Non-Thermal Radiation from the Inner Galaxy

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Mount Stromlo Observatory

THE AUSTRALIAN NATIONAL UNIVERSITY

Introduction

- In this talk: "Galactic center" (**GC**) = inner 300 pc (diameter) of Galactic plane
- GC sitting at bottom of Galactic gravitational potential

$\Rightarrow$ region of brightest radiative signature of

dark matter decay/annihilation

BUT...

Introduction

- In this talk: "Galactic center" (**GC**) = inner 300 pc (diameter) of Galactic plane
- GC sitting at bottom of Galactic gravitational potential

⇒ where the Galaxy's 4 million solar mass super-massive black hole (SMBH) lurks

⇒ where Galactic stellar density and star formation rate density reach a crescendo

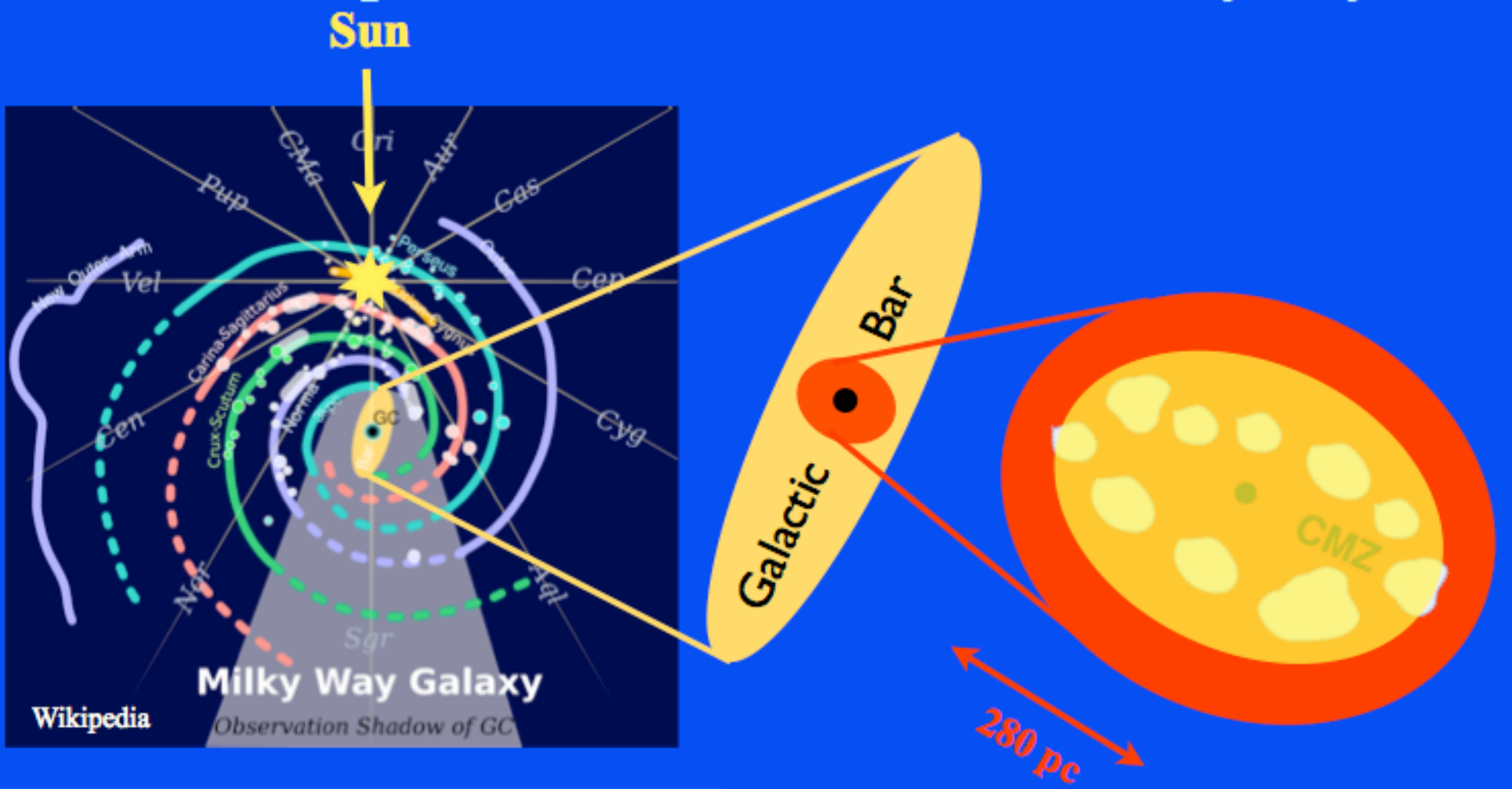
Something to keep in mind...

If we observe an exotic signal from the GC it may have something to do with, e.g., the SMBH, or the very high star formation rate density

To claim detection of a dark matter ***signal*** *we have to subtract off the astrophysical backgrounds. Given the unusual nature of the GC environment, it is very difficult to train our expectations for such backgrounds on the basis of observations elsewhere in the Galaxy.*


ESO

From spiral arms to the center of the Milky Way



Andrea Stolte

Our view of the GC

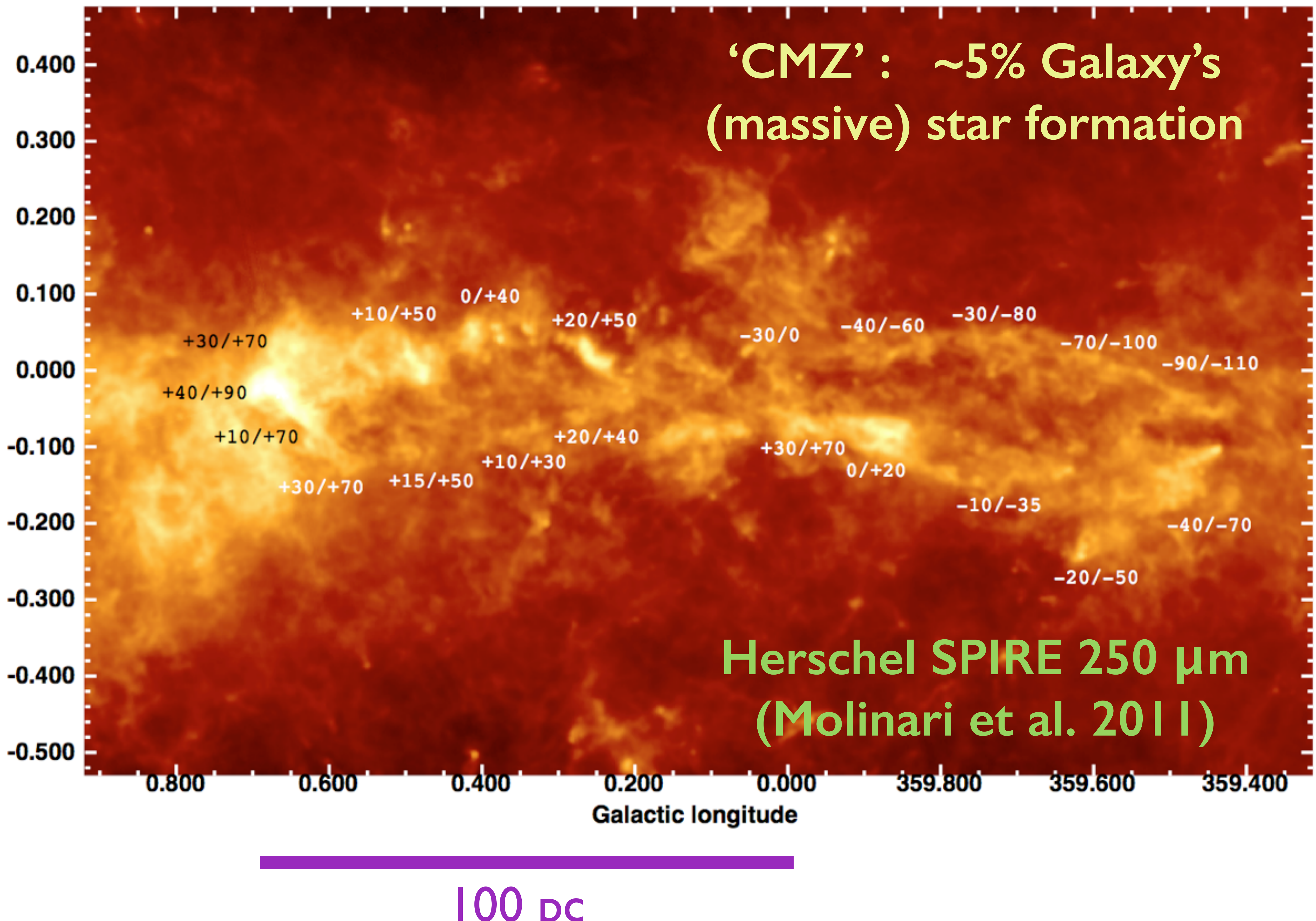
- Spectral windows: we can observe the GC at radio, sub-millimeter, infrared, X-ray and γ-ray wavelengths
- A lot of our information about the GC is from non-thermal emission
- With adaptive NIR optics can image individual massive stars in the Galactic centre

The GC is privileged...

- Any process that causes disk matter to lose angular momentum sends it inwards; *the GC is always accreting gas* (at some level)
- In particular, the non-axisymmetric bar potential torques gas inwards
- ~5% of the Galaxy's H_2 is located in the GC

Central Molecular Zone

- Much of the GC's H_2 is located in a ~30 million solar mass torus of gas
- The torus hosts on-going, intensive, localized star-formation
- This seems to be a small version of the nuclear star forming rings seen in other barred spiral galaxies
- GC hosts ~5-10% of Galaxy's *massive* star formation → important to Galactic star formation ecology


'CMZ' : ~5% Galaxy's
(massive) star formation
Herschel SPIRE 250 μm
(Molinari et al. 2011)
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359.800
359.600
359.400
Galactic longitude
+30/+70
+40/+90
+10/+70
+30/+70
+10/+50
0/+40
+15/+50
+10/+30
+20/+50
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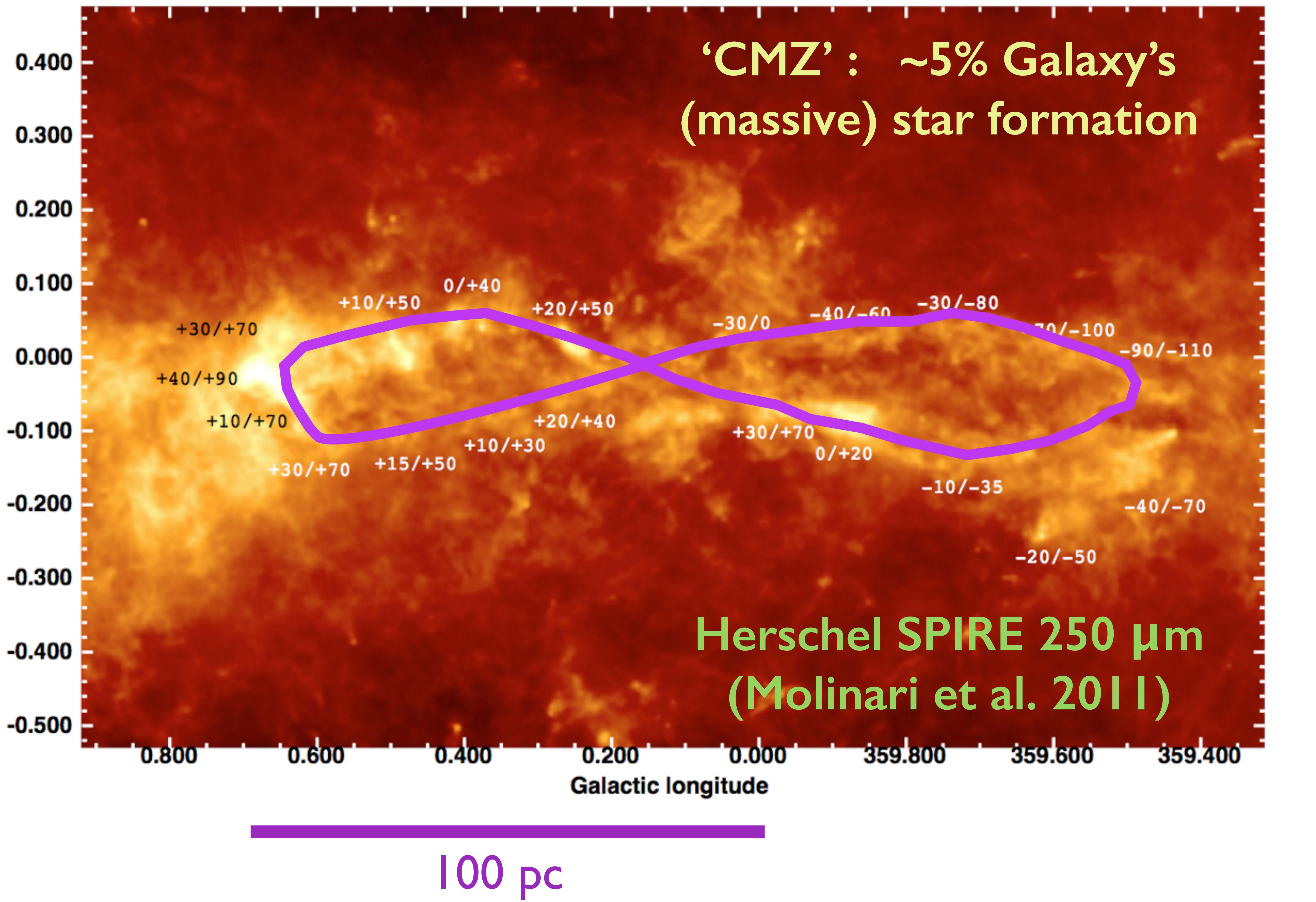
100 pc



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-30/-80
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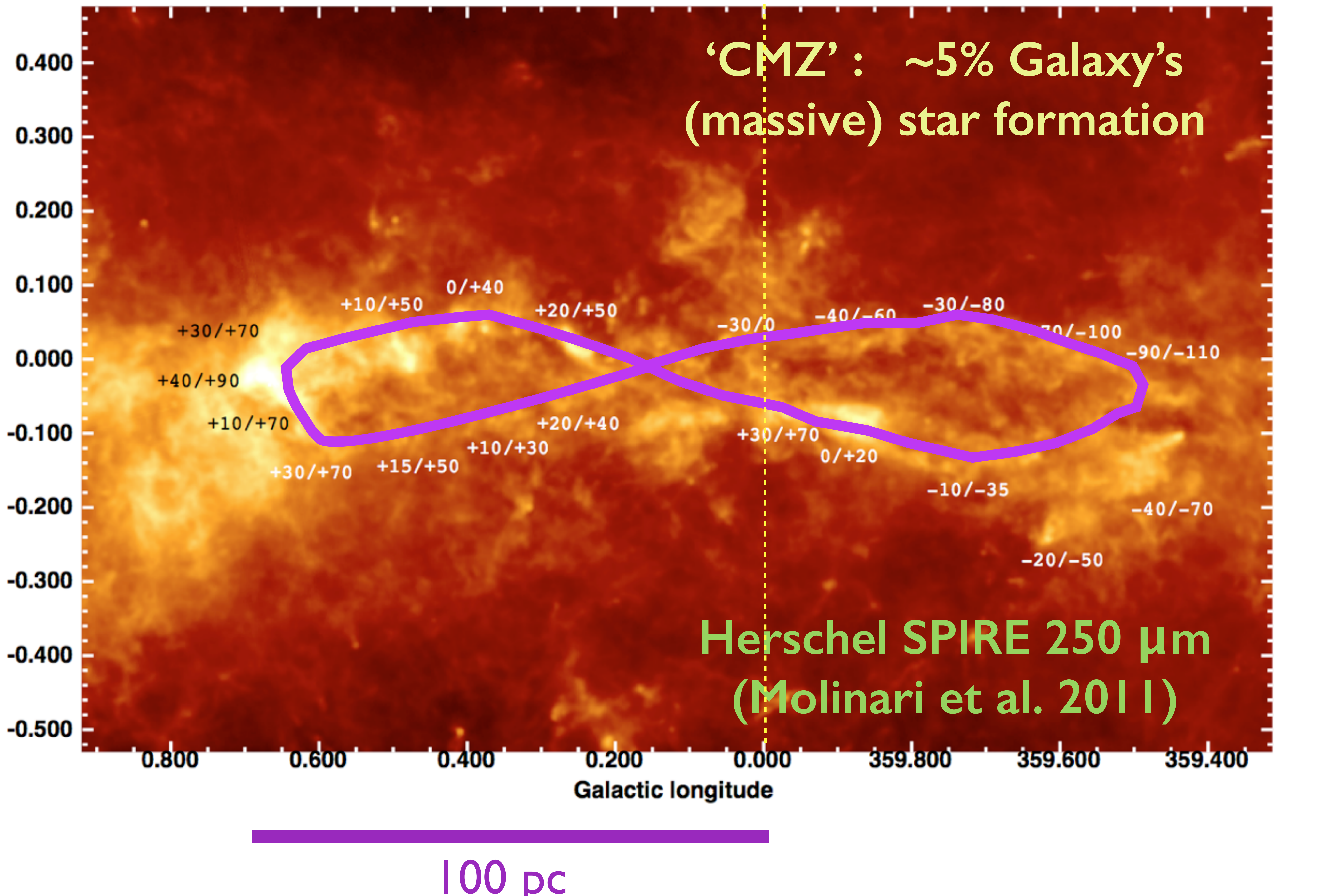
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-30/-80
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0.200
0.000
359.800
359.600
359.400
Galactic longitude
100 pc

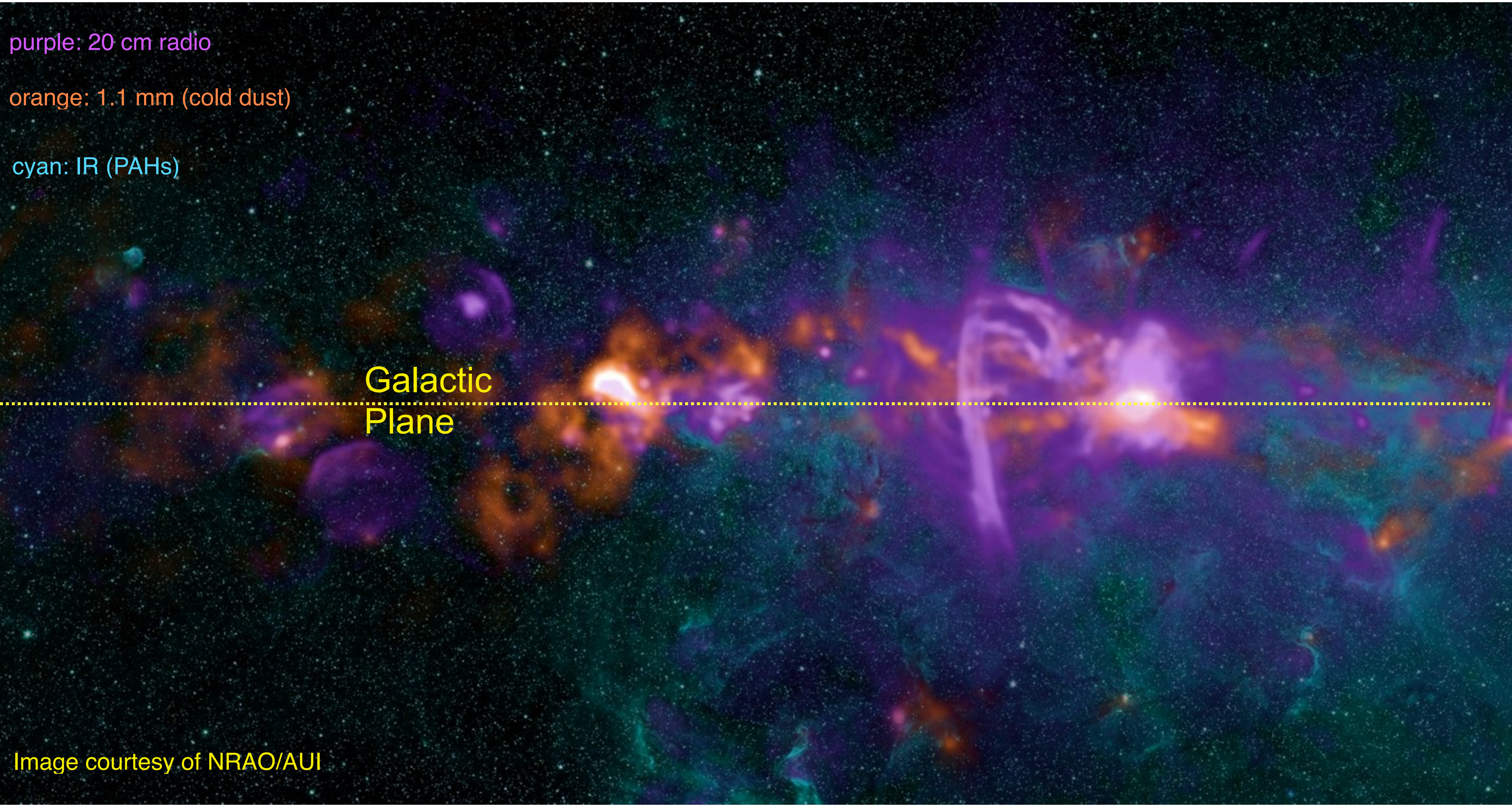
An Extreme ISM in GC...

- SFR surface density over CMZ ≳ **3 orders of magnitude** larger than mean in disk ($\partial_t \Sigma_* \sim 2\ M_\odot\ yr^{-1}\ kpc^{-2}$) and ***sustained***
- The SF activity (stellar winds, supernovae) sustains an energy density in the different GC Interstellar Medium (ISM) phases about **2 orders of magnitude** larger than typically found in the local ISM

GC: $U_B \sim U_{turb} \sim U_{plasma} \sim U_{ISRF} \sim 100\ eV\ cm^{-3}$

local: $U_B \sim U_{turb} \sim U_{plasma} \sim U_{ISRF} \sim 1\ eV\ cm^{-3}$

The region is complicated



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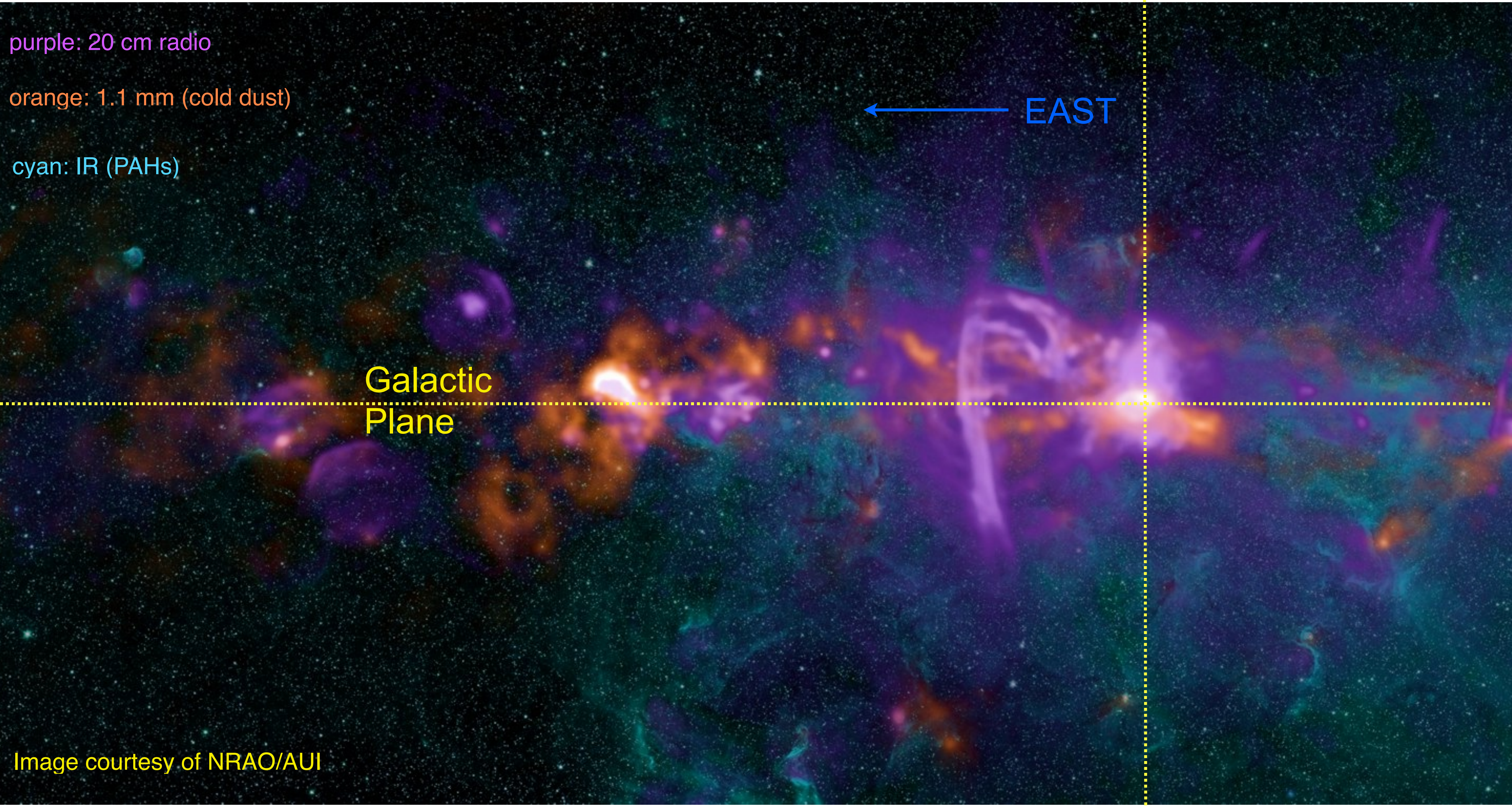

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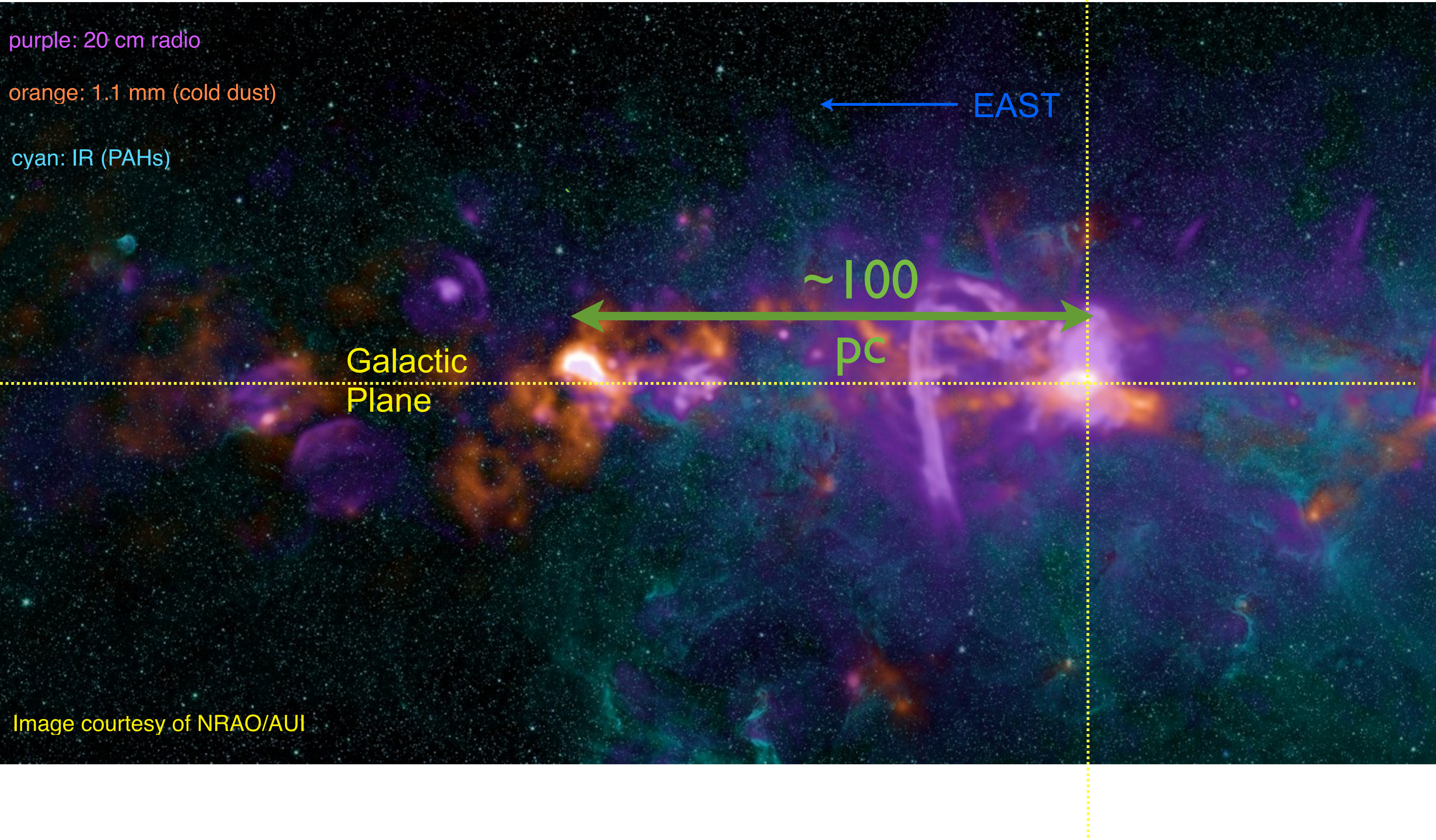
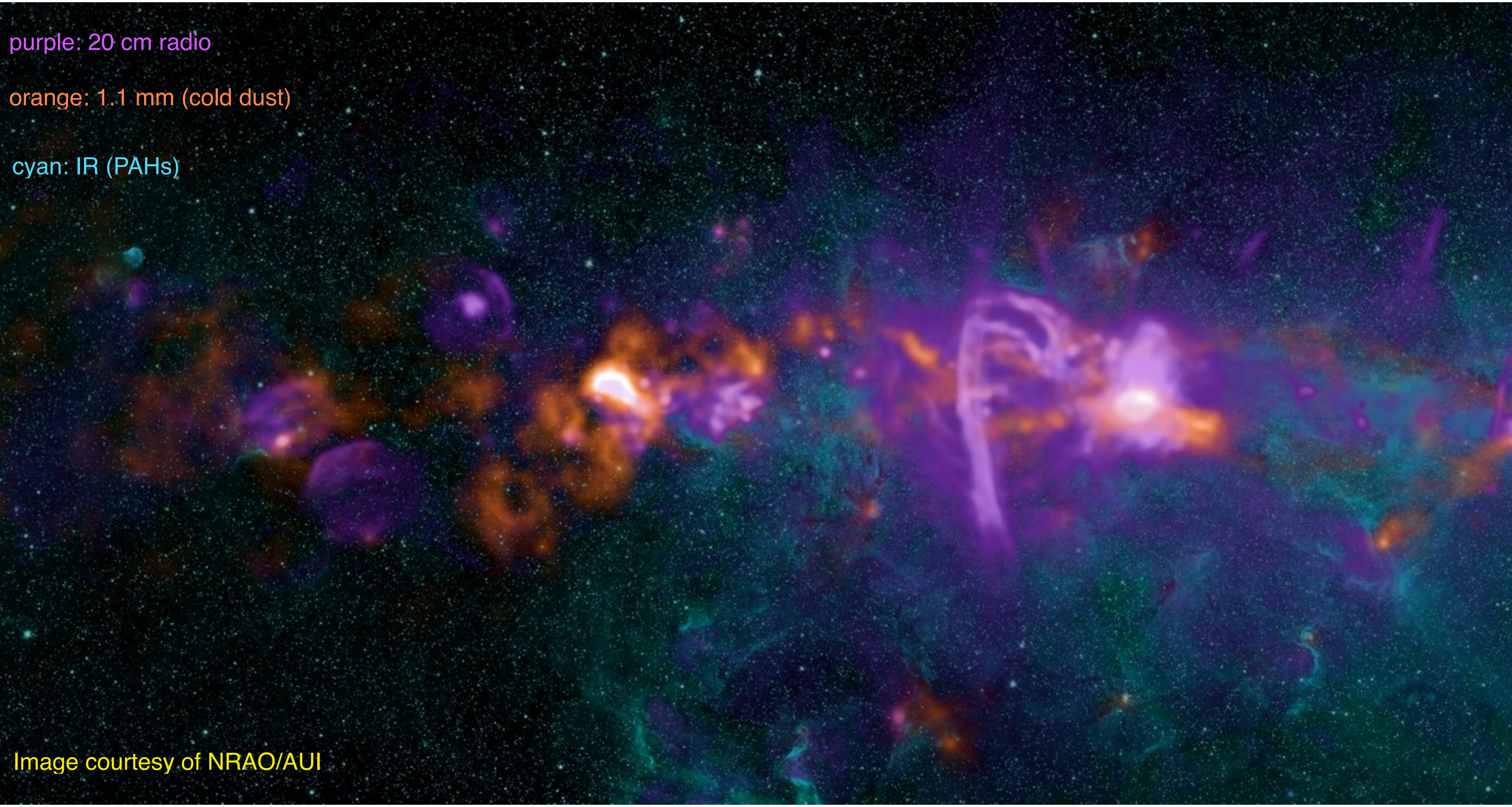
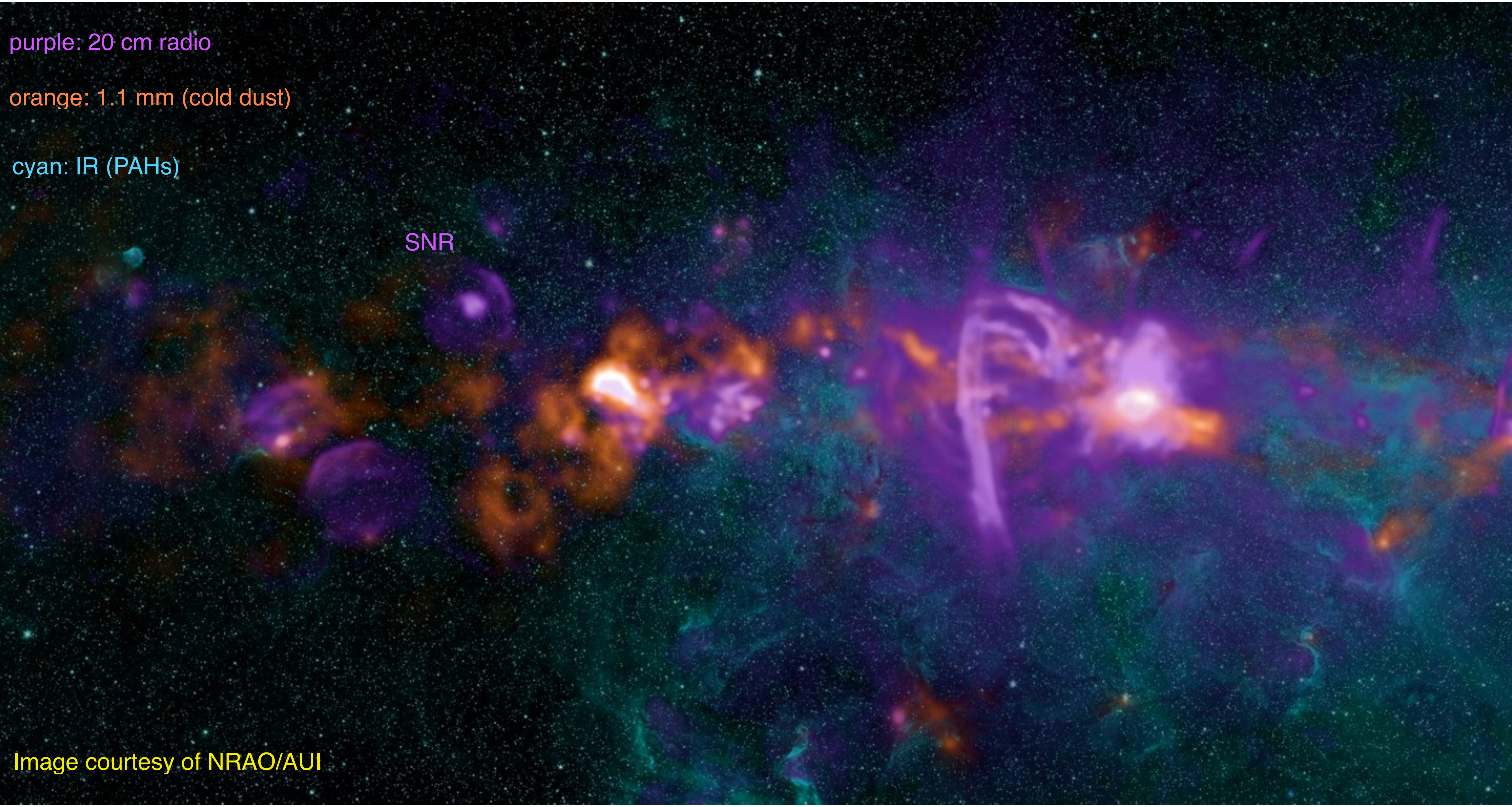



