

A Non-Thermal View of the Galactic Center

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Future Fellow
Mount Stromlo Observatory

Introduction

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

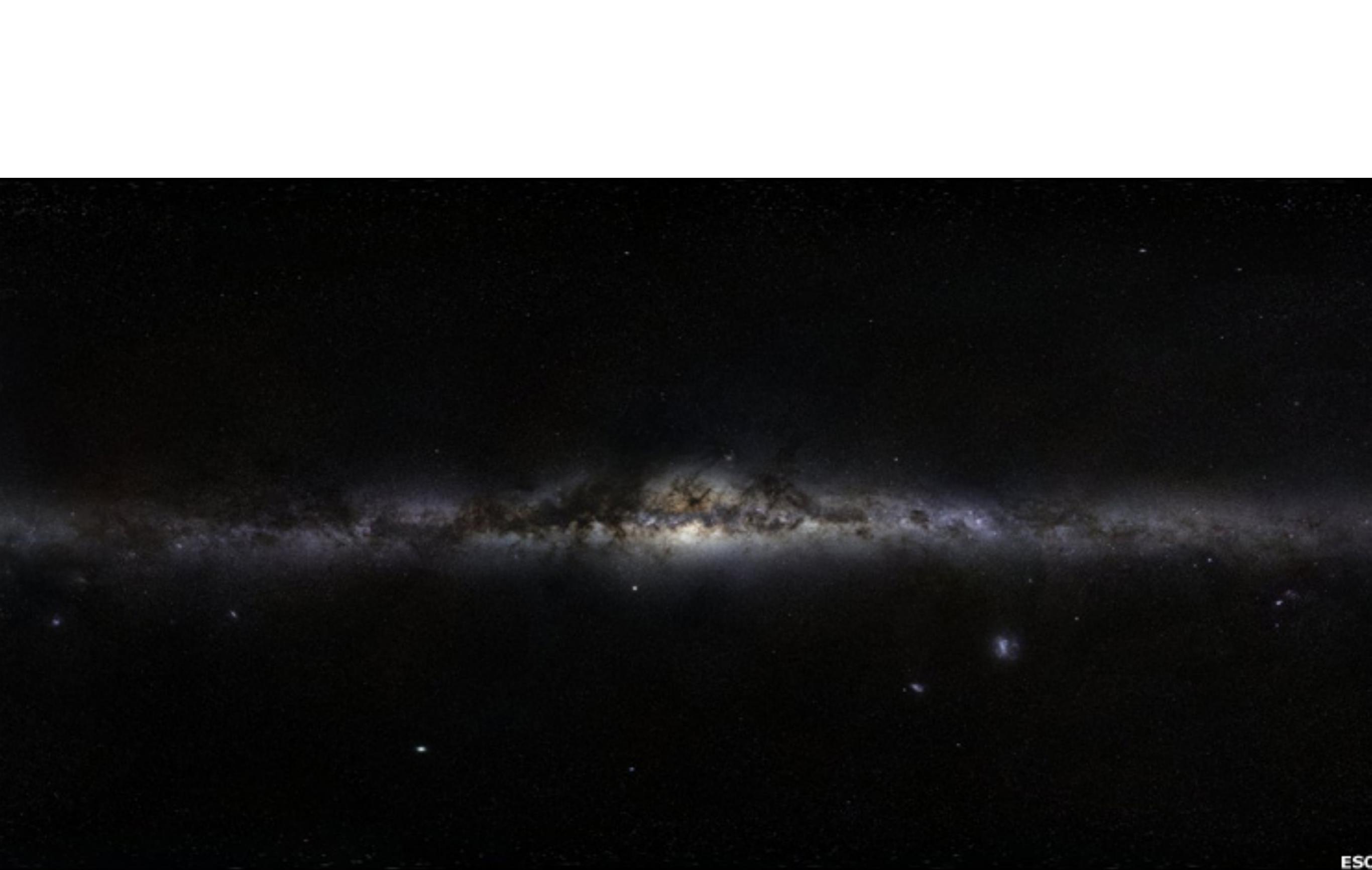
⇒ where Galactic stellar density and star

formation rate density reach a crescendo

Something to keep in mind...

