A Hadronic Model for the Fermi Bubbles

Roland Crocker MPI-K
Heidelberg

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

MARIE CURIE
ACTIONS

Thanks to collaborators:

David Jones

Felix Aharonian

Casey Law

Fulvio Melia

Juergen Ott

Tomo Oka

Introduction

- “Galactic centre” = “GC”=“HESS region” = inner 200 pc (diameter) of Galactic plane
- GC :- closest example of galactic nucleus - intrinsically interesting
- GC hosts >5 % of Galaxy’s H_2 and is responsible for similar fraction of total SFR, ~10% of *massive* star formation
  → important to Galactic ecology

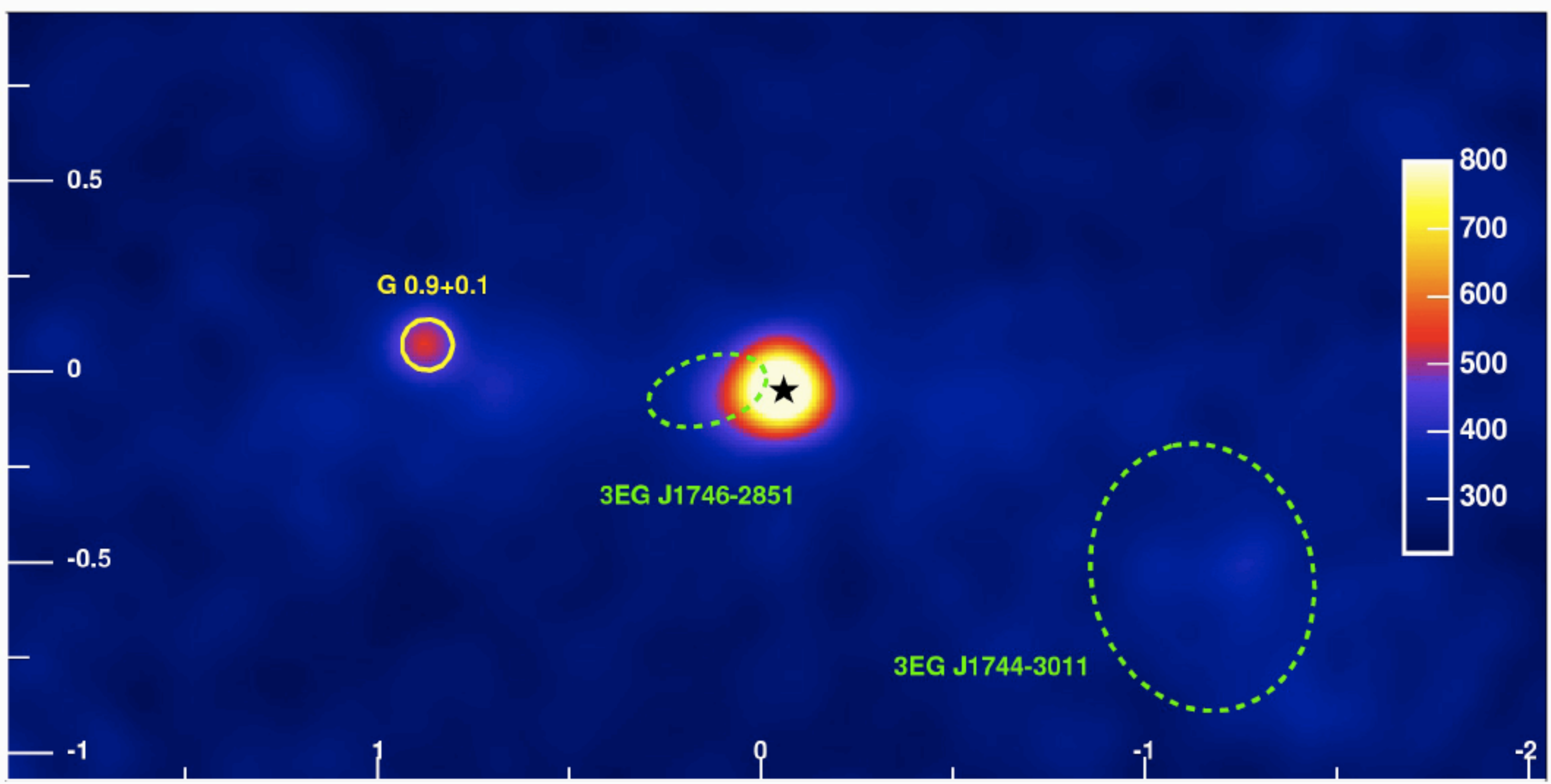
Big picture

- GC ISM params extreme wrt Gal disk - *more akin to a star-burst*: energy densities/ pressures of ISM comps ~2 orders of magnitude larger than in disk (~100's eV cm^{-3})
- Strong B fields, high H_2 densities and turbulence, very hot plasma, ISRF
- SFR density $\gtrsim$ 3 orders of magnitude larger than in disk ($\partial_t \Sigma_* \sim 2\ M_\odot\ yr^{-1}\ kpc^{-2}$)

Big picture II

- Claim: GC star-formation drives a super-wind
- Claim: the GC wind advects plasma and cosmic rays to large distances from the plane and the γ-ray and microwave signatures of these have recently been detected
- Claim: despite similarity to starburst conditions will argue here that GC SF proceeding in more-or-less steady state for $\gtrsim$ Gyrs

Diffuse γs in H.E.S.S. data?



- 50 hour H.E.S.S. Observation of GC in 2005
- Need to subtract the two bright sources

Credit: HESS Collab

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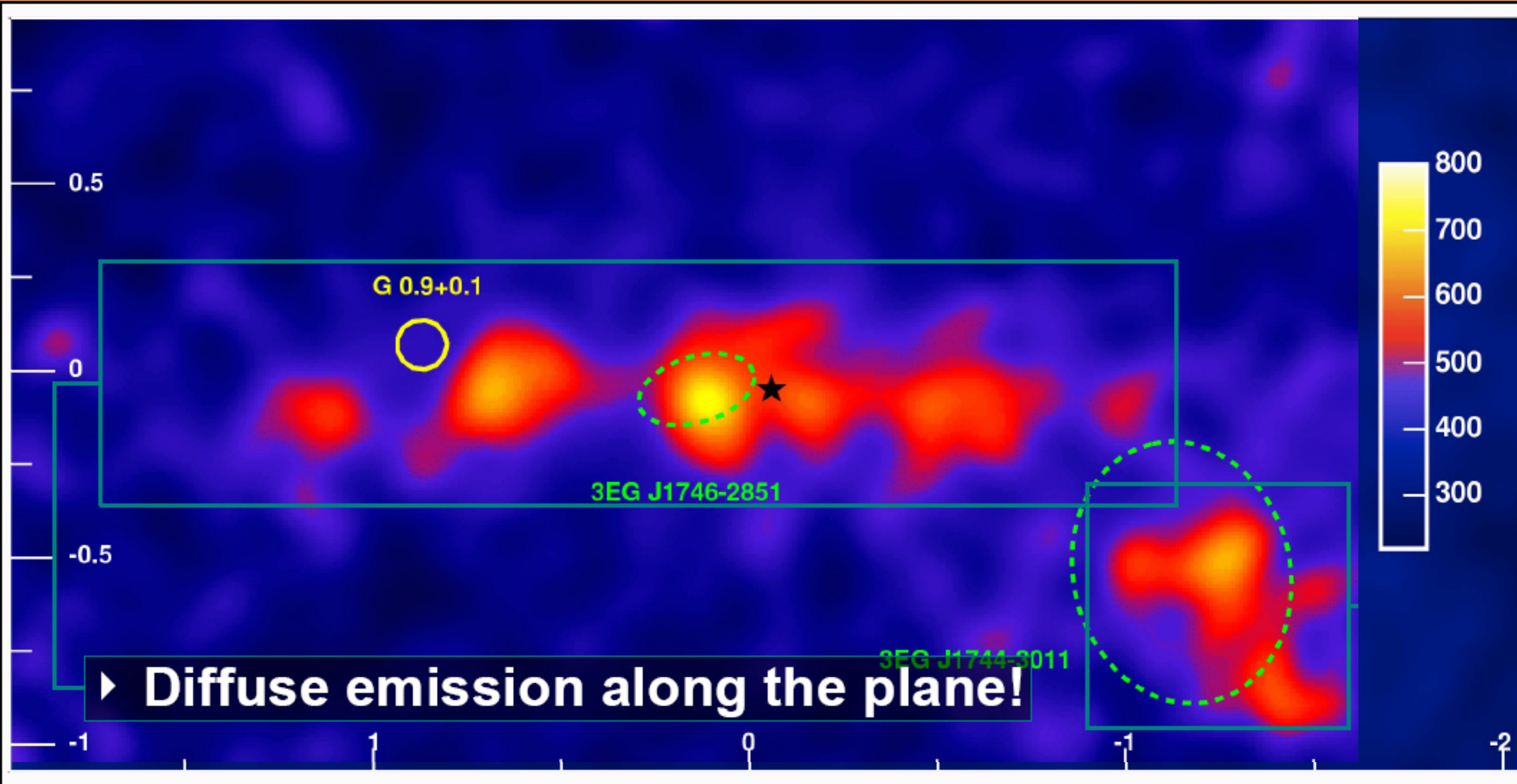

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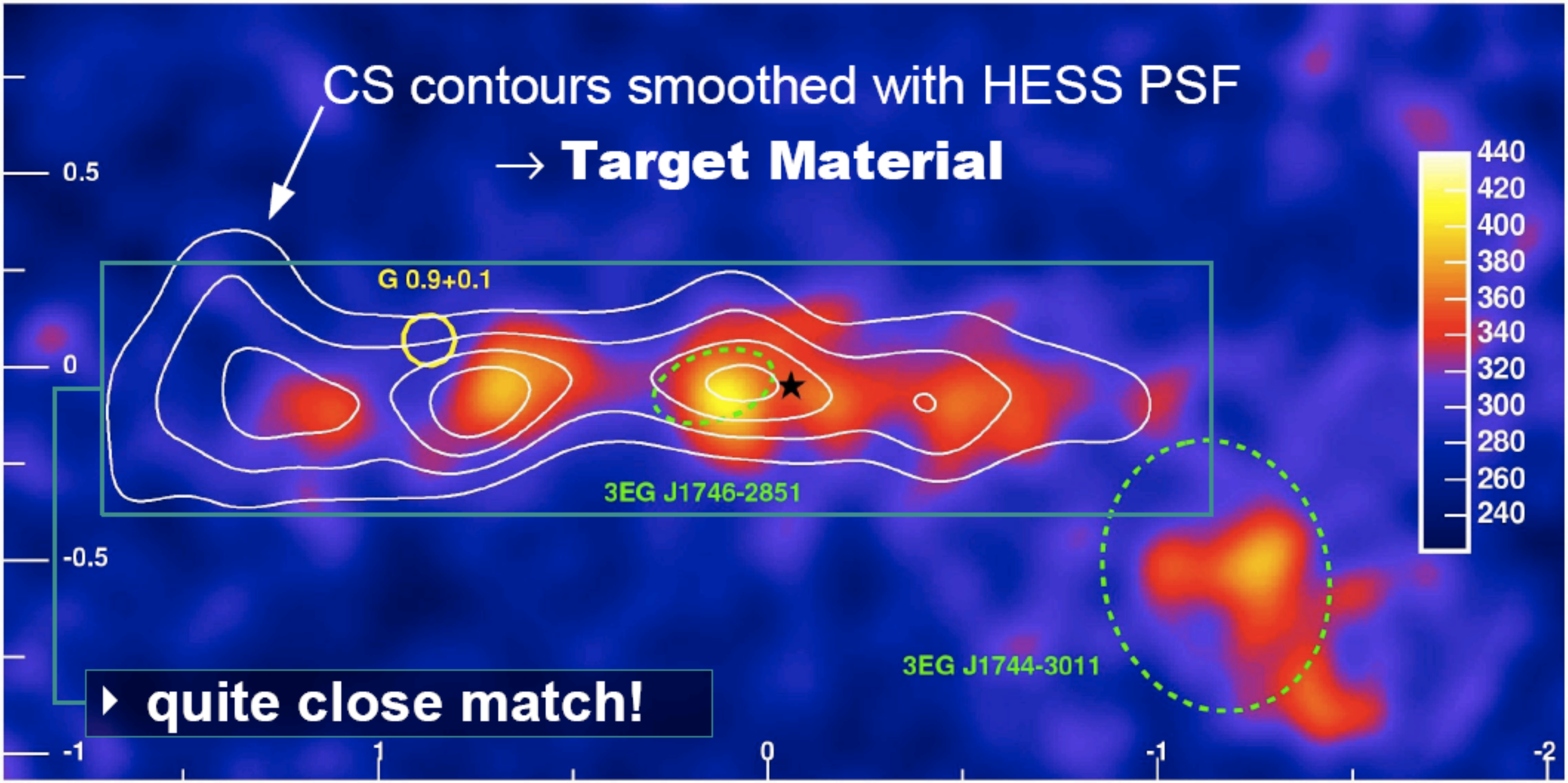
CS contours over H.E.S.S. map



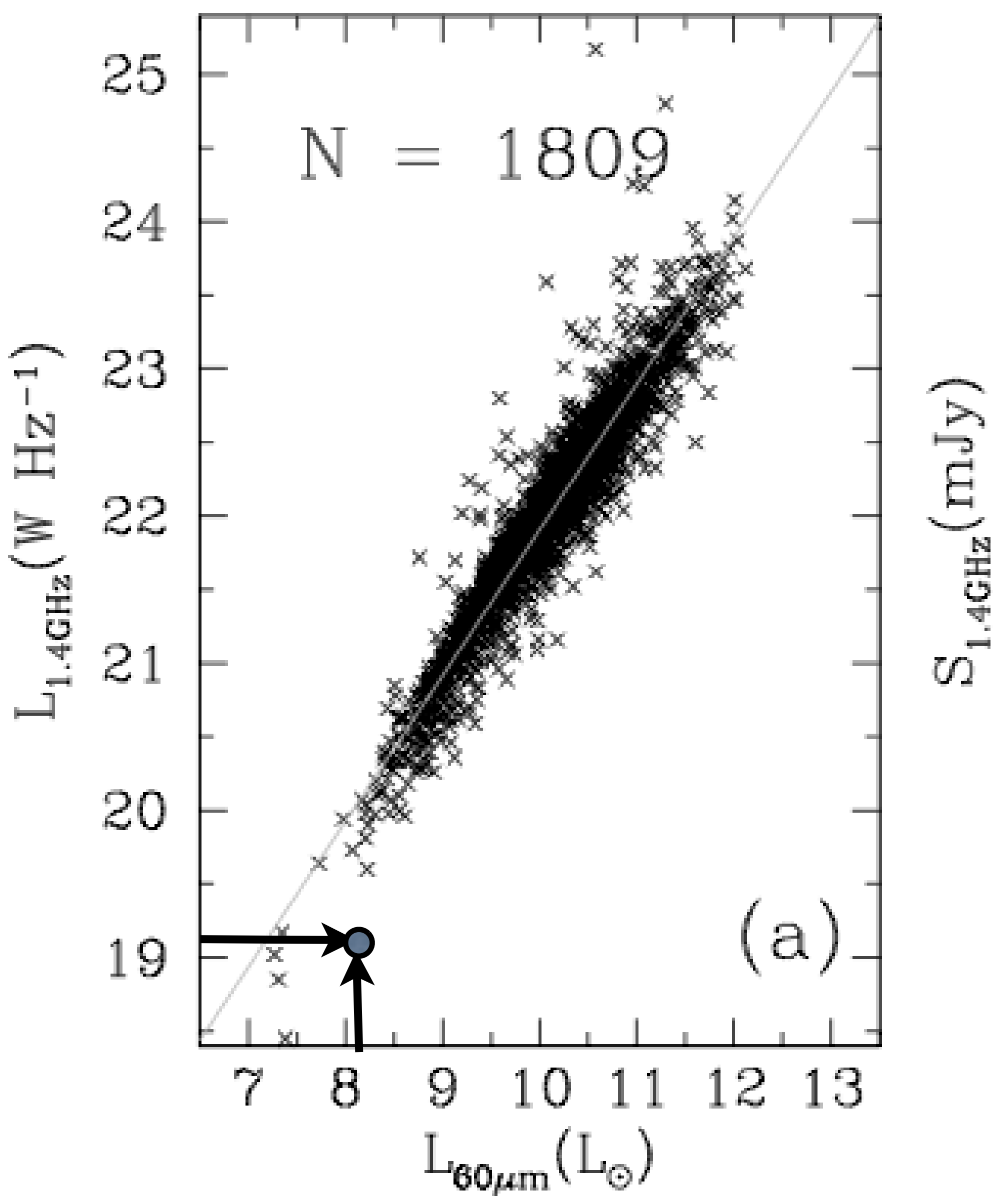
Credit: HESS Collab

CS contours from Tsuboi et al. (1999)

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

$L_{1.4\,\mathrm{GHz}} = 1.2 \times 10^{19}$ Watt/Hz



$L_{60\mu m} = 1.3 \times 10^{8}\ L_\odot$

RC in deficit wrt expectation from FIR

HESS system is 1 dex (> 4σ) off correlation

i.e. **GHz RC emission of HESS region only ~10% expected**

Sidebar: origin of FIR-RC?

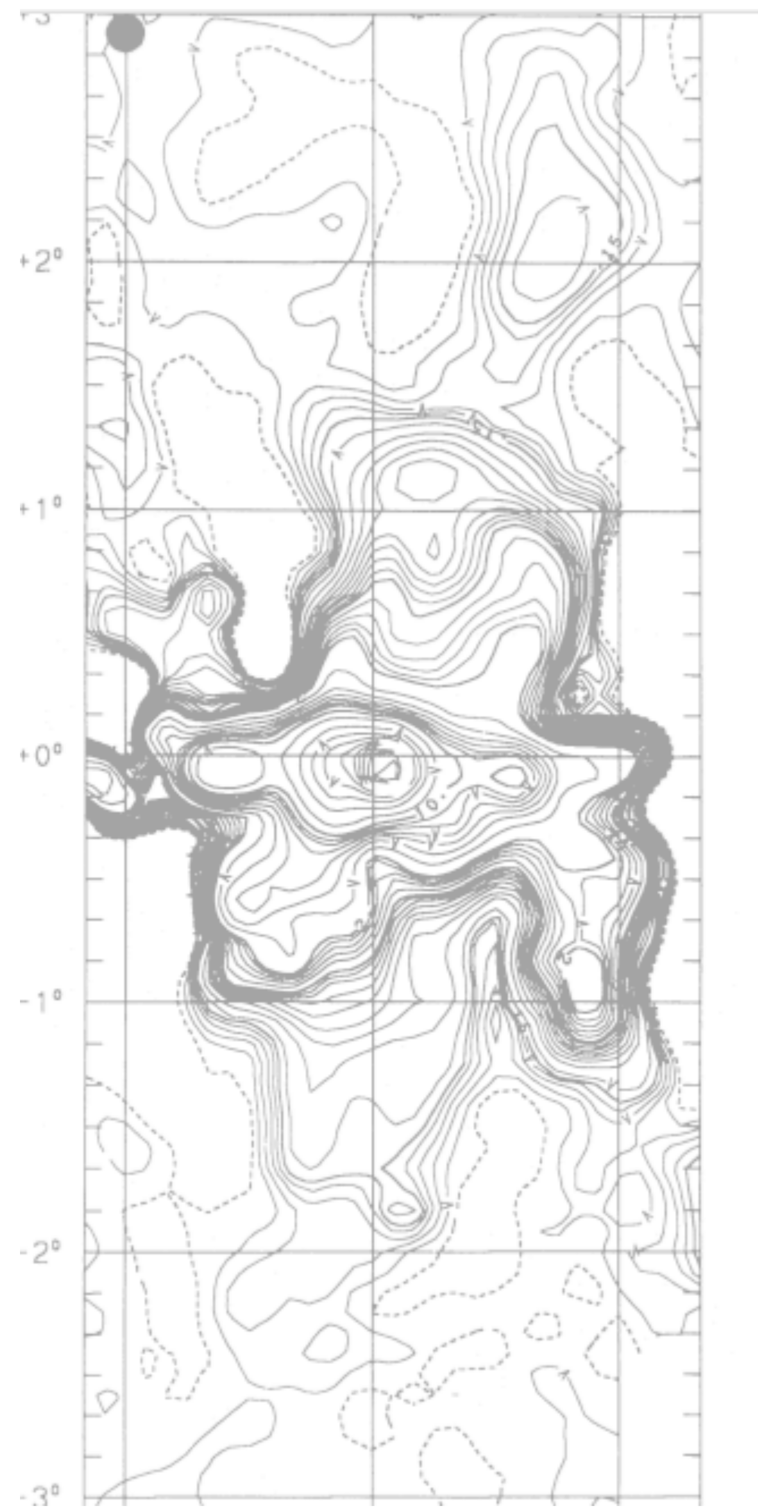
- correlation between FRC and RC ultimately tied back to massive star formation (Voelk 1989)
- massive stars → UV → (dust) → IR
- massive stars → supernovae → SNRs → acceleration of CR e's → (B field) → synchrotron

FIR-γ-ray Scaling?