purple: 20 cm radio
orange: 1.1 mm (cold dust)
cyan: IR (PAHs)
Image courtesy of NRAO/AUI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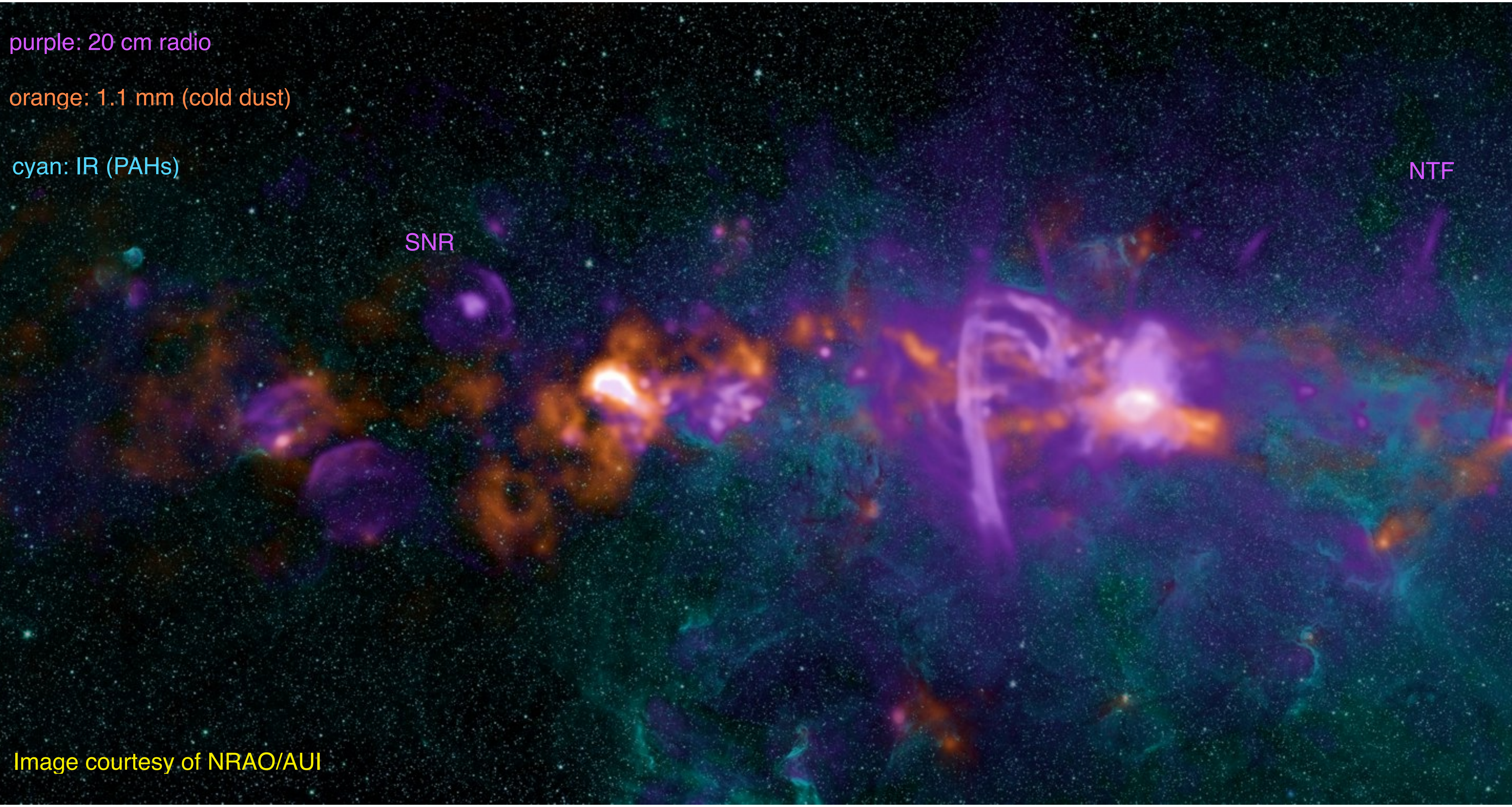
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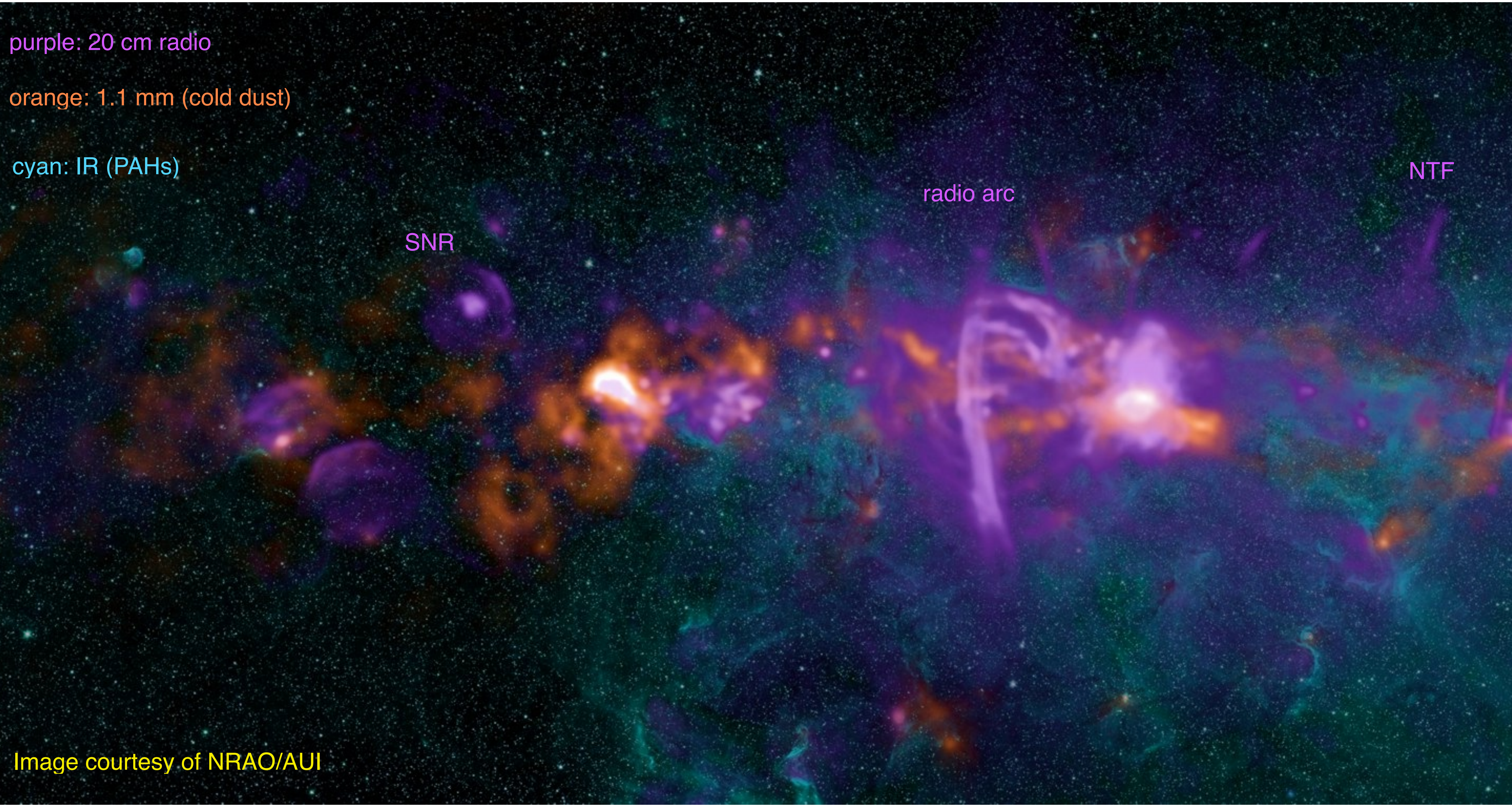
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SNR
radio arc
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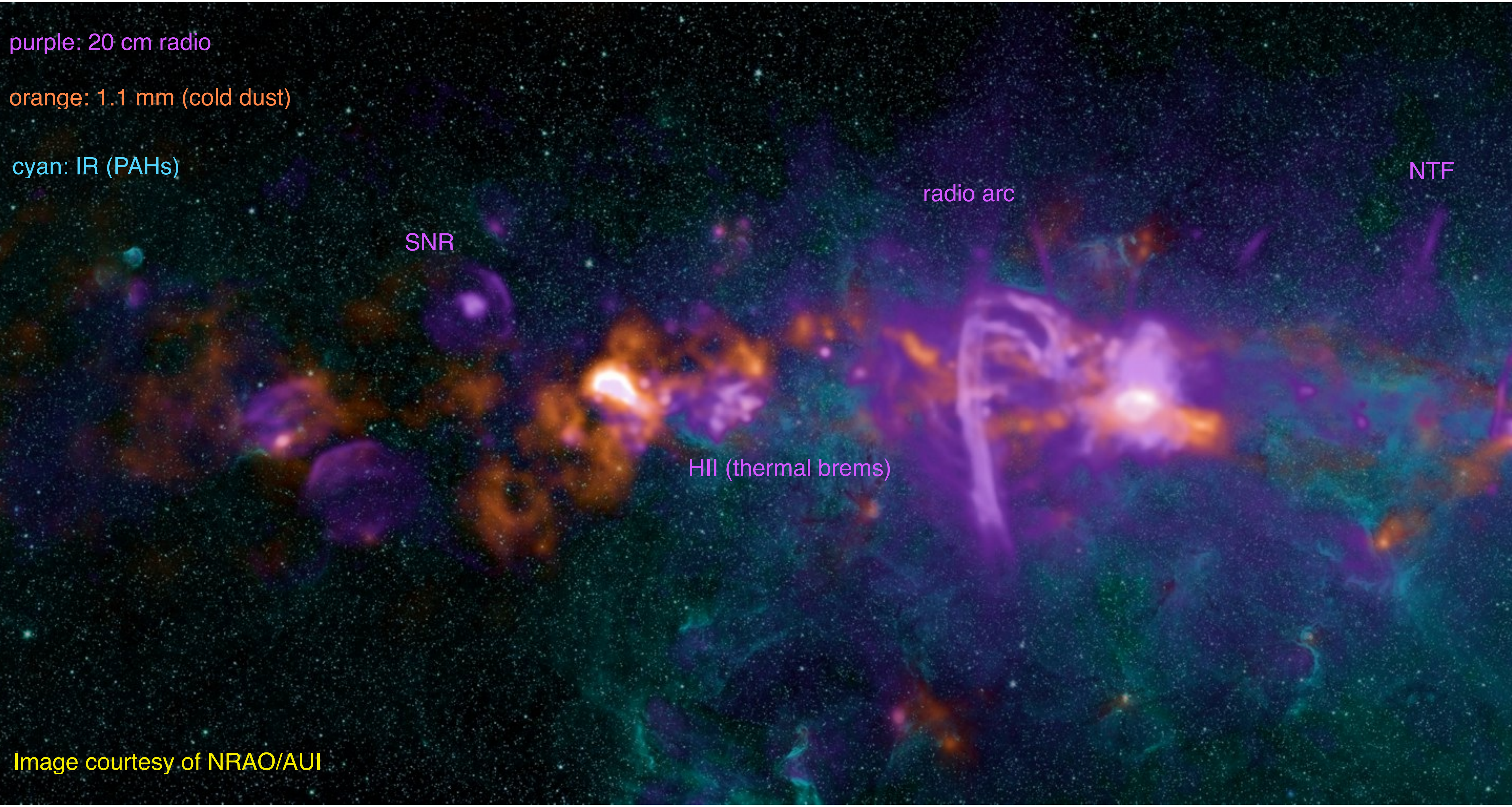
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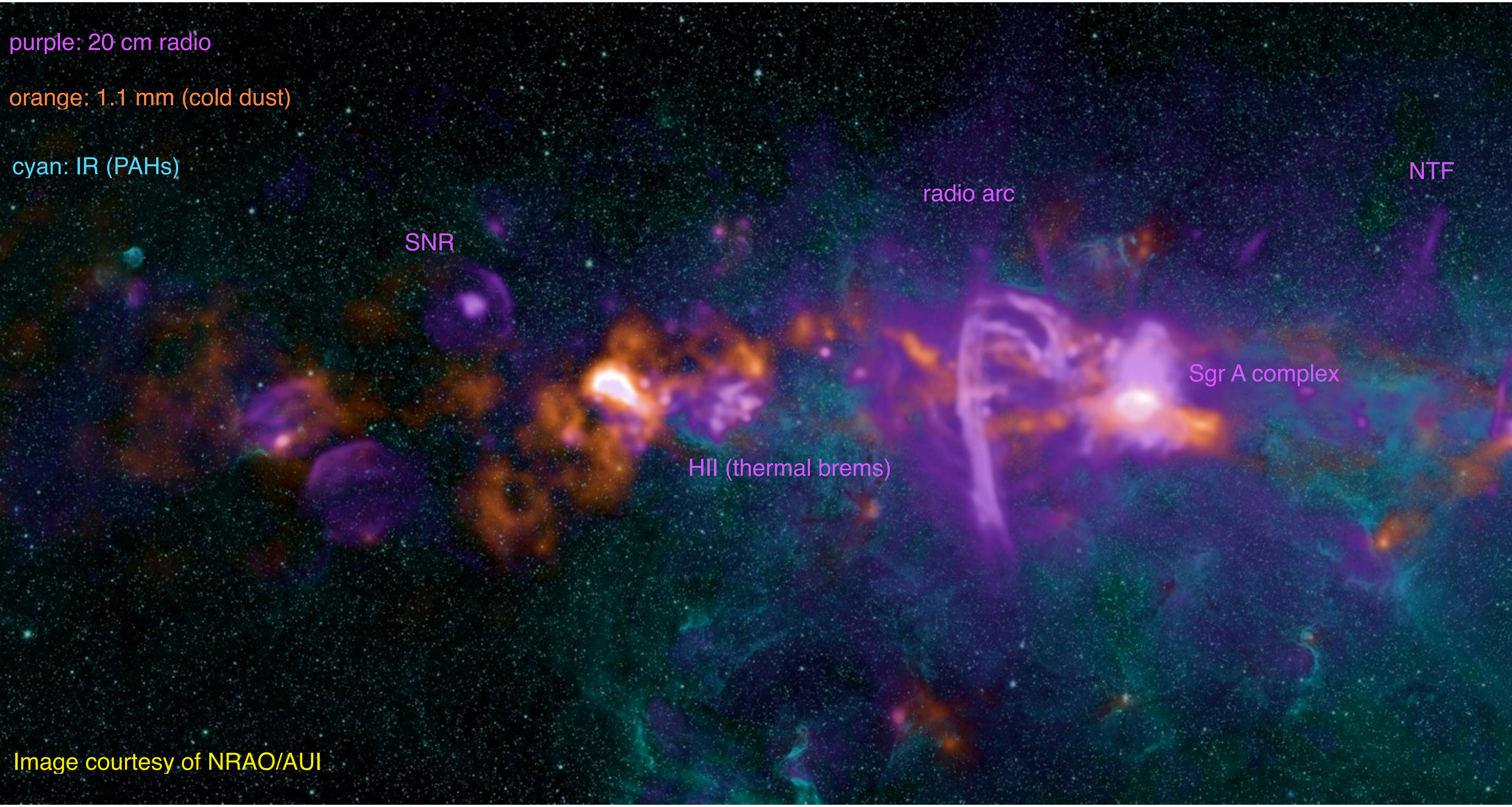
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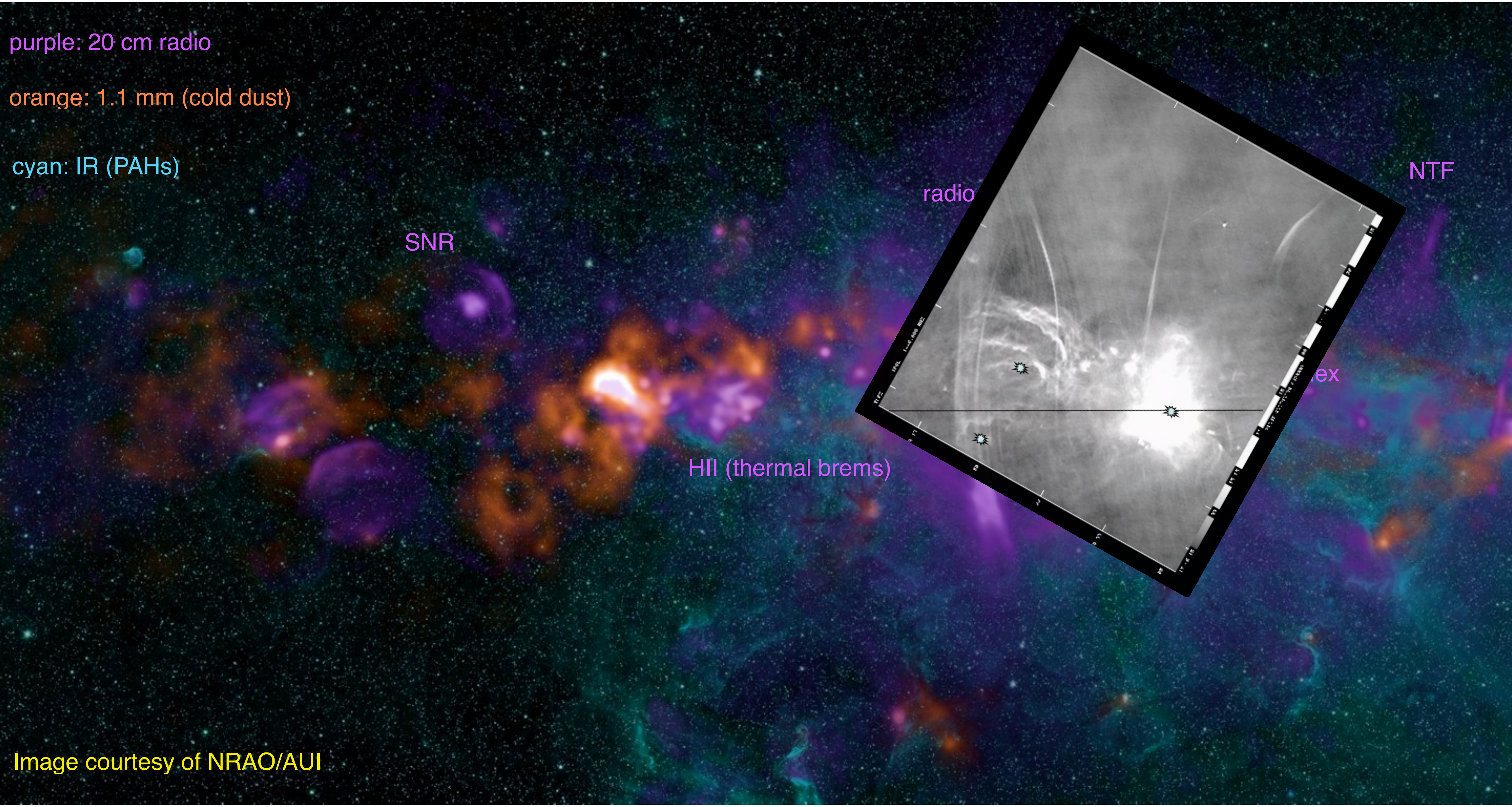
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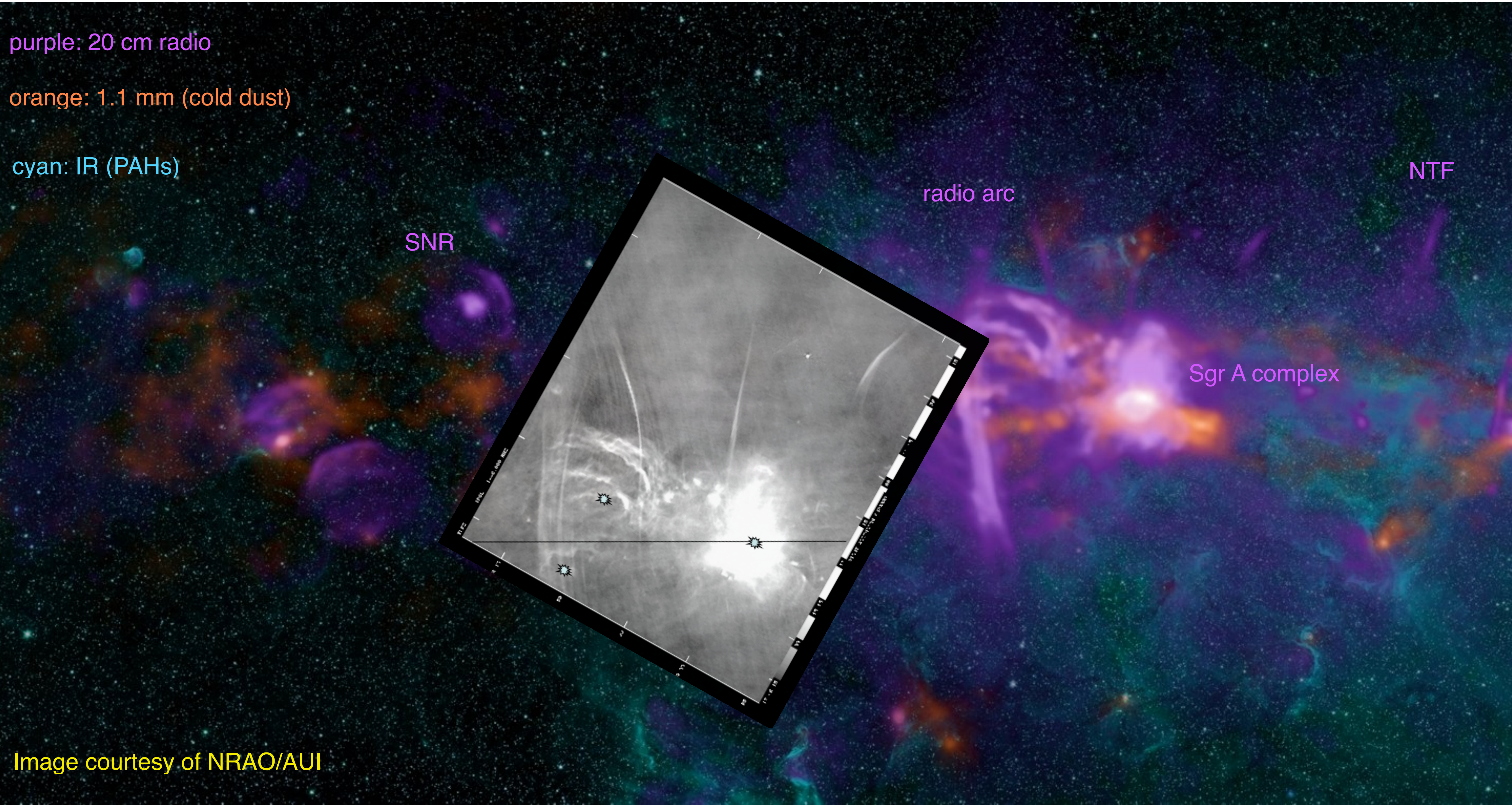

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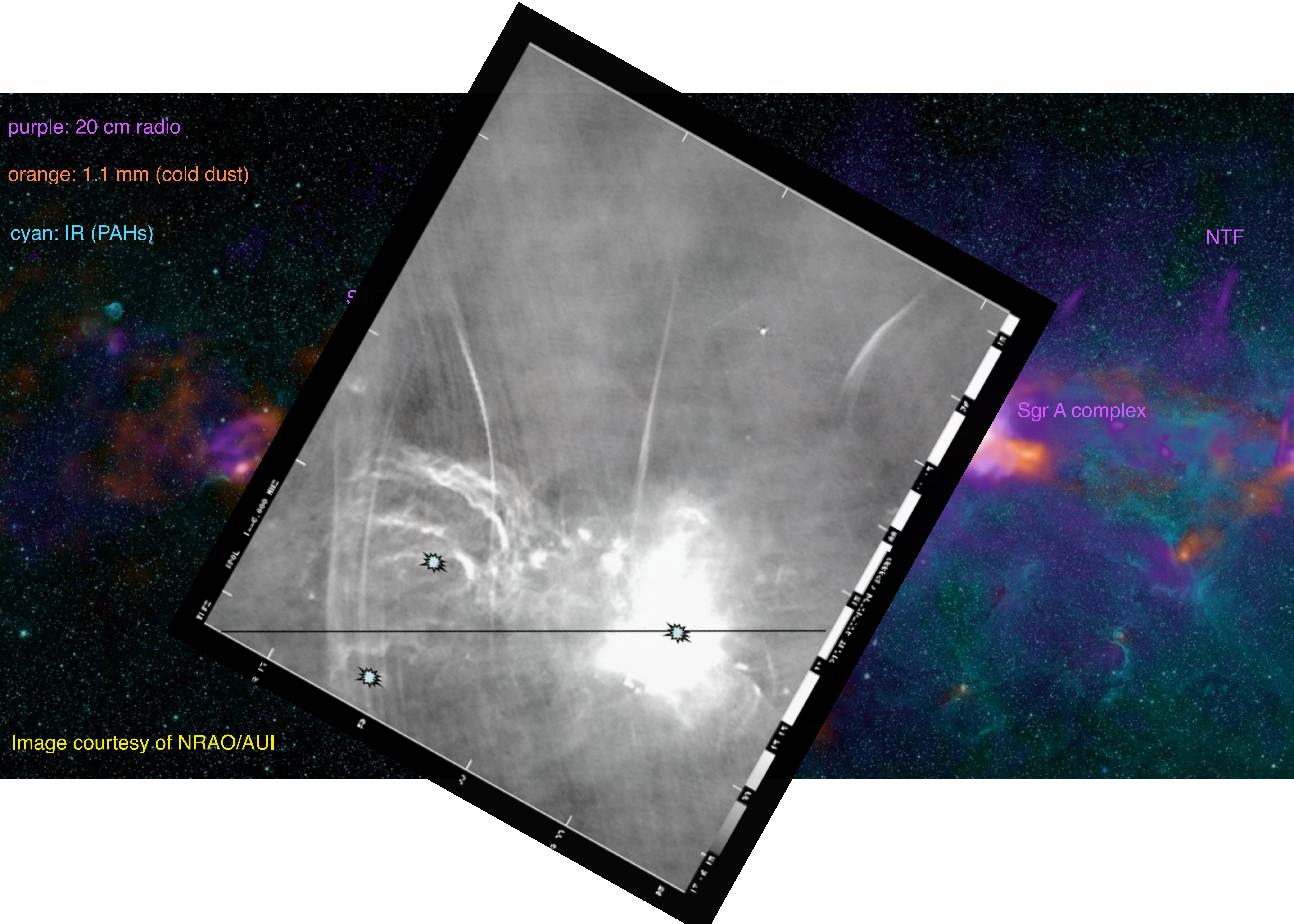

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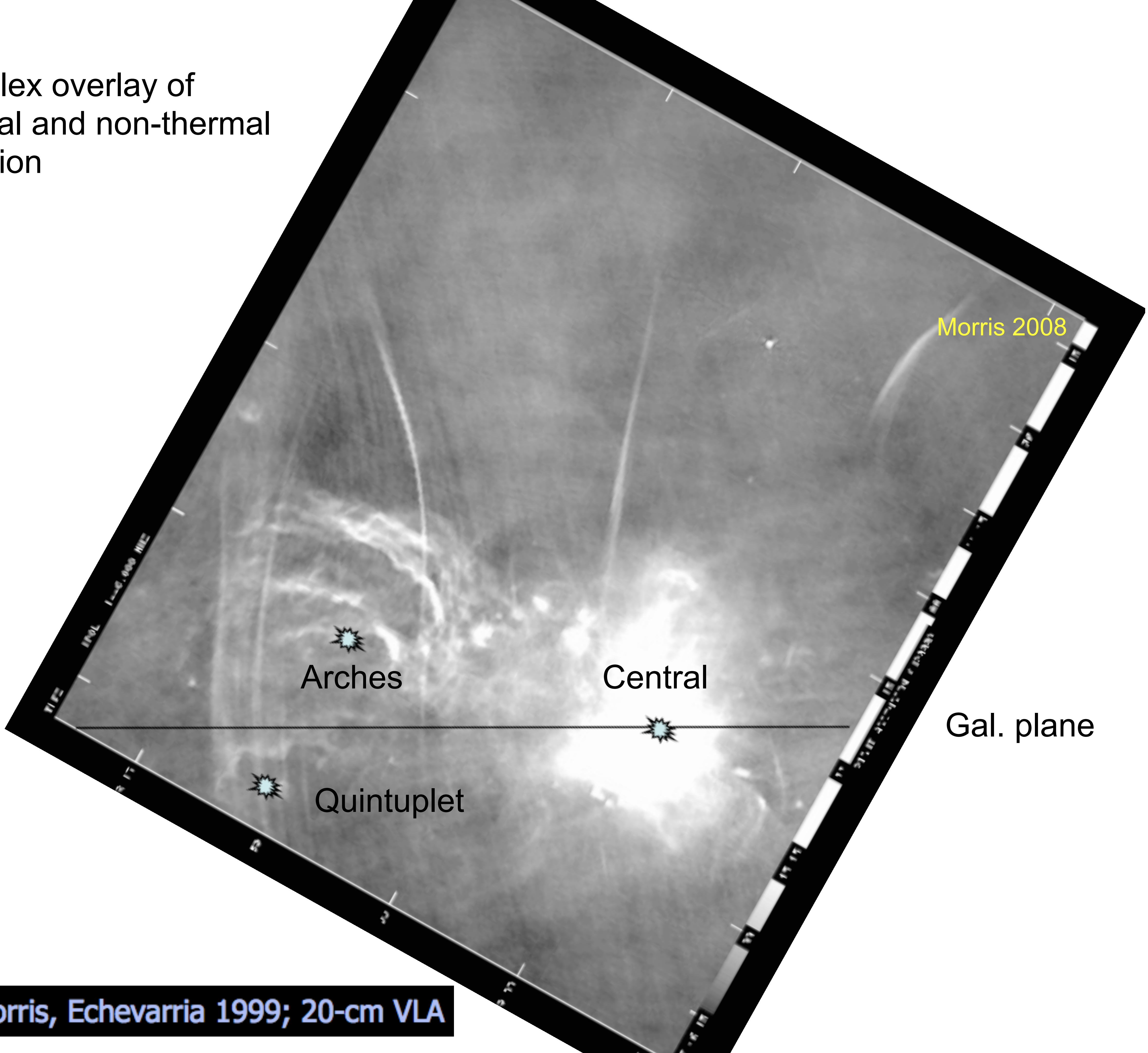
Complex overlay of thermal and non-thermal emission



Lang, Morris, Echevarria 1999; 20-cm VLA

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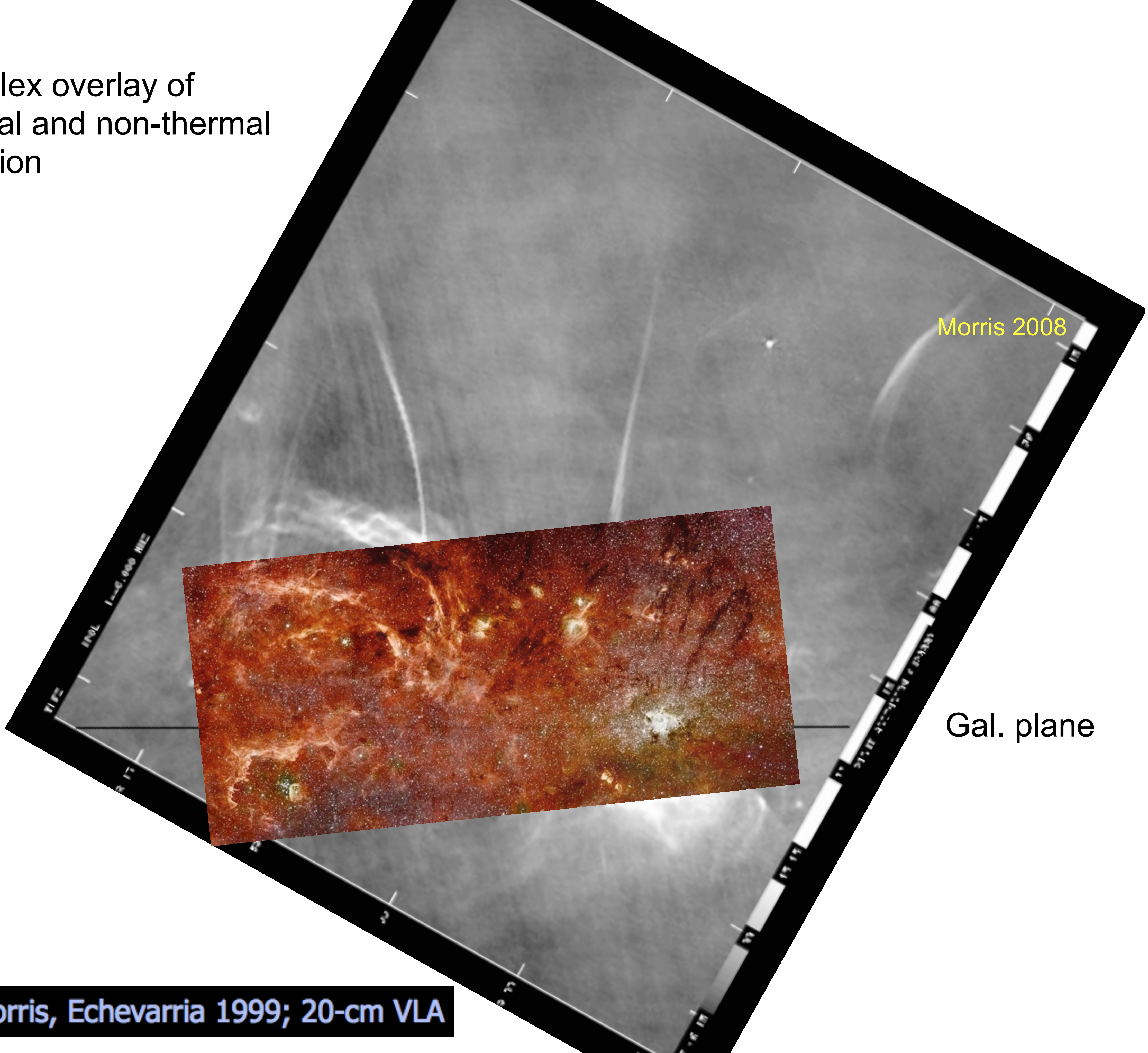

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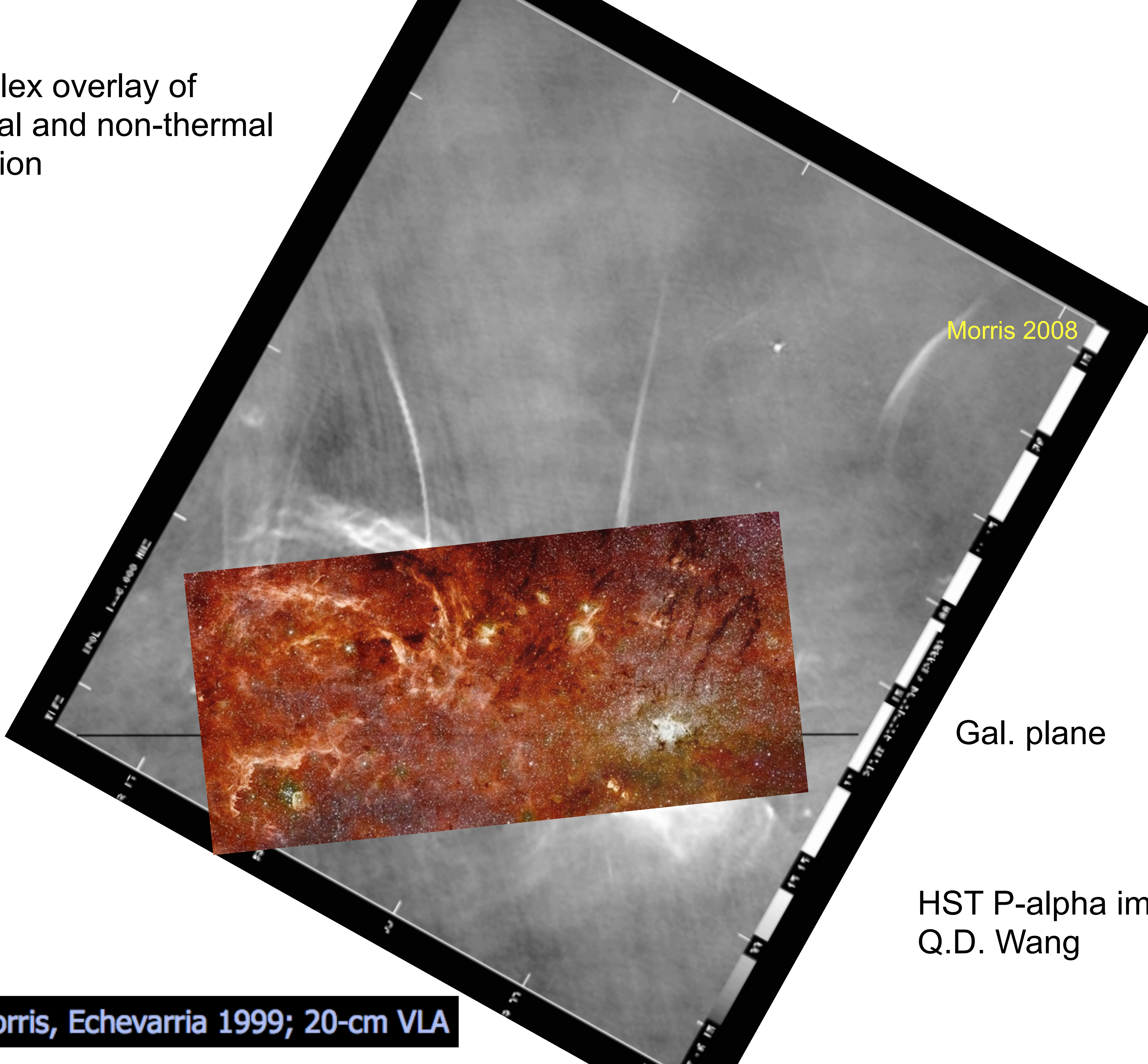

