Exposing Star Formation in our Galaxy's Center: A Window into the Distant Universe

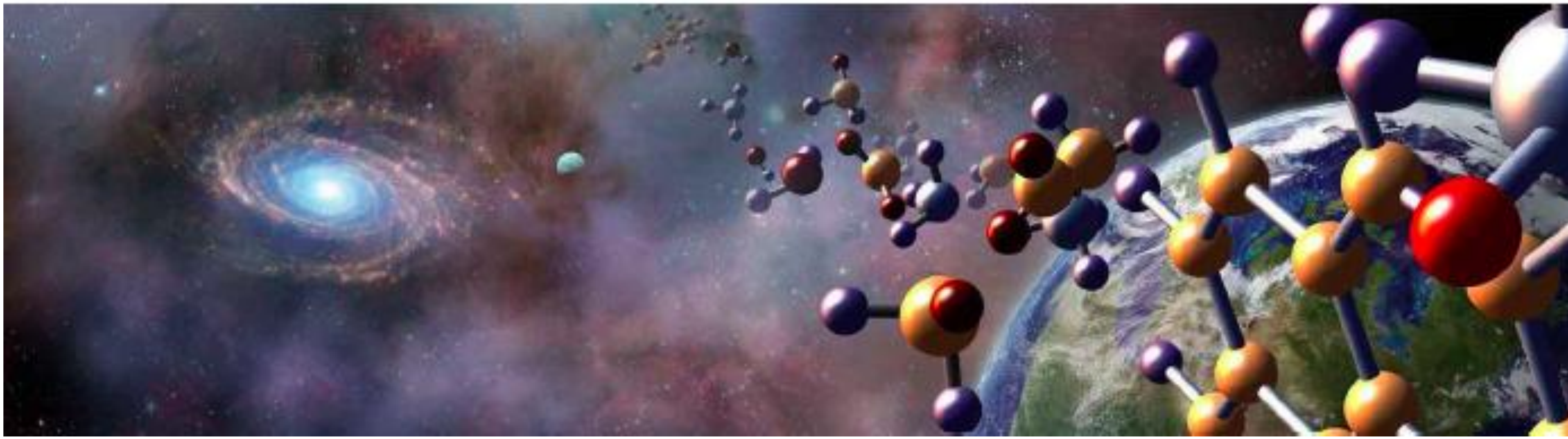
CARA BATTERSBY (CfA)

NSF fellow
Harvard Smithsonian Center for Astrophysics

Eric Keto, Qizhou Zhang, Thushara Pillai, Steve Longmore, Jens Kauffmann, Diederik Kruijssen, Daniel Walker, Xing 'Walker' Lu, Adam Ginsburg, Katharina Immer, Jonny Henshaw, Betsy Mills, Nimesh Patel, Mark Graham, Volker Tolls, John Bally, Katharine Johnston, Luis C. Ho, Andrew Walsh

ORIGINS Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.



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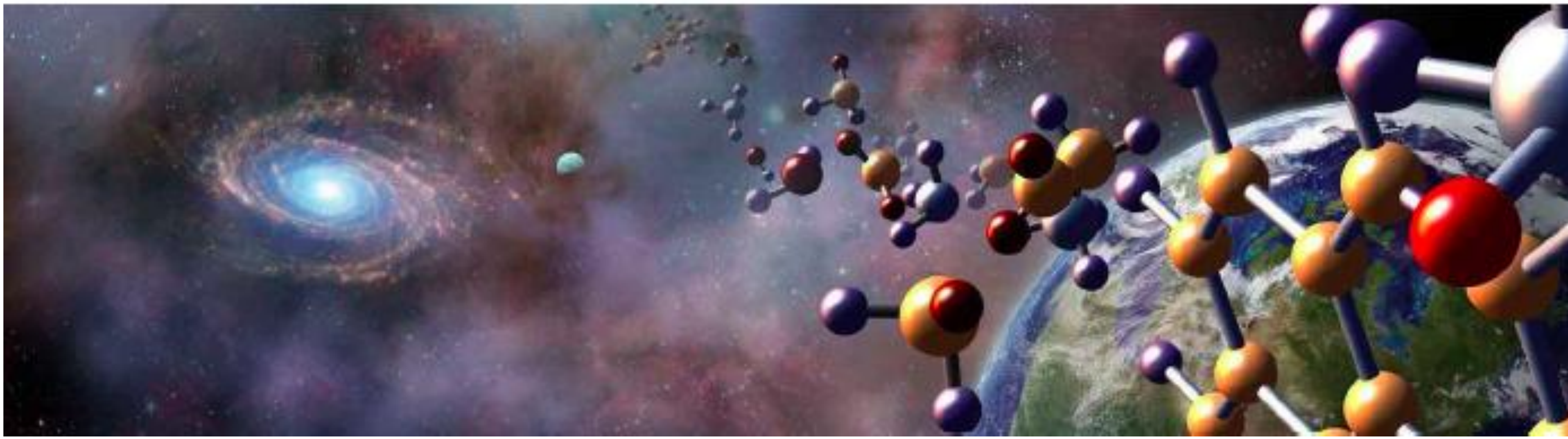
NASA



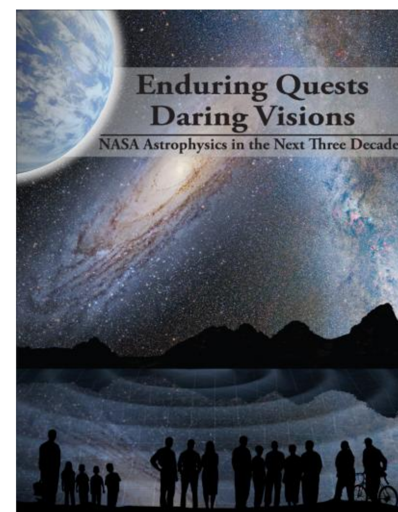
NASA Mission concept for 2020 Decadal review; launch 2030ish

7 μm – 800 μm (ish), Large aperture 8-15 m

Study Chairs: Margaret Meixner & Asantha Cooray

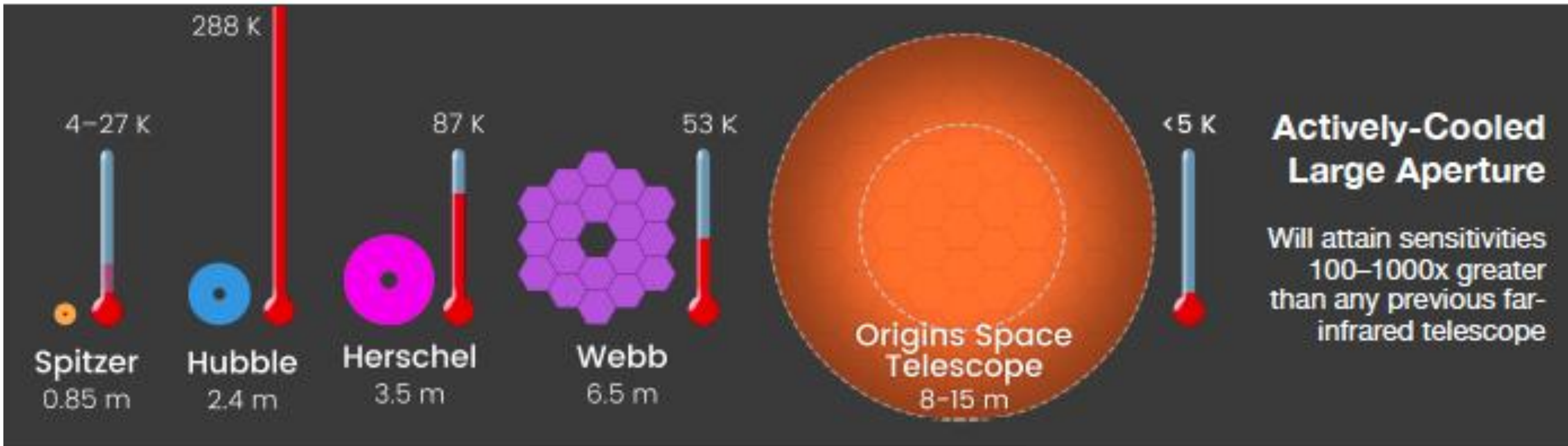
Comes from the NASA Astrophysics Roadmap, Enduring Quests, Daring Visions: Improvements from *Herschel*

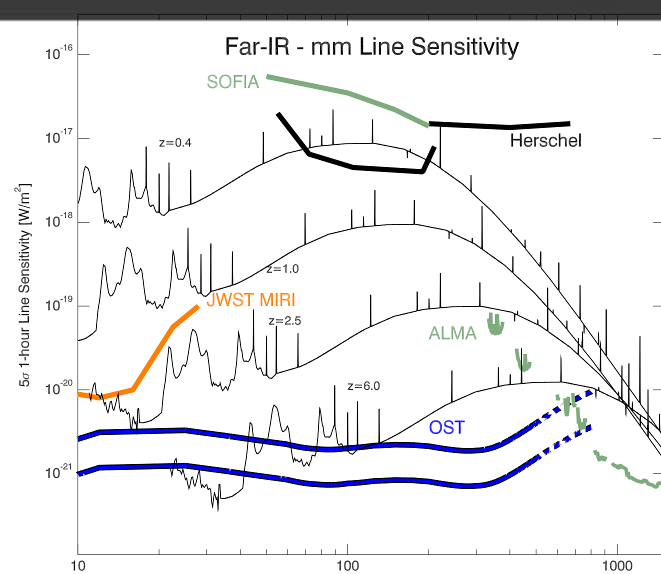
- large gain in sensitivity
- angular resolution sufficient to overcome spatial confusion in deep cosmic surveys
- new spectroscopic capability



ORIGINS Space Telescope

Technical Specifications





ORIGINS Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

Tracing the signatures of life and the ingredients of habitable worlds

Origins will trace the trail of water from interstellar clouds, to proto-planetary disks, to Earth itself facilitating understanding of the abundance and availability of water for habitable planets.

Unveiling the Growth of Black Holes and Galaxies over Cosmic Time

Origins will reveal the co-evolution of super-massive black holes and galaxies, energetic feedback, and the dynamic interstellar medium from which stars are born.

Origins will trace the metal enrichment history of the Universe, probe the first cosmic sources of dust, the earliest star formation, and the birth of galaxies.

Charting the Rise of Metals, Dust, and the First Galaxies

Origins will chart the role of comets in delivering water to the early Earth, and conduct a survey of thousands of ancient Trans Neptunian Objects (TNOs) in the outer reaches of the Solar System.

Characterizing Small Bodies in the Solar System

ORIGINS Space Telescope

Tracing the rise of dust & metals in galaxies and the path of water across cosmic time to Earth and other habitable planets.

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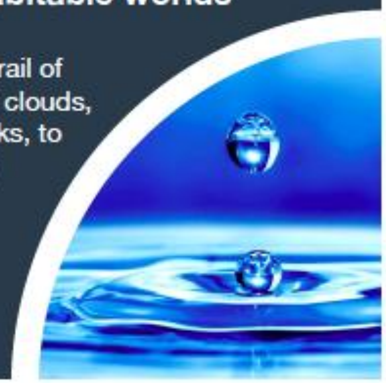


Unveiling the Growth of Black Holes and Galaxies over Cosmic Time

Origins will reveal the co-evolution of super-massive black holes and galaxies, energetic feedback, and the dynamic interstellar medium from which stars are born.

We want your input!
Please contact, if interested in contributing:
cbattersby@cfa.harvard.edu

The Milky Way Laboratory

Extreme SF in our Galactic Center

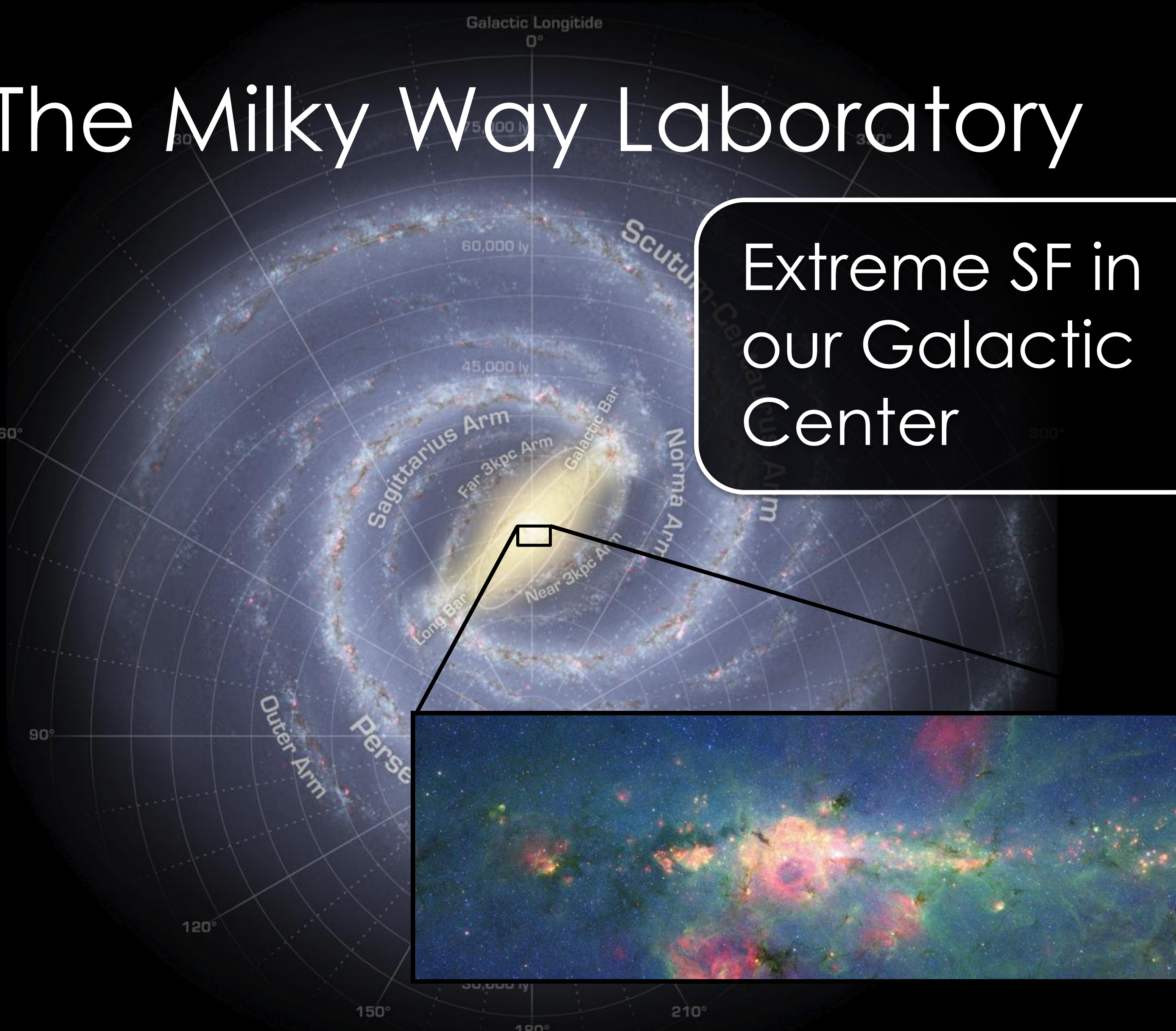


Figure Credit: NASA / JPL-Caltech / R. Hurt (SSC-Caltech)

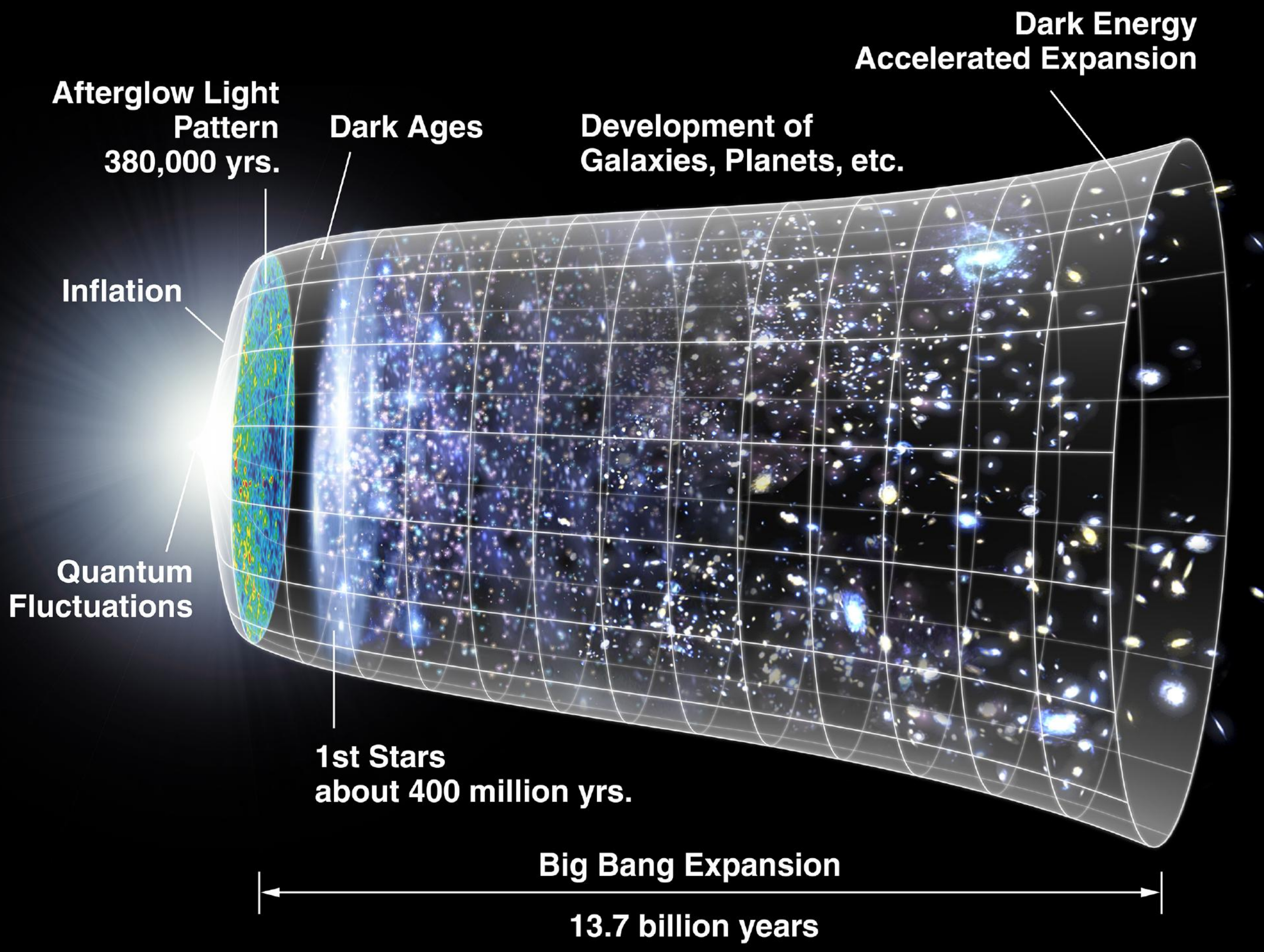
Central Molecular Zone

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

Central Molecular Zone

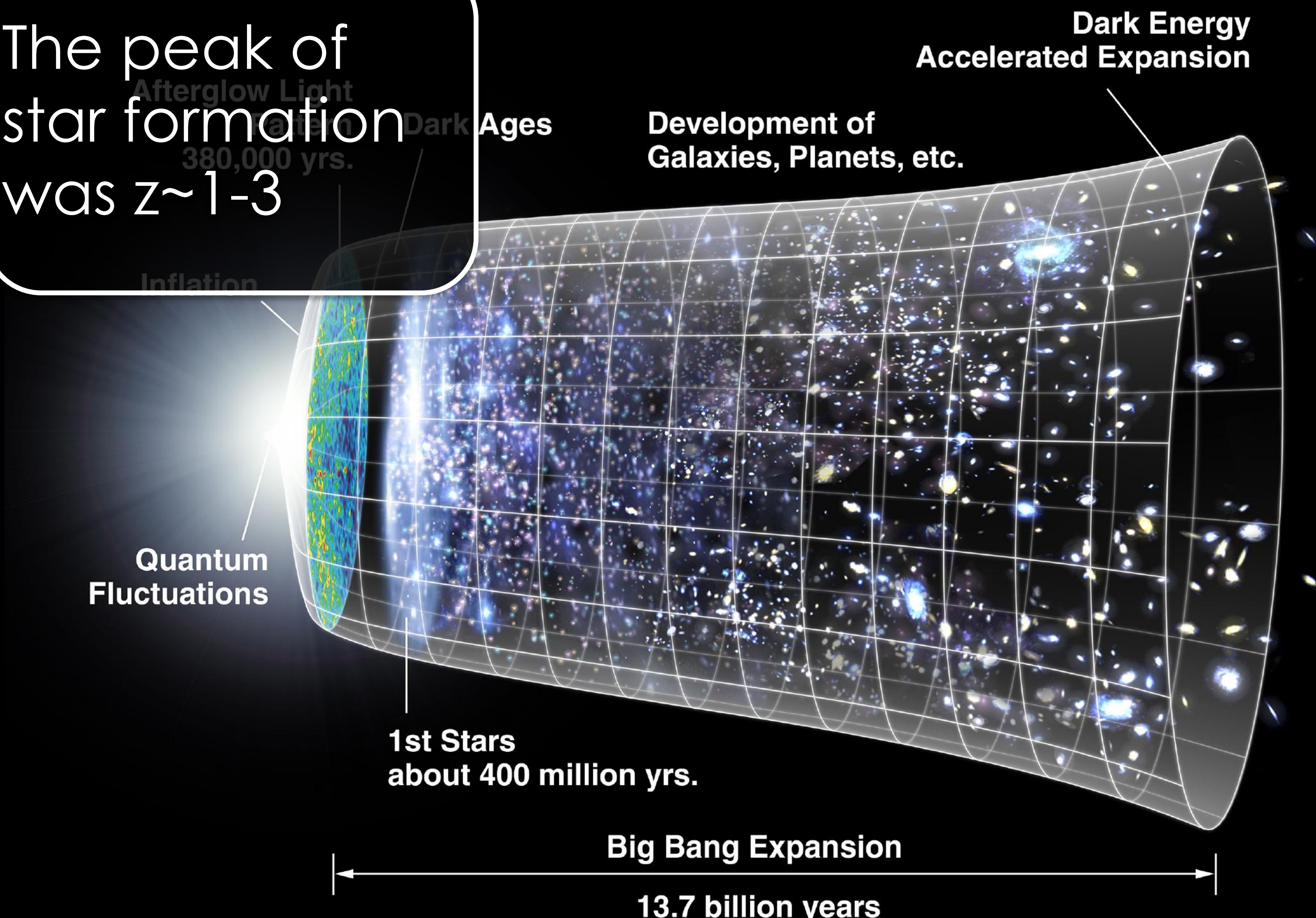
$N(H_2)$ (Battersby+ in prep.), 70 μm (Hi-GAL, Molinari +2011),
8 μm (GLIMPSE, Benjamin+20003)

Star Formation over cosmic time



Star Formation over cosmic time

The peak of star formation was z~1-3



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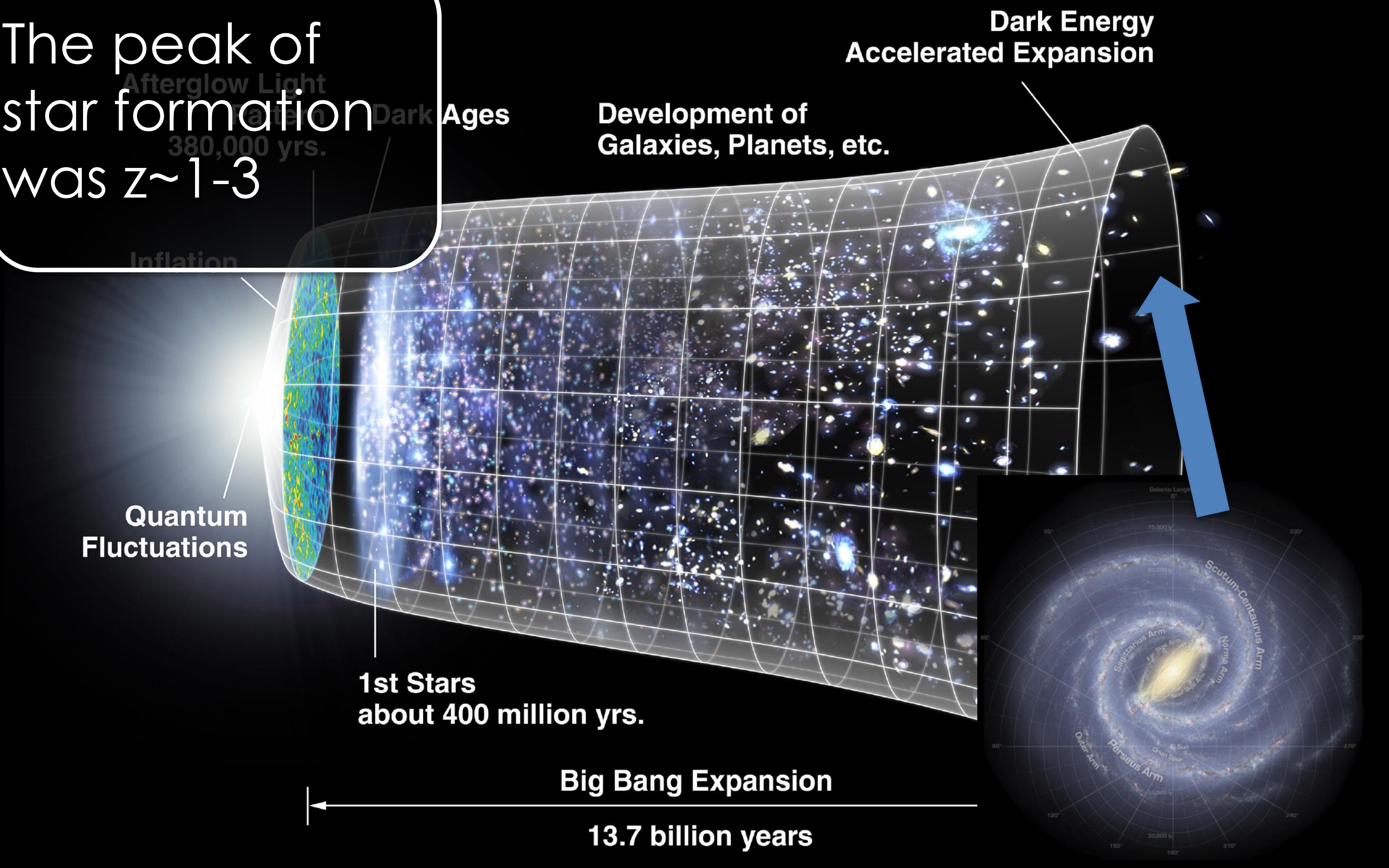
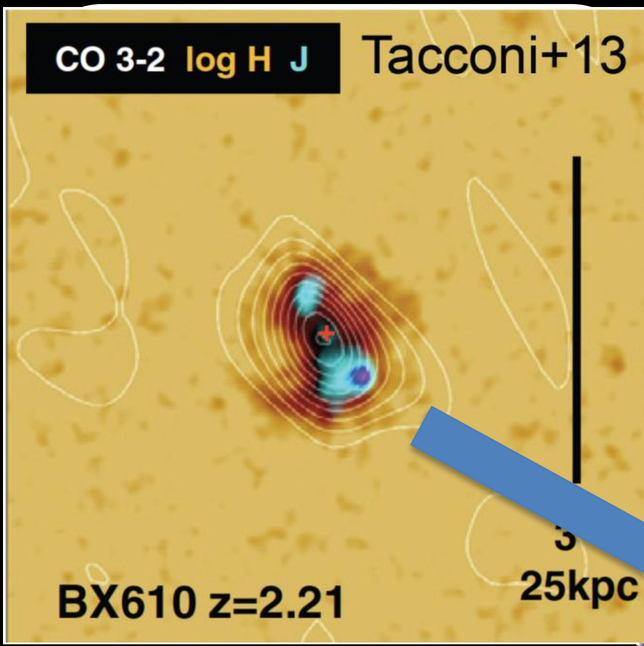
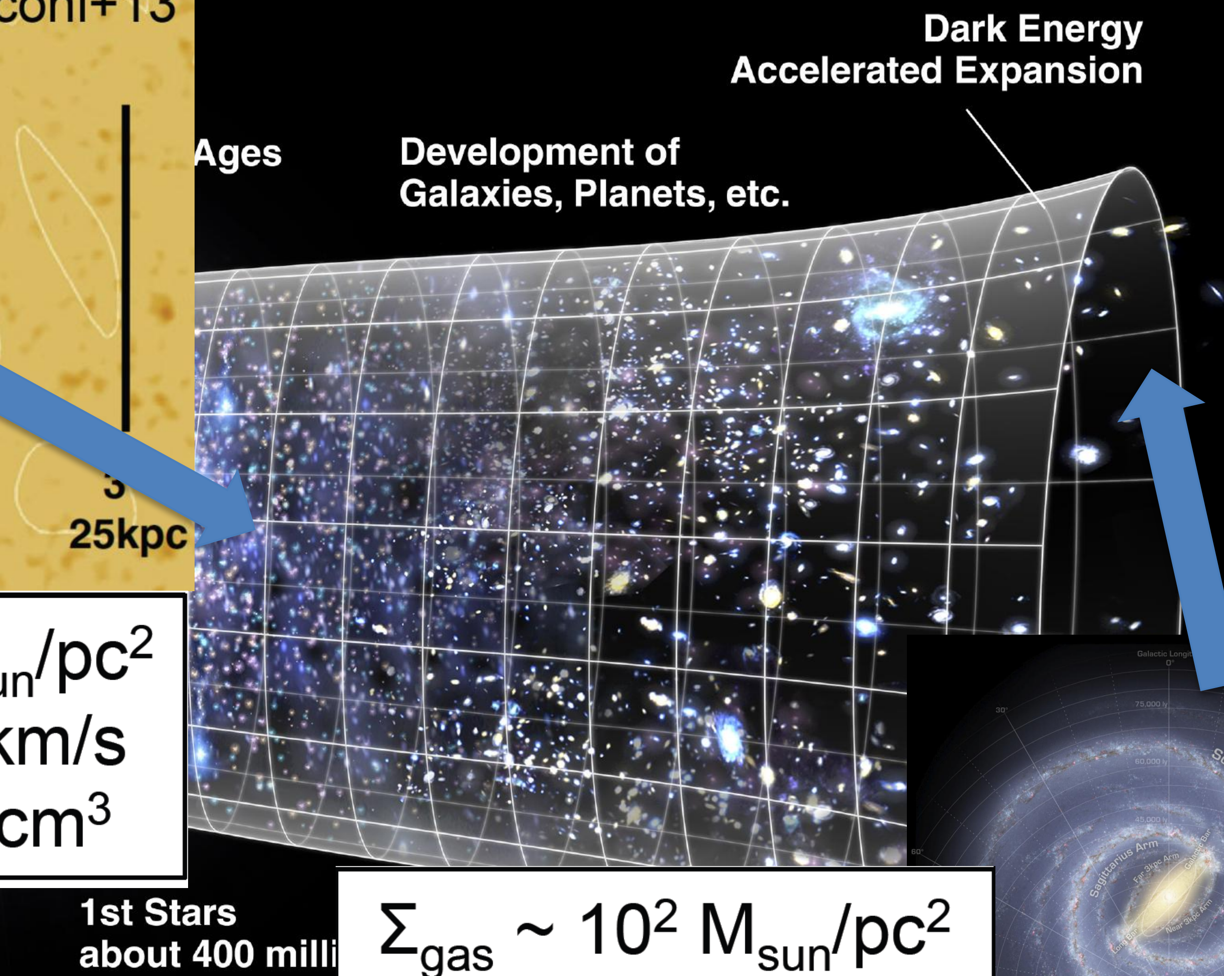
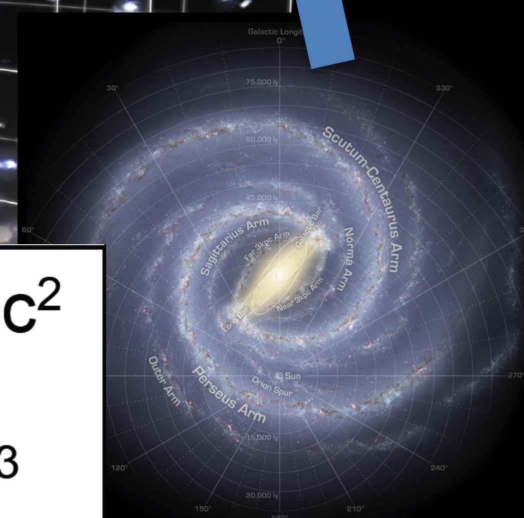


