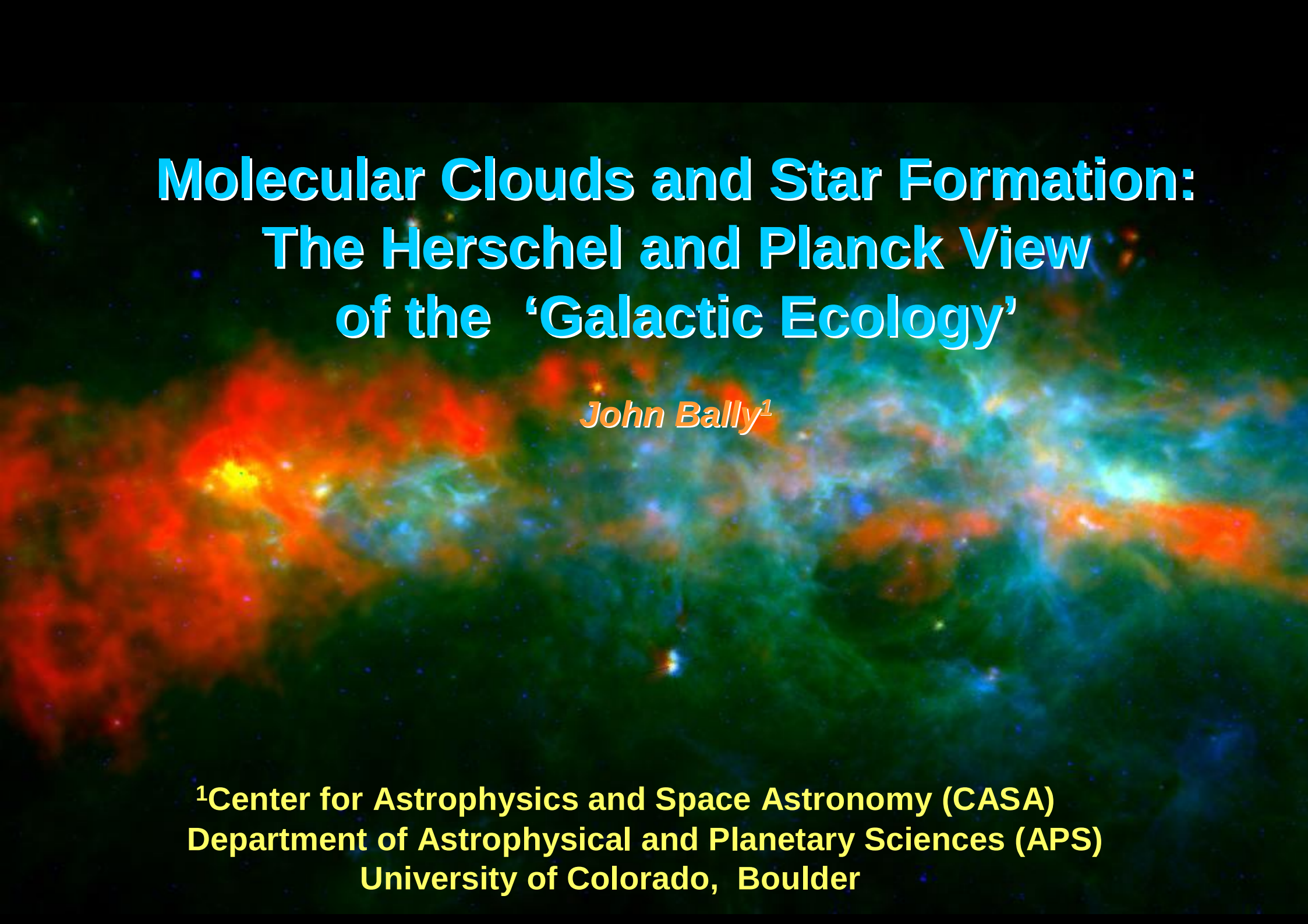
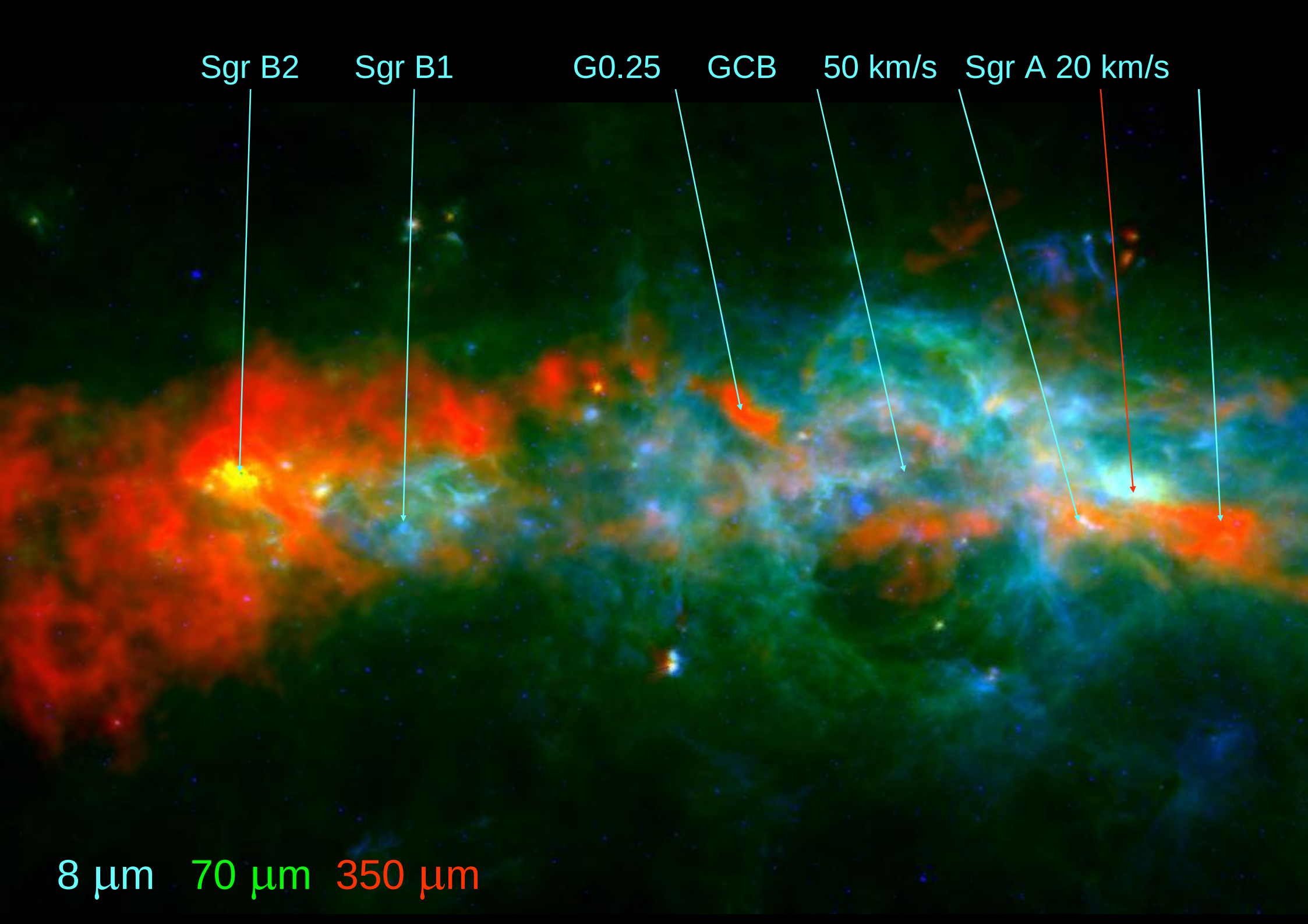


Molecular Clouds and Star Formation: The Herschel and Planck View of the 'Galactic Ecology'

John Bally[1]

[1]Center for Astrophysics and Space Astronomy (CASA)
Department of Astrophysical and Planetary Sciences (APS)
University of Colorado, Boulder


Sgr B2
Sgr B1
G0.25
GCB
50 km/s
Sgr A 20 km/s
8 μm
70 μm
350 μm

mm/ sub-mm 'Galactic Foregrounds'

… in the era of Surveys

- **Planck:**
  All-sky at 5' resolution
  30, 44, 70, 100, 143, 217, 353, 545, 857 GHz

- **Herschel:**
  Galactic Plane at 5" to 35" resolution
  70, 160, 250, 350, 500 μm (Sergio Molinari's talk.)

- **Ground-based: (V_{LSR} => distances!)**
  Galactic Plane 20" to > 60" resolution
  lines: HI, CO, NH_3, CS, N_2H^+, HCO^+, …
  (& cm continuum:
  sub-mm/mm continuum:
  Hi-GAL, BGPS, ATLAGAL, …)

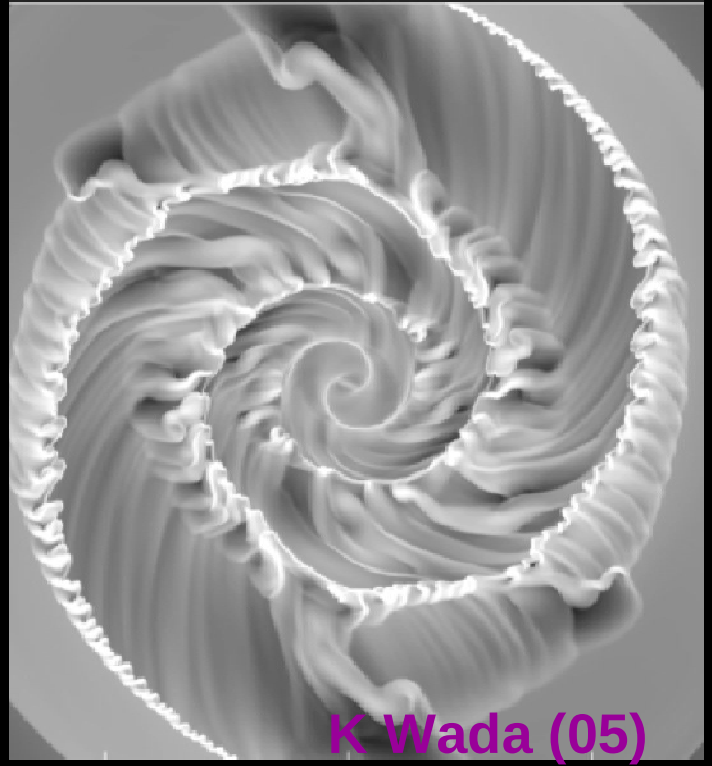
Outline

ISM <=> Star formation: the `Galactic Ecology'

- **Formation, Evolution, & Destruction of GMCs**
  - **Spiral shocks**
  - **Gravo-thermal instabilities**
  - **Parker / Magneto-rotational instabilities**
  - **Super-bubbles (massive-star feedback)**

- **Nearby stars & gas (d < 600 pc)**
  - **Nearby OB associations & super-bubbles**

- **Dust and gas in the Galactic Plane (d > 600 pc)**
  - **Spiral arms, supper-bubbles, the bar, B, …**



Galactic Ecology: 1

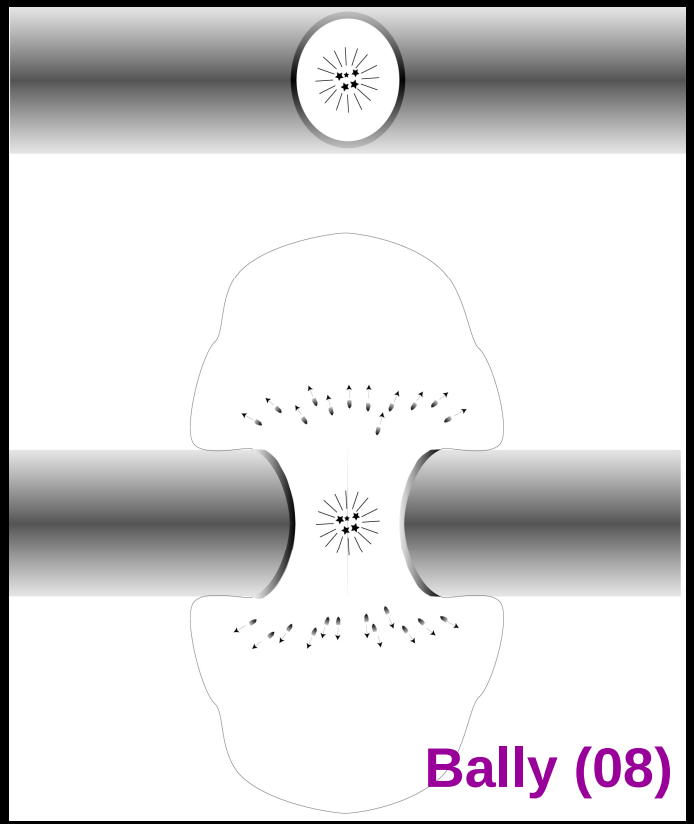
Cloud formation in Converging flows

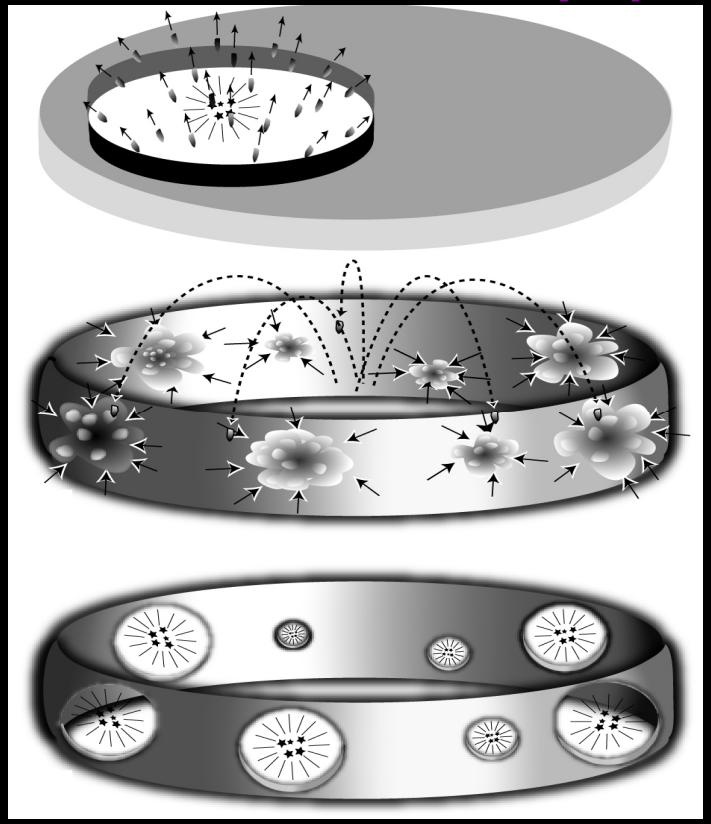
Powered by spiral arms ?
- Spiral shocks + gravity

Gravo-thermal Instability ?
- Cooling + gravity

Magnetic Instabilities ?
- Parker …
- Magneto Rotational Instability (MRI) + gravity

Super-bubbles ?
- SNe => shells + gravity





Galactic Ecology: 2

Cloud destruction: `The Feedback Ladder'

Protostellar jets / outflows - Low Mass

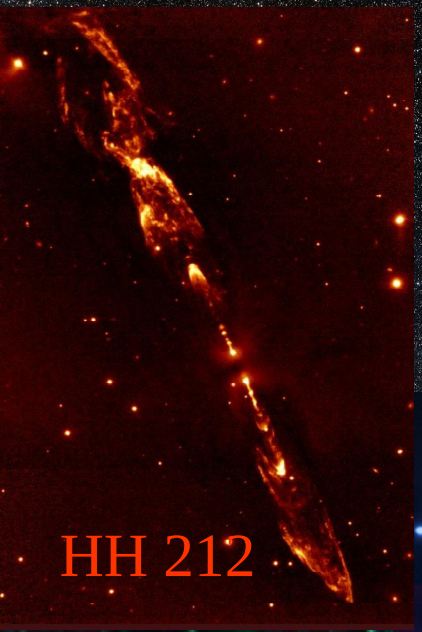
Soft UV - Moderate Mass

Ionizing UV - High Mass

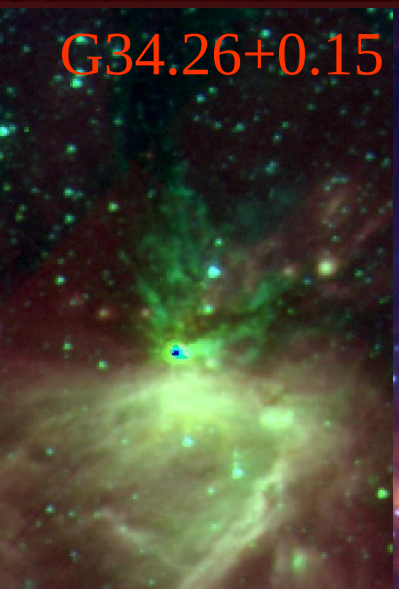
Stellar winds "

Radiation Pressure "

Supernovae "