Gal. plane

HST P-alpha image by Q.D. Wang

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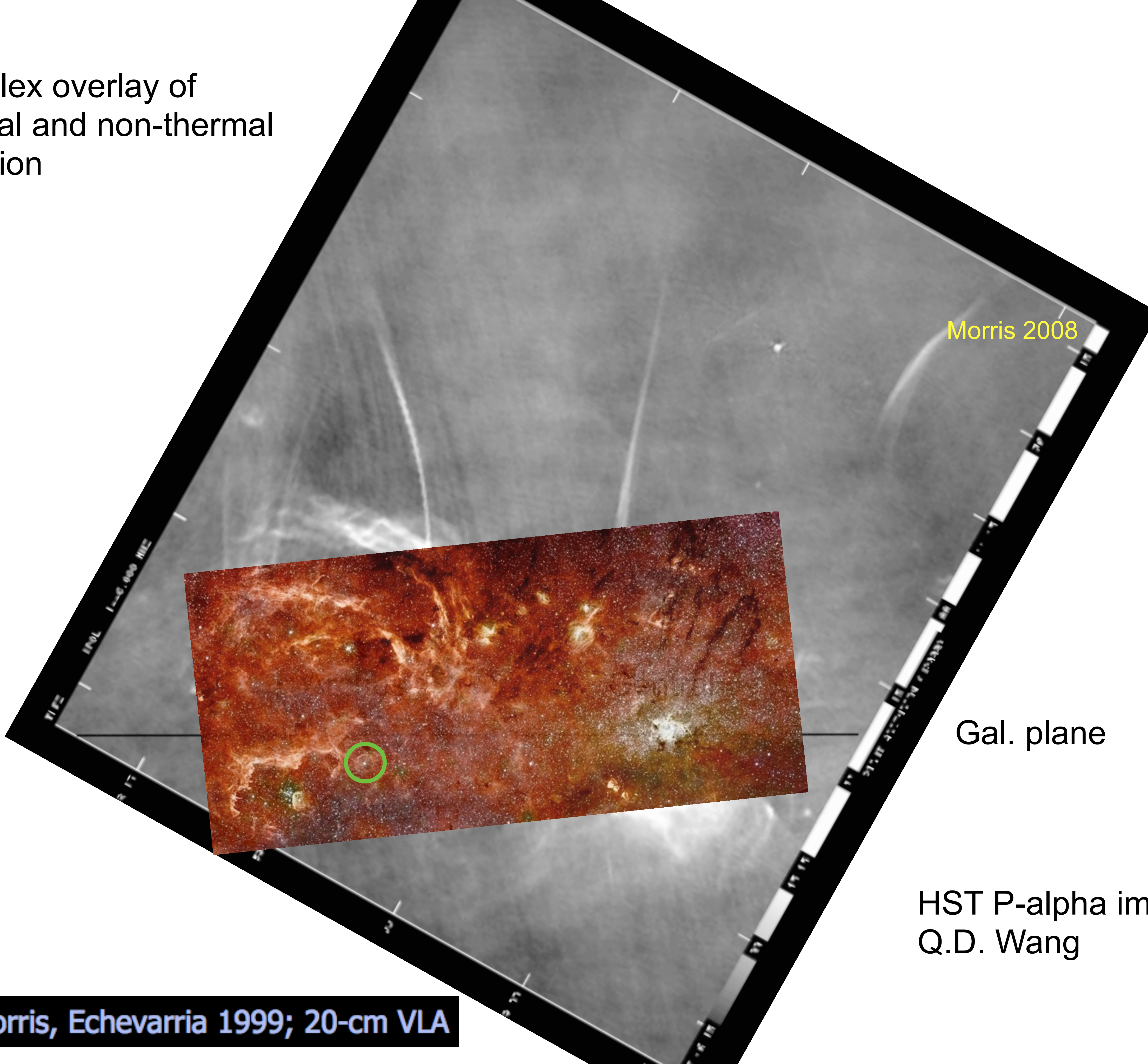

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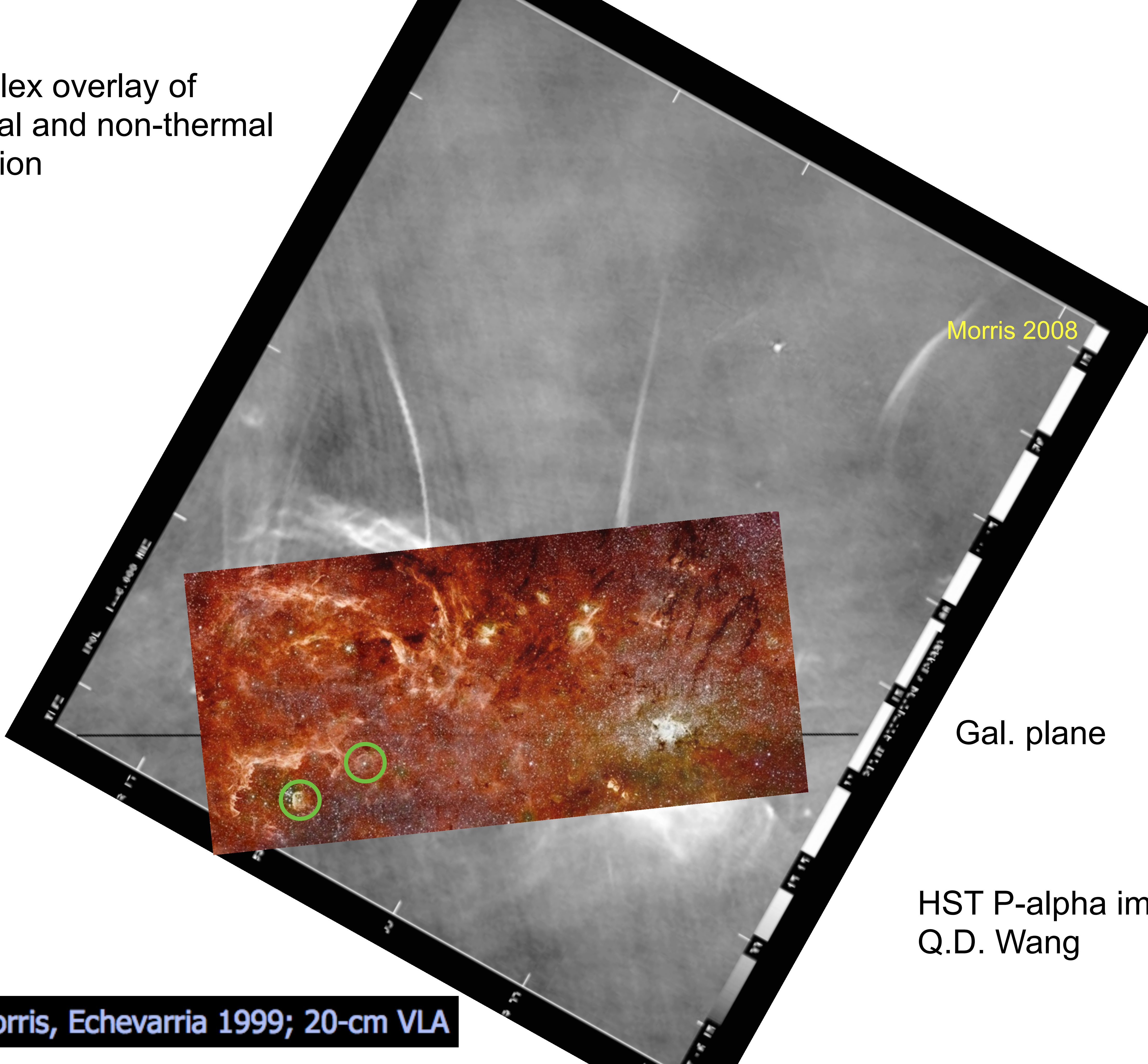

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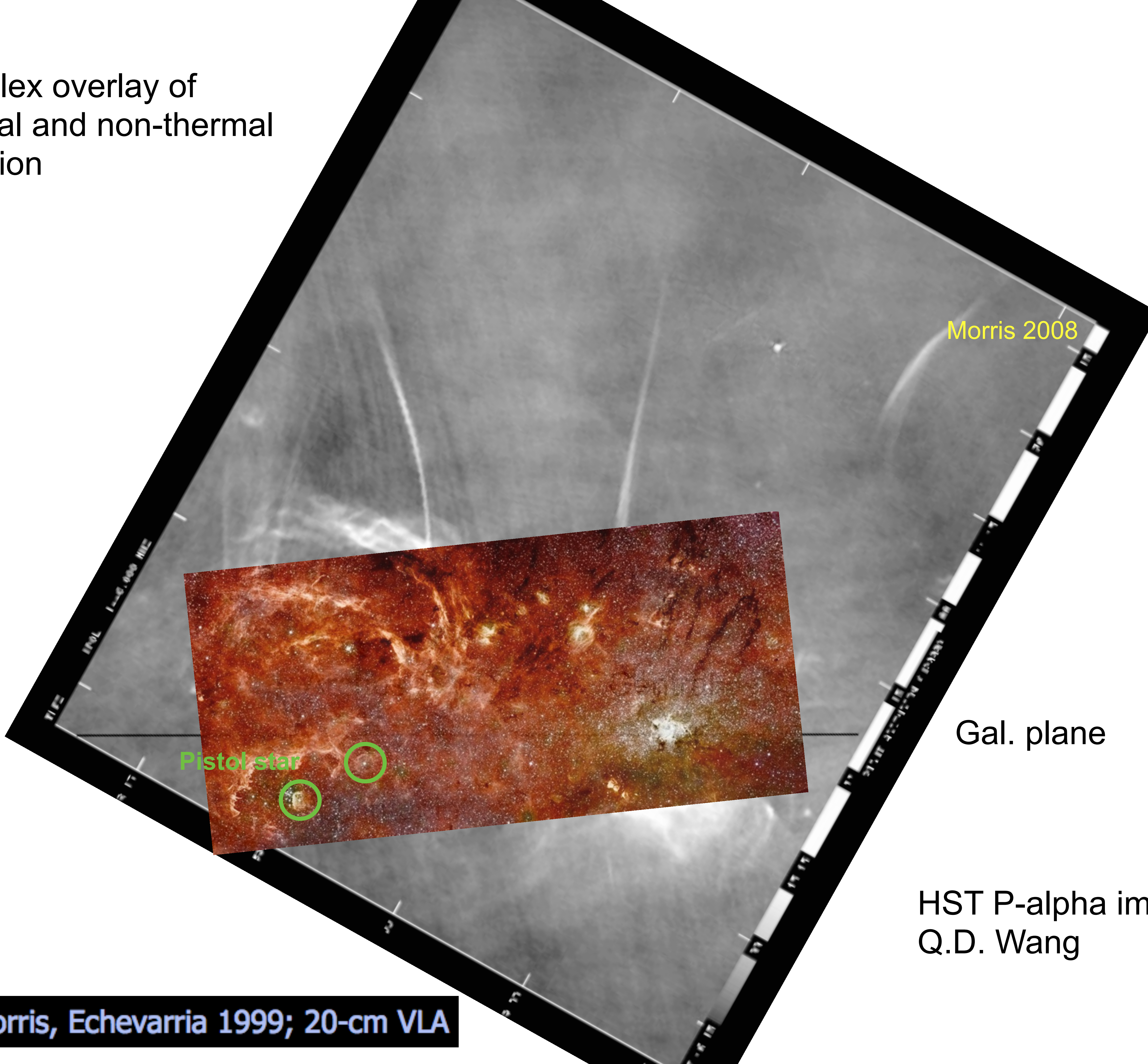

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Exotic/Remarkable Non-Thermal Phenomena of the GC/Inner Galaxy:

- (Quasi) point-like GeV and TeV γ-ray source coincident with Sgr A* (= radio source coincident with SMBH)
- Extended (few degrees) GeV & TeV emission
- Non-Thermal Radio (and X-ray) Filaments (NTFs)
- 130 GeV 'line'
- Few GeV γ-ray spectral bump
- 511 keV positron annihilation line
- Non-thermal microwave 'haze'
- Fermi Bubbles

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Every one of these has been claimed as a possible dark matter signature

Energetics

- The (photon) Eddington luminosity of Sgr A* (4×10^6 M_{Sun}): 5×10^{44} erg/s

- Socrates (2008) extended the momentum balance argument for L_{Edd} to derive an 'Eddington limit in cosmic rays': $L_{Edd}^{CR} \sim 10^{-6}\ L_{Edd} \Rightarrow 5 \times 10^{38}$ erg/s for Sgr A*

- Star formation in the CMZ at a rate ~0.1 M_{Sun}/yr

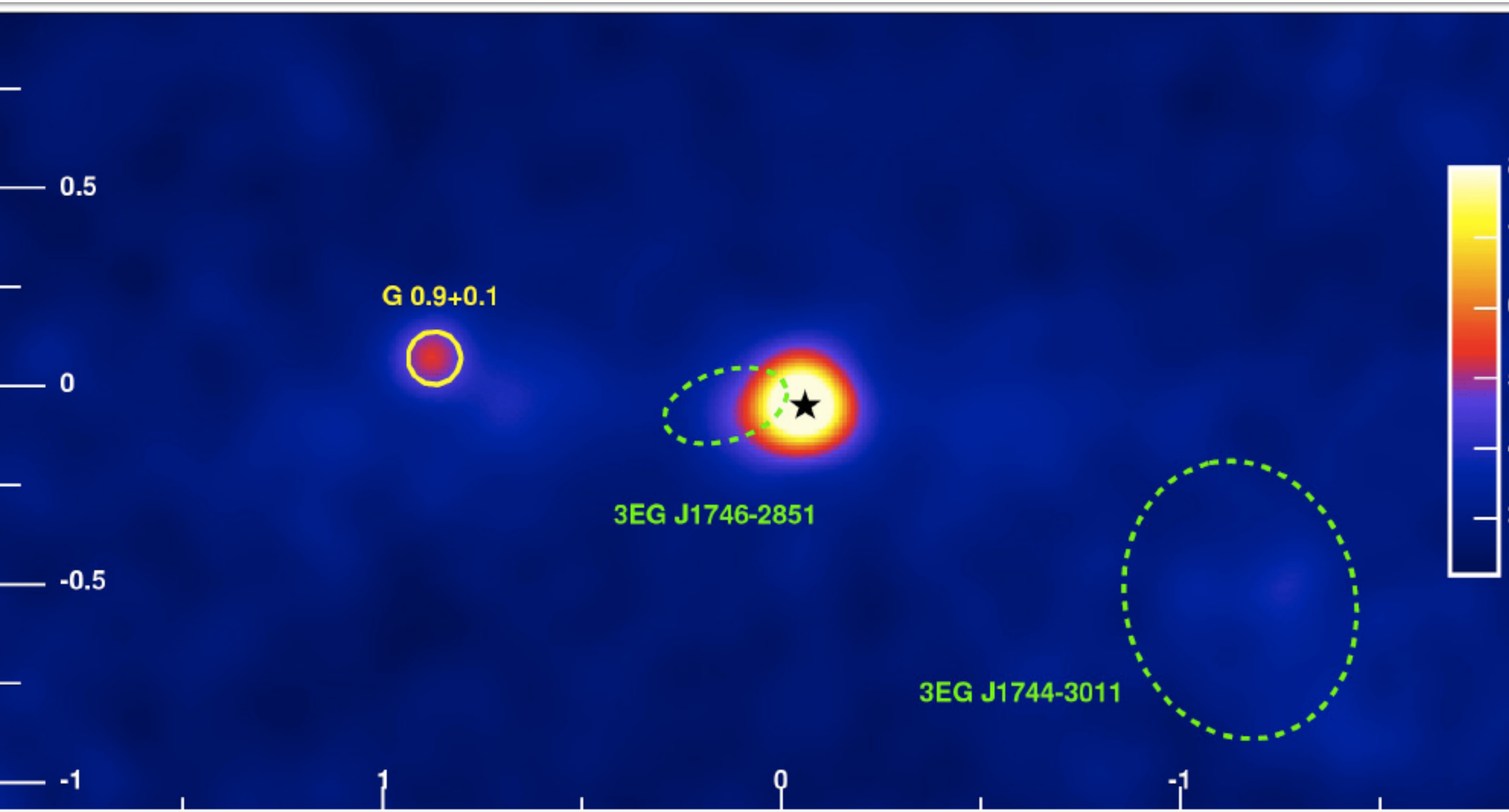
- This injects mechanical power (supernova explosions, stellar winds) of

  $P_{mech} \sim 0.1\ M_{Sun}/\mathrm{yr} \times 1\ \mathrm{SN}/(90\ M_{Sun}) \times 10^{51}\ \mathrm{erg/SN}$

  $= 4 \times 10^{40}$ erg/s

Gamma-ray source coincident with Sgr A*

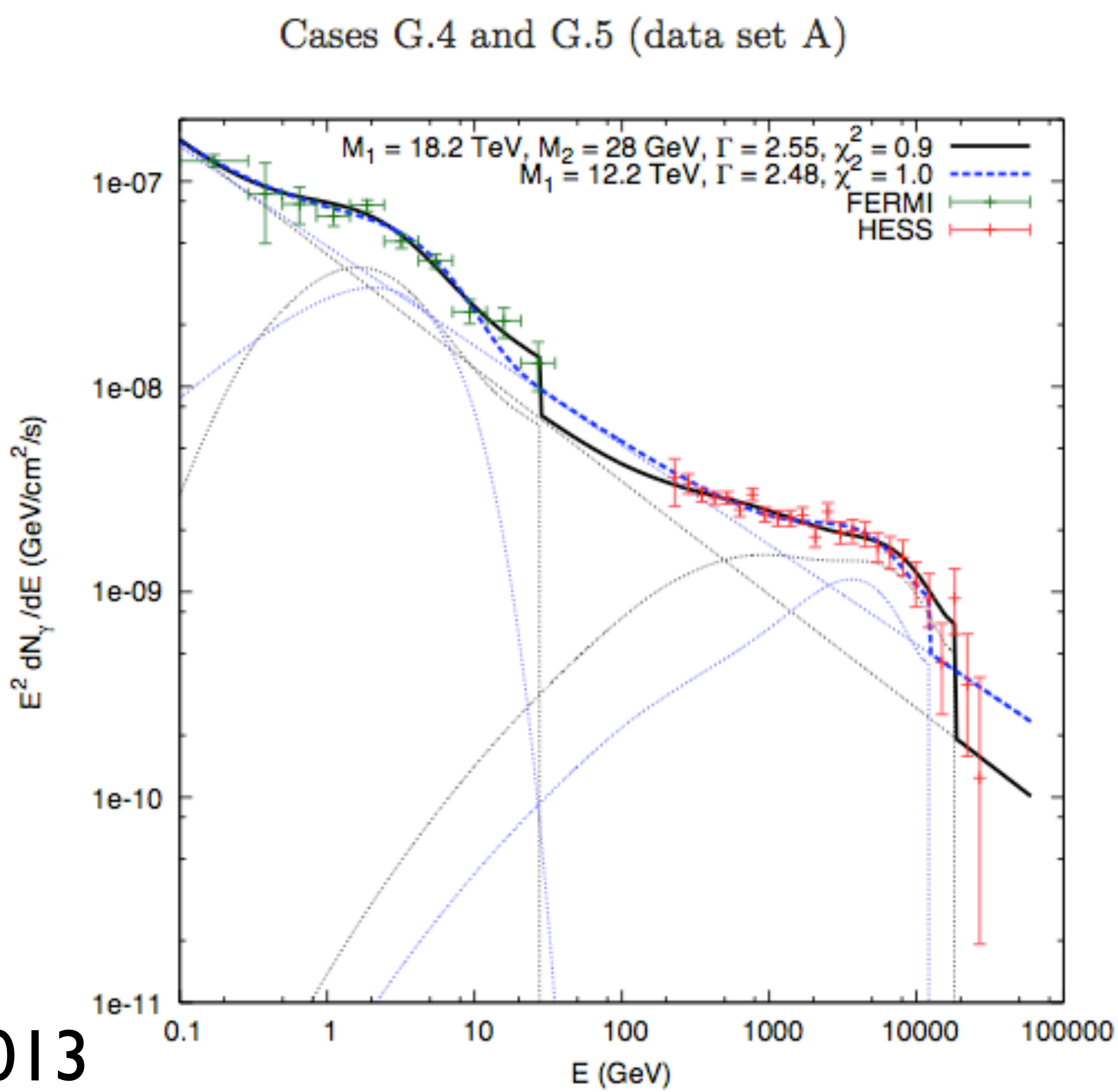
- Detected by Fermi (~GeV) and HESS, MAGIC, VERITAS (~TeV)
- Steady, point-like source for HESS; may be slightly extended for Fermi
- Fermi and HESS spectra off-set from each other; neither is featureless:
  - Fermi spectrum exhibits a bump at few GeV
  - HESS spectrum cut-off above few 10s TeV



HESS TeV (Aharonian et al 2006)

The complicated Sgr A* γ-ray spectrum lends itself to DM interpretations

e.g., 2 x DM annihilation spectra + astrophysical power-law background



Belikov et al. 2013

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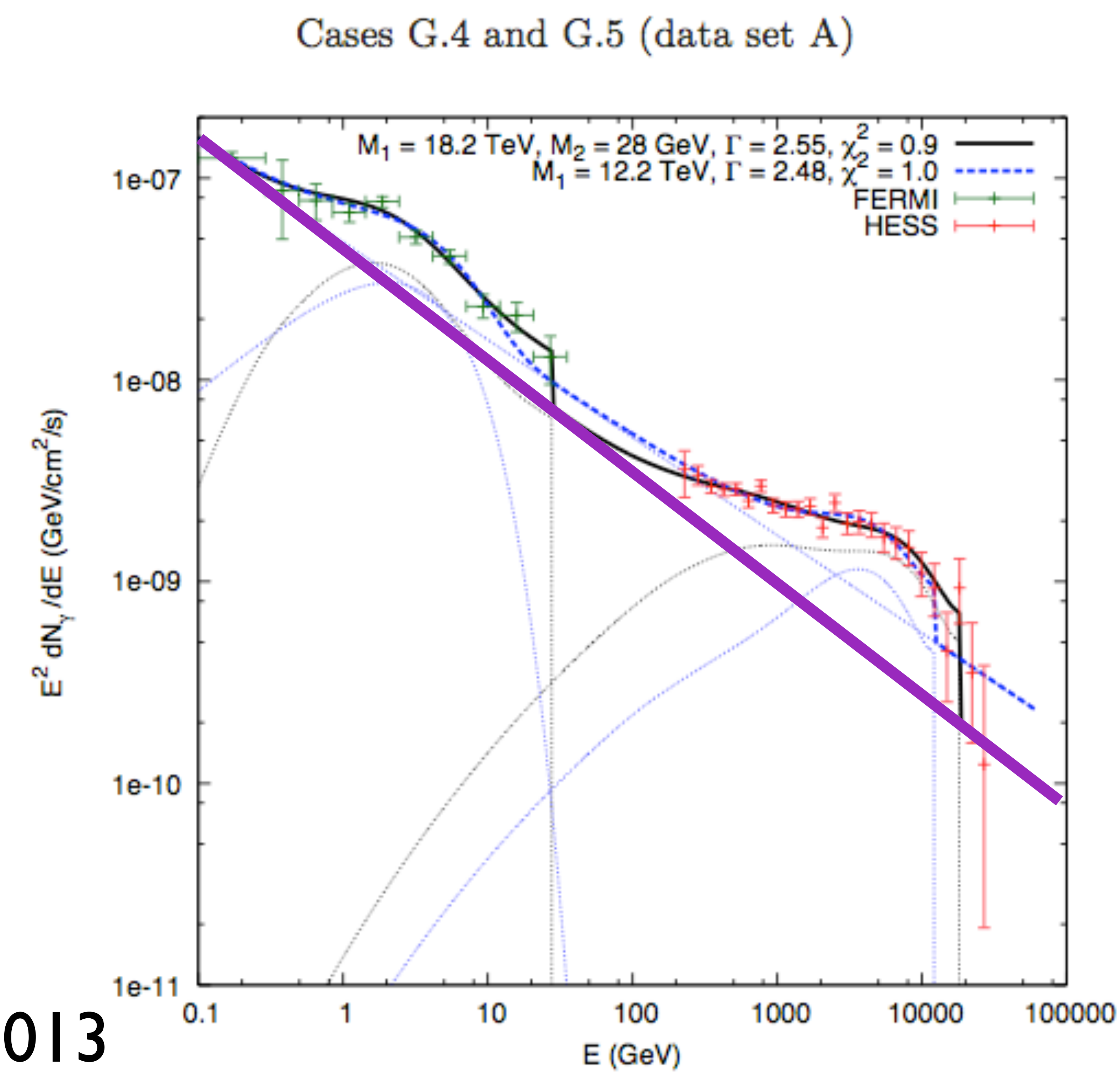

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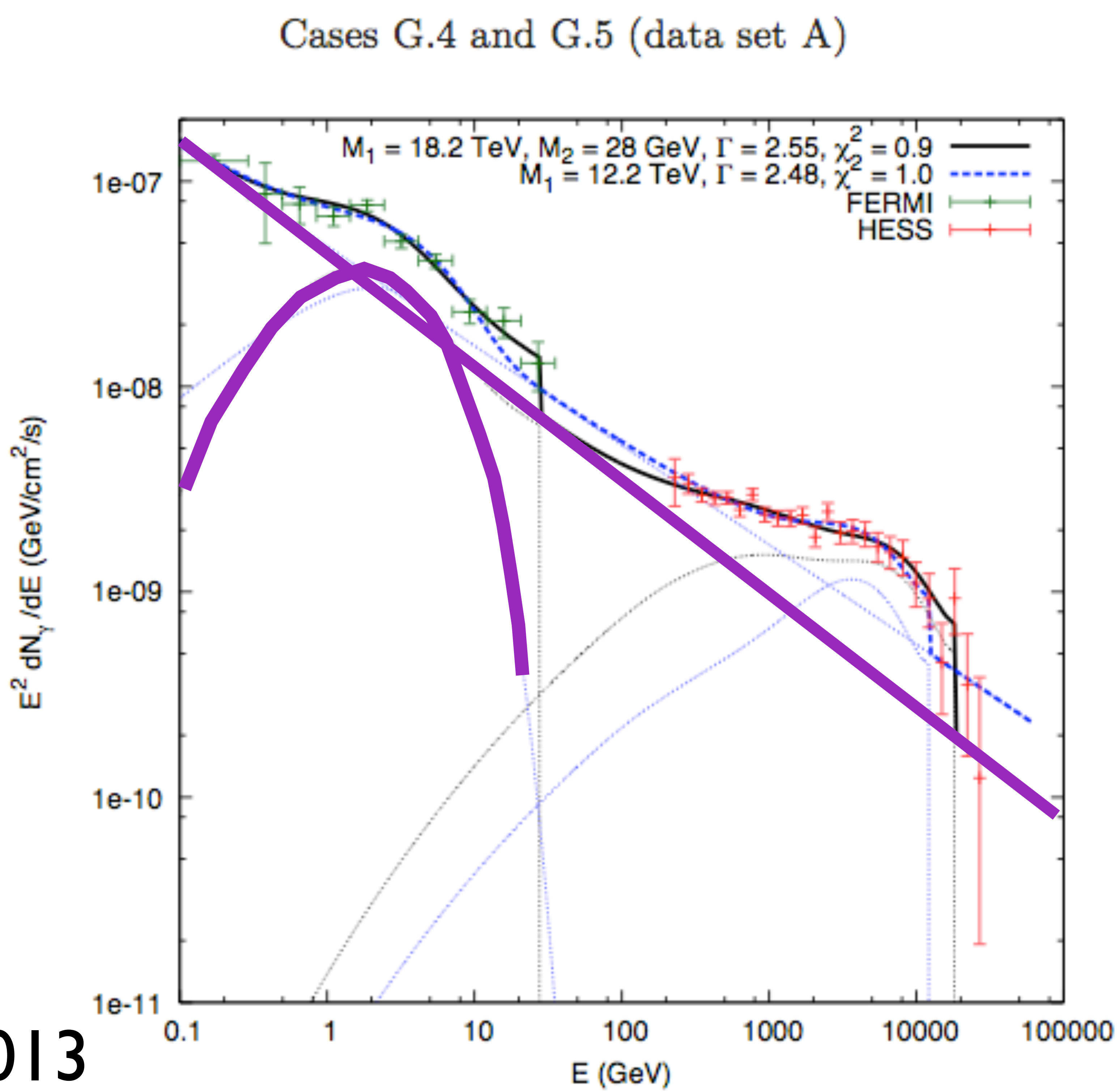

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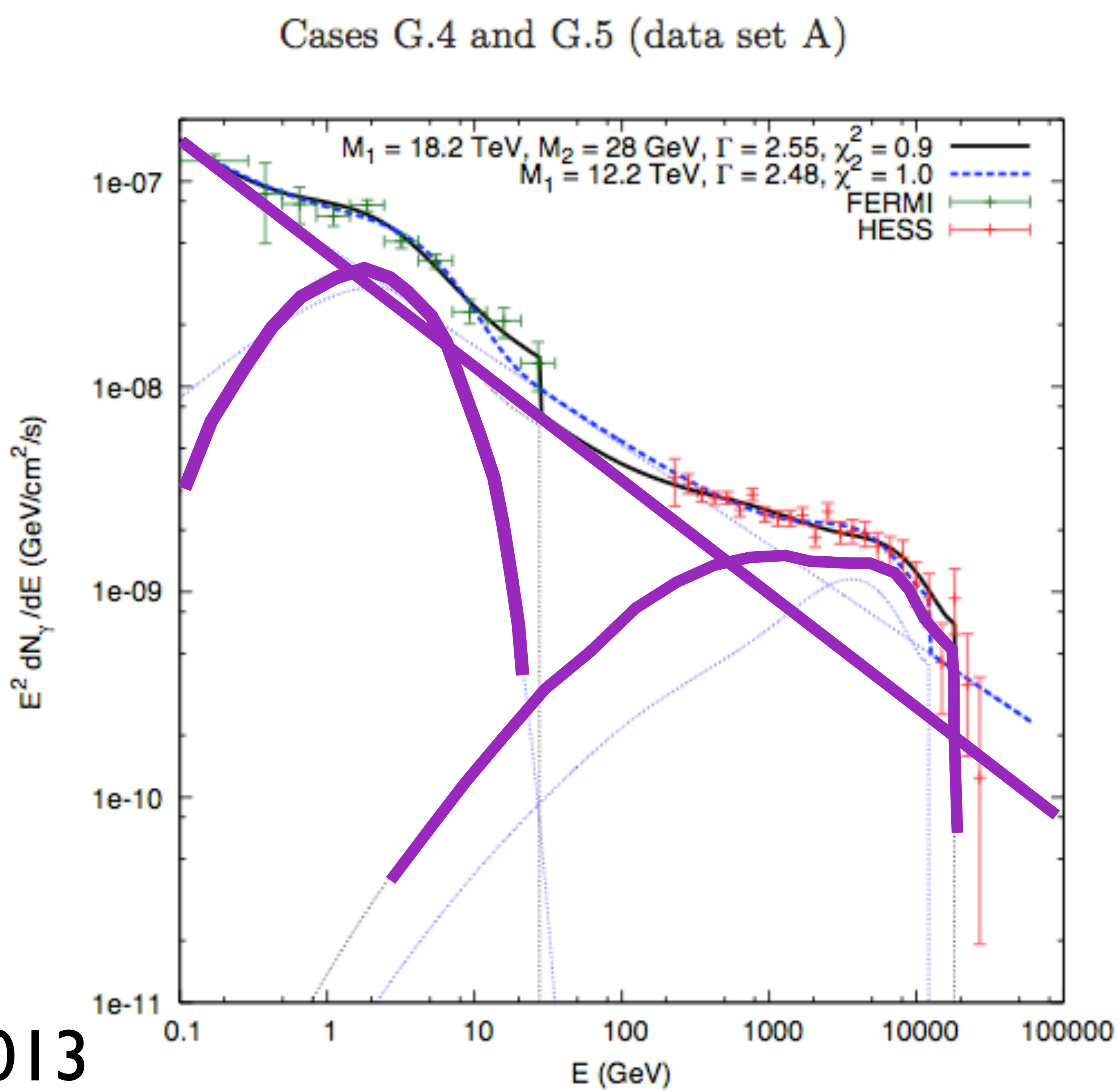
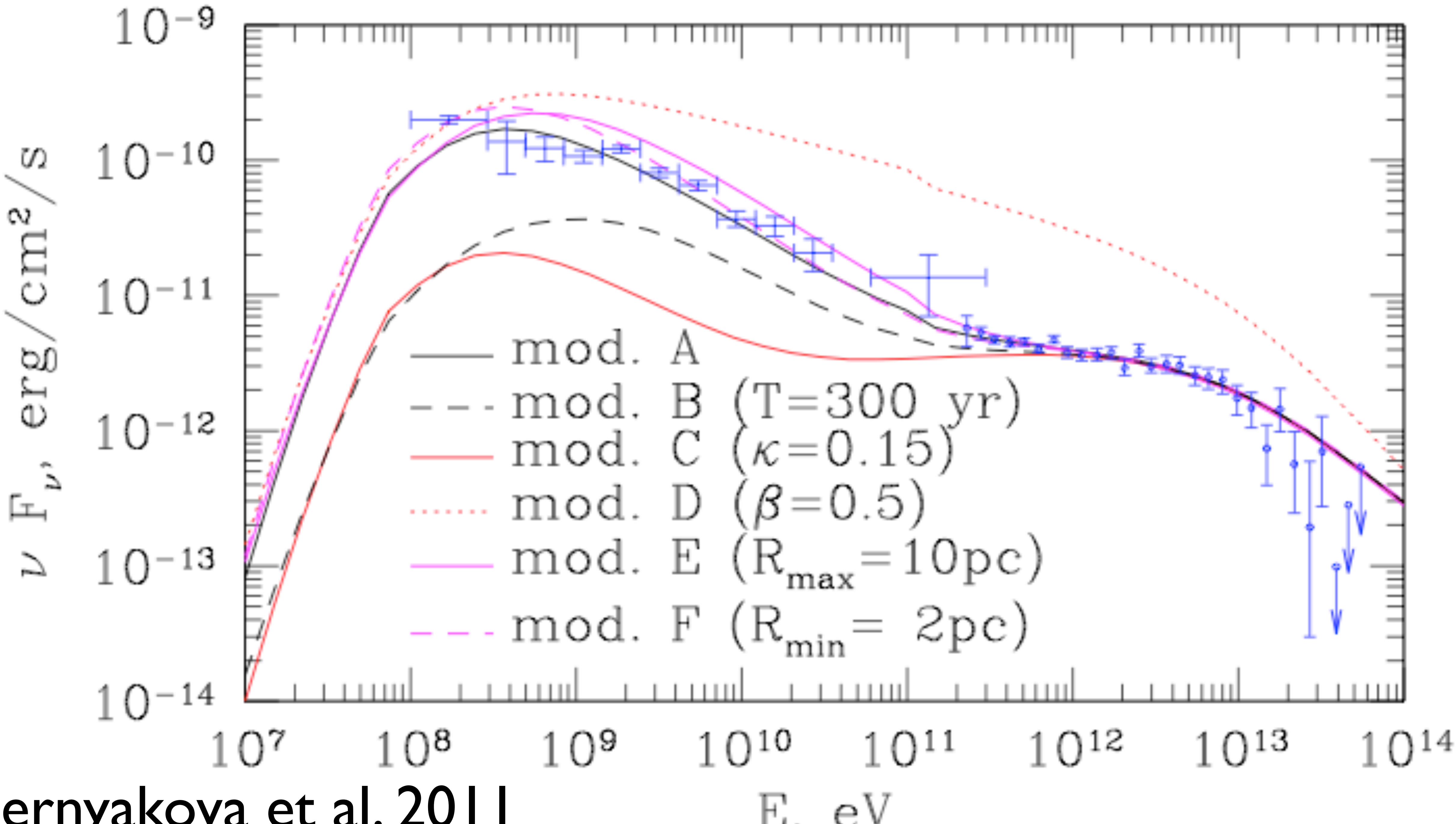


Belikov et al. 2013

...but 'astrophysical' explanations for the γ-ray spectrum are also credible



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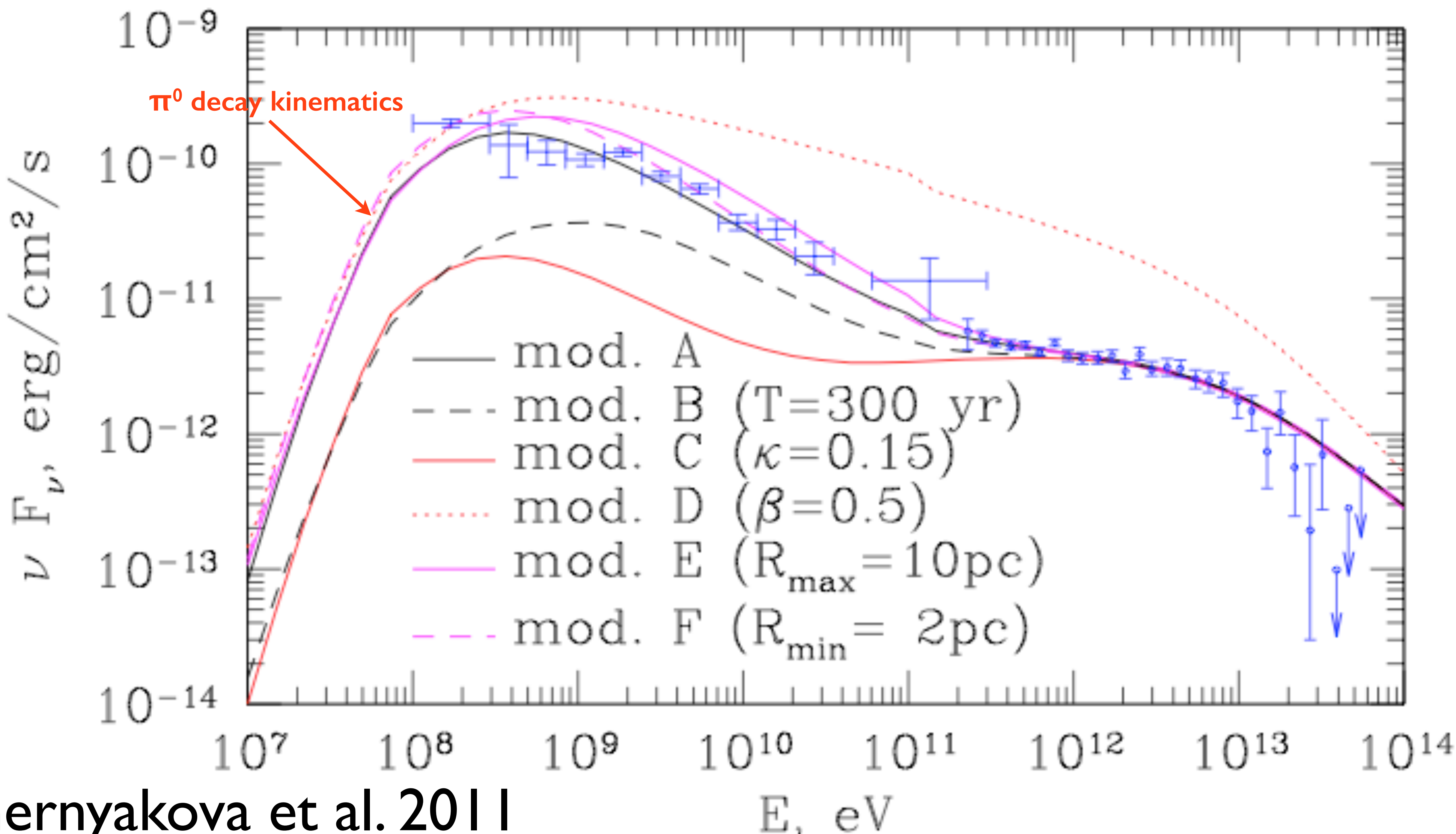

