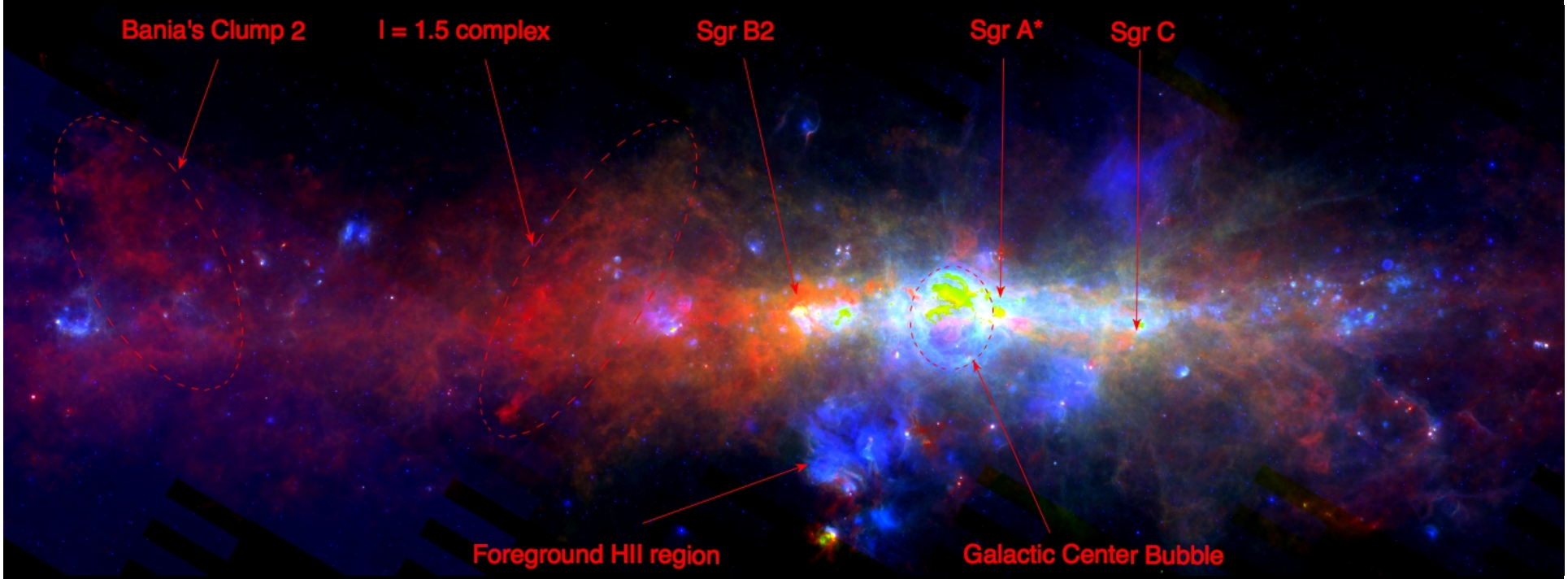
Galactic Center Star Formation:
How & at What Rate?

John Bally[1]



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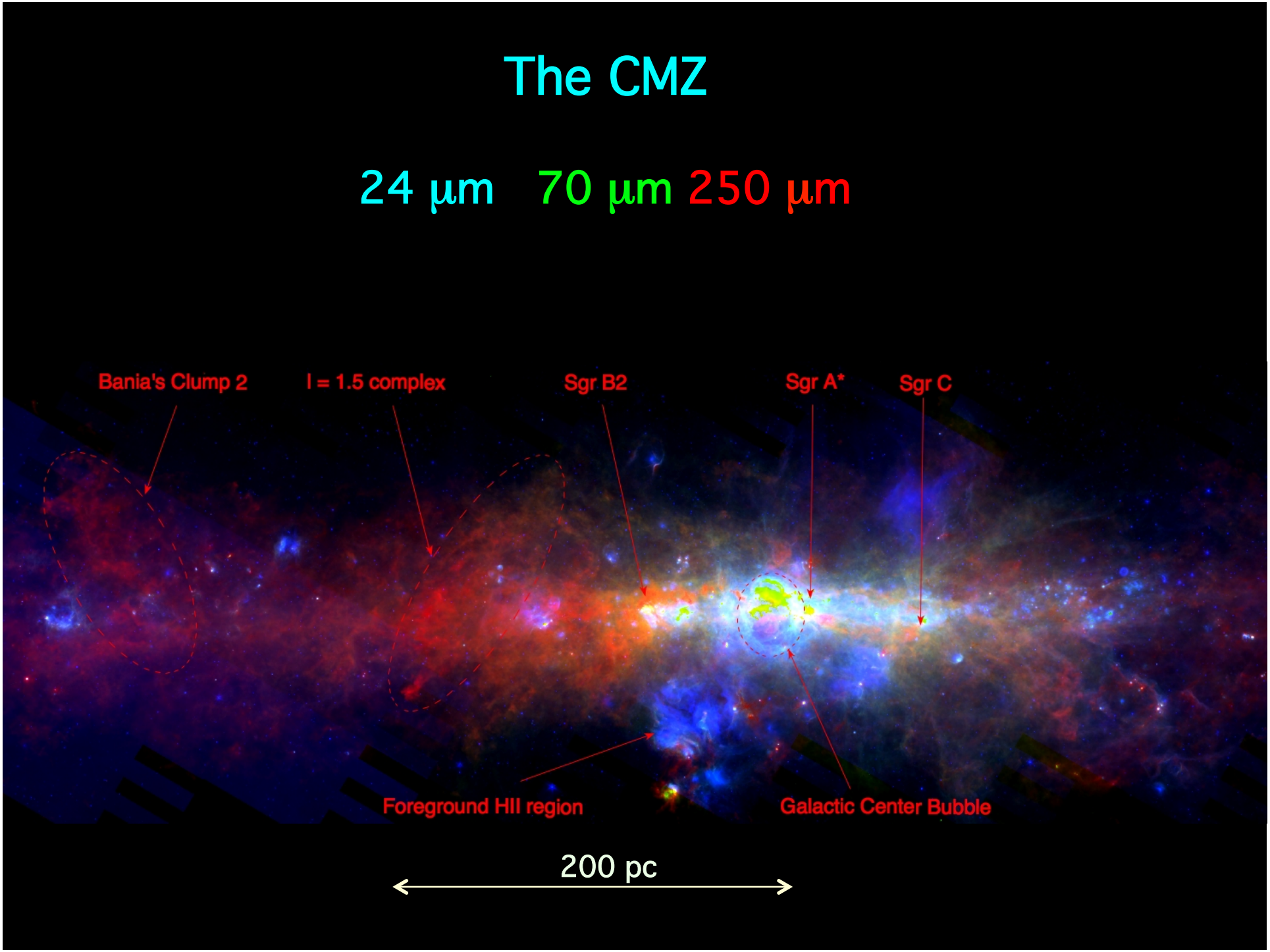
The CMZ

24 μm 70 μm 250 μm



Central Molecular Zone (CMZ)

- x10 - x100 denser, more turbulent than disk GMCs

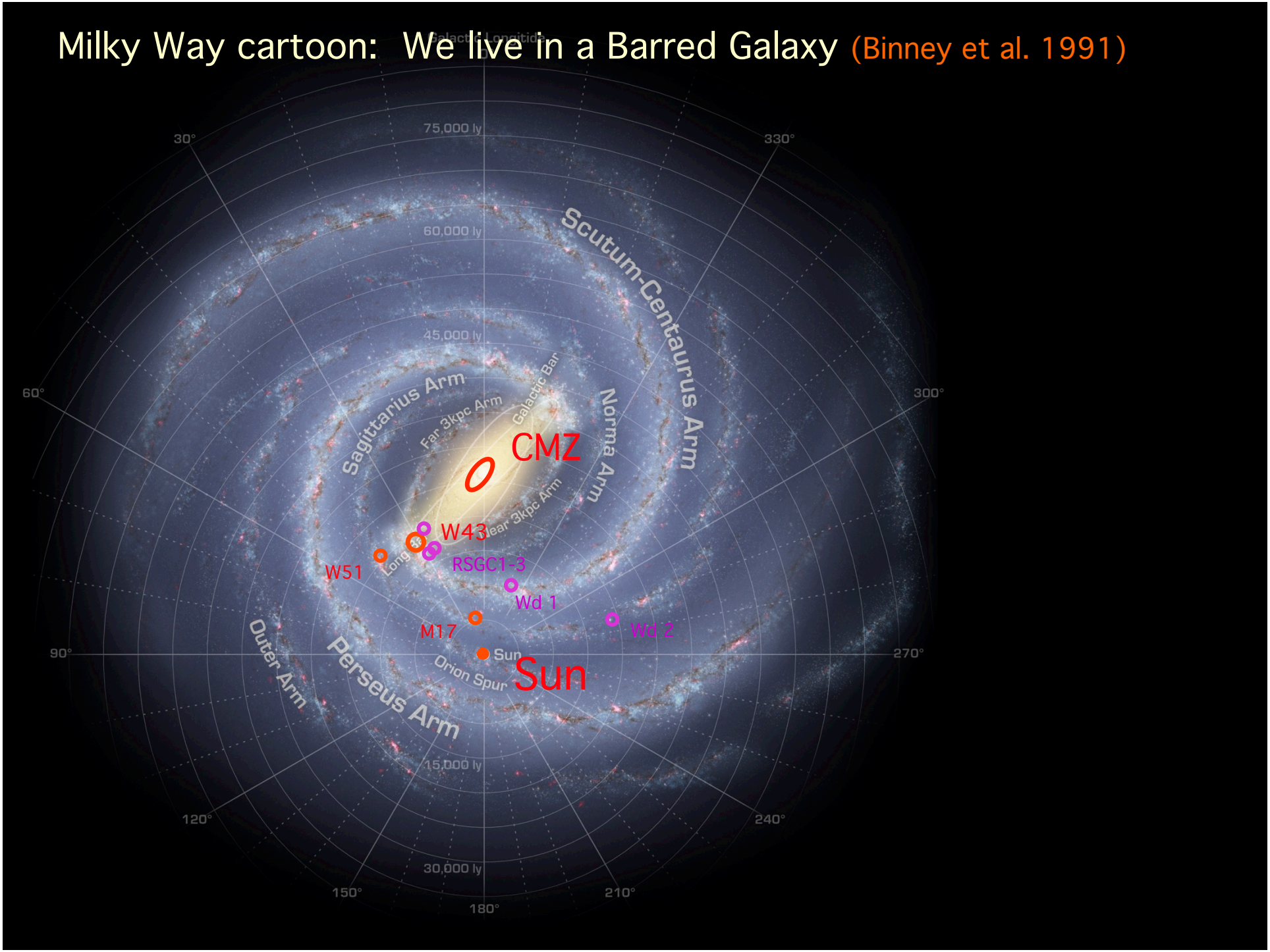
- 80% of Galactic dense gas [$n(H_2) > 10^4$ cm^{-3}] is in the CMZ
  Traced by HCN, CS, etc. $\Delta V > 10$ km/s

- Star formation rate < 0.1 M_o/yr; Mostly at R~100 pc
  A second parameter?
  SFR ~ $C\ \rho^{\alpha}\ \Delta V^{\beta}$ α~ 1 to 2, β~ -1 to -2

- The Asymmetric CMZ:
  Gas & cold dust: >2/3 at POSITIVE longitude, velocity
  24 μm sources: >2/3 at NEGATIVE longitude

