers

— not underestimating SFR based on one method

[a] Approximately |ℓ|<1° and |b|<0.5°

[b] Contaminated by main-sequence stars (see Koepferl+2015)

Ash Barnes
Liverpool PhD! ~~student~~
ITA Postdoc

Barnes et al. 2017

Star Formation Rates of the CMZ

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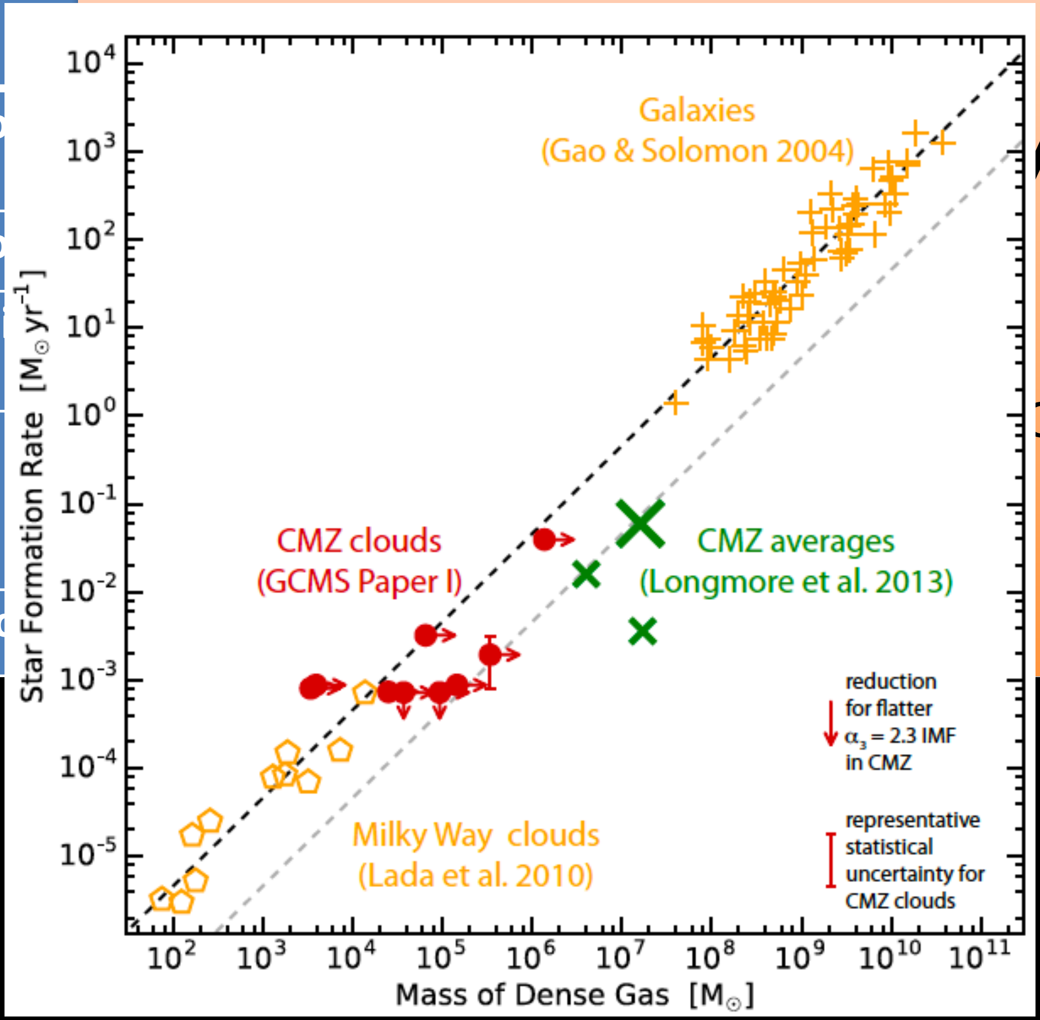
year

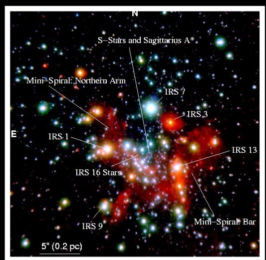
and

ased

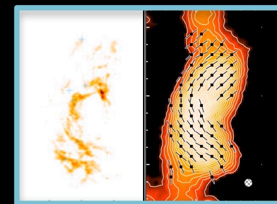


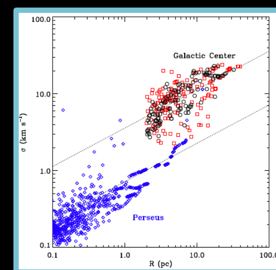
Kauffmann et al. 2016

Star Formation in the CMZ

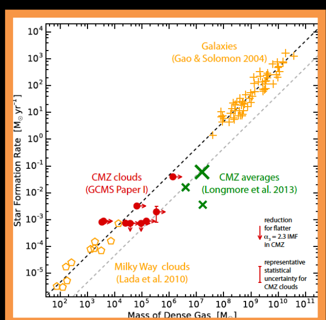


There are many extreme stars and clusters in the CMZ

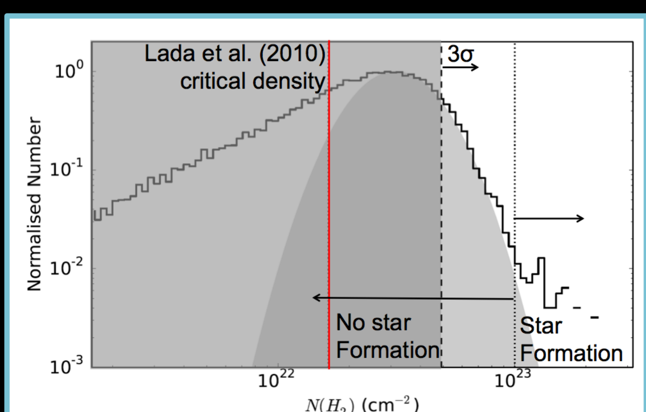




CMZ gas is hot, dense, chemically complex, turbulent, with strong B fields, and the ISRF and CRIR are high → any of these may affect SF



The CMZ is currently underproducing stars by ~10



There is NO universal density threshold for Star Formation — but maybe an environmentally dependent one

***Figures**: ESO/VLT of Young Nuclear Cluster, Brick: Rathborne et al. 2014, Pillai et al. 2015, Dense gas relation: Kauffmann et al. 2016, size-linewidth: Shetty et al. 2012, CMZoom SF threshold: CMZoom in prep.*

SMA Legacy Survey of the Central Molecular Zone

- Large primary beam + wide bandwidth + long wavelength + high angular resolution → detect early star formation across a large area
- First survey of the CMZ ever to be able to do so

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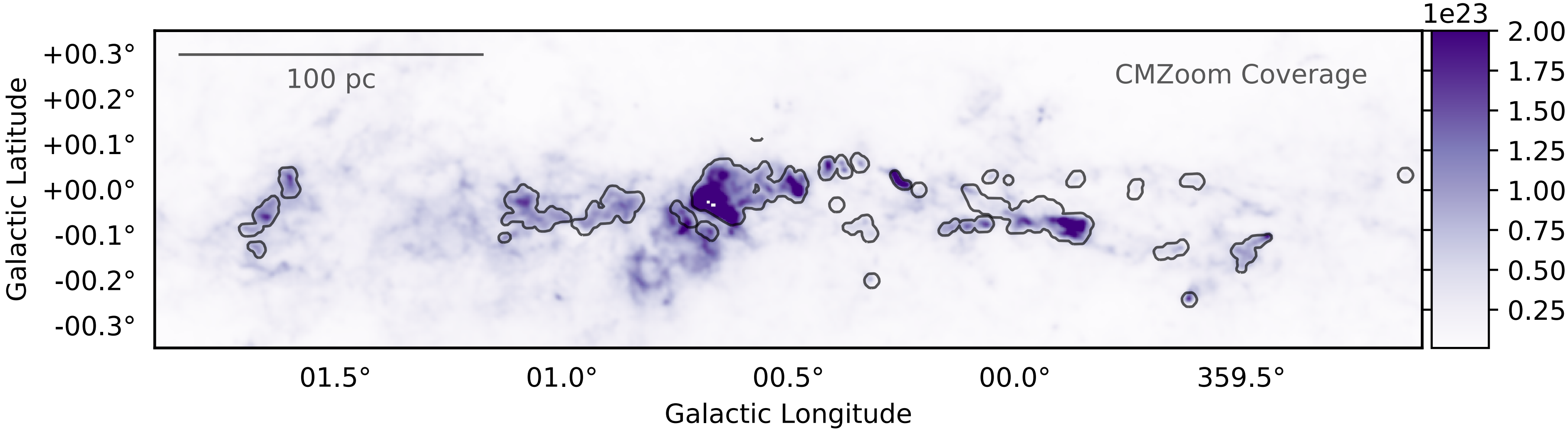
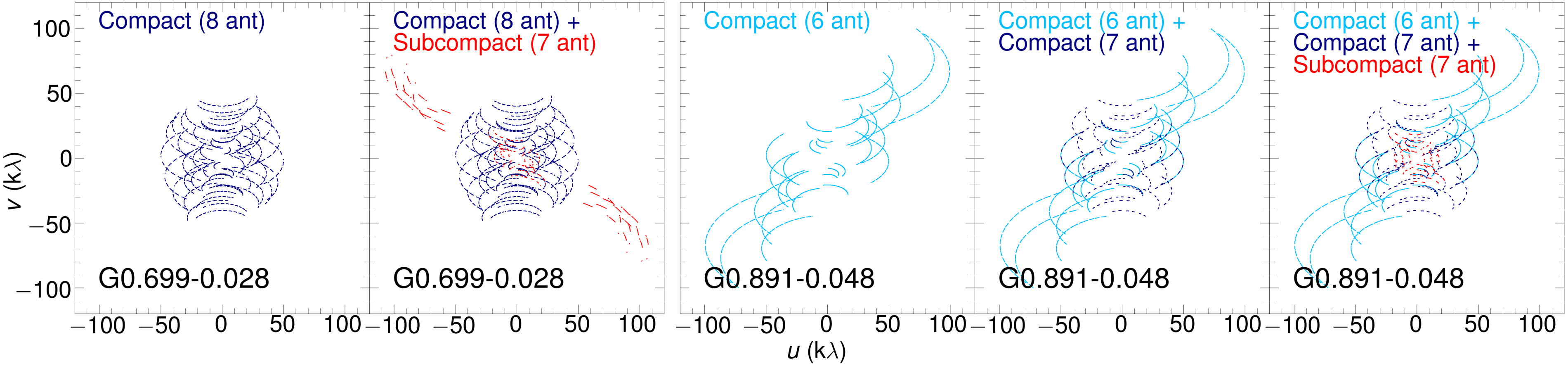
CMZoom



- 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
- 550 hours (50 subcompact, 450 compact/custom) over 4 yrs
- Complement with single-dish (APEX, CSO) observations

Survey overview: Battersby et al. in prep.

CMZoom



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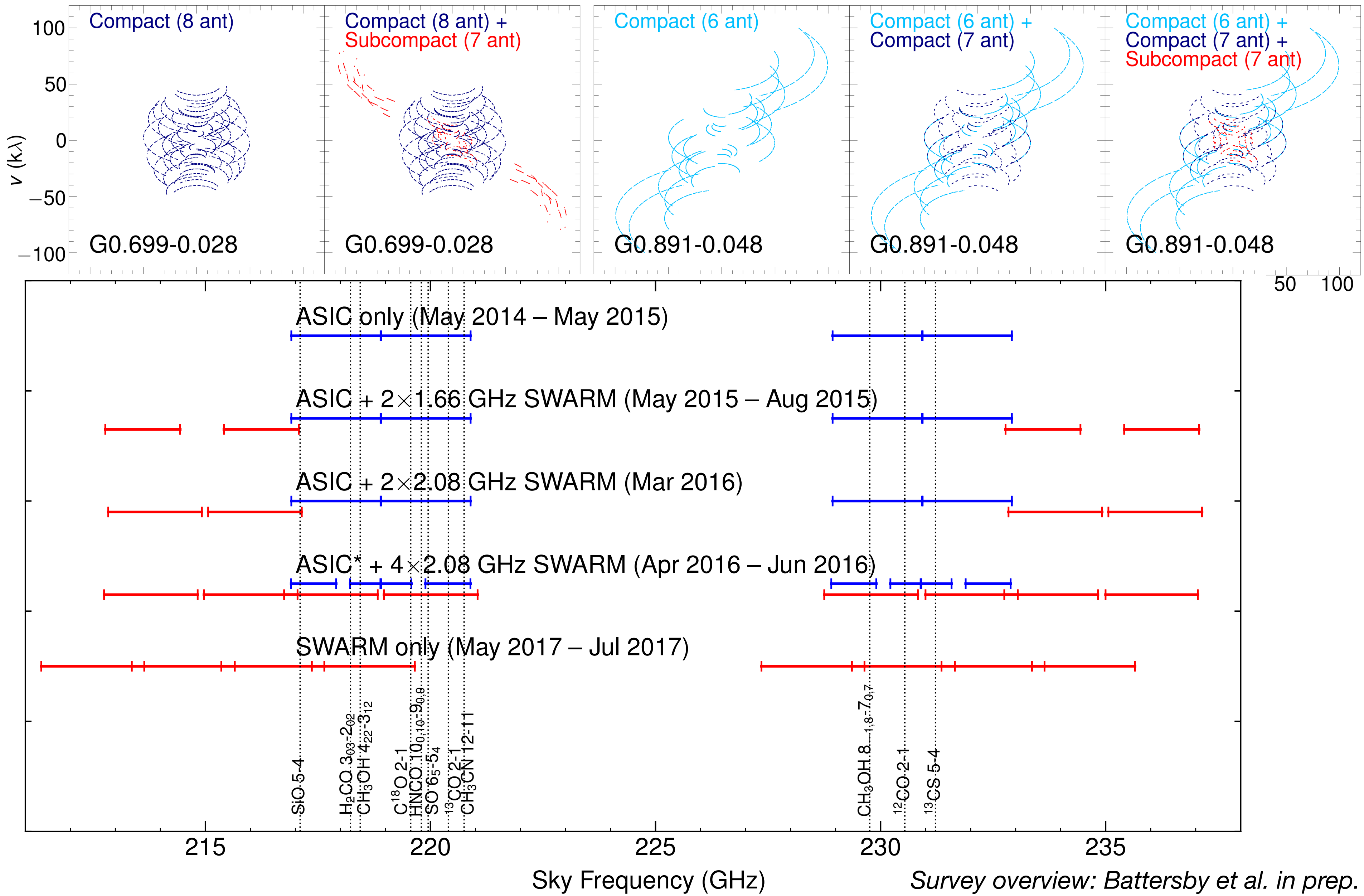

Survey overview: Battersby et al. in prep.

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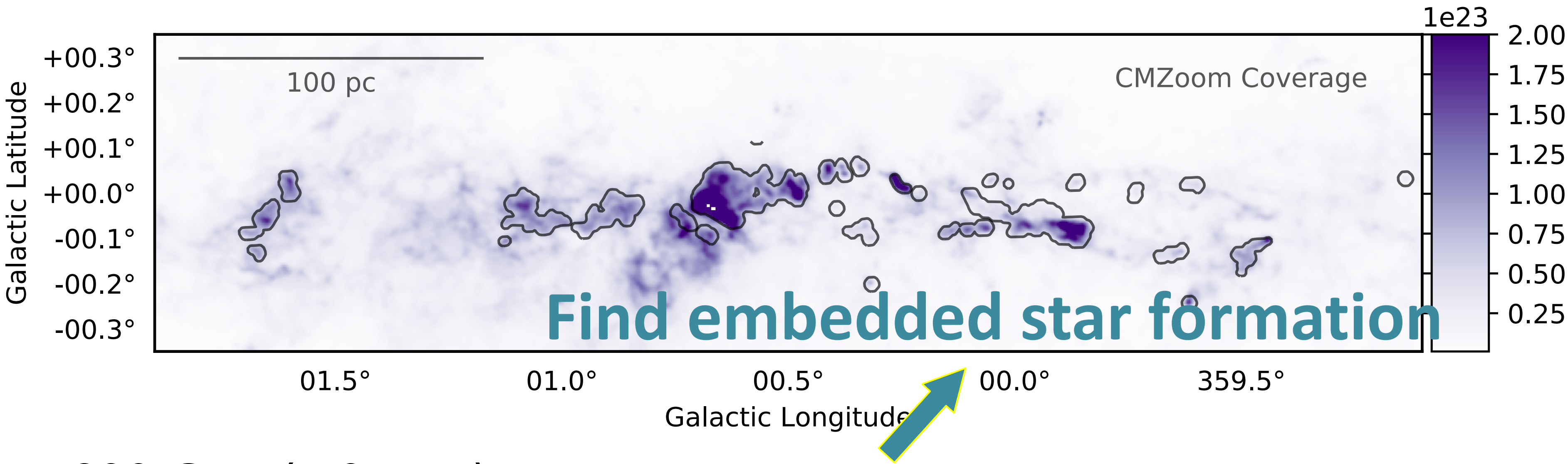

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Survey overview: Battersby et al. in prep.

CMZoom

Team:

CfA: Cara Battersby, Eric Keto, Qizhou Zhang, Xing 'Walker' Lu (NAOJ), Mark Graham (Oxford), Nimesh Patel, Volker Tolls, Dennis Lee, Jimmy Castaño, Liz Gehret, Irene Vargas-Salzar, Perry Hatchfield, Daniel Callanan, Elizabeth Gutierrez

Bonn: Jens Kauffmann, Thushara Pillai

Liverpool: Steve Longmore, Daniel Walker (CfA), Jonny Henshaw

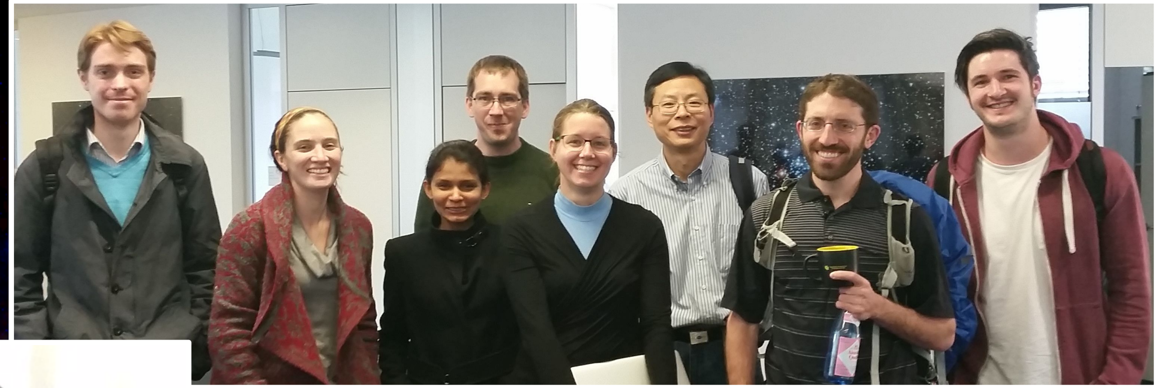
University of Colorado, Boulder: John Bally

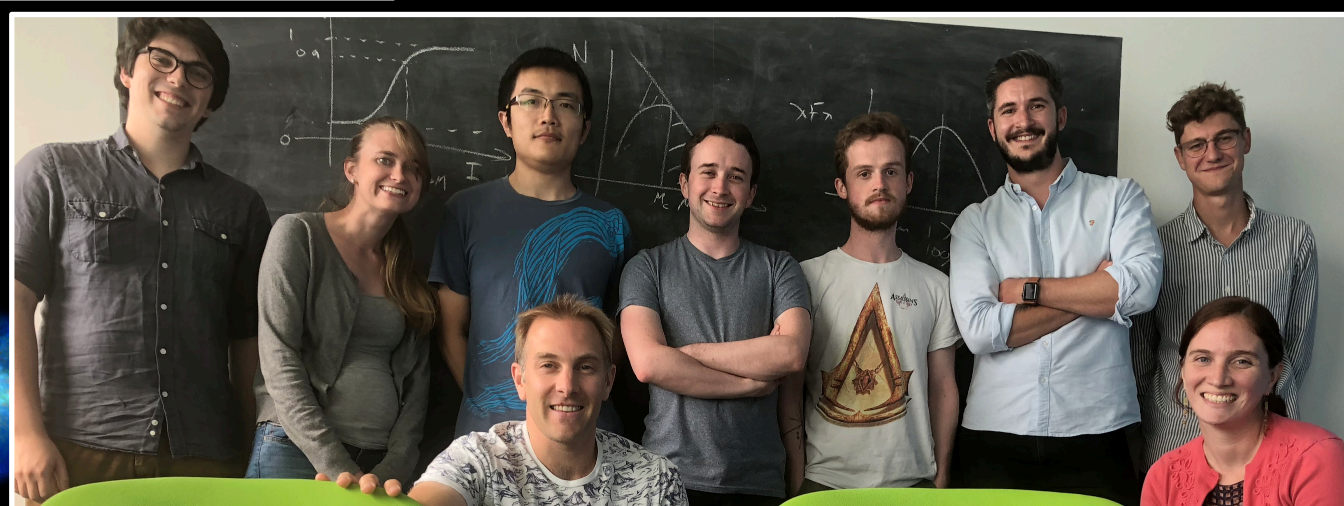
Heidelberg: Diederik Kruijssen, Ash Barnes NRAO: Betsy Mills, Natalie Butterfield ESO: Adam Ginsburg, Katharina Immer, Leeds: Katharine Johnston

Peking University: Luis C. Ho, Perth: Andrew Walsh

CMZoom

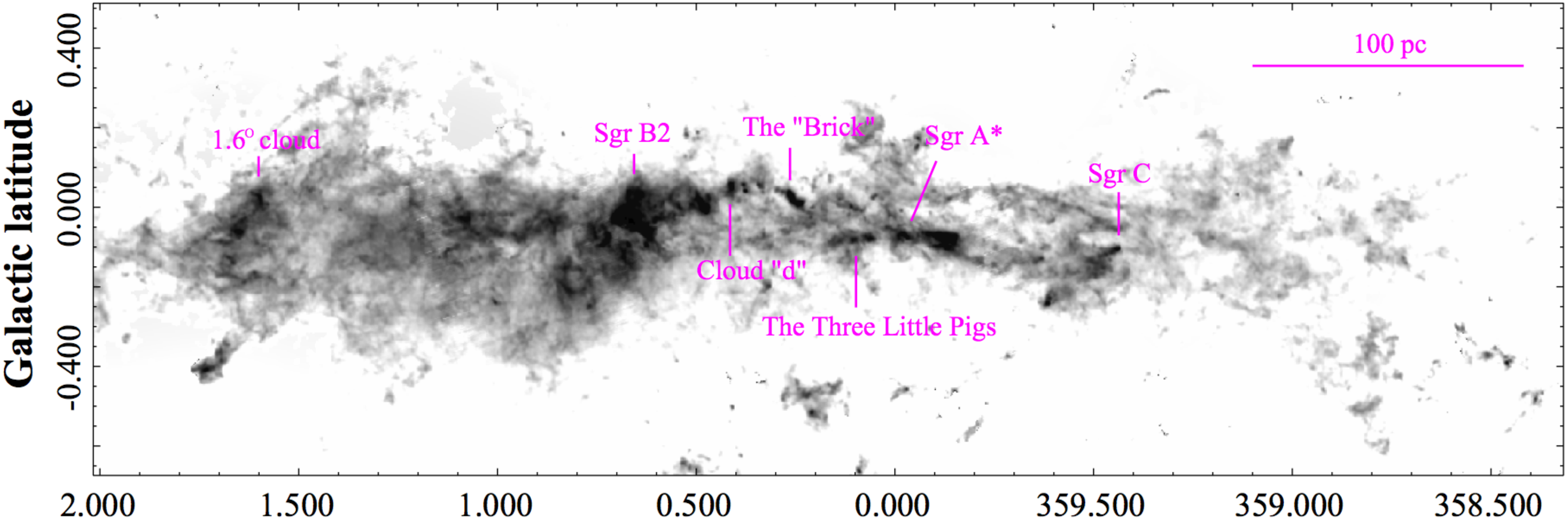
Team

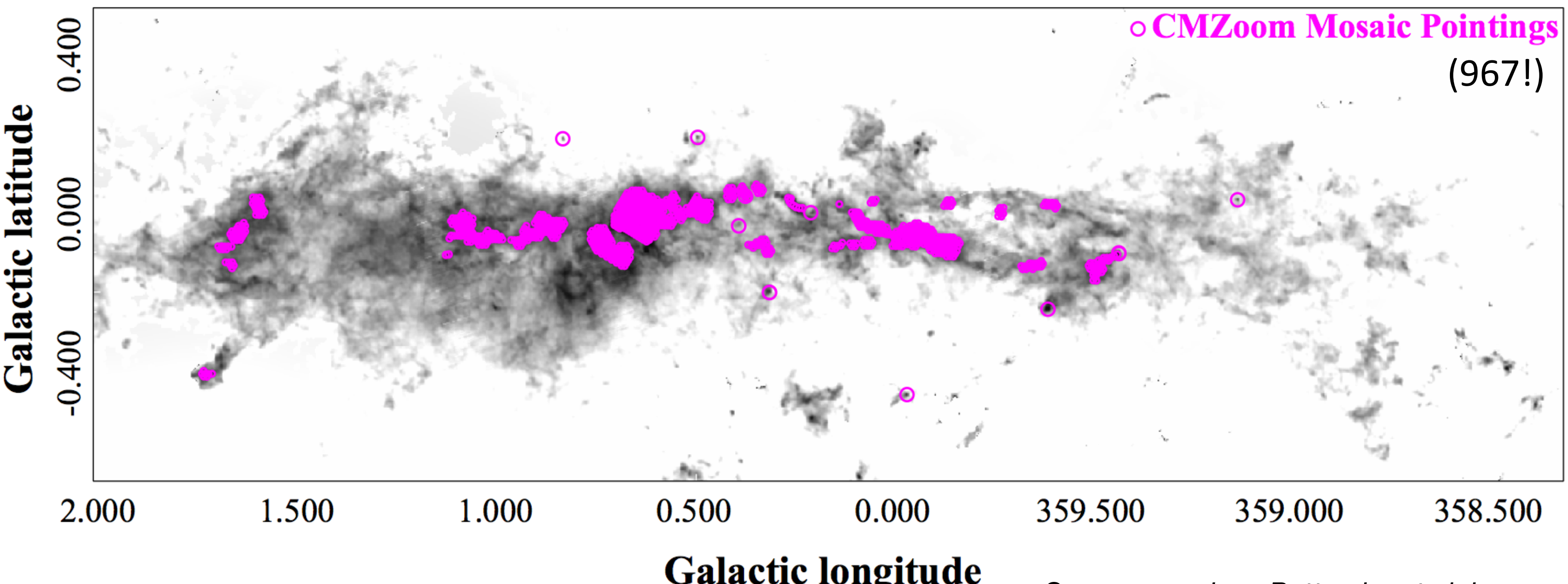




Next Generation CMZoomers

The Milky Way Laboratory at UConn
Battersby Research Group Fall 2017





Survey overview: Battersby et al. in prep.