HH 212

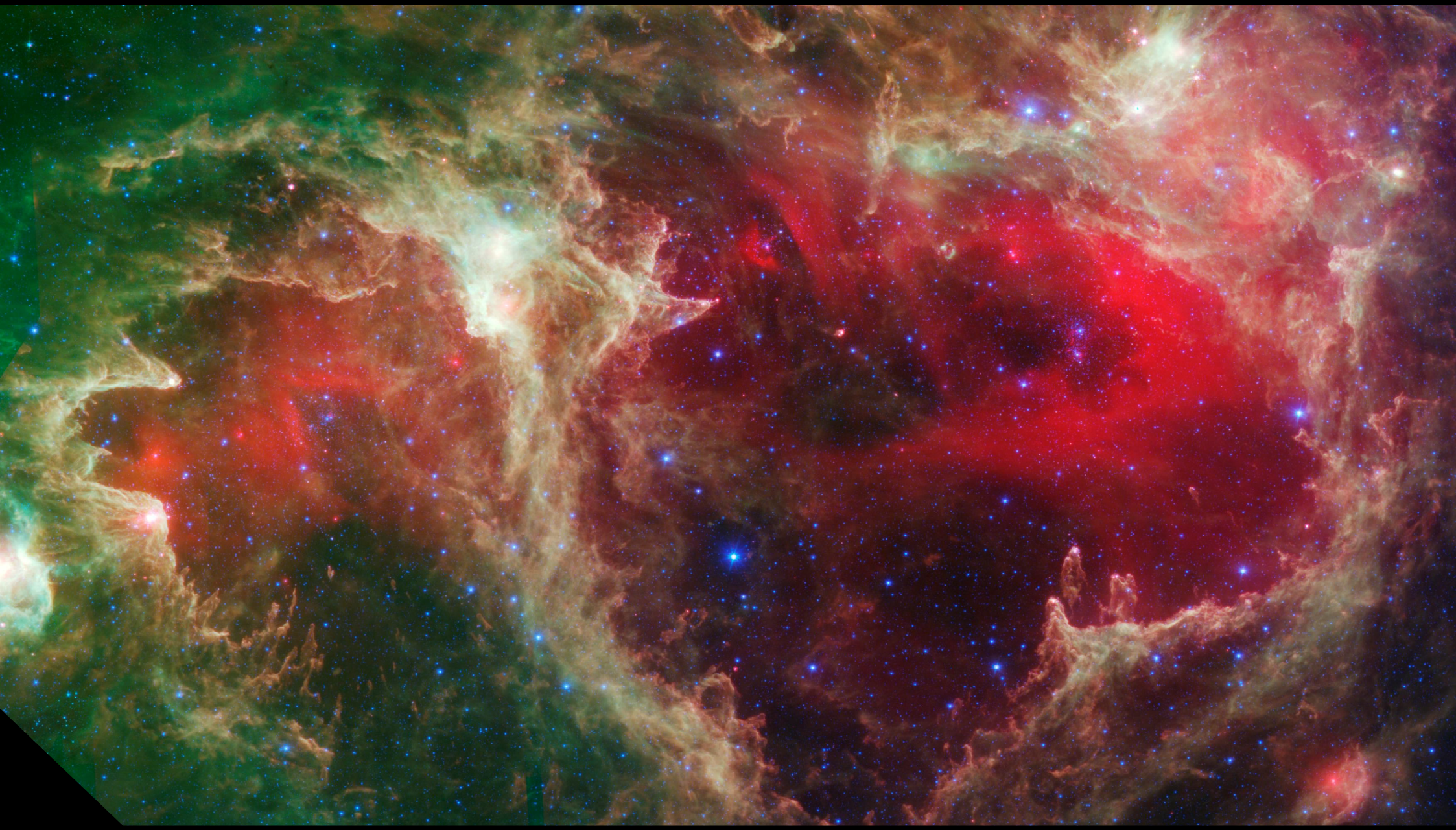


G34.26+0.15

OMC1

W4 / W3

Galactic Ecology: W5 HII region



~100 Myr Galactic Ecology Cycle

- **GMCs (t ~ 10 - 20 Myr) => HI => HII => HIM**

  Star formation efficiency (SFE) ~ 5% =>

  H-atom stays in ISM ~20 cycles => ~ 2 Gyr

  OB stars form, evolve, die in 3 - 40 Myr

  Heating / disruption:

  - FUV bubbles (10^3 K)

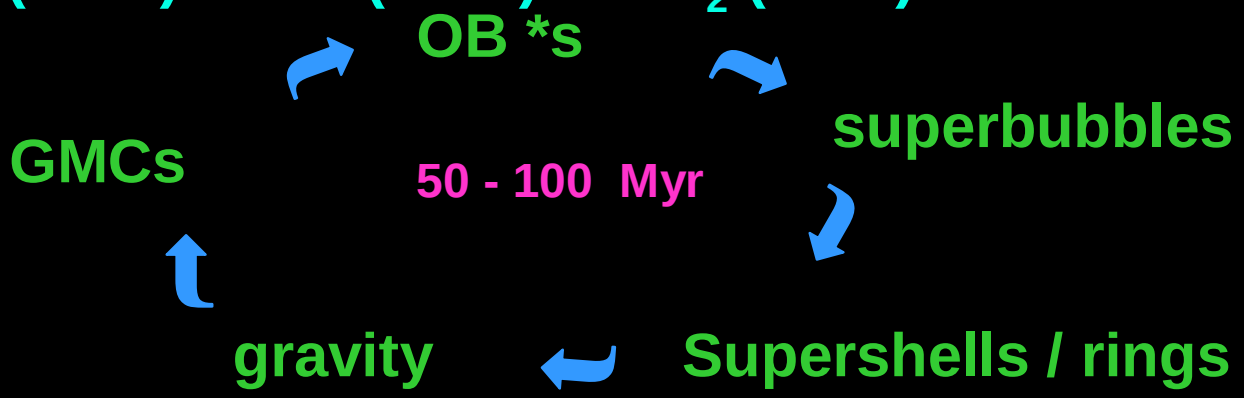
  - HII region / wind-bubbles (10^4K)

  - SNe (>10^6 K)

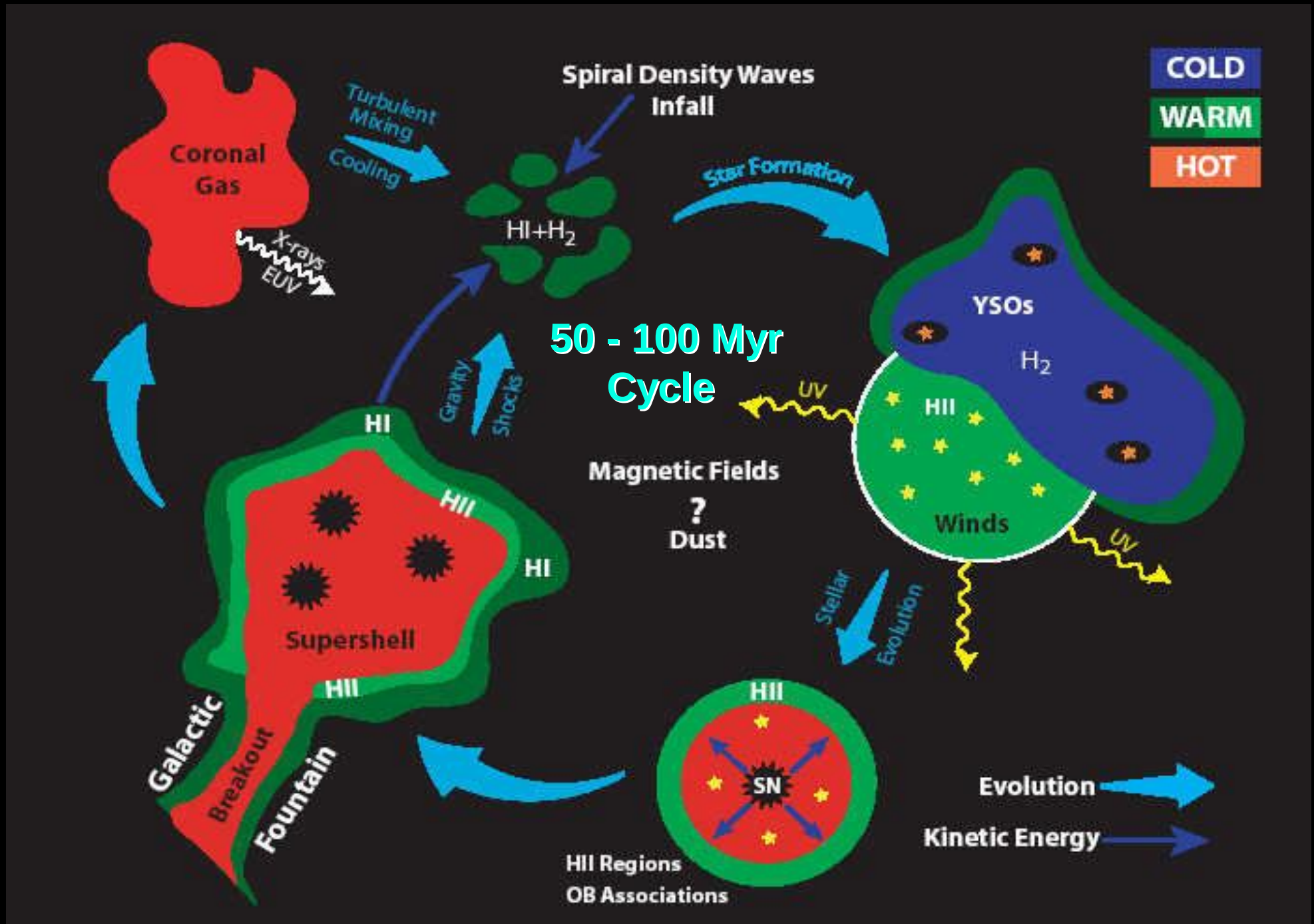
- **Super-rings => GMCs**

  Cooling / condensation:

  HIM (>10^6 K) => HII (10^4K) => HI (10^3K) => H_2 (10 K)



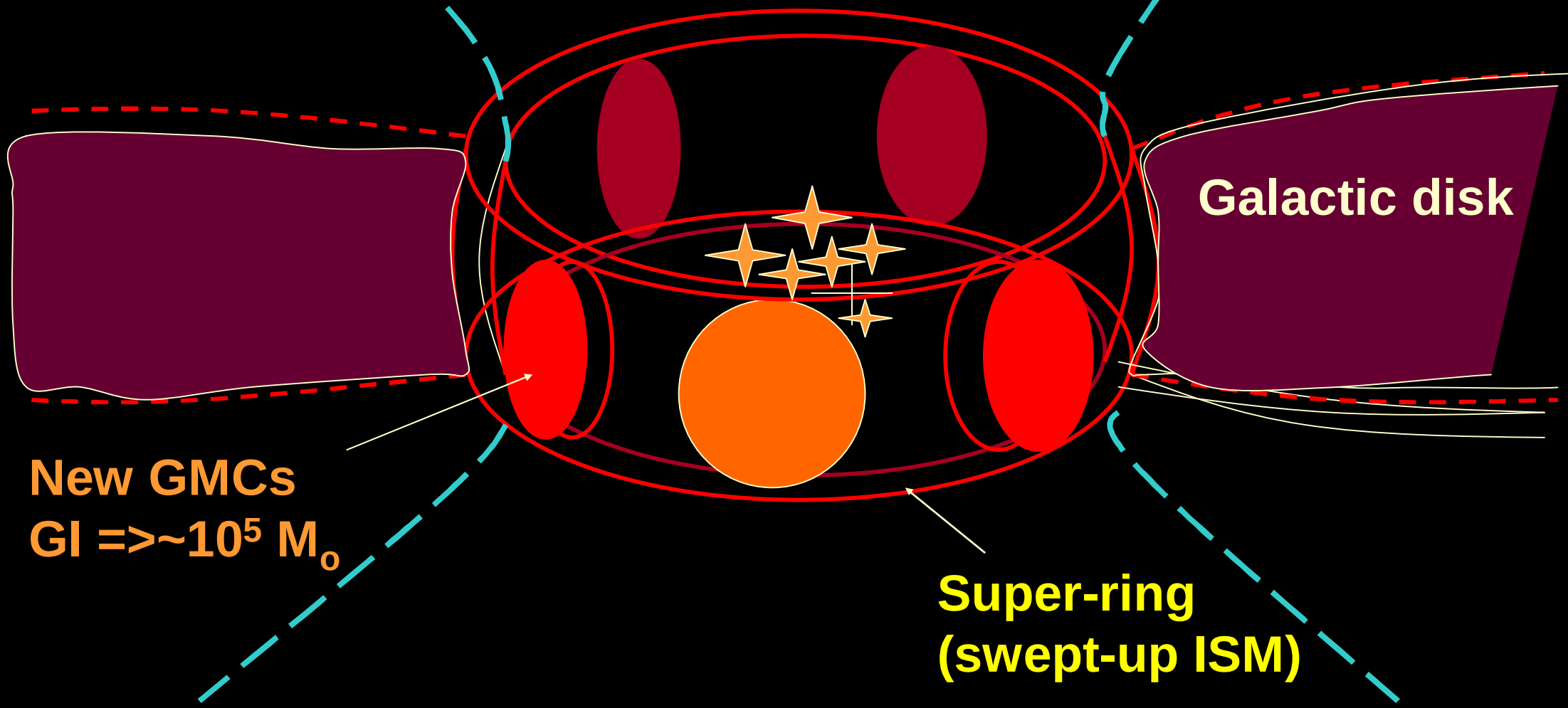
Galactic Ecology: Star Formation & the Interstellar Medium

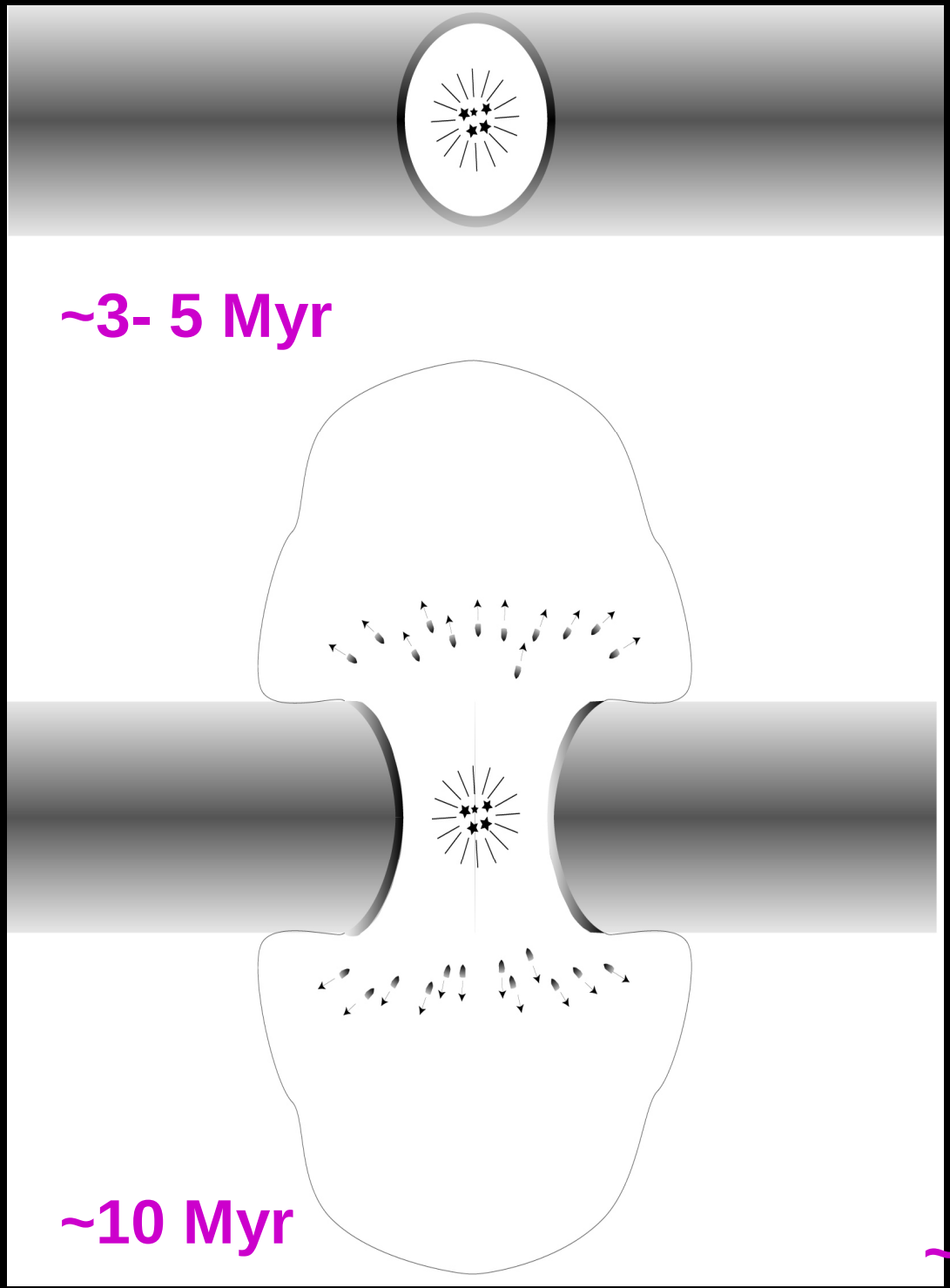


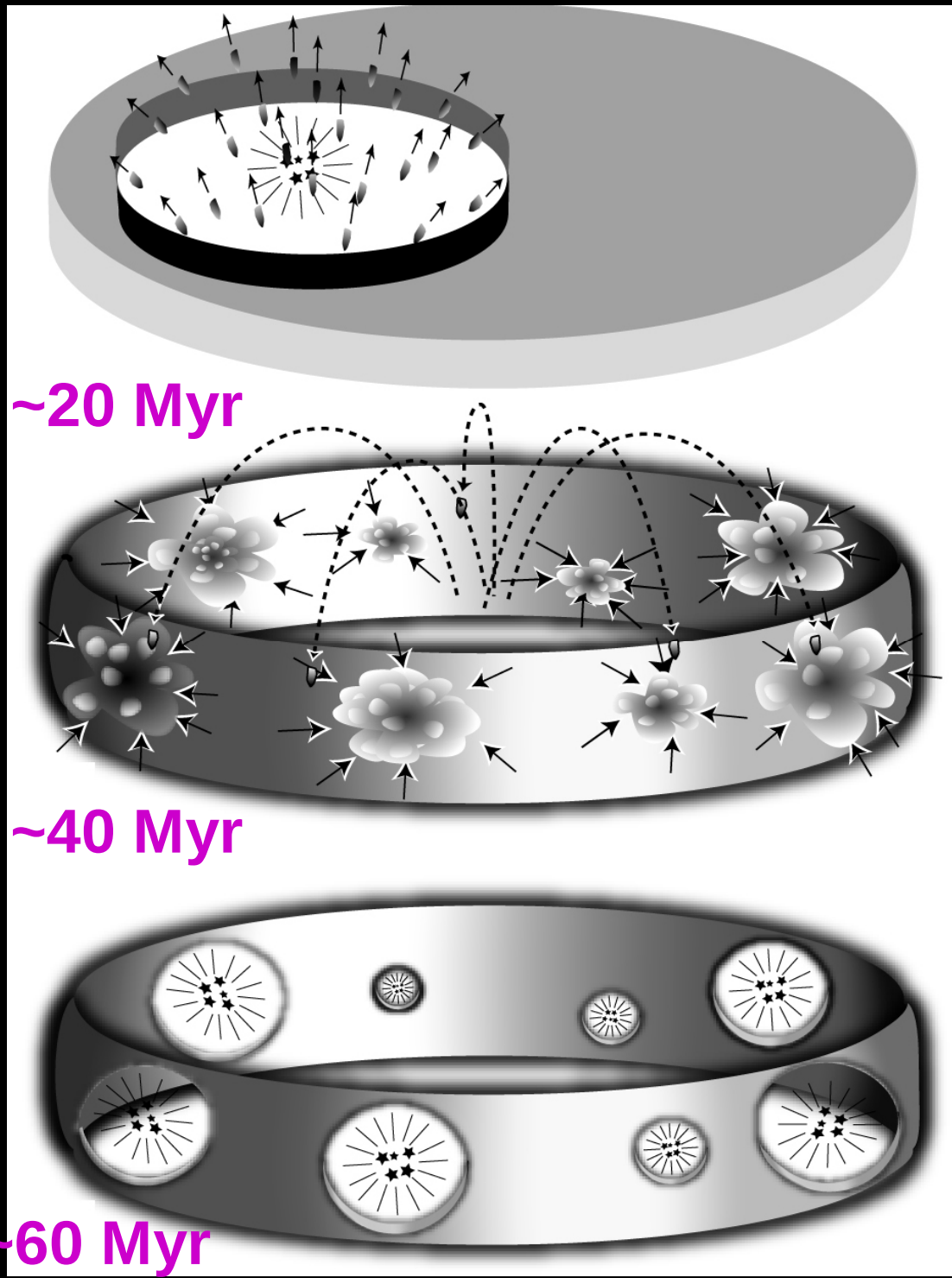
GMC Formation in swept-up Super rings

Gravitational instability of super-rings=> ~10^5 M_o clouds

(Kafatos & McCray 87; Mac Low 80s)




