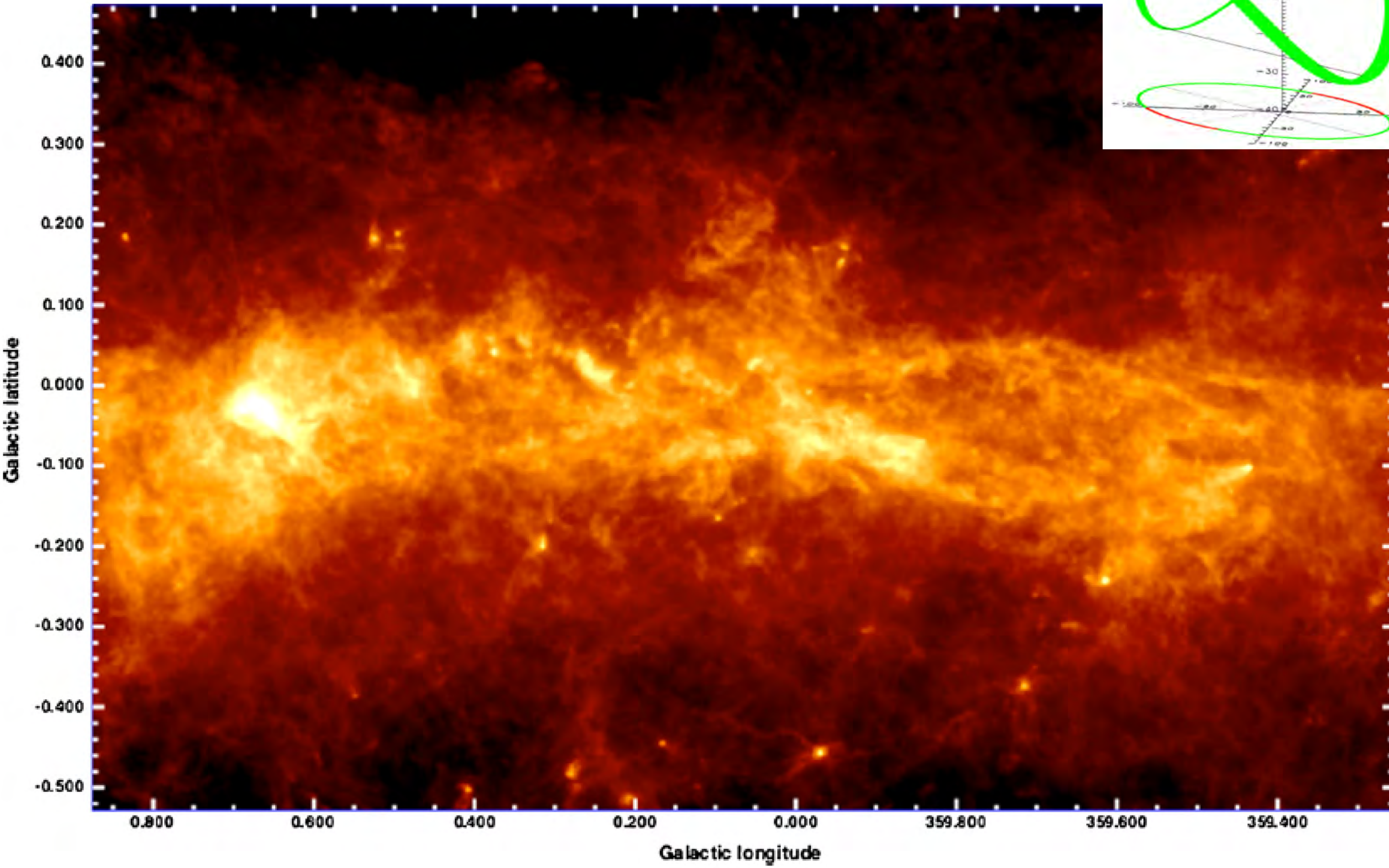
Star Formation at the Galactic Center

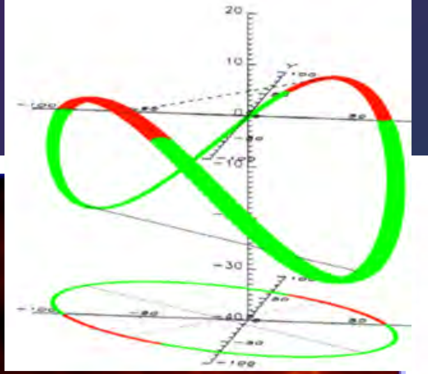
Mark Morris UCLA

Outline

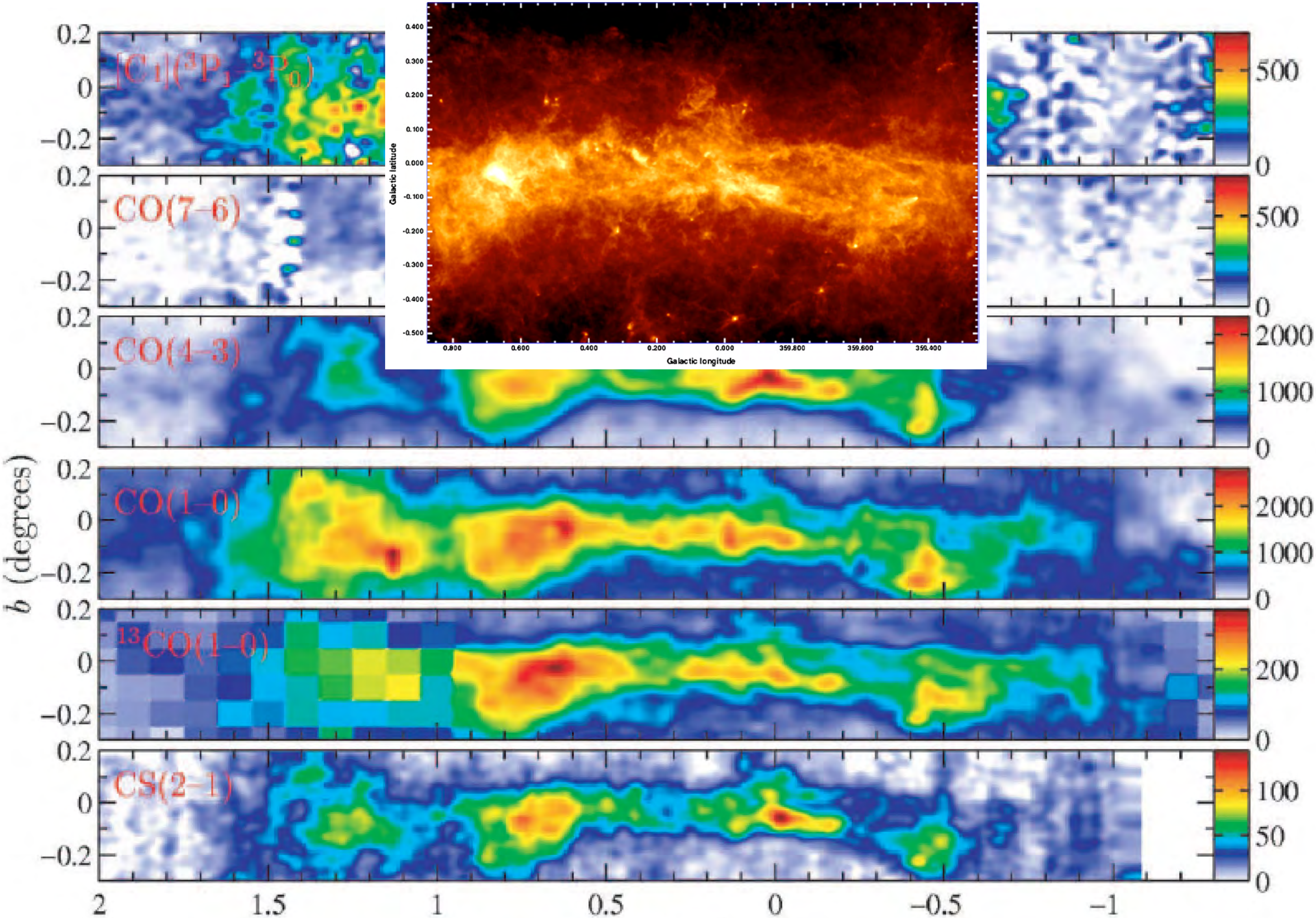
- The Arena – central molecular zone, & the twisted ring
- General dearth of star formation, relative to amount of gas
- Orbital influence on star formation
- Mode of star formation: Massive young clusters *vs.* isolated YSOs
- Star formation in the Central parsec
- Cyclical star formation in the central parsec ?
- Magnetic fields – a pitch for HAWC+

The inner Central Molecular Zone





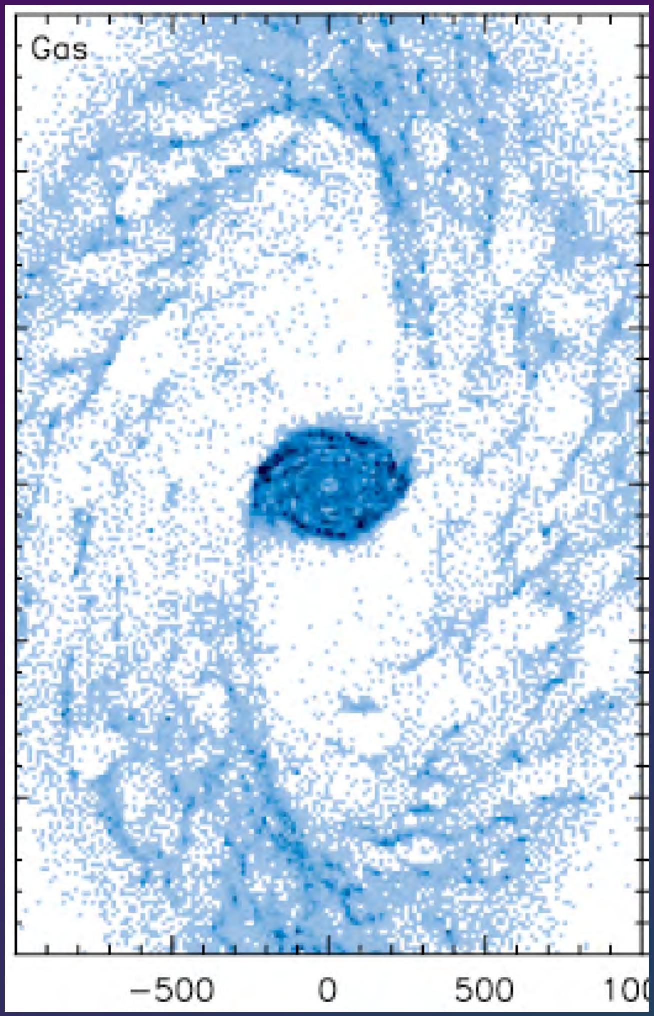
Molinari *et al.* 2011 … Herschel/SPIRE 250 μm



Martin et al. 2004

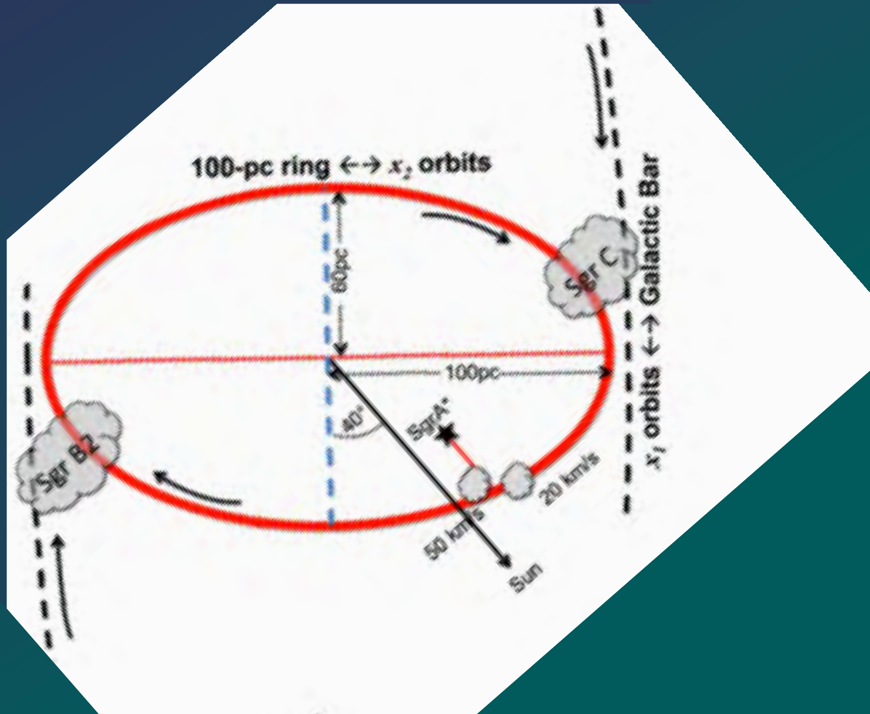
CMZ: ~3 x 10^7 $M_\odot$, ±170 pc

Warm, turbulent molecular gas
Having large-scale order.



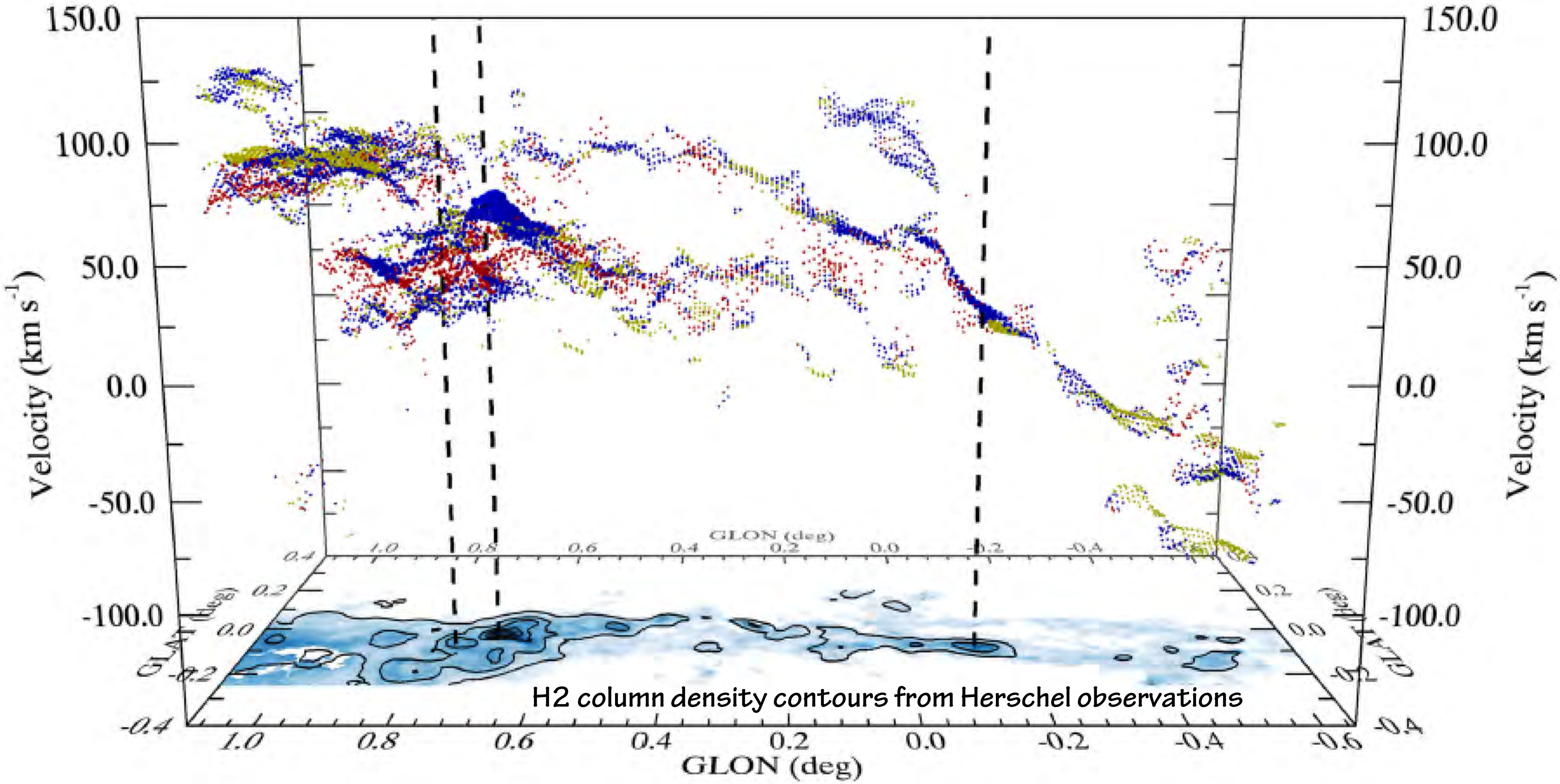
Simulation of gas distribution in the CMZ
(Sungsoo Kim + 2011)