- SNR also accelerate CR p's (and heavier ions)
- there should exist a global scaling b/w FIR and gamma-ray emission from region (Thompson et al. 2007): $L_{GeV} \sim 10^{-5} L_{TIR}$ (assuming 10^{50} erg per SN in CRs)
- Given scaling, **TeV emission of HESS region only about 1% expected, GeV emission only ~10% expected**

CR Transport

- *Flat* spectrum of in-situ electron and proton population → transport is advective not diffusive, i.e. via a *wind*
- [contrast situation in Galactic plane]
- there is much prior evidence for such a wind



2.7 GHz radio data
(unsharp mask, 9.4`)
Pohl, Reich &
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HESS TeV data: Aharonian et al 2006

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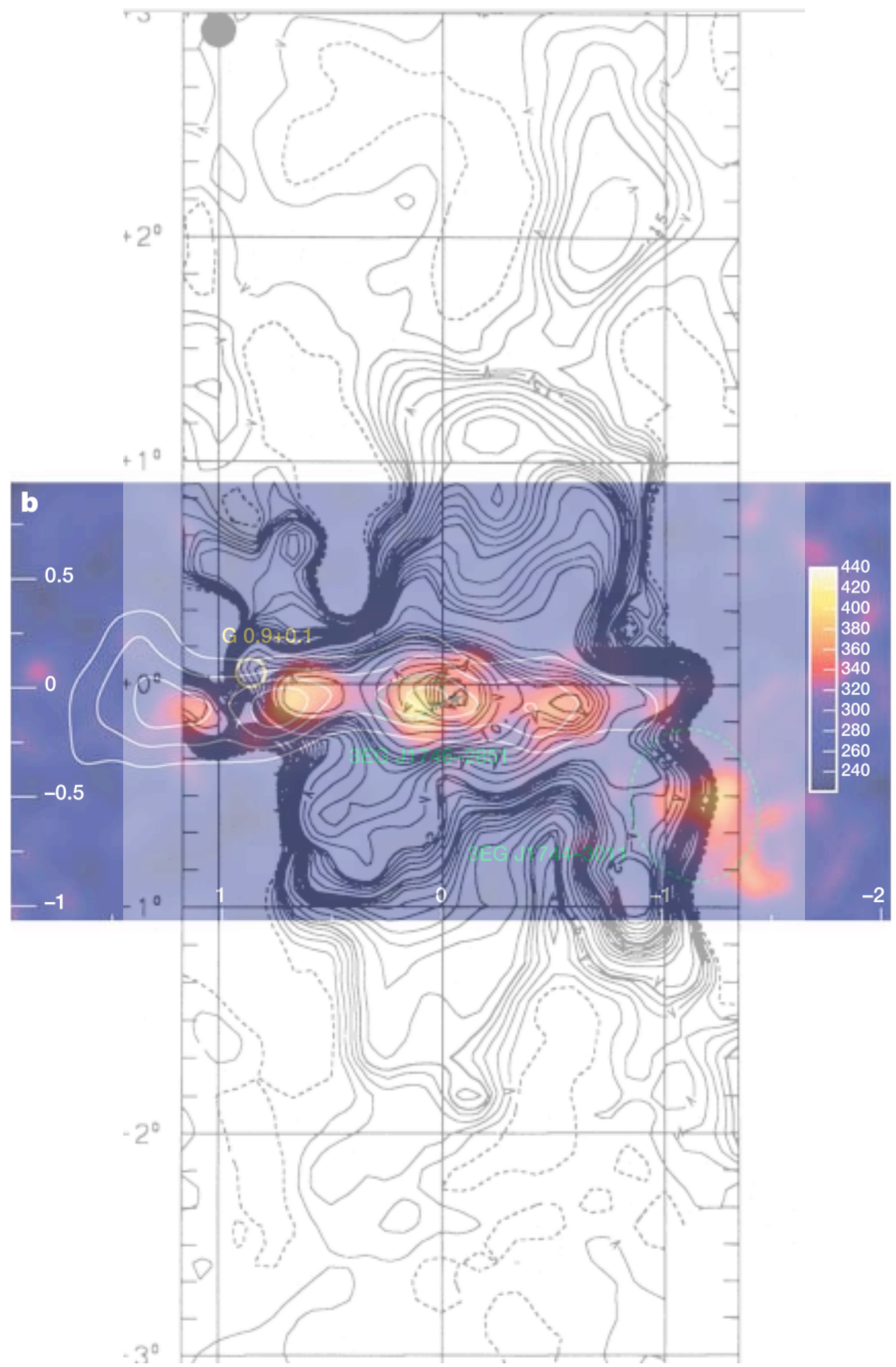

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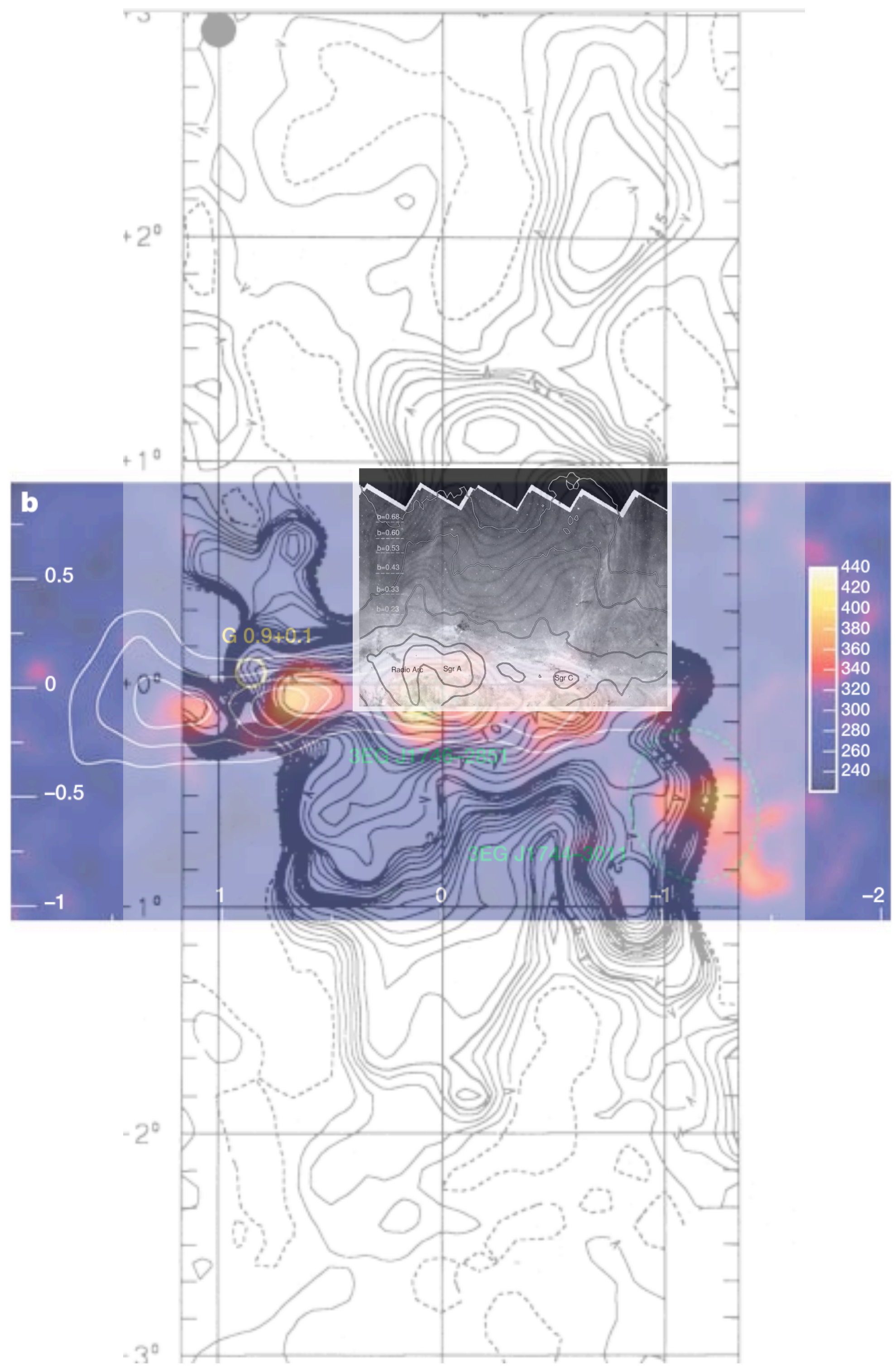
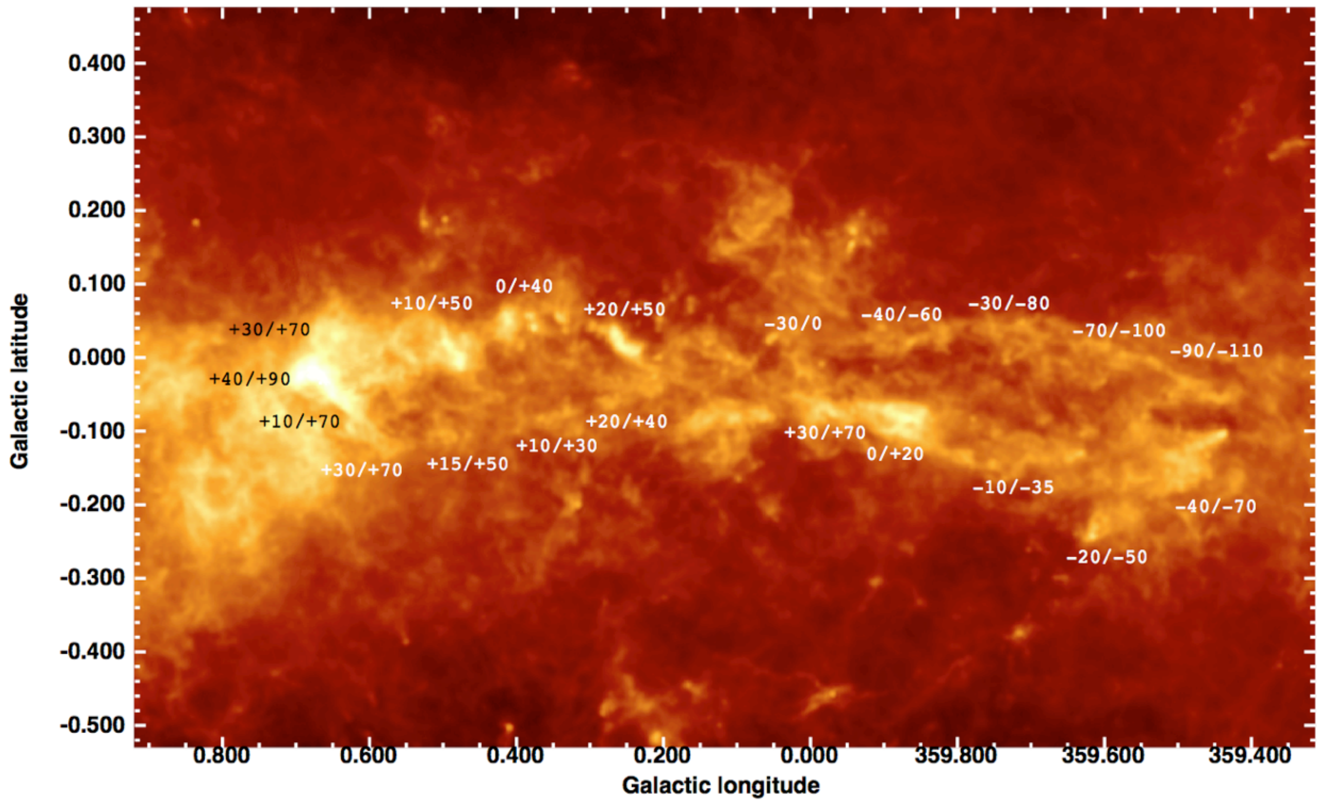


Spitzer 8 micron Stolovy 2006

Herschel SPIRE 250 μm
(Molinari et al. 2011)



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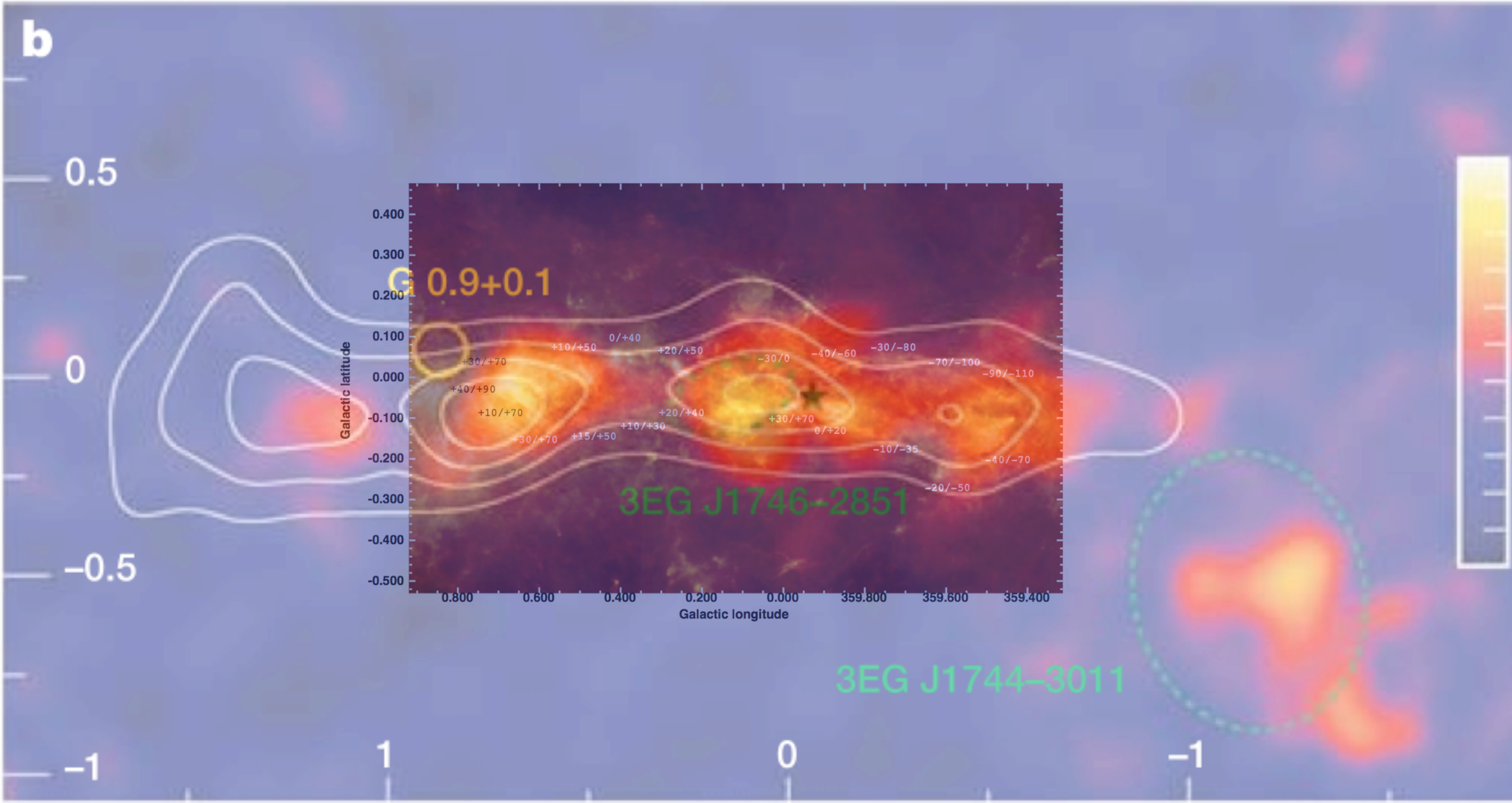

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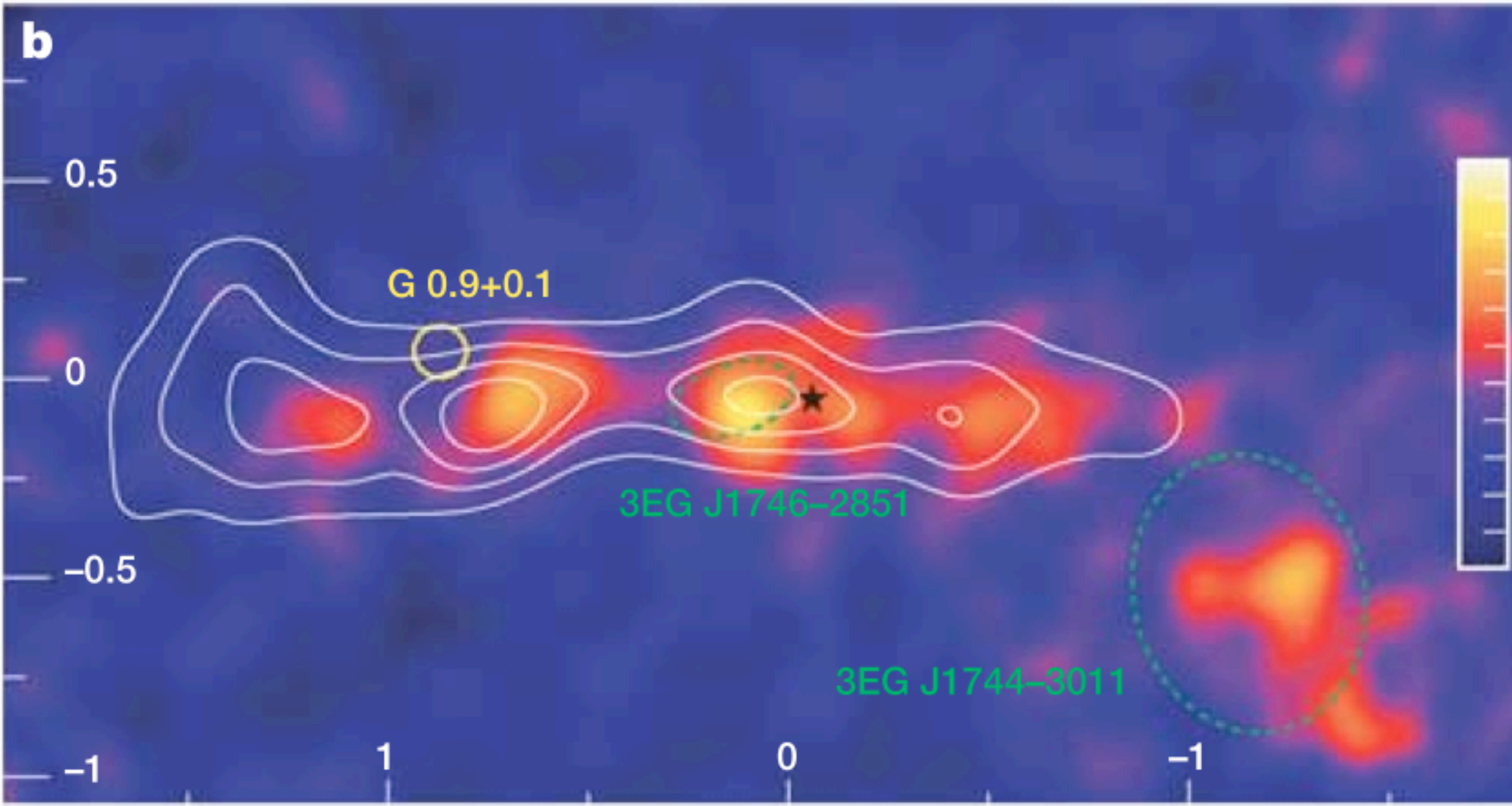

