# Fermi Bubbles

## Galactic Centre Star Formation Writ Large

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MARIE CURIE ACTIONS

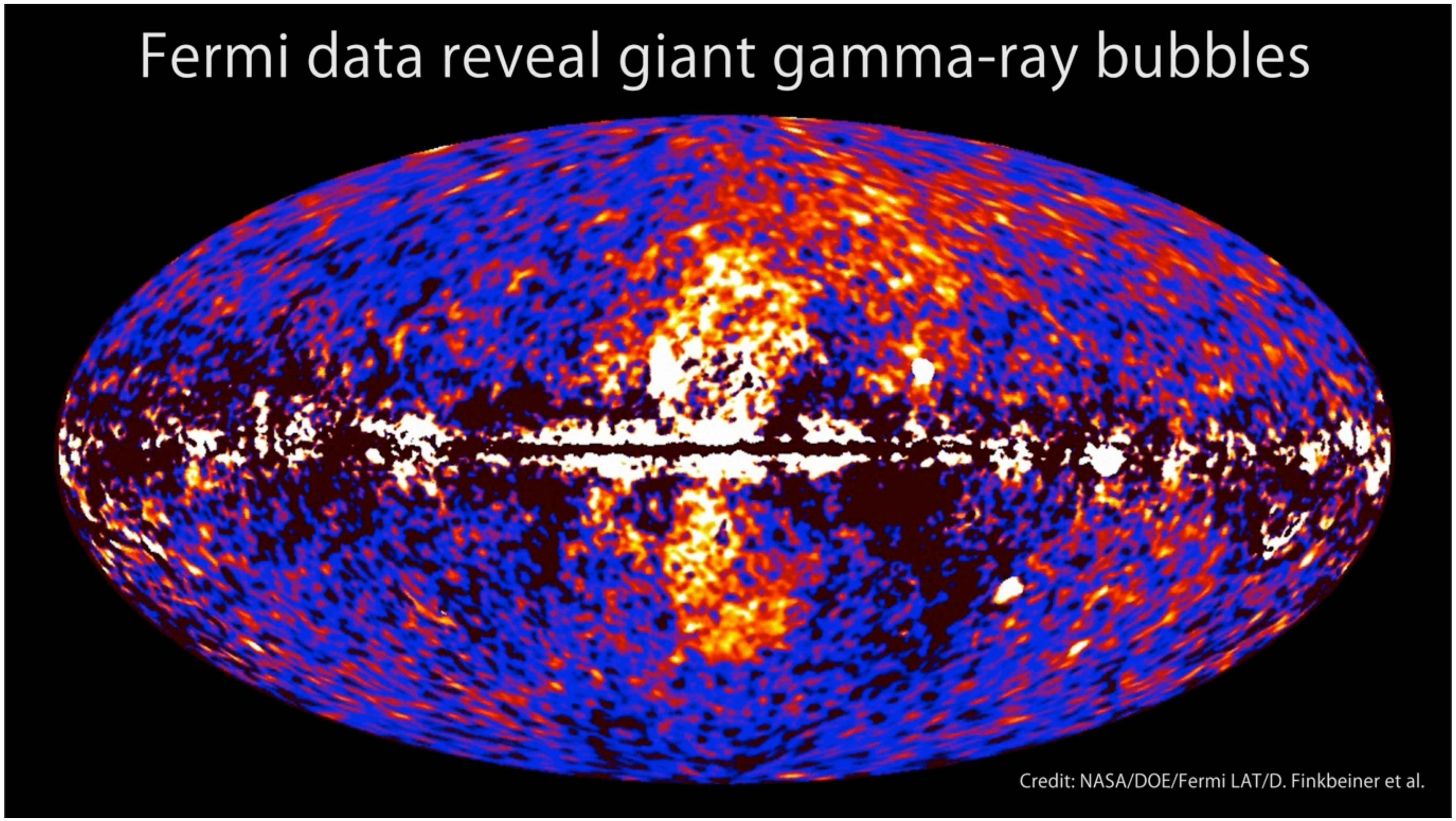
# Refs and collaborators

**The Fermi Bubbles: Giant, Multi-Billion-Year-Old Reservoirs of Galactic Center Cosmic Rays**
Roland M. Crocker & Felix Aharonian PRL 2011 (**arXiv:1008.2658**)

**Wild at Heart:-The Particle Astrophysics of the Galactic Centre,**
Roland M. Crocker, David I. Jones, Felix Aharonian, Casey J. Law, Fulvio Melia, Tomoharu Oka, Juergen Ott MNRAS 2011 (**arXiv:1011.0206**)

**Gamma-Rays and the Far-Infrared-Radio Continuum Correlation Reveal a Powerful Galactic Center Wind,**
Roland M. Crocker, David I. Jones, Felix Aharonian, Casey J. Law, Fulvio Melia, Juergen Ott
MNRAS Letters 2011(**arXiv:1009.4340**)

# Fermi Bubbles




Su, Slatyer and Finkbeiner 2010 (ApJ)

# Fermi Bubbles

- 4 x $10^{37}$ erg/s
- enthalpy ~$10^{57}$ erg
- *uniform* and *hard* spectrum, but spectral down-break below ~ GeV in SED
- uniform intensity
- sharp edges
- vast extension: ~10 kpc from plane
- something to do with GC

# Mirroring emission at other wavelengths

- in microwaves (WMAP): also hard, non-thermal spectrum, uniform intensity, few x $10^{36}$ erg/s
- in soft X-rays (ROSAT): apparently limb-brightened, thermal bremsstrahlung from $\sim 10^7$ K, $\lesssim 0.01$ $cm^{-3}$ plasma, $\gtrsim 10^{39}$ erg/s

# ‘Natural’ explanation: HE, primary electrons

- ~GeV $\gamma$-ray emission from IC by hypothesised population of hard-spectrum $\gtrsim$50 GeV electrons
- same population synchrotron-radiates into microwave frequencies

# ‘Natural’ explanation: HE, primary electrons

- ~GeV γ-ray emission from IC by hypothesised population of hard-spectrum $\gtrsim \cancel{10}$ GeV electrons
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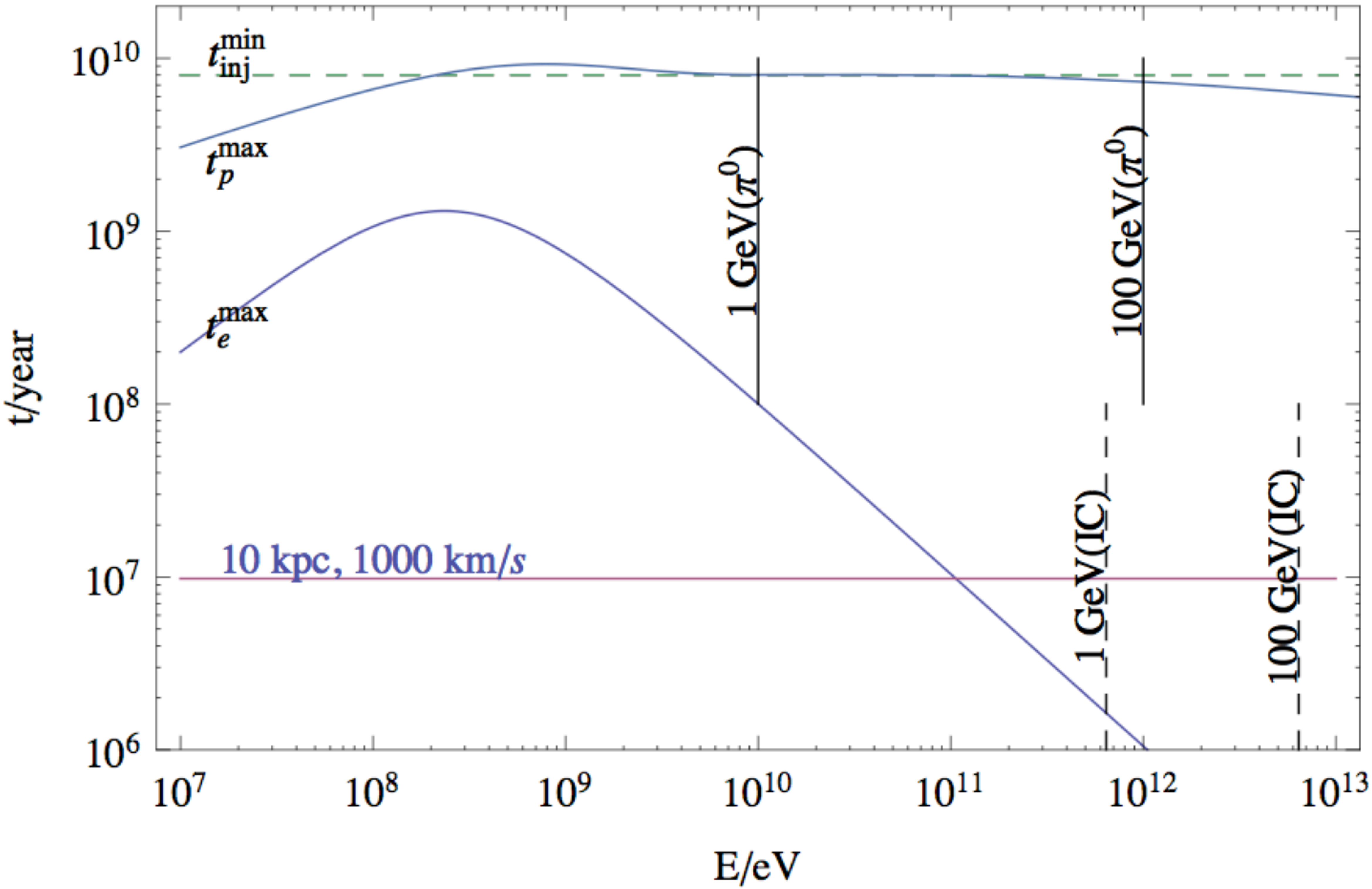
# ‘Natural’ explanation: HE, primary electrons

- ~GeV γ-ray emission from IC by hypothesised population of hard-spectrum $\gtrsim$ 1 TeV electrons
- same population synchrotron-radiates into microwave frequencies

# Problem with electrons



# Electron scenarios

- **Very fast transport** (>3% c) ⇒ relativistic outflow ⇒ AGN jet from Sgr A* (Guo and Matthews 2011)
- **In situ acceleration**;
  - 1st order Fermi, e.g. shocks associated with tidal disruptions of stars near Sgr A* (Cheng, Chernyshov et al 2011)
  - 2nd order Fermi on turbulence (stochastic acceleration; Mertsch and Sarkar 2011)

# Electron scenarios

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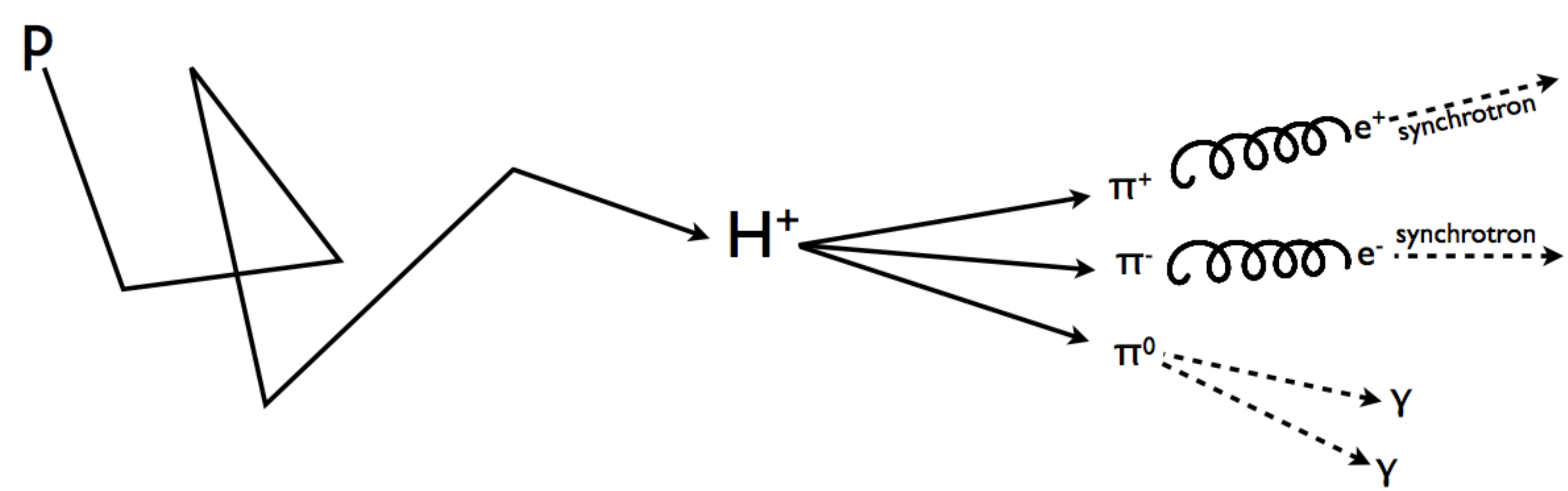
  - ...er Fermi on turbulence ...chastic acceleration; Mertsch and ...arkar 2011)

What about variation in ISRF with Galactic latitude and consequent IC γ-ray spectrum evolution?

# What about protons?

- hard spectrum explained if protons confined in bubbles → the *in situ* spectrum shape = *injection* spectrum shape
- spectral down-turn below 1 GeV on SED explained by $\pi^0$ decay kinematics
- uniform intensity → saturation scenario
- *secondary* electrons generate microwave emission (WMAP haze) of correct luminosity

# Secondaries from pp collisions



# Proton *saturation* scenario

- But shouldn't the $\pi^0$ decay $\gamma$-rays trace the matter column density?
- Not in *saturation* (= *thick target* + *steady state*)

$L_\gamma \simeq N_p / t[pp \mapsto \pi^0]$ $\qquad$ $t[pp \mapsto \pi^0] \propto 1/n_H$

$N_p \simeq \partial_t Q_p \, t[pp]$

$t[pp] \simeq t[pp \mapsto \pi^0]/3$

$\Rightarrow L_\gamma \simeq \partial_t Q_p / 3$

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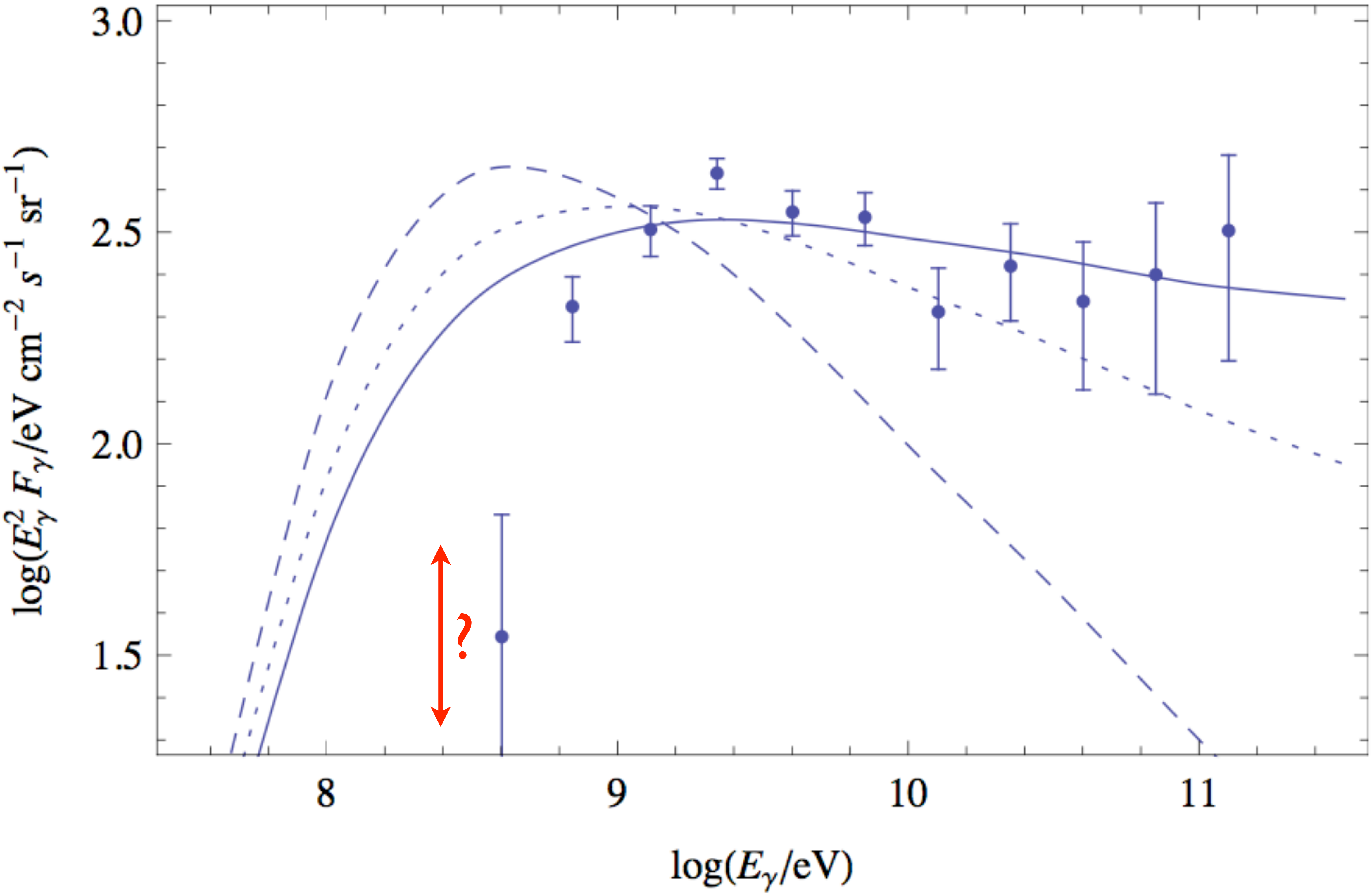
$$\Rightarrow L_\gamma \simeq \partial_t Q_p / 3$$

...around 1/3 proton power emerges in $\gamma$-rays over all energies *independent* of $n_H$

# Bubble spectrum



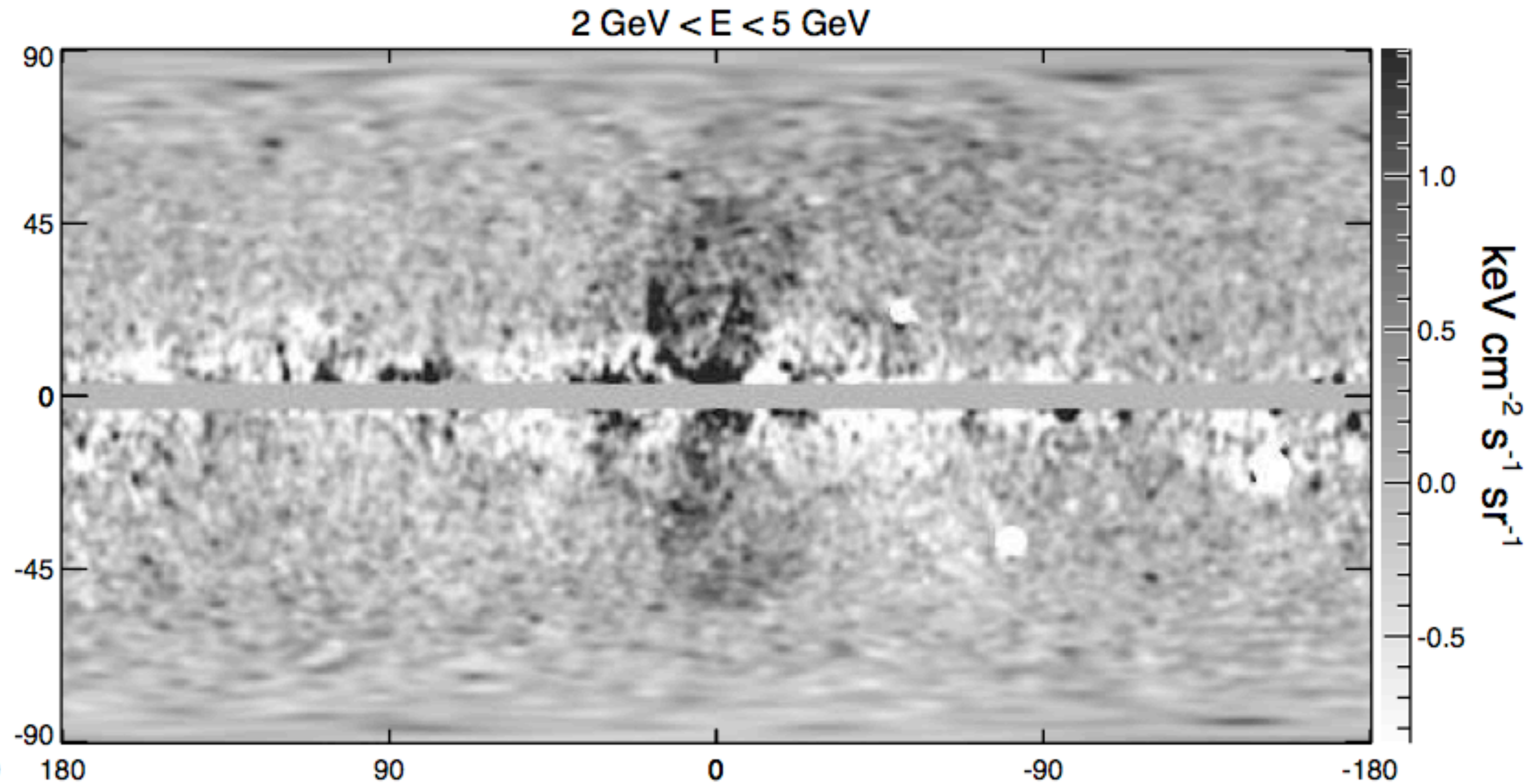
# What about protons II?