overhead view of the
Molinari et al. 2011 twisted ring



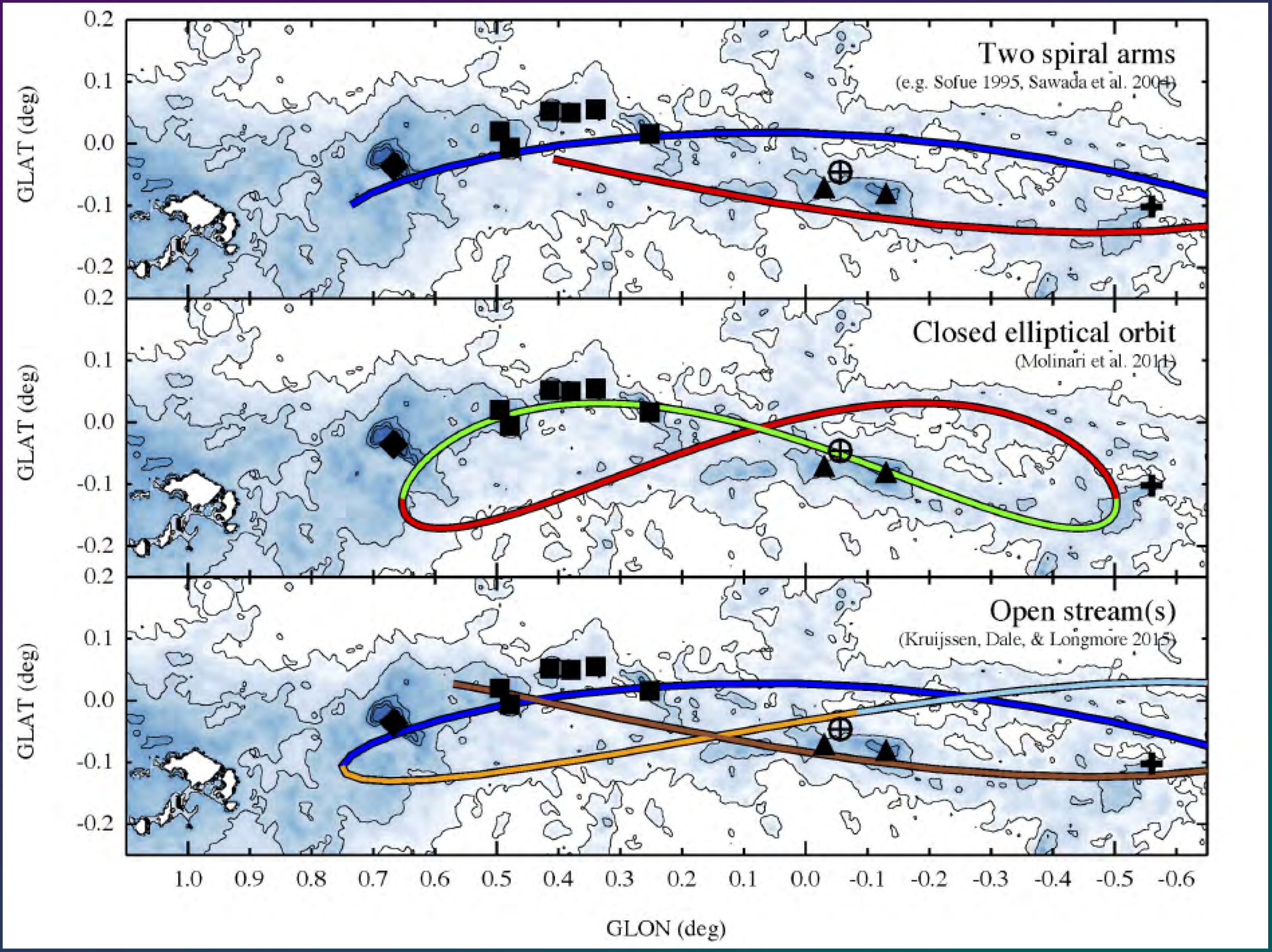
Henshaw et al. 2016   Top: HNCO, extracted using SCOUSE*

*SCOUSE: Semi-automated multi-COmponent Universal Spectral-line fitting Engine



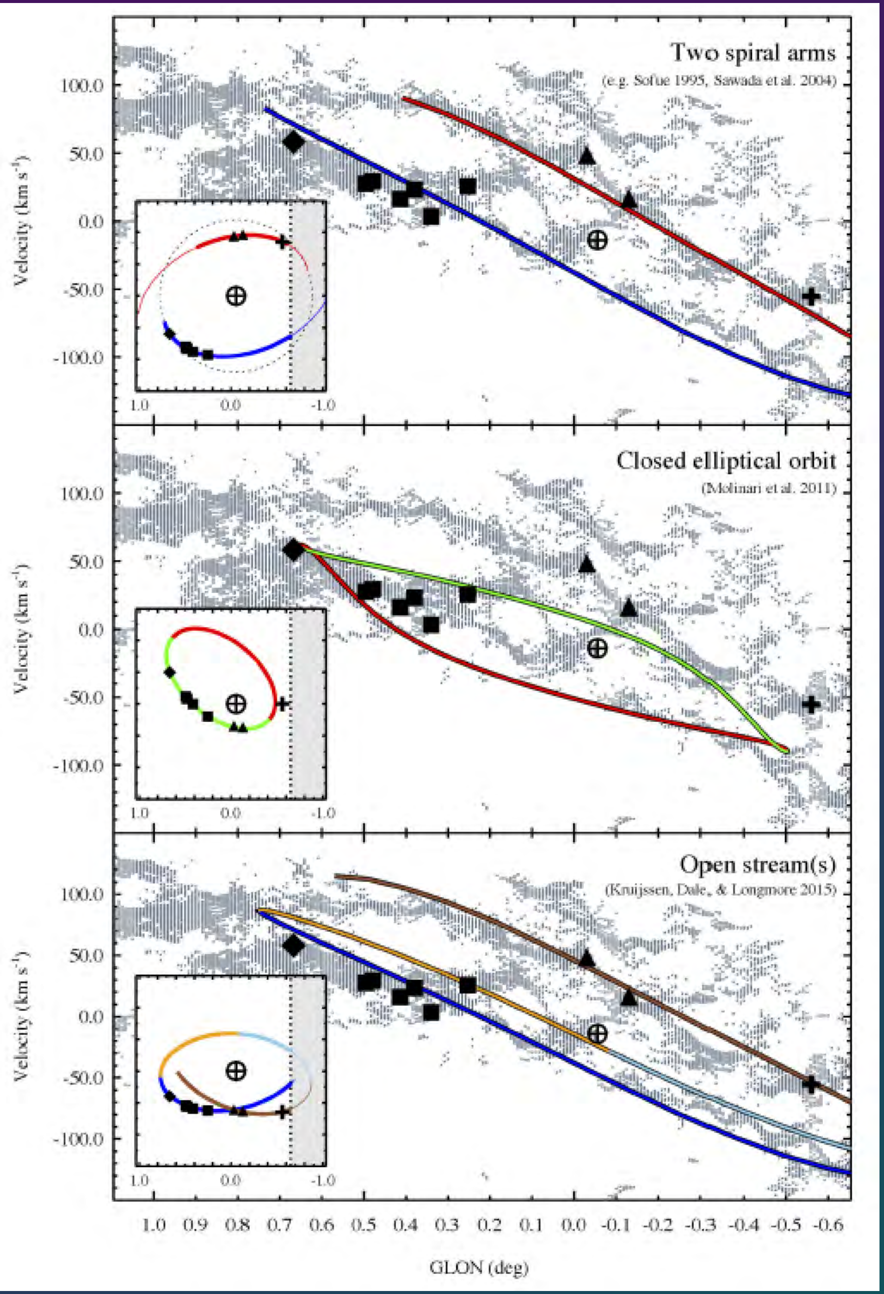
Color-coded to show velocity dispersion.

Possible models:



Henshaw et al. 2016 (Battersby et al., in prep)

Henshaw+16



- Gas distribution dominated by two roughly parallel extended features in **longitude-velocity** space.
- Henshaw+16 → the bulk of molecular line emission associated with the 20 & 50 km/s clouds is just a small segment of one of the extended features, in agreement with the Kruijssen+15 orbit, which places the clouds at a Galactocentric radius of ~60 pc.
- But this in inconsistent with the evidence that Sgr A East is interacting with the 50 km/s cloud and that the 20 km/s cloud is feeding gas into the central parsecs.

Star Formation in the CMZ

- It has been known for some time that the CMZ has a much higher ratio of dense gas mass to star-formation tracers than elsewhere in the Galaxy [Morris 1989, 1993, Lis & Carlstrom 1994, Yusef-Zadeh et al. 2009, Immer et al. 2012, Kauffmann et al. 2013, Longmore et al. 2012, 2013a, 2013b, Barnes et al. 2016]

- The inhibition of star formation is attributable to the peculiar physical conditions of the CMZ:
  - High pressure, 10^2 – 10^3 times that in Galactic disk clouds
  - Turbulence, which sets an increased threshold for gravitational collapse [Kruijssen et al. 2014; Krumholz & Kruijssen 2015, Rathborne et al. 2014]

<u>Sources of turbulence</u>: feedback from star formation, supernovae, feedback from the SMBH, shear instabilities, hydromagnetic waves

The star formation rate (SFR) on large scales depends on the surface mass density of gas, Σ

- The Schmidt-Kennicut law:

$$\text{SFR} \sim \Sigma^{\beta}$$

$\beta \cong 1.4$ (Kennicut 1999)

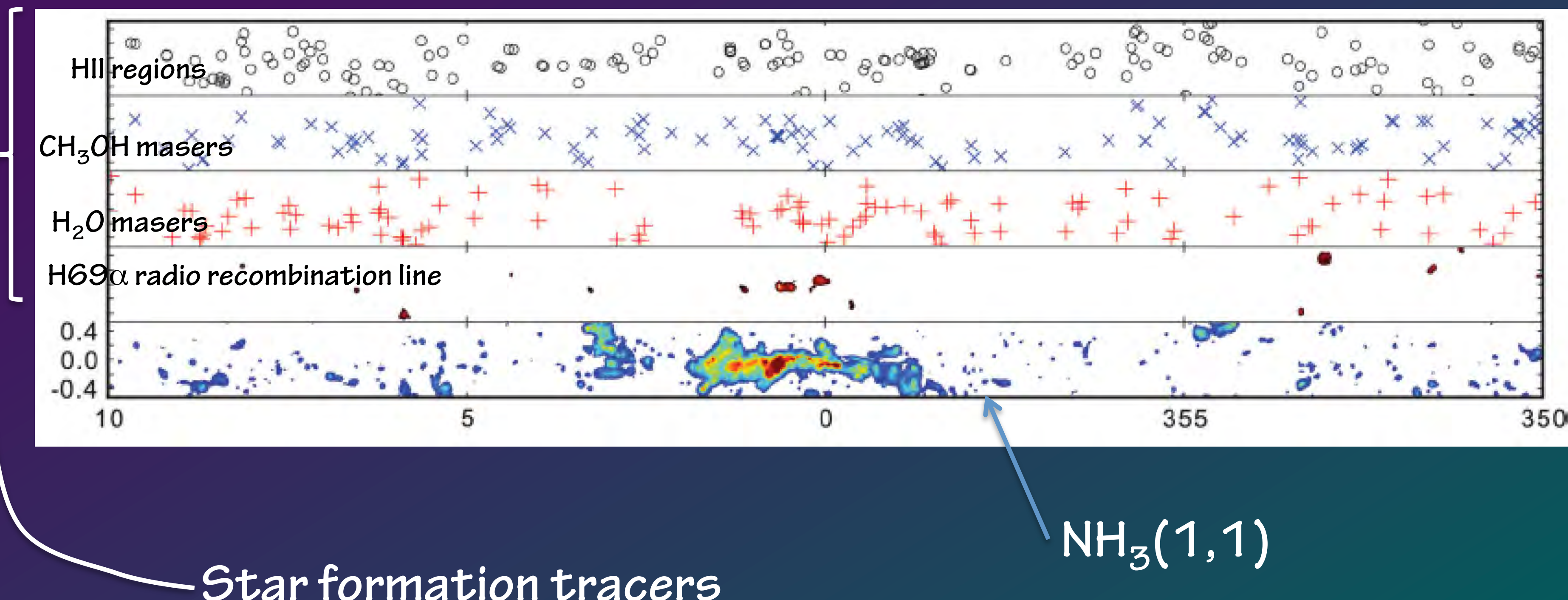
- Alternatively,

SFR density = ε(total gas mass)/(free-fall time)

Where ε is an efficiency factor ≈ 1%

(Schmidt 1959; Kennicutt 1998; Krumholz et al. 2012)

In the Galactic center … (from Longmore et al. 2013)



Longmore et al. (2013) find that the SFR is only 0.01 - 0.02 $M_\odot$ yr^{-1} in the Central Molecular Zone, but it should be as much as 20 times larger by the standard estimates.

- Jeans mass: $M_{Jeans} \propto T^{3/2}/\rho^{1/2} \sim \Delta v^3/\rho^{1/2}$

- Magnetic Jeans mass $\propto B^3/\rho^2$

- Since the turbulent energy density is comparable to the magnetic energy density,

$$\rho \Delta v^2 \sim B^2/8\pi,$$

these are comparable,

and large, $10^{4\text{-}5}\ M_\odot$

→ So the Jeans mass would tell us that massive clusters should form in the Galactic center.

Densities are also delimited by ***tidal forces***; only high-density gas can resist tidal shear to form "clouds" (Güsten & Downes 1980):

$$n_{H_2} > 2 \times 10^7 \ cm^{-3} \ (1.6 \ pc/R)^{1.8} \ , \ R > 1.6 \ pc$$

$$n_{H_2} > 2 \times 10^7 \ cm^{-3} \ (1.6 \ pc/R)^3 \ , \quad R < 1.6 \ pc$$

e.g., at 30 pc,

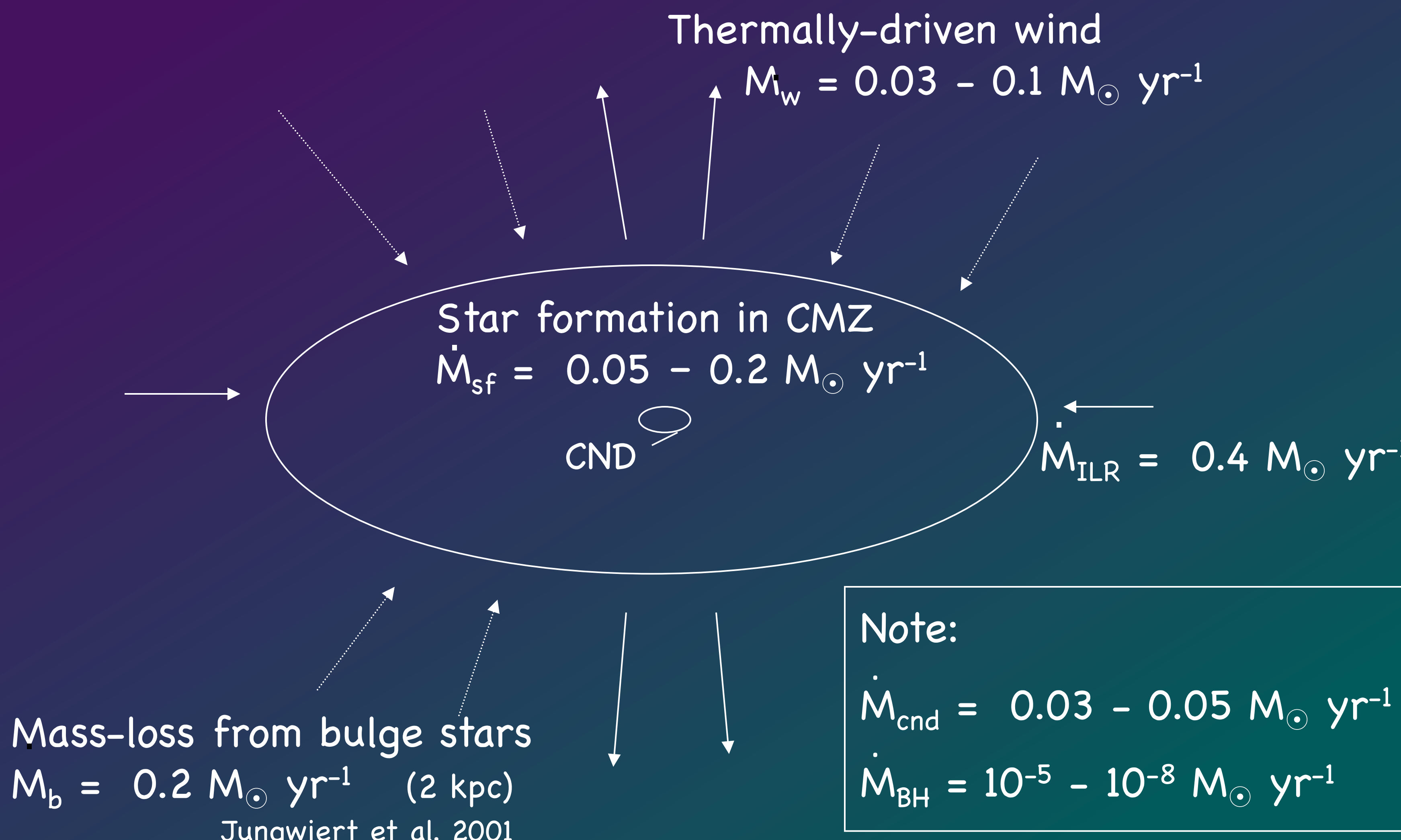
$n_{H_2} > 5 \times 10^4 \ cm^{-3}$, found only in cloud cores in the Galactic disk.

or at 0.2 pc, where the massive emission-line stars of the central stellar cluster are located,

$n_{H_2} > 10^{10} \ cm^{-3}$ -- a challenge for in situ formation models

Lower density gas forms tidal streams....

