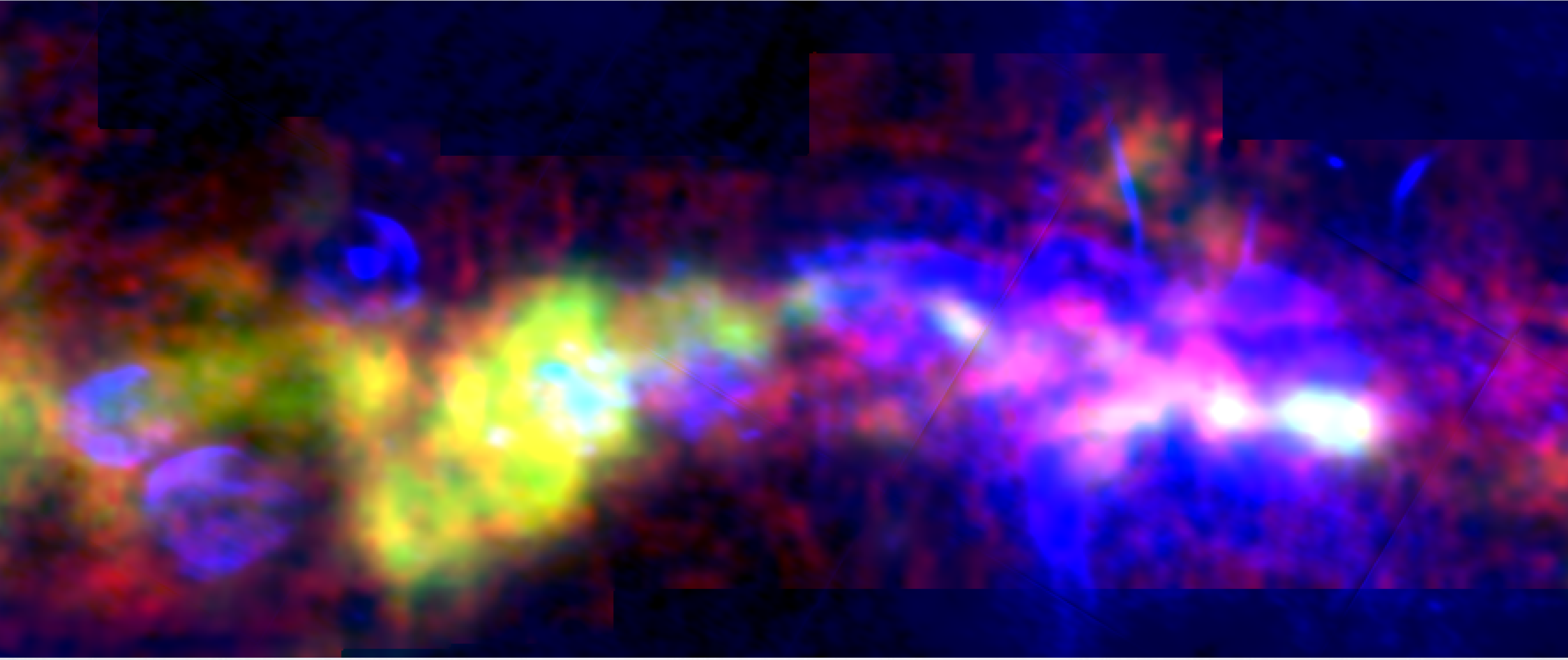


THE INTERSTELLAR MEDIUM OF THE GALACTIC CENTRE REGION

David Jones (Radboud University, Nijmegen, The Netherlands)

Workshop on Off-the-Beaten-Track Dark Matter and Astrophysical Probes of Fundamental Physics, Trieste, 13-17 April, 2015.

INTRODUCTION

- The workshop will bring together experimental, observational and theoretical communities, in the fields of astro-particle physics, early universe cosmology and dark matter searches and phenomenology.

- We will focus on both astrophysical probes or hints of new physics, as well as 'non standard' dark matter signatures.

- We aim to assess current anomalies, the constraining power of near future astrophysical or cosmological probes and the status of promising particle physics models.

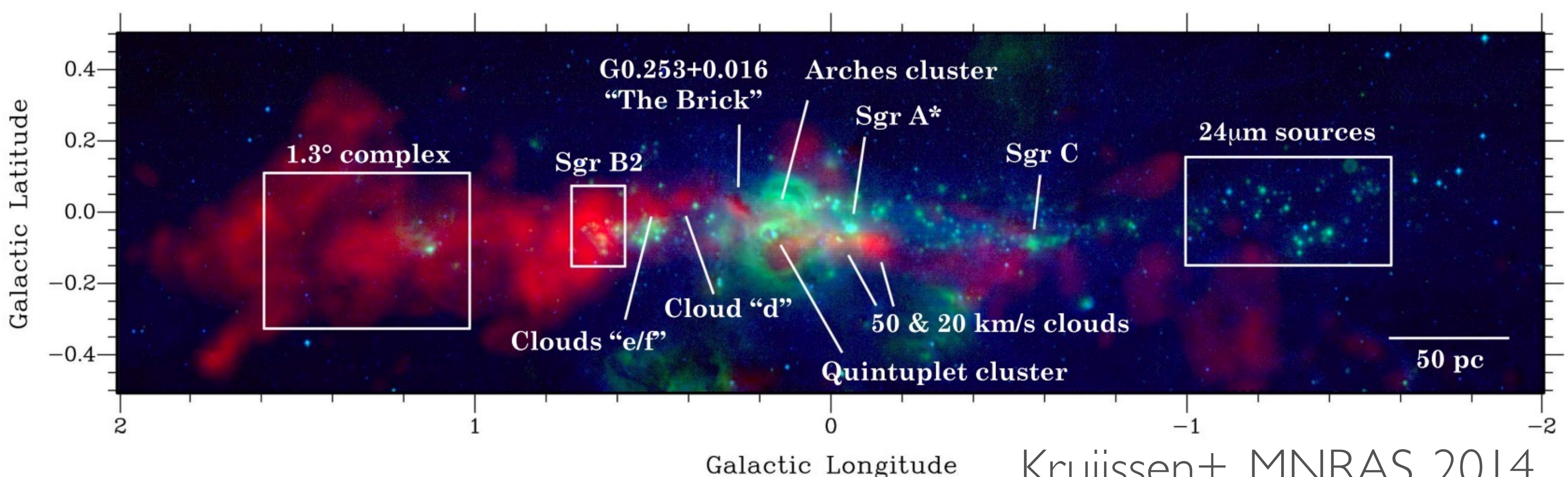
Last page: 3-colour composite; blue = 330 MHz; green = $NH_3(1,1)$; red = CO(1—0)

INTRODUCTION

- How does the previous slide have to do with the Galactic centre?
- Galaxies are expected to have “cuspy” dark matter distributions centred on their dynamical centres, hence the centre of our Galaxy is important as a test of dark matter theory and detection.
- My task, then as I see it, is to talk about the structure of the Galactic centre as it purports to dark matter: its **cosmic-ray** and **molecular gas** content, in-so-far as our knowledge of its mass composition, distribution and the dynamical processes they instigate are concerned.

THE GALACTIC CENTRE (GC)

- Where is it? It's at the centre of the Galaxy, duh!
- But seriously, it's about 8-8.5 kpc from the Sun — making it, by definition, the closest example of a galactic nucleus (high-resolution) and is the dynamical centre of the Galaxy.



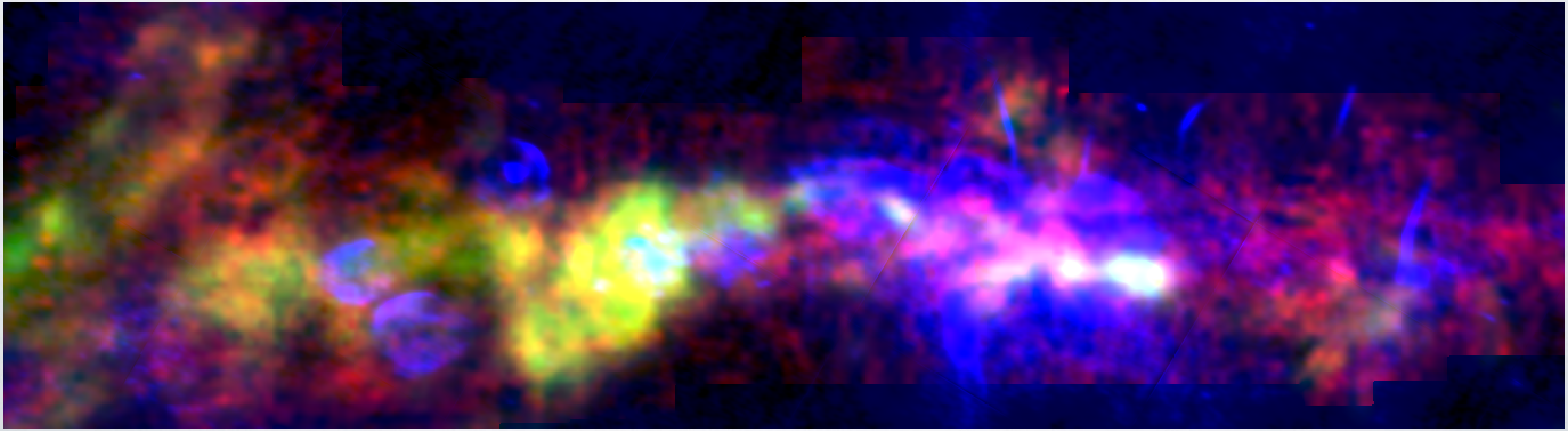
Kruijssen+, MNRAS, 2014

Figure 1. Three-colour composite of the CMZ, with in red the HOPS $NH_3(1,1)$ emission (Walsh et al. 2011; Purcell et al. 2012) to indicate the gas with a volume density above a few times 10^3 cm^{-3}, in green the MSX 21.3μm image (Egan et al. 1998; Price et al. 2001), and in blue the MSX 8.28μm image. The MSX data shows PAH emission (mostly tracing cloud edges), young stellar objects, and evolved stars. The labels indicate several key objects and regions.

