Triggered Star Formation on the Thermal Radio Arches of the Galactic Center Bubble (?)

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Based on the manuscript by Molinari, Noriega-Crespo, Testi, Bally et al. 2013

Based on parallel PACS/SPIRE Herschel Observations of the OTKP HiGAL

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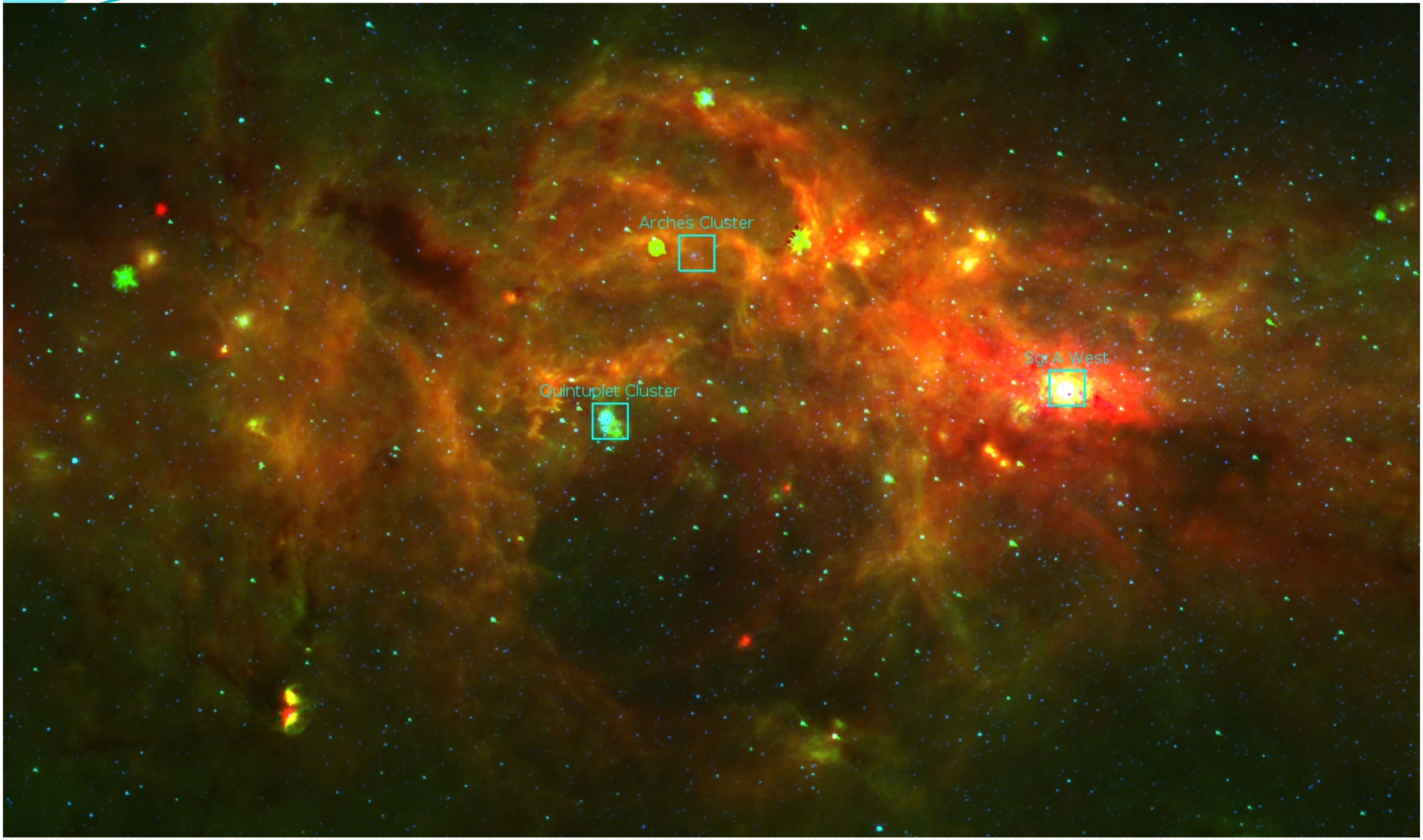
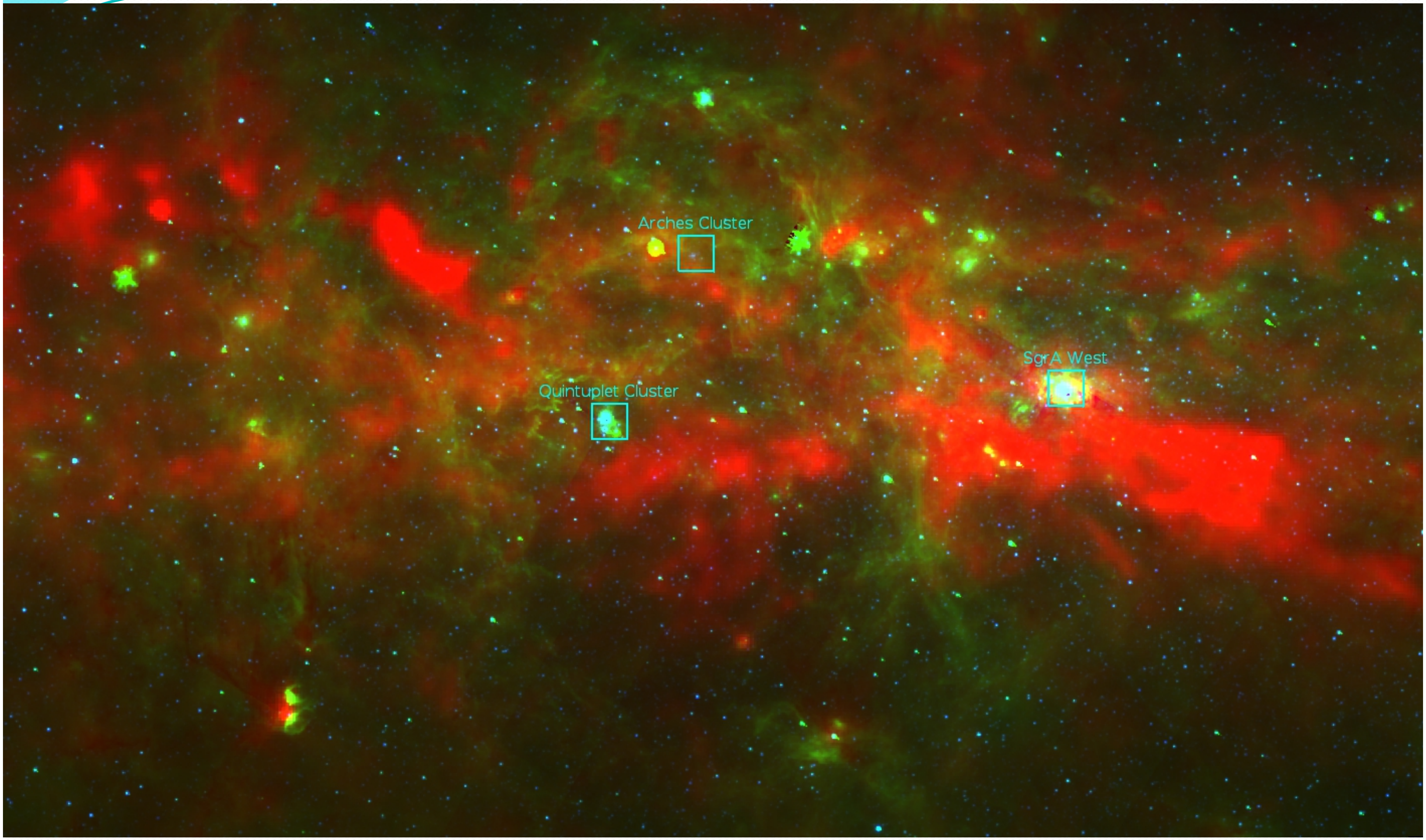
The Thermal Arches & Galactic Center Bubble



~0.7°×0.4°   4.6, 8 & 70μm

The Thermal Arches & Galactic Center Bubble



~0.7°×0.4° 4.6, 8 & 250μm

Introduction

* Three major clusters with massive young stars in the GC

  Sgr A West,(Nuclear Cluster) & Arches and Quintuple (within 25pc projected distance)

  Arches: ~10^4 $M_\odot$ *(Stolte et al. 2002)* emits ~$10^{51.6}$ ionizing photons/s and ~2.5Myr old *(Figer et al. 2002)*.