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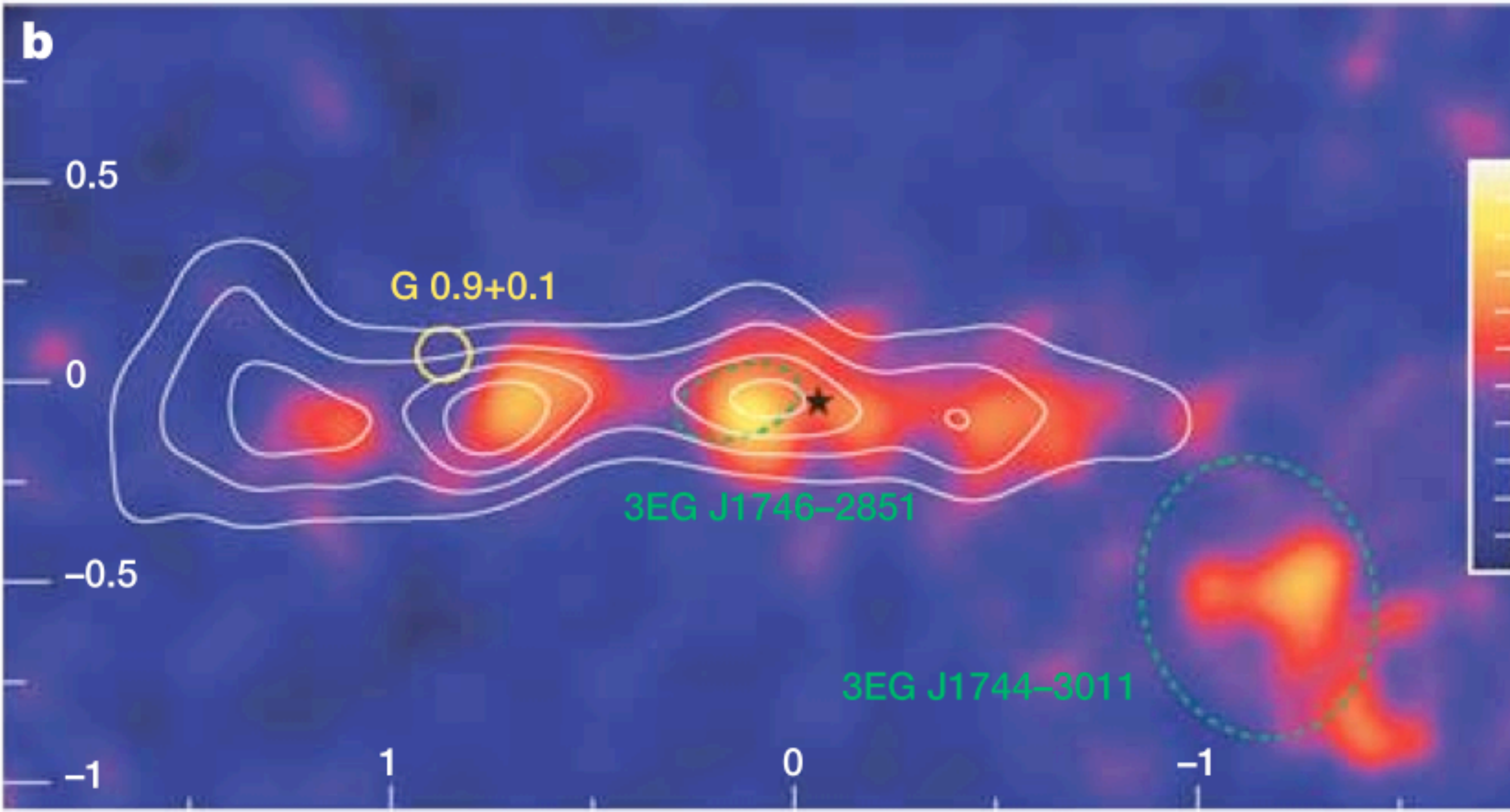

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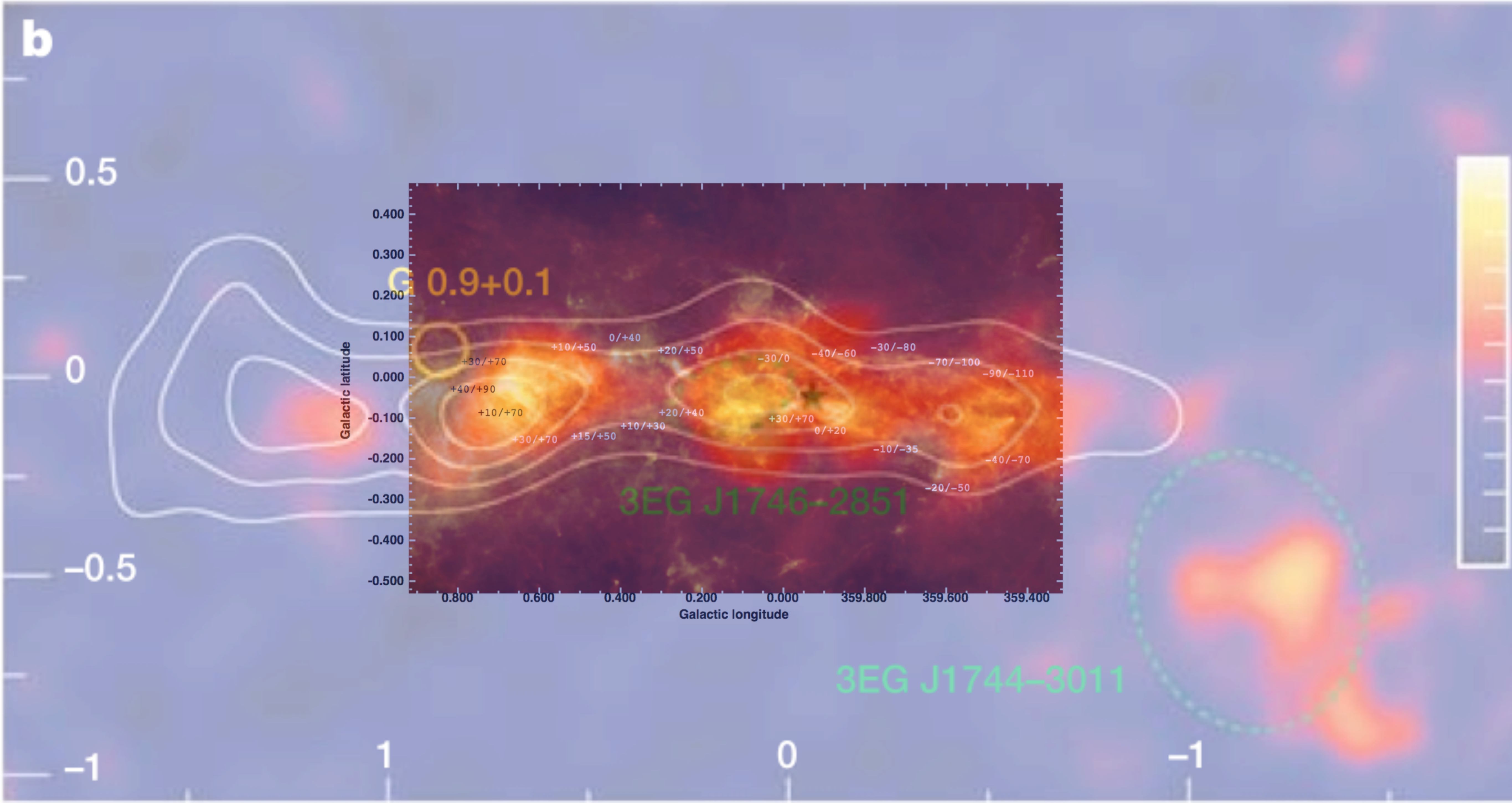

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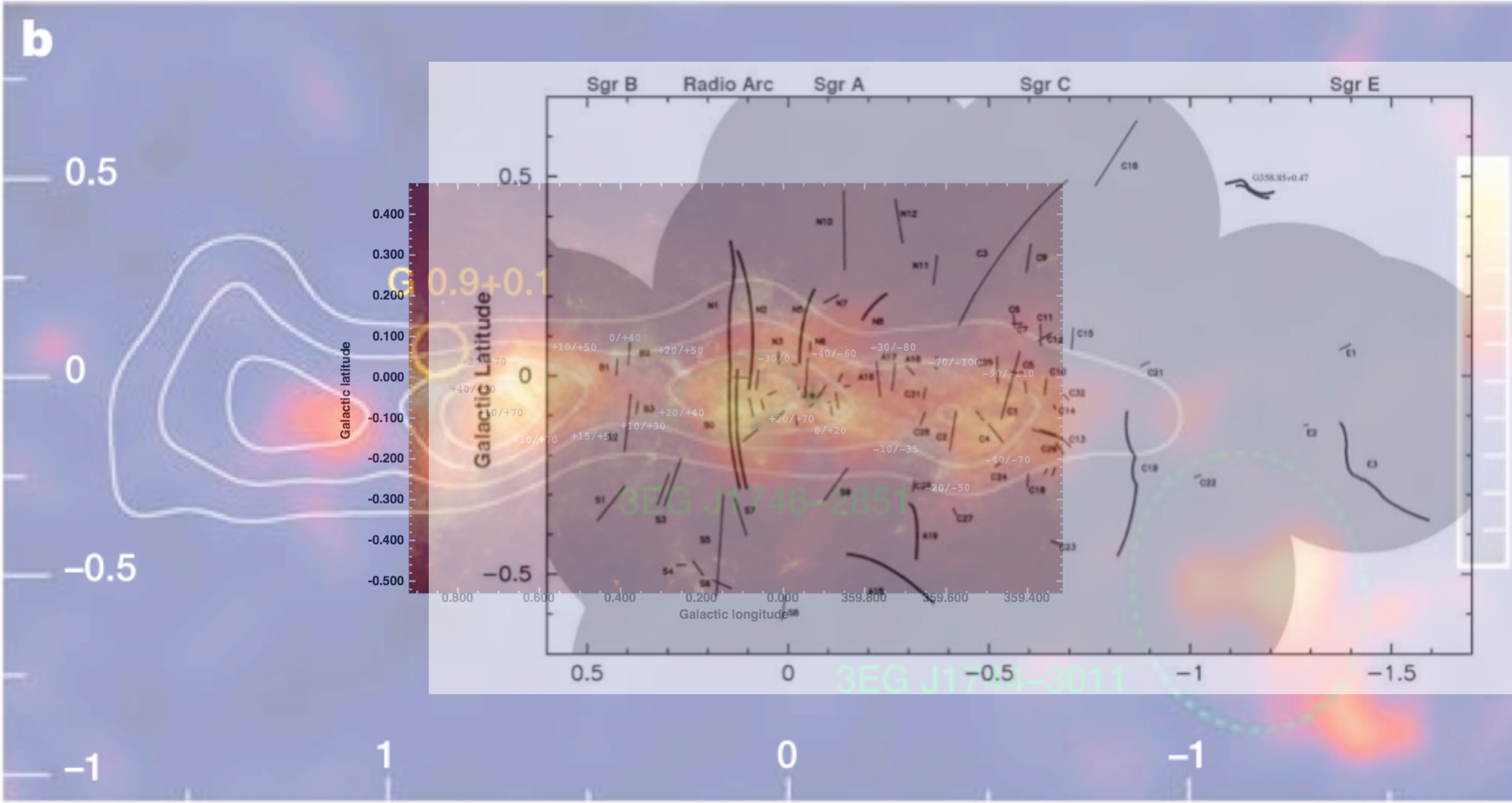

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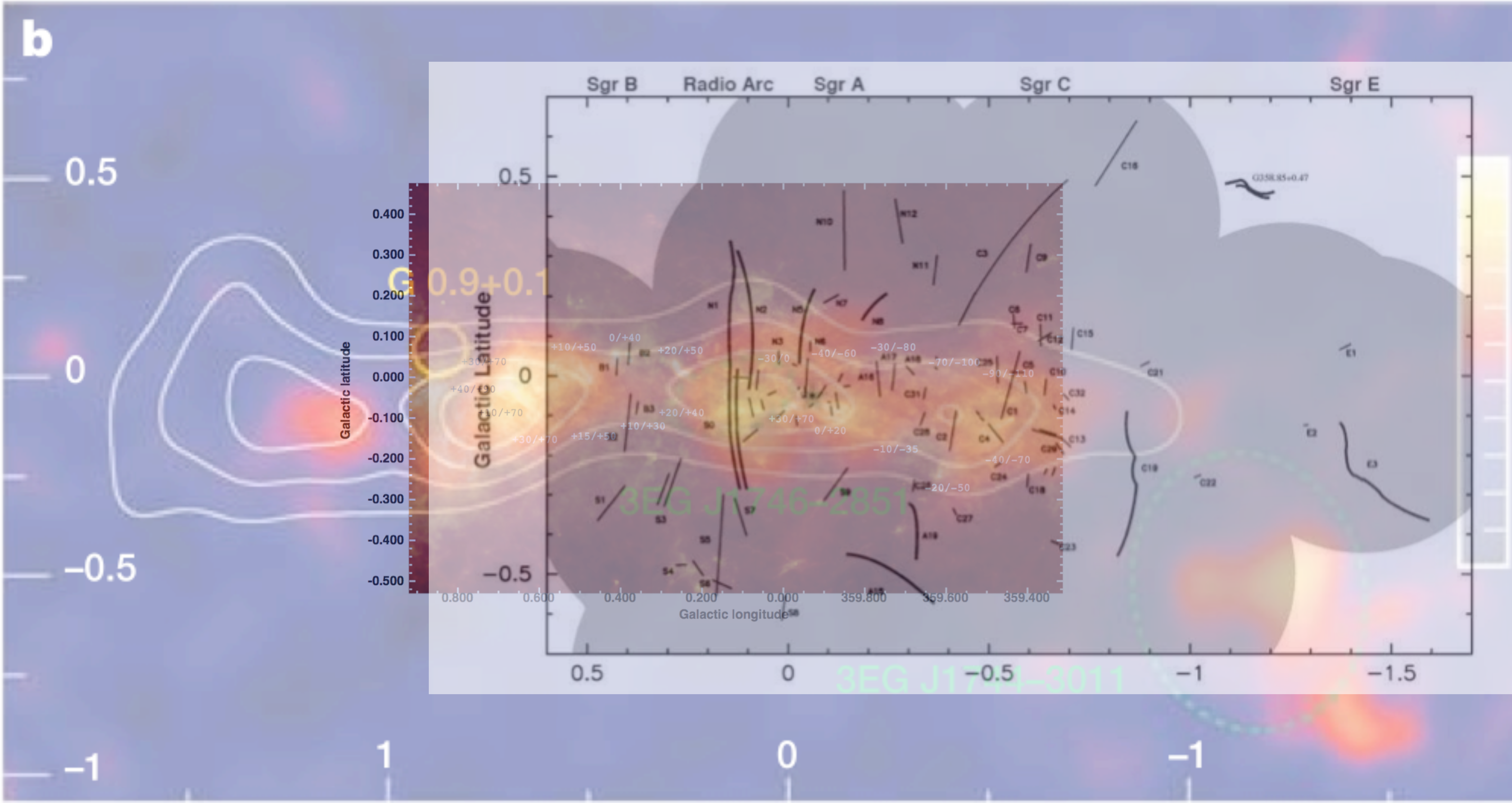
NTFs, Yusef-Zadeh et al 2004



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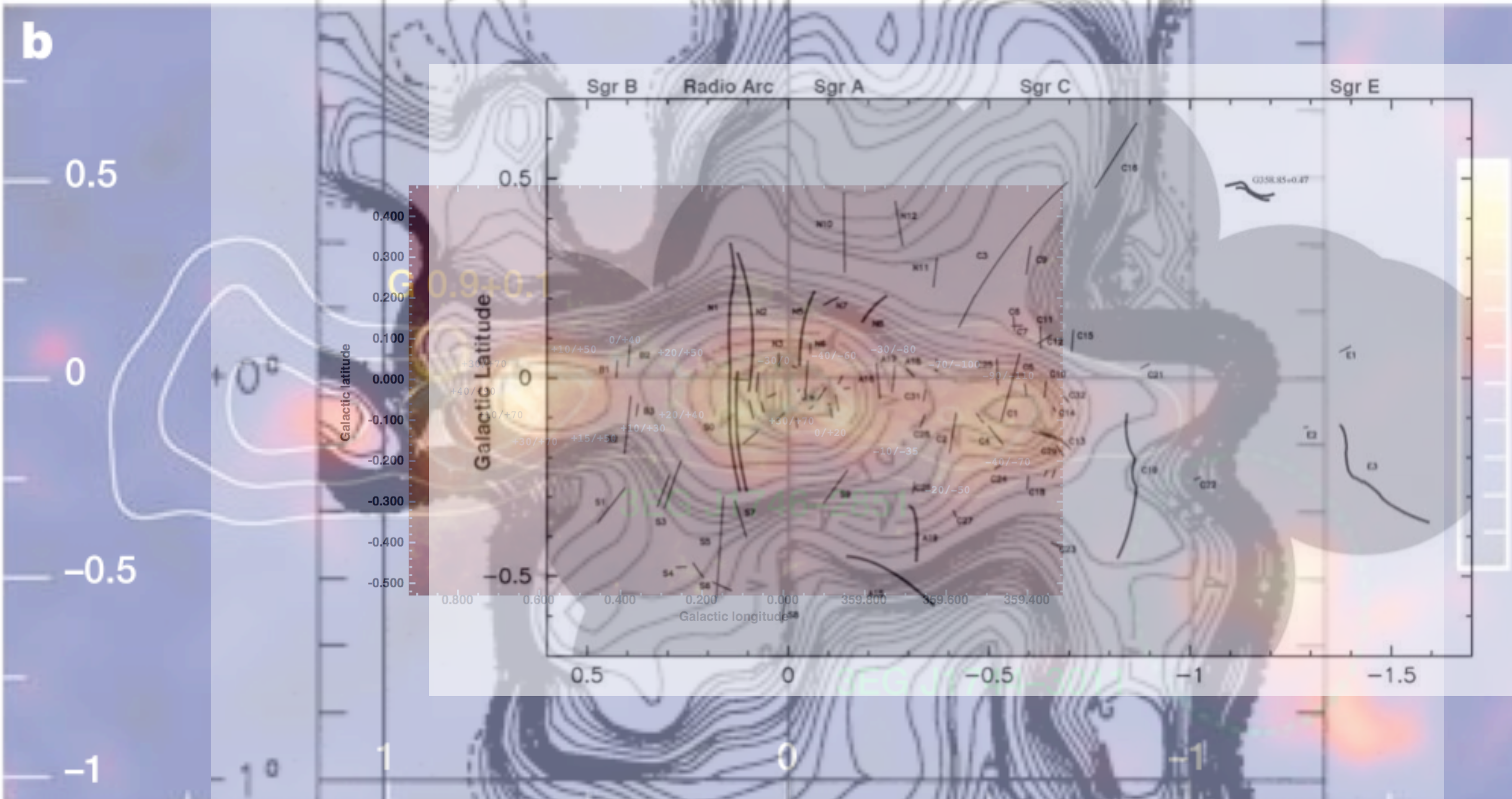