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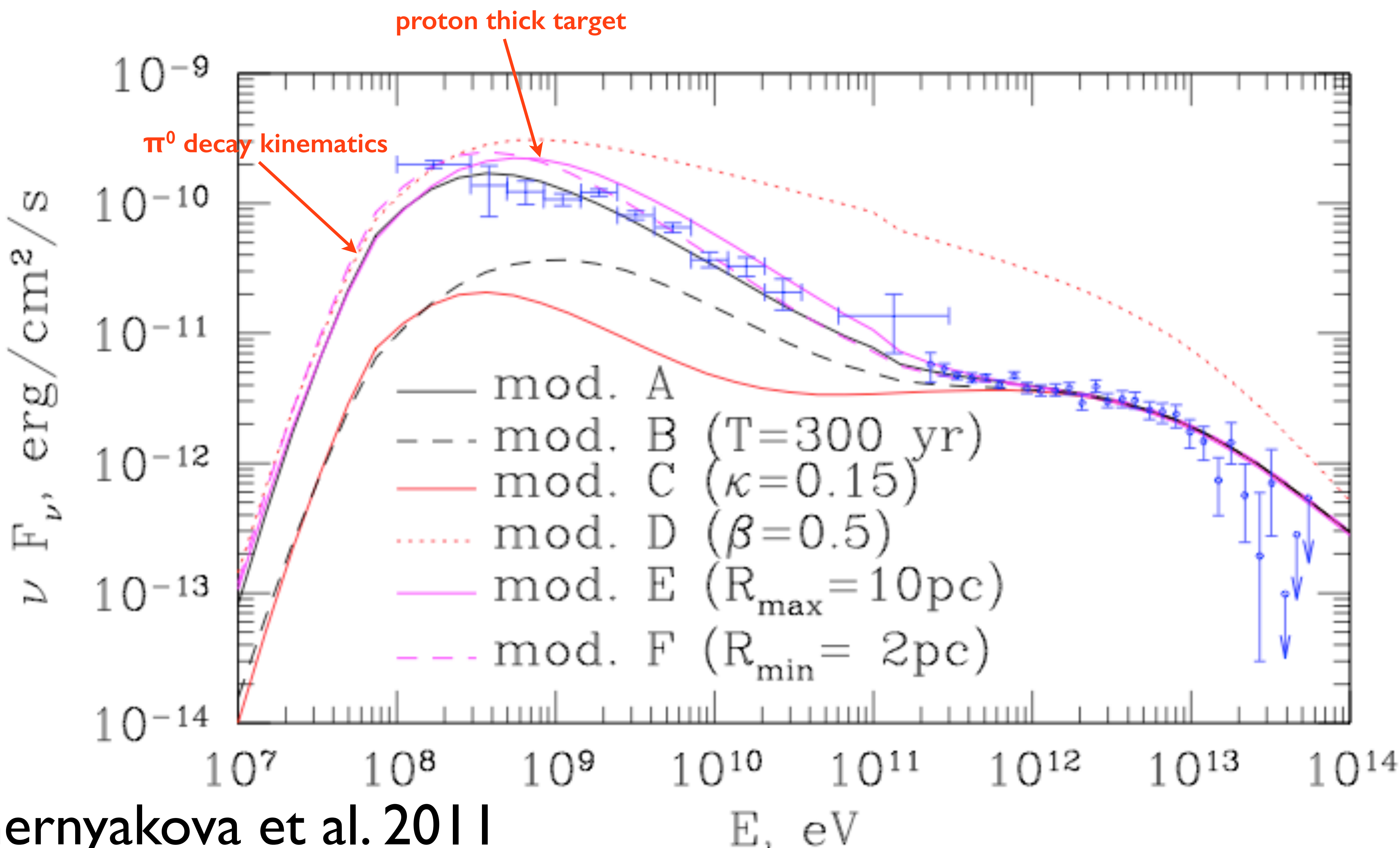

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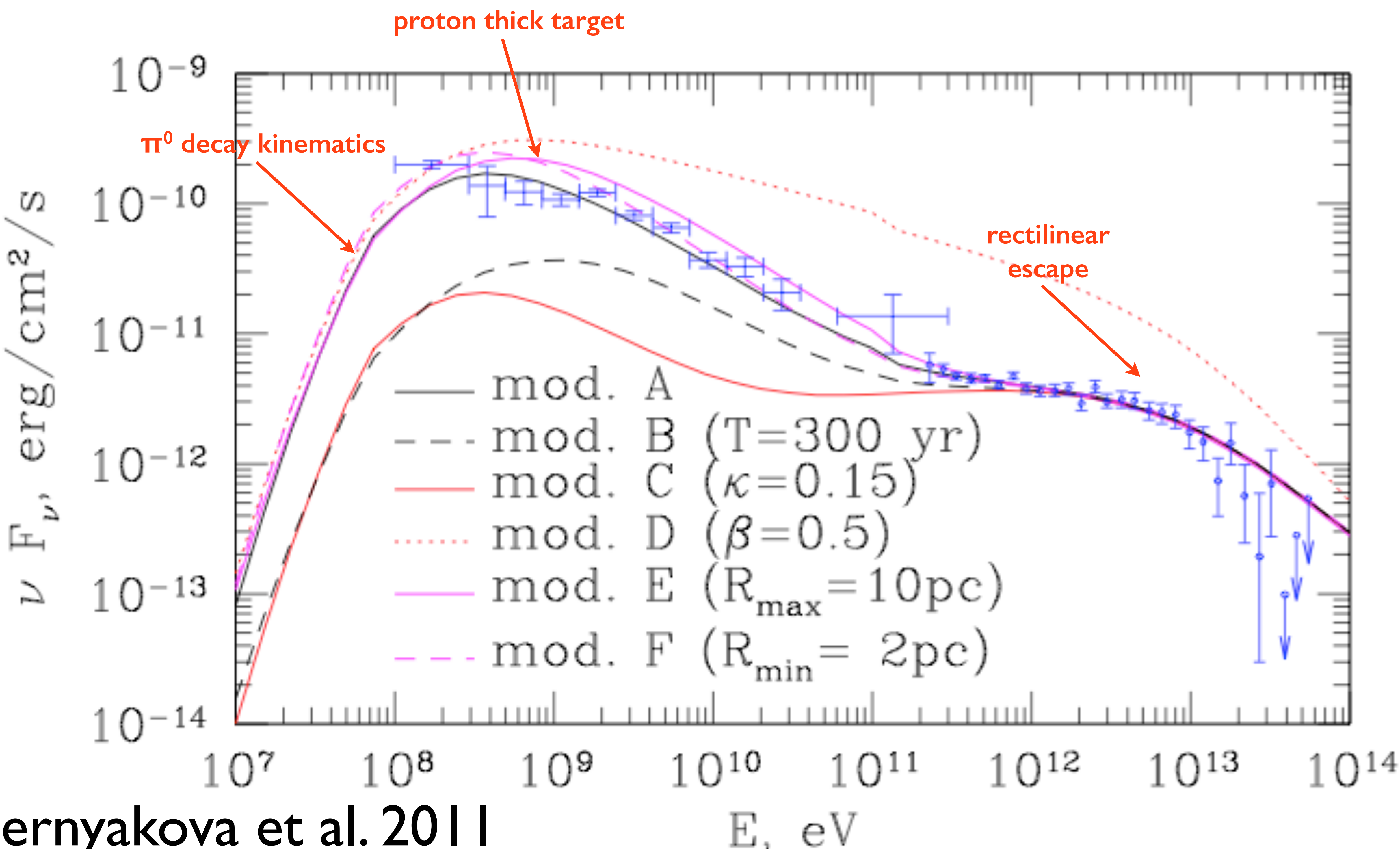

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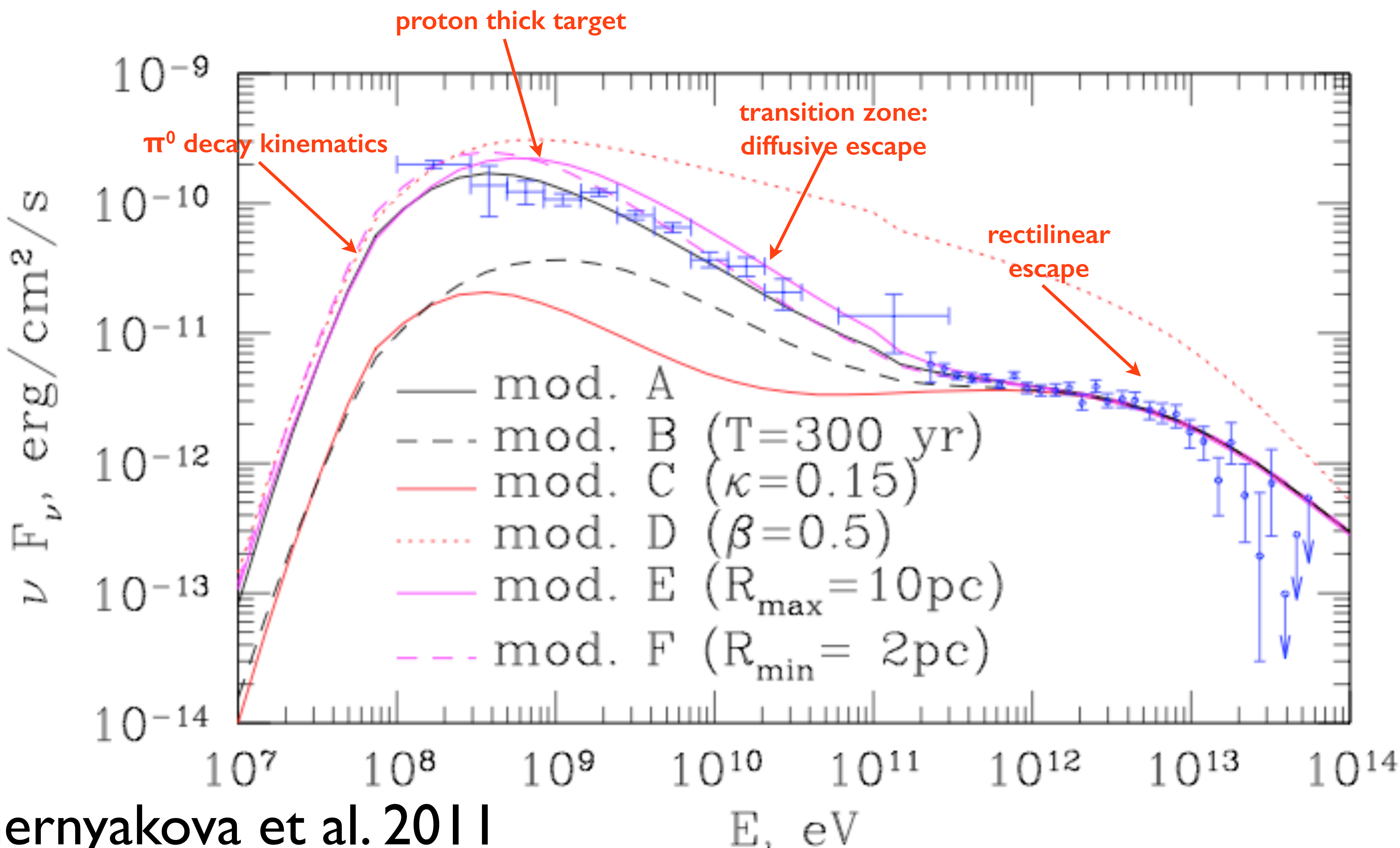

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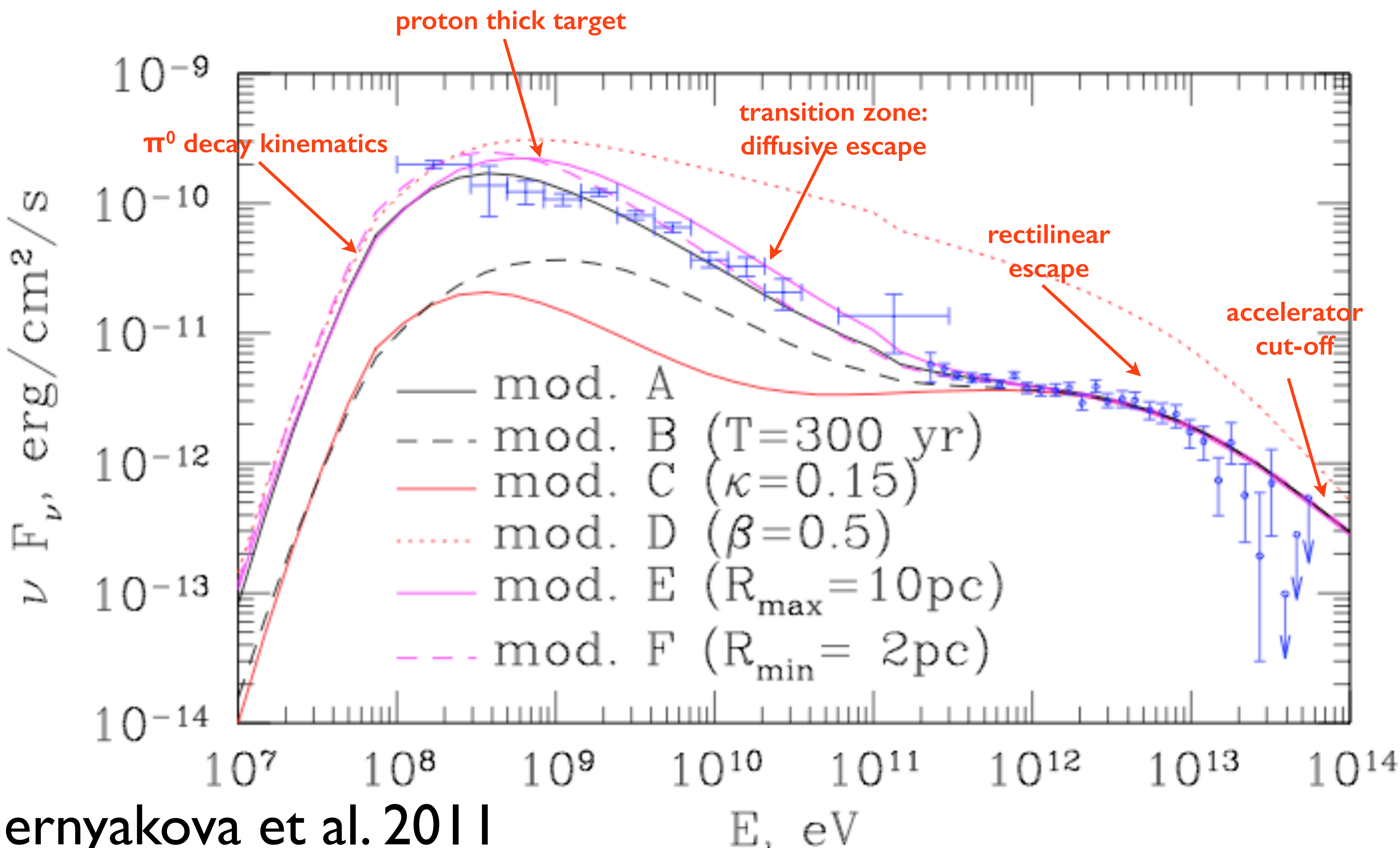

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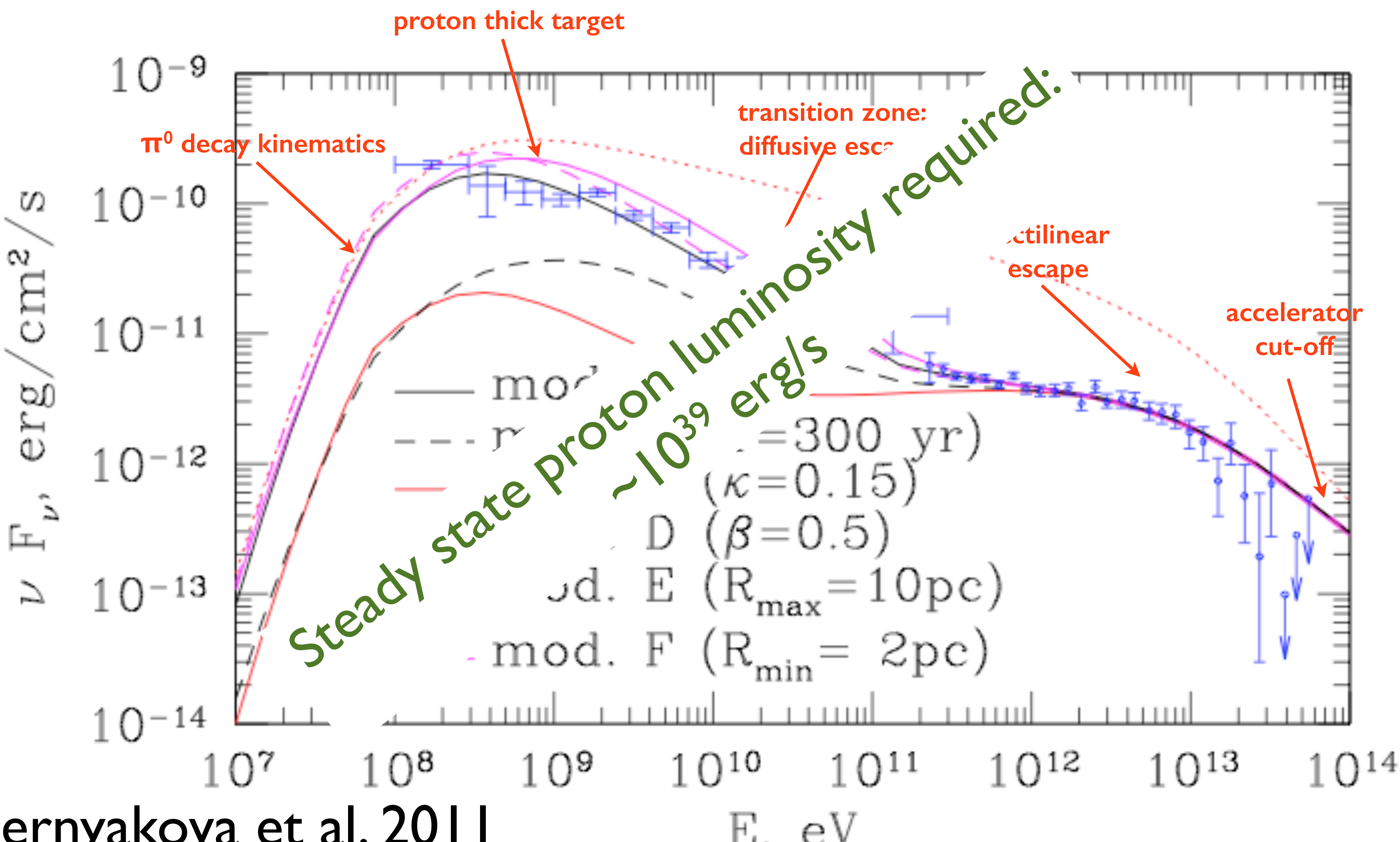

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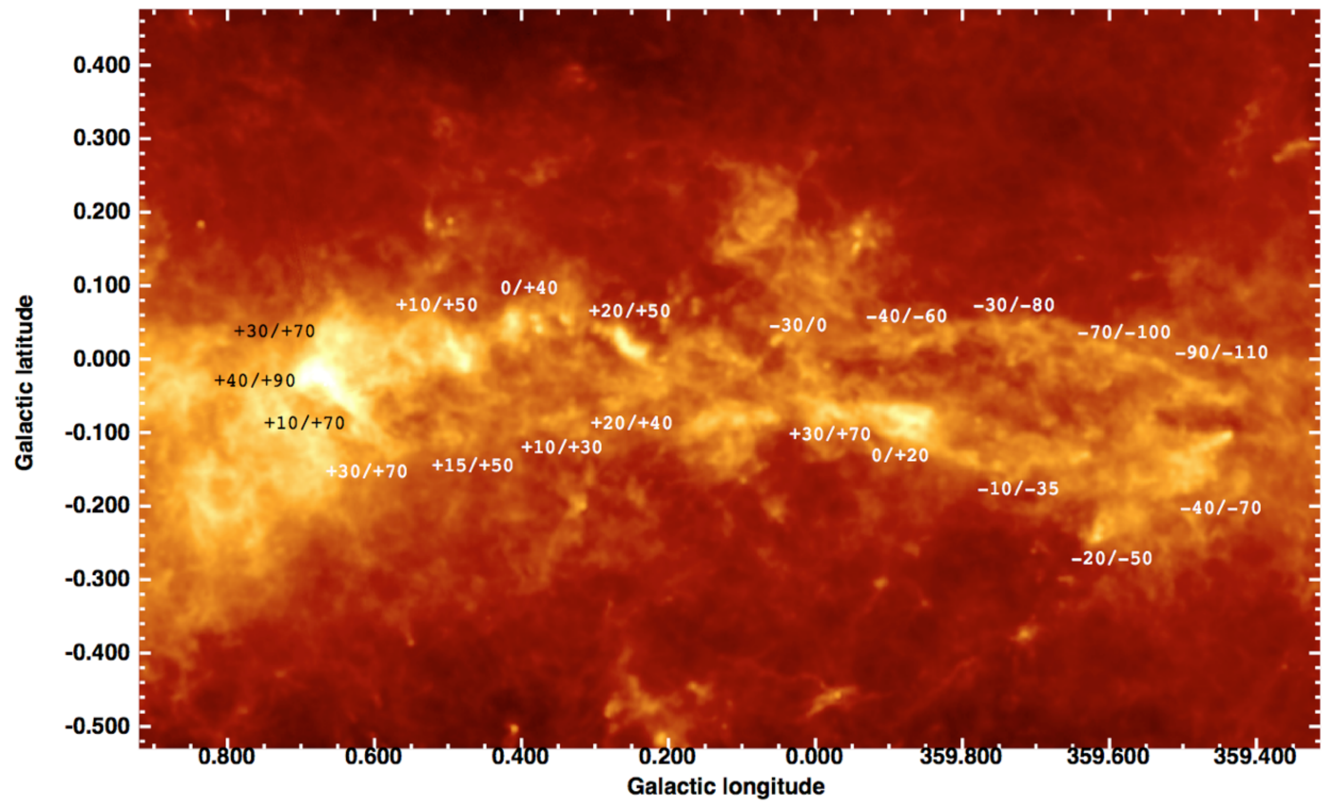
GC Ridge



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Galactic longitude
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+15/+50
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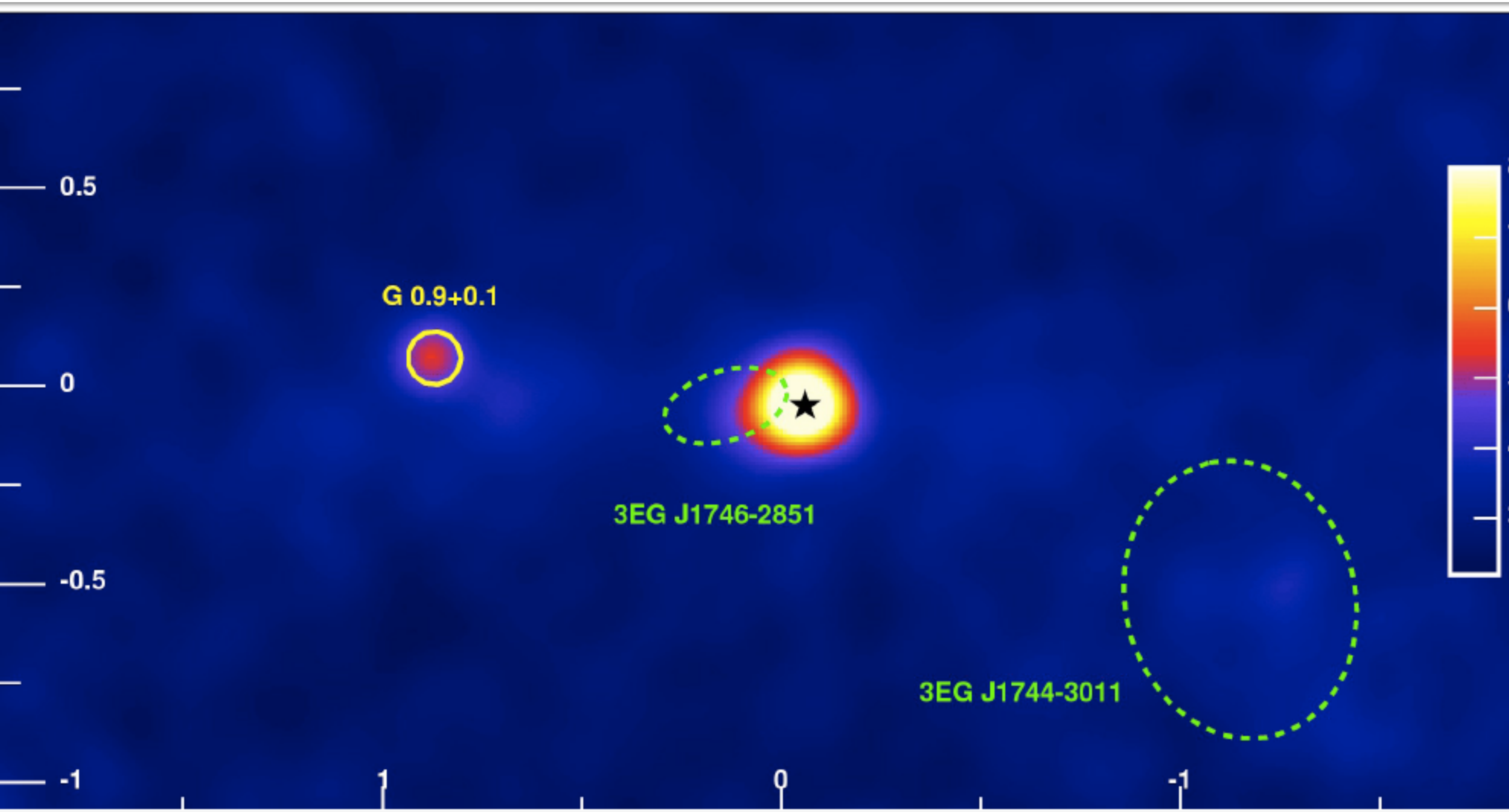

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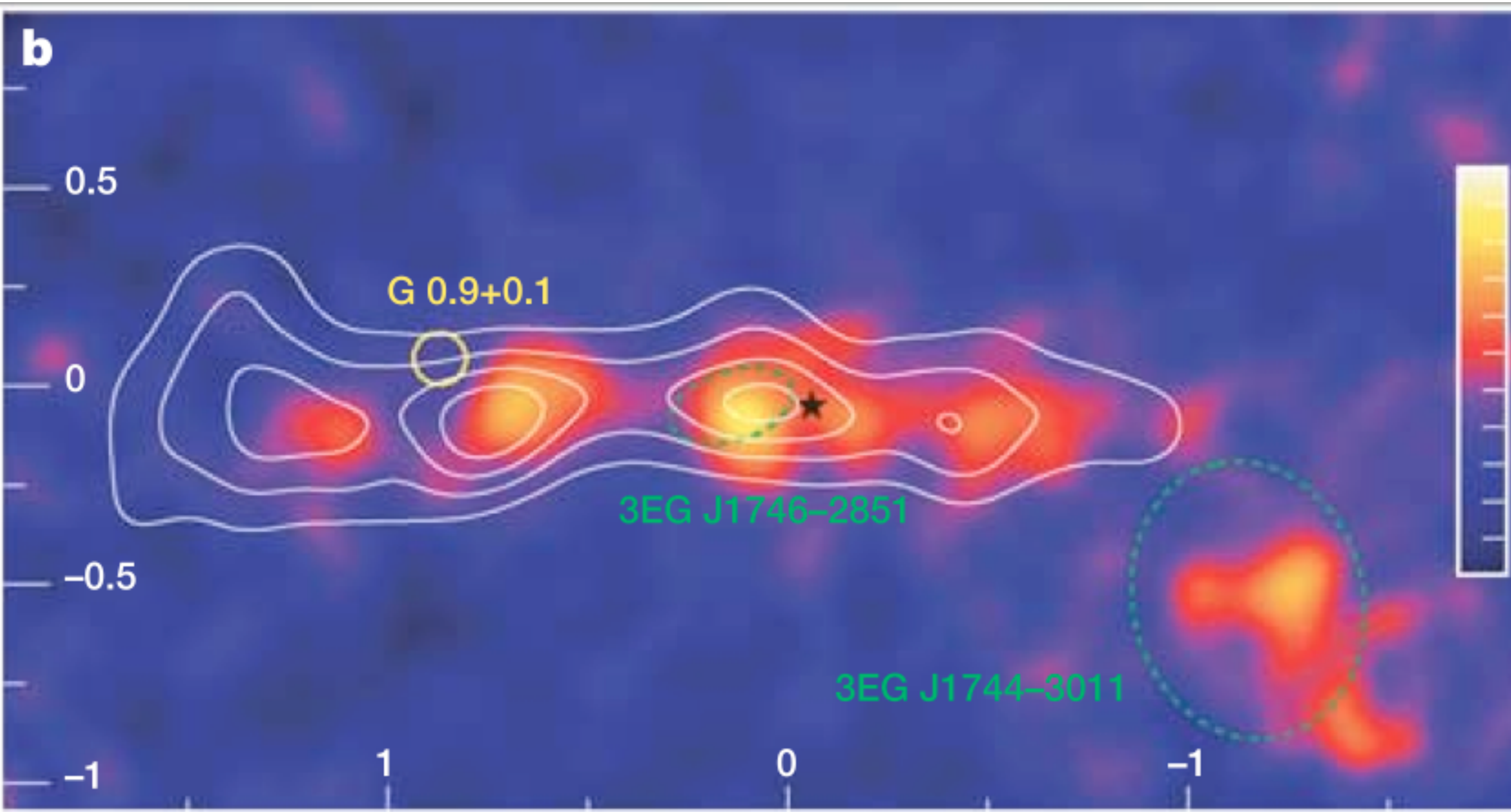
3EG J1746-2851
3EG J1744-3011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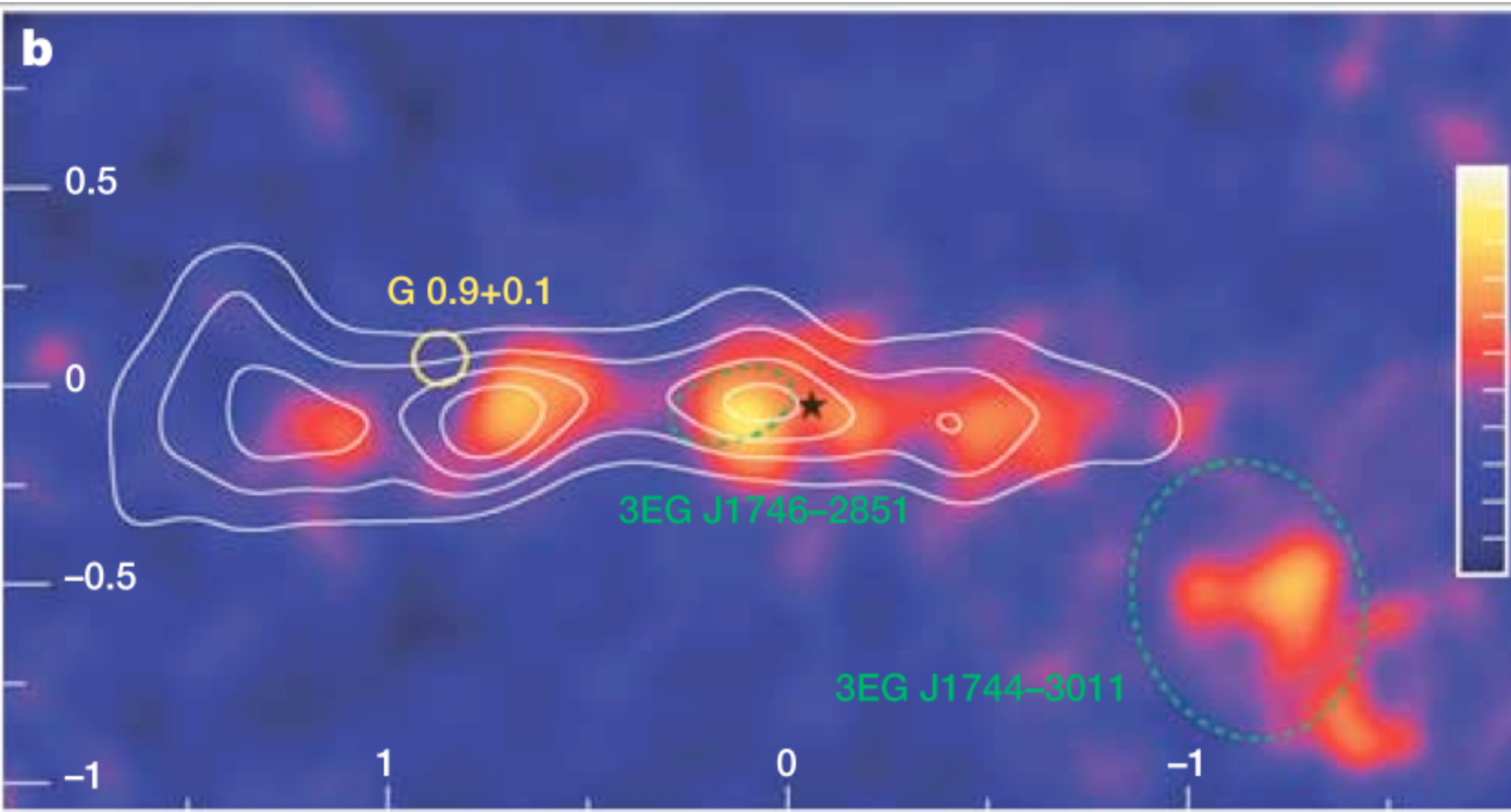
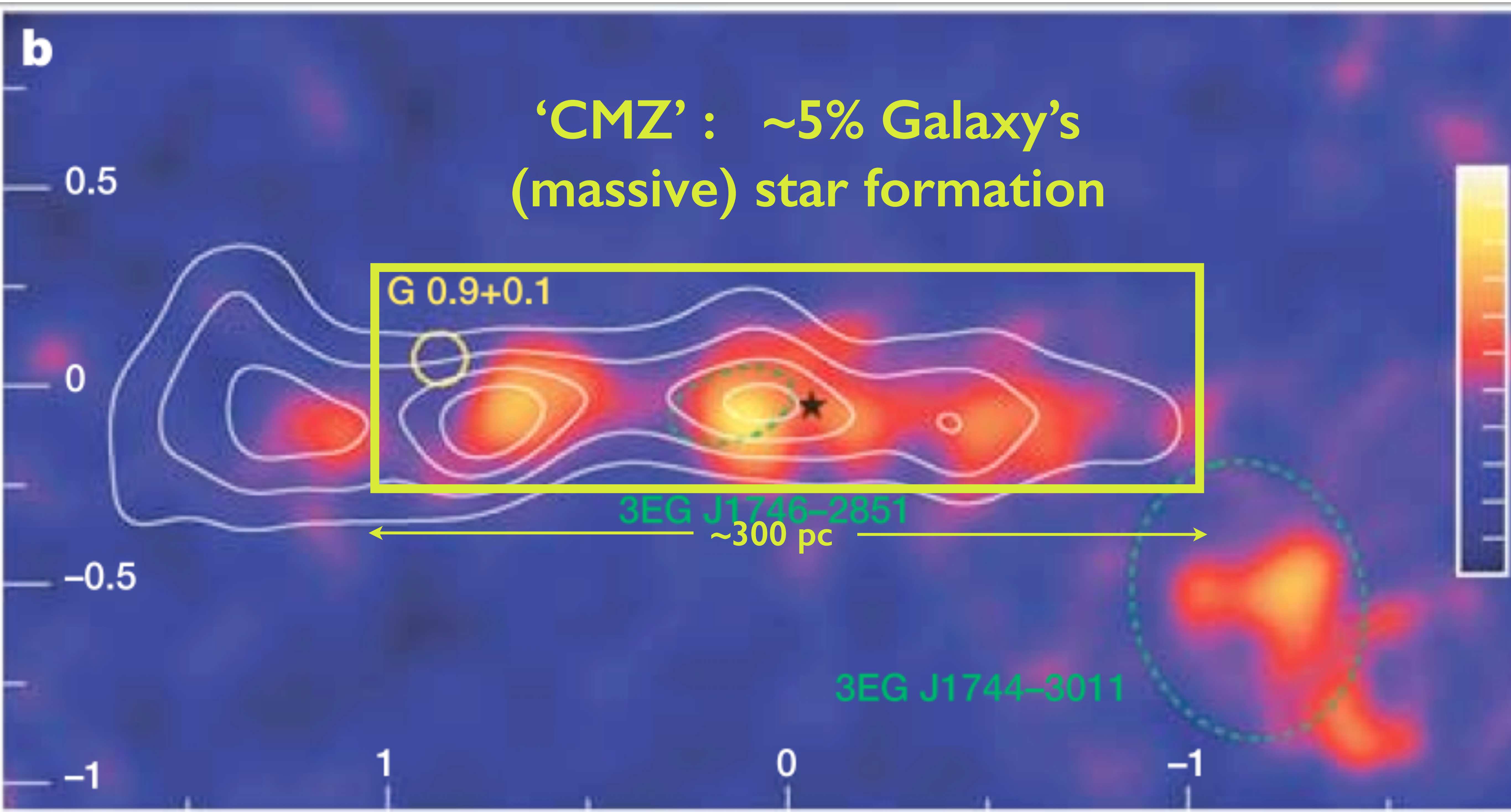


HESS TeV (Aharonian et al 2006)



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Wider Scales

The positron signal remains unexplained

- Gamma-ray constraints (Beacom et al.) imply positrons injected into the ISM with E_{e+} < few MeV - seems difficult to relate to DM annihilation or decay given expected WIMP mass scale

- Power in freshly injected positrons:

  $\sim 10^{43}$ e^+/s x few MeV/e^+ $\sim$ few 10^{37} erg/s

- ...this is easily supplied by astrophysical sources - but how are the positrons created?