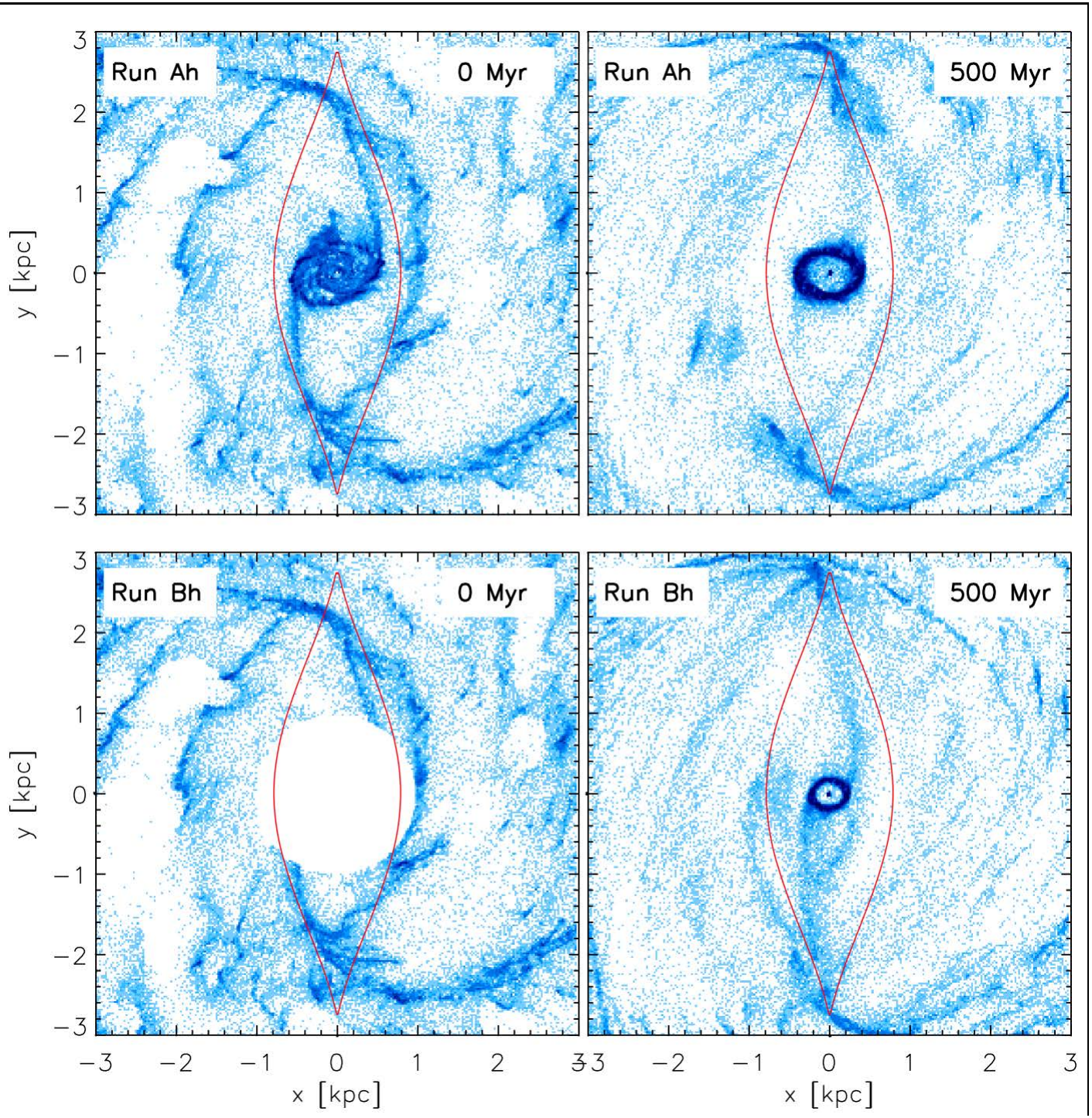
- Short orbit times:
  t_{orbit} ~ 6 Myr $R_{100\ pc}$ / $V_{100\ km/s}$
  (1 to 10 Myr)

Milky Way cartoon: We live in a Barred Galaxy (Binney et al. 1991)



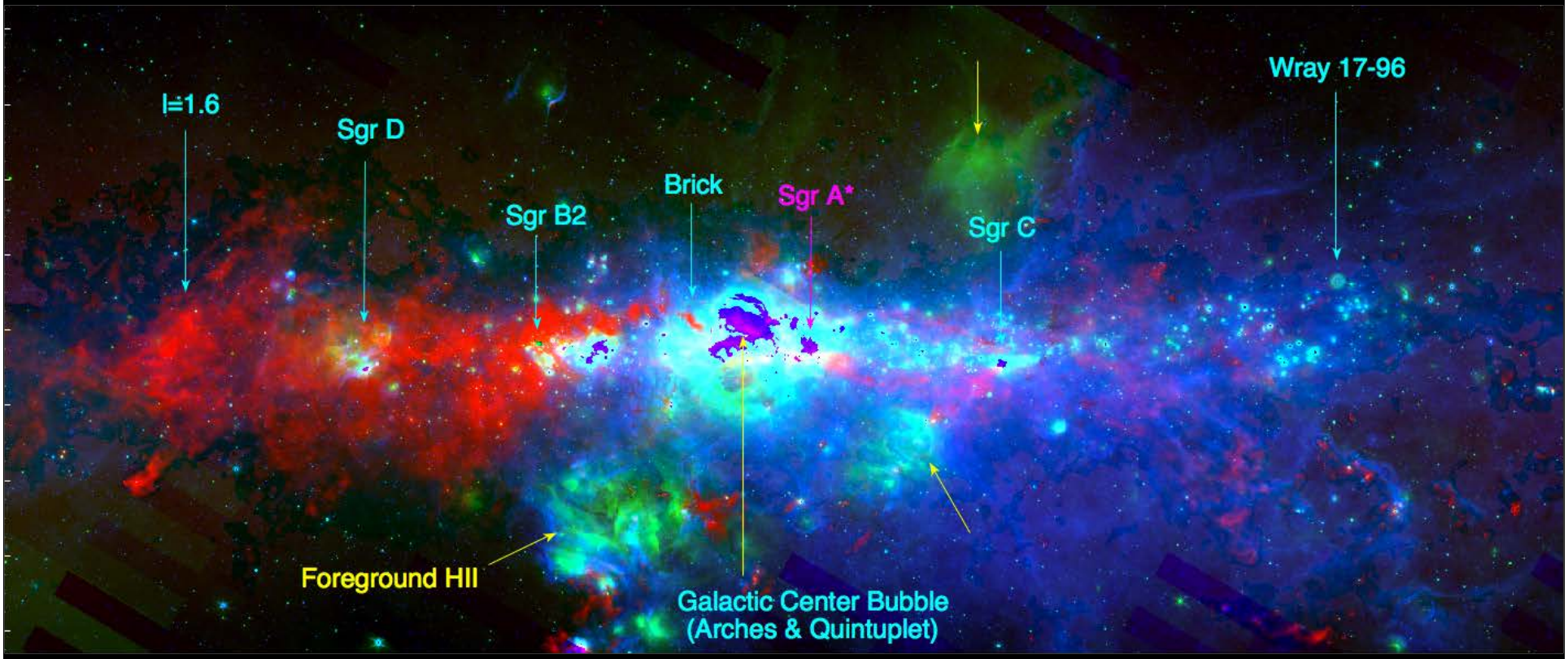
Life in a barred potential

(Shim & Kim+ 2017)

