Feedback from Massive Stars: SOFIA Observations of the Horsehead, W43, and the CMZ

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Outline

Introduction: Star Formation:
Balance between
Gravity, N-body dynamics, Turbulence, and Feedback
Feedback: outflows, winds, soft UV, EUV, SNe

Feedback in massive star forming regions:

Horsehead Nebula in Orion
L(LyC) ~ 2×10^{49} ionizing photons s^{-1} (~2 OB-stars)
SOFIA C^+

W43 'mini-starburst' at the end of the Galactic Bar
L(LyC) ~ 10^{51} (~10 to 100 OB-stars)
SOFIA FORCAST

Central Molecular Zone "Blow-Out by Superbubbles"
L(LyC) ~ 10^{53} (~$10^{3\text{-}4}$ OB-stars)
SOFIA C^+, N+

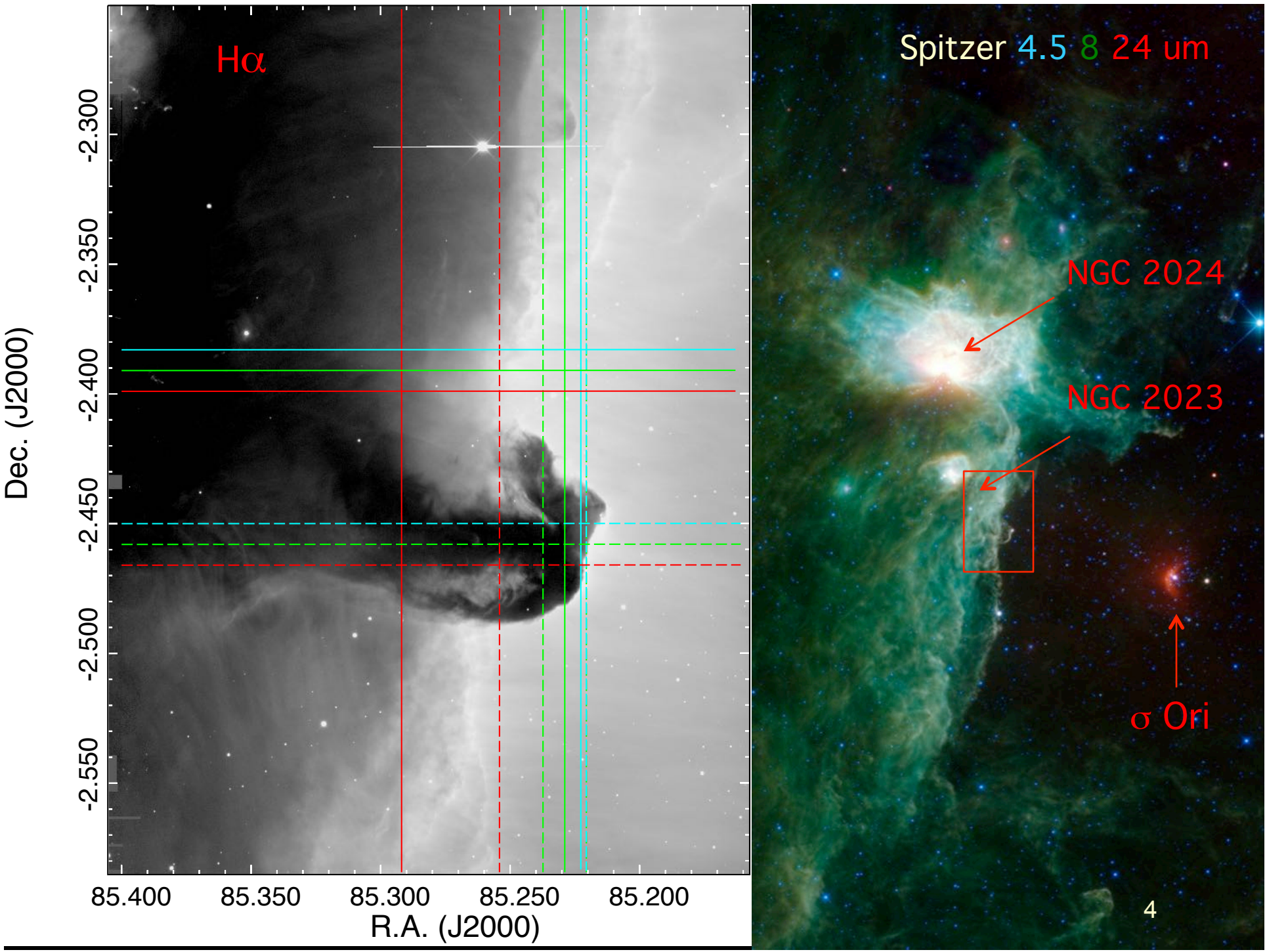
The Orion B molecular Cloud

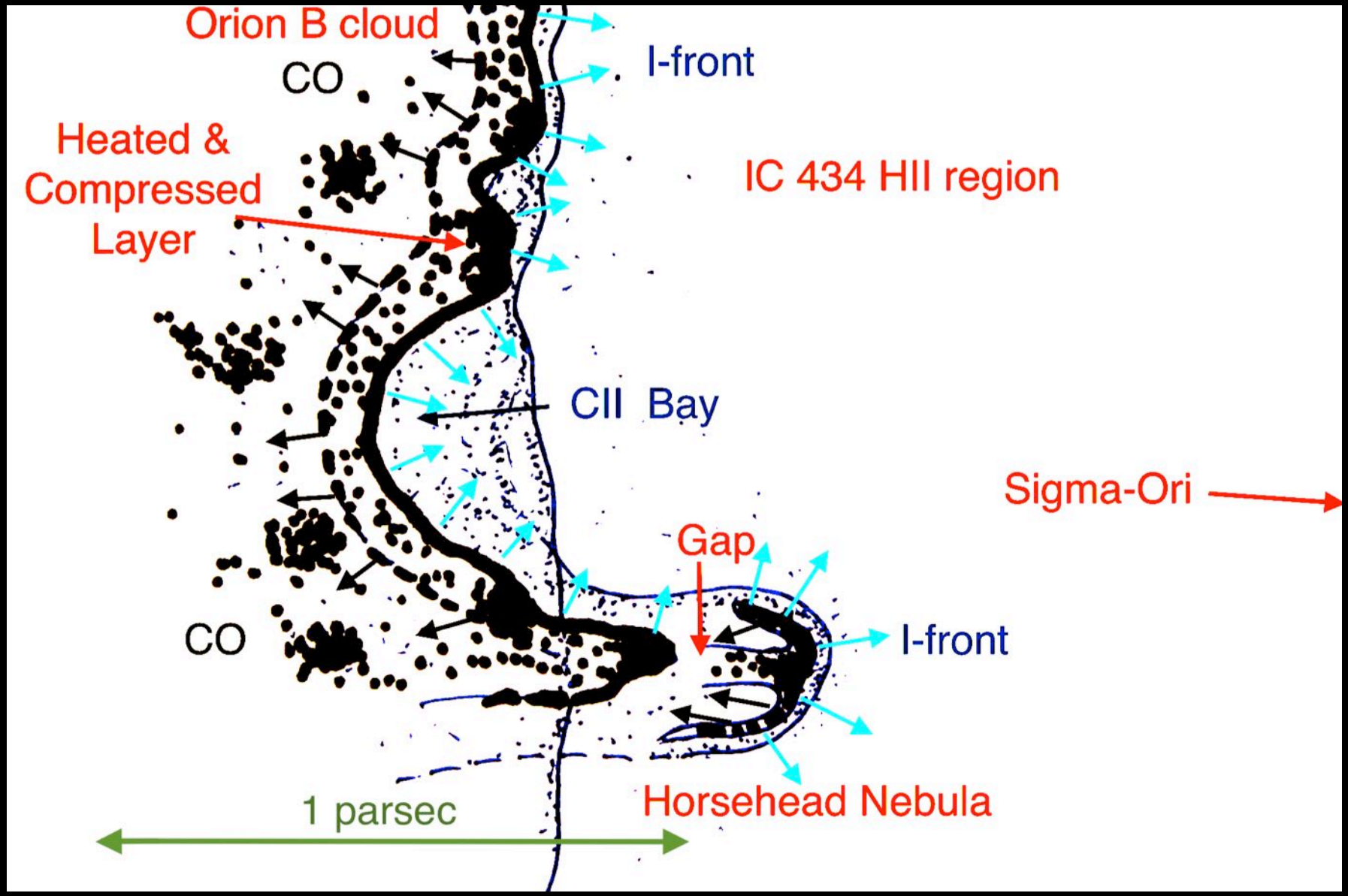
North

Herschel 70 160 350 um

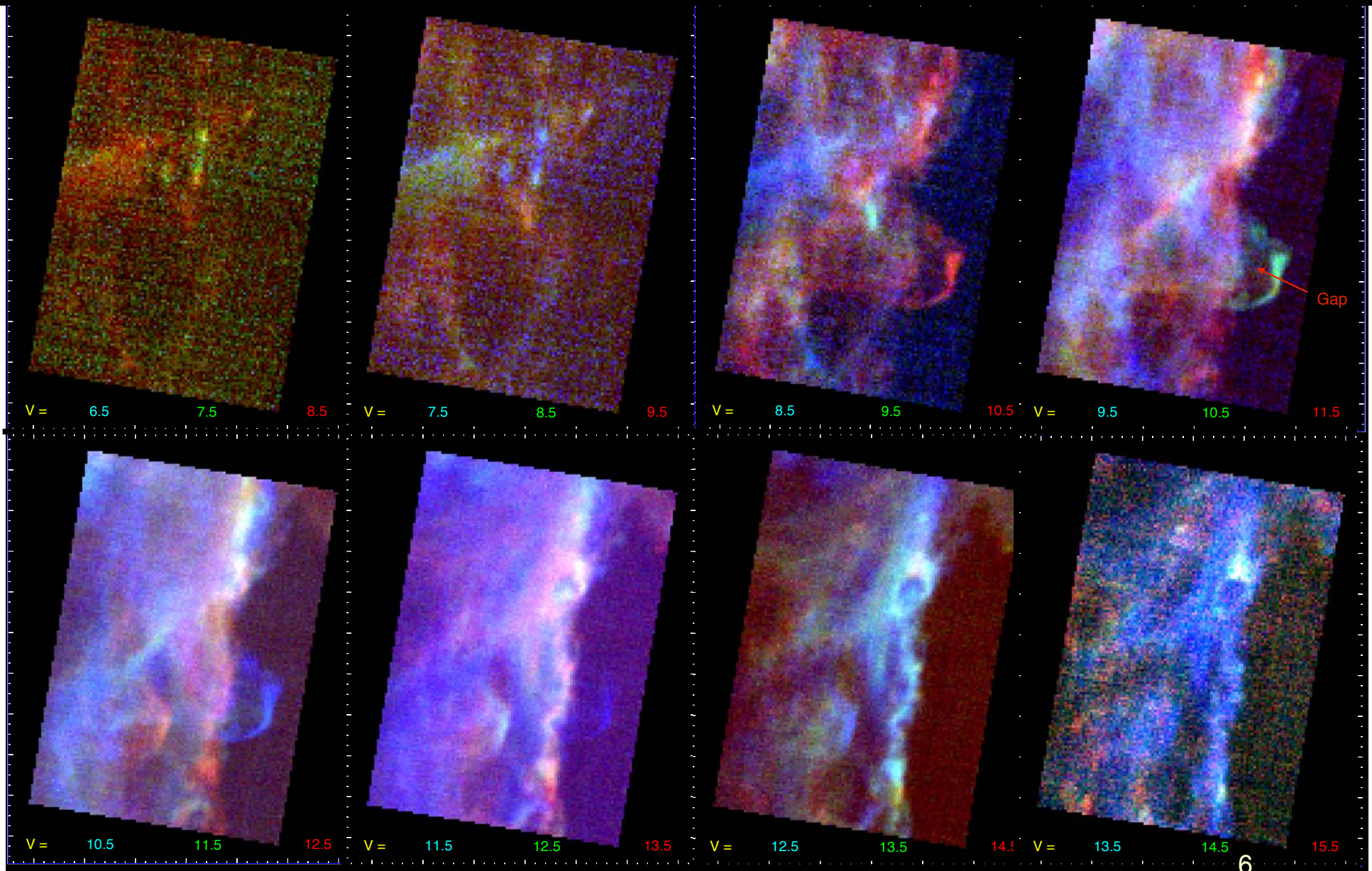
D ~ 400 , M ~ 5 x 10^4 M_o

Horsehead Nebula

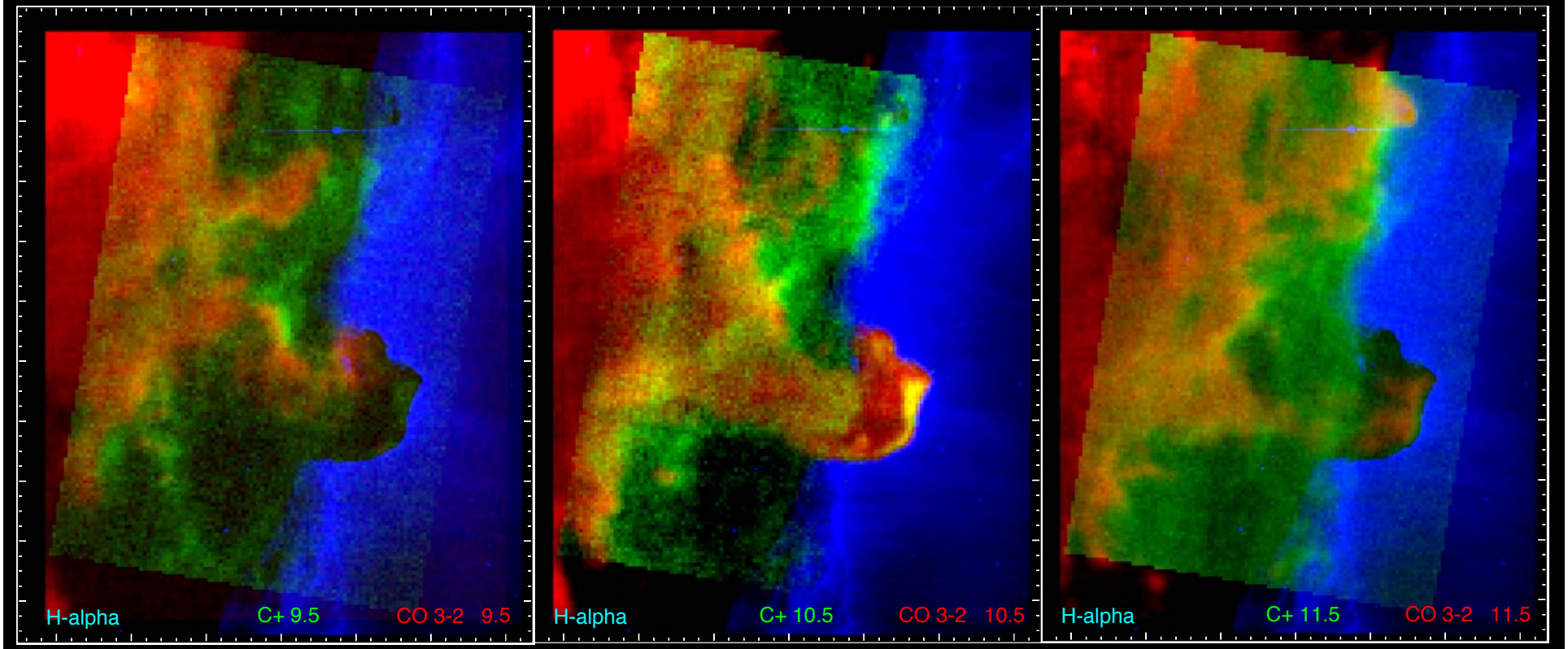

Hα
Spitzer 4.5 8 24 um
NGC 2024
NGC 2023
σ Ori
Dec. (J2000)
-2.300
-2.350
-2.400
-2.450
-2.500
-2.550
85.400
85.350
85.300
85.250
85.200
R.A. (J2000)