Hooper et al.: few GeV Bump

The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,[1] Douglas P. Finkbeiner,[1,2] Dan Hooper,[3,4] Tim Linden,[5]
Stephen K. N. Portillo,[2] Nicholas L. Rodd,[6] and Tracy R. Slatyer[6,7]

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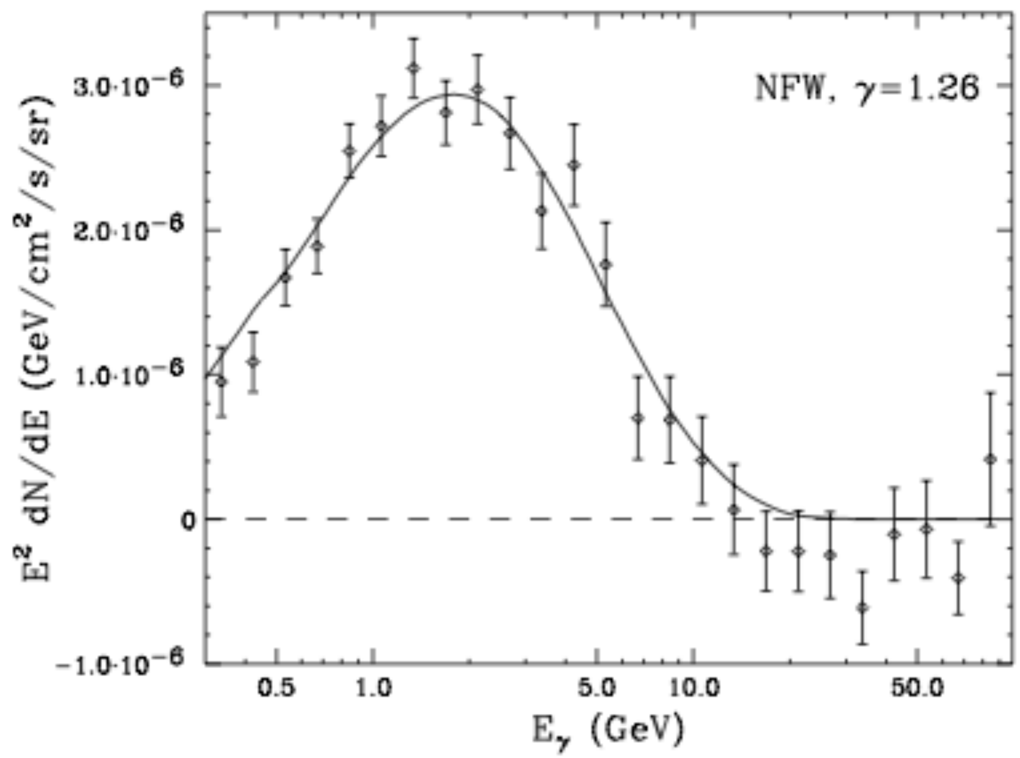
[2]*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA*
[3]*Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL*
[4]*University of Chicago, Department of Astronomy and Astrophysics, Chicago, IL*
[5]*University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL*
[6]*Center for Theoretical Physics, Massachusetts Institute of Technology, Boston, MA*
[7]*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ*

Past studies have identified a spatially extended excess of ~1-3 GeV gamma rays from the region surrounding the Galactic Center, consistent with the emission expected from annihilating dark matter. We revisit and scrutinize this signal with the intention of further constraining its characteristics and origin. By applying cuts to the *Fermi* event parameter CTBCORE, we suppress the tails of the point spread function and generate high resolution gamma-ray maps, enabling us to more easily separate the various gamma-ray components. Within these maps, we find the GeV excess to be robust and highly statistically significant, with a spectrum, angular distribution, and overall normalization that is in good agreement with that predicted by simple annihilating dark matter models. For example, the signal is very well fit by a 31-40 GeV dark matter particle annihilating to $b\bar{b}$ with an annihilation cross section of $\sigma v = (1.4 - 2.0) \times 10^{-26}$ cm^3/s (normalized to a local dark matter density of 0.3 GeV/cm^3). Furthermore, we confirm that the angular distribution of the excess is approximately spherically symmetric and centered around the dynamical center of the Milky Way (within ~0.05° of Sgr A*), showing no sign of elongation along or perpendicular to the Galactic Plane. The signal is observed to extend to at least $\simeq 10^\circ$ from the Galactic Center, disfavoring the possibility that this emission originates from millisecond pulsars.

Daylan et al. 2014
(arXiv:1402.6703v1)

- Claimed bump peaks at ~2 GeV
- Extends to at least 10° from GC, radially symmetric with DM-like profile
- Extension is similar to 511 keV signal (Boehm et al. 2014, arXiv:1406.4683v1)



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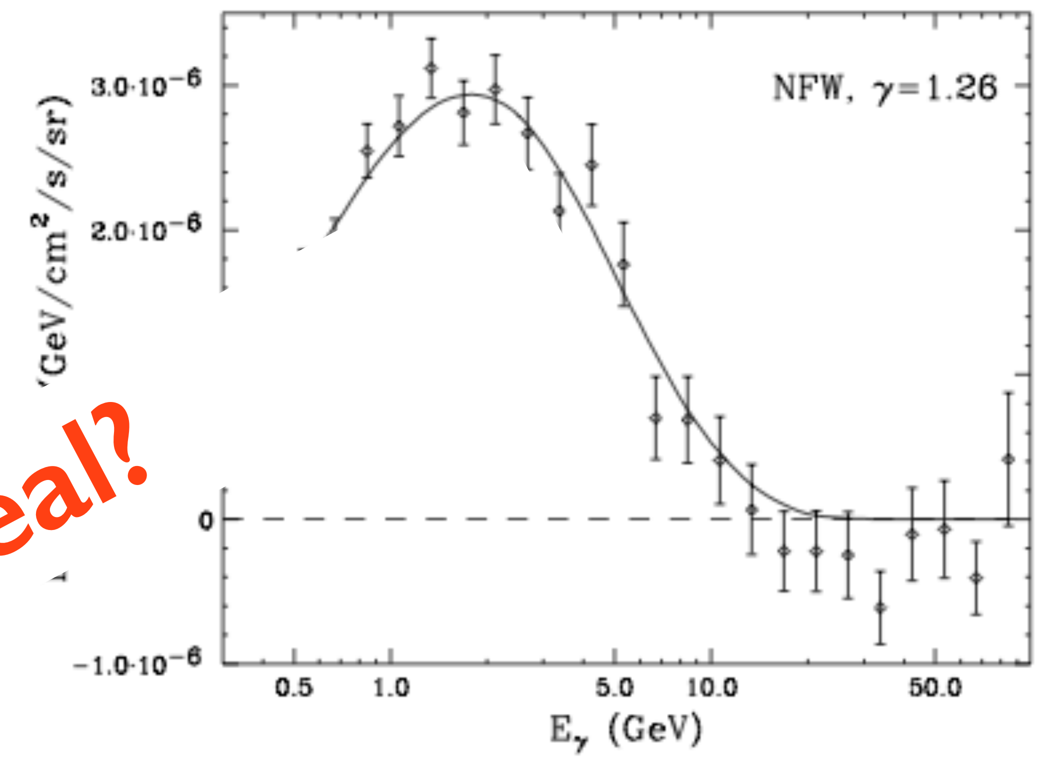
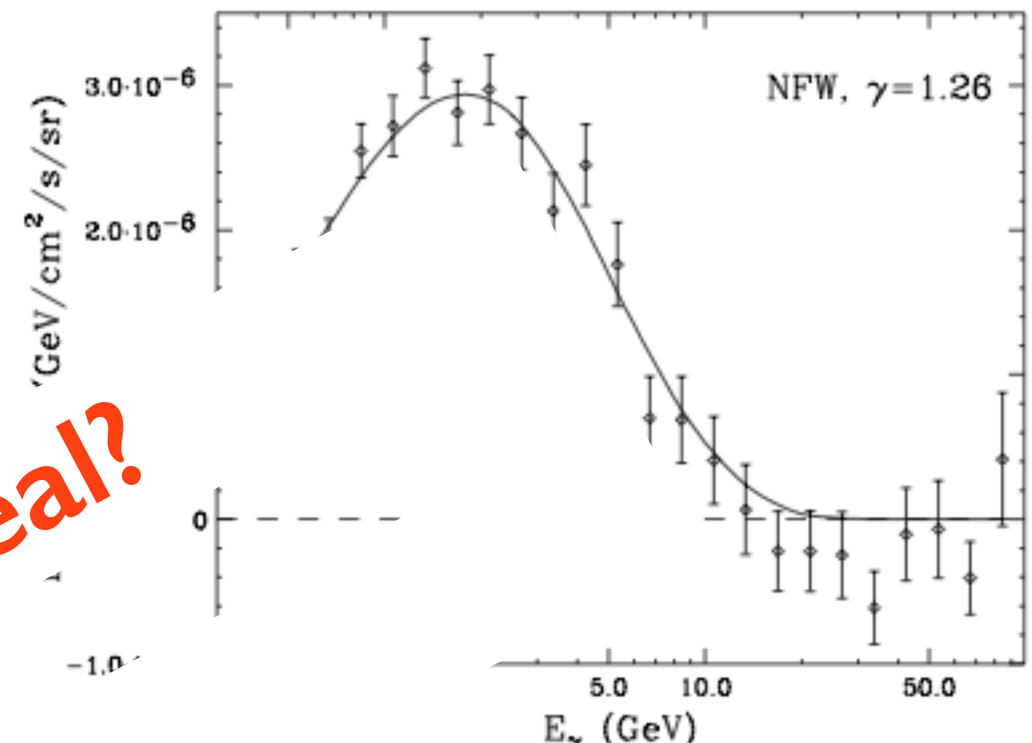


Is the signal real?

Daylan et al. 2014

(arXiv:1402.6703v1)

- Claimed bump peaks at ~2 GeV
- Extends to at least 10° from GC, radially symmetric with … profile
- F… is sim… k… signal … et al. 2014 …06.4683v1)



Is the signal real?

What is it?

What is the signal?

… Can we explain it with ‘conventional’ astrophysics?

- E.g., several 1000 MSPs? e.g., Gordon & Macías (2013)
- No according to Hooper et al.: signal too extended

What is the signal?

- The DM candidate distributed as $\rho_{DM} \propto r^{-1.3}$ would release energy in annihilation products at a rate of **3 x 10^{37} erg/s** within the innermost 150 parsecs around the Galactic Center
- BUT: in the same region star-formation (supernovae, stellar winds) injects ~10^{39} erg/s in accelerated hadrons and **~10^{38} erg/s** in accelerated leptons (i.e., cosmic ray electrons) - *energetically* this is a good match to Hooper et al.'s putative DM signature.
- Preliminary attempts to explain the spectral anomalies identified by Hooper et al. with diffuse cosmic ray populations have started to appear: Carlson & Profumo (2014); Petrovic et al. (2014)

Indeed, there *are* strong, *a priori* ‘astrophysical’ reasons for the spectrum of the GC’s diffuse cosmic rays (& diffuse non-thermal radiation) to be rather different to the typical Galaxy-wide spectrum….

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…*watch this space*

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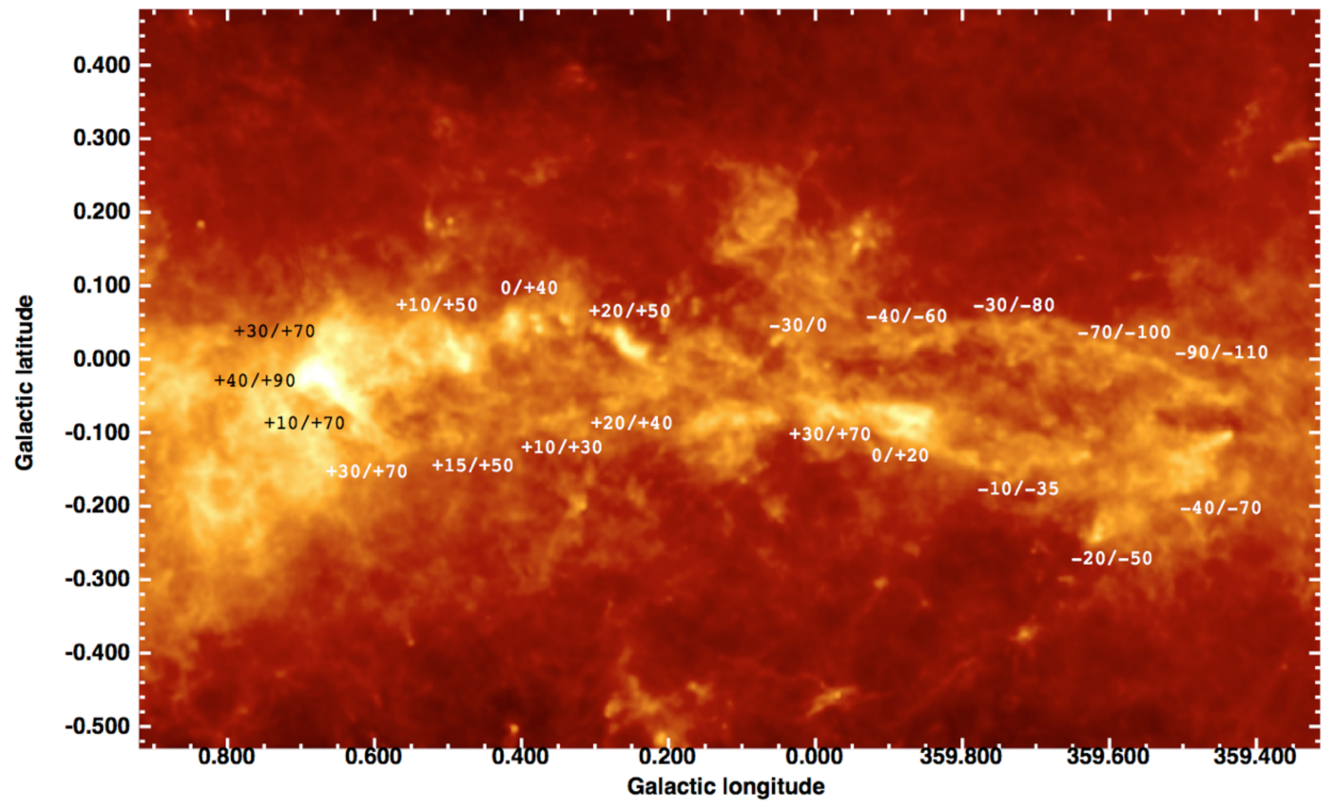
…*watch this space*

Cosmic Ray Transport on ~100 pc scales in the GC

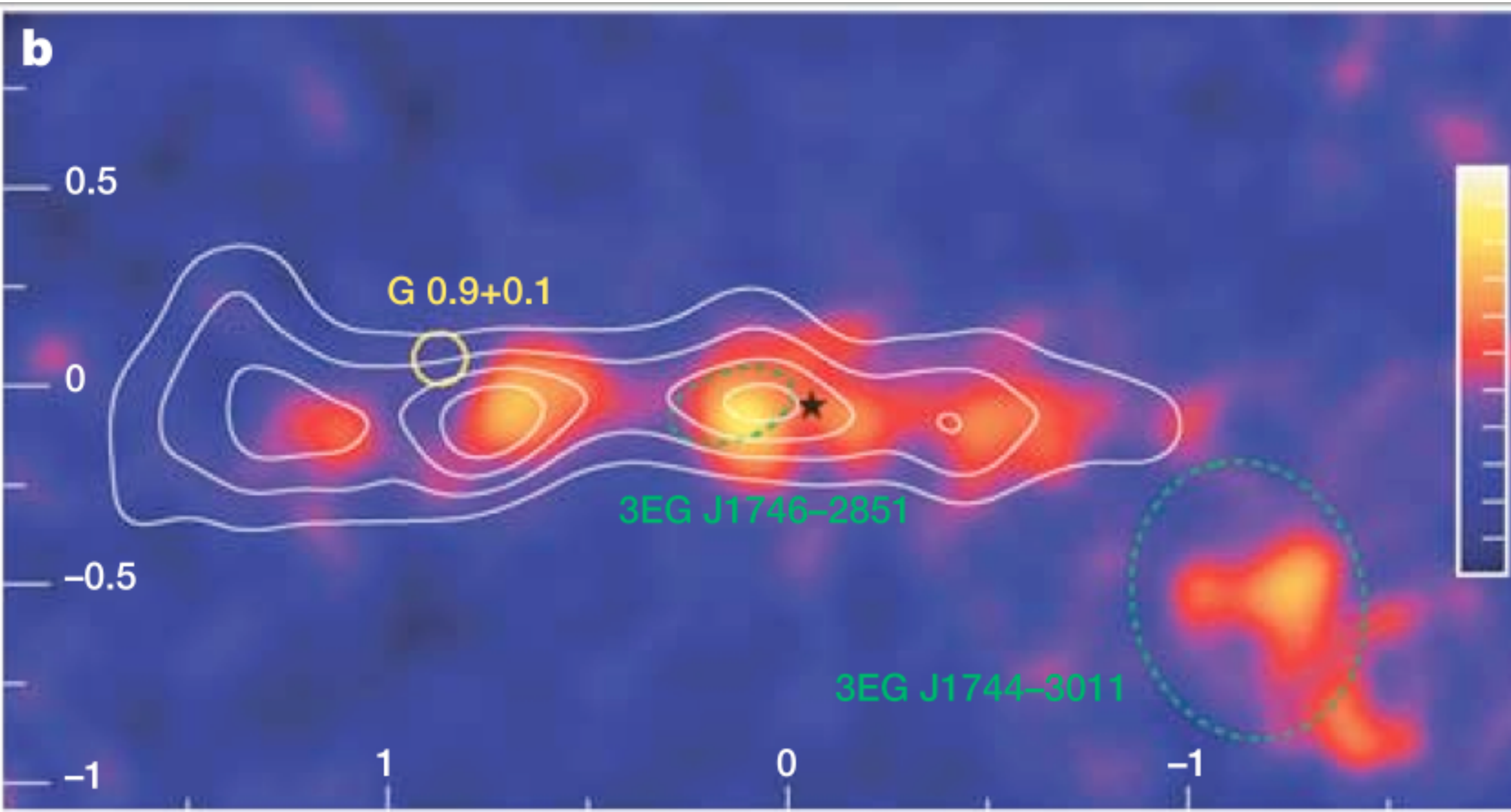
- Both transport and cooling processes affect the steady-state distributions of non-thermal particles
- In the disk, diffusive escape of cosmic ray ions steepens the steady state population because higher energy particles scatter less and escape the disk more quickly
- In the GC, [CLAIM] the star-formation intensity is sufficient to drive a large-scale outflow akin to a (low power) nuclear star-burst wind
- This wind advects most non-thermal particles before they can lose their energy radiatively

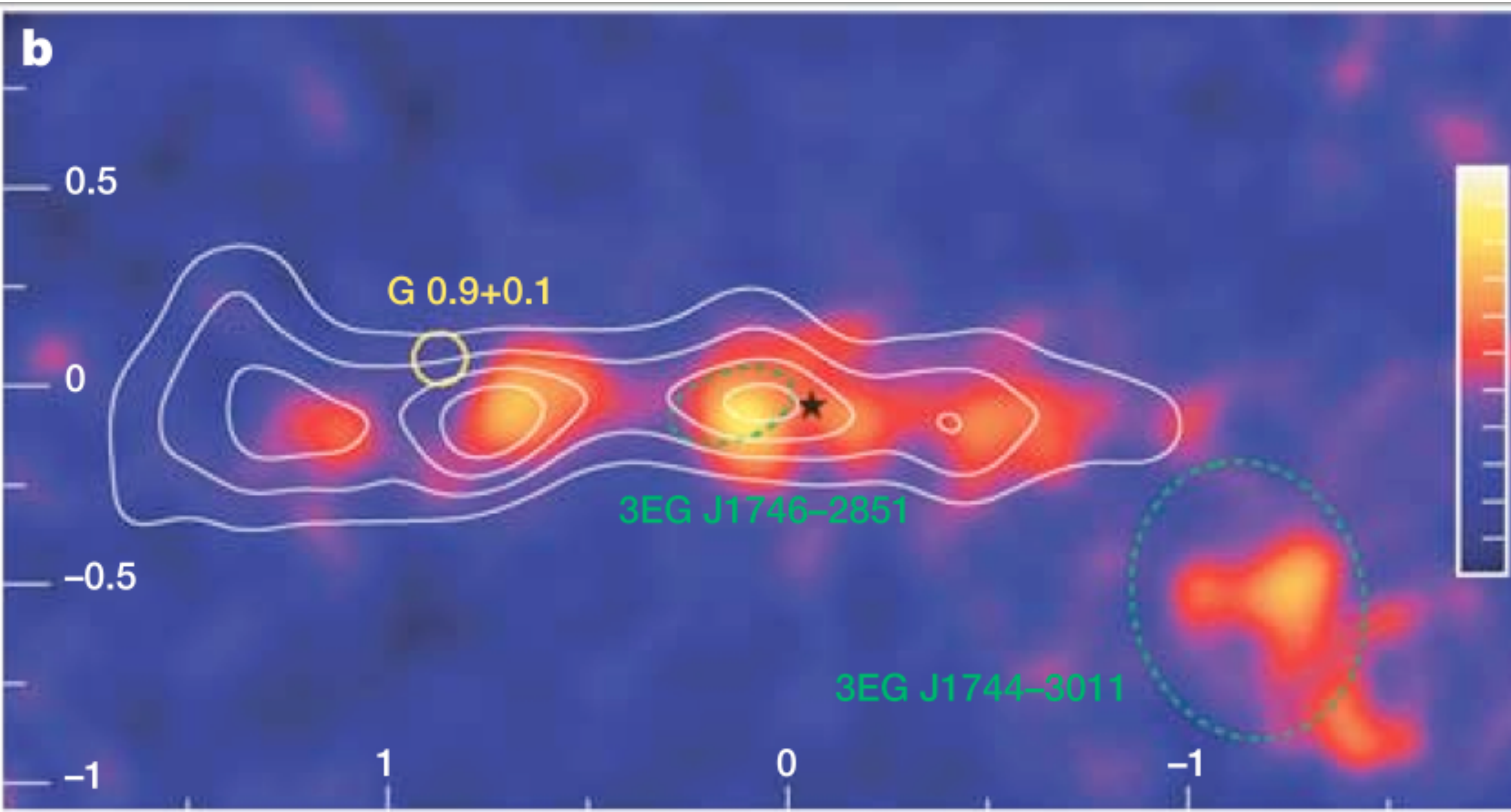
Cosmic Ray Transport in the GC

- *Hard* spectrum of in-situ electron **and** proton population → transport is advective not diffusive, i.e. via a *wind*
- there is much prior evidence for such a wind

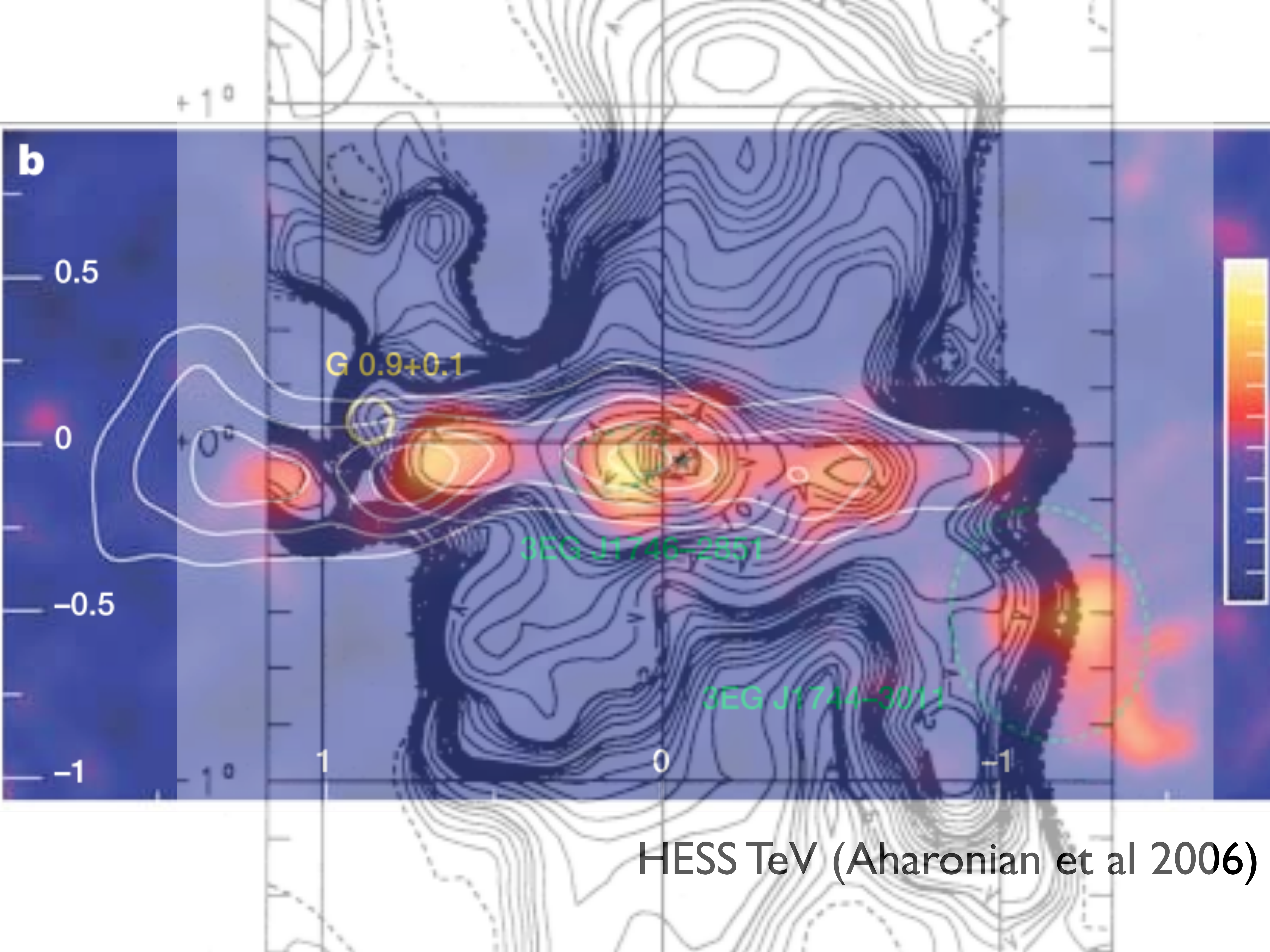


Galactic latitude
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
-0.300
-0.400
-0.500
0.800
0.600
0.400
0.200
0.000
359.800
359.600
359.400
Galactic longitude
+30/+70
+40/+90
+10/+70
+30/+70
+10/+50
0/+40
+15/+50
+10/+30
+20/+50
+20/+40
-30/0
-40/-60
-30/-80
-70/-100
-90/-110
+30/+70
0/+20
-10/-35
-20/-50
-40/-70


b
0.5
0
−0.5
−1
G 0.9+0.1
3EG J1746−2851
3EG J1744−3011
1
0
−1



HESS TeV (Aharonian et al 2006)



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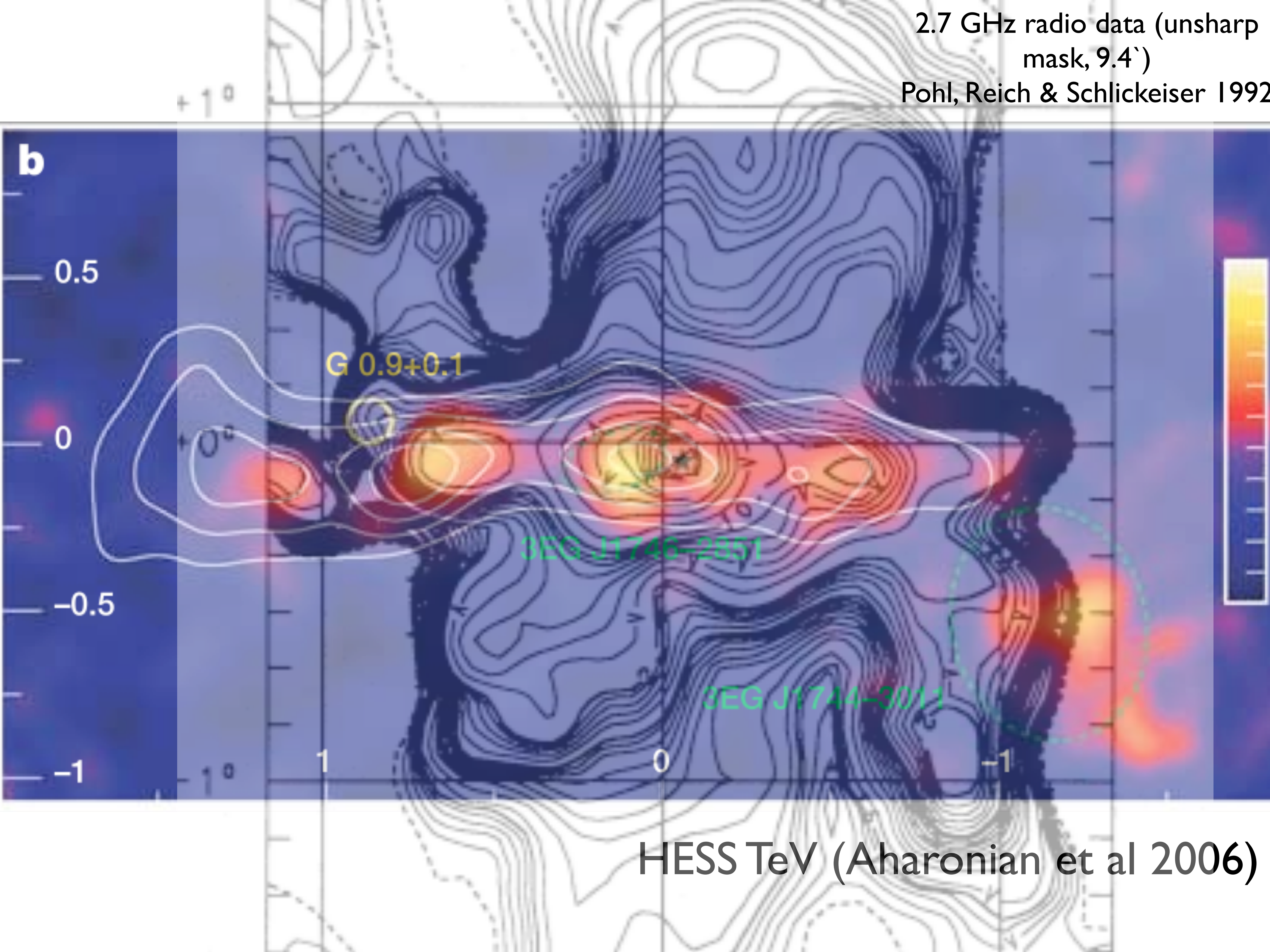
2.7 GHz radio data (unsharp mask, 9.4`)
Pohl, Reich & Schlickeiser 1992
b
0.5
0
–0.5
–1
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3EG J1746–2851
3EG J1744–3011
1
0
–1
+1°
+0°
-1°
HESS TeV (Aharonian et al 2006)

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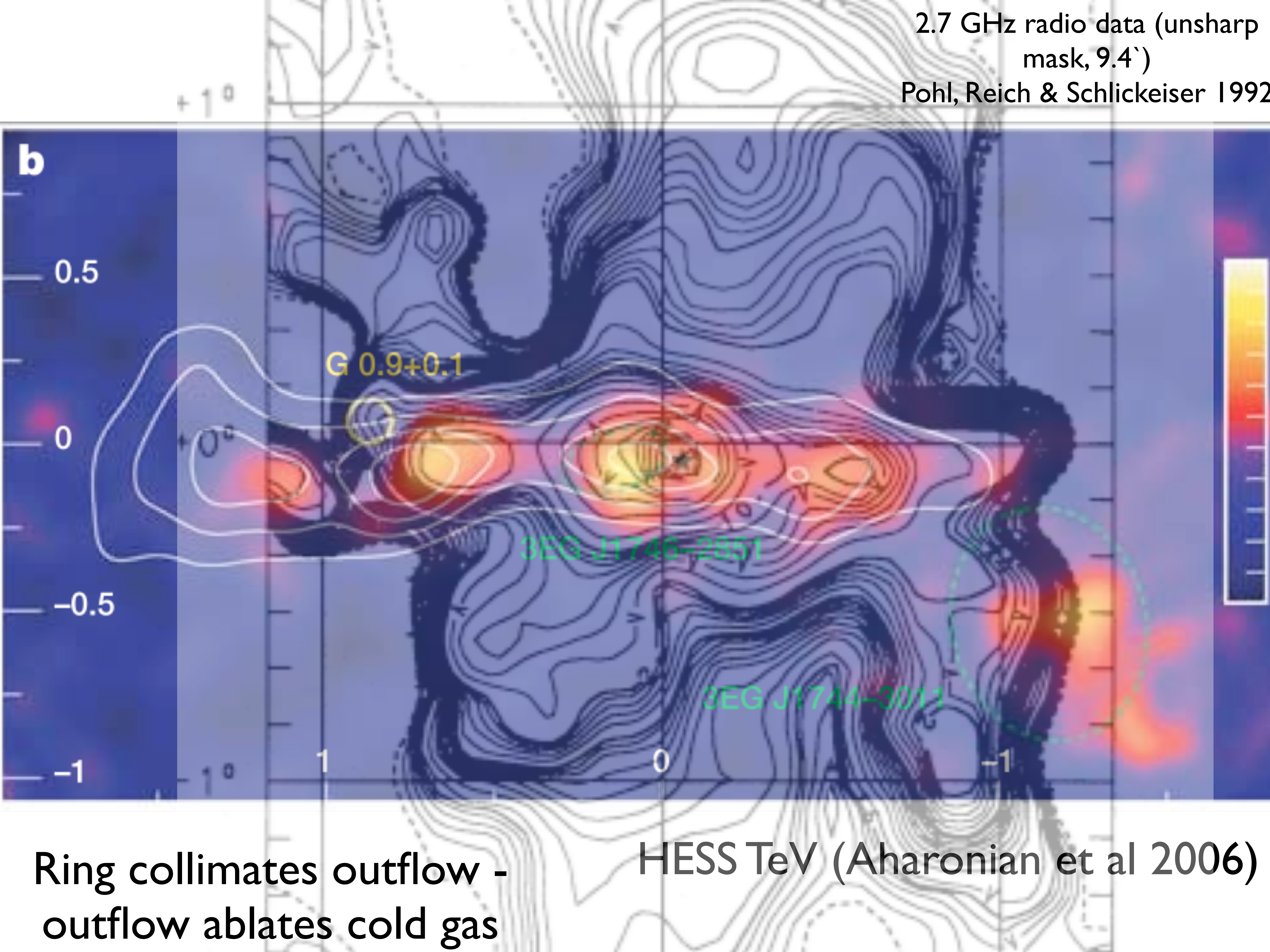


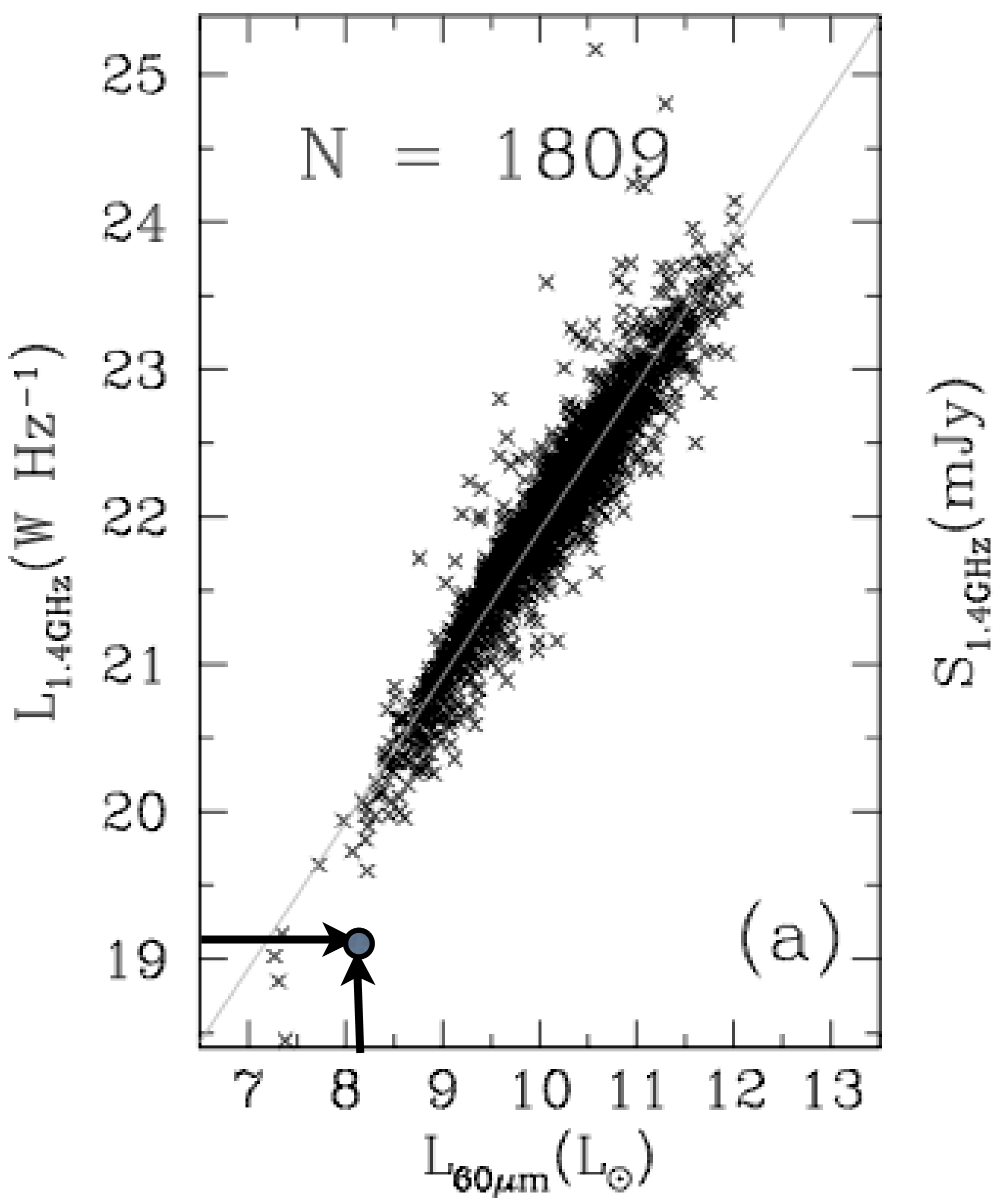
Ring collimates outflow - outflow ablates cold gas