The Mass Budget



Note:

$\dot{M}_{cnd} = 0.03 - 0.05\ M_\odot\ yr^{-1}$

$\dot{M}_{BH} = 10^{-5} - 10^{-8}\ M_\odot\ yr^{-1}$

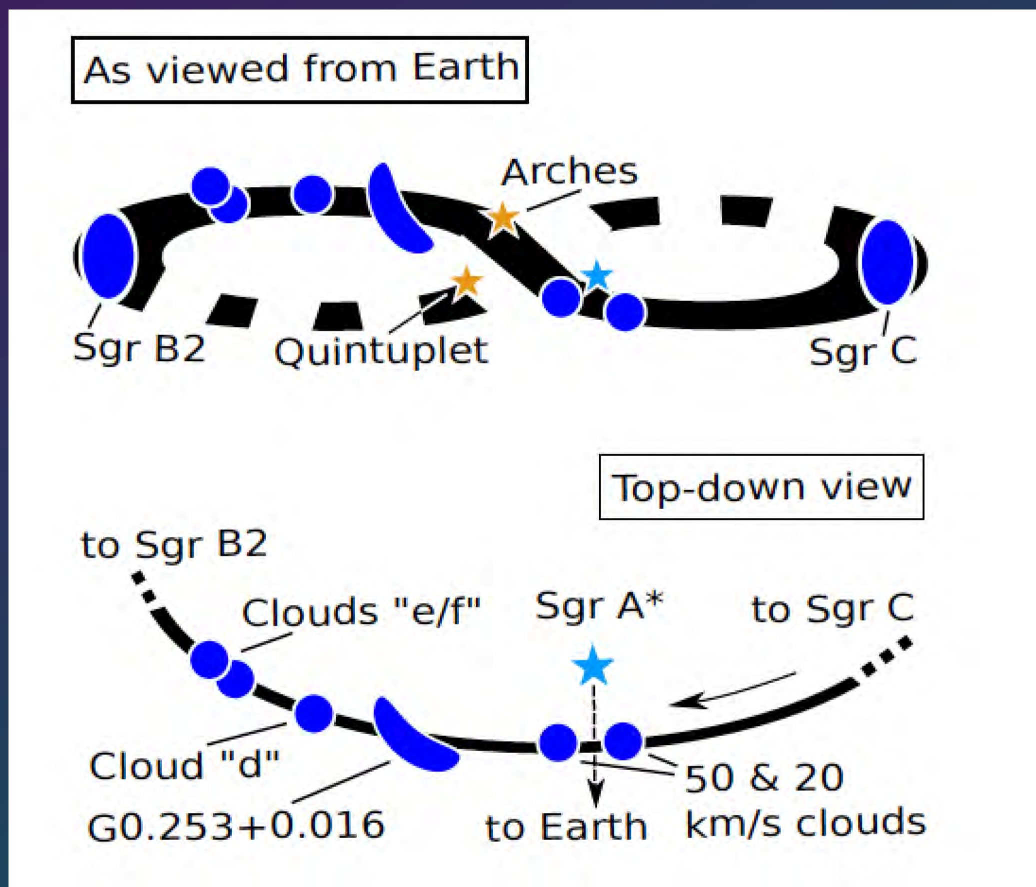
Note: these estimates aren't balanced, so the various rates need refinement !

Orbital Influence on Star Formation

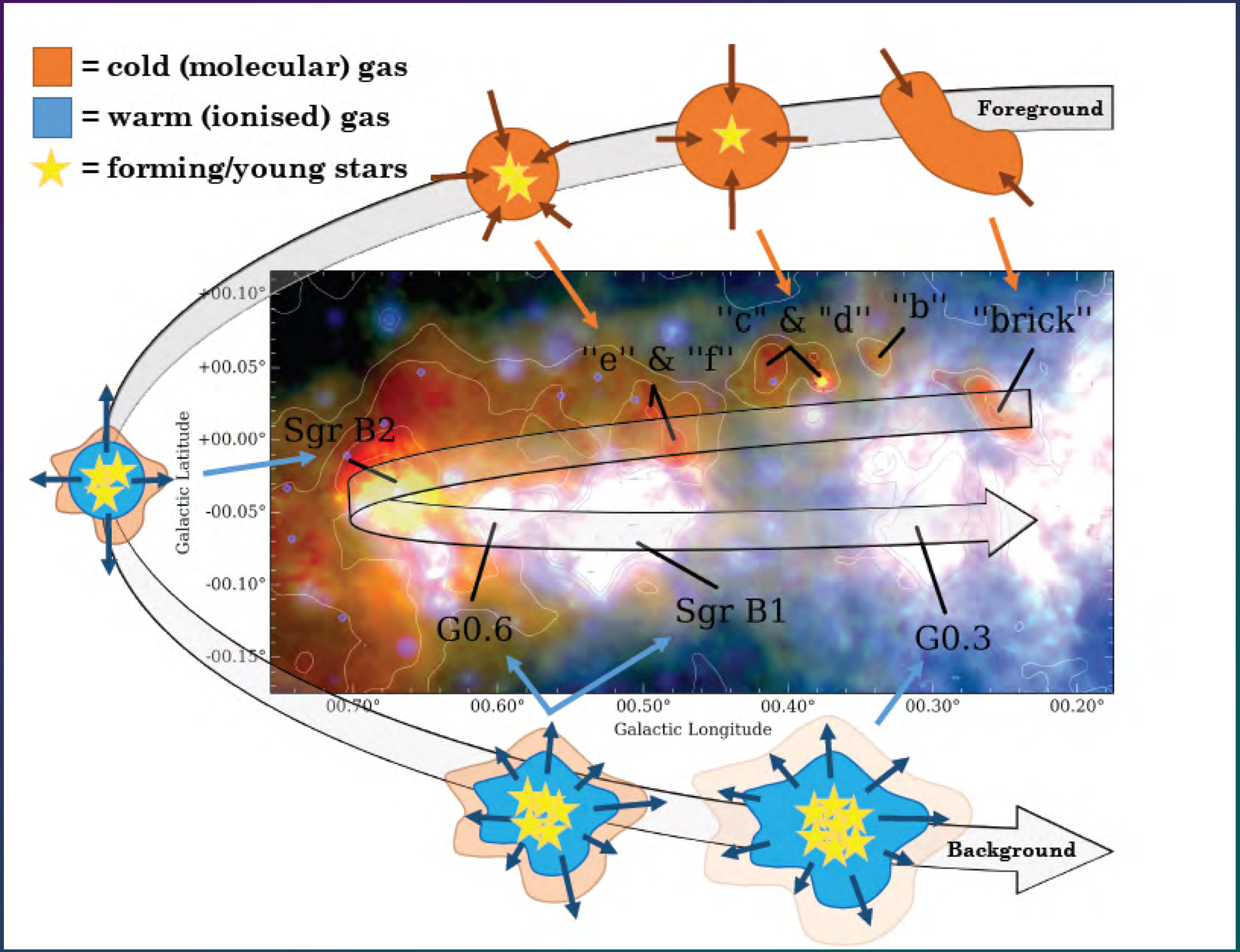
Candidate super star cluster progenitor gas clouds possibly triggered by close passage to Sgr A*

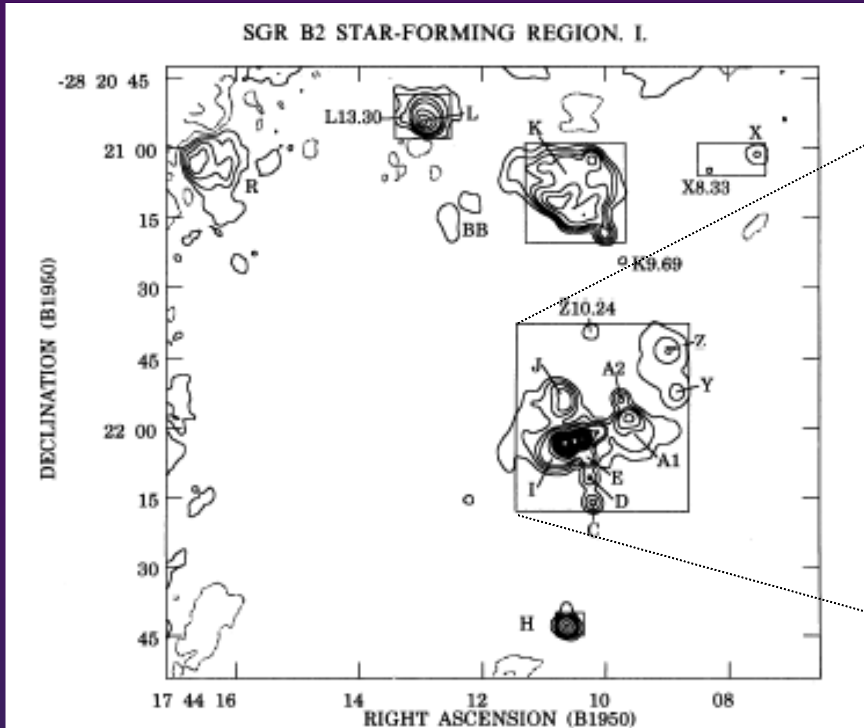
2013

S. N. Longmore[1,2⋆], J. M. D. Kruijssen[3], J. Bally[4], J. Ott[5], L. Testi[1,6], J. Rathborne[7] N. Bastian[2], E. Bressert[7], S. Molinari[8], C. Battersby[4], A. J. Walsh[9]



the model: star formation within the dust ridge molecular clouds (from G0.253+ 0.016 to Sgr B2) follows an evolutionary time sequence, triggered by tidal compression during their preceding pericentre passage.



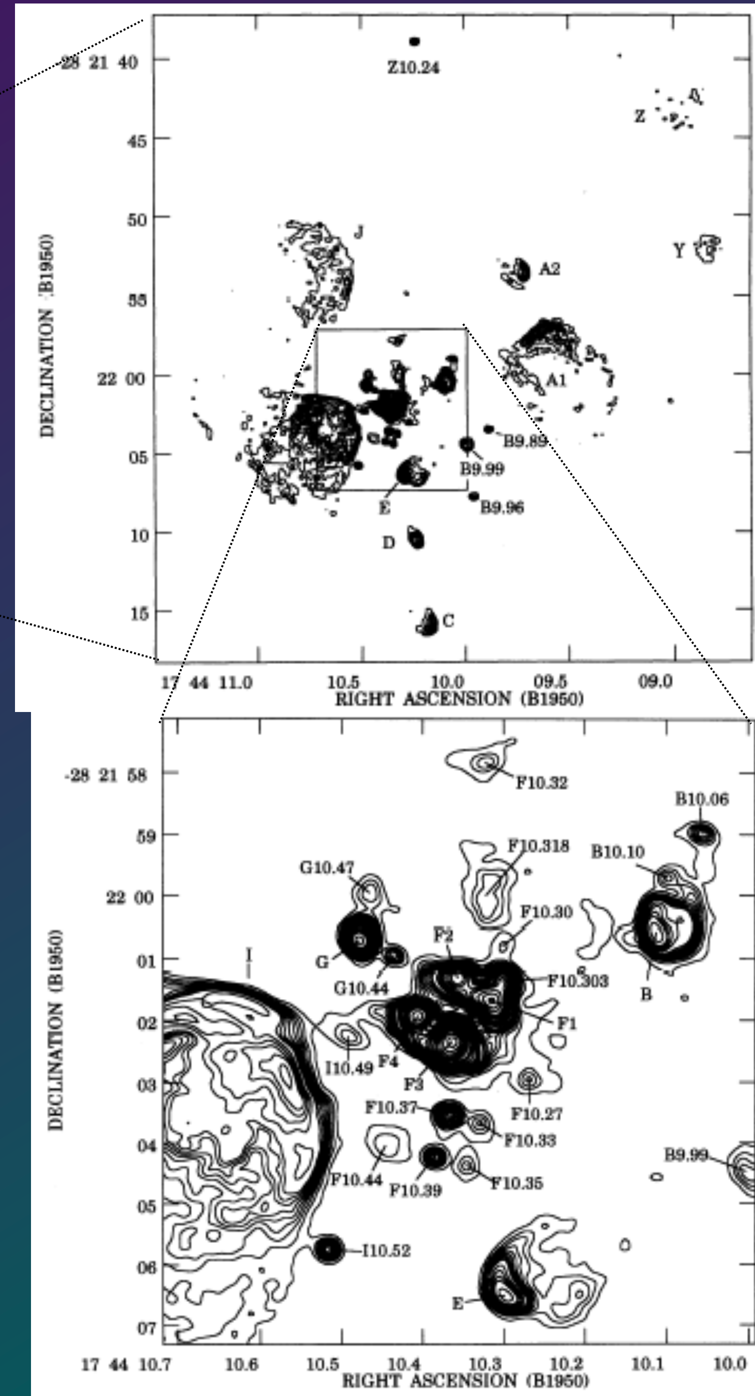


Sgr B2 (Gaume et al. 1995):

→ over 50 different HII regions in the complex.

→ An Arches cluster in the making? (perhaps a "messier" version)

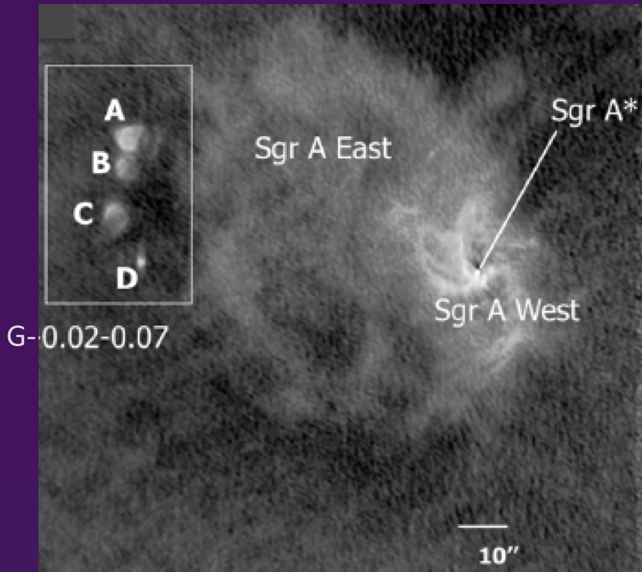
→ ALMA (Adam Ginzburg+): 120 Identifiable 3mm point sources in a 6′ x 6′ mosaic

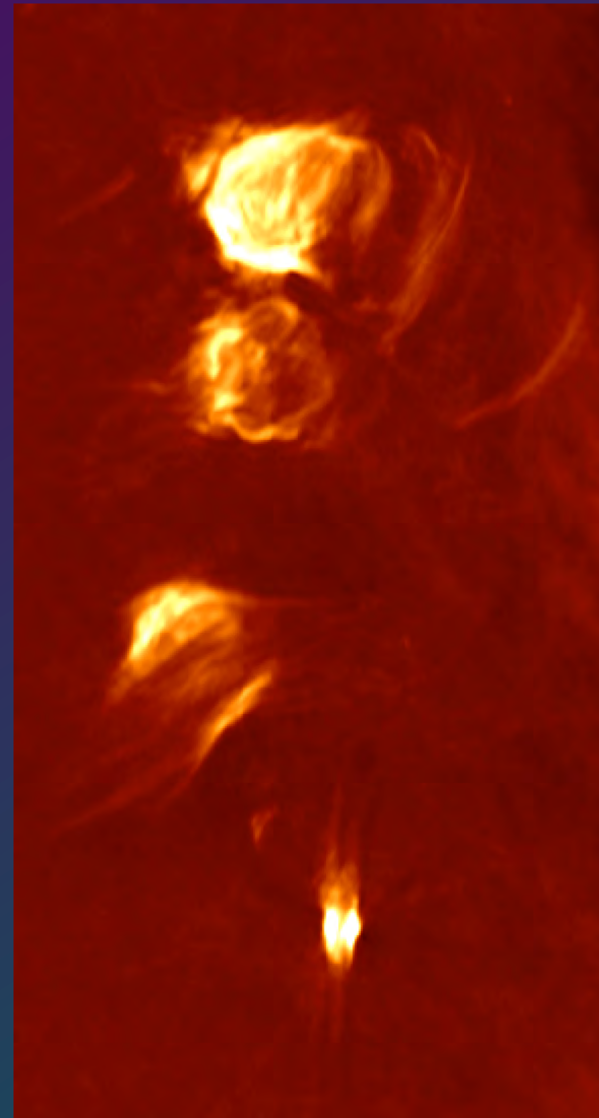


Mode of Star Formation in the Galactic Center

→ Massive clusters versus single-star or small cluster

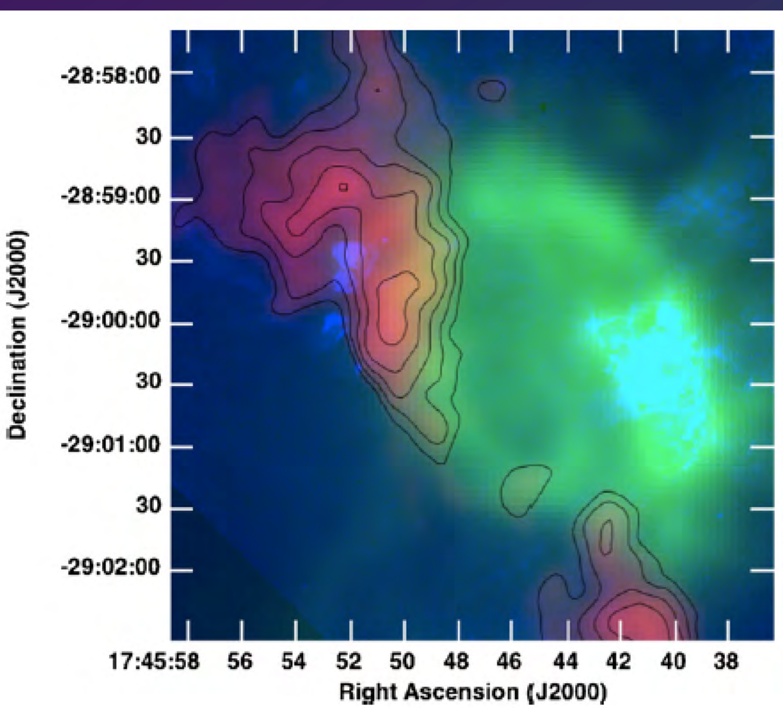
Start by examining relatively isolated sites of star formation