Track Number	Observation Date	# of Antennas	Array Config.
KJ2012*	6/09/2012	7	compact
Pilot1*	5/21/2013	5	subcompact
Pilot2*	8/23/2013	5	subcompact
Pilot3*	7/24/2013	6	compact
	8/3/2013	5	compact
	8/9/2013	5	compact
Pilot4*	7/25/2013	6	compact
Pilot5*	8/1/2013	6	compact
	8/2/2013	6	compact
Pilot6*	3/10/2014	7	subcompact
	3/21/2014	7	subcompact
1	5/25/2014	7	compact-1
2	5/24/2014	7	compact-1
3	5/30/2014	7	compact-1
4	6/02/2014	7	compact-1
5	6/04/2014	7	compact-1
6	6/07/2014	8	compact-1
7	6/10/2014	8	compact-1
8	6/13/2014	8	compact-1
9	6/14/2014	8	compact-1
10	6/15/2014	7	compact-1
	6/20/2014	7	compact-1
11	6/16/2014	7	compact-1
12	6/22/2014	8	compact-1
	7/15/2017[a]	8	compact-6
13	6/24/2014	8	compact-1
14	6/27/2014	8	compact-1
	5/30/2016[b]	7	compact-5
15	7/09/2014	8	compact-1
16	7/10/2014	8	compact-1
	4/14/2015	7	compact-2
17	4/16/2015	7	compact-2
	5/3/2016[b]	7	compact-5
	7/15/2017[a]	8	compact-6
18	5/09/2015	6	compact-2
	5/3/2016[b]	7	compact-5
19	5/10/2015	6	compact-2
	5/4/2016[c]	7	compact-5
	7/31/2017[d]	8	compact-6
20	5/11/2015	6	compact-2
	5/4/2016[c]	7	compact-5
	7/31/2017[d]	8	compact-6
21	7/25/2014	7	subcompact
22	7/27/2014	7	subcompact
23	7/28/2014	7	subcompact
24	7/29/2014	7	subcompact
25	8/04/2014	7	subcompact

Track Number	Observation Date	# of Antennas	Array Config.
26	5/22/2015	7	compact-2
	5/30/2016[b]	7	compact-5
27	5/23/2015	7	compact-2
	6/1/2016[e]	7	compact-5
28	5/24/2015	7	compact-2
	6/1/2016[e]	7	compact-5
29	5/26/2015	7	compact-2
	6/4/2016[f]	7	compact-5
30	6/02/2015	7	compact-2
	6/4/2016[f]	7	compact-5
31	3/25/2016	8	compact-4
32	7/10/2015	6	compact-3
	3/16/2016	7	compact-4
33	7/22/2015	6	compact-3
	3/29/2016	8	compact-4
34	6/05/2015	6	subcompact
35	6/07/2015	7	subcompact
36	6/06/2015	7	subcompact
37	6/09/2015	7	subcompact
38	6/10/2015	7	subcompact
39	6/13/2015	7	subcompact
40	6/15/2015	7	subcompact
41	6/17/2015	6	subcompact
42	6/18/2015	7	subcompact
43	6/22/2015	7	subcompact
44	5/31/2017	7	subcompact
45	7/23/2015	6	compact-3
	3/28/2016	8	compact-4
46	7/27/2015	6	compact-3
	4/30/2016	7	compact-5
47	7/28/2015	6	compact-3
	5/01/2016	7	compact-5
48	5/07/2016	7	compact-5
49	5/02/2016	7	compact-5
50	5/08/2016	7	compact-5
51	5/10/2016	6	compact-5
52	5/14/2016	7	compact-5
	5/17/2016	7	compact-5
53	5/28/2016	7	compact-5
54	5/29/2016	7	compact-5
55	5/21/2016	7	compact-5
56	5/22/2016	7	compact-5
57	5/23/2016	7	compact-5
58	6/5/2016	7	compact-5
59	6/07/2016	7	compact-5
60	6/11/2016	7	compact-5
61	6/17/2016	8	compact-5

Track Number	Observation Date	# of Antennas	Array Config.
KJ2012[*]	6/09/2012	7	compact
Pilot1[*]	5/21/2013	5	subcompact
Pilot2[*]	8/23/2013	5	subcompact
Pilot3[*]	7/24/2013	6	compact
	8/3/2013	5	compact
	8/9/2013	5	compact
Pilot4[*]	7/25/2013	6	compact
Pilot5[*]	8/1/2013	6	compact
	8/2/2013	6	compact
Pilot6[*]	3/10/2014	7	subcompact
	3/21/2014	7	subcompact
1	5/25/2014	7	compact-1
2	5/24/2014	7	compact-1
3	5/30/2014	7	compact-1
4	6/02/2014	7	compact-1
5	6/04/2014	7	compact-1
6	6/07/2014	8	compact-1
7	6/10/2014	8	compact-1
8	6/13/2014	8	compact-1
9	6/14/2014	8	compact-1
10	6/15/2014	7	compact-1
	6/20/2014	7	compact-1
11	6/16/2014	7	compact-1
12	6/22/2014	8	compact-1
	7/15/2017[a]	8	compact-6
13	6/24/2014	8	compact-1
14	6/27/2014	8	compact-1
	5/30/2016[b]	7	compact-5
15	7/09/2014	8	compact-1
16	7/10/2014	8	compact-1
	4/14/2015	7	compact-2
17	4/16/2015	7	compact-2
	5/3/2016[b]	7	compact-5
	7/15/2017[a]	8	compact-6
18	5/09/2015	6	compact-2
	5/3/2016[b]	7	compact-5
19	5/10/2015	6	compact-2
	5/4/2016[c]	7	compact-5
	7/31/2017[d]	8	compact-6
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21	7/25/2014	7	subcompact
22	7/27/2014	7	subcompact
23	7/28/2014	7	subcompact
24	7/29/2014	7	subcompact
25	8/04/2014	7	subcompact
26	5/22/2015	7	compact-2
	5/30/2016[b]	7	compact-5
27	5/23/2015	7	compact-2
	6/1/2016[e]	7	compact-5
28	5/24/2015	7	compact-2
	6/1/2016[e]	7	compact-5
29	5/26/2015	7	compact-2
	6/4/2016[f]	7	compact-5
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	6/4/2016[f]	7	compact-5
31	3/25/2016	8	compact-4
32	7/10/2015	6	compact-3
	3/16/2016	7	compact-4
33	7/22/2015	6	compact-3
	3/29/2016	8	compact-4
34	6/05/2015	6	subcompact
35	6/07/2015	7	subcompact
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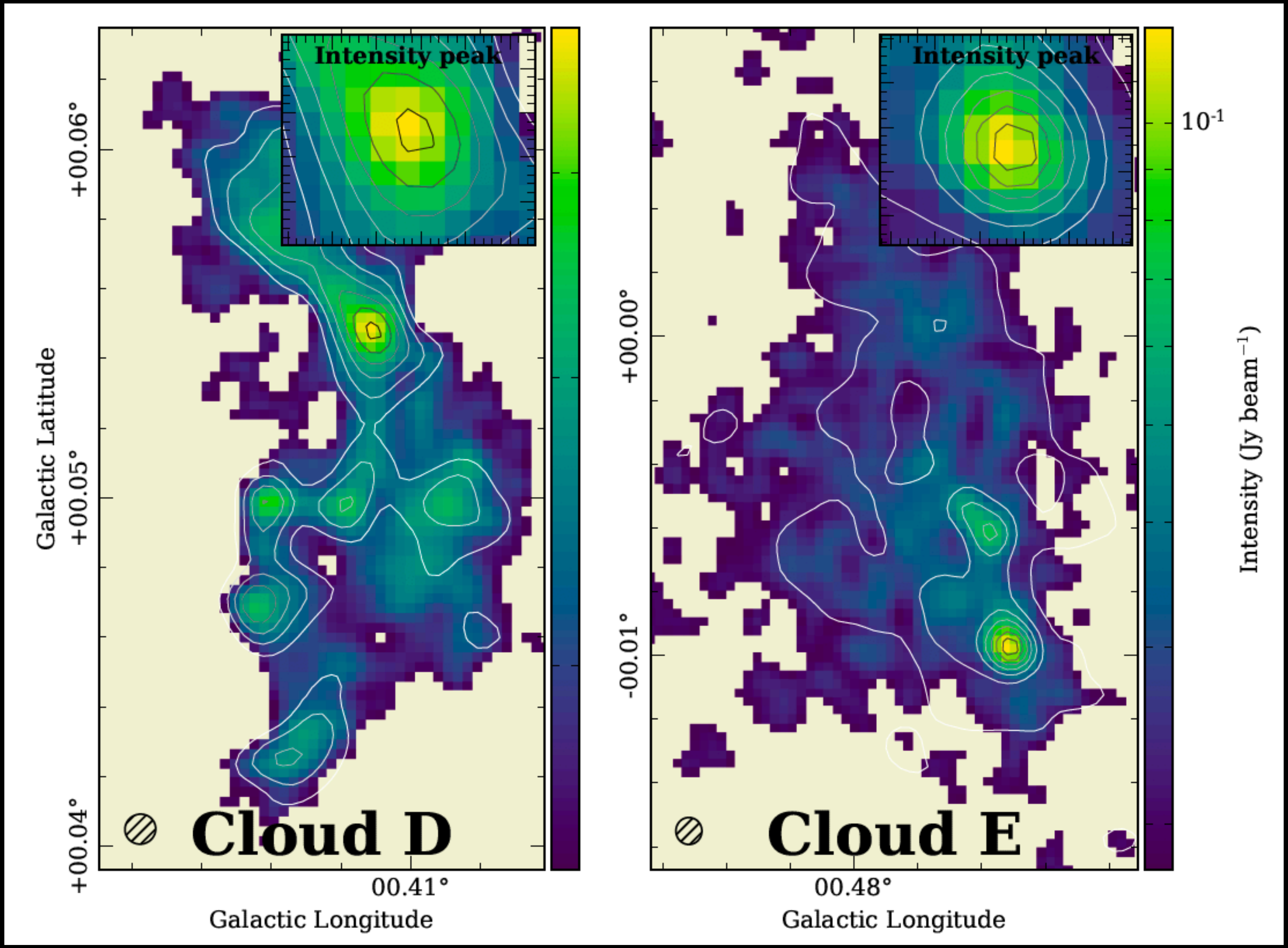
38	6/10/2015	7	subcompact
39	6/13/2015	7	subcompact
40	6/15/2015	7	subcompact
41	6/17/2015	6	subcompact
42	6/18/2015	7	subcompact
43	6/22/2015	7	subcompact
44	5/31/2017	7	subcompact
45	7/23/2015	6	compact-3
	3/28/2016	8	compact-4
46	7/27/2015	6	compact-3
	4/30/2016	7	compact-5
47	7/28/2015	6	compact-3
	5/01/2016	7	compact-5
48	5/07/2016	7	compact-5
49	5/02/2016	7	compact-5
50	5/08/2016	7	compact-5
51	5/10/2016	6	compact-5
52	5/14/2016	7	compact-5
	5/17/2016	7	compact-5
53	5/28/2016	7	compact-5
54	5/29/2016	7	compact-5
55	5/21/2016	7	compact-5
56	5/22/2016	7	compact-5
57	5/23/2016	7	compact-5
58	6/5/2016	7	compact-5
59	6/07/2016	7	compact-5
60	6/11/2016	7	compact-5
61	6/17/2016	8	compact-5

Region Name and Location	Colloquiual Name	Track Numbers	# of Pointings
G0.326-0.085	(far-side candidate)	1, 21	20
G0.340+0.055	Dust Ridge: Cloud b	2, 21	9
G0.380+0.050	Dust Ridge: Cloud c	2, 21	9
G0.412+0.052	Dust Ridge: Cloud d	3, 21	13
G0.489+0.010	Dust Ridge: Clouds e/f or Sgr B1-off	3, 4, 5, 21, 22	44
–	Dust Ridge: Clouds e/f or Sgr B1-off	Pilot2, Pilot5	6
G359.734+0.002	(far-side candidate)	6, 22	8
G359.611+0.018	(far-side candidate)	6, 22	10
G0.699-0.028[a]	SgrB2	7, 8, 9	74
G1.602+0.018	1.6° cloud	10, 23	21
G1.651-0.050	1.6° cloud	11, 23	24
G1.737-0.406	1.1° cloud	12, 23	7
G359.615-0.243	(isolated massive SF candidate)	12, 23	7
G0.212-0.001	(isolated massive SF candidate)	12, 23	7
G0.316-0.201	(isolated massive SF candidate)	13, 24	7
G0.376+0.040	(isolated massive SF candidate)	13, 24	7
G0.393-0.034	(isolated massive SF candidate)	13, 24	7
G0.068-0.075	Three Little Pigs: Stone Cloud	14, 24	10
G0.106-0.082	Three Little Pigs: Sticks Cloud	14, 24	5
G0.145-0.086	Three Little Pigs: Straw Cloud	14, 24	6
G1.085-0.027	1.1° cloud	15, 16, 24, 37	34
G0.891-0.048	1.1° cloud	17, 18, 19, 20, 34, 35	82
G359.863-0.069	20 km s^{-1} cloud	26, 38	18
G359.889-0.093	20 km s^{-1} cloud	27, 28, 36	49
–	20 km s^{-1} Cloud	Pilot1, Pilot3	8
G0.001-0.058	50 km s^{-1} Cloud	29, 35	24
–	50 km s^{-1} Cloud	Pilot2, Pilot4	4
G359.865+0.022	(far-side candidate)	30, 37	8
G359.648-0.133	(bridge from SgrC to 20kms cloud)	30, 38	16
G359.484-0.132	SgrC	31, 32, 38	28
–	SgrC	Pilot1, Pilot4	3
G0.253+0.016	Brick	KJ2012, Pilot6	6
G0.070-0.035	(h2co bridge from sgra to dust ridge)	32, 33, 37	39
G0.619+0.012	SgrB2 NW	39, 40, 41, 45, 46, 47, 48, 49, 50, 51, 52	175
G0.014+0.021	Arches e1	43, 52	1
G0.054+0.027	Arches w1	43, 57	4
G1.68-0.09	1.6° cloud	41, 53	8
G1.67-0.13	1.6° cloud	41, 53	6
G1.038-0.074	1.1° cloud	42, 53, 54, 55	46
G359.948-0.052	Circumnuclear Disk	42, 43, 55, 56, 57	40
G0.714-0.100	SgrB2 extended	43, 44, 57, 58, 59, 60, 61	94

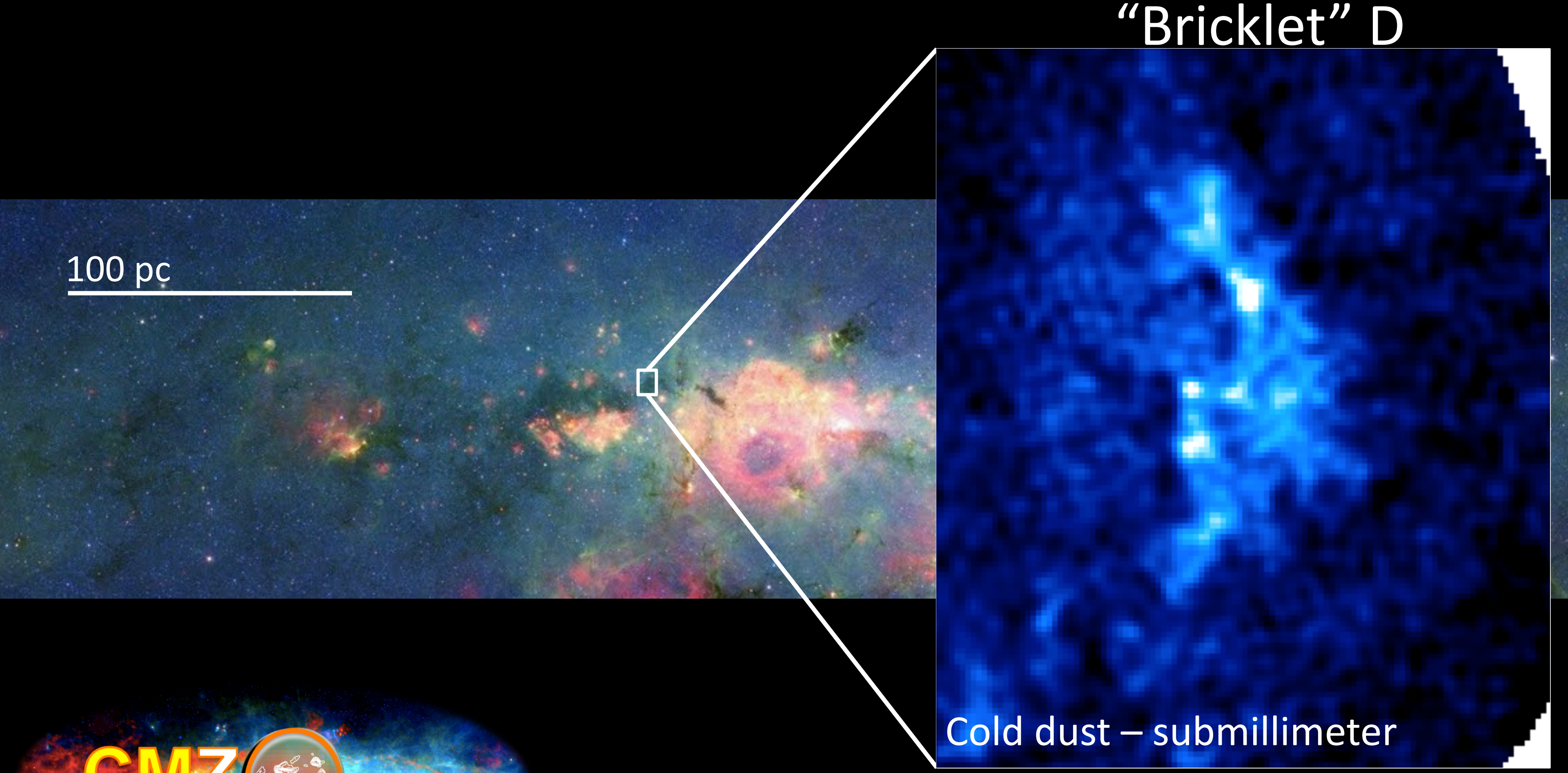
CMZoom



Pointing comparison -
SMA color scale, smoothed ALMA data as contours

Survey overview: Battersby et al. in prep.