- 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 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)
- 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
- slow wind (rather than fast jet) collimated by dense gas in plane explains why Bubbles perpendicular to Galactic disk

# HESS TeV observations



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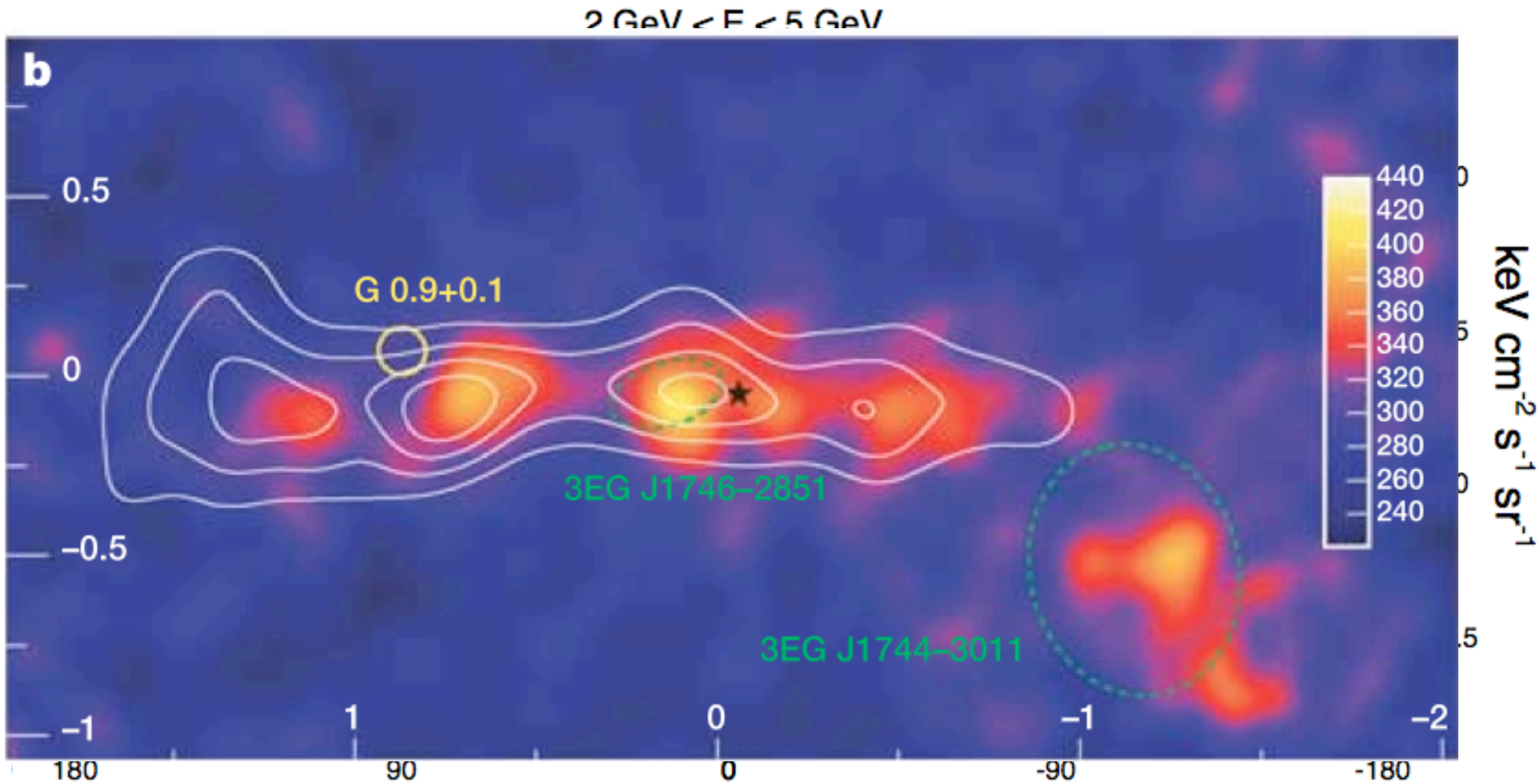

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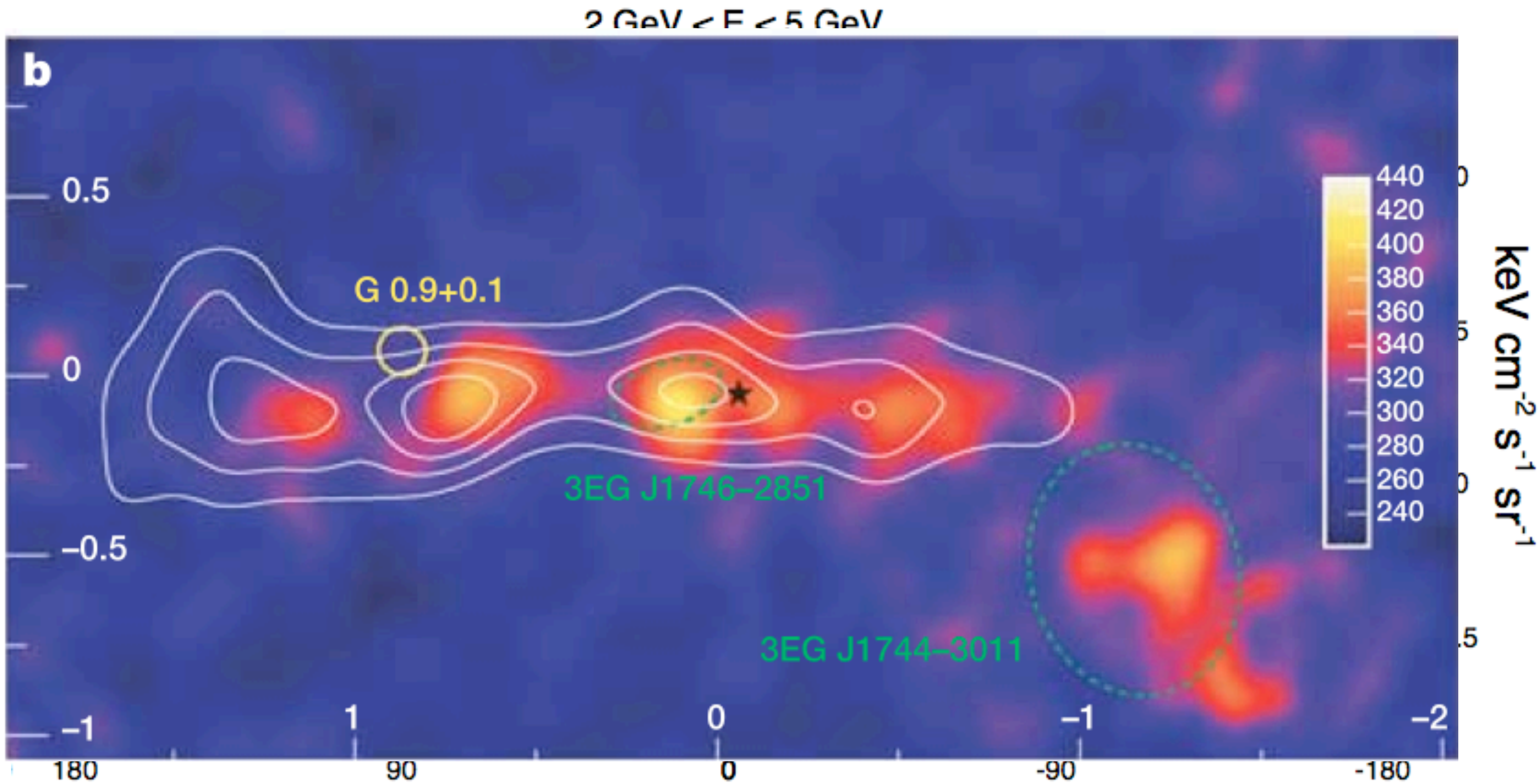


Hard spectrum, diffuse TeV emission from the Galactic centre roughly correlated with molecular gas column (Aharonian et al 2006)

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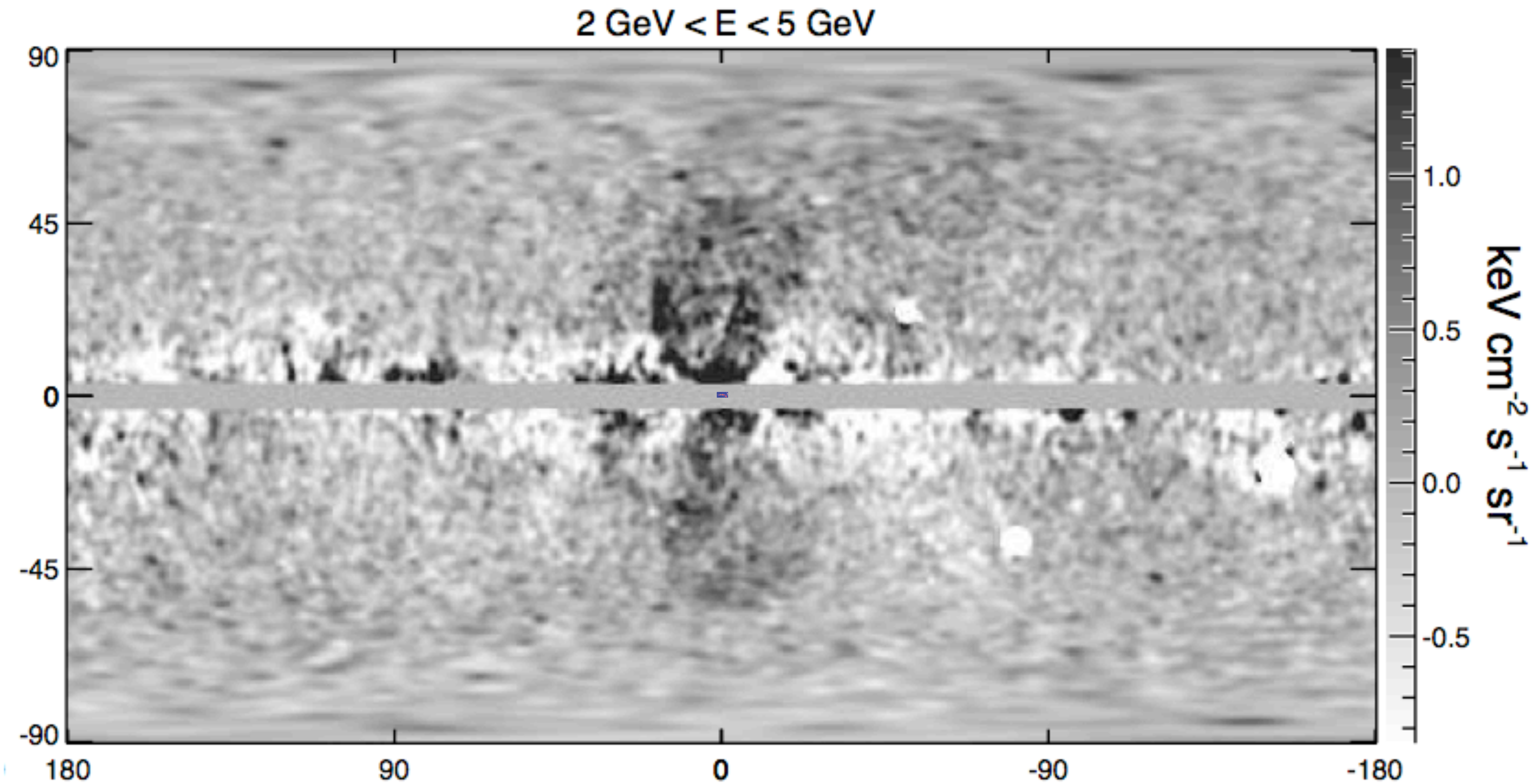


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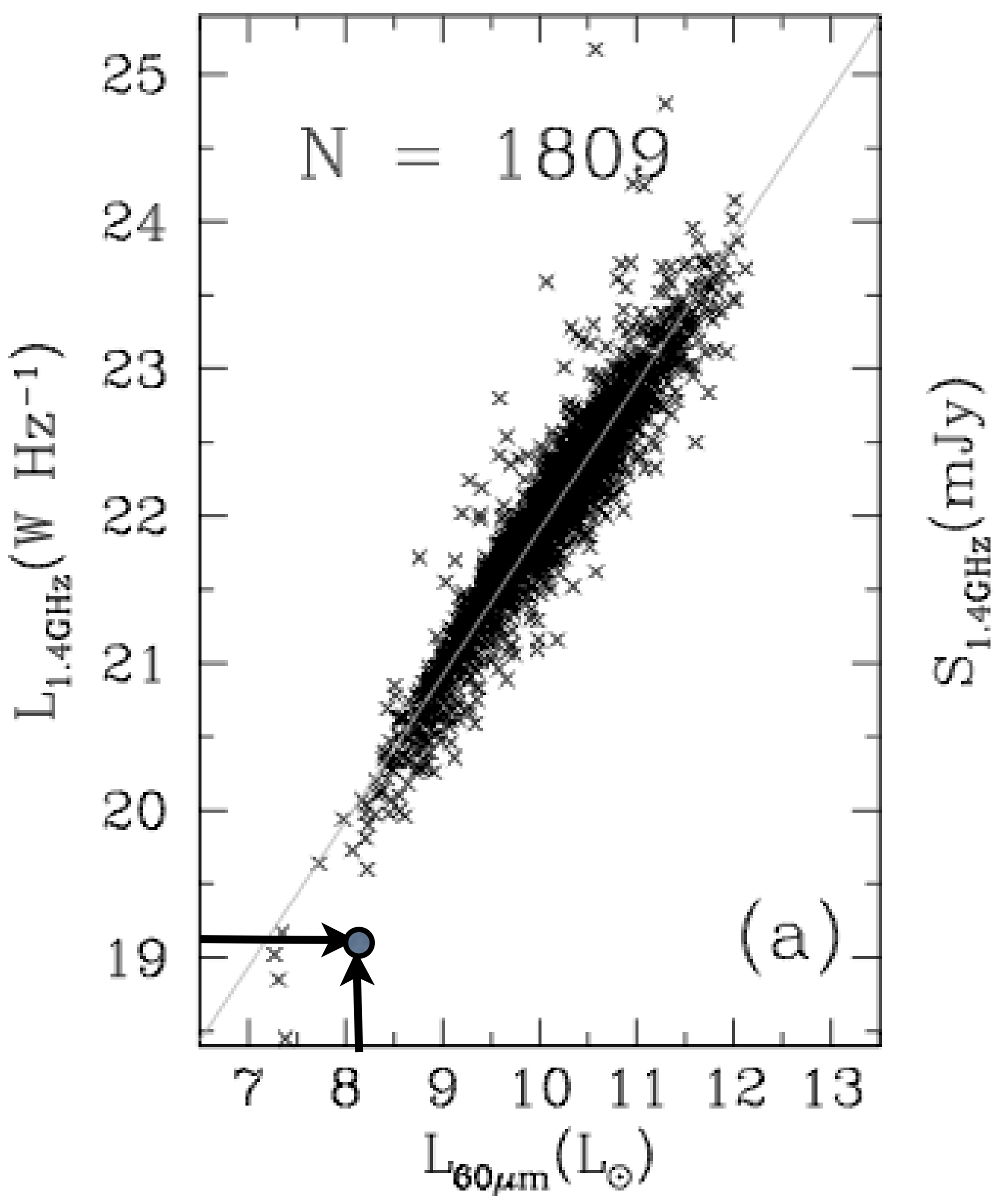
# FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

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




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

RC in deficit wrt expectation from FIR

GC is 1 dex (~4σ) off correlation

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

# 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 (or SN rate):

**GeV emission of GC <5% expected**

**TeV emission of GC ~1% expected**

# Why is GC's non-thermal emission much less than expected given its FIR?

- Explanation 1: a star-burst occurred more recently than the lifetime ($\sim 10^7$ years) of the massive stars which produce most UV and whose lives end in supernovae
- Explanation 2: GC SNRs are intrinsically low-efficiency CR-accelerators
- Explanation 3: some transport process removing non-thermal particles from system

# Explanation 1: Starburst?

NO: luminosity function studies of GC stellar population show GC star-formation has been sustained over long timescales (2 Gyr) at more-or-less current rate (Figer et al 2004)

# Explanation 2: Low efficiency of SN as CR accelerators in GC?

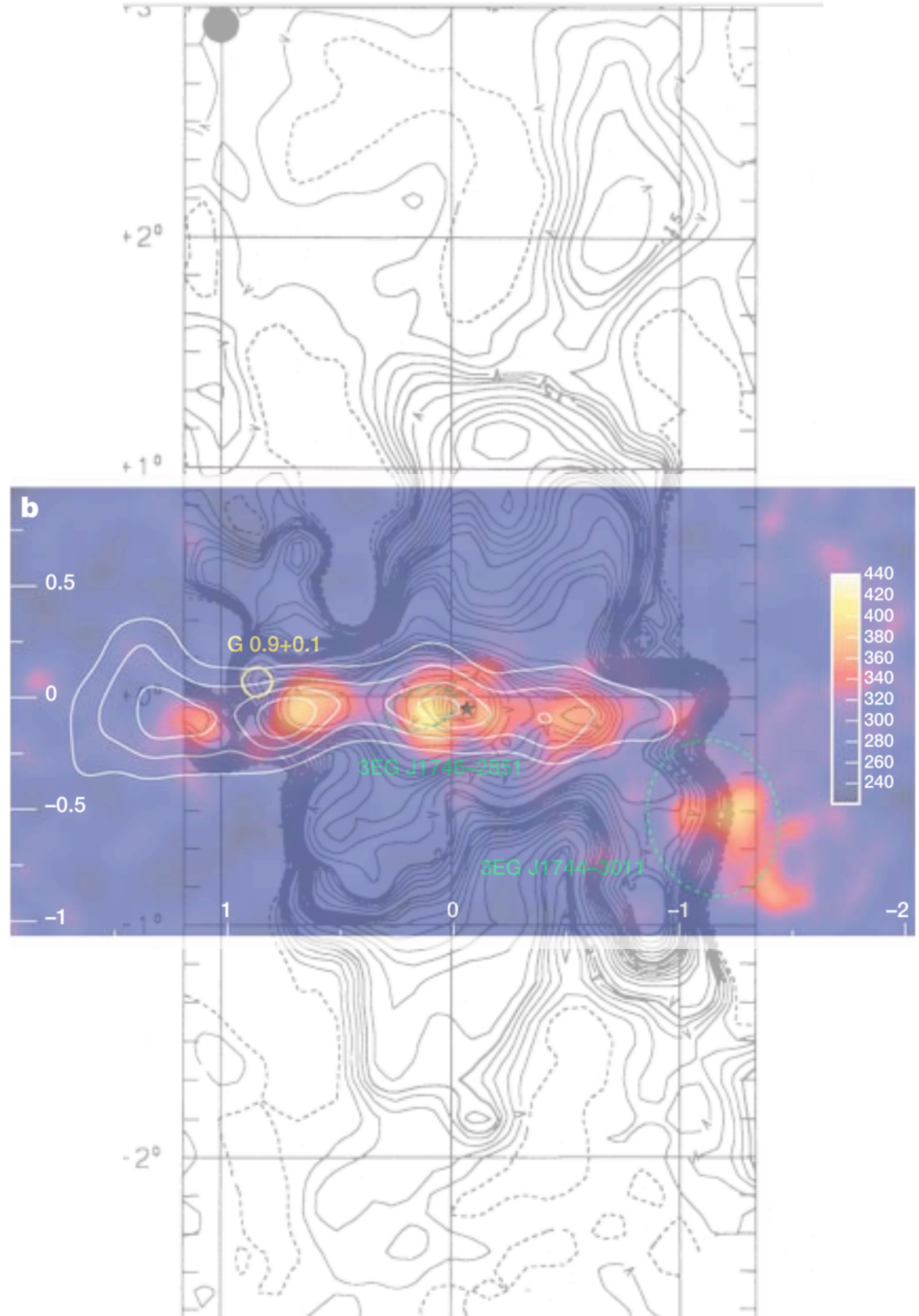
NO: our detailed modelling shows that GC SN act with *at least* typical efficiency as cosmic ray accelerators