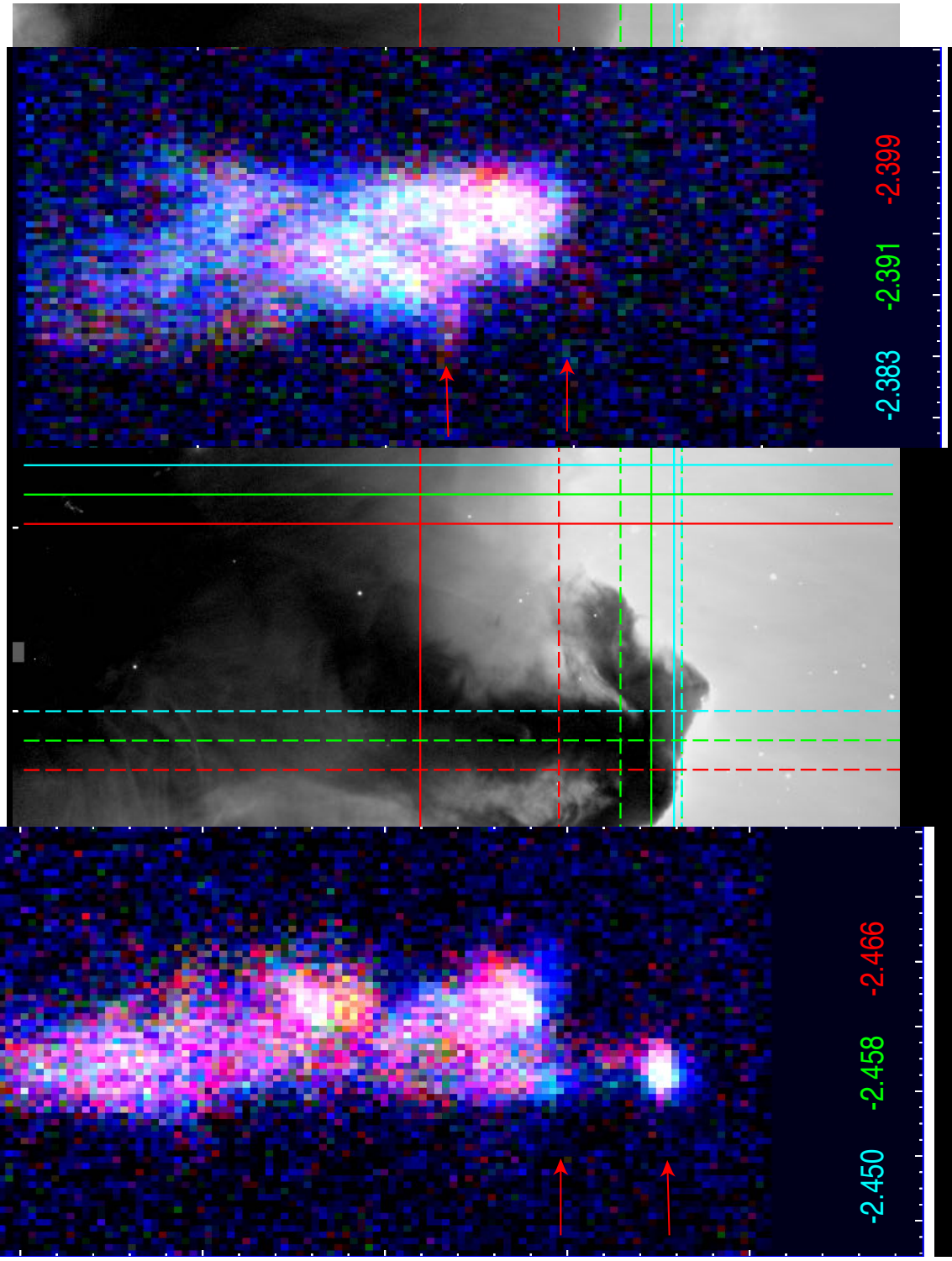

Orion B cloud
CO
I-front
Heated &
Compressed
Layer
IC 434 HII region
CII Bay
Sigma-Ori
Gap
CO
I-front
1 parsec
Horsehead Nebula

C^+ in the Horsehead Nebula



C+ CO 3-2 and Hα in the Horsehead Nebula





C^+ Kinematic Horsehead Nebula

R.A. - V

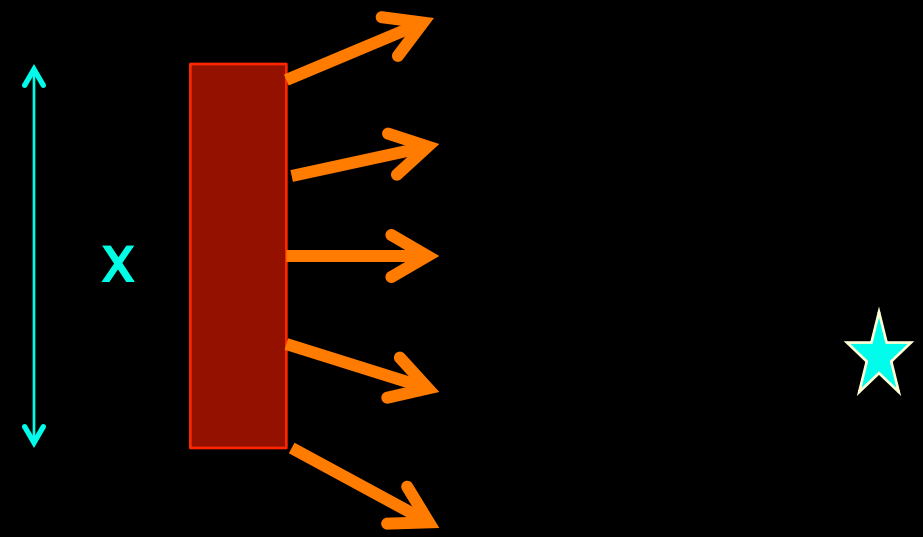
Photo-erosion dynamics

FUV (l > 912 A): PDR heating => Expansion toward illuminating source

$$dM/dt \sim \mu m_H \, n(H) \, x^2 \, c_s$$

$$c_s \sim (k\,T / \mu\, m_H)^{1/2}$$

~ 1 – 3 km/s in PDR
~ 10 – 15 km/s in HII



W43

Location:

Intersection of Galactic Bar / Molecualar Ring

Base of Scutum Arm

Giant Molecular Association: (Luong 2011)

$M \sim 10^7 M_o$, 1 - 2 deg => ~100 - 200 pc

Giant HII region:

WR + O stars => f-f => $L(LyC) \sim 10^{51}$ γ s^{-1}

Extended H.E.S.S. TeV γ-rays => shocks (Chaves 2009)

Triggered, sequential star formation?

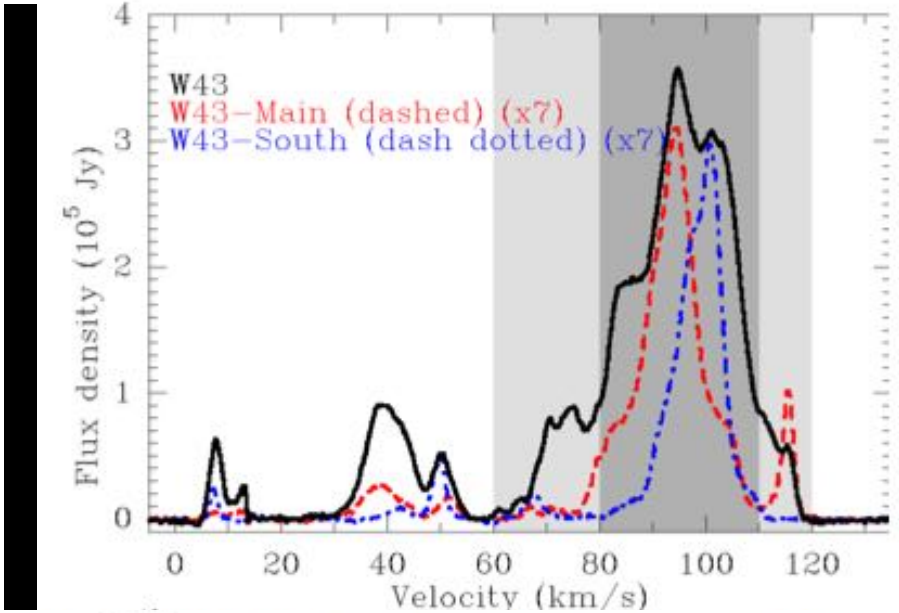
Cometary Clouds + 24 um dust => Older OB stars

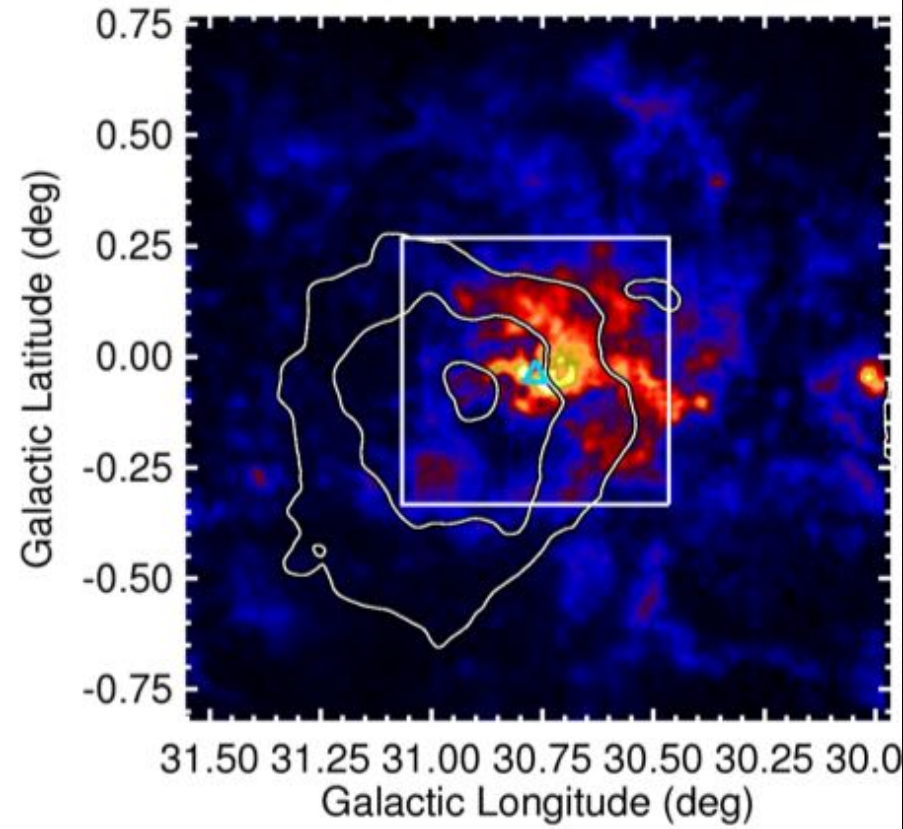
'Up-stream' from Red SuperGiant Clusters (RSGCs)

Will W43 Evolve into an RSGC in 5 - 20 Myr?

RSGC 1, 2, 3, Wd 1, 2?

Distances, longitudes, ages => Ω of the Bar ?





W43

^{13}CO 1-0 (Luong 2011)

^{13}CO 1-0 (BU-FCRAO)
+ TeV gamma-rays

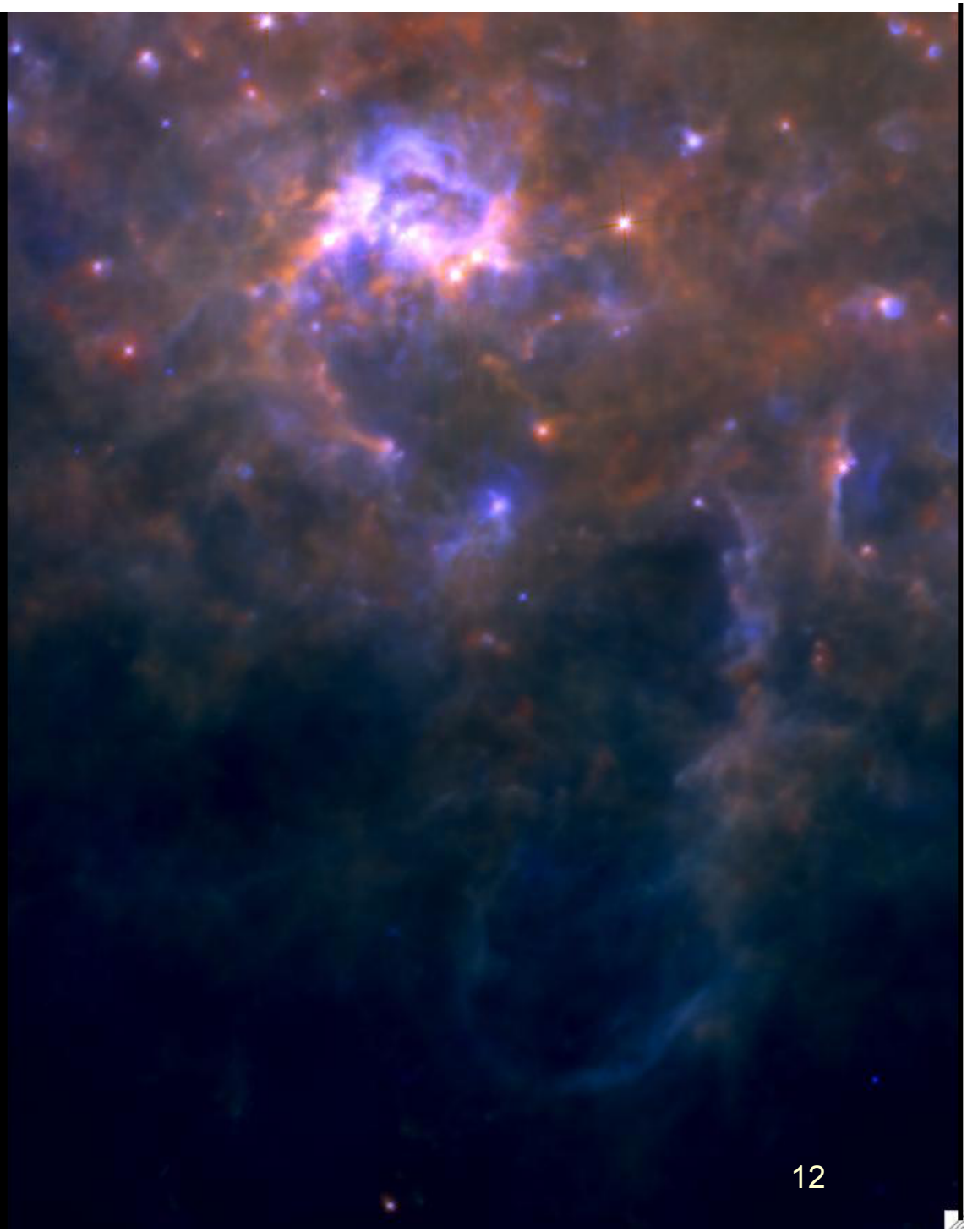
HESS 1848-018
Chaves (2009)