Star Formation over cosmic time



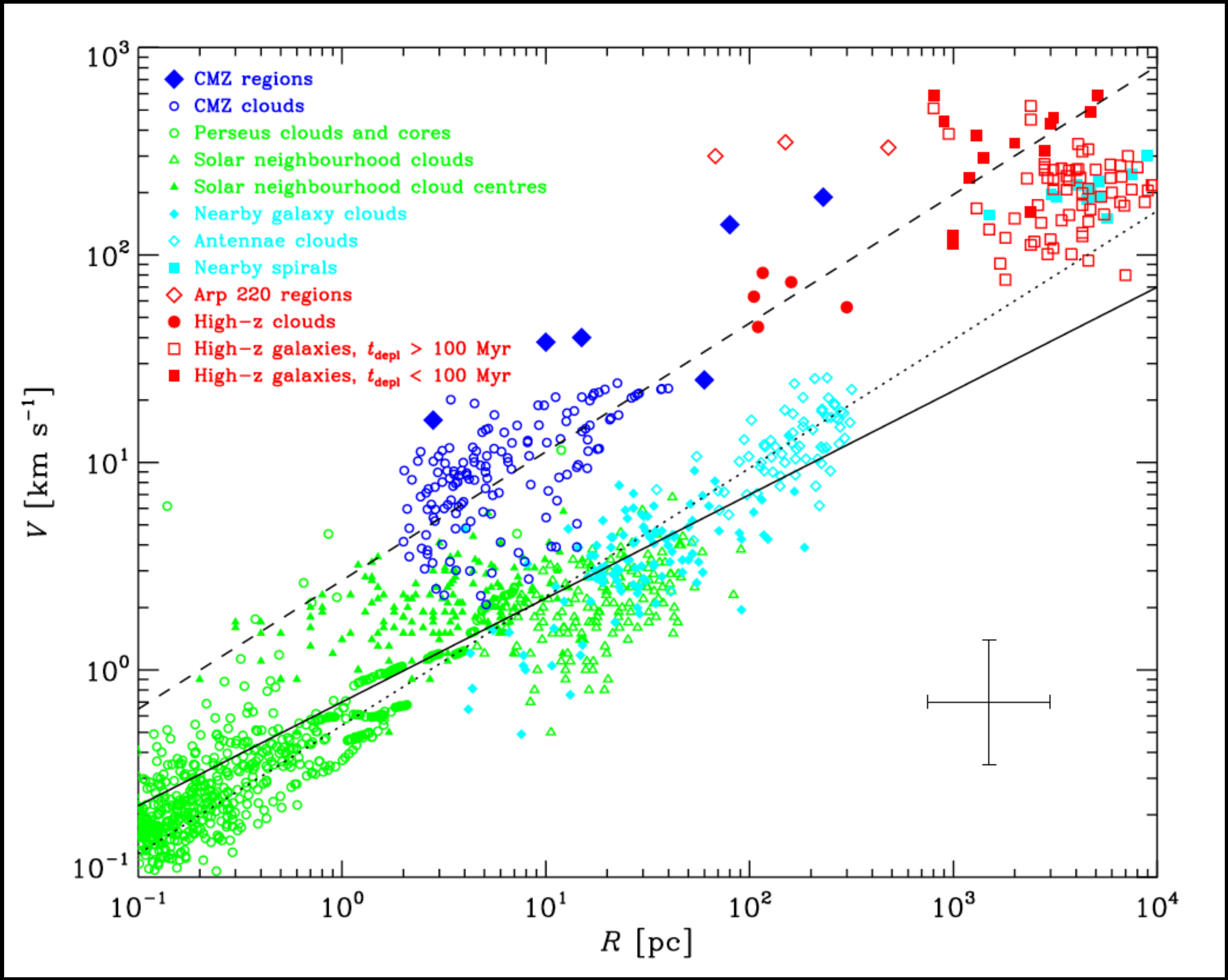
$$\Sigma_{gas} \sim 10^3\ M_{sun}/pc^2$$
$$\sigma \sim 20 - 50\ km/s$$
$$P/k \sim 10^7\ K/cm^3$$





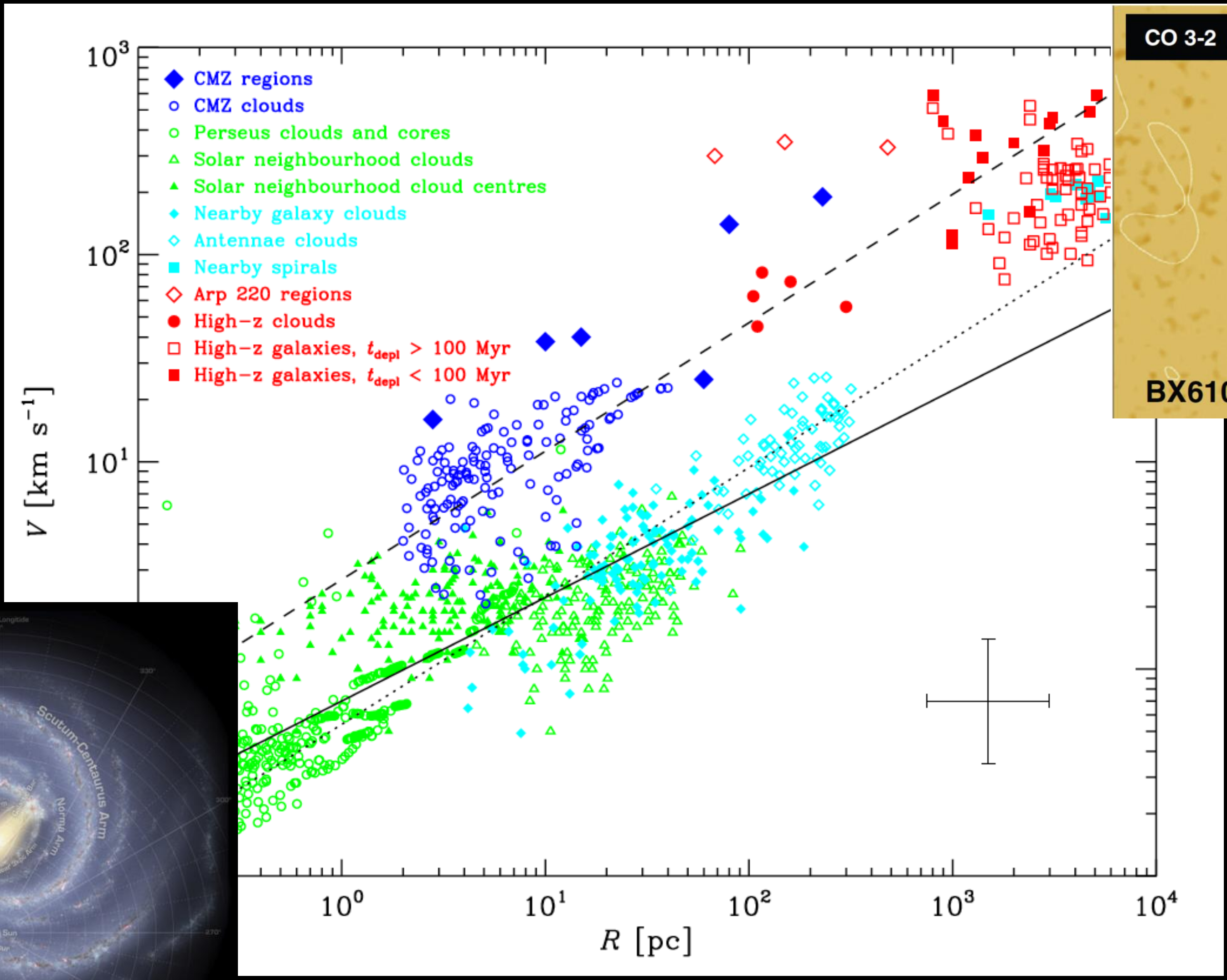
$$\Sigma_{gas} \sim 10^2\ M_{sun}/pc^2$$
$$\sigma \sim 10\ km/s$$
$$P/k \sim 10^4\ K/cm^3$$

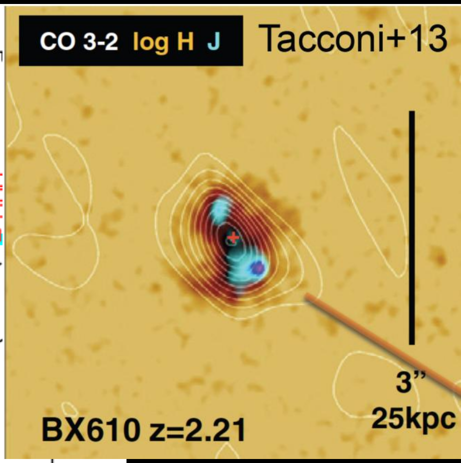
Star Formation over cosmic time

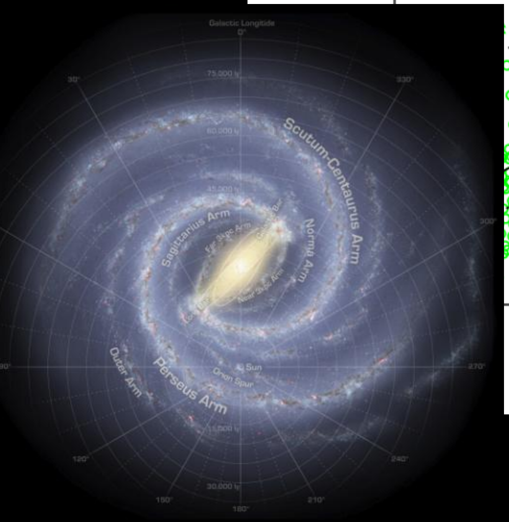


Kruijssen & Longmore 2013

Star Formation over cosmic time







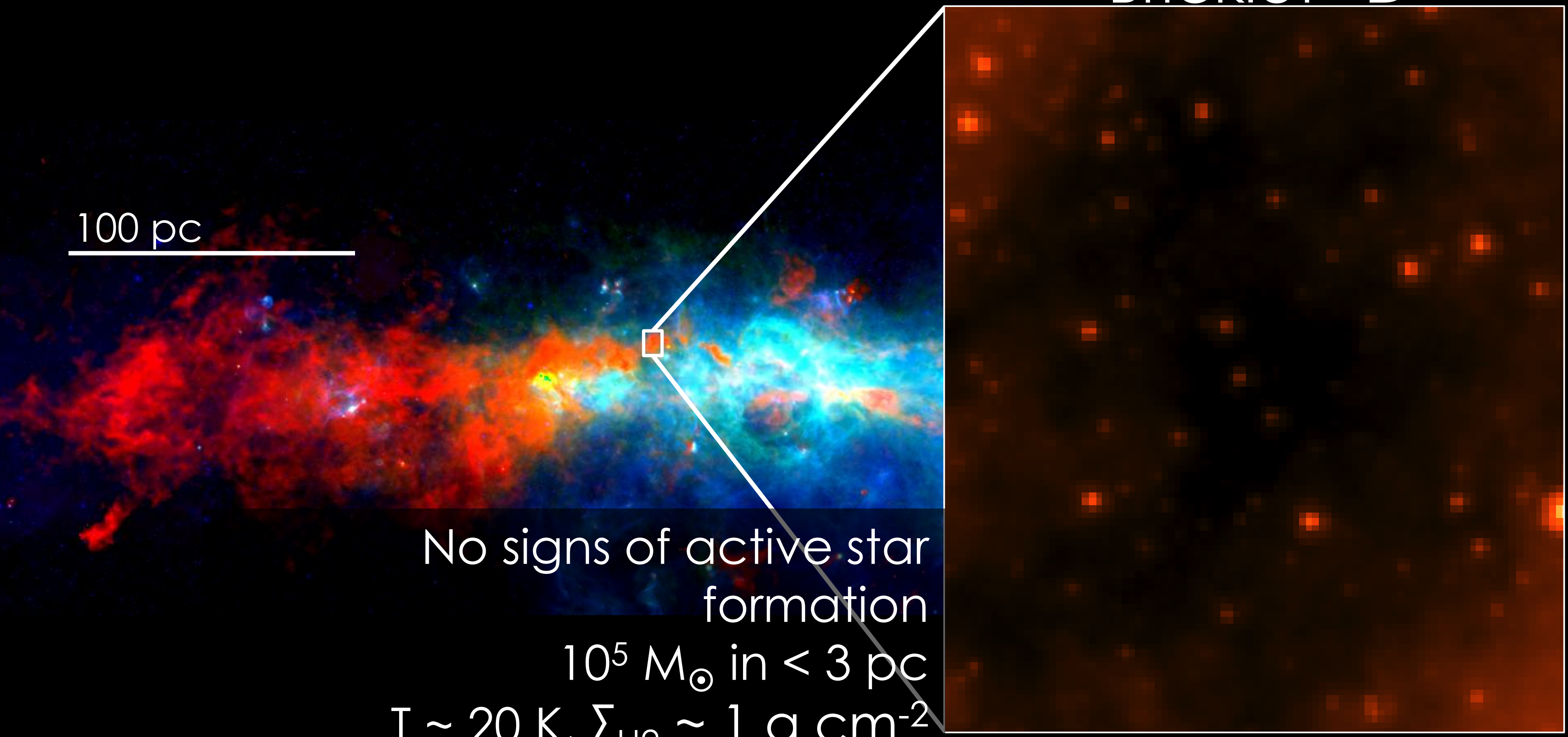
Kruijssen & Longmore 2013

Central Molecular Zone

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

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

Central Molecular Zone



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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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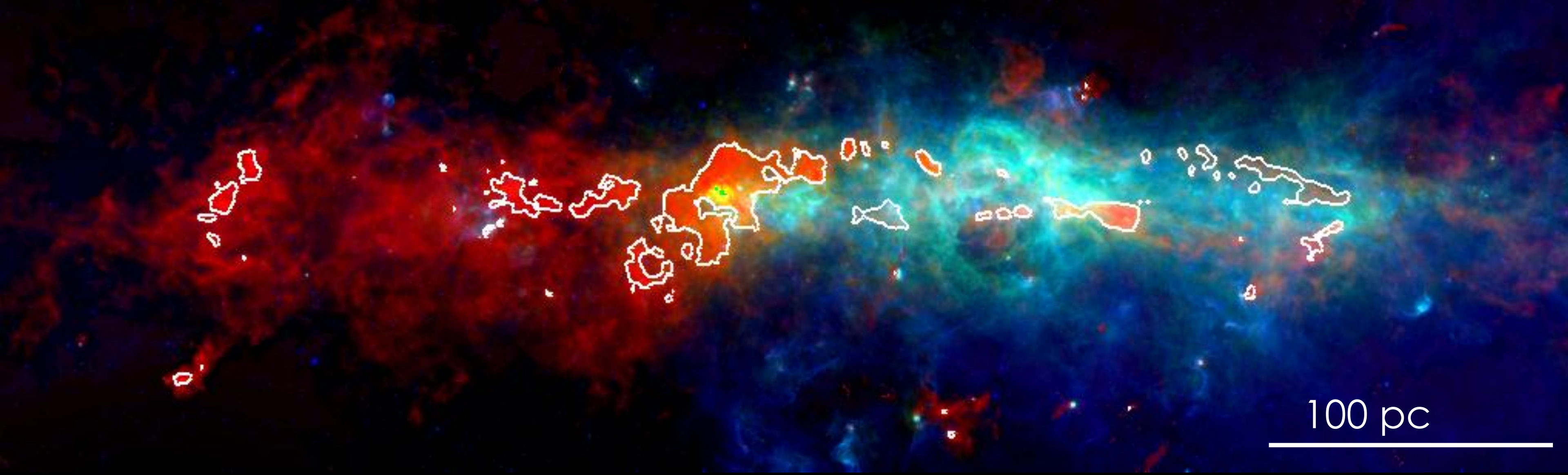
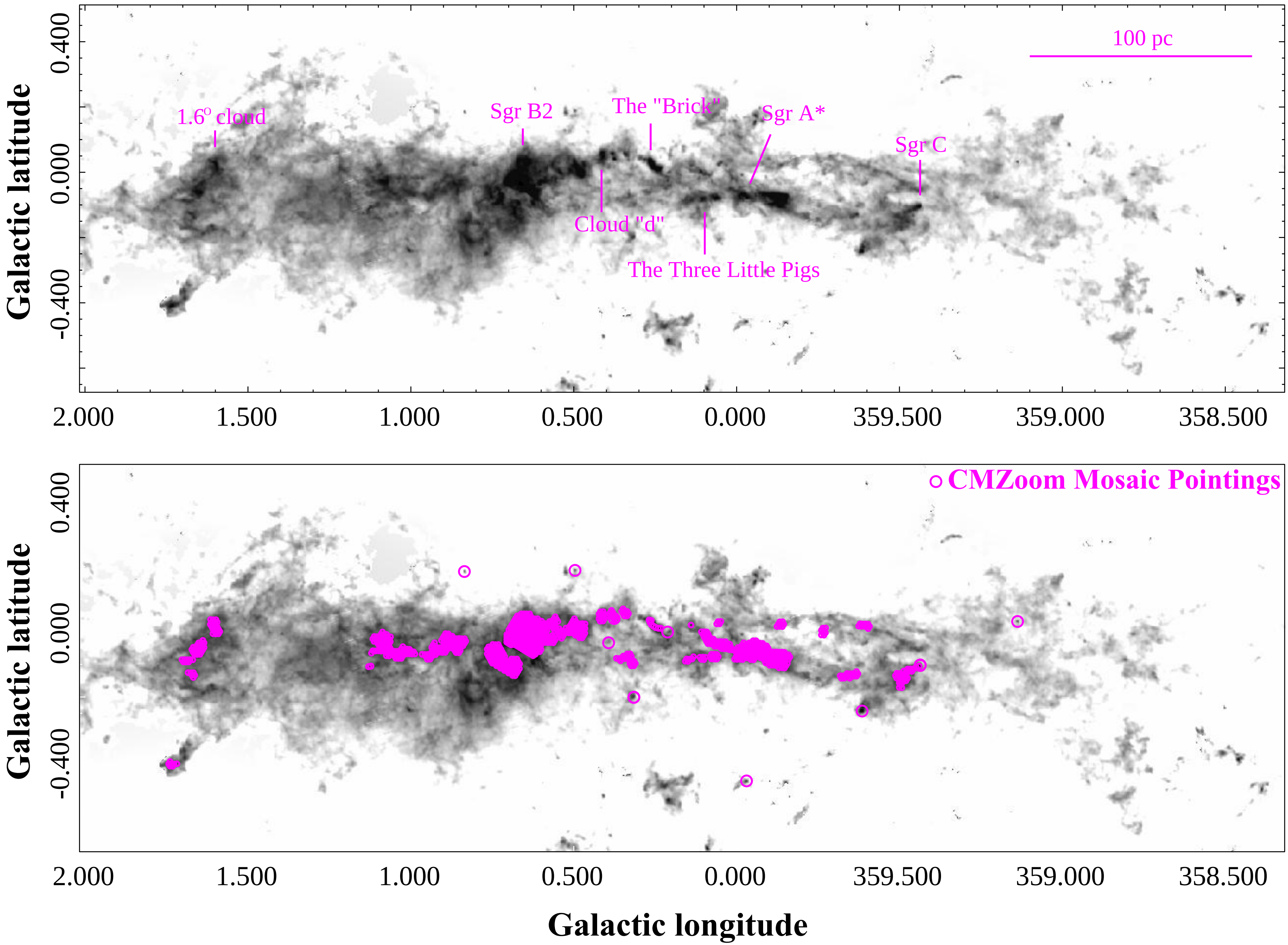
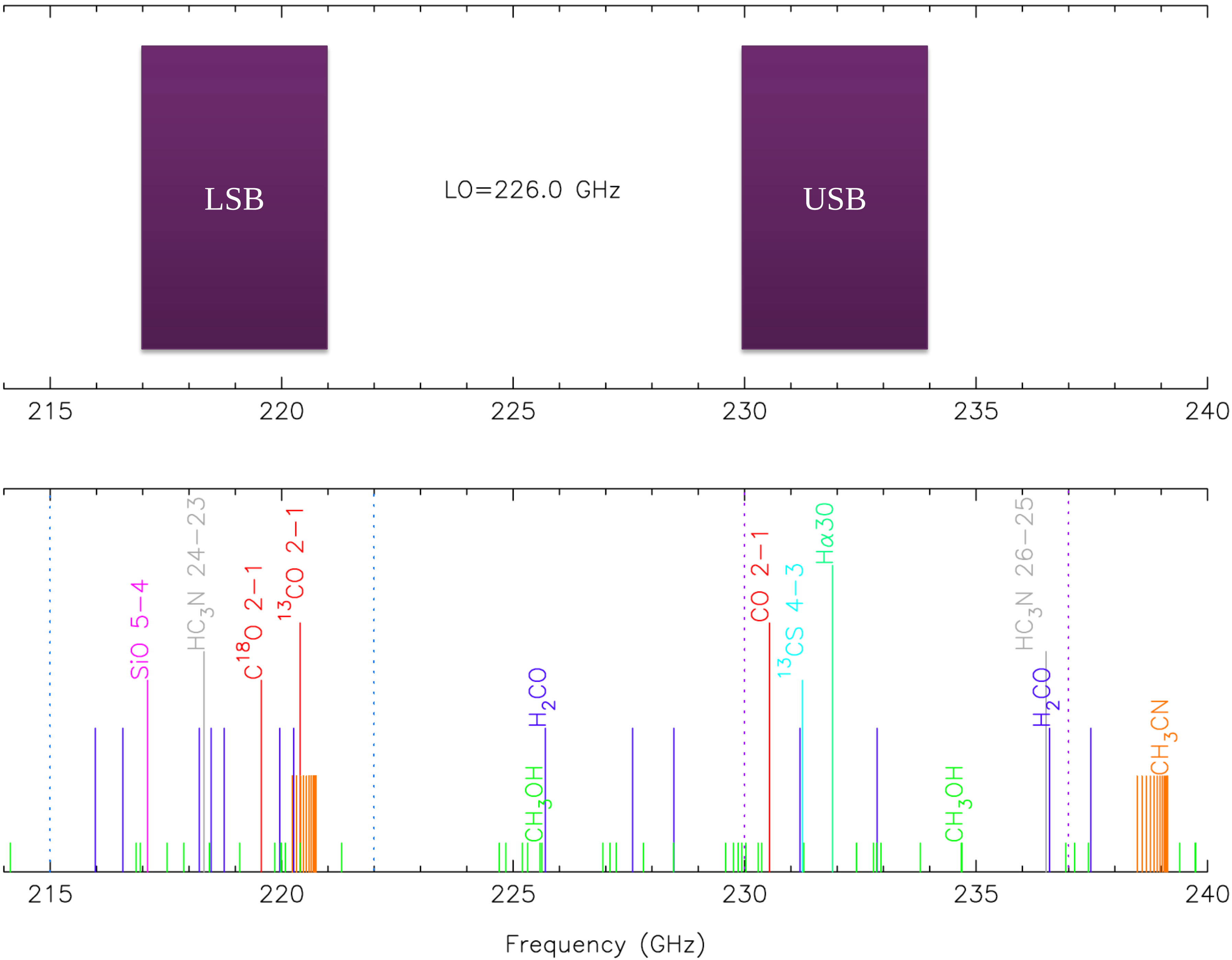
CMZoom



- 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
- 500 hours (60 tracks; 15 tracks subcompact, 45 tracks compact) over 3 yrs
- Complement with single-dish (APEX, CSO) observations

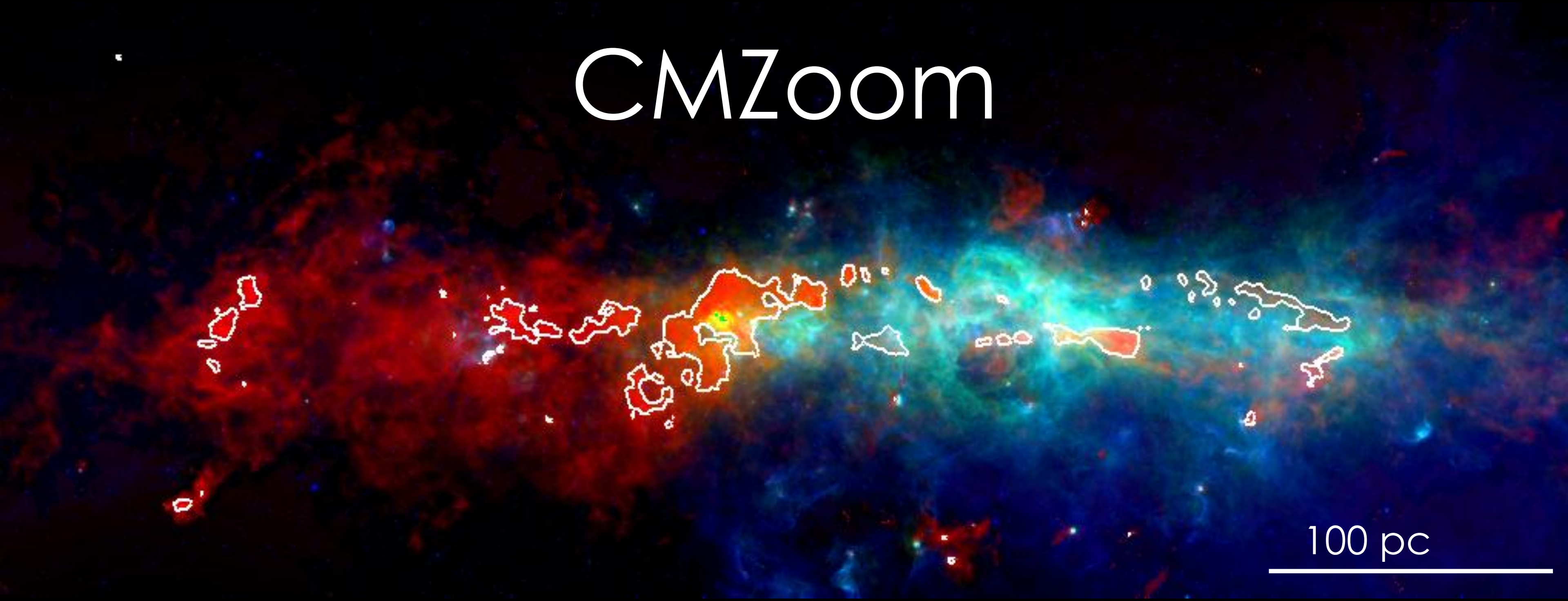


100 pc
1.6° cloud
Sgr B2
The "Brick"
Sgr A*
Sgr C
Cloud "d"
The Three Little Pigs
CMZoom Mosaic Pointings
Galactic latitude
Galactic longitude
0.400
0.000
-0.400
2.000
1.500
1.000
0.500
0.000
359.500
359.000
358.500



LSB
LO=226.0 GHz
USB
215
220
225
230
235
240
SiO 5−4
HC3N 24−23
C18O 2−1
13CO 2−1
CH3OH
H2CO
CO 2−1
13CS 4−3
Hα30
CH3OH
HC3N 26−25
H2CO
CH3CN
Frequency (GHz)

CMZoom



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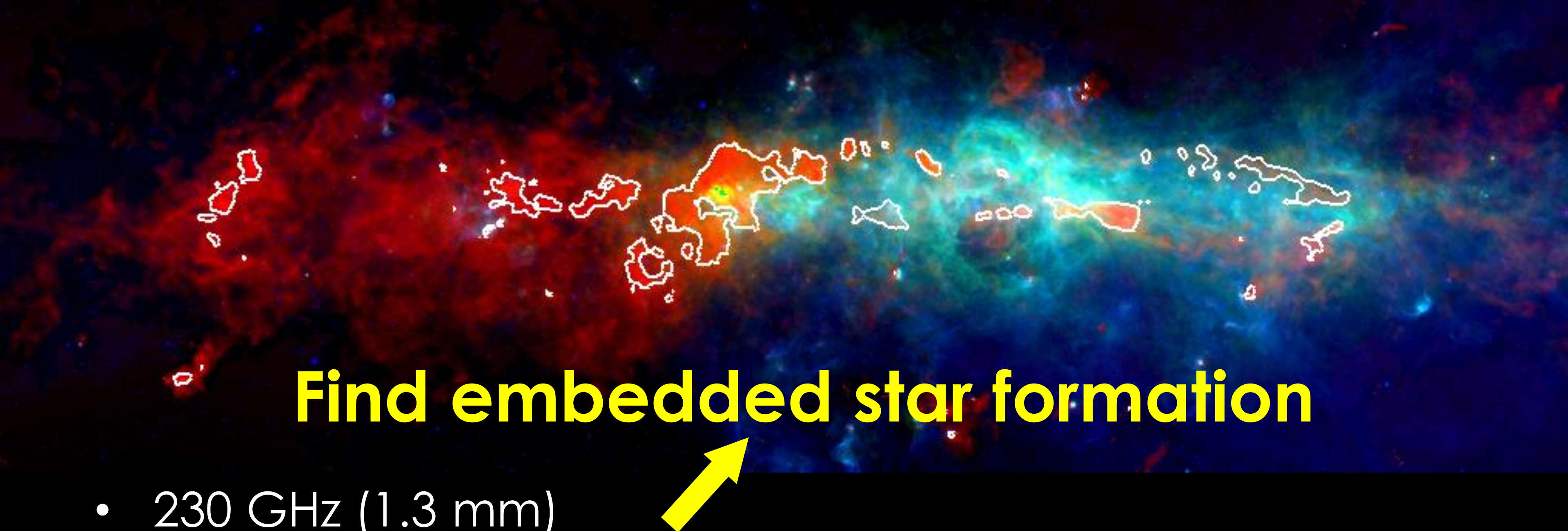

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- 3 mJy RMS continuum, 0.4 K
- 500 hours (50 subcompact, 450 compact/custom) over 3 yrs
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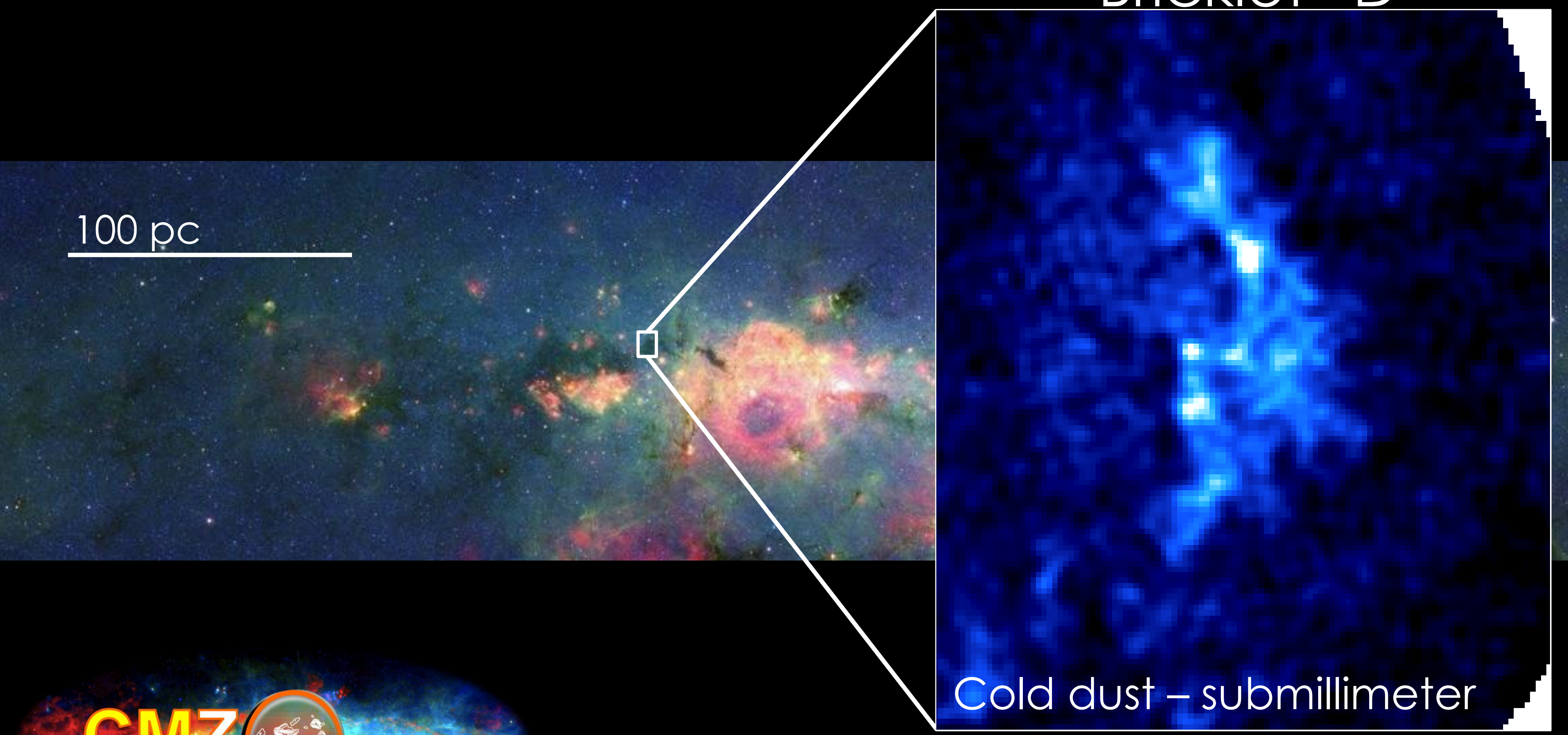
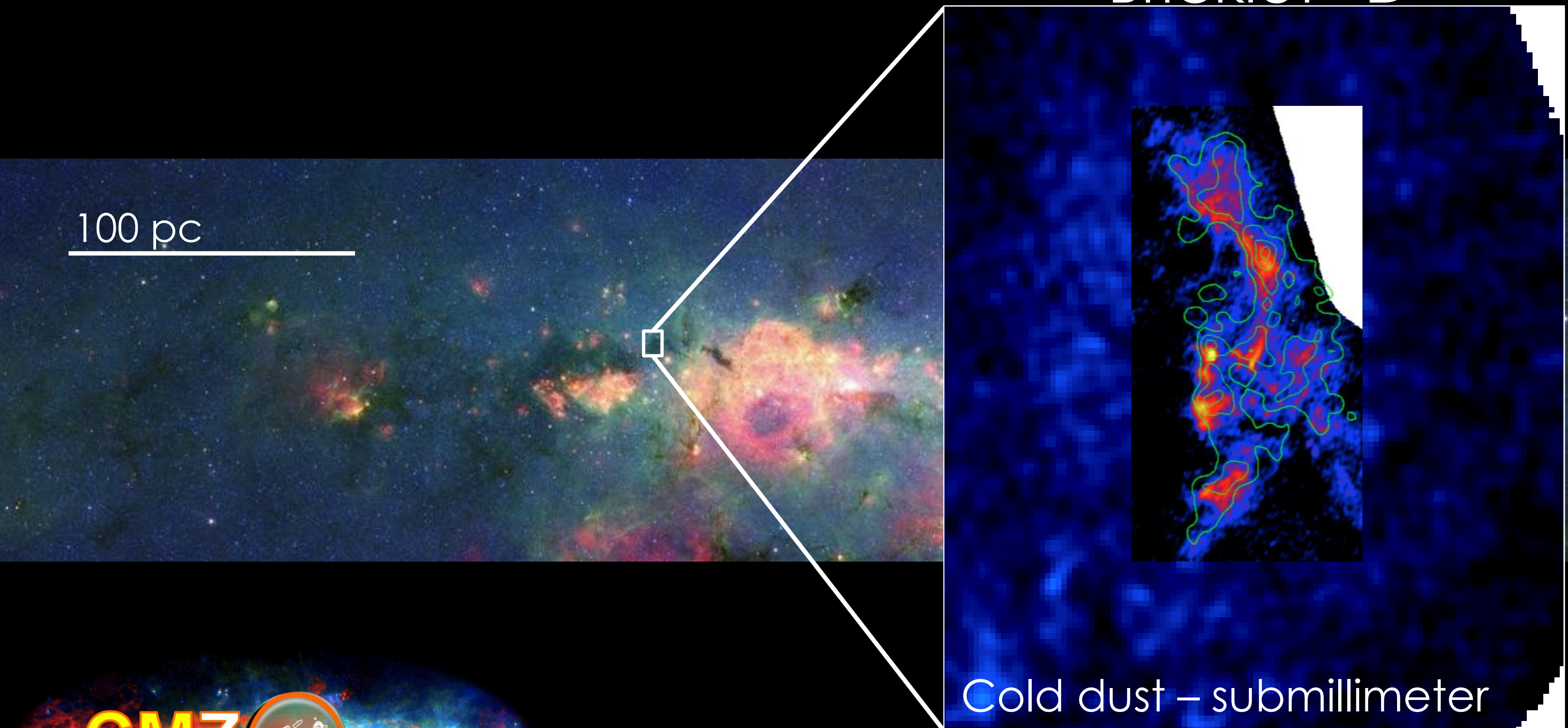
Central Molecular Zone