HESS TeV (Aharonian et al 2006)

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

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



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

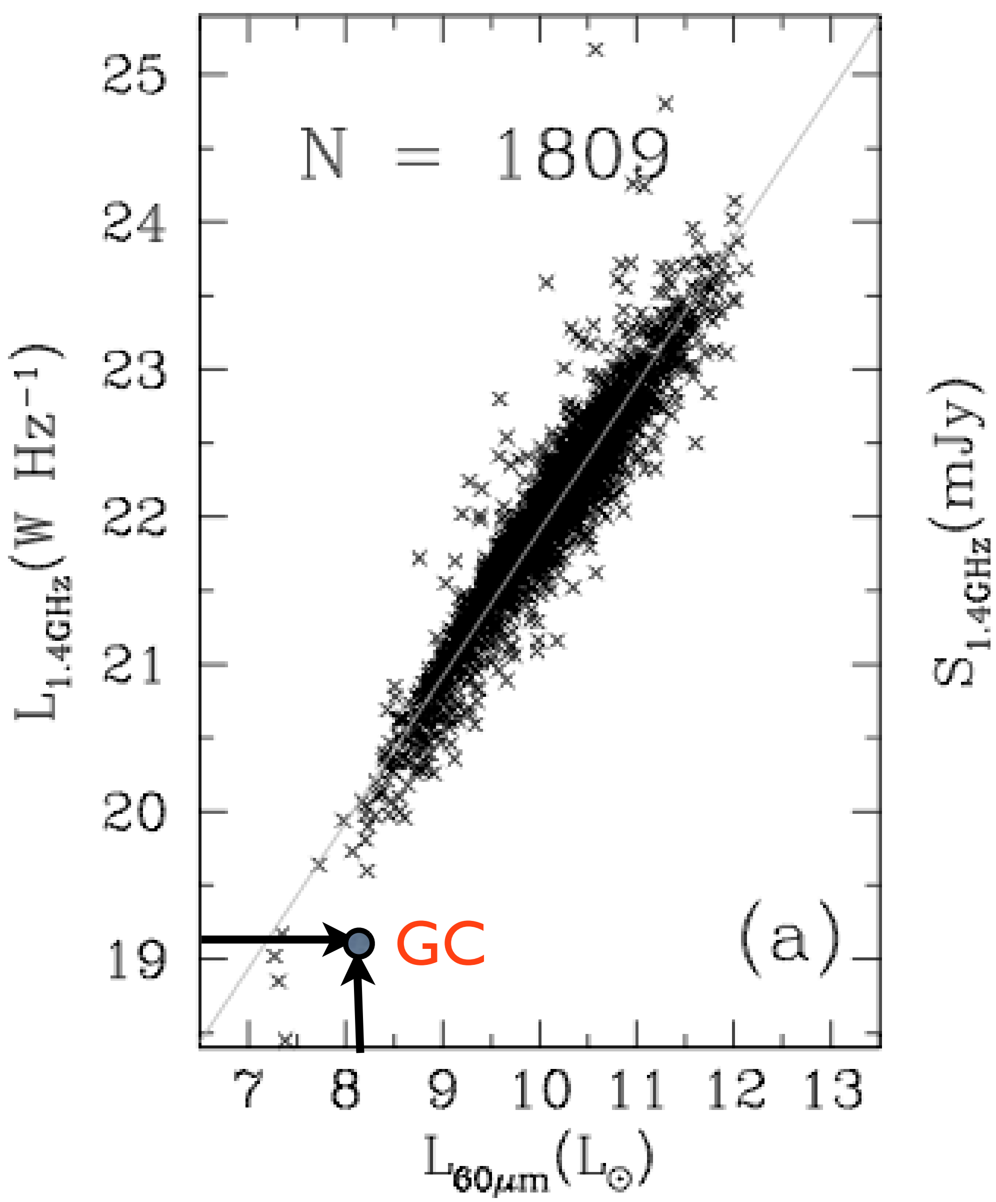
RC in deficit wrt expectation from FIR

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

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

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5



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RC in deficit wrt expectation from FIR

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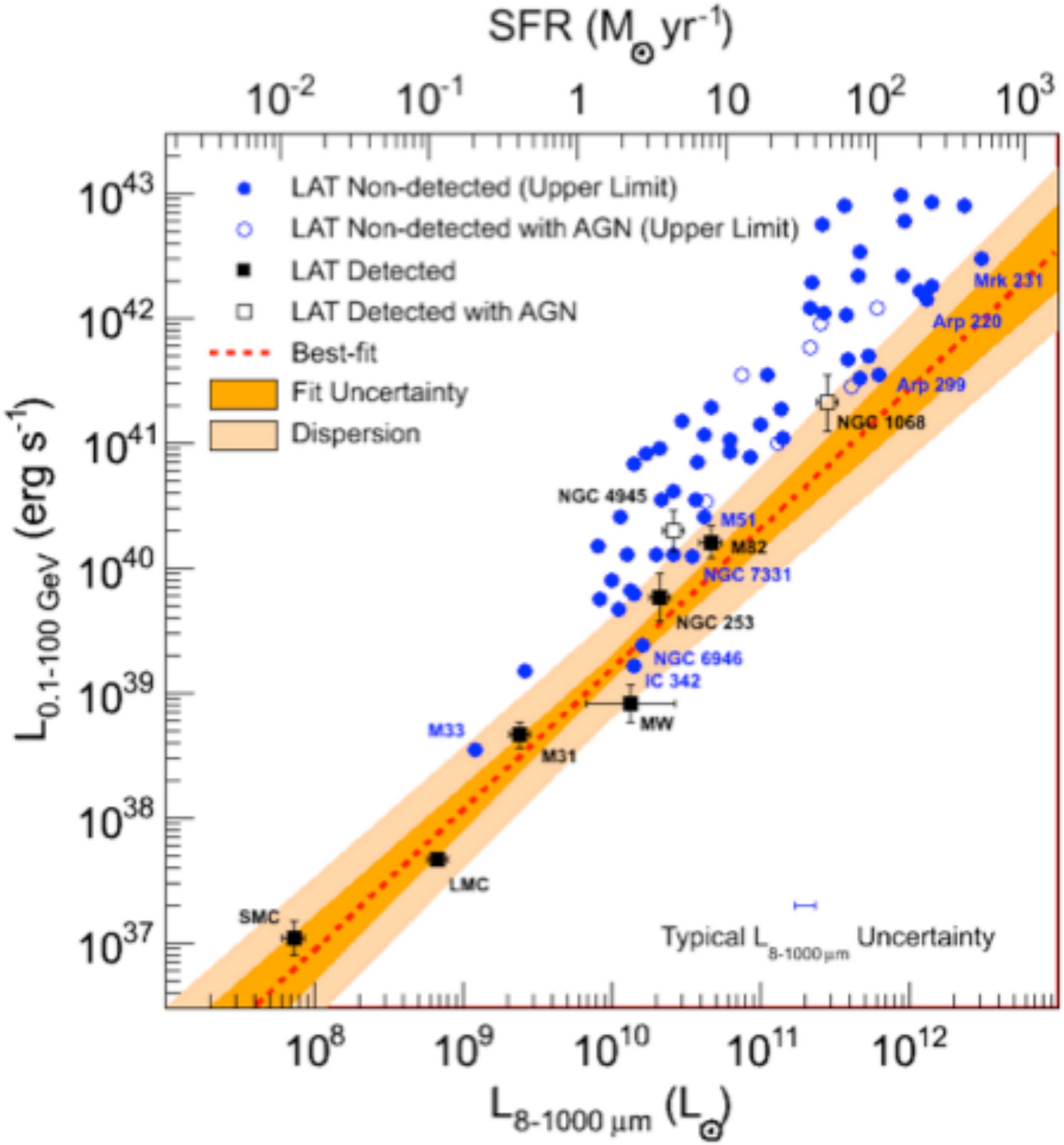
i.e. **GHz RC emission of HESS region only ~10% expected**

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

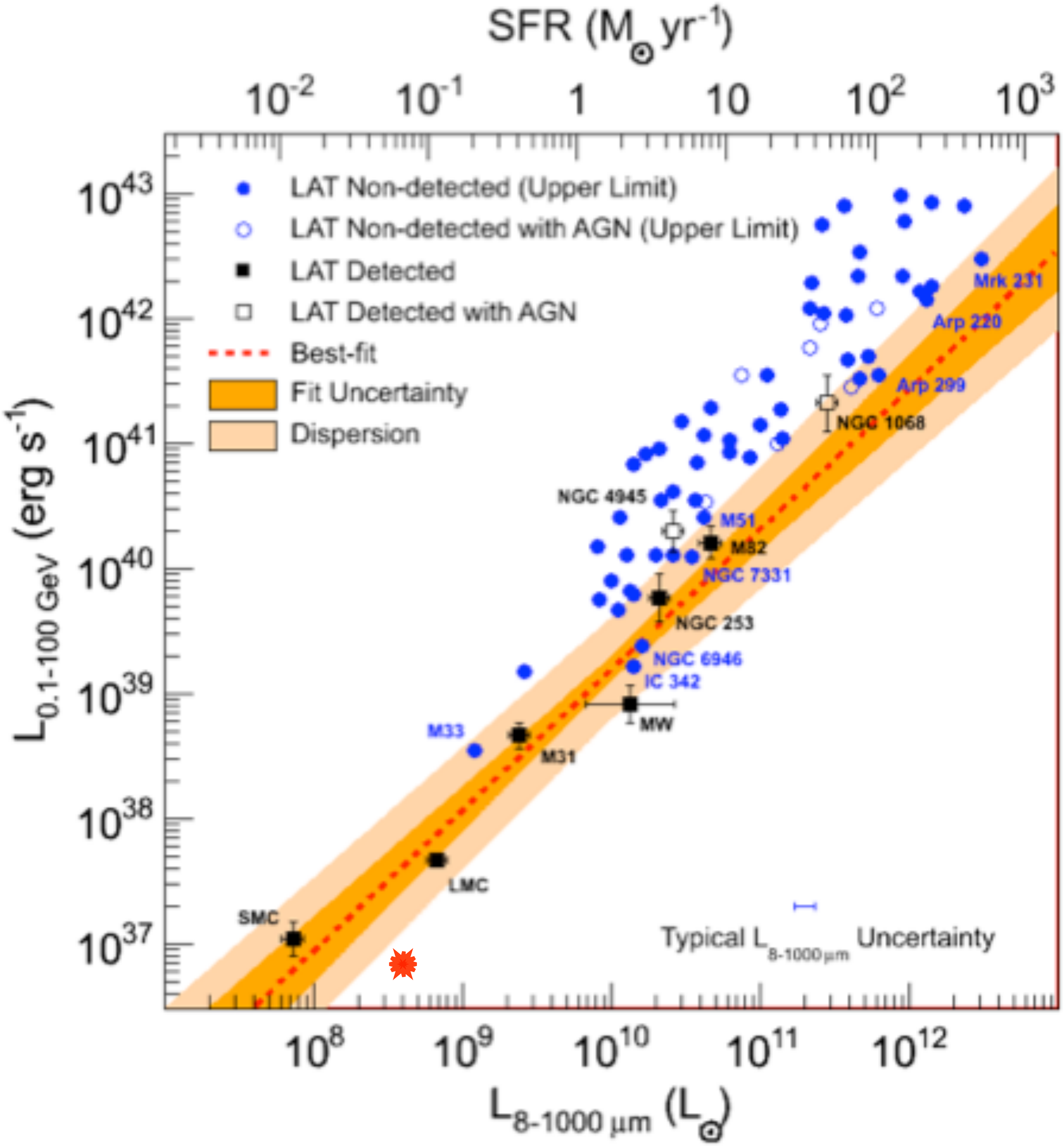
FIR-γ-ray Scaling?

- 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, **GeV emission only ~10% expected, TeV emission of HESS region only about 1% expected,**



Martin 2011, *Fermi collab*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).



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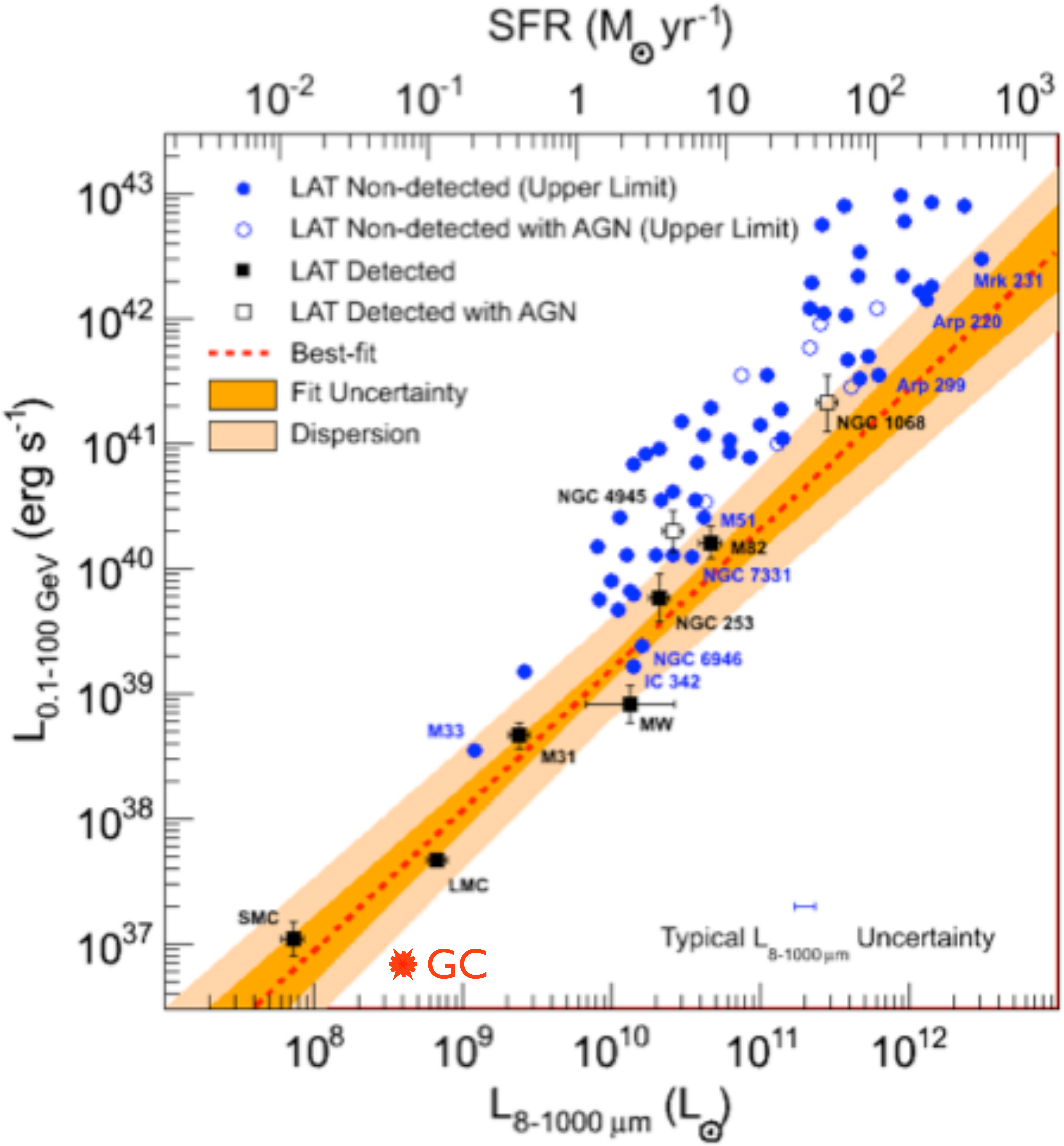


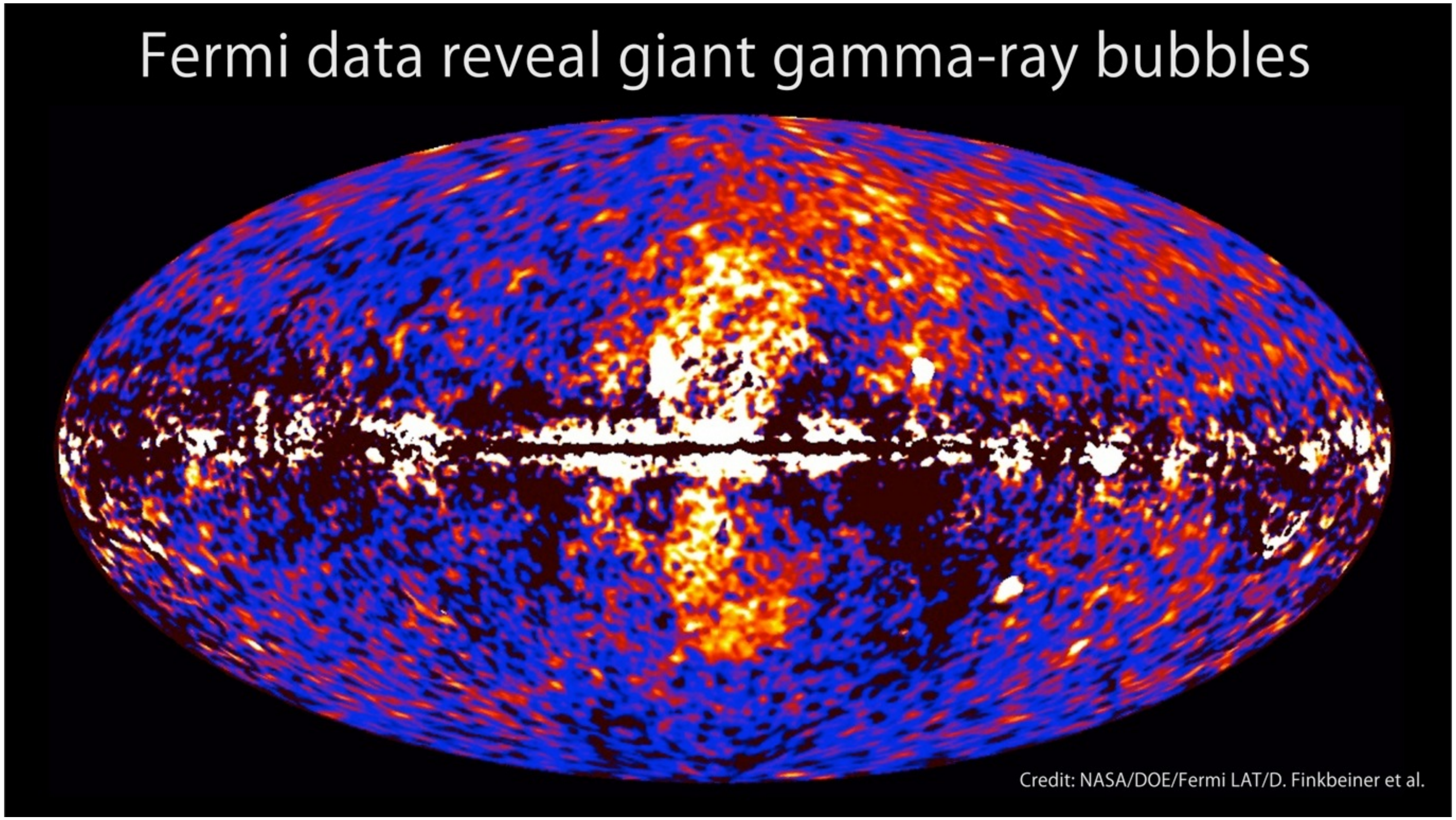
Martin 2011, *Fermi collab*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

…so, what is the fate of the advected cosmic rays?

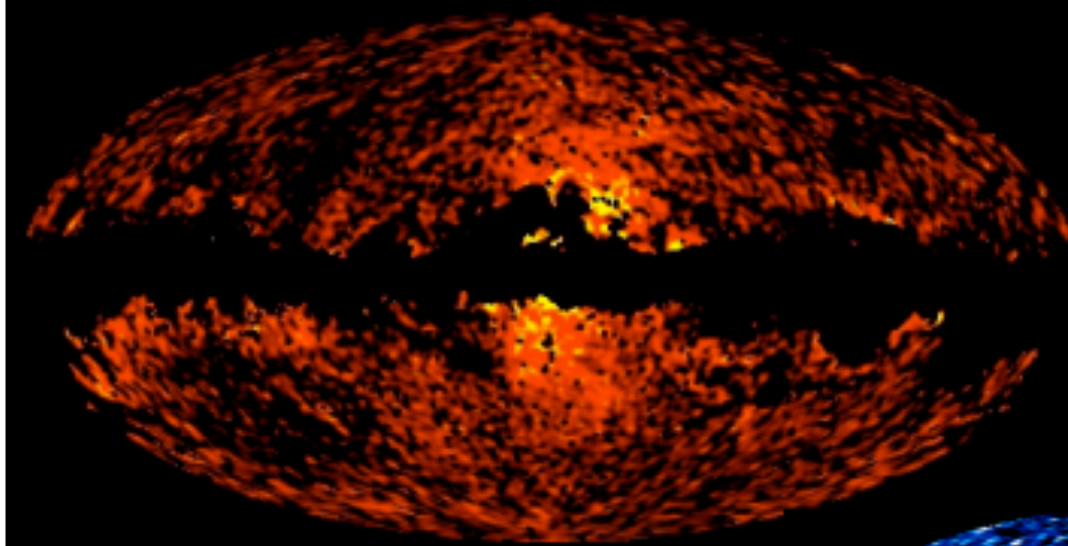
Much Wider Scales

Fermi Bubbles

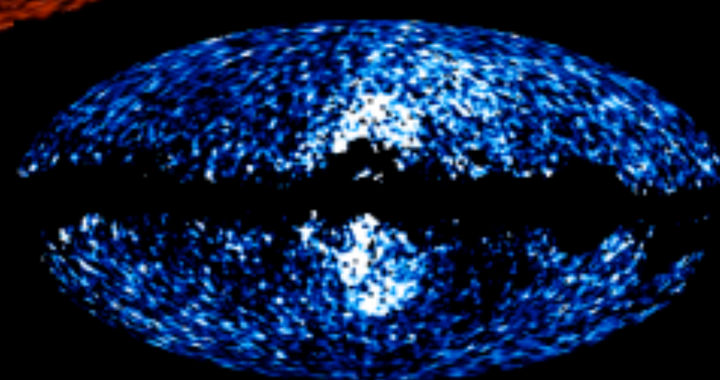


Su, Slatyer and Finkbeiner 2010 (ApJ)

PLANCK images a giant eruption from the heart of the Milky Way

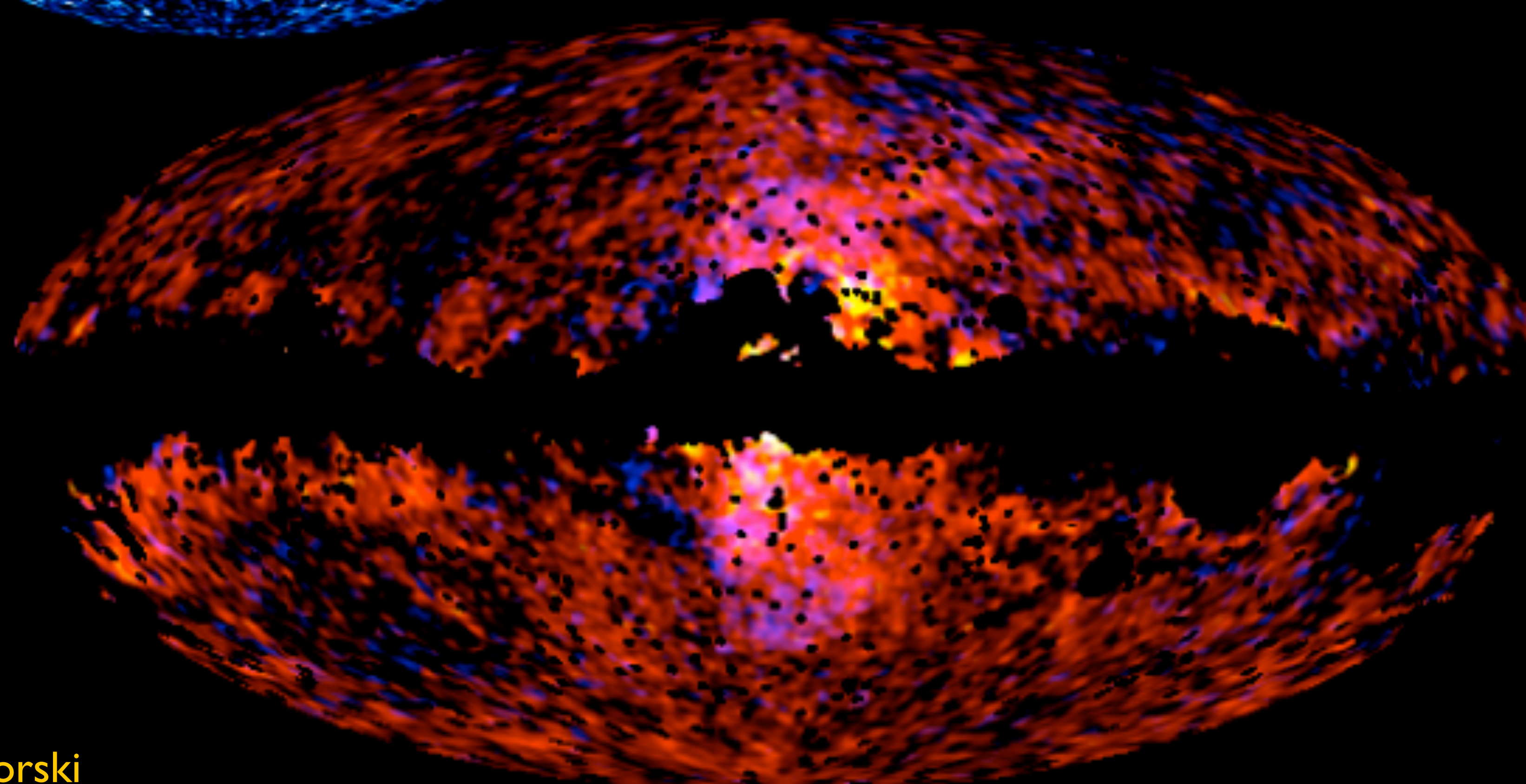


The Galactic haze/bubbles is shown here in *PLANCK* data from *30-44* GHz



The same structure at 2-5 GeV as seen by the *Fermi Gamma-Ray Space Telescope*

A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK 30* GHz (red), *44* GHz (green), and *Fermi* 2-5 GeV (blue).



Slide credit: D. Pietrobon & K.M. Gorski
Planck Collab.

Fermi Bubbles

- 2 x 10^{37} erg/s [1-100 GeV]
- hard spectrum, but spectral down-break below ~ GeV in SED
- uniform intensity
- sharp edges
- coincident emission at other wavelengths
- vast extension: ~7 kpc from plane
- $\gtrsim$ few 10^{55} erg

Fermi Bubbles: Two Interlocking Questions

1. What is the radiation mechanism?

Cosmic ray electrons/Inverse Compton emission

OR Cosmic ray protons/gas collisions

2. What energizes the outflow?

Recent Seyfert-like activity of Sgr A*

OR Nuclear star formation **OR** tidal disruption of stars by SMBH **OR** dark matter **OR** ….

Leptonic Scenarios

- ~GeV γ-ray emission from IC on CMB and ISRF by hypothesised population of hard-spectrum ~TeV electrons
- same population synchrotron-radiates into microwave frequencies
- BUT short cooling time (Myr) ⇒ near-relativistic transport OR in situ acceleration

Hadronic Scenario

Crocker & Aharonian PRL 2011

- Bubbles' gamma-ray luminosity requires a source of protons of power ~10^{39} erg/s *in saturation*
- This *is* the power supplied by nuclear SF
- BUT low $n_H \Rightarrow$ long pp cooling time, ~few Gyr (!) to establish steady state

A New Twist on the Fermi Bubbles

Ettore Carretti (**PI**), Roland M. Crocker,
Lister Staveley-Smith, Marijke Haverkorn,
Cormac Purcell, B. M. Gaensler,
Gianni Bernardi, Michael J. Kesteven, Sergio Poppi

Nature 2013, 493, 66

S-PASS Survey

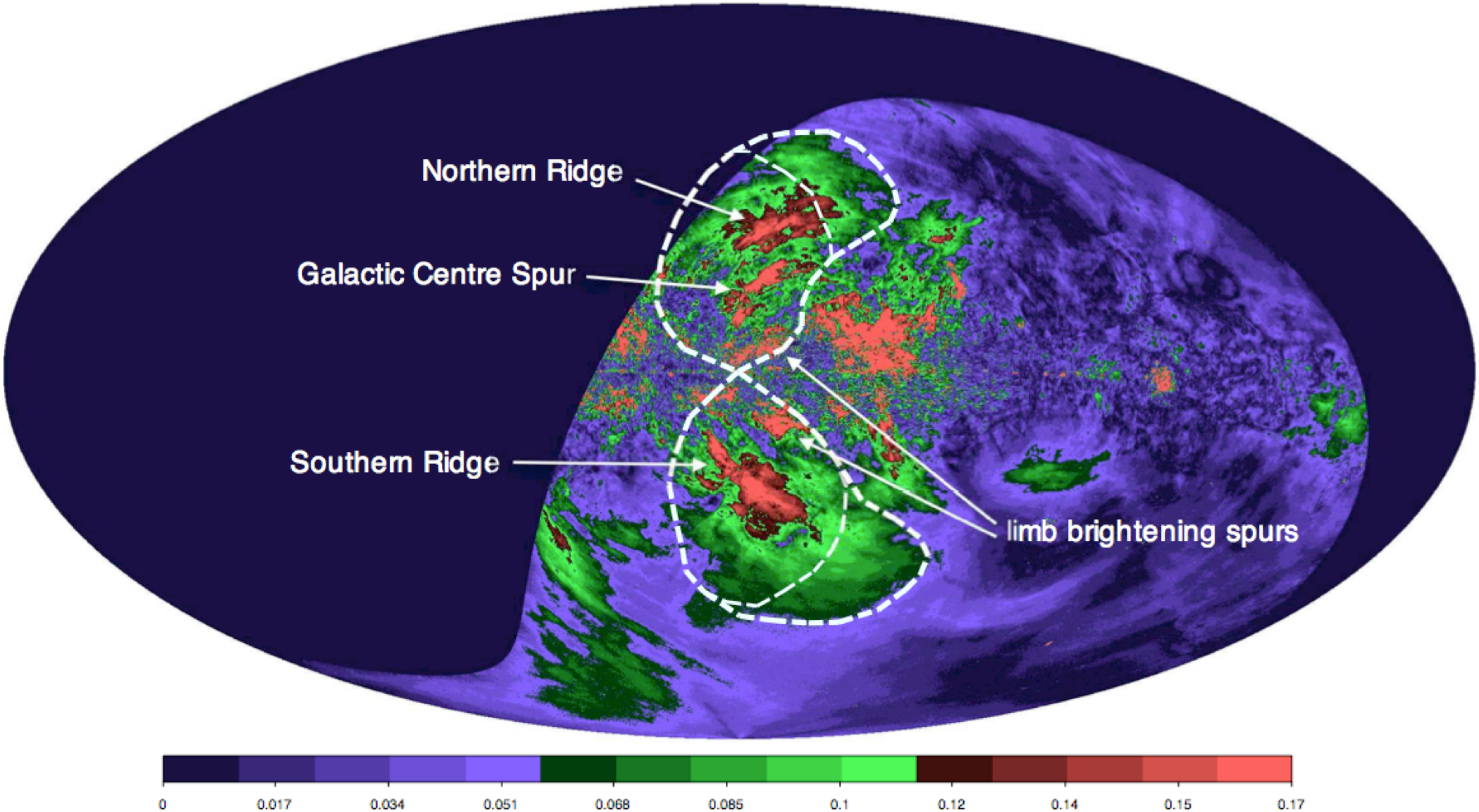
2.3 GHz RC polarization survey of southern sky with Parkes 64-m single disk, 184 MHz BW

S-PASS Survey

2.3 GHz RC polarization survey of southern sky with Parkes 64-m single disk, 184 MHz BW

‘The Dish’, 51 years old

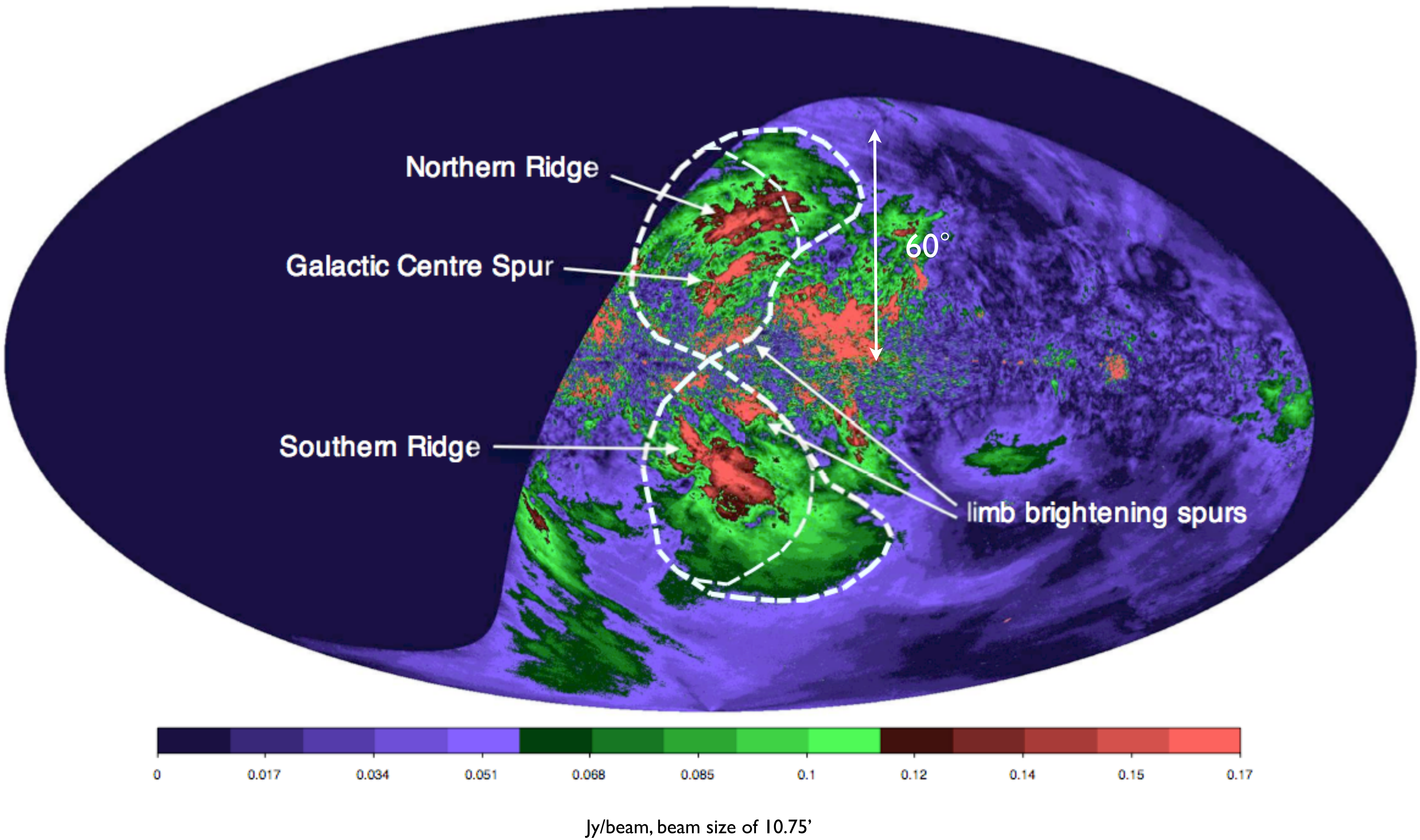
The ‘S-PASS Lobes’



Jy/beam, beam size of 10.75’

Carretti et al. Nature 2013

The ‘S-PASS Lobes’