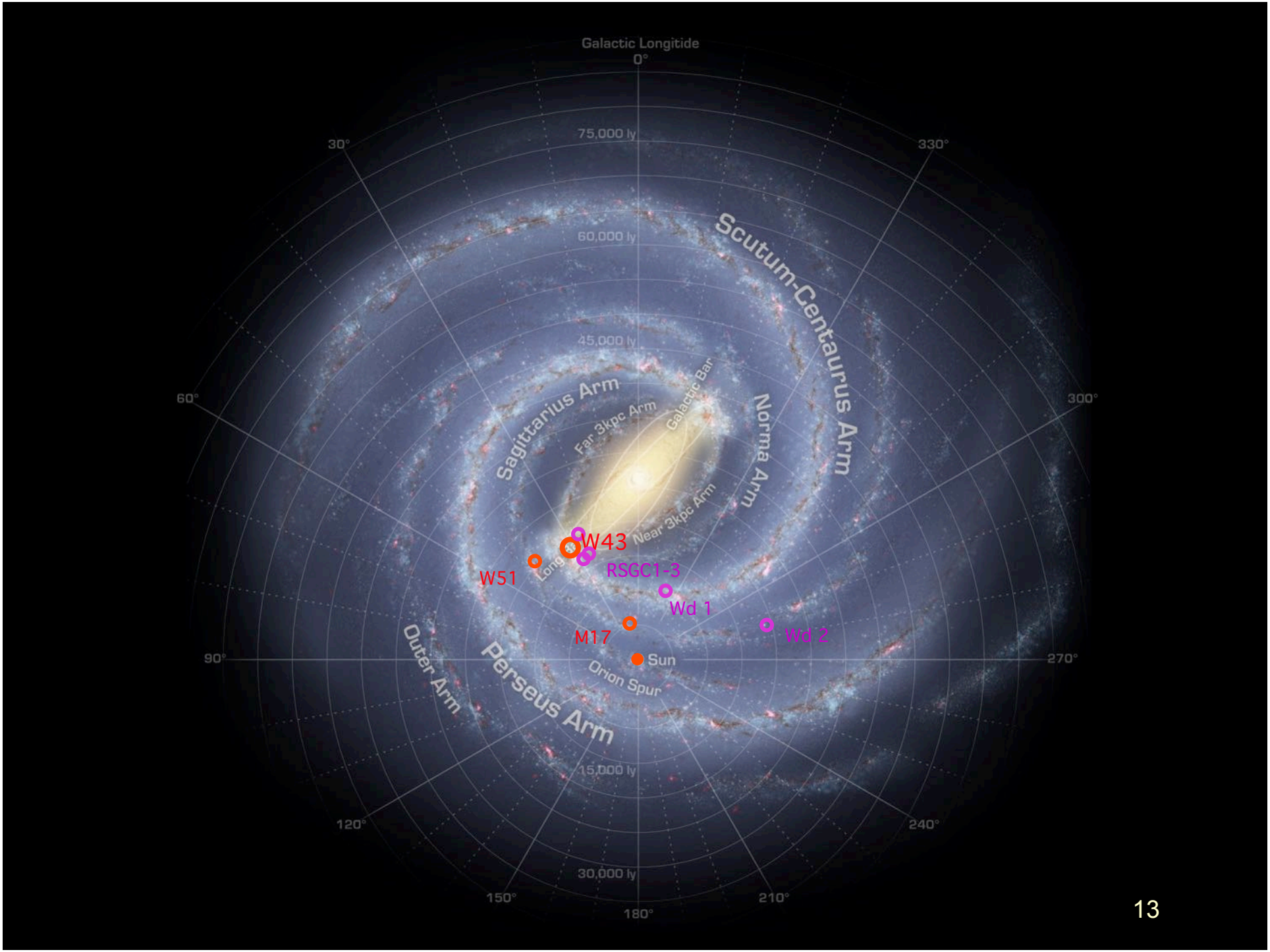
W43
Giant HII region mini-starburst

[l,b] = 30.77, -0.04
V_{lsr} ~ 86 to 106 km/s

D ~ 5.5 - 7 kpc
L > 3.5 x 10^6 L_o
M_{GMC} ~ 10^6 M_o

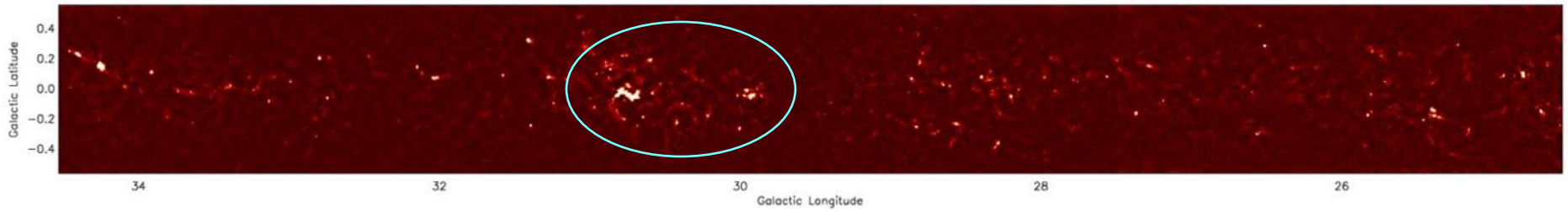
L_{LyC}~ 10^{51} ionizing γ s^{-1}
(50 x Orion Neb.
=> 50 O7 stars!)
O3 and WR stars
=> age >3 Myr

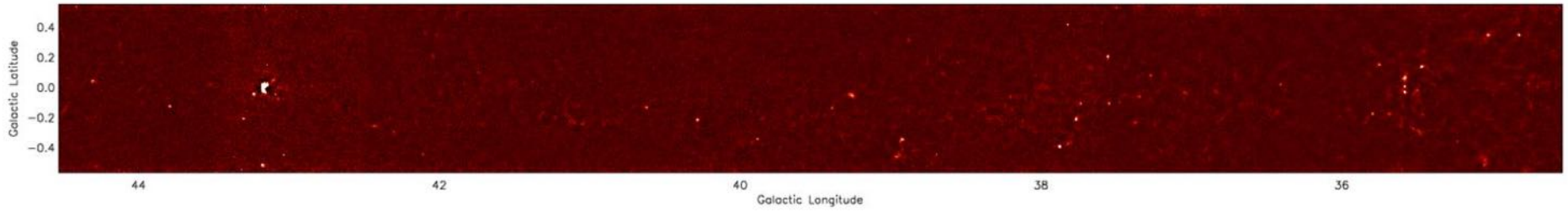



Galactic Longitide
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Perseus Arm
Outer Arm
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Orion Spur
W43
W51
RSGC1-3
Wd 1
Wd 2
M17
Sun

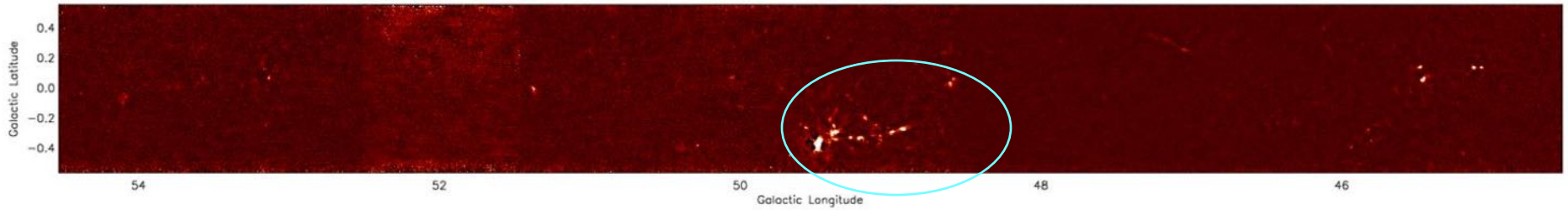
λ = 1.1 mm Bolocam Galactic Plane Survey (BGPS):
(Aguirre 2010; Rosolowski 2010; Bally 2010)