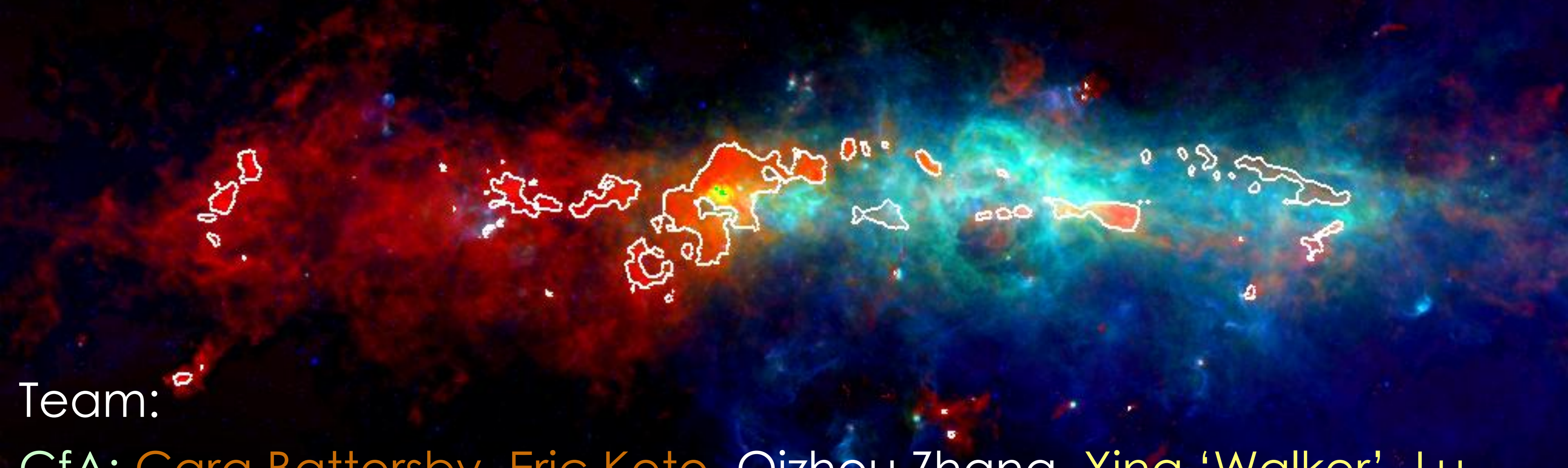
CMZoom

Central Molecular Zone

"Bricklet" D



CMZoom



Team:

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

Bonn: Jens Kauffmann, Thushara Pillai

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

University of Colorado, Boulder: John Bally

Heidelberg: Diederik Kruijssen, NRAO: Betsy Mills

ESO: Adam Ginsburg, Katharina Immer, Leeds: Katharine Johnston

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

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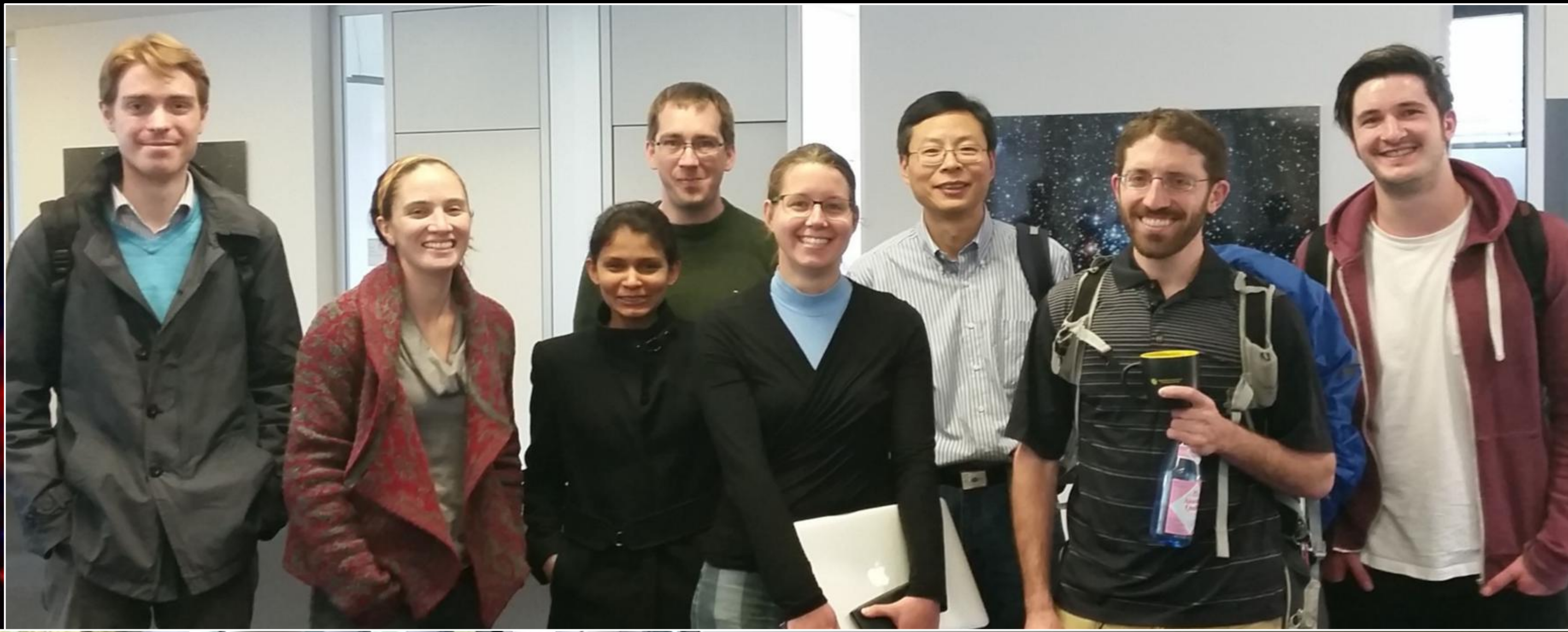

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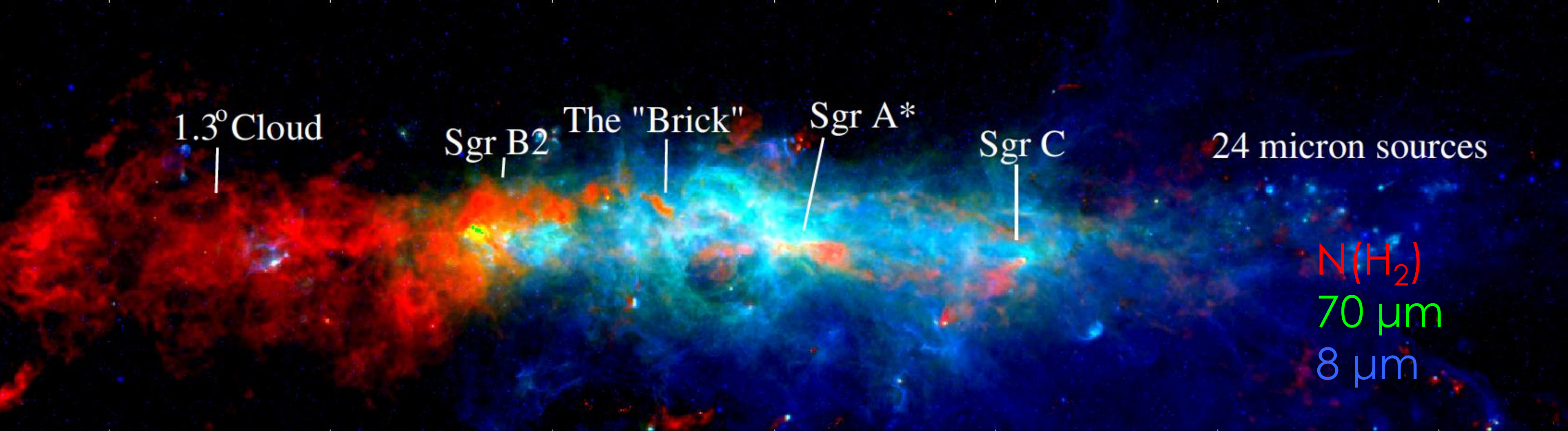
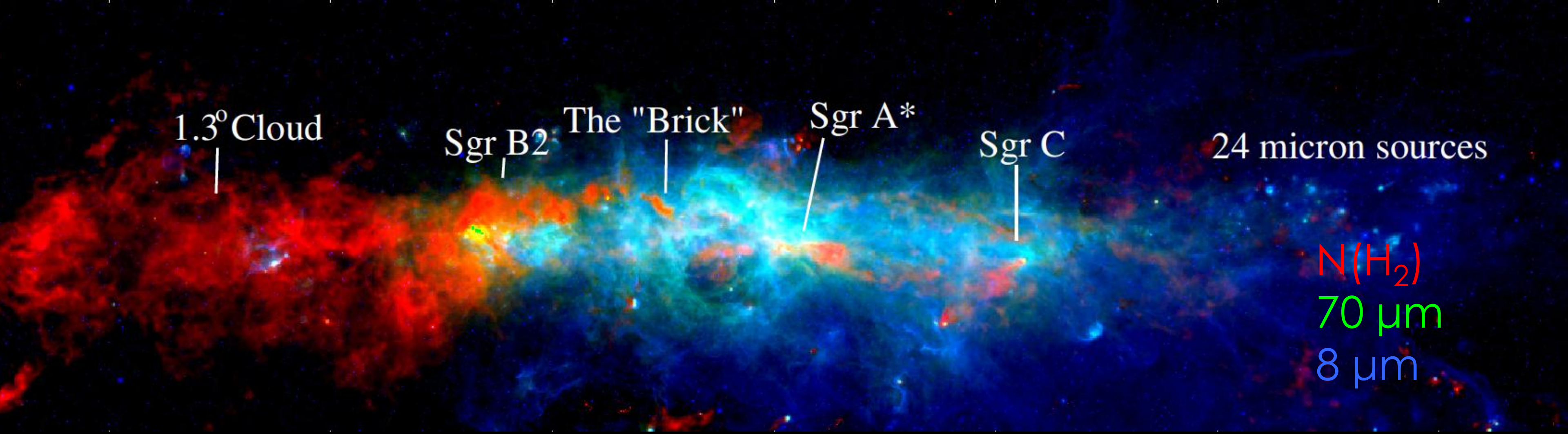


Driving Science Questions:

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?



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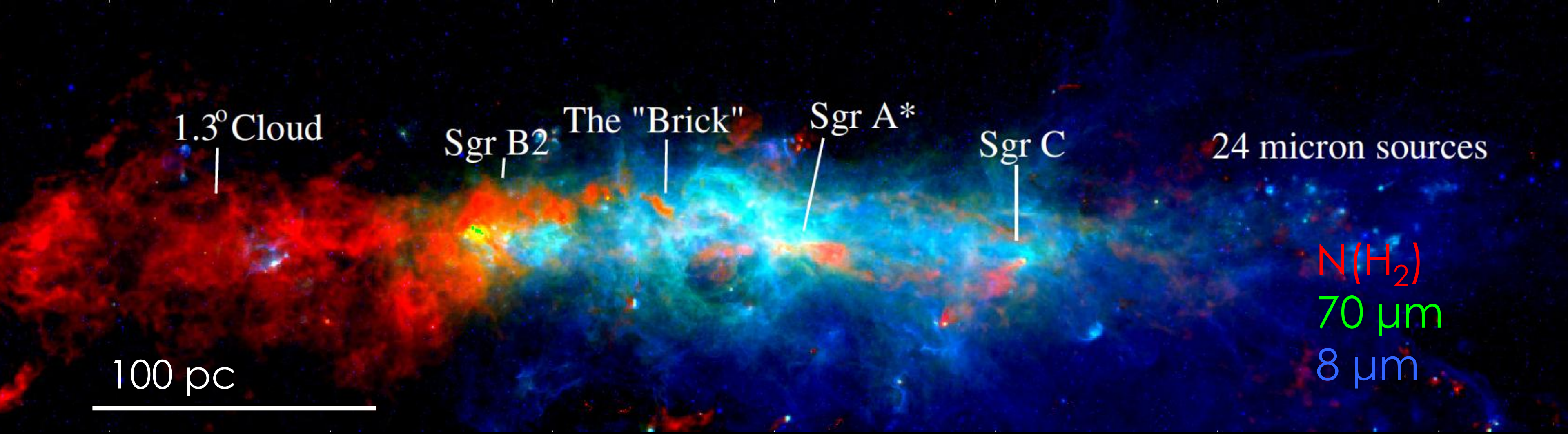
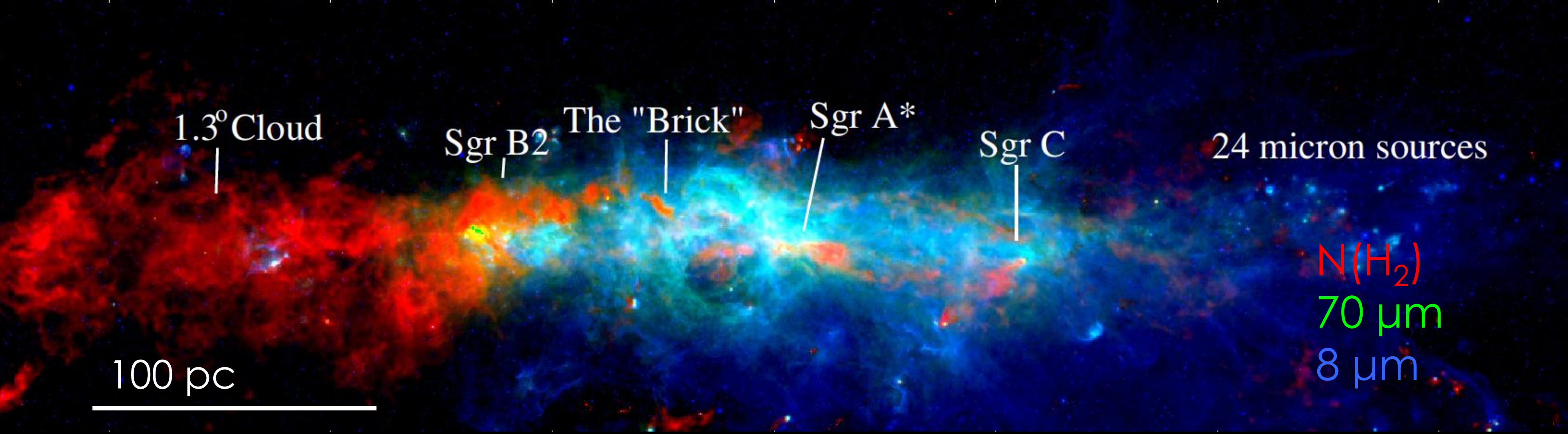
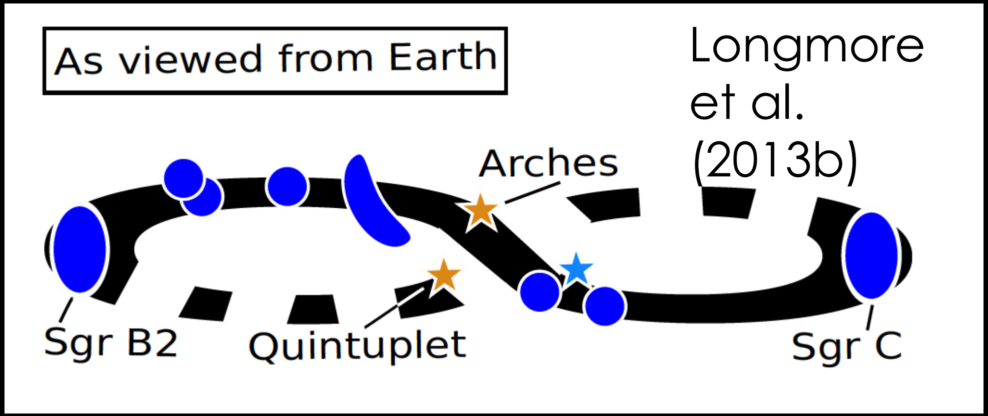
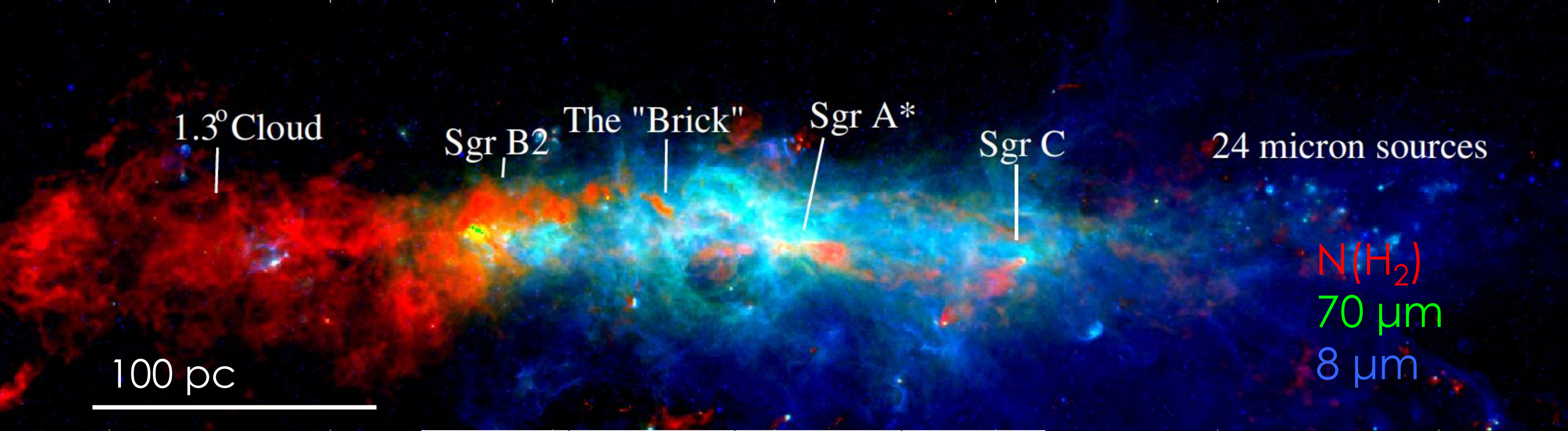
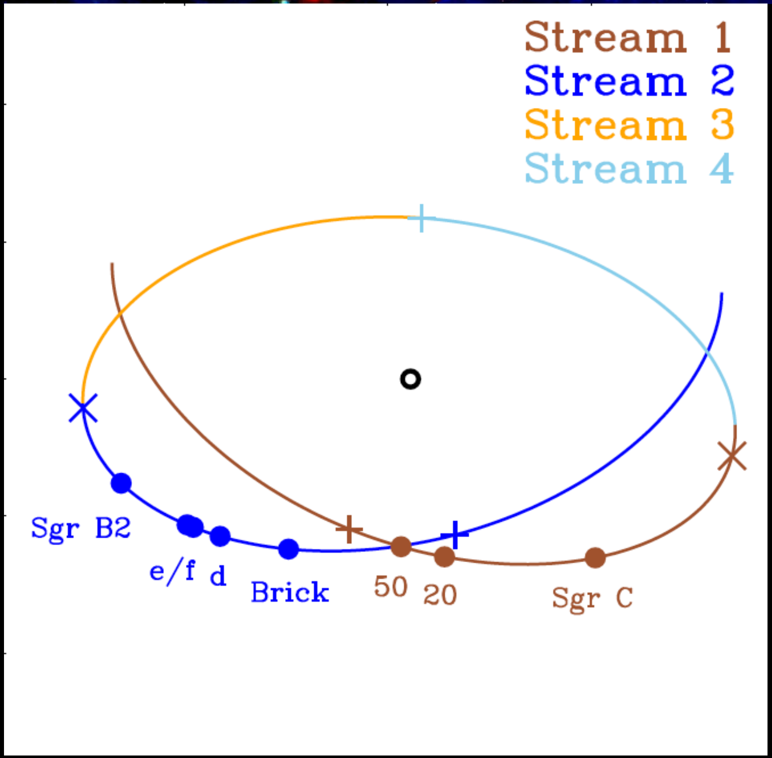

1.3° Cloud
Sgr B2
The "Brick"
Sgr A*
Sgr C
24 micron sources
N(H2)
70 μm
8 μm
100 pc





The “Molinari Ring” (Molinari+2011)





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)

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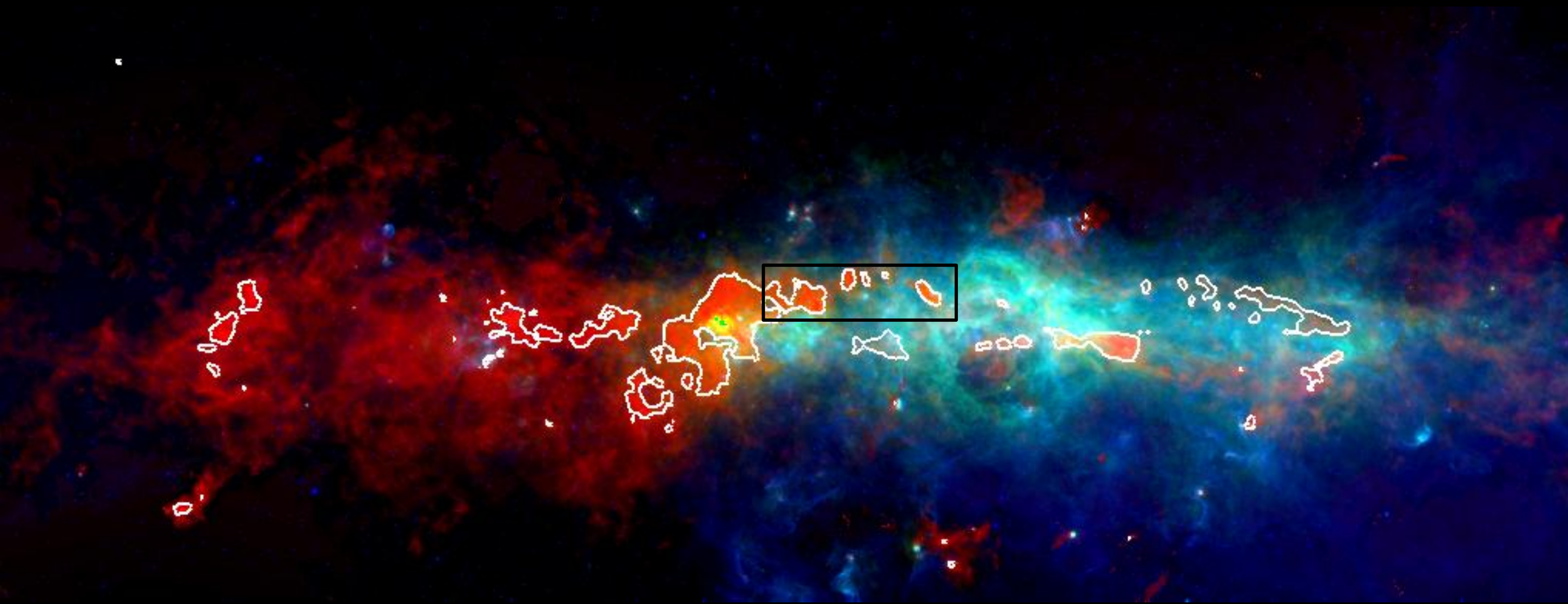

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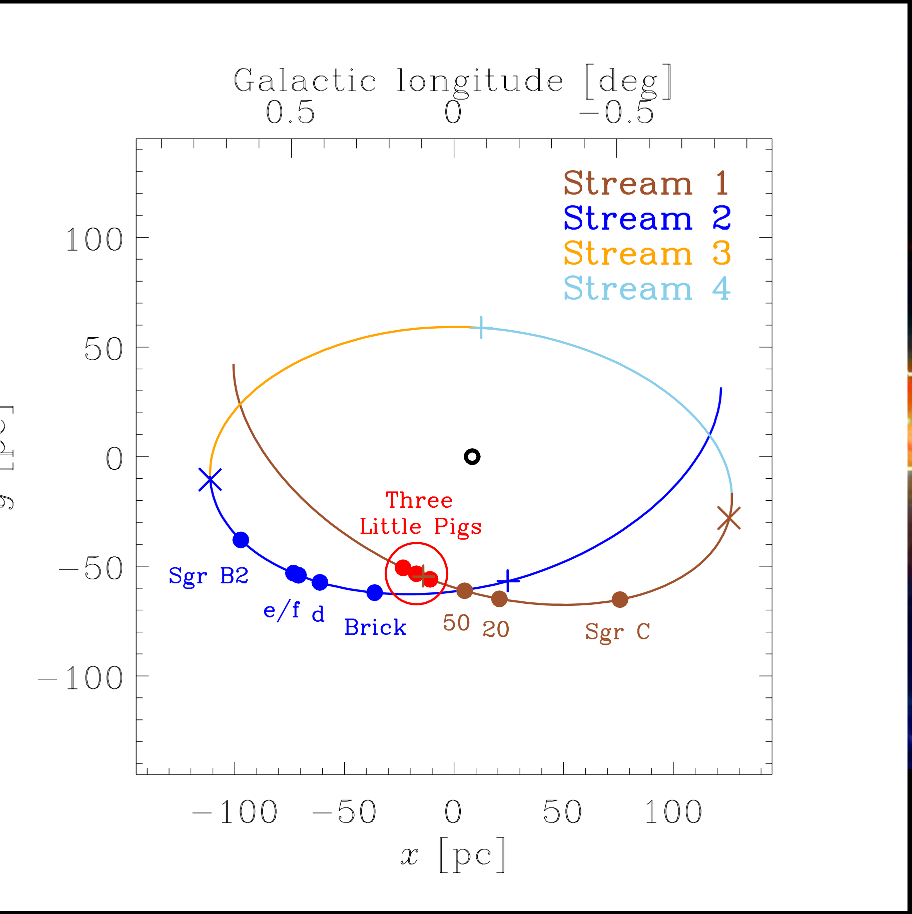

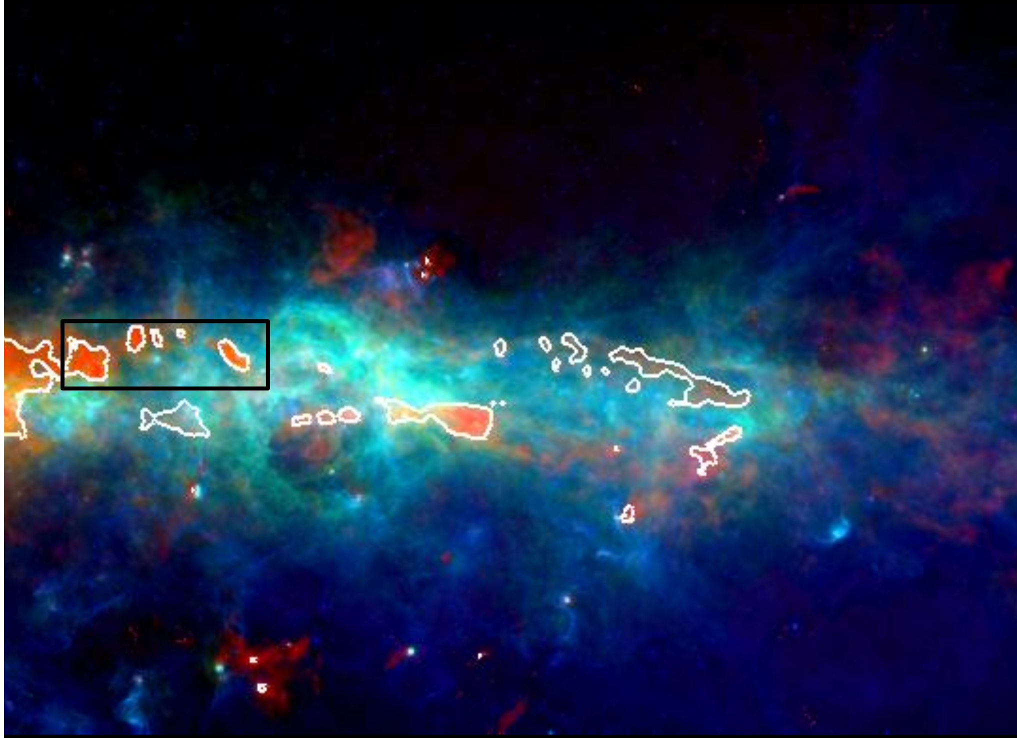

Kruijssen, Dale, Longmore 2015

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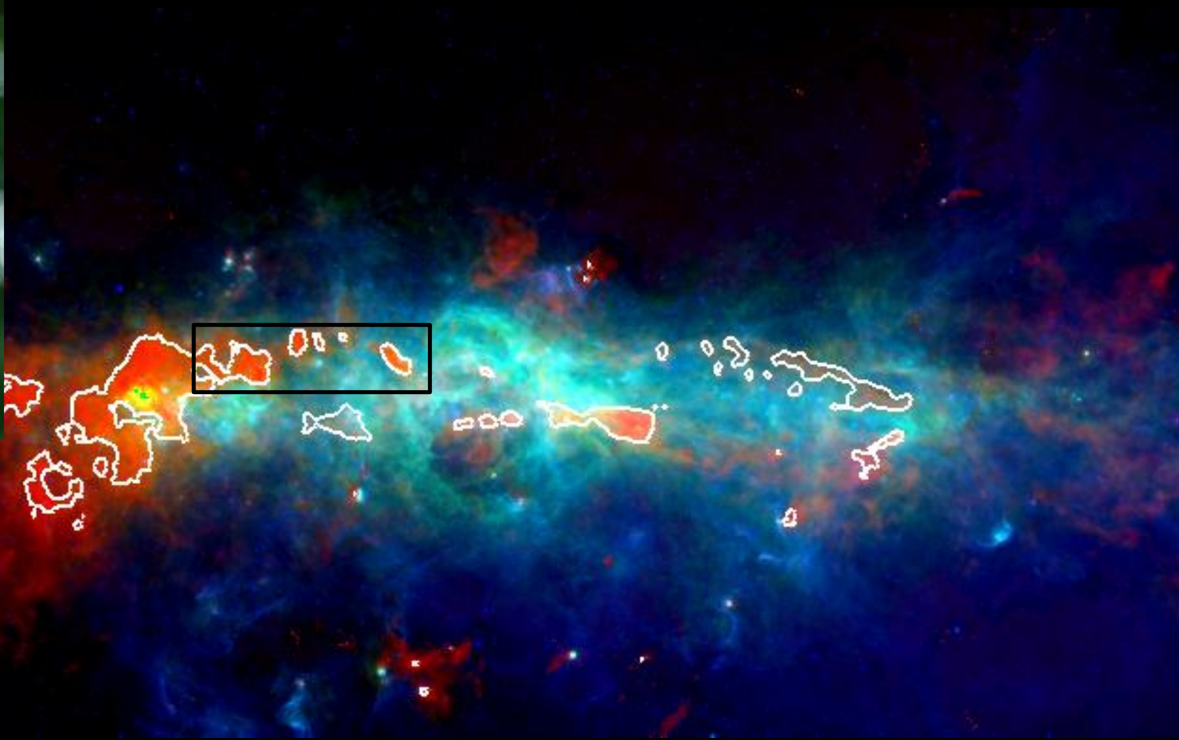