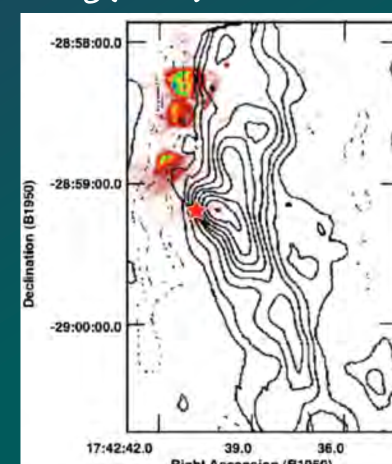
Sgr A East HII regions

← VLA 6cm
Zhao, MRM, Goss



Mills et al. 2011
blue: Paschen-α
green: VLA 1.4 GHz
red: SCUBA 450 μm

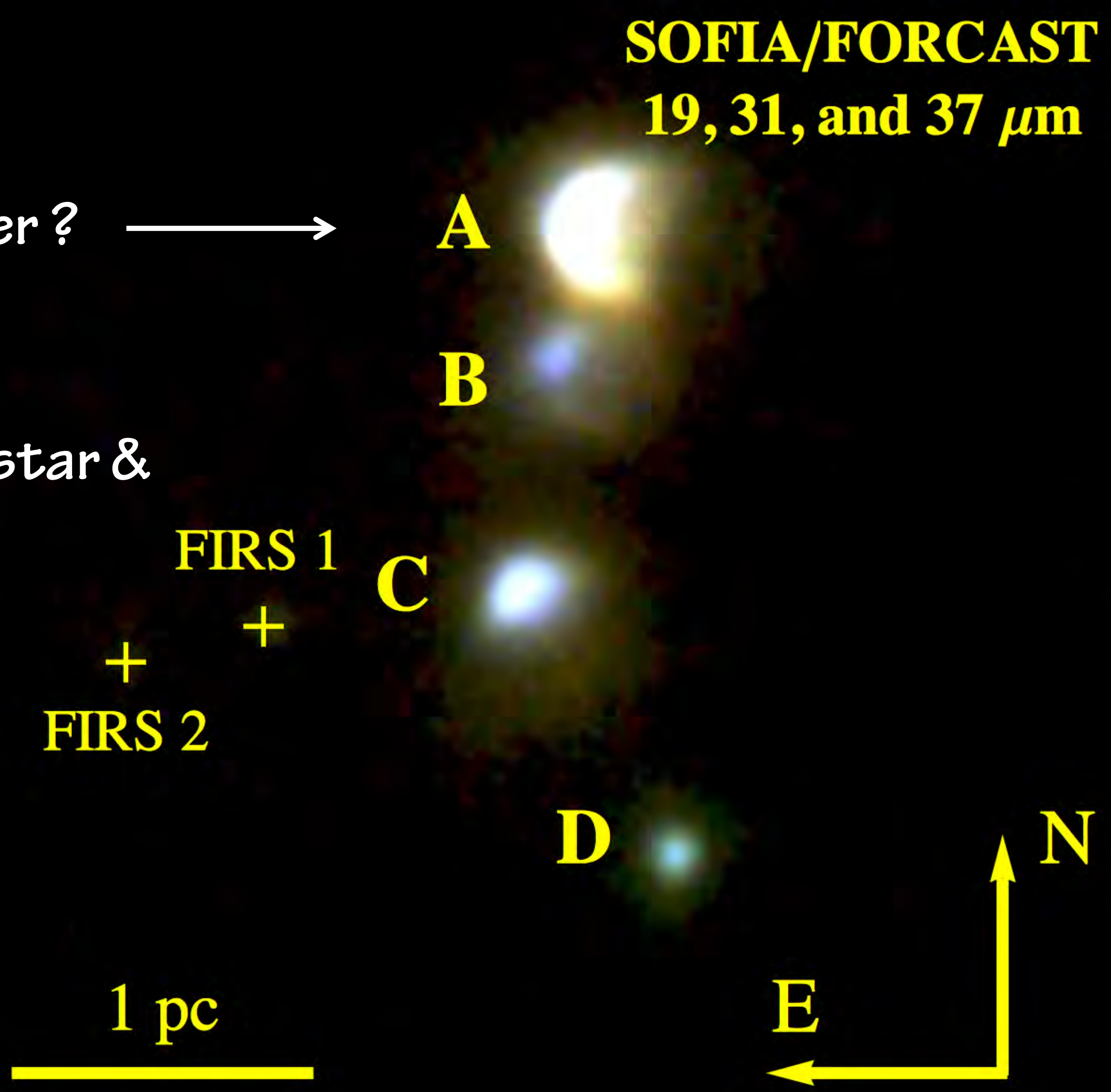
Coil & Ho 2000 – $NH_3(1,1)$ contours



Bow shock or blister ?

NW displacement of star & gas kinematics

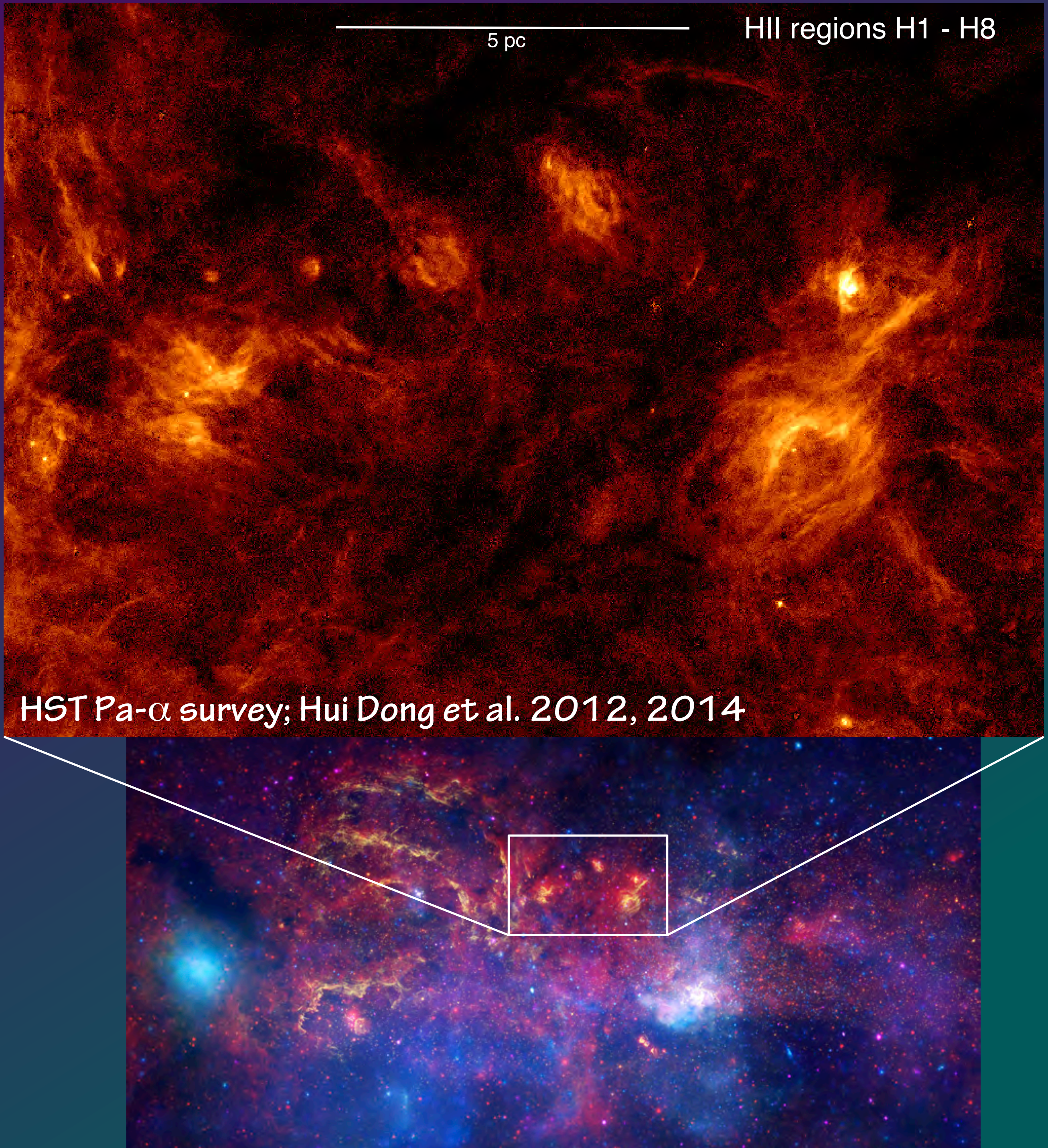
Stars are not in their natal cloud



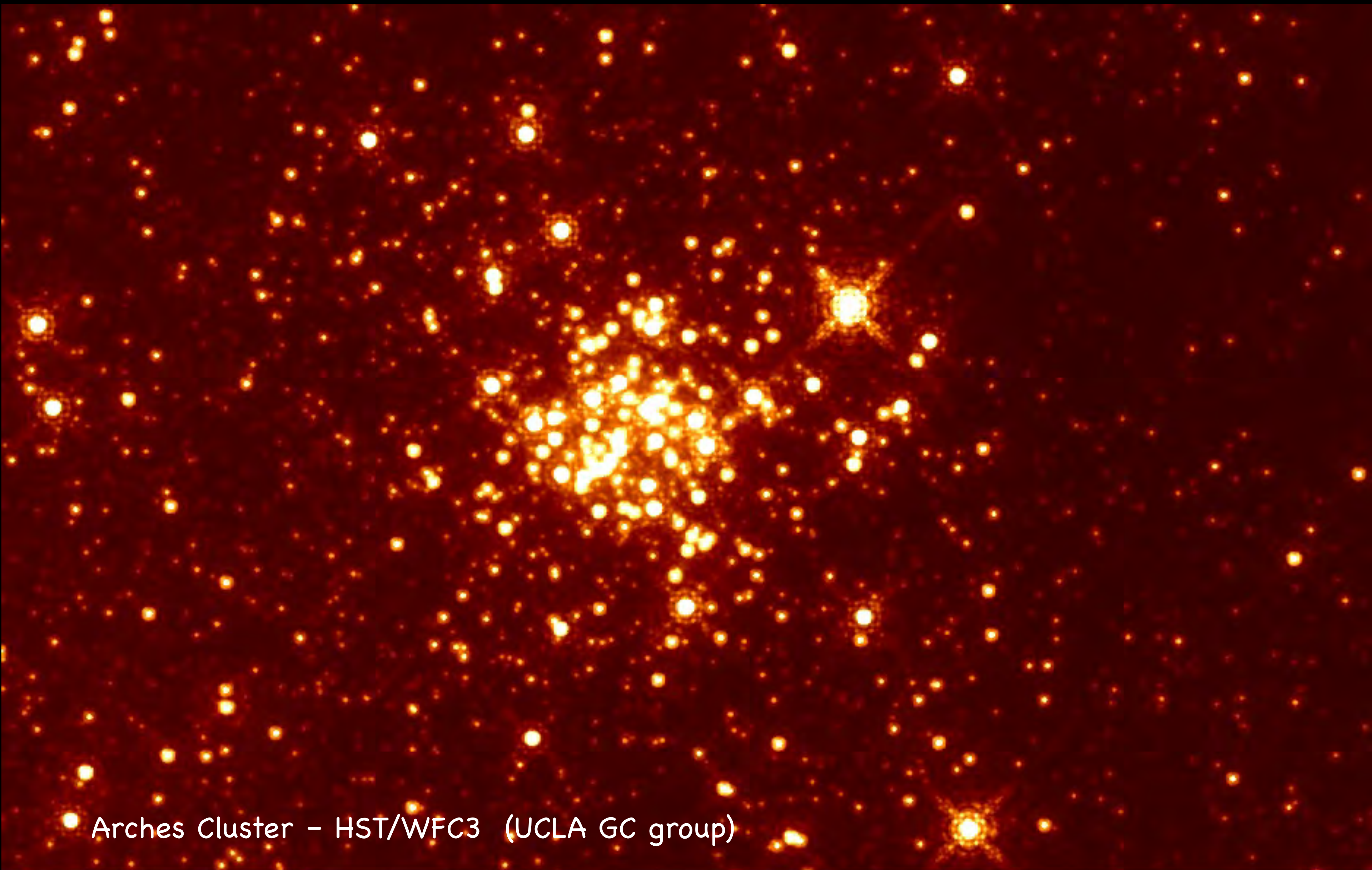
Lau, Herter, Morris, Adams 2014
see also Yusef-Zadeh+2010

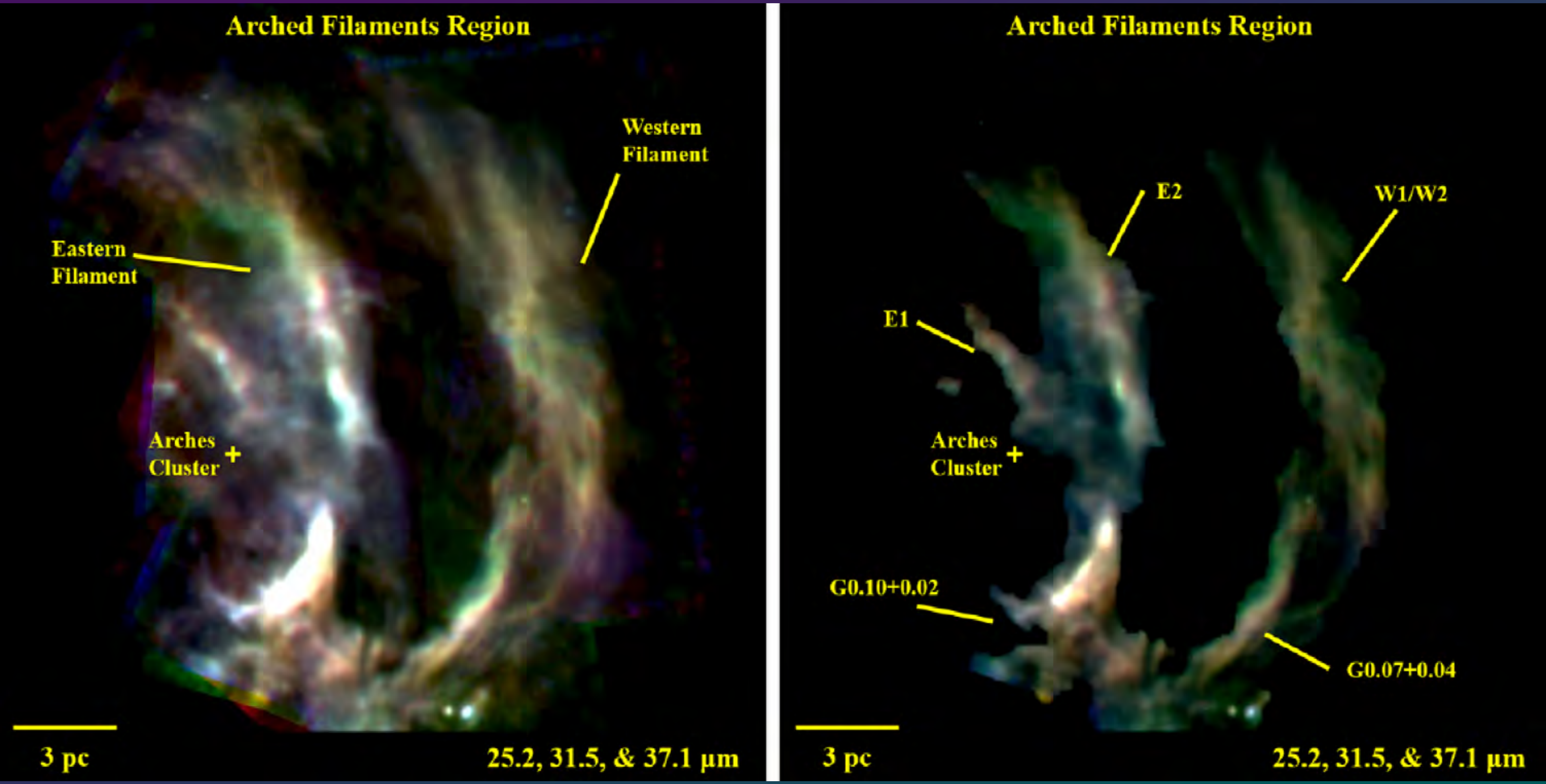
Massive stars have formed within the past 5 – 10 Myr,