THE MOLECULAR ENVIRONMENT OF THE GC

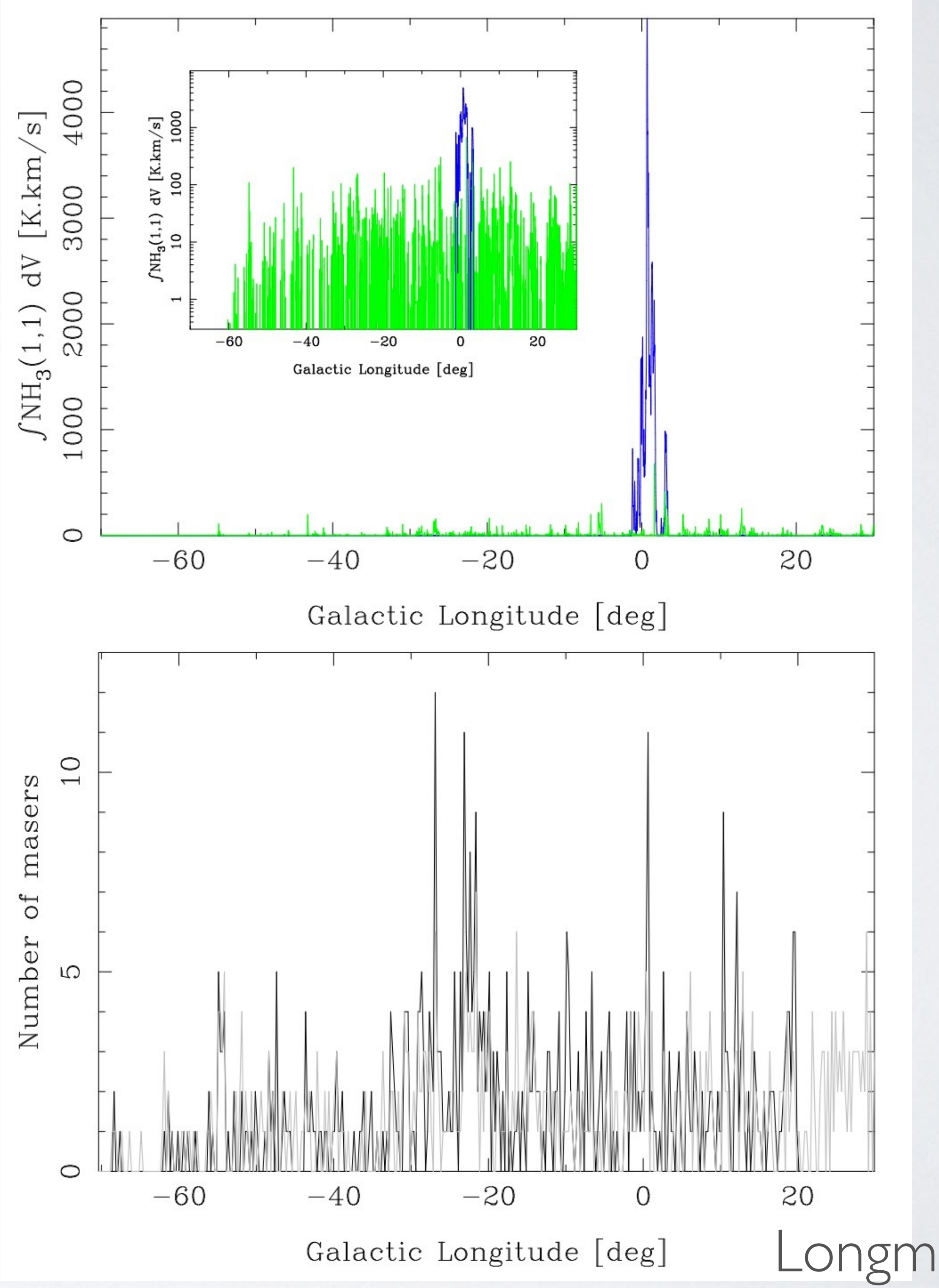
- The Galactic centre contains the central molecular zone (CMZ).
- This region contains ~10% of all current star formation and the Galaxies' molecular gas, in about 0.001% of its volume.
- The gas density is x100 that of the disk.
- Stellar clusters with $10^6\,M_\odot$ (c.f. globular clusters, dwarf galaxies).

Below: 3-colour composite; blue = 330 MHz; green = NH_3(1,1); red = CO(1—0)



WHY ISN'T THE GC MORE ACTIVE?

- Given that the Galactic centre contains a SMBH, as well as:
  - A strong magnetic field (>100μG; Crocker, Jones+, 2010);
  - Massive dust and gas reservoirs;
  - A complex radio morphology implying a large SNR-rate, high CR flux (evidenced by point-like & diffuse gamma-ray emission).
- Why do we not observe the GC to be brighter and forming stars at a greater rate?



Longmore+, 2013

SHOCKS, STAR FORMATION & THE GC

- Many surveys have been done of molecular lines in the GC
- Indeed Sgr B2 is home to almost all known interstellar molecules ever observed; it is the most massive star-forming region in the Galaxy.
- The most recent and systematic of these have been the 3mm (40''), 7mm (1.3') and 12mm (2.6') Mopra+ATCA surveys of the CMZ (Jones+2011, Ott +2014).
- Different molecules trace different environments.