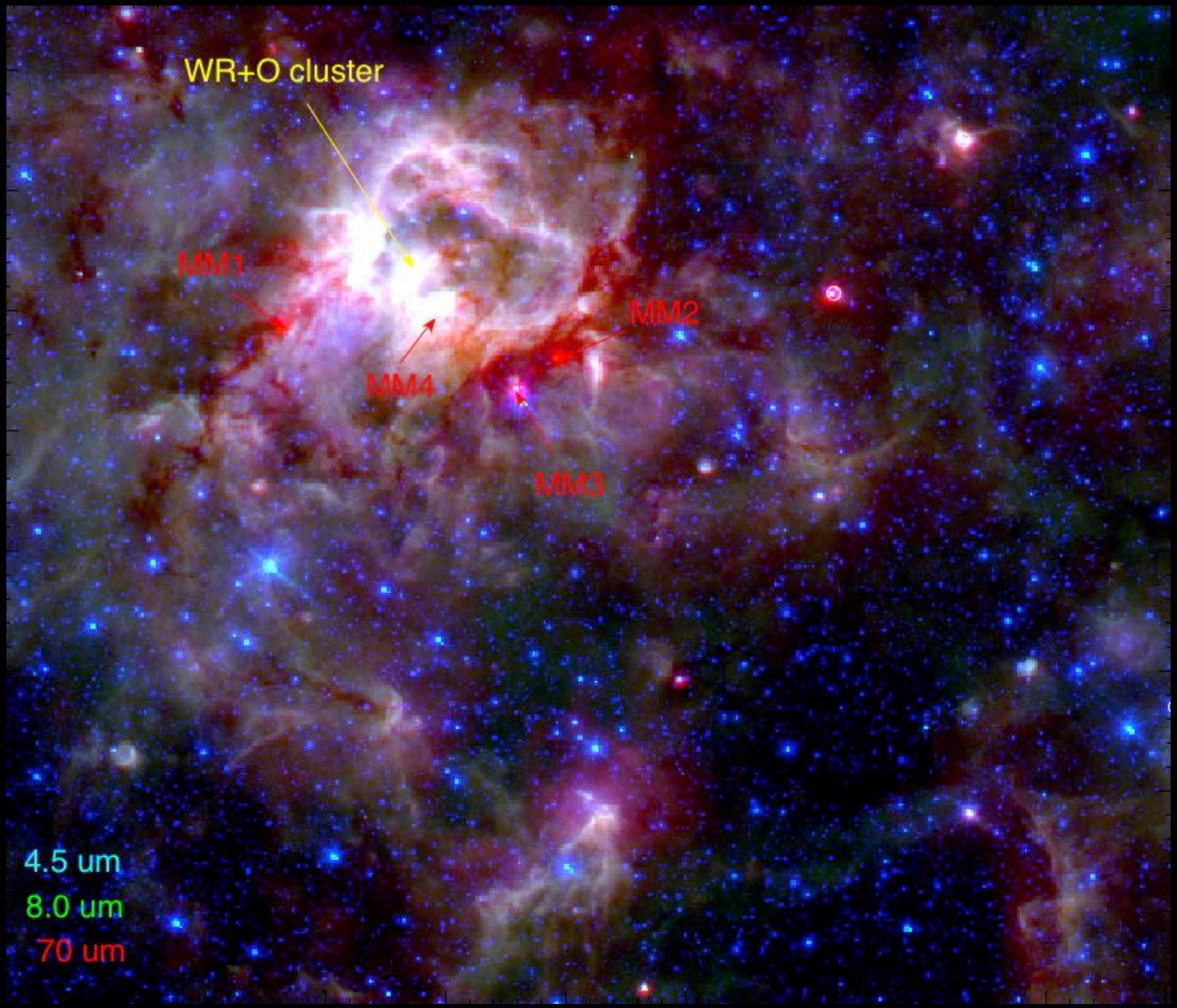
W43 Giant Molecular Association

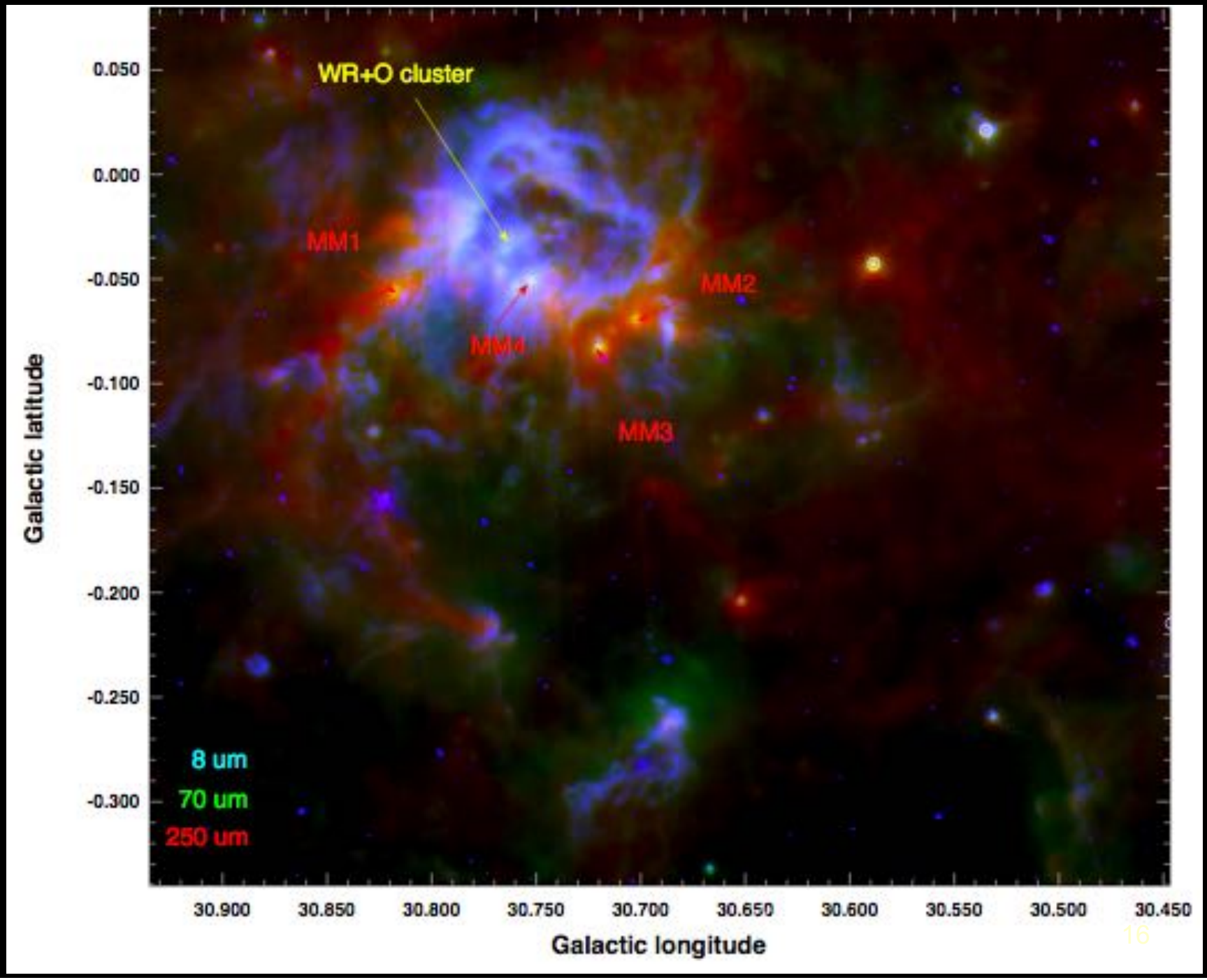


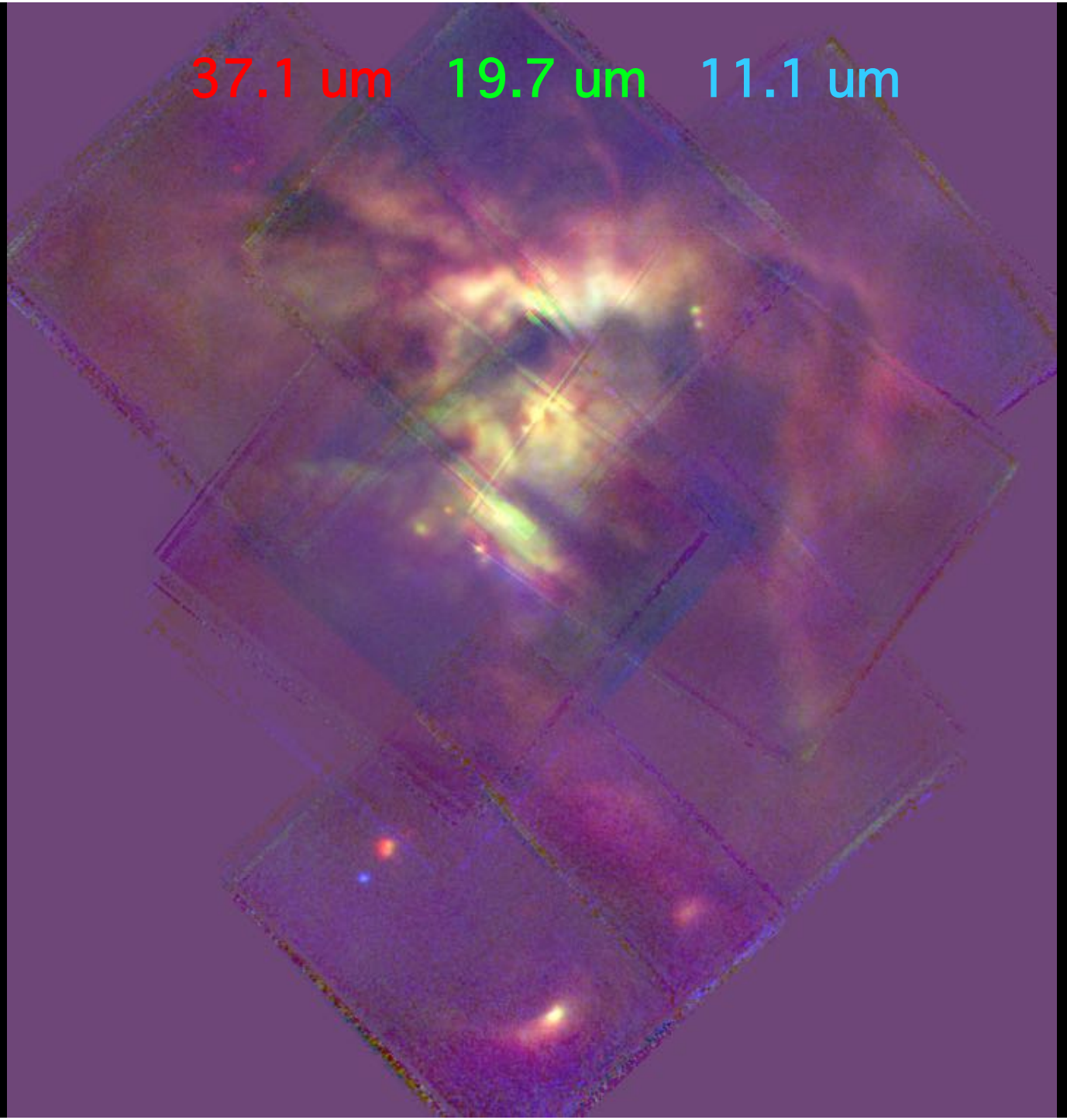


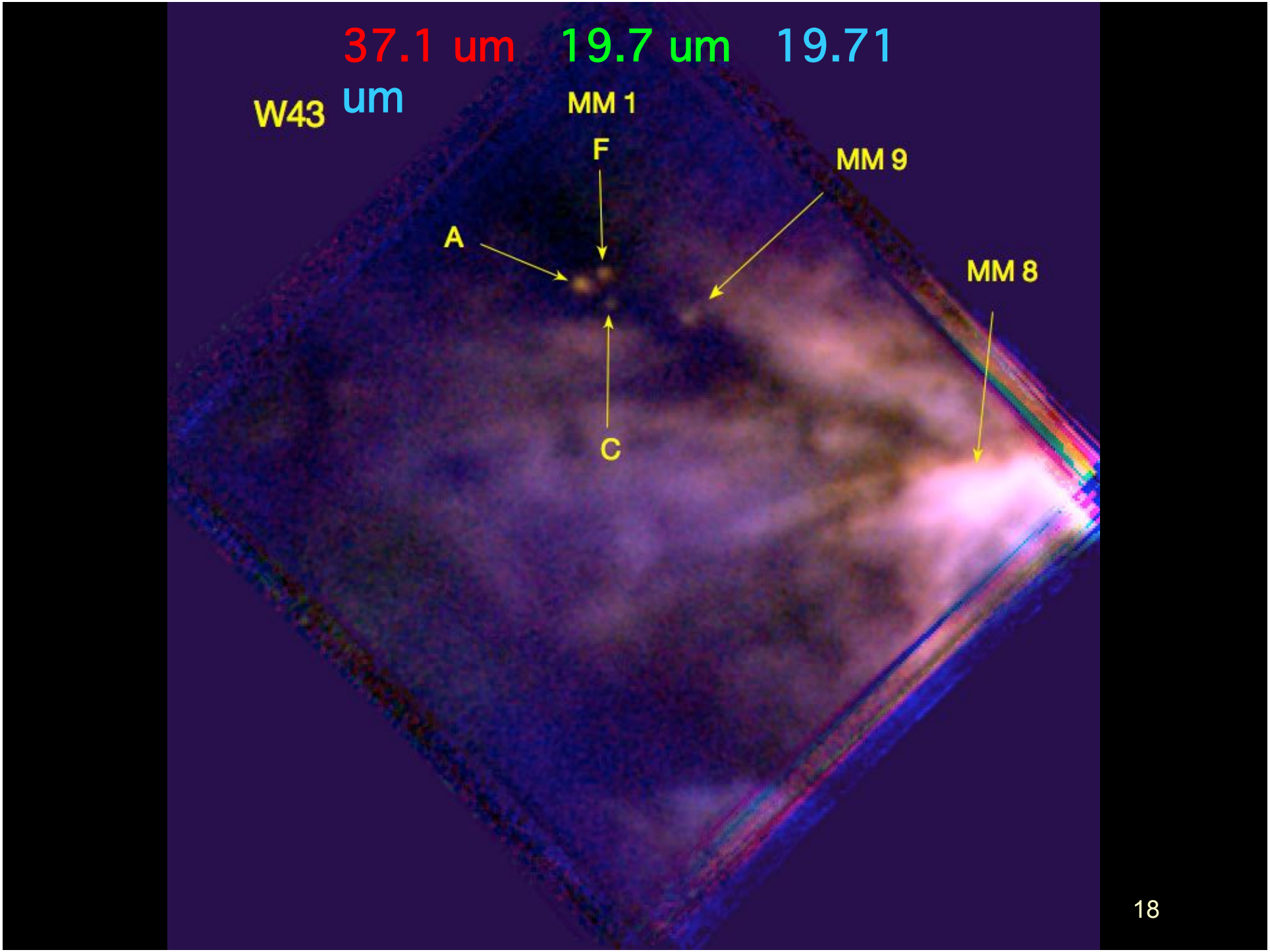
W51

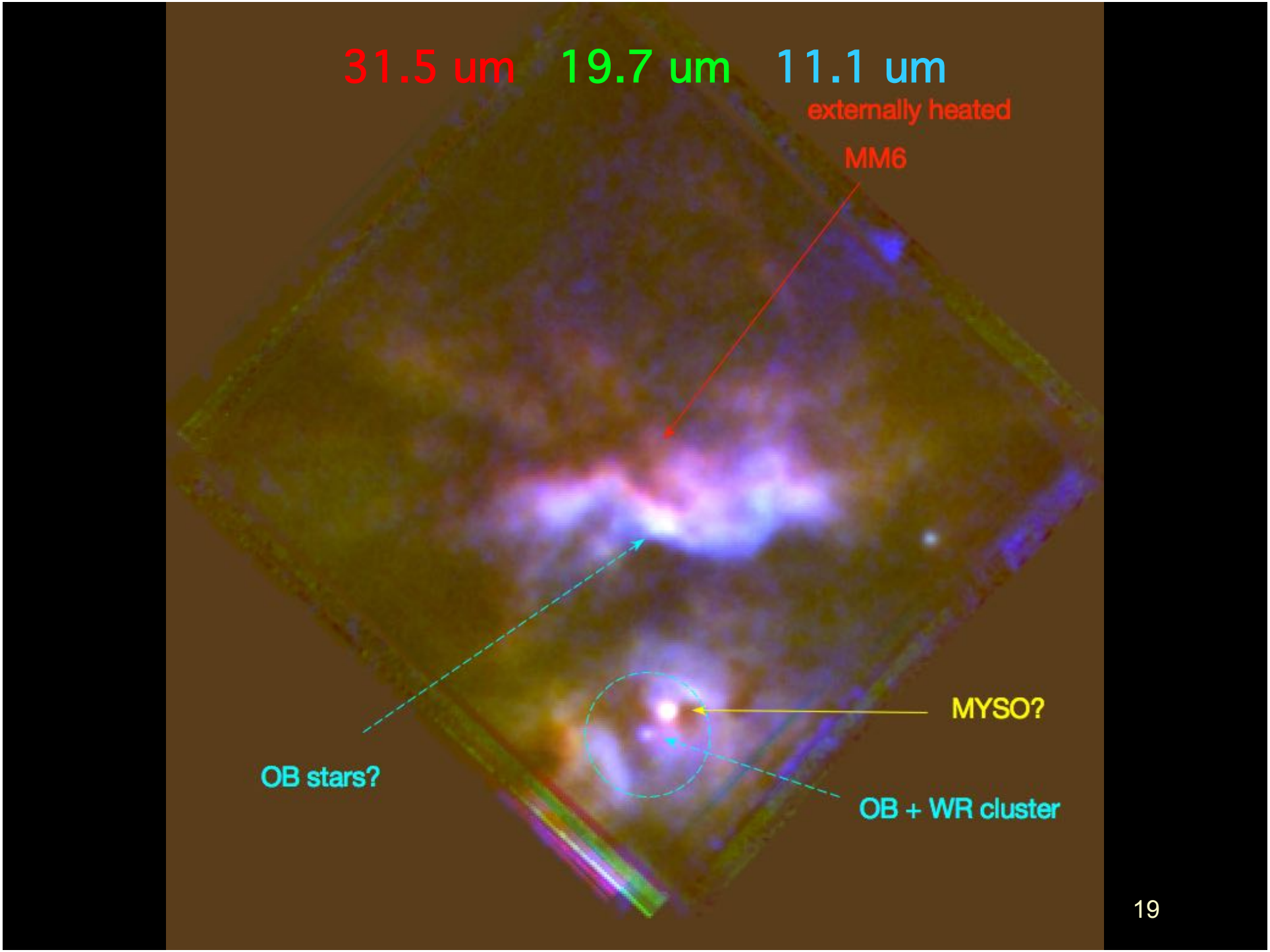


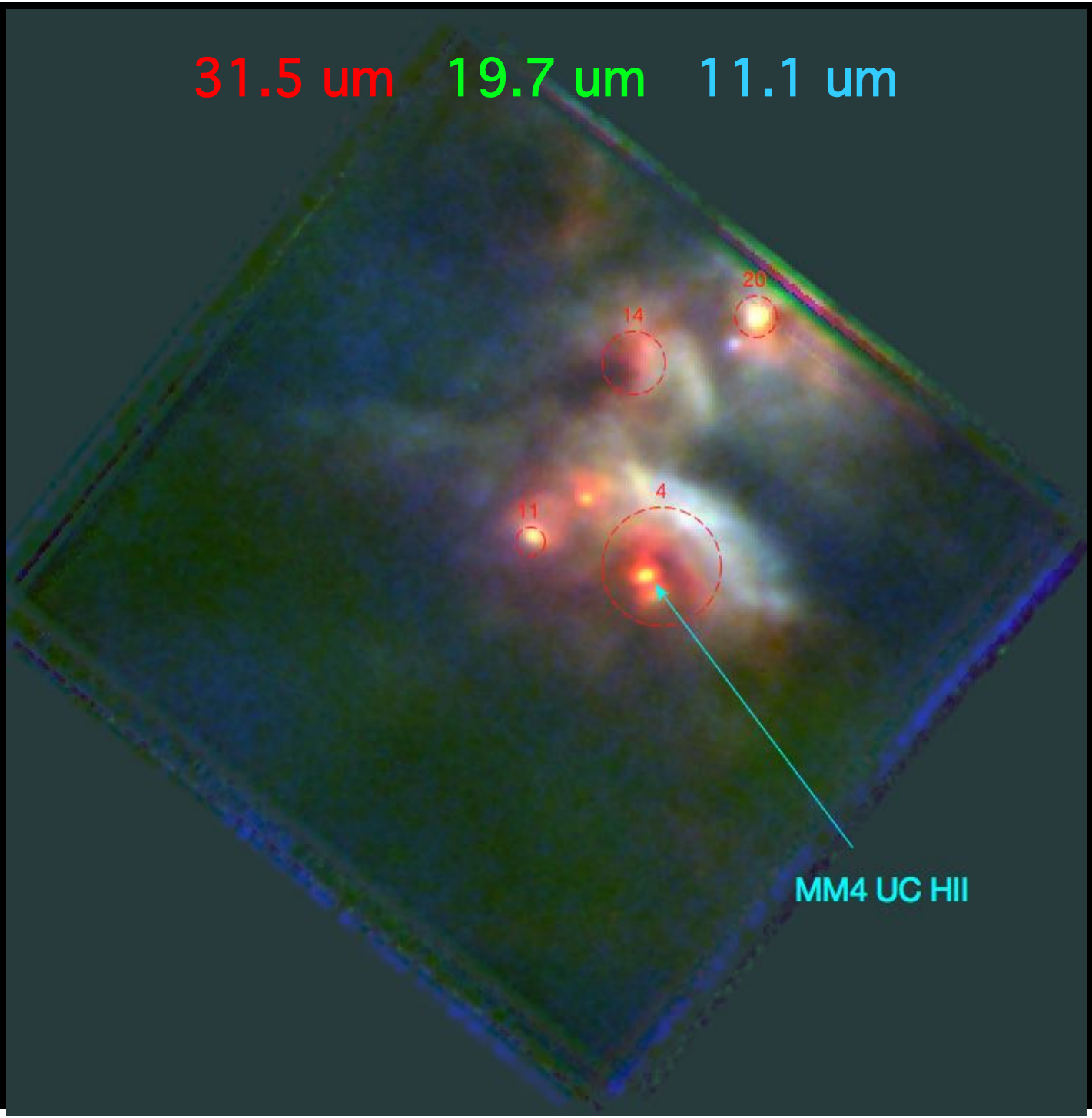

WR+O cluster
MM1
MM2
MM4
MM3
4.5 um
8.0 um
70 um

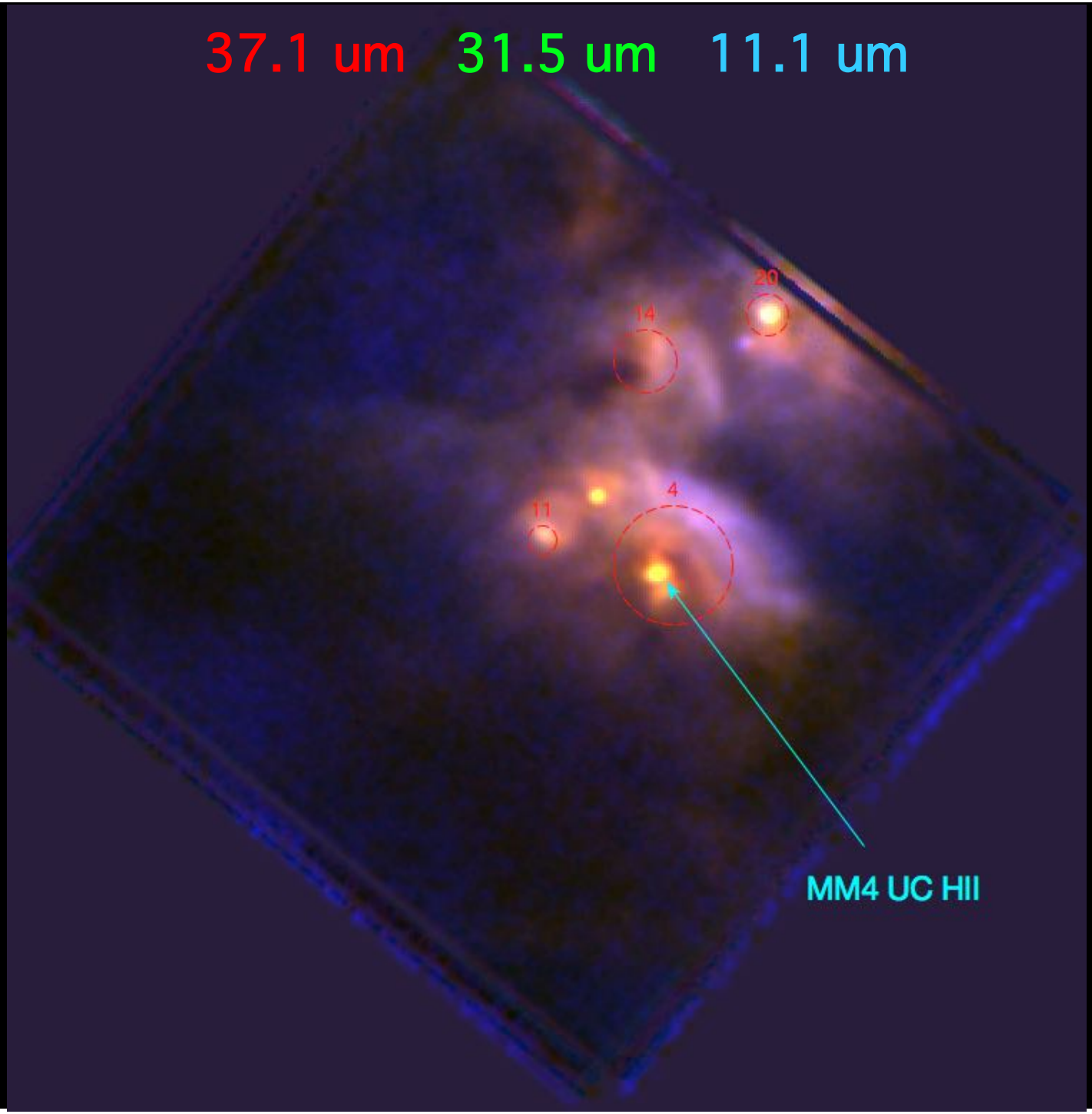

WR+O cluster
MM1
MM2
MM4
MM3
8 um
70 um
250 um
0.050
0.000
-0.050
-0.100
-0.150
-0.200
-0.250
-0.300
Galactic latitude
30.900
30.850
30.800
30.750
30.700
30.650
30.600
30.550
30.500
30.450
Galactic longitude