some isolated and distributed ……

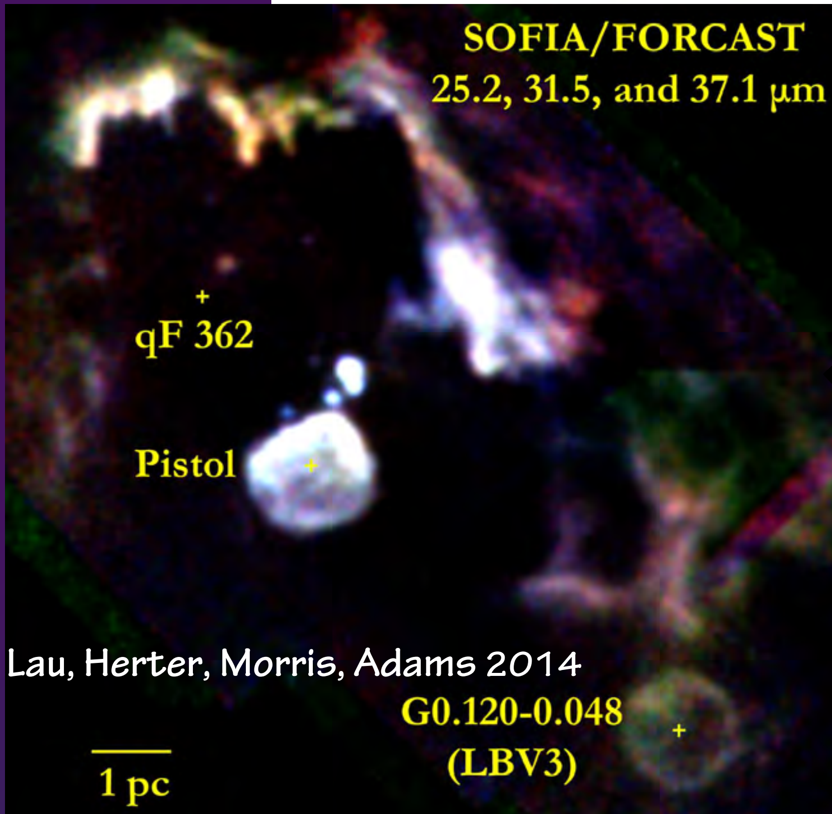


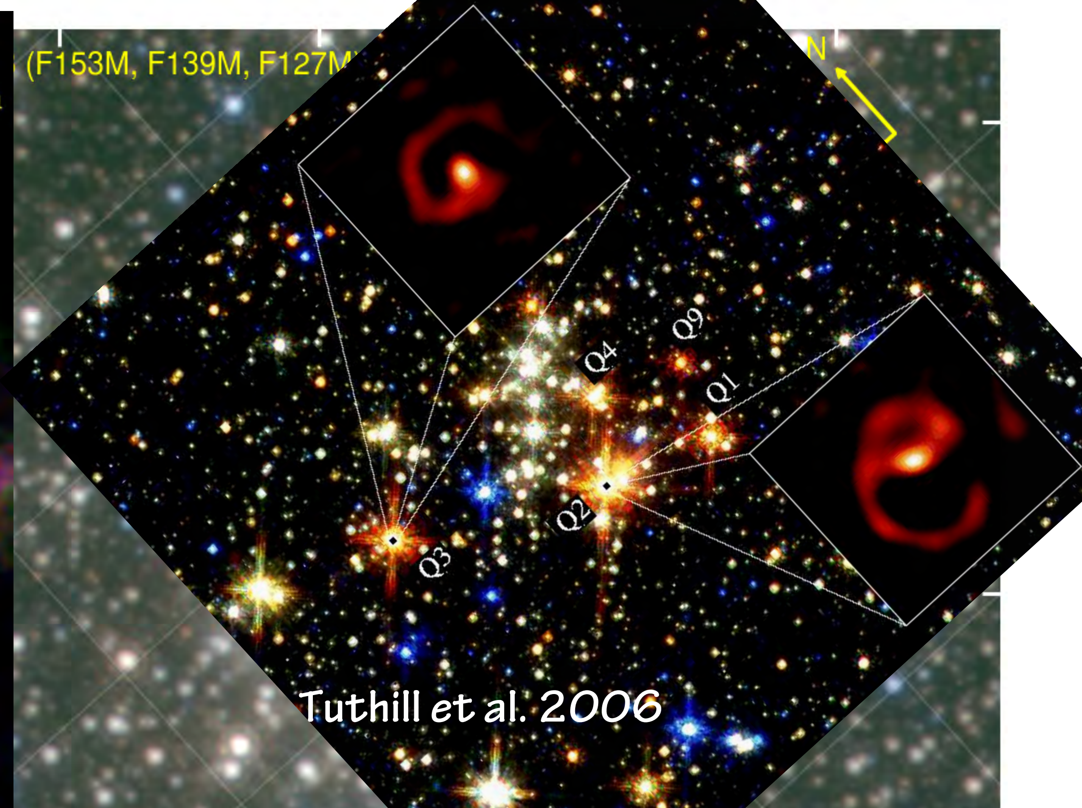
And some in massive clusters …

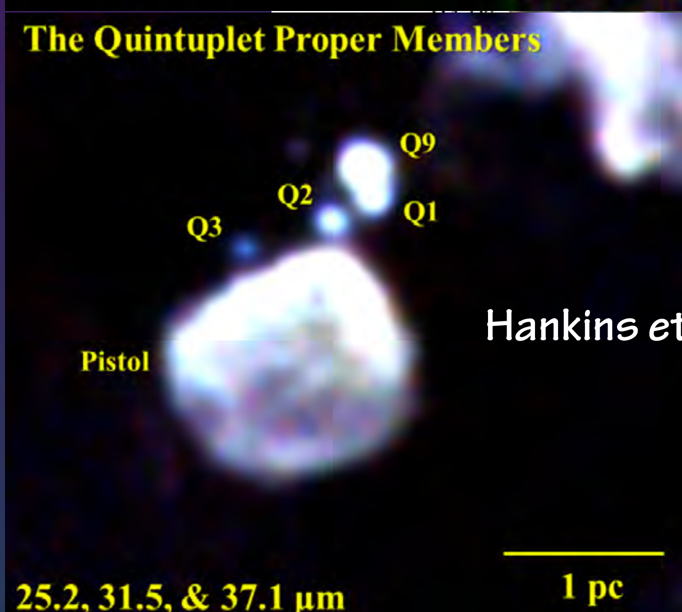


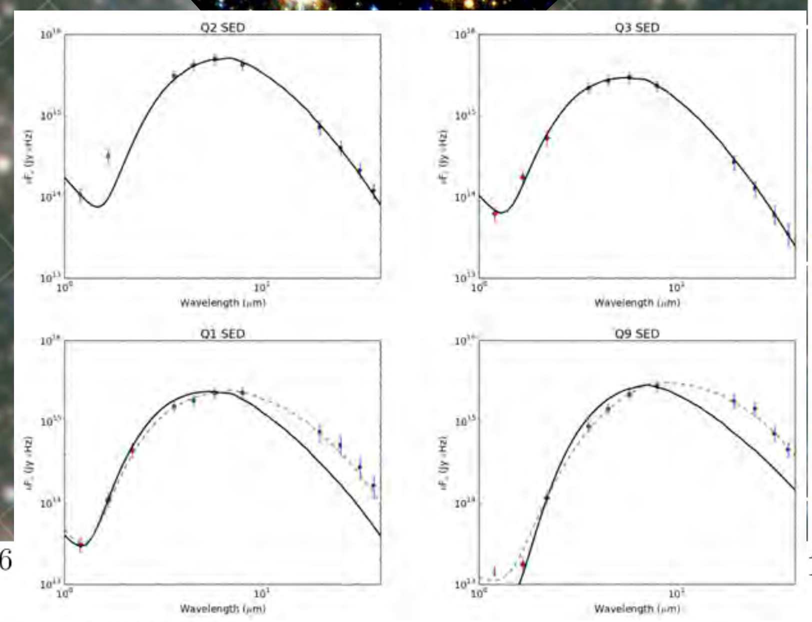


Hankins et al. *See poster* …. SOFIA/FORCAST

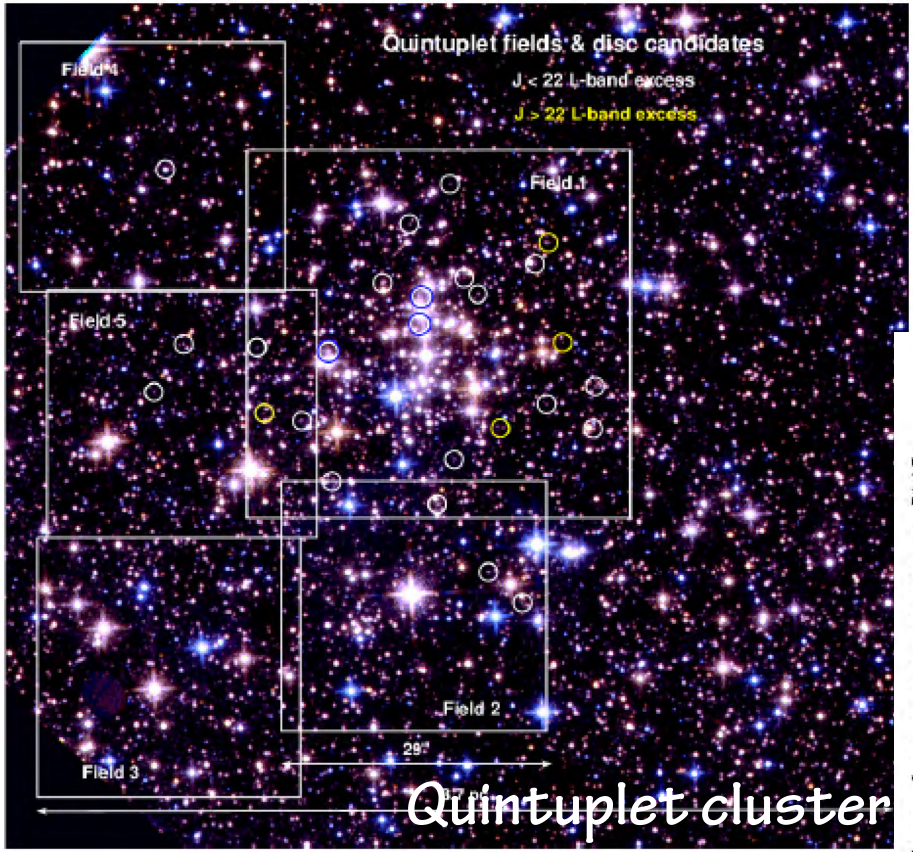

SOFIA/FORCAST
25.2, 31.5, and 37.1 μm
qF 362
Pistol
Lau, Herter, Morris, Adams 2014
G0.120-0.048
(LBV3)
1 pc

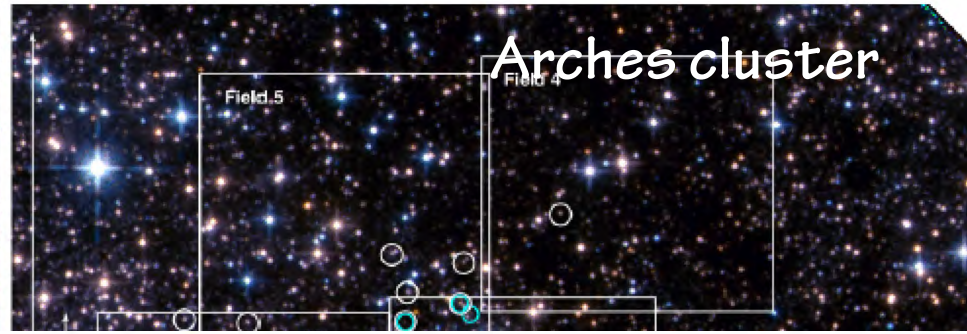

(F153M, F139M, F127M
N
Q9
Q4
Q1
Q2
Q3
Tuthill et al. 2006
17.0s
16
15.0s

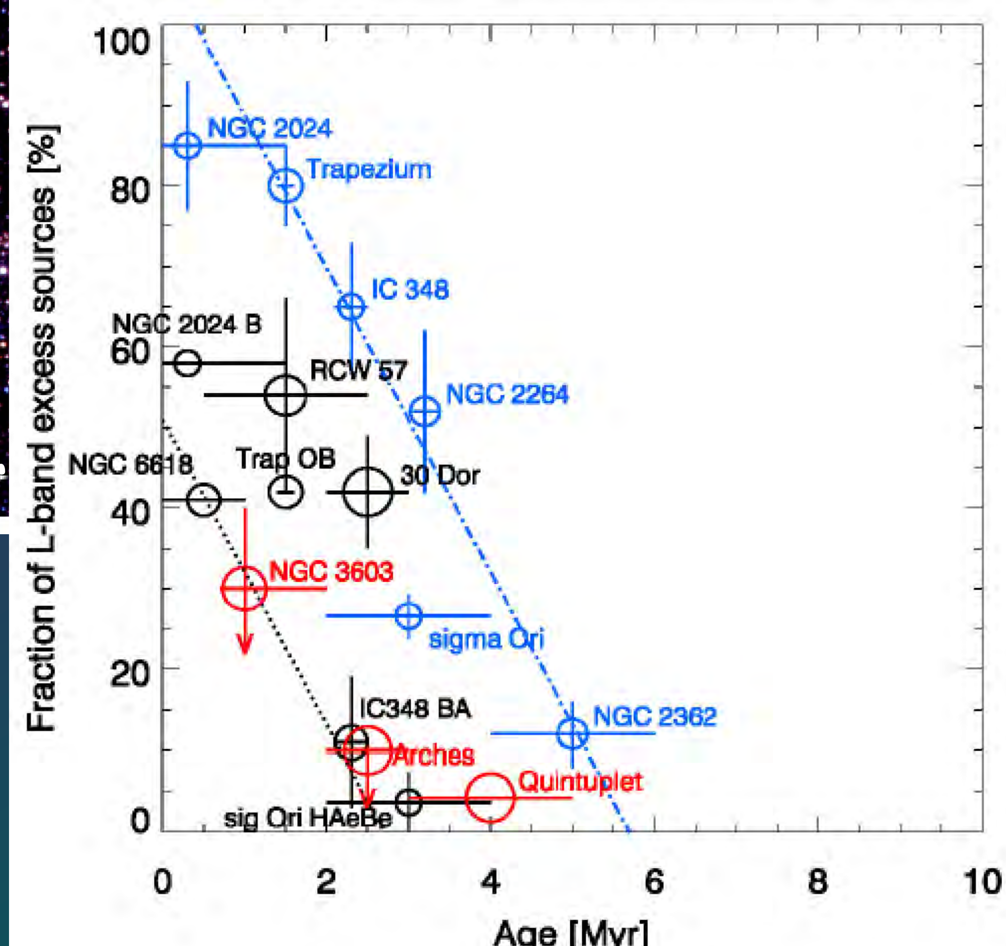

The Quintuplet Proper Members
Q9
Q2
Q1
Q3
Pistol
Hankins et al. 2016
1 pc
25.2, 31.5, & 37.1 μm


Q2 SED
Q3 SED
Q1 SED
Q9 SED
Wavelength (μm)

Circumstellar disks in the massive young GC clusters





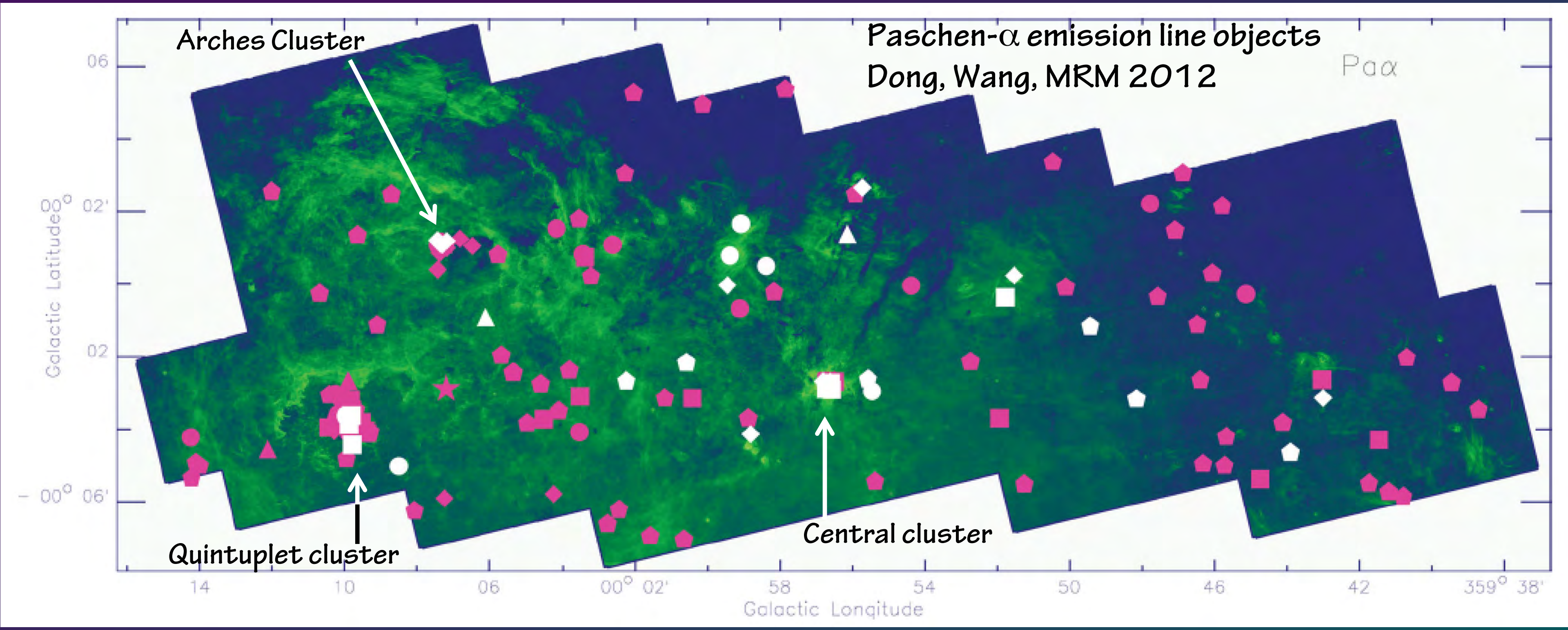


Stolte et al. 2015

Disks around 2 < M < 15 $M_\odot$ stars

- Primordial?
- Mass-transfer disks in binaries?