# Explanation 3: CR Transport

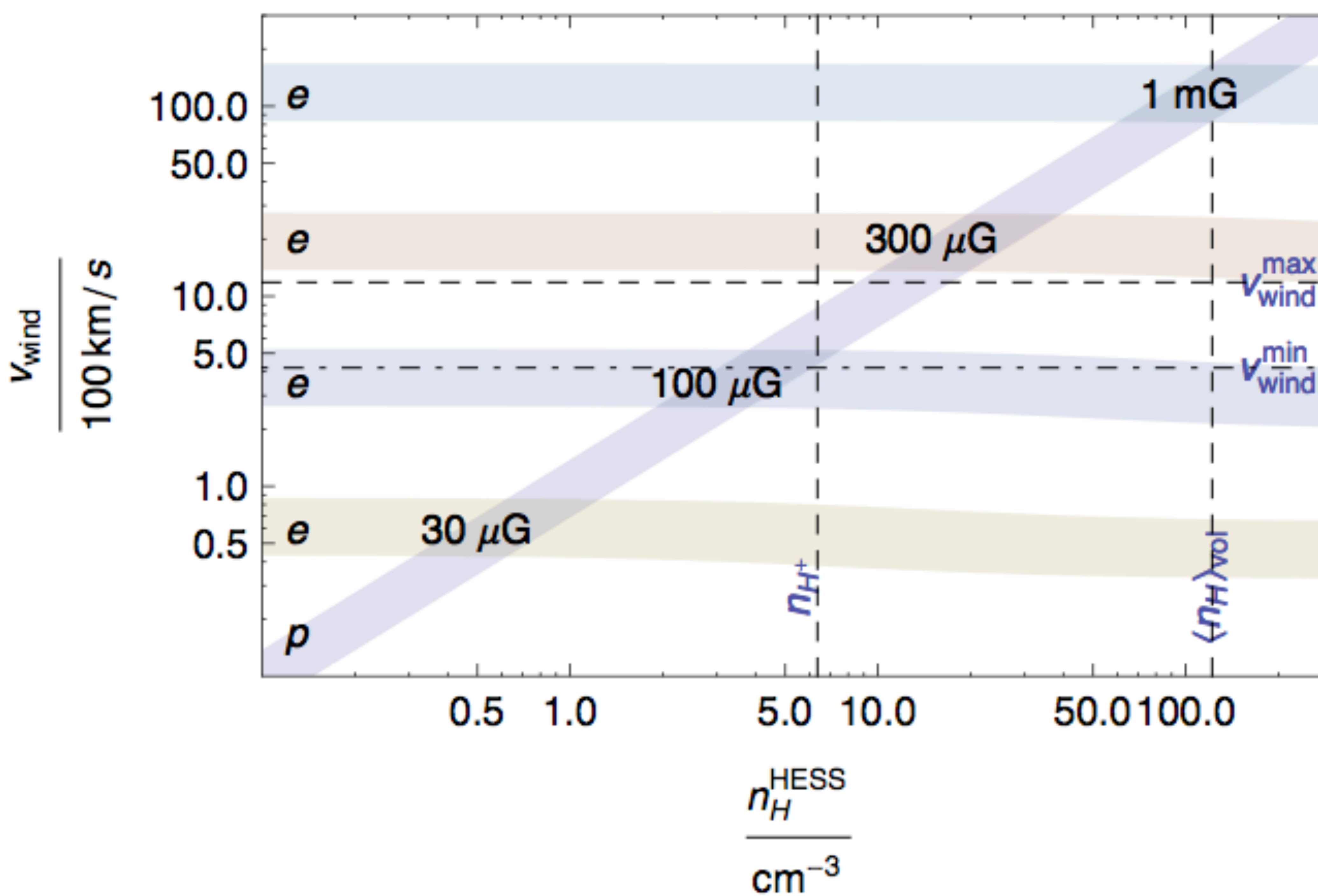
- Flat spectrum of is-situ electron and proton population → transport is advective not diffusive, i.e. via a *wind*
- [contrast situation in Galactic plane]
- there is much prior evidence for such a wind

HESS TeV data:
Aharonian et al 2006

2.7 GHz radio data
(unsharp mask)
Pohl, Reich &
Schlickeiser 1992



# Gas/Wind/Mag. Field



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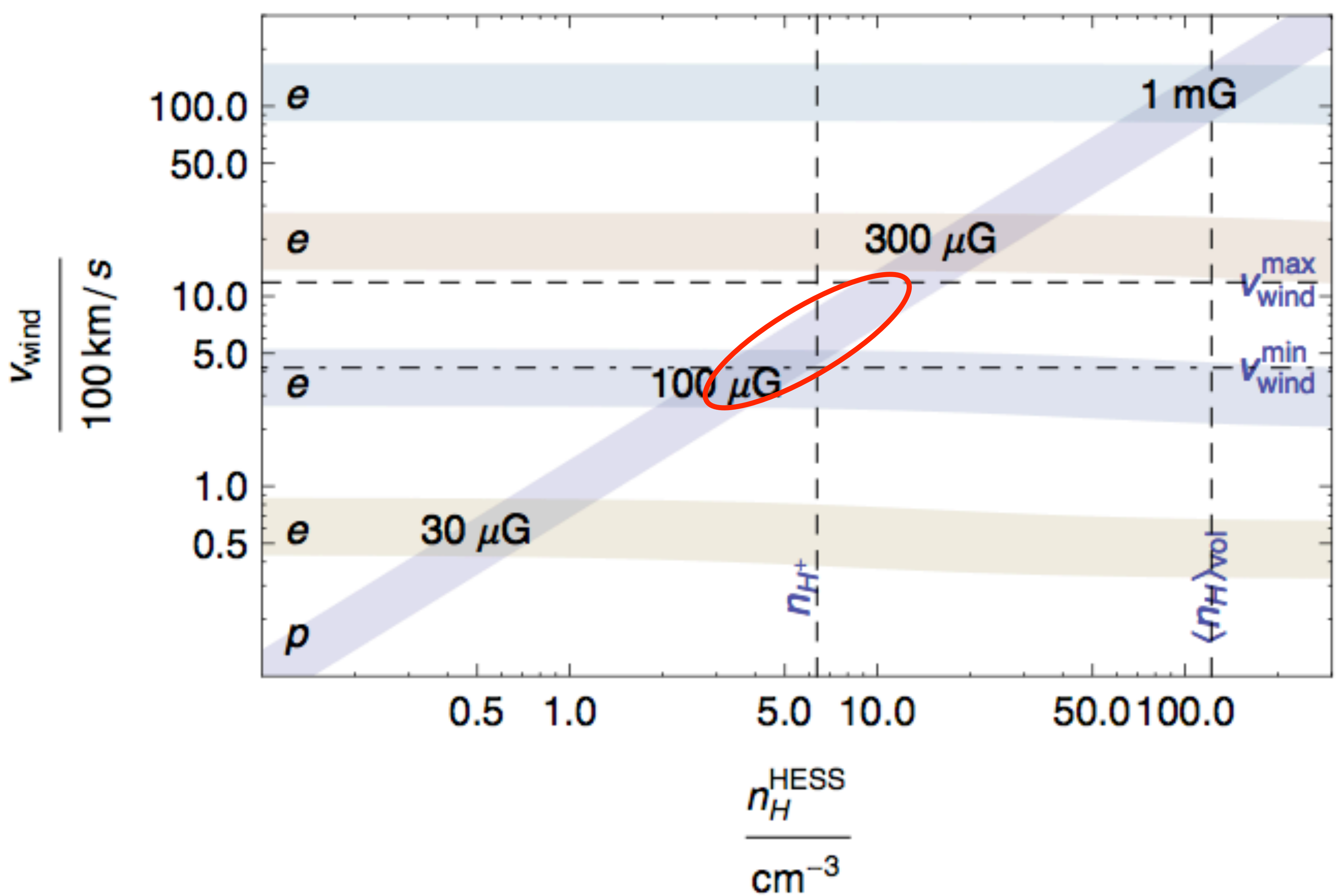


# Bottom Line:

- Star formation activity in inner 200 pc of MW generates $\gtrsim 1/(3000\ \mathrm{yr}) \times 10^{51}$ erg x 10% $= 10^{39}$ erg/s is hadronic cosmic rays
- This is precisely enough (in saturation) to sustain the $\gamma$-ray luminosity of the Bubbles

# Other features

- p's and plasma in Bubbles close to eqprtn
- GC outflow supplies enthalpy $E = L_{\rm jet} t = \frac{\gamma}{\gamma - 1} P_{\rm ext} V(t)$ of Bubbles over same *few x Gyr* timescale
- GC outflow supplies plasma mass of Bubbles ($\sim 10^8$ $M_{sun}$) over same *few x Gyr* timescale
- plasma density is tightly constrained:
  - Min[$n_H$] = 0.004 $cm^{-3}$ for $t_{pp} = t_{Hubble}$
  - Max[$n_H$] = 0.006 $cm^{-3}$ saturates power of outflow ($\sim 10^{40}$ erg/s)

# Shortcomings/To Do

- Single zone model → CR transport not treated
- In particular, dynamics near edges not addressed

    → edge profile

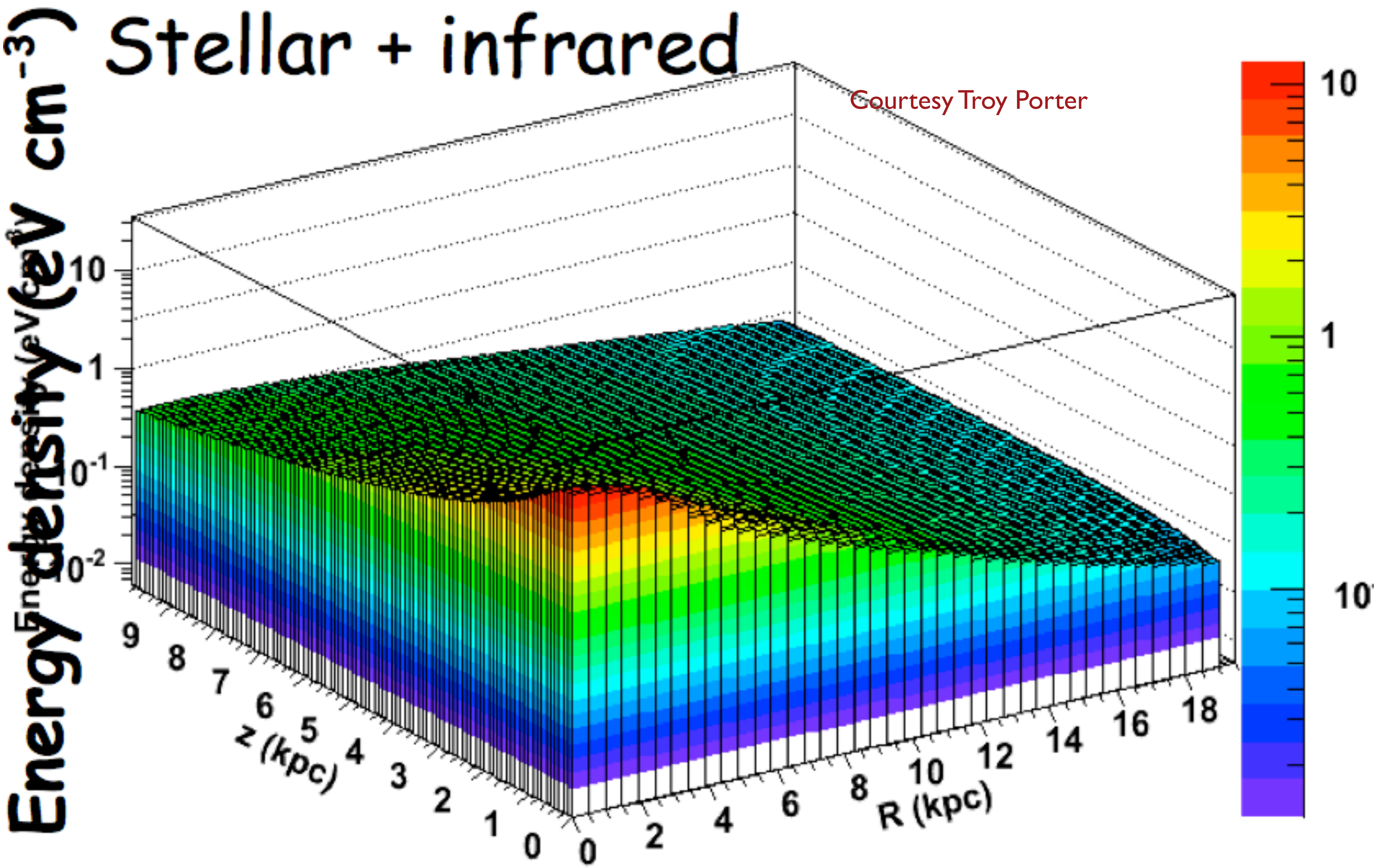
    → CR trapping

- Hard spectrum of microwave haze
- Can these structures really last so long?

# Discussion points

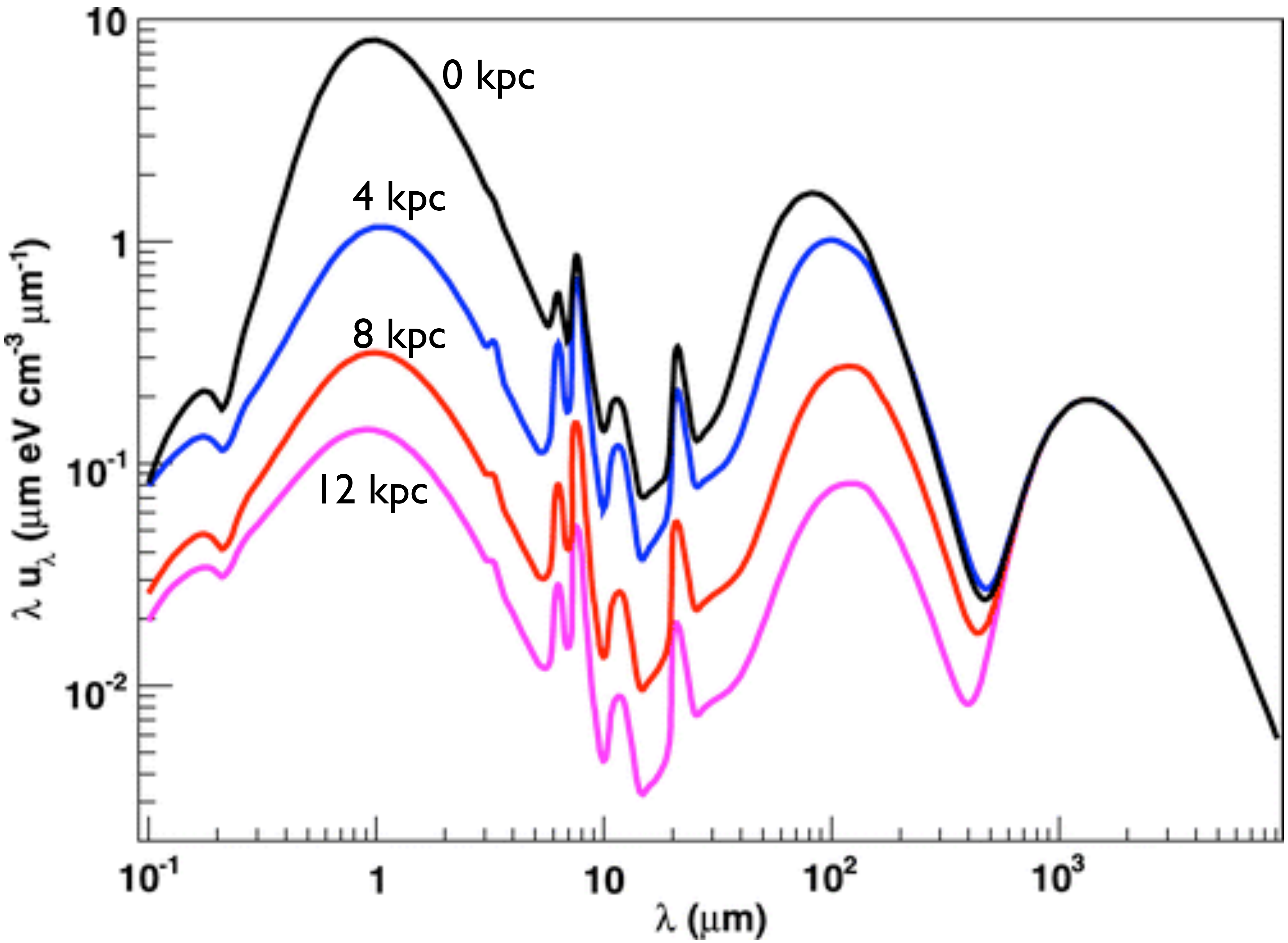
- Results consistent with GC SF in more-or-less steady state for >Gyr timescales → self-regulation?
- Our scenario implies that the bubbles are a calorimetric recording of GC activity over the lifetime of the Galaxy
- Bubbles should be good TeV $\gamma$-ray sources
- Good neutrino sources: $\lesssim$40 signal events above 10 TeV per annum (vs. ~100 background) for northern km$^3$ detector

# Extra Slides


Stellar + infrared
Energy density (eV cm$^{-3}$)
Courtesy Troy Porter
10
1
$10^{-1}$
$10^{-2}$
z (kpc)
R (kpc)
0 1 2 3 4 5 6 7 8 9
0 2 4 6 8 10 12 14 16 18

- $L_{GeV} \sim 10^{-5}\, L_{TIR}[GC] \rightarrow L_{GeV} \sim 2\ 10^{37}$ erg/s

# Problem with electrons II




Porter et al 2008;

SED of the MW ISRF in the Galactic plane: kpc, black; kpc, blue; kpc, red; and kpc, magenta.