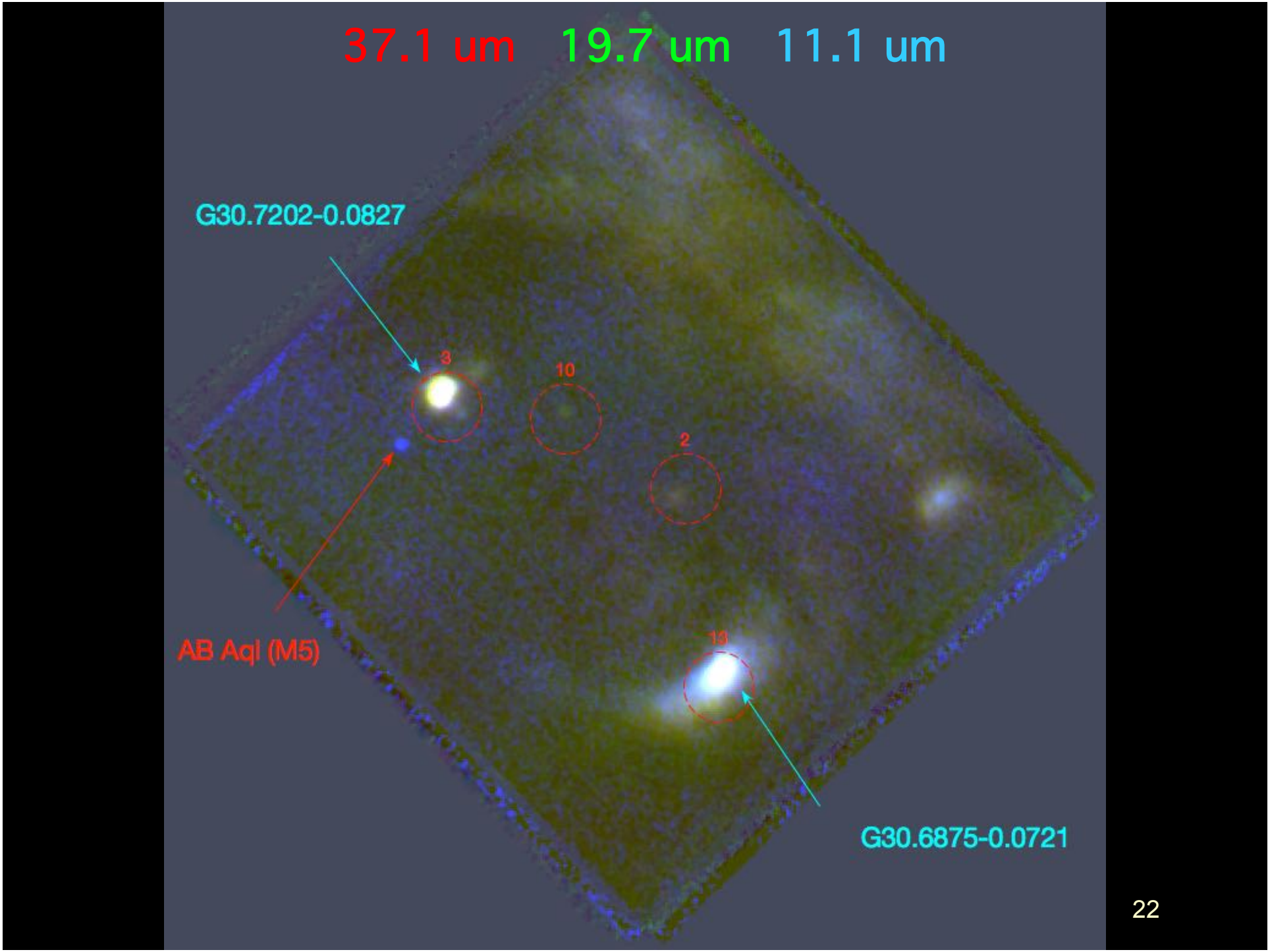

37.1 um
19.7 um
11.1 um

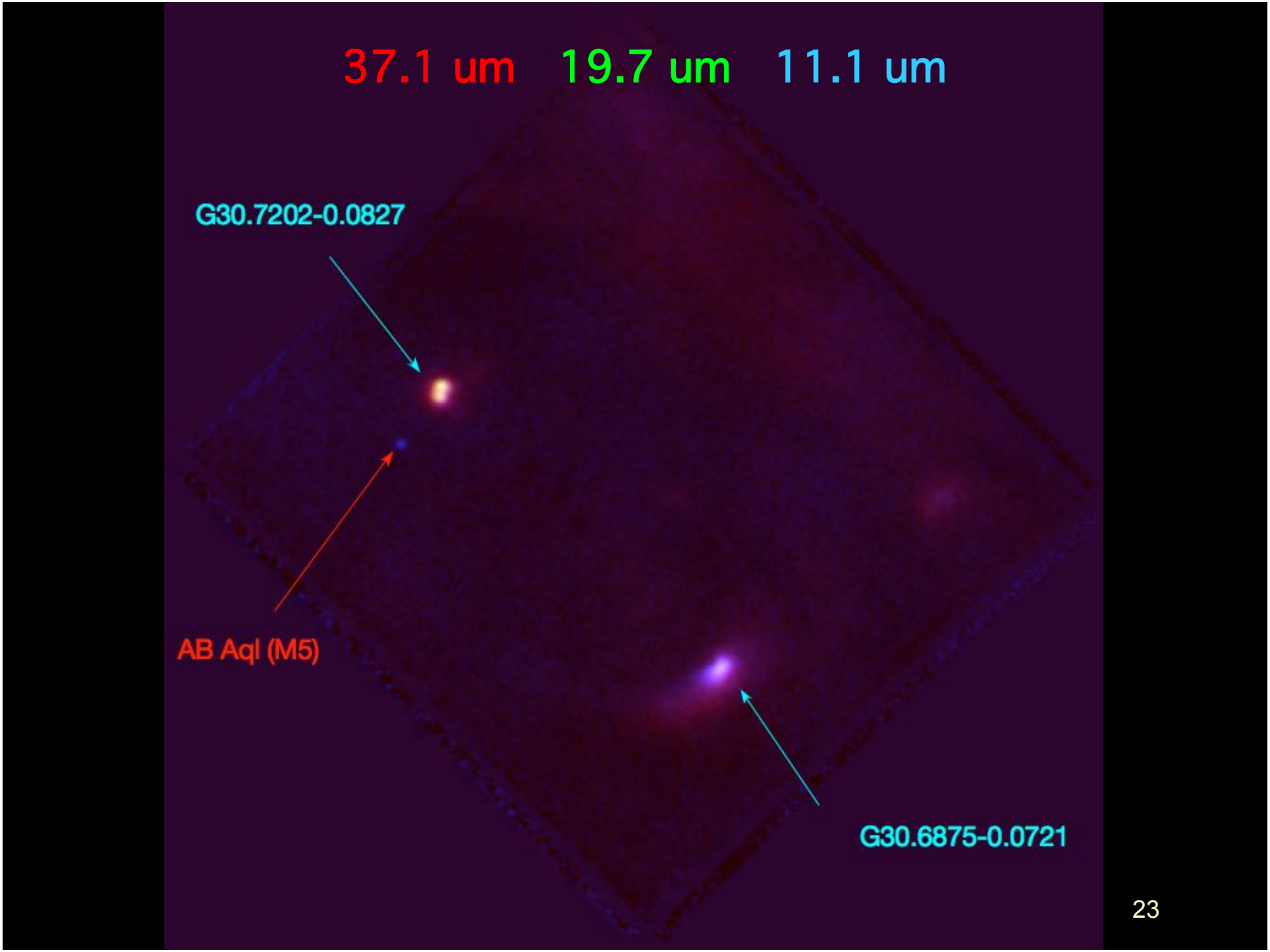

37.1 um
19.7 um
19.71 um
W43
MM 1
F
MM 9
A
MM 8
C

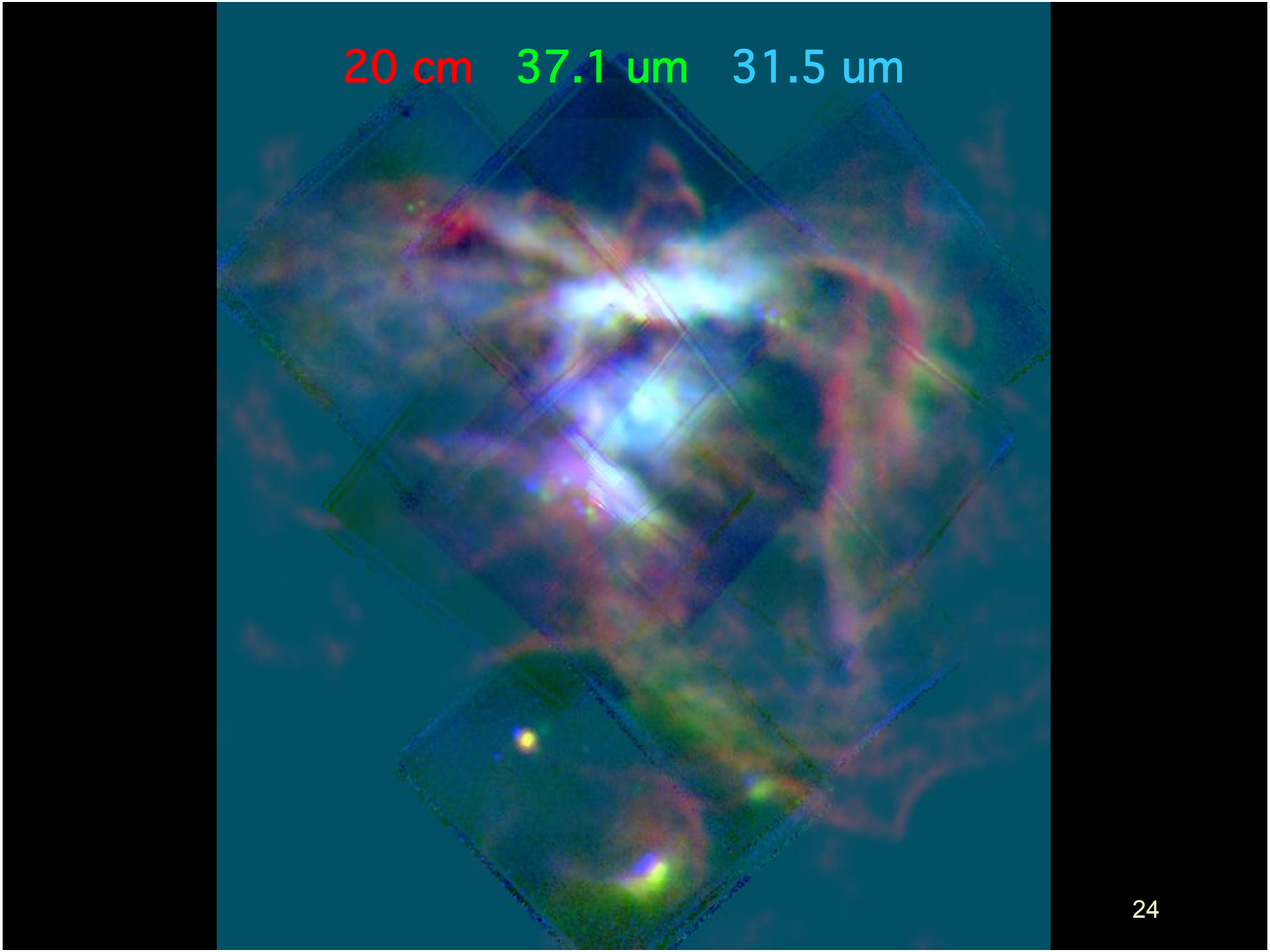

31.5 um 19.7 um 11.1 um
externally heated
MM6
MYSO?
OB stars?
OB + WR cluster


31.5 um 19.7 um 11.1 um
20
14
4
11
MM4 UC HII


37.1 um 31.5 um 11.1 um
20
14
11
4
MM4 UC HII


37.1 um 19.7 um 11.1 um
G30.7202-0.0827
3
10
2
AB Aql (M5)
13
G30.6875-0.0721


37.1 um 19.7 um 11.1 um
G30.7202-0.0827
AB Aql (M5)
G30.6875-0.0721


20 cm
37.1 um
31.5 um

Why study the Galactic Center?

Nearest super-massive black hole (SMBH)

Extreme ISM & star formation conditions

Test "star-formation laws"

(Schmidt-Kennicutt relations)

Only galactic nucleus with resolved stellar pops

Template for other galaxies

- Difficulties

  Extinction

  Edge-on perspective

Central Molecular Zone (CMZ)

Asymmetry:

Dense Gas & cold dust: $M \sim 5 \times 10^7 M_o$; $\Delta V \sim 30$ km/s

$\langle SFR \rangle \sim 0.04 - 0.08 (M_o/yr)$

(Longmore et al. 2012)

2/3 at POSITIVE longitude, velocity

24 μm compact sources:

2/3 at NEGATIVE longitude

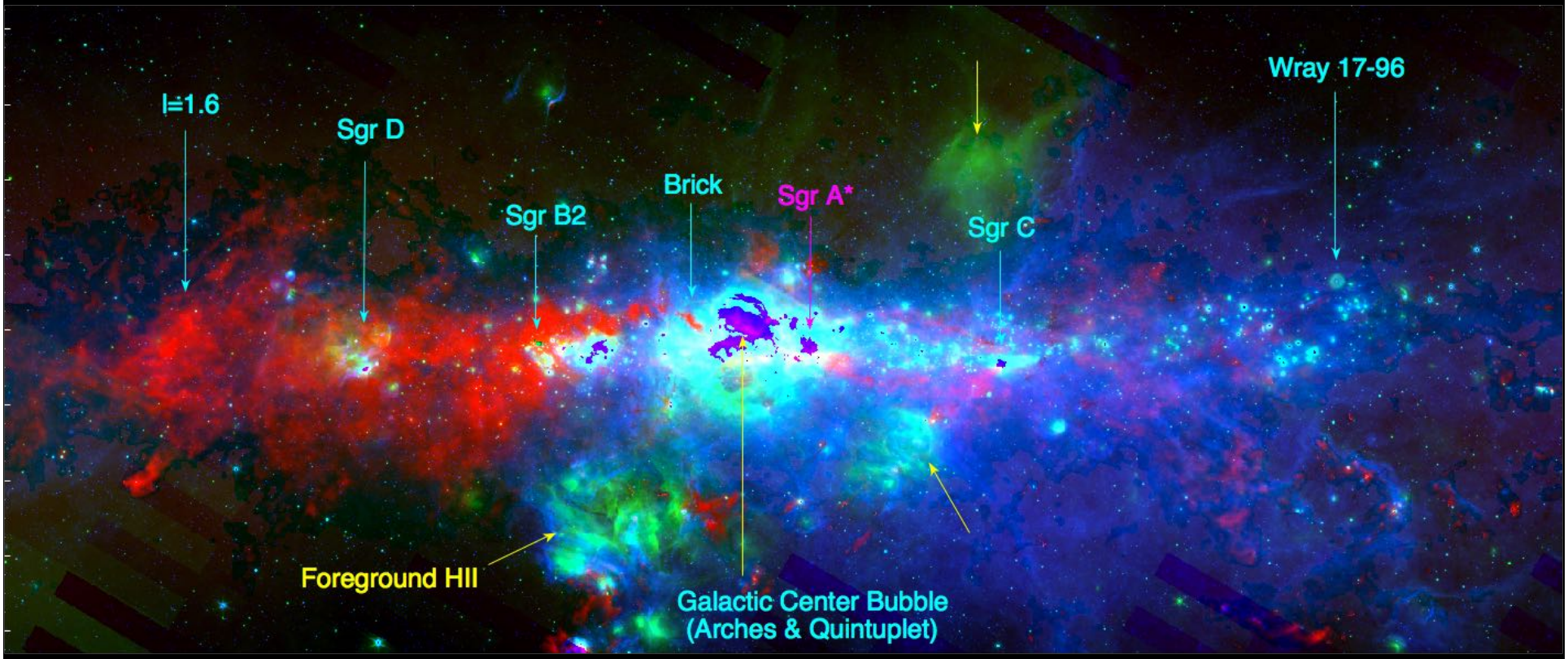
Note: $t_{orbit} \sim 6$ Myr $r_{100\ pc}\ V_{100\ km/s}^{-1}$ (3 to 30 Myr)

Shear should smear out the CMZ in ~10s of Myr

=> Asymmetric Feeding – or- Violent Feedback?