Carretti et al. Nature 2013

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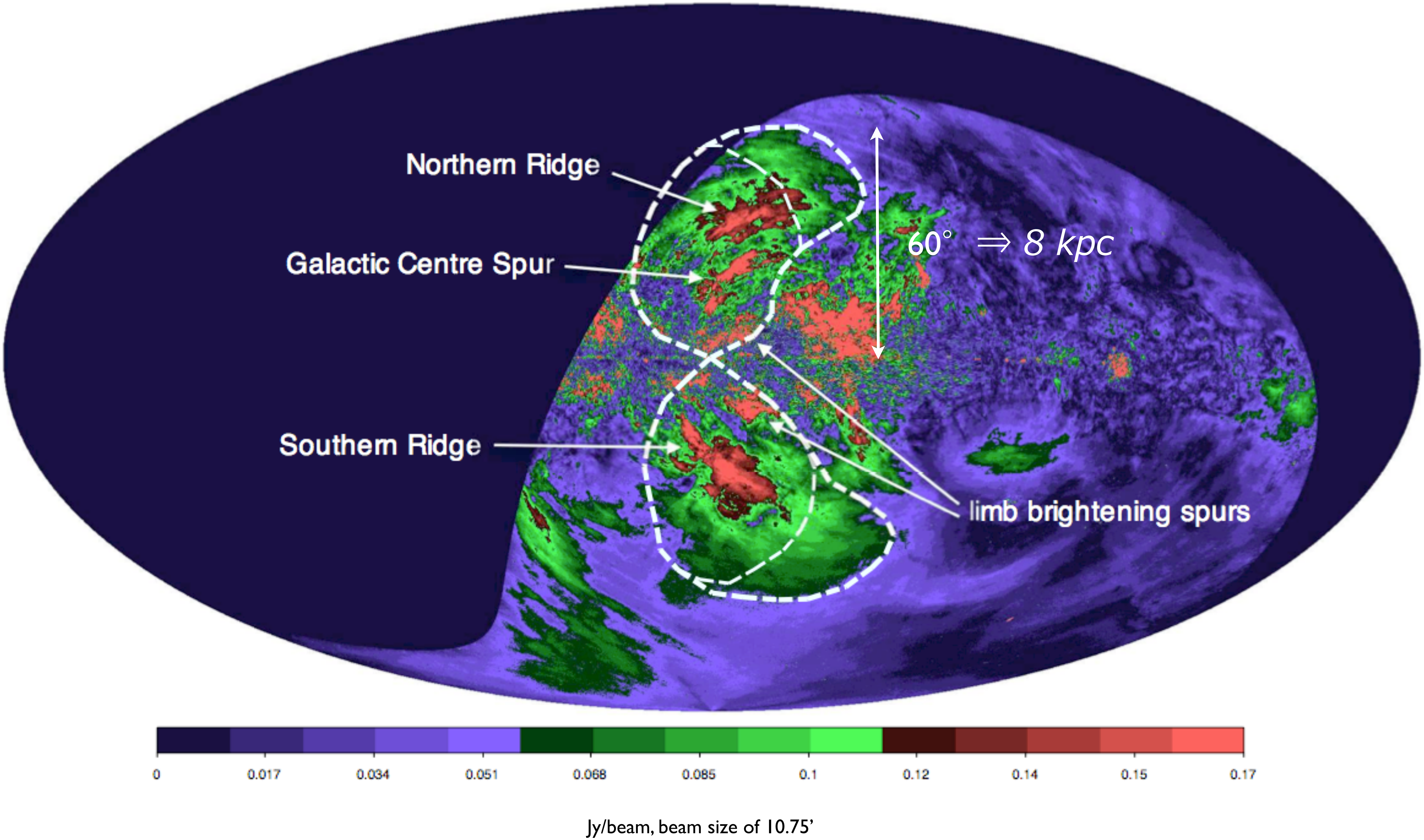

Carretti et al. Nature 2013

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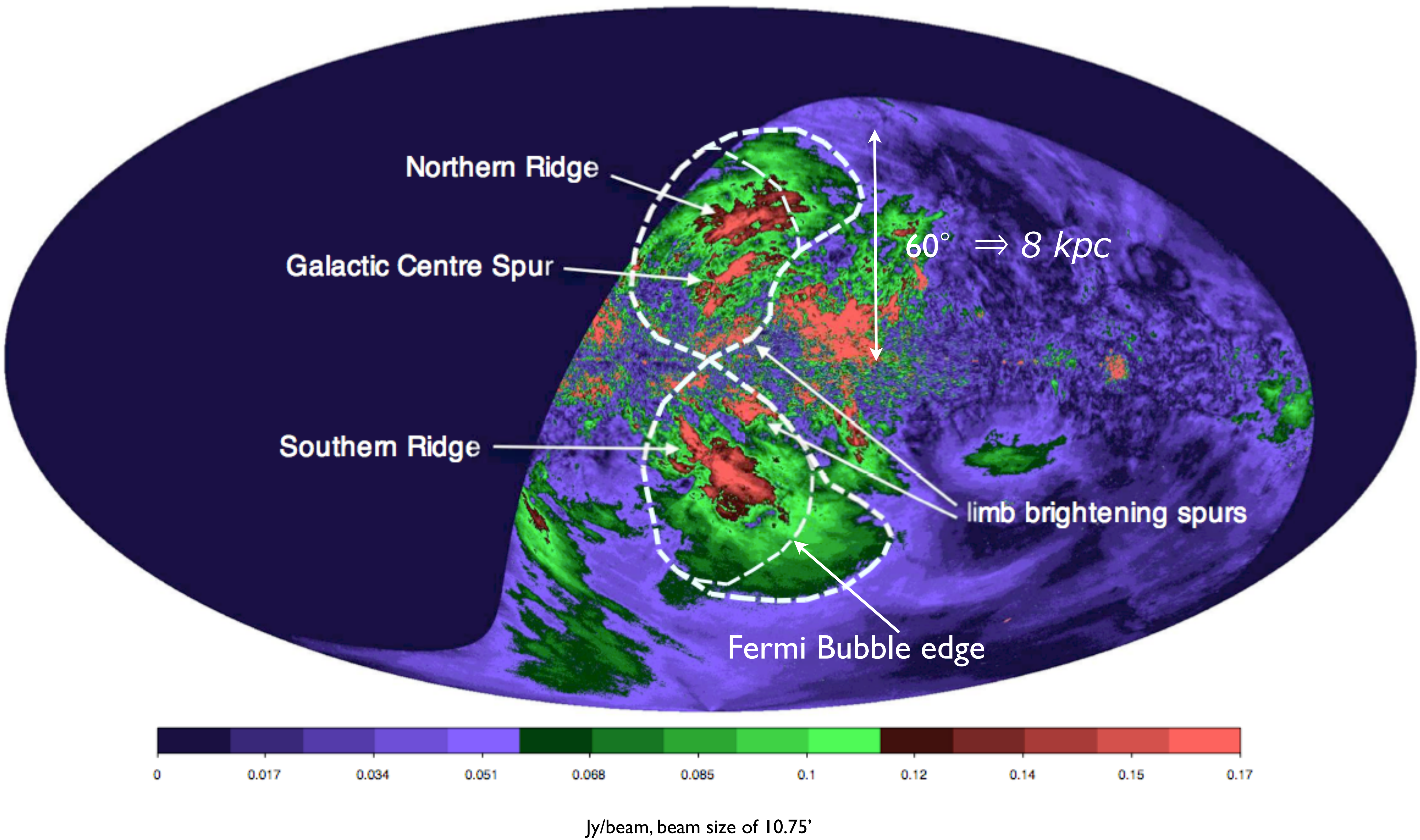

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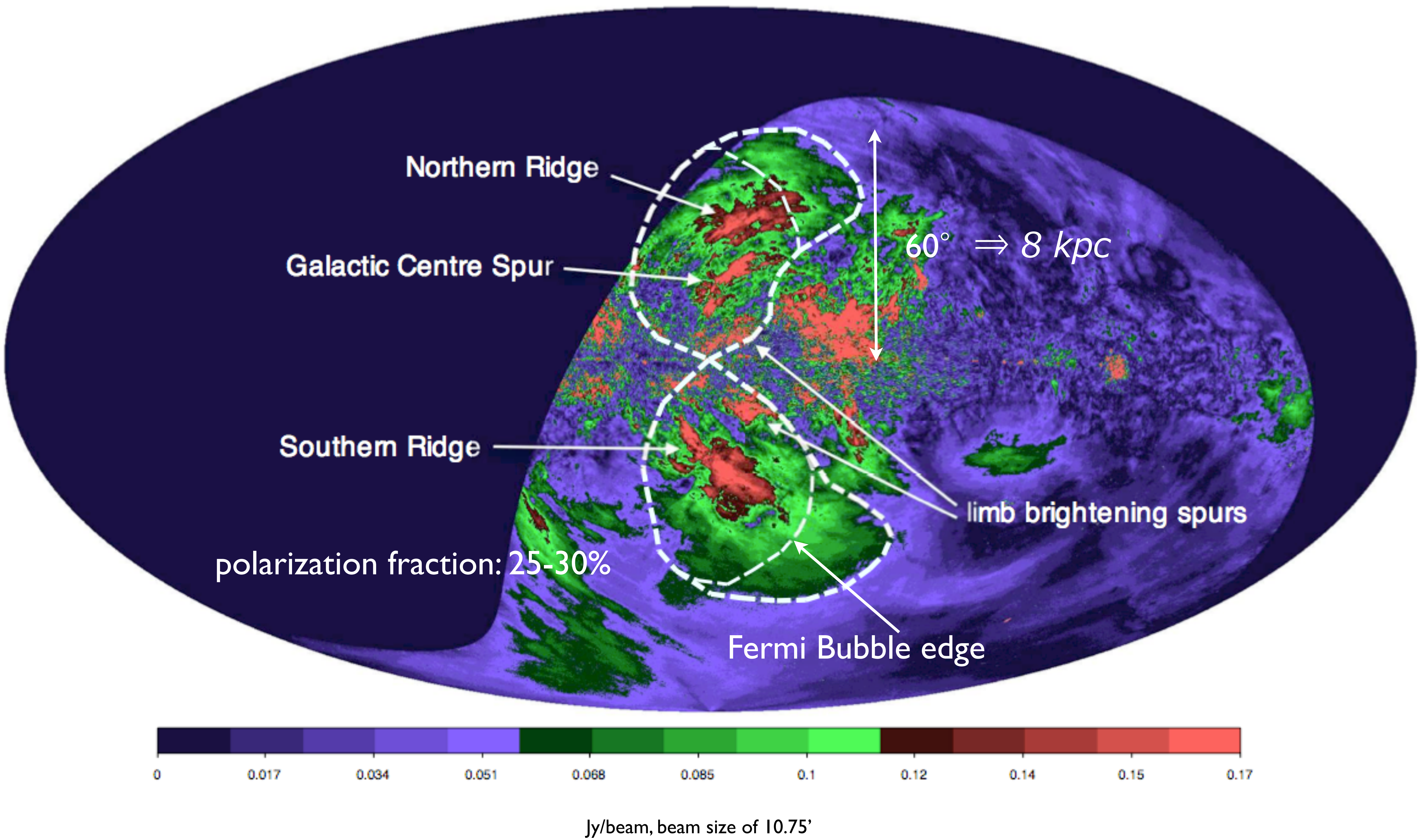
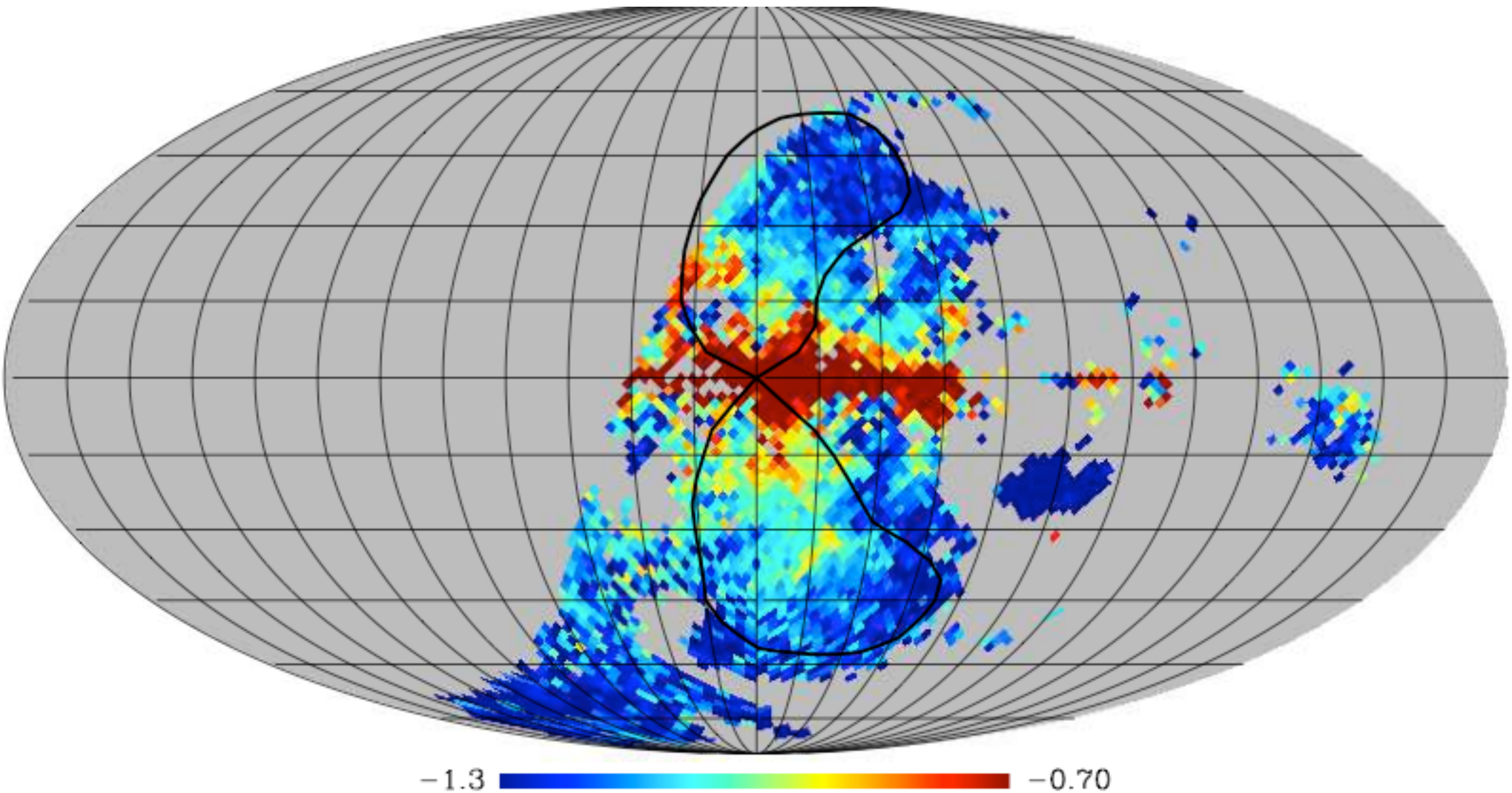


Carretti et al. Nature 2013

Spectral index between *polarized* 2.3 and 23 GHz emission

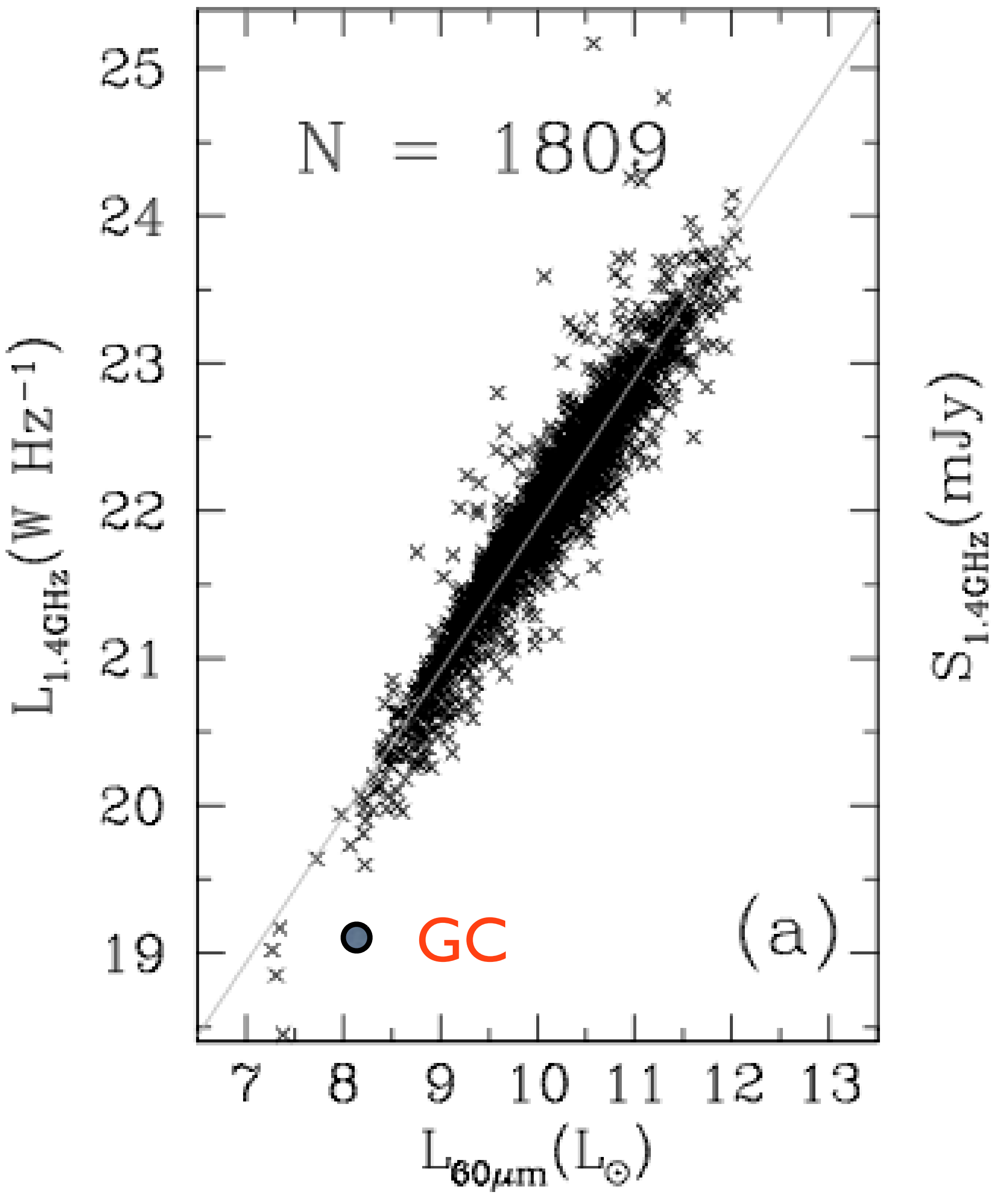


linearly-polarized emission interior to the Lobes spans the range

$\alpha = [-1.0, -1.2] \quad (S_\nu \propto \nu^\alpha)$

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5



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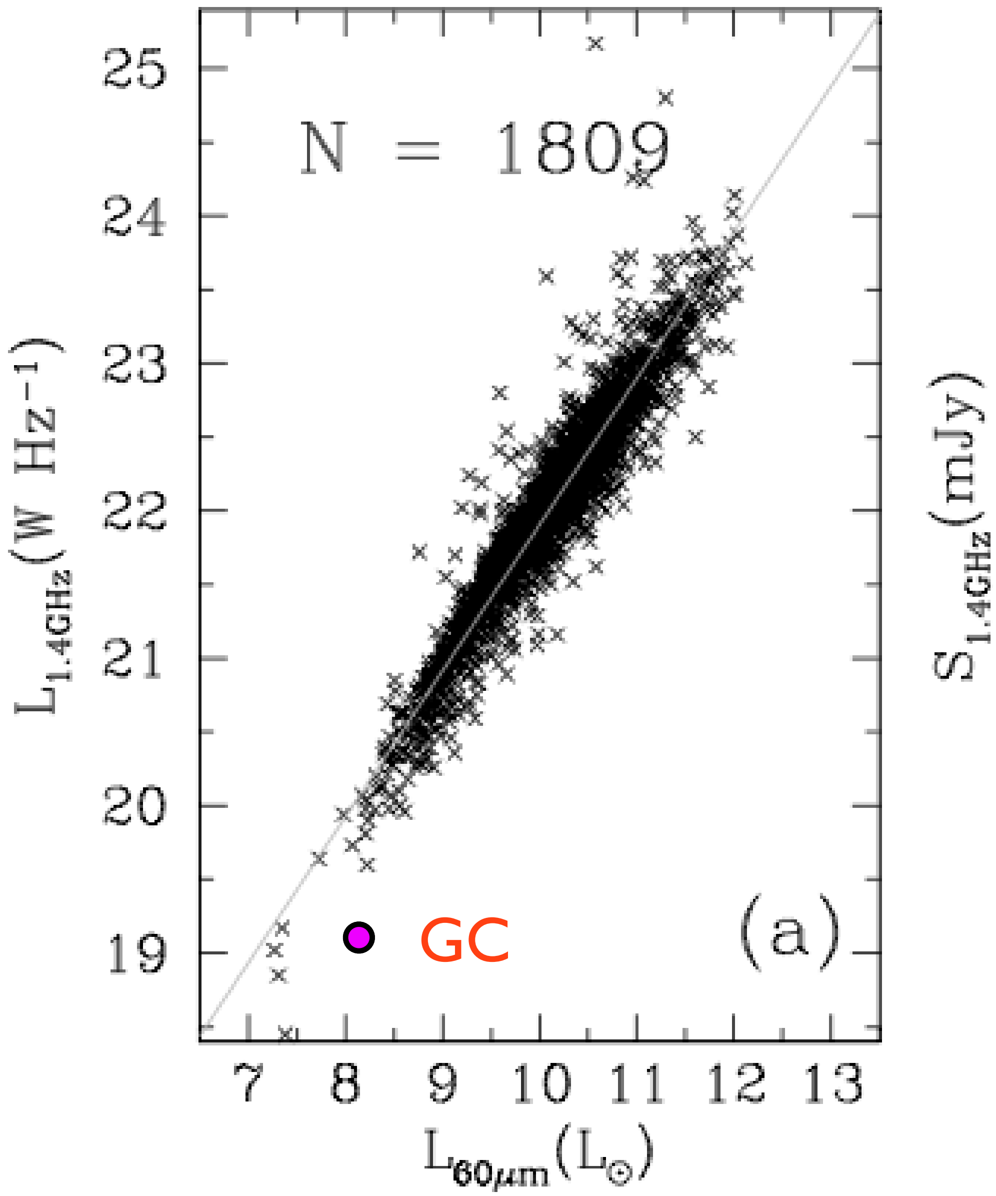

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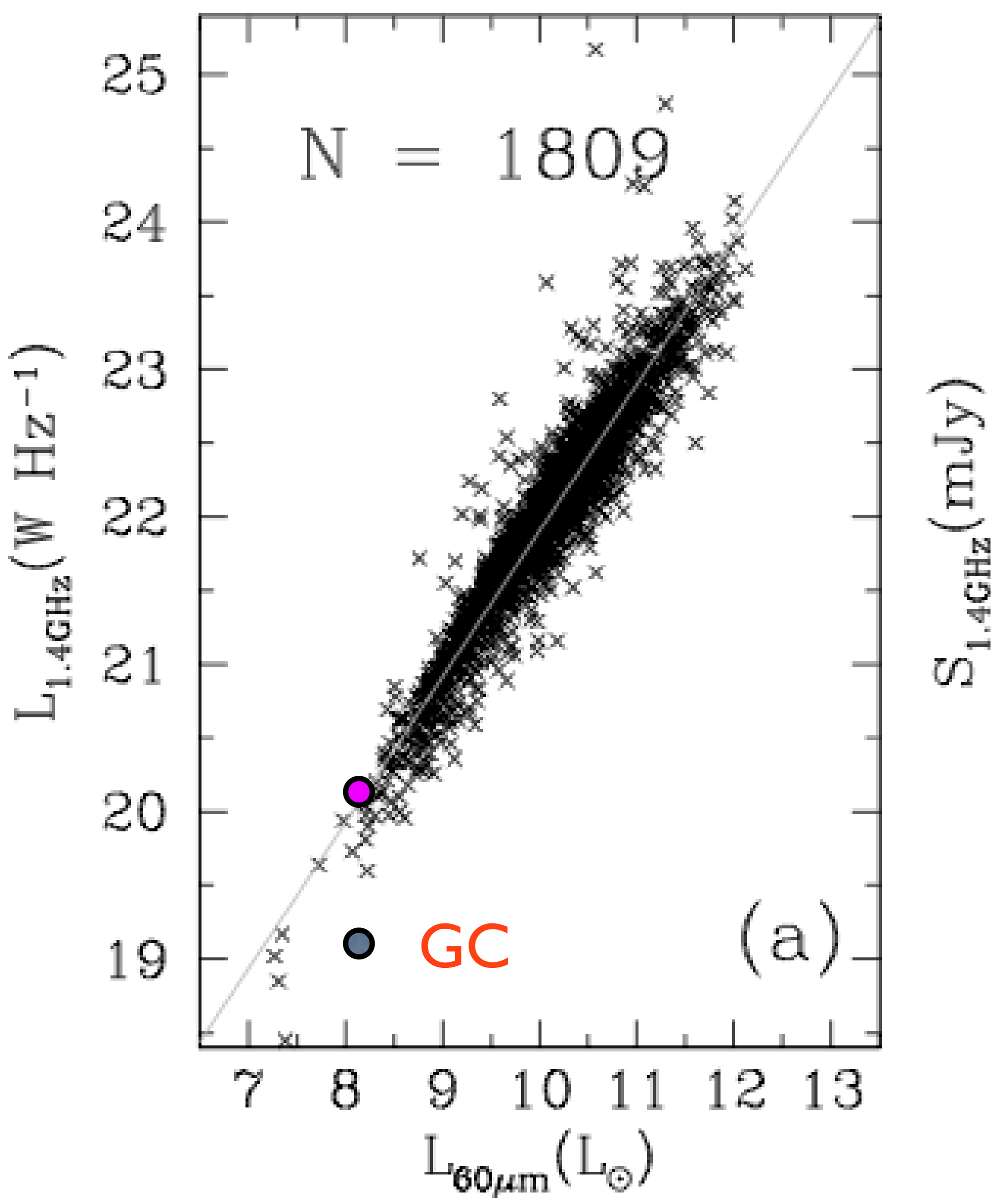

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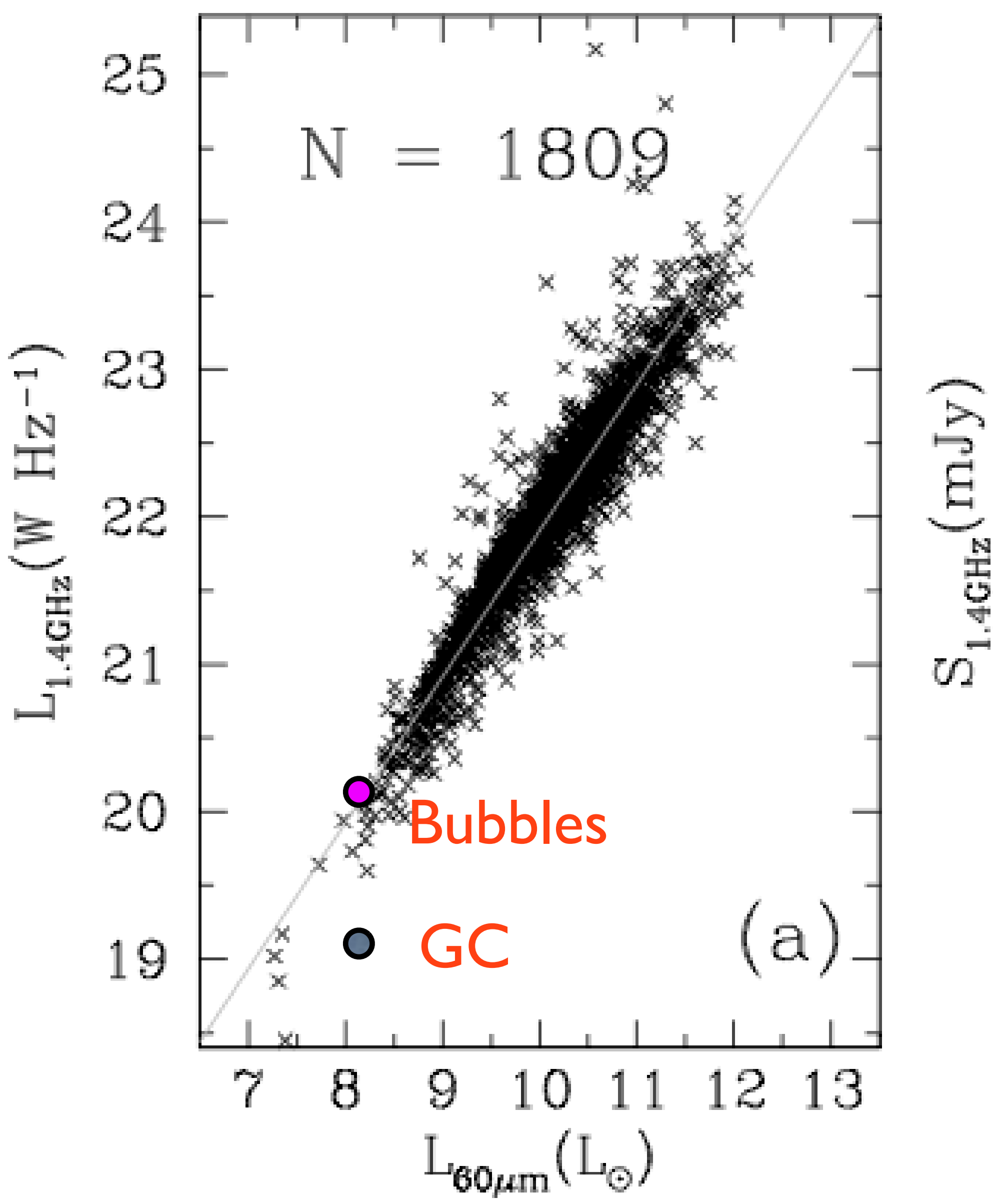

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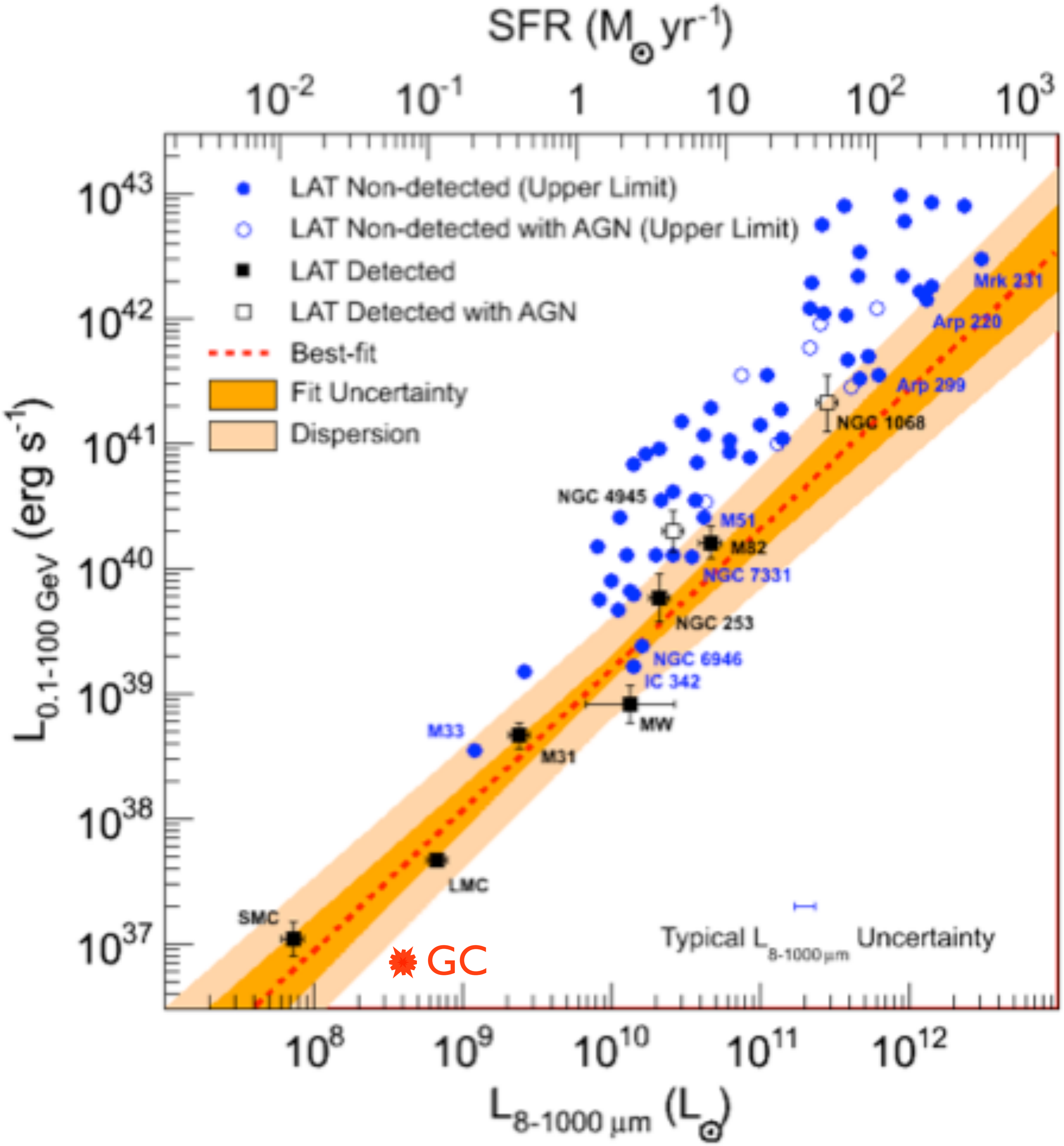
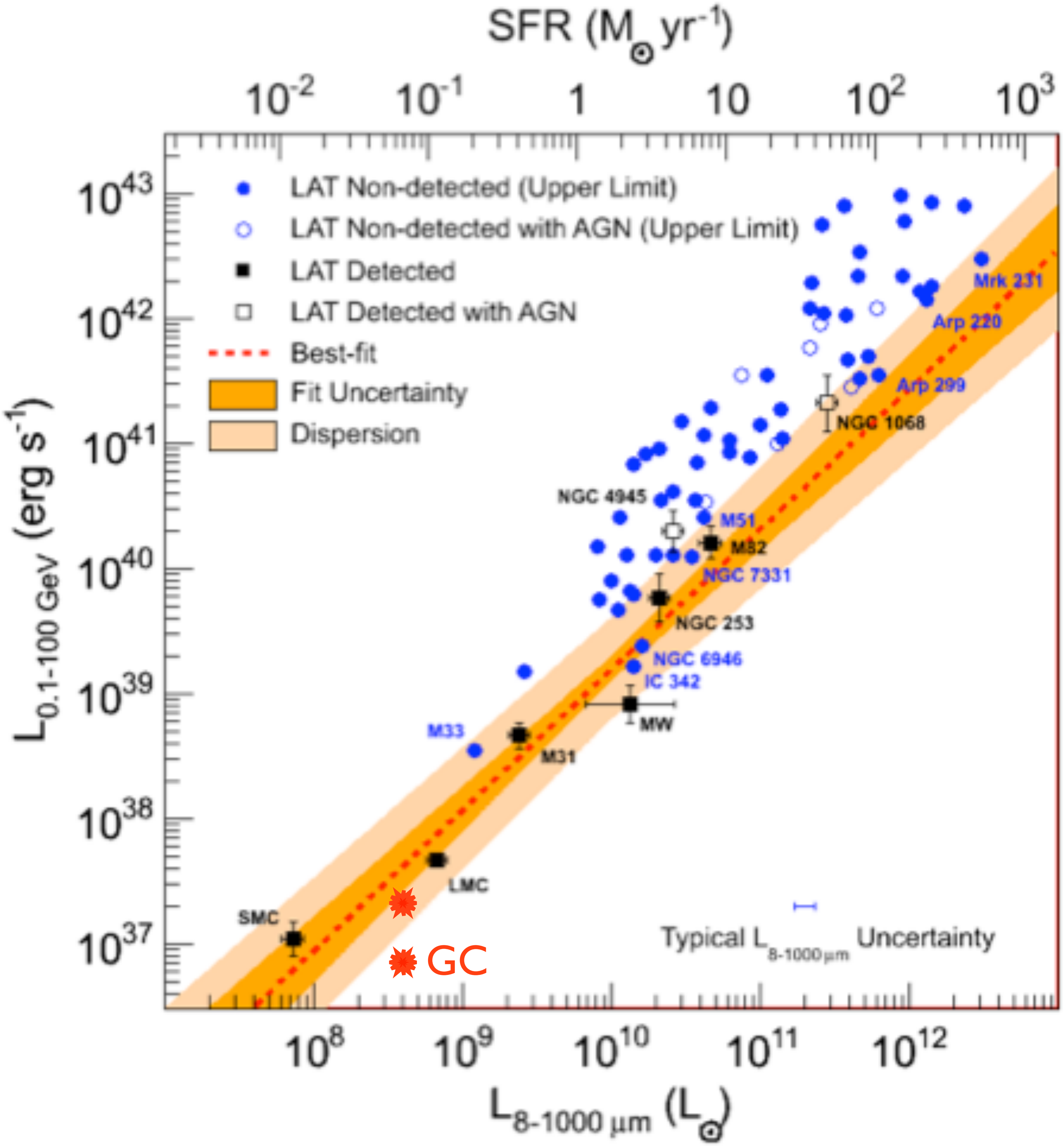


Martin, *Fermi collab*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).