  Quintuple: a bit smaller w/ $10^{50.9}$ s^{-1} and older ~4Myr old *(Figer et al. 1999)*.

* Enough ionizing flux to account for the thermal ionized gas within GCB *(Lang et al. 2001).*

  In the Thermal Arches the gas excitation decreases as one moves away

  from the Arches Cluster, i.e. consistent with photoionization and acting over distances of 7-13pc *(Rodriguez-Fernandez et al. 2001).*

* Around both Arches & Quintuple clusters there are molecular clouds with similar radial velocities to those of the ionized gas *(Serabyn & GÜsten 1987, 1991; Lang et al. 2002).*

* The ionized gas is most likely tracing the edges of these clouds *(Lang et al. 2001; Simpson et al. 2007).*

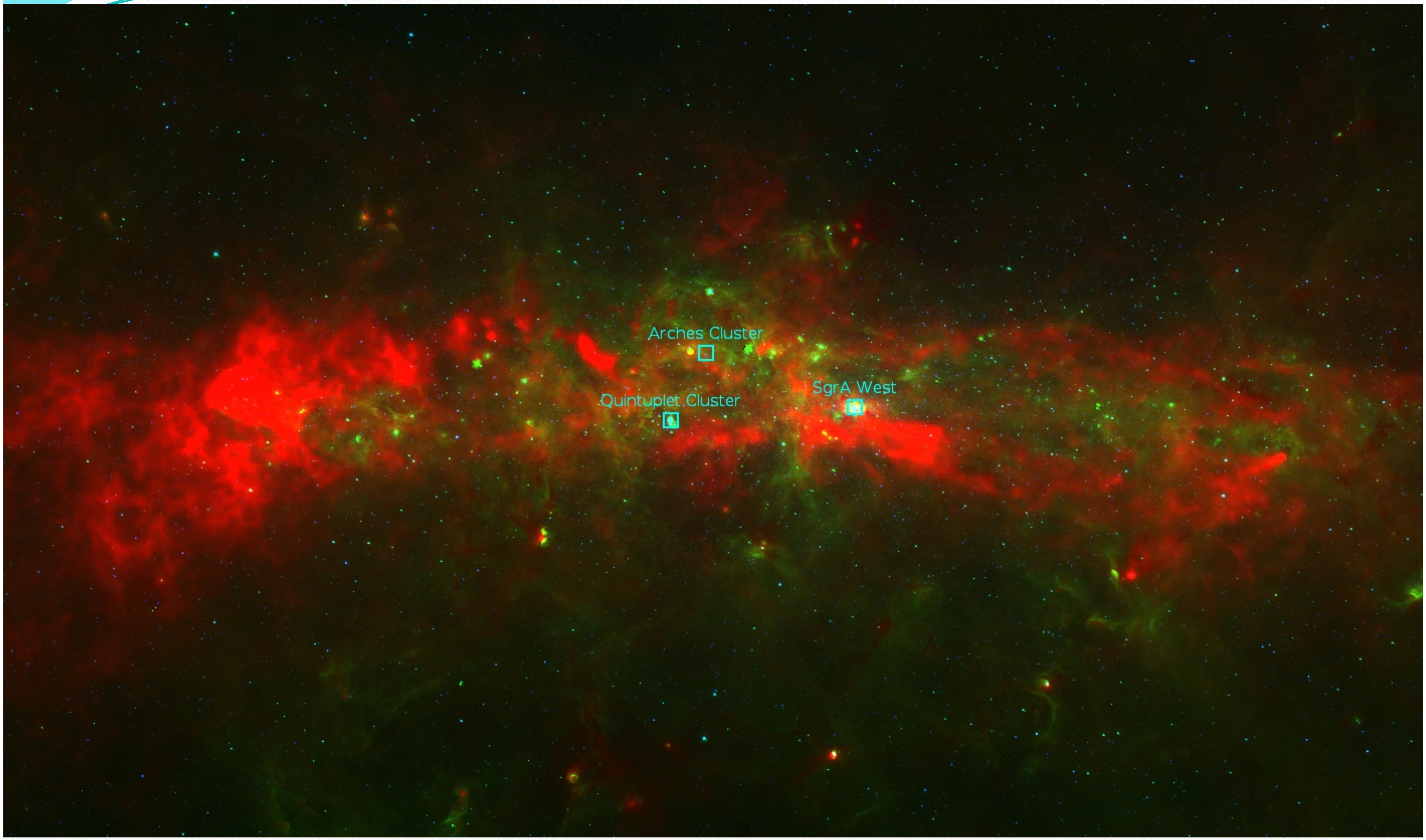
* Complex radial velocity distribution for stars and gas, and likely large differences between the line of sight distances between the star clusters and ionized gas *(Simpson et al. 2007; Stolte et al. 2008).*

* Even simple orbits around the GC (~1Myr period) implies they were formed somewhere else (and the orbits are not simple).

What's New?

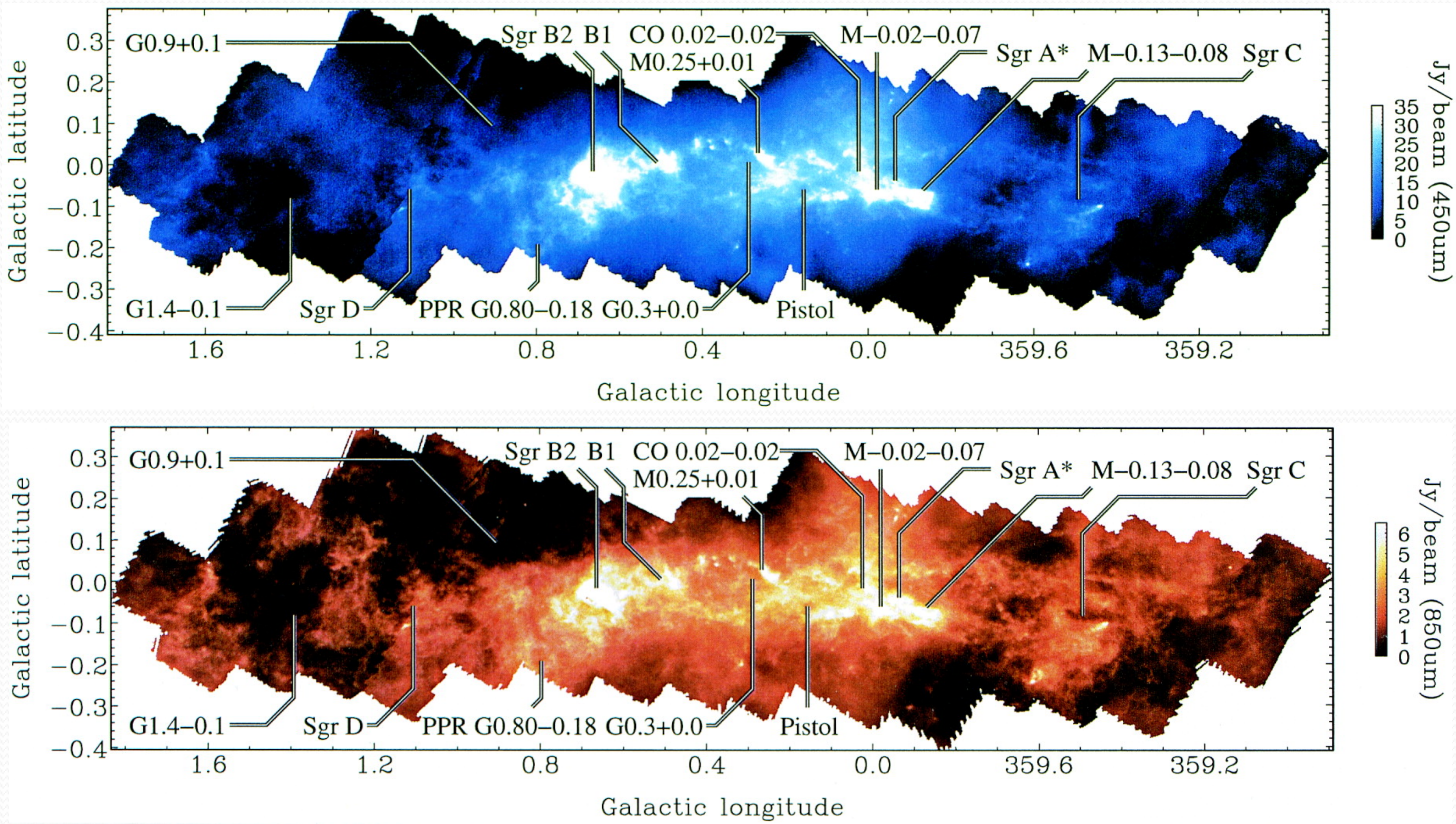
* A dense molecular gas ring (100pc-ring) with an orbital velocity ~80 km/s *(Molinari et al. 2011; Kim et al. 2011).*
* A more "elliptical symmetric" structure at 70um, the Galactic Center Bubble (GBC), i.e 'organized' structures *(Molinari et al. 2011).*
* Clear spectroscopic evidence of shocked excited emission (besides photoionization) *(Simpson et al. 2007; An, Ramirez & Sellgren 2013).*
* Large Proper motion of the Arches Cluster (~170 km/s) *(Stolte et al. 2008; Clarkson et al. 2012).*
* Bright compact condensations at 70um similar to those objects we believe to be massive YSOs in HiGAL Survey*(Elia et al. 2010; Veneziani et al. 2012).*
* More evidence of dense gas (HCN; $10^6 cm^{-3}$) around the GCB *(Jones et al. 2012).*
* "Statistical evidence" of triggered massive SF in the Spitzer mid-IR bubbles *(322 bubbles - 14-30% Thompson et al. 2012; 102 bubbles - 25% Deharveng et al. 2012).*