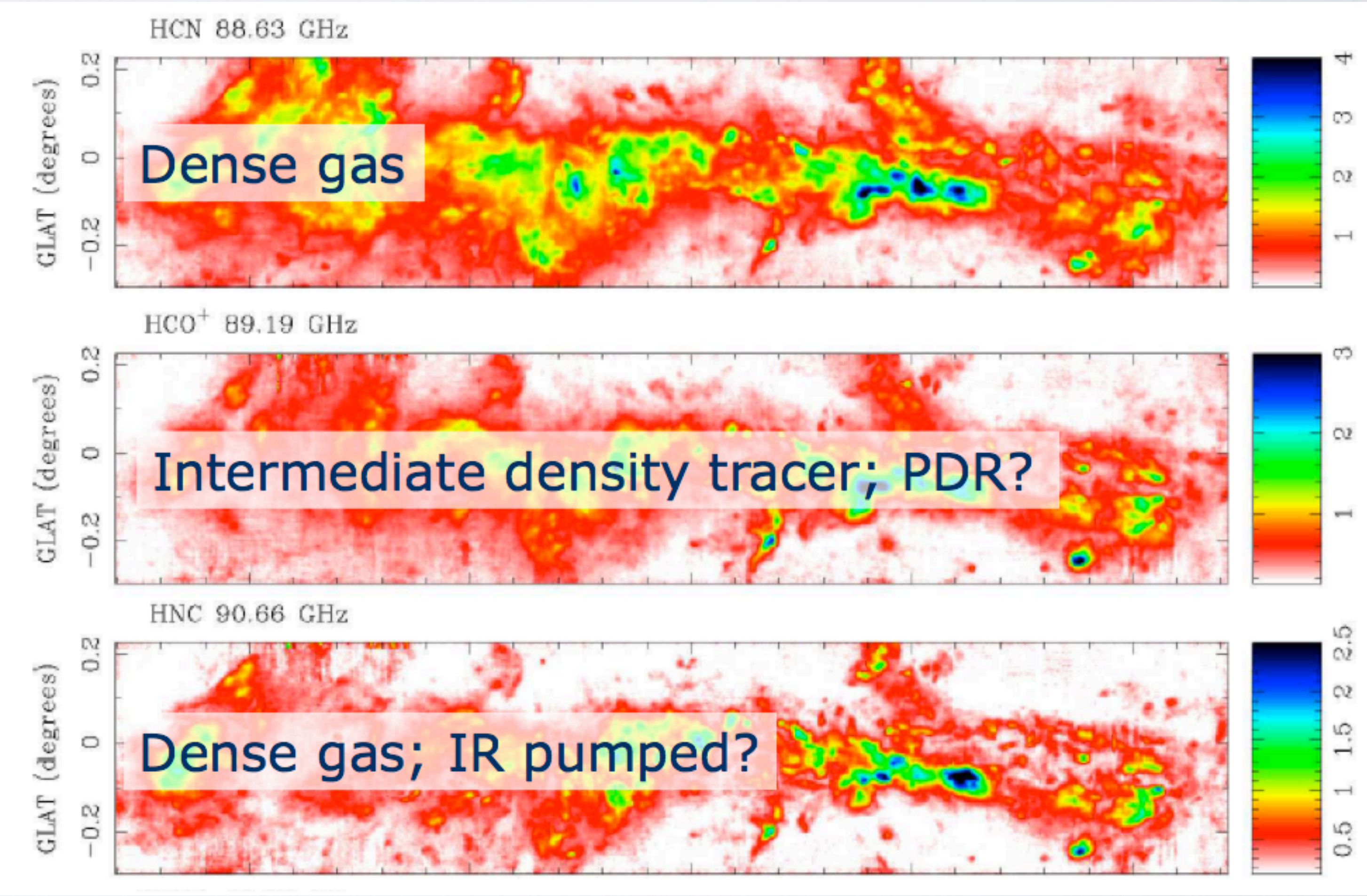


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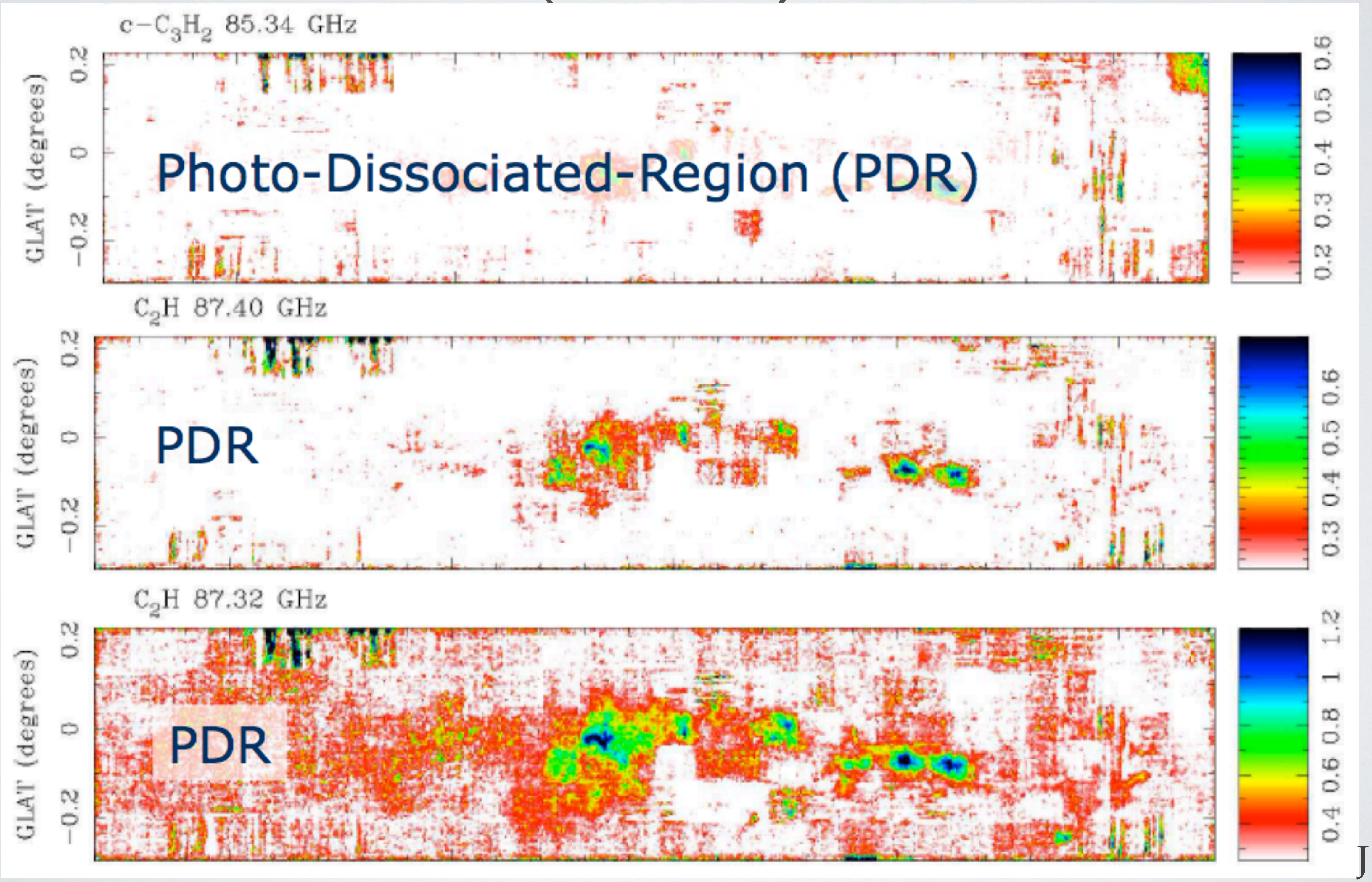
PHOTO-DISSOCIATION REGION (PDR) TRACERS



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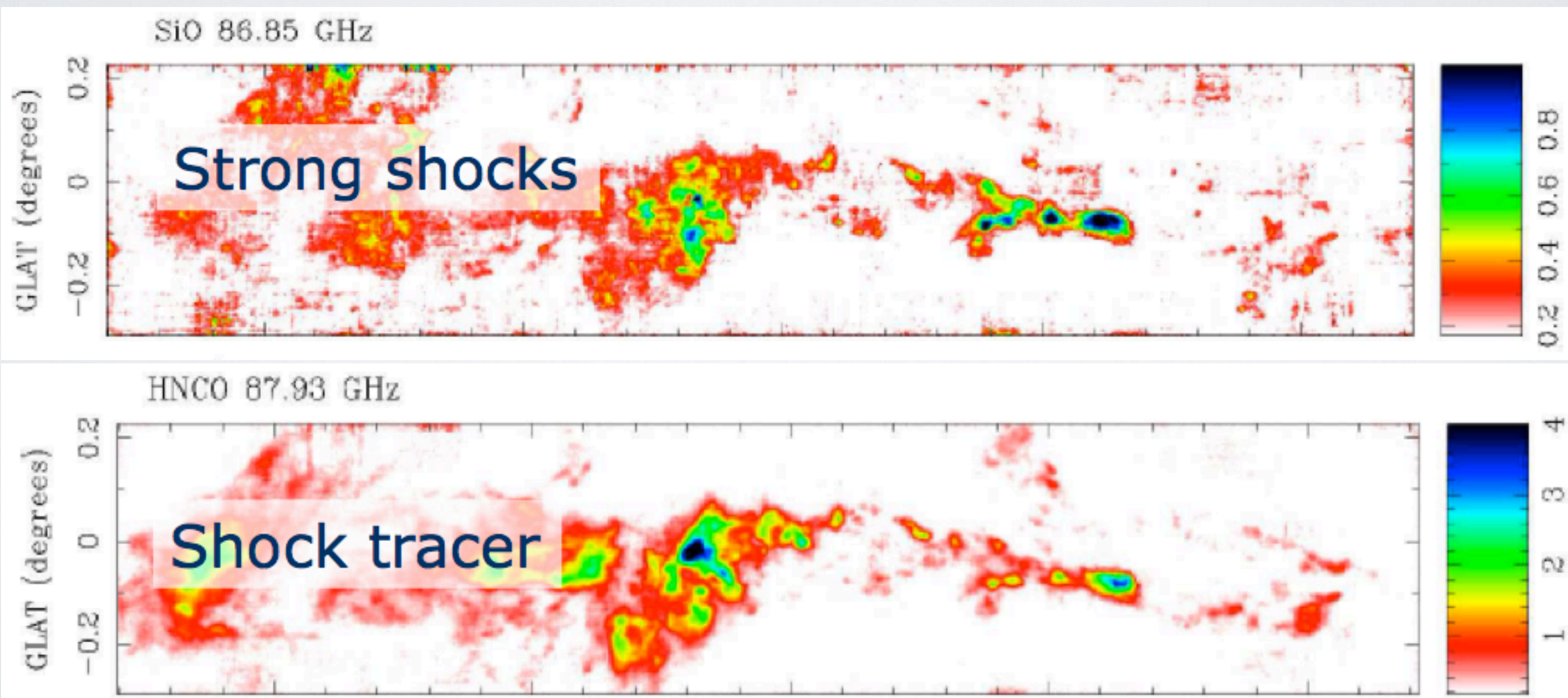
SHOCK TRACERS

- Typically, SiO traces strong shocks, whilst HNCO is more easily dissociated by UV radiation