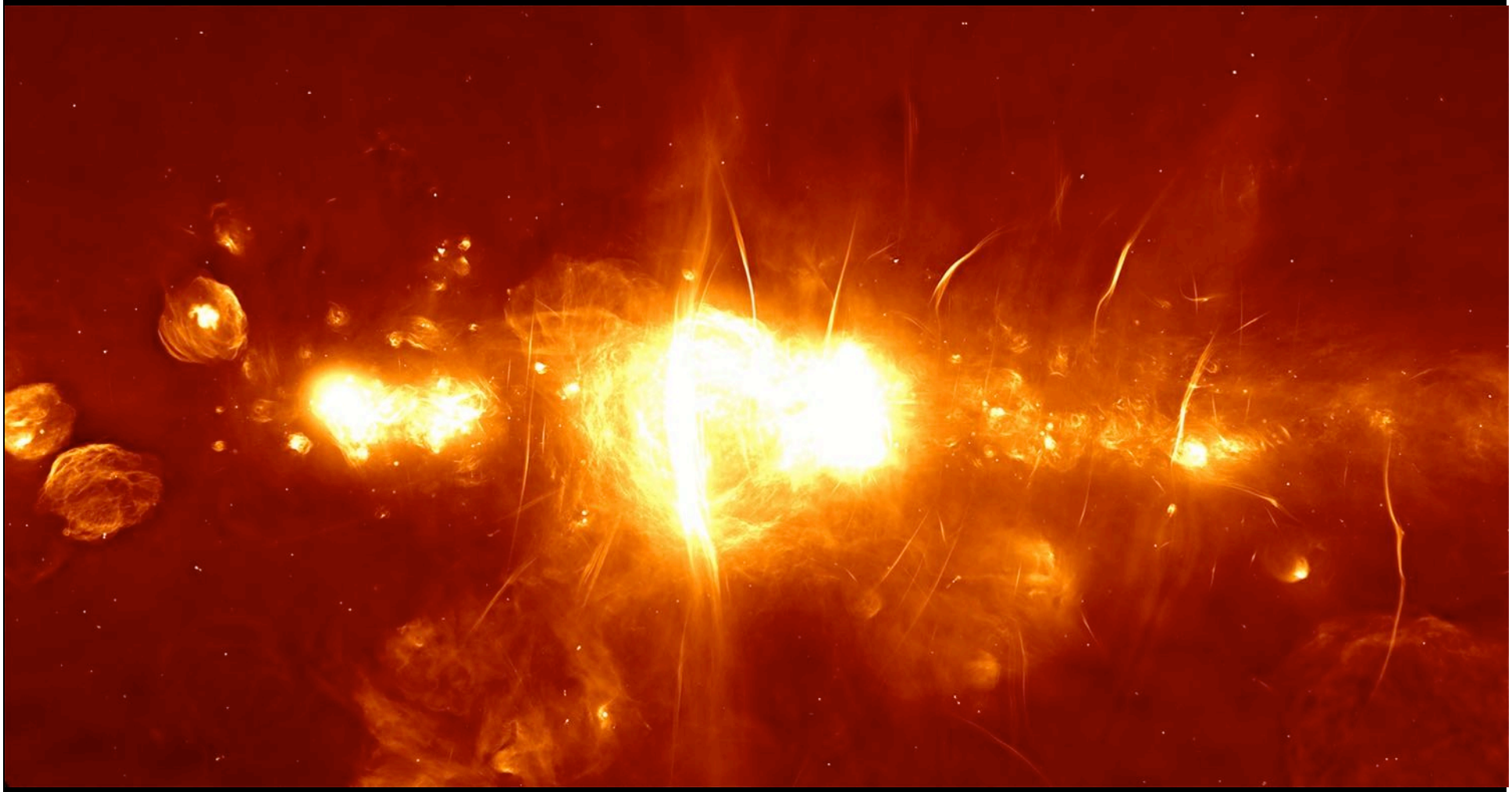
CMZ

8 um 24 um NH_2



+2.0° -2.0°

SKA-MeerKAT 0.9 – 1.6 GHz



Press release of inauguration image: 13 July 2018

http://www.ska.ac.za/media-releases/

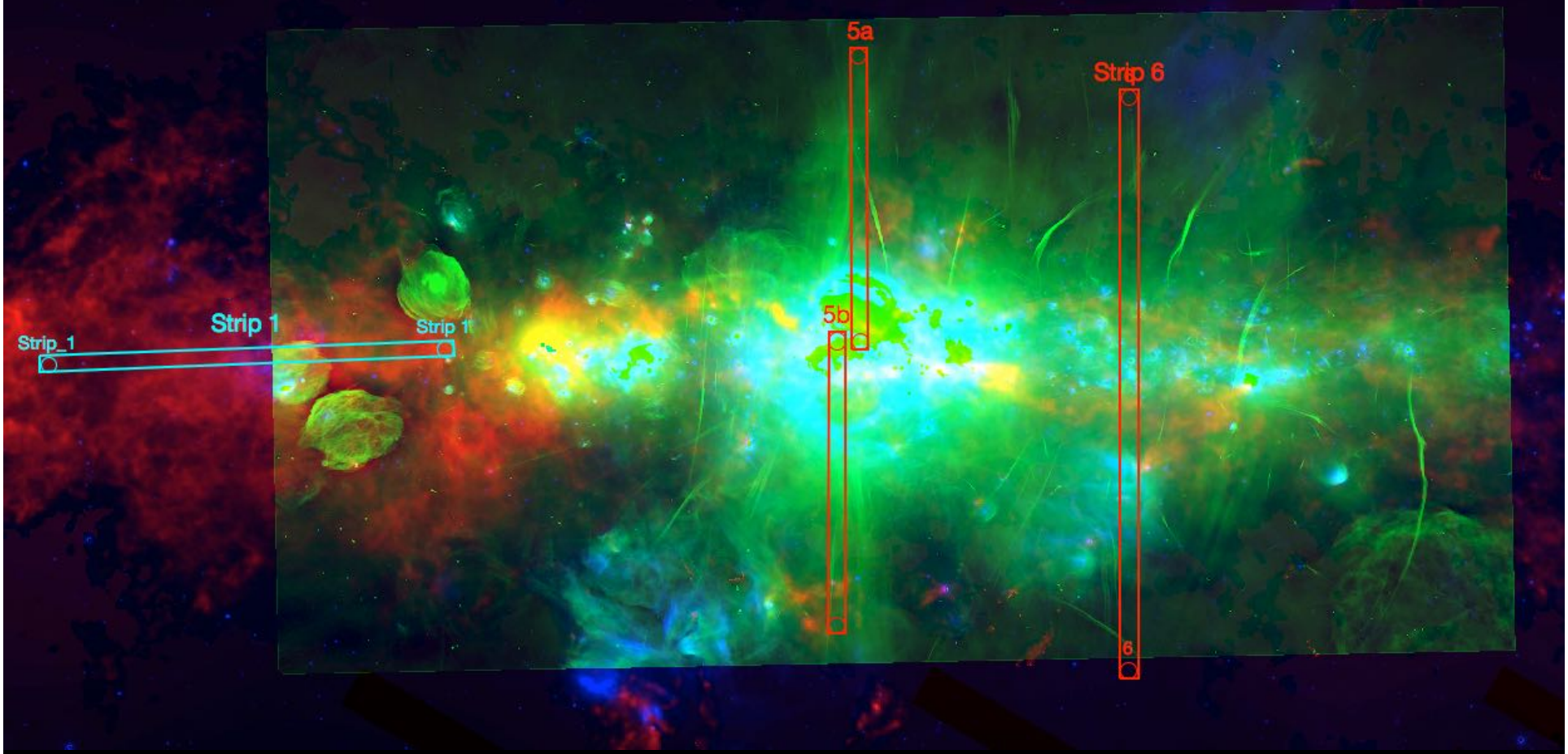
MeerKAT 1 GHz 70 um 8 um

MeerKAT 1 GHz 24 um 8 um

MeerKAT 1 GHz N(H_2) from dust (Hi-GAL) 24 um

upGREAT 158 um C^+ Strips

$N(H_2)$ 1 GHz (MeerKAT) 24 um



Some Order of Magnitude CMZ Energies: $\sim 10^{54-55}$ ergs

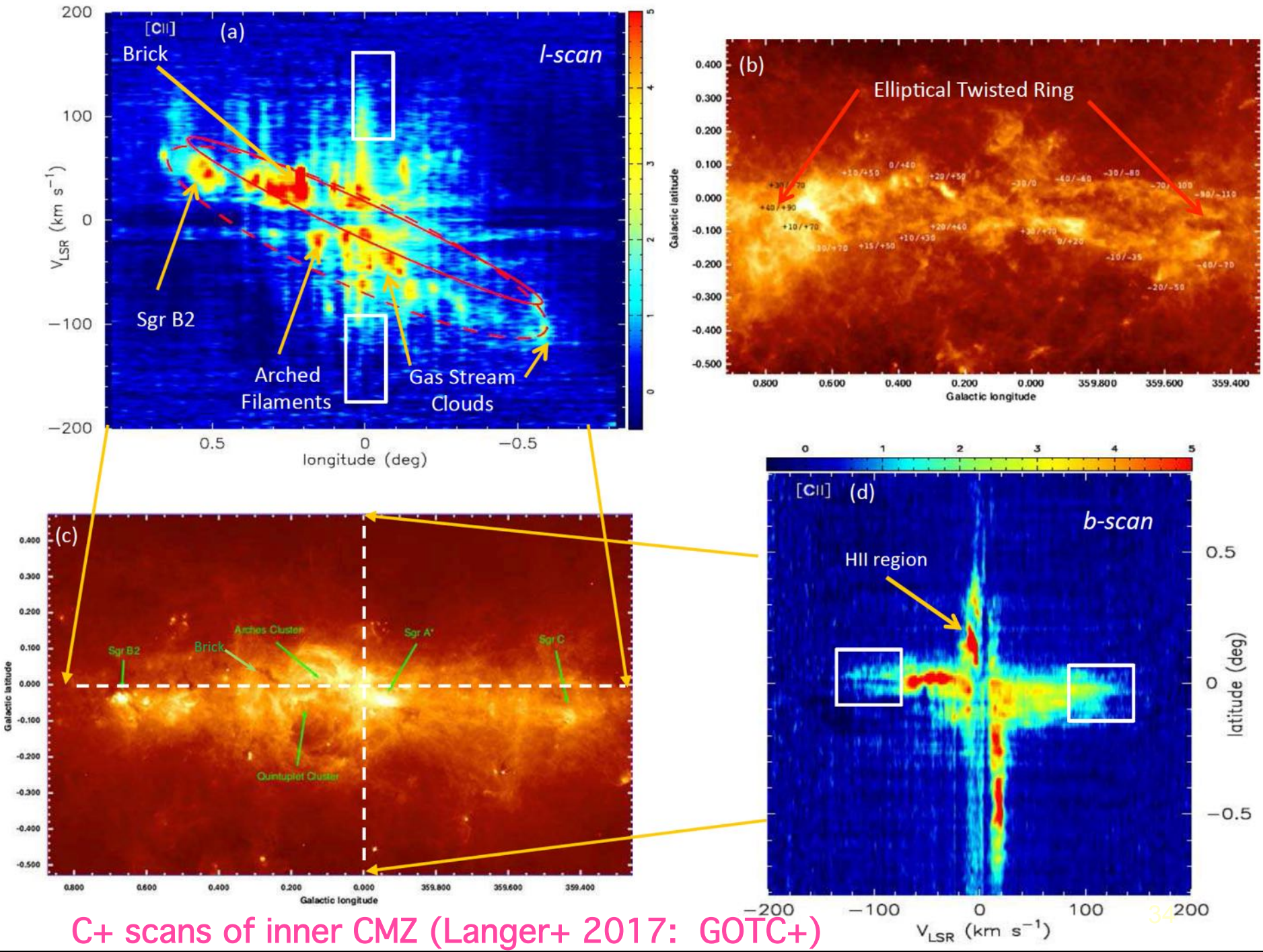
$E_{Self} \sim N_{cloud} G M_{cloud}^2 / R_{cloud}$
$\sim 10^{53} - 10^{54}$ erg — Cloud self gravity

$E_{chem} \sim 5 \times 10^7 M_o * 5$ eV $/ m_H$
$\sim 10^{53}$ erg — Chemical binding

Accelerate 30% of CMZ to ~100 km/s $\sim 10^{54}$ ergs — CMZ to V = 100 km/s

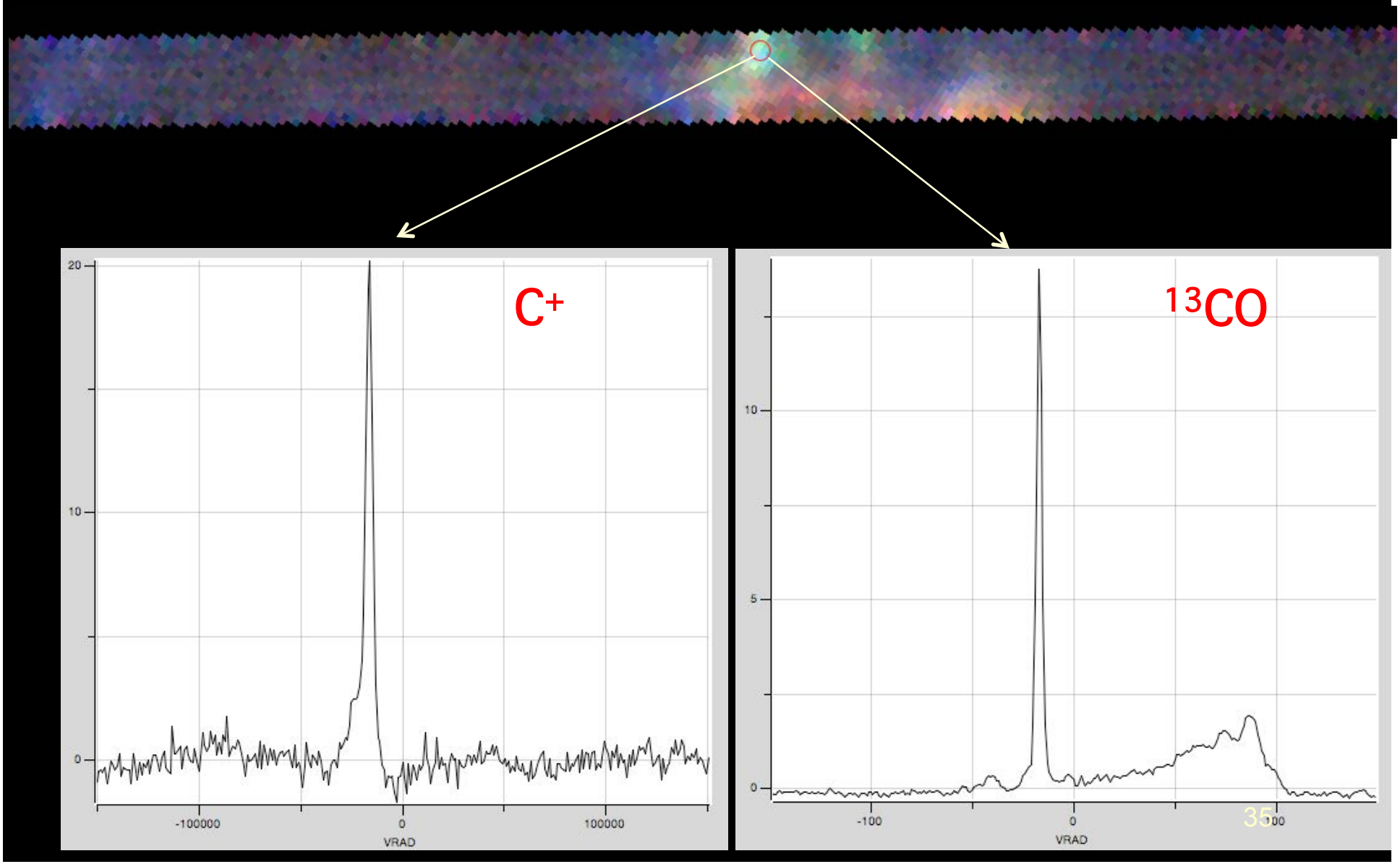
10^3 OB stars => L(UV) t(10 Myr) $\sim 10^{54}$ ergs — Stellar UV