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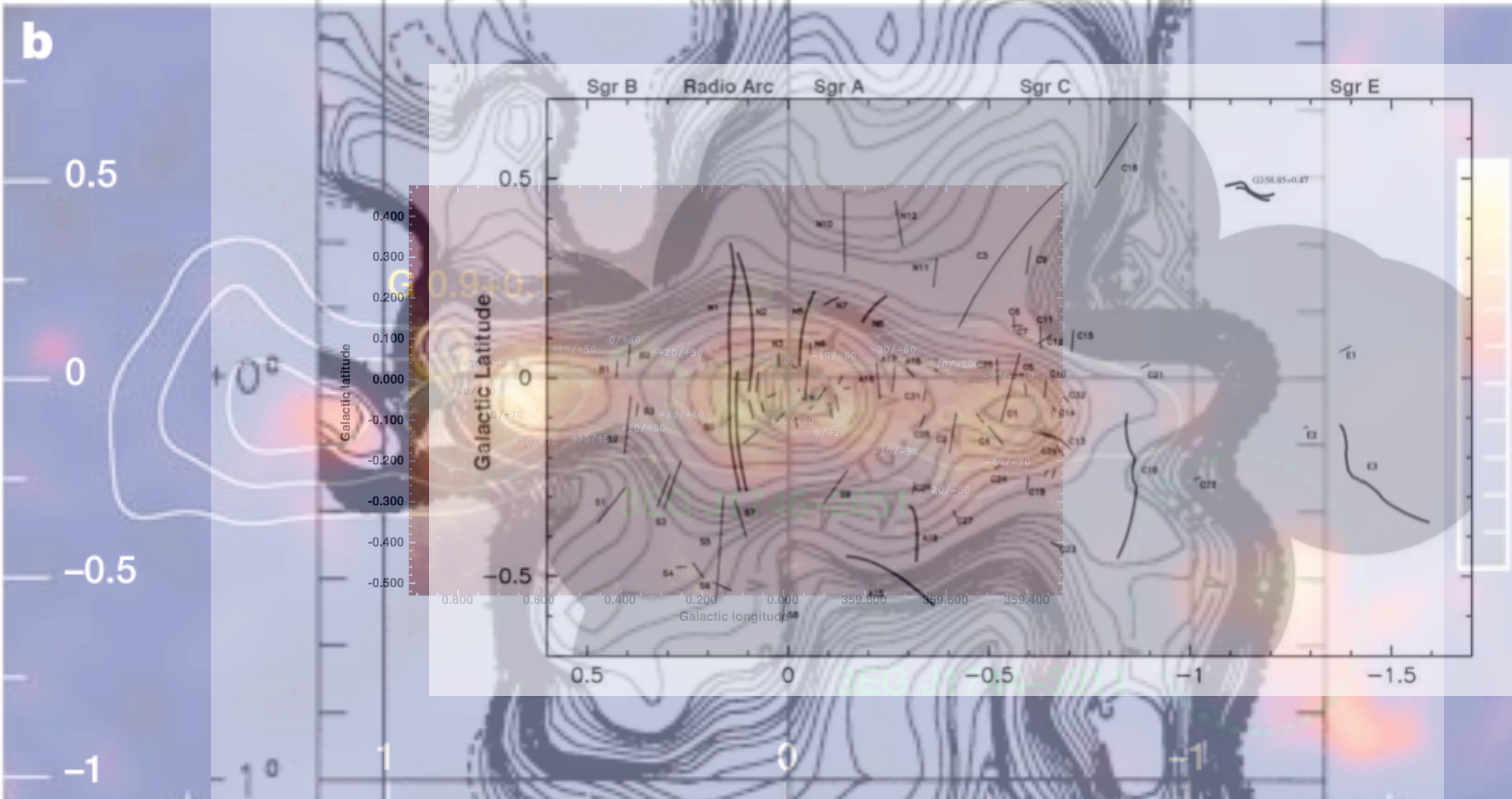
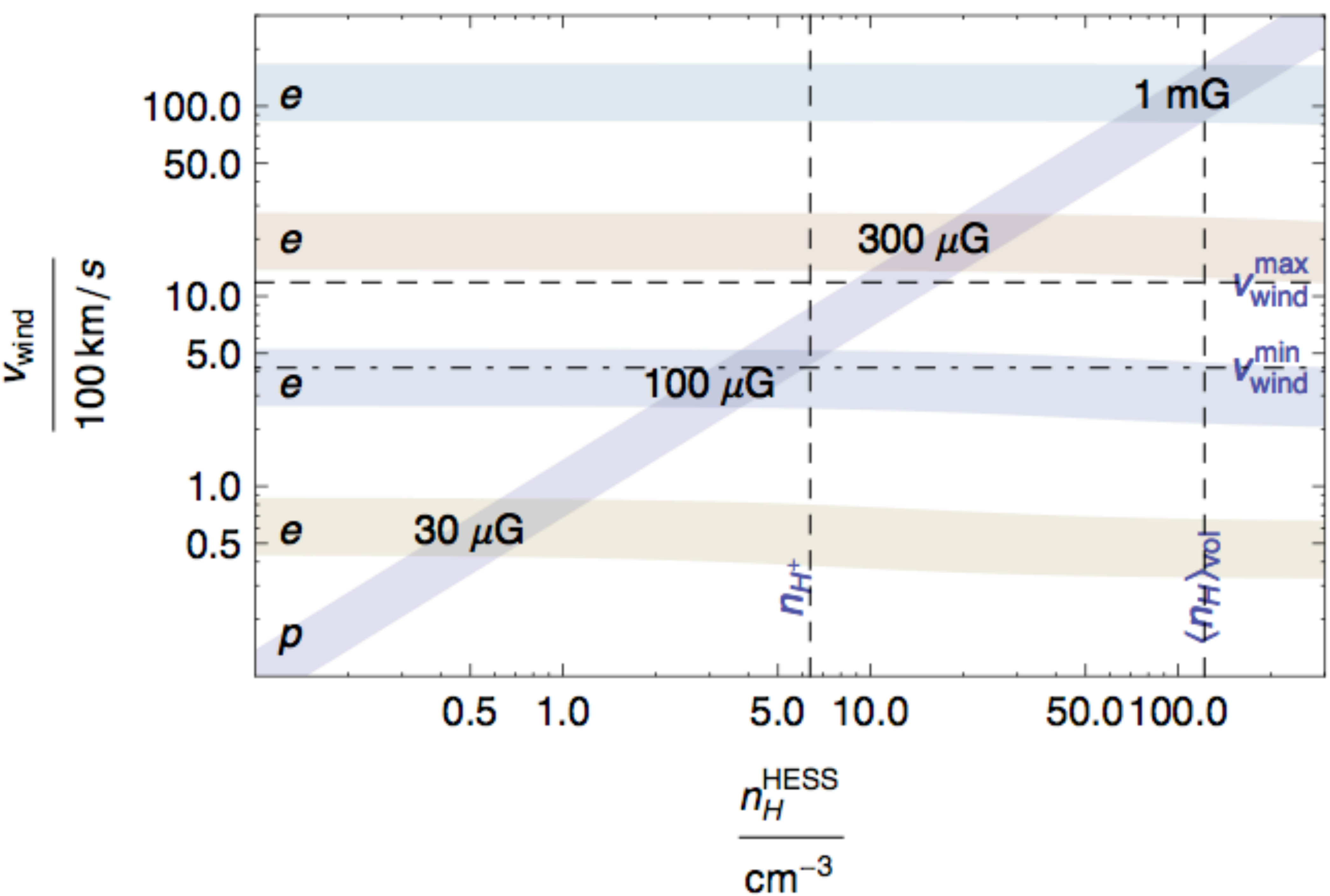


Ring collimates outflow - outflow ablates cold gas

HESS TeV (Aharonian et al 2006)

Gas/Wind/Mag. Field



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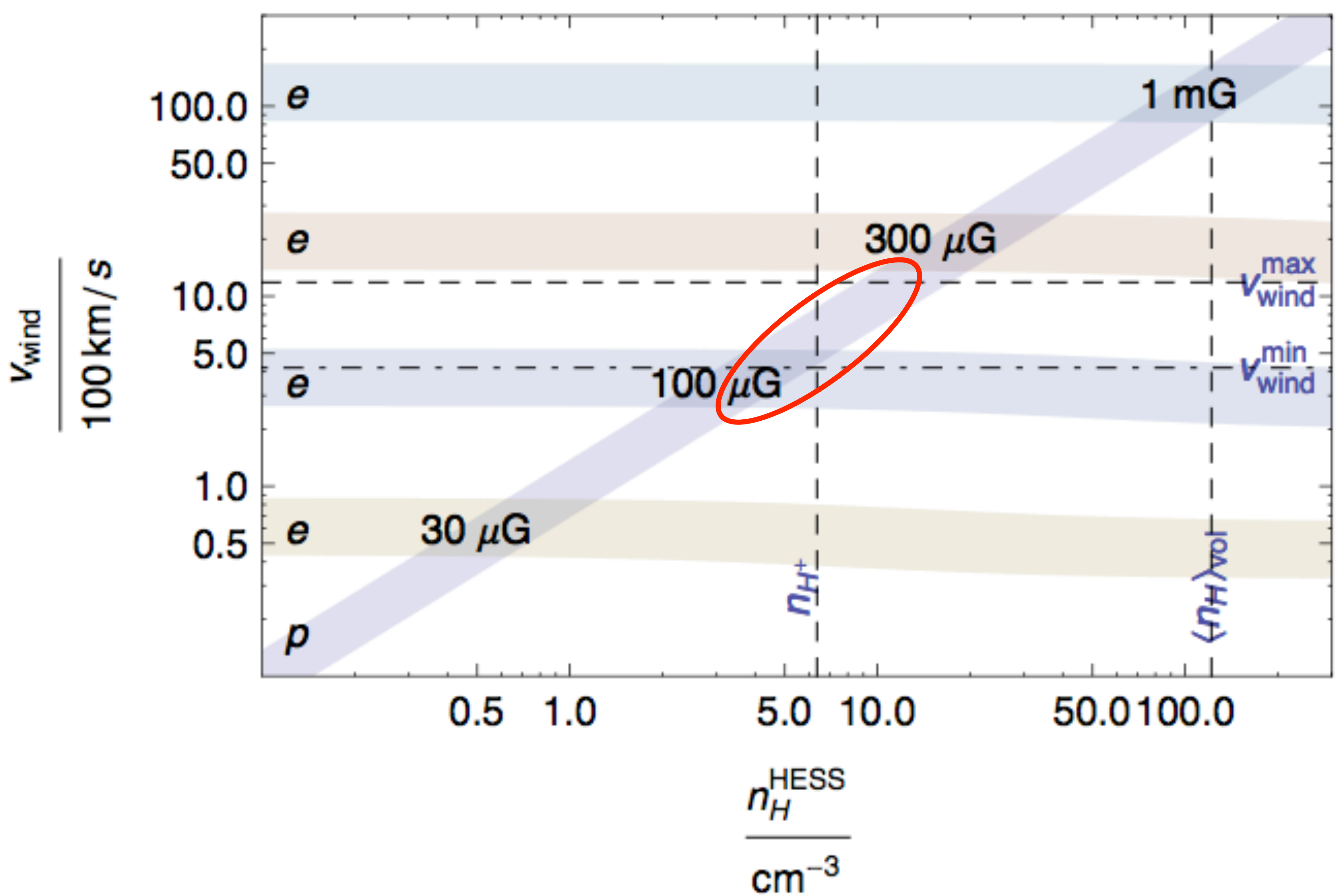
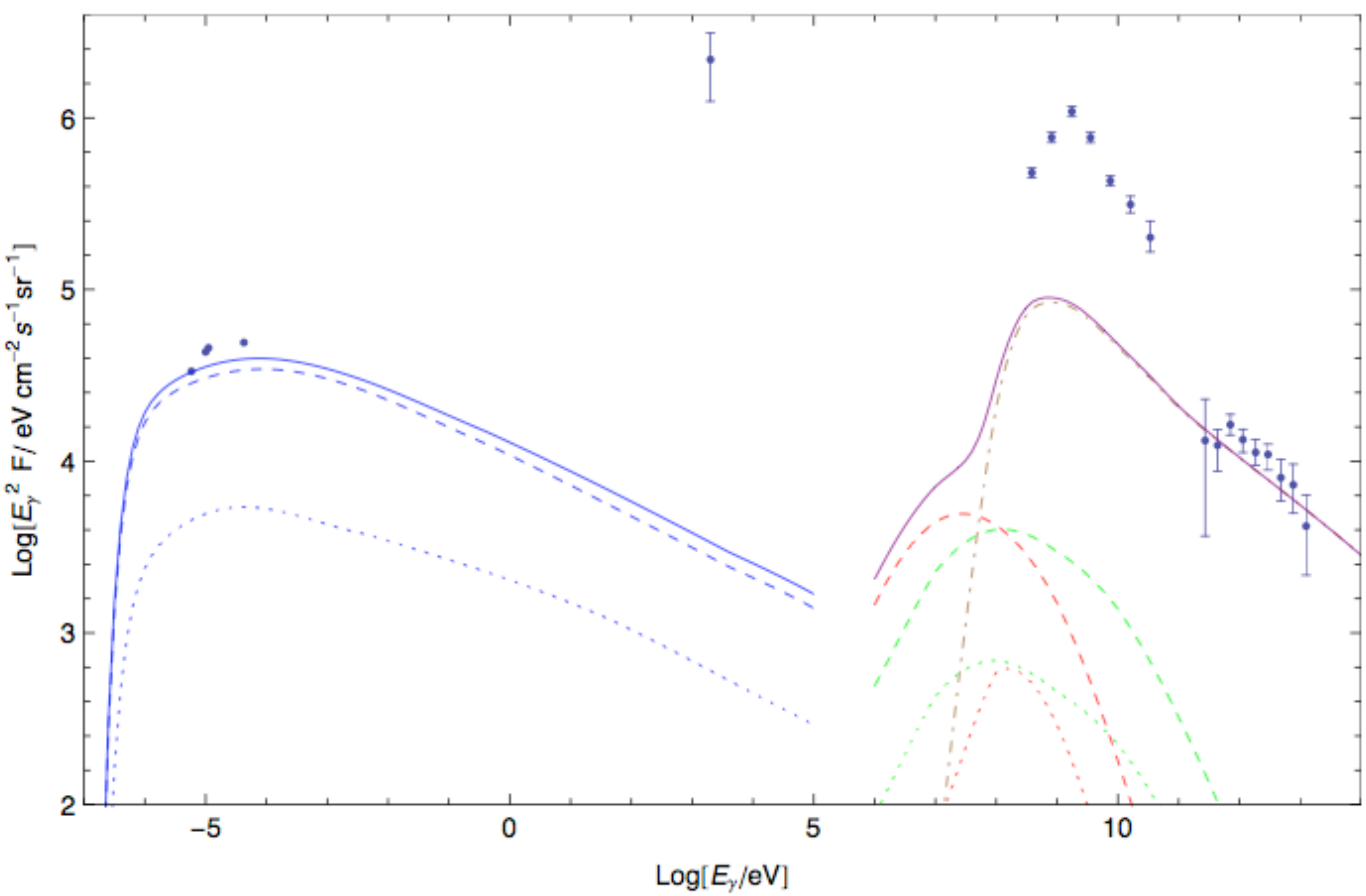


Modelling

- One-zone, steady-state modelling of in-situ electron and proton population
- Particle transport advective (wind)
- Try to reproduce observed, broad-band (non-thermal) emission from the region

Best-fit broadband SED



dashed: primary electron emission

dotted: secondary electron (and positron) emission

solid: total emission

Emission processes are:

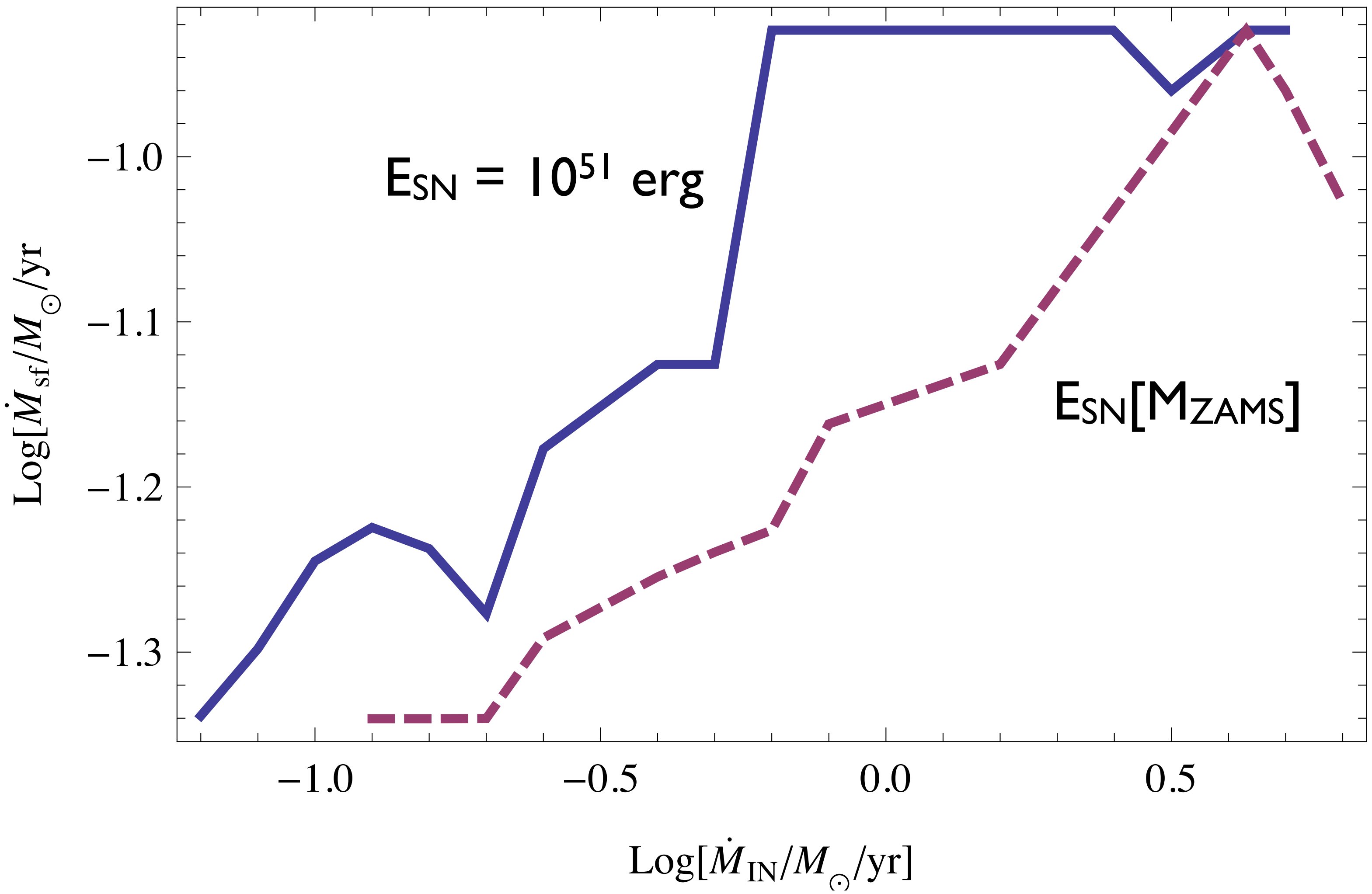
blue: synchrotron

red: bremsstrahlung

green: inverse Compton

brown, dot-dashed: neutral meson decay

Preliminary result: SFR from non-thermal data

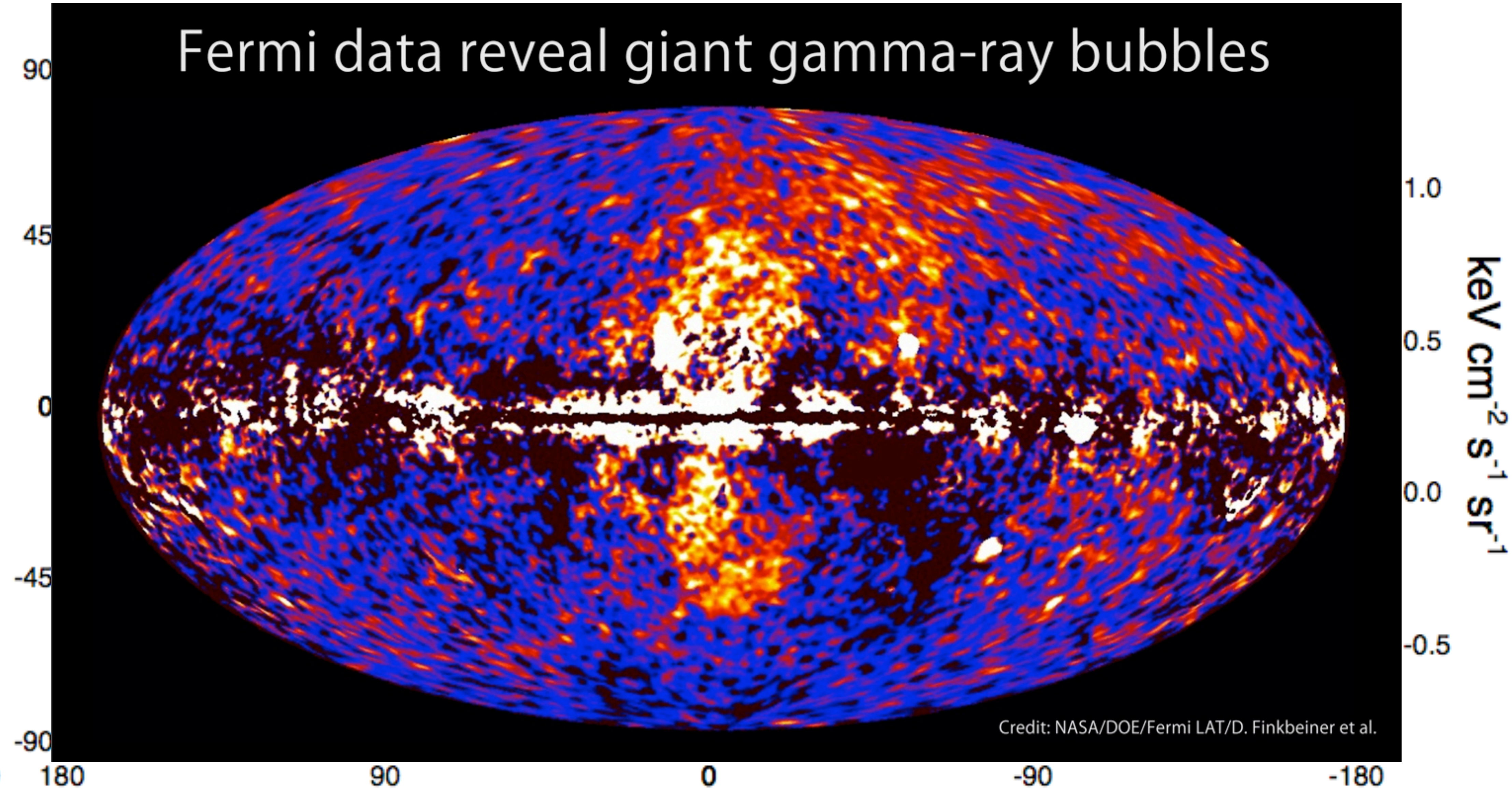


SFR

Summary thus far...