# Big picture

- GC ISM params extreme wrt Gal disk - arguably *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 → CR transport in GC is advective not diffusive (cf. Disk)
- Claim: HE CRs (GeV$^-$ → 10 TeV$^+$) do not penetrate into the densest molecular gas
- Claim: BUT there is enough power in the CR spectrum to warm/ionize the low density $H_2$ phase

# Big picture III

- Claim: the GC wind advects plasma and cosmic ray **ions** to large distances from the plane and the $\gamma$-ray and microwave signatures of these have recently been detected as the *Fermi Bubbles*
- Claim: despite similarity to starburst conditions will argue here that GC SF proceeding in more-or-less steady state for $\gtrsim$ Gyrs

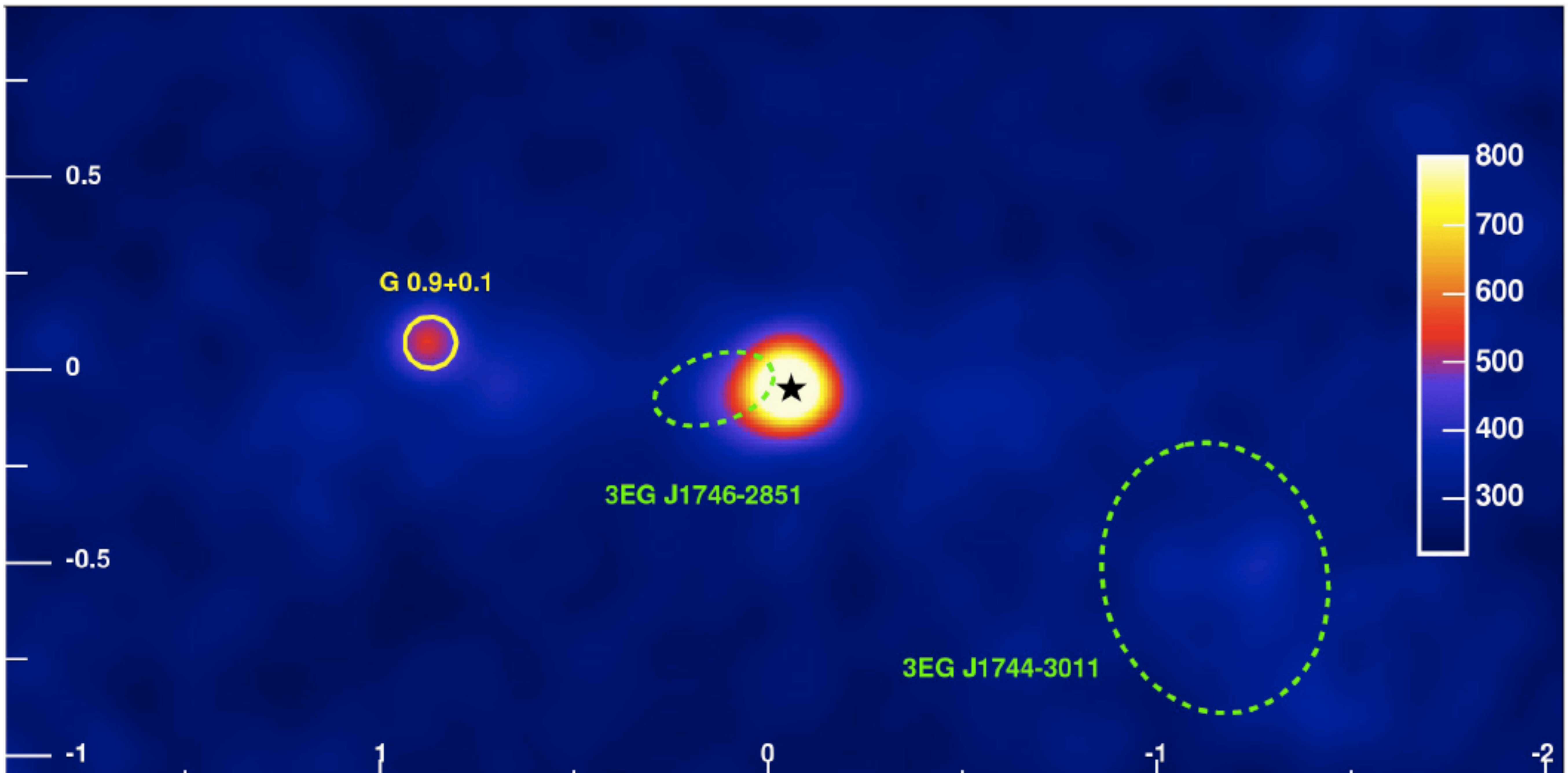
# Discussion points

- Star-formation (and concomitant supernovae) sufficient to drive activity of region
- The SMBH is not a significant actor beyond a few pc radius
- SN in GC seem to act with at least typical efficiency (> 10%) as CR accelerators
- GC mag field v. strong (100-200 μG)

# Discussion points 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 → role for CRs in modifying conditions for SF seems to be disfavoured (unless *local* acceleration)
- No evidence for/against biasing of IMF
- GC a star-burst analogue ...?

# HESS (TeV) GC Data (2005) - 50 hours




Credit: HESS Collab

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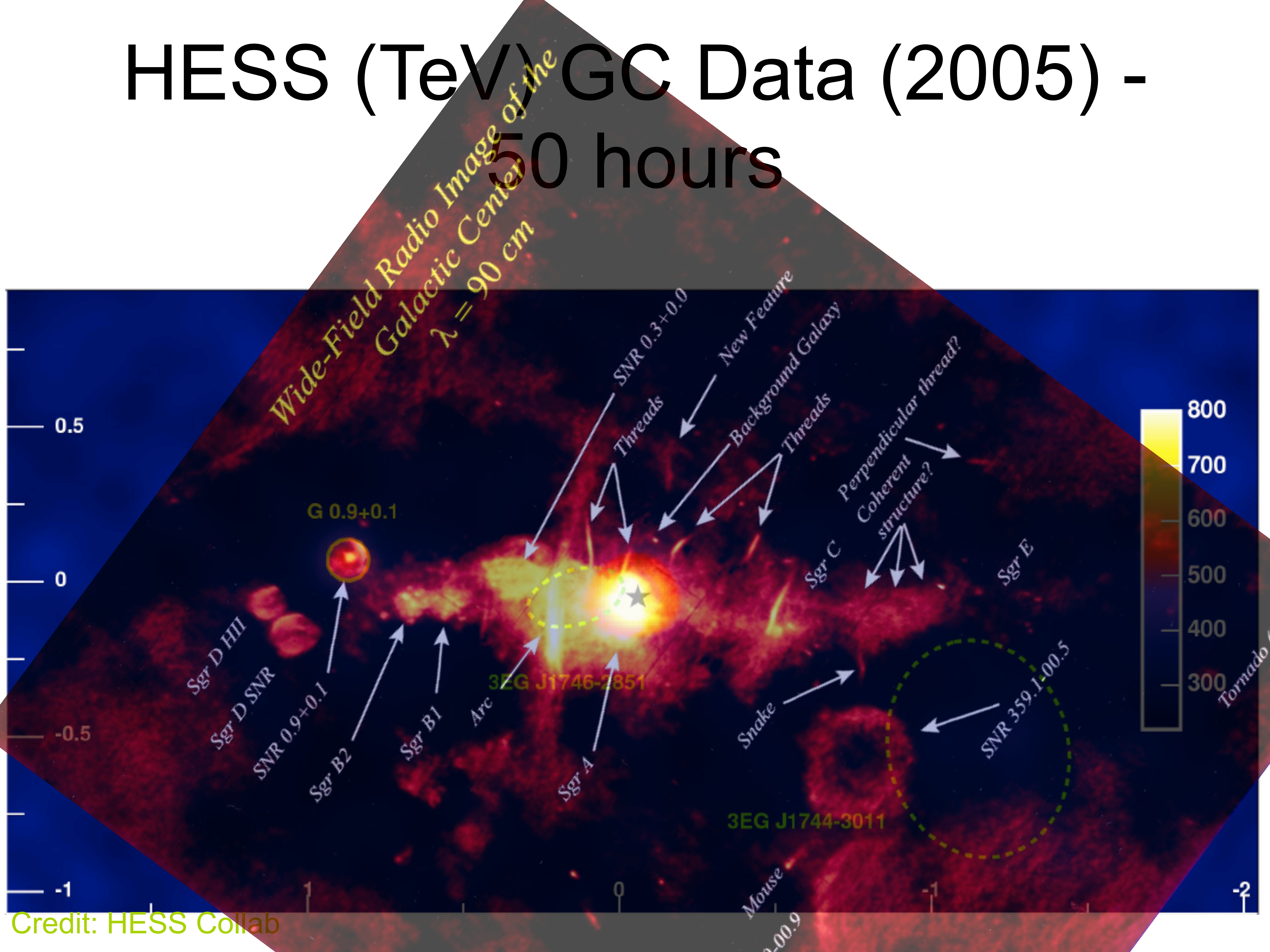


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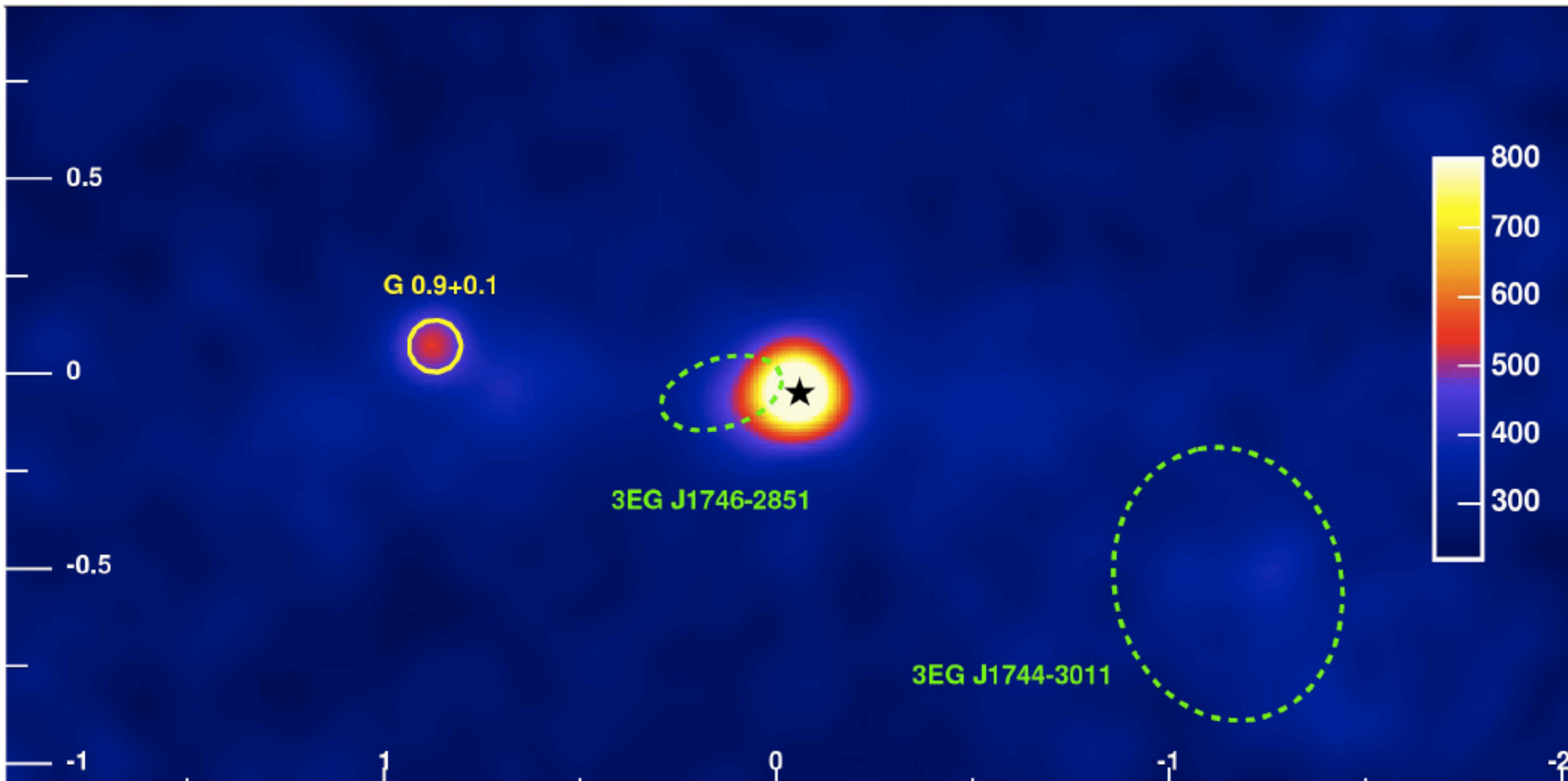


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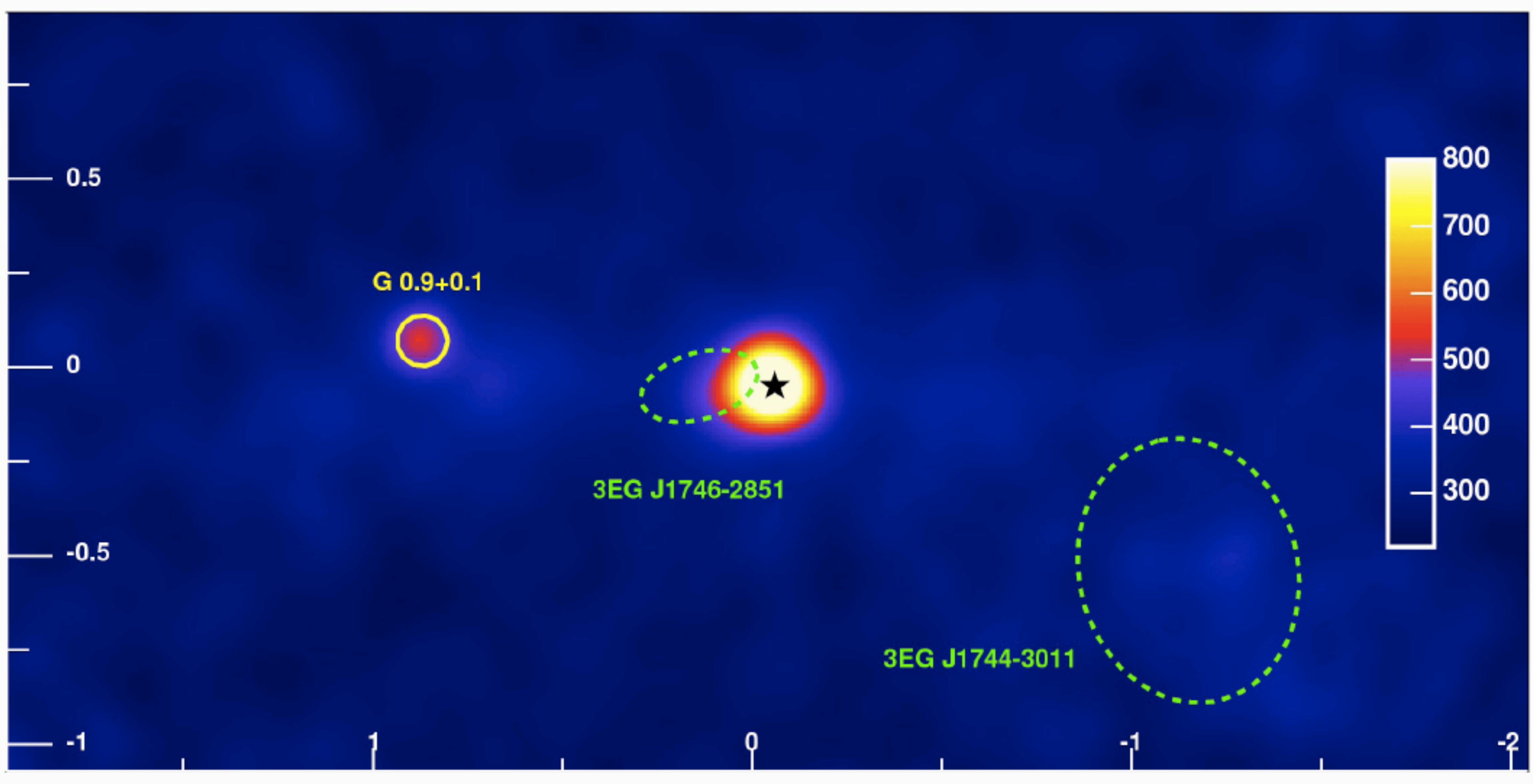
# Diffuse γs in H.E.S.S. data?




- 50 hour H.E.S.S. Observation of GC in 2005
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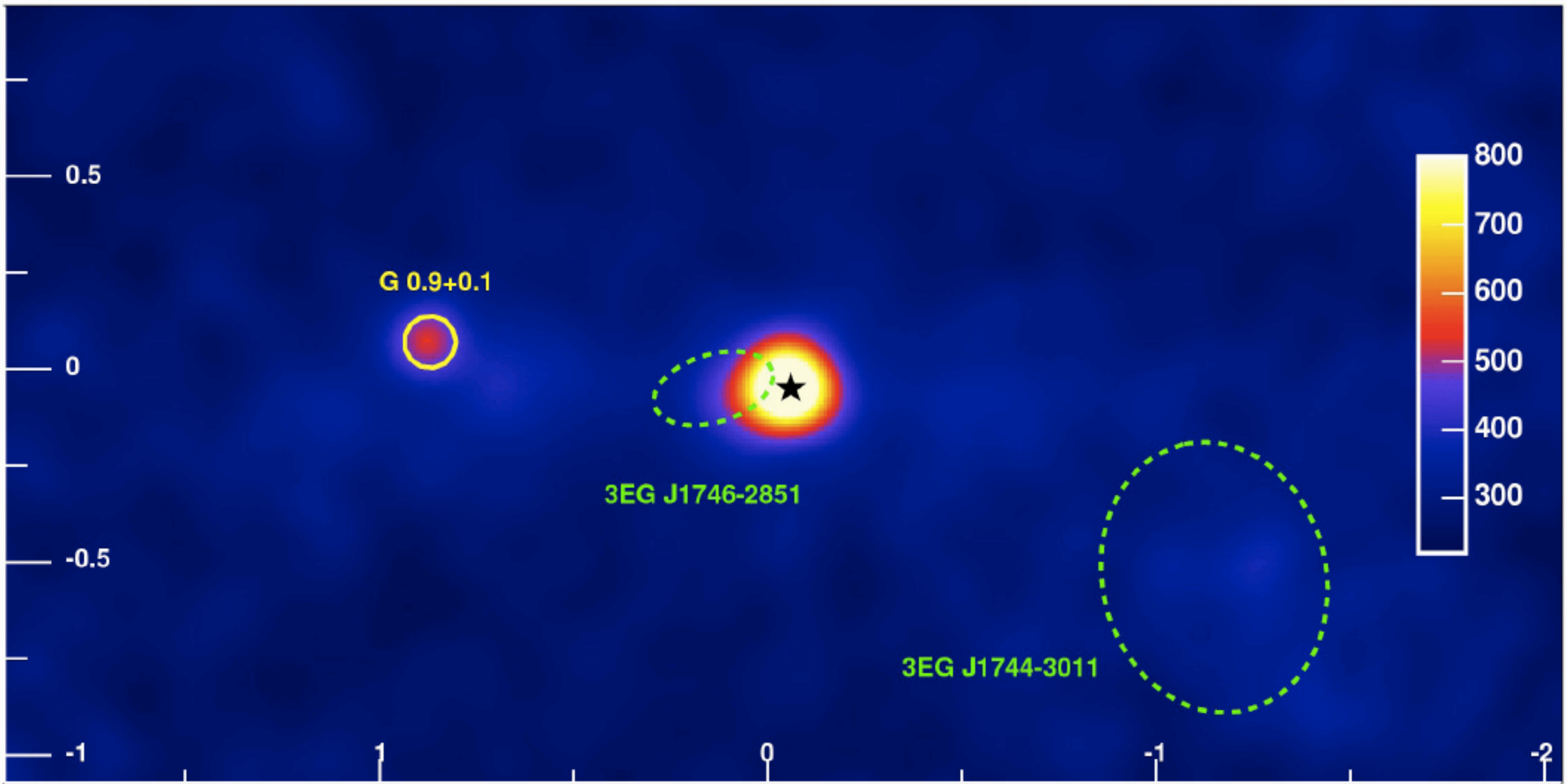