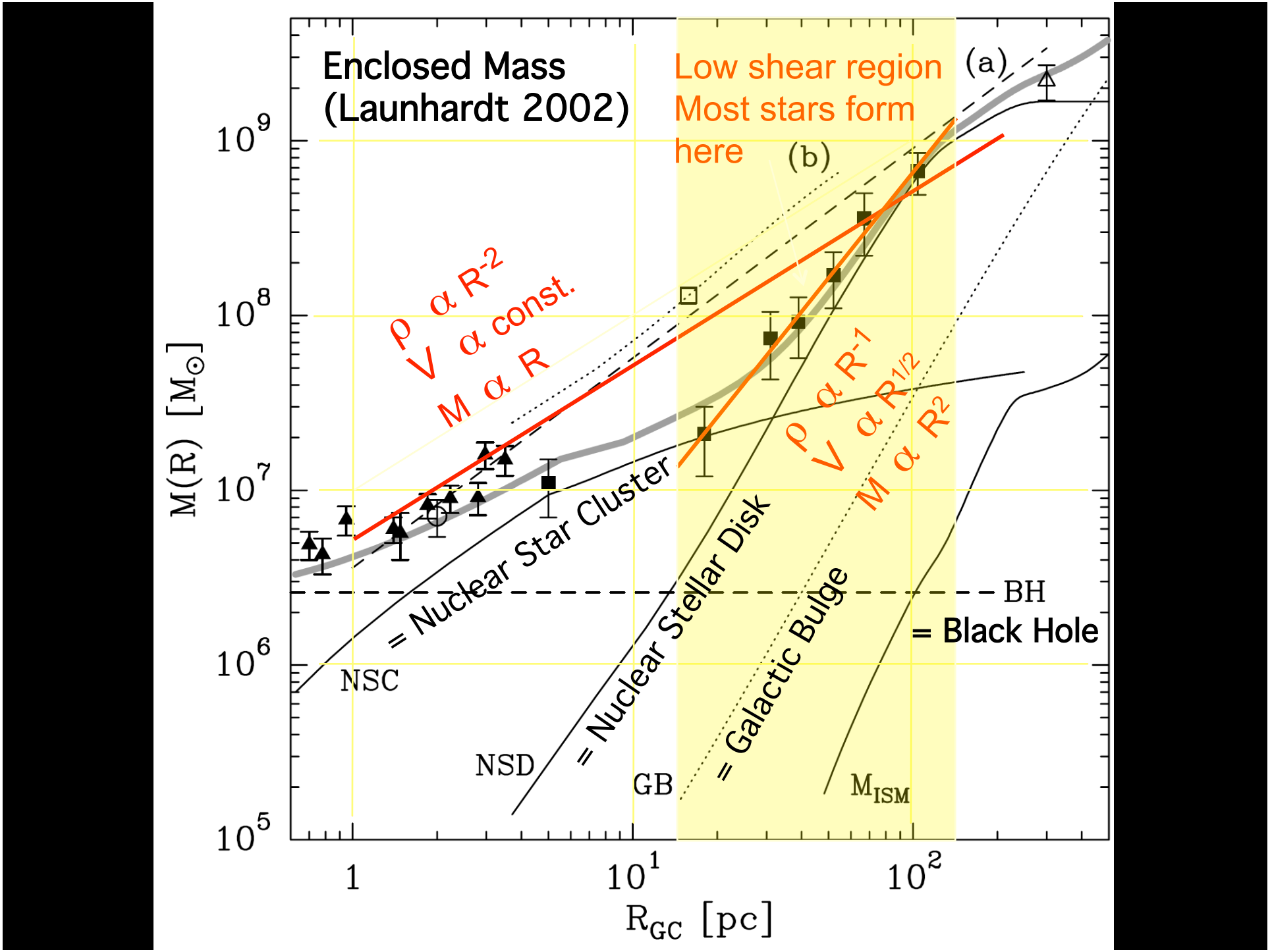


Inner CMZ

8 um 24 um $N(H_2)$

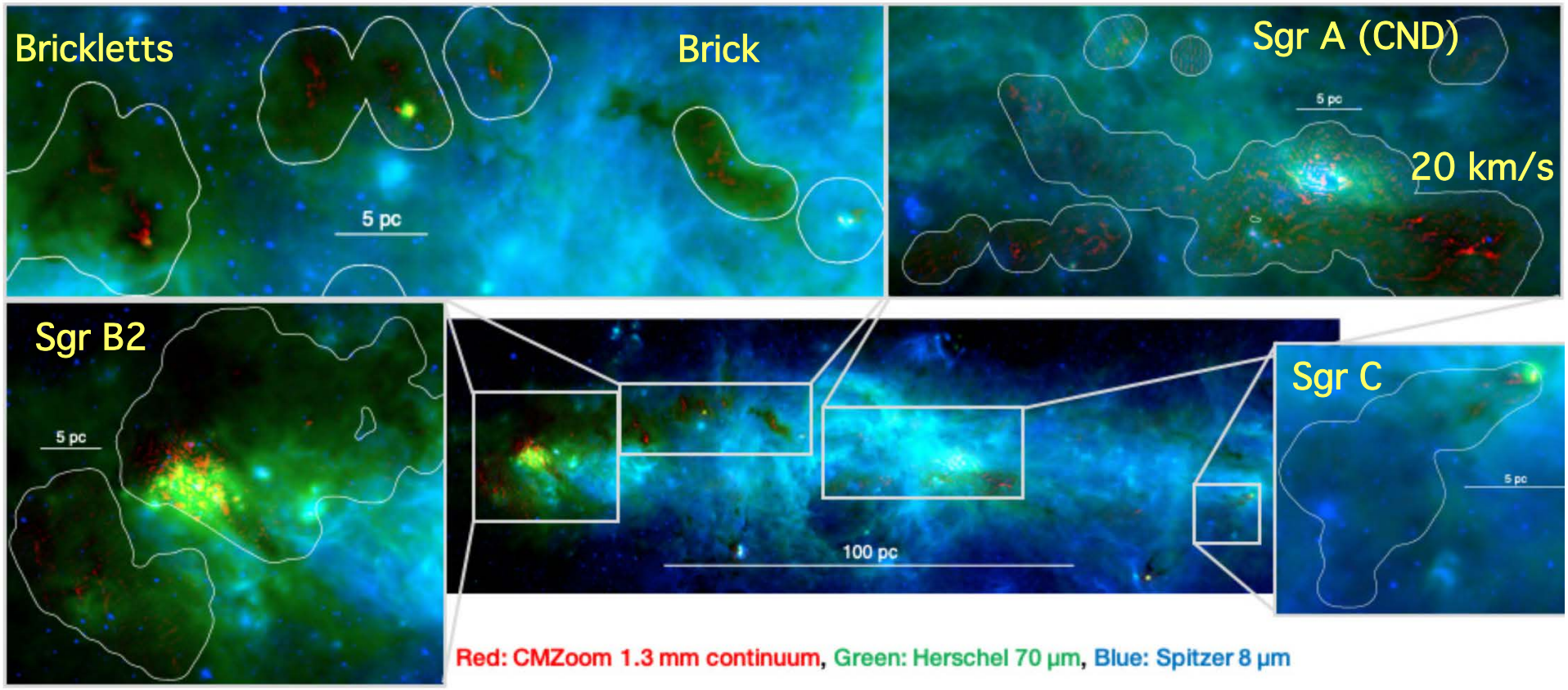


+2.0° -2.0°


Enclosed Mass
(Launhardt 2002)
Low shear region
Most stars form
here
(a)
(b)
ρ α R-2
V α const.
M α R
ρ α R-1
V α R1/2
M α R2
= Nuclear Star Cluster
= Nuclear Stellar Disk
= Galactic Bulge
BH
= Black Hole
NSC
NSD
GB
MISM
M(R) [M⊙]
RGC [pc]
10^9
10^8
10^7
10^6
10^5
1
10^1
10^2

SMA CMZoom survey of the inner CMZ

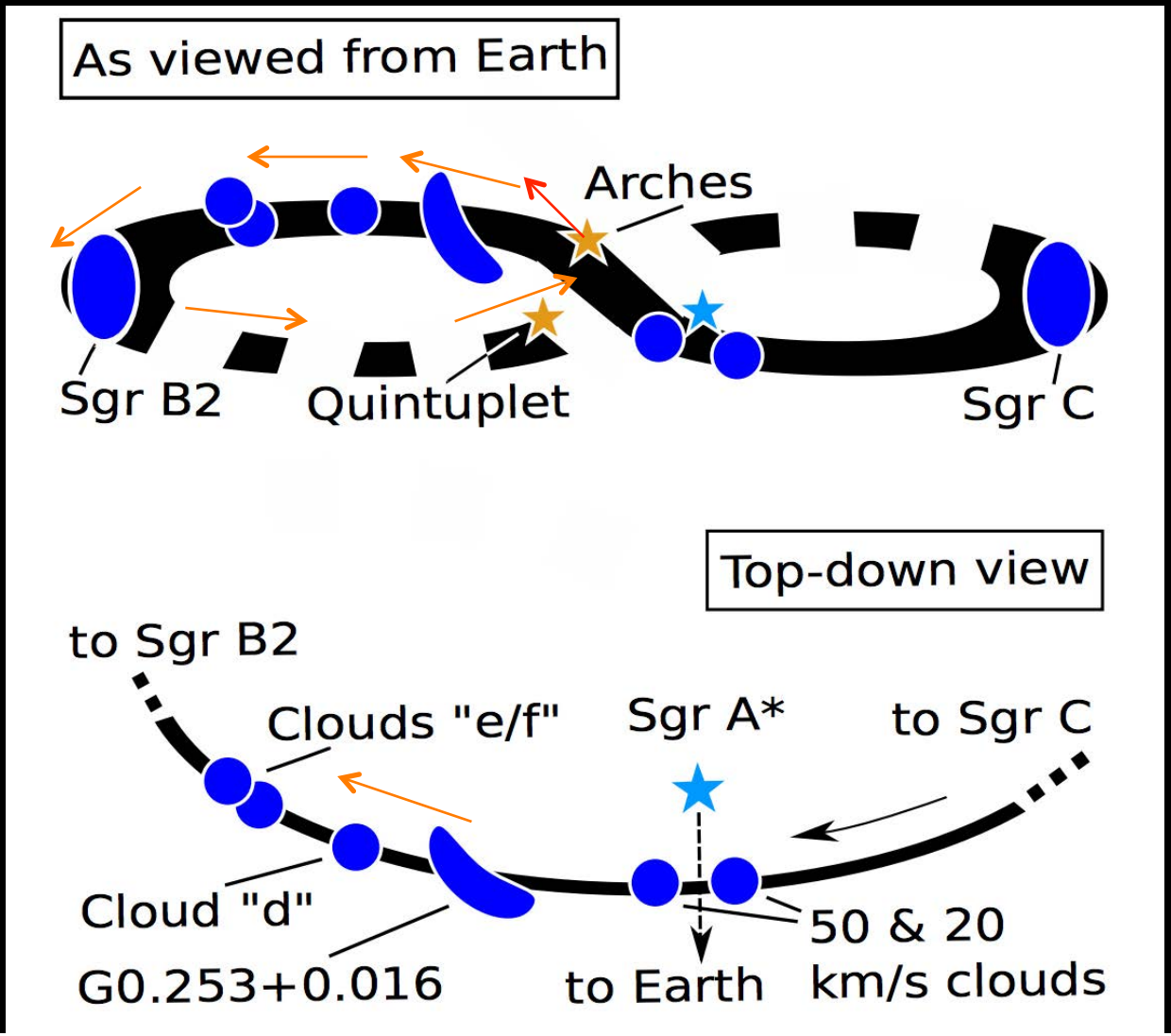
Battersby et al. 2020



Conveyor Belt of Star Formation?

Close passage to Sgr A => tidal compression

Brick => Bricklets (“b”, “c”, “d”, “e/f”) => Sgr B2 => SgrB1



(Barnes et al. 2017; 2019)

Conveyor Belt of Star Formation ?:

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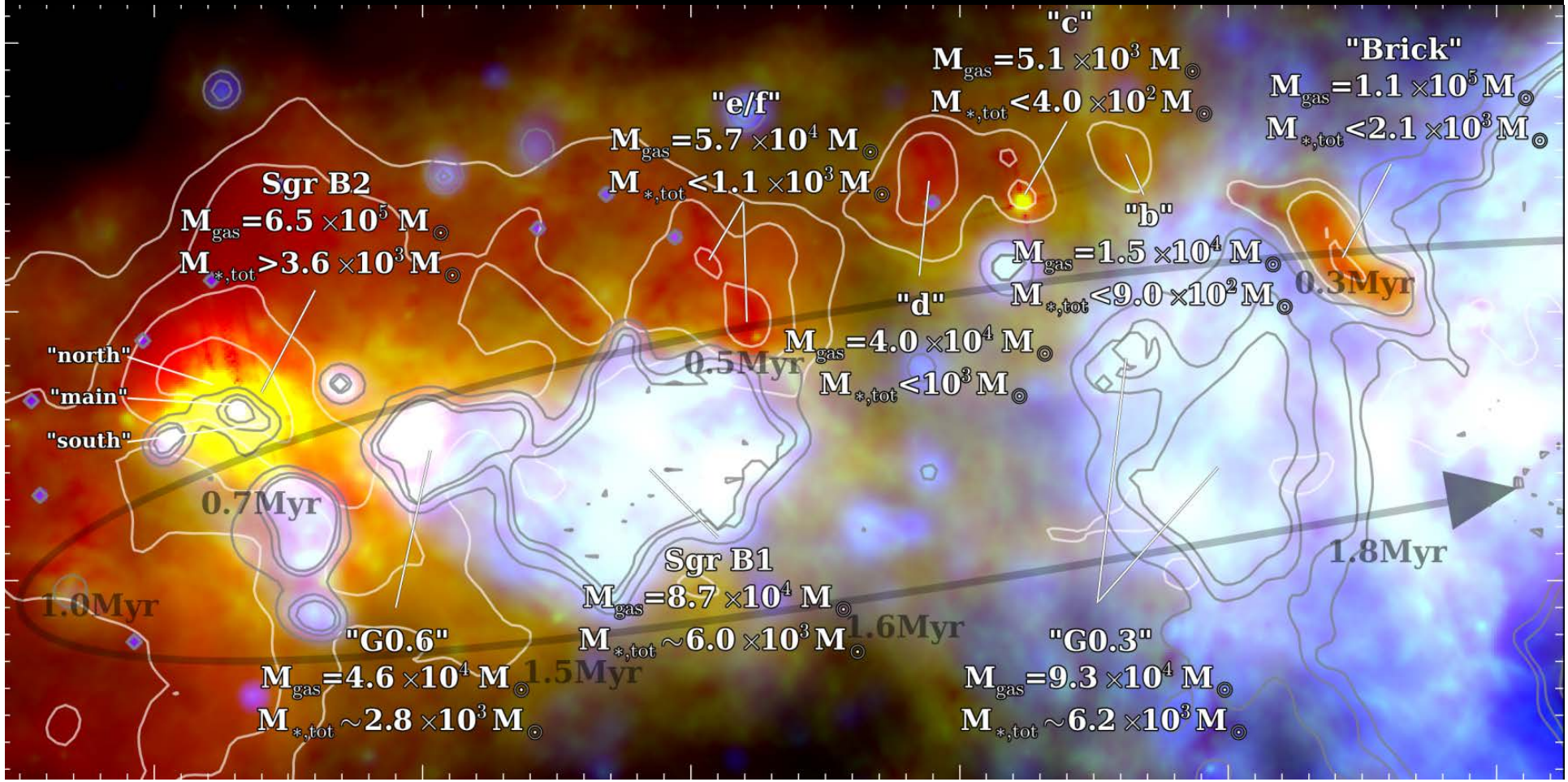
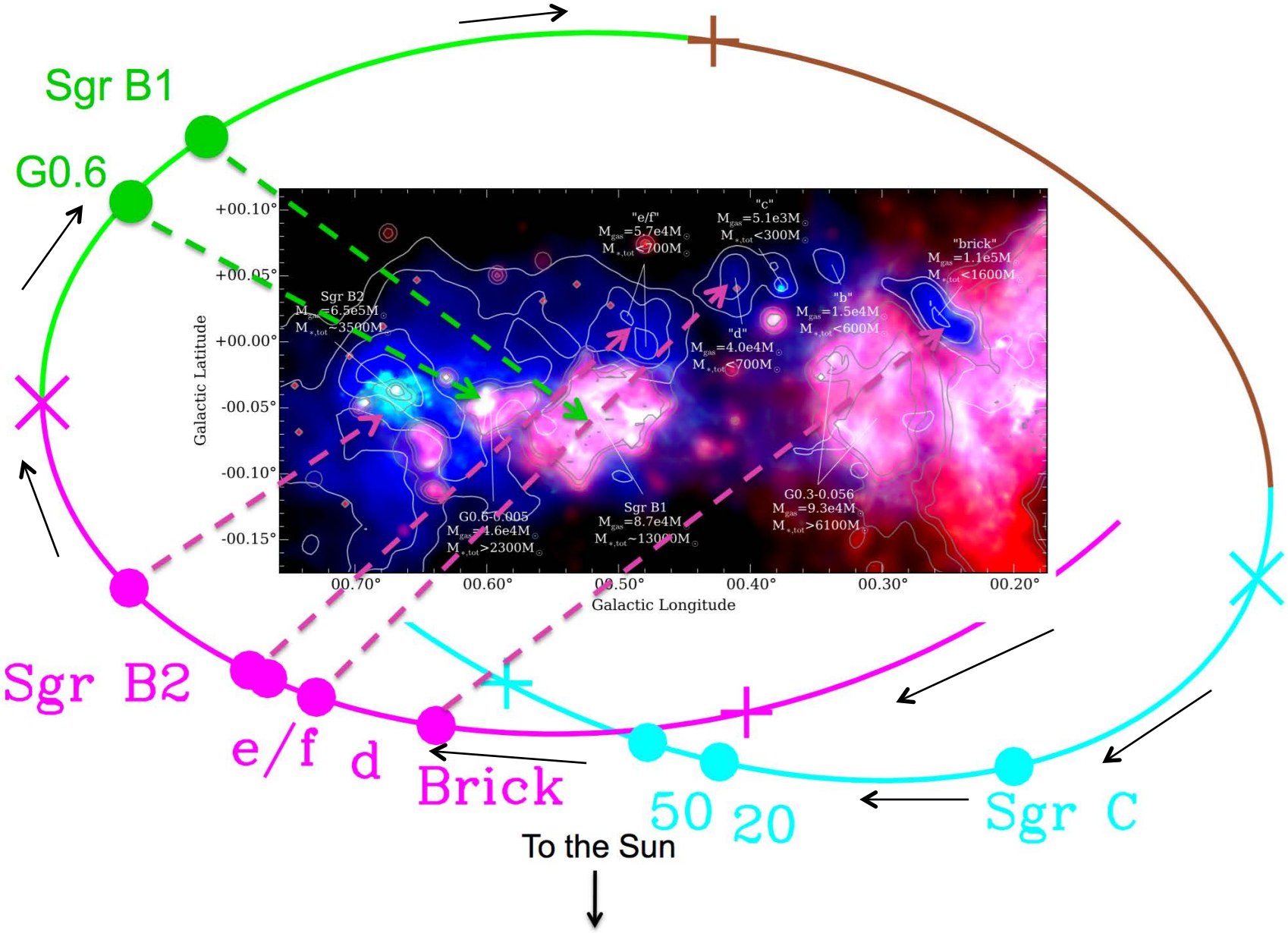
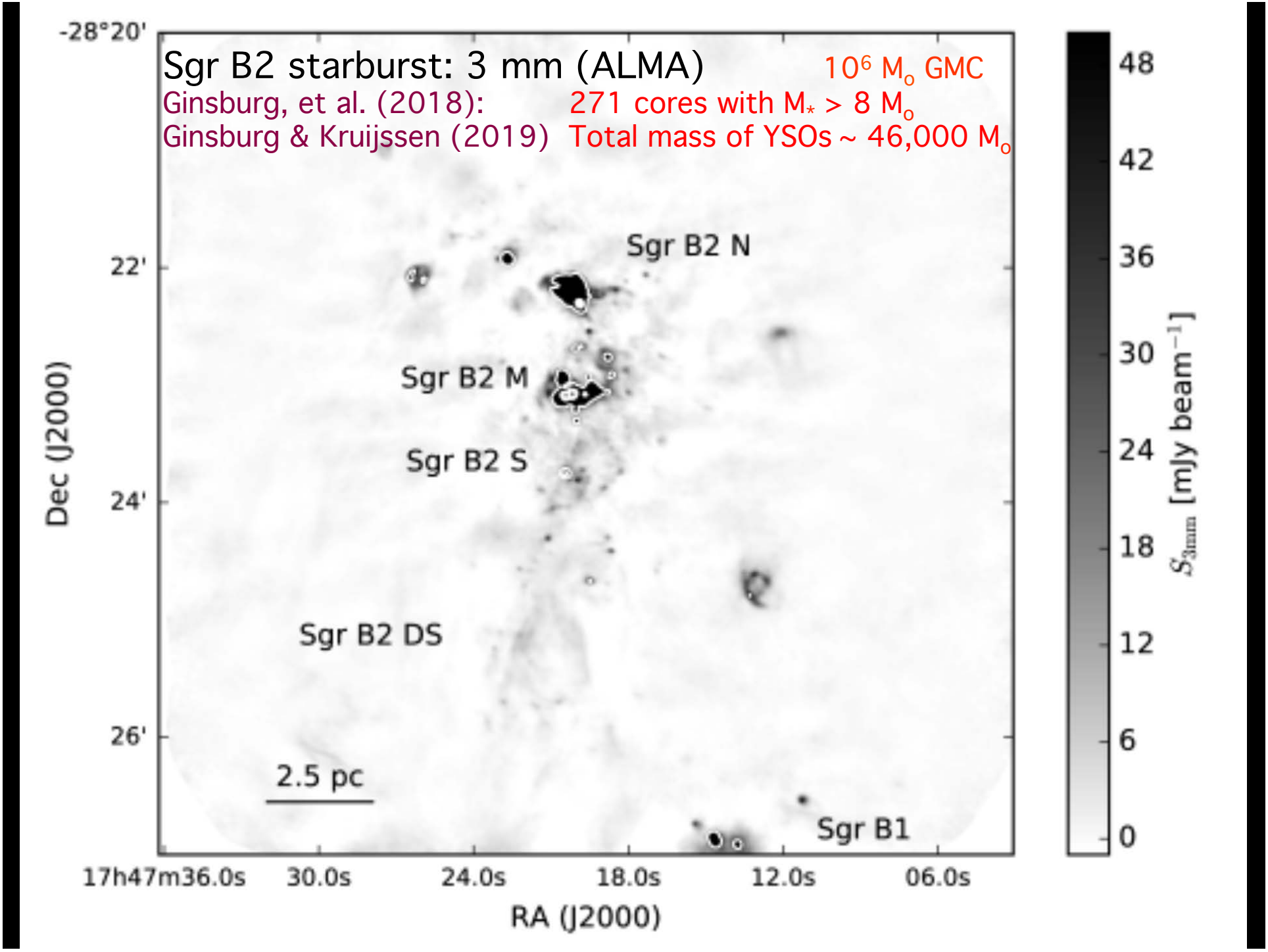
(Barnes et al. 2017; 2019)



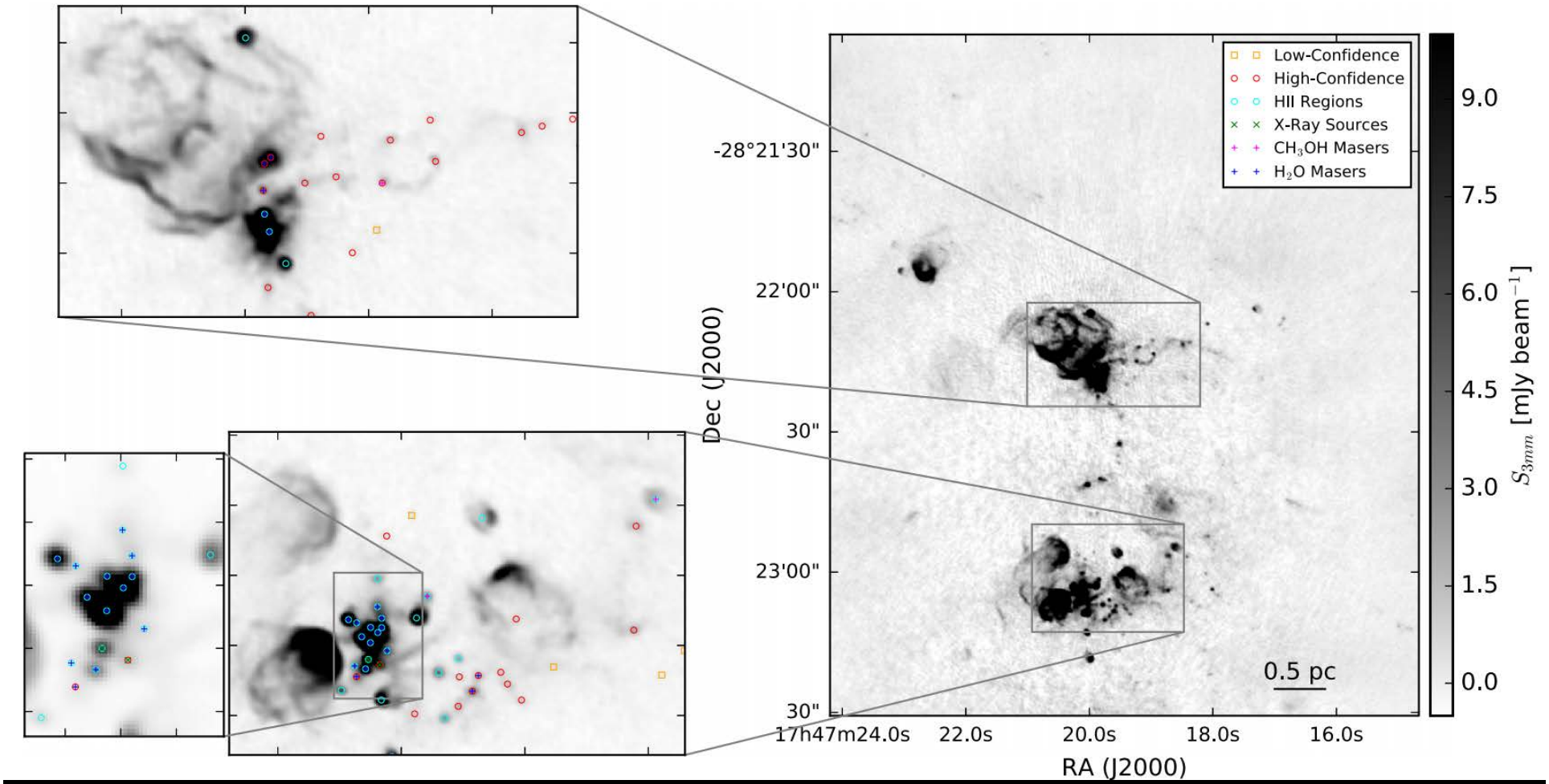
Kruijssen, Dale, & Longmore 2015, Kruijssen et al. 2019