Dan Walker – PhD student in Liverpool
SAO Pre-doc

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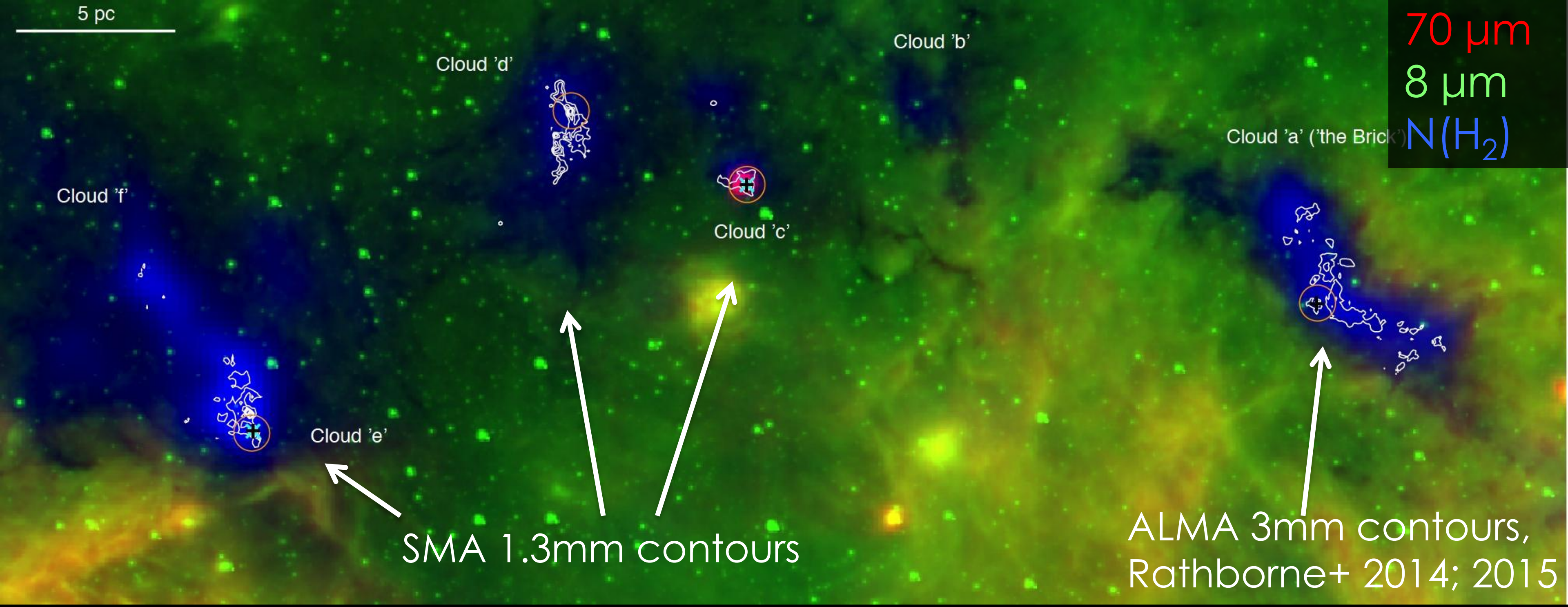
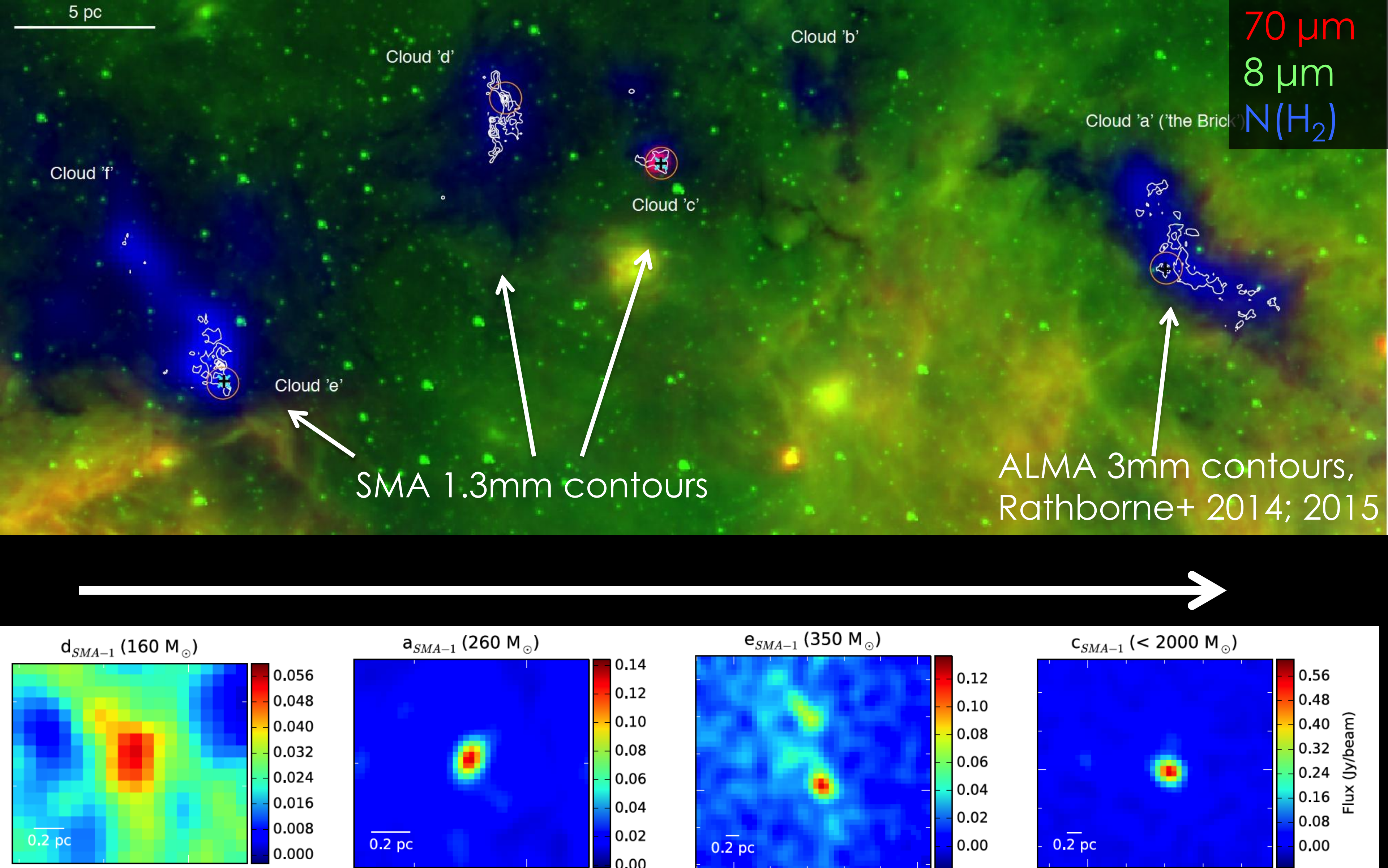

5 pc
Cloud 'd'
Cloud 'b'
70 µm
8 µm
N(H2)
Cloud 'a' ('the Brick')
Cloud 'f'
Cloud 'c'
Cloud 'e'
SMA 1.3mm contours
ALMA 3mm contours,
Rathborne+ 2014; 2015

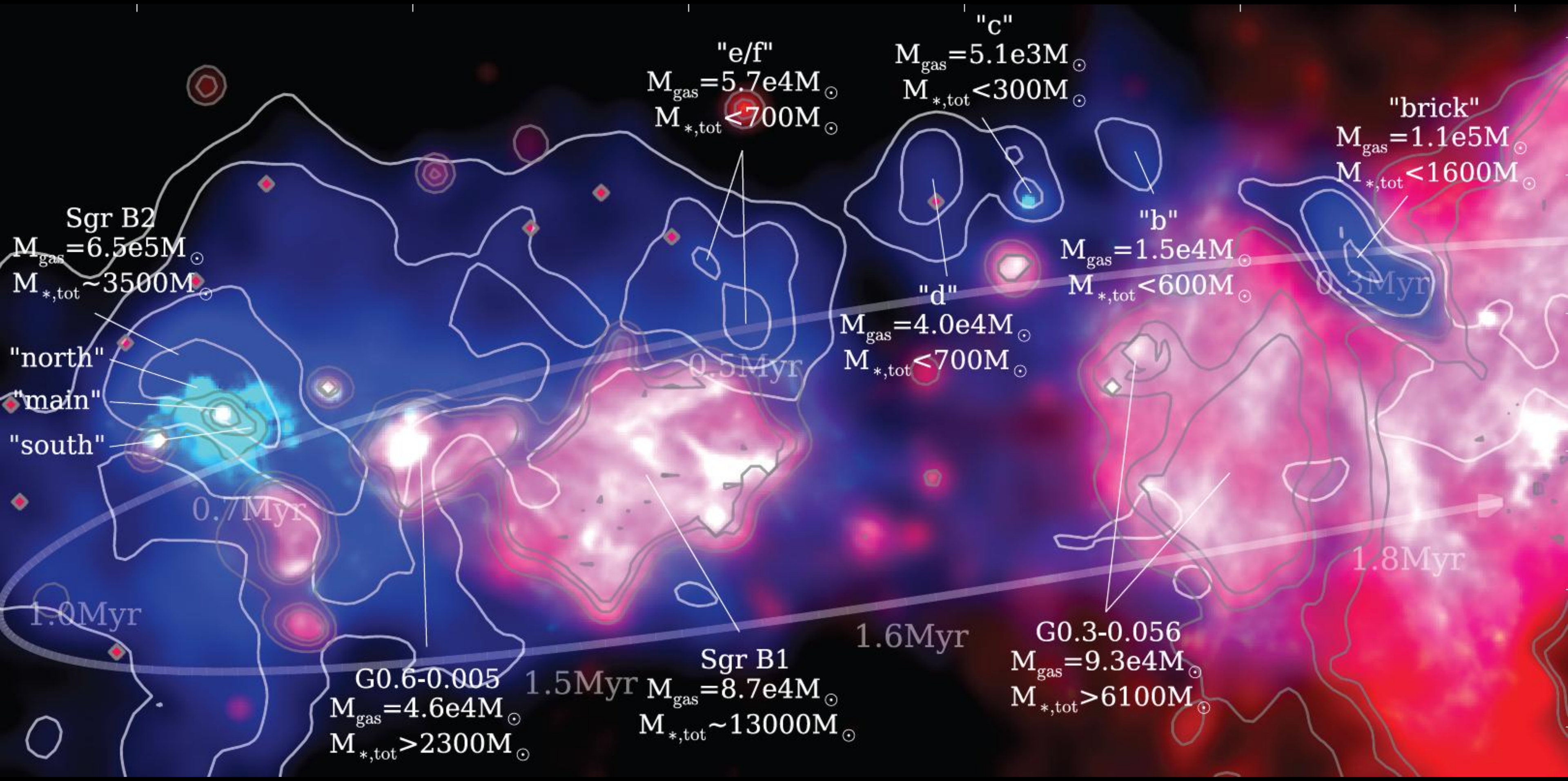


N_{ff} = 0.61
No SF tracers

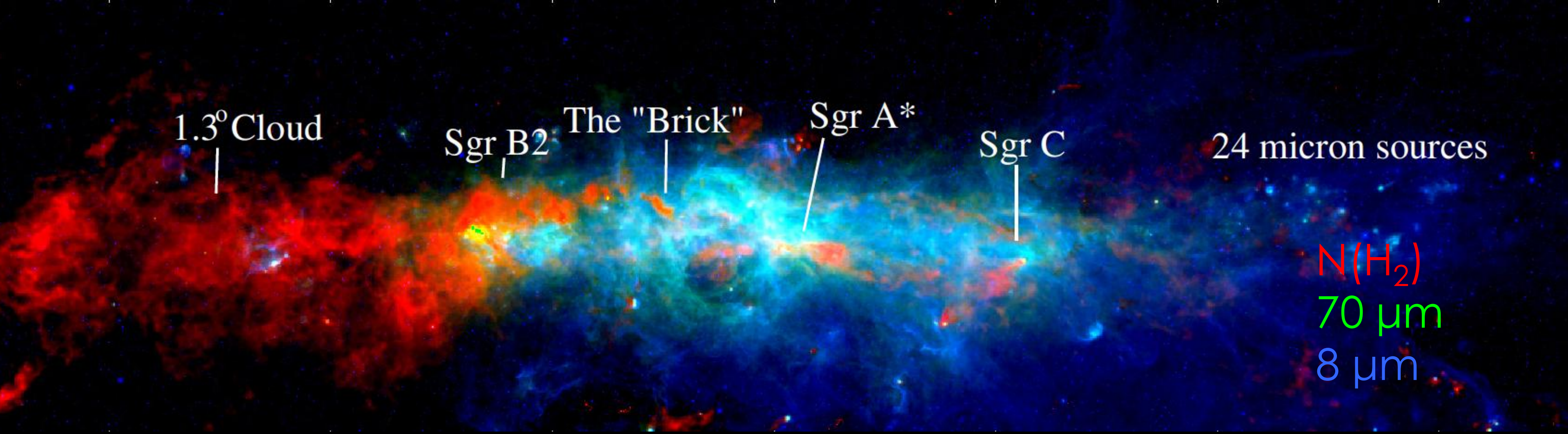
N_{ff} = 0.65
H_2O maser

N_{ff} = 1.28
H_2O and CH_3OH masers

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



Barnes, Longmore, Battersby, & Bally in prep.



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Why is the SFR low in the CMZ?

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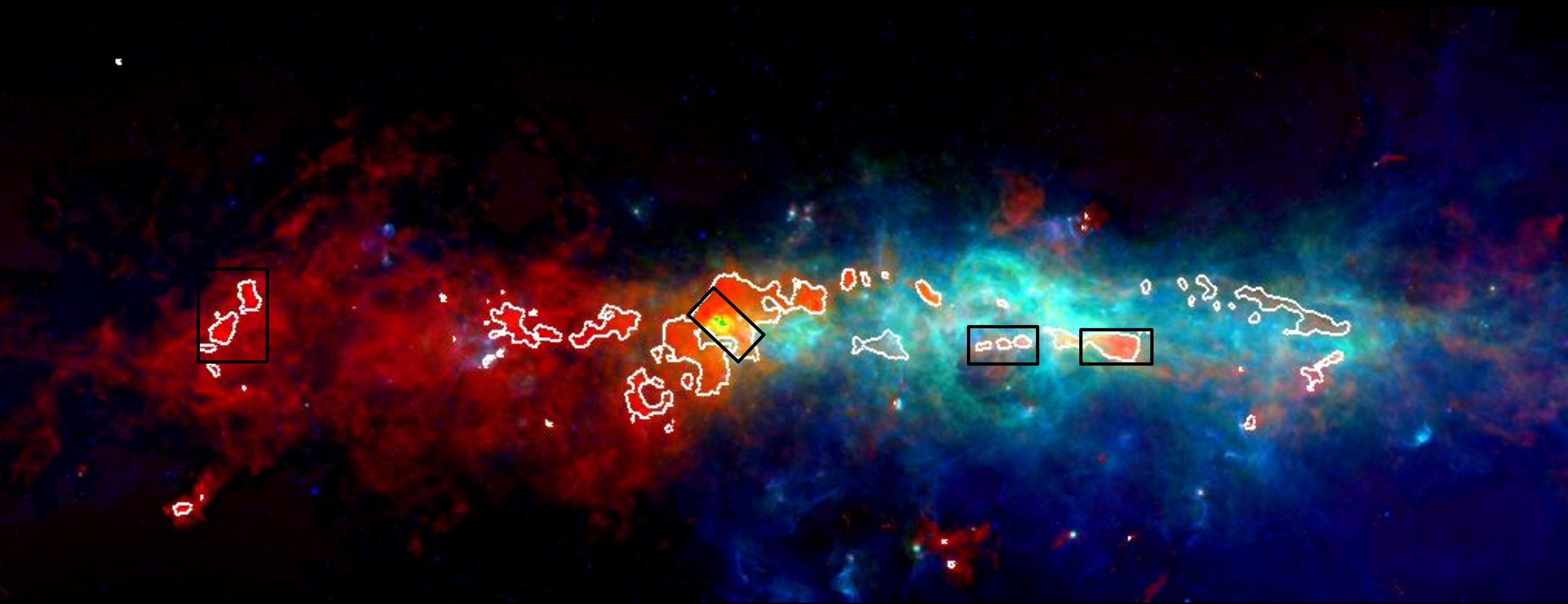

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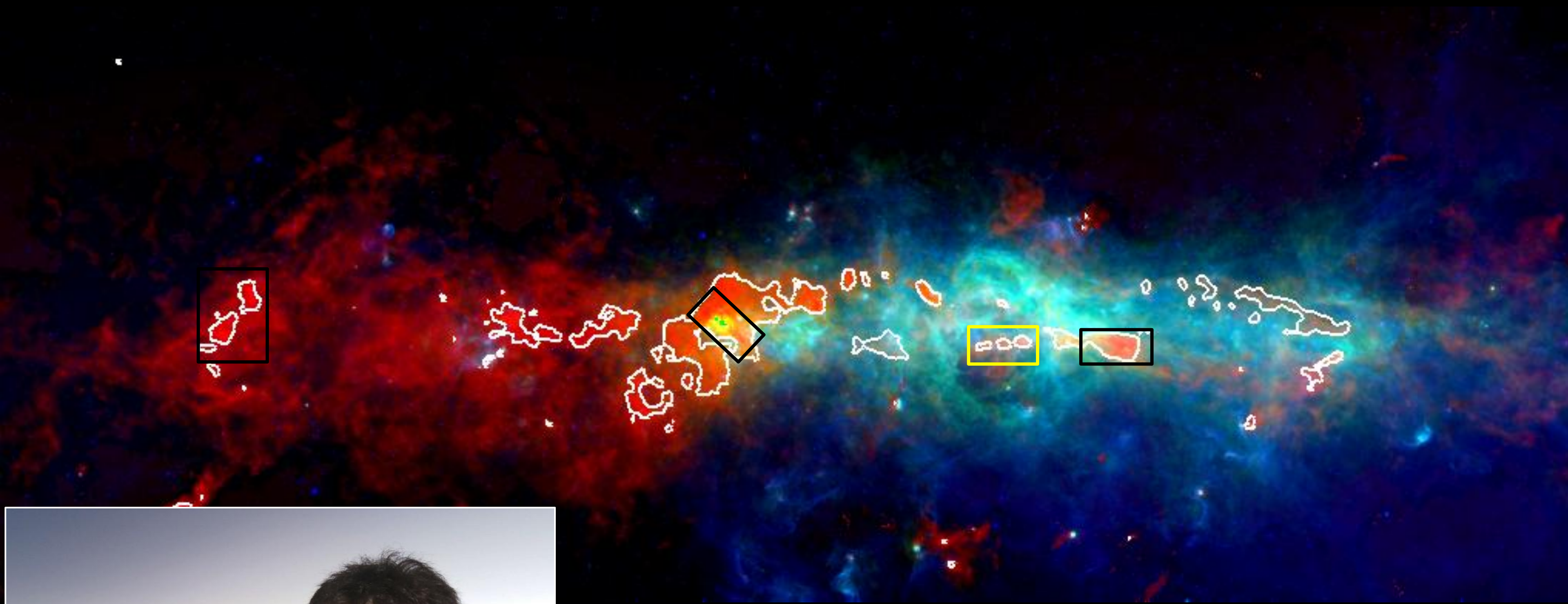

Mark Graham
SAO Pre-doc, now a
PhD student at

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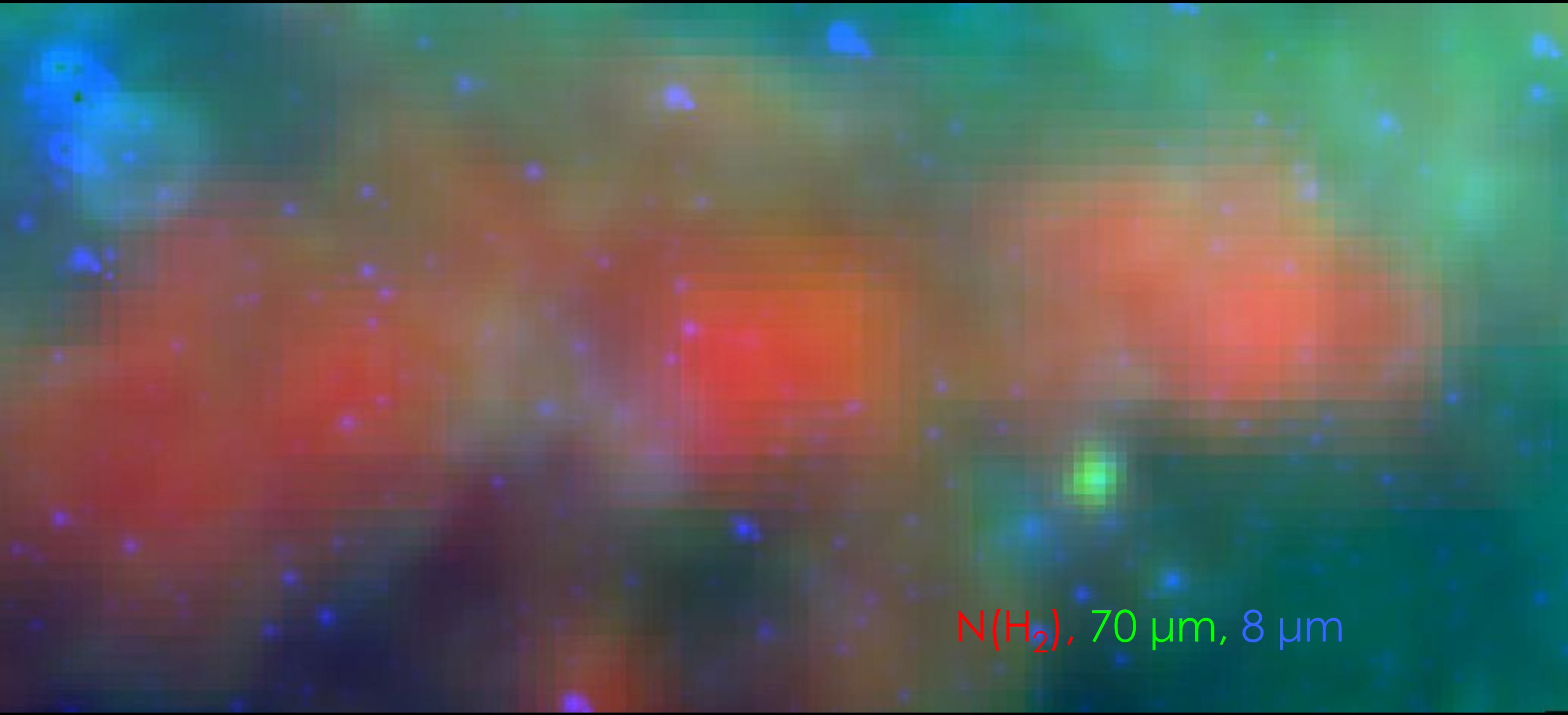

CMZoom

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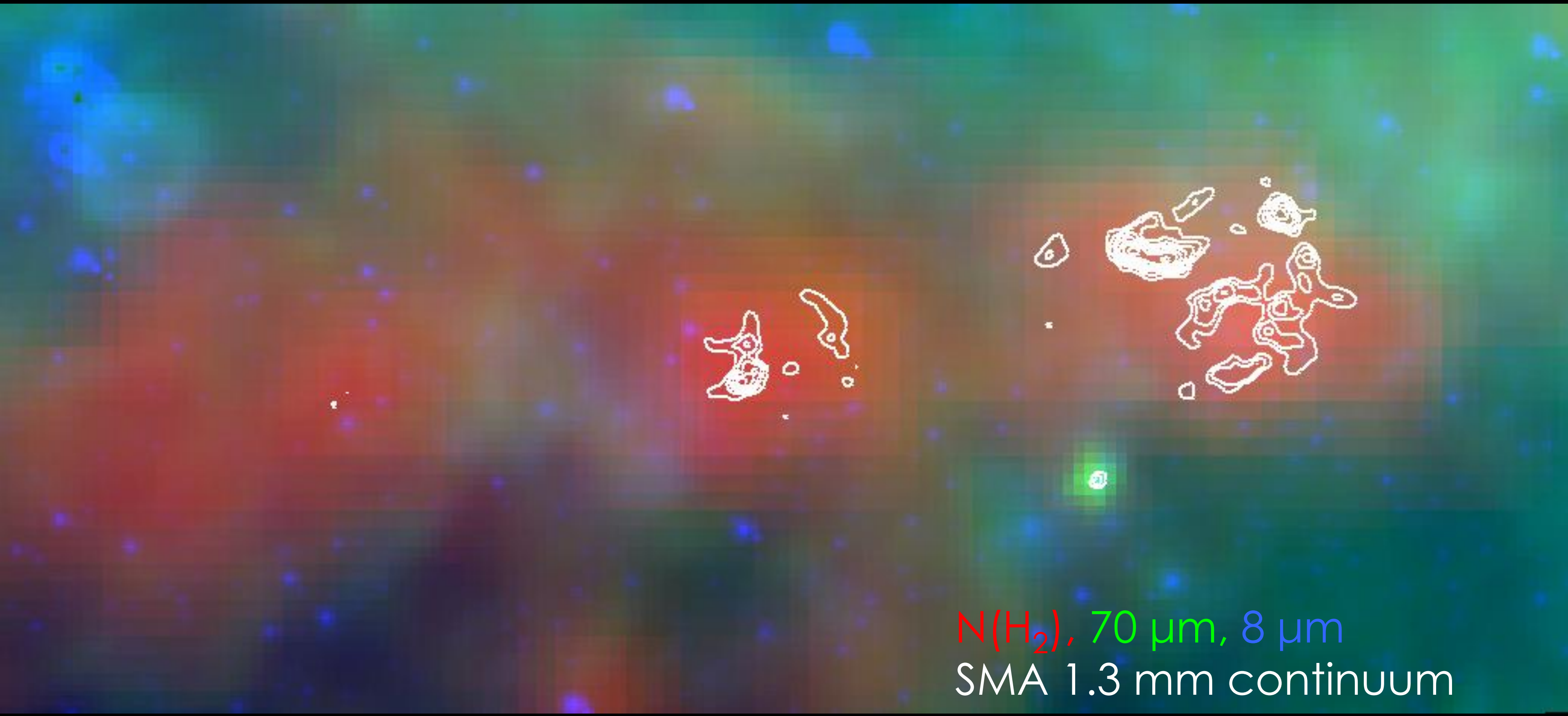

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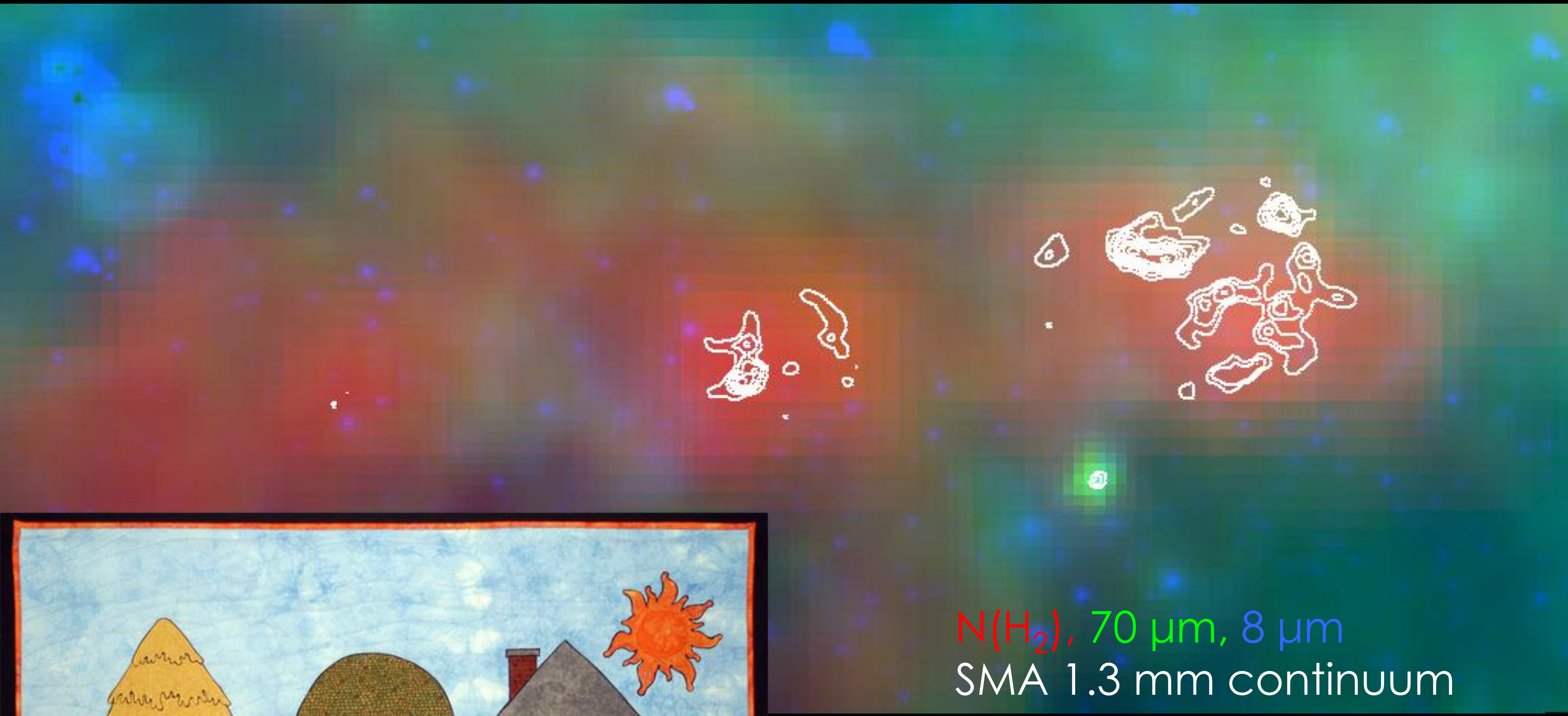

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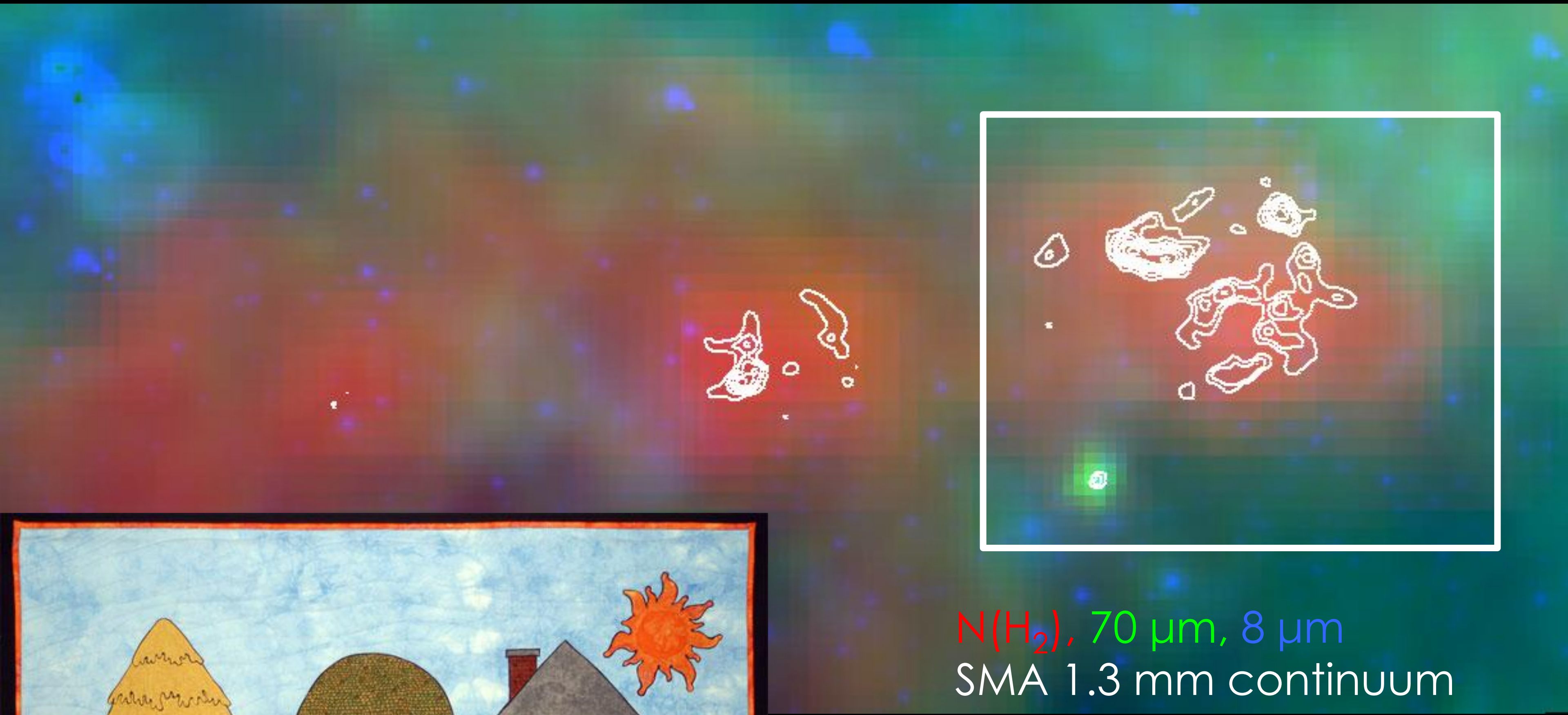