Herschel "100-pc Ring"



~1.7°×1° 4.6, 8 & 250μm

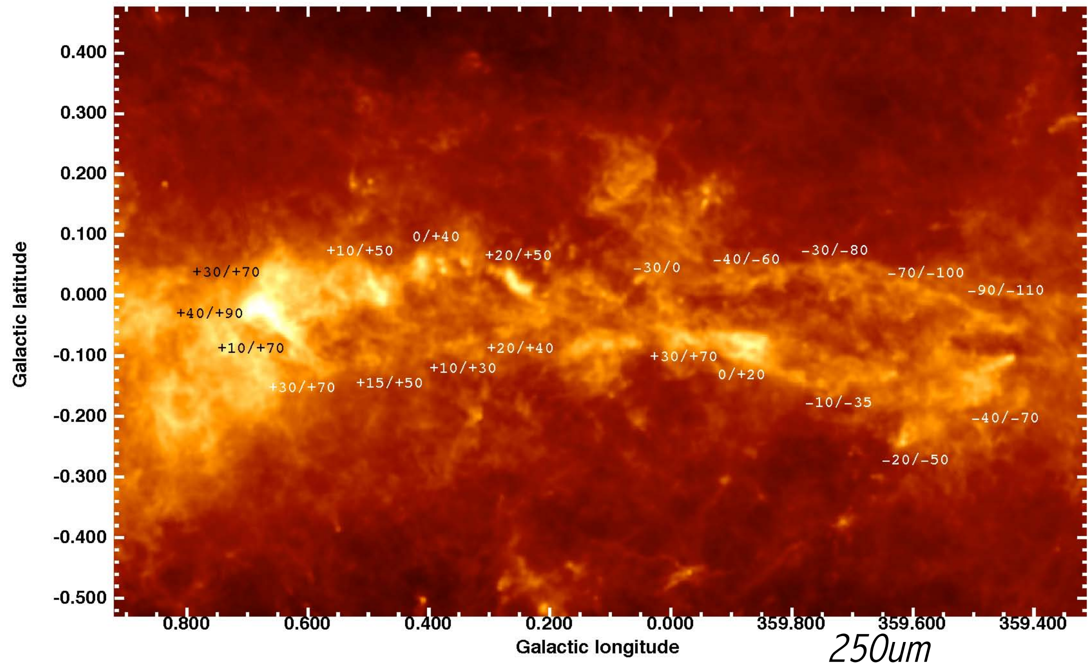
SCUBA GC Observations



450 & 850 um; Pierce-Price et al. 2000

Herschel GC 100pc Ring

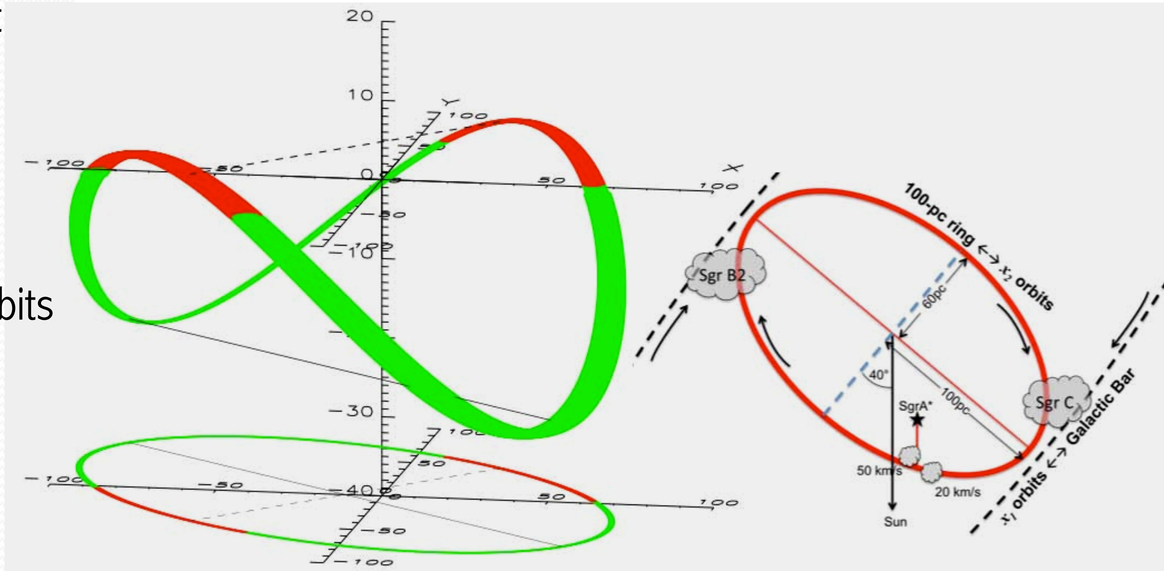
HiGAL images of the Central Molecular Zone (CMZ) [PACS 160um & SPIRE bands] showed a 'twisted elliptical structure' *(Molinari et al. 2011)* .
Combined with the CS (dense gas) radial velocities (*Tsuboi et al. 1999*) is interpreted as dense gas elliptical twisted ring with a 100pc x 60pc semi-major/minor axes, with an orbital velocity of ~80 km/s.