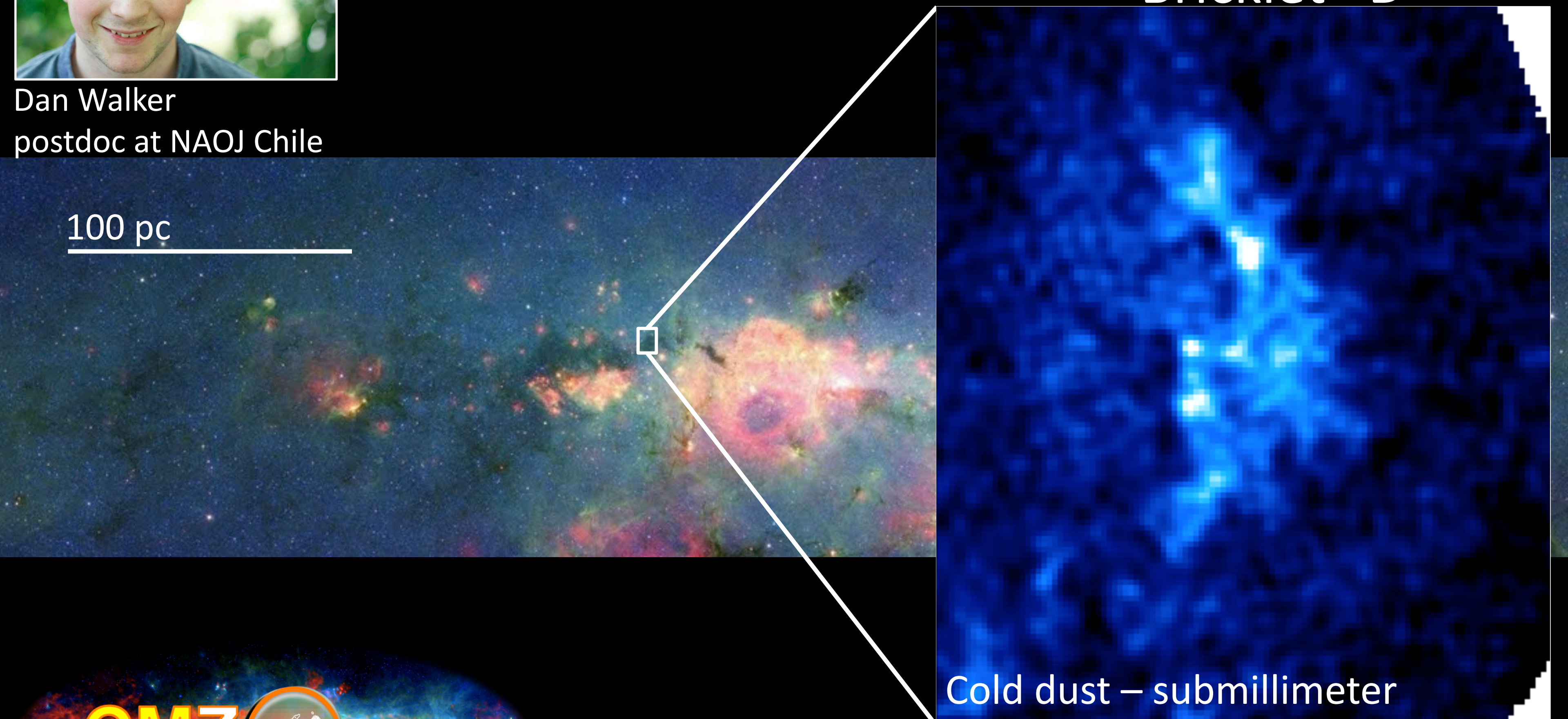
Central Molecular Zone



Central Molecular Zone

Dan Walker
postdoc at NAOJ Chile

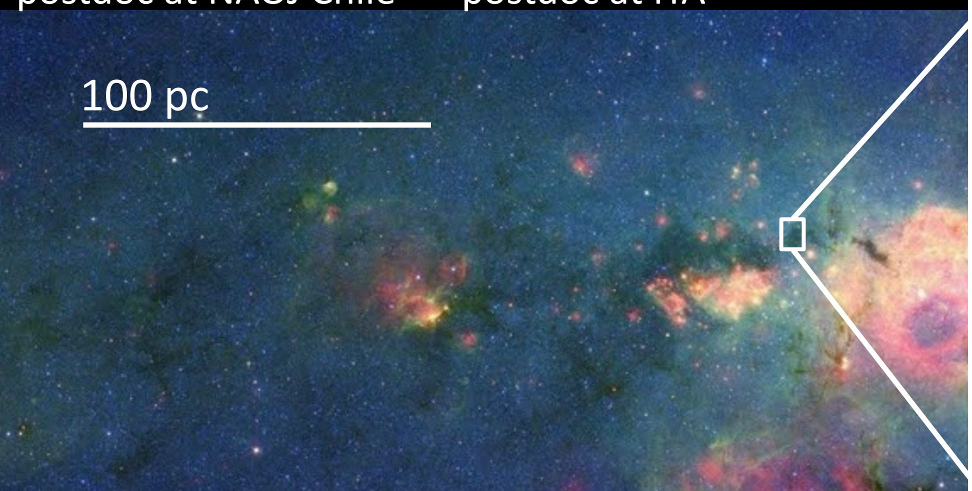
"Bricklet" D

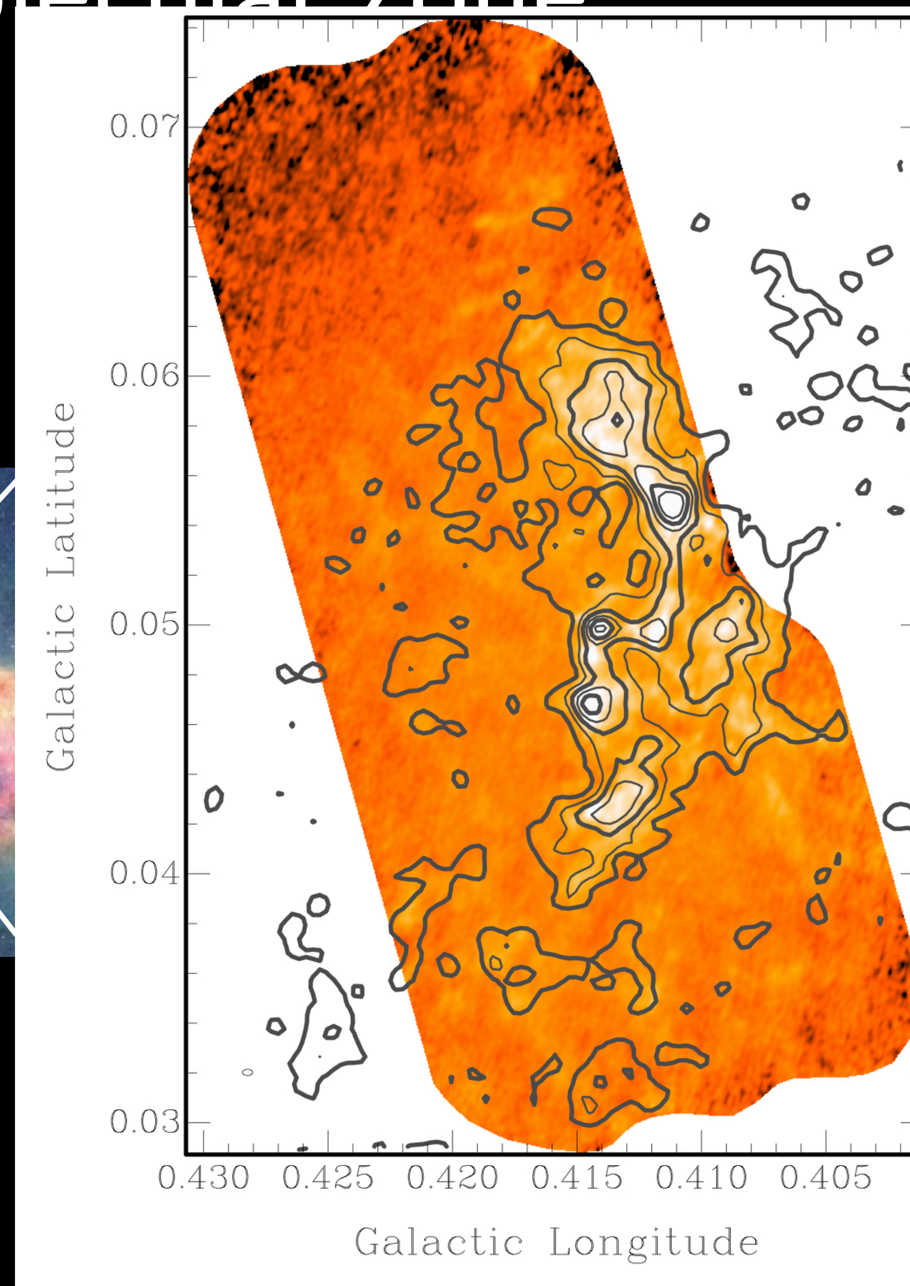


Central Molecular Zone

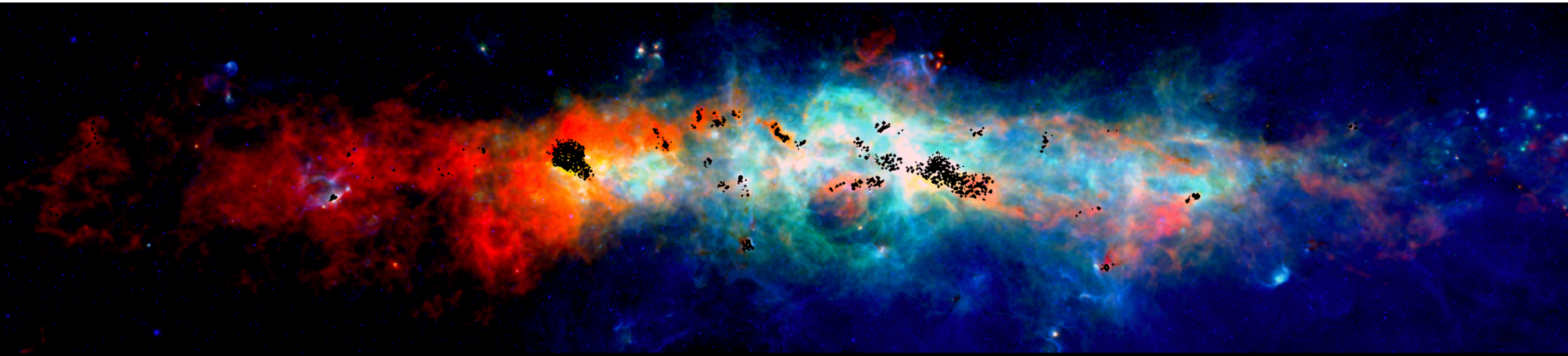
Dan Walker
postdoc at NAOJ Chile

Ash Barnes
postdoc at ITA

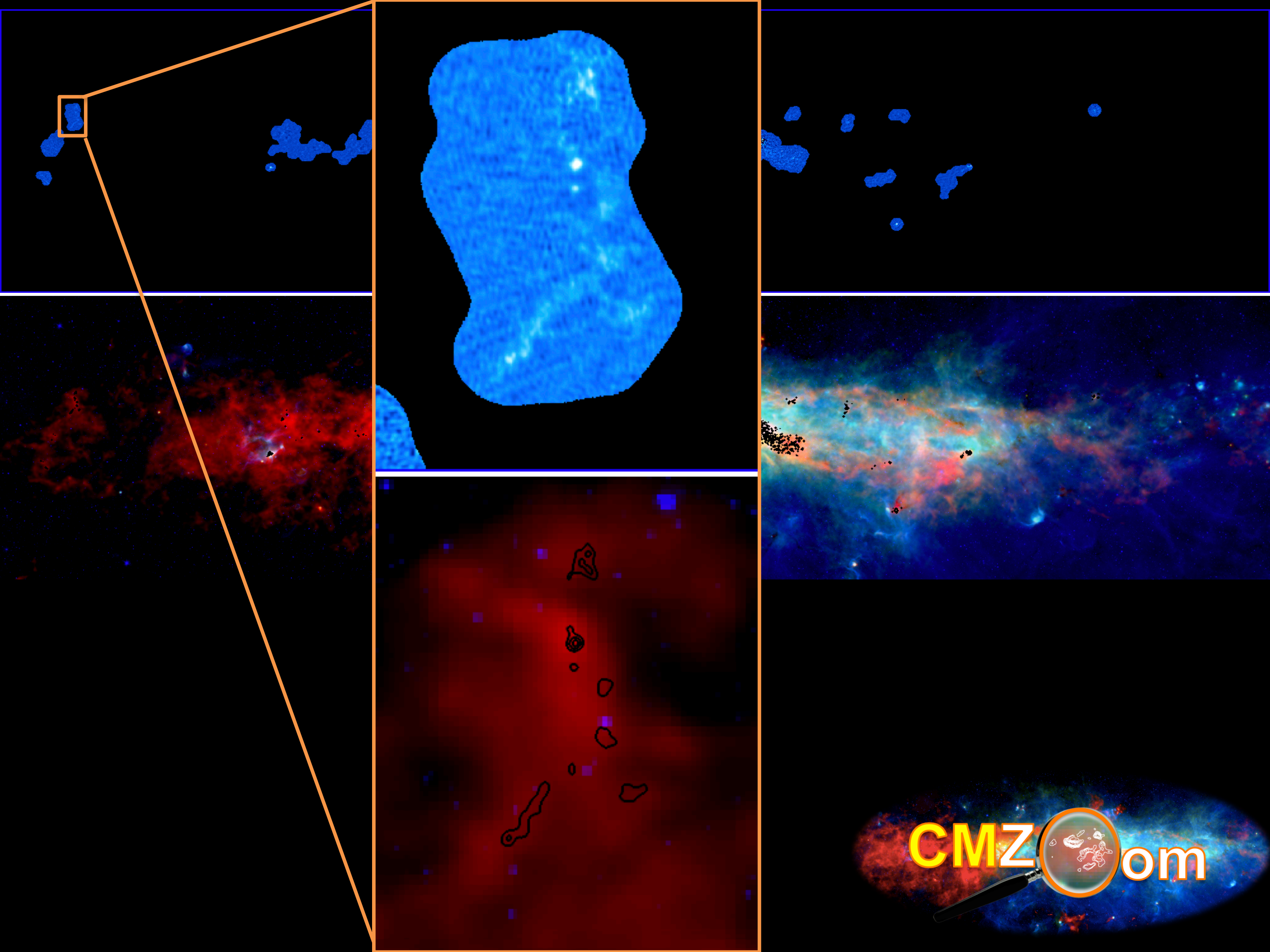


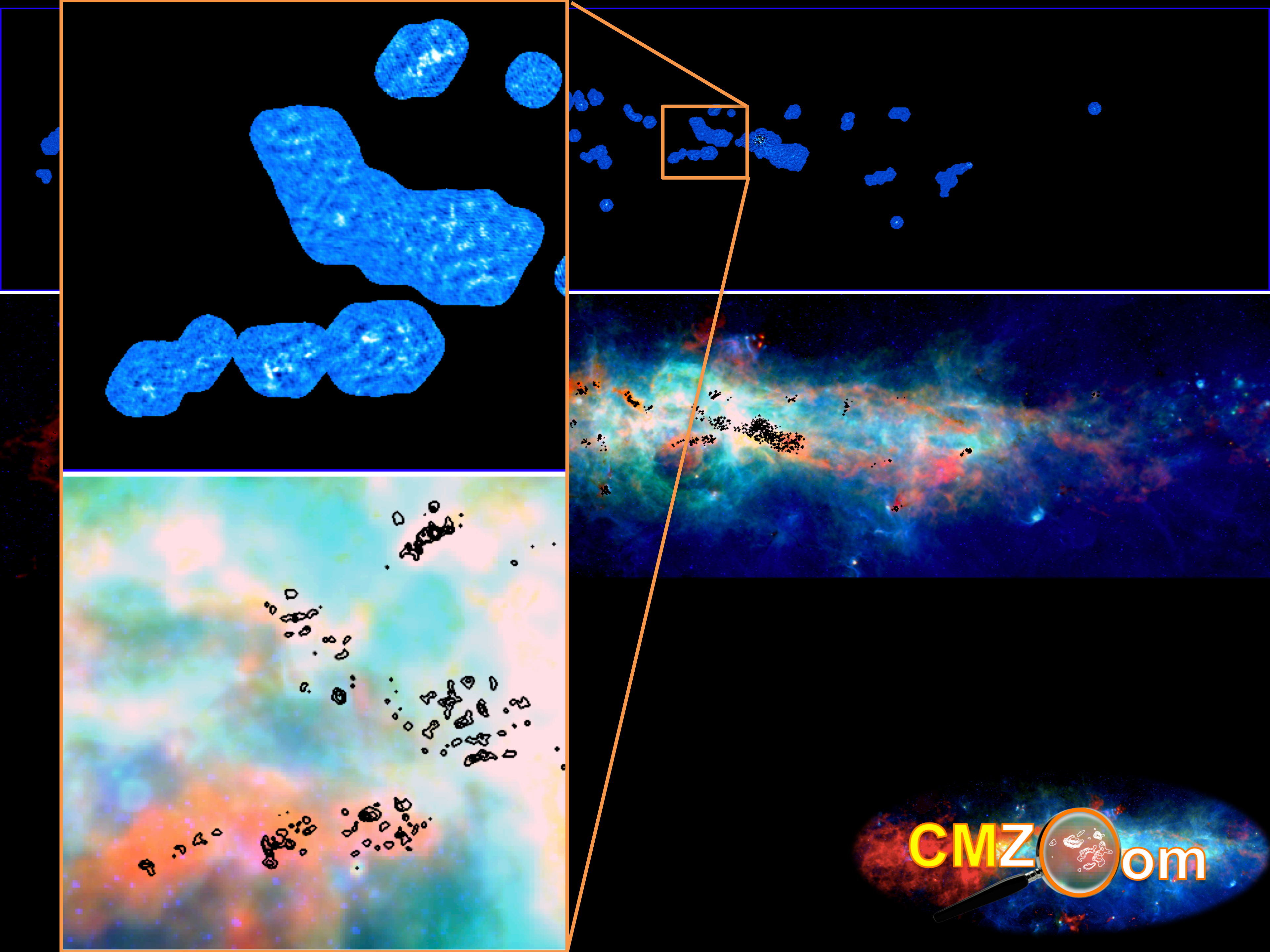


CMZoom



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


CMZoom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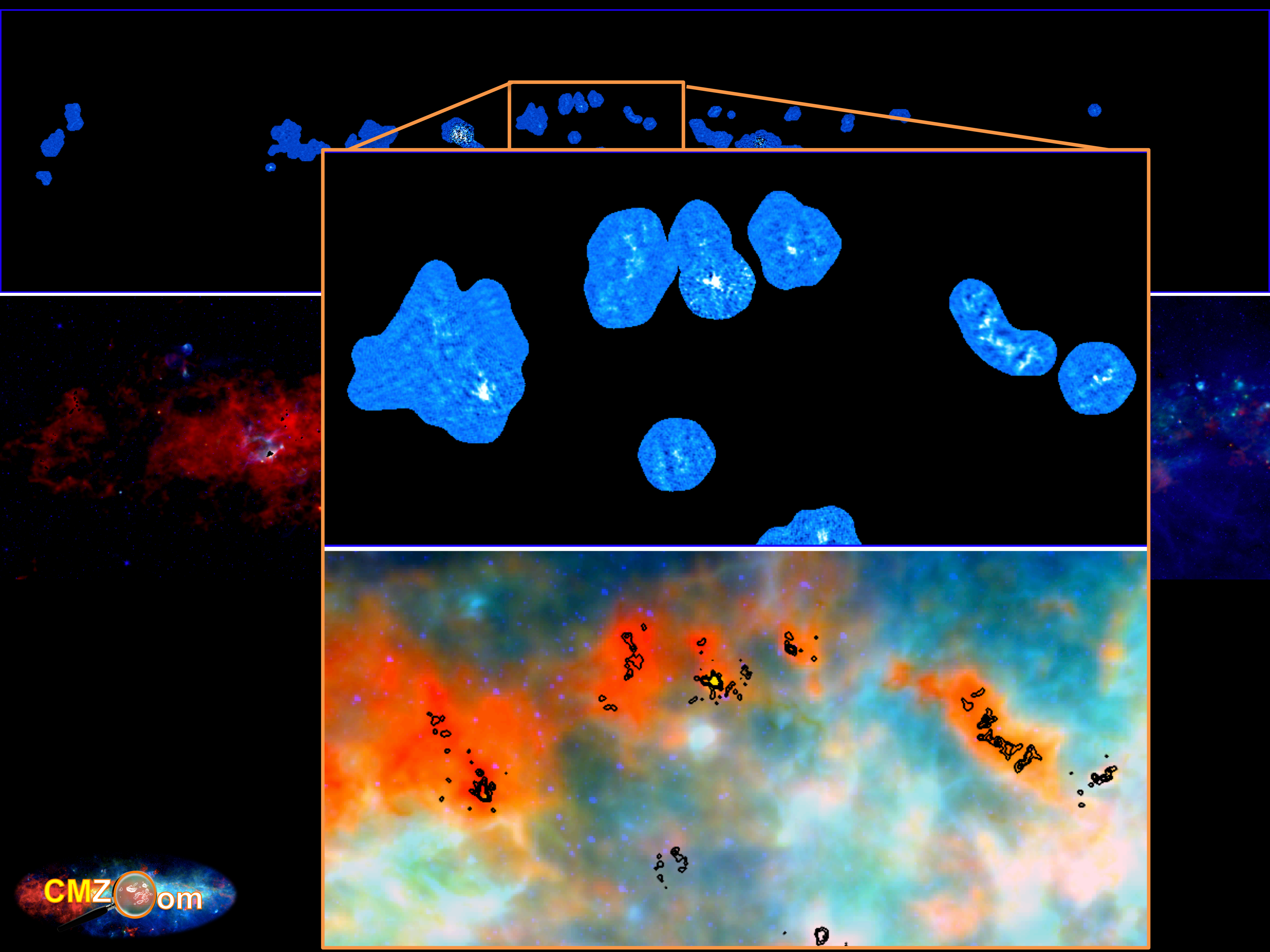
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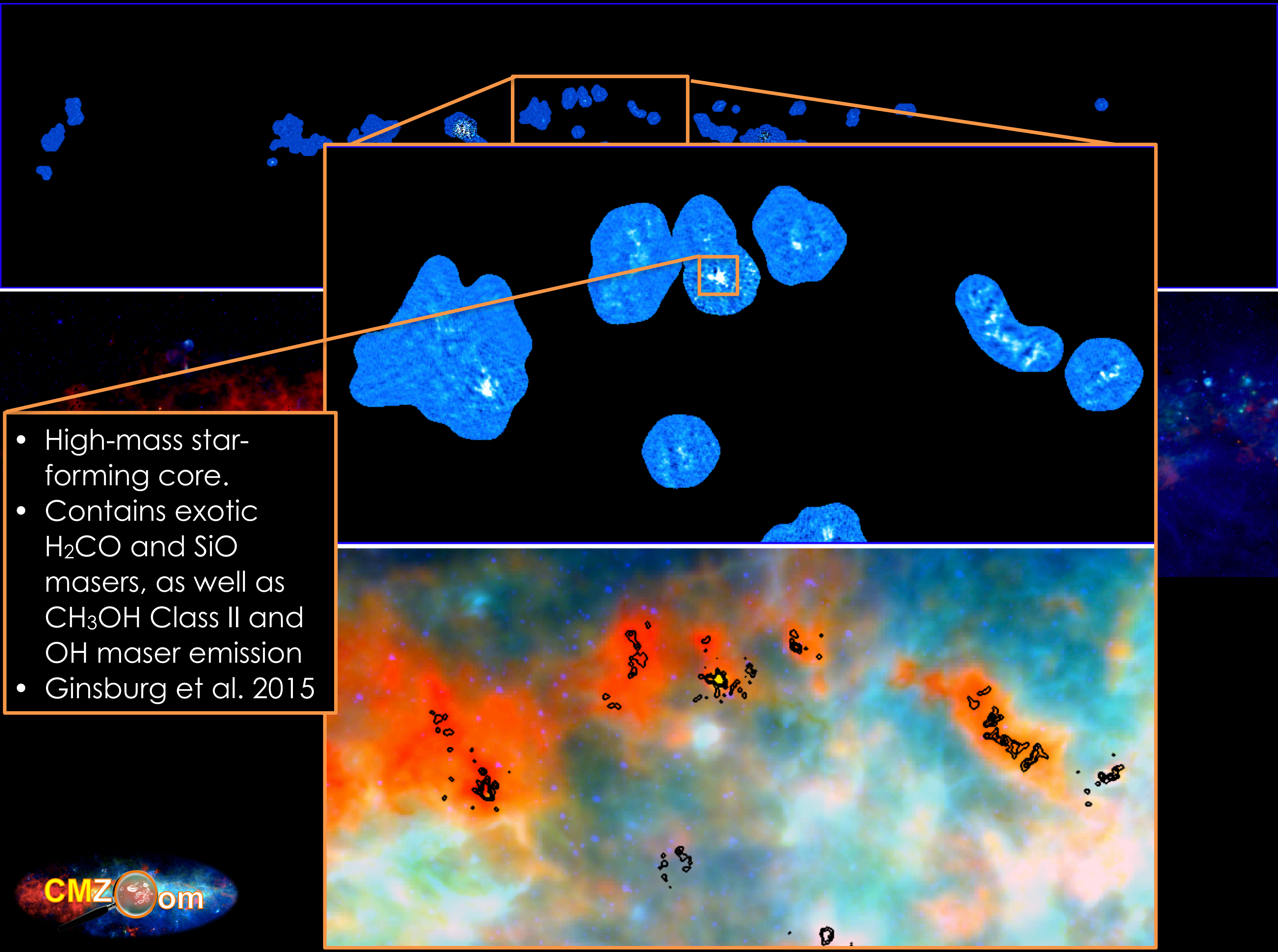
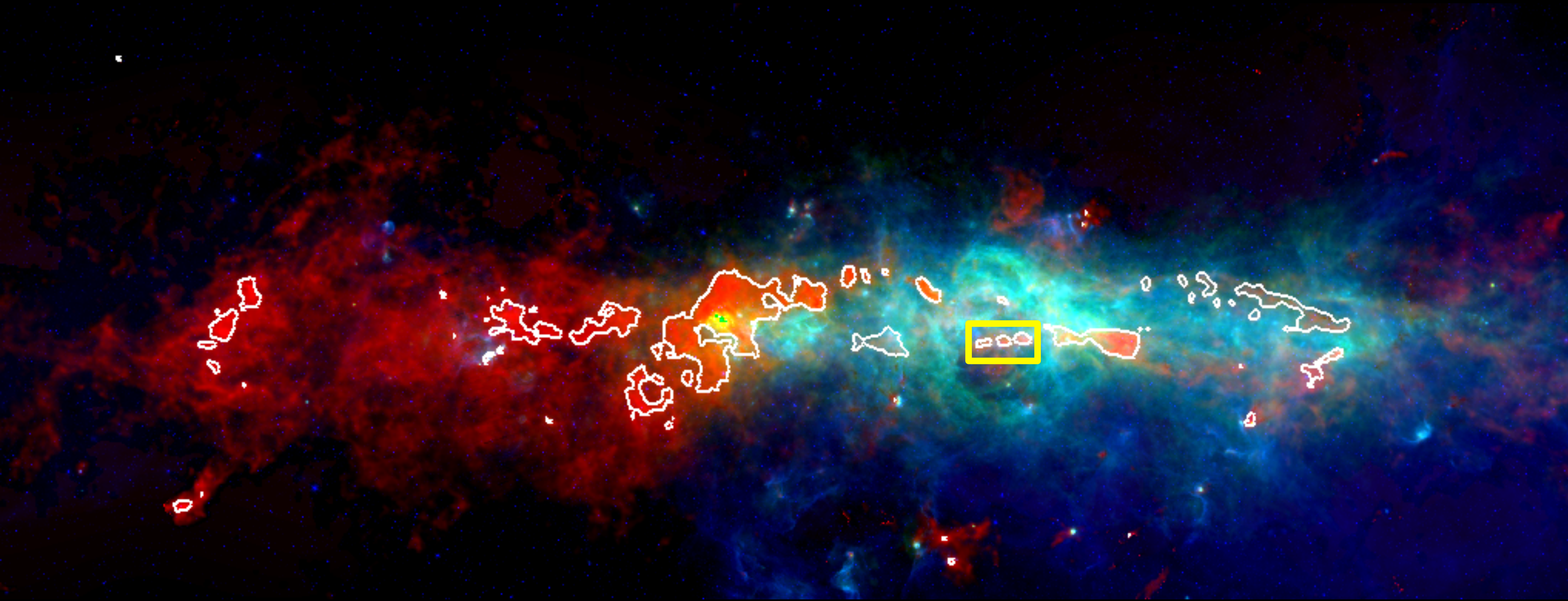
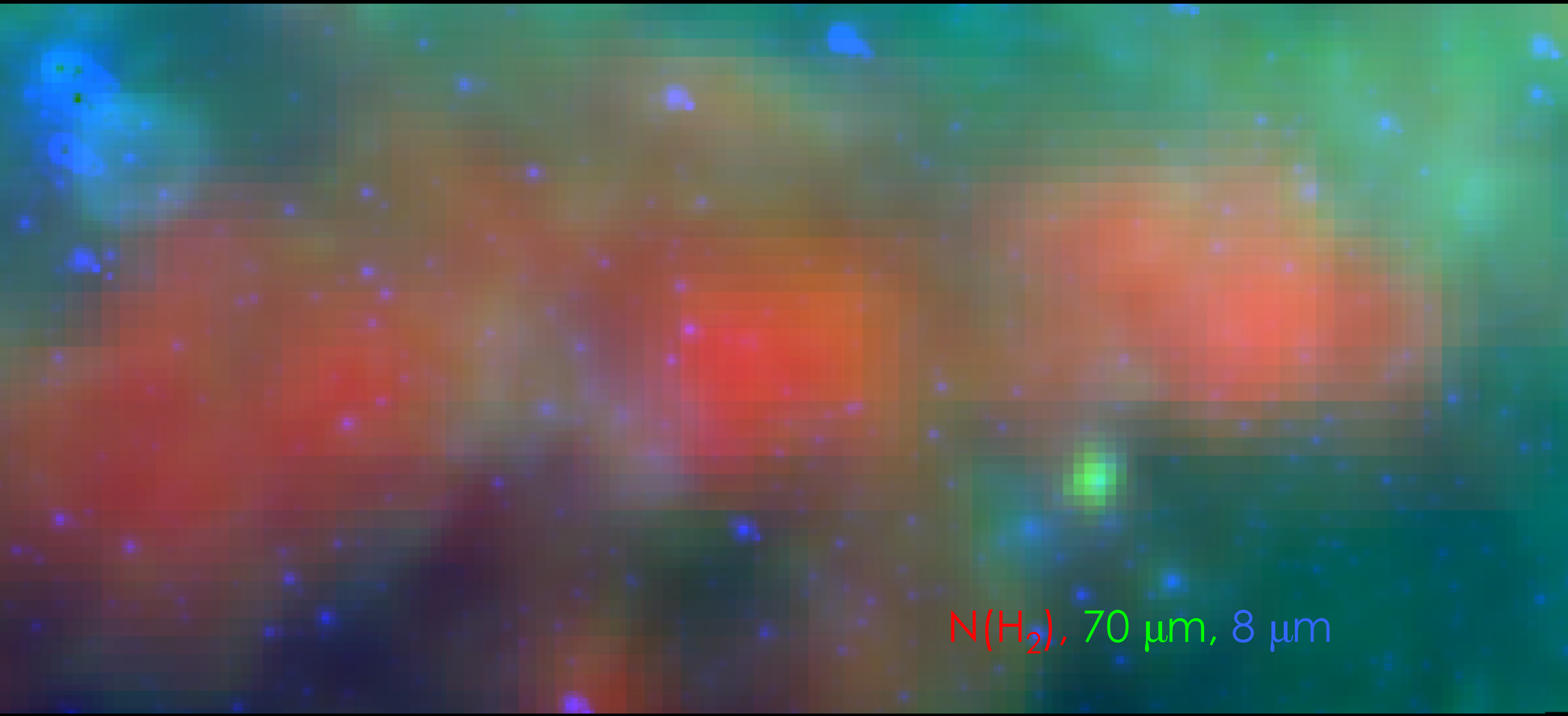