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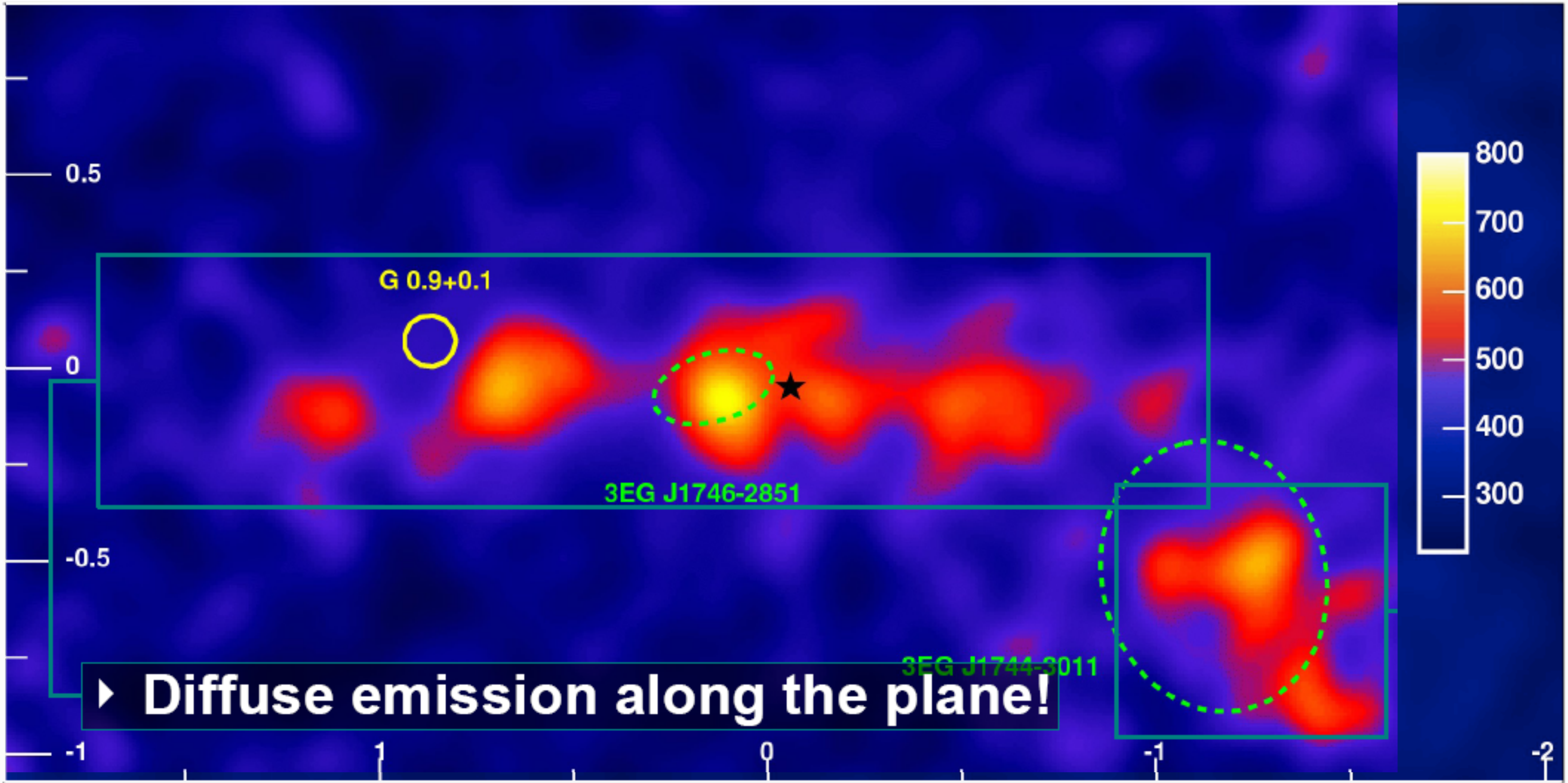
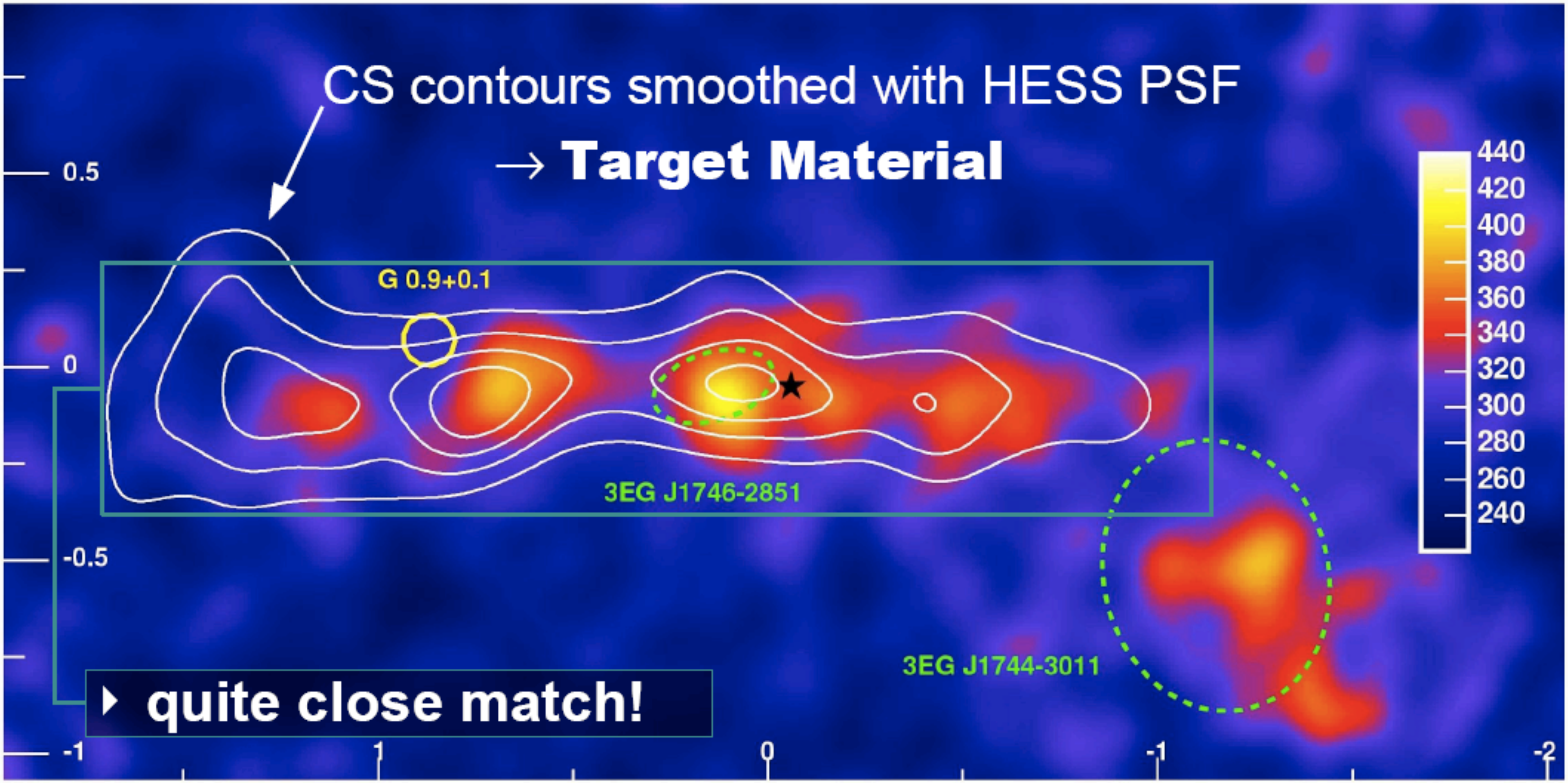



- Diffuse emission along the plane!

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

Credit: HESS Collab

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




Credit: HESS Collab

CS contours from Tsuboi et al. (1999)

# GC molecular clouds

GC giant molecular clouds are unusually

- dense (~$10^4$ $cm^{-3}$),
- turbulent (velocity dispersion > 15 km/s)
- warm (10's K)

...when compared with Disk clouds

# Diffuse, non-thermal RC

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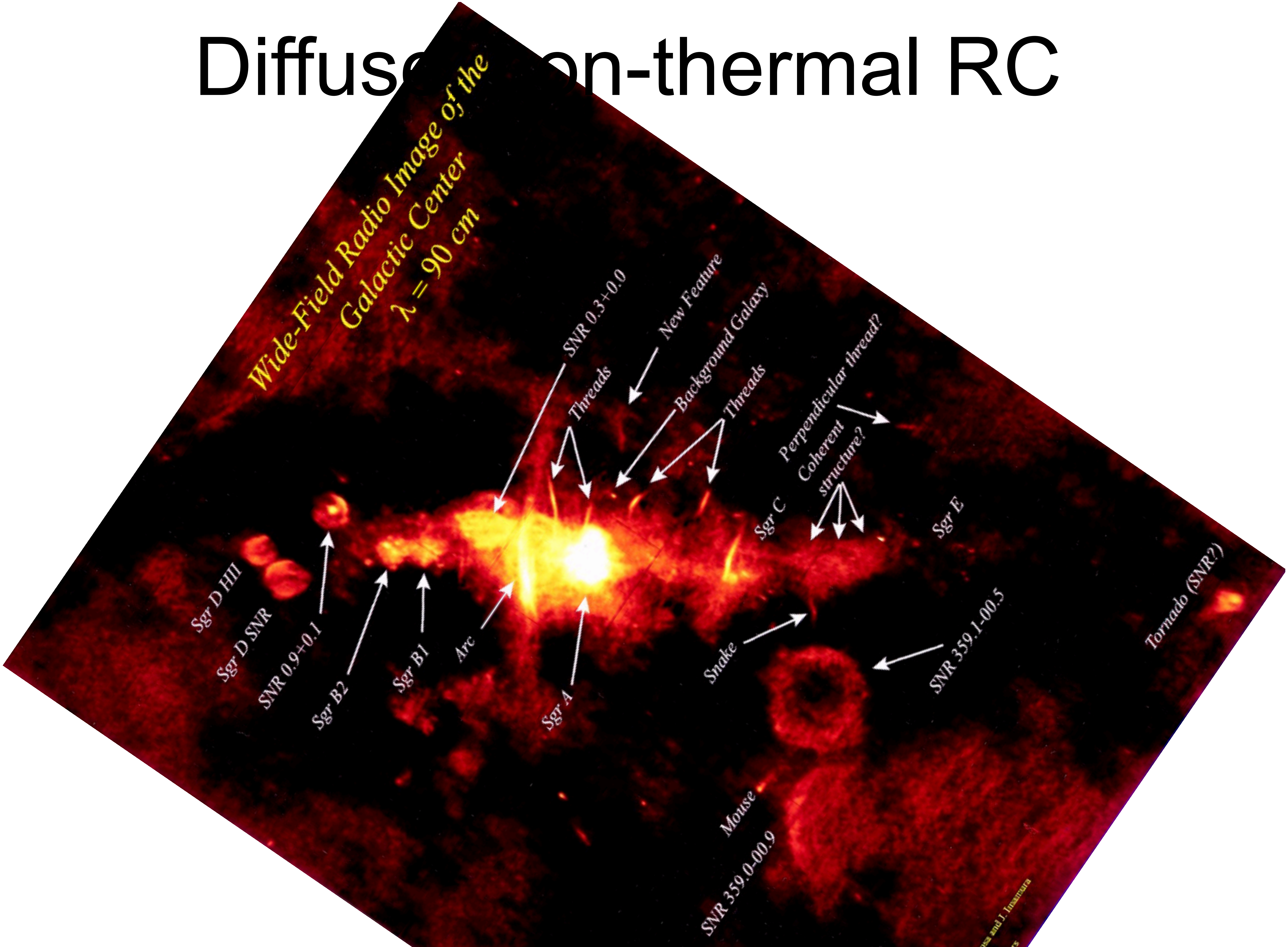

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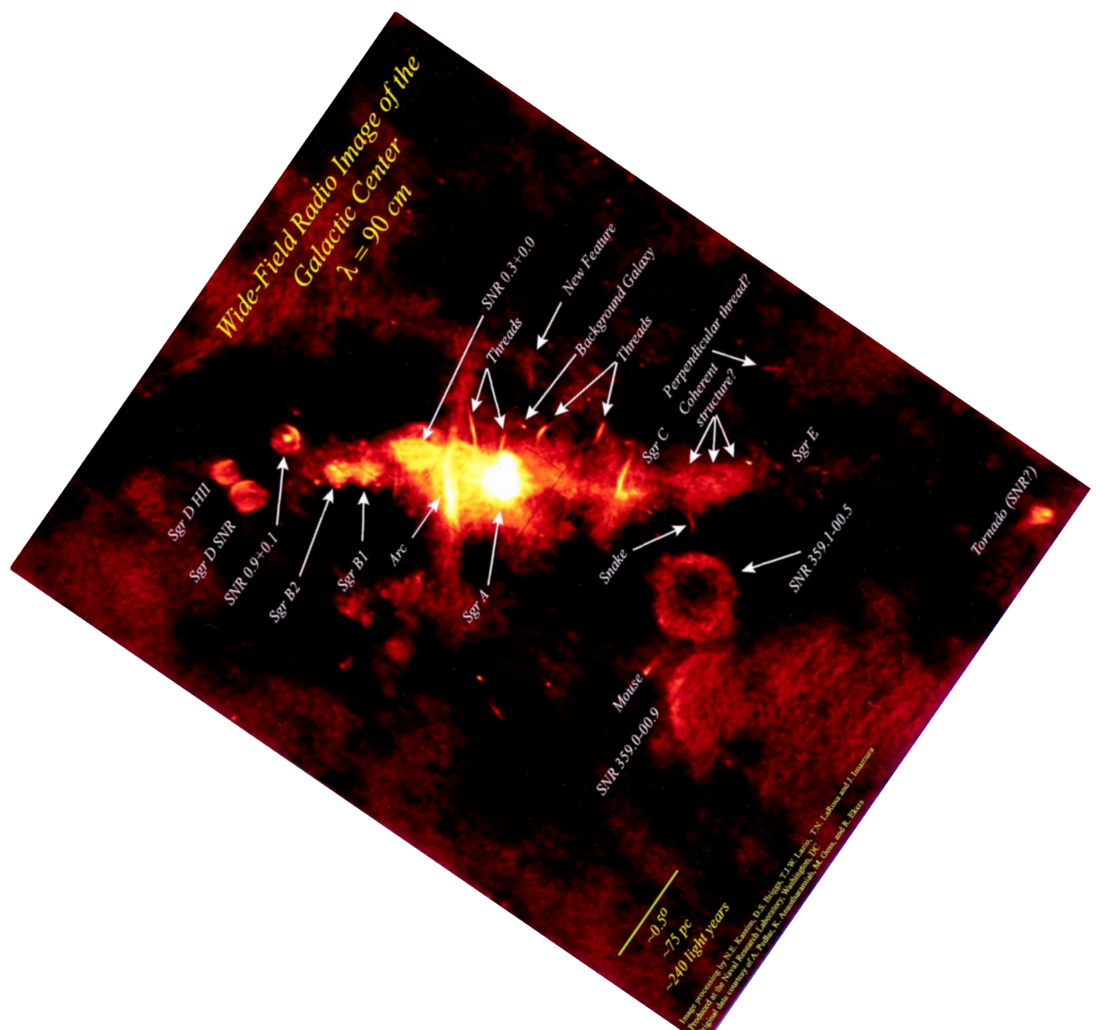

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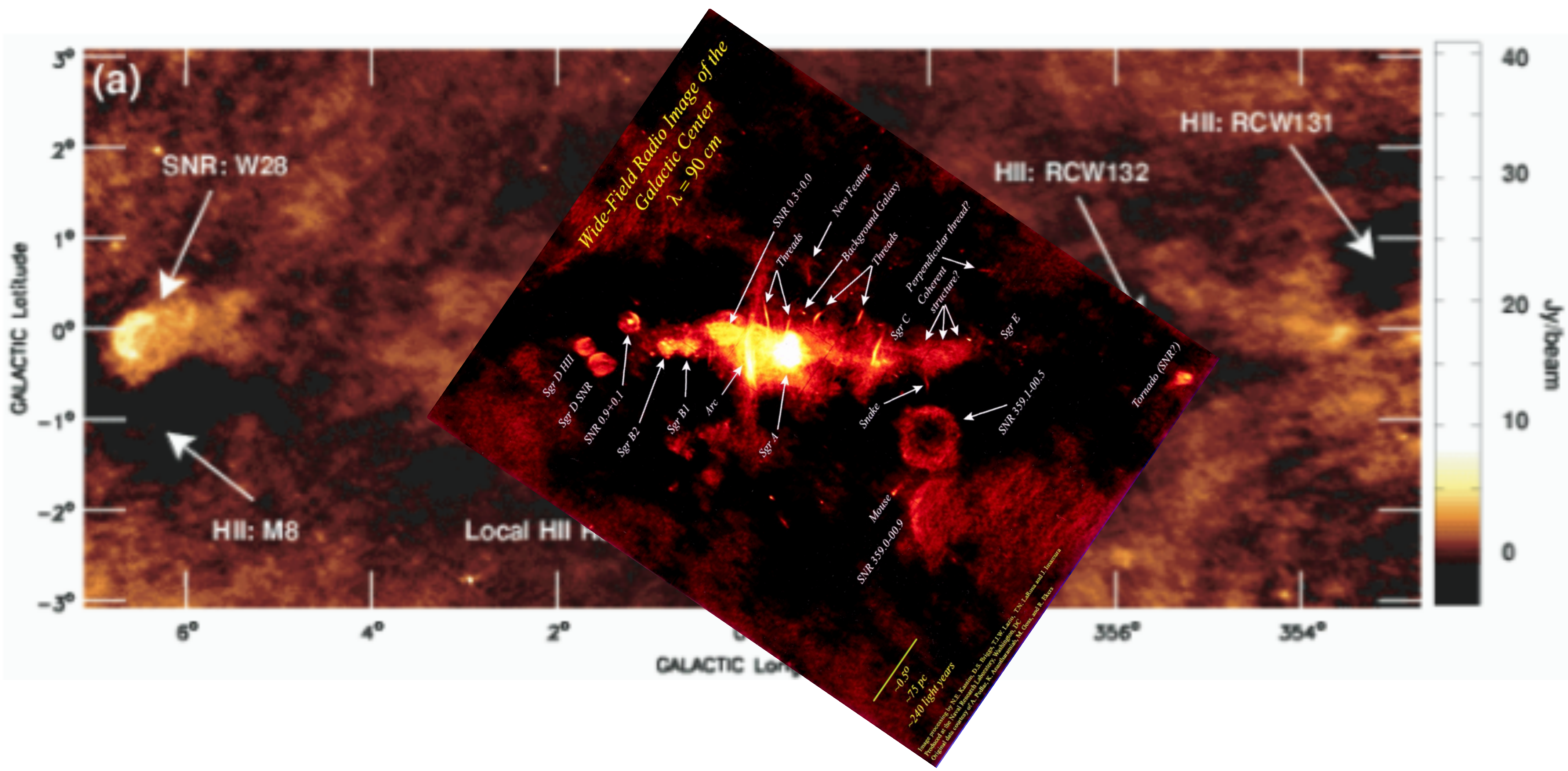