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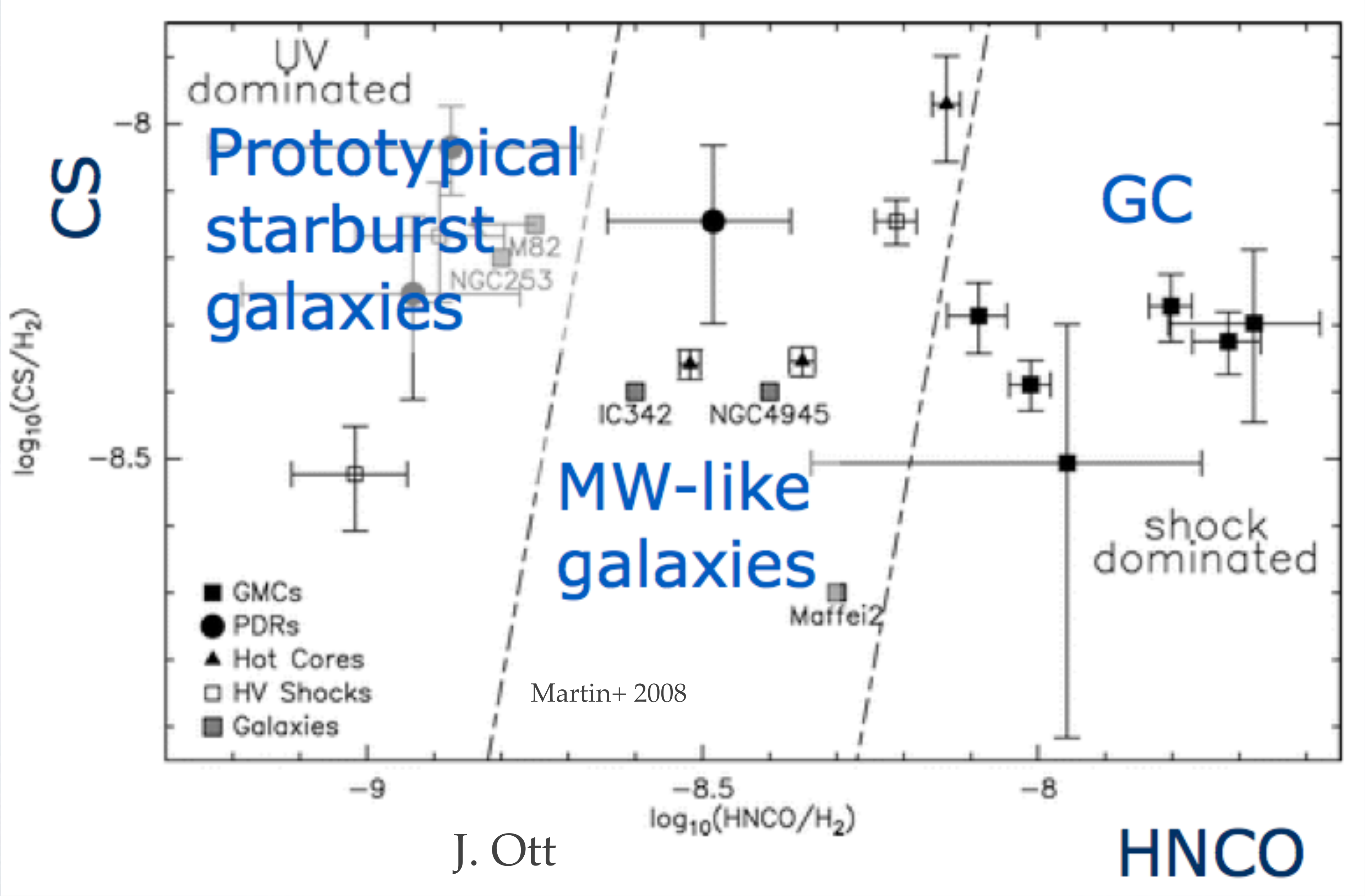
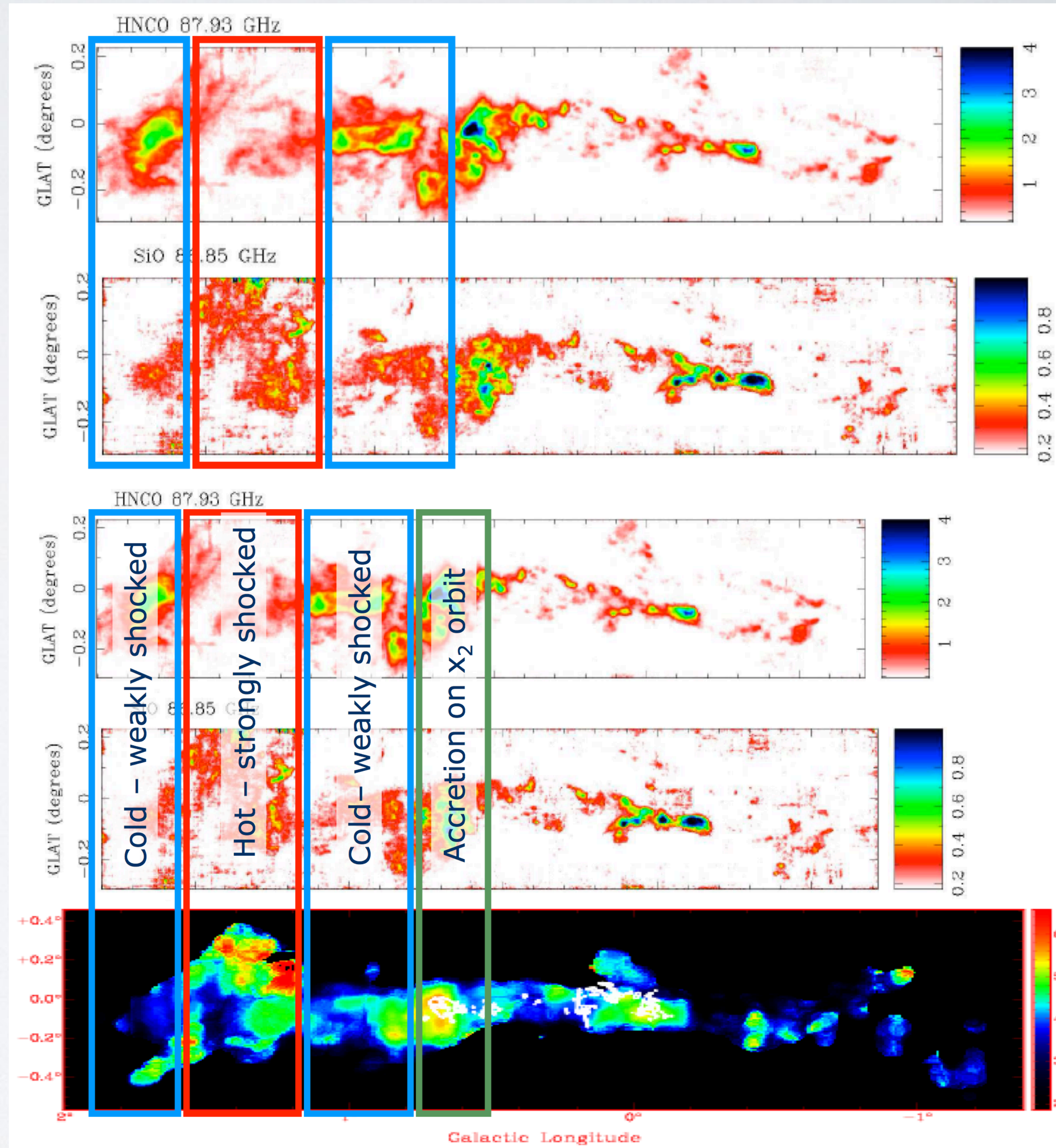
SHOCKS VS PDRS IN THE GC

- Comparing the CS to HNCO, shows that the GC is dominated by shocks, and not PDRs



SHOCK TRACERS CORRESPOND WITH TEMPERATURE

- SiO and HNCO in the CMZ do not correlate well (top, right).
- When compared to a temperature map (obtained using the $NH_3(1,1)$ and (2,2) inversion transition (below, right), this can be seen to match with the interaction of the bar with the CMZ (below).
- Warm temperatures (~60 K) correspond to strong (SiO) shocks, cold with weak (HNCO & ~30 K).



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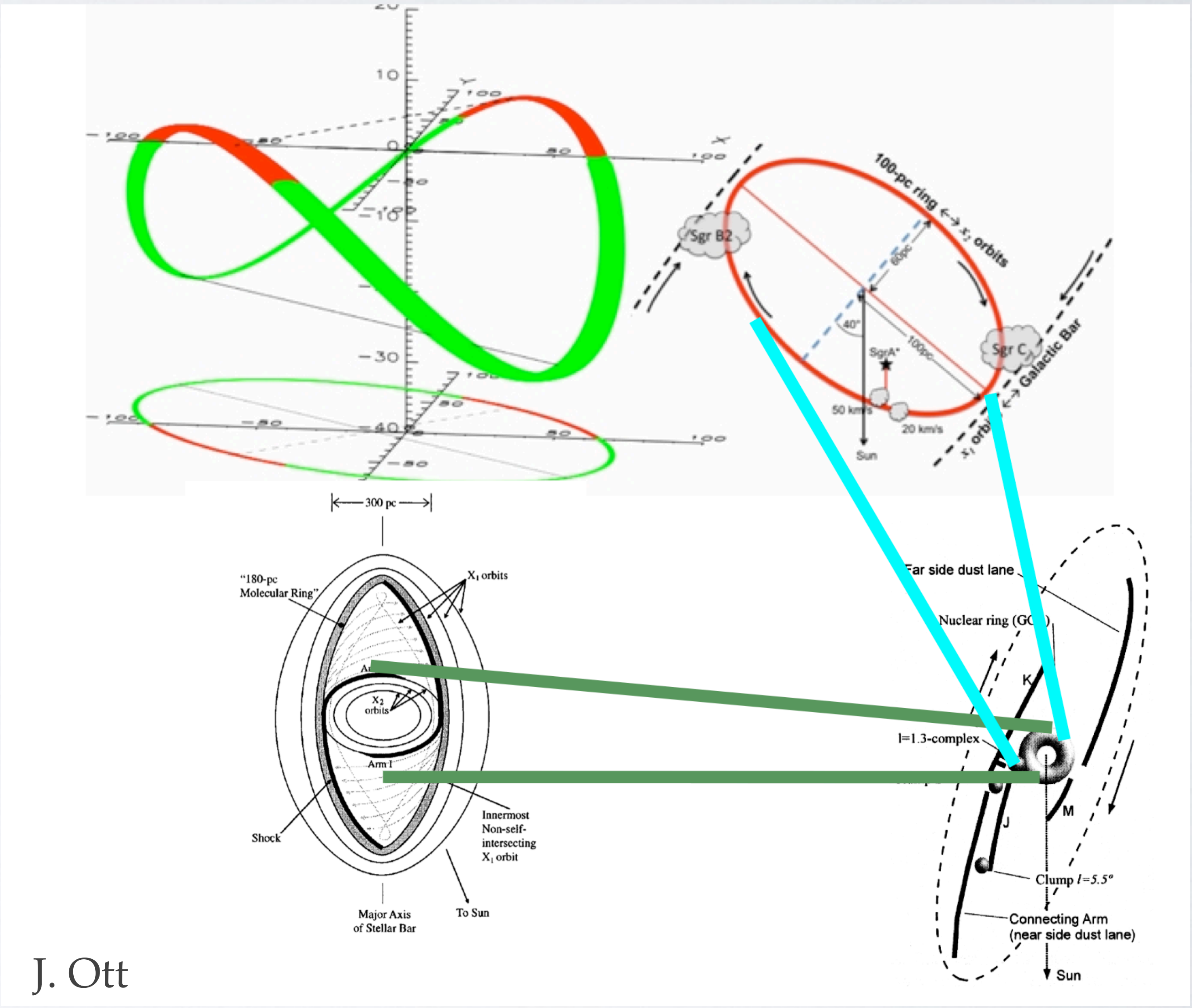
THE DISTRIBUTION OF MOLECULAR MATERIAL IN THE GC

- The dynamics of the central regions suggests that gas is falling onto the CMZ, hence its large mass.