- High-mass star-forming core.
- Contains exotic H_2CO and SiO masers, as well as CH_3OH Class II and OH maser emission
- Ginsburg et al. 2015

Star Formation in the CMZ



Why is the SFR low in the CMZ?



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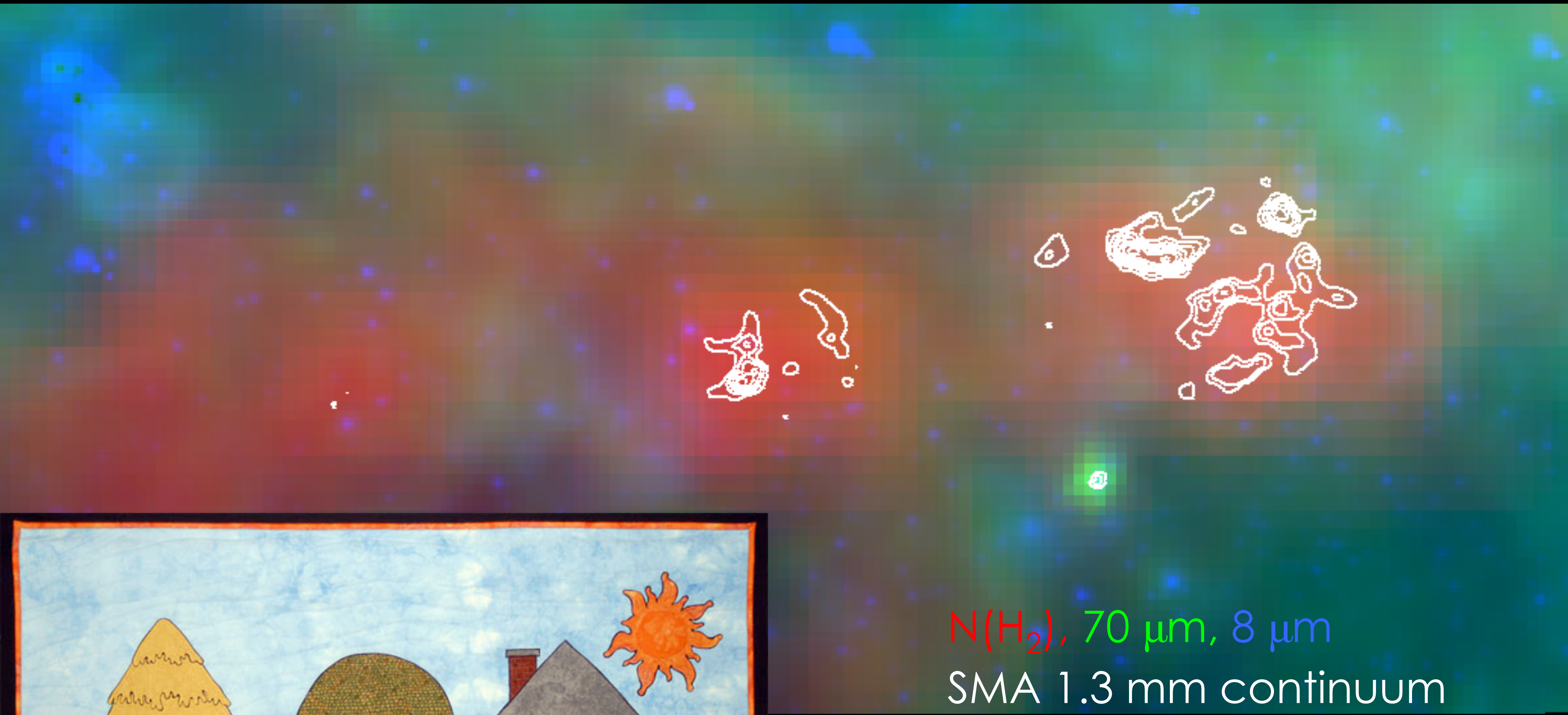

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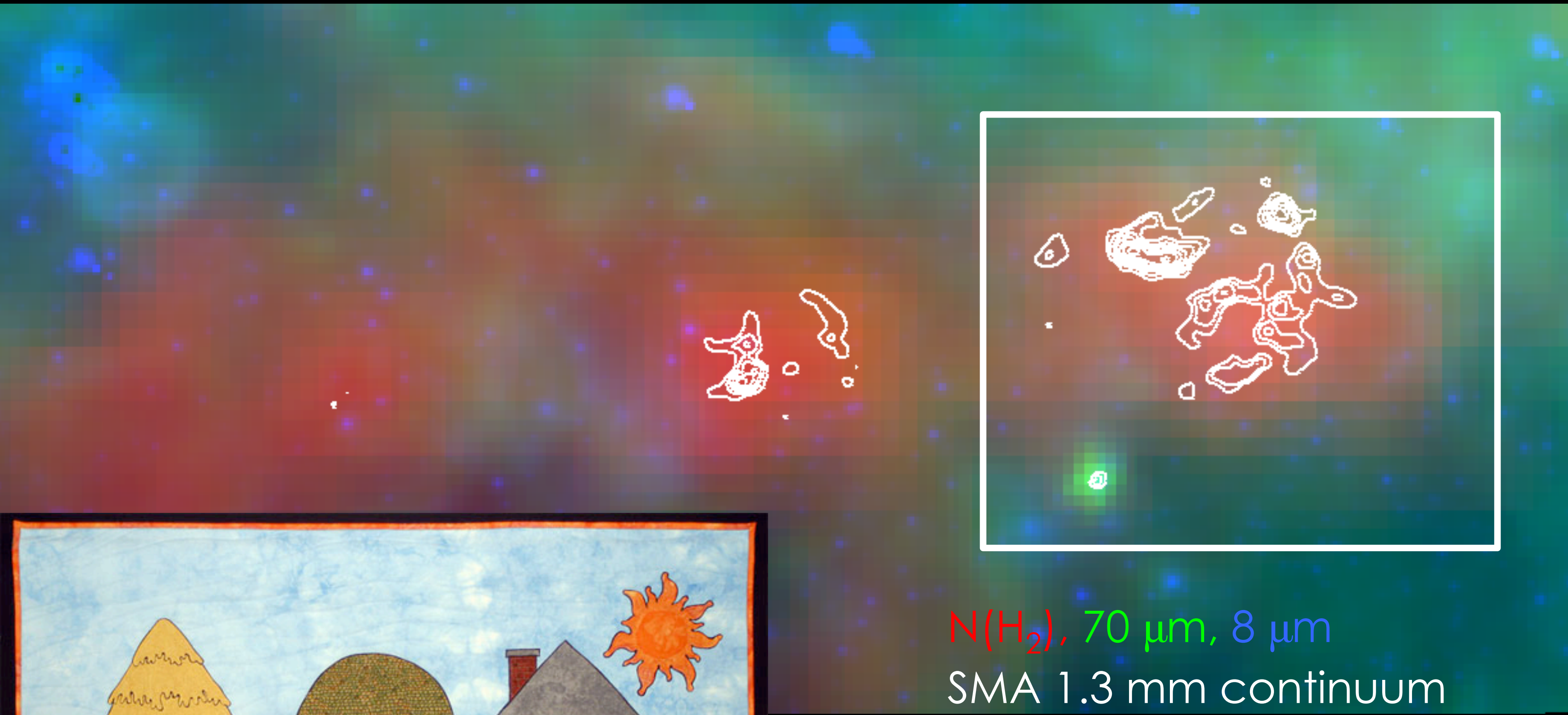

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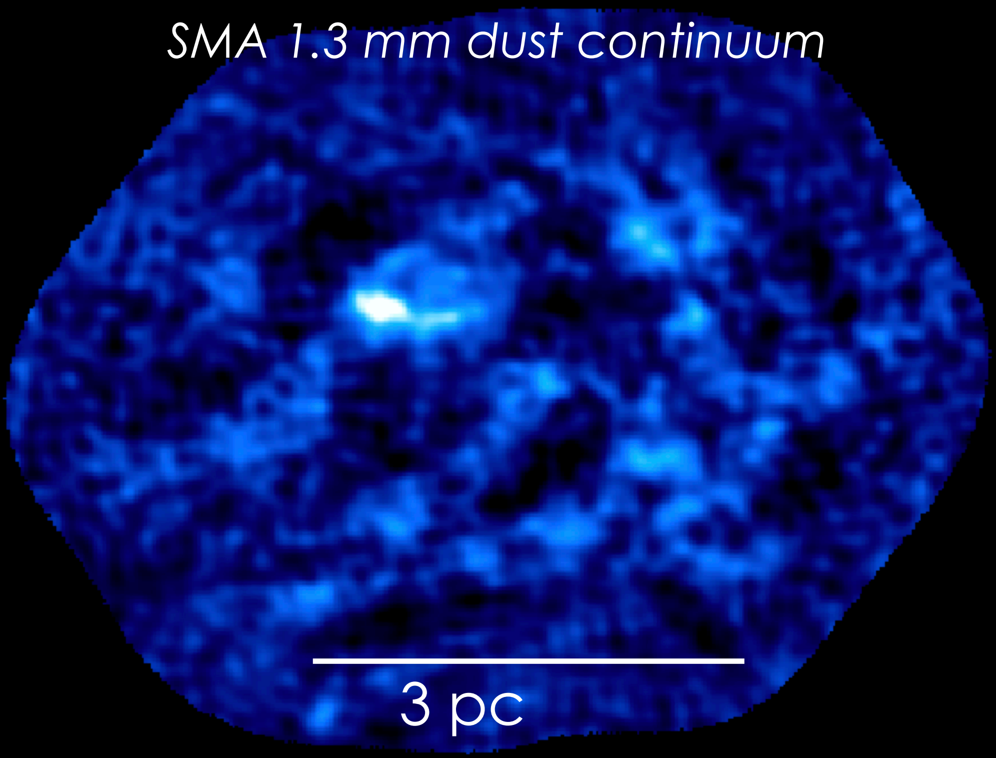

Is it star forming?

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

CMZoom

Why is the SFR low in the CMZ?

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✓ Dense gas
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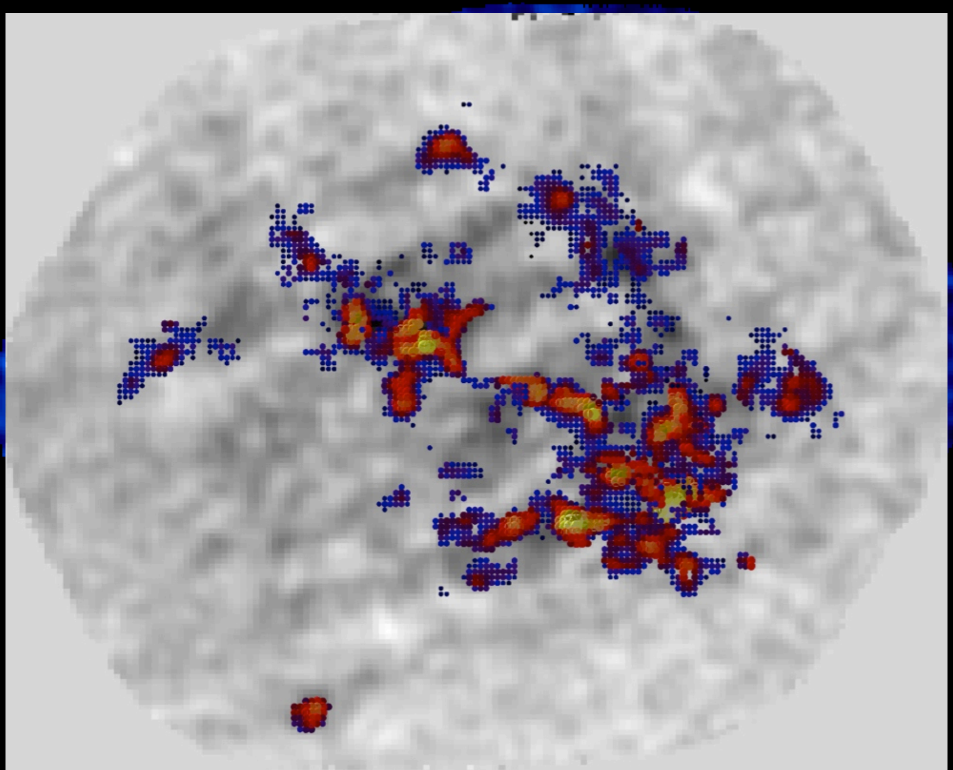
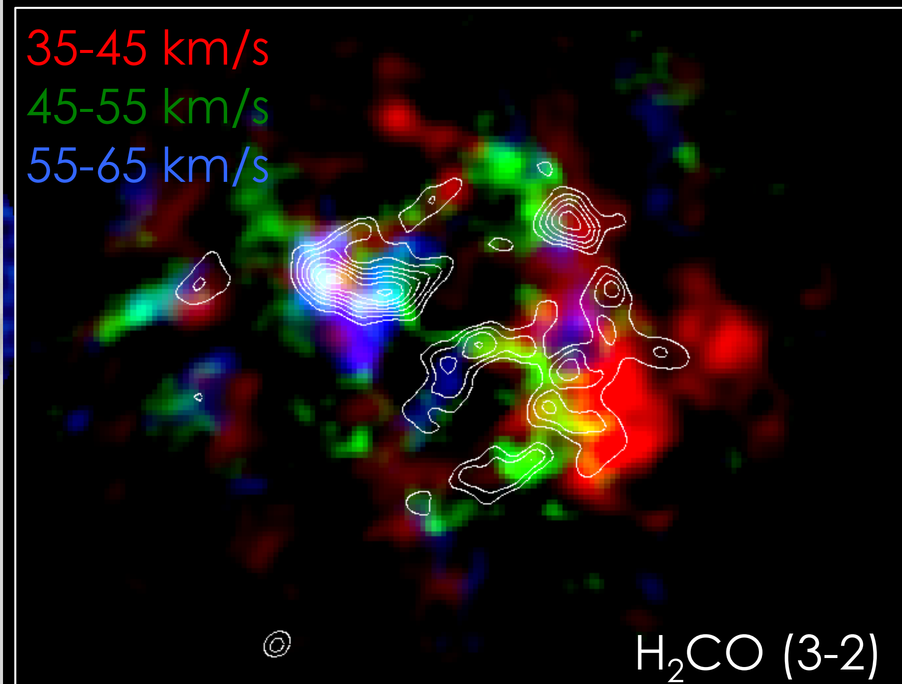
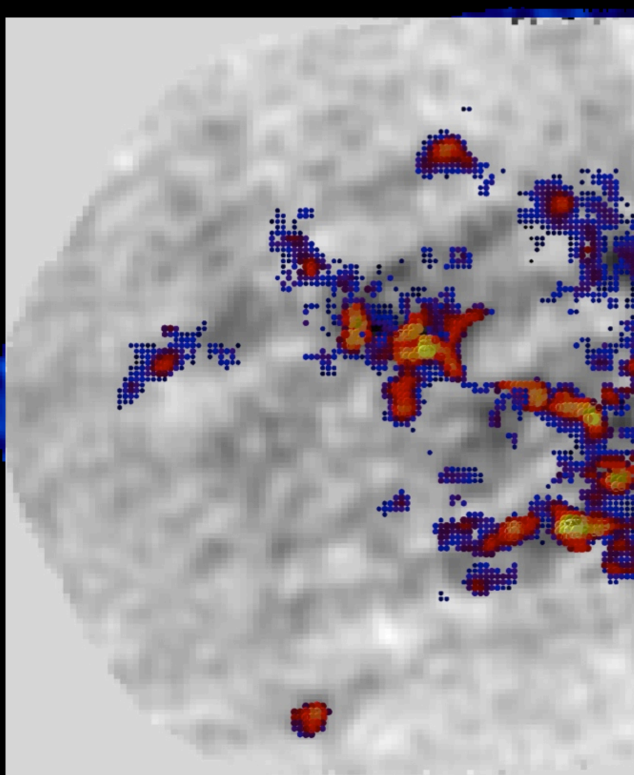
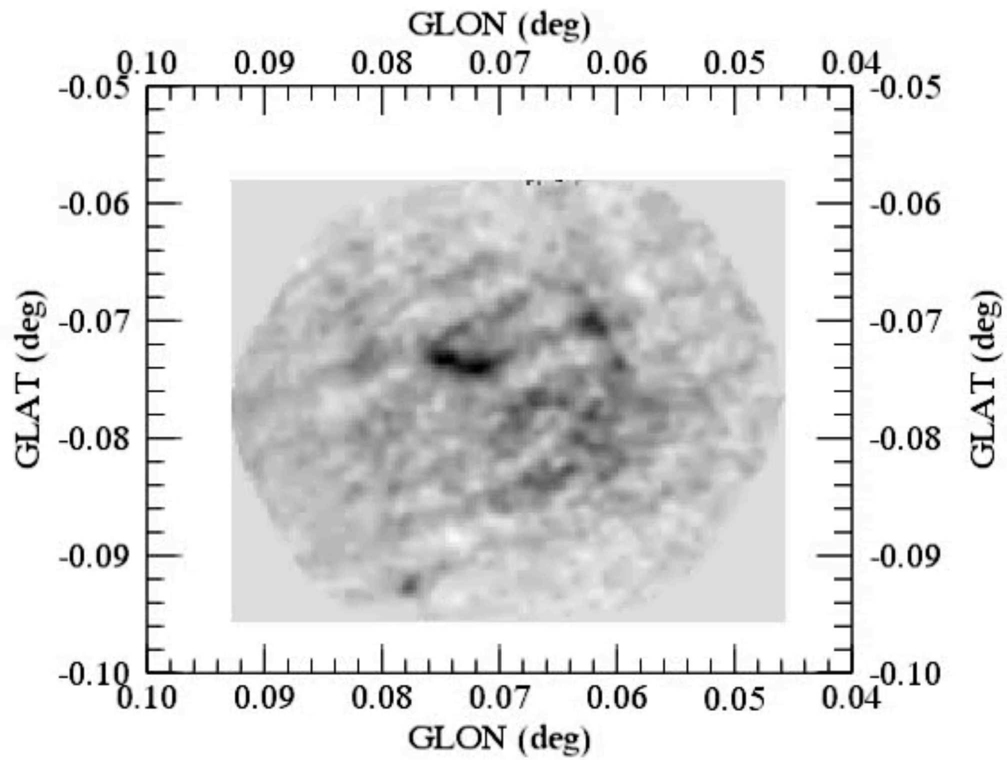




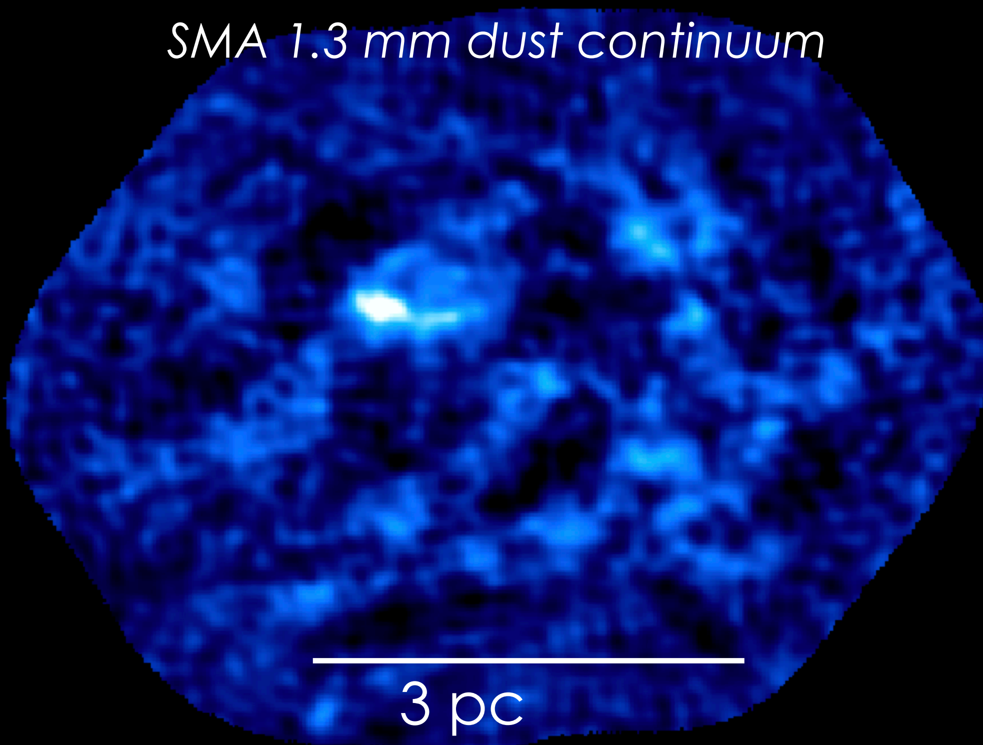
SCOUSE line fitting
Jonny Henshaw, MPIA

Why is the SFR low in the CMZ?