Overall massive star distribution…



White: massive stars with X-ray counterparts, presumably colliding-wind binaries

Pink: WNL, WNE, WC, OB supergiants, LBVs

Mauerhan 2010 → There are about as many isolated massive stars as there are stars in clusters

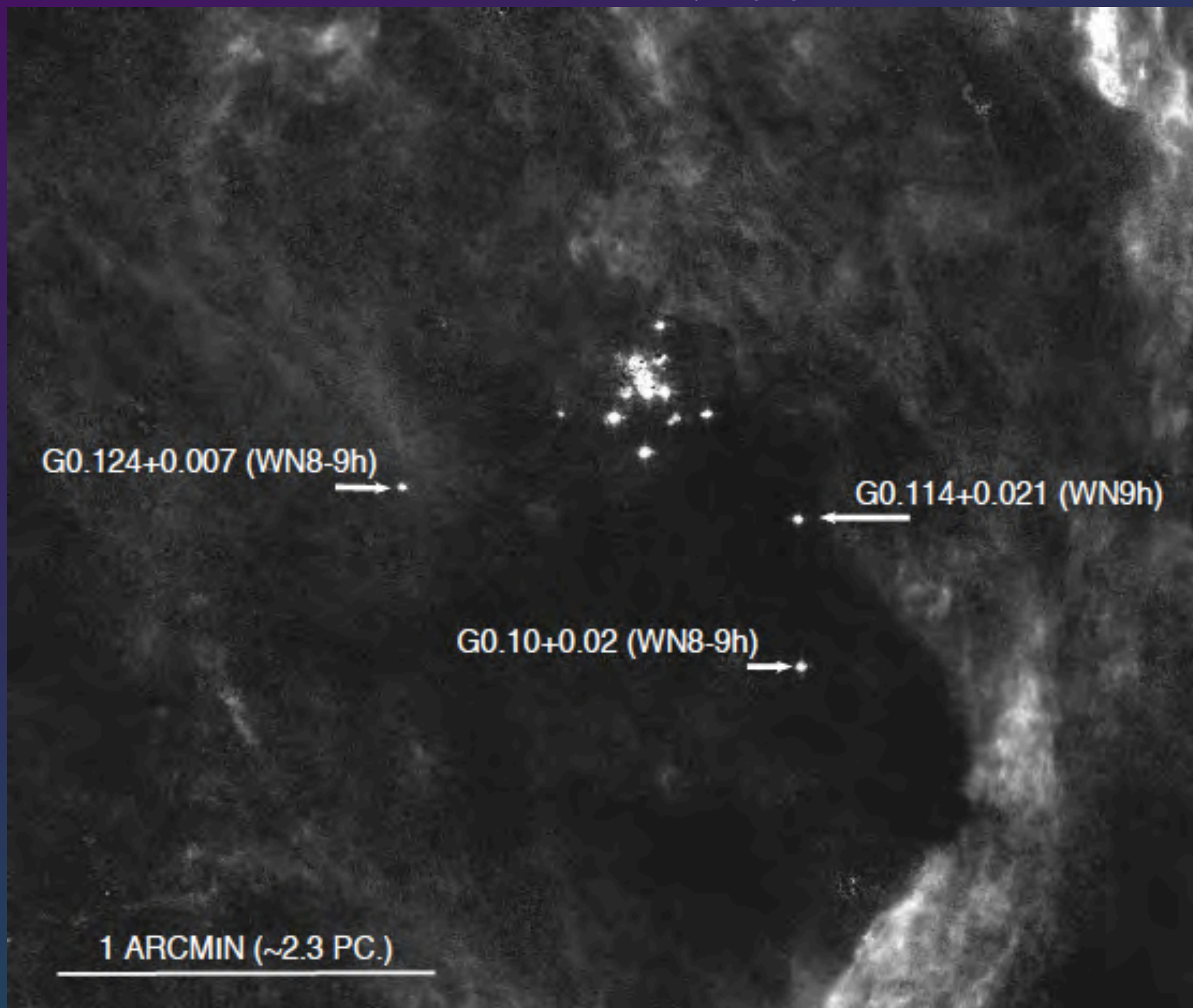
Outstanding question → are they escapees from the evaporating clusters?

Are the isolated stars escapees from cluster?

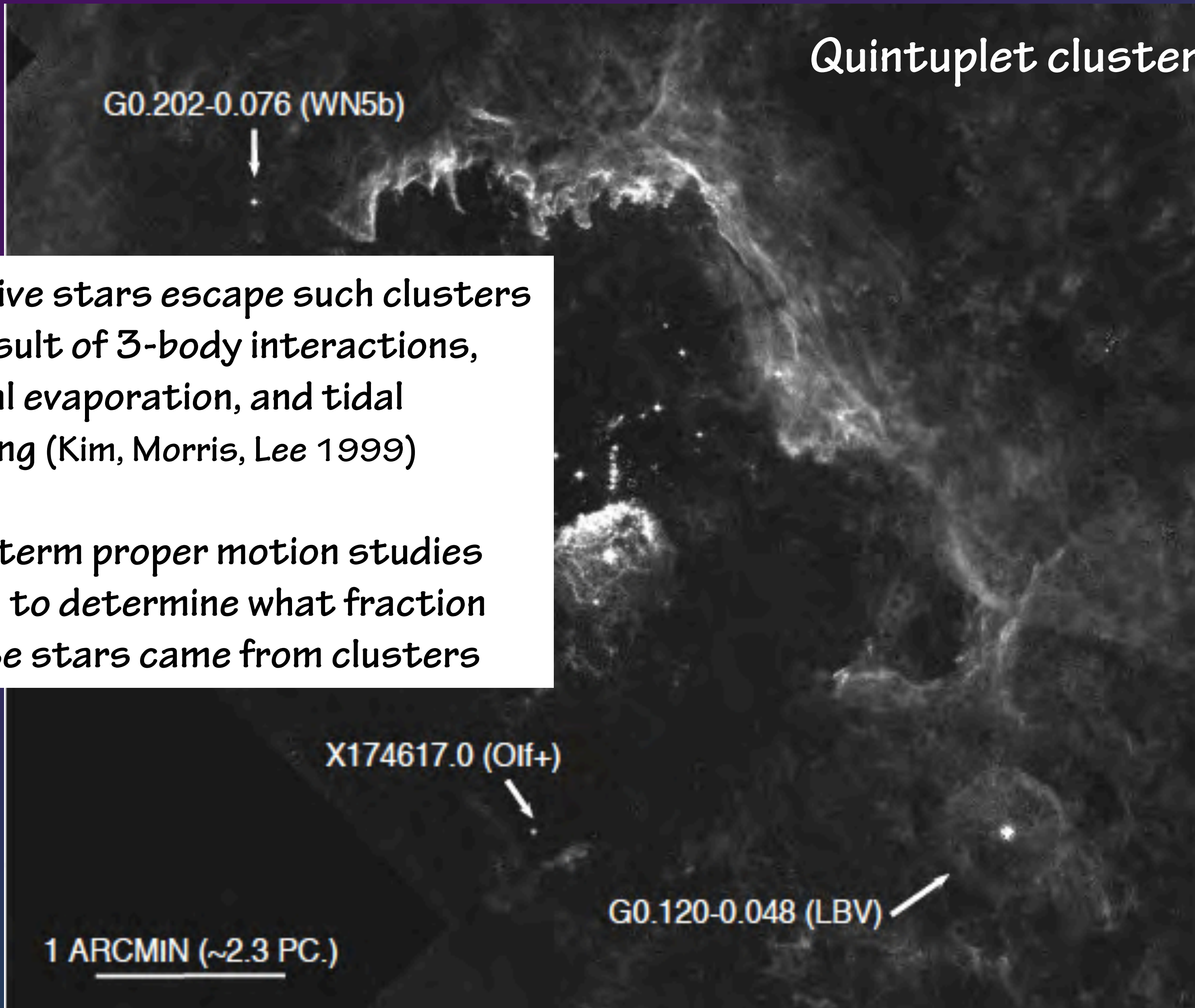
Several of the isolated stars are located near the massive clusters, which raises the question of whether they have escaped from the clusters

Mauerhan et al. 2010

Arches:



Quintuplet cluster

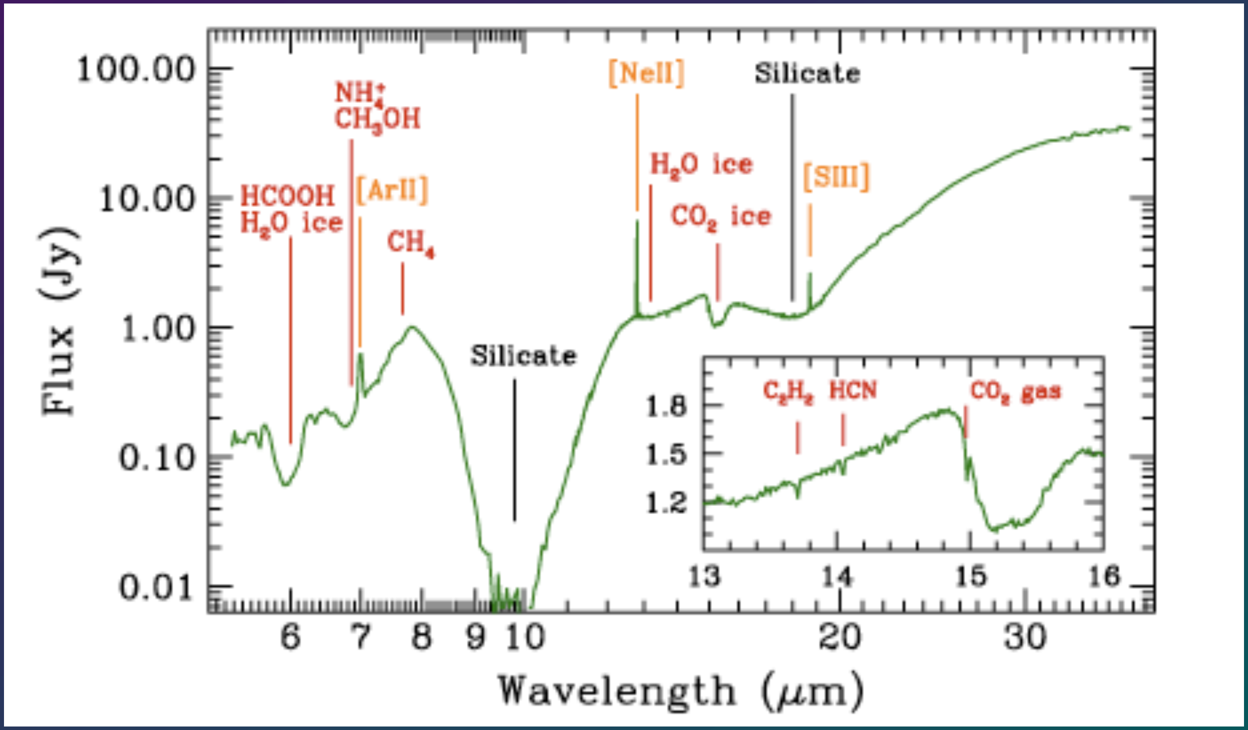


- Massive stars escape such clusters as a result of 3-body interactions, thermal evaporation, and tidal stripping (Kim, Morris, Lee 1999)

- Long-term proper motion studies needed to determine what fraction of these stars came from clusters

Protostars

First massive YSO's in the GC:
Deokkeun An et al. (2009) using Spitzer IRS –
3 protostar candidates with ice features characteristic of protostellar sources

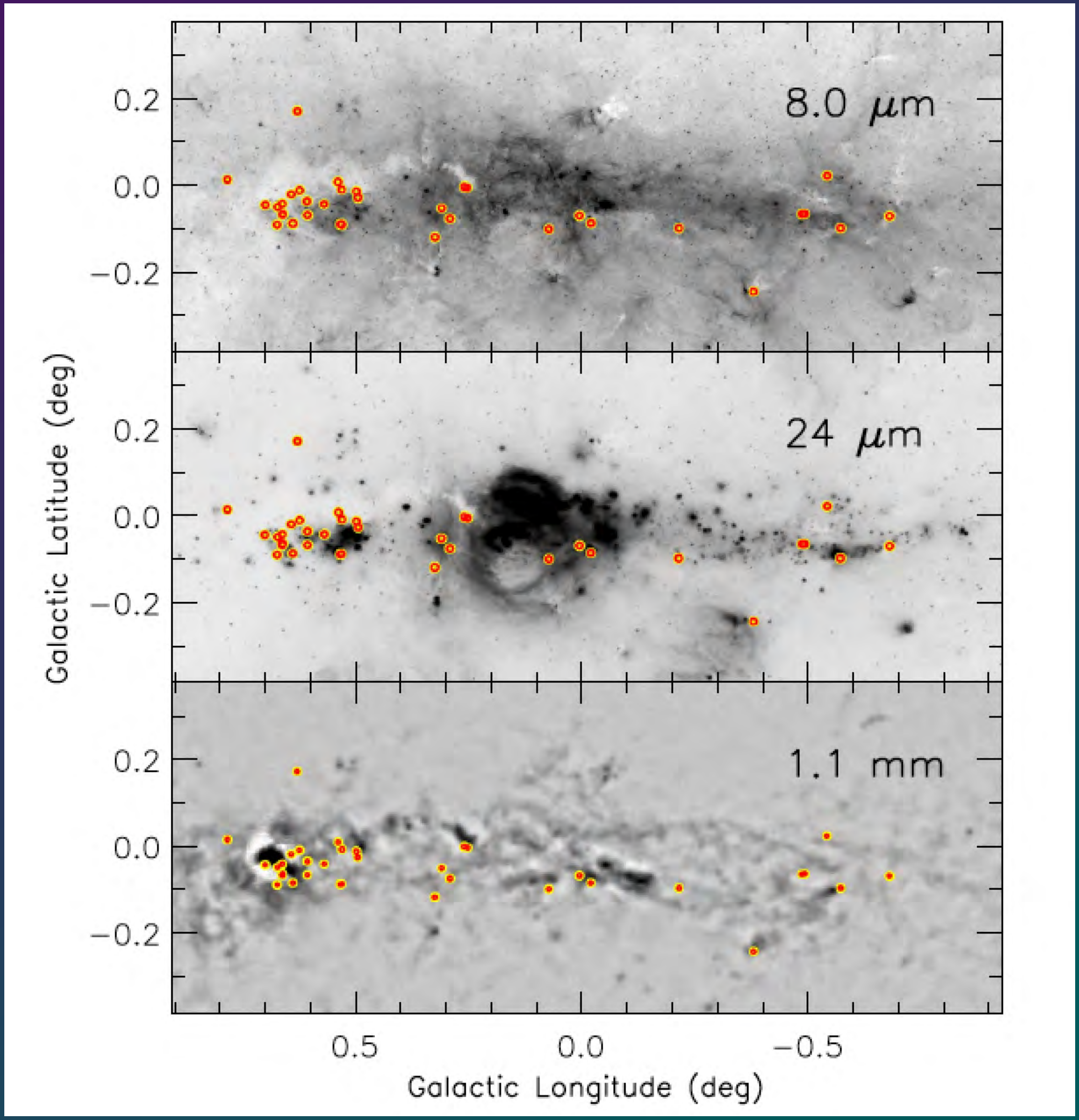


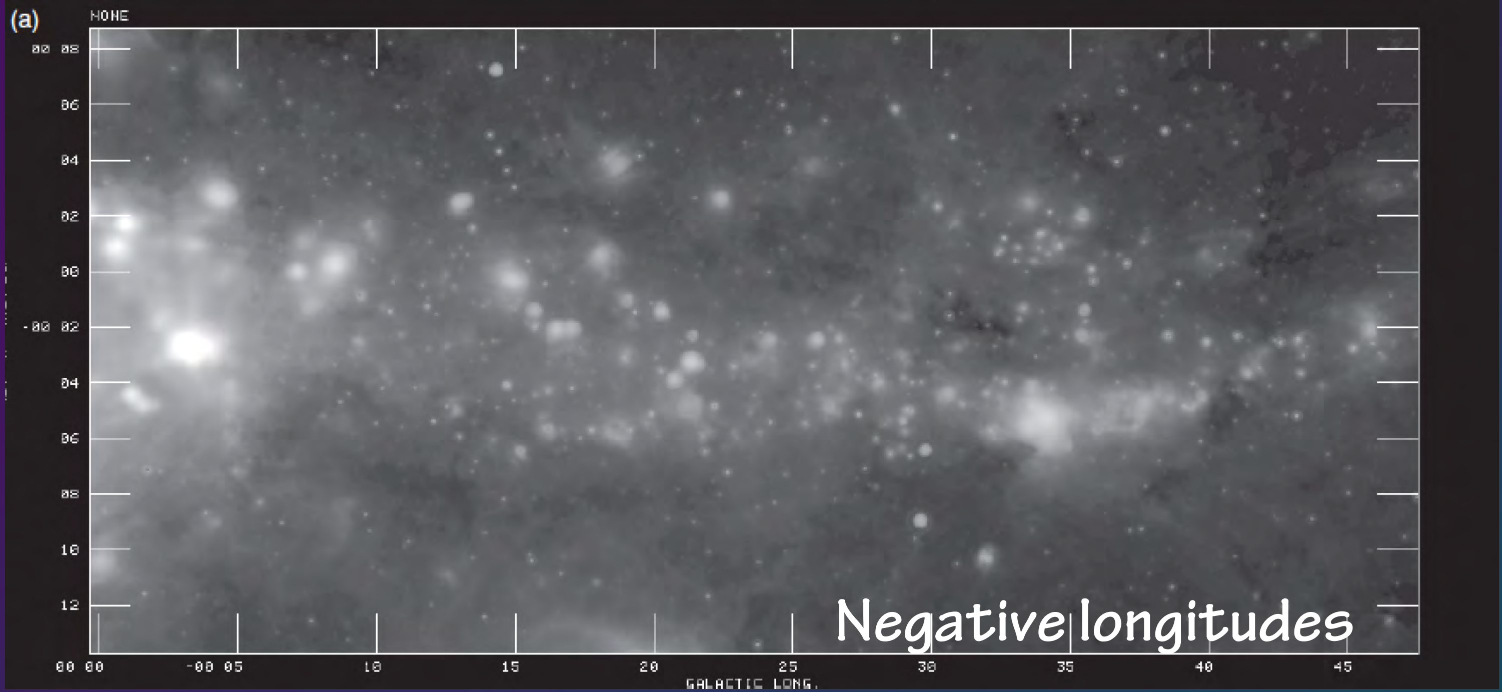
→ Evidence for isolated massive star formation