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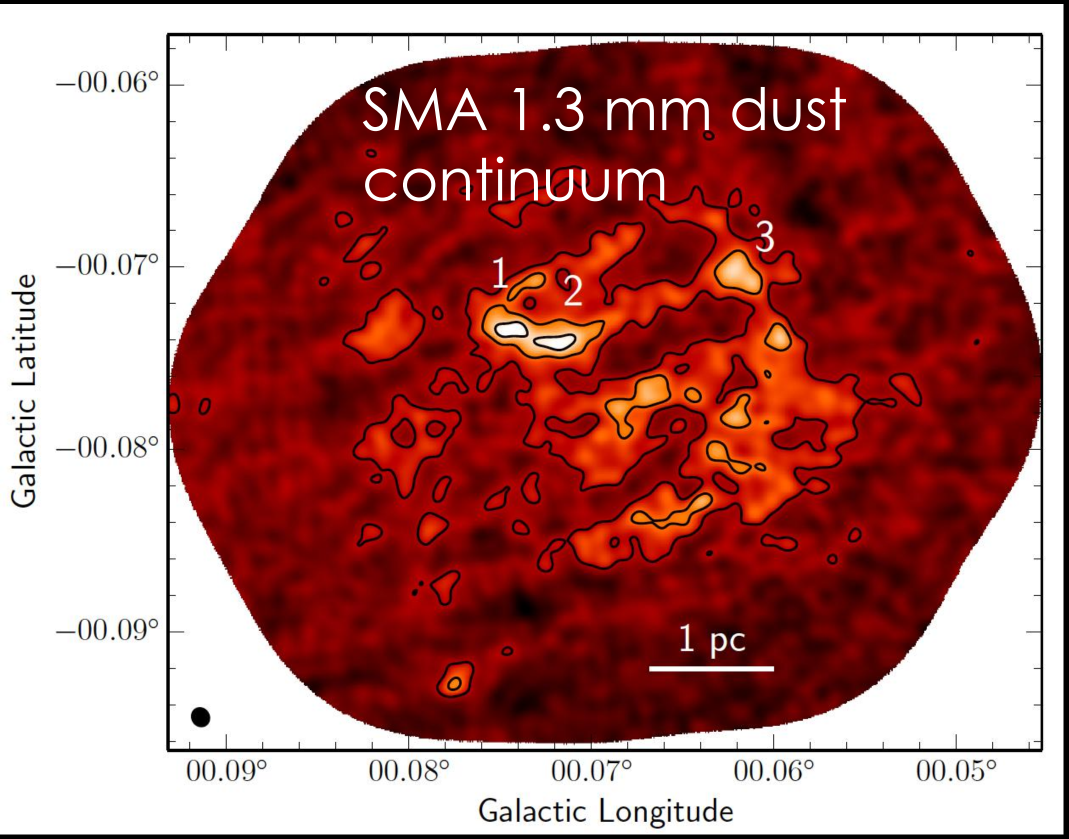

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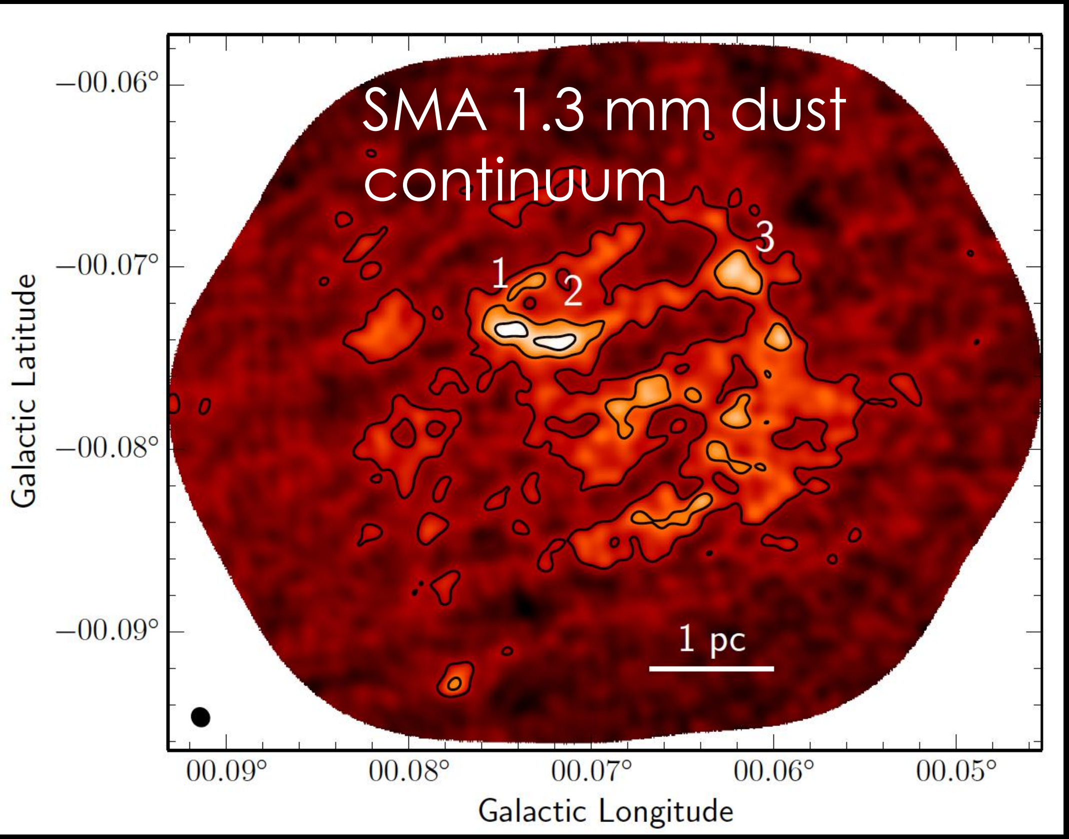

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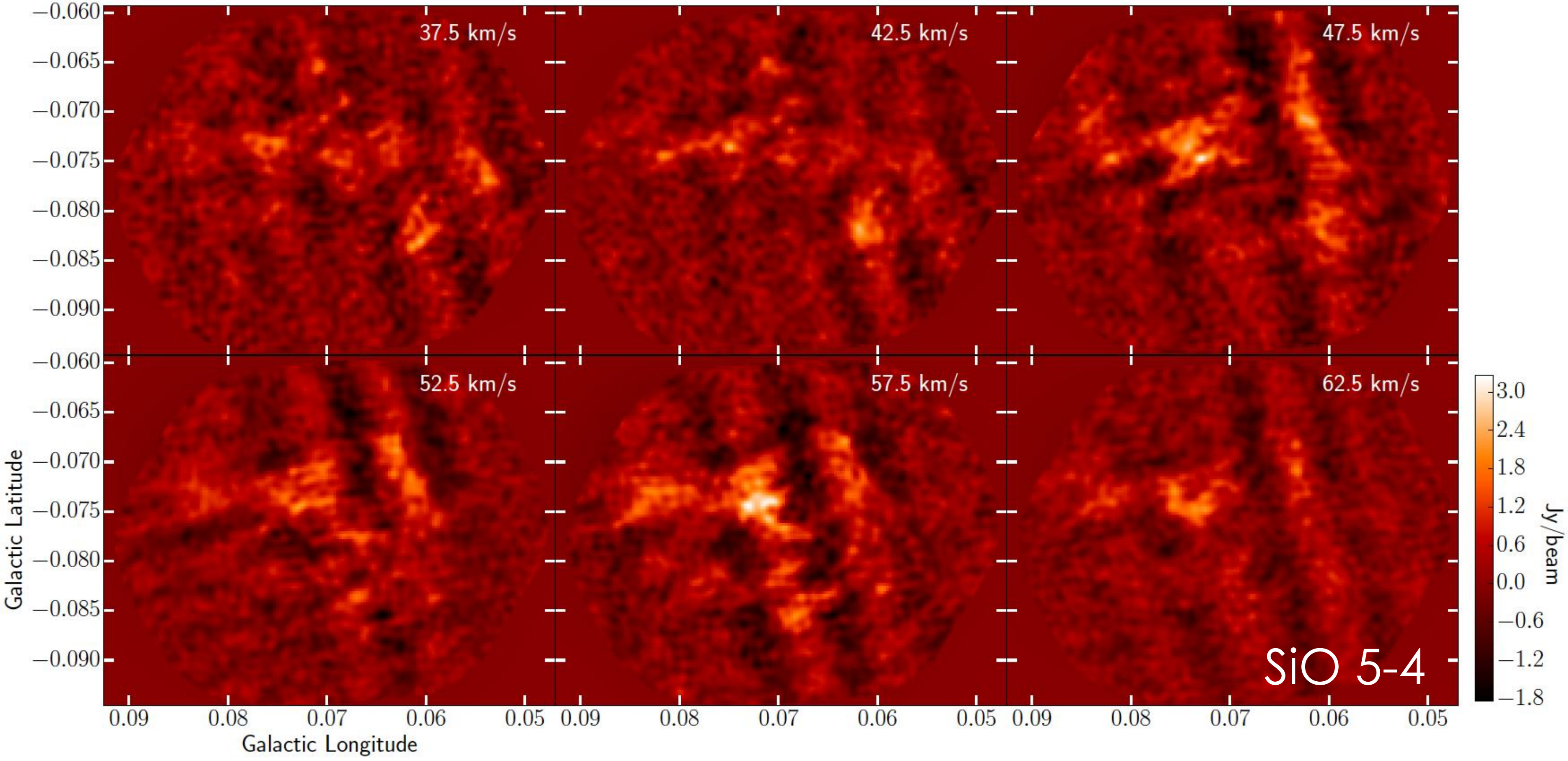

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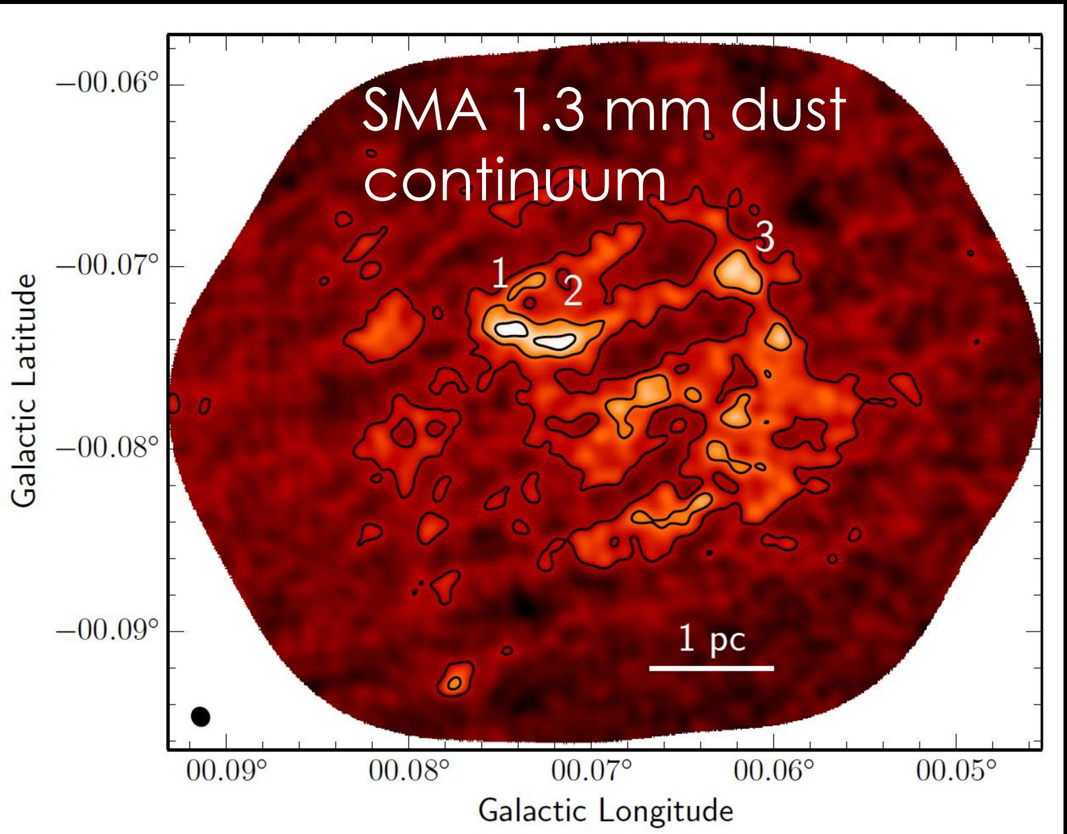

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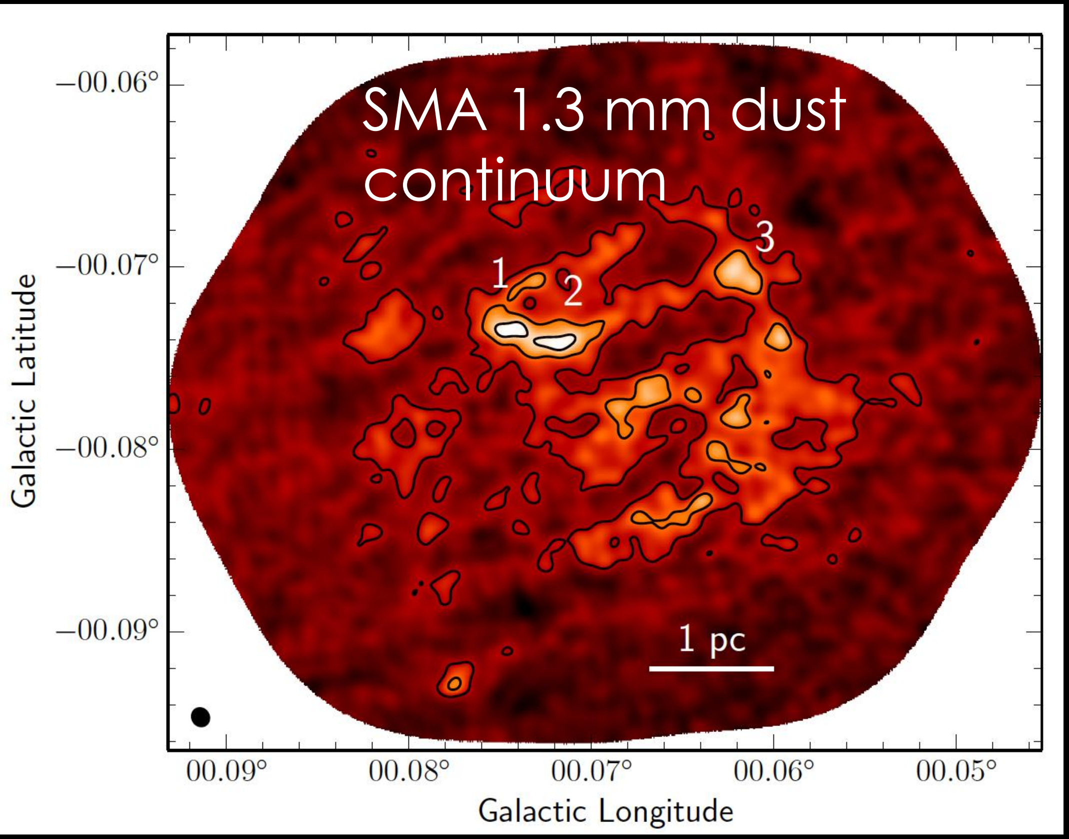

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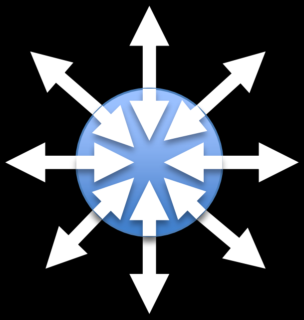

Gravity vs. pressure (thermal and turbulence)

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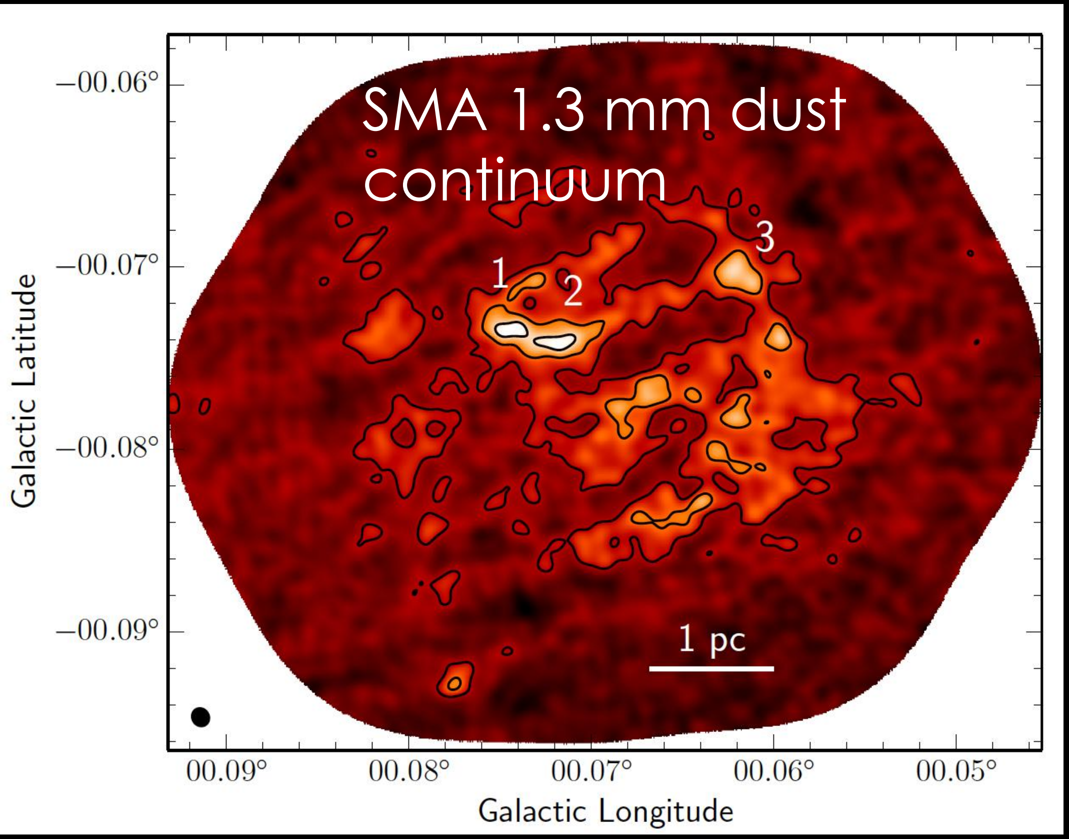
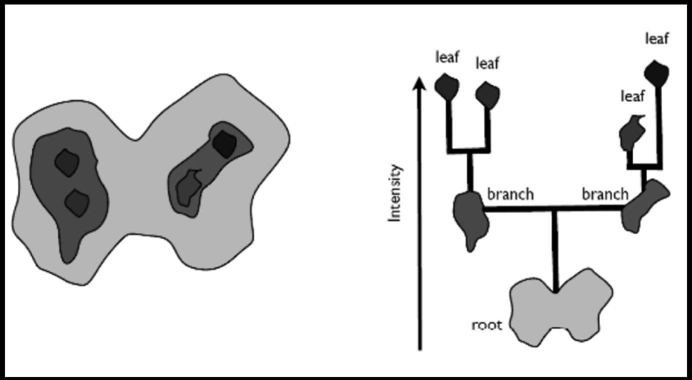
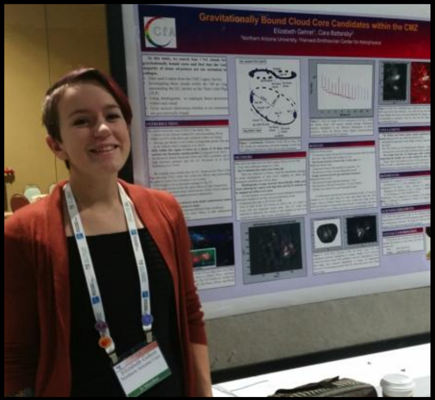




Dendrograms, e.g.
Shetty et al. 2012,
Rosolowsky et al. 2008

Liz Gehret
SAO REU
student



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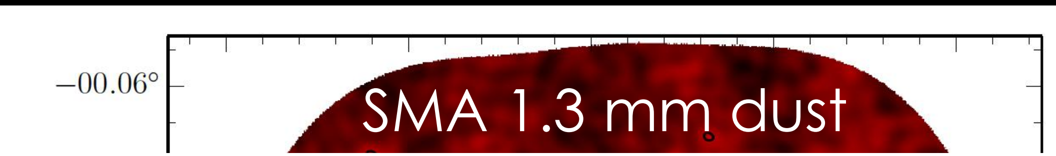

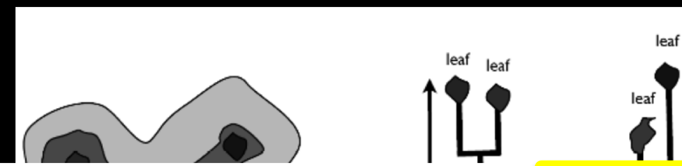

Structure ID	H_2CO Flux (Jy)	Dust Flux (Jy)	Central Velocity (km/s)	$\Delta\nu_{FWHM}$ (km/s)	M_{dust} ($M_\odot$)	M_{vir} ($M_\odot$)	Virial Ratio (M_{vir}/M_{dust})
0	1.085	4.224	49.66	20.63	7.15E+03	6.22E+04	8.70
1	1.012	4.197	49.34	20.03	7.10E+03	5.85E+04	8.23
2	0.879	3.997	49.36	19.96	6.77E+03	5.70E+04	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
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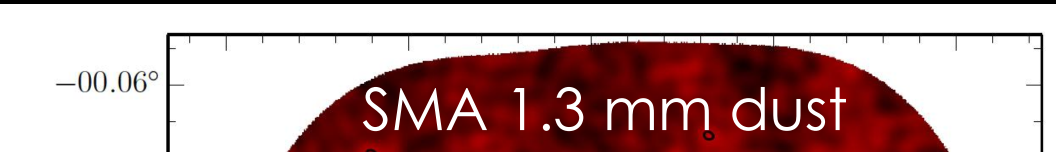

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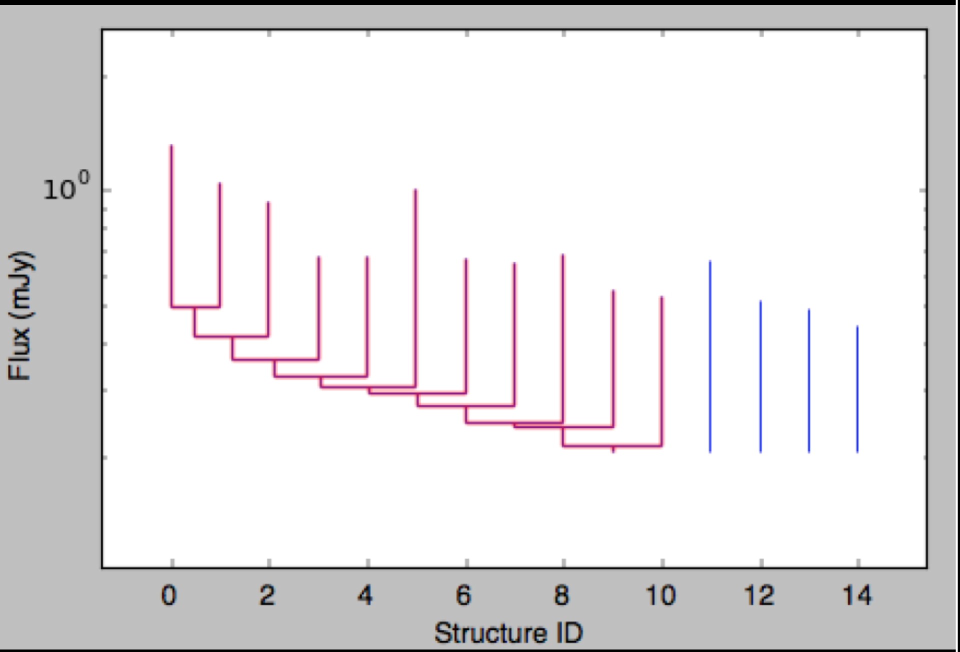
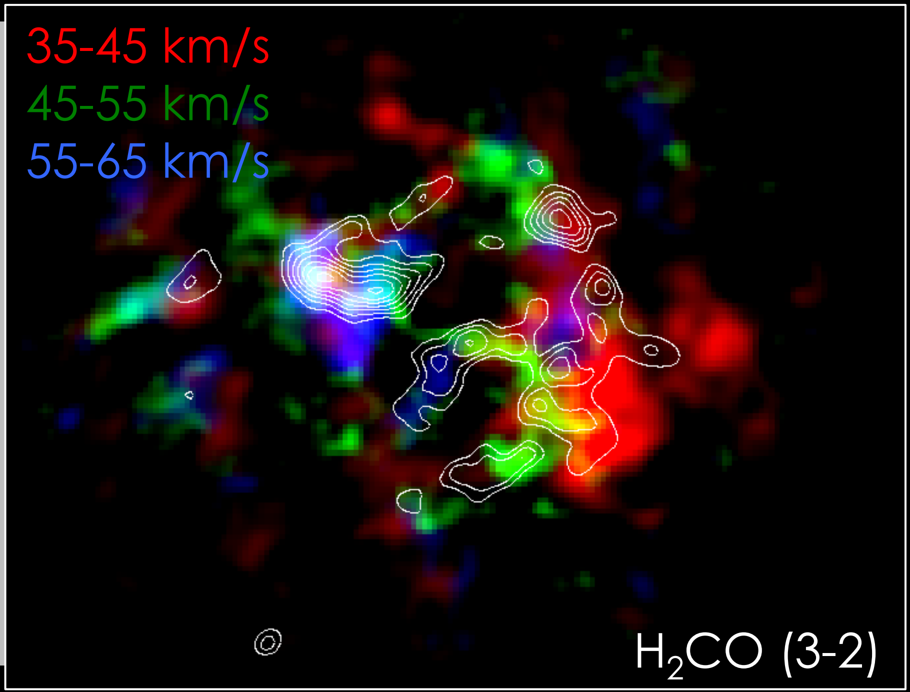
High levels of turbulence are preventing star formation

Structure Identification





Battersby, Gehret, et al., in prep.

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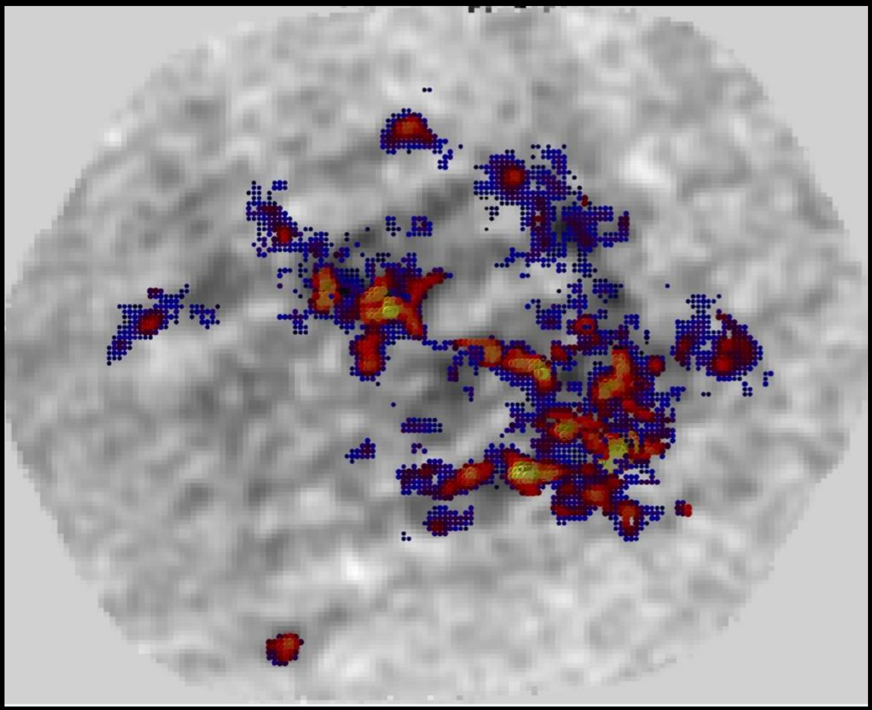

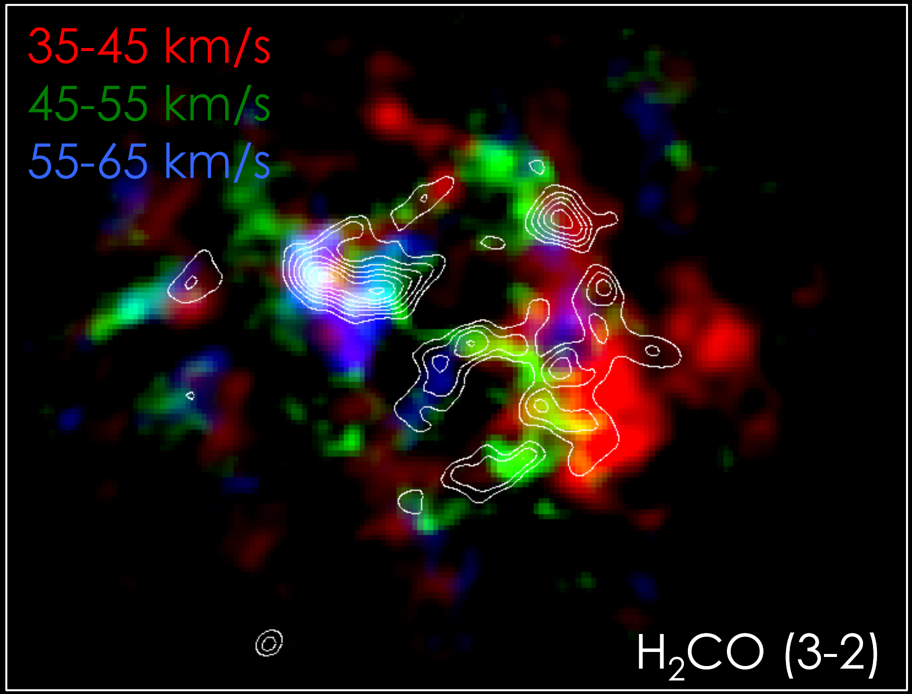

SCOUSE line fitting
Jonny Henshaw
Liverpool

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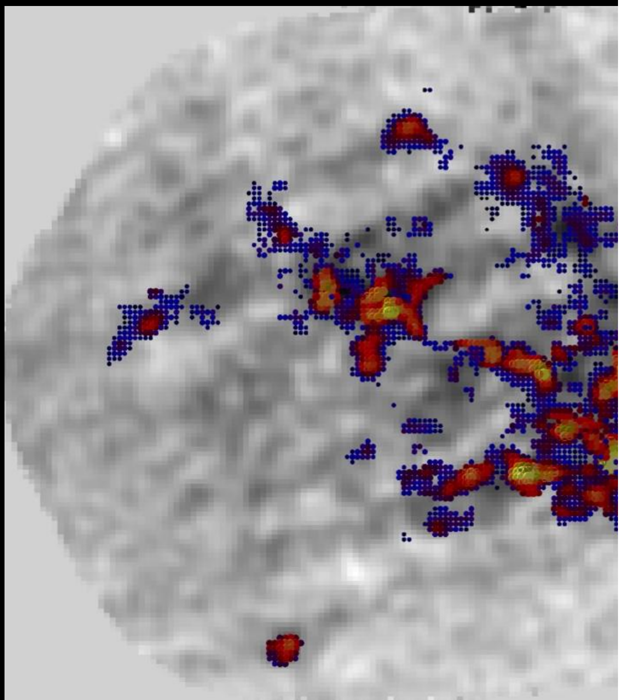
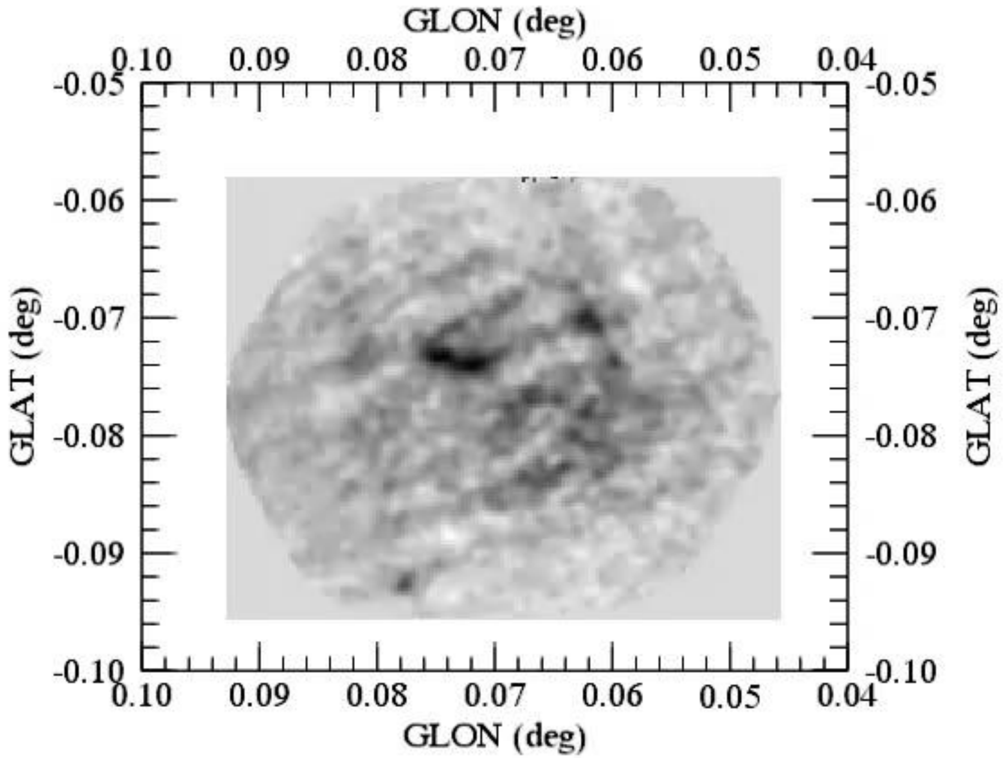
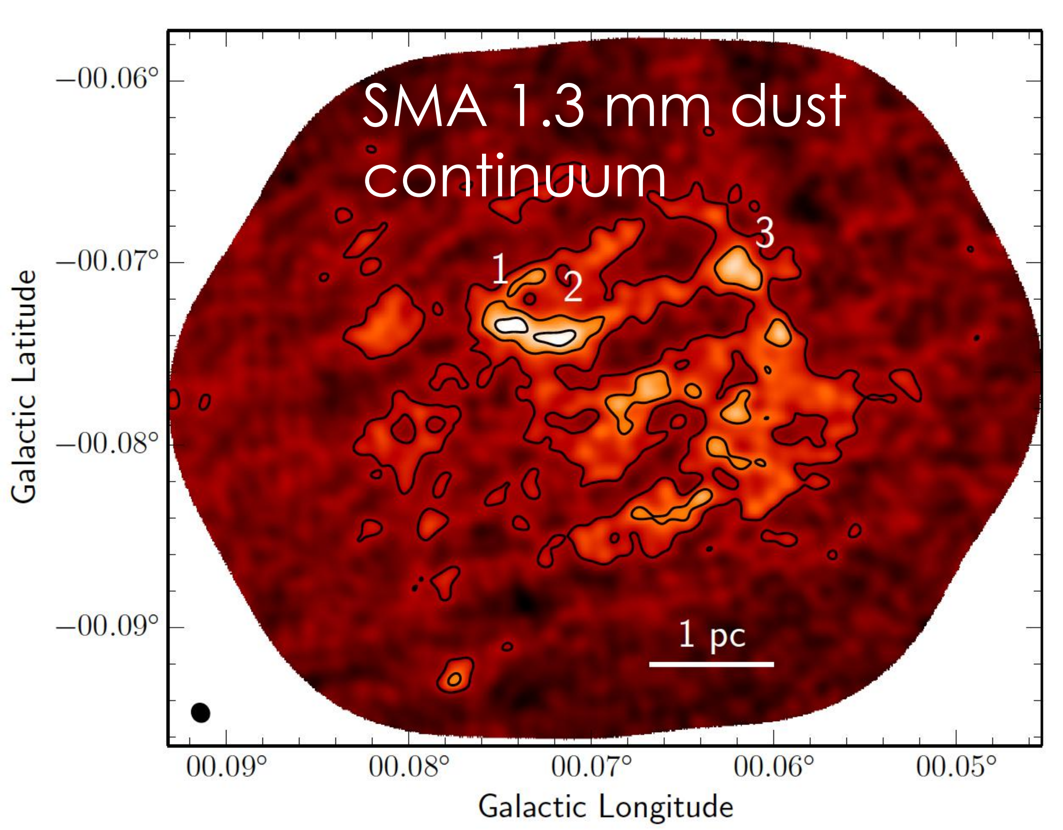




Why is the SFR low in the CMZ?