Why is the SFR low in the CMZ?



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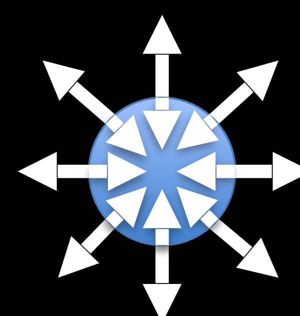
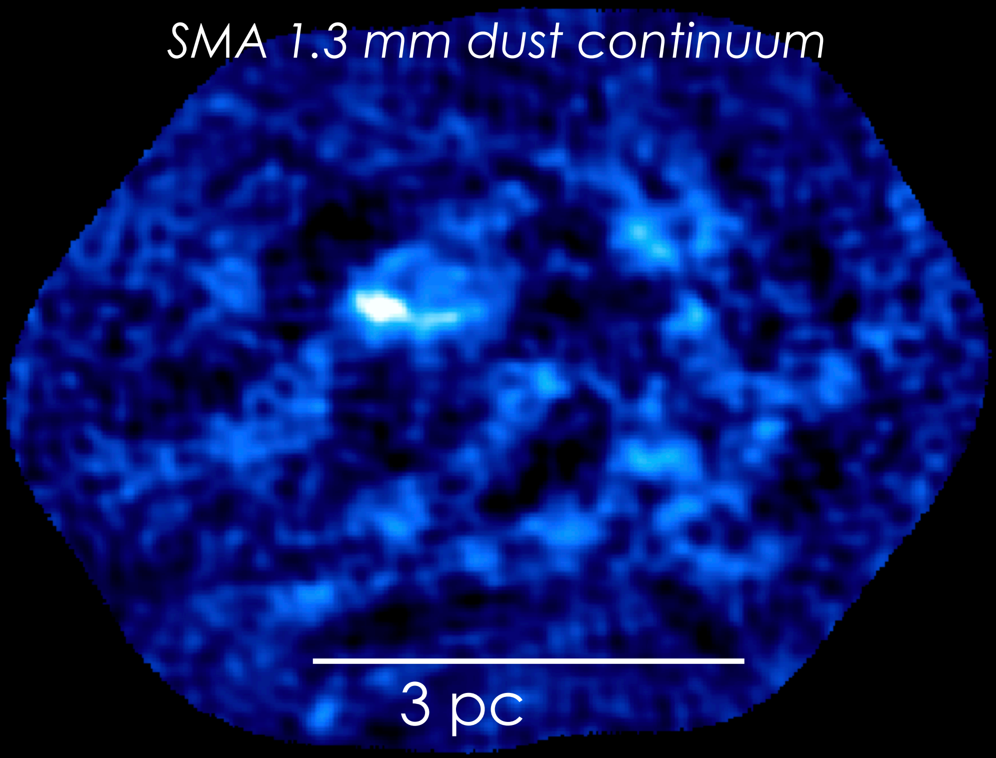


Gravity vs. pressure (thermal and turbulence)

Why is the SFR low in the CMZ?



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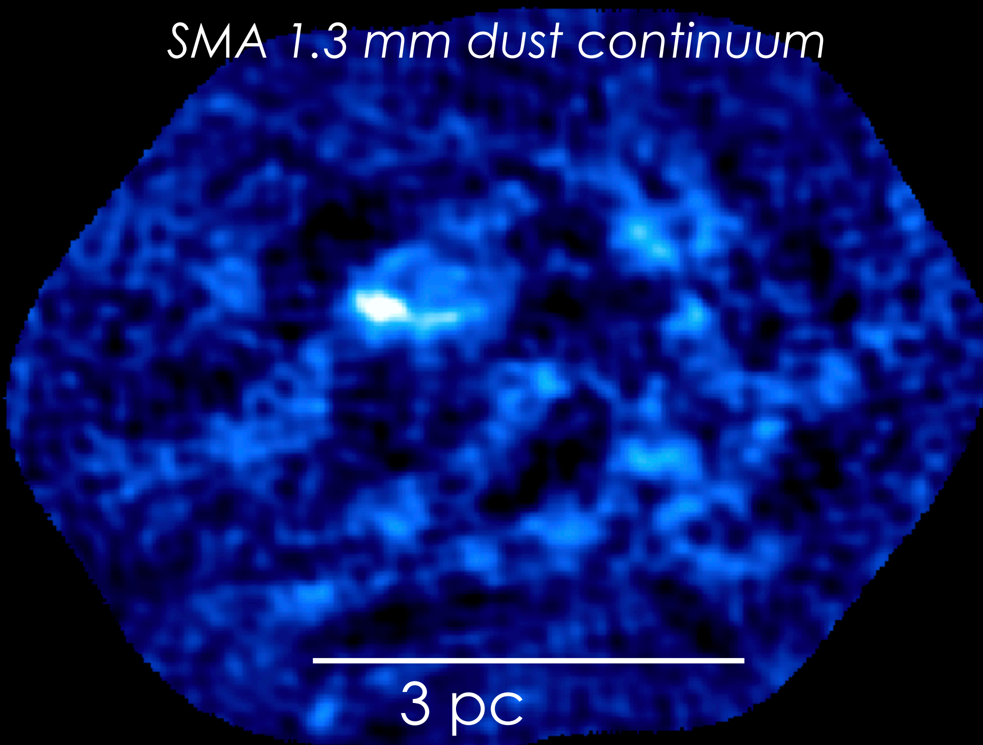

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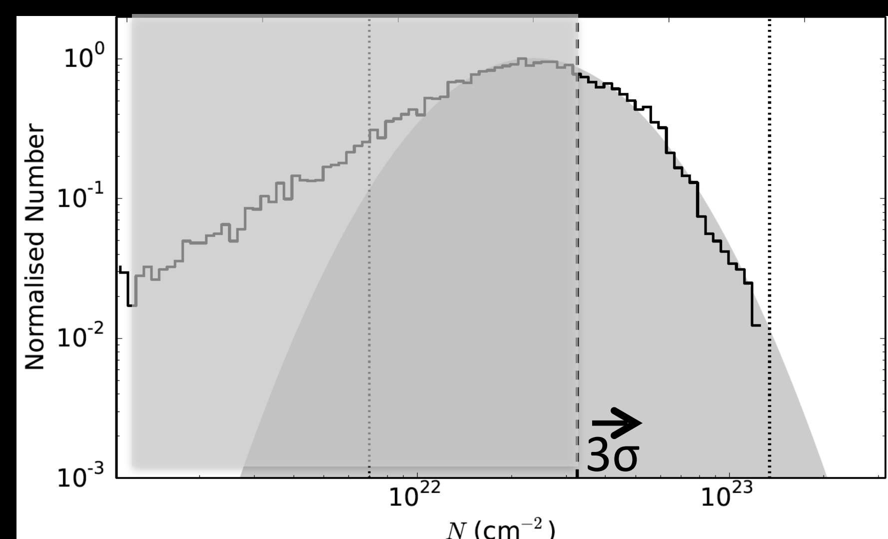

Why is the SFR low in the CMZ?

Is it star forming?

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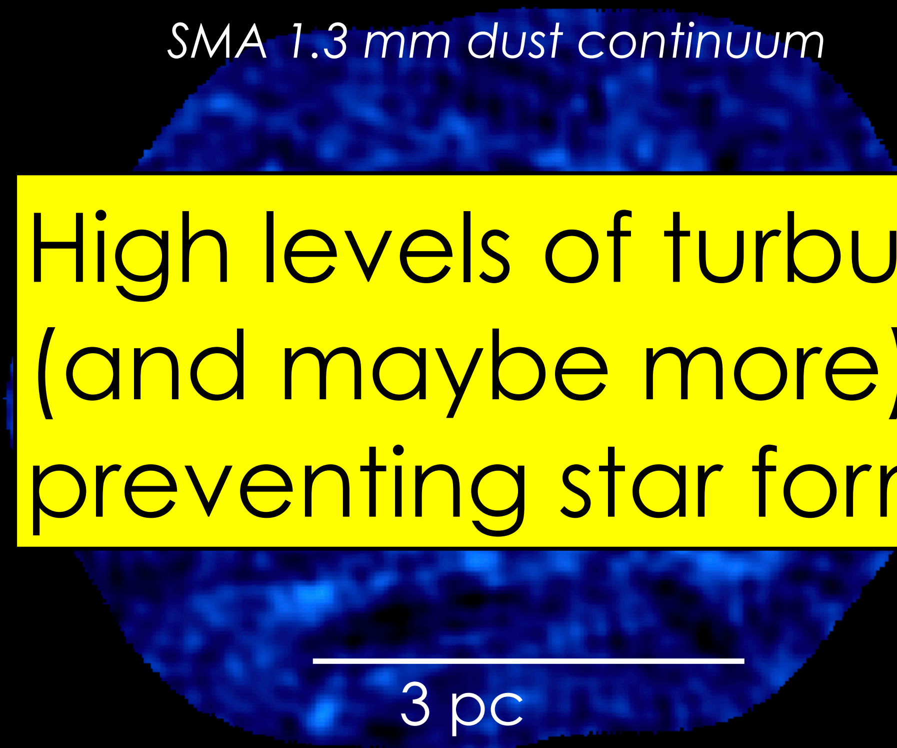
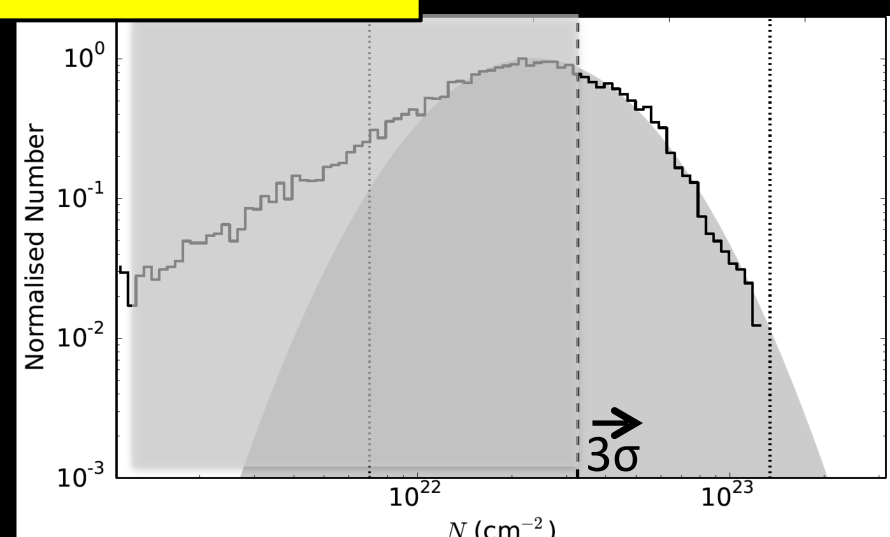
- ✓ Shocked, highly excited gas
- ☒ Virial ratio < 2
- ...w tail in N-PDF
- ... localized hot-
- ...emistry, masers,
- ...gions…



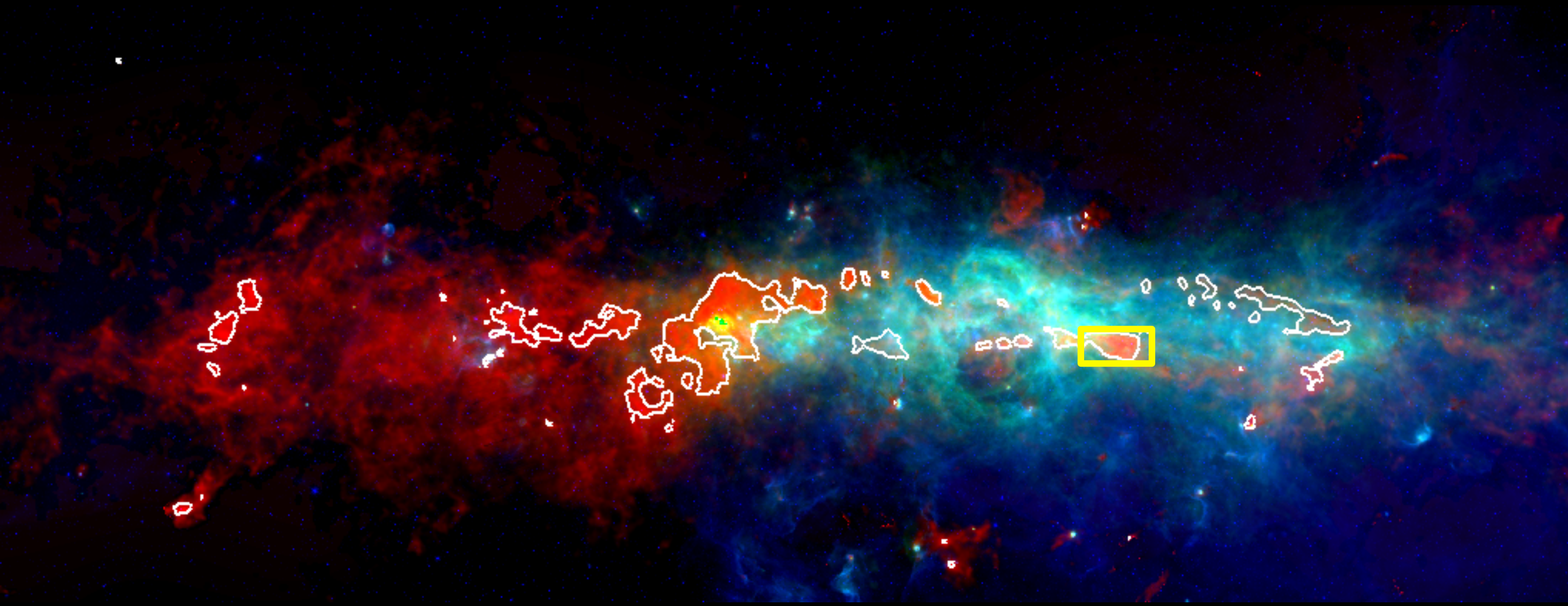
High levels of turbulence[1] (and maybe more) are preventing star formation



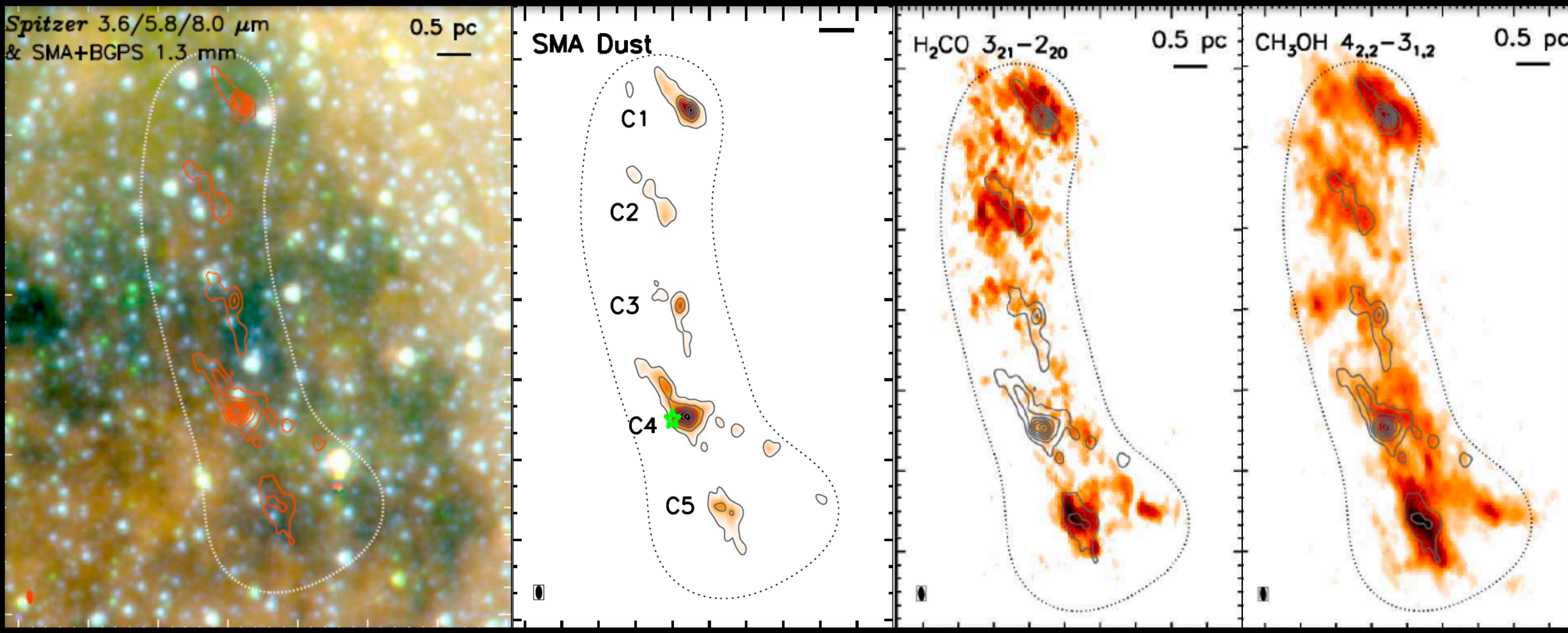
[1]This also heats the gas!