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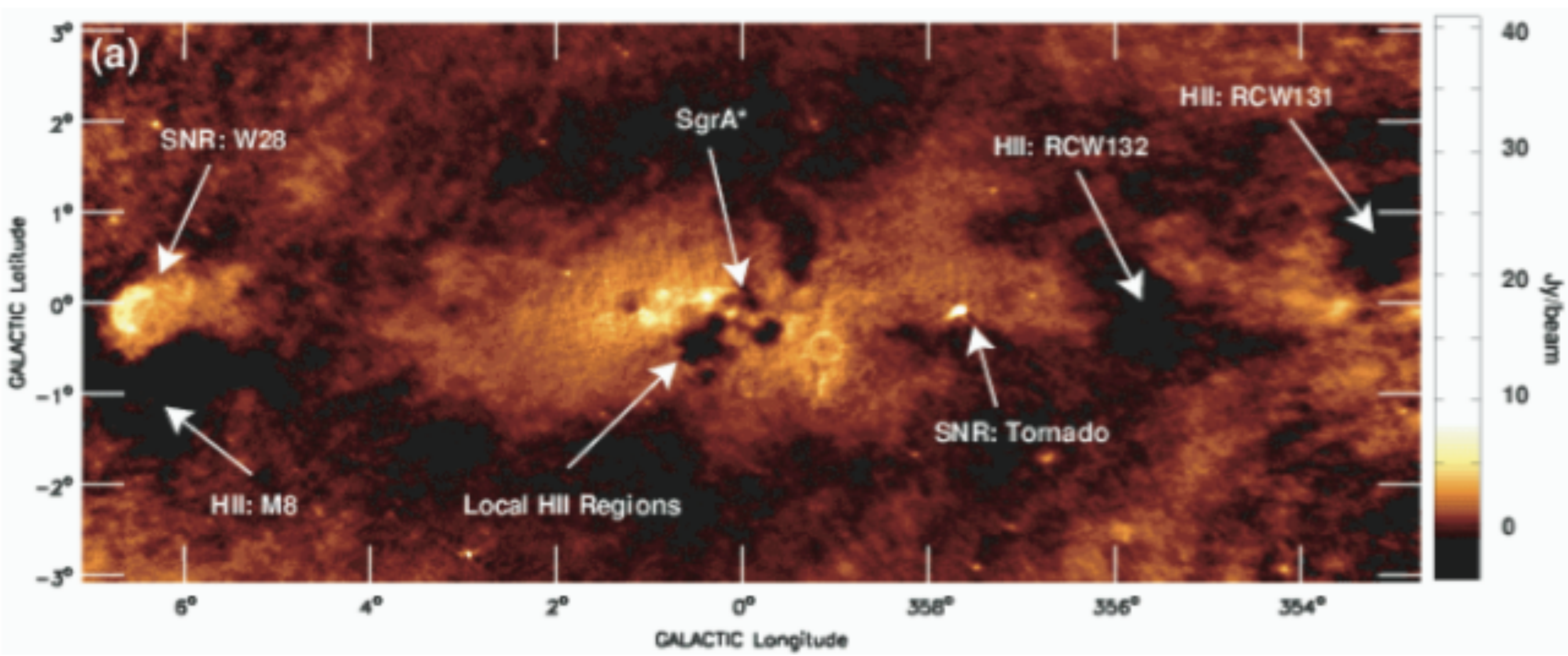

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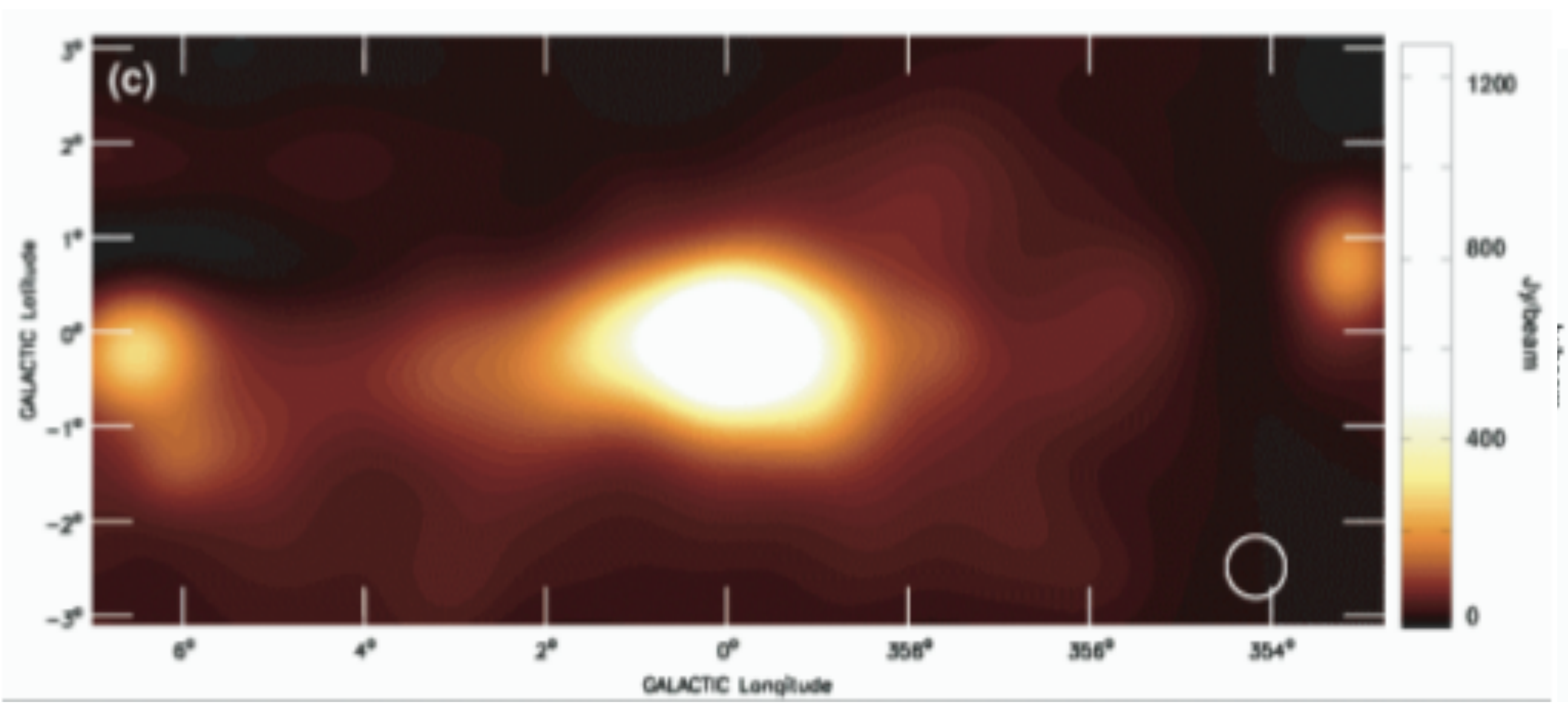

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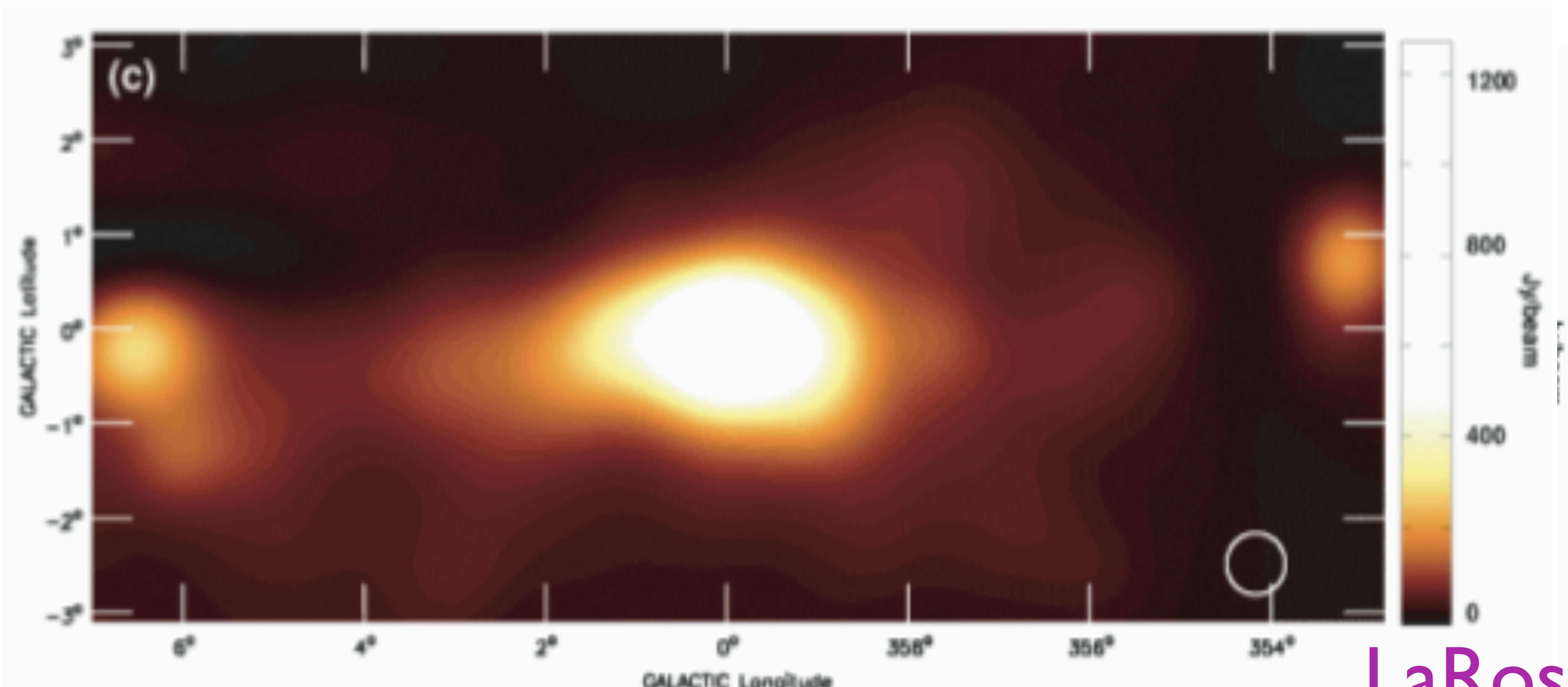
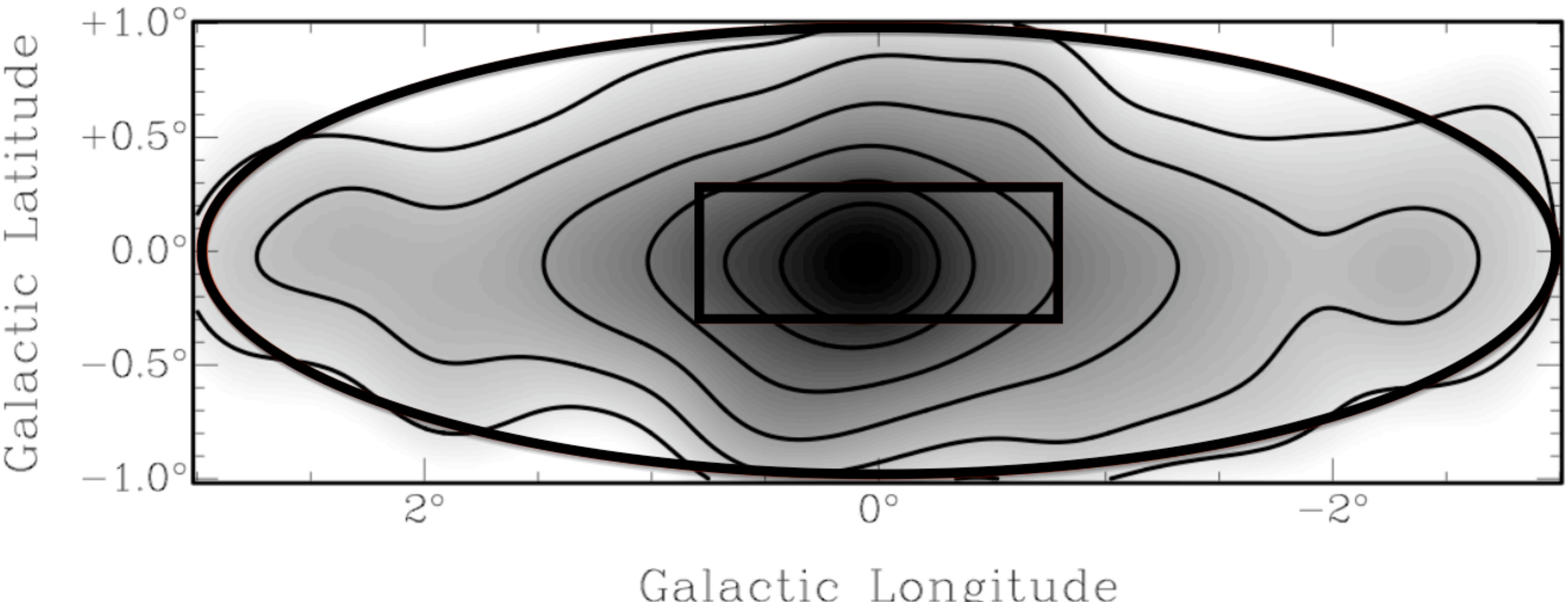



LaRosa et al. 2005

# ‘DNS’




10 GHz Nobeyama data - spectrum is non-thermal up to 10 GHz

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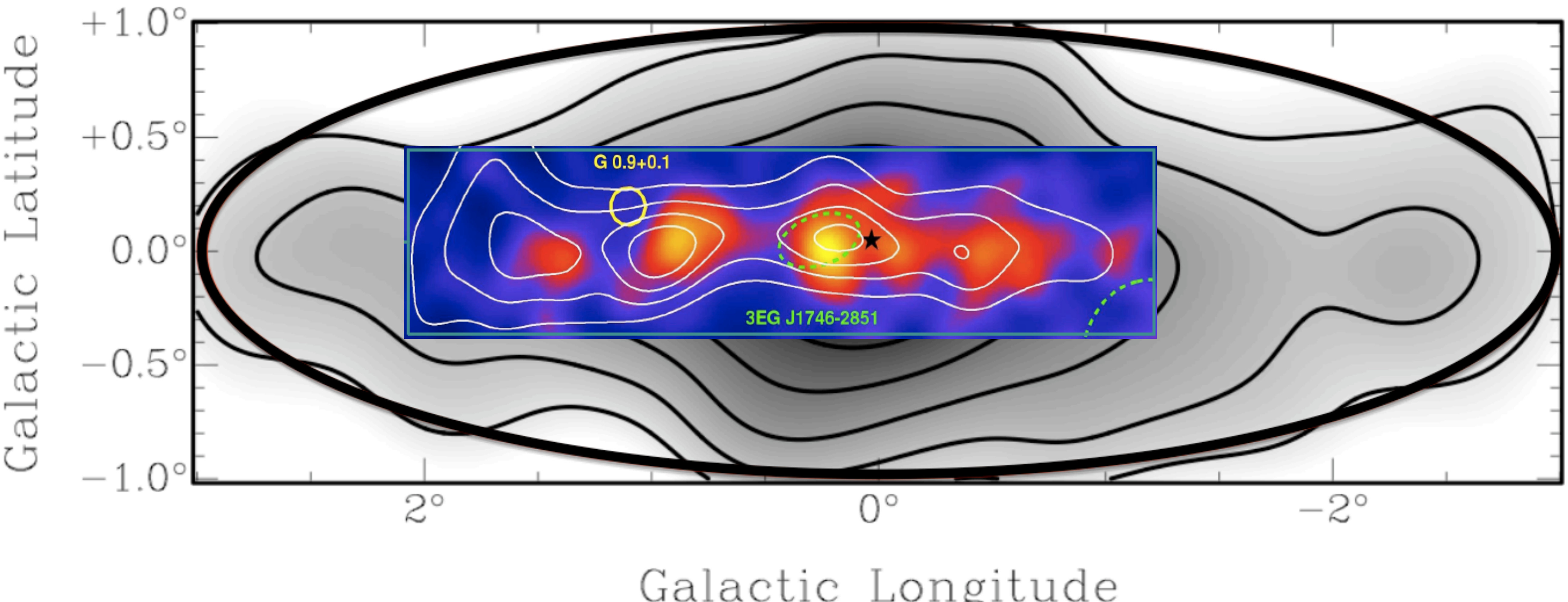


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# FIR-RC?

Yun et al. 2001 ApJ 554, 803 fig 5

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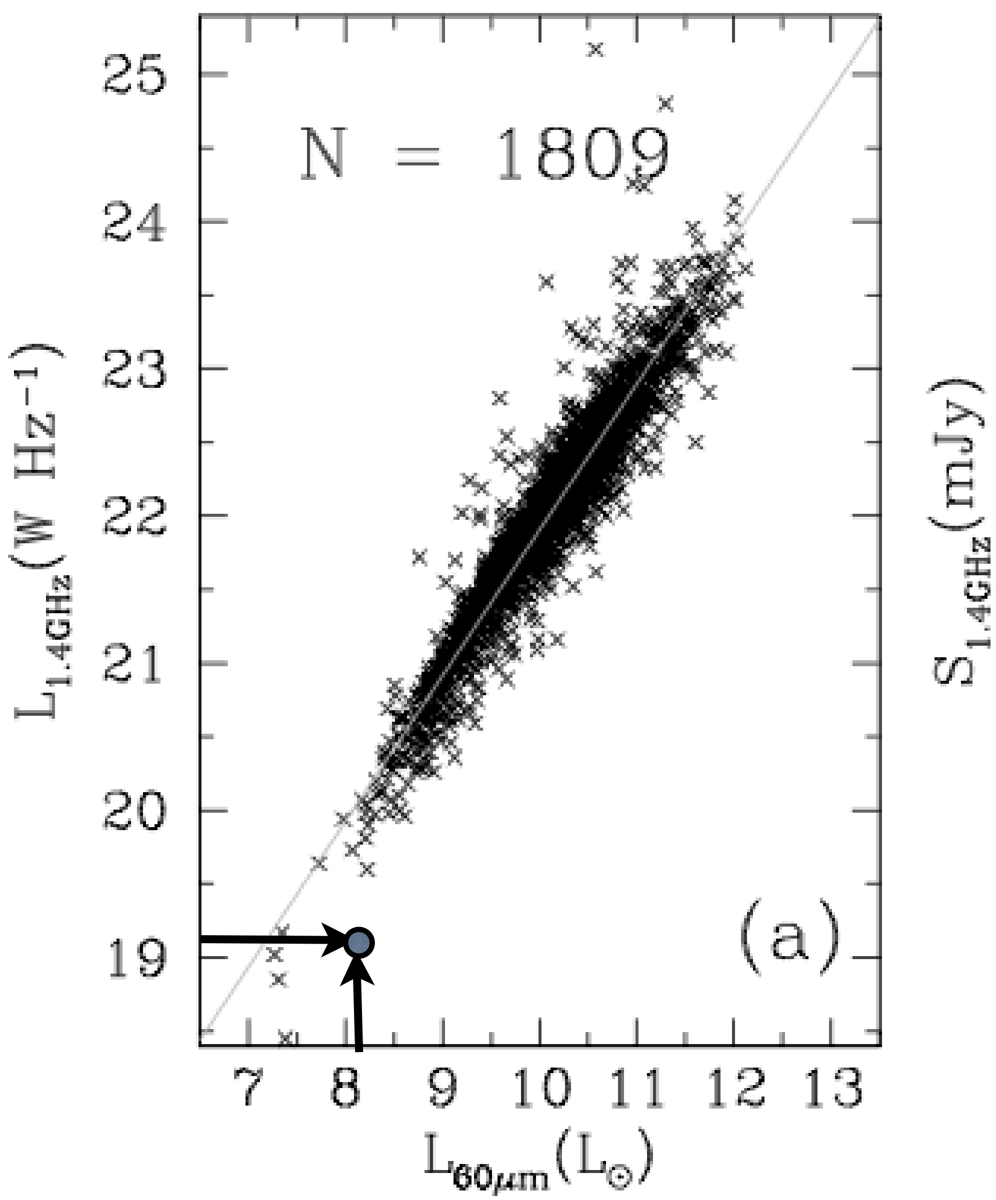


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RC in deficit wrt expectation from FIR

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 (or SN rate), (**GeV and) TeV emission of HESS region < few % expected**

# Why is GC's non-thermal emission much less than expected given its FIR?

- Explanation 1: a star-burst occurred more recently than the lifetime (~$10^7$ years) of the massive stars which produce most UV and whose lives end in supernovae
- Explanation 2: GC SNRs are intrinsically low-efficiency CR-accelerators
- Explanation 3: some transport process removing non-thermal particles from system

# Starburst?

- Star-formation history of GC is a subject of debate and we expect stochastic variation in SFR at some level
- BUT stellar population studies show GC star-formation has been sustained over long timescales (Gyr) at (some authors argue) more-or-less current rate
- Other tracers of supernova rate also show it is more-or-less in steady state

# Low efficiency of SN as CR accelerators in GC?

- NO: detailed modelling (see below) shows that GC SN act with at least typical efficiency