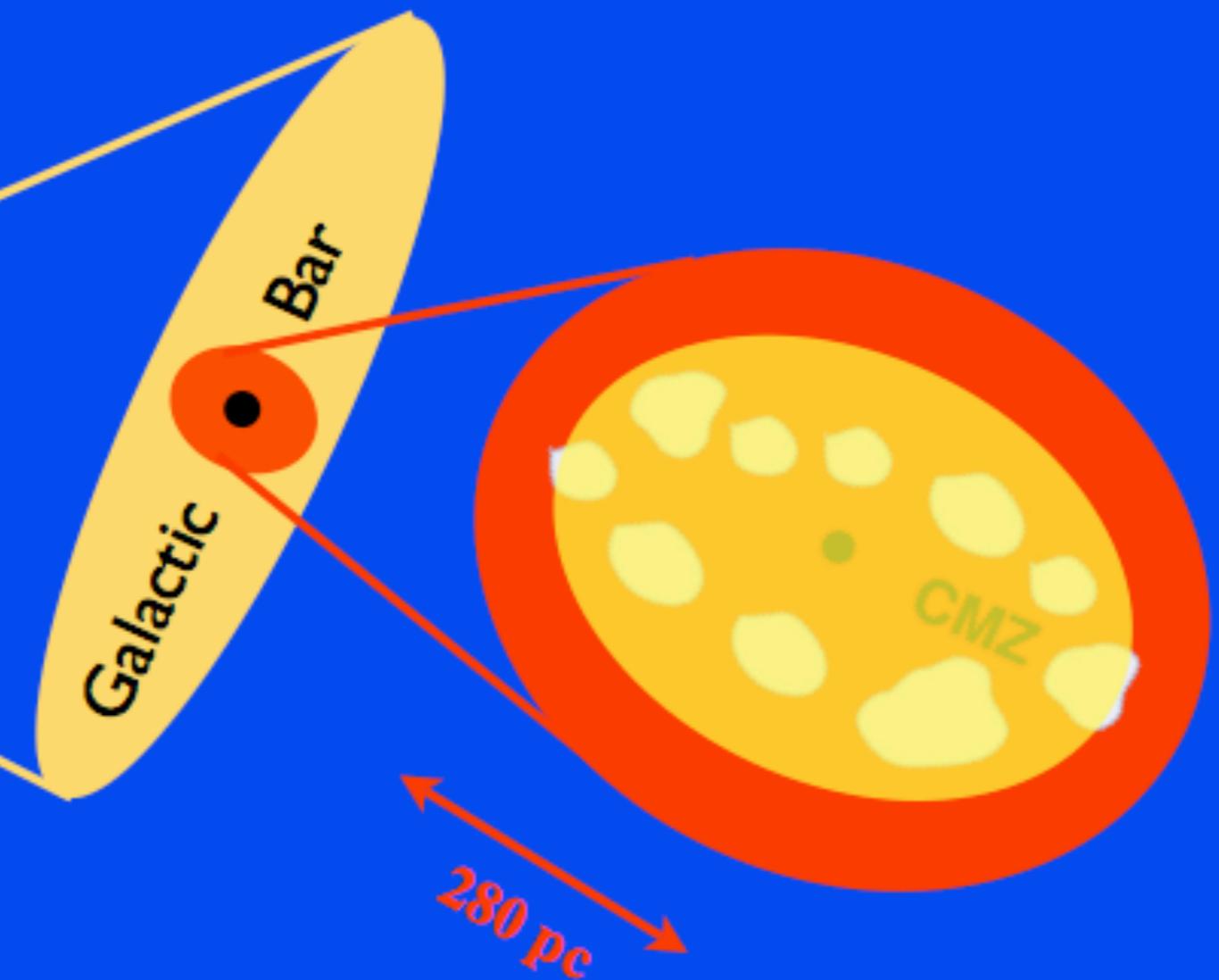
If we observe an exotic signal from the GC it may have something to do with, e.g., the SMBH, or the very high star formation rate density