~3- 5 Myr
~10 Myr


~20 Myr
~40 Myr
~60 Myr

Effects on Super-ring Evolution

- Non-coeval star formation (Saken & Shull 94)
- Poisoning
- Blow-Out (r > z) (MacLow & Mc Cray 88, 89)
- Shear (Galactic differential rotation) (Olano 82; Poppel 96)
- B fields (Ferriere er al. 1992; Tomisaka 90)
- Clumps & structure in ISM
- Spiral Density Waves (Wada 2005)
- Gravitational Fragmentation (Kafatos & McCray 87)

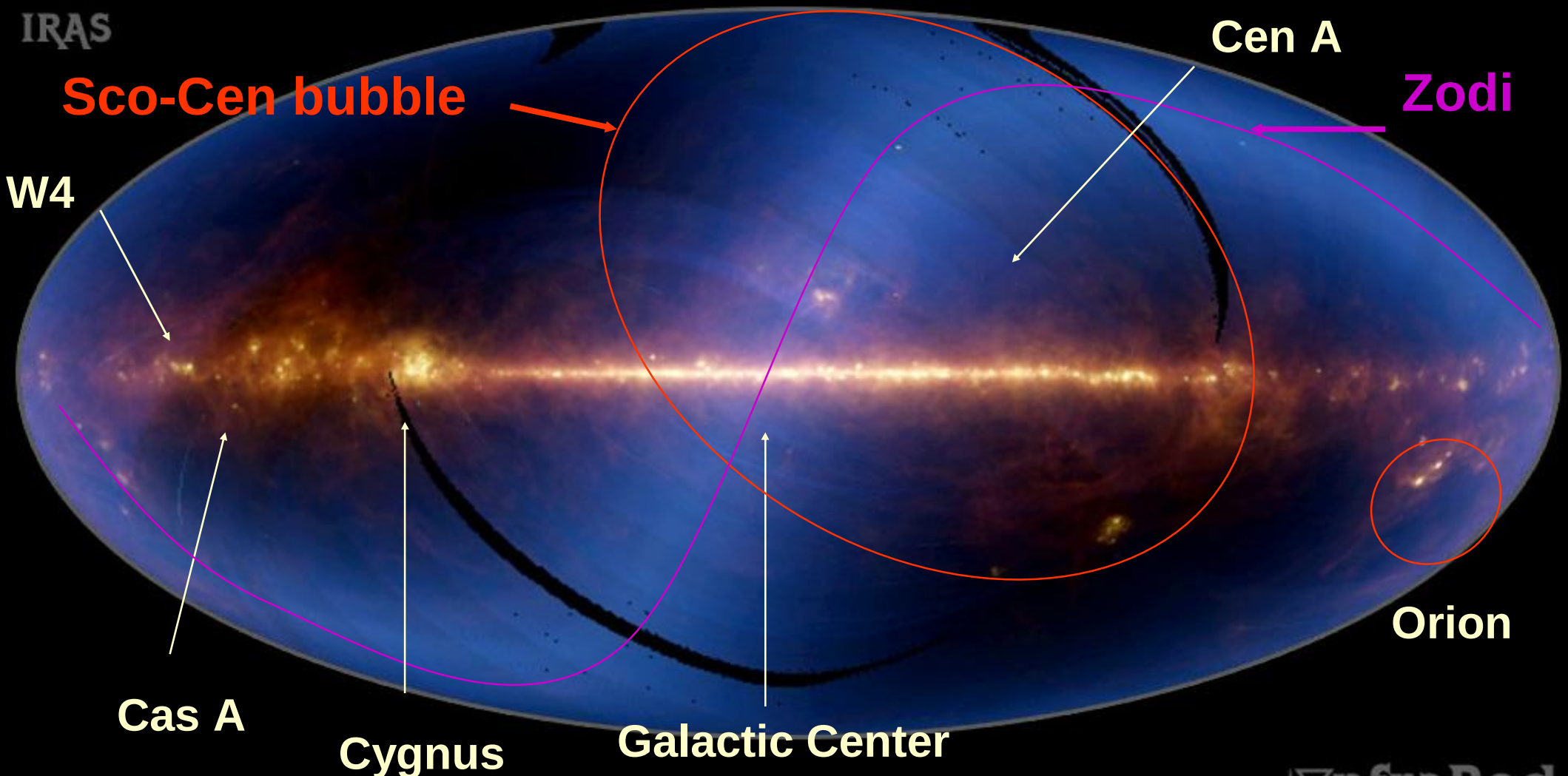
Nearby Star Formation: D < 600 pc; <100 Myr

- **Stars:**
  - **OB Associations (< 40 Myr):**
    Sco-Cen, Per OB2, Orion, (Lac OB1)
  - **Fossil OB associations**
    Cas-Tau (α Persi cluster) (>40 Myr)
  - **Gould's Belt stars**
- **Gas & Dust:**
  - **Linblad's expanding 21 cm HI ring**
  - **HI (Lockman) hole [*l* ~ 150°, *b* ~ +/- 45°]**
  - **COBE hole "**
  - **HI & Hα super-bubbles**
  - **Dame et al. CO survey radial velocity**