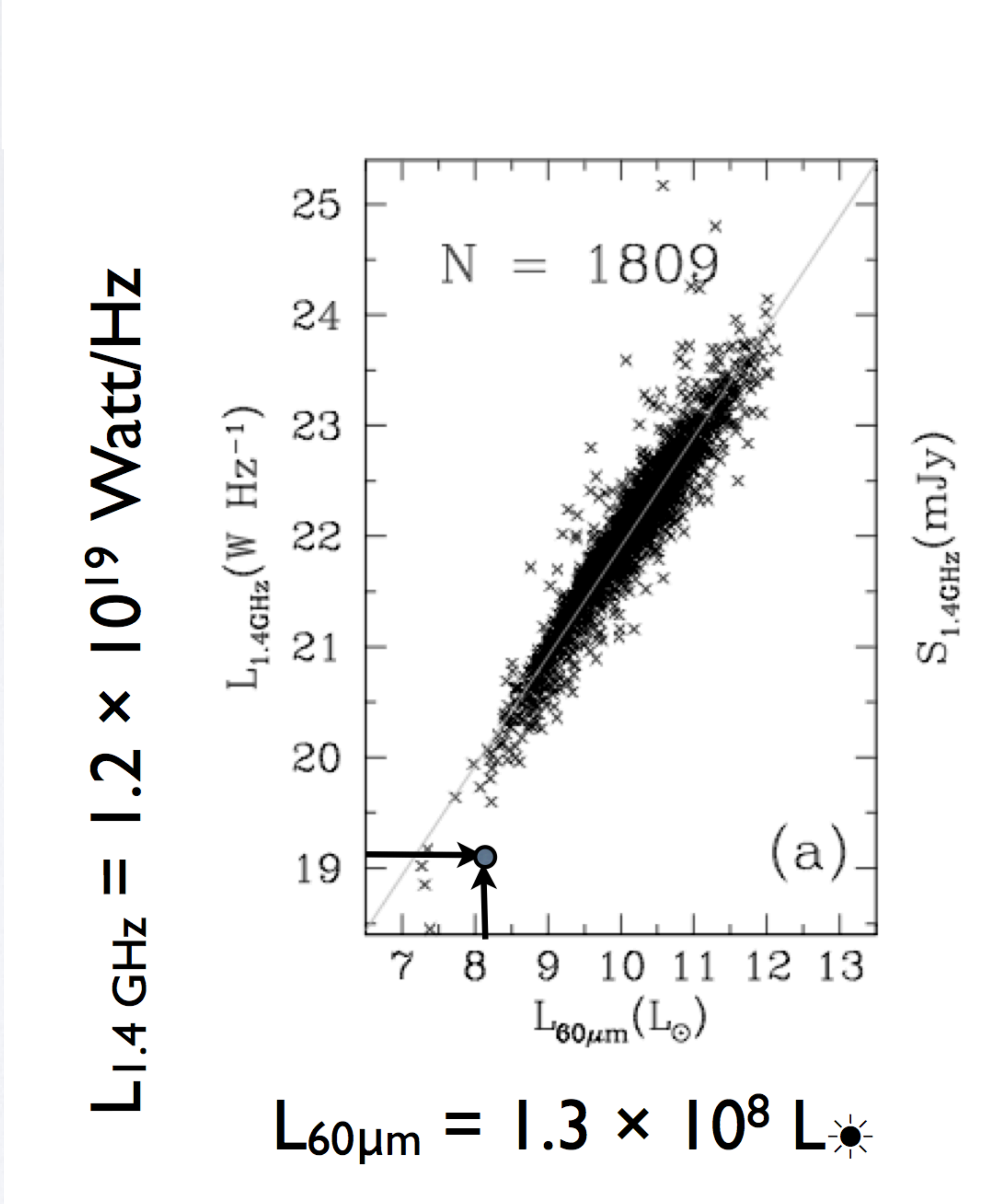
- But it is thought that the geometry of the region leads to a high rate of star formation, through cloud-cloud collisions which create the shocked regions seen above.

- This in turn creates a high SNR rate (~0.4/century; Crocker, Jones+, 2011), and drives a ***wind*** from the GC.



EVIDENCE FOR A GC WIND

- The well-known far-infrared/radio-continuum (FIR-RC) correlation suggests that stars — through star formation and death — connect UV and optical photons to ionised particles.
- If the ionised particles lose all their energy in-situ (Völk, 1989), then there should also be a radio-FIR-gamma-ray correlation (Thompson+, 2006).
- However, the GC is not on this correlation by ~4σ (Crocker, Jones+, 2011).



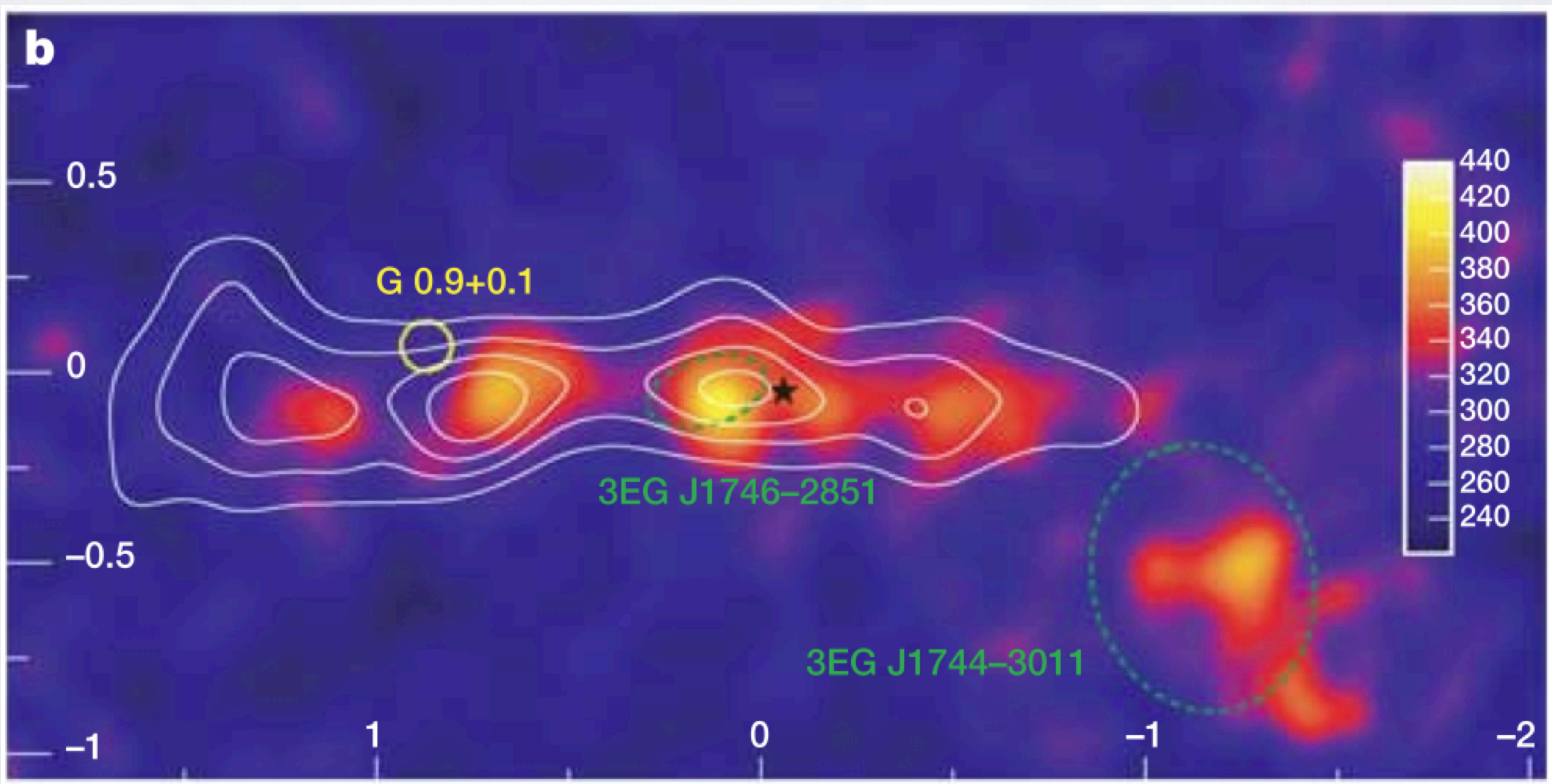
EVIDENCE FOR A GC WIND

- On the basis of the FIR-RC correlation, one would expect (Thompson+, 2006; Crocker, Jones+, 2011) the gamma-ray emission to scale as:

  υL_υ (GeV) ~ 2×10^{-5} $(\eta_{10} L_{TIR})$,

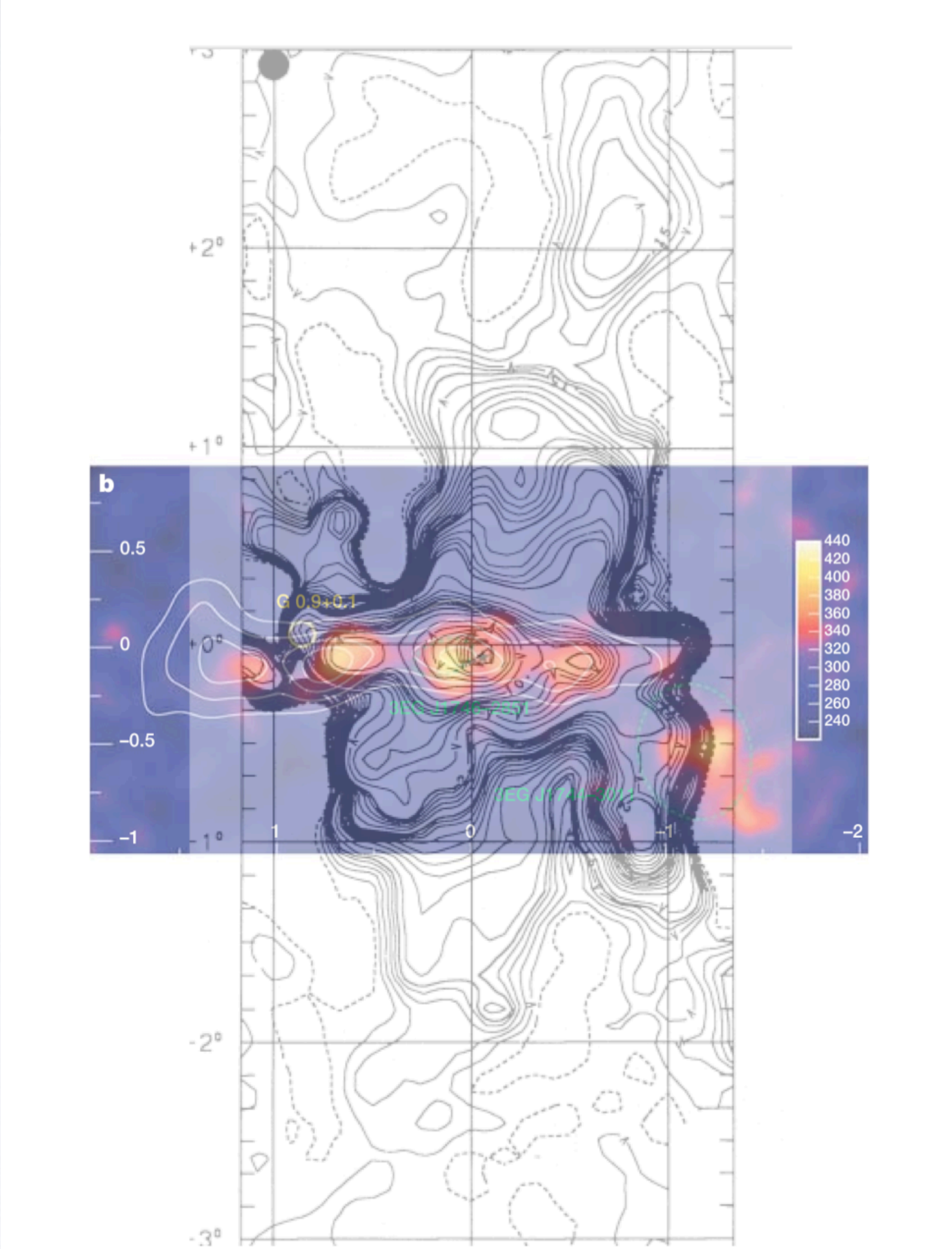
  where η_{10} is the canonical 10% of SNR energy going into CRs.

- *Fermi* and HESS data obtain a luminosity of ~3×10^{36} and 1×10^{35} erg/s, respectively (Crocker, Jones+, 2011).
- This is only ~10 and 2% of the flux expected on the basis of this relation; about a 4σ deficit.



EVIDENCE FOR A GC WIND

- Spectral steepening of electrons is seen in the GC Lobe (Law, 2010), suggesting synchrotron ageing.
- As Crocker, Jones+ (2011) showed, the large-scale (400 pc) radio spectrum (viz. $S_{\upsilon} \propto \upsilon^{-0.54}$) requires a hard (i.e., $F \propto E^{-2.1}$) electron population.
- The flat γ-ray spectrum ($F \propto E^{-2.2}$) also suggests that the particles are being *advected* out of the region.



Crocker, 2012

WHERE HAVE ALL THE CRS GONE?

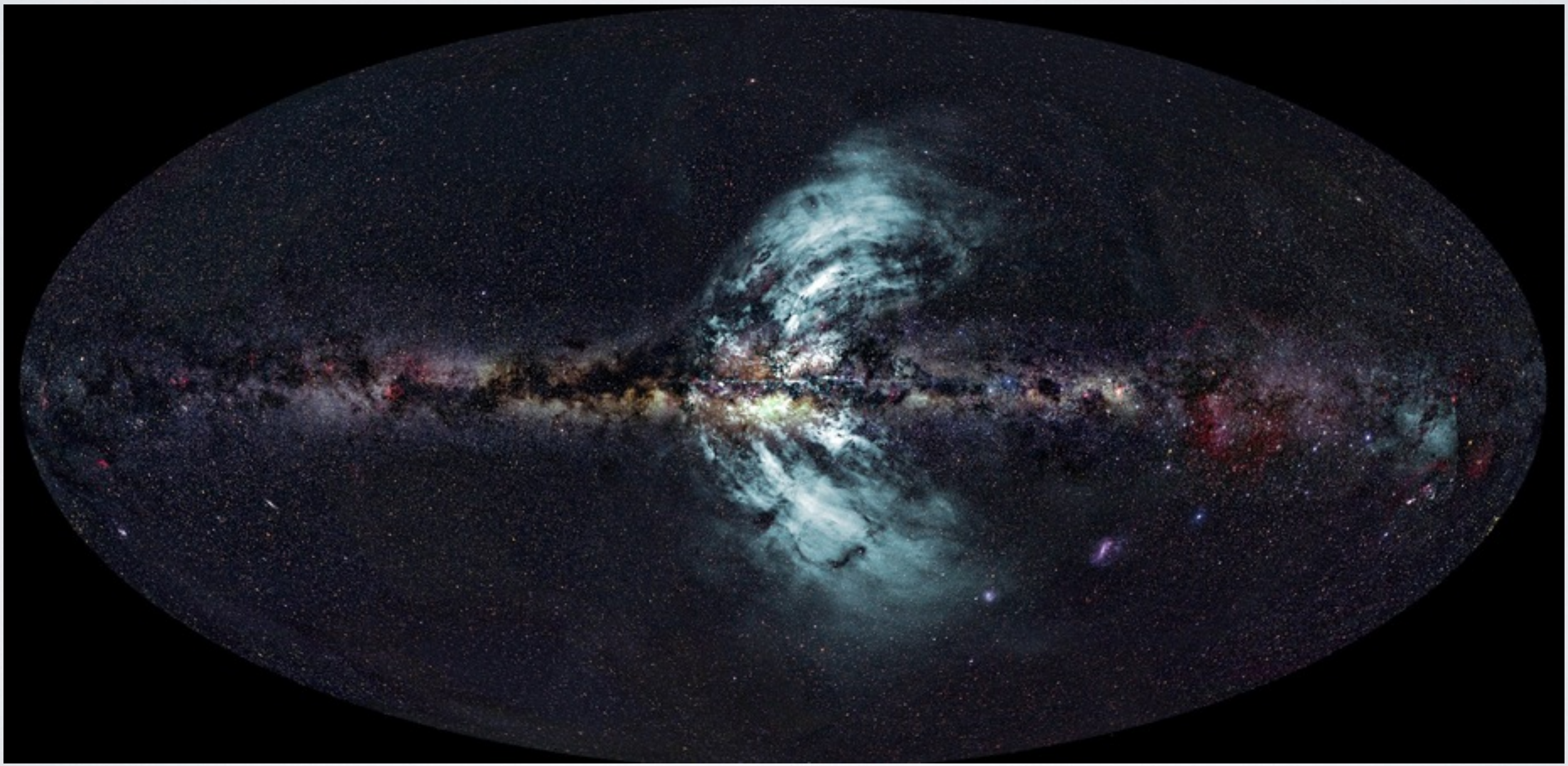
- The GC can be thought of as a star-burst in miniature (Crocker, 2012; Crocker, Jones+, 2010, 2011):
  - 10% of gas, dust in 0.001% of Galaxies' volume
  - High SF and SNR rate.
  - High B-field (x100 that of the disk).
- Yet it falls *off* the FIR/RC and RC/gamma-ray (and hence FIR/gamma-ray) correlations.
- Has molecular signatures (i.e., shocks vs PDR chemistry) that are *inconsistent* with star-bursting galaxies.
- Implies a *large-scale* (i.e., $\Omega_{GC} \gtrsim 0.5°$) *wind* dominating the radio+gamma-ray flux, whilst the *diffused* CRs dominate the small scale (i.e., Jones, 2014).
- It is this wind that is supplying the energy for the recently-discovered *Fermi* Bubbles (Su+, 2010) and S-PASS Lobes (Carretti+, 2013).

THE FERMI BUBBLES

- They are enormous, bilateral “bubbles” of emission extending to 50 degrees from the Galactic plane.
- Discovered in the data of the Fermi gamma-ray telescope by Su+ (2010).
- Robustly detected in the residual images from the 1.6-year Fermi data between 1 and 100 GeV.
- Now even detected in non-background-subtracted data.

Source: http://article.wn.com/view/2012/02/20/Fermi_telescope_unveils_gammaray_bursts_highest_power_side/