# CR Transport

- Flat spectrum of is-situ electron and proton population → transport is advective not diffusive (cf. Galactic plane)
- → GC wind
- there is much prior evidence for such a wind

# GC Wind Evidence

- RC studies show extended emission ($1.2^\circ$) north of the plane whose spectrum steepens with distance (Law 2010)
- extended NIR emission mirroring RC (Bland-Hawthorn and Cohen 2003)
- X-rays $\rightarrow$ apparent, diffuse, very hot plasma in inner ~100 pc ... cf. external star-burst systems
- very extended X-ray emission (10's degrees)

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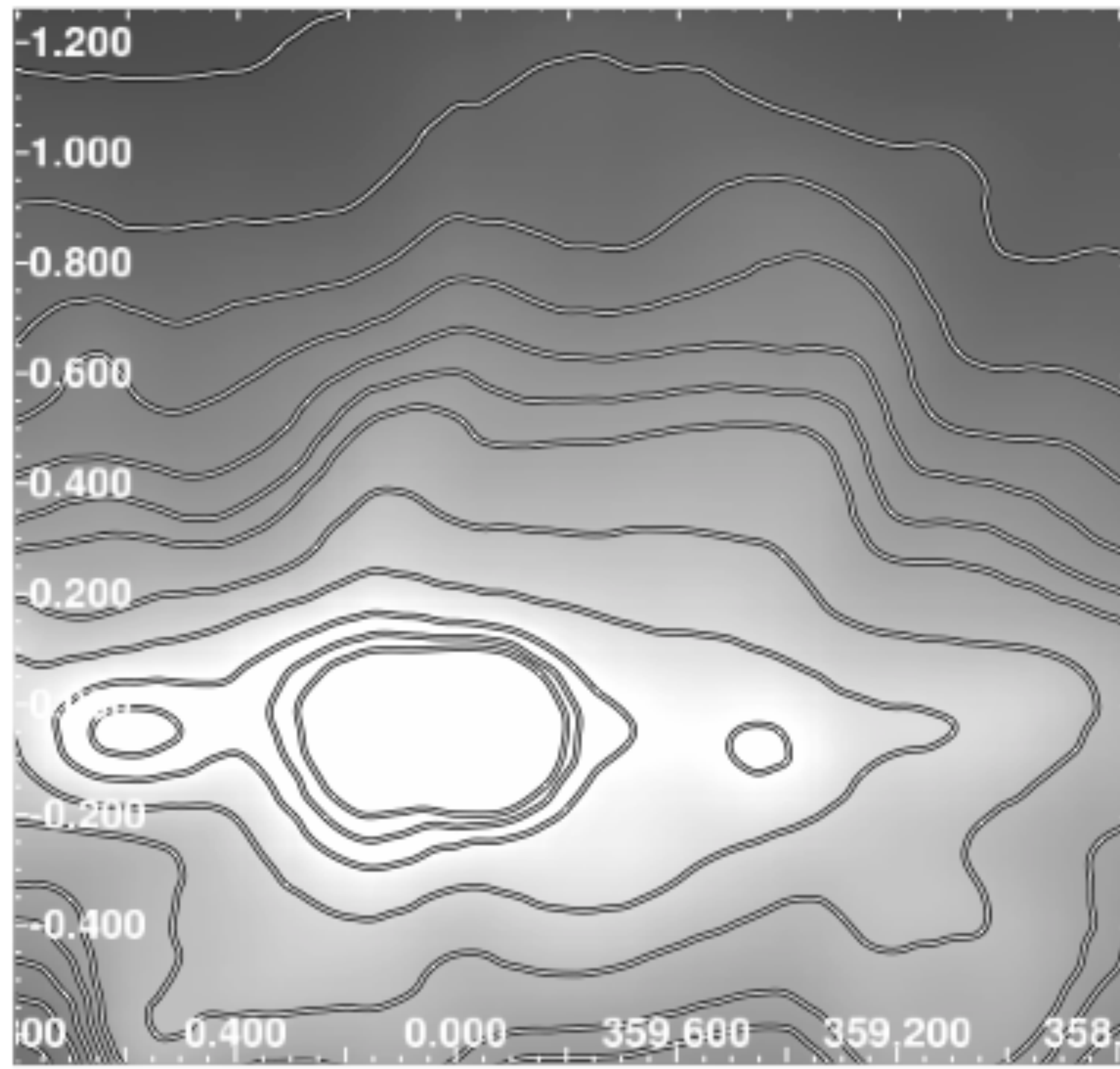

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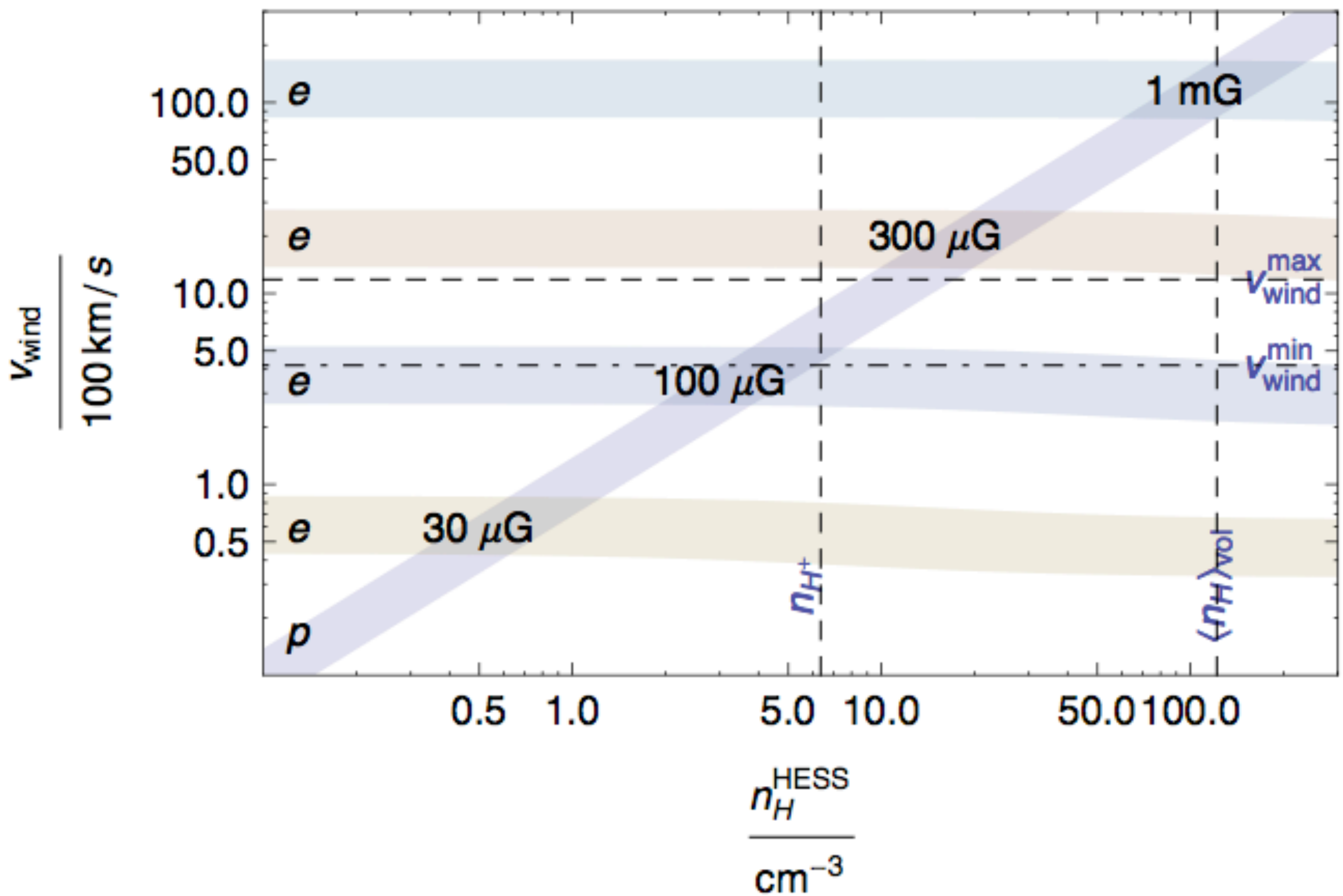

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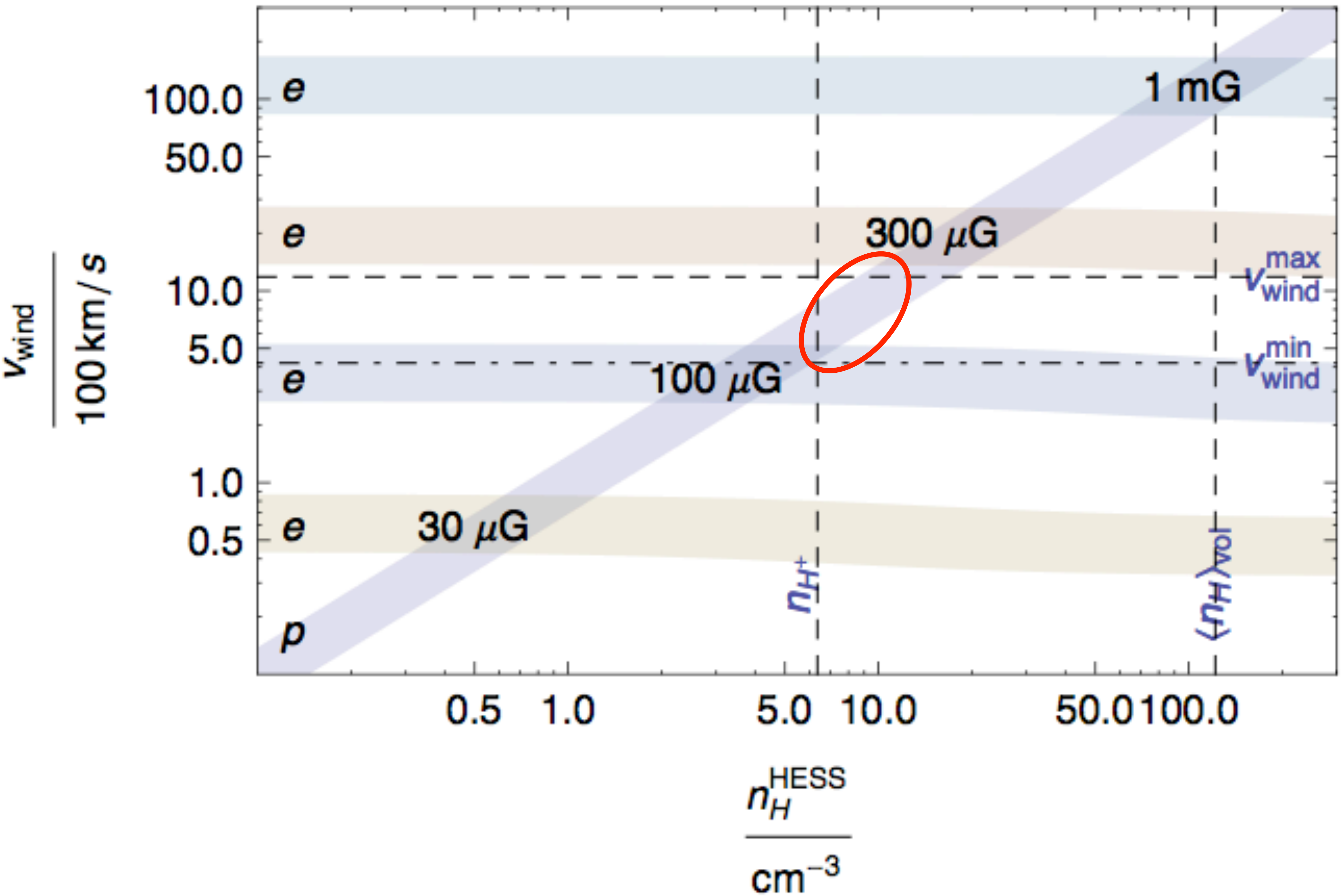
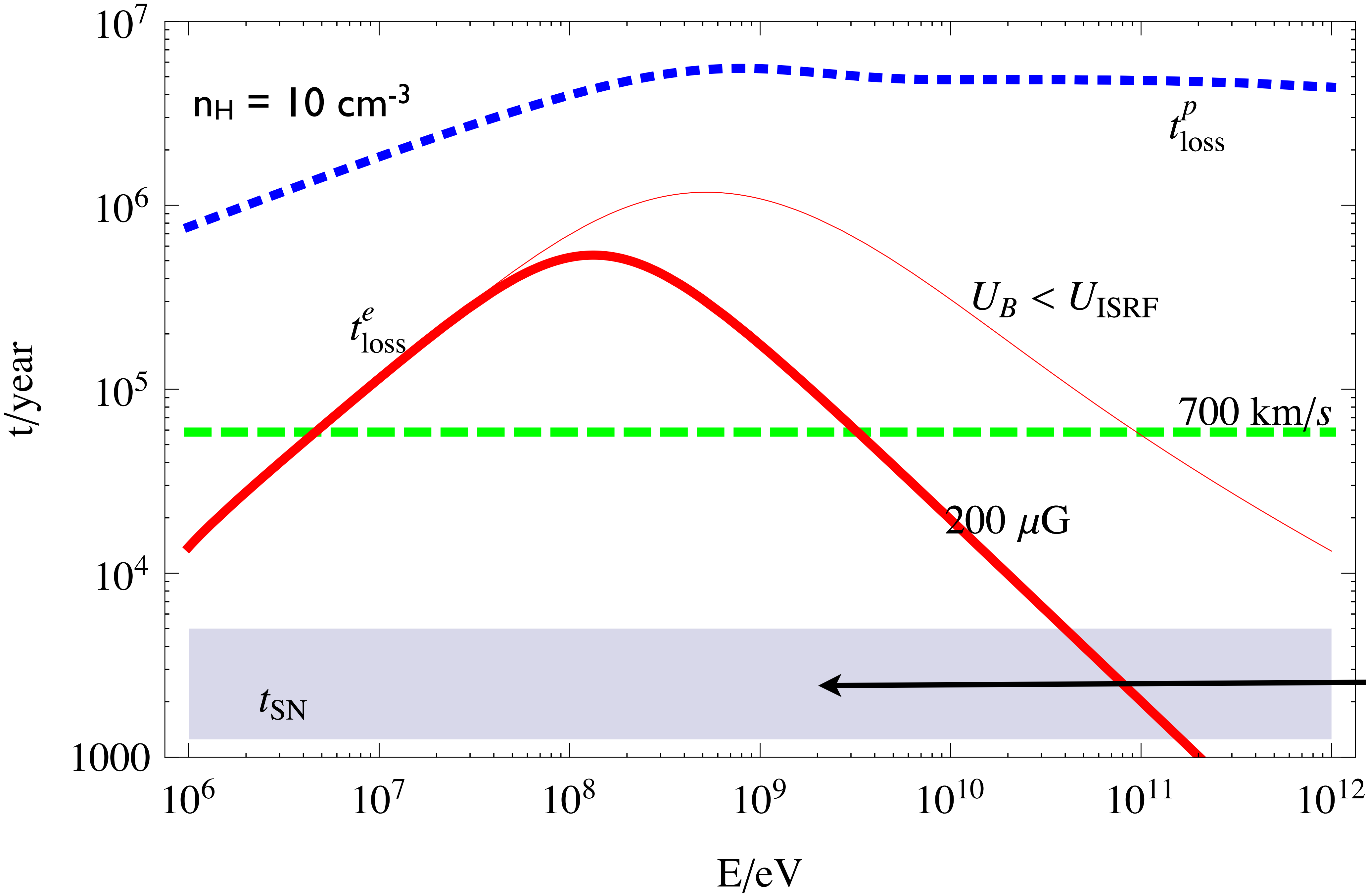


# Modelling

- 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

# Timescales: steady state justified

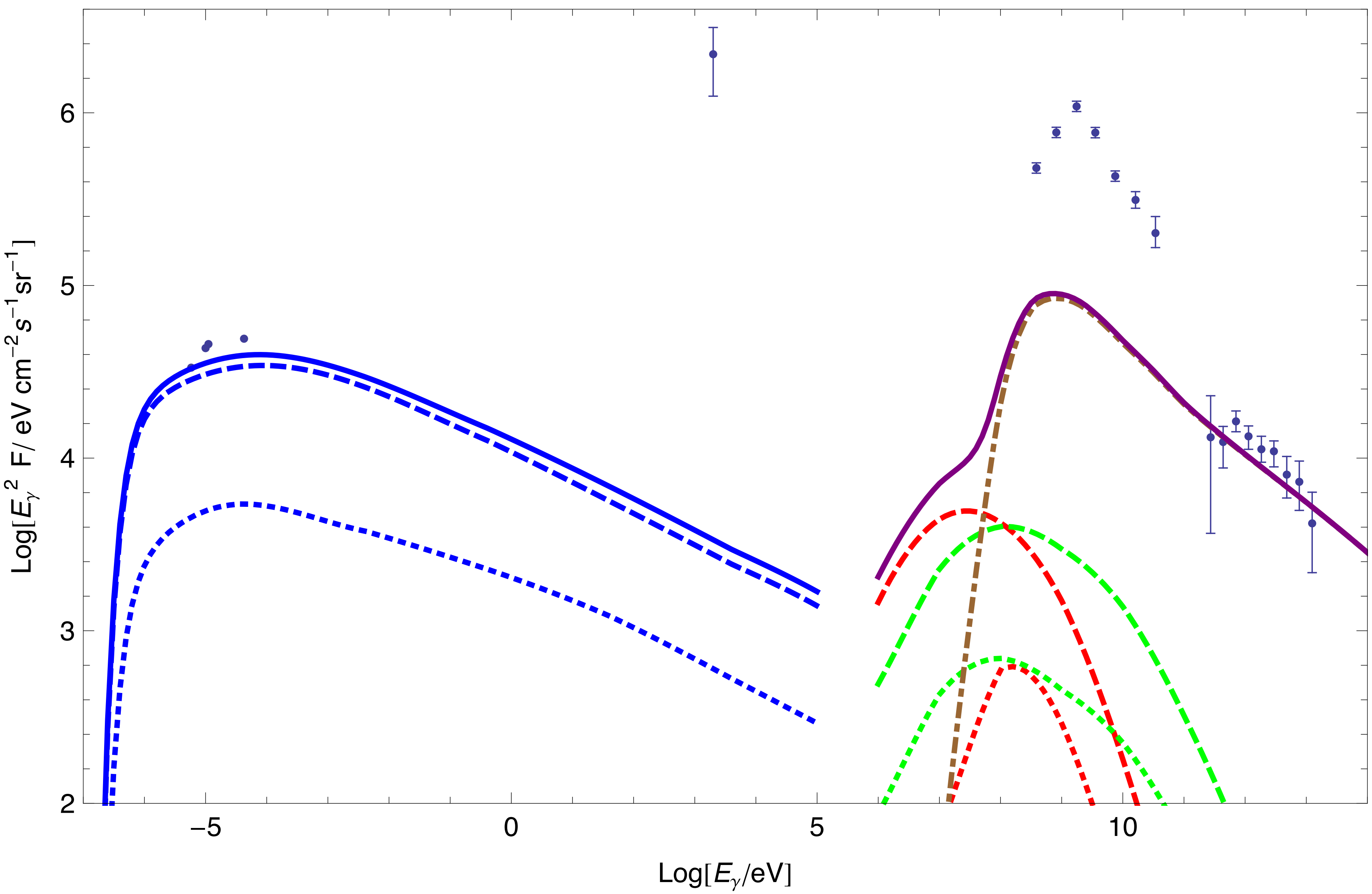



1 SN per ~2500 years

# Results of Modelling

- ‘Pure’ hadronic scenarios do not work
- ‘Pure’ leptonic scenarios do not work
- Get good fits for mixed models

# Best-fit broadband spectrum




dashed: primary electron emission

dotted: secondary electron (and positron) emission

solid: total emission

Emission processes are:

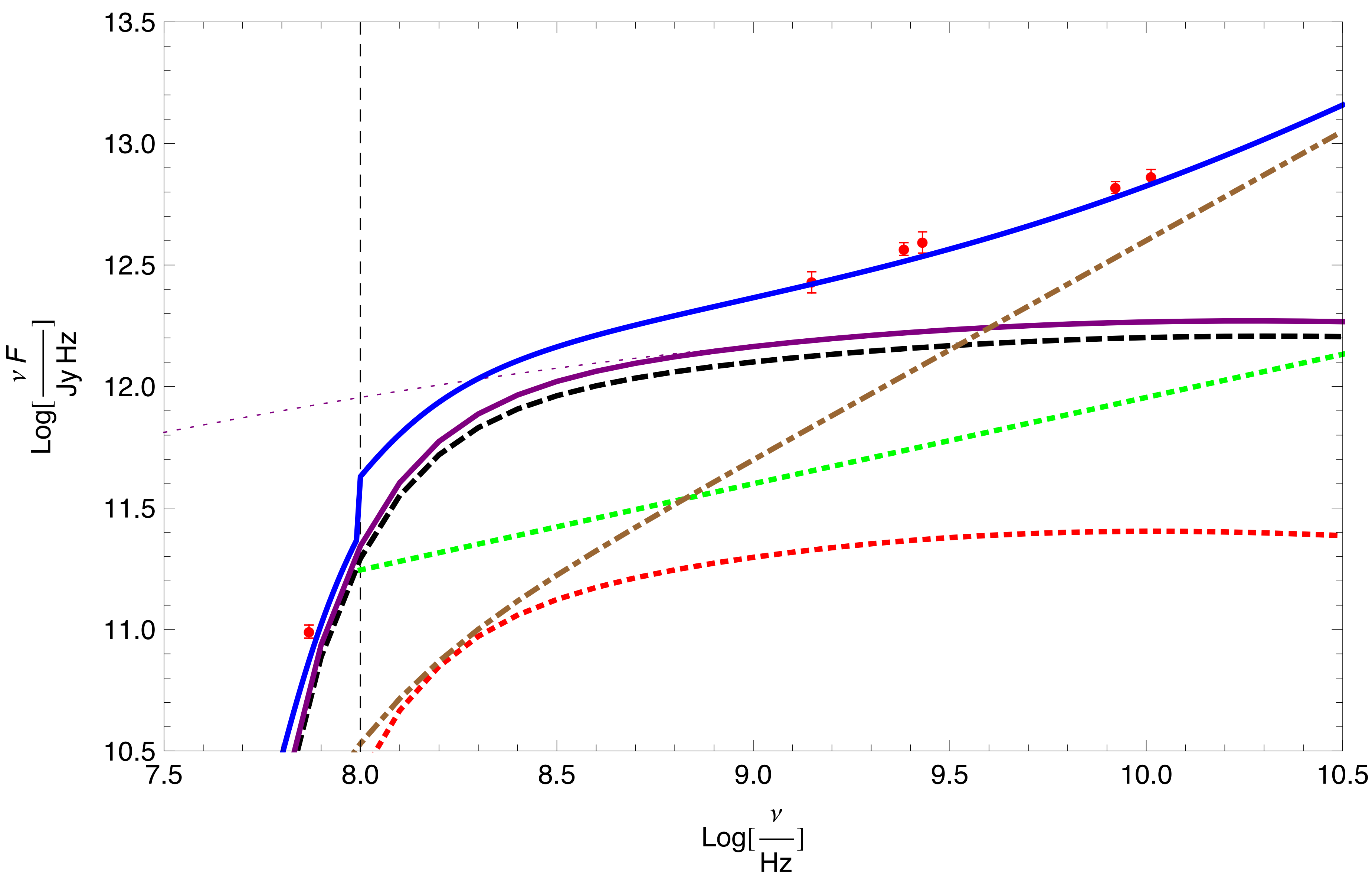
blue: synchrotron

red: bremsstrahlung

green: inverse Compton

brown, dot-dashed: neutral meson decay

# Best-fit radio spectrum




solid blue curve: total emission curve

solid, purple: total synchrotron

dotted, purple: total synchrotron in absence of free-free absorption

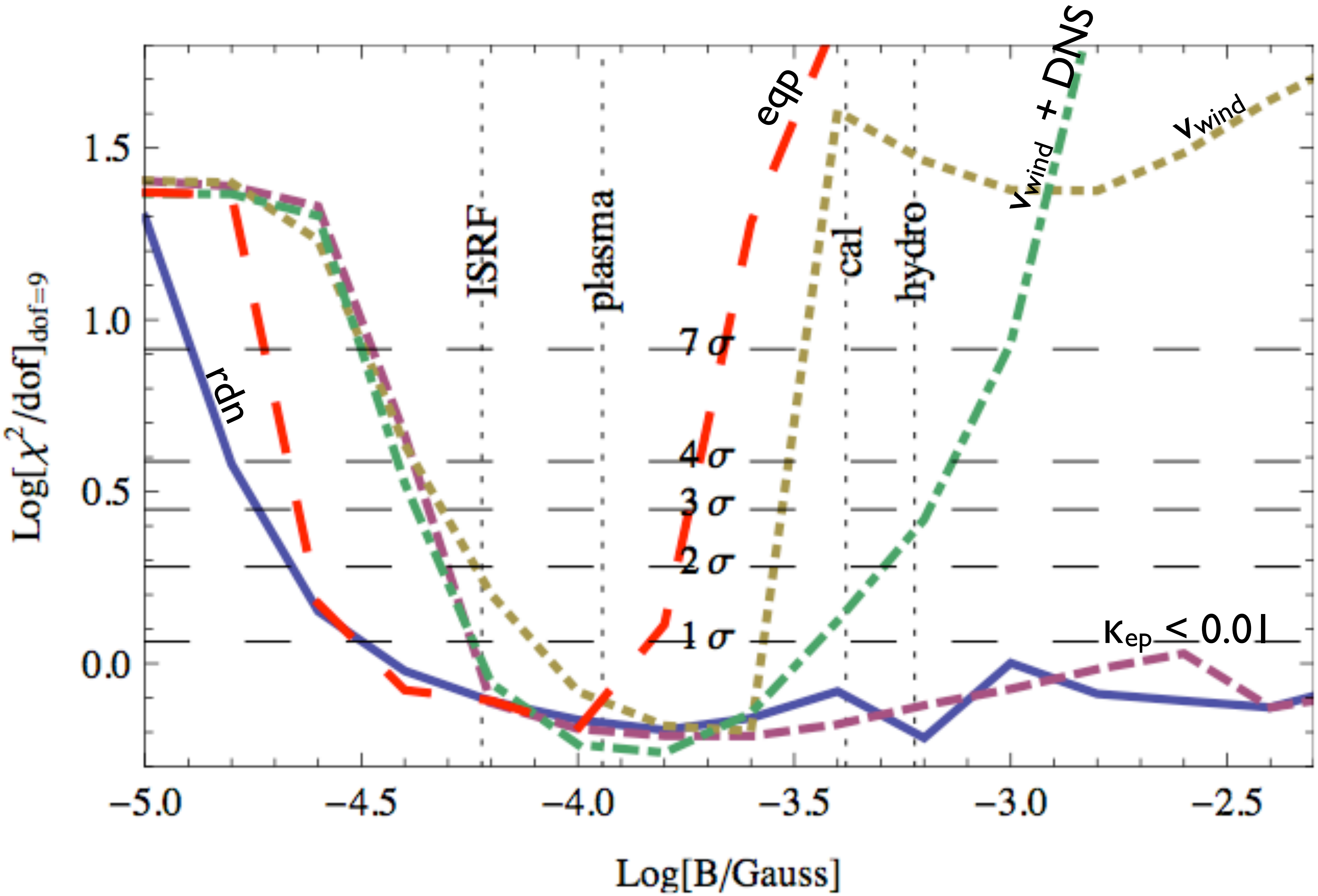
dashed, black: primary electron synchrotron

dotted, red: secondary electron synchrotron

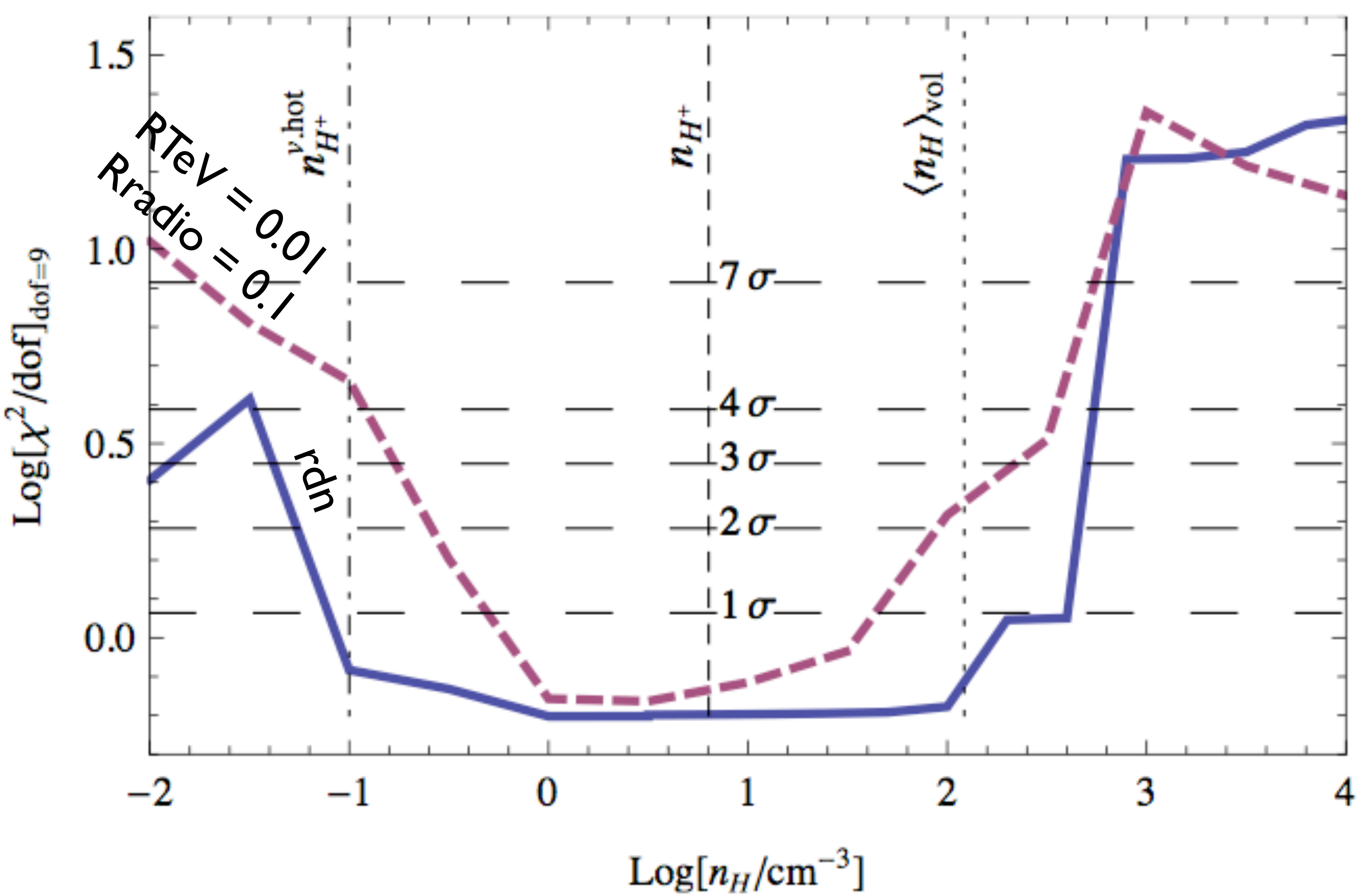
dotted, green: GSB

dot-dashed, brown: free-free emission.

# Magnetic field



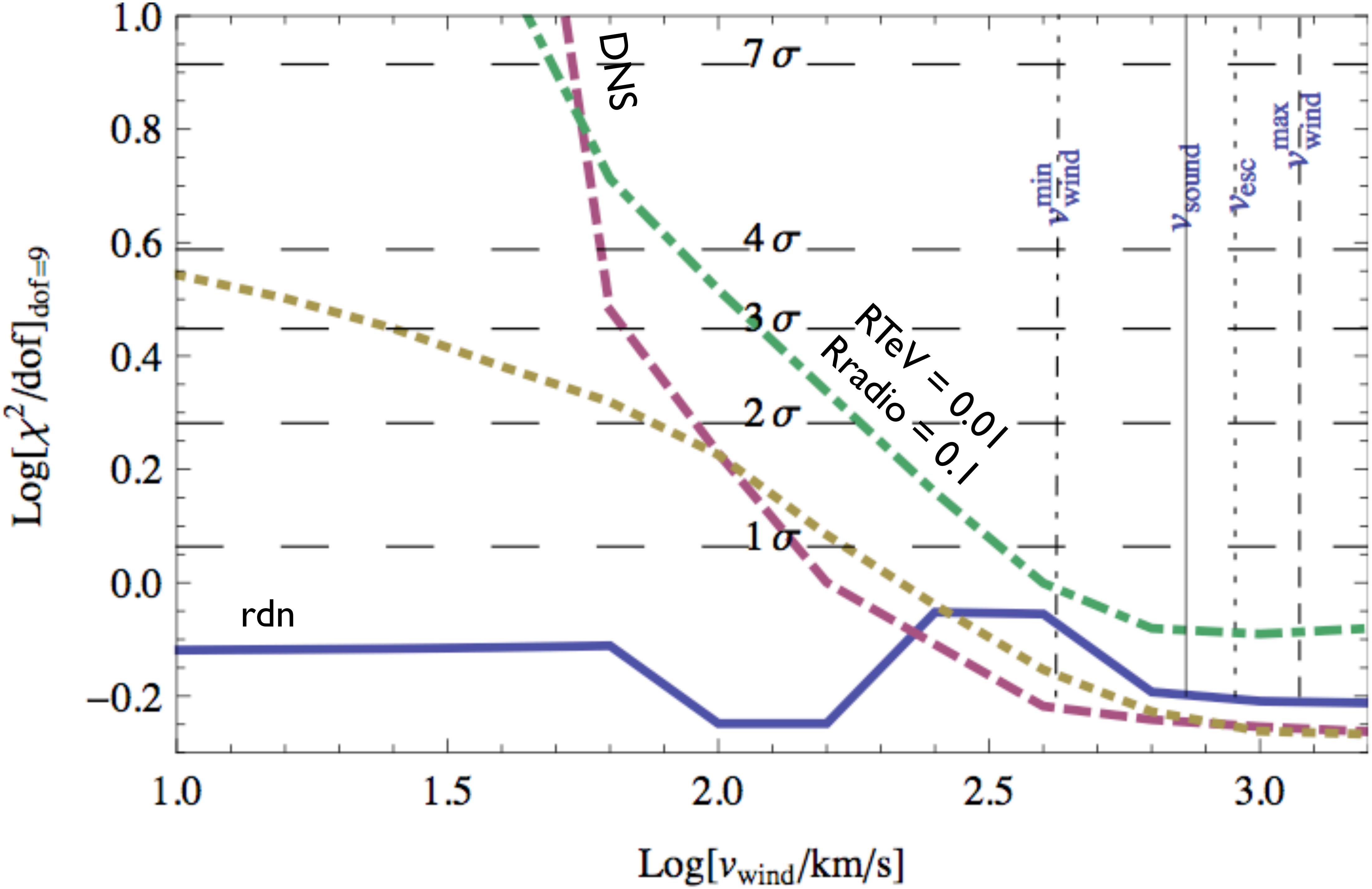
# Gas density




CRs do not penetrate into densest gas

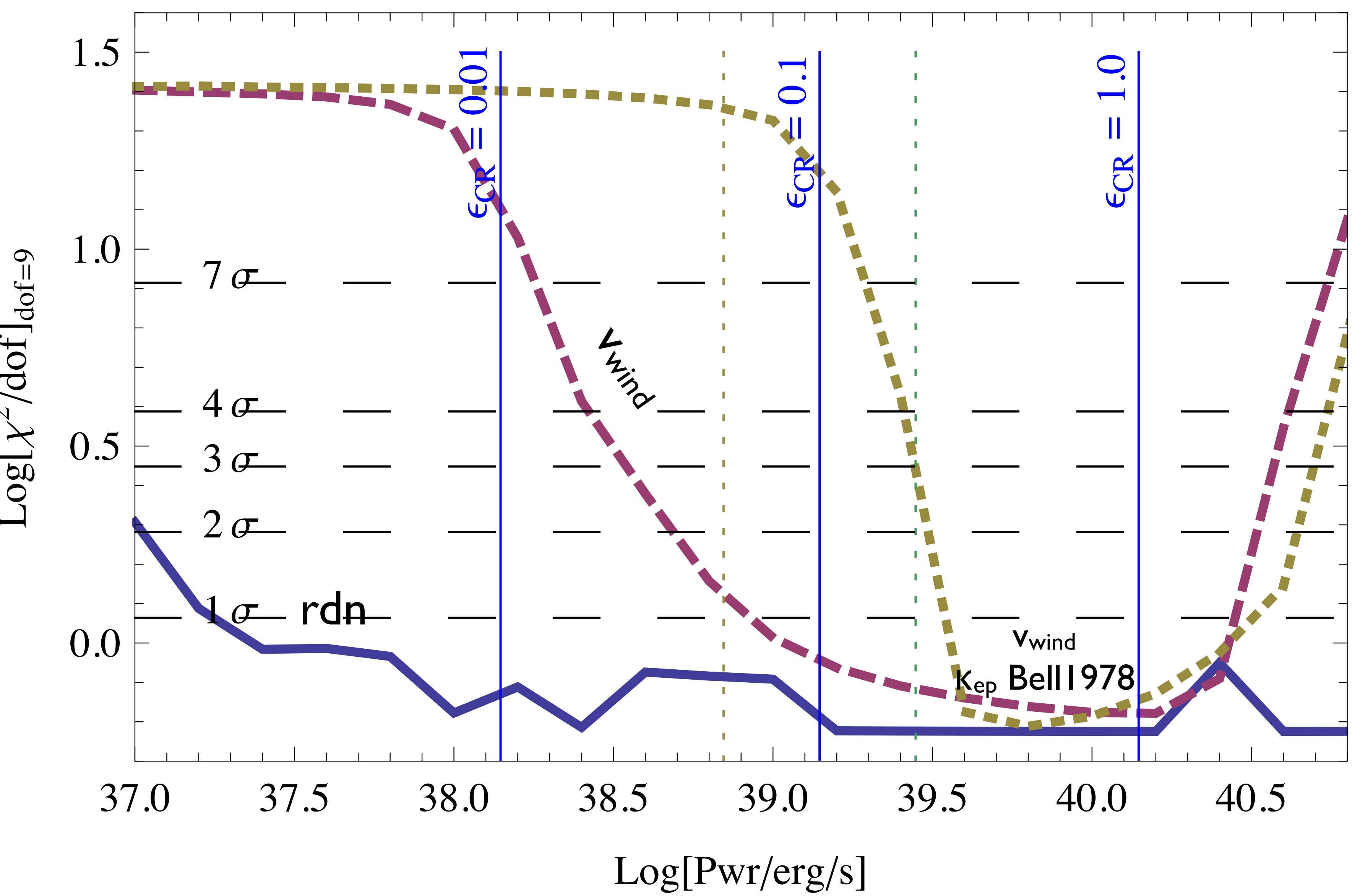
BUT they can heat/ionize the low-density (warm) H2

# Wind speed



DNS
7 σ
4 σ
3 σ
2 σ
1 σ
RTeV = 0.01
Rradio = 0.1
rdn
$v_{\rm wind}^{\rm min}$
$v_{\rm sound}$
$v_{\rm esc}$
$v_{\rm wind}^{\rm max}$
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
1.0
1.5
2.0
2.5
3.0
$\mathrm{Log}[\chi^2/\mathrm{dof}]_{\mathrm{dof}=9}$
$\mathrm{Log}[v_{\rm wind}/\mathrm{km/s}]$

# Non-thermal power




Self-consistent modelling confirms $\gtrsim 10^{39}$ erg/s *independent* of SN rate estimate

# 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?