*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.*



From spiral arms to the center of the Milky Way

Sun



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

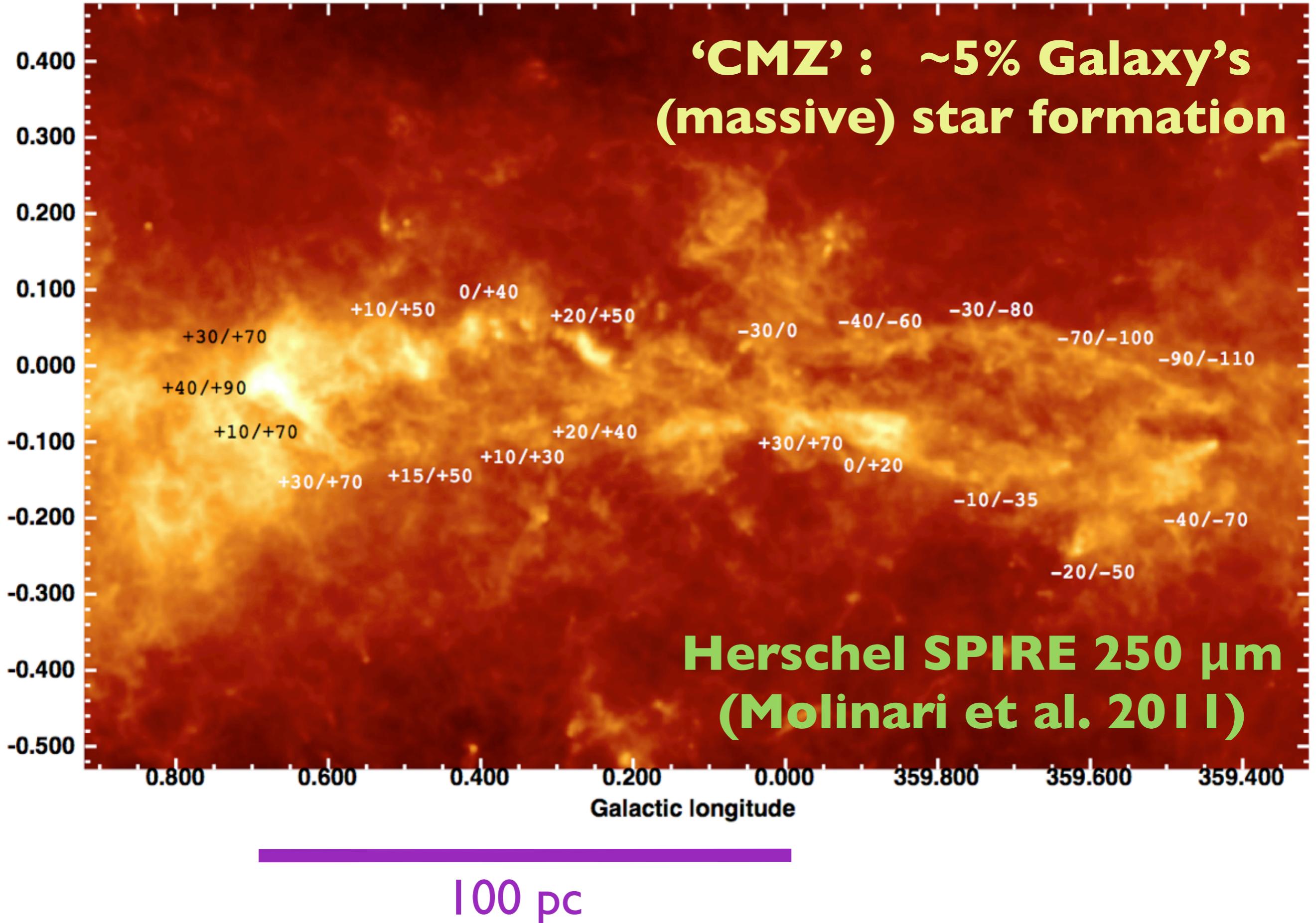
The GC is privileged...