- Modelling of broadband emission from GC suggests that star-formation-related processes launch $\gtrsim 10^{39}$ erg/s in CRs into the Galaxy-at-large on a few 100 km/s wind
- ...Implications of these CRs?

Fermi Bubbles



Su, Slatyer and Finkbeiner 2010 (ApJ)

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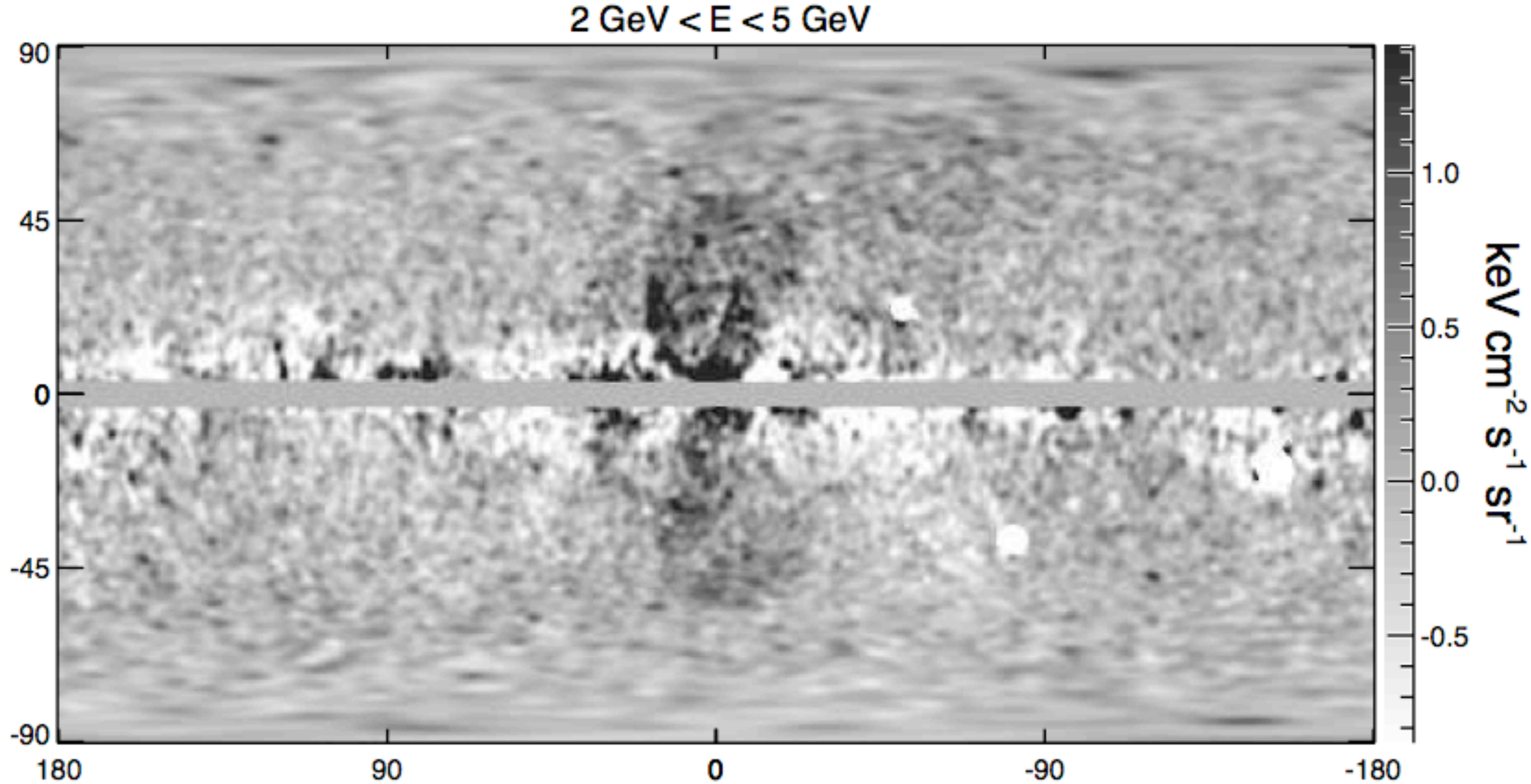

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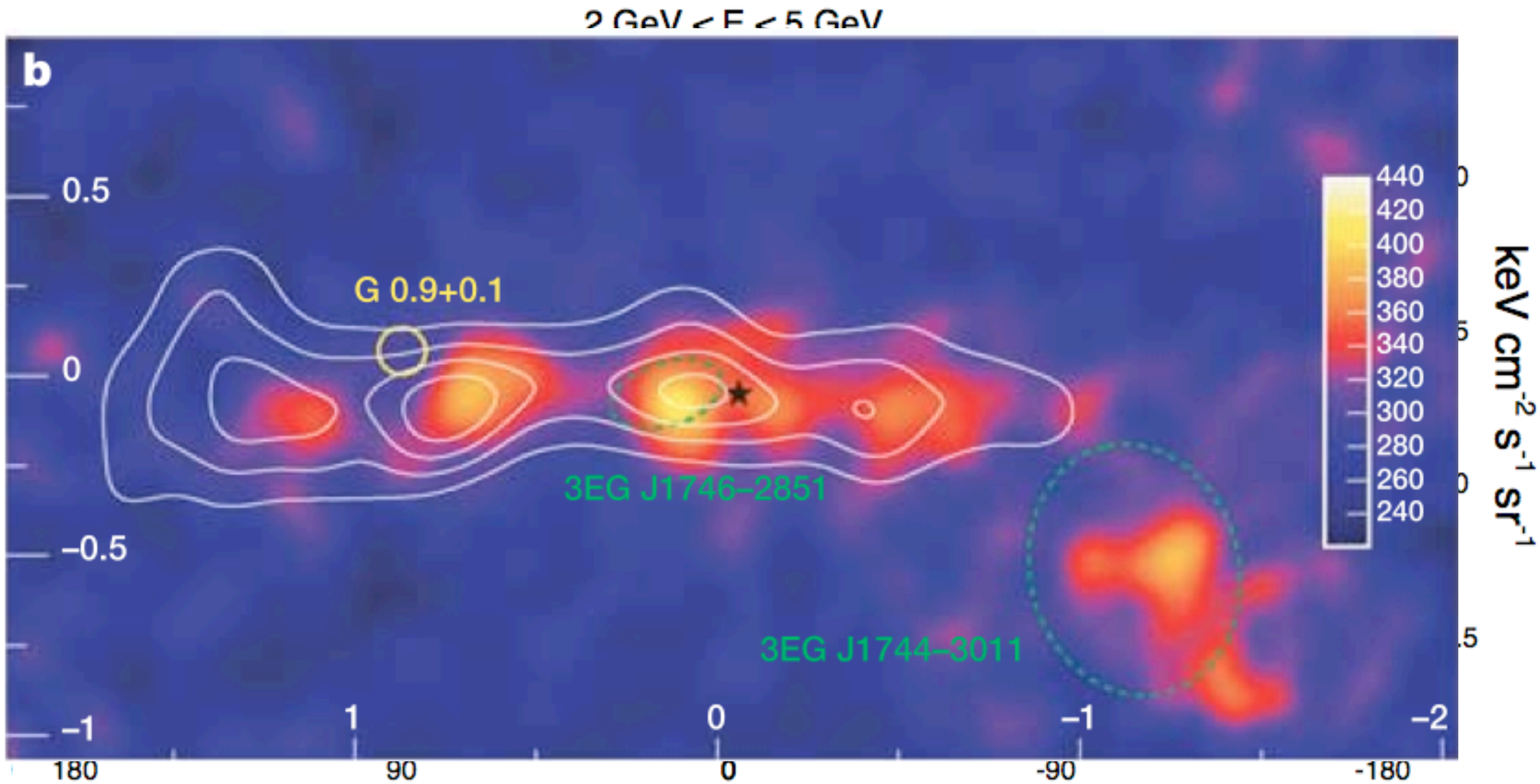

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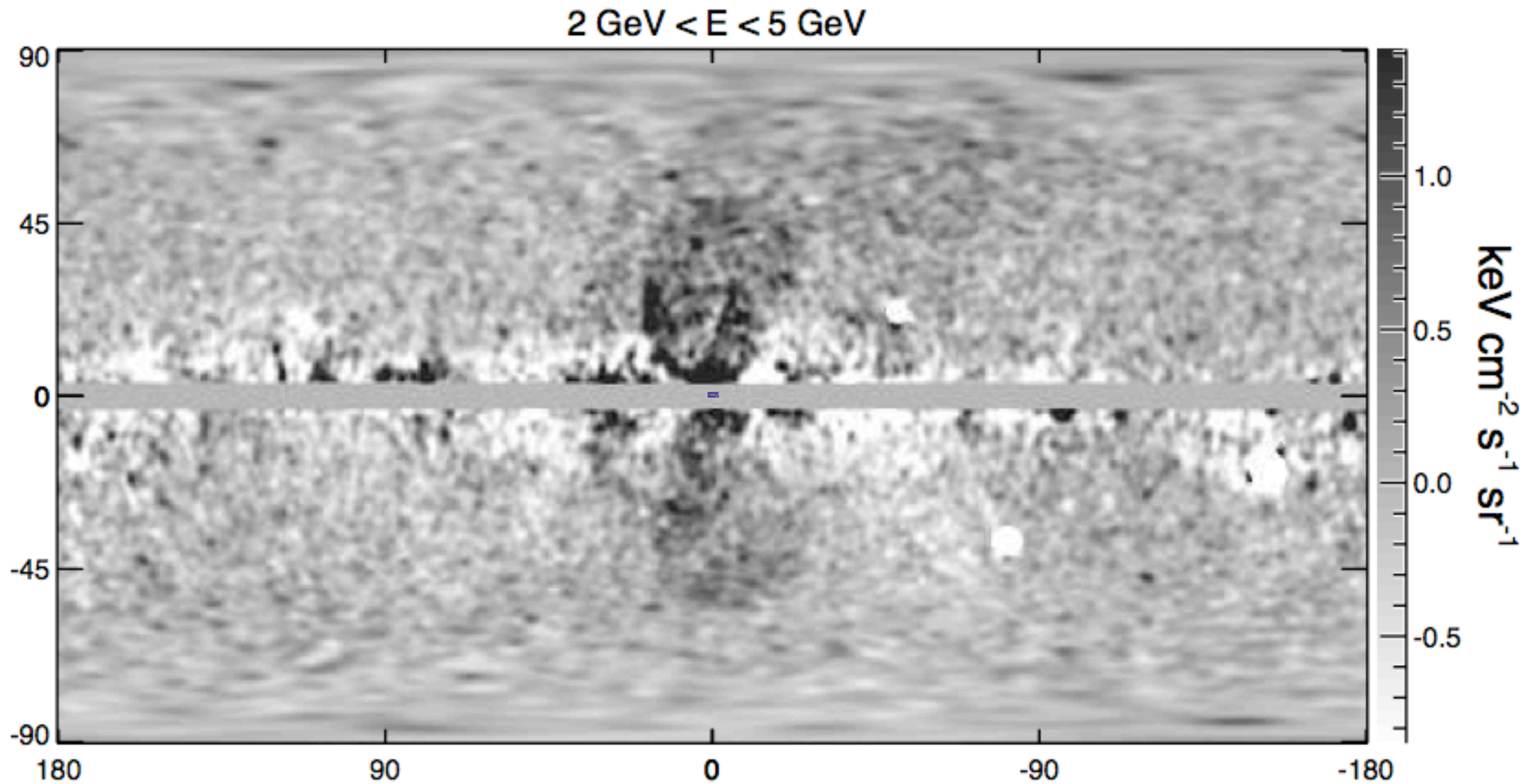

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Fermi Bubbles

- 4×10^{37} erg/s
- hard spectrum, but spectral down-break below ~ GeV in SED
- uniform intensity
- sharp edges
- vast extension: ~10 kpc from plane
- mirroring at other wavelengths

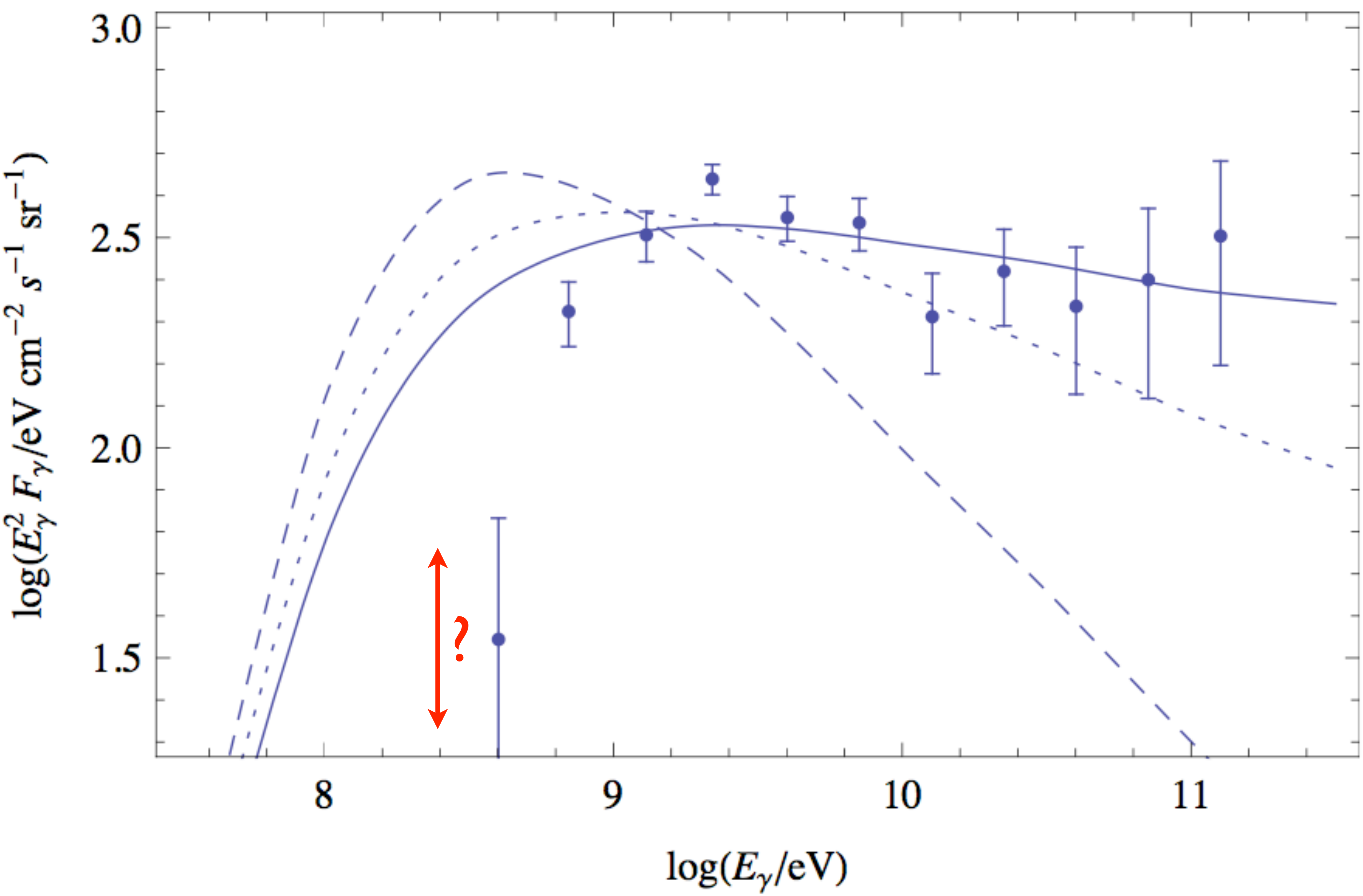
Electron Scenarios

- ~GeV γ-ray emission from IC by hypothesised population of hard-spectrum ~TeV electrons
- same population synchrotron-radiates into microwave frequencies
- BUT short cooling time

Proton scenario

- hard spectrum explained if protons confined in bubbles → the *in situ* spectrum shape = *injection* spectrum shape
- spectral down-turn explained by π^0 decay kinematics
- uniform intensity → saturation scenario
- *secondary* electrons generate microwave emission of correct luminosity

Bubble spectrum



Proton scenario

- BUT gas in bubbles is low-density plasma: nH < 0.01 cm^{-3}
- pp loss time is > 5 Gyr (!)
- need a source of hard spectrum CR p's with average power $\sim 10^{39}$ erg/s that has lasted for > 5 Gyr
- CRAZY

...actually not

- the morphology of the bubbles privileges the GC
- the GC has been sustaining a high level of star formation for Gyrs (~5% Galactic SFR) at *more-or-less current rate*
- have independent, *a priori* evidence that the Galactic centre (GC) *currently* accelerates exactly the required CR proton population
- >95% of these CR p's leave the region on a wind

other points

- power supplied by the outflow $\sim 10^{40}$ erg/s can supply total ~few 10^{57} erg enthalpy of Bubbles over same ~Gyr+ timescale
- end up with CR p's and plasma in ~equipartition, B field somewhat below equipartition
- nH in Bubble very tightly constrained
- slow wind (rather than fast jet) collimated by dense gas in plane explains why Bubbles perpendicular to Galactic disk

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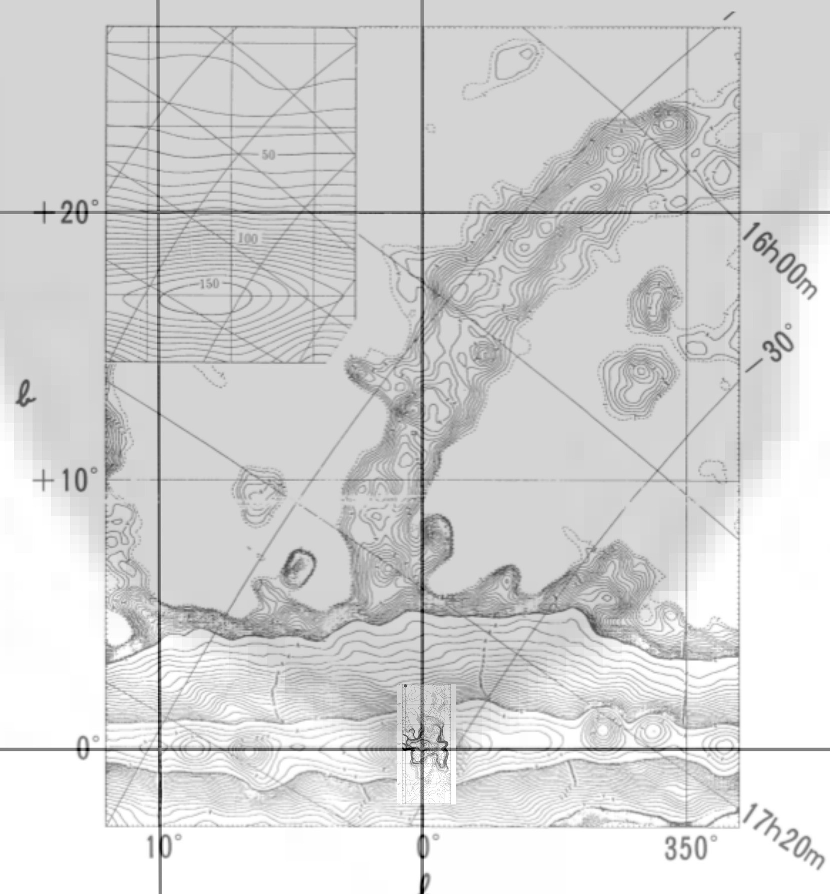

The Astrophysical Journal, **341**: L47–L49, 1989 June 15

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2-5 GeV
Su et al.