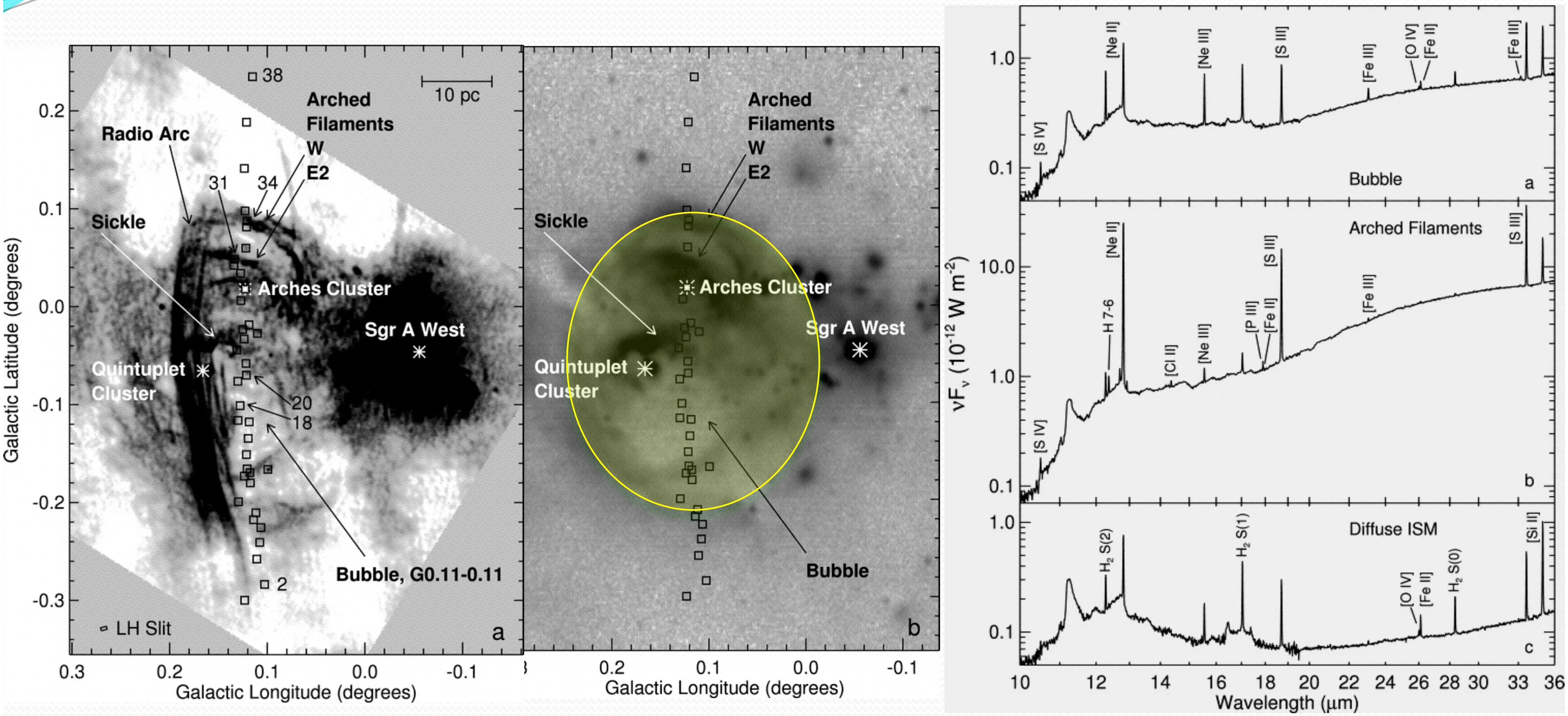
Major axis is inclined about 40° w/respect the plane of the sky and oriented perpendicular to the major axes of the Galactic bar.

It seems to trace a stable system of x2 orbits *(e.g. Kim et al. 2011).*

It has a mass of $\sim 3 \times 10^{7} M_{\odot}$



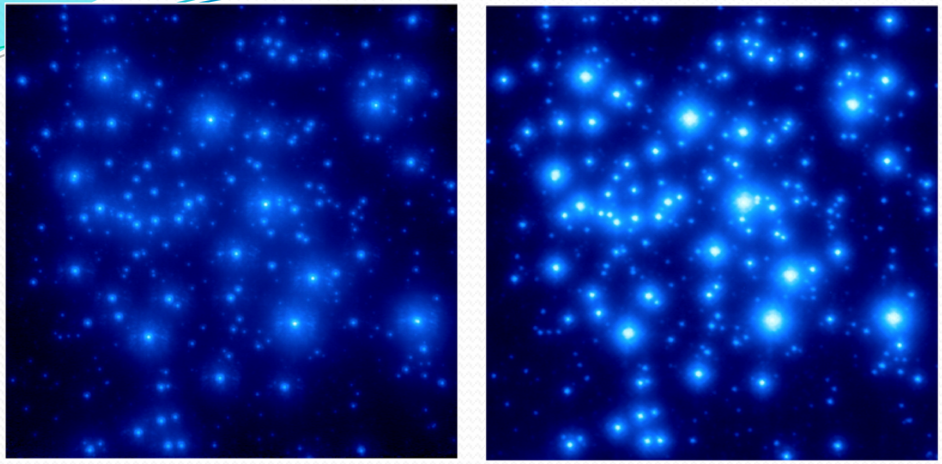
Shocked Gas in the GC Radio Bubble & Arches



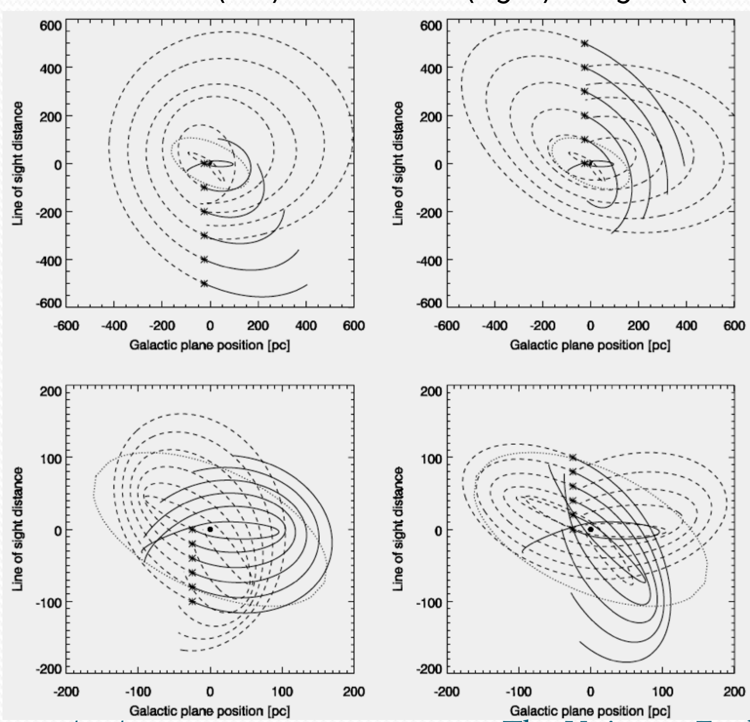
From Simpson et al. 2007

Evidence of high velocity gas and relatively high excitation: shocks (100 km/s).
Photoionization models cannot explain the [OIV] and [NeII/[NeIII] observed values.

Arches Cluster Proper Motion



AO Keck K' (left) and VLT Ks (right) images (FOV~10")

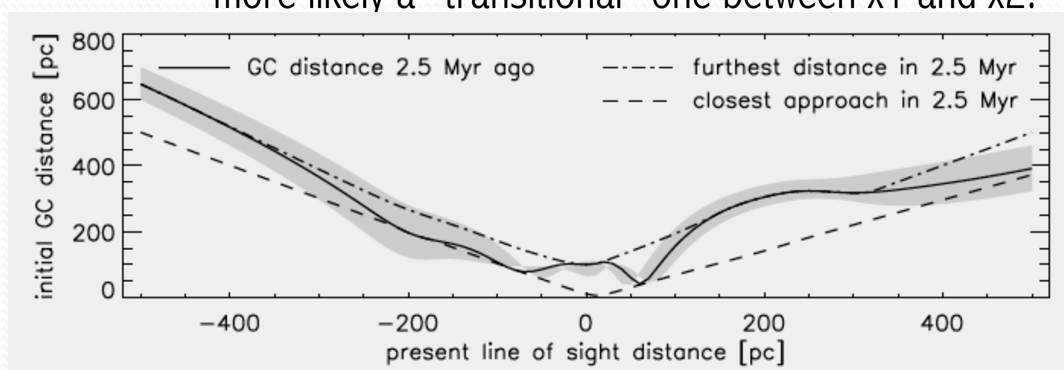


Age of the Cluster is estimated to be ~2.5Myr.

Proper Motion based on two epochs (VLT & Keck) separated by 4.3yr (Stolte et al. 2008)
5.6±0.5 mas/yr or 212±29 km/s at 8 Kpc.

Refined recently with more Keck observations(Clarkson et al. 2012) to 172±15 km/s
[Plus V_{LSR} implies a 3D motion of 200 ±30 km/s].

The trajectory "inconsistent" with x1 or x2 orbits; more likely a "transitional" one between x1 and x2.



Arches Cluster modeled orbits

Star Formation along the Thermal Arcs?