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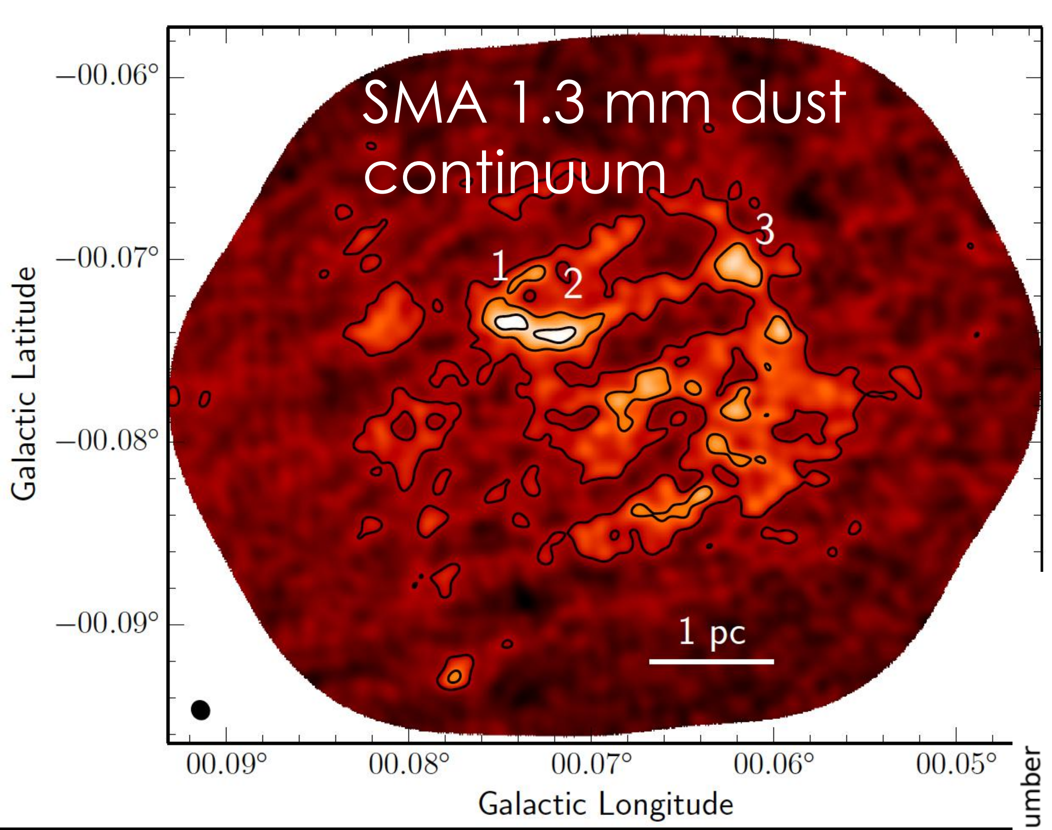

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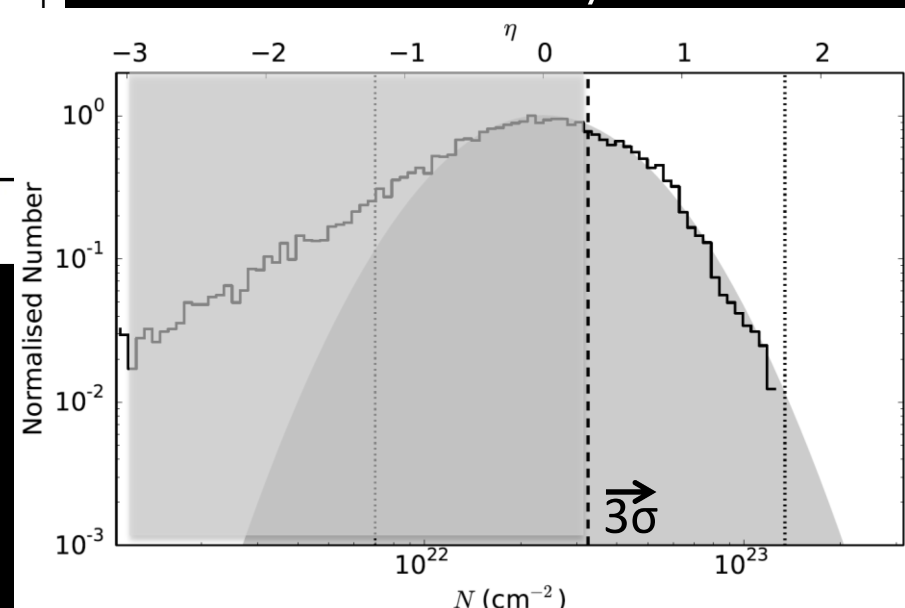

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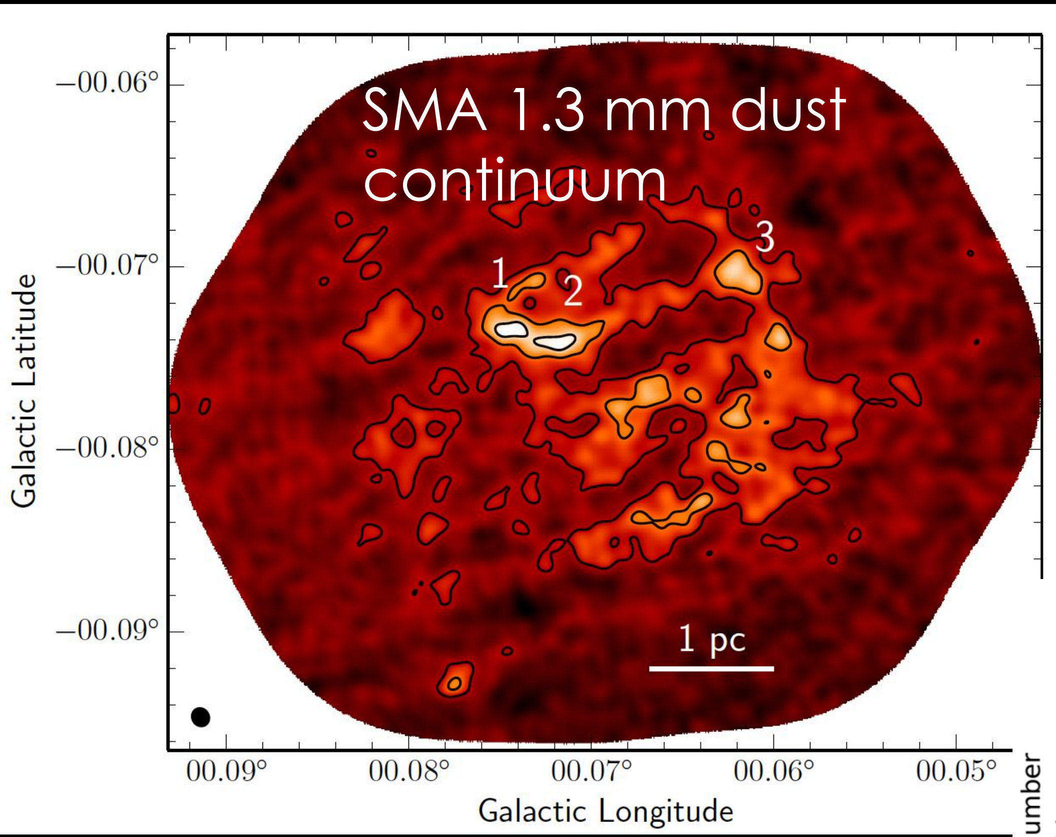

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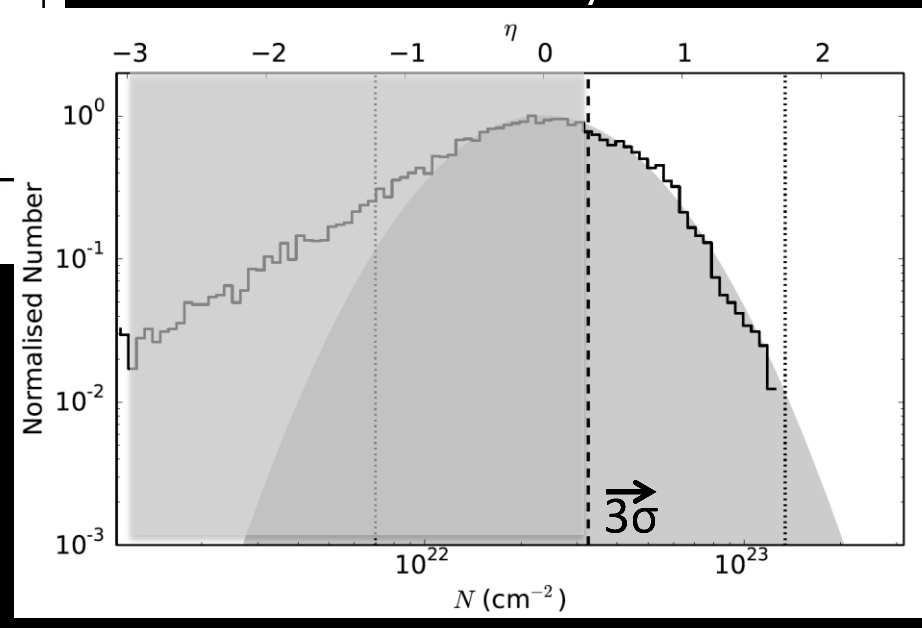

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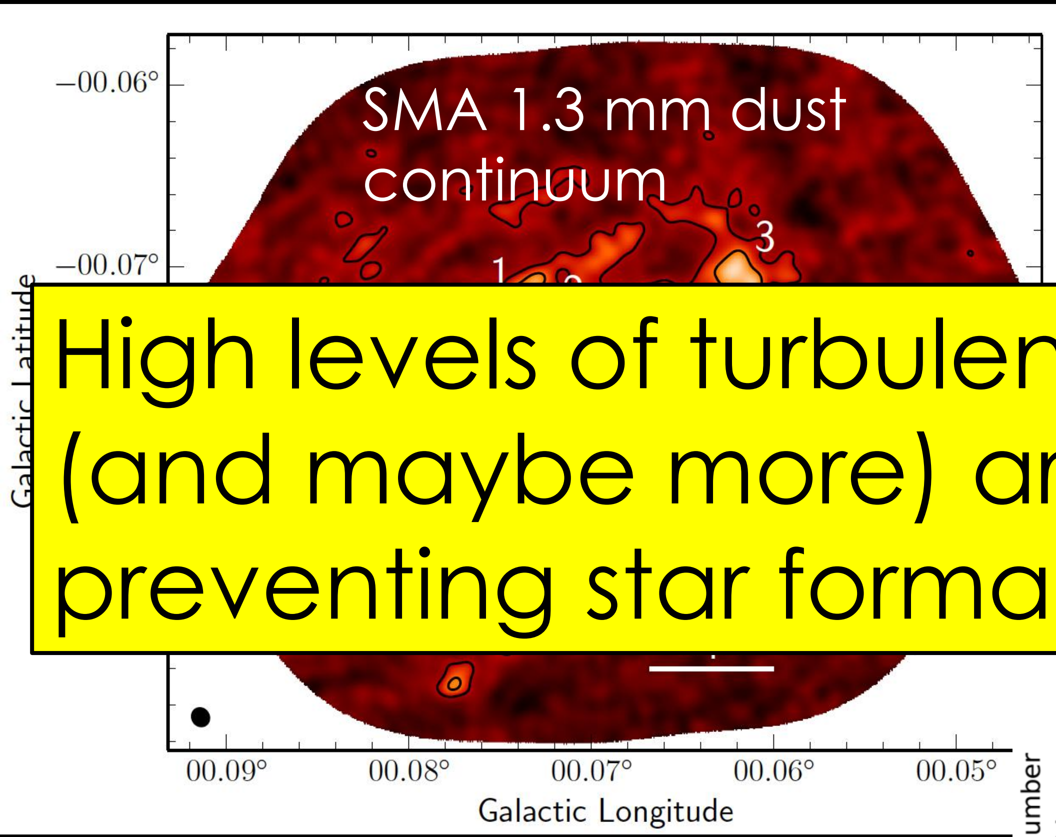

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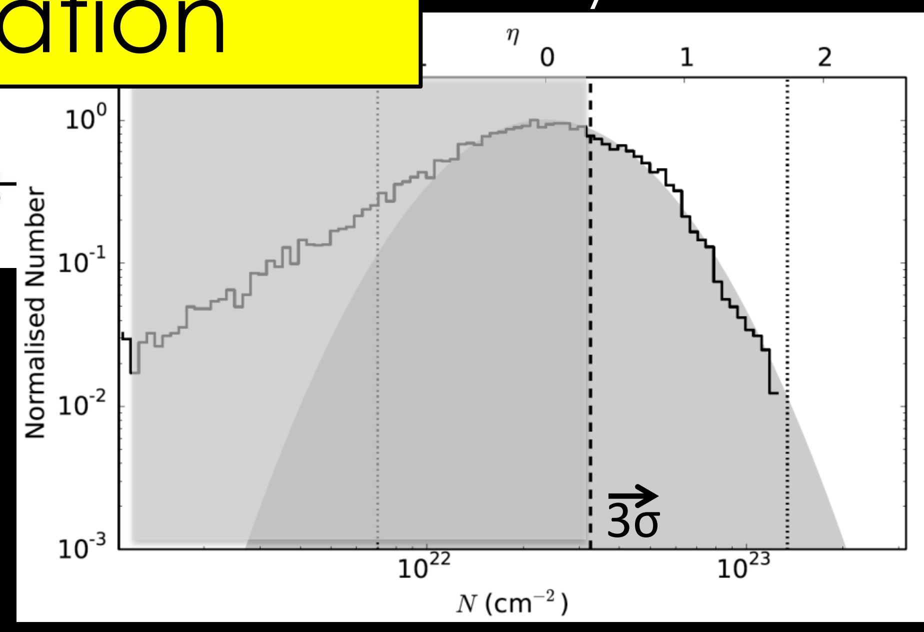
High levels of turbulence (and maybe more) are preventing star formation



CMZoom

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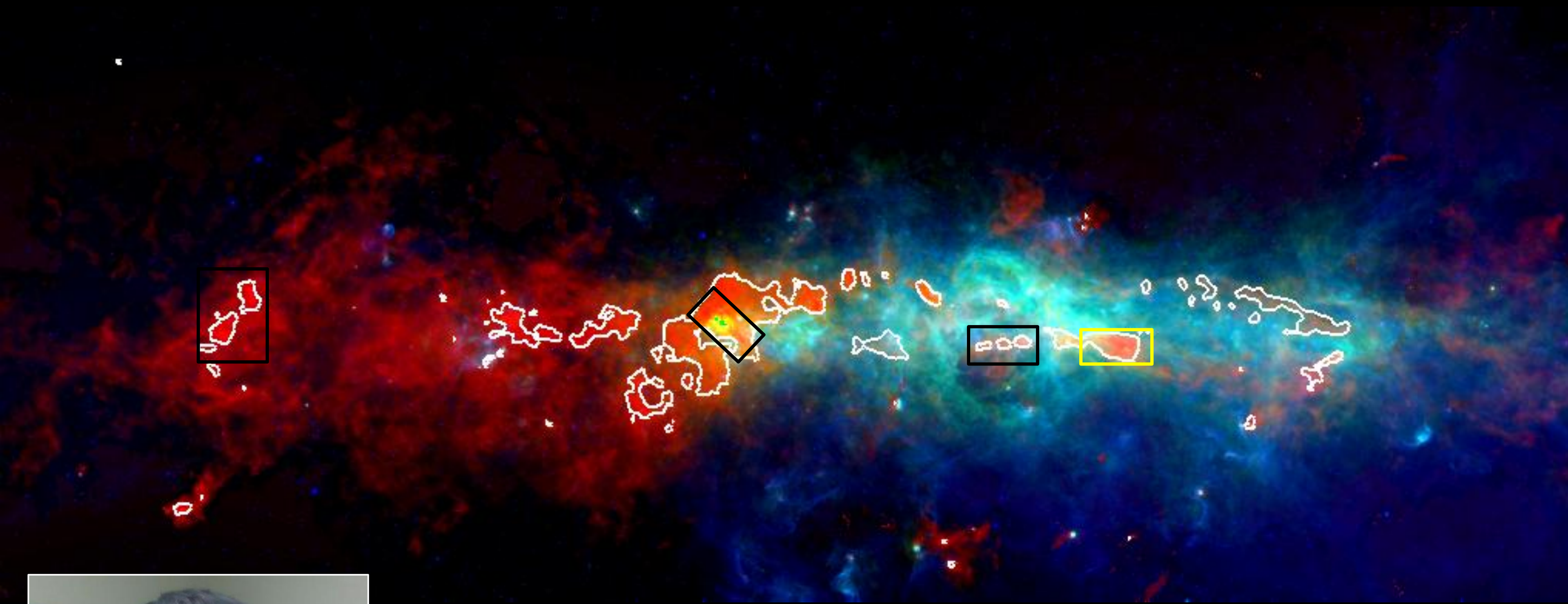

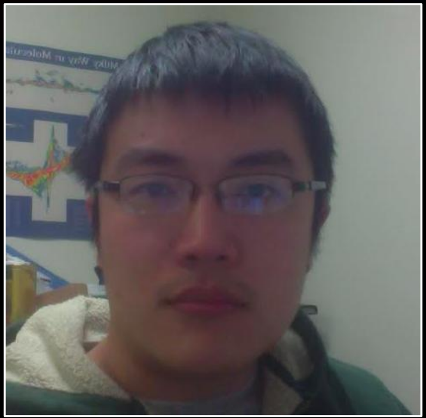

Xing ‘Walker’ Lu
CfA / Nanjing Univ.

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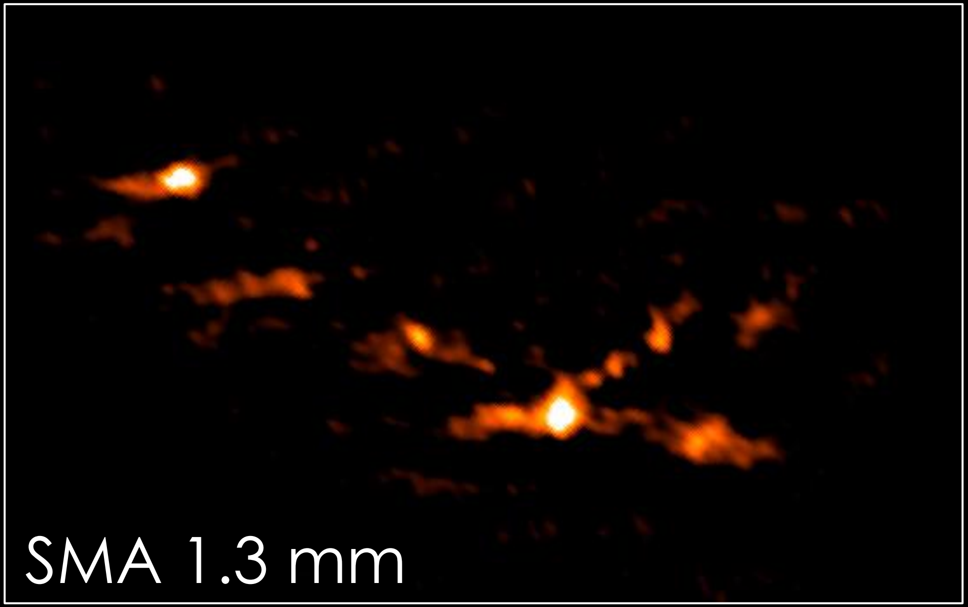

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Lu, et al., 2015

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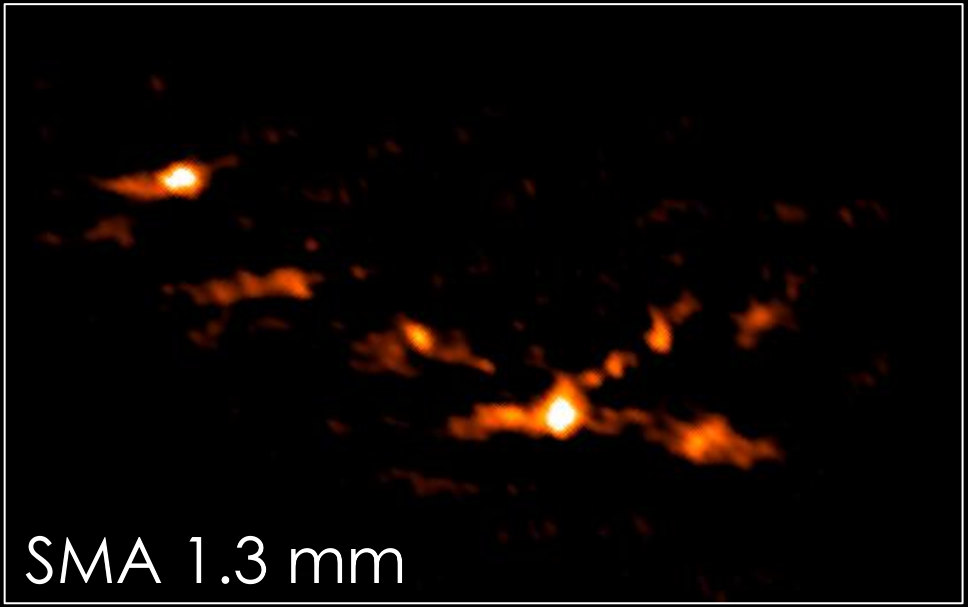

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Discovered hidden star formation

Lu, et al., 2015

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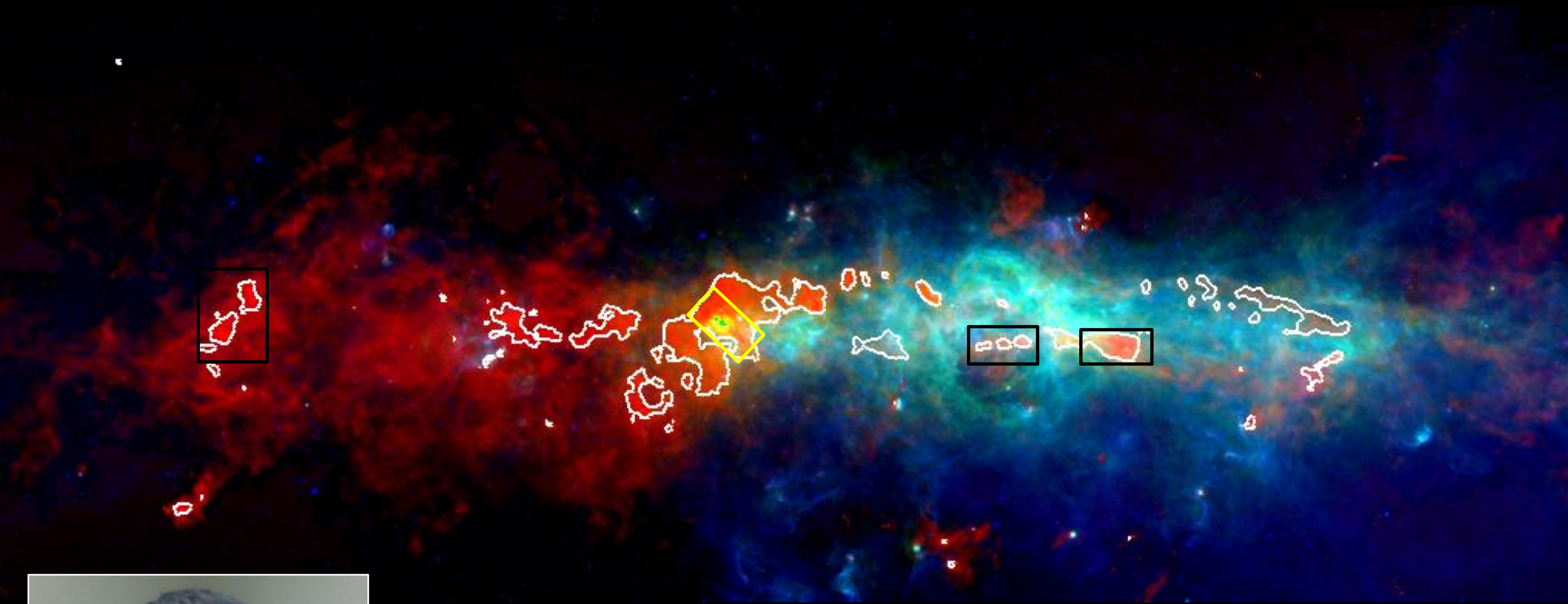

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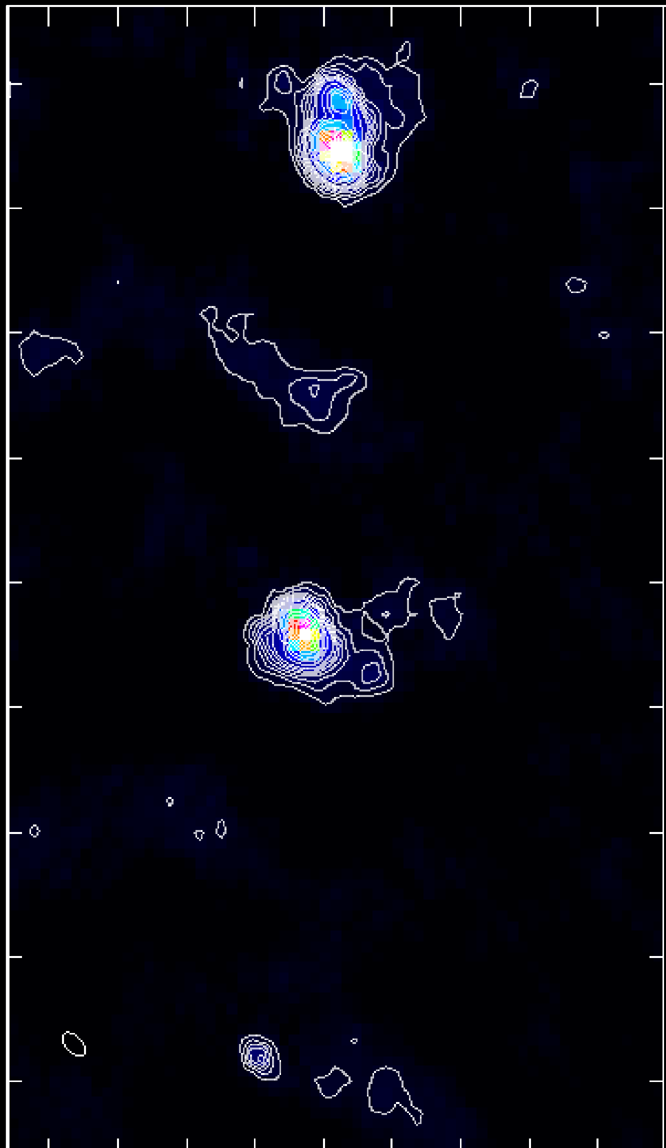
SMA
1.3 mm



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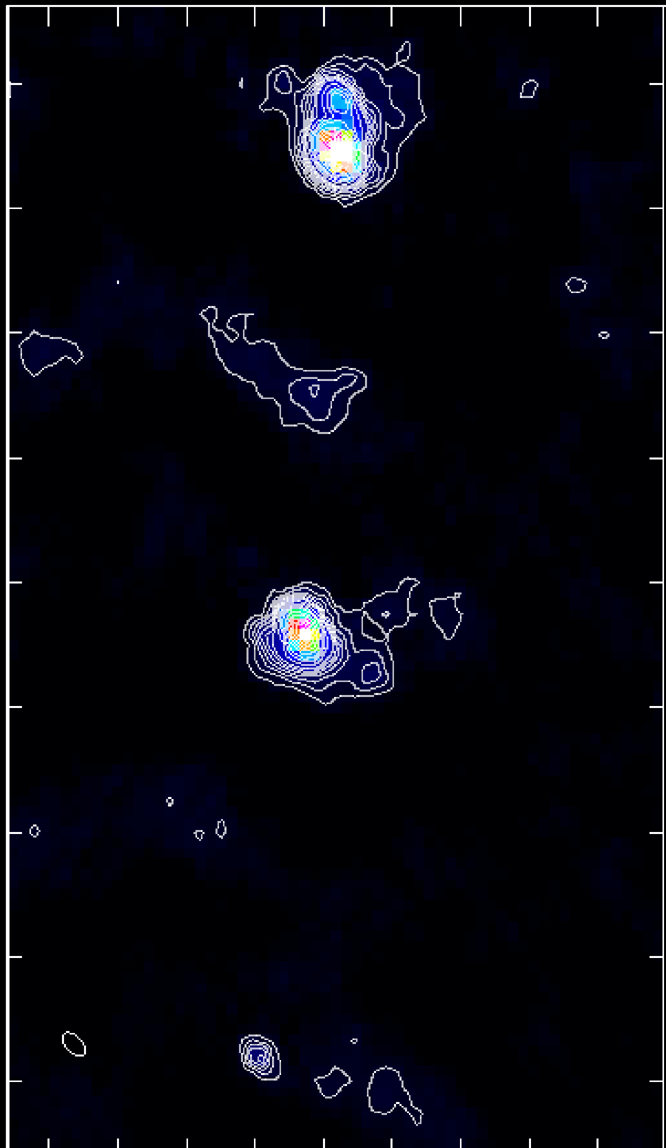