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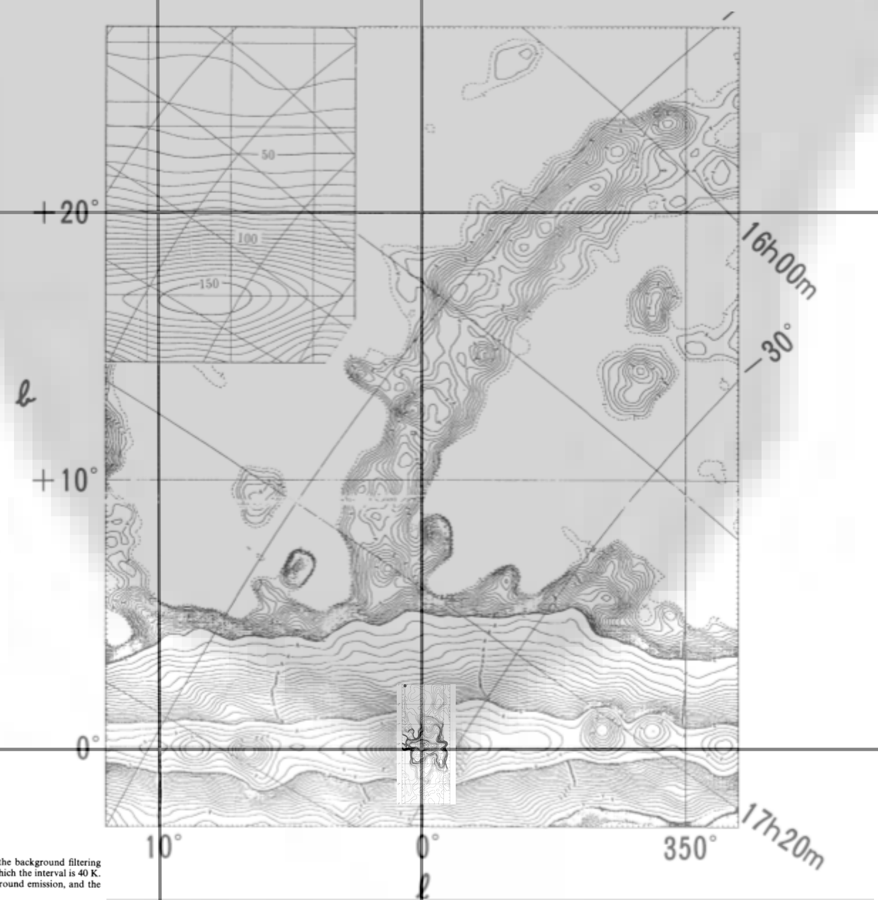

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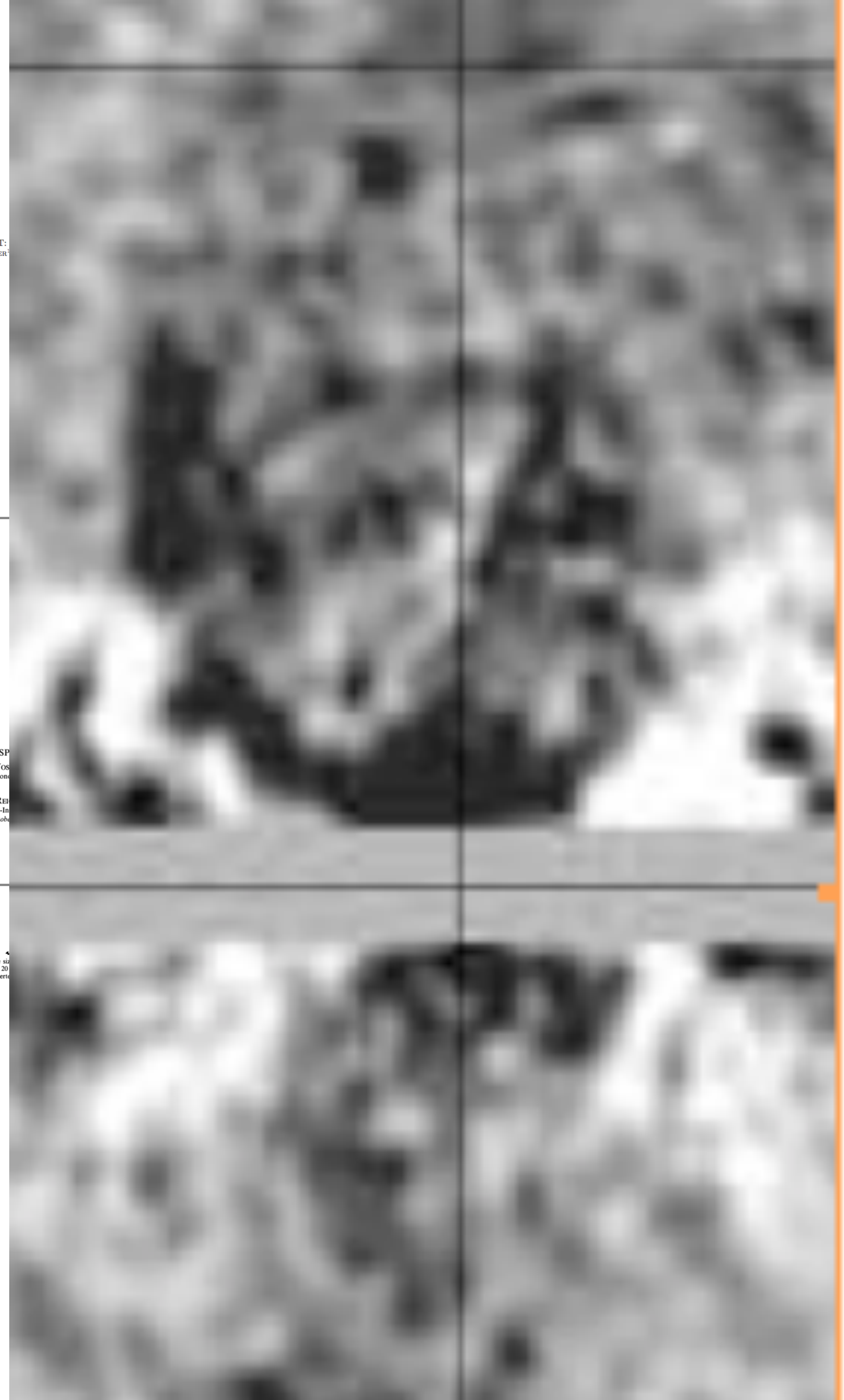

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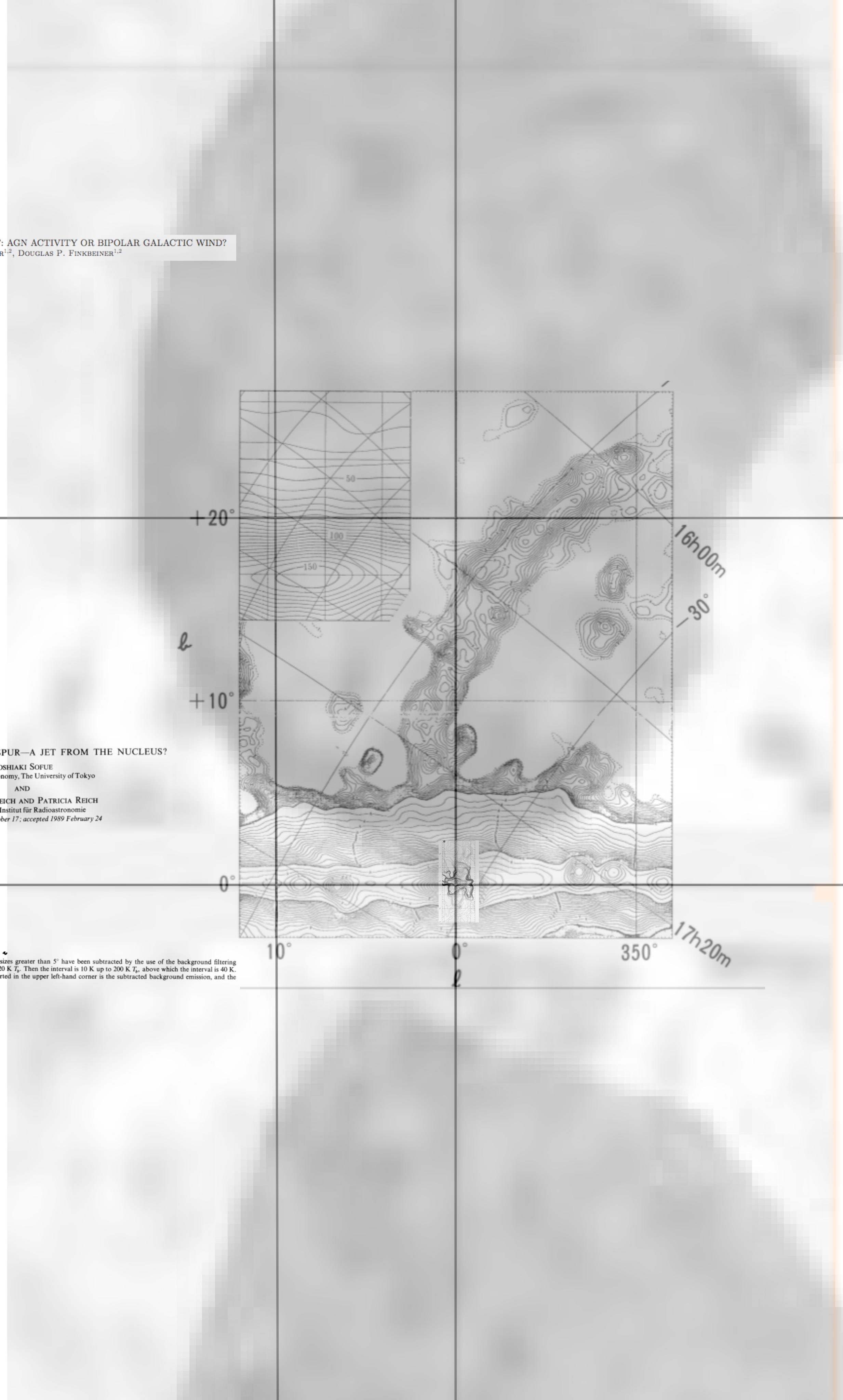

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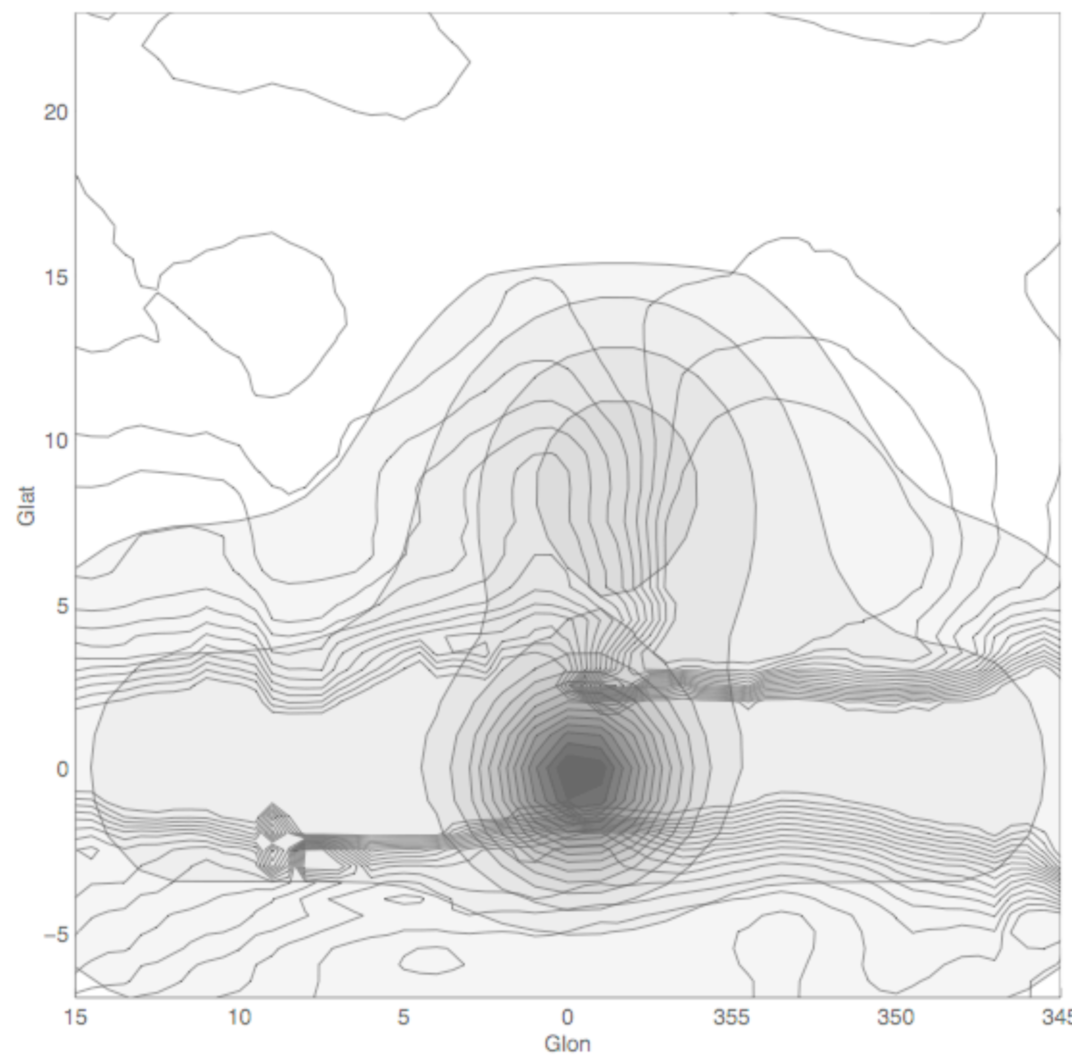
Sofue1989
408 MHz

Hartmann
GeV EGRET



Glon

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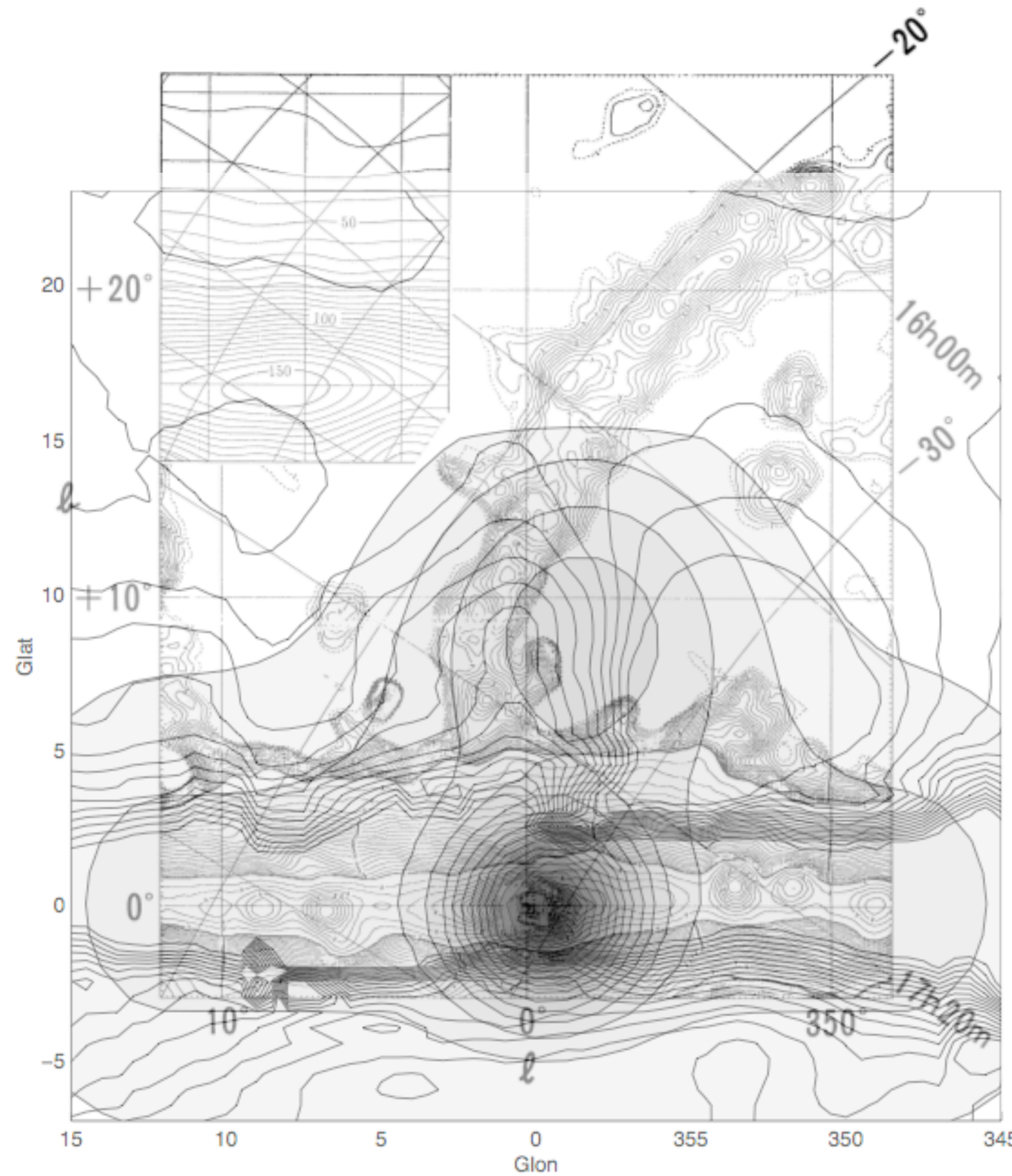

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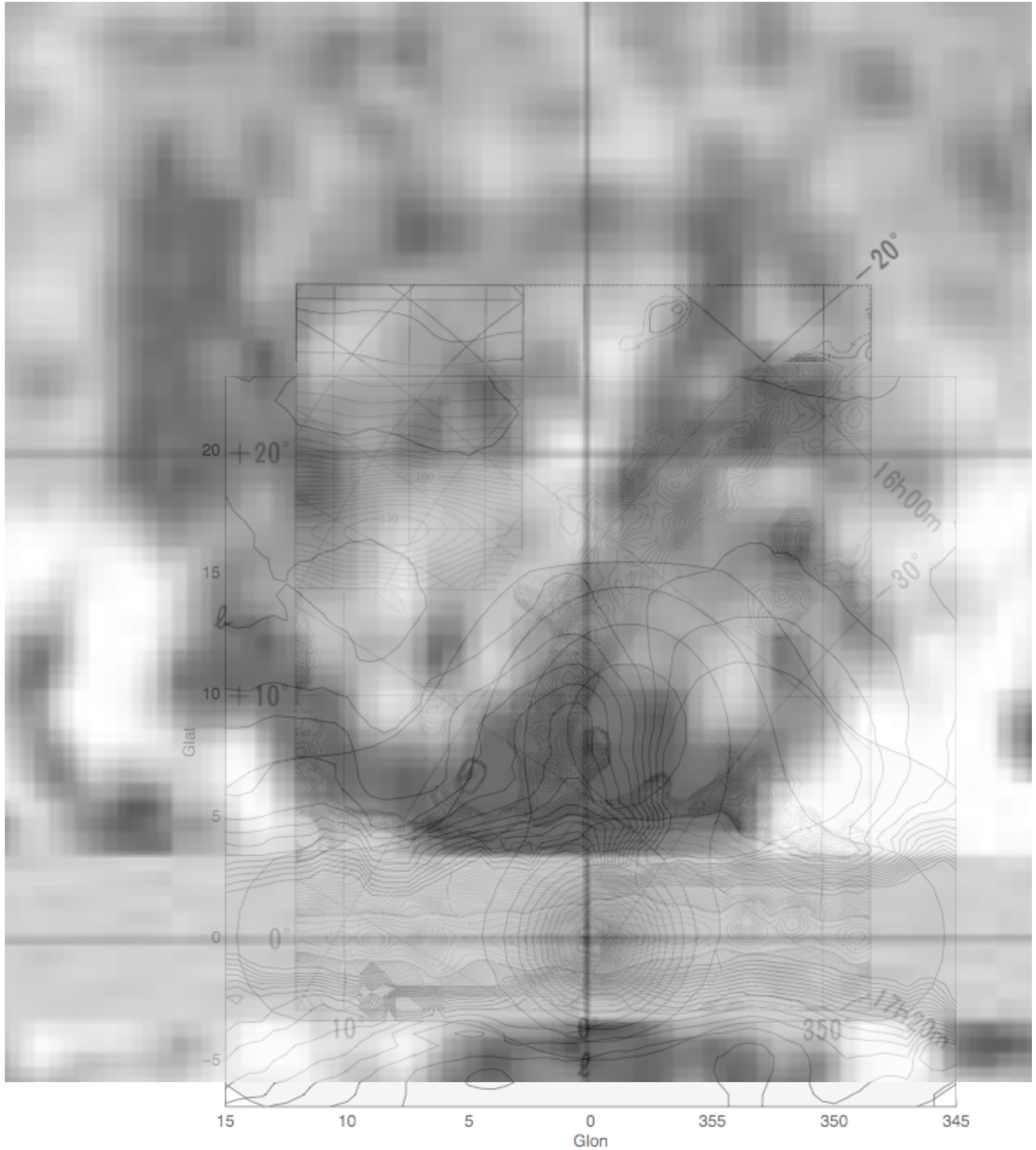