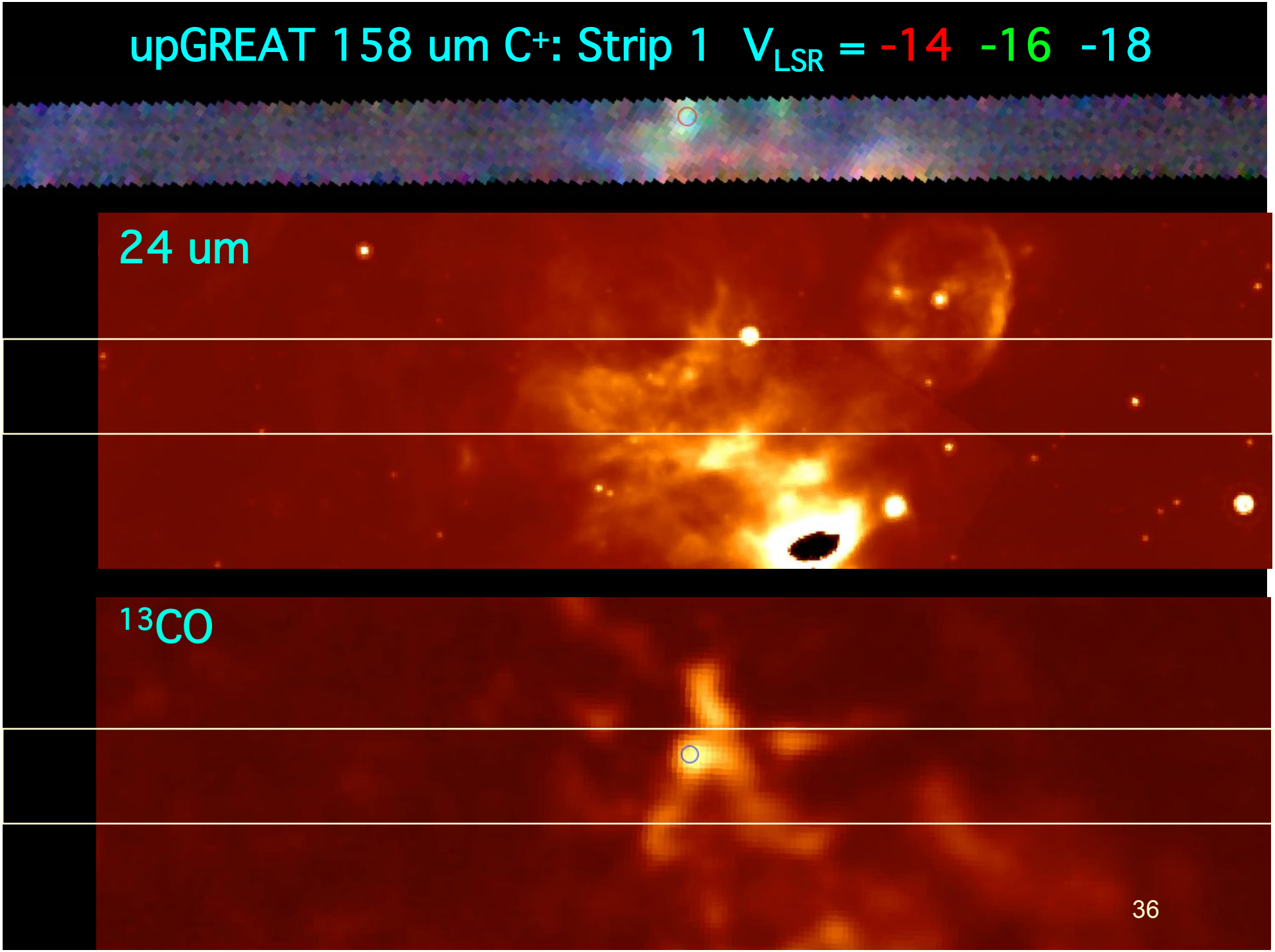
10^3 SNe $\sim 10^{54}$ ergs — SNe

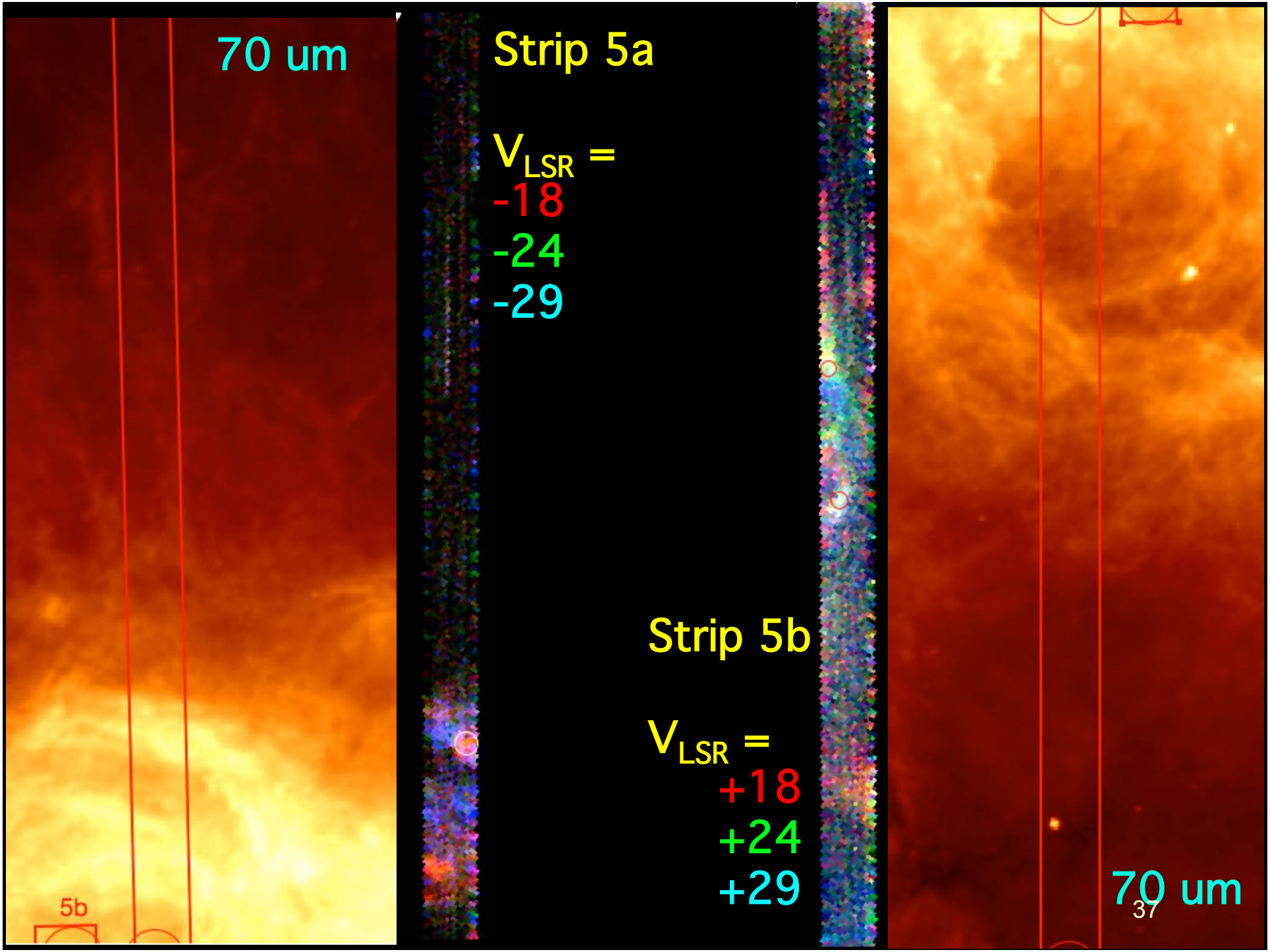


C+ scans of inner CMZ (Langer+ 2017: GOTC+)

upGREAT 158 um C+: Strip 1 V_{LSR} = -14 -16 -18

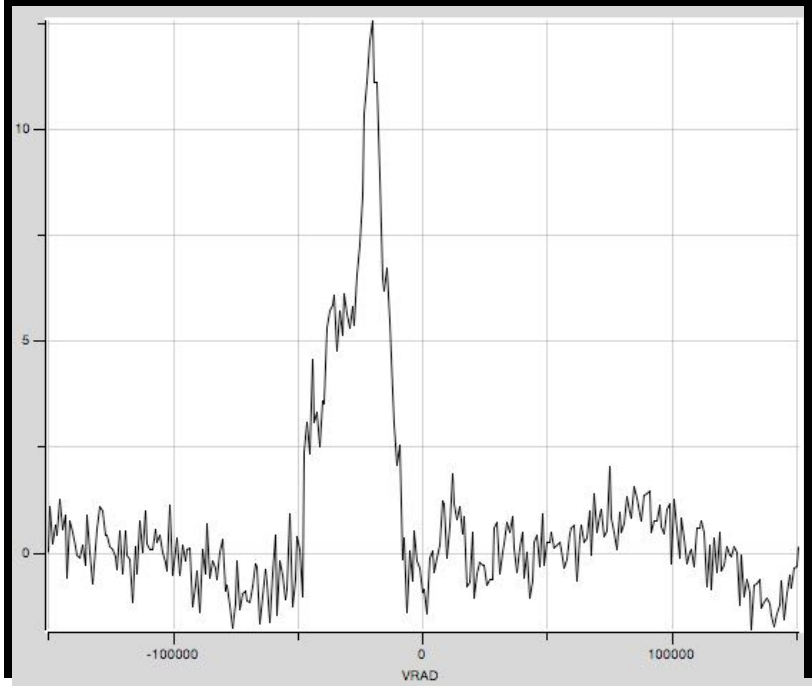



upGREAT 158 um C+: Strip 1 VLSR = -14 -16 -18
24 um
13CO


70 um
Strip 5a
V_{LSR} =
-18
-24
-29
Strip 5b
V_{LSR} =
+18
+24
+29
5b
70 um

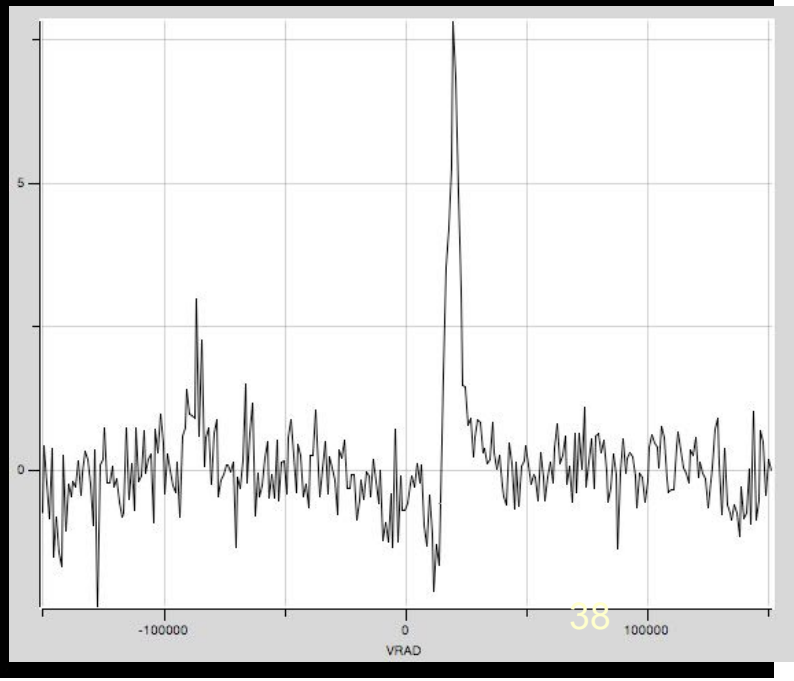
Strip 5a

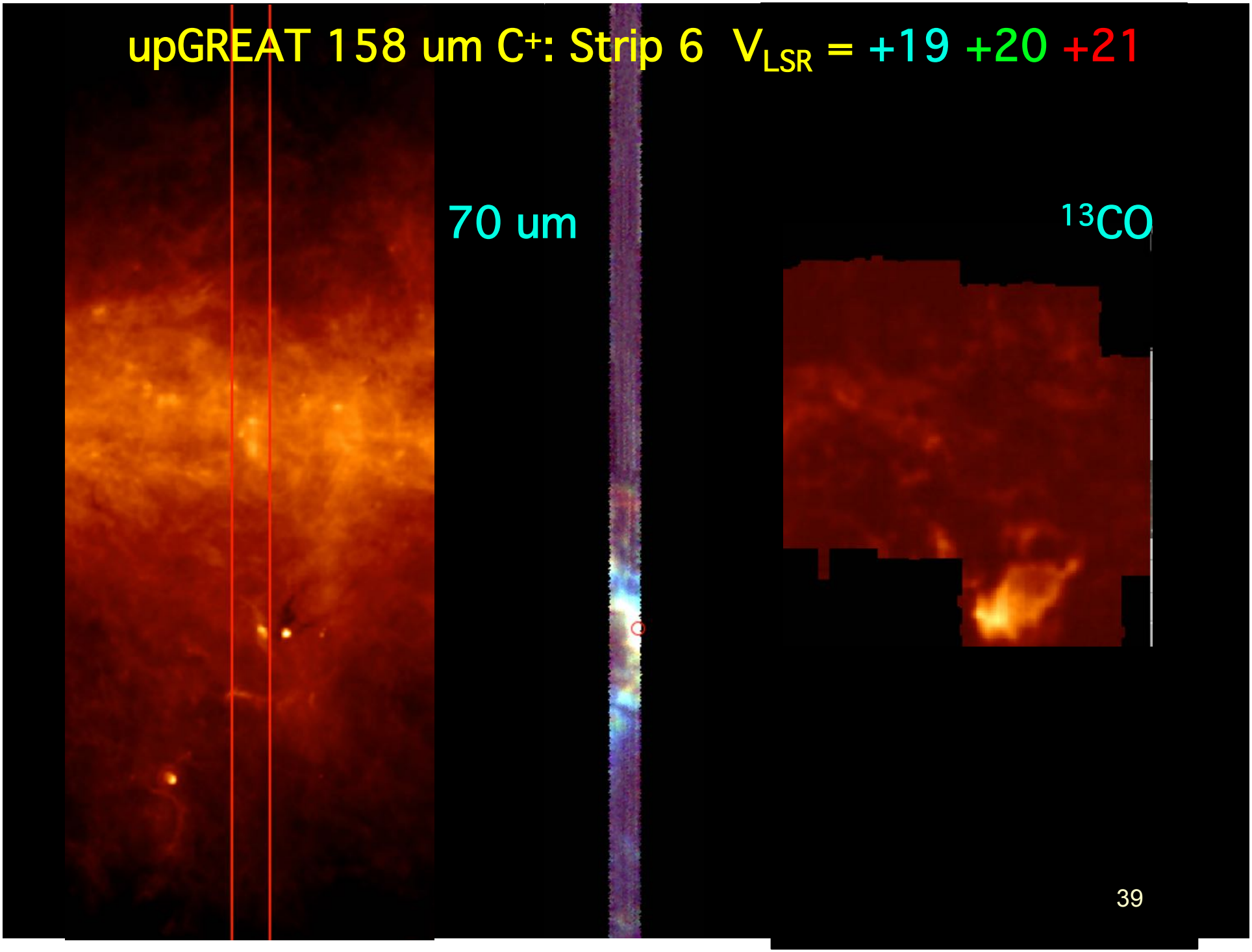
V_{LSR} =
-18
-24
-29



Strip 5b

V_{LSR} =
+18
+24
+29




upGREAT 158 um C+: Strip 6 VLSR = +19 +20 +21
70 um
13CO

CMZ Conclusions

- Bright Narrow linewidth C^+ emission
  - Foreground PDRs

- Broad, dimmer C^+ emission
  - Arched Filaments& some CMZ GMCs

- No bright emission from Sofue-Handa Lobe
  Or HII Regions associated with 1 GHz or
  24 um Compact sources

Conclusions

Mid-far IR sub-km/s spectroscopy essential for diagnosing feedback

Orion Horsehead:

Sharp edge-on PDRs

Soft-UV and ionization induced motions

(in mostly neutral gas) has $\Delta V \sim < 1$ km/s

W43:

'Mini-starburst' at end of Galactic Bar

Ring geometry of PDR / I-fronts

Giant pillars forming around MYSOs / clusters

Responsible for bipolar outflow of HII region ?