Sgr B2 starburst: 3 mm (ALMA)
10^6 M_o GMC
Ginsburg, et al. (2018): 271 cores with M_* > 8 M_o
Ginsburg & Kruijssen (2019) Total mass of YSOs ~ 46,000 M_o
Sgr B2 N
Sgr B2 M
Sgr B2 S
Sgr B2 DS
Sgr B1
2.5 pc
-28°20'
22'
24'
26'
Dec (J2000)
17h47m36.0s
30.0s
24.0s
18.0s
12.0s
06.0s
RA (J2000)
48
42
36
30
24
18
12
6
0
S3mm [mJy beam−1]

Sgr B2 starburst: 3 mm dust continuum(ALMA)

~ 50 – 100 OB stars + 40,000 M_o lower mass stars

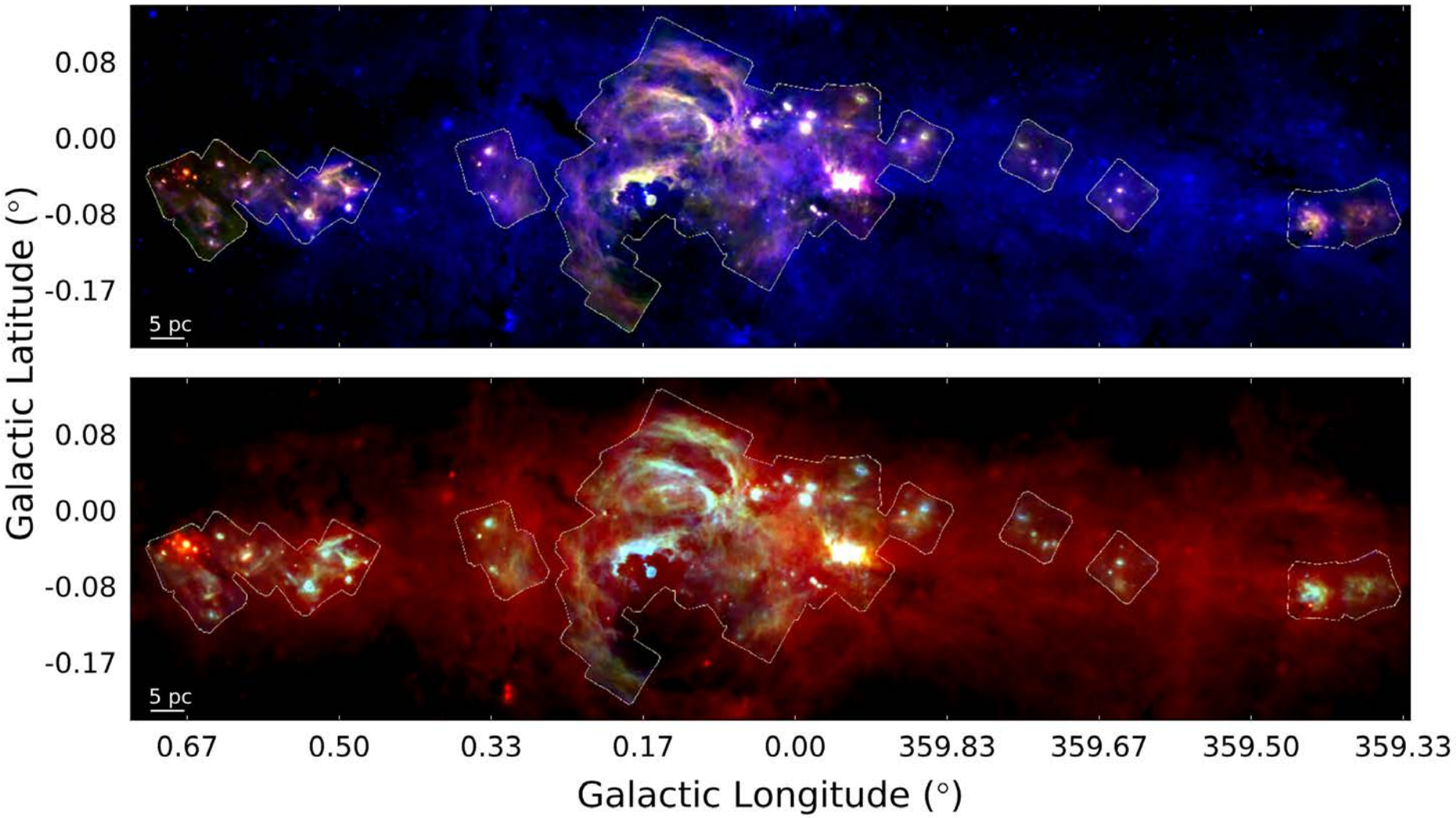


Ginsburg, et al. (2018)

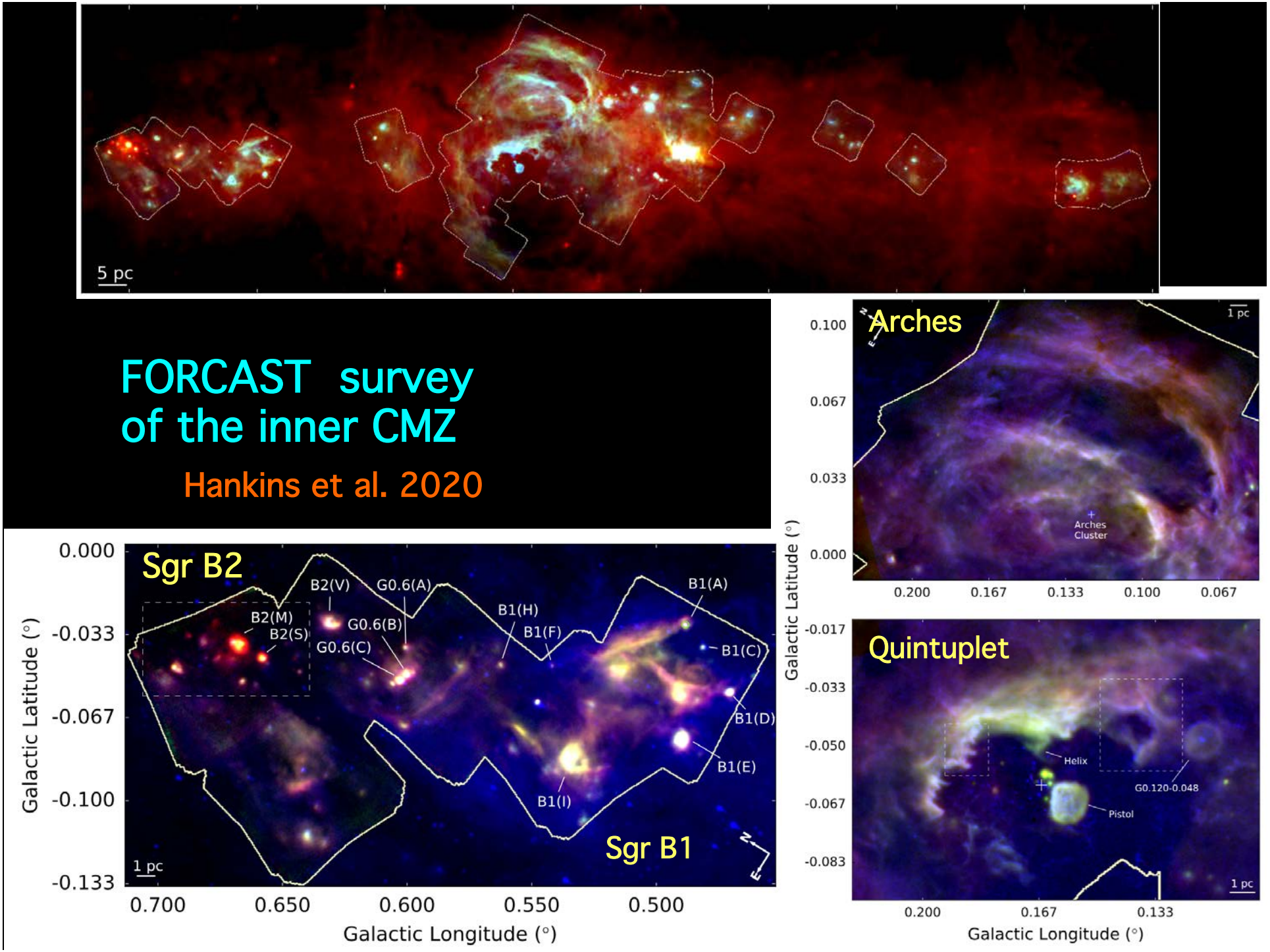
FORCAST survey of the inner CMZ

Hankins et al. 2020

8 um 25 um 37 μm

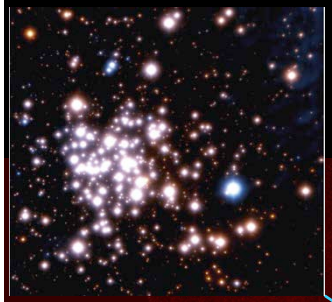


25 um 37 um 70 μm


5 pc
FORCAST survey
of the inner CMZ
Hankins et al. 2020
Sgr B2
B2(V)
G0.6(A)
B2(M)
B2(S)
G0.6(B)
G0.6(C)
B1(H)
B1(F)
B1(A)
B1(C)
B1(D)
B1(E)
B1(I)
Sgr B1
1 pc
0.000
-0.033
-0.067
-0.100
-0.133
0.700
0.650
0.600
0.550
0.500
Galactic Latitude (°)
Galactic Longitude (°)
Arches
Arches Cluster
1 pc
0.100
0.067
0.033
0.000
0.200
0.167
0.133
0.100
0.067
Quintuplet
Helix
G0.120-0.048
Pistol
1 pc
-0.017
-0.033
-0.050
-0.067
-0.083
0.200
0.167
0.133
Galactic Latitude (°)
Galactic Longitude (°)

Arches, Quintuplet, Nuclear Star Cluster: Paschen α:

Dong, H., Wang, Q.D., Cotera, A. et al. 2011; Wang, Q.D., Dong, H., Cotera, A. et al. 2010



Arches cluster (~3 Myr)
3×10^4 M_o

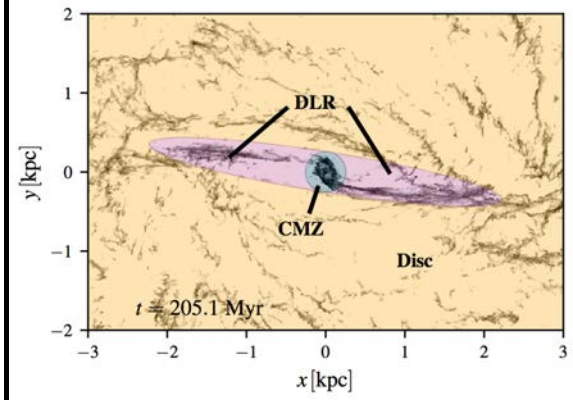
Nuclear Star Cluster,
Mini-spiral, Sgr A*
10^7 M_o (old & young)