d < 500 pc: Only place where we know X, V in 3D

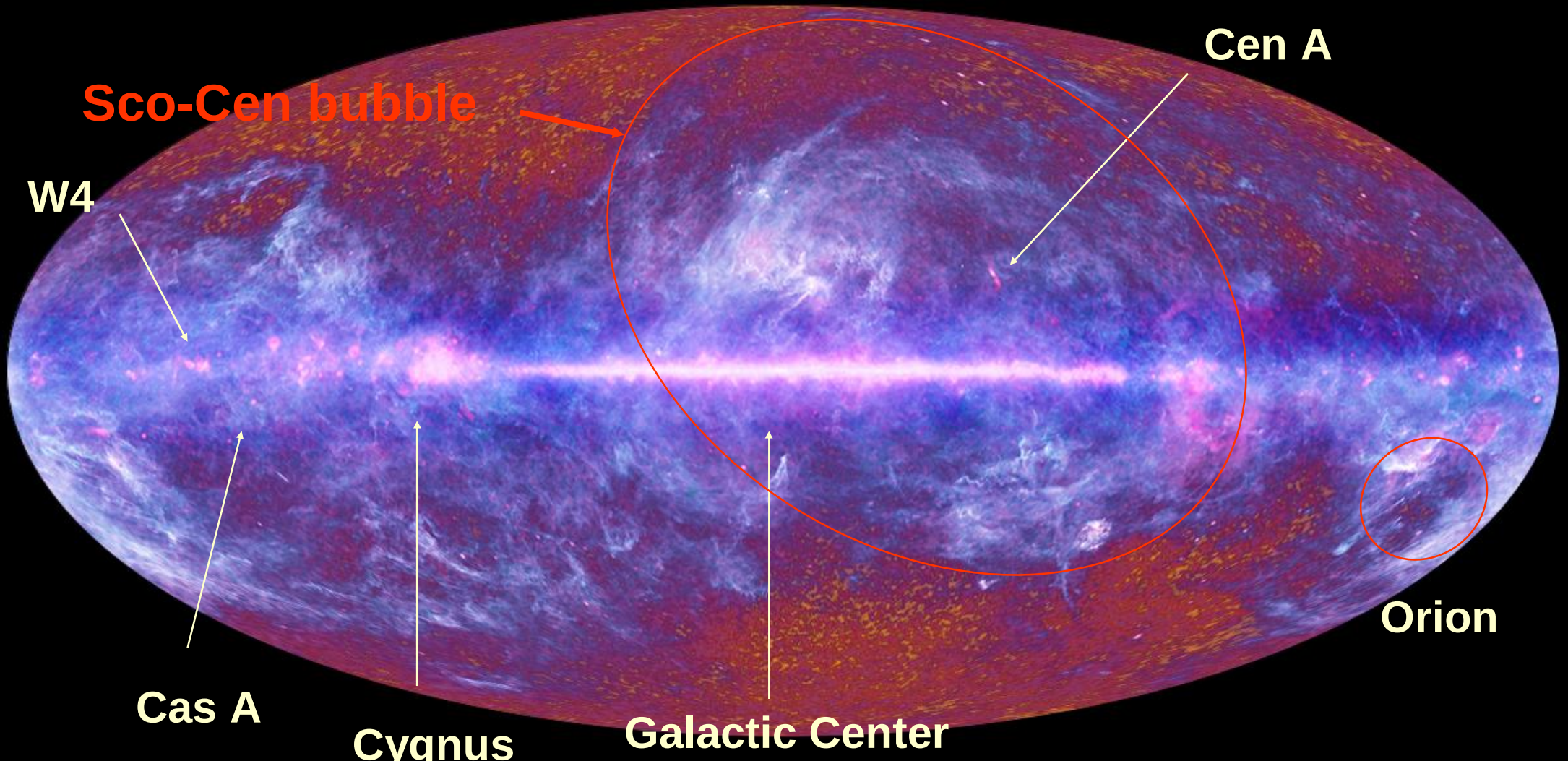
Milky Way: MIR 12 60 100 μm

InfraRed Sky
IRAS



InfraRed Legacy

Milky Way: Planck

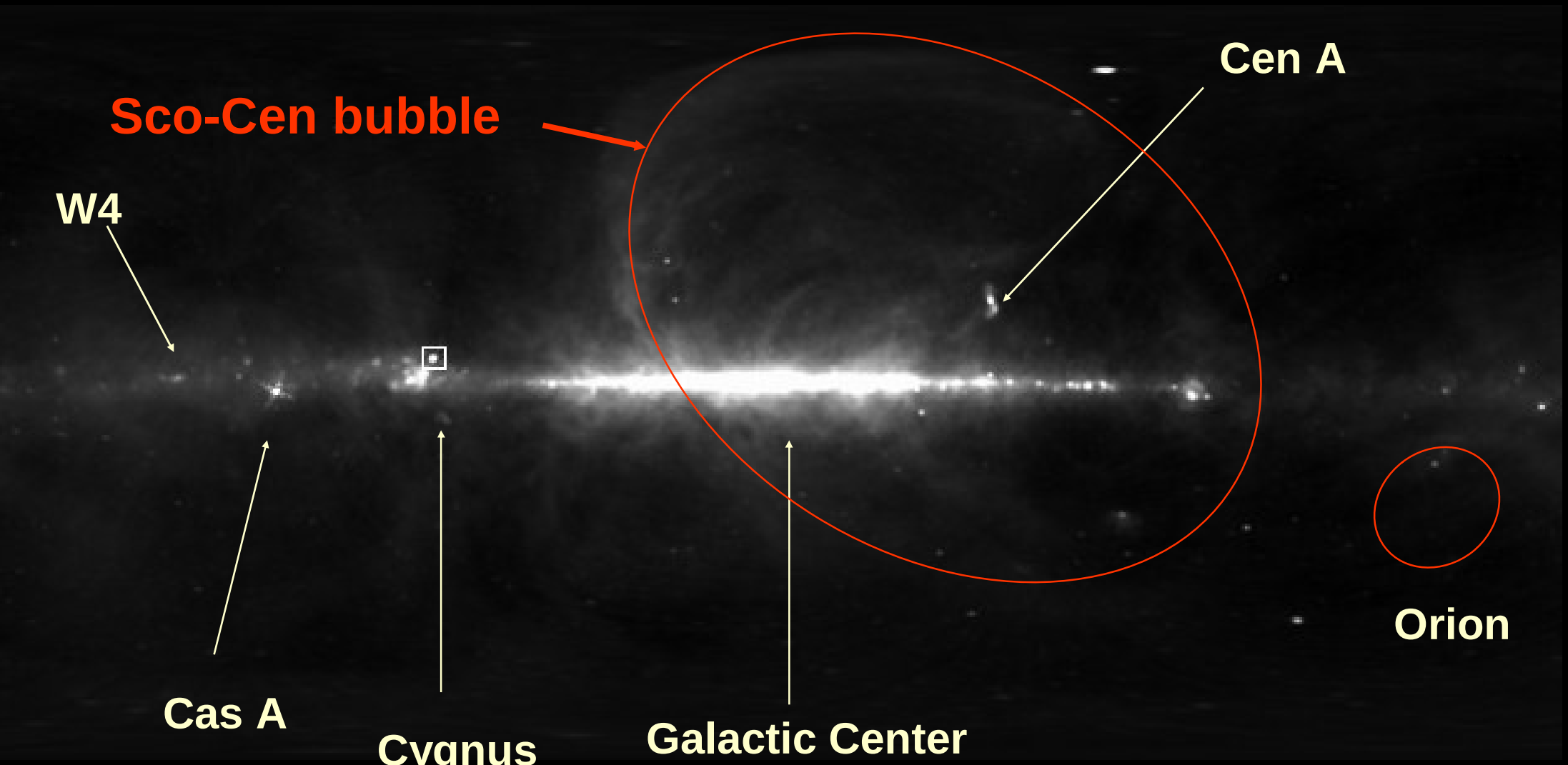


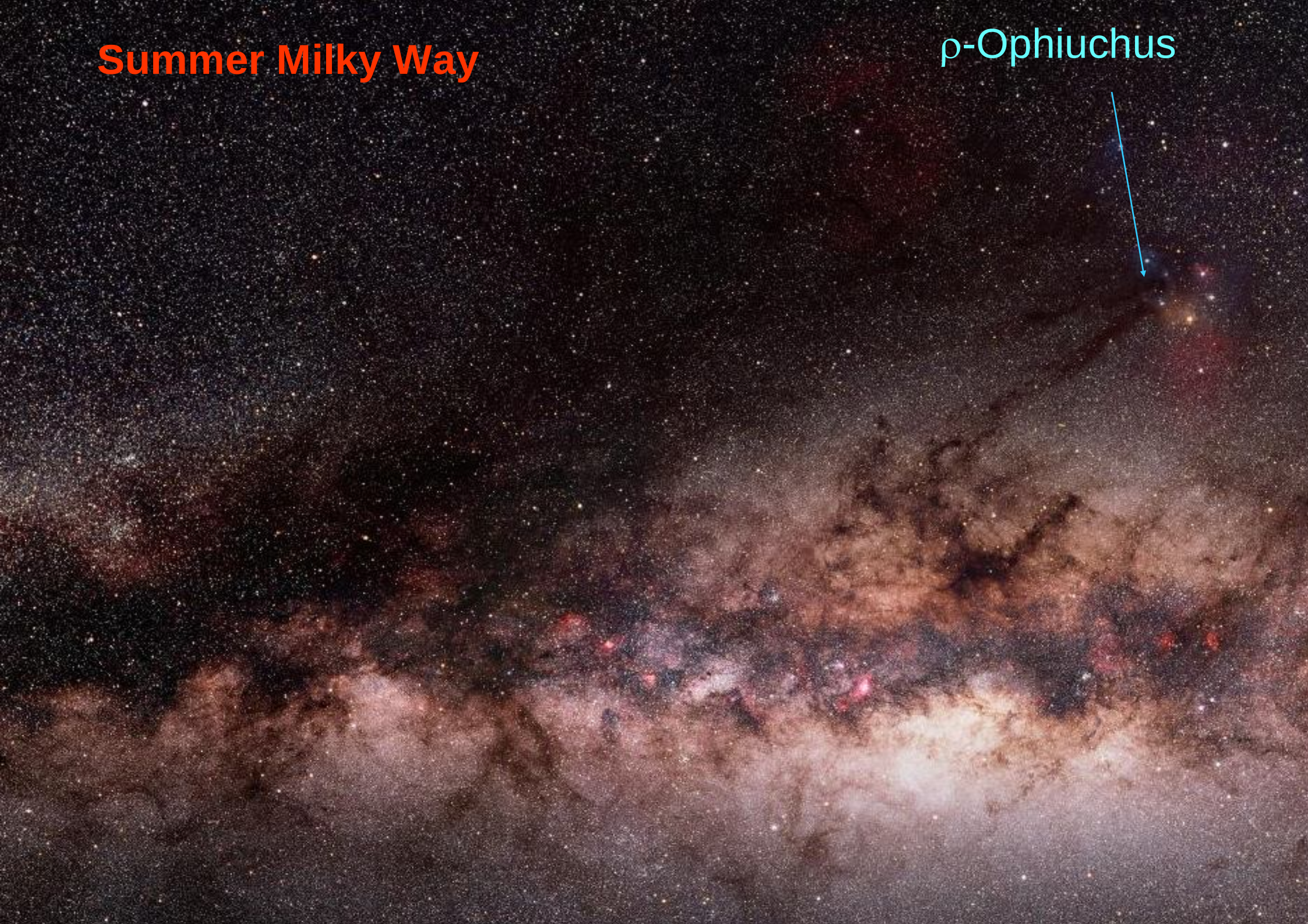
e Planck one-year all-sky survey

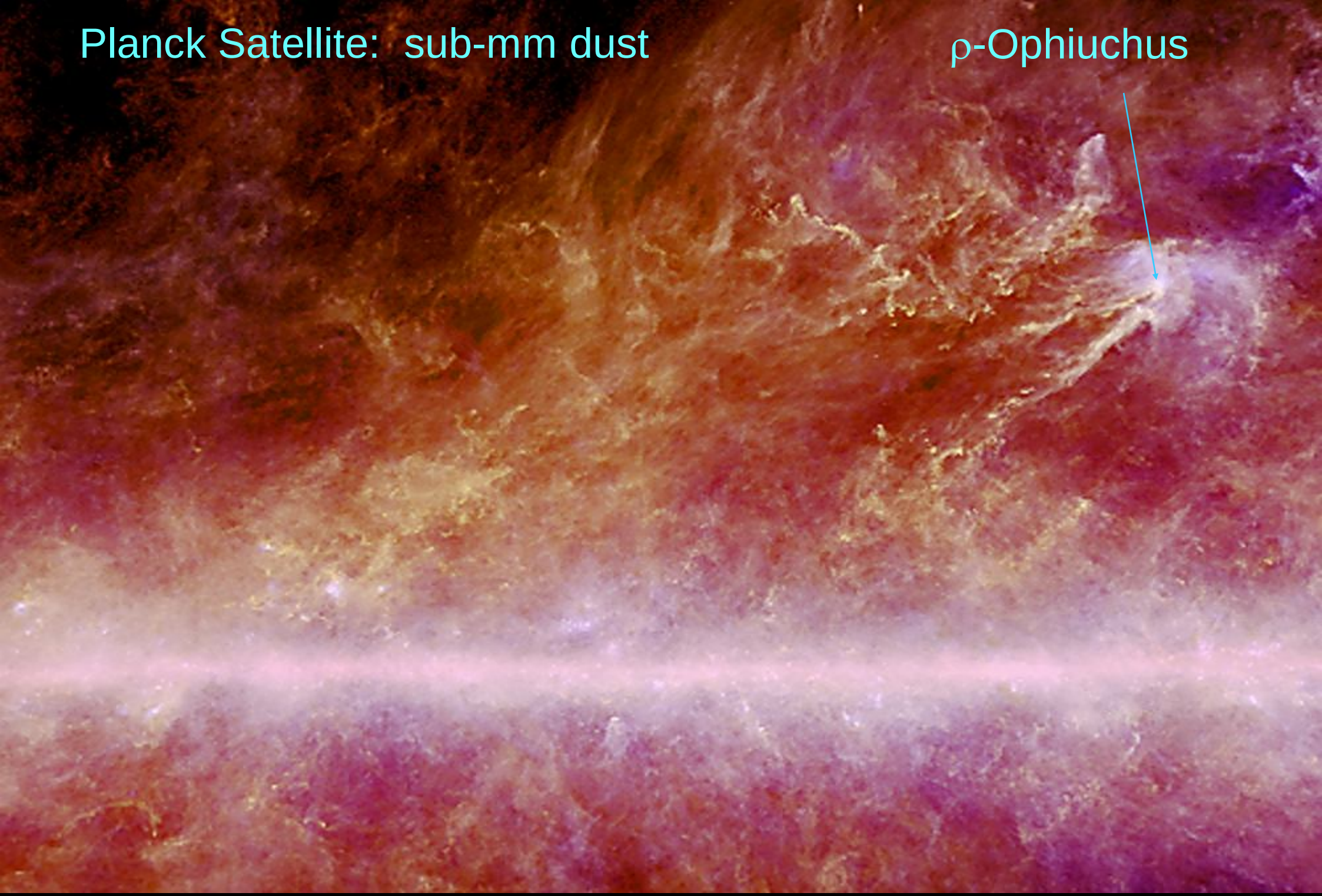
esa

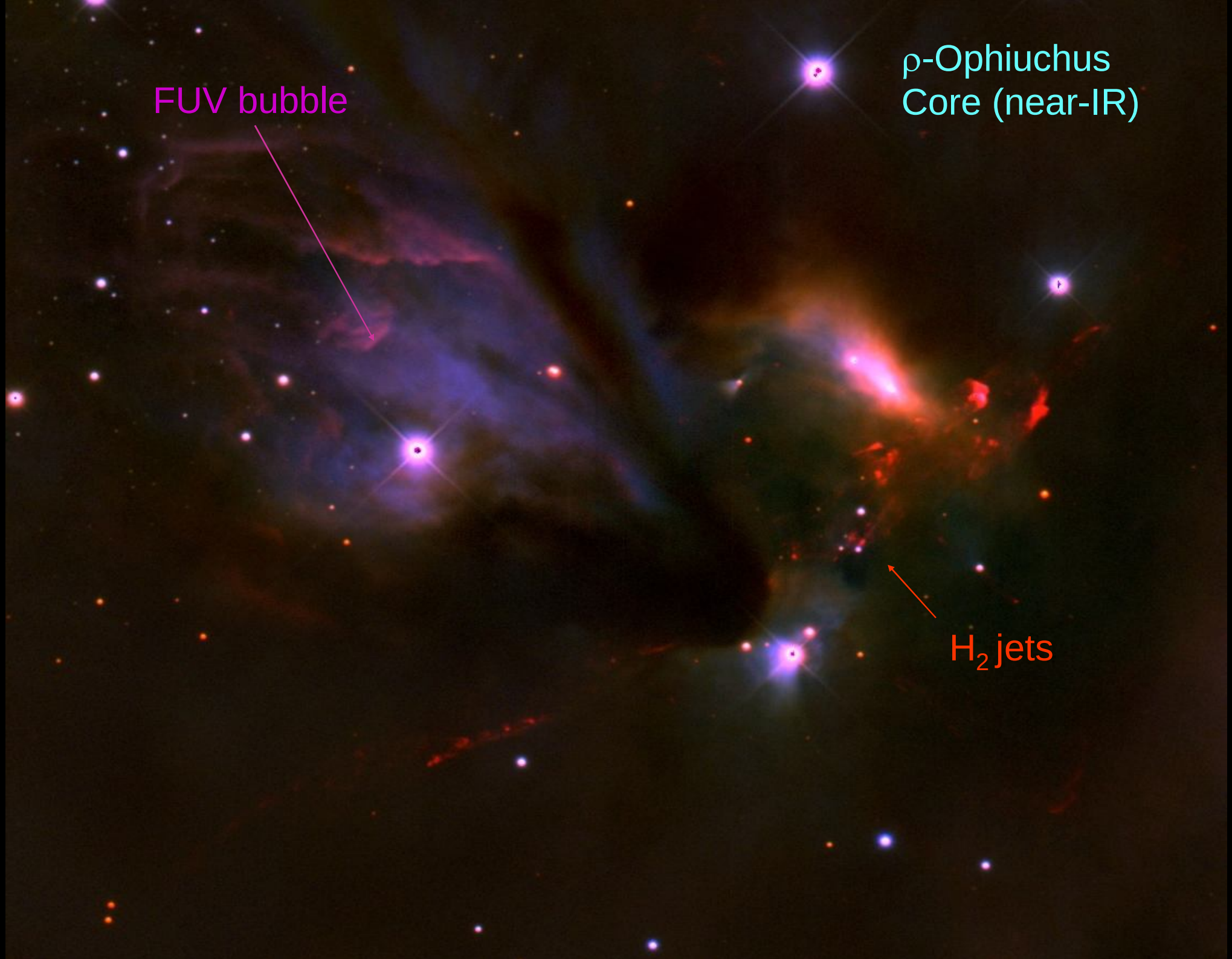
(c) ESA, HFI and LFI consortia, Jul

Milky Way @ 408 MHz

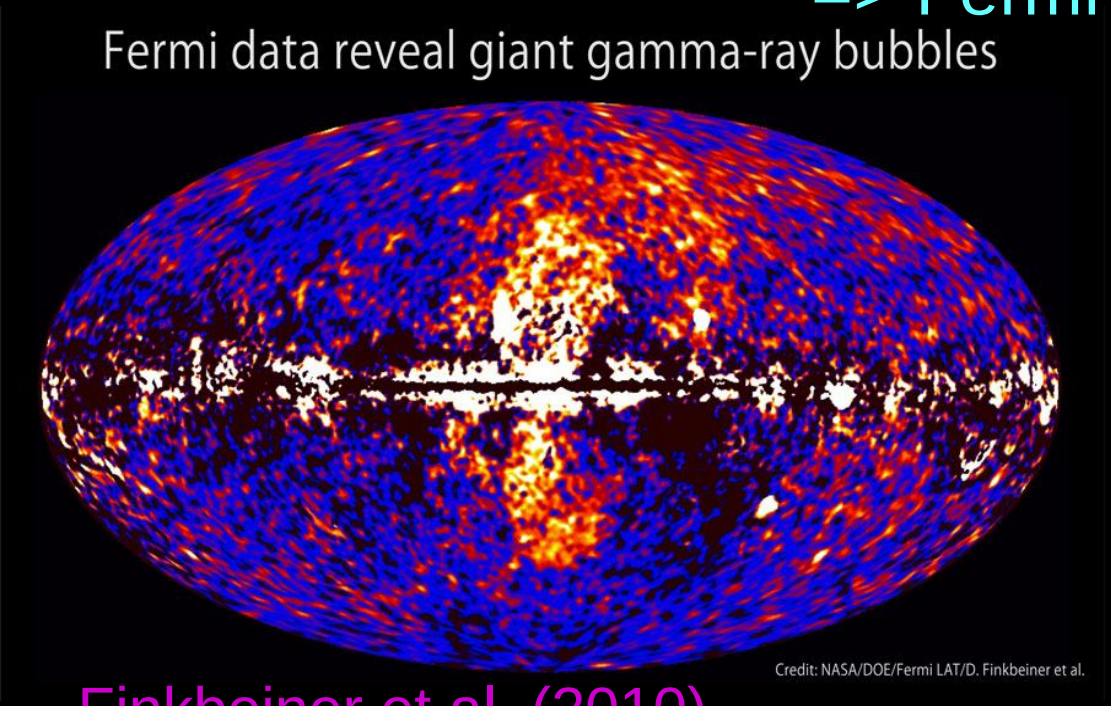



Summer Milky Way
ρ-Ophiuchus

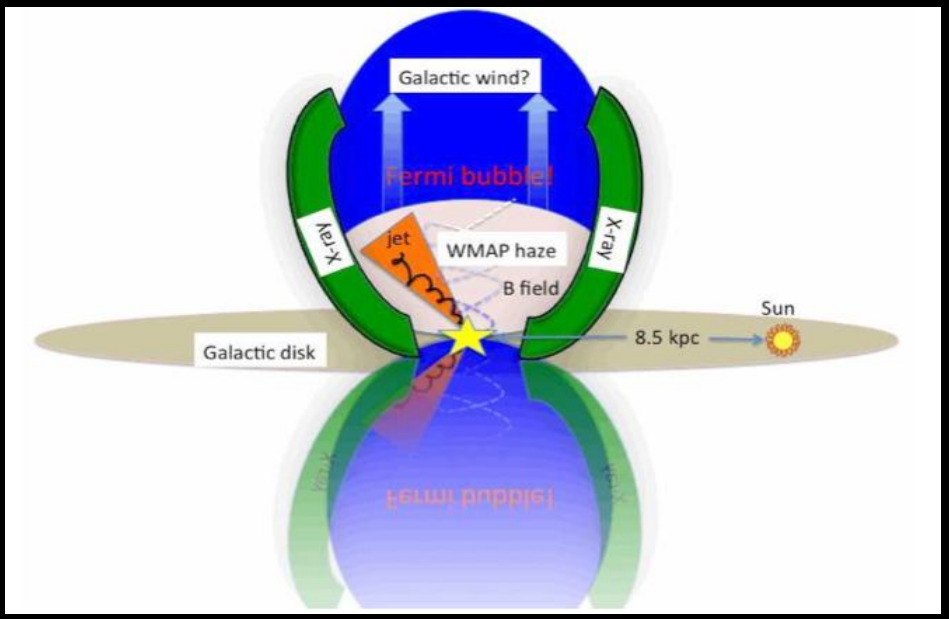

Planck Satellite: sub-mm dust
ρ-Ophiuchus

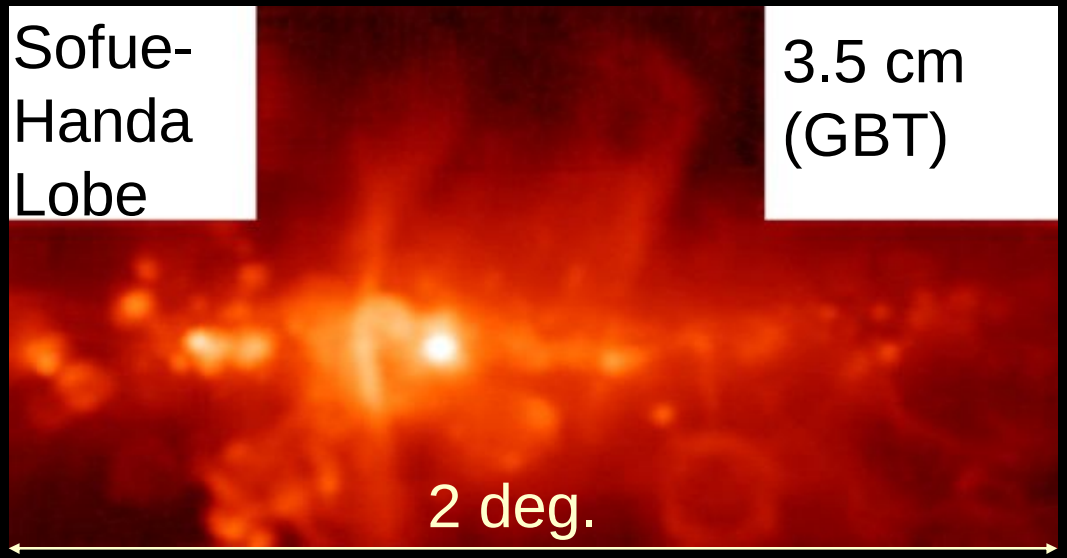

FUV bubble
ρ-Ophiuchus
Core (near-IR)
H_2 jets

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



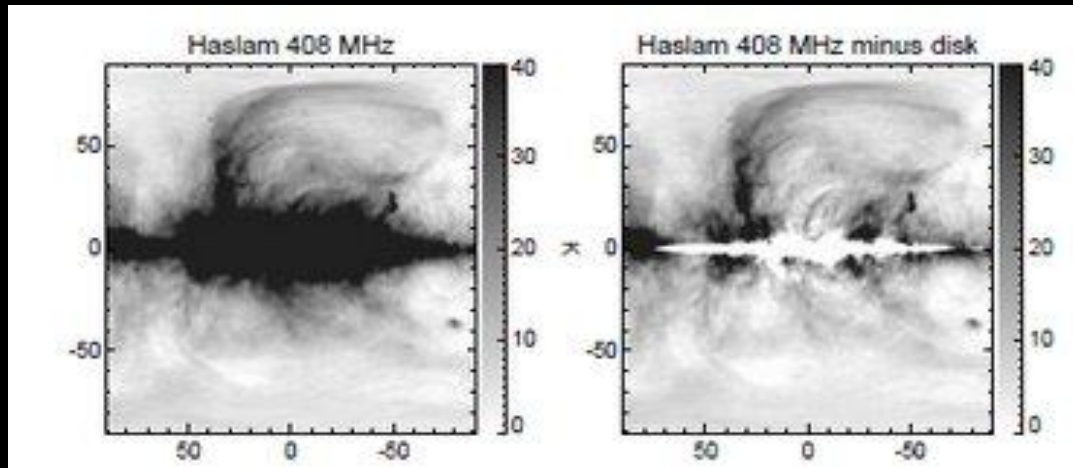
Finkbeiner et al. (2010)



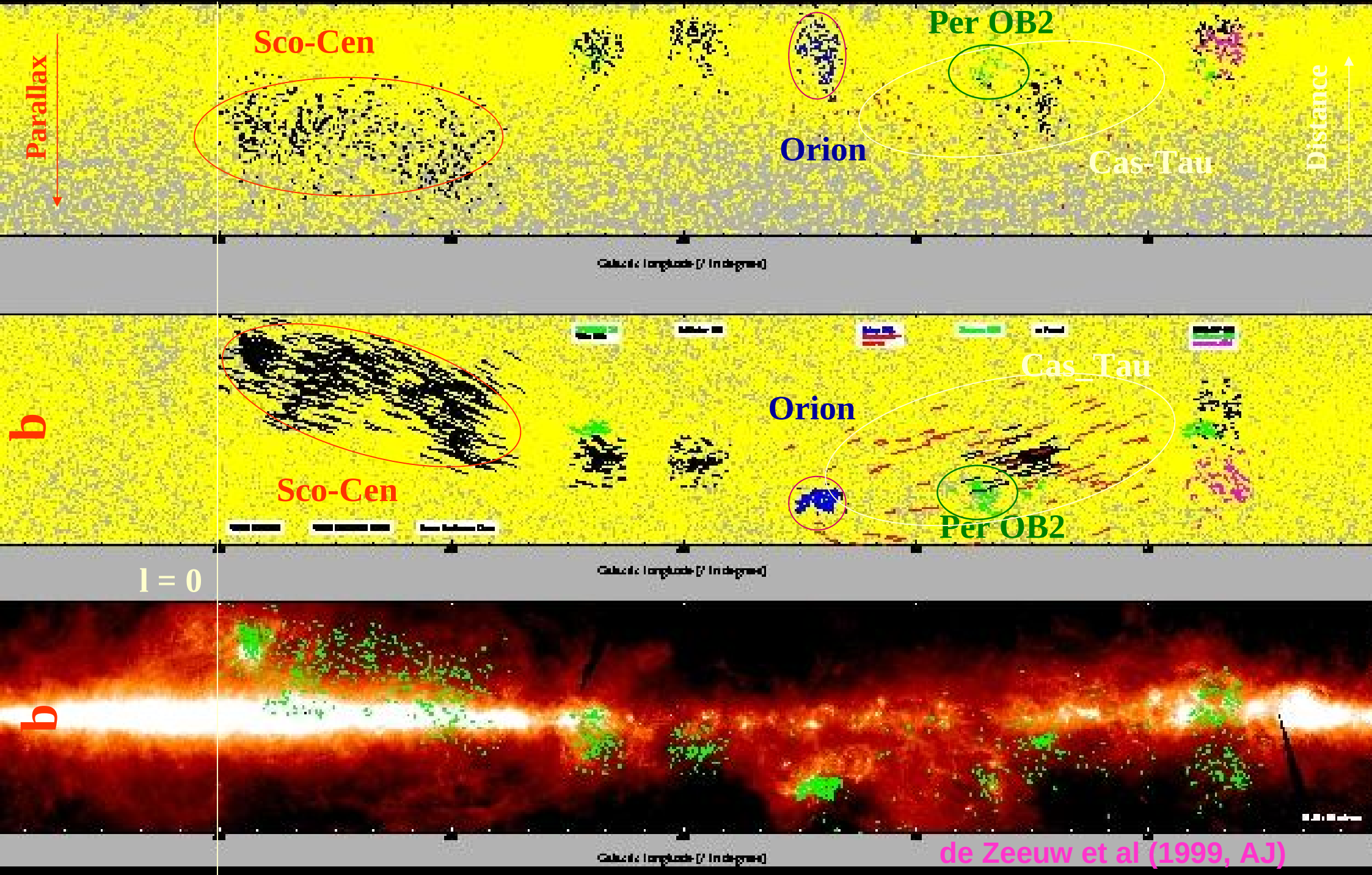


Law et al. (2008)

… or Sco-Cen superbubble
150 pc from Sun?