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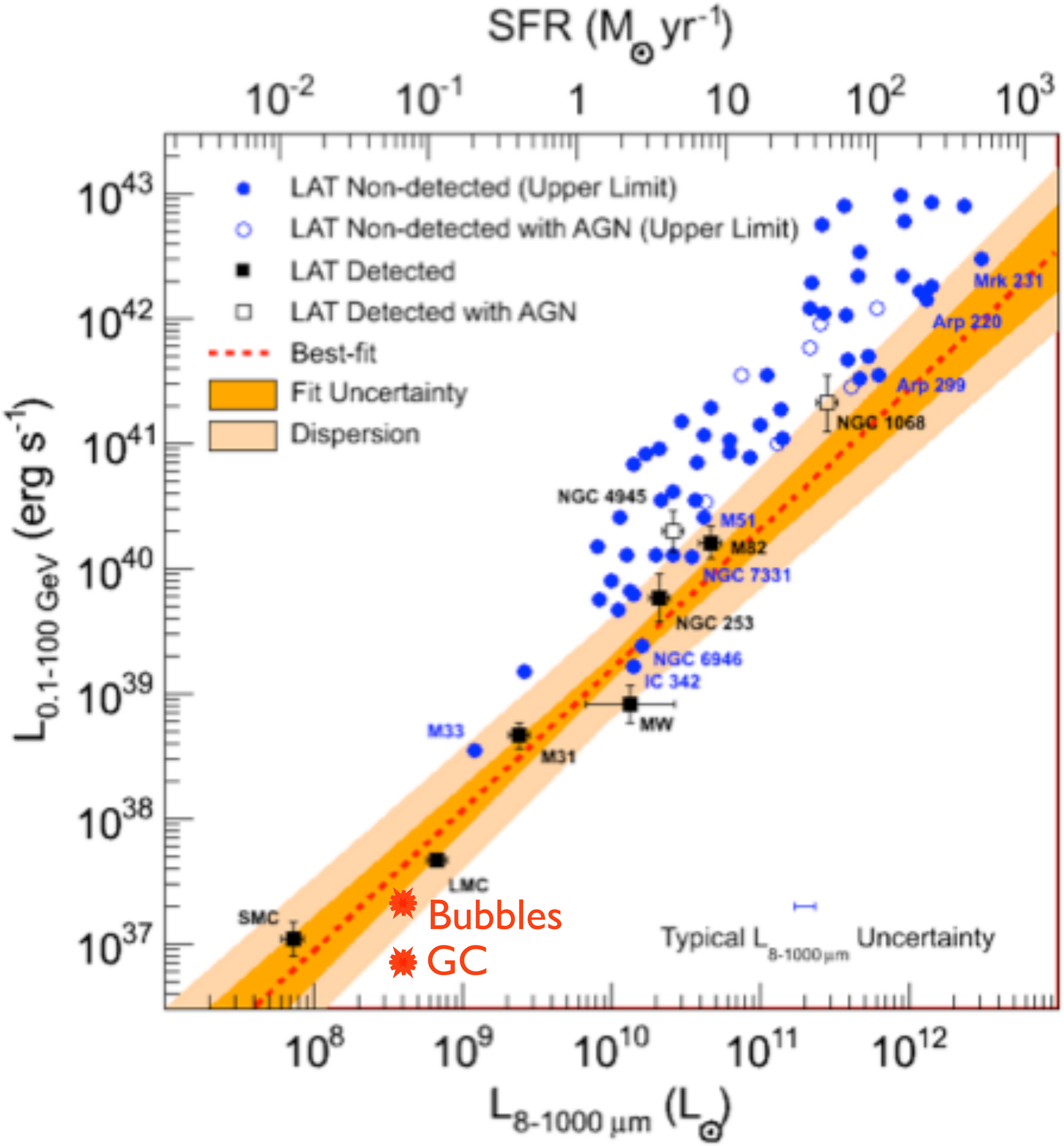


Martin, *Fermi collab*

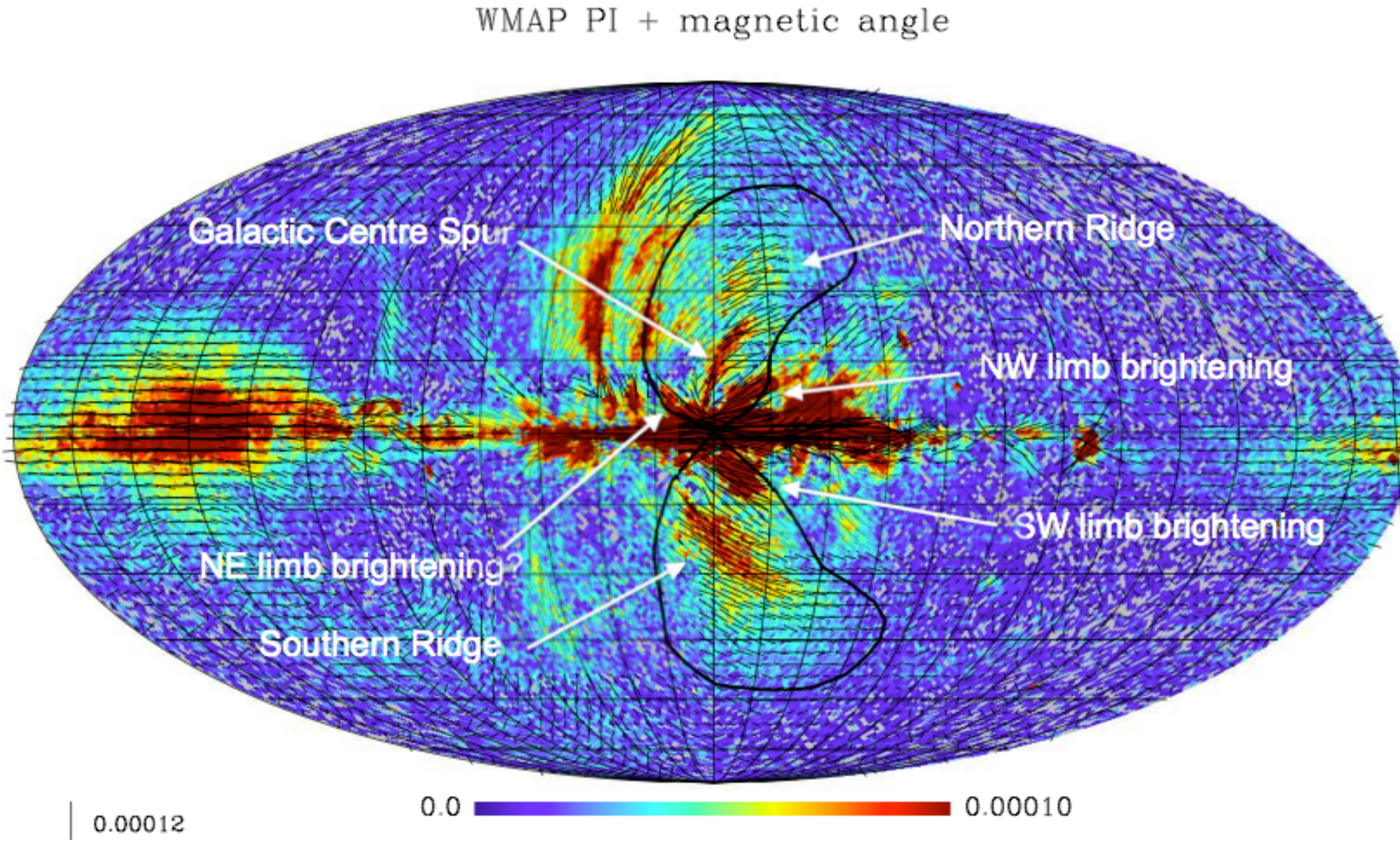
Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

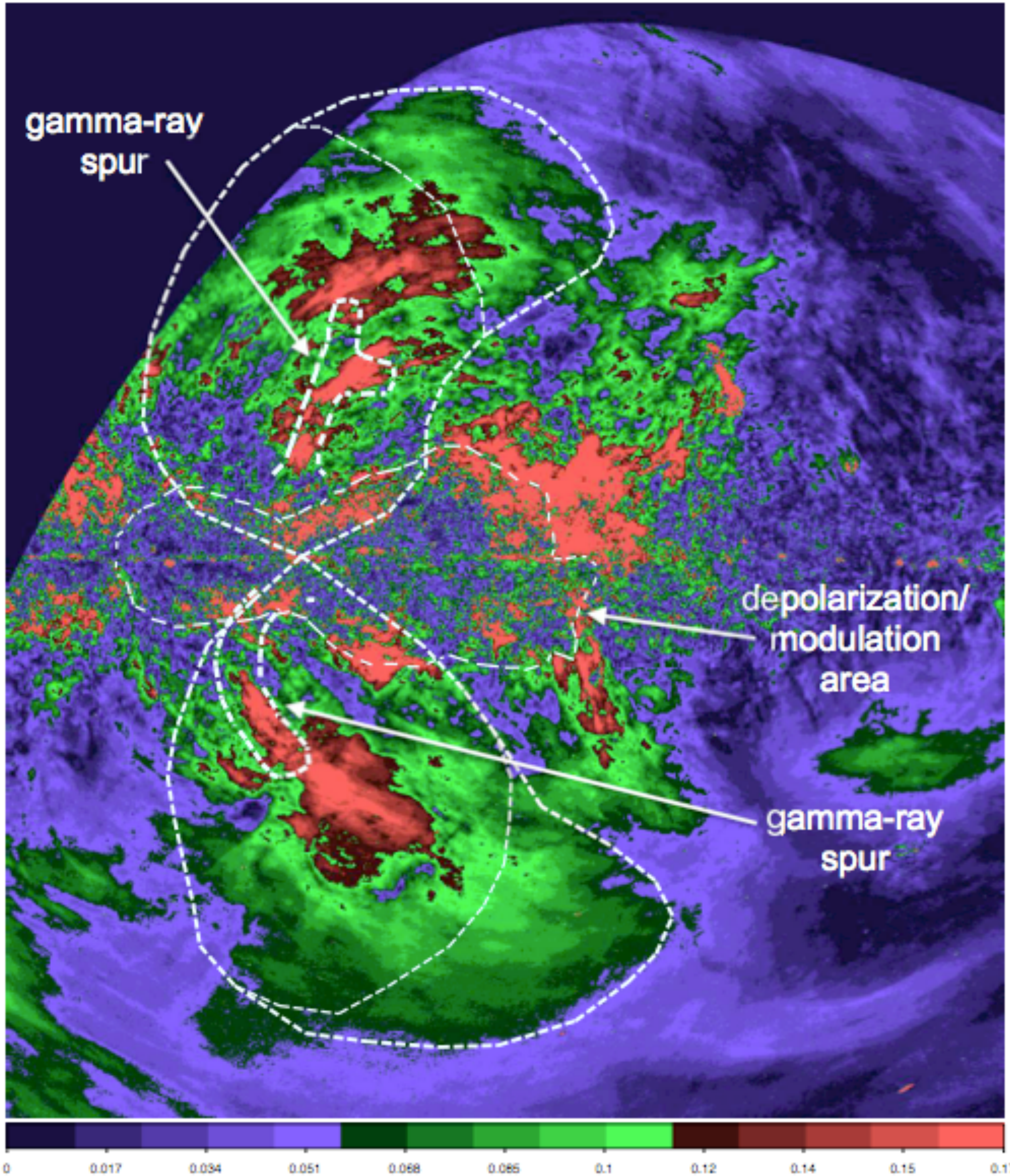
Points

- S-PASS Lobes are the second largest structures in the Galaxy ***only discovered in 2012***
- ~10 μG field extends from GC many kpc out into halo ⇒ consequences for cosmic ray propagation/confinement

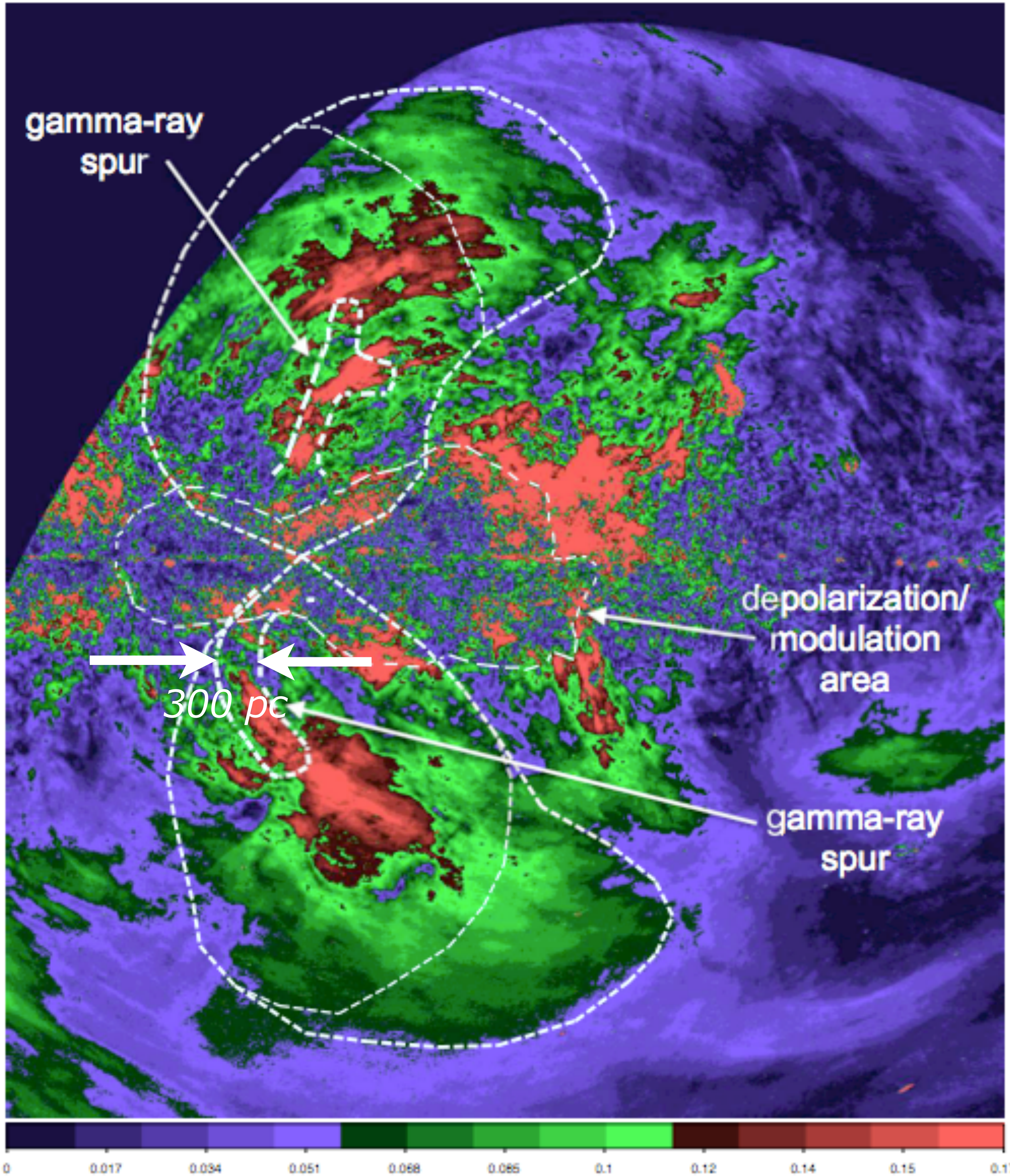
Extra Slides

23 GHz Polarized Intensity from WMAP





depolarization phenomenology implies in Bulge



depolarization
phenomenology
implies in Bulge

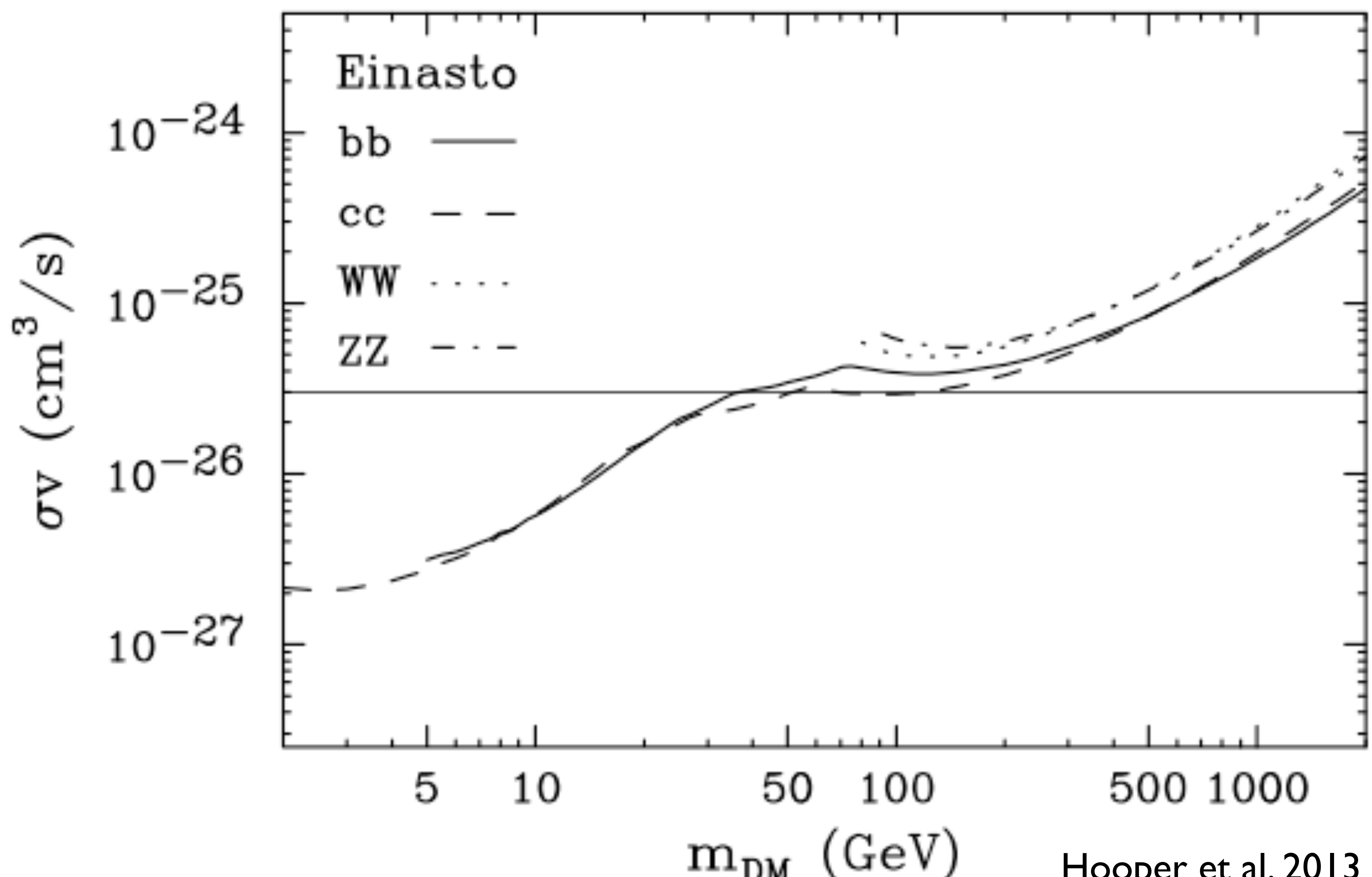
Hooper et al.: few GeV Bump

- Claim: ~10-30 GeV WIMP annihilating to leptons with a weak-scale cross-section $\langle v\sigma \rangle$~2 x 10^{26} cm^3/s can explain a number of anomalies:
  - spectrum and angular distribution of gamma rays from the Inner Galaxy ($|b| < 20^\circ$)
  - the spectra of the NTFs
  - the microwave "haze"
  - low-energy signals claimed by/for direct detection experiments DAMA/LIBRA, CoGeNT and CRESST-II.

Conservative approach:

- use the non-thermal GC observations to present upper limits to DM annihilation cross-sections
- e.g., recent approach of Hooper, Kelso, & Queiroz to establish upper limits: subtract off a larger and larger DM component from the observed signal until significant region of the sky has negative flux
- these limits depend on decay/annihilation mode branching ratios
- and strongly depend on the DM density profile assumed

Conservative approach:

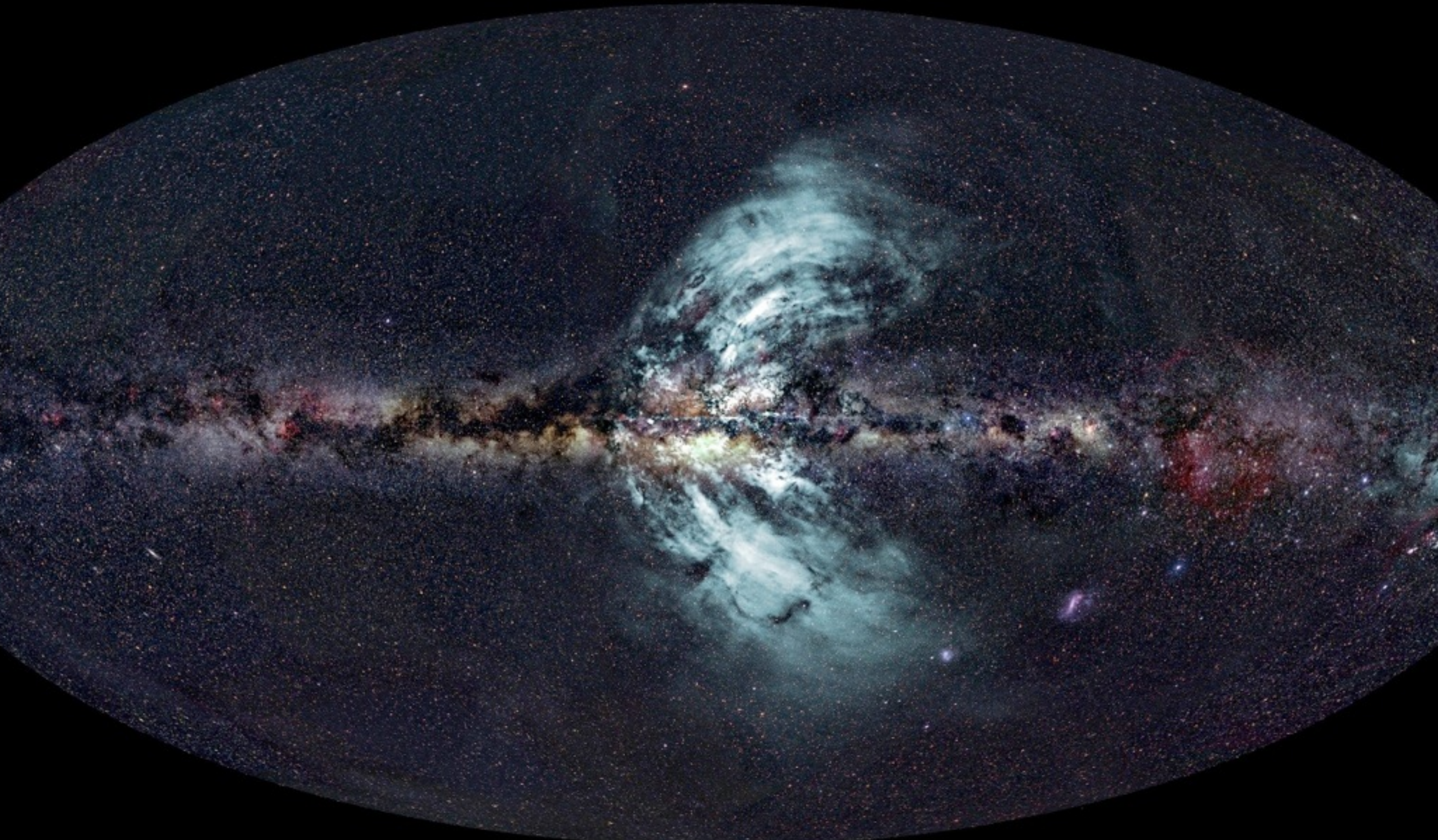


Hooper et al. 2013

Conservative approach:

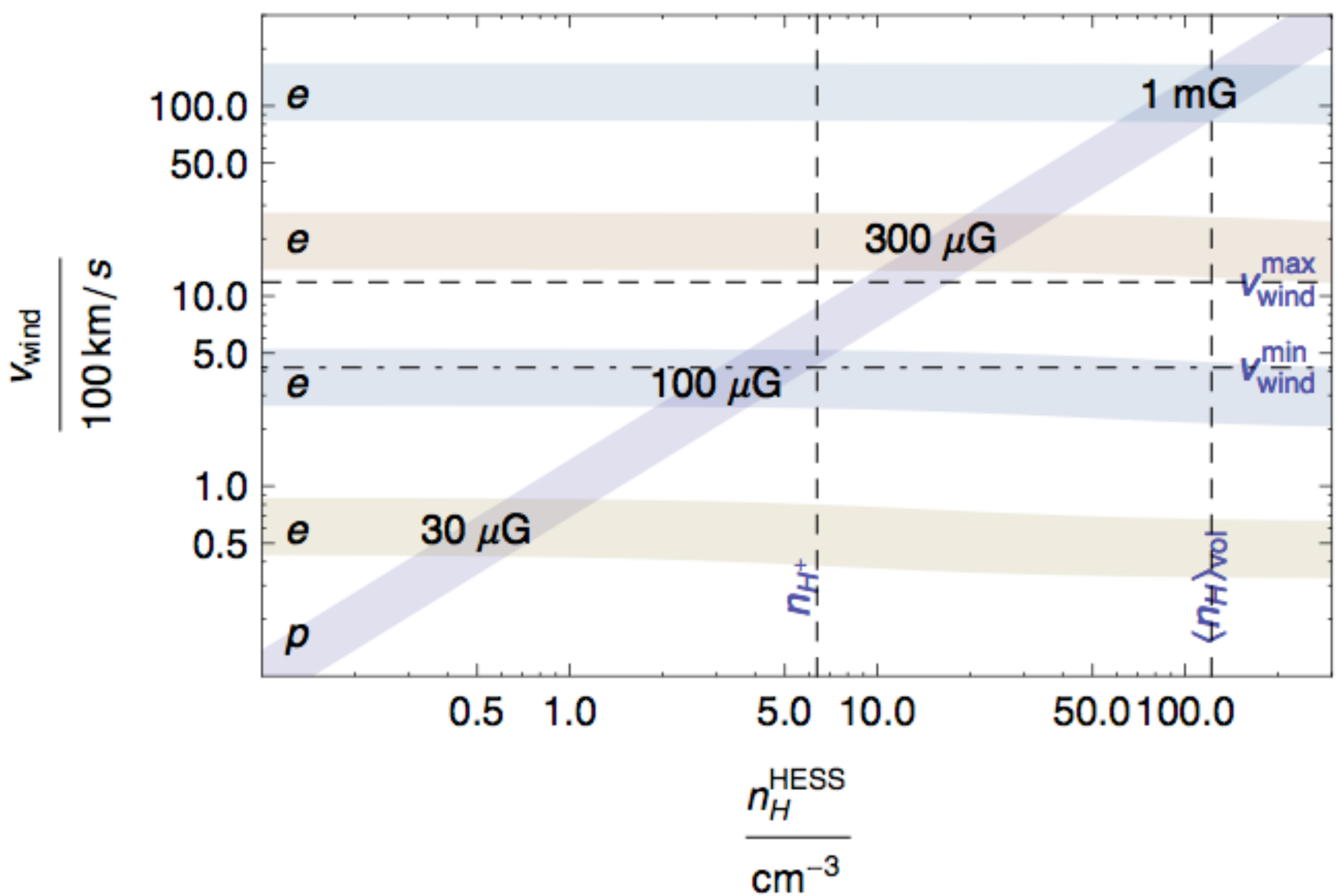
- AND even with the conservative approach: *astrophysical* uncertainties can limit our knowledge of what the theoretical dark matter signal should look like.

- E.g., recent paper by Cirelli, Serpico and Zaharijas: bremsstrahlung cooling important in forming the steady state, (dark matter annihilation) secondary electron distribution and uncertainties around gas distribution in the GC are large



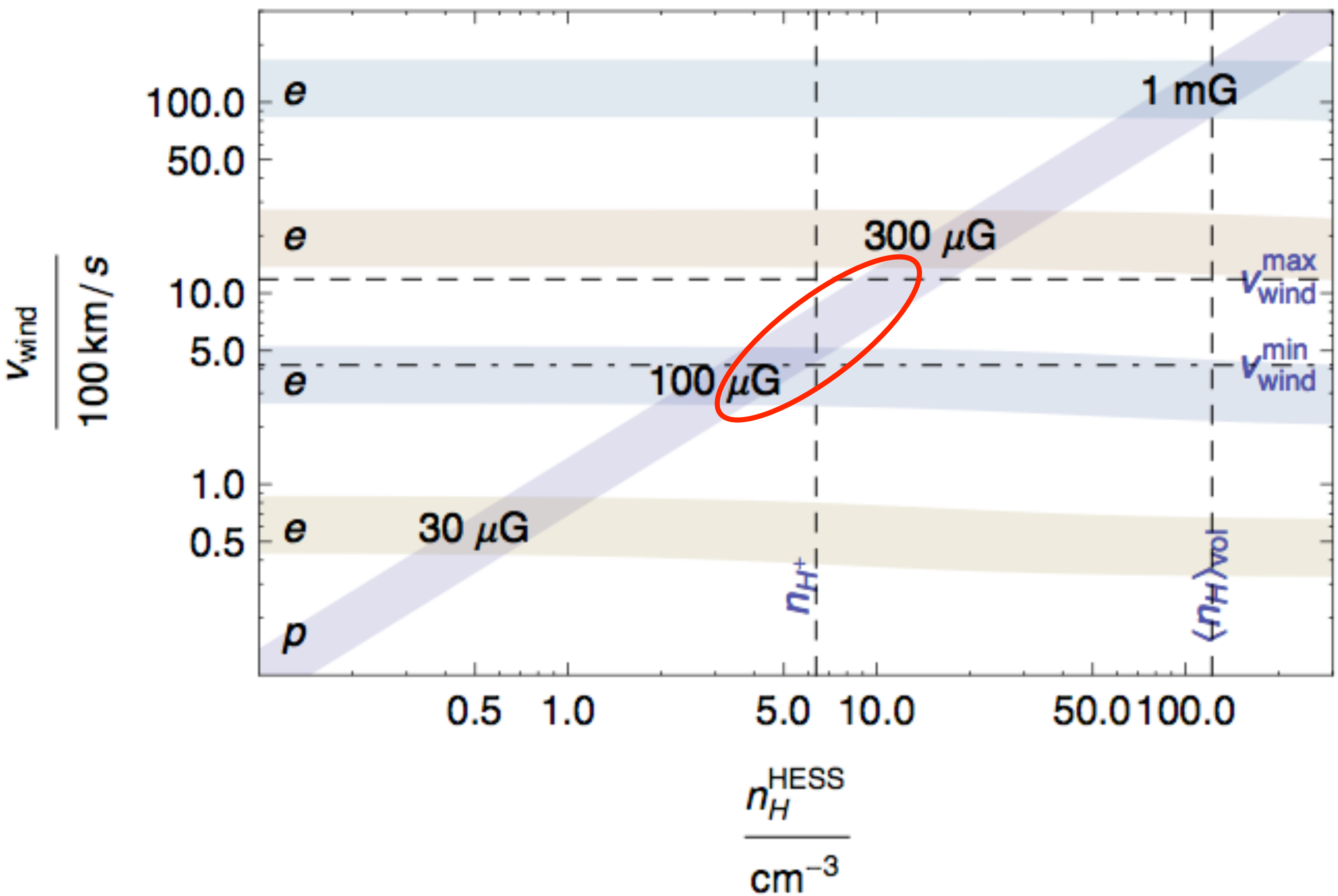
Credits: Ettore Carretti, CSIRO (radio image); S-PASS survey team (radio data); Axel Mellinger, Central Michigan University (optical image); Eli Bressert, CSIRO (composition).

Gas/Wind/Mag. Field



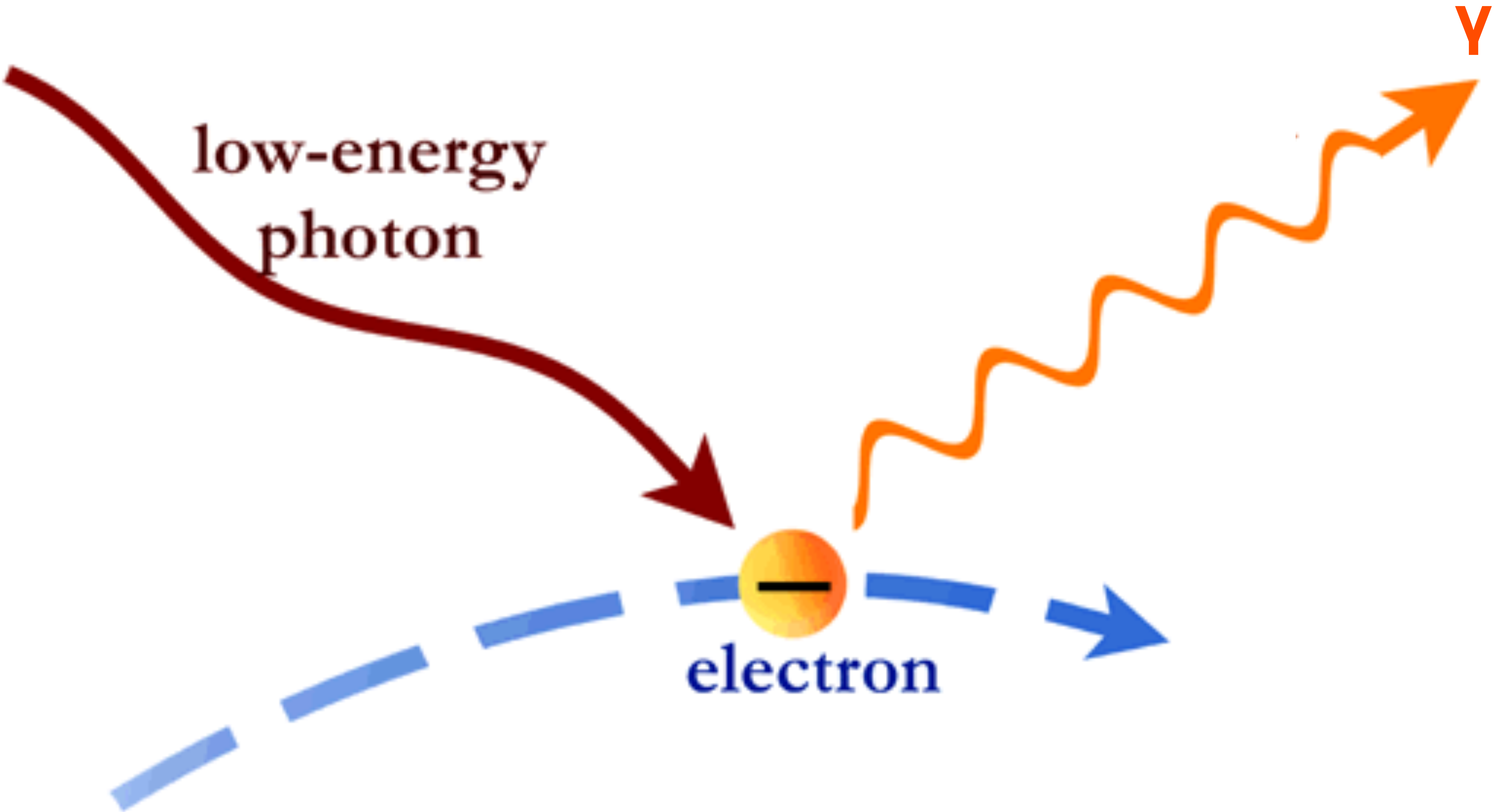
Crocker et al. 2011

Gas/Wind/Mag. Field

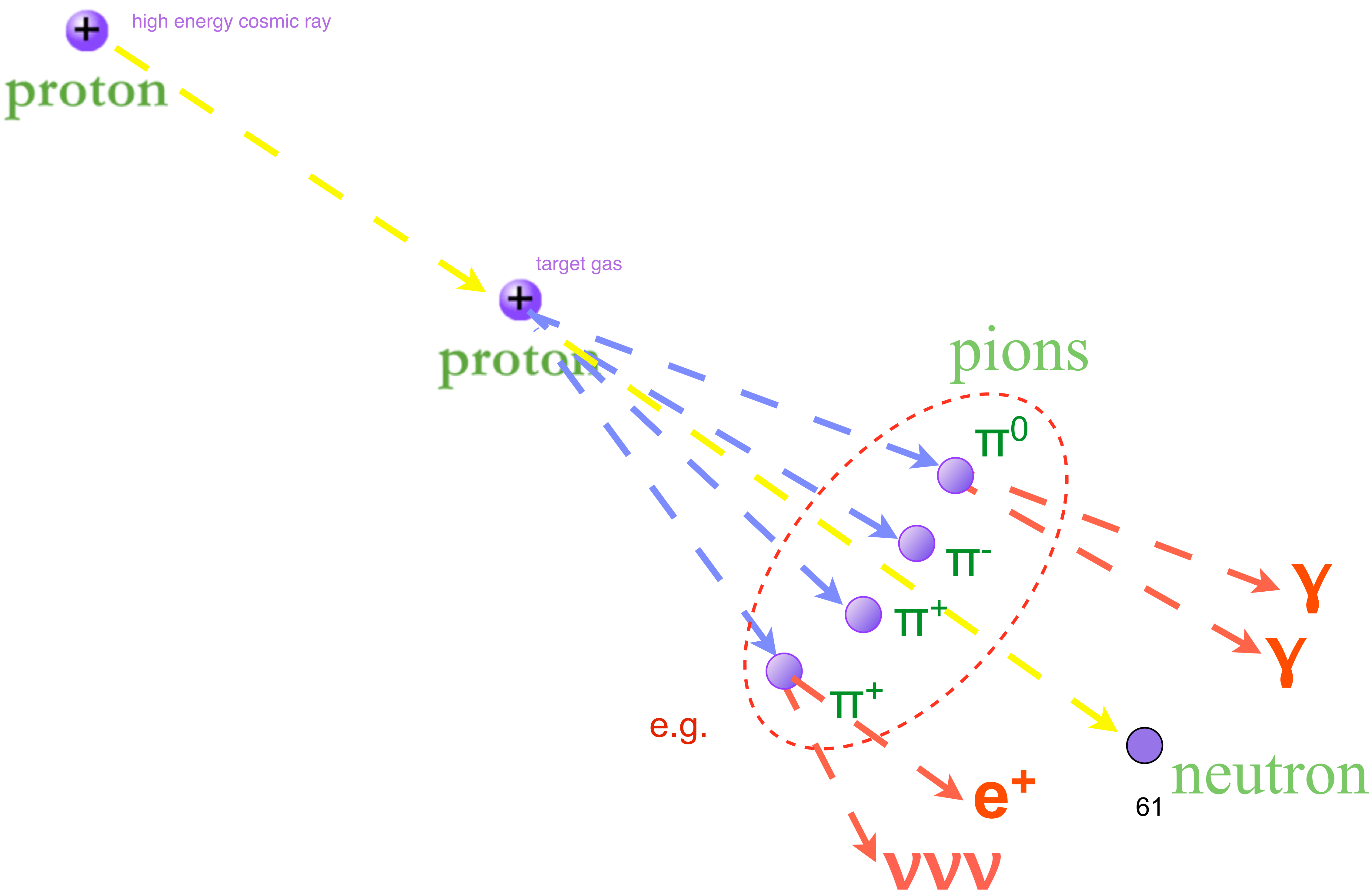


Crocker et al. 2011

Inverse Compton Scattering



pp → Pion Decay → secondaries



LHC: The Large Hadron Collider