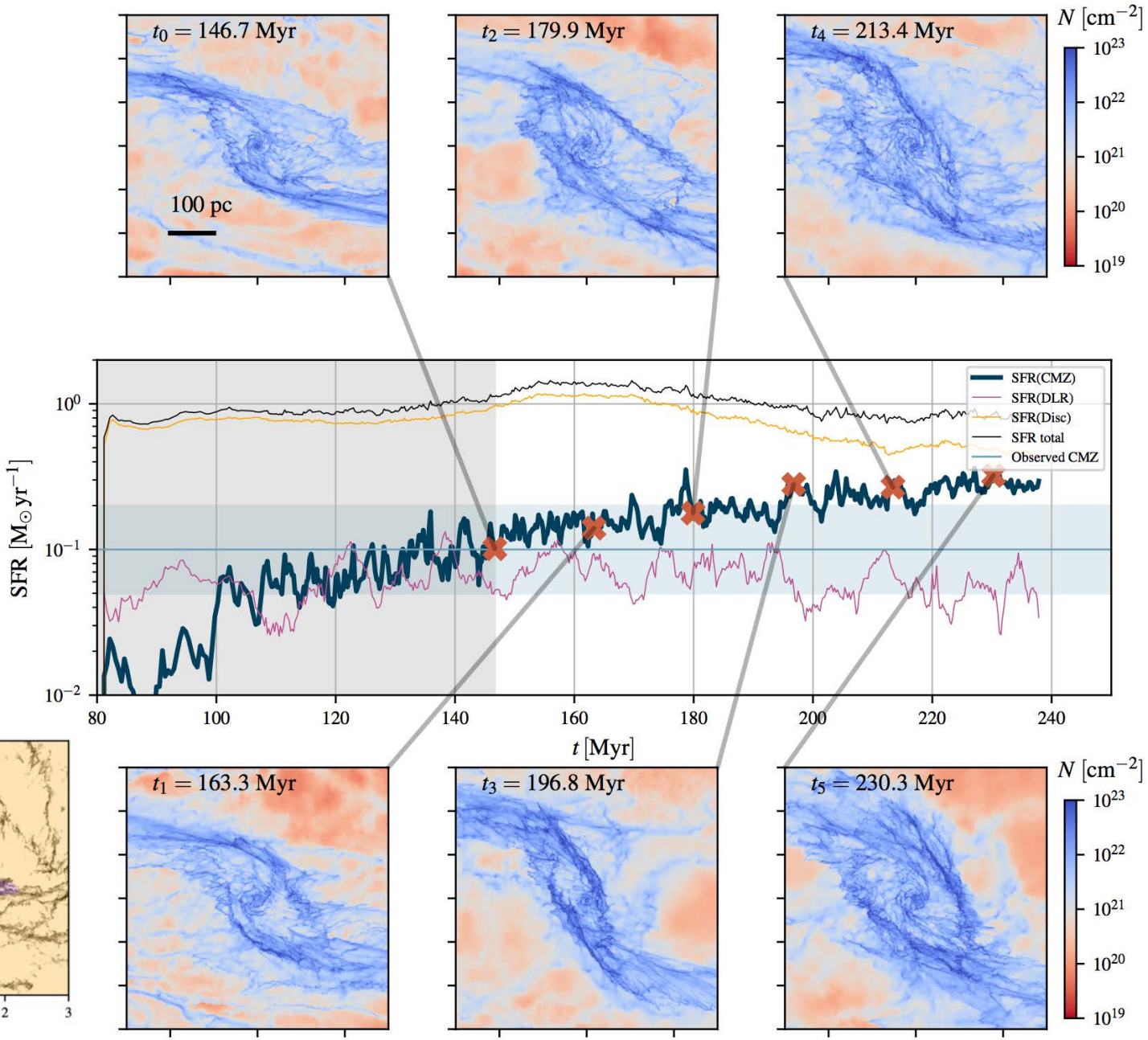
Quinuplet cluster (~5 Myr) 10^4 M_o

Models of the CMZ: Sormani M., C. et al. 2020 arXiv2004.06731

Quasi-static SFR?
~ 0.1 Mo/yr

DLR =
"Dust Lane Region"





Orbits of Arches & Quintuplet cluster in Sormani model

Arches:

V_{PM} ~ 172+/-15 km/s
V_r ~ +80+/-5 km/s

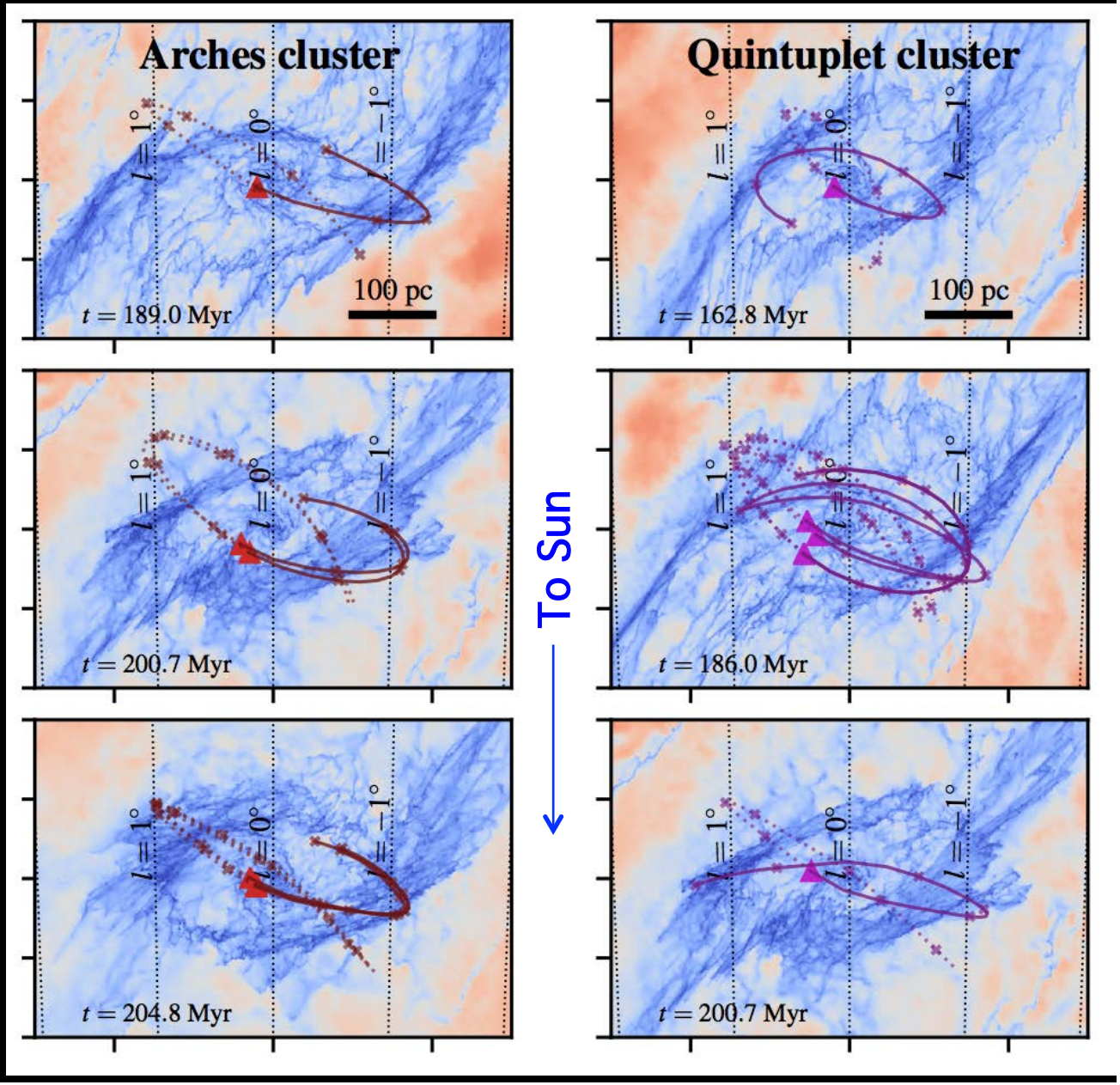
Clarkson, W.I,+ 2012

Arches:

V_{PM} ~ 132+/-15 km/s
V_r ~+102+/-5 km/s

Stolte, A,+ 2014

Sormani, M+ 2020



Feedback:

The Sofu-Handa Lobe

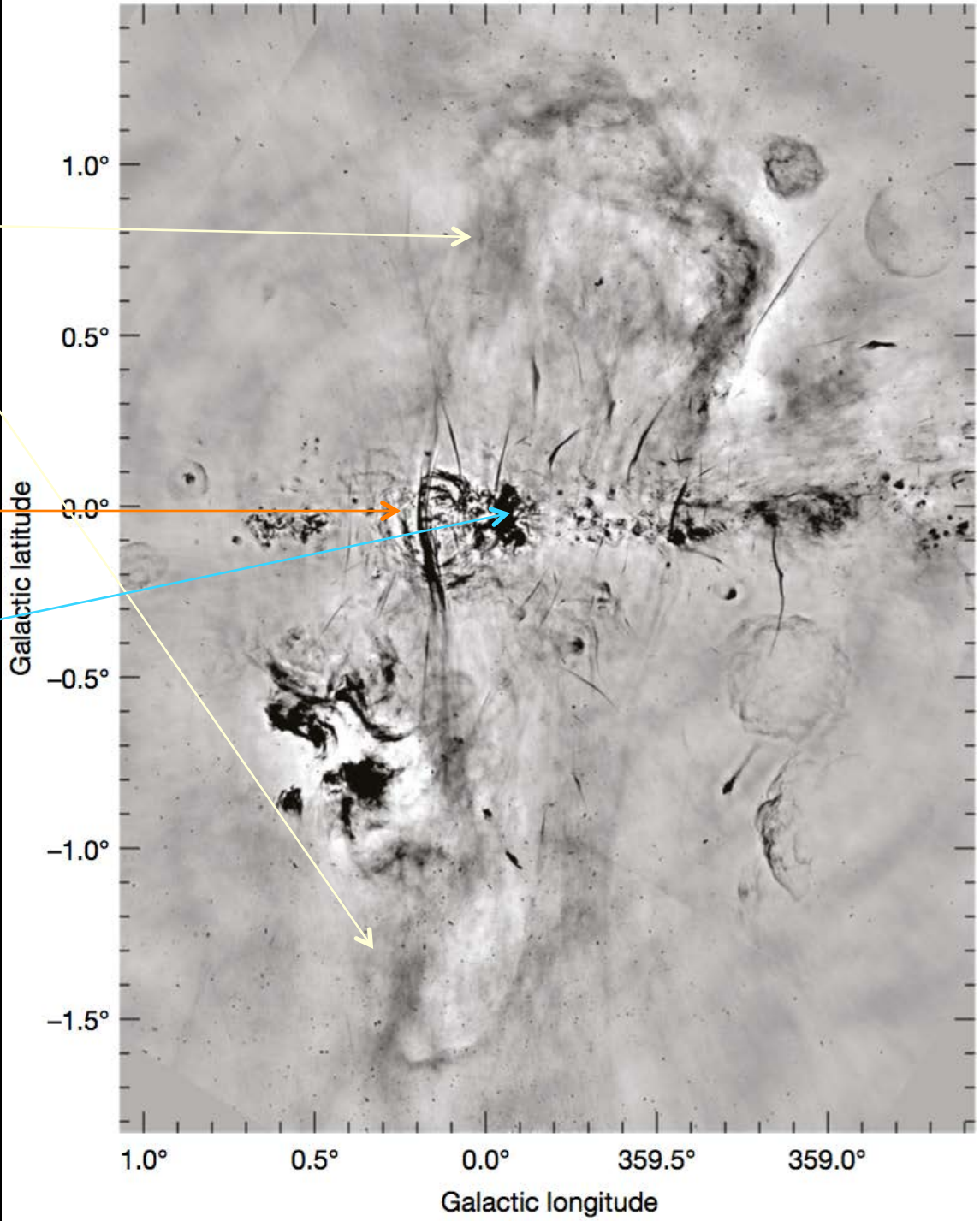
Sofue & Handa1984
Nature

Galactic Center Bubble
& the Arches

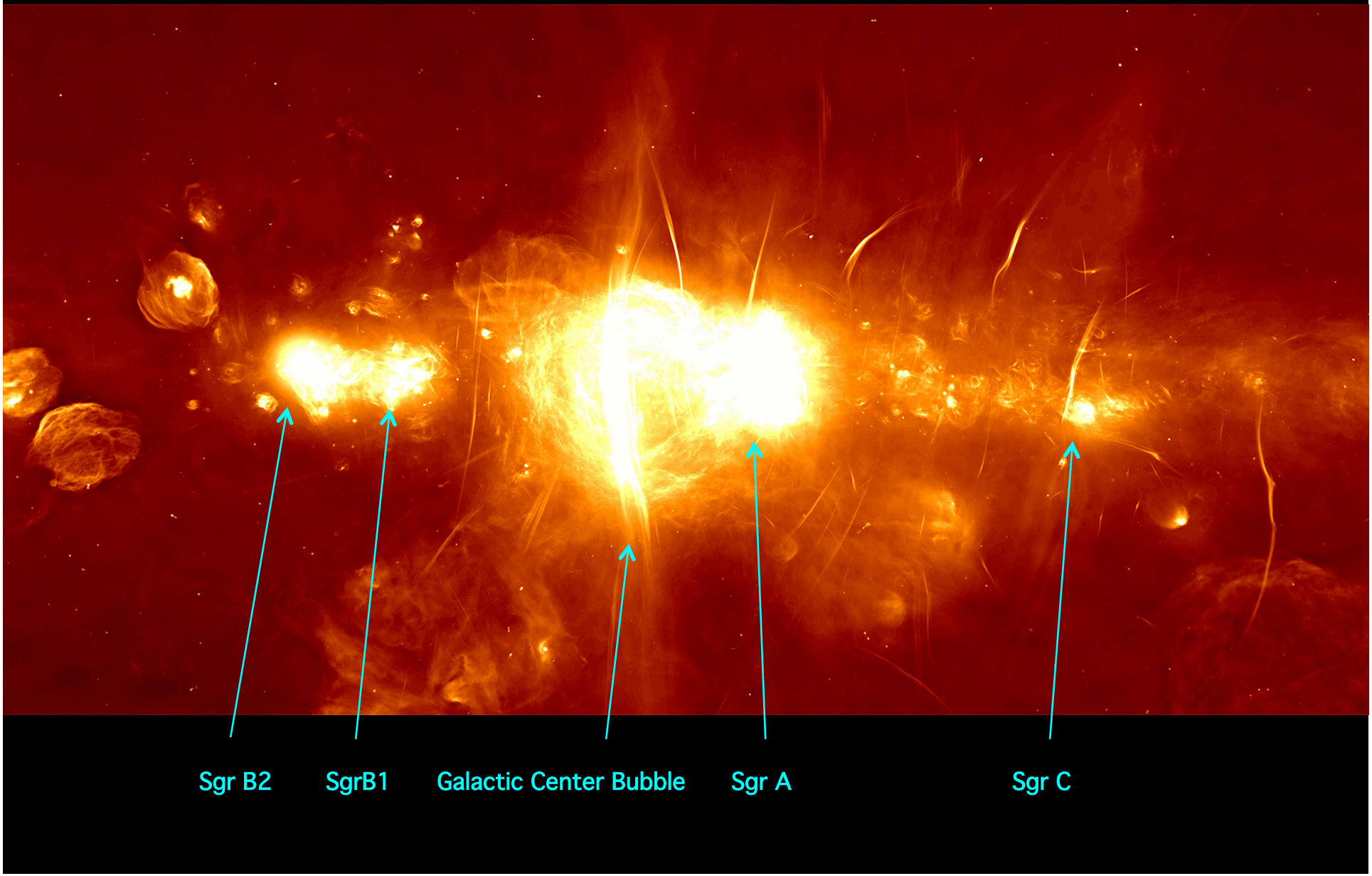
Sgr A*

MeerKat; 1 GHz

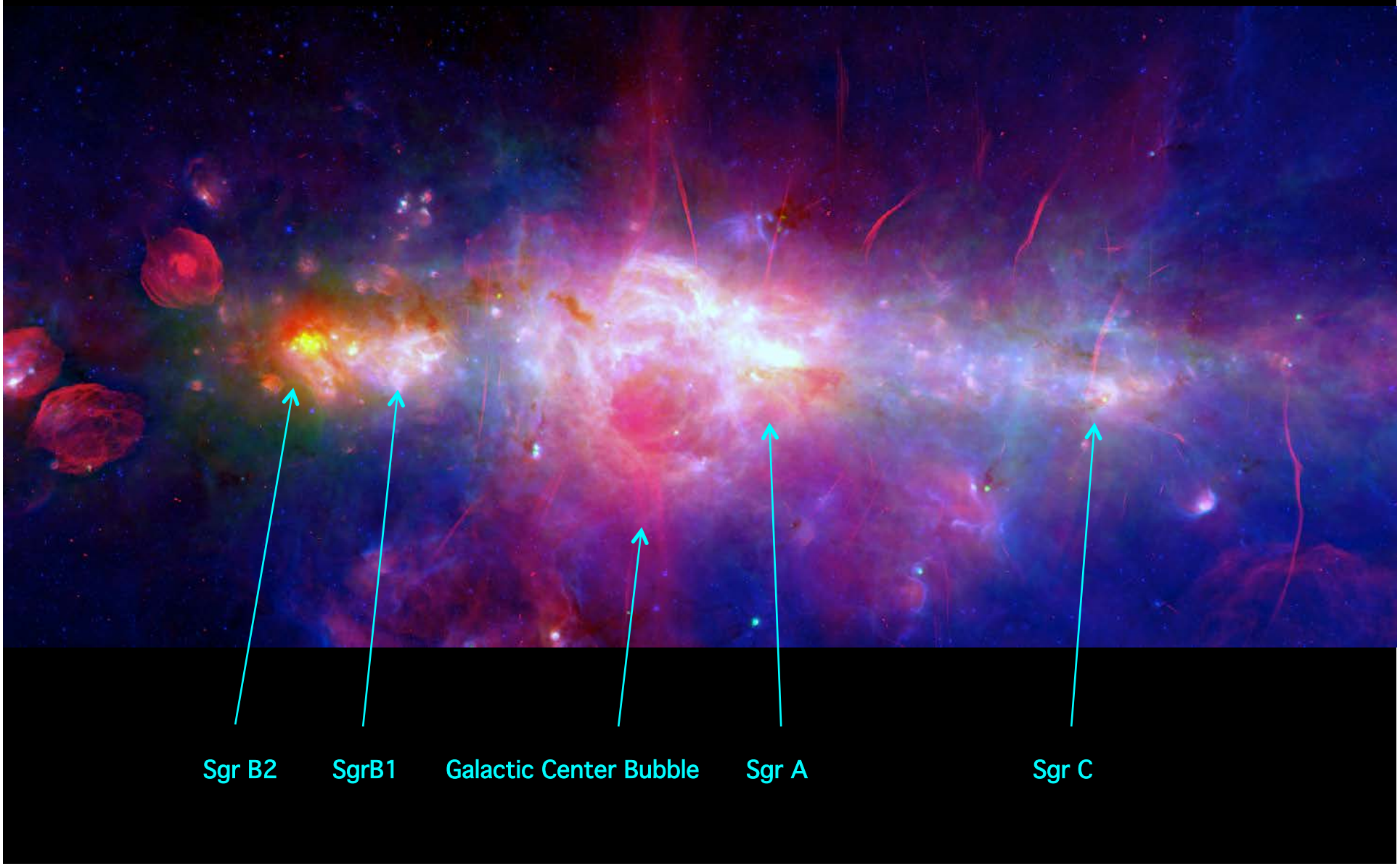
Heywood et al. 2019
Nature



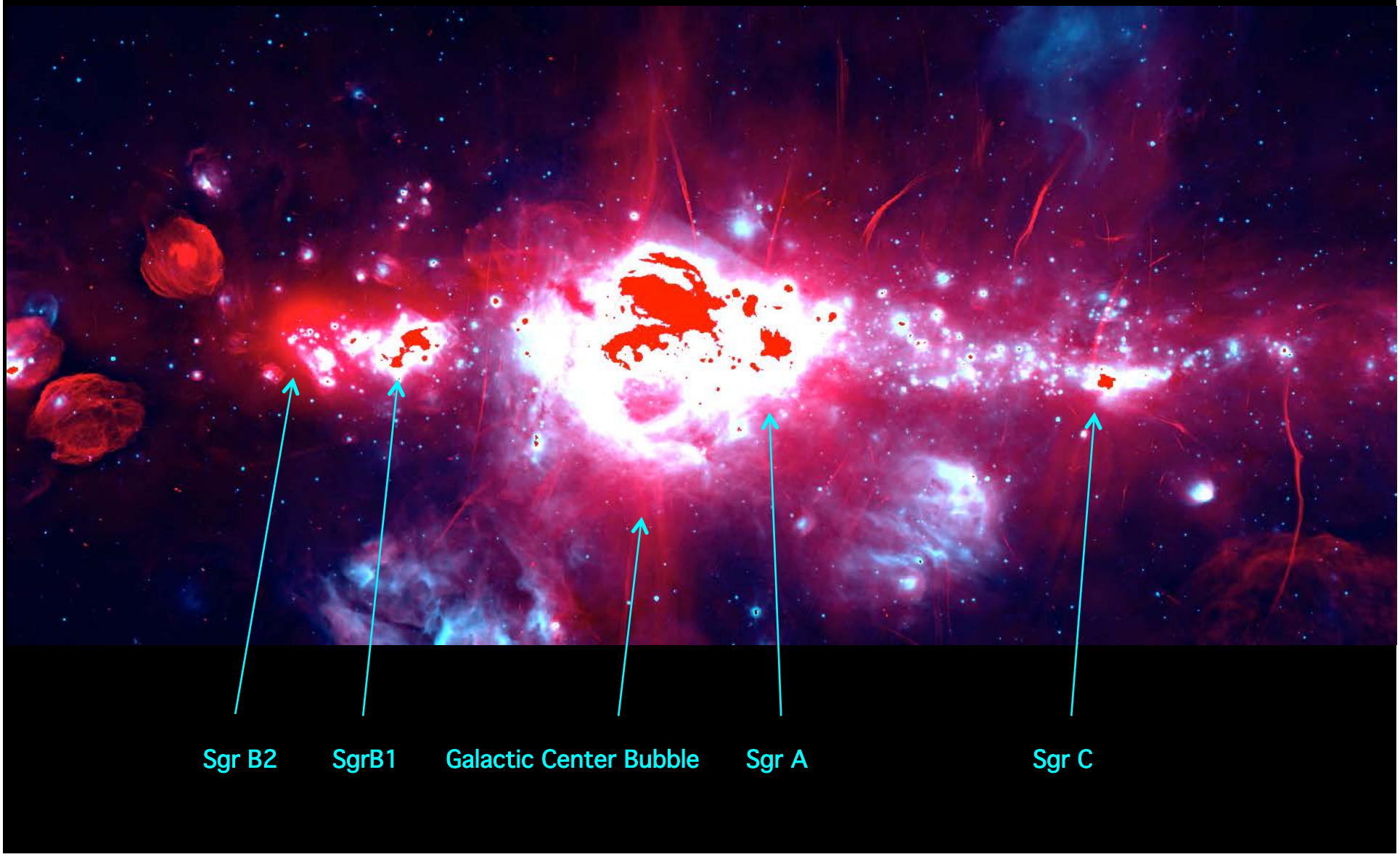
MeerKAT ~1 GHz (July 2018 press release)