Ginsburg et al. 2016

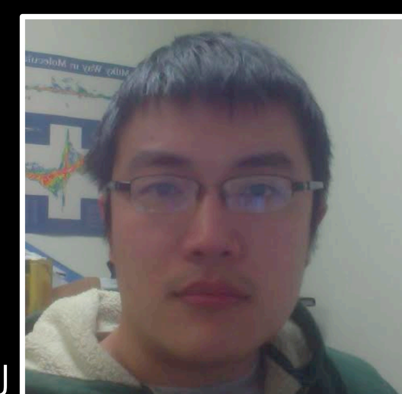
Star Formation in the CMZ



Uncovering Hidden Star Formation



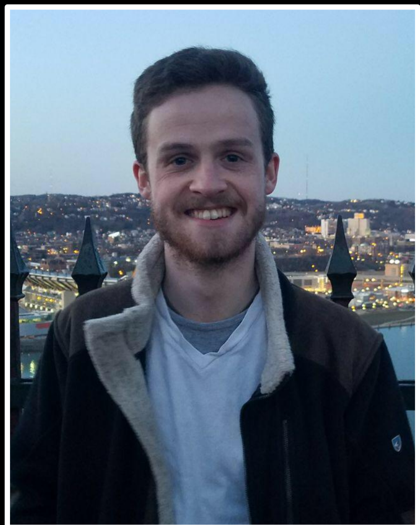
Lu et al 2015, 2017



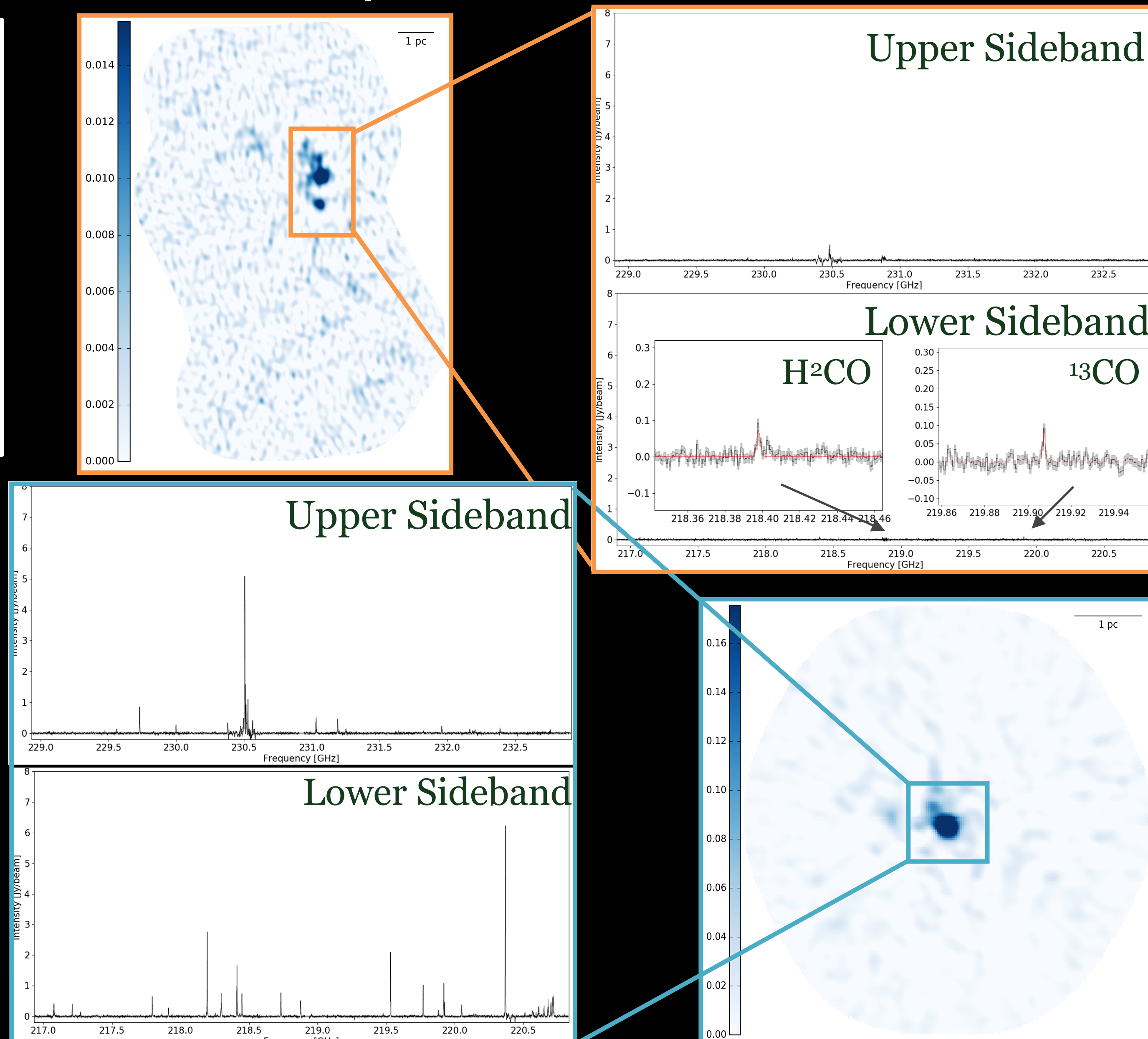
Xing “Walker” Lu
Postdoc at NAOJ

Star Formation in the CMZ

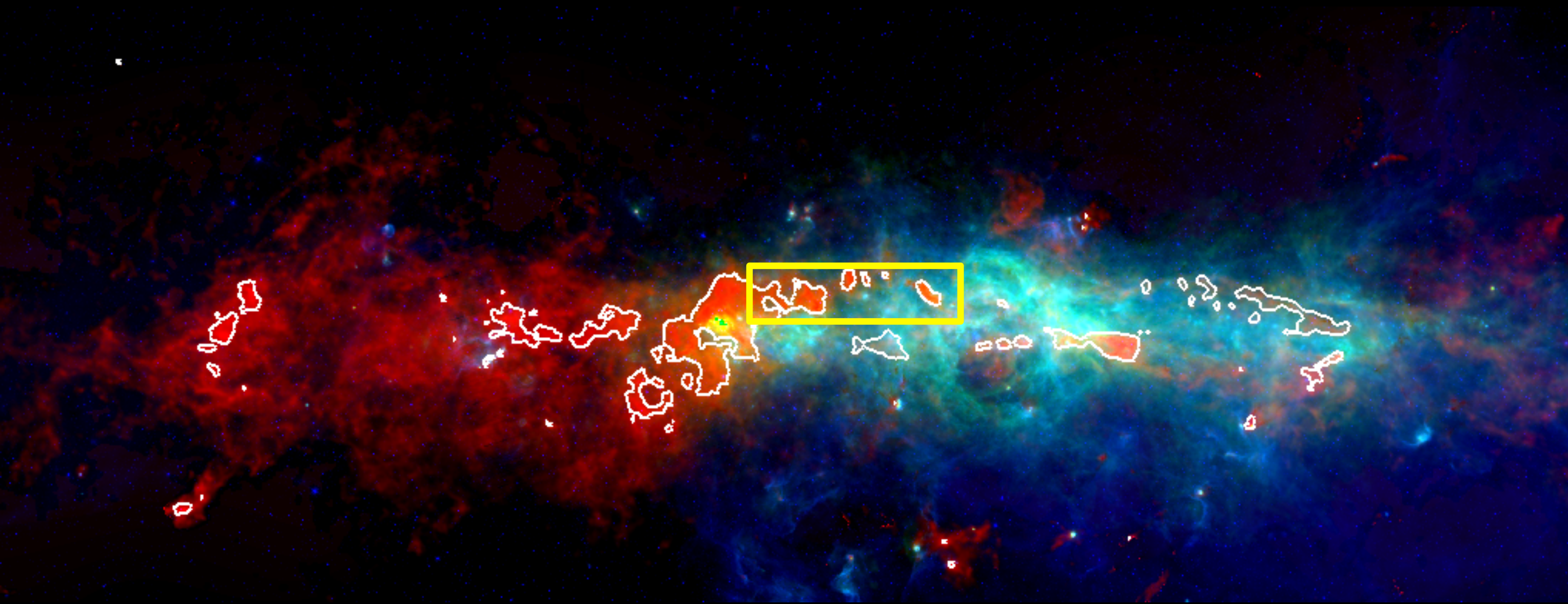
Chemistry in the CMZ



Daniel Callanan
PhD student at
Liverpool/CfA

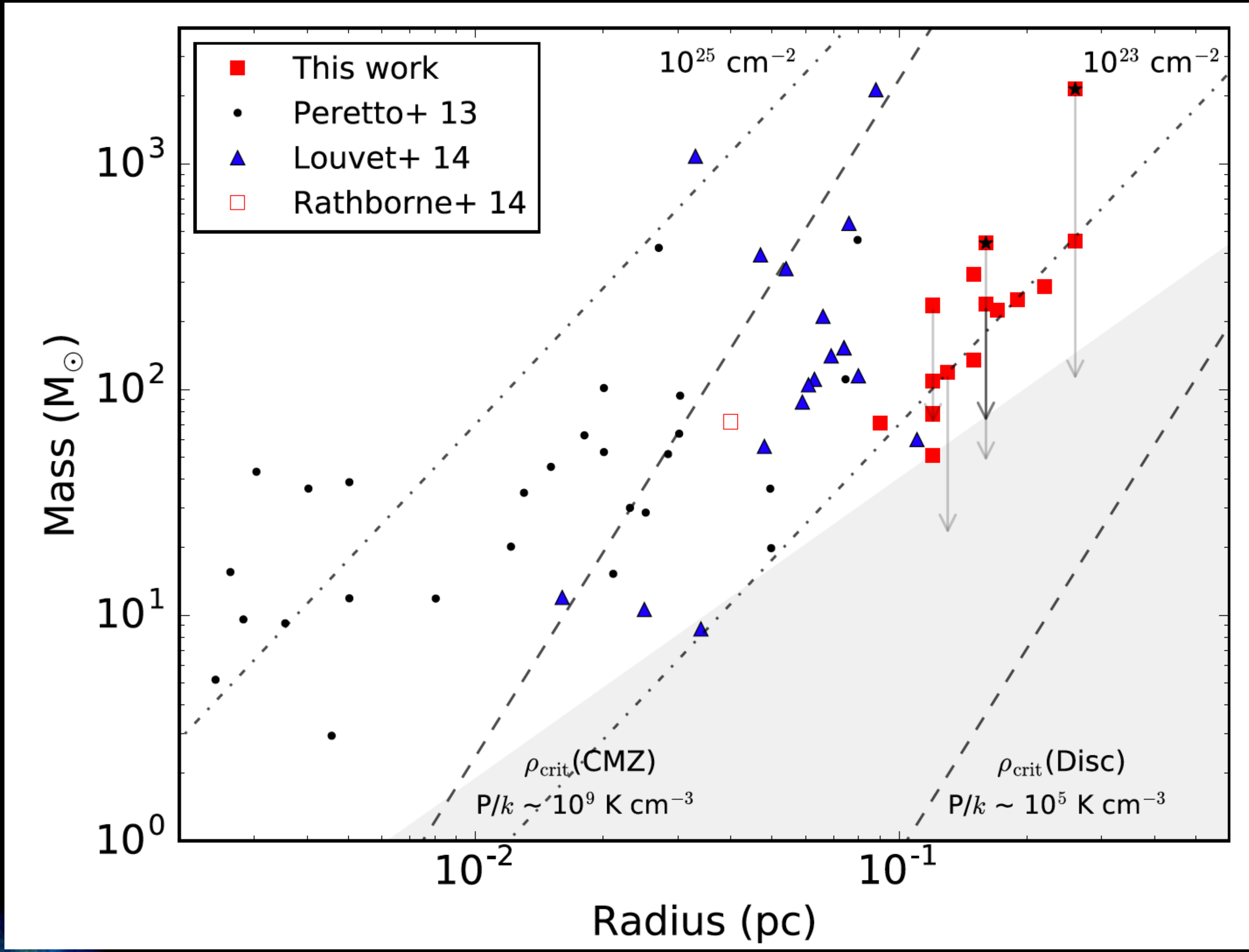


Star Formation in the CMZ



Detailed Study of Core Properties

Dan Walker
postdoc at NAOJ Chile

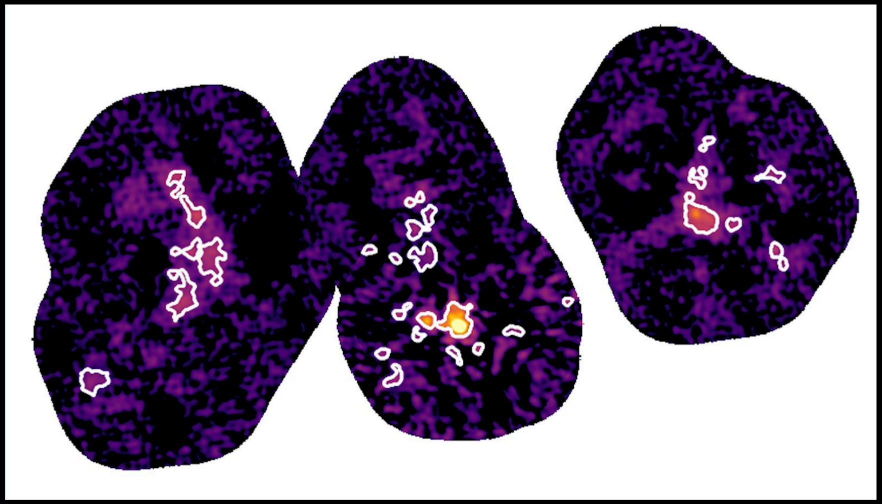


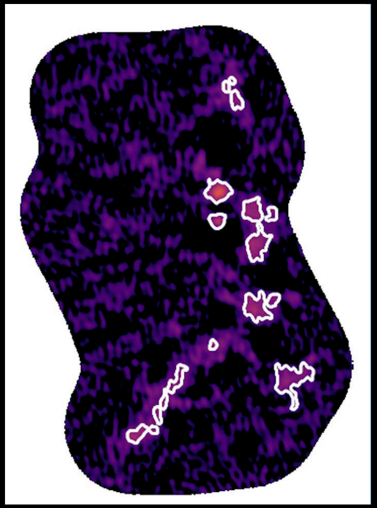
core gas temperatures of about 50-200 K

Walker et al. 2018

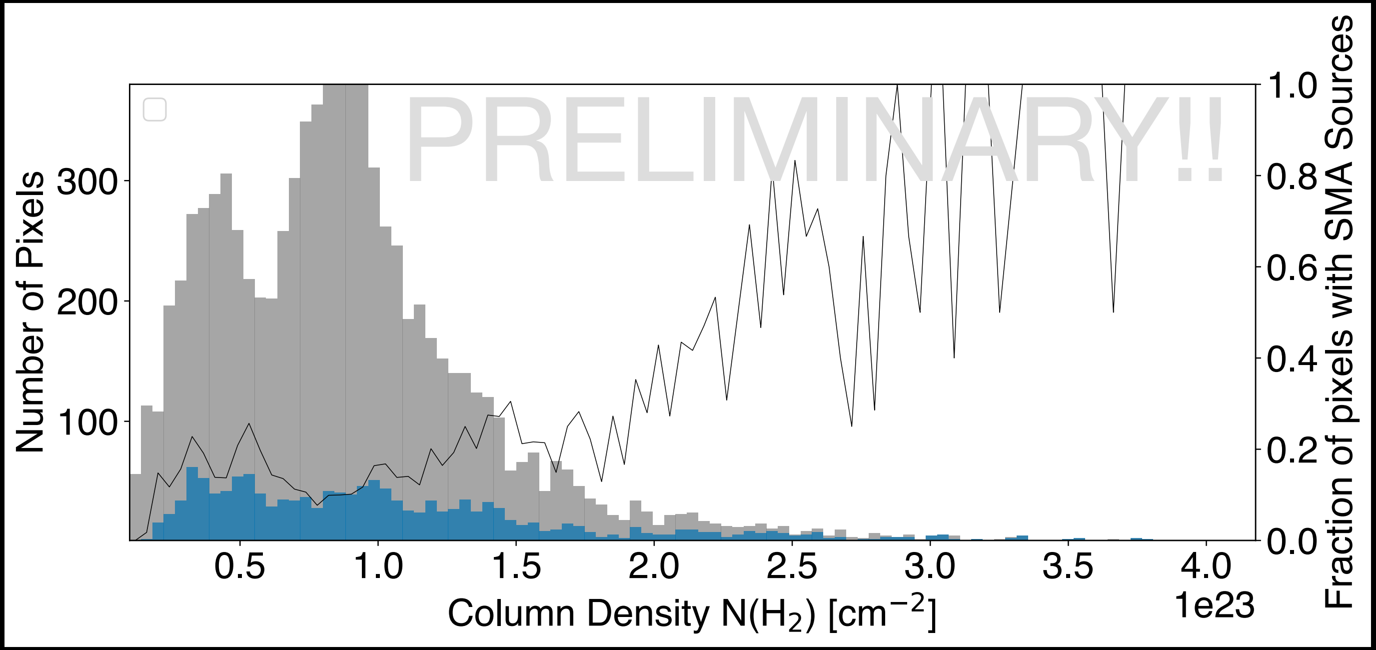
Catalog and Simulated Observations

Perry Hatchfield
PhD student at
UConn





CMZoom Core
Catalog:
Hatchfield et
al. in prep



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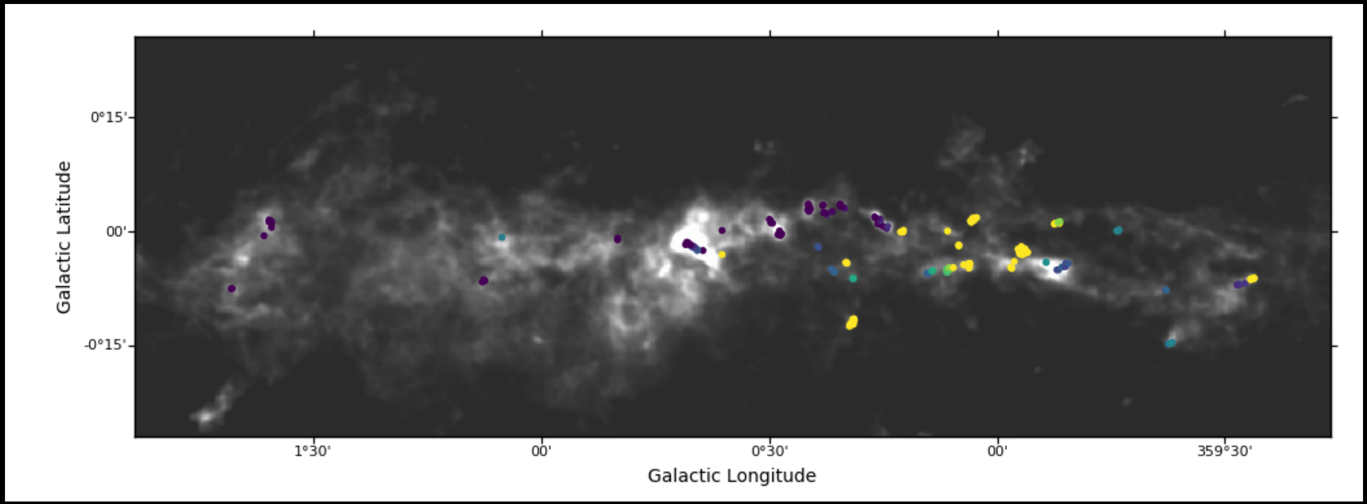
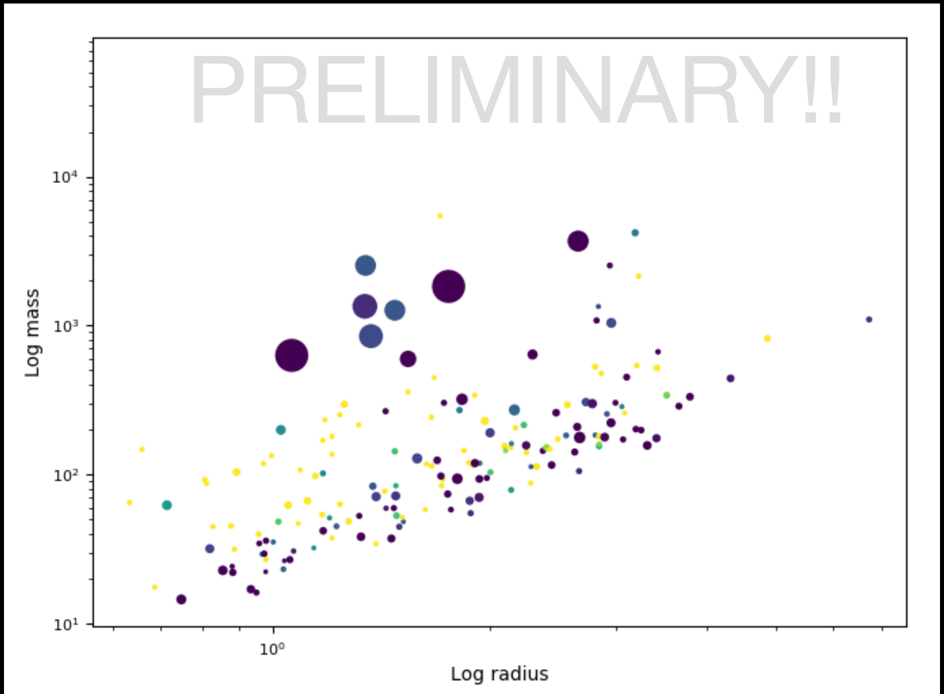
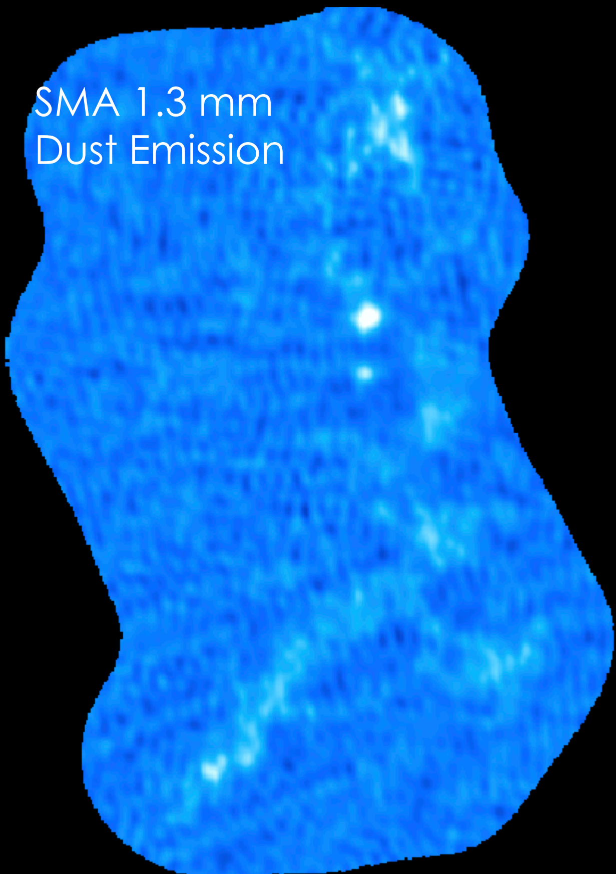


CMZoom Core Catalog: Hatchfield et al. in prep



Star Formation in the CMZ

Why is the SFR so low in the CMZ?



Low-level isolated star formation

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

Battersby et al., in prep.

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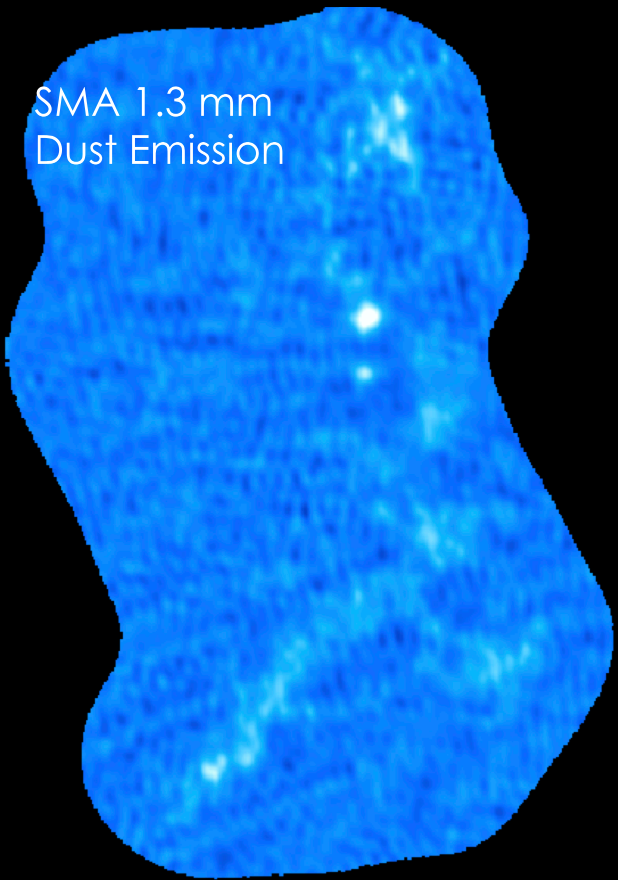

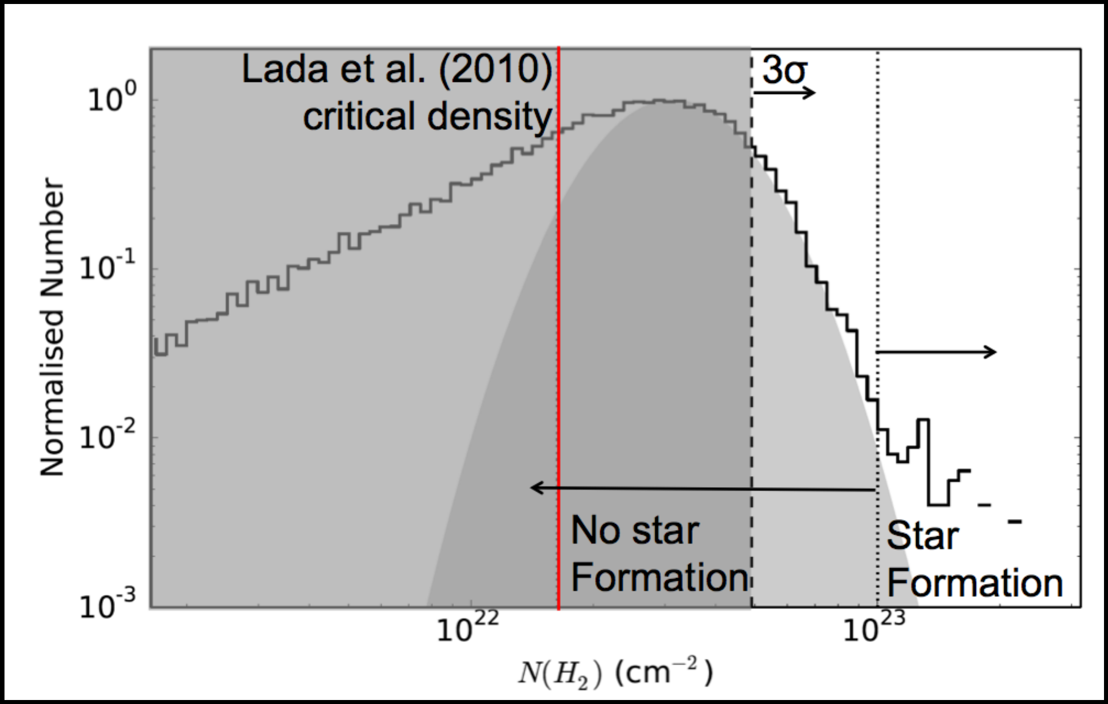

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Battersby et al., in prep.