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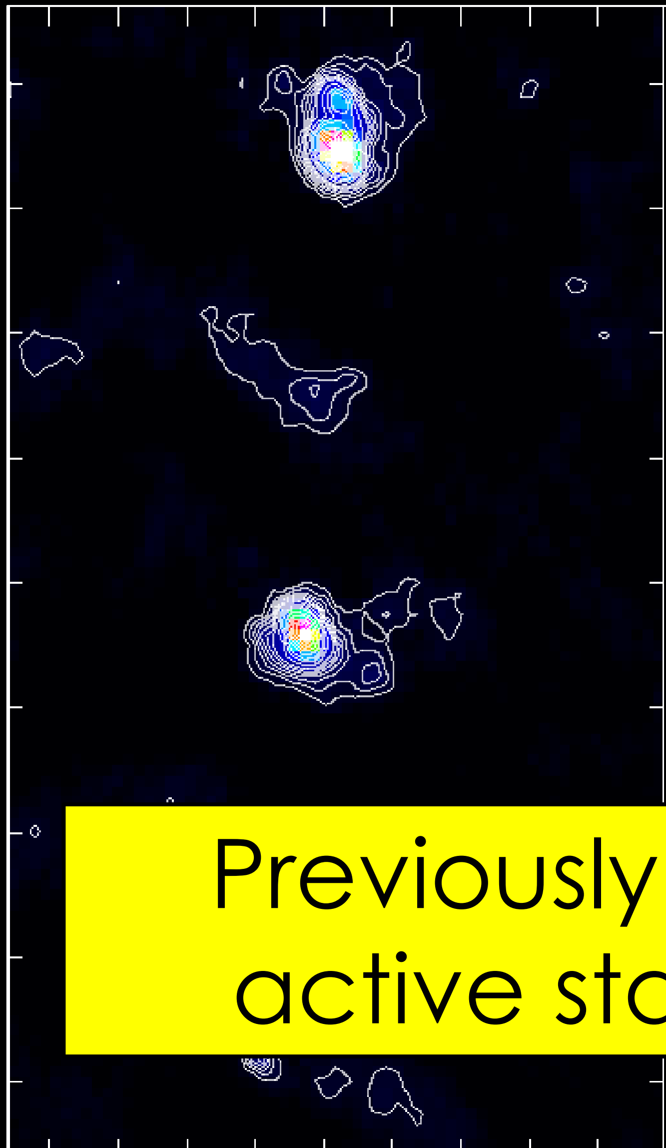

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Previously known very active star formation

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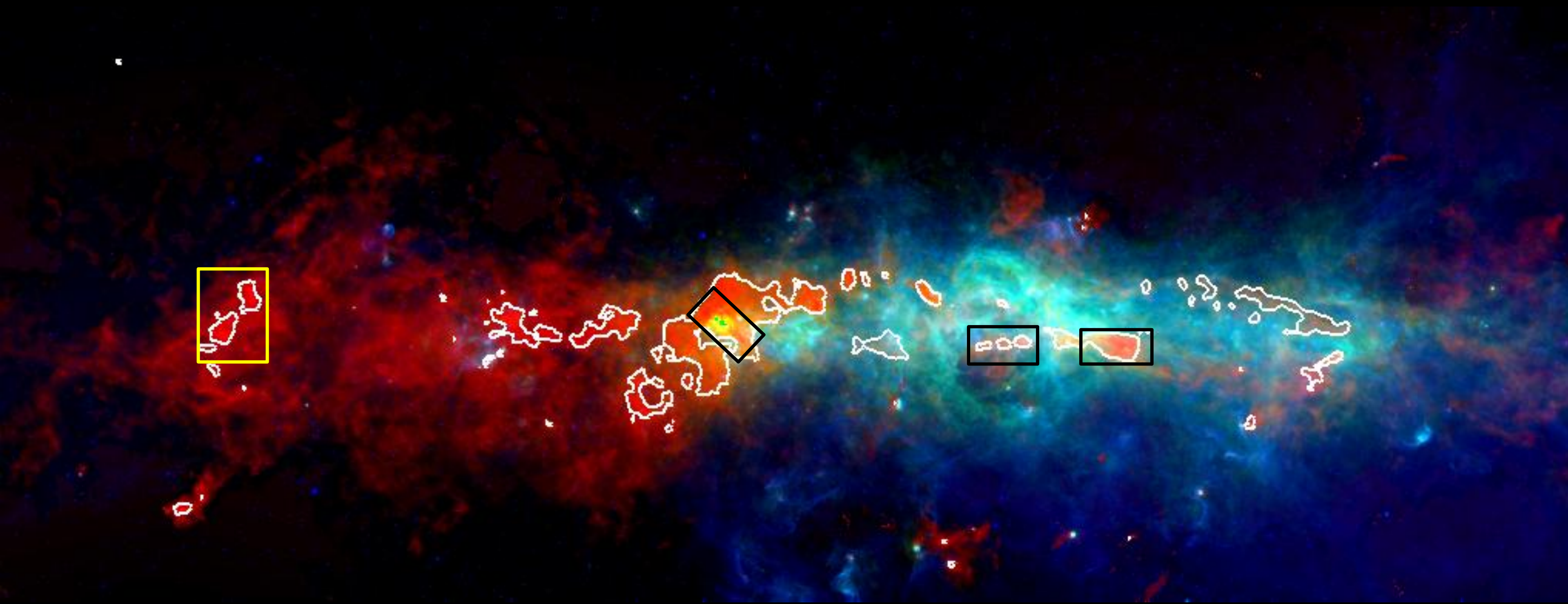
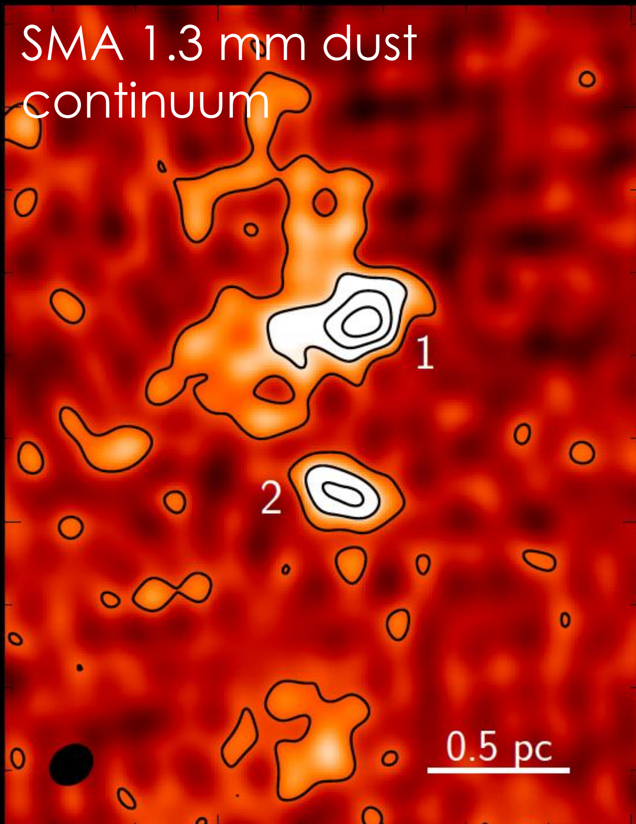


$N(H_2)$ from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)

Pre-cursors to high-mass stars



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Preliminary Core mass estimates, assuming 20 K
Core 1: 550 $M_{\odot}$
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Battersby, Graham, et al., in prep.

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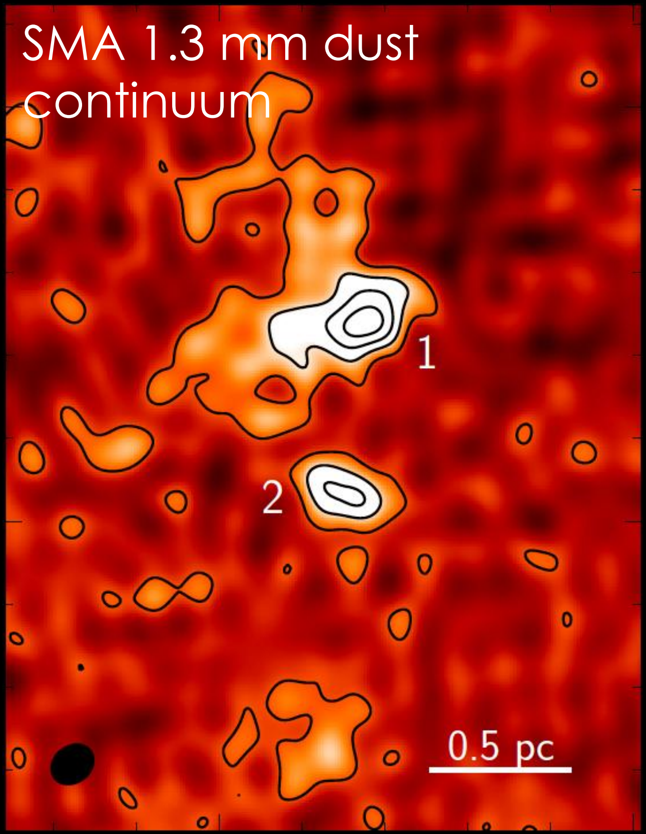

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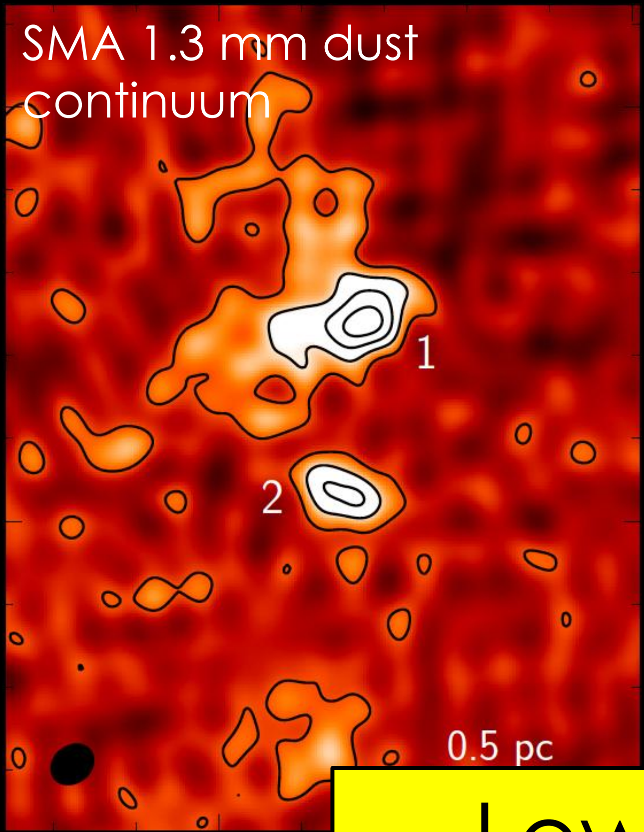

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Low-level isolated star formation

Battersby, Graham, et al., in prep.

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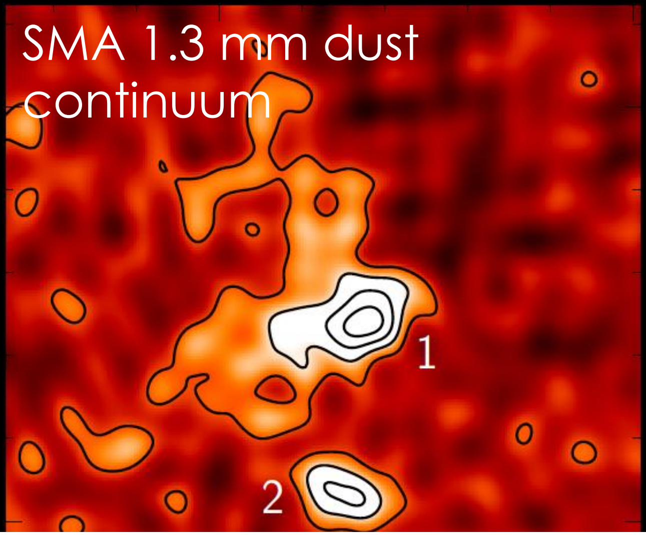

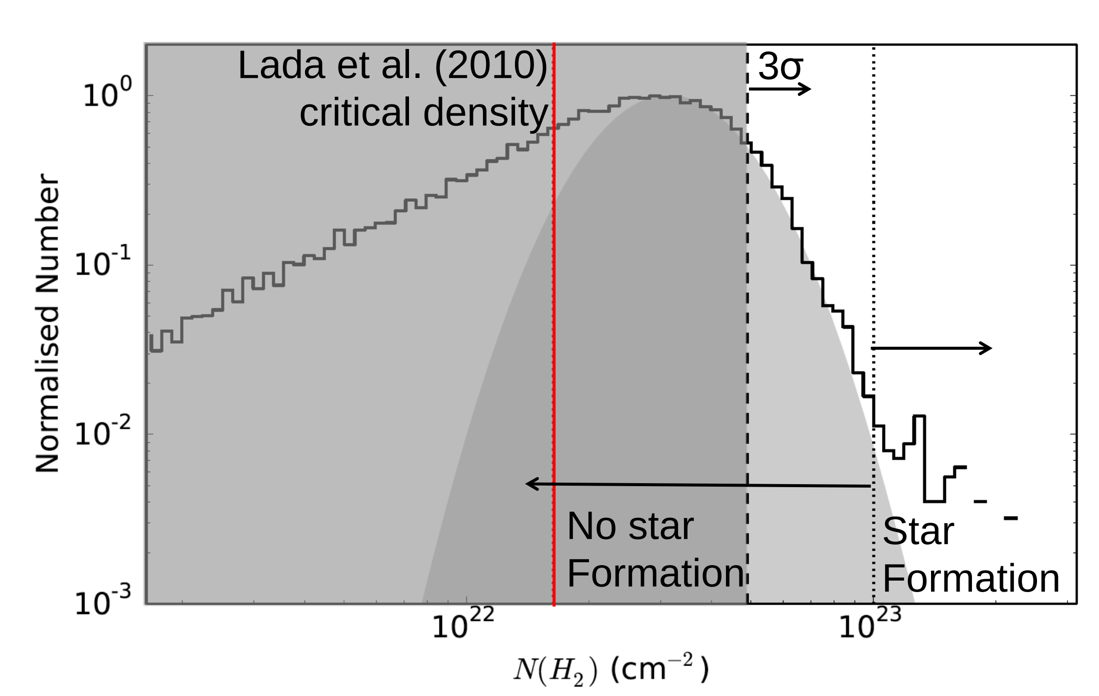

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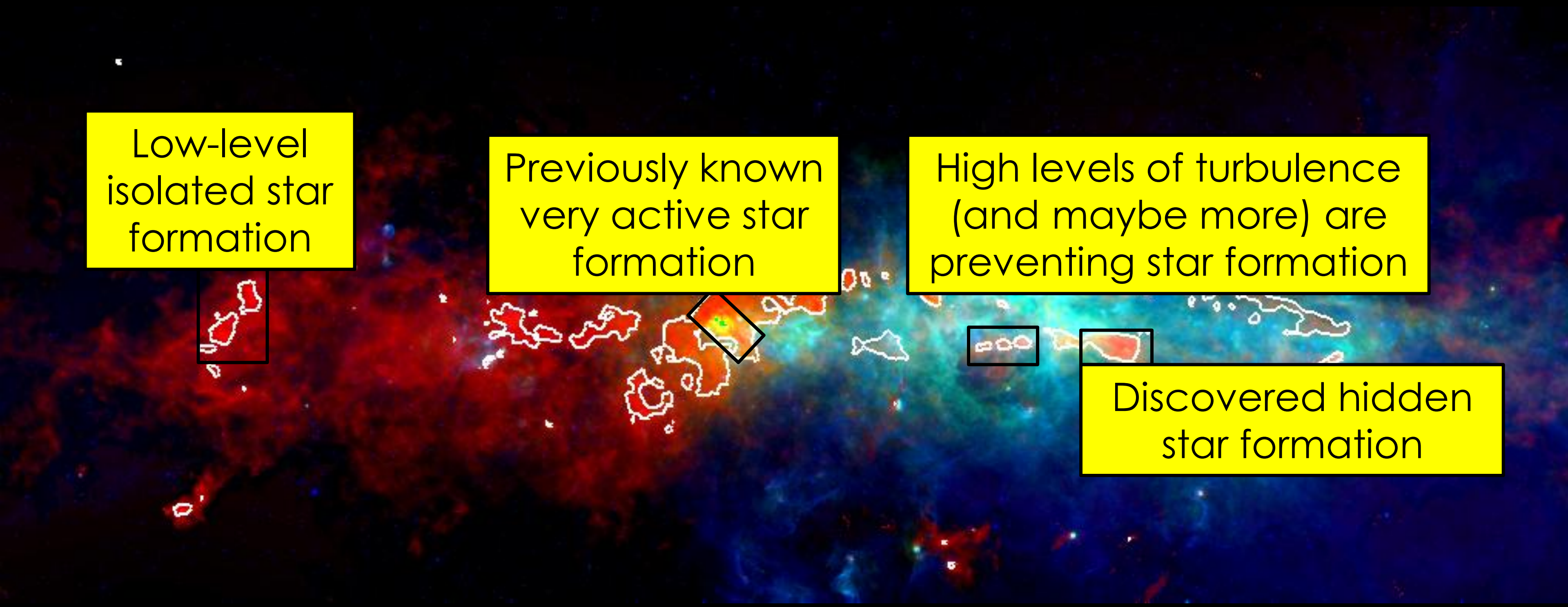

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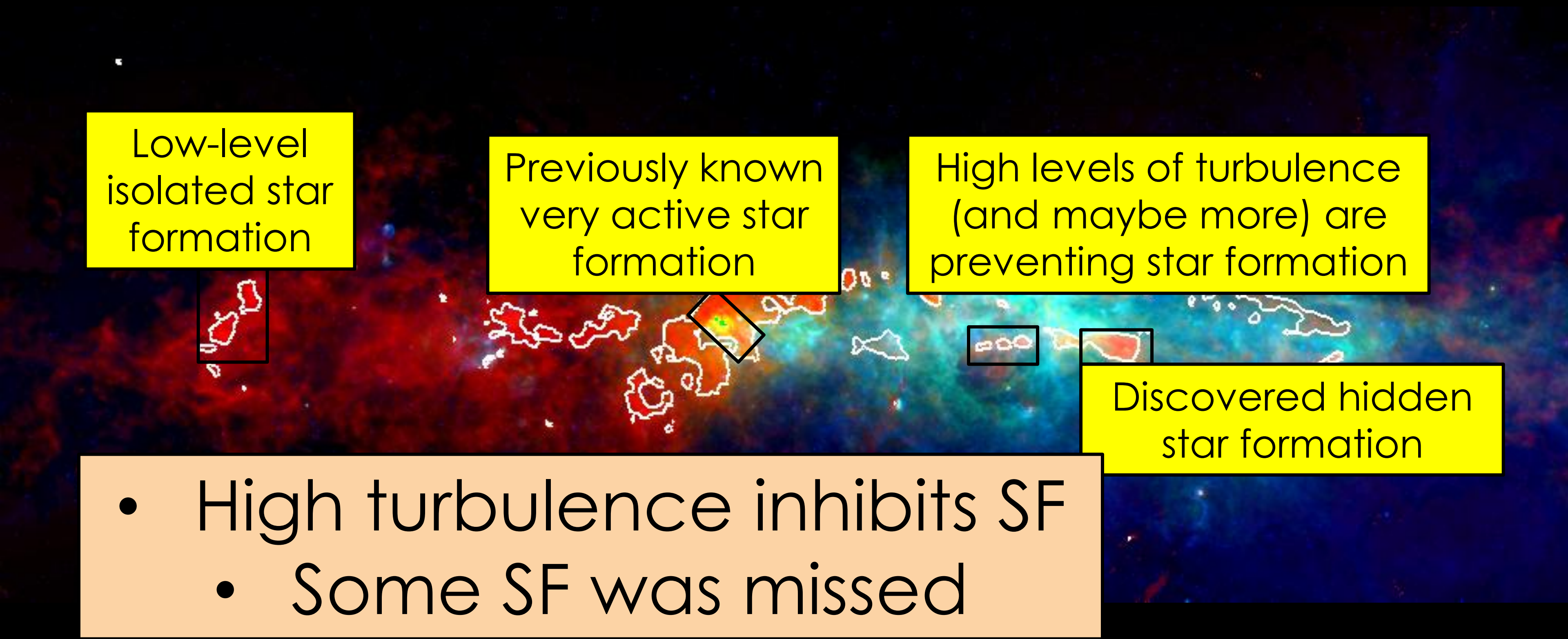
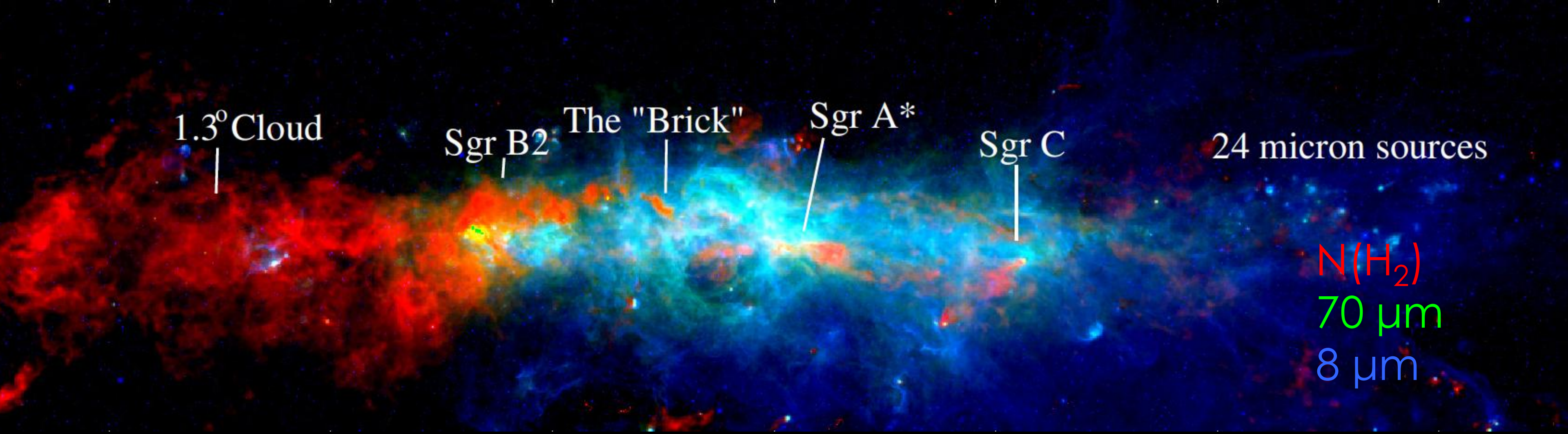
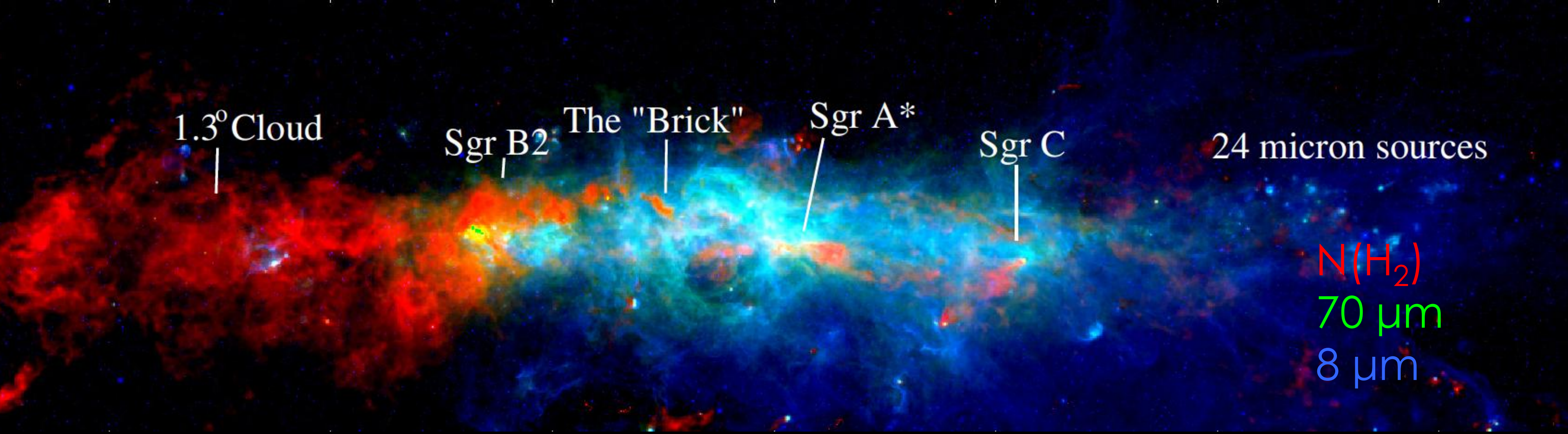


$N(H_2)$ from HiGAL Battersby+, in prep., 70 μm from HiGAL, Molinari+ 2011, 8 μm from GLIMPSE (Benjamin+ 2003)



Driving 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?



Driving Science Questions:

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

→ Some places are *very* active, in others, high levels of turbulence are important in inhibiting star formation

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*?

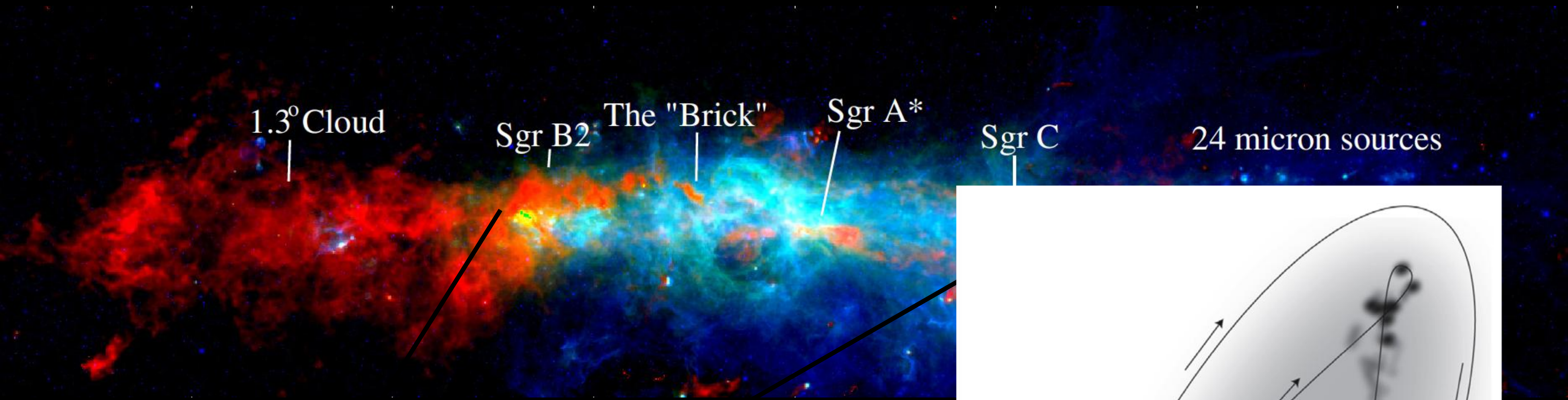
→Observations consistent

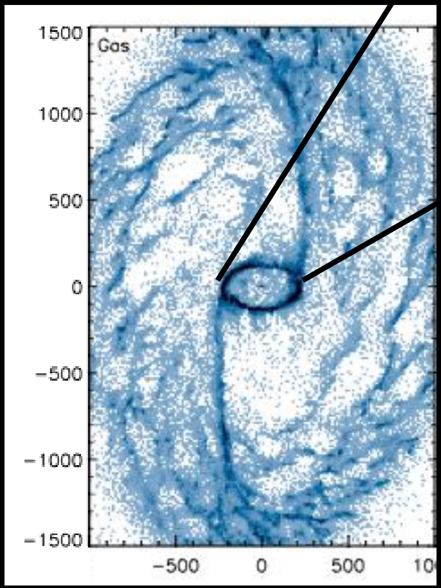
4) Can we find precursors to the most massive stars in the Galaxy?

→ We have some good candidates

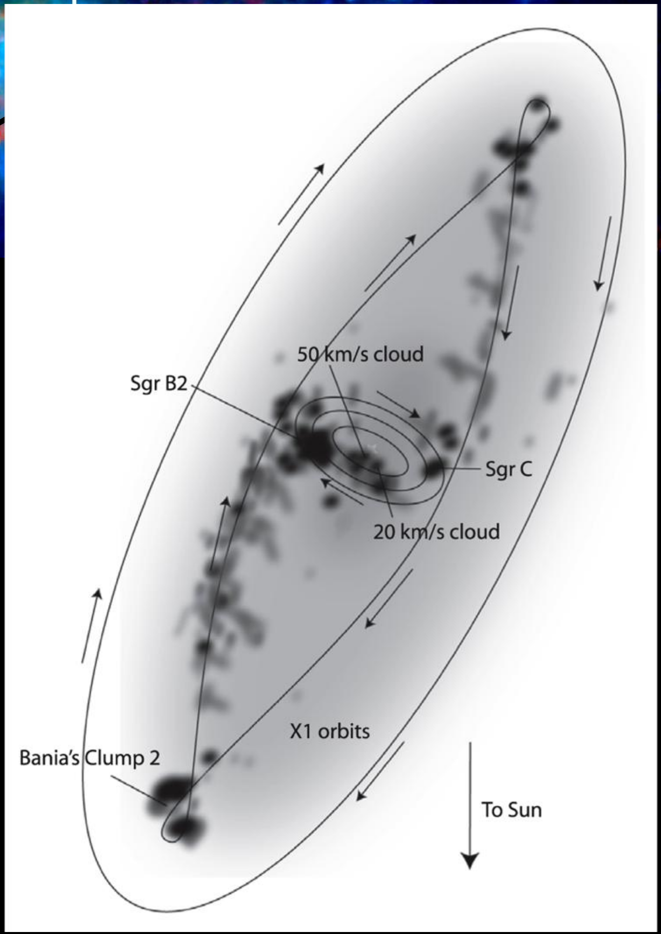
Extreme SF in our Galactic Center:
new, large survey shows turbulence can inhibit SF, tidal compression can (maybe) trigger it, and it can happen where we least expect it.

Our infinite thanks to the many many people at the SMA who made this survey possible!