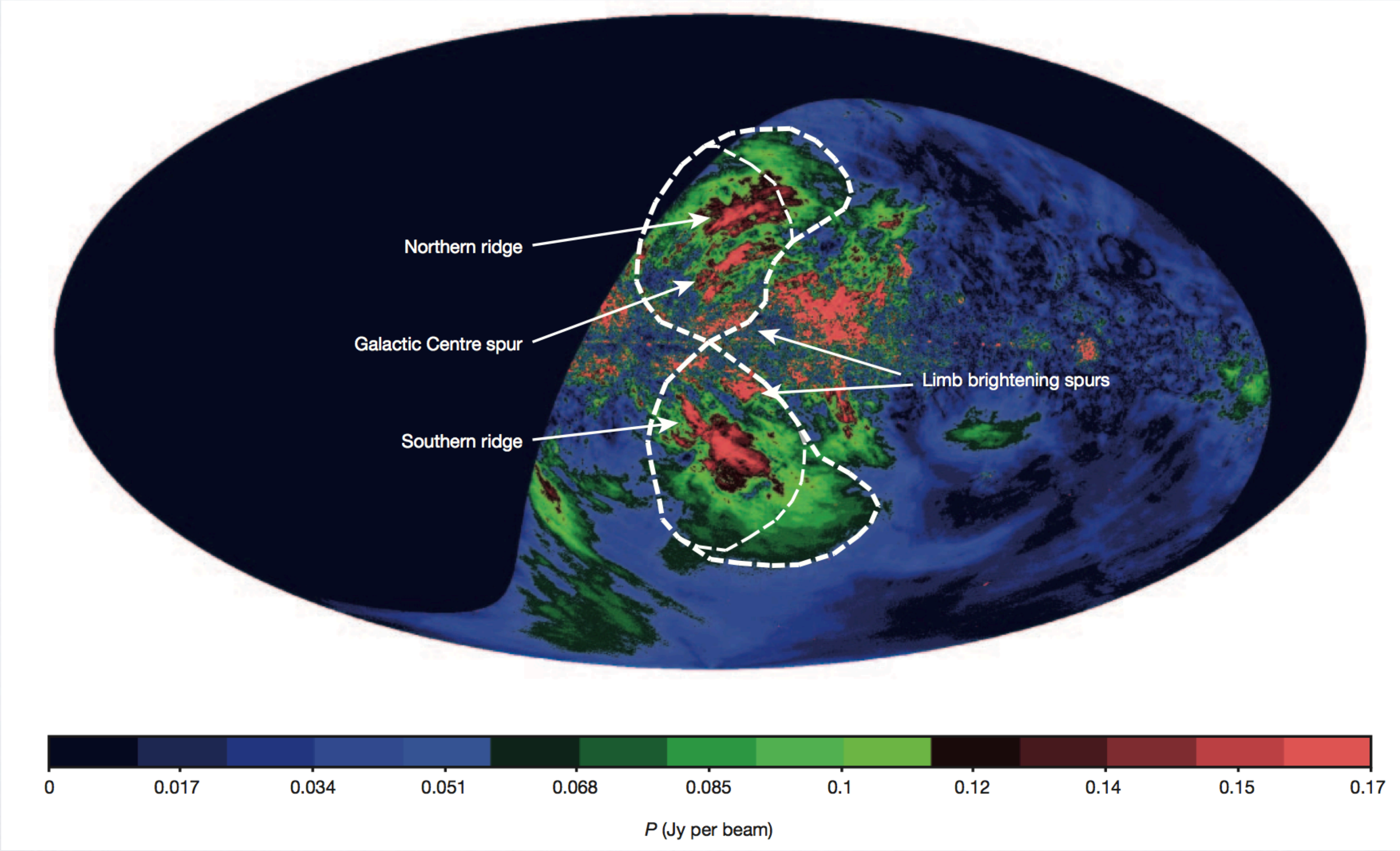
THE S-PASS LOBES



Carretti, et al, Nature, 2013

THE S-PASS LOBES

- The S-PASS Lobes are similar structures seen in the polarised Parkes southern sky survey at 2.3 GHz (Carretti+, 2013).
- Survey at 2.3 GHz, with 184 MHz bandwidth and 9' resolution.
- Seen to 'envelop' the Fermi Bubbles and curve to the Galactic west.
- The spectral index (with 23 GHz WMAP data) spans -1 to -1.2 and steepens with distance from the plane.
- Polarisation fractions of 25-31%, and inferred B-field values of 6-12 μG.



BUBBLE-LOBE FORMATION THEORIES

- The Bubbles are difficult to explain in a consistent manner due to:

1. The **large luminosity** of ~4×10^{37} erg s^{-1} in the gamma-ray domain — an order of magnitude larger than the Bubbles' microwave luminosity but more than order of magnitude less than their X-ray luminosity; Su+ (2010)

2. A **hard spectrum** of $dN/dE \sim E^{-2}$ from 1 to 100 GeV

3. Their **vast extent** and relatively **uniform gamma-ray intensity**.

BUBBLES AS OUTFLOWS FROM SGR A*

- The Bubbles could be revealed via inverse Compton (IC) losses of a population of electrons simultaneously producing the GeV and multi-GHz photons.

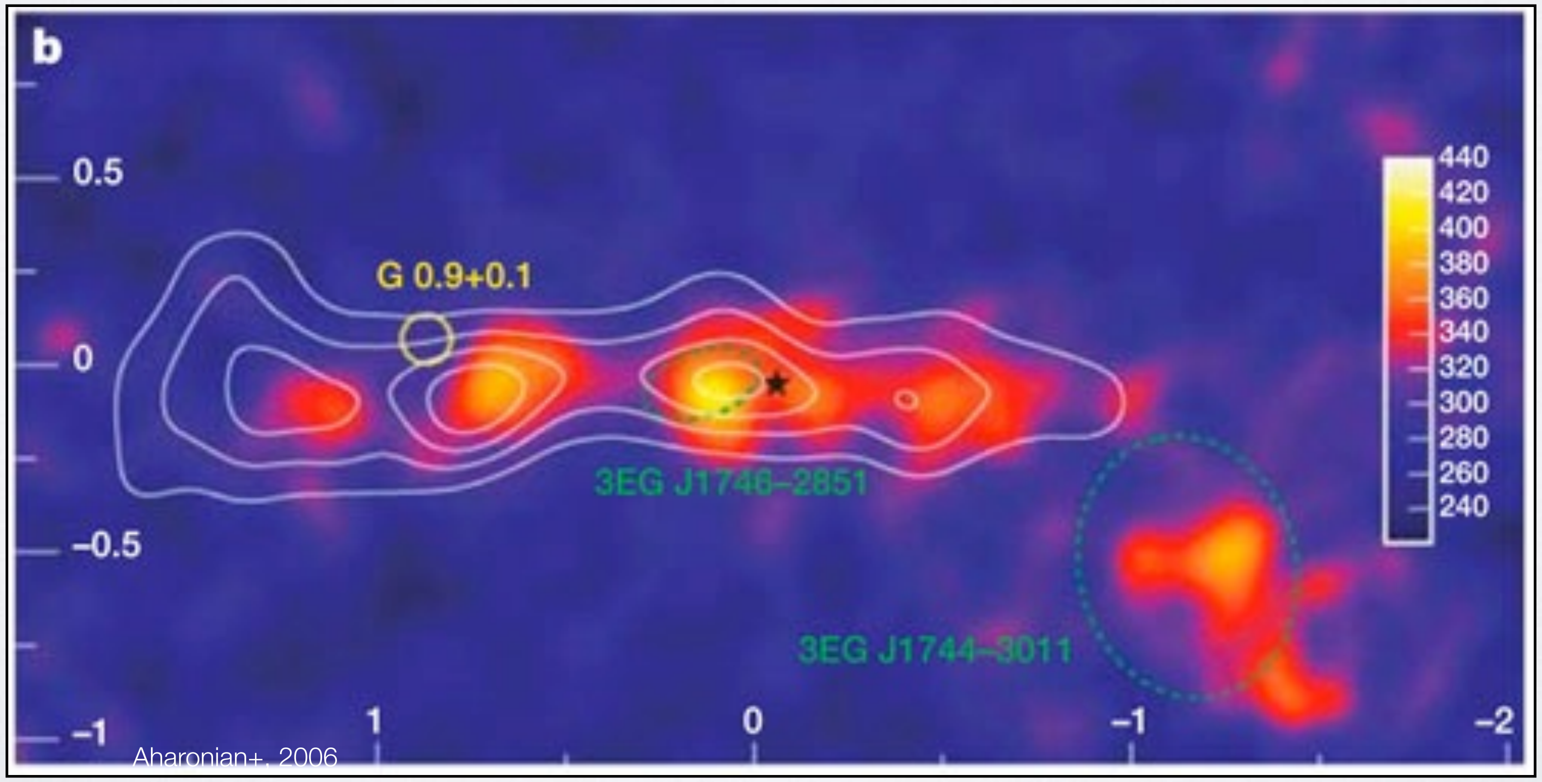
- Hypotheses for the acceleration of these electrons have included:

  - Bubble-pervading shocks (Cheng+, 2011), or distributed, stochastic, acceleration on plasma wave turbulence (Mertsch & Sarkar, 2011).

  - A prior outburst by an AGN-like outburst from the central black hole, Sgr A*, in the past few million years (Su+, 2010).

BUBBLES FROM HADRONS

- An explanation that can reconcile the seemingly difficult parts of the Bubbles' nature are cosmic-ray protons (strictly CR protons + heavier ions but hereafter simply protons).
- Here, CR protons, accelerated by supernovae in the Galactic centre region and advected into the Bubbles on a wind (Crocker & Aharonian, 2011, Crocker, Jones+, 2010, Crocker, Jones+, 2011).
- The protons (that are not advected) are also observed as the diffuse TeV gamma-ray glow in the Galactic centre.
- This gives a prediction for the connection of the Bubbles: they should connect to the TeV gamma-ray "glow-points".



THE BUBBLE-LOBE-GC CONNECTION

- The use of the H-α emission from the SHASSA survey shows a correlation with the depolarisation region surrounding the GC.

- This was used by Carretti+ (2013) to argue that the S-PASS Lobes are a GC phenomenon.

- If one assumes that they are related to the Fermi Bubbles, this also places them there.