The Gould's Belt: O, B, & A stars, D < 500 pc

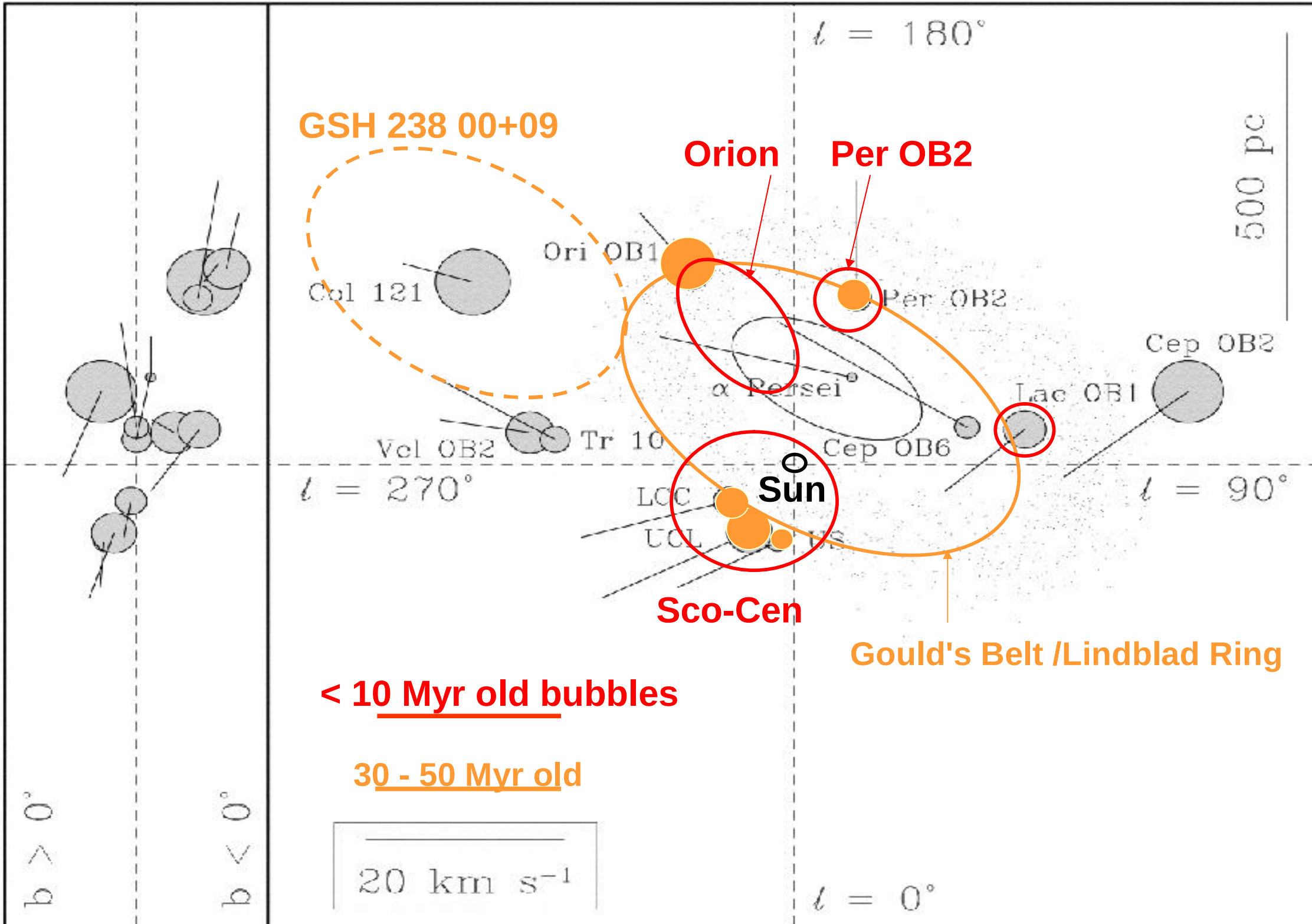


de Zeeuw et al (1999, AJ)

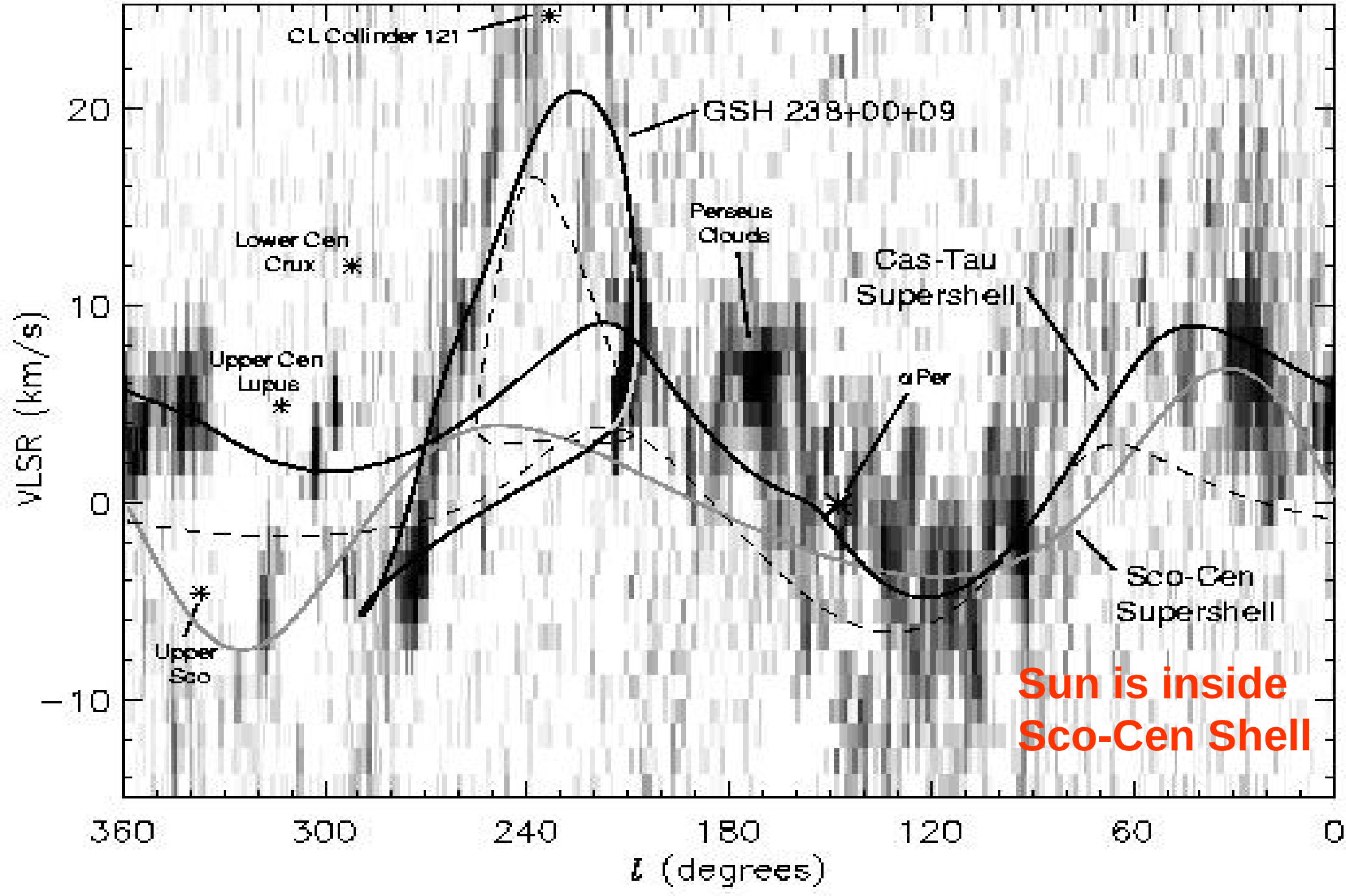
Nearby OB Associations:

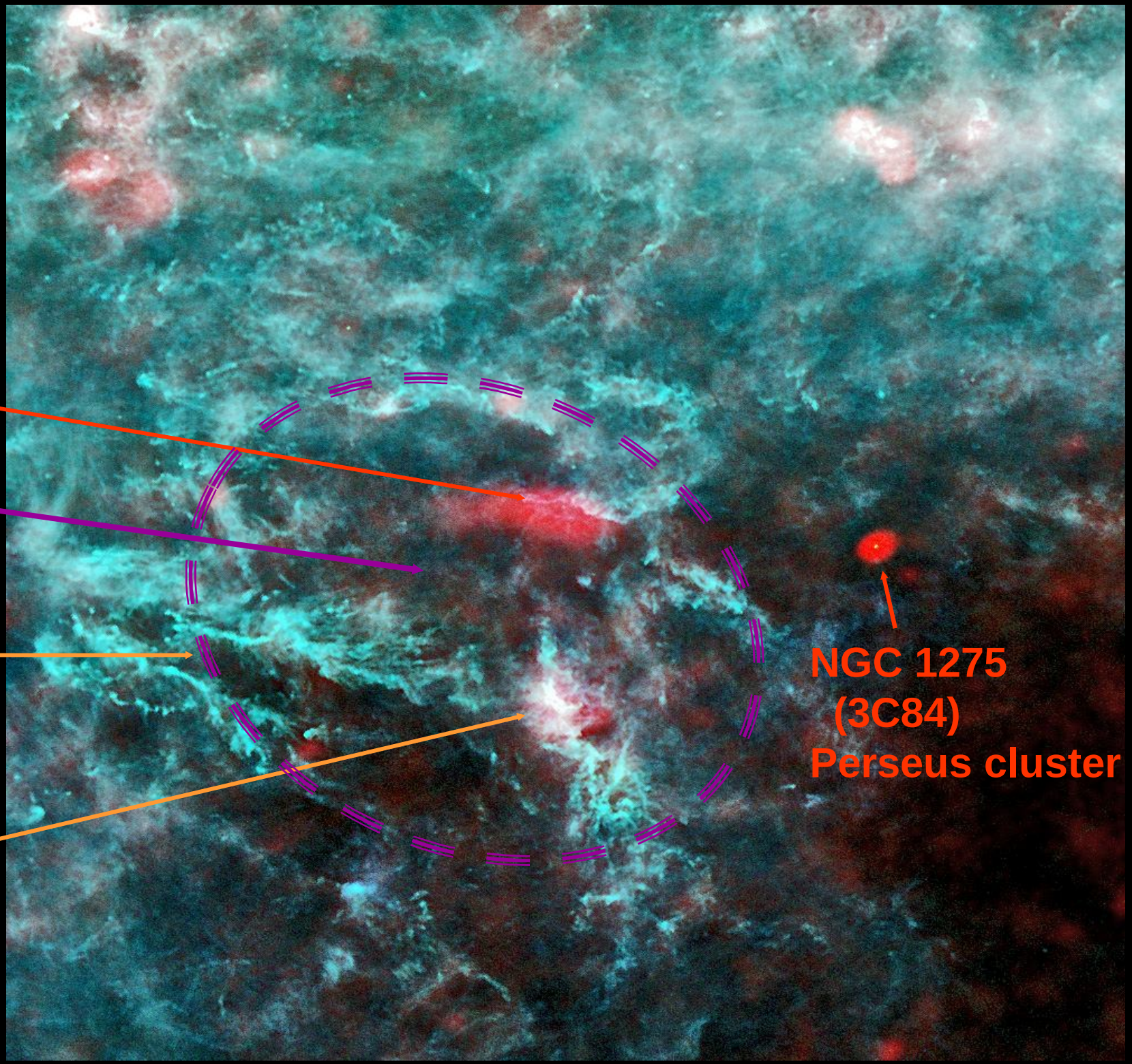
d < 600 pc, age < 15 Myr:	D(pc)	Age(Myr)
Scorpius-Centaurus:		
Lower Centaurus-Crux (LCC)	150	4 - 6
Upper Centaurus-Lupus (UCL)	180	6 - 8
Upper-Scorpius (US)	125	3 - 5
Per OB2	300	3 - 7
Orion 1a (NW of Belt)	350	12 - 15
1b (Belt)	380	4 - 8
1c (Sword + σ Ori)	390	2 - 6
1d (M42 + NGC2024)	410	< 2
Lac OB1	400	~ 6

d < 600 pc, age > 15 Myr:		
Cas-Tau (α-Persi)	180	50 - 100


GSH 238 00+09
Orion
Per OB2
Ori OB1
Col 121
Per OB2
Cep OB2
α Persei
Lac OB1
Vel OB2
Tr 10
Cep OB6
Sun
LCC
UCL
Sco-Cen
Gould's Belt /Lindblad Ring
< 10 Myr old bubbles
30 - 50 Myr old
20 km s⁻¹
500 pc
l = 180°
l = 270°
l = 90°
l = 0°
b > 0°
b < 0°

High-Latitude CO: An expanding Ring centered on α Per!

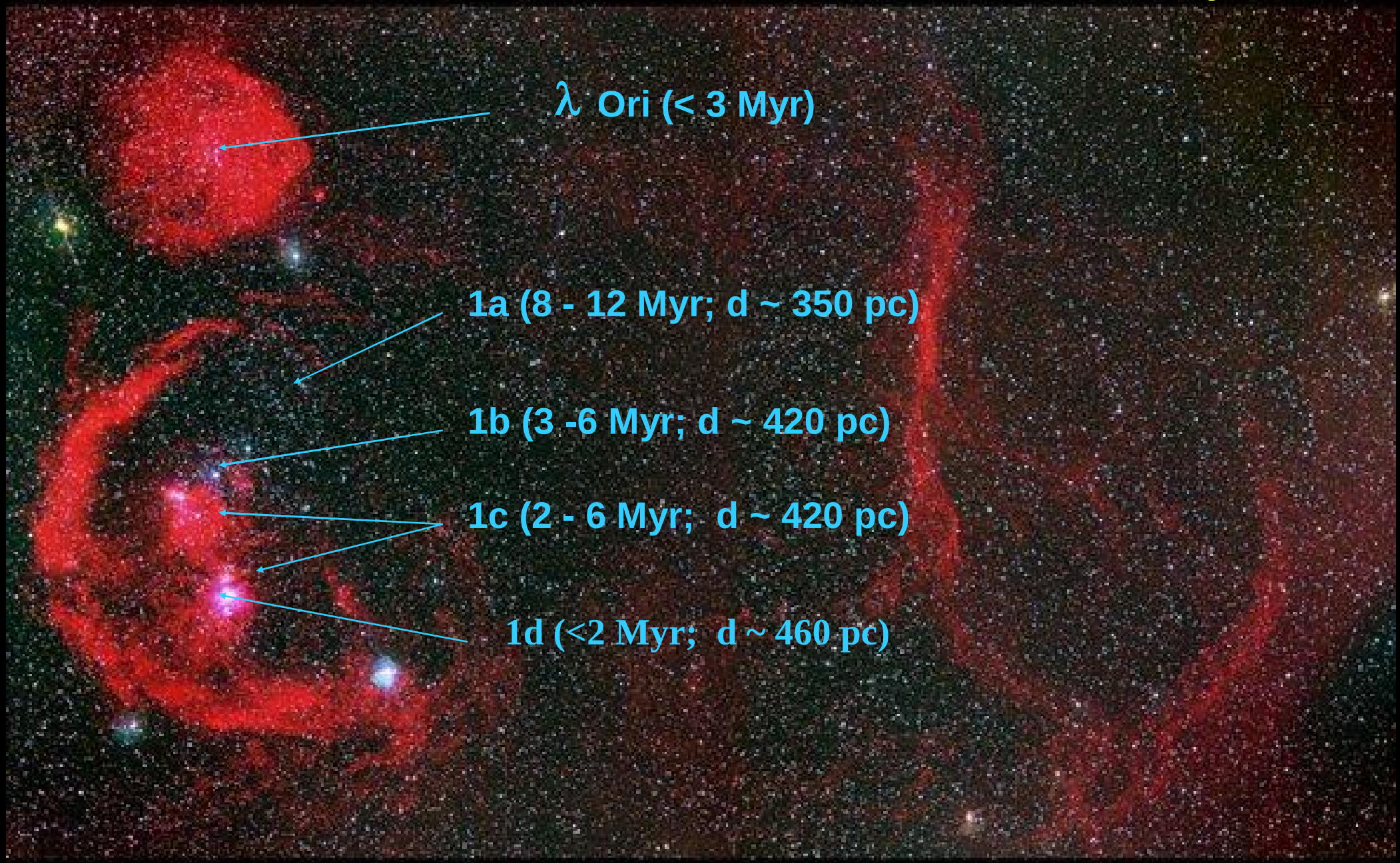



Perseus OB2
+ Taurus
California Nebula
Per OB2
d ~ 300 pc
Taurus clouds
d ~ 100-170 pc
Perseus Clouds
(GMC)
d ~ 220-300 pc
NGC 1275
(3C84)
Perseus cluster