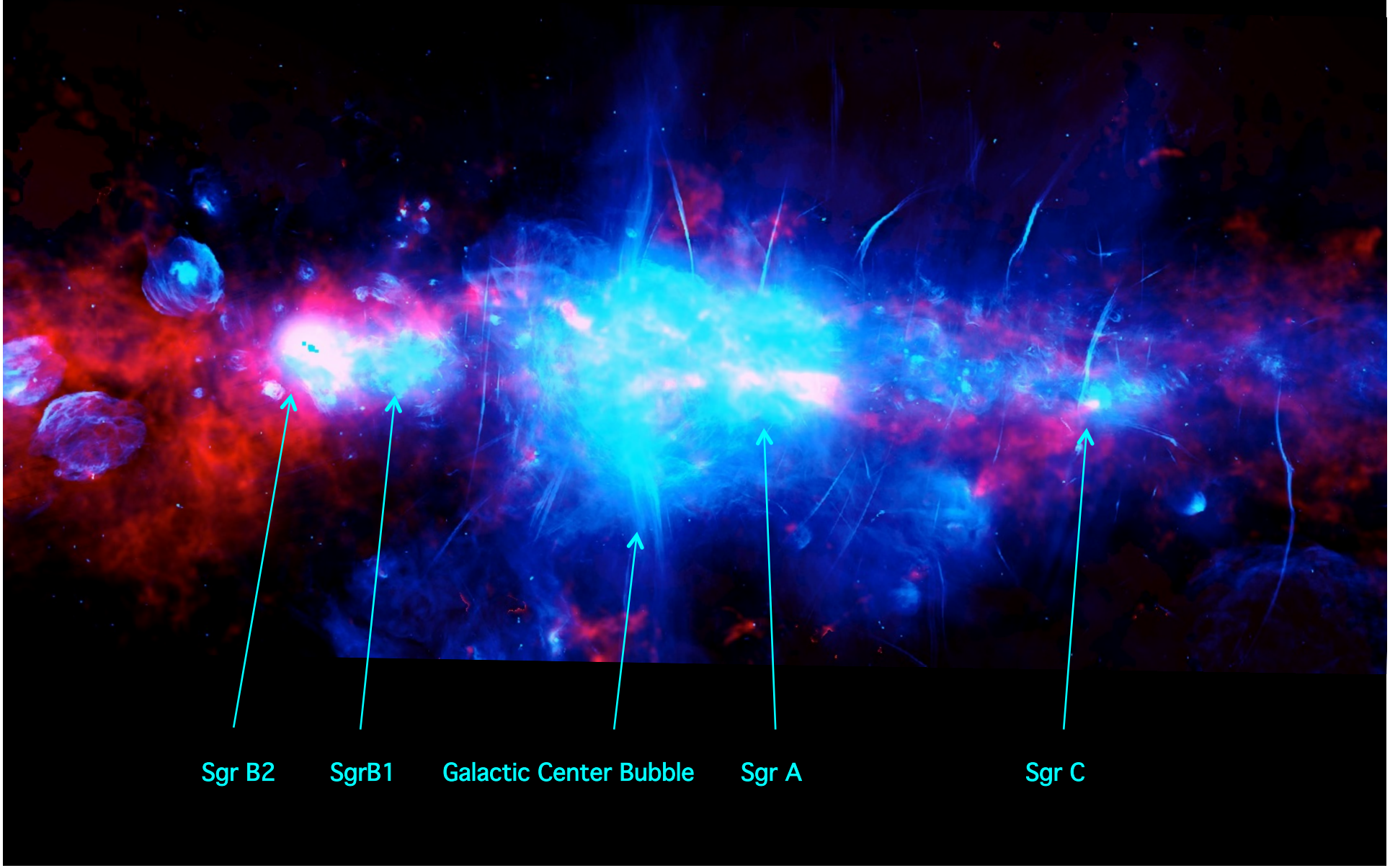
Inner CMZ ~1 GHz, 70 μm, 24 μm



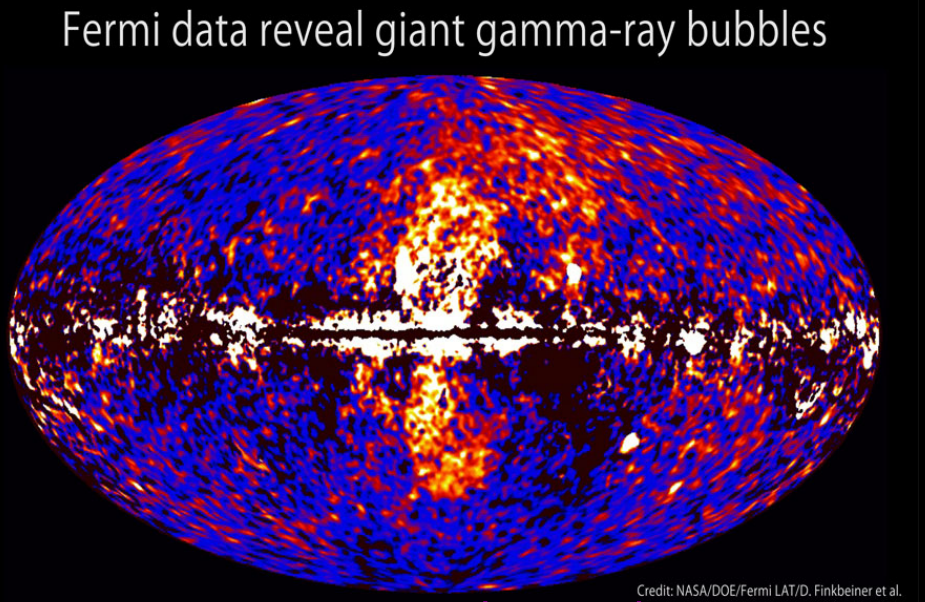
Inner CMZ ~1 GHz (July 2018 MeerKAT press release)
24 μm (Spitzer)



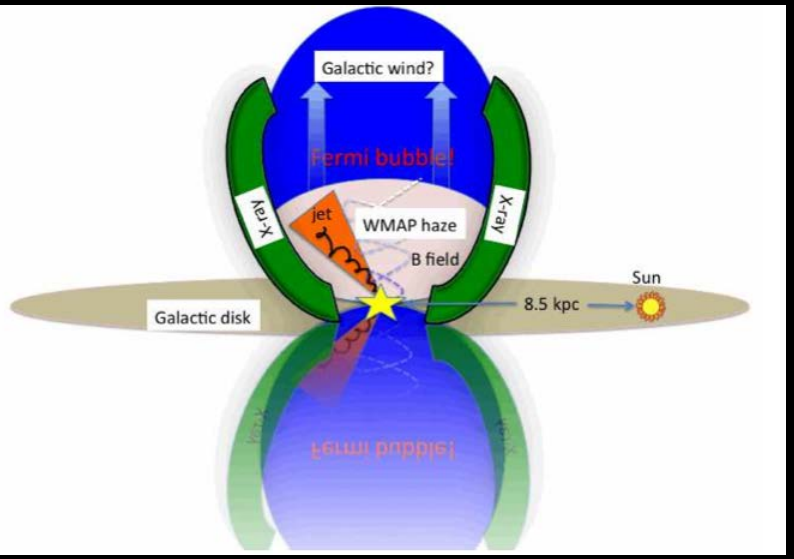
Inner CMZ ~1 GHz (July 2018 MeerKAT press release)
$N(H_2)$ (Hi-GAL – Battersby et al.)

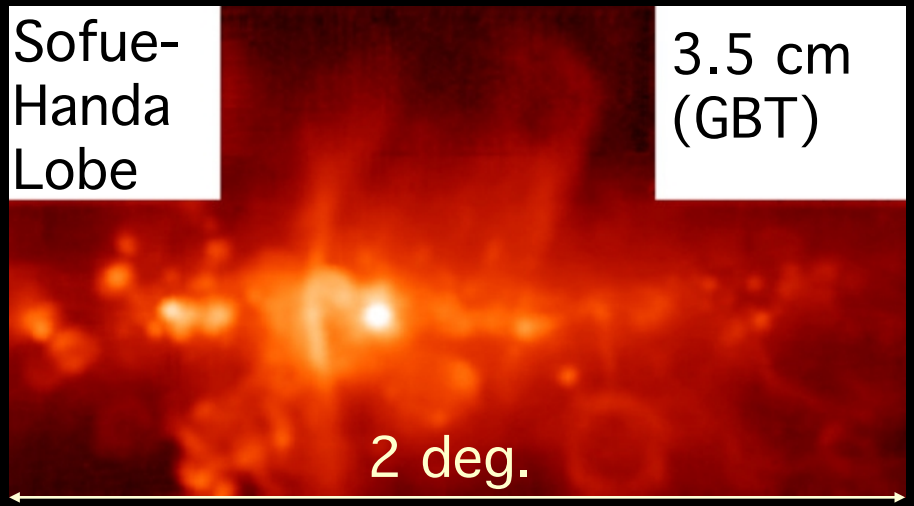


Galactic Center Bubble => Sofue-Handa Lobe
=> Fermi-LAT Bubble ?



Finkbeiner et al. (2010)





Law et al. (2008)

Beware of foreground confusion:

- Sco-Cen superbubble
  150 pc from Sun
- Intervening spiral arms

Questions:

What is the gas infall rate from R ~ 3 kpc?

~ 1 M_o/yr ? (Tress+ 2020)

Why is the ~5 x 10^7 M_o CMZ so asymmetric? ($t_{\text{orbit 100pc}}$ ~ 6 Myr)

Starburst + blow-out by feedback ? Stochastic infall?

Star Formation Rate: Is there a 2-nd parameter? (SFR ~ $C\ \rho^{\alpha}\ \Delta V^{-\beta}$)

Quasi-Steady @ ~0.04 – 0.1 M_o/yr? (Sormani+ 2020)

Quasi-periodic bursts ~ 30 -50 Myr? (Armillotta+ 2019, 2020)

Conveyor-Belt? (Kruijjsen, Longmore 2015, 2019)

Where Does Most Gas Go? (Low-M stars or ejected: Not the SMBH!)

Nuclear Superwind? Fermi/LAT Bubbles?

What ejects it?

OB star feedback? Transient AGN outbursts?

What Can SOFIA Do?

- Develop highly multiplexed, high-R, mid-IR 'data-cube generators'
- Develop new detector and instrument technologies for future missions!
- Future CMZ Legacy Programs:
  * Map CMZ, GCB, Sofue-Handa Lobes, base of Fermi-Bubbles
    5 to 250 μm emission lines
    (C+, O, O++, N+, Ar, Ar+, Ar++, Fe, Fe+, N+, OH, H_2, HD, high-J CO..)
  * Polarization Survey
    Toroidal B in CMZ? Relation to Poloidal B?
  * Characterize compact 24 μm sources
    MYSOs? main-sequence stars ("impostor MYSOs")? W-R ? or RSGs,?

Summary

The CMZ:

Fed by infall from Galactic disk @ ~1 M_o/yr ?

M ~5x10^7 M_o, 80% of dense (n > 10^4 cm^{-3}) gas in Galaxy

Lab. for high pressure, density S.F. e.g. High-z S.F.

Star Formation in ~100 pc low-shear region: SFR ~ 0.04 – 0.1 M_o/yr

"Conveyor Belt"? Eccentric orbits => tidal "crush" in z

=> Brick=>Sgr B2 => Sgr B1 ...

Bursts? quasi-steady?

> 3x10^4 M_o clusters: Arches, Quinuplet, Nuclear star cluster

Asymmetries: Blow out by feedback? Or Stochastic feeding?

Gas-dust, MYSOs, at Positive longitude/velocity

24 μm compact sources at Negative longitude

Compact 24 μm Sources

MYSO (t < 0.1 Myr) ?

Main-Sequence stars encountering CMZ ISM ? (Impostor MYSOs)?

post-Main-Sequence OH/IR, RSGs? (t >3 to 30 Myr old stars)

CMZ Star Formation Feedback:

UV, winds,~10^3 SNe in ~few x 10 Myr => Mass-load Fermi Bubble ?

Does Feedback prevent SMBH growth?