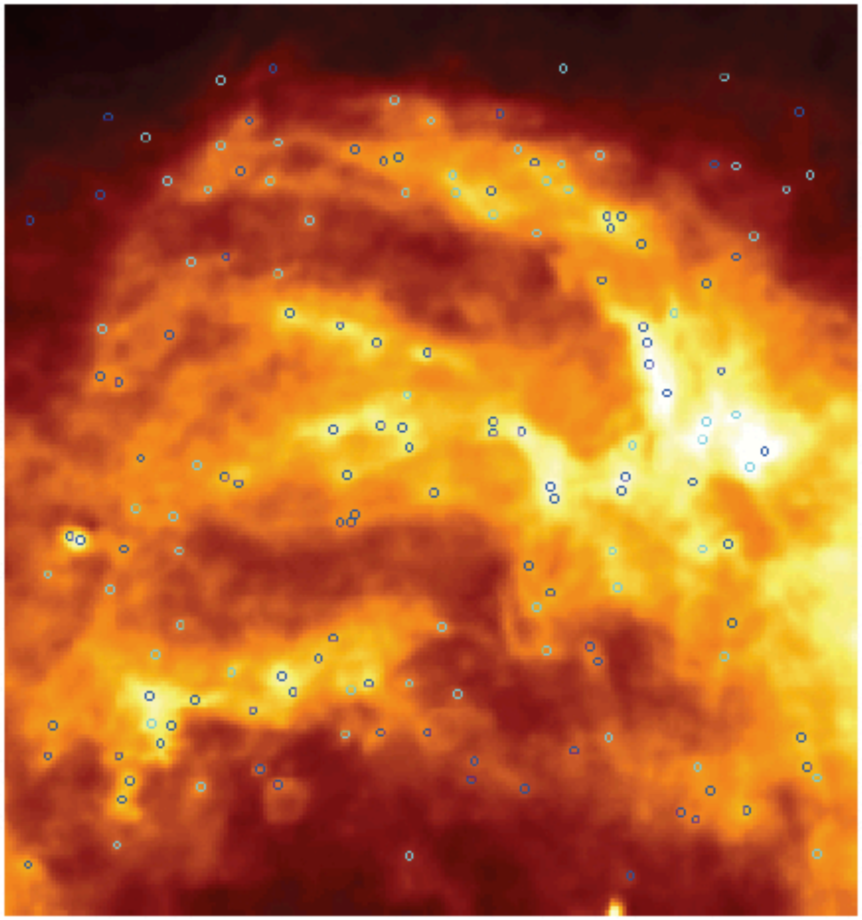


Fig. 3. Herschel PACS 70 μm image of the bright emission ridges corresponding to the thermal radio arches. Circles represent compact sources extracted from the Herschel images and with at least a valid flux at 70μm; cyan/blue circles represent sources with/without a counterpart in the Mid-IR from the MSX6C catalogue.

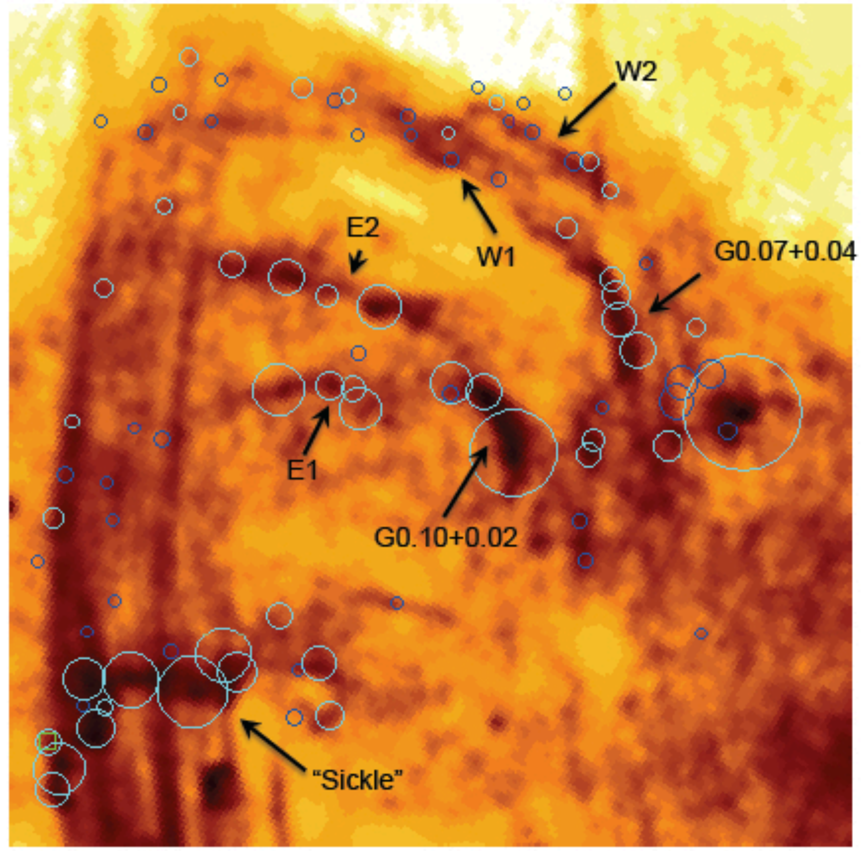


Fig. 4. VLA 20cm continuum map (courtesy F. Yusef-Zadeh), with superimposed circles representing the compact sources detected with Herschel. Sources in cyan/blue are those with/without MSX counterpart, respectively; the size of the circles proportional to the source bolometric luminosity. Nomenclature of radio features is reported following Morris & Yusef-Zadeh (1989).

VLA 20cm

PACS 70um;
~65 sources

Source Extraction with CUTEX (Molinari et al. 2011)

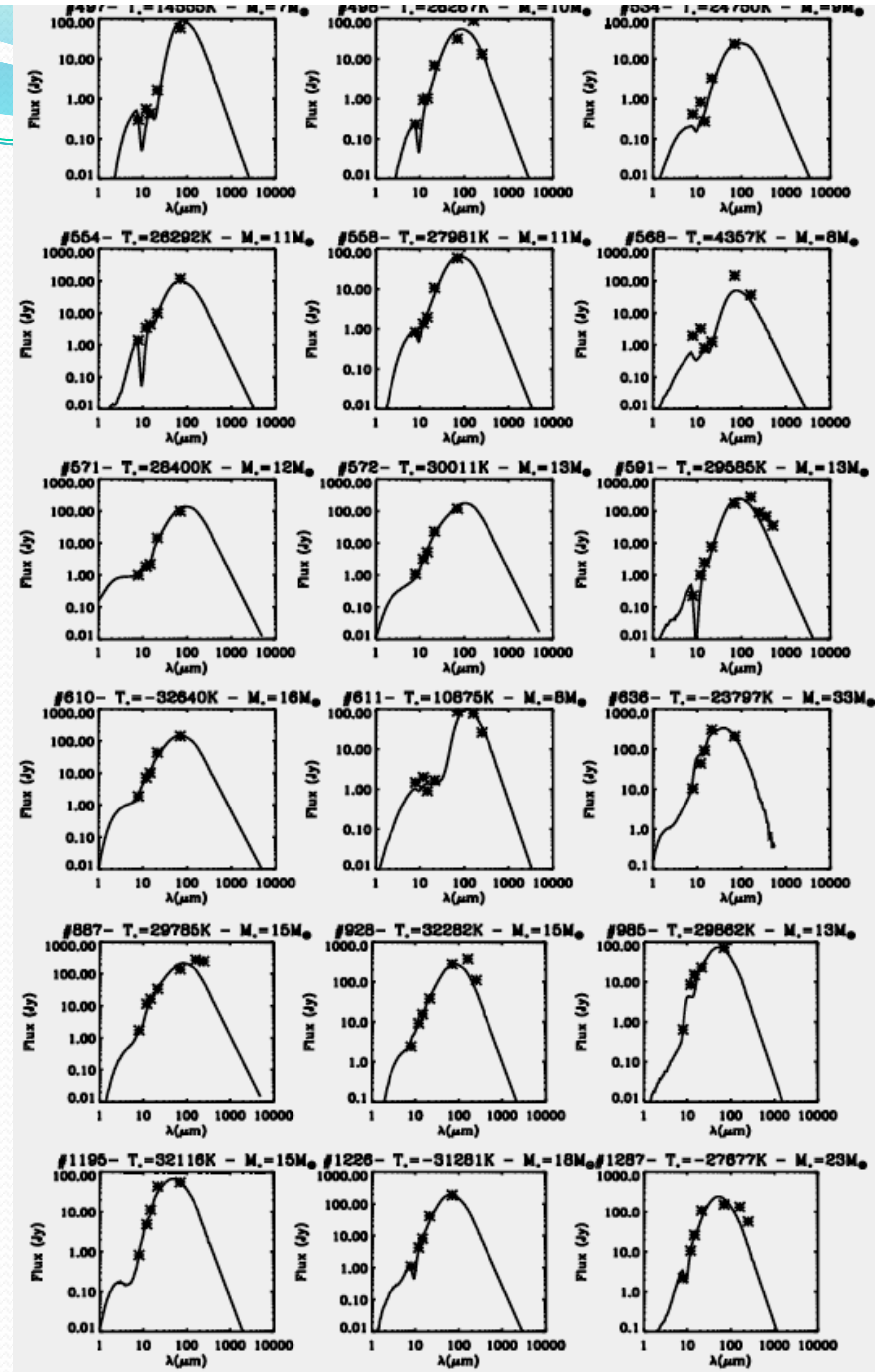
YSO SEDs

SEDs of the extracted sources w/ MSX counterparts modeled as embedded YSOs using Robitaille et al. (2006) grid models. [20models, best χ^2; median value]. 65 YSO candidates.