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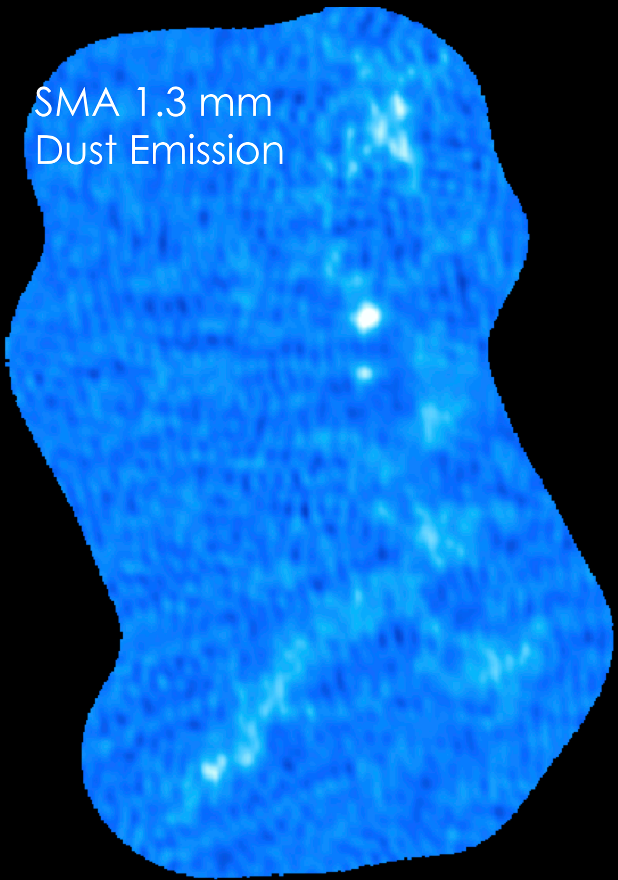

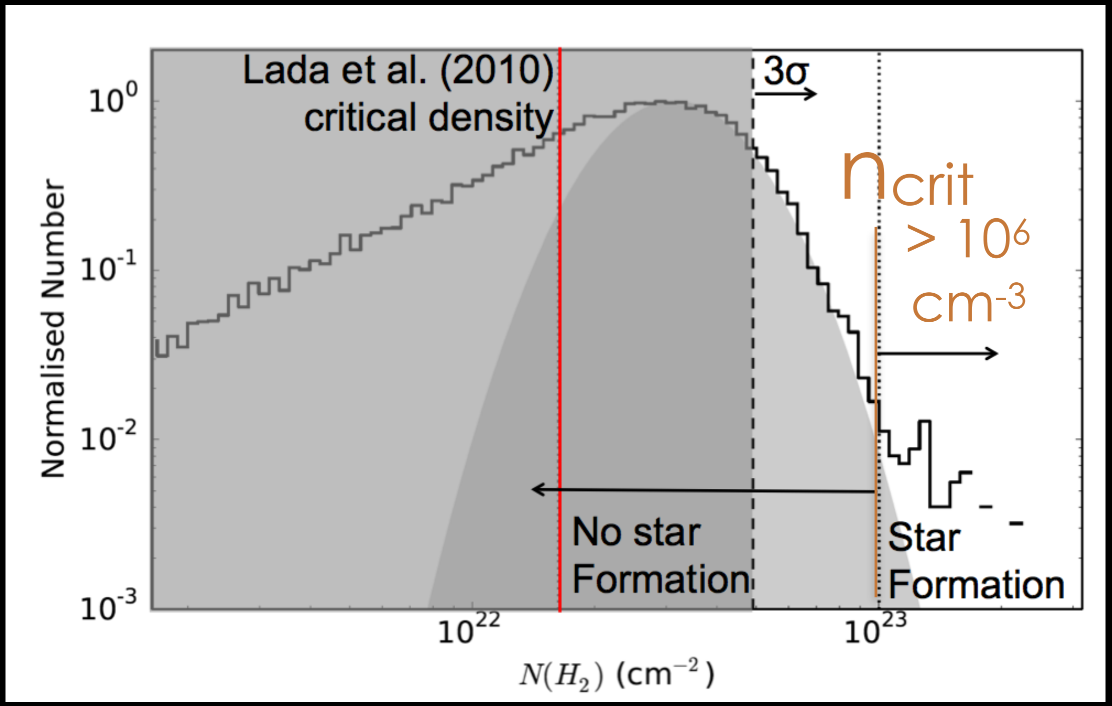

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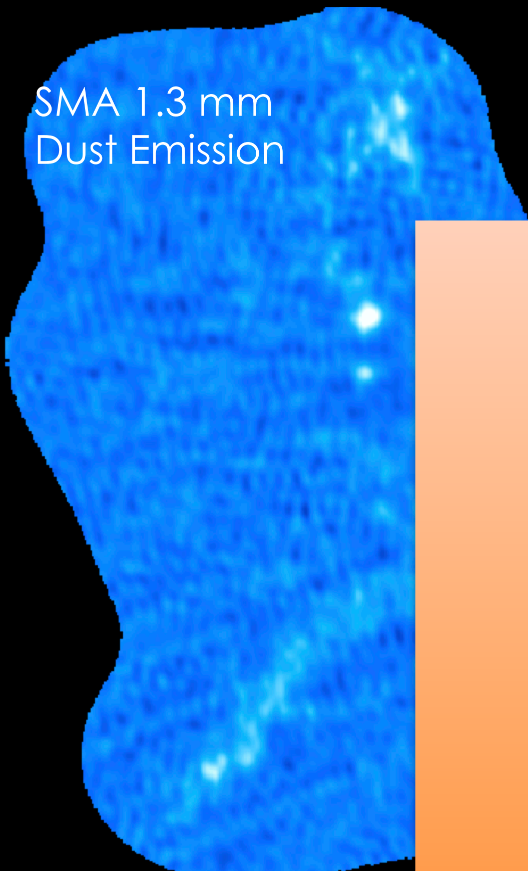
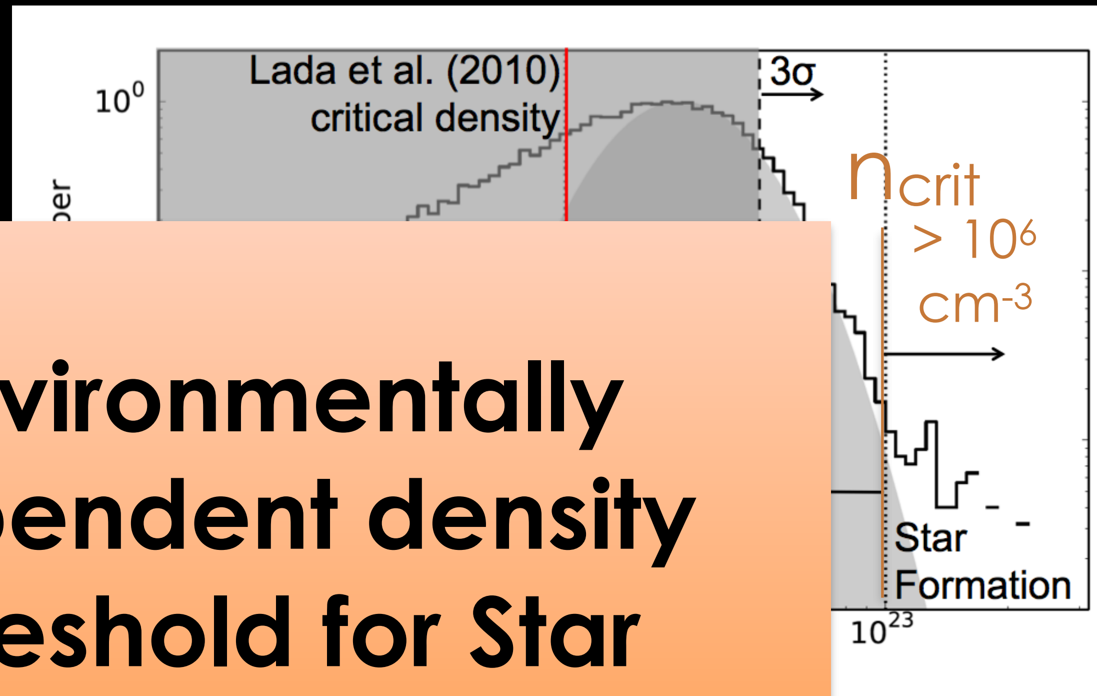




Environmentally Dependent density threshold for Star Formation?

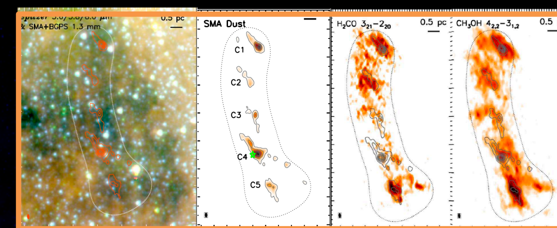
Low-level isolated star formation

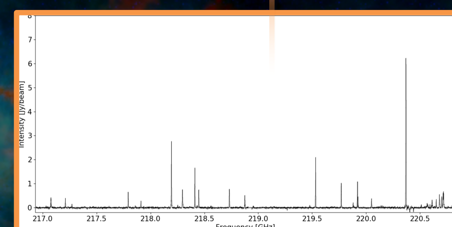
Battersby et al., in prep.

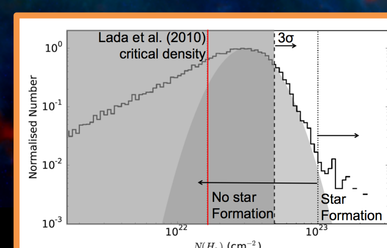
Star Formation in our Extreme Galactic Center: Results from the CMZoom Survey

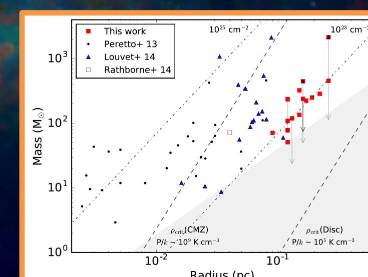
New survey, CMZoom, mapped all the highest column density gas in inner 500 pc and:

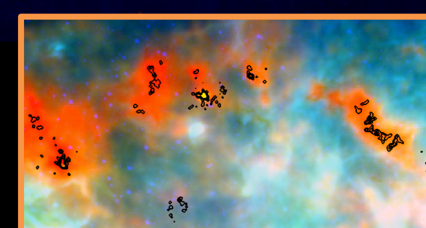
* Uncovered hidden star formation
* CMZ cores demonstrate very different excitation/chemistry
* CMZ cores are on the same mass-radius relation as disk cores
* High levels of turbulence seem capable of inhibiting SF in the CMZ
* Meaning that SFR should depend on environment





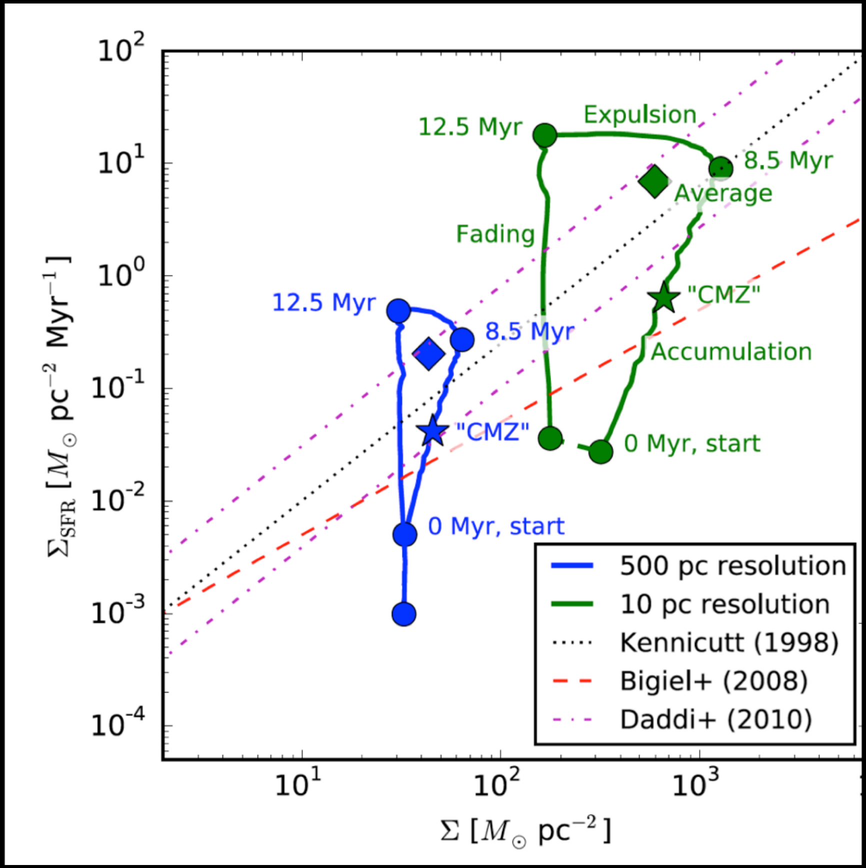






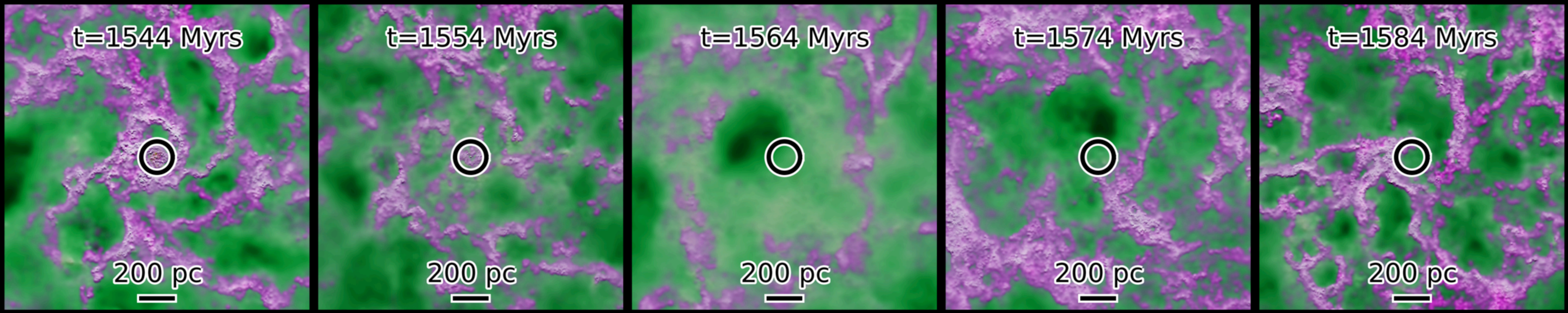
Extra Slides

Why is the SFR low in the CMZ?