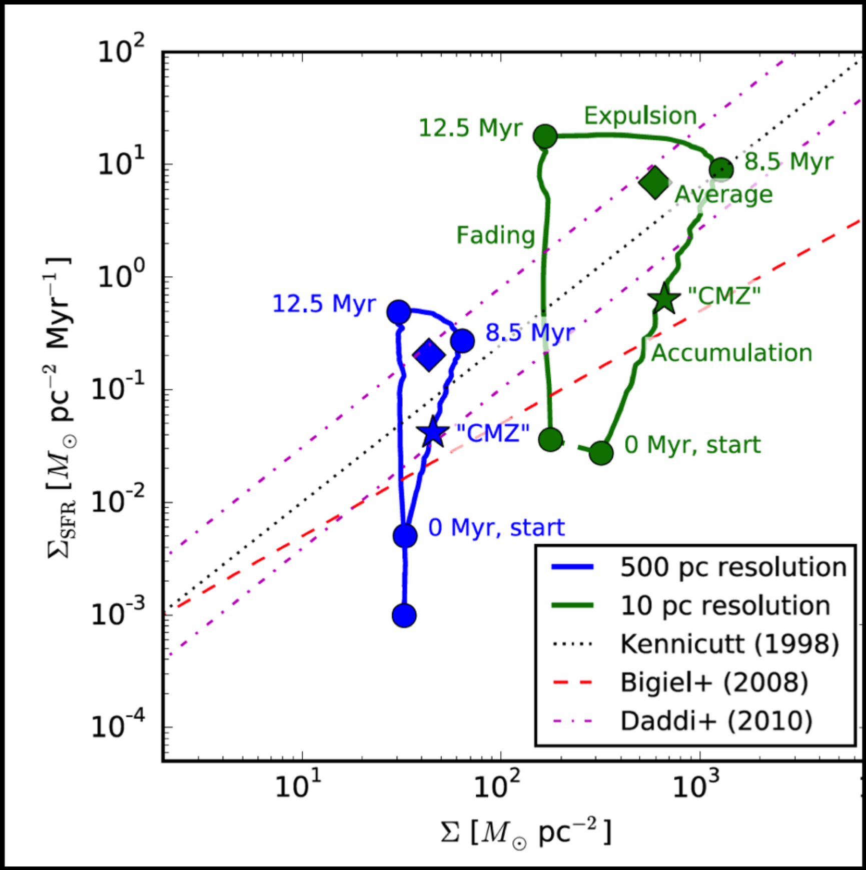




Bally et al. 2010 from Binney et al. 1991

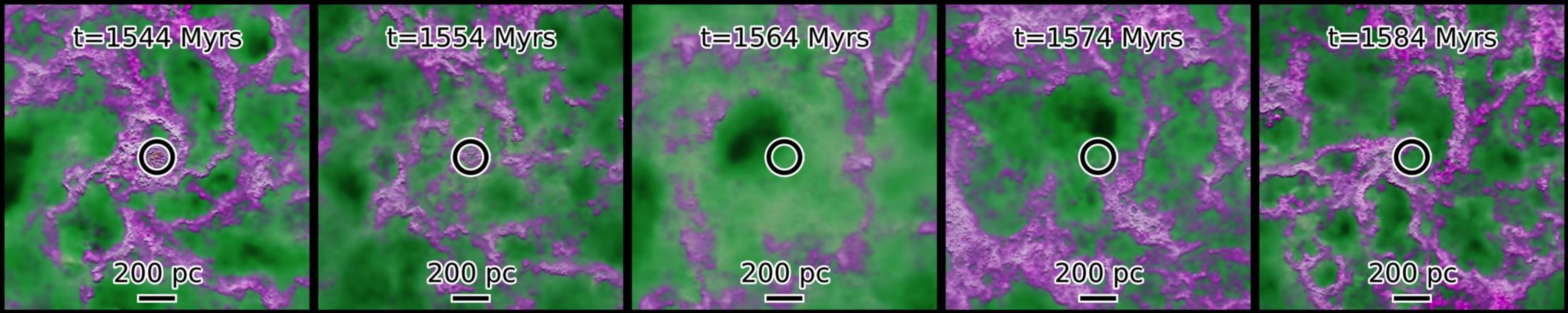


Why is the SFR low in the CMZ?

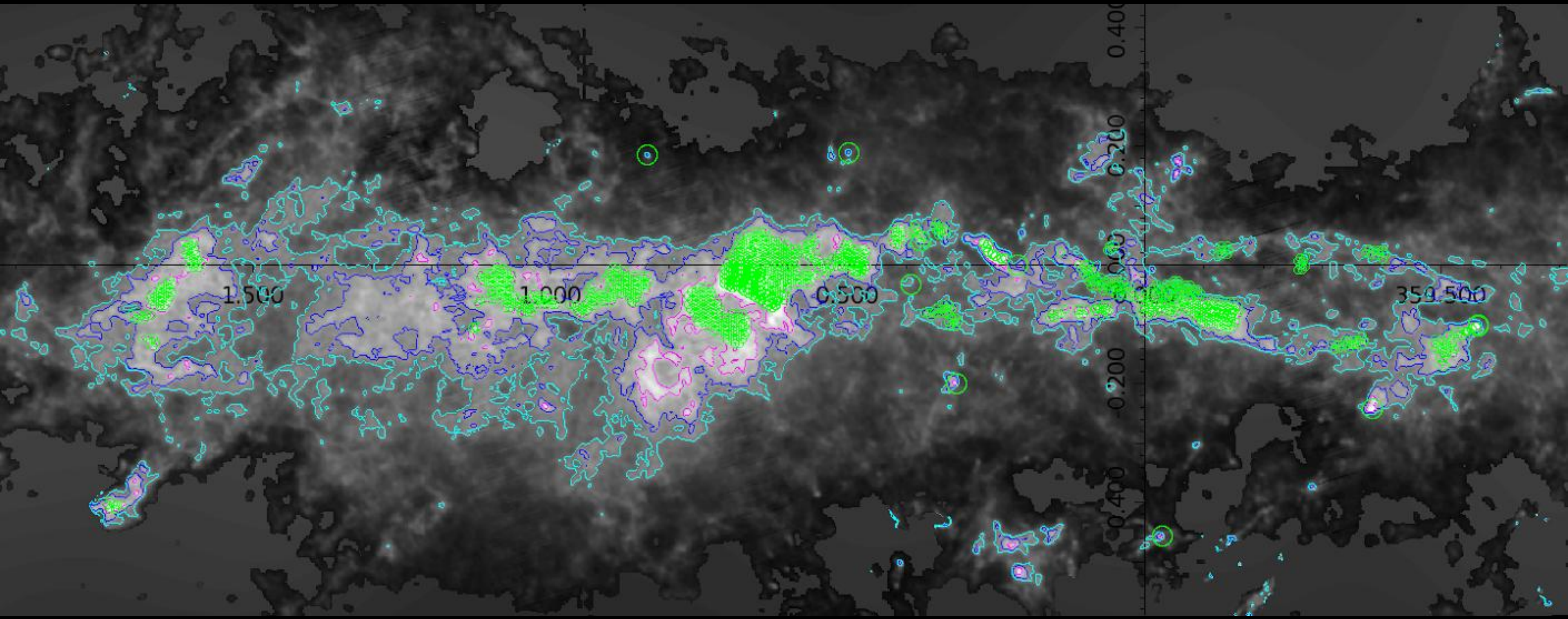


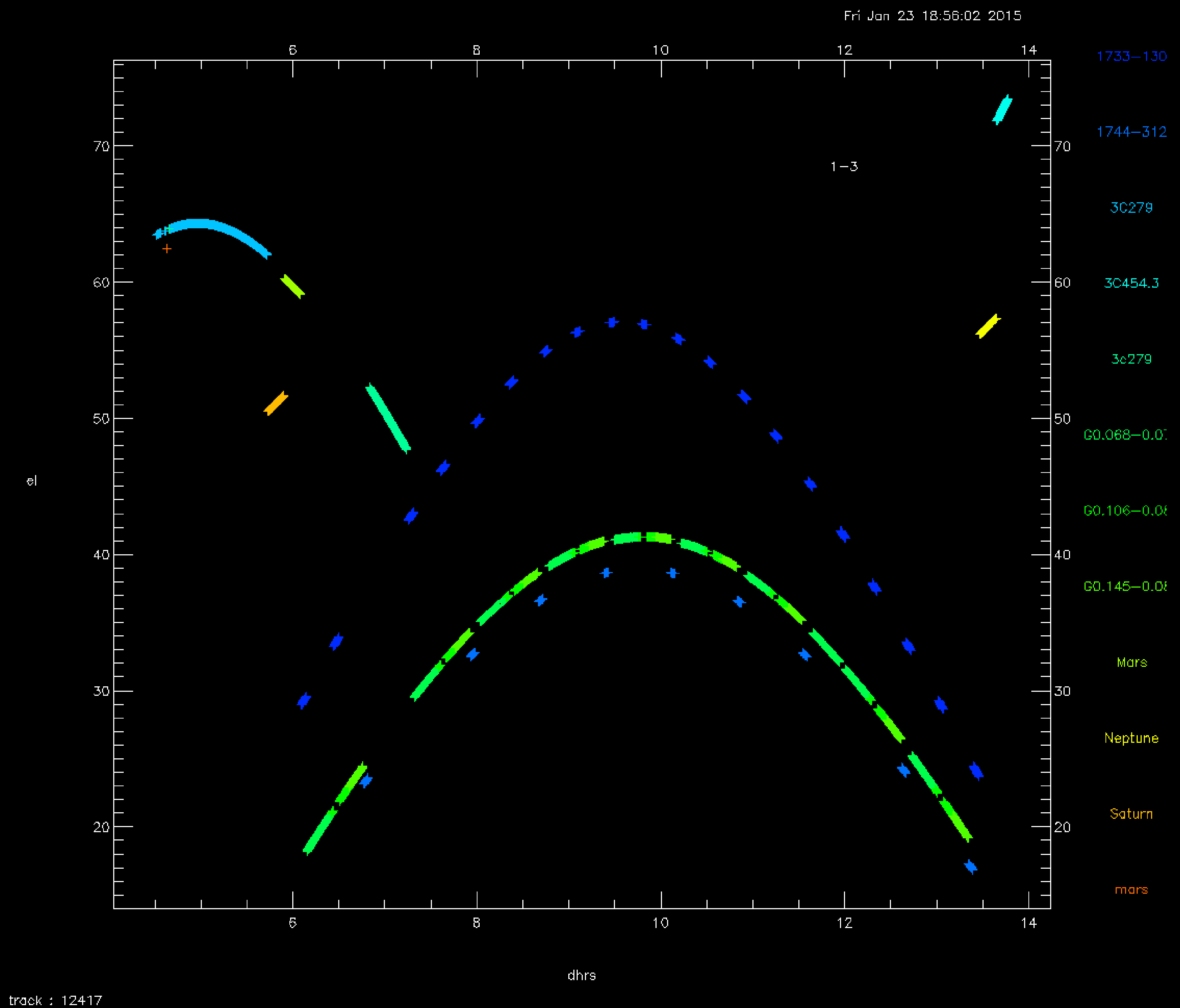
Krumholz & Kruijssen 2015

Torrey et al., 2016



All Total

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1744−312
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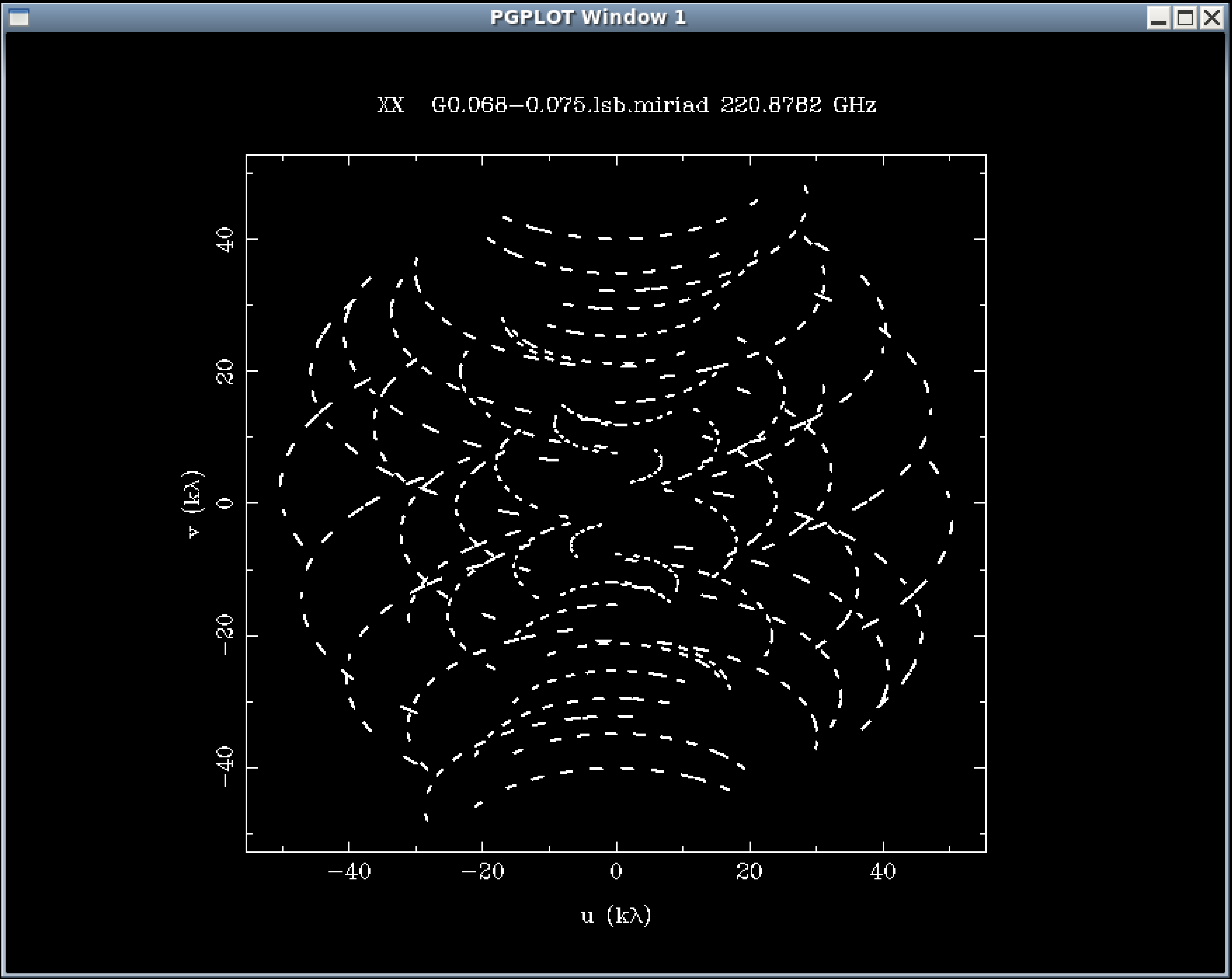
track : 12417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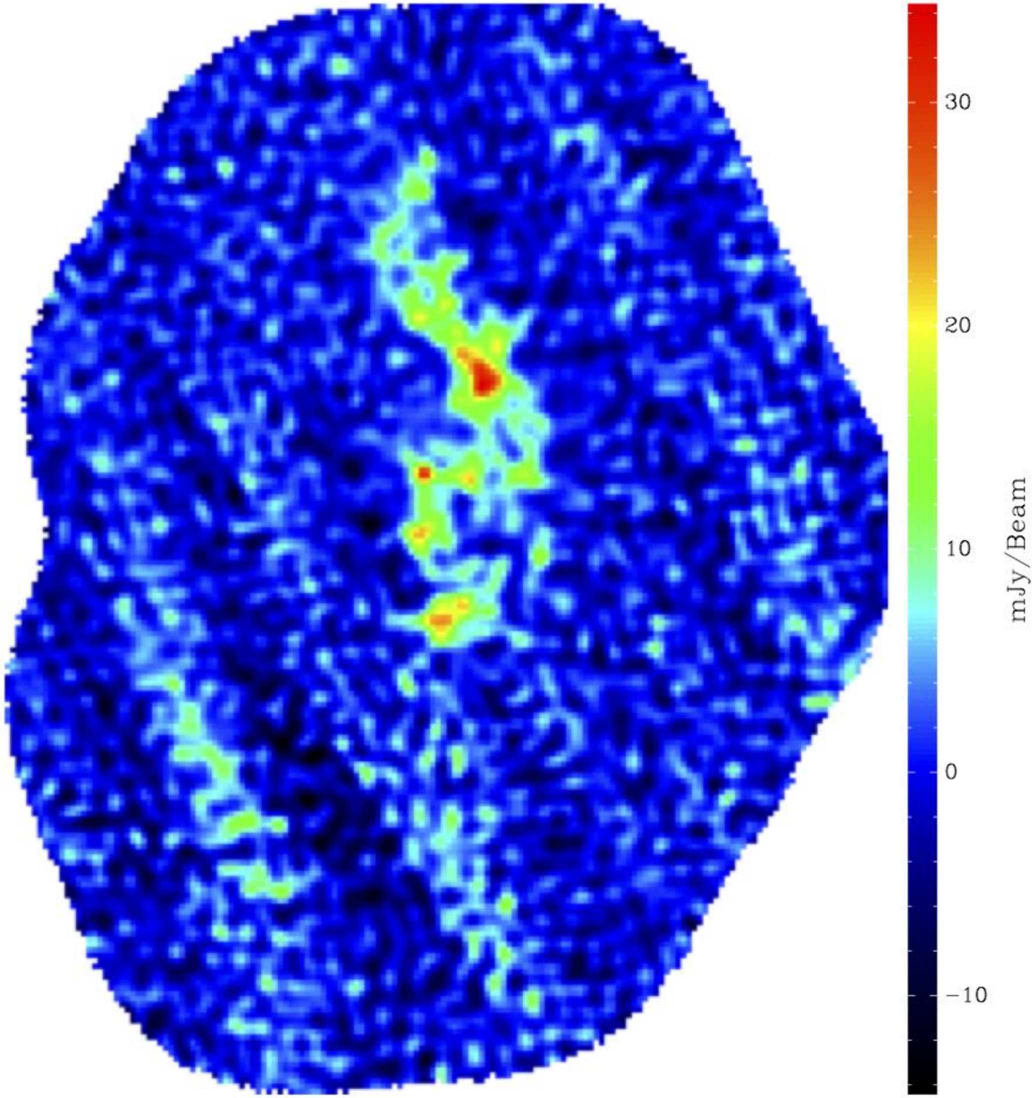
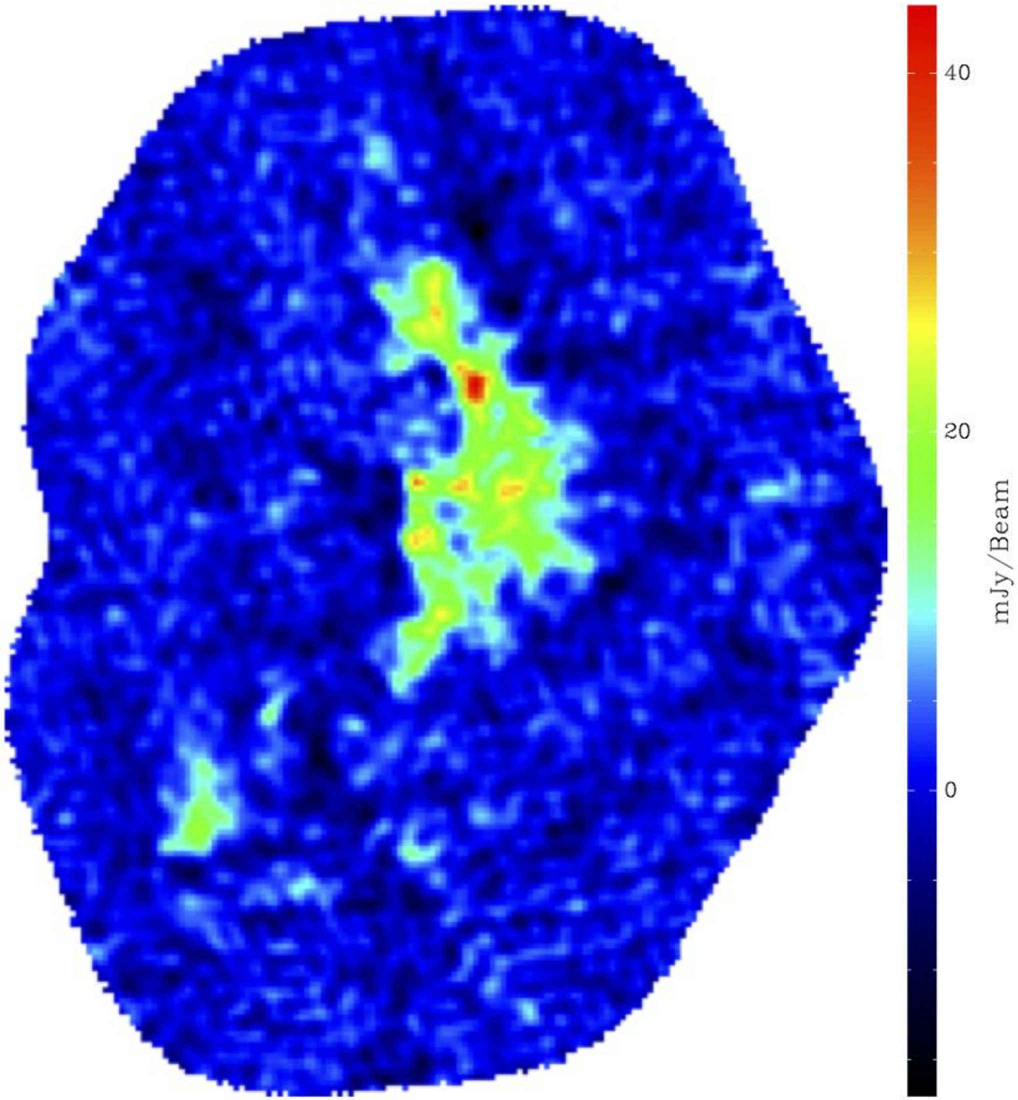
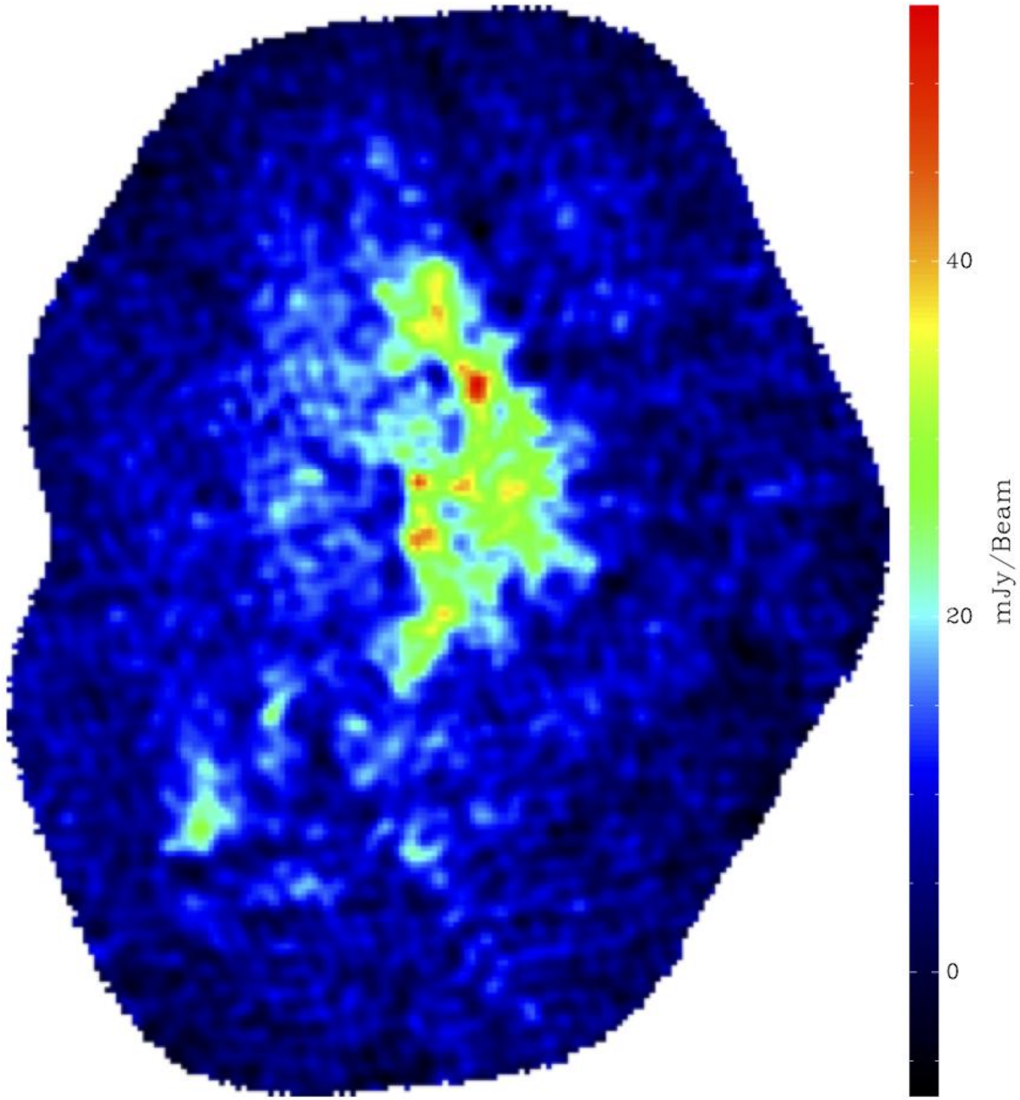
Compact only

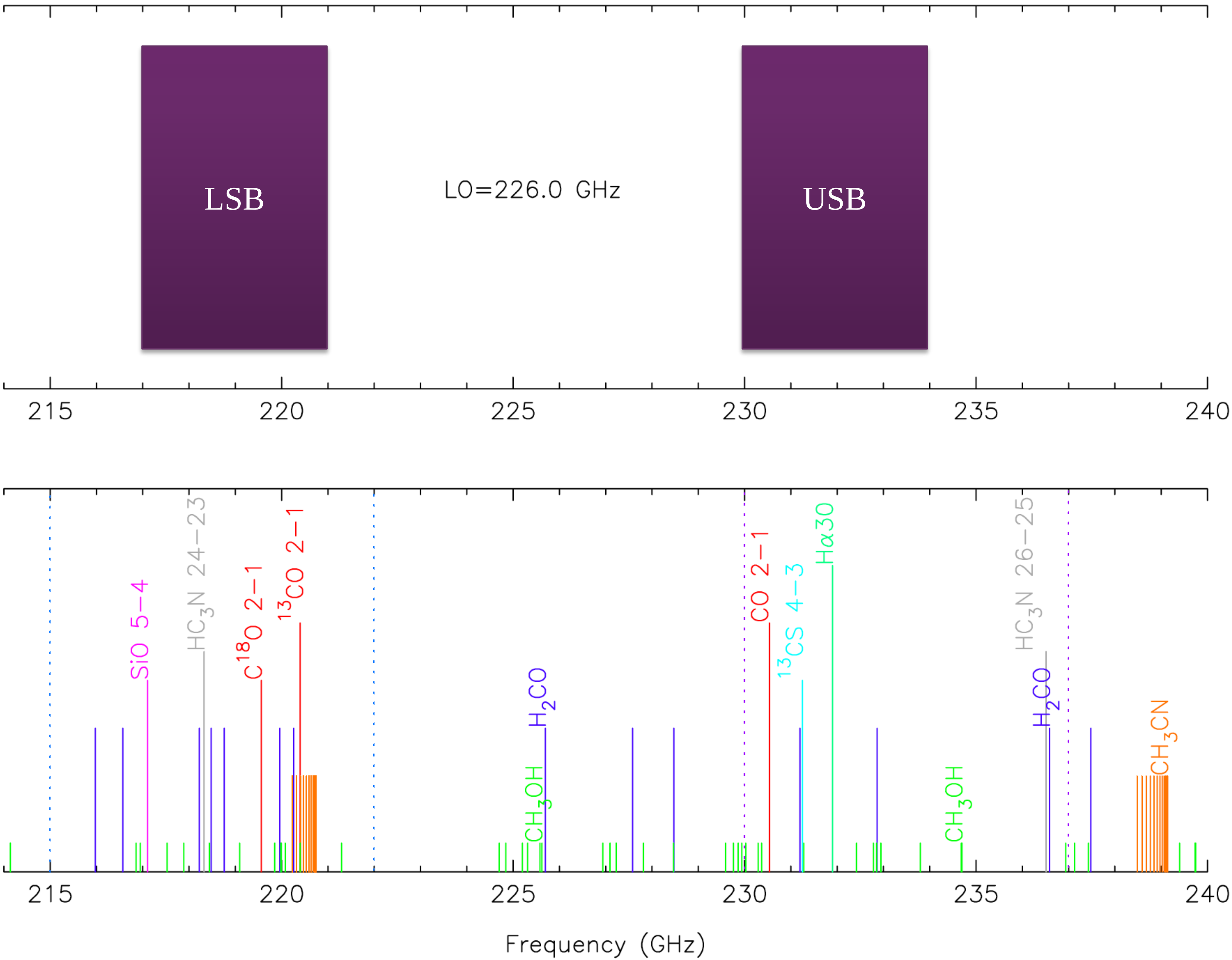


Compact + subcompact



Compact + subcompact + single dish





LSB
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220
225
230
235
240
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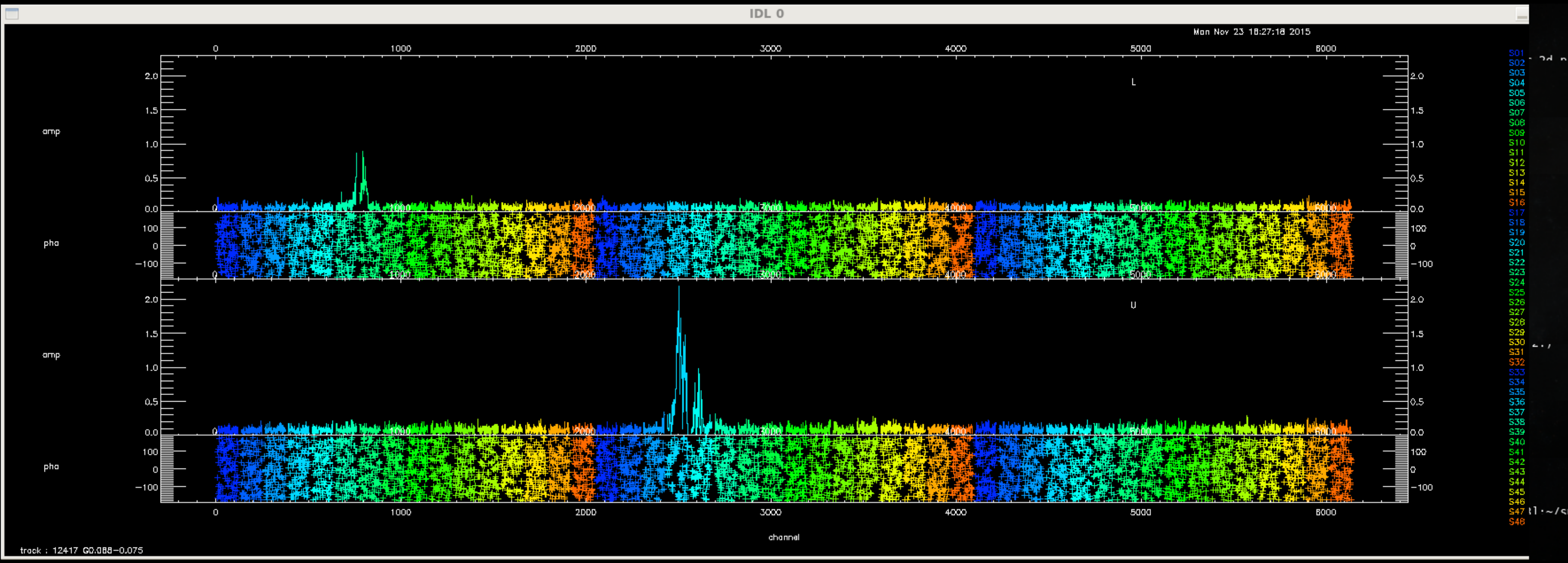
HC3N 24−23
C18O 2−1
13CO 2−1
H2CO
CH3OH
CO 2−1
13CS 4−3
Hα30
HC3N 26−25
H2CO
CH3OH
CH3CN
Frequency (GHz)



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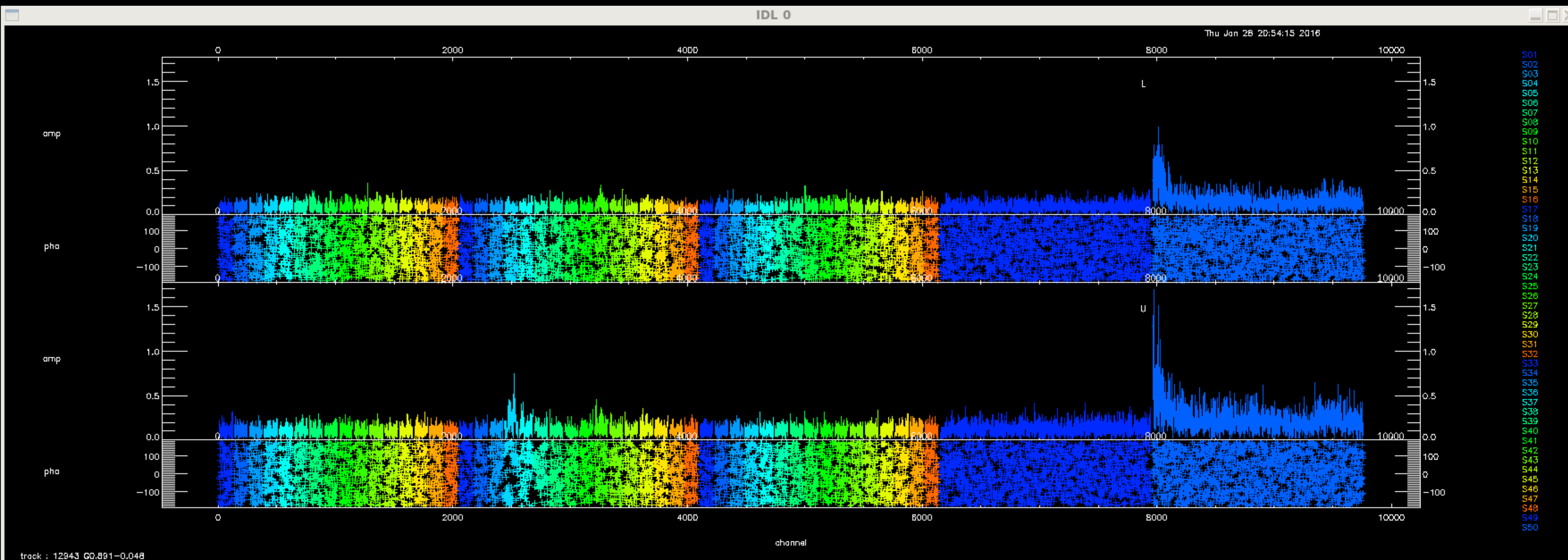
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Team
CMZoom
Laugh
Love