An et al. 2011: 16 YSOs and 19 possible YSOs from among 107 IRS targets in the GC

Masses: 8 – 23 $M_\odot$

Estimate GC SFR of $0.07\ M_\odot/yr$

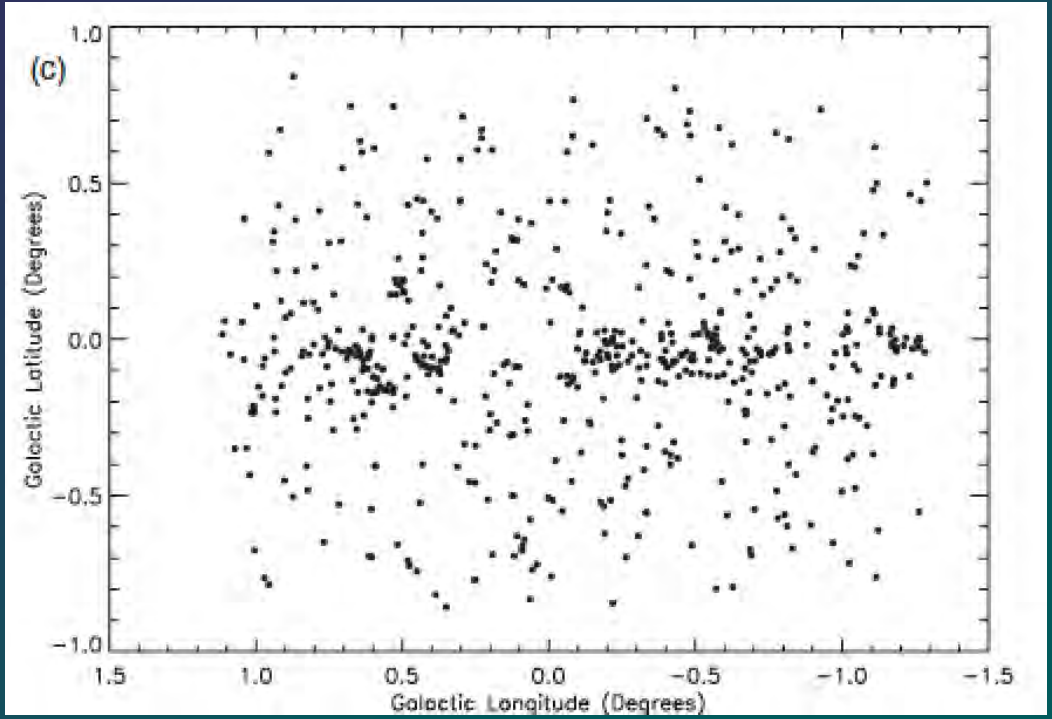


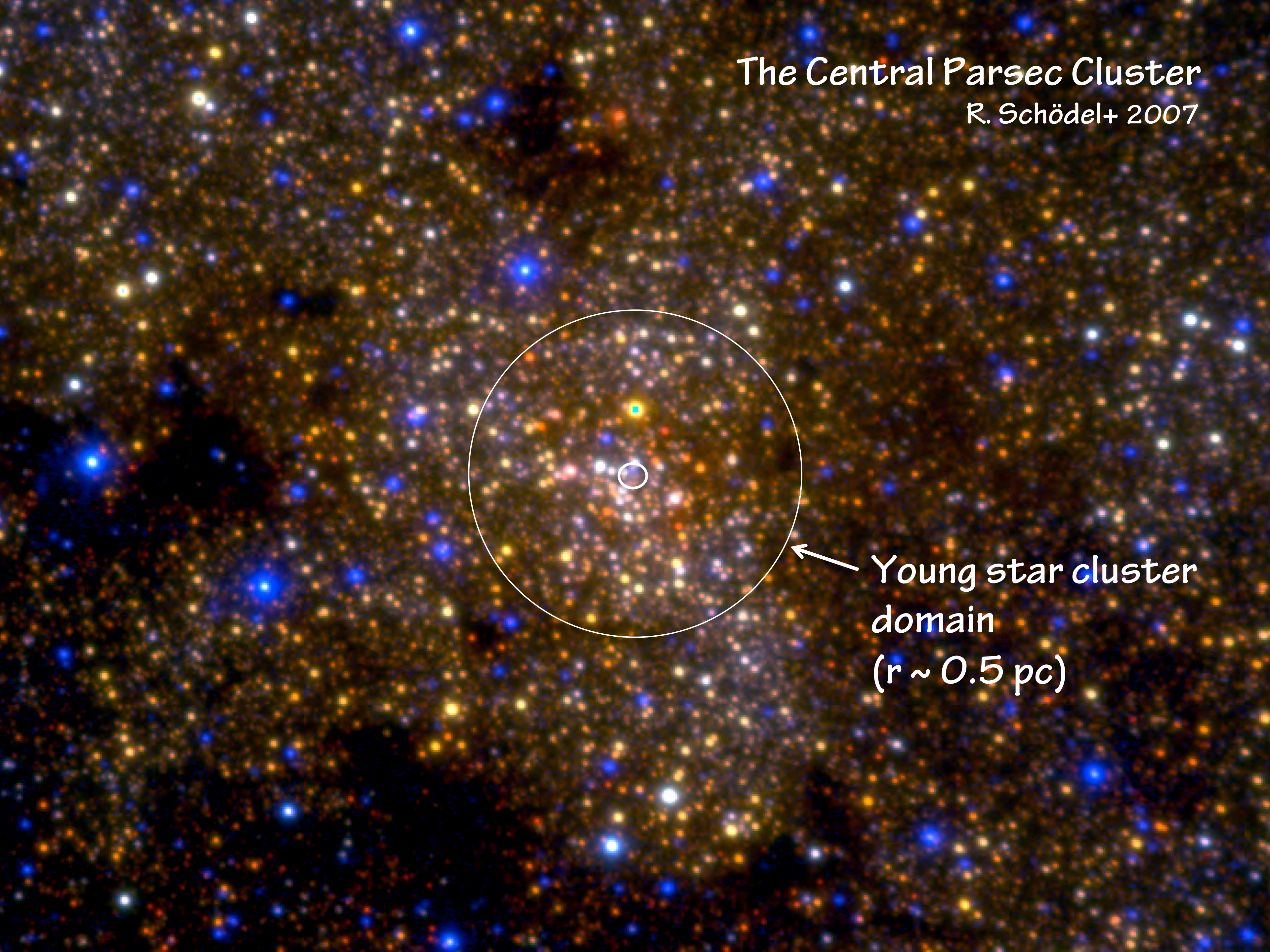


Yusef-Zadeh et al.2009

24 μm MIPS point sources

YSO's ???



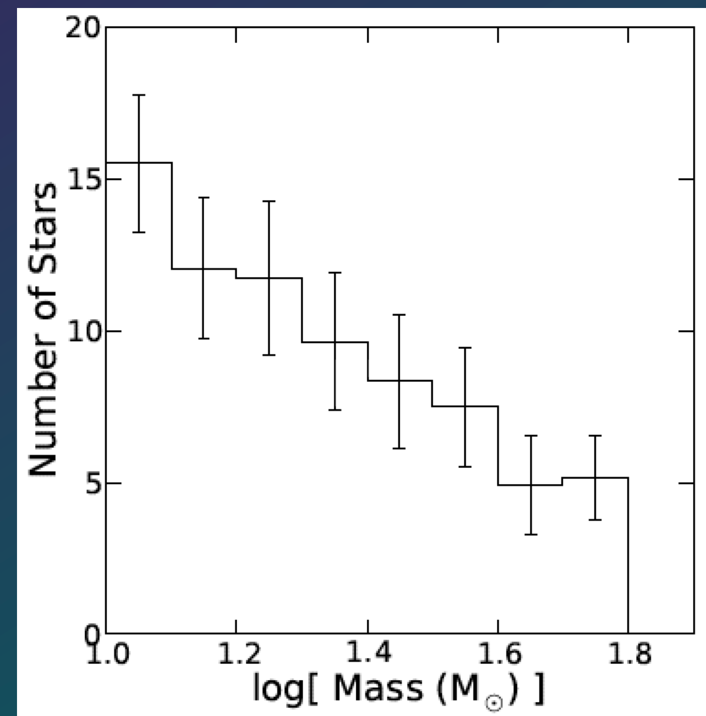

The Central Parsec Cluster
R. Schödel+ 2007
Young star cluster
domain
(r ~ 0.5 pc)

The central cluster

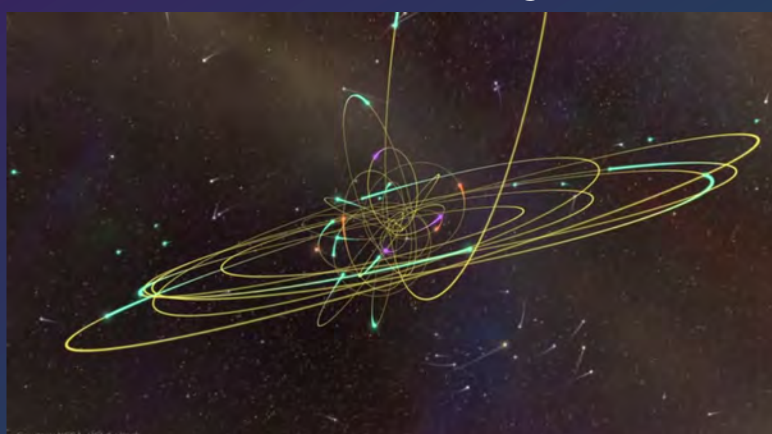
(from Jessica Lu+ 2013, Tuan Do+ 2013, & Sylvana Yelda + 2014)

- Young stars distinguished from old using AO spectroscopy
- Consistent with being coeval, at an age of 4 Myr
- Mass ~ $2.5 \pm 1 \times 10^4\ M_\odot$
- Slightly top-heavy: $\alpha = 1.7$ →

  $dN/dm \sim m^{-\alpha}$



- 20% of the stars are present in a clockwise-moving disk



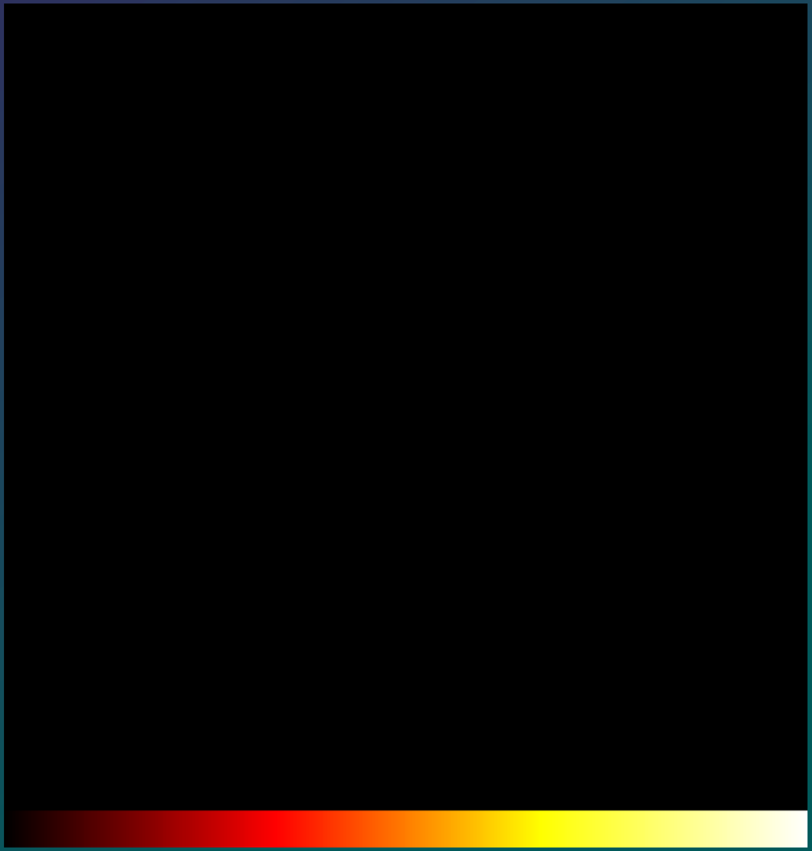
- Radial surface density profile: $\Sigma(R) \sim R^{-0.93}$, all within ~0.5 pc

How and where did the central cluster form?

Stellar density profile (~r^{-2}) rules out the inspiralling cluster hypothesis of Gerhard 2001 (Stostad+ 2015)

→ *in situ* hypothesis remains… two basic possibilities:

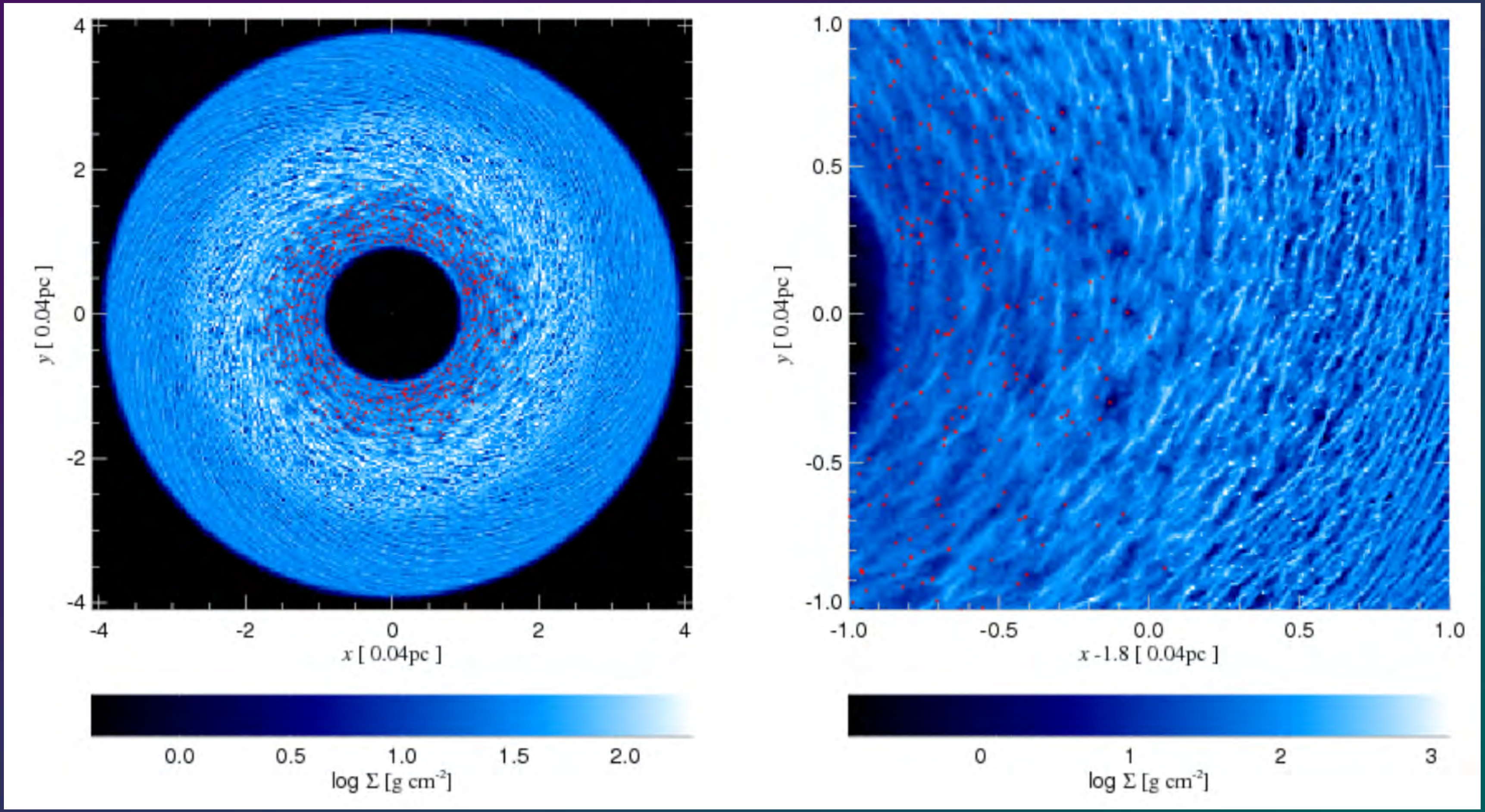
1) Infalling or colliding cloud
(Bonnell & Rice 2008; Hobbs & Nayakshin 2009; Mapelli et al. 2008; Wardle & Yusef-Zadeh 2008; Hobbs & Nayakshin 2009; Alig et al. 2011; Mapelli et al. 2012; Lucas et al. 2013; Alig et al. 2013)



The challenge →
getting a cloud to have essentially zero angular momentum

2) Accretion disk fragmentation

(Nayakshin+ 2007; Cuadra+ 2008; Alexander+ 2008)



Probems → doesn't reproduce the eccentricity distribution or the small fraction (20%) of stars presently in the disk.