Models provide T_*, M_* and age of the YSO.

Cross-check with the properties of ZAMS sources (e.g. Panagia 1973; Thompson 1994) shows that their properties are indeed consistent with those of embedded YSOs.

The cumulative distribution of ages shows that 80% of the modeled sources are younger than 3×10^5 yr.



Formation Scenario(s)

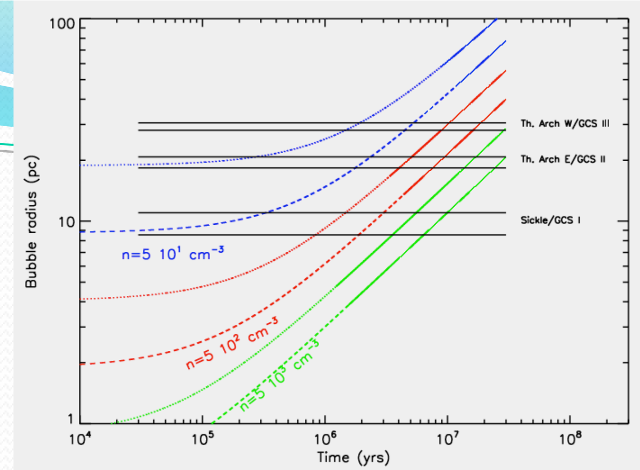
There are 3 physical processes to create a shell: HII region expansion, Stellar Winds and Supernova explosion.

Setting the age of star formation of 3×10^5 yr as the time limit, the only process fast enough to create structures at different distances and allow them to fragment to form stars is a supernova explosion.

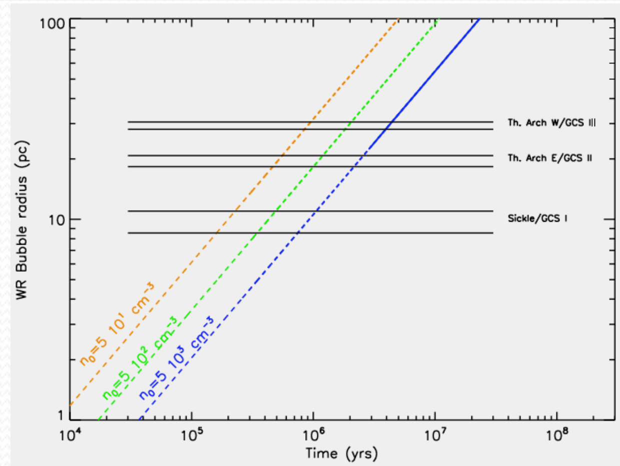
The diffuse X-rays seem to support the idea as well. And recently (*Rea et al. 2013, ApJL, 775, 34*) the discovery of a magnetar (pulsar) ~2.4arcsec from Sgr A* (~10^4yr).

Proposed already for the 'bubble' (Sofue 2003; Simpson et al. 2007). However a supernova requires an older cluster than the Quintuplet and Arches. The Nuclear Cluster (Sgr A West) the only one old enough to harbor such explosion [4-5 Myr].

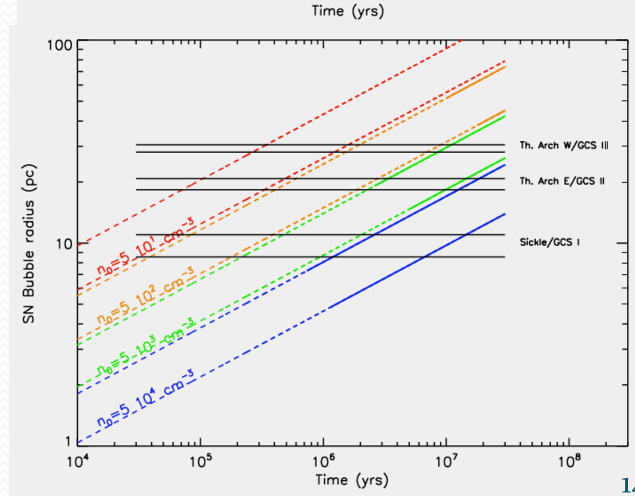
HII Region



Stellar Winds

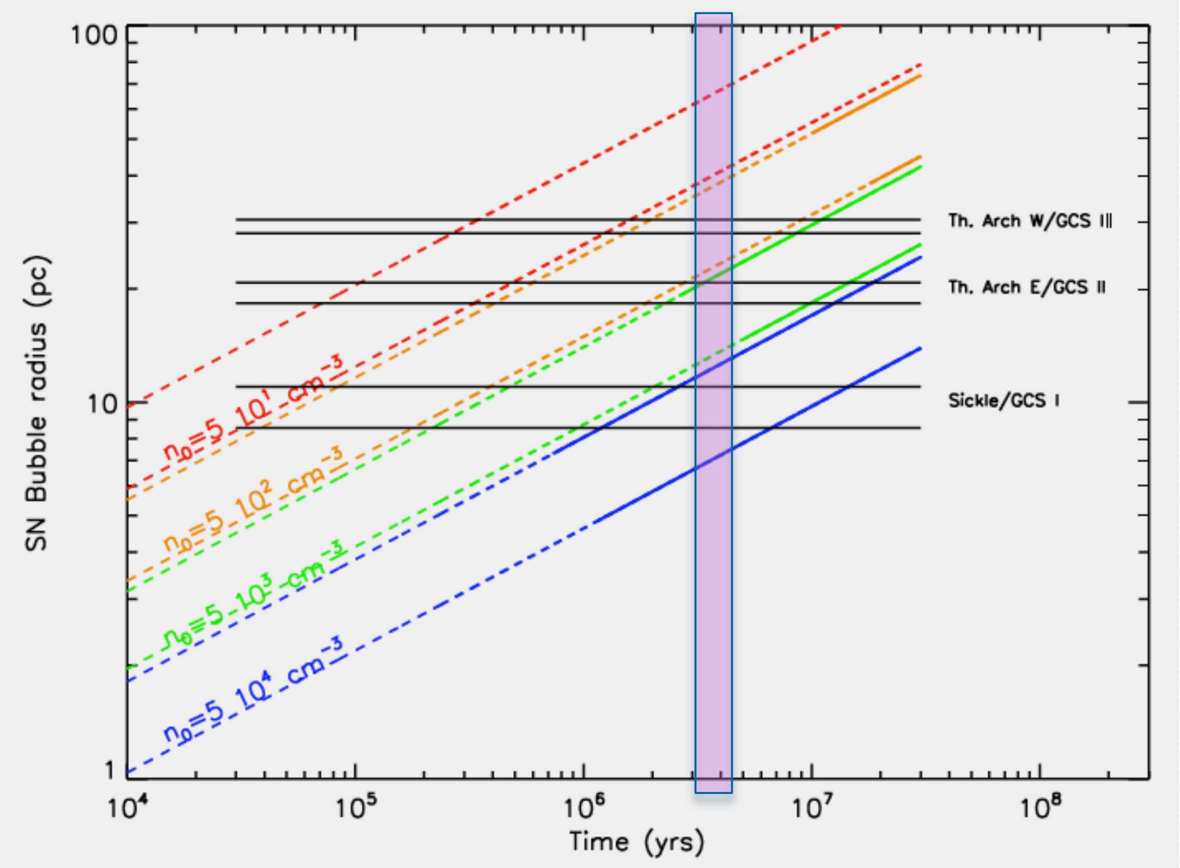


Supernova Explosion



SNR Expansion

- ISM density radial gradient with α =-0.8
- 4 models with initial 5×10^4(blue), 5×10^3(green), 5×10^2(orange) & 50 (red) cm^{-3}
- Two SN events 10^{51}(upp. line) & 10^{52}(low. line) erg/s.
- Dash to continuum when shell fragmentation could start.
- Horizontal lines, distance in latitude for the major features from the geometrical center of the innermost bubble (GCS 1).