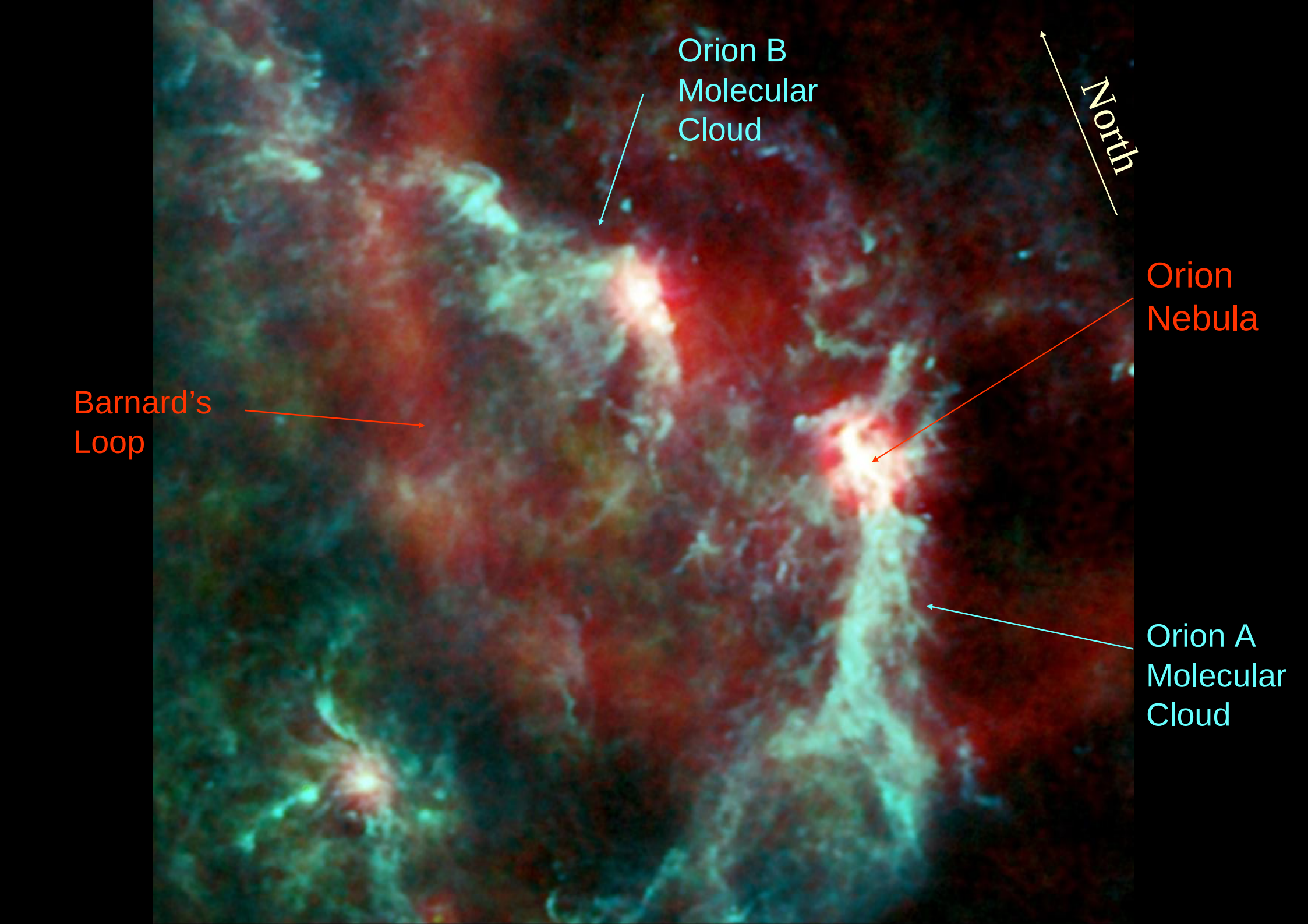
The Orion Star Forming Complex

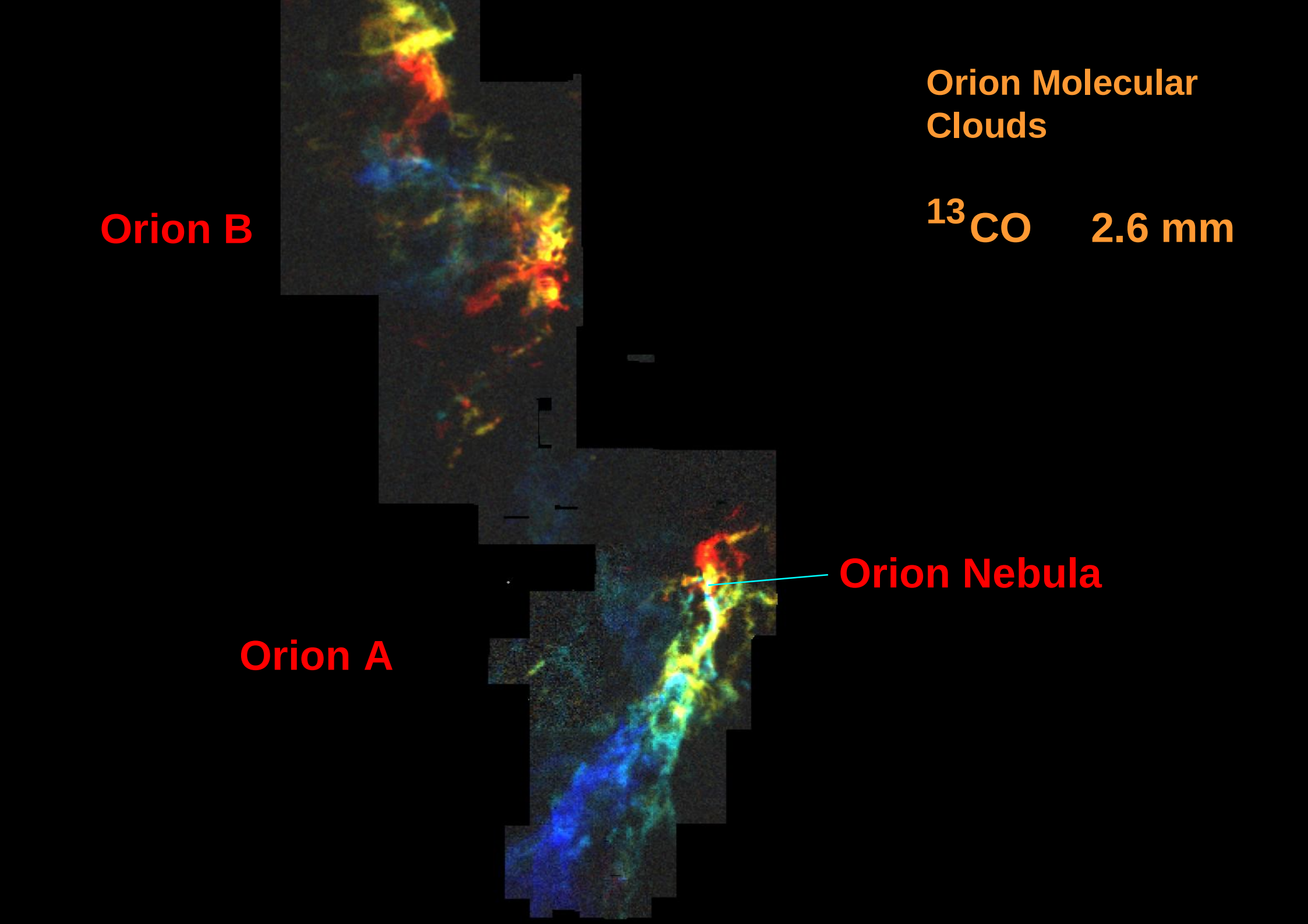
The Orion/Eridanus Bubble (Ha): d=180 to 500pc; l > 300 pc

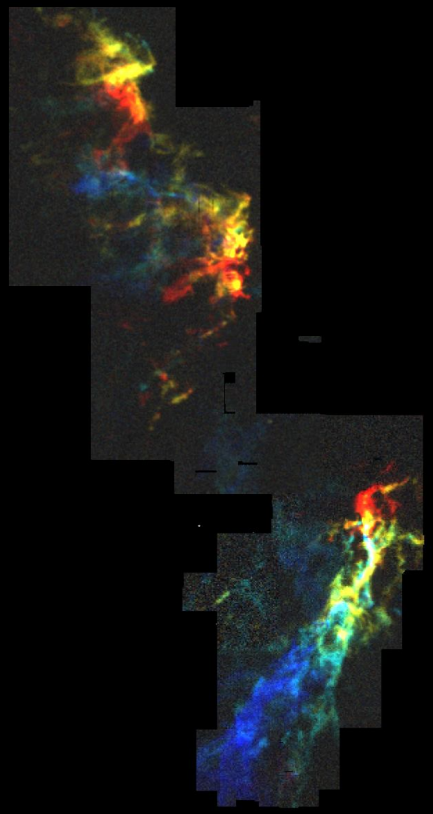
Orion OB1 Association: ~40 > 8 M stars: ~20 SN in 10 Myr

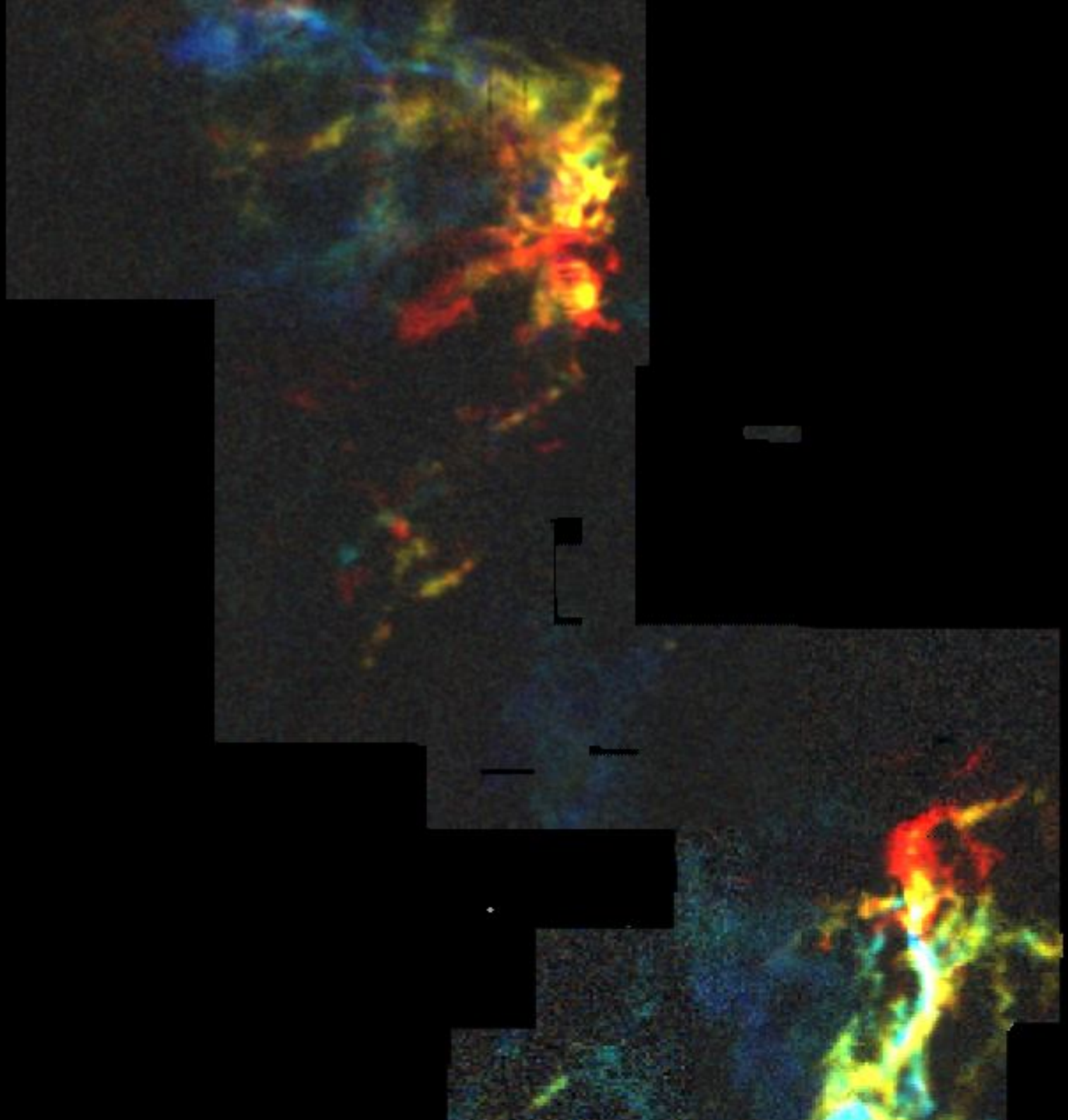


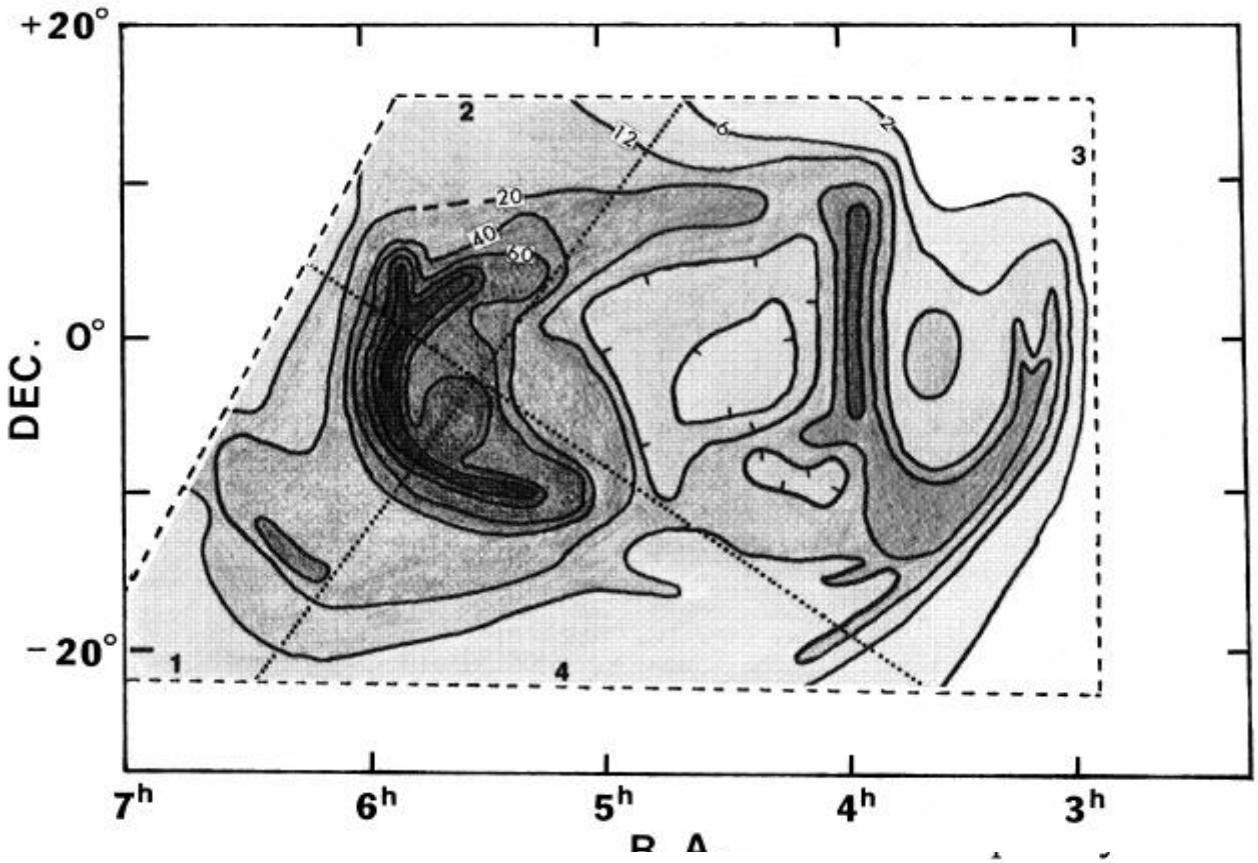
Infrared view of winter sky (10 - 120 µm)

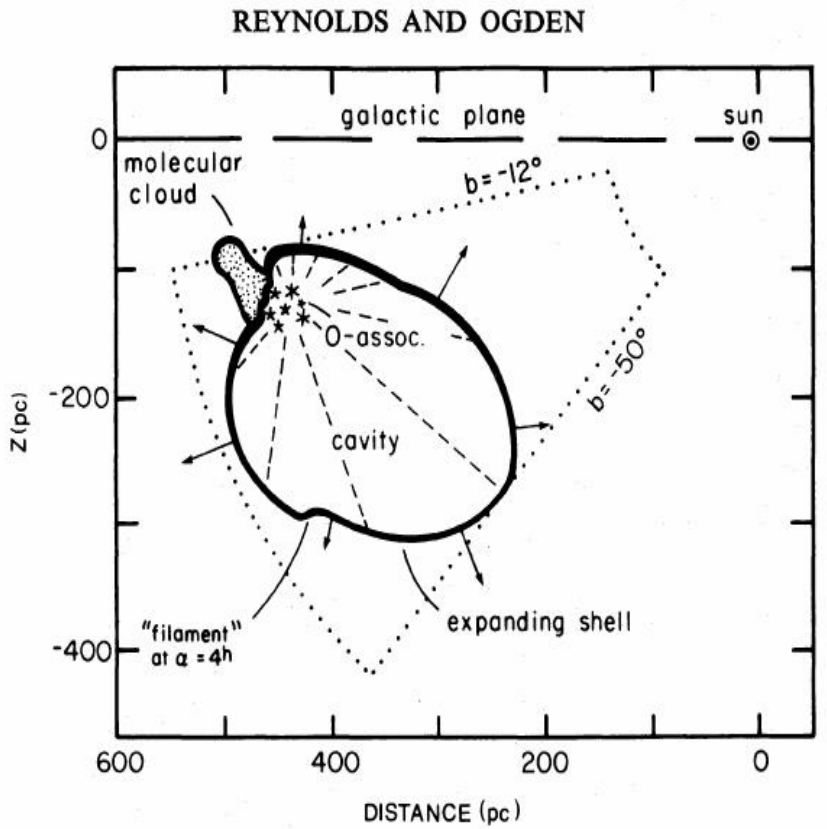

Orion B
Molecular
Cloud
North
Orion
Nebula
Barnard's
Loop
Orion A
Molecular
Cloud