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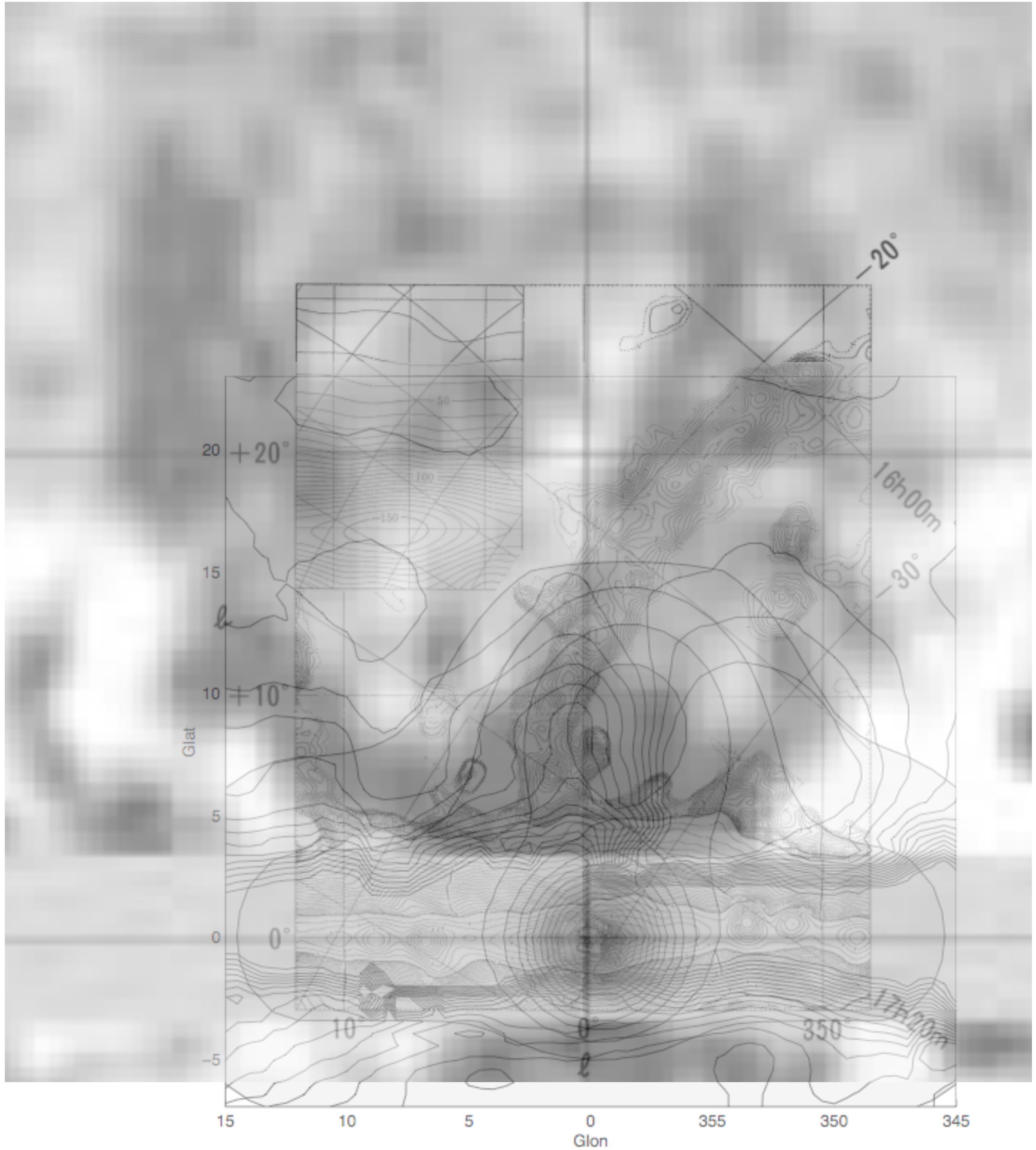

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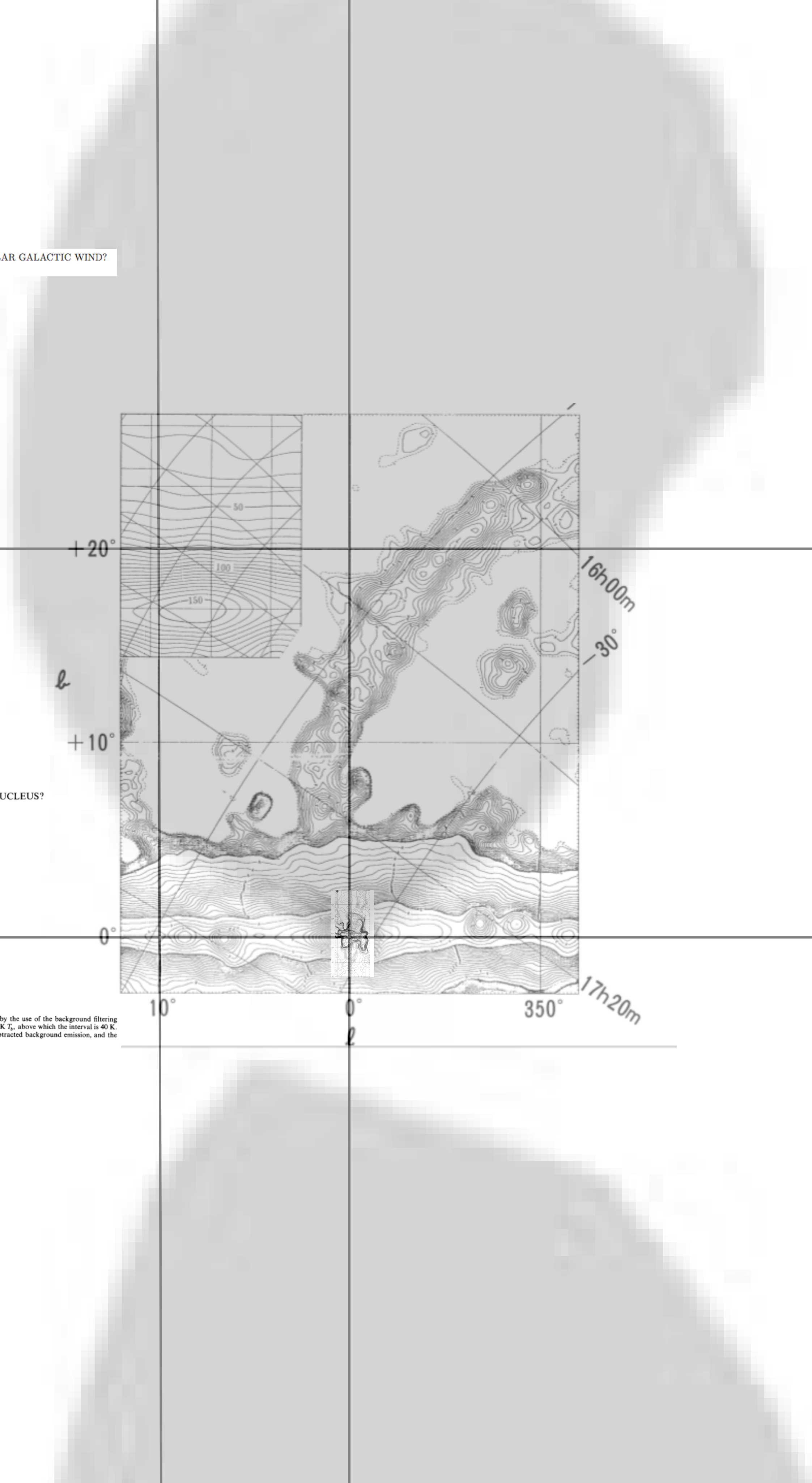

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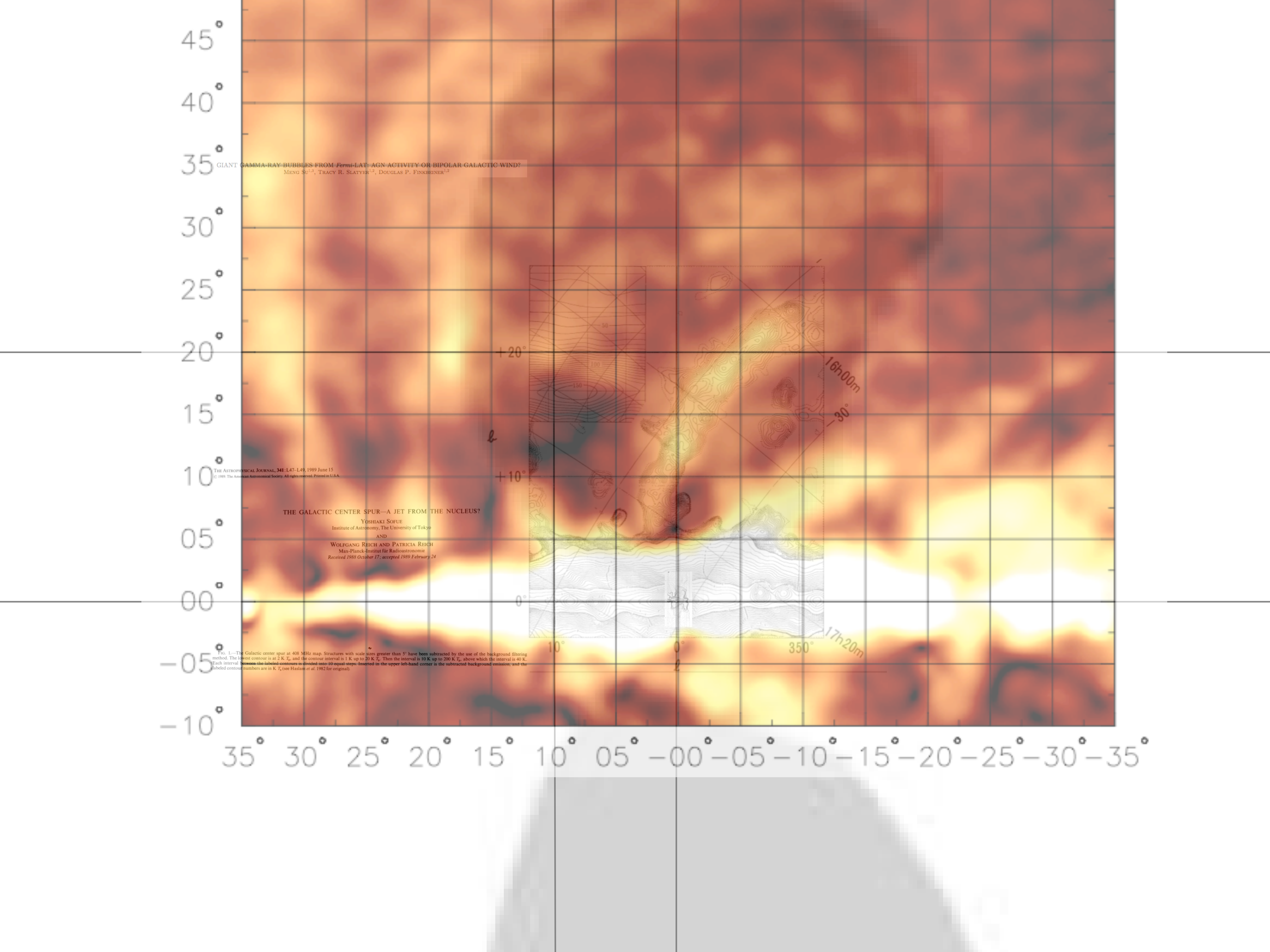
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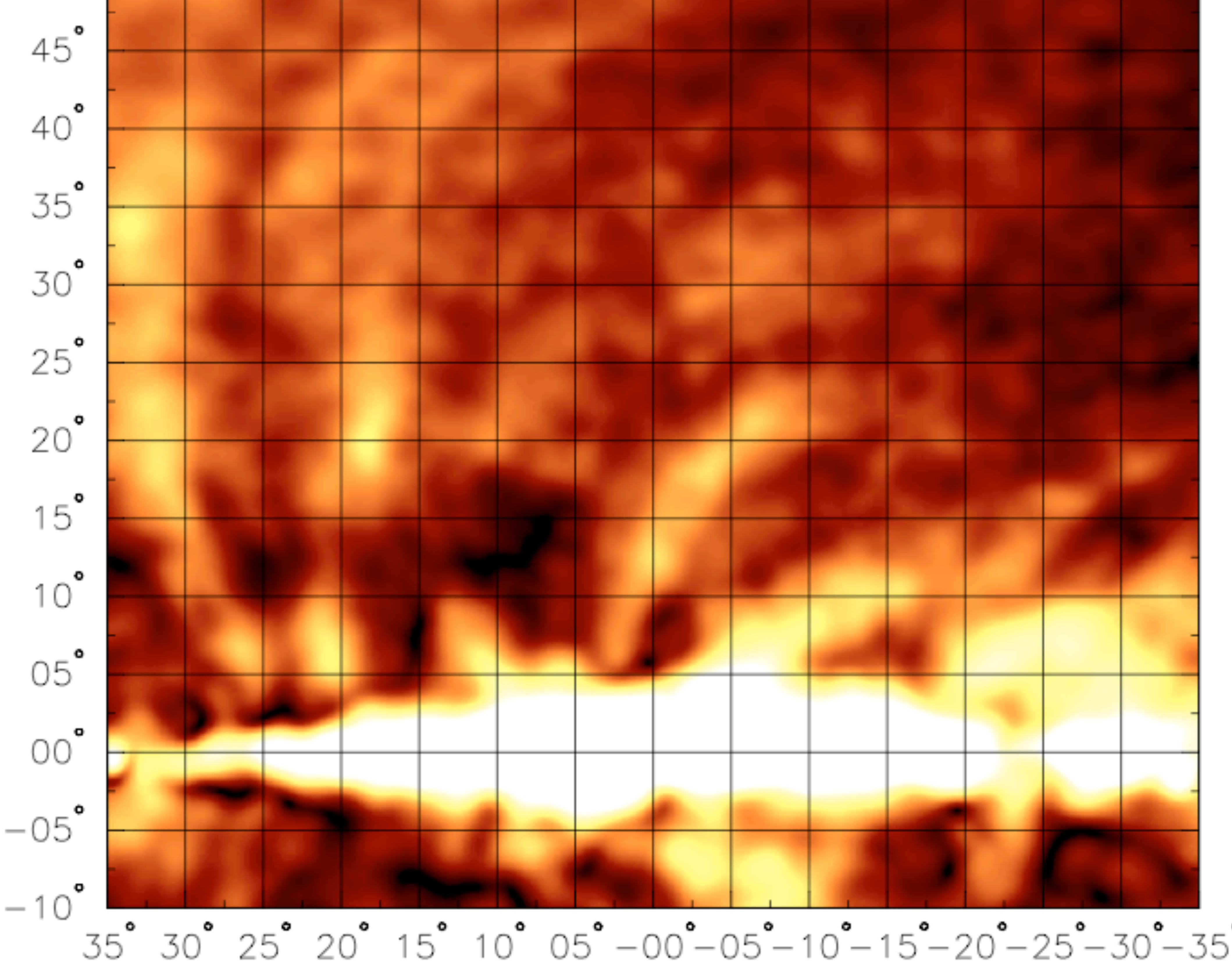
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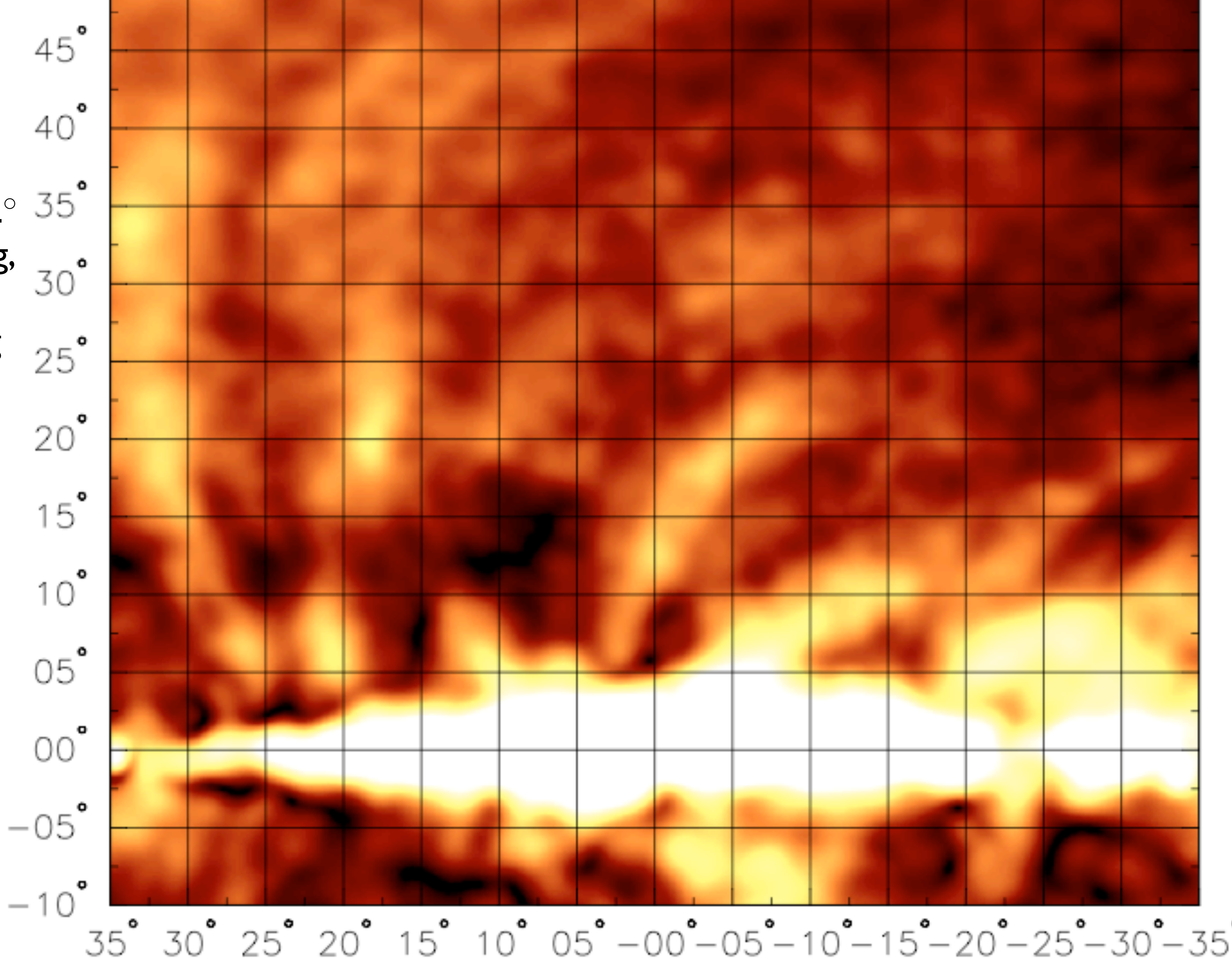
−05°
−10°
35° 30° 25° 20° 15° 10° 05° −00° −05° −10° −15° −20° −25° −30° −35°