A Limit Cycle, based on the assumption of a steady inward migration of gas toward the center:

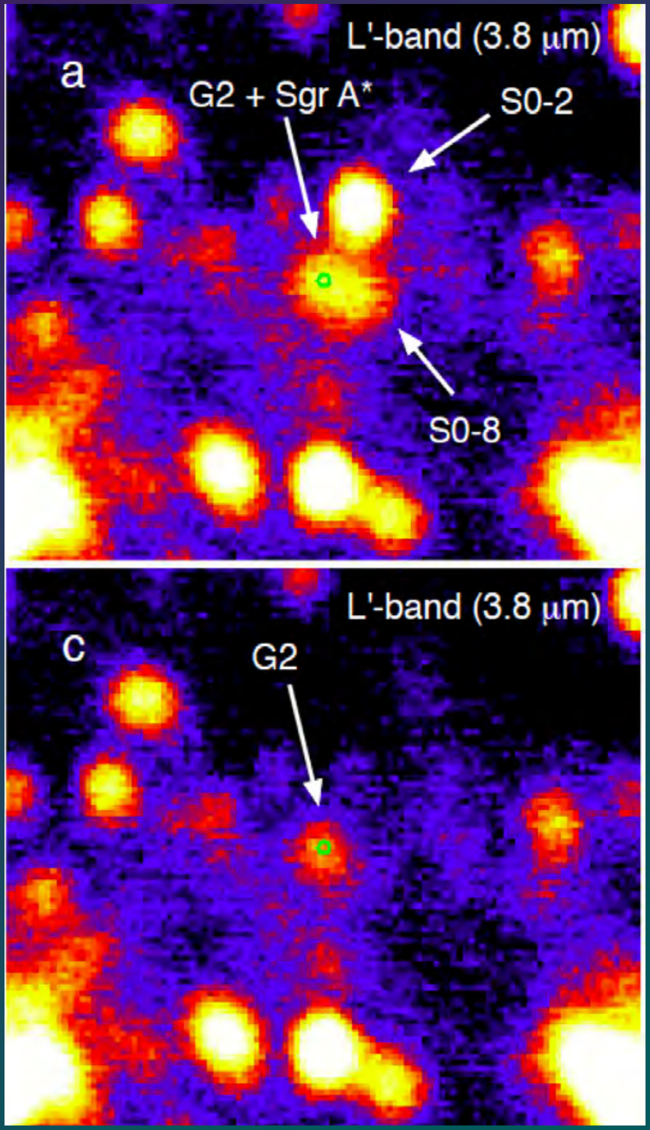
1. Disk
2. Starburst in disk, triggered by accretion onto central BH or by achieving critical surface mass density.
3. Central disk evacuated
4. Stellar winds, supernovae maintain central cavity (outer disk builds up)
5. Stellar winds fade out (~10^7 yrs)
6. Disk undergoes viscous evolution and migrates into cavity

Quasi-steady gas inflow

Stellar rejuvenation:
mergers caused by the Kozai-Lidov mechanism

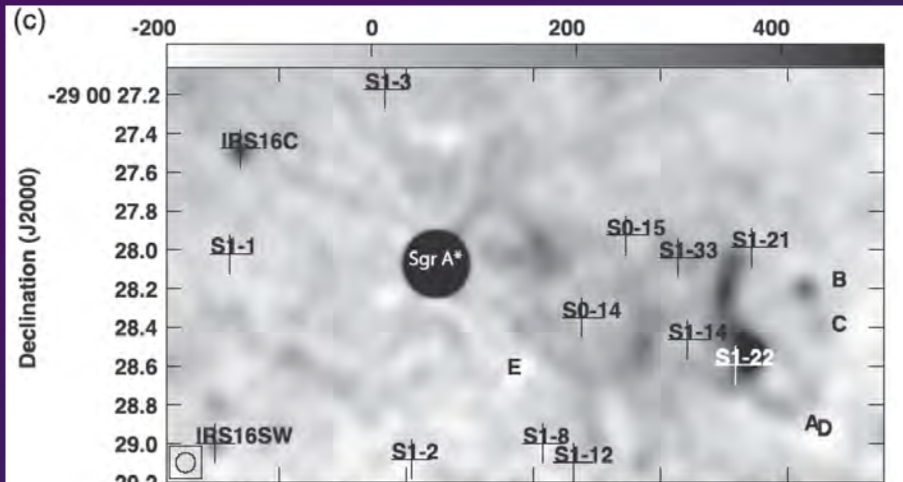
The famous G2 object is hypothesized by Witzel+14 to be a merger product resulting from the interaction of a binary with the black hole

This dust-enshrouded stellar object is not alone – studies of G1 by Sitarski+16 show it to have similar properties, and to have undergone clear tidal interactions with Sgr A*

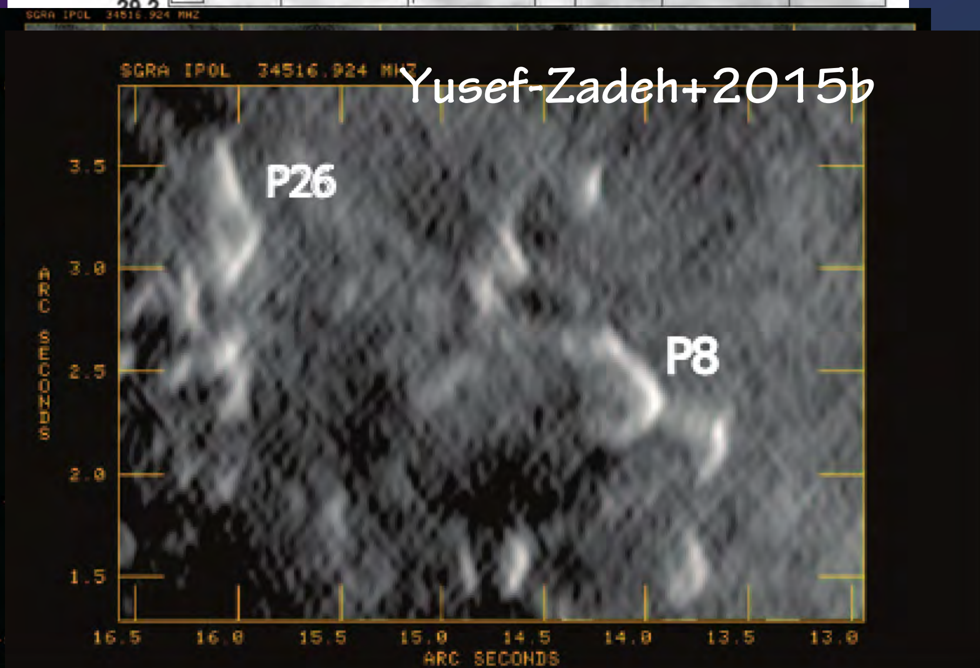


Current or Recent Star Formation in the Central Parsec ???

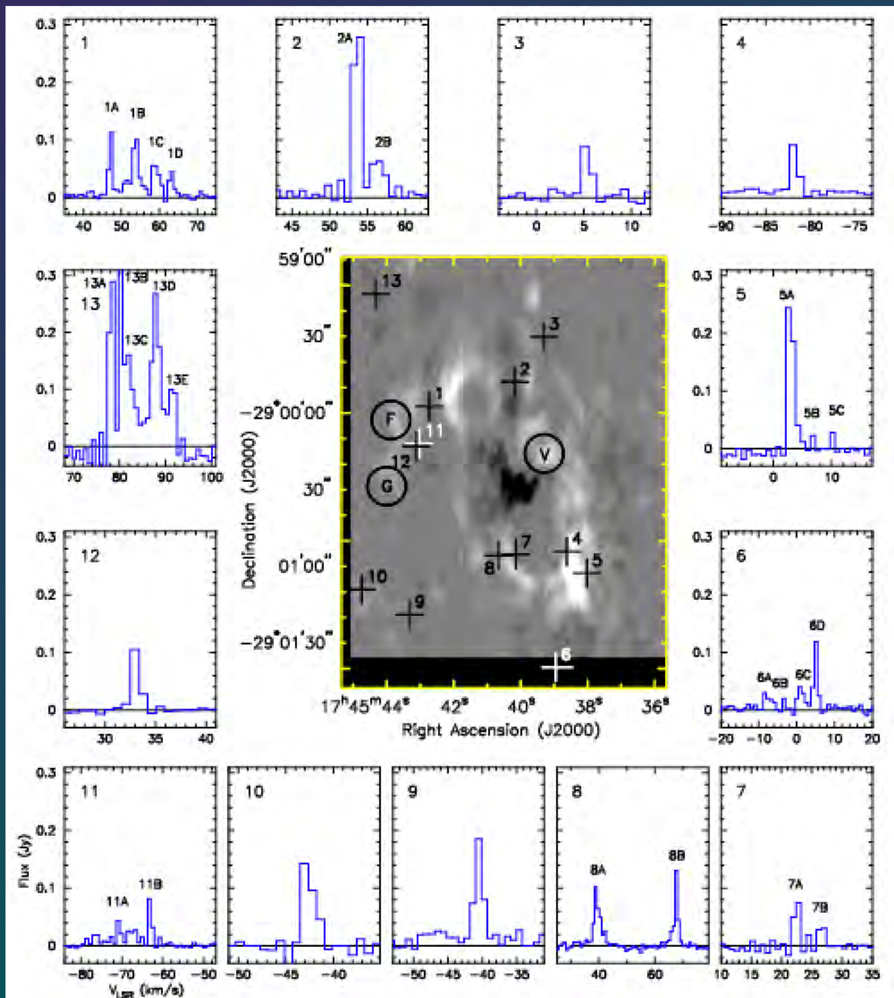
Yusef-Zadeh et al. 2016



Yusef-Zadeh+2015b



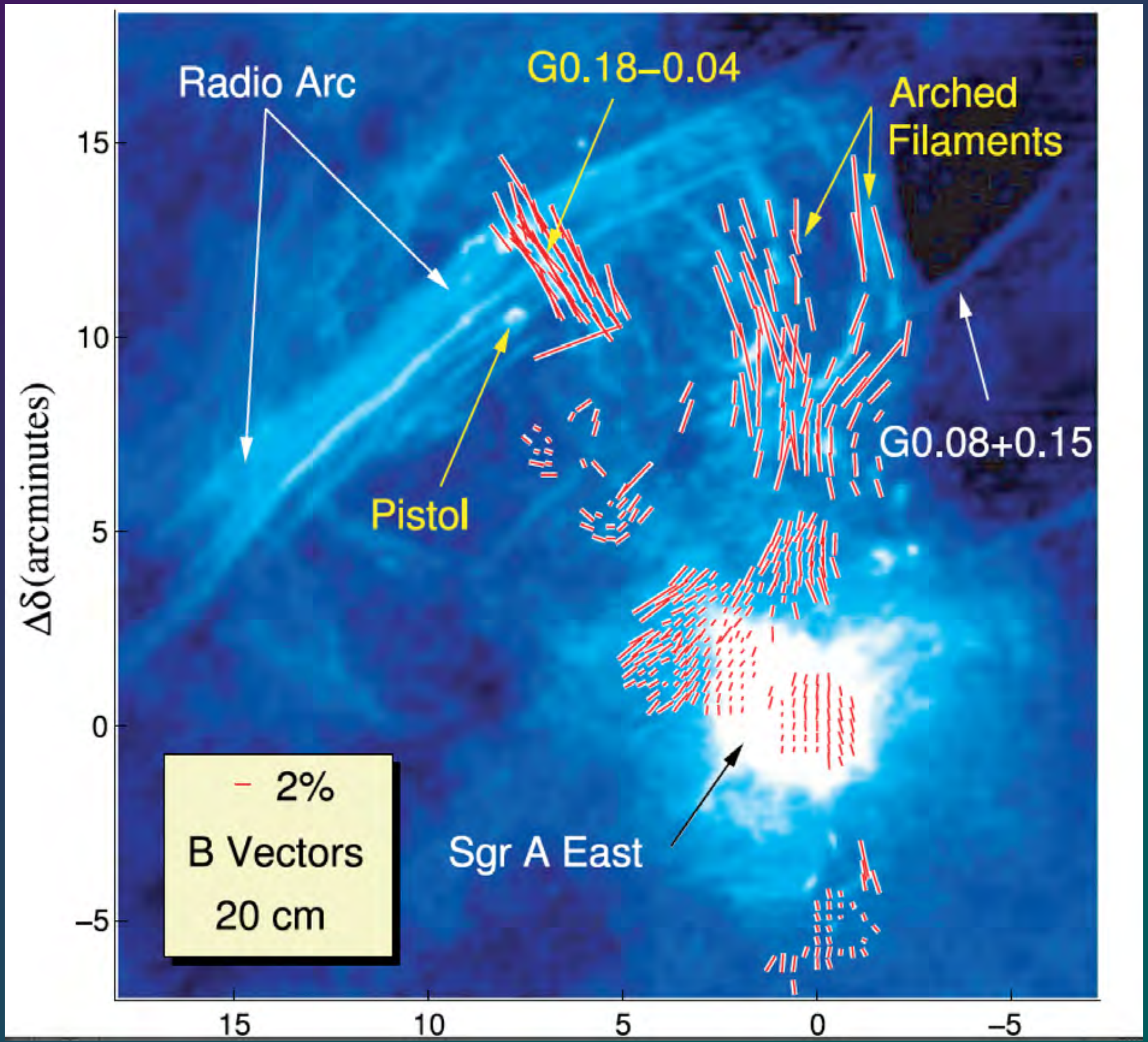
Yusef-Zadeh+ 2015: masers



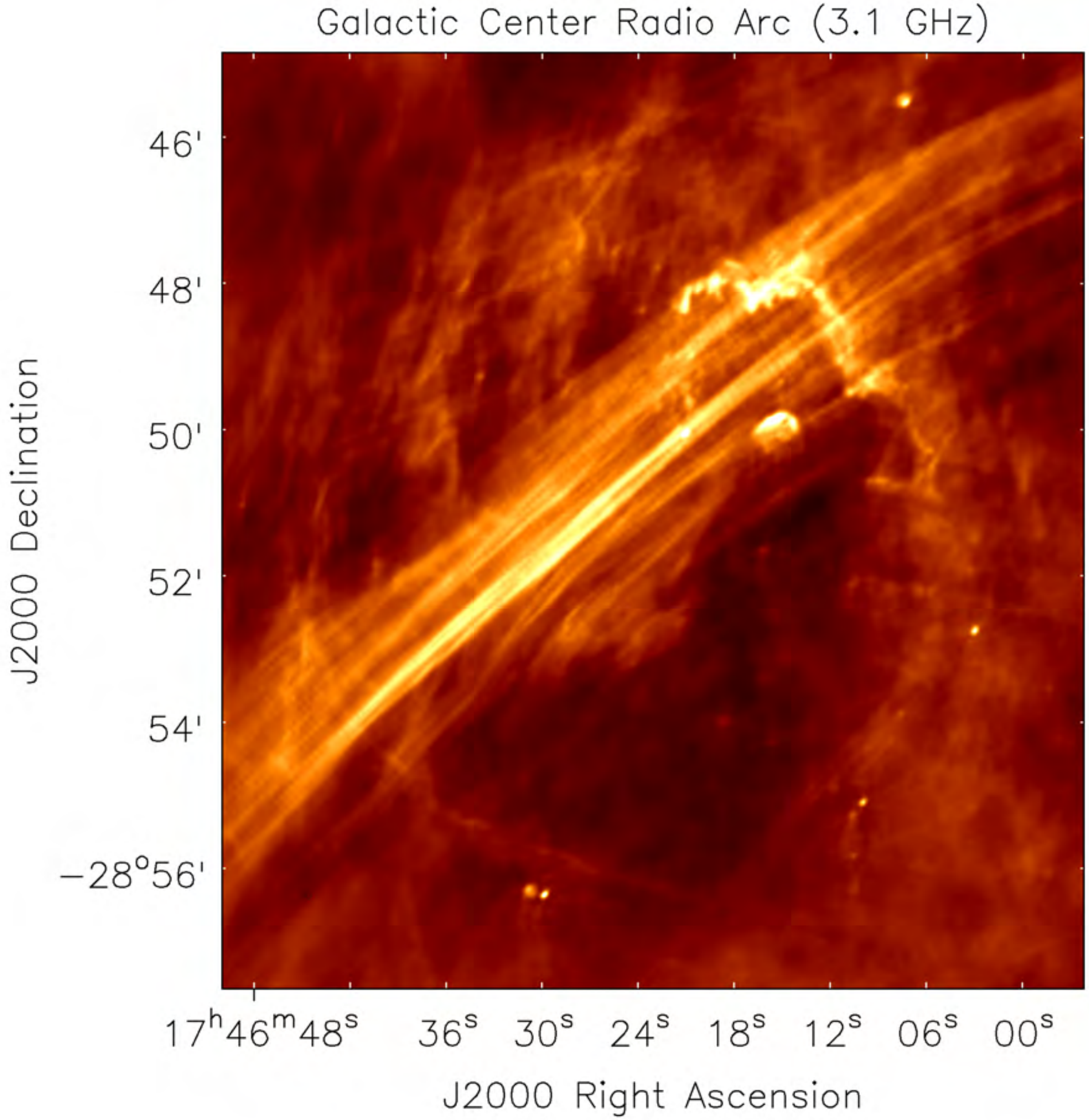
Magnetic Fields are Very Important !!!!!

Chuss et al. 2002

The HAWC+ era is now upon us !



The Radio Arc, ~ 40 pc from Sgr A* -- Cornelia Lang et al.



Thanks !