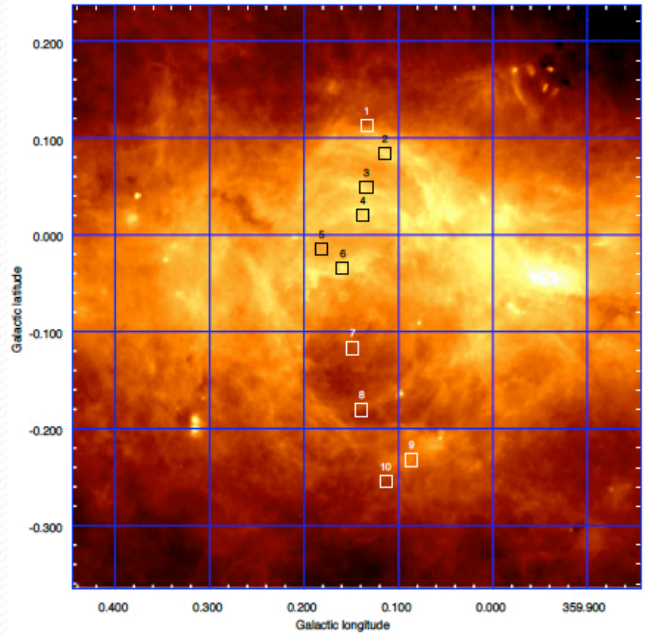
$$R_{exp} \sim 7.2pc\left(\frac{E}{10^{51}\,erg\,s^{-1}}\right)^{13/56}\left(\frac{n}{10^3\,cm^{-3}}\right)^{-2/7}\left(\frac{t}{10^6\,yrs}\right)^{1/4}$$

$$R_{frag} \sim 7.4pc\left(\frac{c_s}{0.2\,km\,s^{-1}}\right)^{1/5}\left(\frac{E}{10^{51}\,erg\,s^{-1}}\right)^{13/70}\left(\frac{n}{10^3\,cm^{-3}}\right)^{-3/7}$$

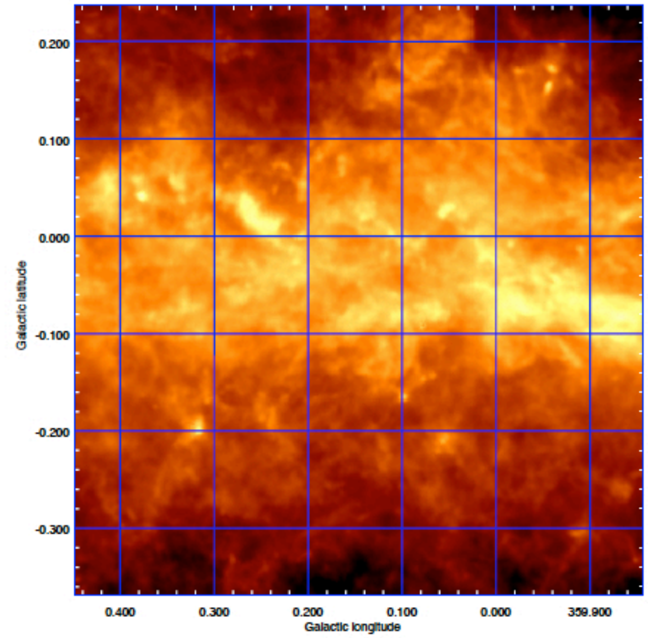
(*Whitworth et al. 1994*)

Dust Properties around the Thermal Arches

70um



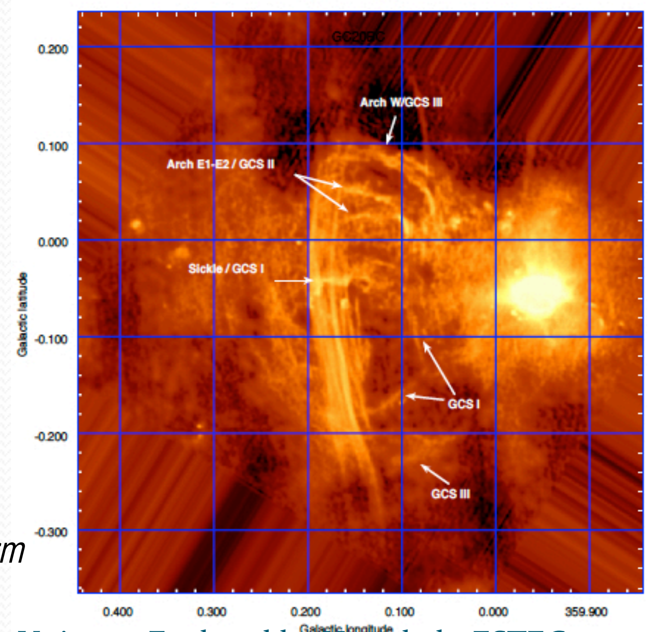
250um



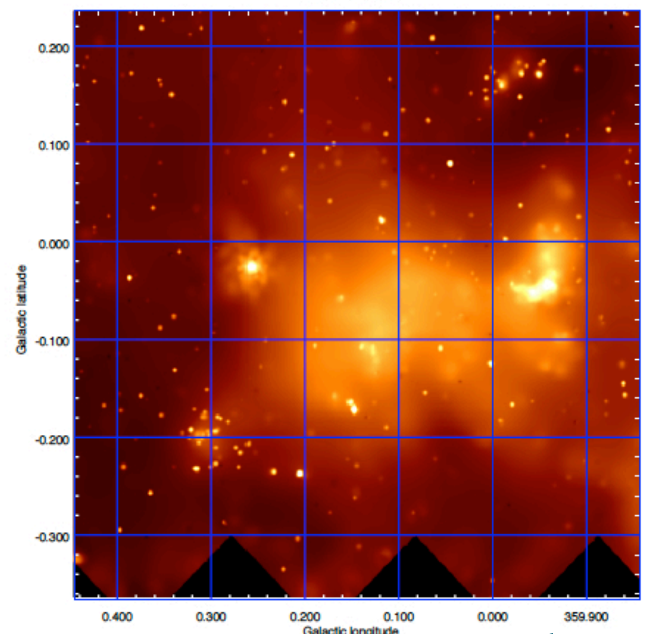
We use DustEM (Compiegne et al. 2011) modified two-component model
[one for the LOS environment; another "in-situ"]

We use 7 bands data
[8, 21.9 or 24, 70, 160, 250, 350 & 500um] and fit 7 parameters.
Column Density and Interstellar radiation field (Temperature) and the main one in this case.

We fit 10 positions across the GCB.