23 GHz (WMAP) polarized intensity, 2° smoothing, courtesy Wolfgang Reich



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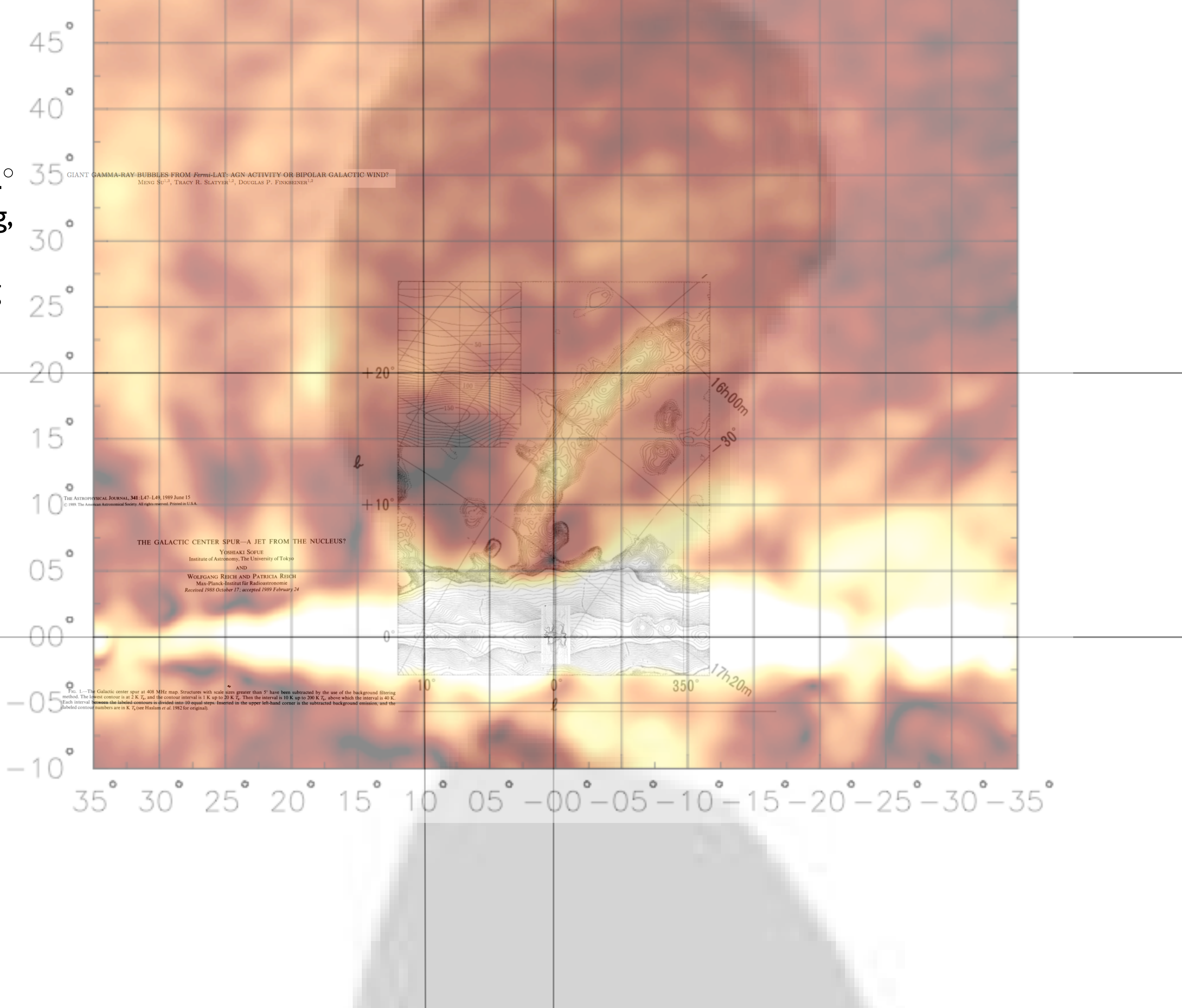

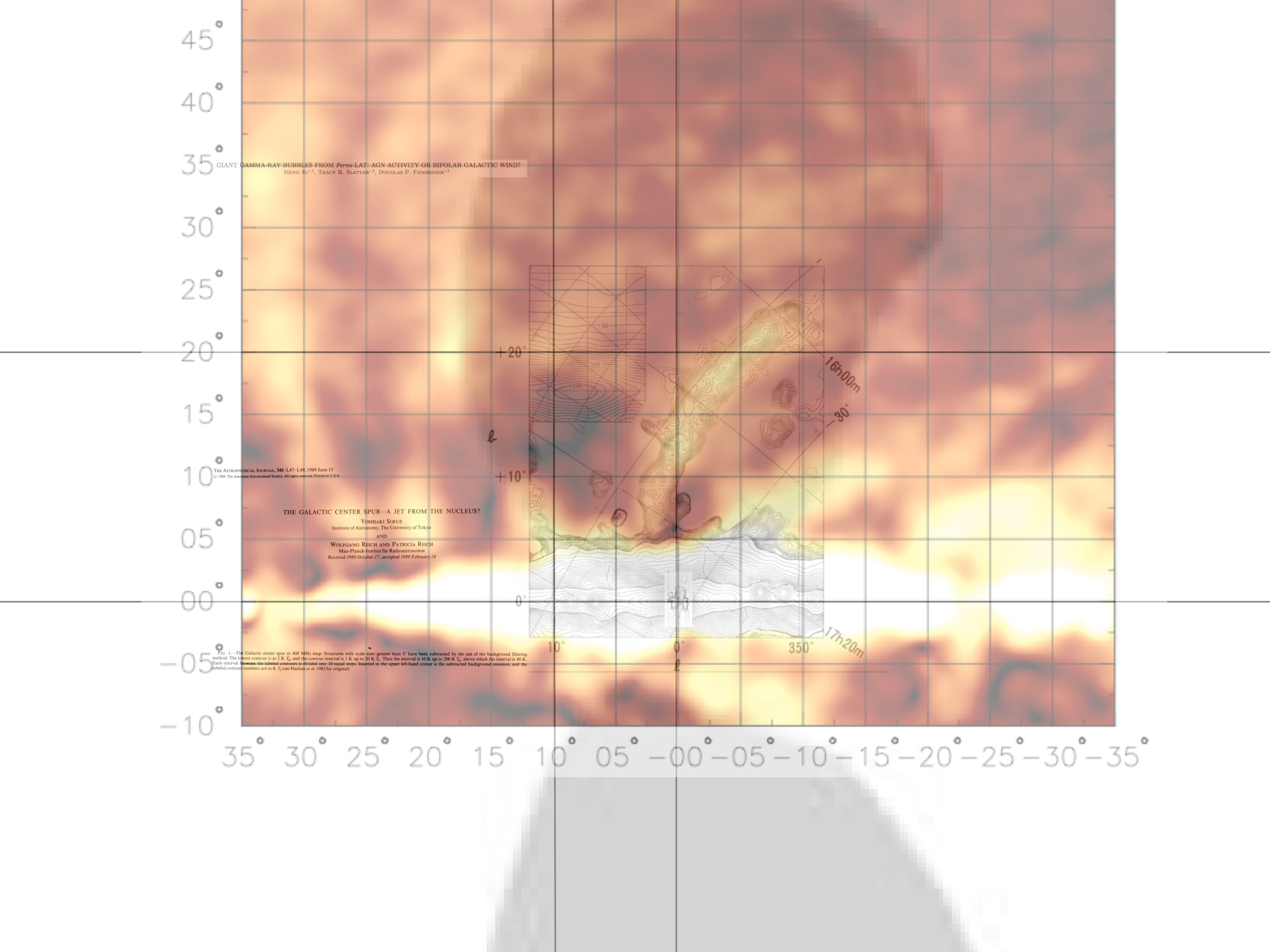
GIANT GAMMA-RAY BUBBLES FROM Fermi-LAT: AGN ACTIVITY OR BIPOLAR GALACTIC WIND?
Meng Su[1,3], Tracy R. Slatyer[1,2], Douglas P. Finkbeiner[1,2]
The Astrophysical Journal, 341: L47–L49, 1989 June 15
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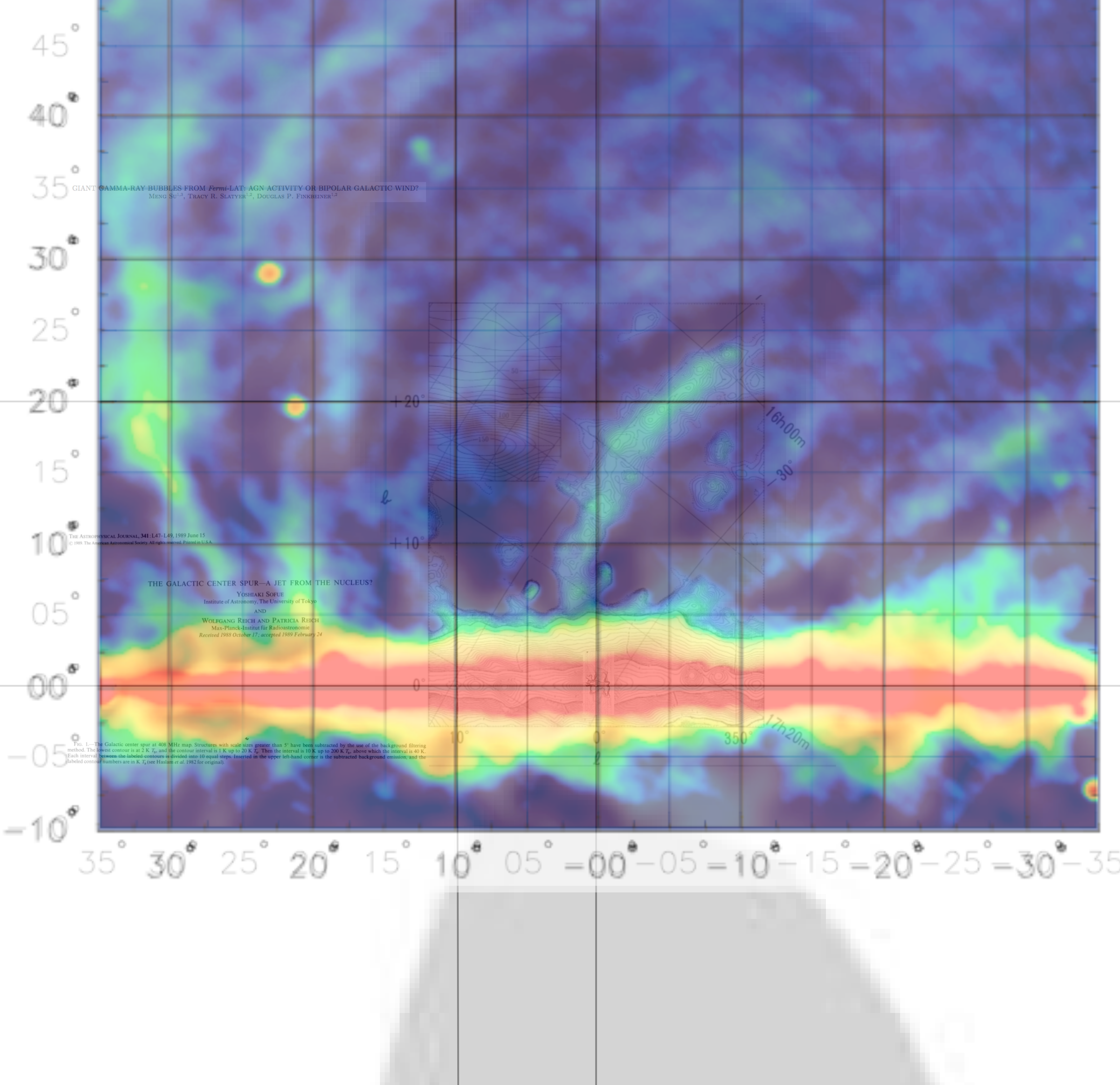
THE GALACTIC CENTER SPUR—A JET FROM THE NUCLEUS?
Yoshiaki Sofue
Institute of Astronomy, The University of Tokyo
and
Wolfgang Reich and Patricia Reich
Max-Planck-Institut für Radioastronomie
Received 1988 October 17; accepted 1989 February 24
Fig. 1.—The Galactic center spur at 408 MHz map. Structures with scale sizes greater than 5° have been subtracted by the use of the background filtering method. The lowest contour is at 2 K T_b, and the contour interval is 1 K up to 20 K T_b. Then the interval is 10 K up to 200 K T_b, above which the interval is 40 K. Each interval between the labeled contours is divided into 10 equal steps. Inserted in the upper left-hand corner is the subtracted background emission, and the labeled contour numbers are in K T_b (see Haslam et al. 1982 for original).
45°
40°
35°
30°
25°
20°
15°
10°
05°
00°
−05°
−10°
35° 30° 25° 20° 15° 10° 05° −00° −05° −10° −15° −20° −25° −30° −35°
+20°
+10°
0°
b
10° 0° 350°
l
16h00m
−30°
17h20m
50
100
150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16h00m
−30°
17h20m
+20°
+10°
0°
10°
0°
350°
45°
40°
35°
30°
25°
20°
15°
10°
05°
00°
−05°
−10°
35°
30°
25°
20°
15°
10°
05°
−00°
−05°
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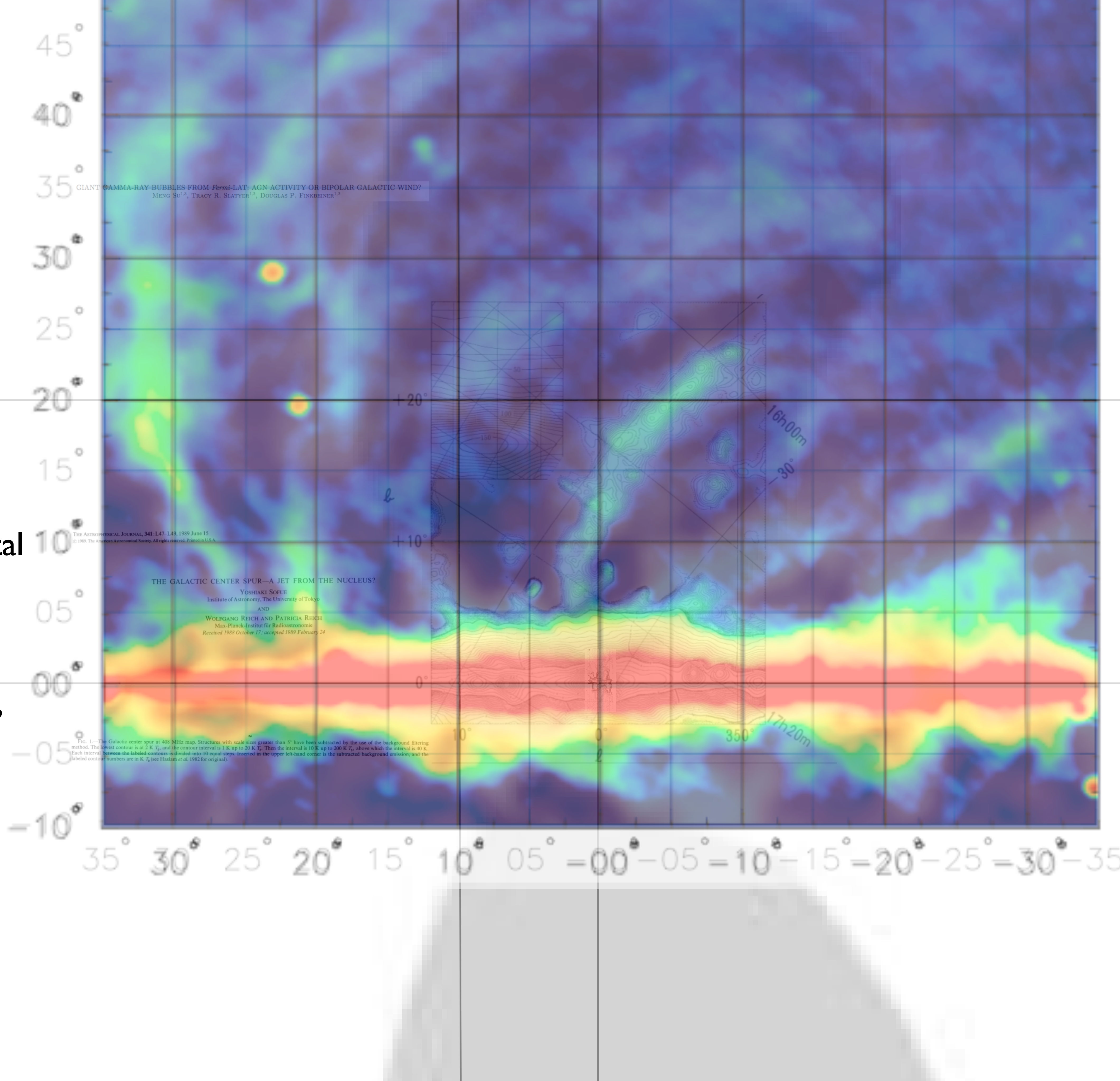
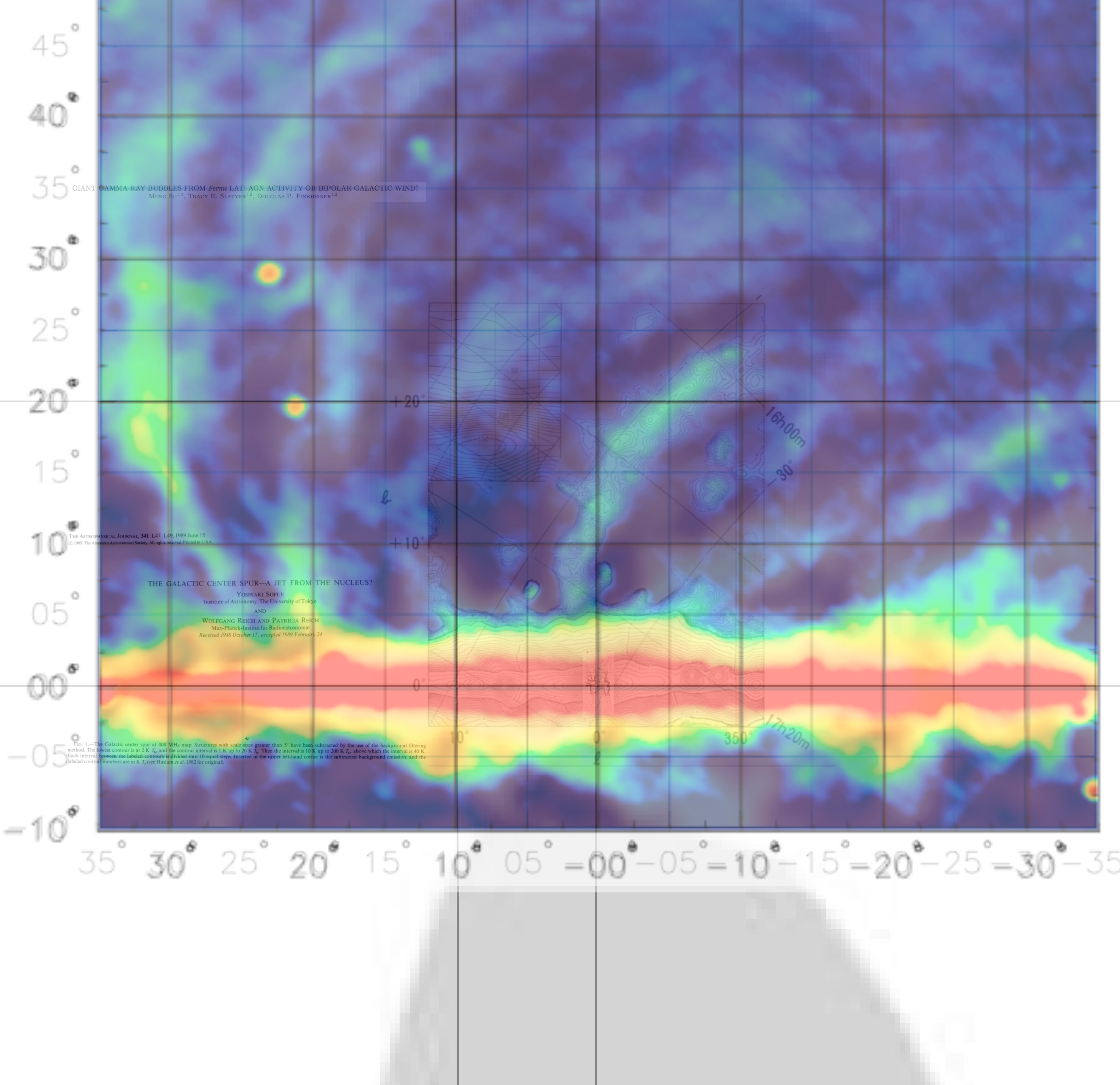
−15°
−20°
−25°
−30°
−35°



408 MHz (Haslam) total intensity, unsharp-masked, 2° smoothing, courtesy Wolfgang Reich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45°
40°
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30°
25°
20°
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10°
05°
00°
−05°
−10°
35° 30° 25° 20° 15° 10° 05° −00° −05° −10° −15° −20° −25° −30° −35°
+20°
+10°
0°
10° 0° 350°
16h00m
−30°
17h20m
b
ℓ

Conclusions

- Star-formation (and concomitant supernovae) sufficient to drive activity of region
- The SMBH is not a significant actor beyond a few pc radius
- GC mag field v. strong (100-200 μG)

Conclusions II

- GC launches a ‘super-wind’, $v_{wind} > 200$ km/s
- the wind stops the GC ISM energy density growing too much
- CRs heat/ionize low density, hot (envelope) H_2
- BUT the wind advects even >TeV CRs before they penetrate into dense H_2 cores → GC *not* a hadron calorimeter
- role for CRs in modifying conditions for SF seems to be disfavoured (unless *local* acceleration)

Discussion points

- Highly porous gas distribution
- GC SF seems to be progressing in more-or-less steady state and has been doing so for Gyr+ timescales $\rightarrow$ self-regulation
- *not* a star*burst*
- Our scenario requires that the bubbles trap the CR's for Gyr+ timescales (!)