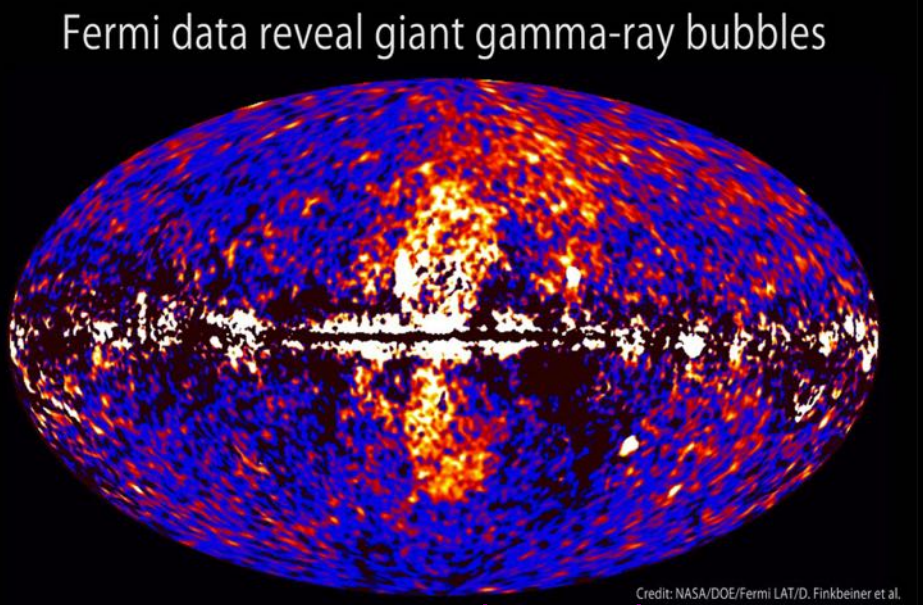
MM1 likely pre-existing, not triggered

CMZ:

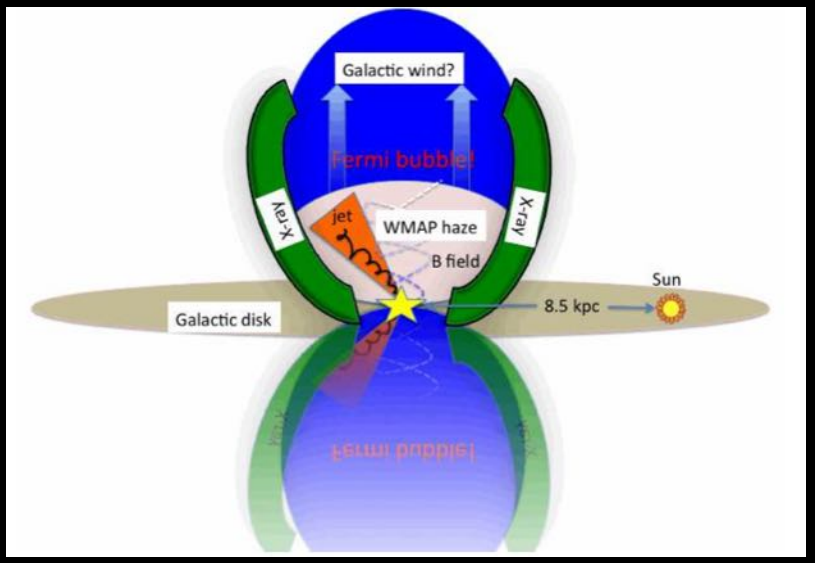
C+ dominated by foreground PDRs

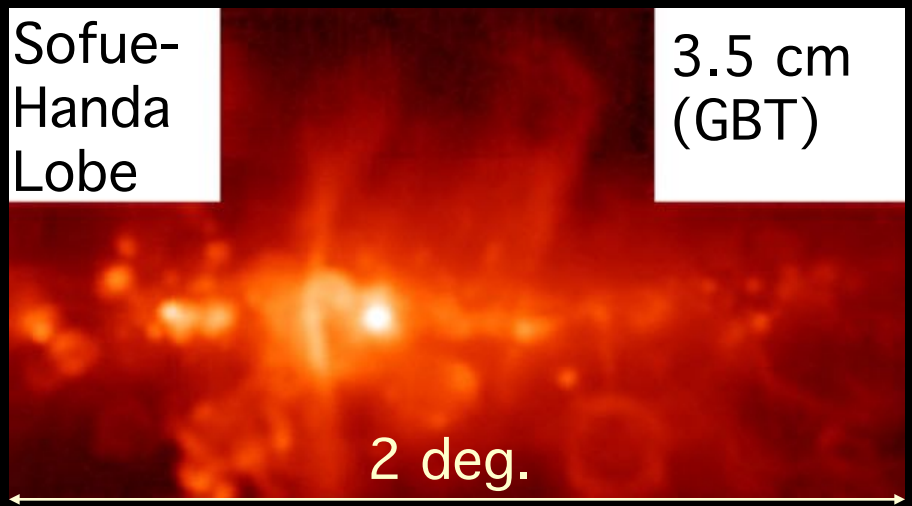
CMZ Blow-out not evident in C+ ... likely fully ionized

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



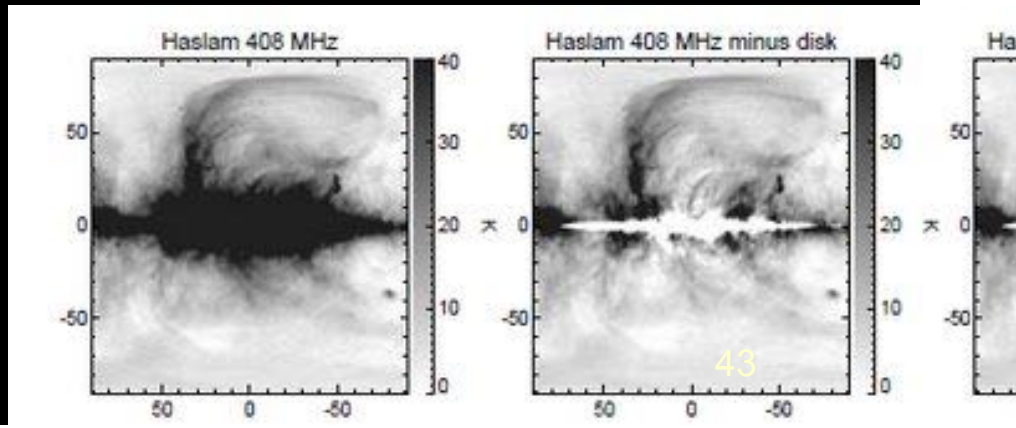
Finkbeiner et al. (2010)

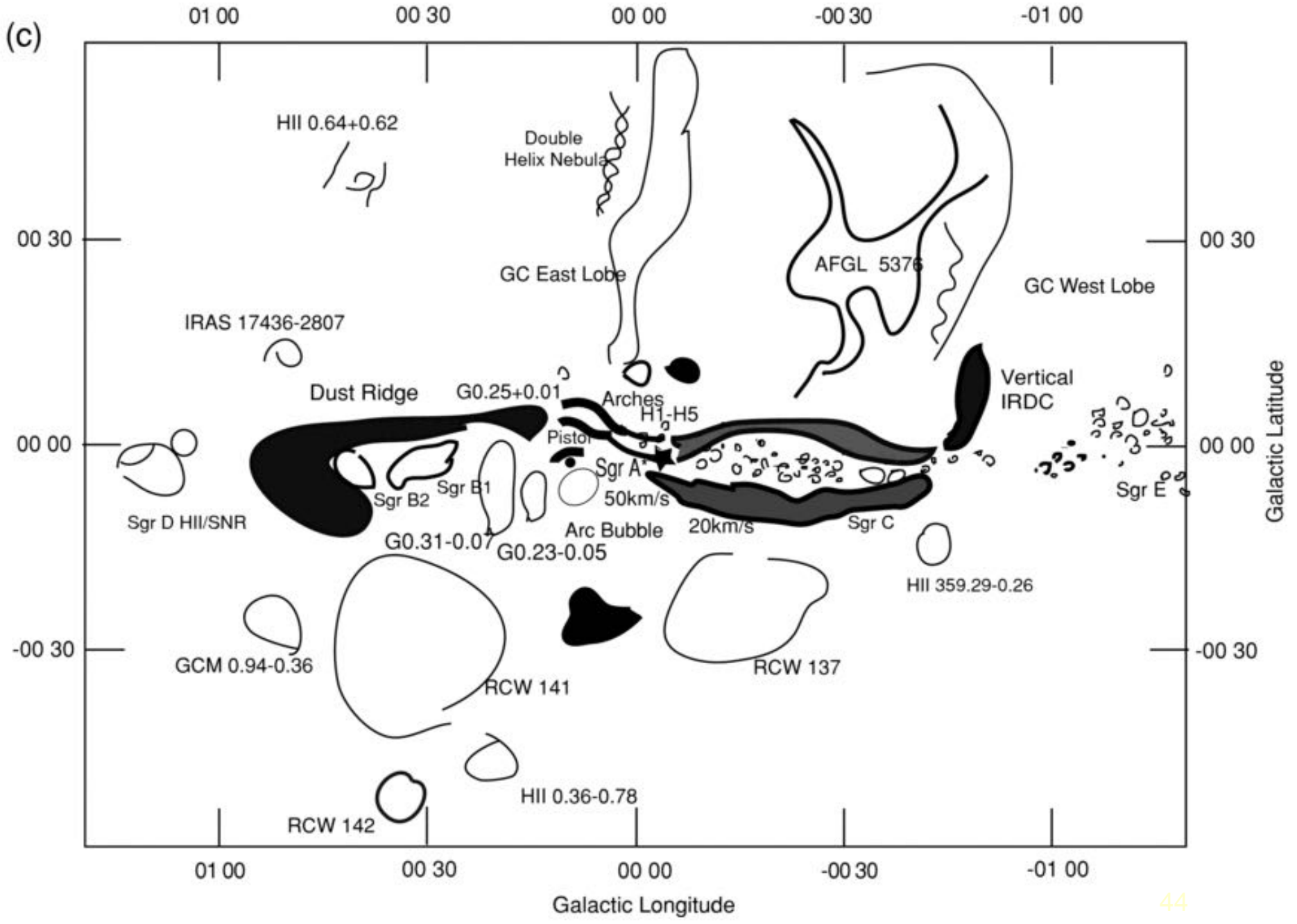


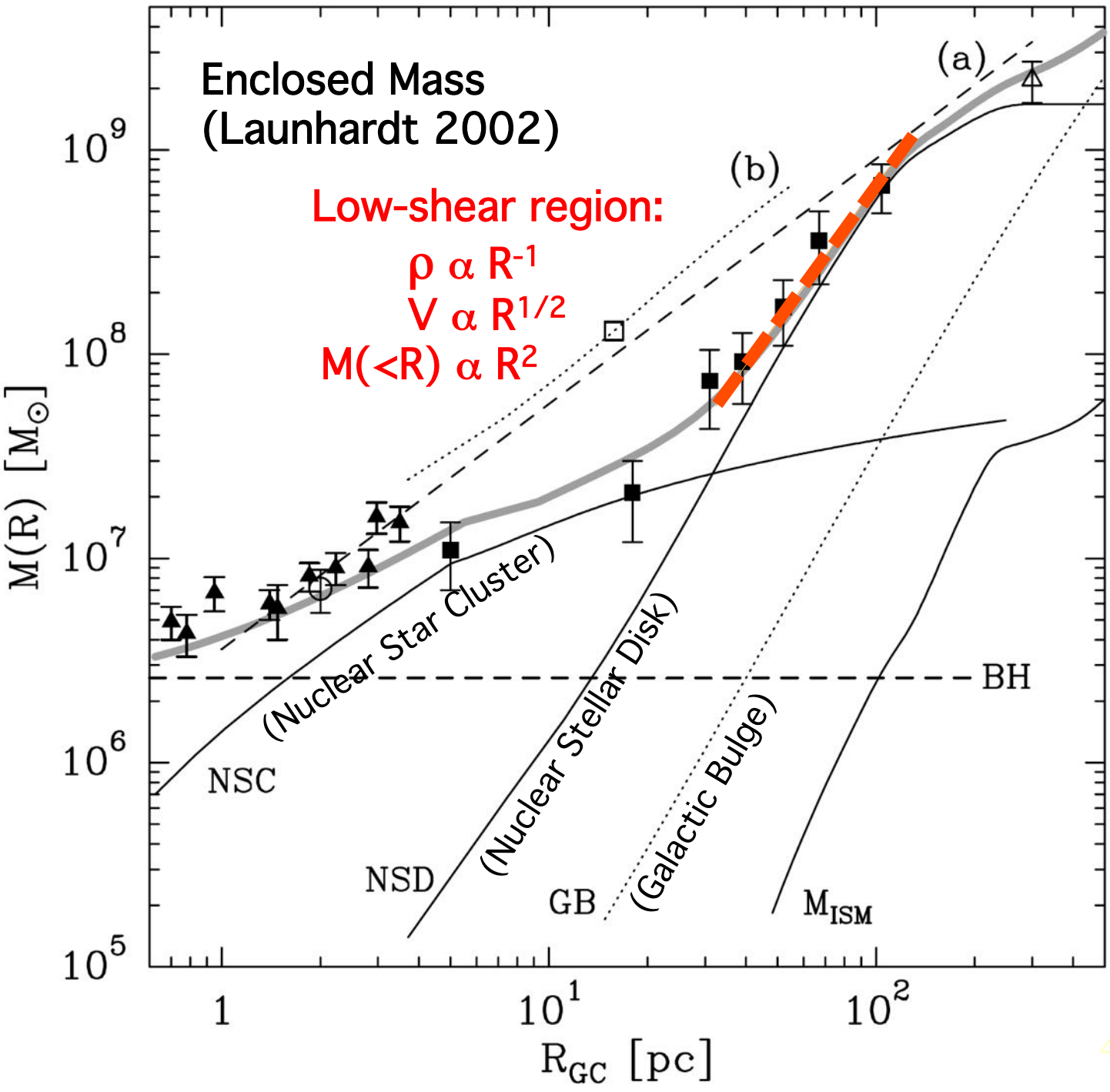


Law et al. (2008)

... or Sco-Cen superbubble 150 pc from Sun?




(c)
01 00
00 30
00 00
-00 30
-01 00
HII 0.64+0.62
Double
Helix Nebula
GC East Lobe
AFGL 5376
GC West Lobe
IRAS 17436-2807
Dust Ridge
G0.25+0.01
Arches
H1-H5
Vertical
IRDC
Pistol
Sgr A*
Sgr B2
Sgr B1
50km/s
Sgr E
Sgr D HII/SNR
Arc Bubble
20km/s
Sgr C
G0.31-0.07
G0.23-0.05
HII 359.29-0.26
GCM 0.94-0.36
RCW 141
RCW 137
HII 0.36-0.78
RCW 142
Galactic Latitude
Galactic Longitude


Enclosed Mass
(Launhardt 2002)
Low-shear region:
ρ α R-1
V α R1/2
M(<R) α R2
(a)
(b)
M(R) [M⊙]
RGC [pc]
(Nuclear Star Cluster)
(Nuclear Stellar Disk)
(Galactic Bulge)
NSC
NSD
GB
MISM
BH