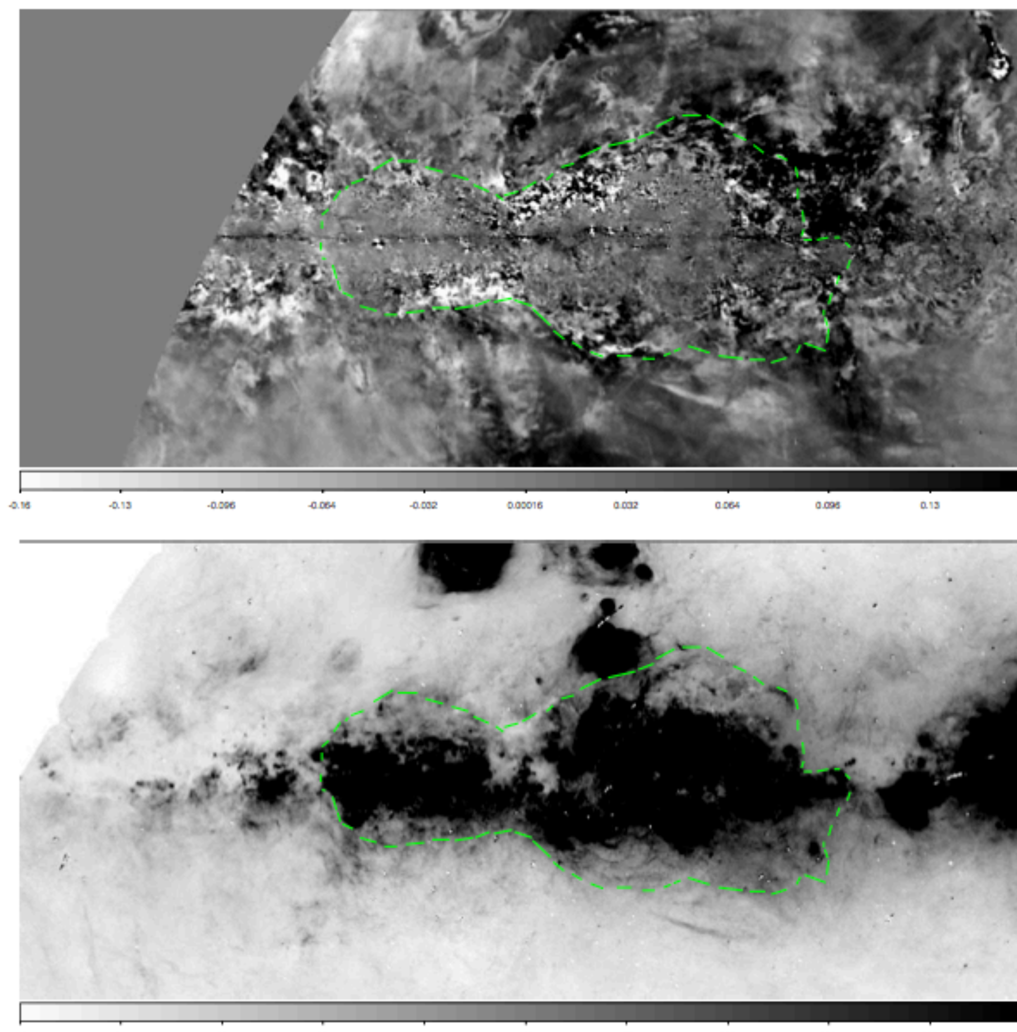
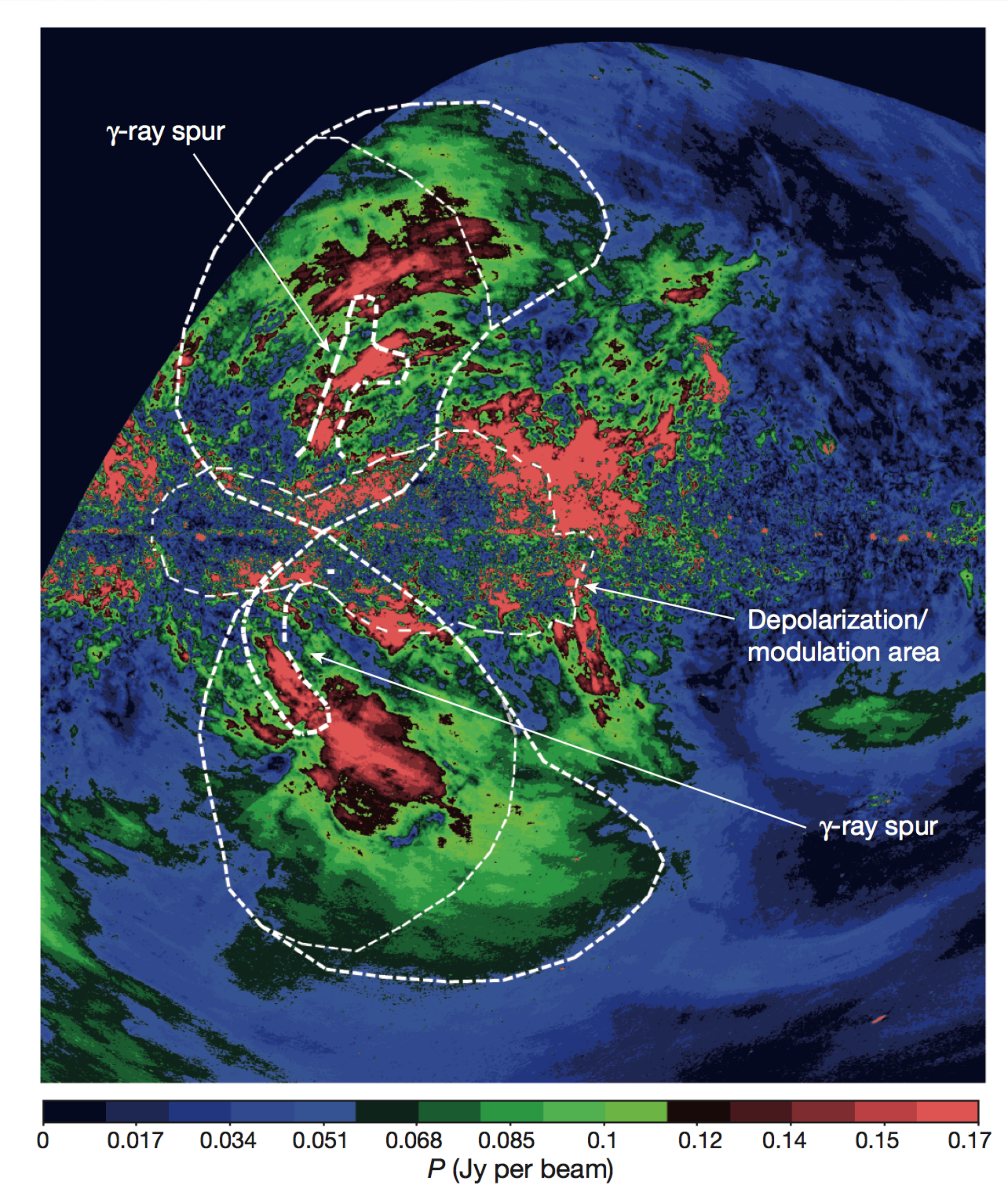


Figure S1: Top: **Stokes Q image of the area around the Galactic Centre.** The Galactic plane is horizontal across the picture and the emission unit is Jy/beam with a beam of FWHM=10.75'. The green dashed line indicates the two areas of depolarization on either side of the Galactic Centre and the belt encompassing them of emission modulated to small angular scales by Faraday Rotation effects. Bottom: **H-α emission image of the same area from the SHASSA survey**. The emission unit is decirayleighs (dR); The resolution is FHWM=6'. The area affected by Faraday Rotation effects is reported as well and corresponds to H-α emission regions from the Sagittarius and Scutum-Centaurus arms – see text.

THE BUBBLE-LOBE-GC CONNECTION

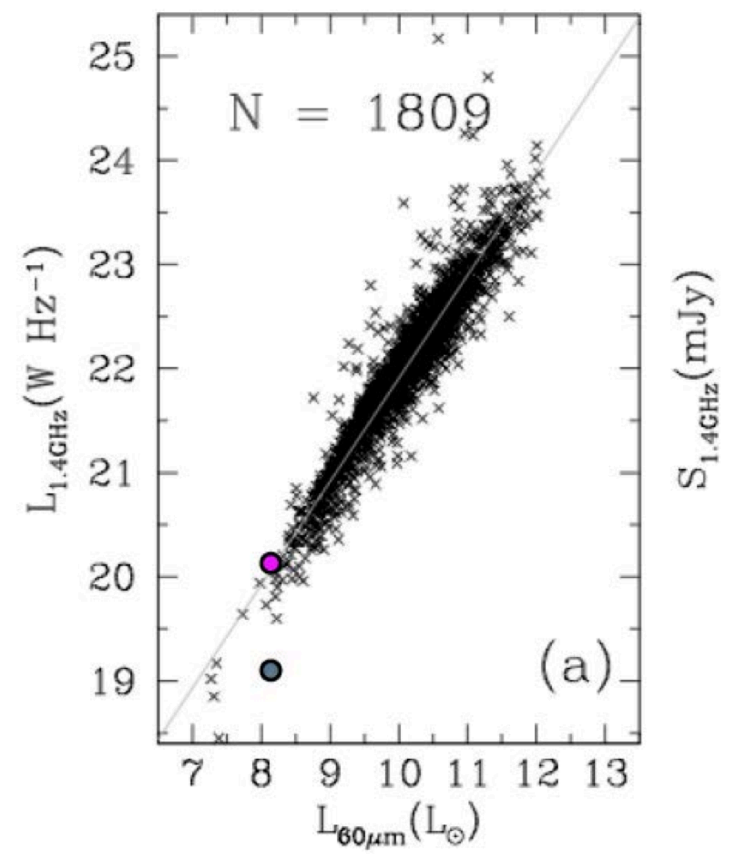
- There are reasons to think that the Bubbles and the Lobes are connected:
  - Similar morphology, including to the Bubble substructures.
  - Similar energetics: $U_B \sim 10^{55}$ erg, which implies $\sim 10^{38}$ erg/s over 10^{10} years for the proton scenario.



THE BUBBLE-LOBE-GC CONNECTION

Radio emission from the lobes

- 21 kJy @ 2.3 GHz
- Equates the missing RC
- RC emitting gas:
  - generated in the Galactic Centre
  - Then transported away as outflows



Yun et al. 2001 ApJ 554, 803

CONCLUSIONS

- The Galactic centre is a complex and dynamic place.
- New observations are revealing a complex morphology in the region that suggests “blotchy” star formation, perhaps due to the geometry of the region.
- A wind / outflow seems to be in operation, keeping the star-formation rate high, but hampering outflows from the central black hole (Sgr A*).
- This outflow may be feeding the Fermi Bubbles and S-PASS Lobes.