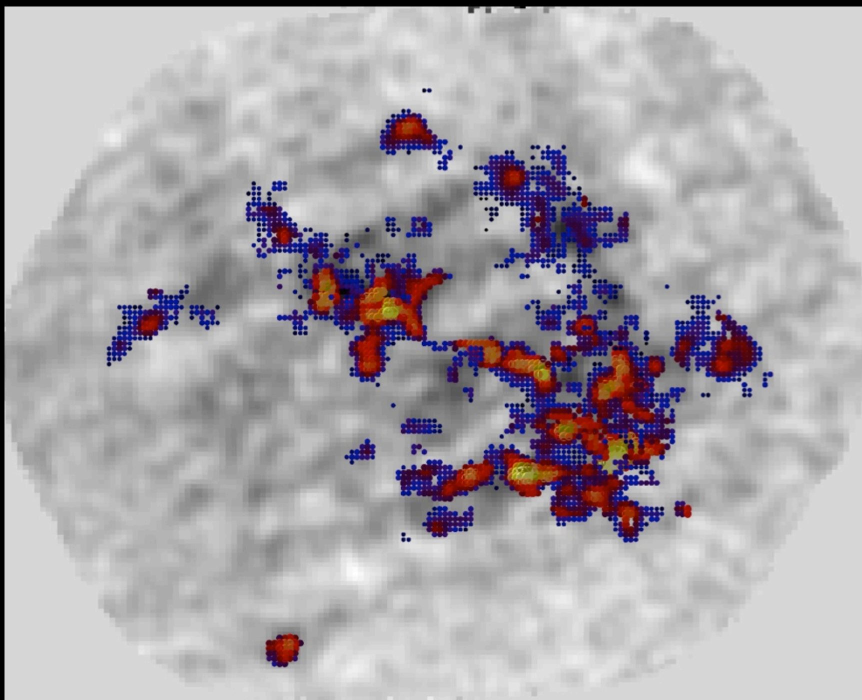


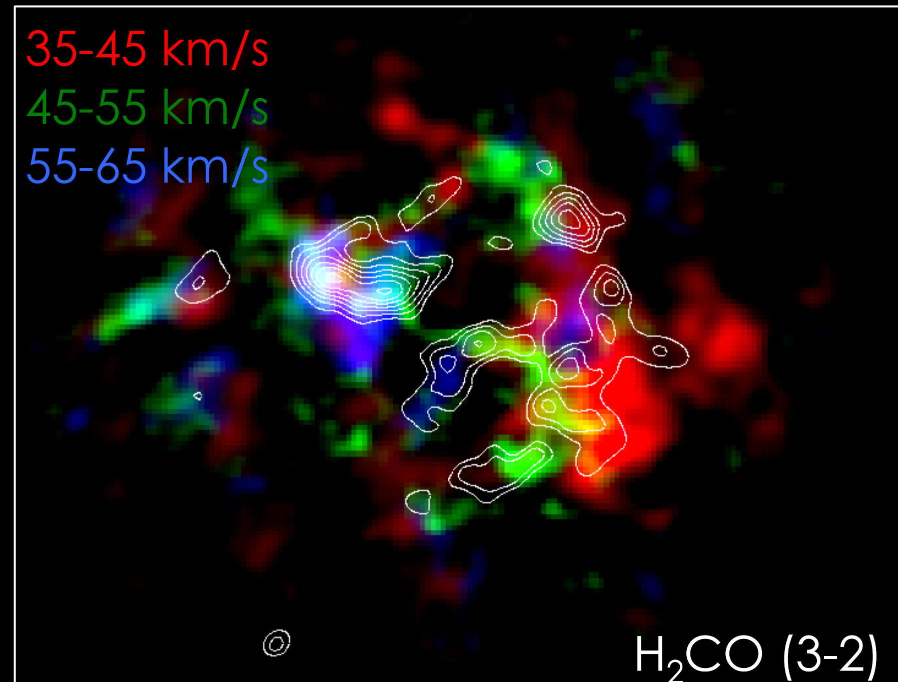
Krumholz & Kruijssen 2015

Torrey, Hopkins et al., 2017



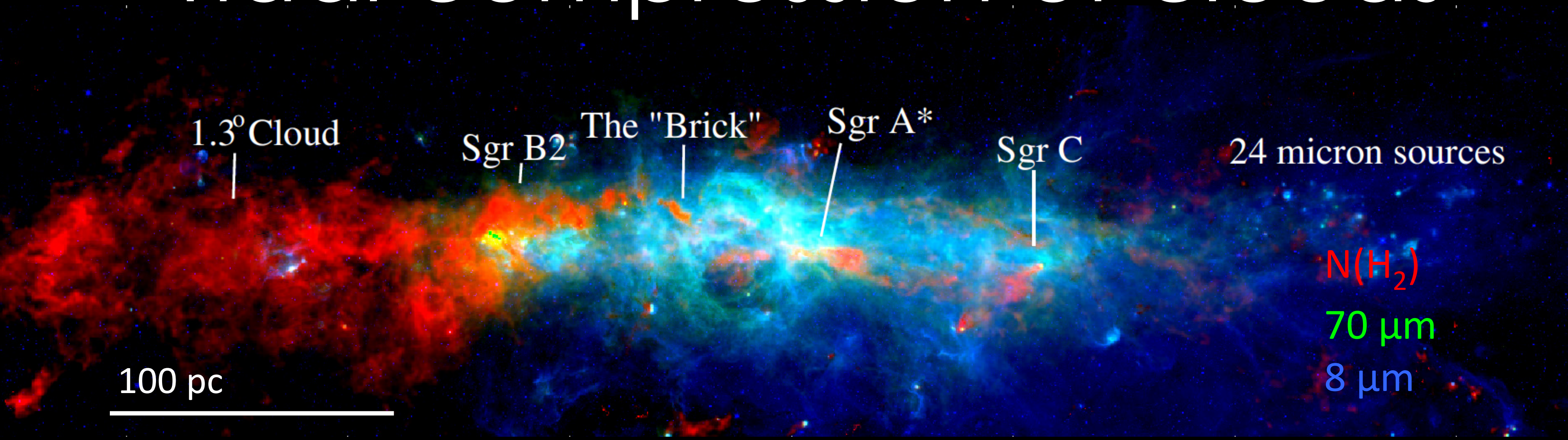
Structure Identification

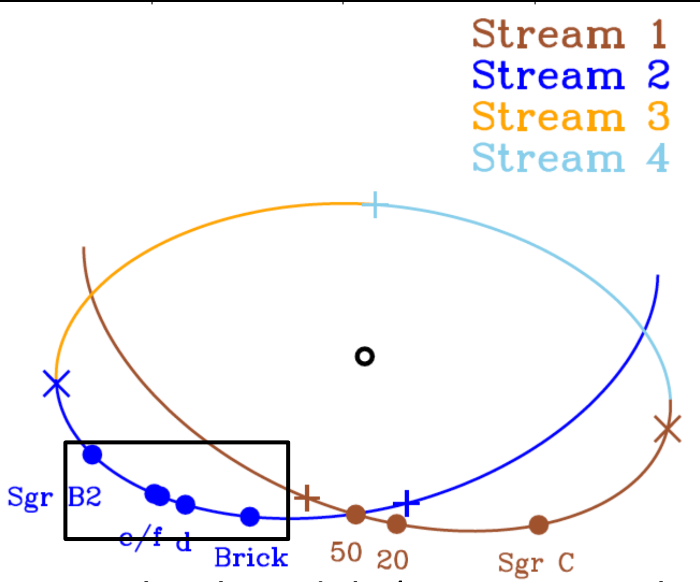




SCOUSE line fitting
Jonny Henshaw
Liverpool

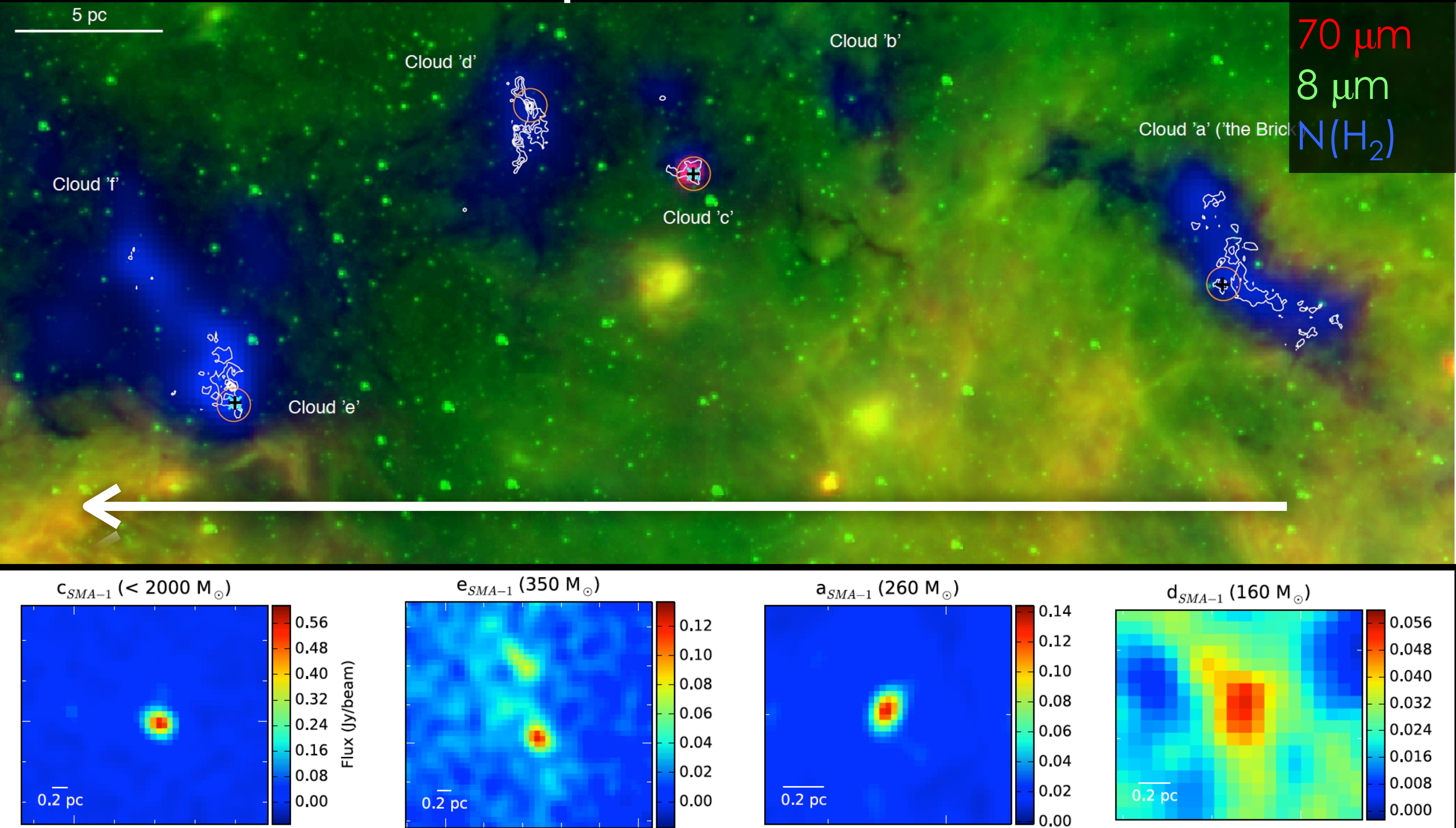
Tidal compression of clouds





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

Tidal compression of clouds

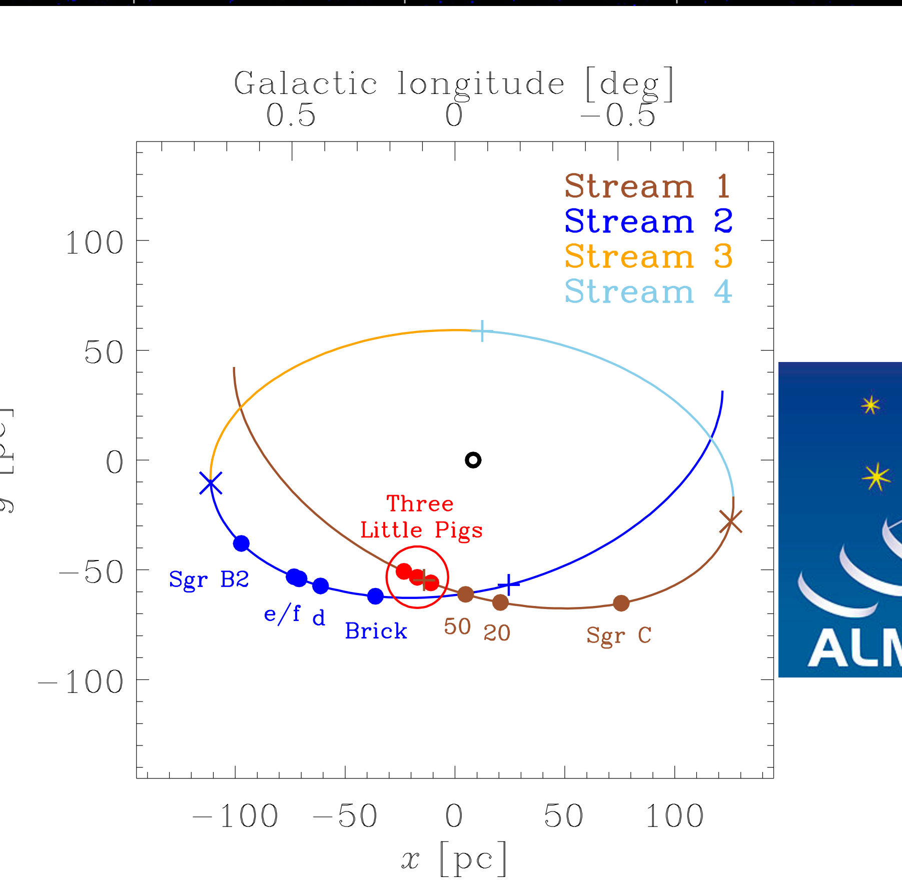


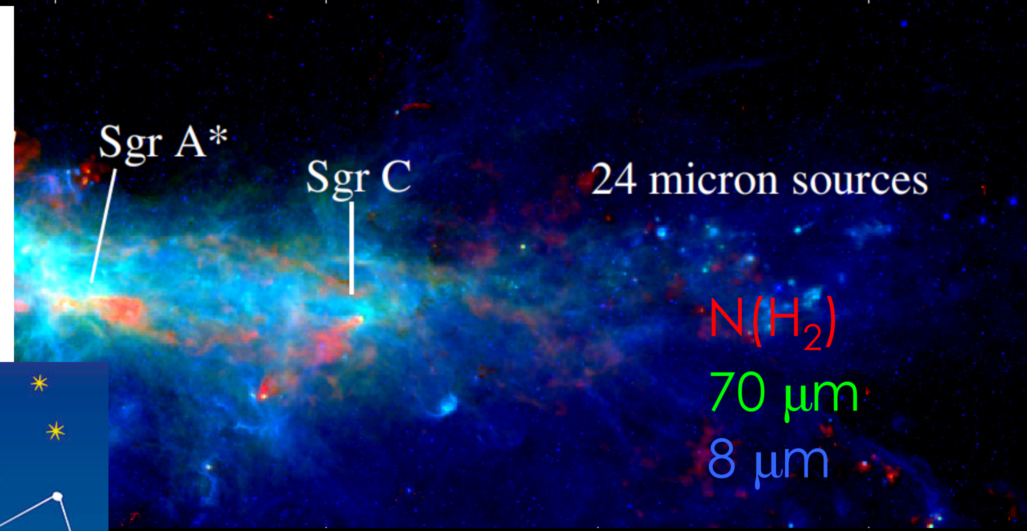
N_{ff} = 1.76
H_2O, CH_3OH, SiO, H_2CO masers + 70 μm

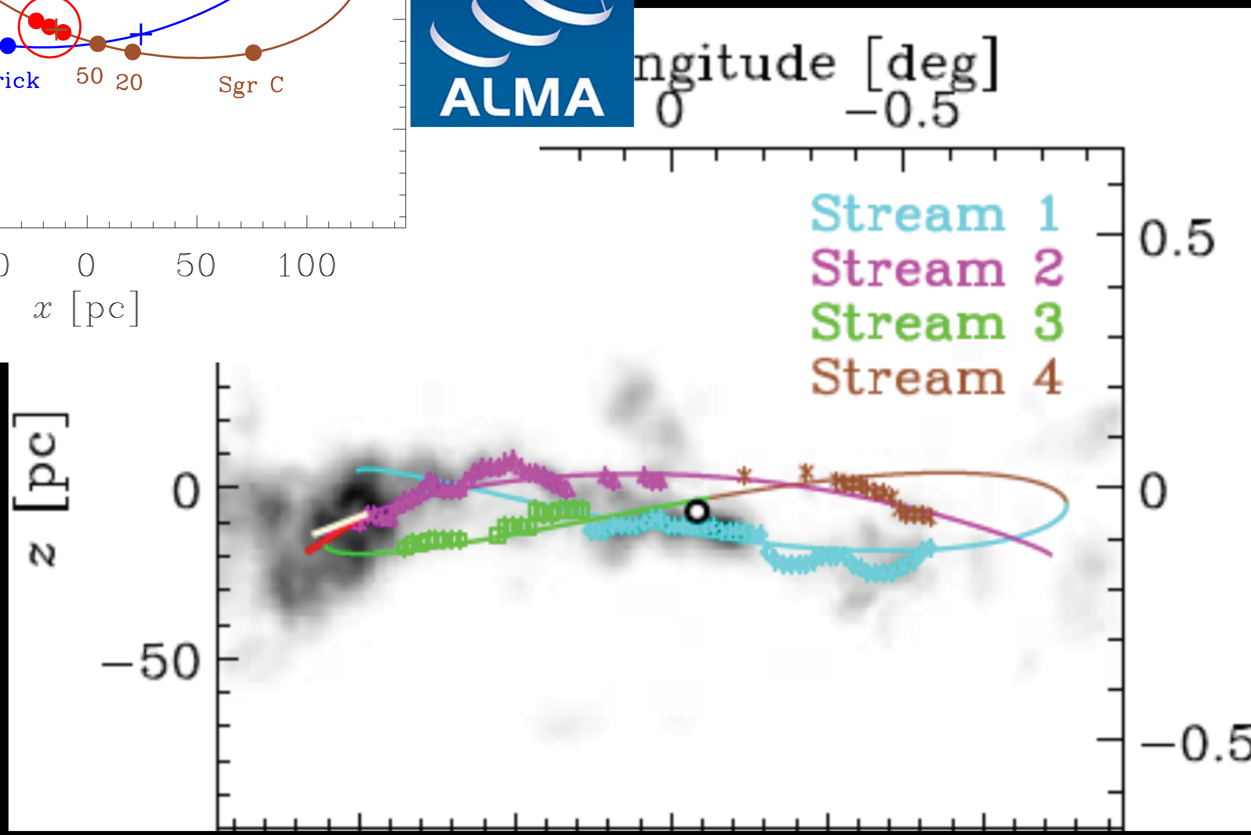
N_{ff} = 1.28
H_2O and CH_3OH masers

N_{ff} = 0.65
H_2O maser

N_{ff} = 0.61
No SF tracers

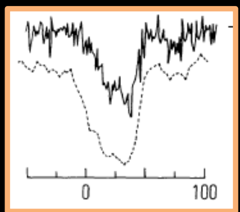






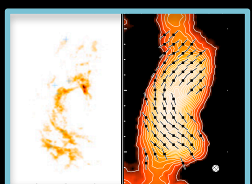
New orbital models (Kruijssen, Dale, & Longmore 2015)

Why is SF low? - Gas properties



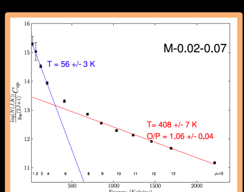
Gas is dense, n> 10^5 cm^{-3}

Guesten et al. 1983, Zylka et al. 1992, Serabyn et al. 1992, Walmsley et al. 1986



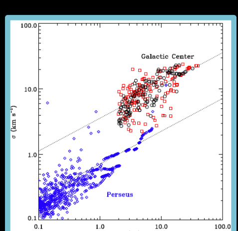
Gas is chemically complex, with ~mG magnetic fields, high ISRF, and high CRIR

complex: e.g. Rathborne et al., 2014, Requena-Torres et al. 2008, **magnetic fields:** e.g. Pillai et al. 2015, Yusef-Zadeh & Morris 1987, **high ISFR and CRIR:** e.g. Clarke et al. 2013, Goto et al. 2013, etc.



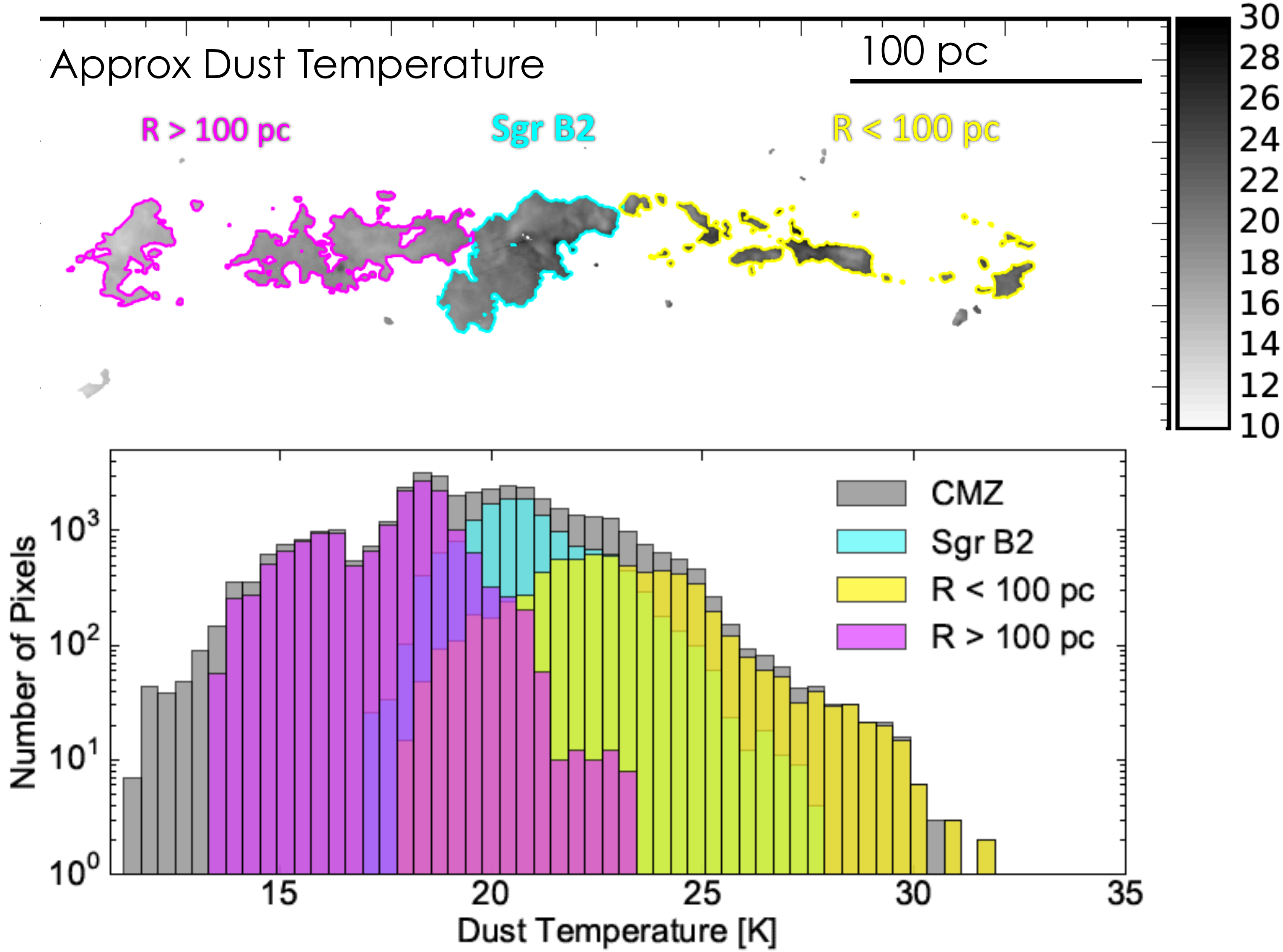
The dense gas is hot (>65 K), and 10% is 400 K

Ginsburg et al. 2016, Mills et al. 2013, Immer et al. 2016, Ott et al. 2014, Krieger et al. in prep.

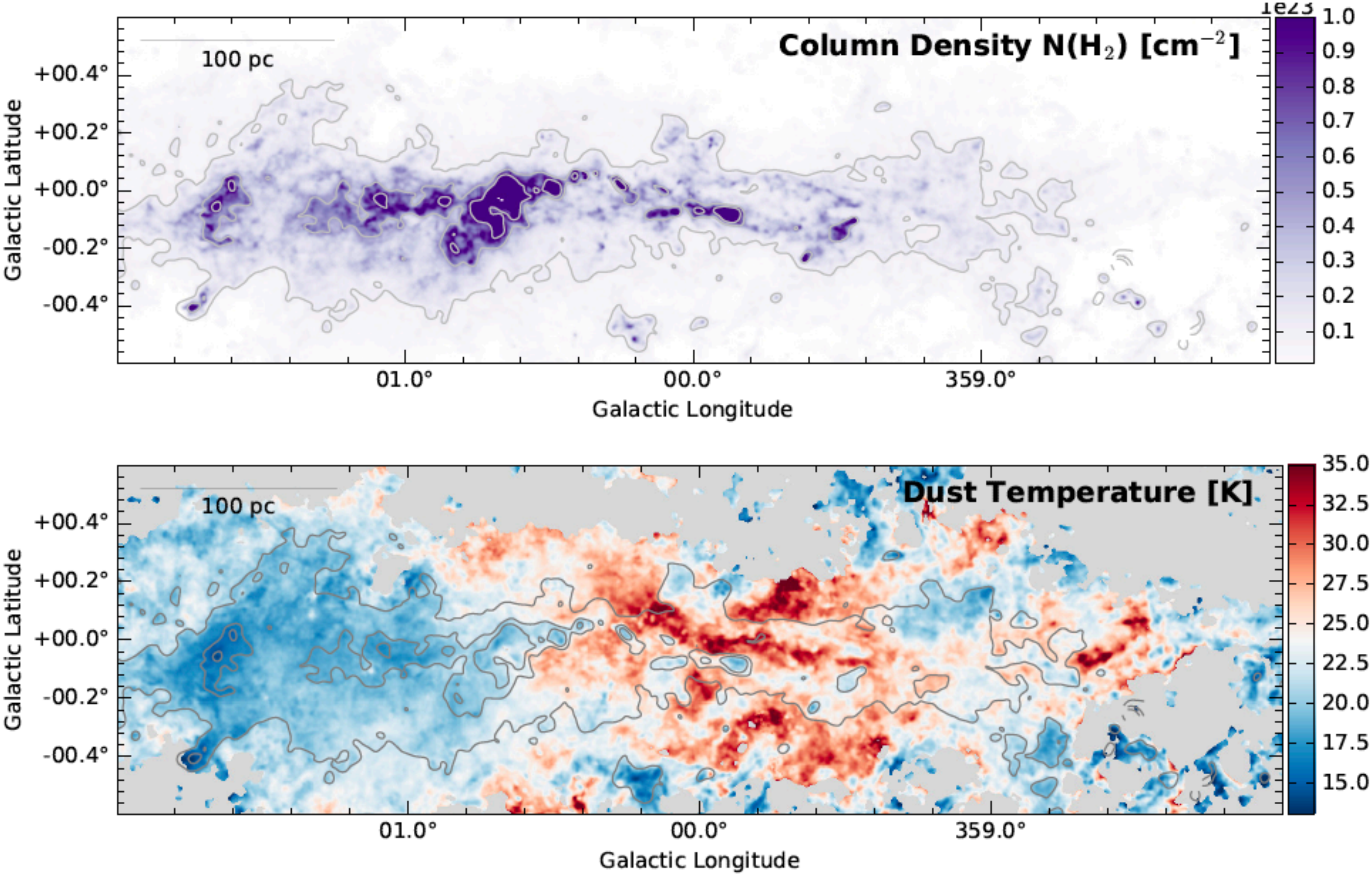


The gas is turbulent (Δv ~10 km/s, $\mathcal{M}$~10-40)

Shetty et al. 2012, Rathborne et al. 2015, Kauffmann et al. 2017 Ginsburg et al. 2016, Mills et al. 2013, Immer et al. 2016, etc.



Battersby, Longmore, Bally, Barnes, Ginsburg, & Mills in prep.



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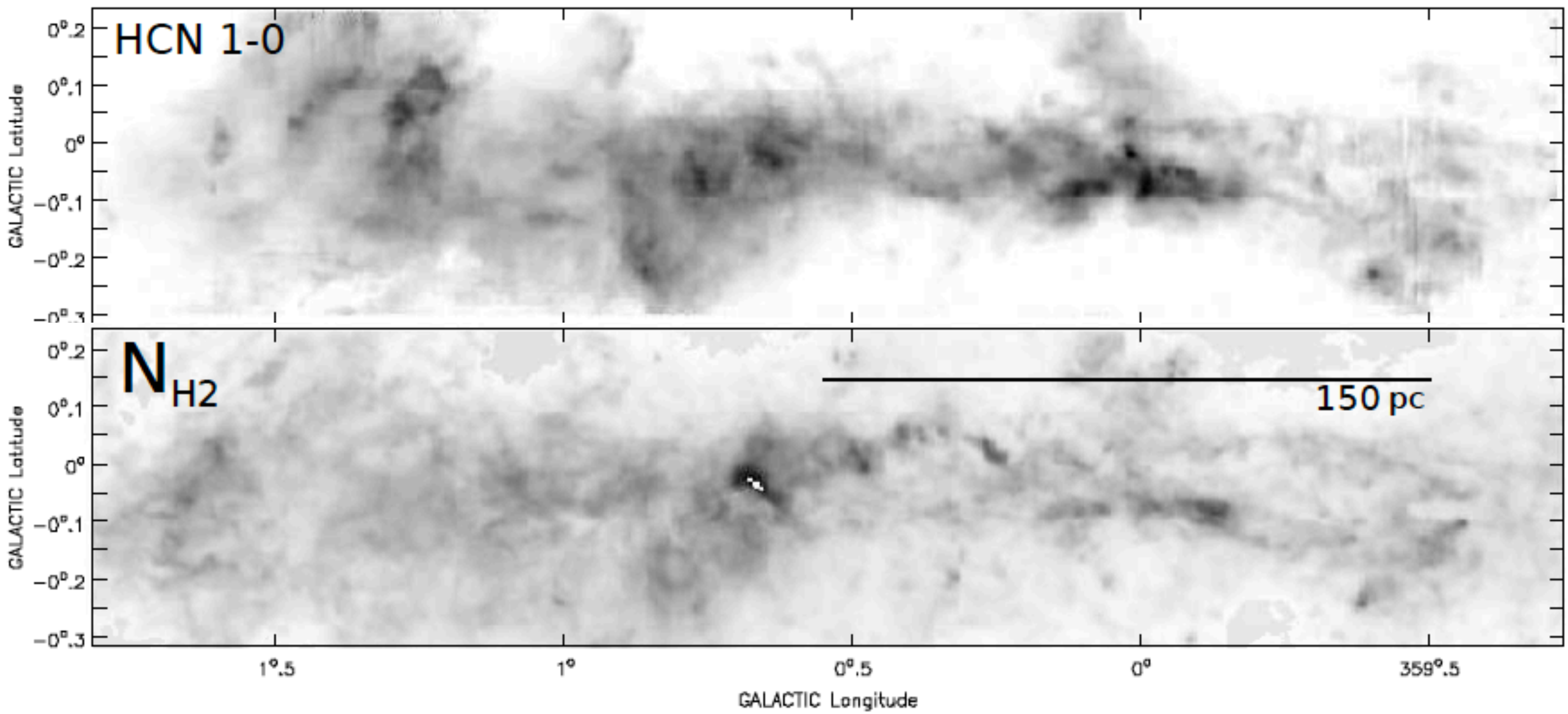

- HCN is well-correlated with dense gas overall in the CMZ - variations would only yield a 10% error in the dense gas mass
  - However, there is a lot of scatter (0.75 dex)
  - Some clouds are under-bright or over-bright by factors of 2-3
  - This is bad if you are looking at an AGN or shock-dominated region of a galaxy
- A lot of the HCN comes from more diffuse gas
- HNCO is better correlated with dense gas

Mills & Battersby 2017