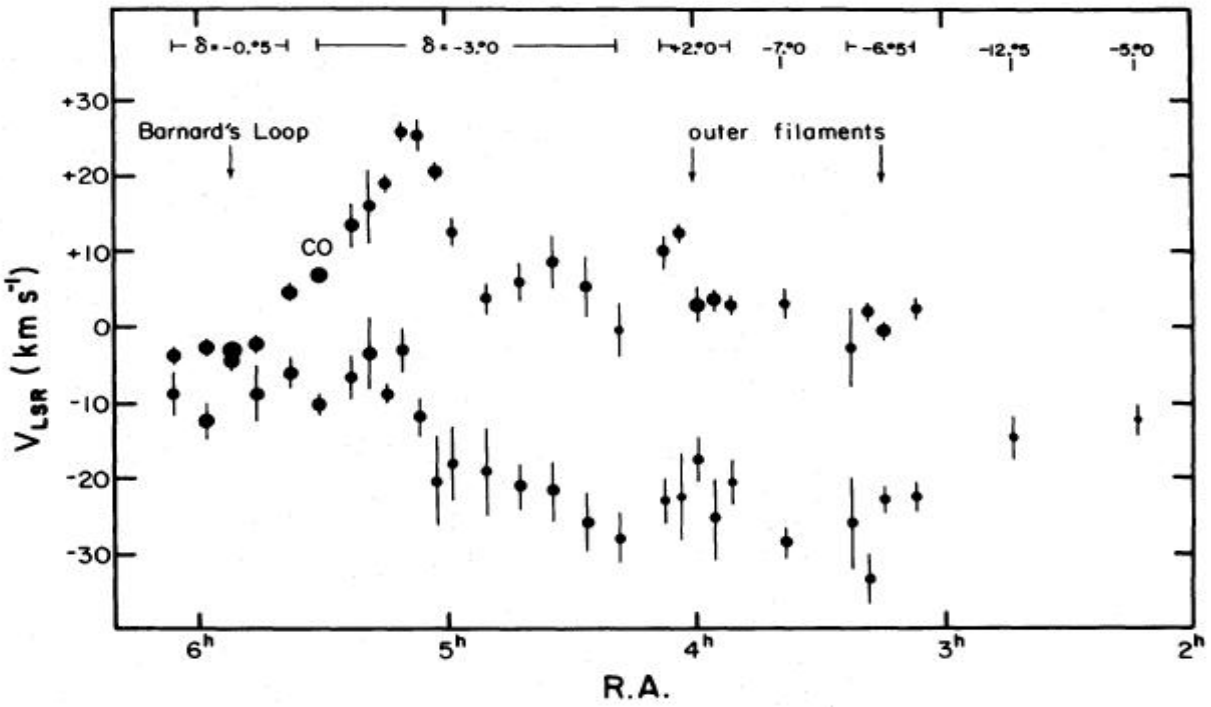

Orion Molecular Clouds
^{13}CO 2.6 mm
Orion B
Orion Nebula
Orion A







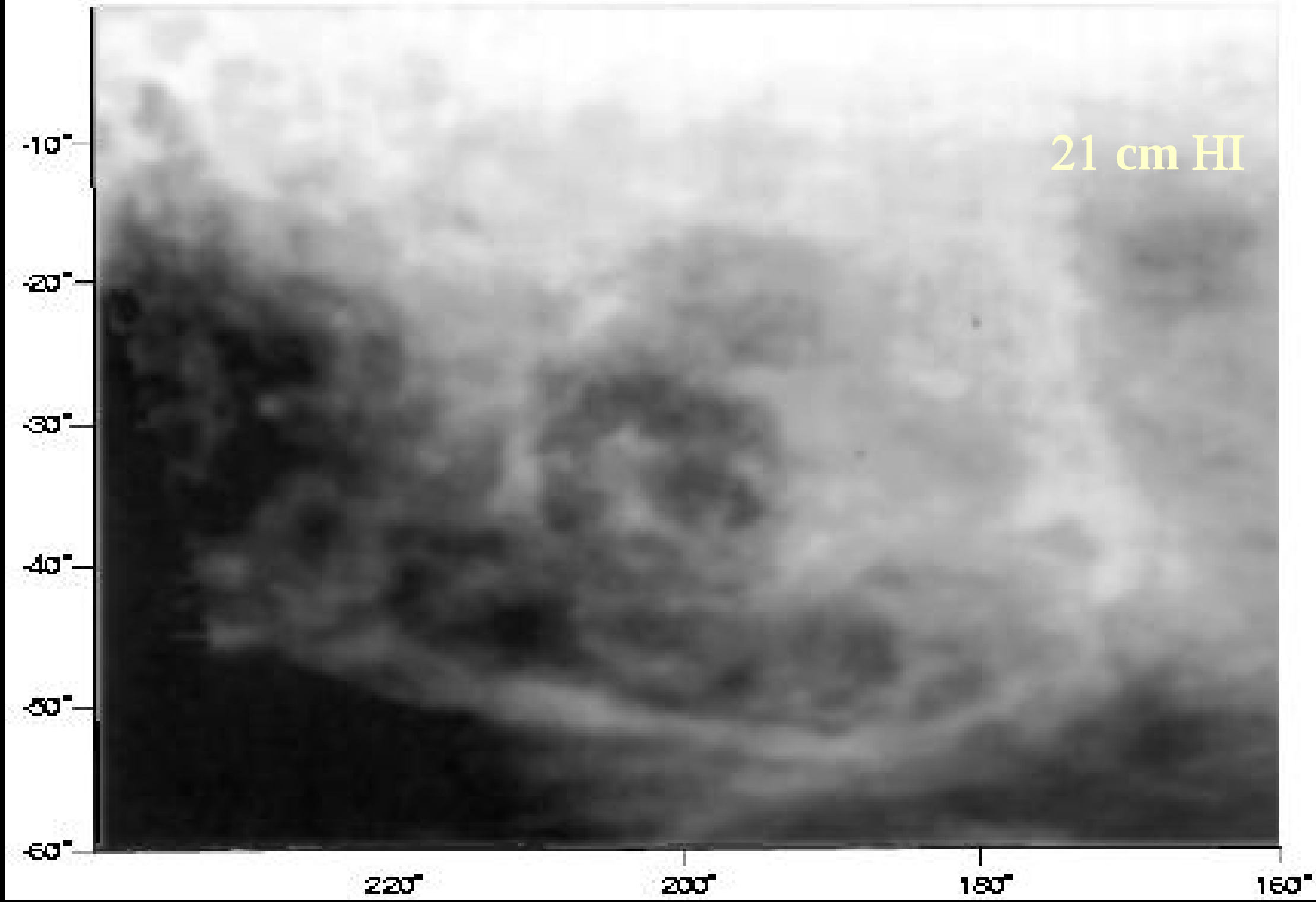


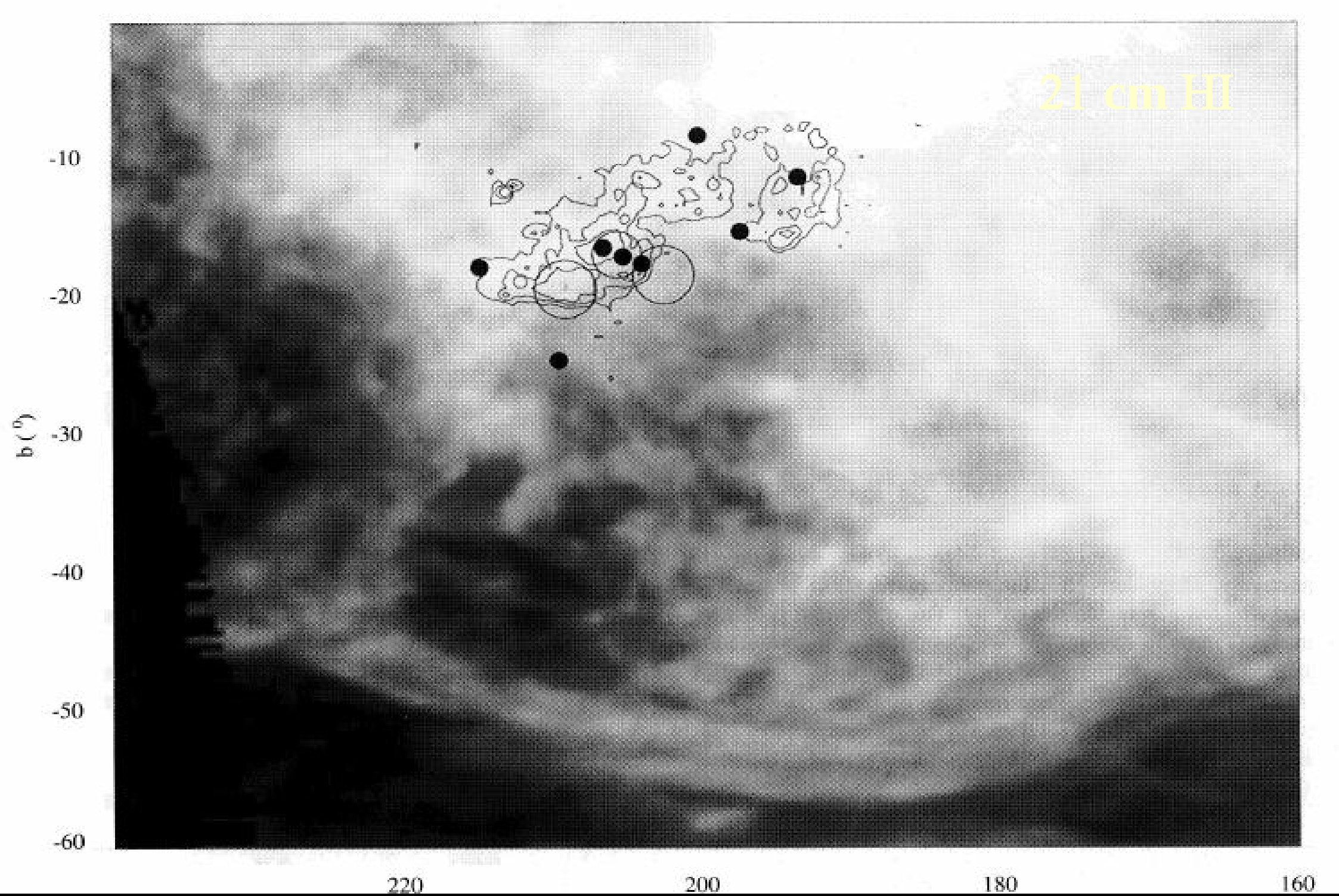


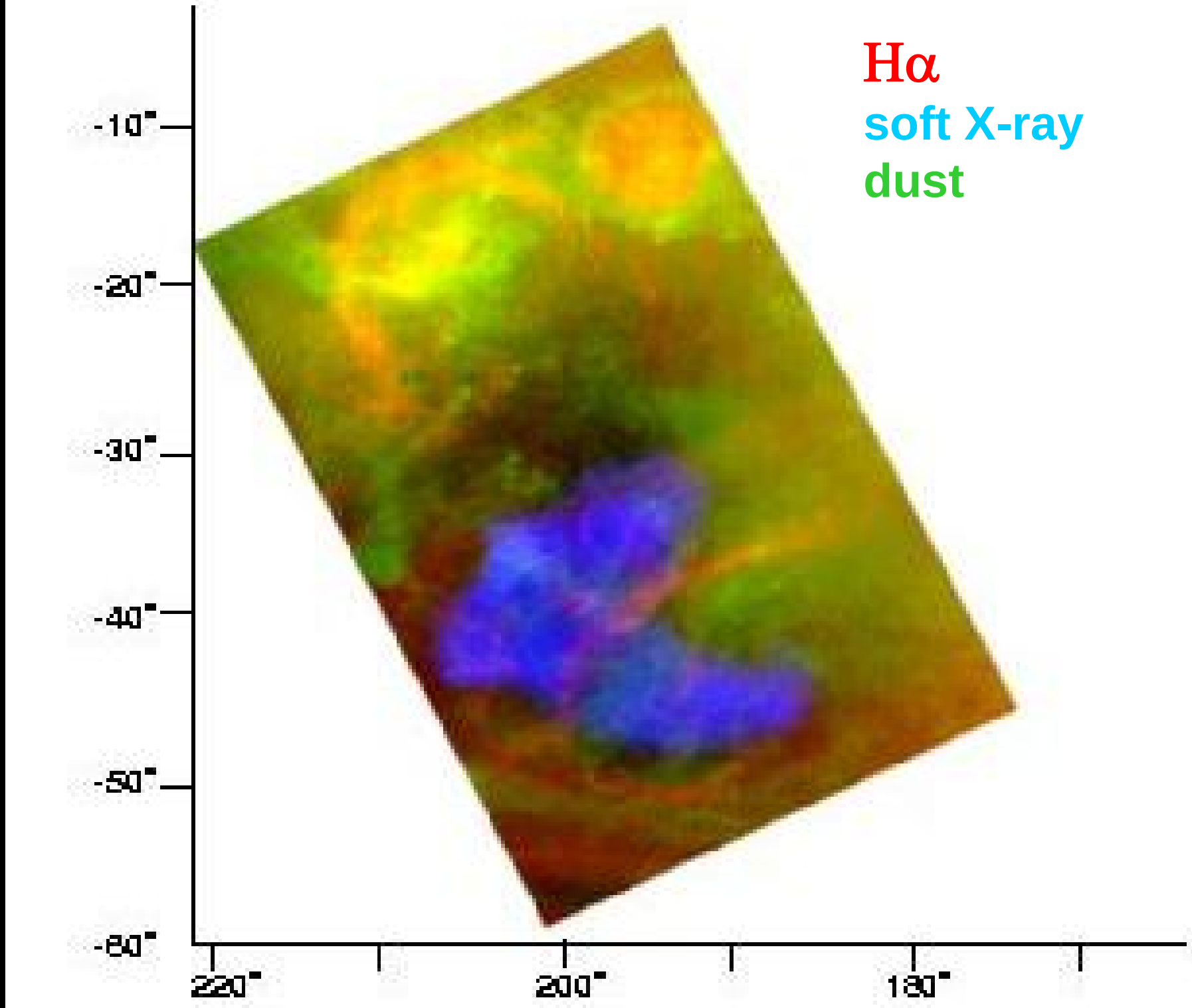
Orion / Eridanus Bubble kinematics

K.E. ~ 10^{52} ergs

Reynolds & Ogden (1979)

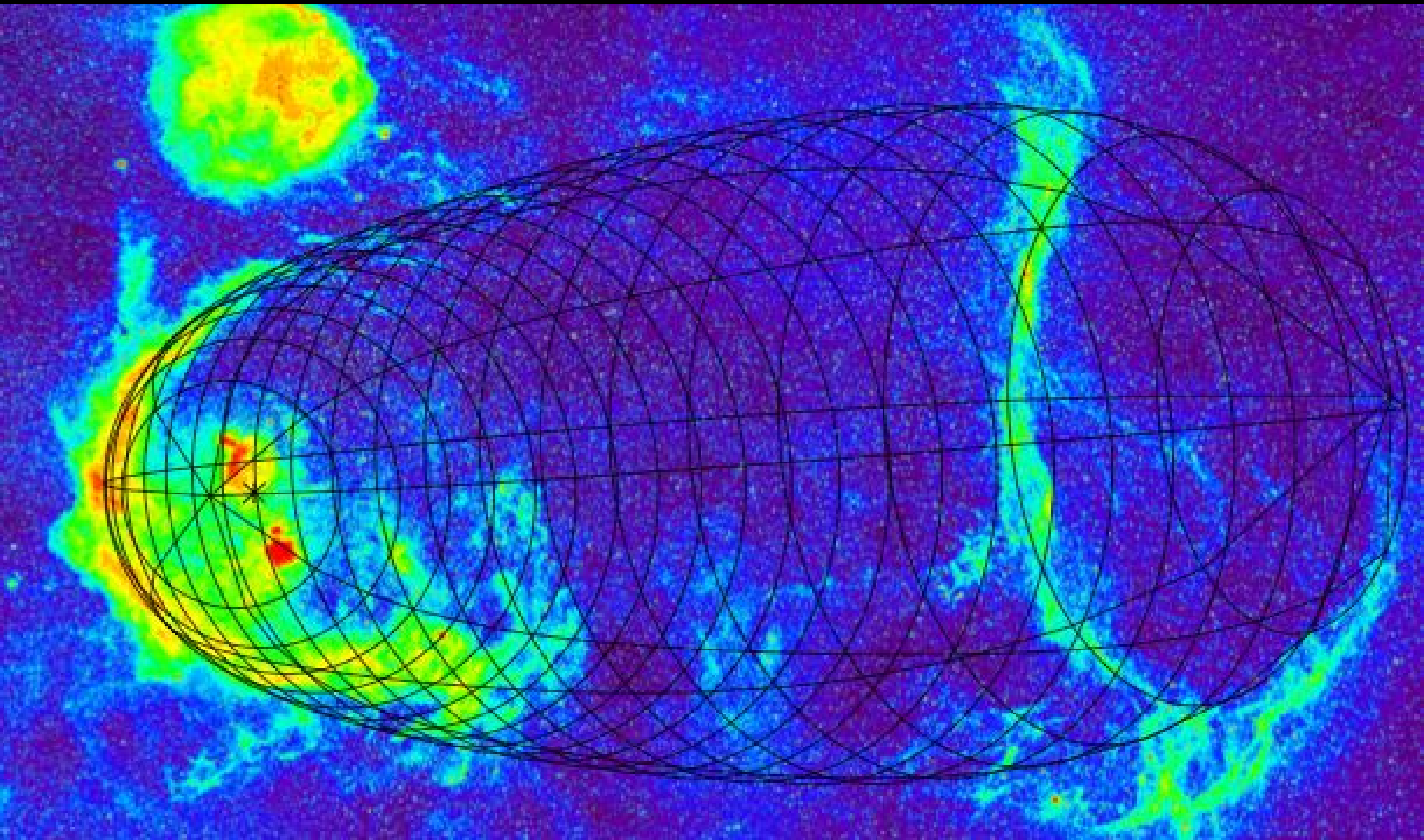

21 cm HI
-10°
-20°
-30°
-40°
-50°
-60°
220°
200°
180°
160°


21 cm HI
-10
-20
-30
-40
-50
-60
b (°)
220
200
180
160


Hα
soft X-ray
dust
-10°
-20°
-30°
-40°
-50°
-60°
220°
200°
180°

Orion / Eridanus superbubble:

(Pon, Johnstone, & Bally 2012) model



Massive Star forming complex:

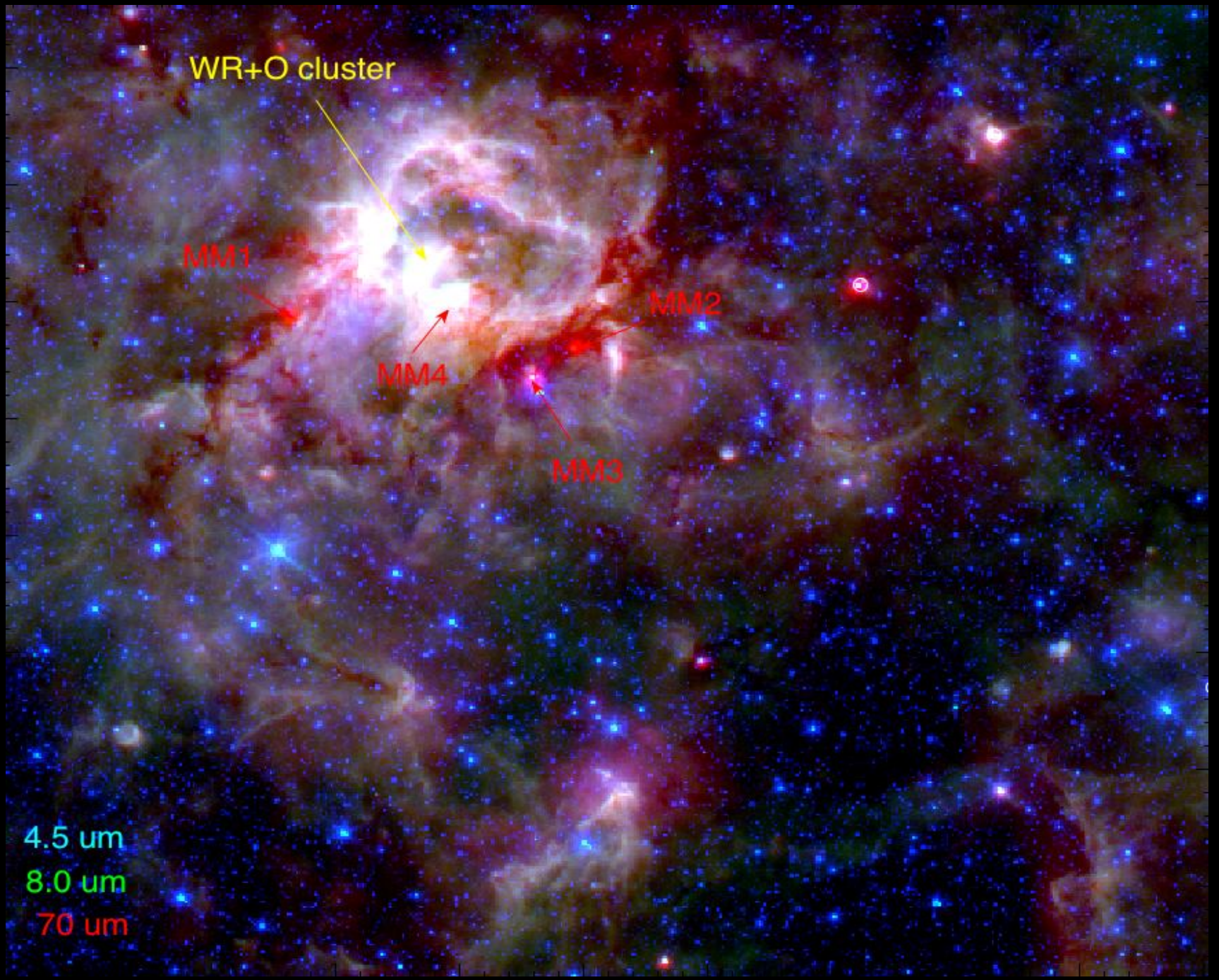
W51 70 160 350 μm Hi-GAL

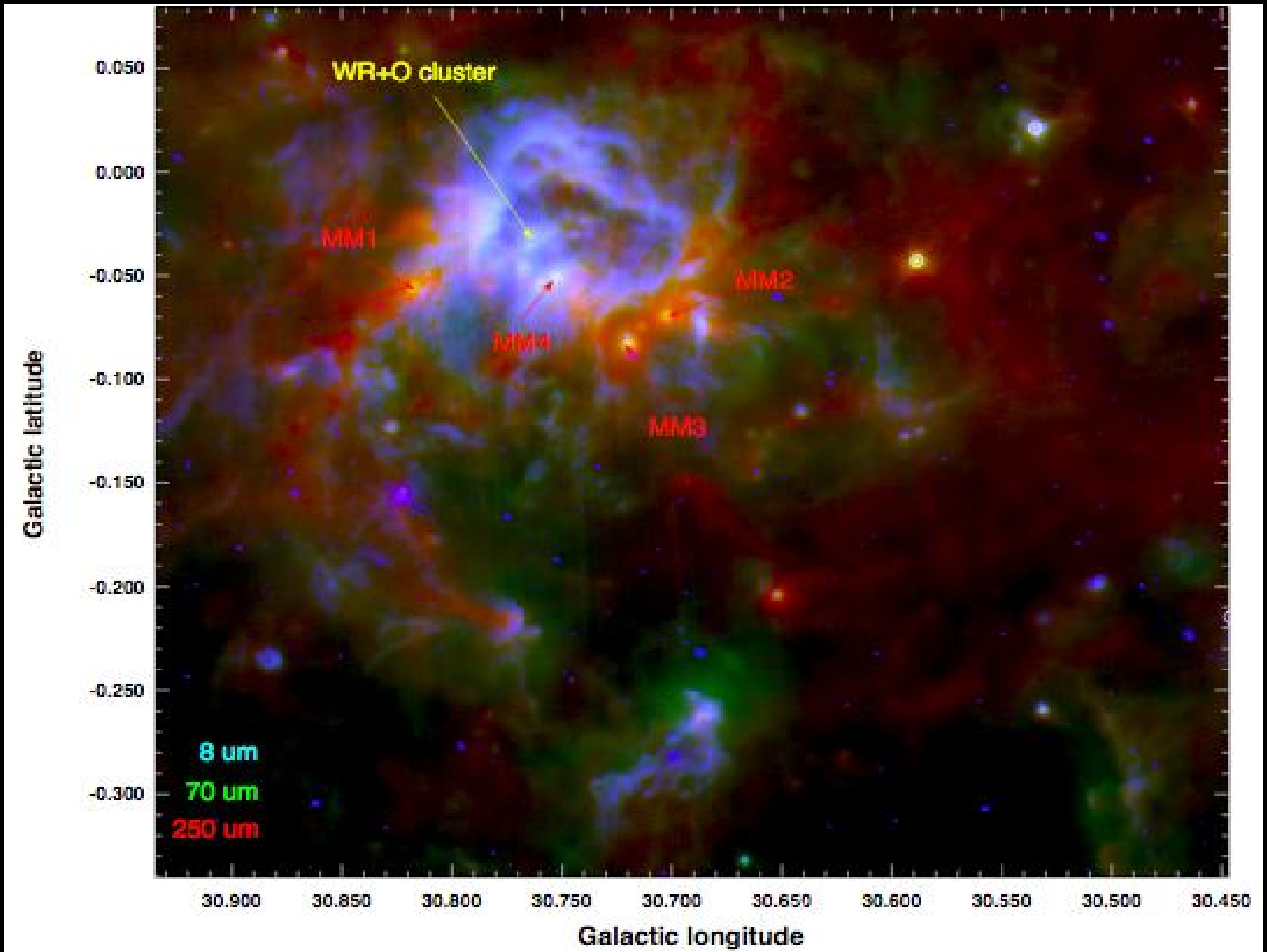
W43
Giant HII region mini-starburst

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

D ~ 5.5 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


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

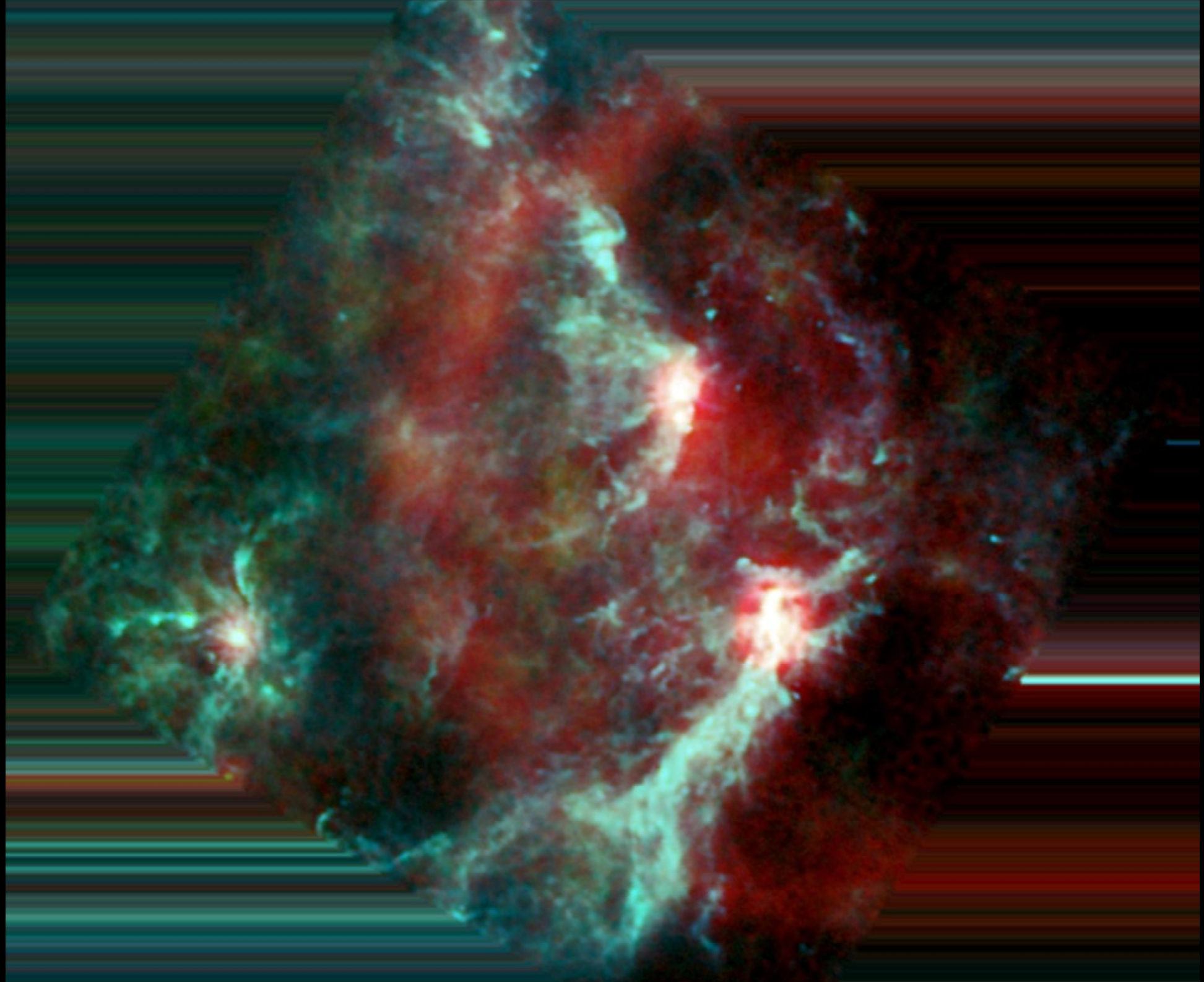
The Central Molecular Zone: Hi-GAL

Conclusions

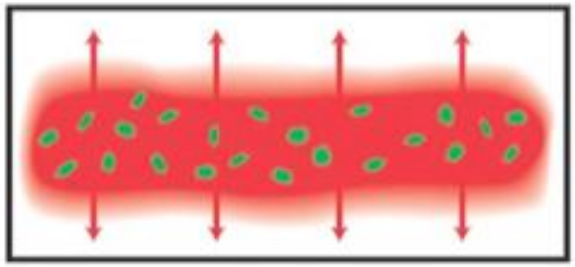
ISM <=> Star formation: the `Galactic Ecology'

- **Formation, Evolution, & Destruction of GMCs**
  - **Convergent Flows + Gravity**
    - **- Spiral waves,**
    - **- Cooling instabilities**
    - **- Magnetic instabilities**
    - **- Super-rings**
  - **Destruction**
    - **- Massive stars!**
  - **Cycle time ~ 100 Myr in near Sun**

- **Key to Galactic / near-Universe `Foregrounds'**

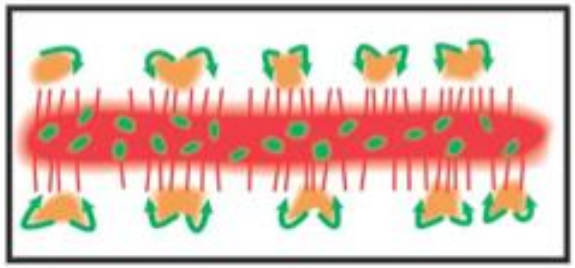


CONCEPTIONS: Vertical

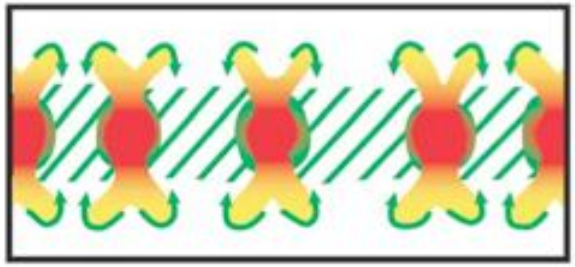


Thermal wind
- From escaping hot intercloud gas

Or, a hot halo

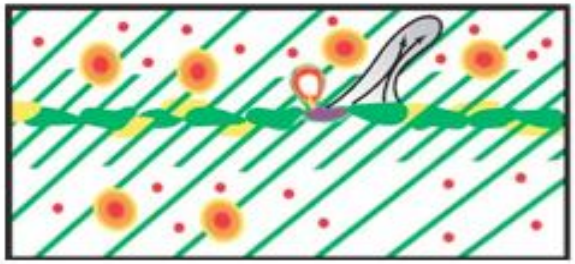


Galactic fountain 1
- From escaping hot intercloud gas which cools



Galactic fountain 2
- From superbubbles breaking out above the disk

Thick quiescent disk
- Superbubbles confined
- Spiral density waves
- Ionization mechanism?

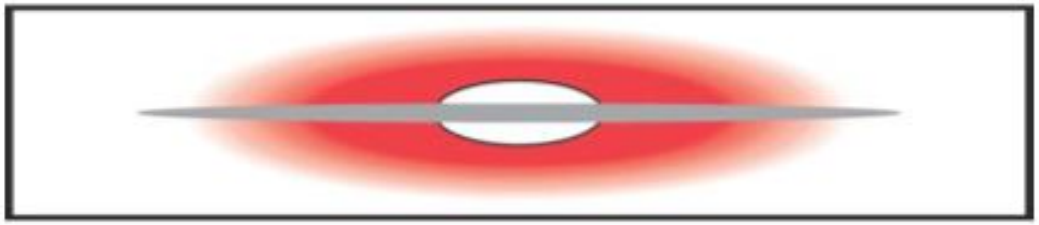


Active halo
- Cosmic ray wind
- Microflares
- High z supernovae

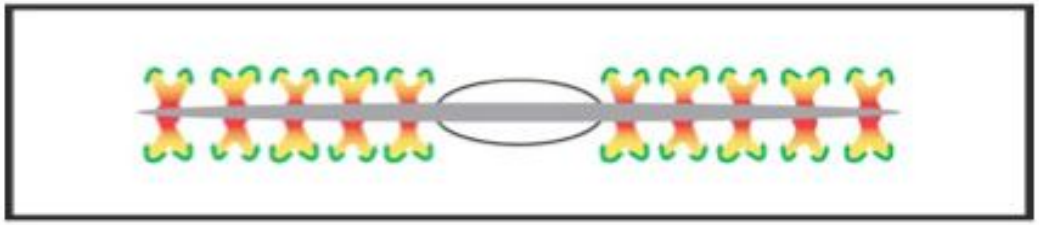
CONCEPTIONS: Global

Global thermal wind...

...or a hot halo?

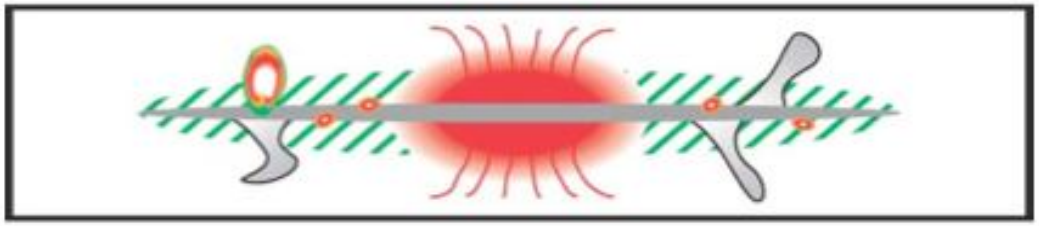


Galactic fountain

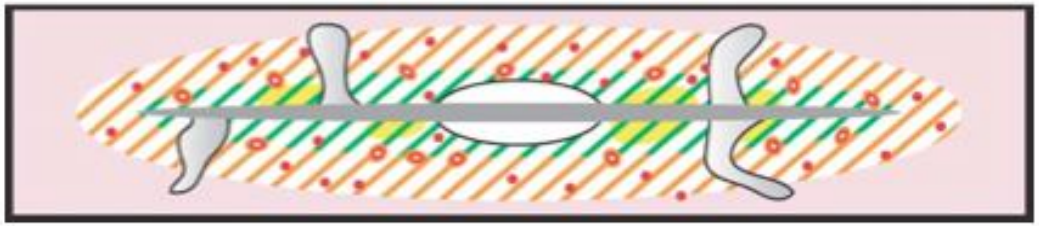


Thick Quiescent Disk...

...with nuclear wind?



Active halo

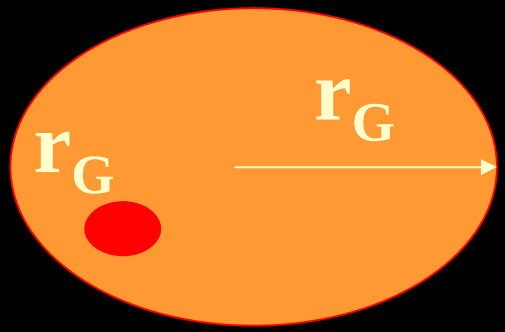


Cox, D. P. 2005, ARA&A, 43, 337

Impact of Massive ($M > 8M_o$) Stars:

SN Rate in Galaxy: $R_{SN} \sim 1/20$ to $1/100$ (yr^{-1})

SN Rate in Gould's Belt:



$$R_{SN,GB} \sim R_{SN} (r_{GB} / r_G)^2 \sim 4x10^{-4} R_{SN}$$

for $r_G \sim 10$ kpc

Swept-Up Mass:

$$M_{GB} \sim (r_{GB} / r_G)^2 M_{ISM} \sim 4x10^{-4} M_{ISM} \sim 2x10^{6} M_o$$

Shell Expansion Speed:

$V \sim 2 - 10$ km/s