VLA 20cm



X-rays 1-3keV

DustEM Two Component Models

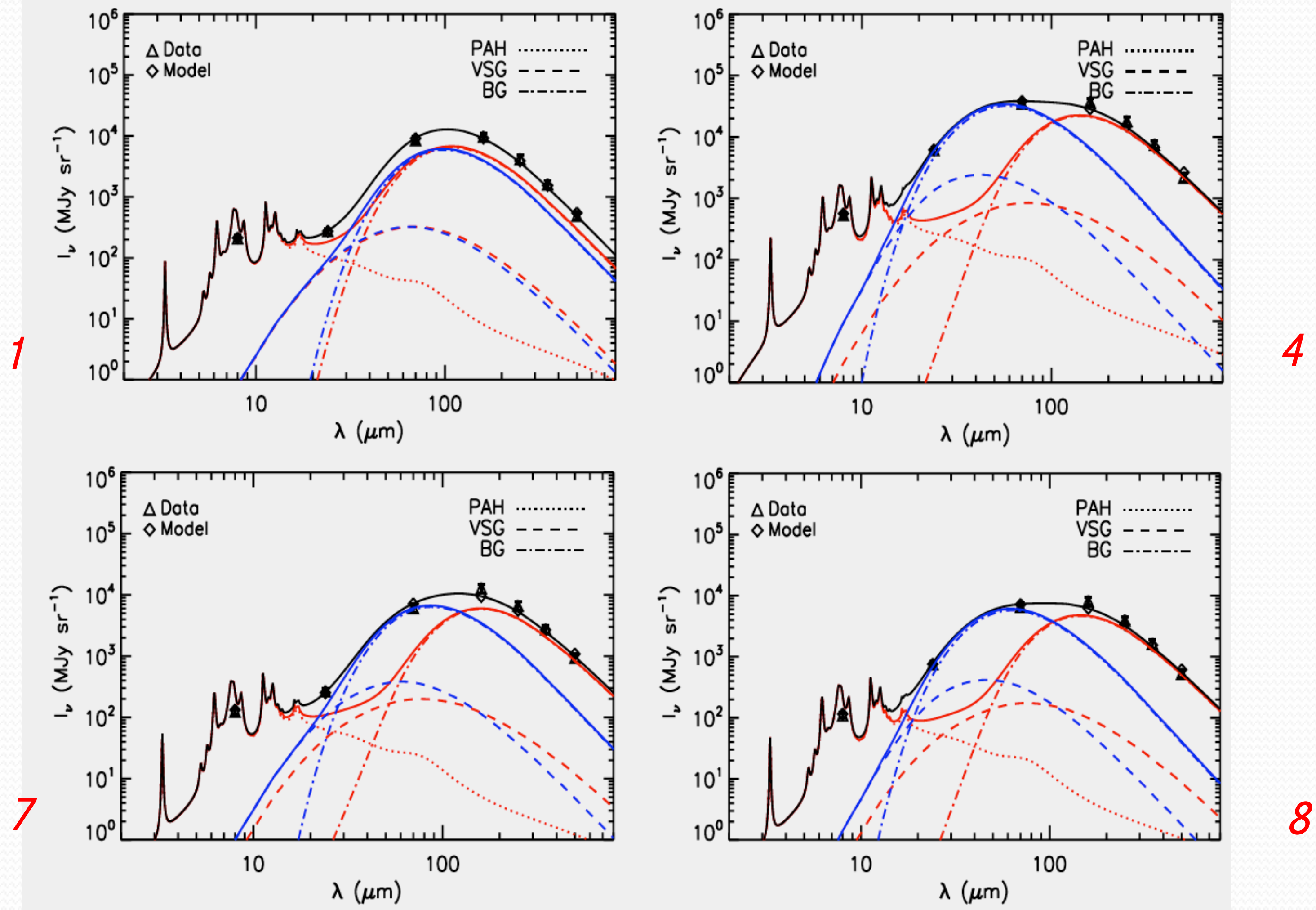


Fig. 2. Results of the DUSTEM fitting to our two-components dust model for four of the ten modeled positions: 1 (top-left), 4 (top-right), 7 (bottom-left) and 8 (bottom-right). In each panel the red/blue are the "LOS" and "bubble" dust components, respectively; for each of them we report the emission from the Big Grains (dash-dotted), the VSG (dashed), the PAH (dotted, only for the "LOS" component), and the total emission (full line).

DustEM Fits

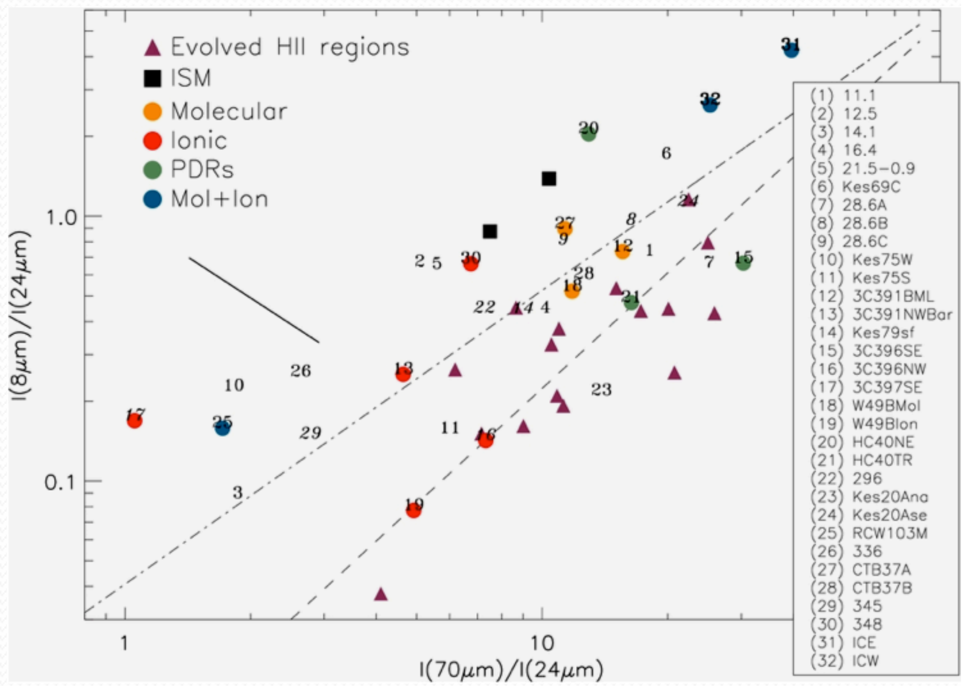
LOS#		Bubble comp.			LOS comp.		
		I_{ISRF} G_0	Temp (K)	N_H cm^{-2}	I_{ISRF} G_0	Temp (K)	N_H cm^{-2}
1	fore/background	20	29	$4.6\ 10^{22}$	11	26	$8.5\ 10^{22}$
2	Arch W1/GCS III	260	44	$2.1\ 10^{22}$	8	25	$2.4\ 10^{23}$
3	Arch E2/GCS II	350	47	$9.9\ 10^{21}$	5	23	$2.4\ 10^{23}$
4	Arch E1/GCS II	480	49	$1.8\ 10^{22}$	2	20	$1.0\ 10^{24}$
5	Inter-Arch	155	40	$2.5\ 10^{22}$	1	19	$9.9\ 10^{23}$
6	Sickle/GCS I	670	52	$1.3\ 10^{22}$	3	20	$7.5\ 10^{23}$
7	GCB Center	60	34	$2.4\ 10^{22}$	1	17	$5.7\ 10^{23}$
8	Southern GCB Rim /GCS I	280	45	$5.0\ 10^{21}$	2	19	$2.6\ 10^{23}$
9	Southern GCB Rim /GCS III	85	37	$1.8\ 10^{22}$	7	24	$1.3\ 10^{23}$
10	fore/background	55	34	$1.5\ 10^{22}$	5	23	$1.3\ 10^{23}$

The Bubble component models consistent with PDRs/ HII Regions *(see Paladini et al. 2012)*.[P84, session A]

IC 443 (4×10^4yr old) 18-30 K (*Noriega-Crespo et al. 2009)*

A tendency for the Northern part to be warmer (T>44 K) than the south.

The LOS component ISRF and Temp. consistent with that of the ISM; NH too large (i.e. a fraction of NH could belong to the 'in-situ' medium).



 Pinheiro-Goncalves et al. 2011

Summary

* The Herschel Observations of the Galactic Center have provided us with solid evidence for complex dense gas structures in the CMZ.

* Using essentially the same methodology to identify massive embedded YSOs in the HiGAL Survey we propose that star formation is likely to take place in the molecular gas associated with the Thermal Arches, with an age of $\sim 3 \times 10^5$ yr.

* Taking advantage of new observational results (e.g. large proper motion of the Arches Cluster, the 80 km/s orbital velocity of the 100pc-ring, diffuse X-rays in the GCB, etc), we propose a scenario to explain the multiple morphological organized shell structures in the GB and their recent star formation, in which a supernova(e) explosion(s) took place near the Nuclear Cluster, driving the current expansion and fragmentation of the shells.

And THANKS to all of those that have made possible this extraordinary IR space mission