- 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 H₂ is located in the GC

Central Molecular Zone

- Much of the GC's H₂ 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
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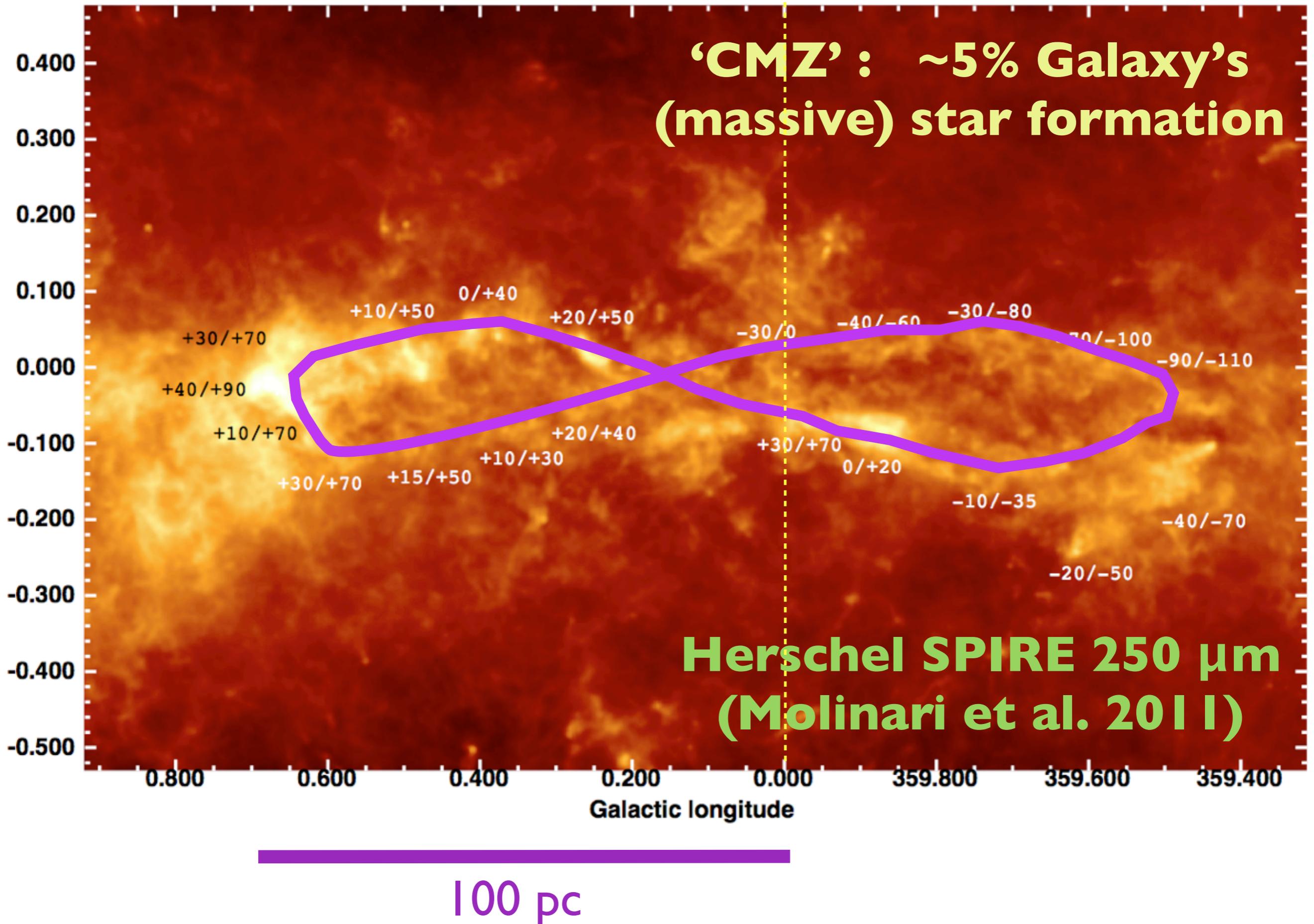
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+15/+50
+10/+30
+20/+40
0/+40
+20/+50
-30/0
-40/-60
-30/-80
-70/-100
-90/-110

**Herschel SPIRE 250 μ m
(Molinari et al. 2011)**

Galactic longitude

100 pc

**‘CMZ’ : ~5% Galaxy’s
(massive) star formation**



An Extreme ISM in GC...

- SFR surface density over CMZ **≥ 3 orders of magnitude** larger than mean in disk ($\partial_t \Sigma_* \sim 2 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$)
- 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: $U_B \sim U_{\text{turb}} \sim U_{\text{plasma}} \sim U_{\text{ISRF}} \sim 100 \text{ eV cm}^{-3}$

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

The region is complicated

purple: 20 cm radio

orange: 1.1 mm (cold dust)

cyan: IR (PAHs)

Galactic
Plane

Image courtesy of NRAO/AUI

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Galactic
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← EAST

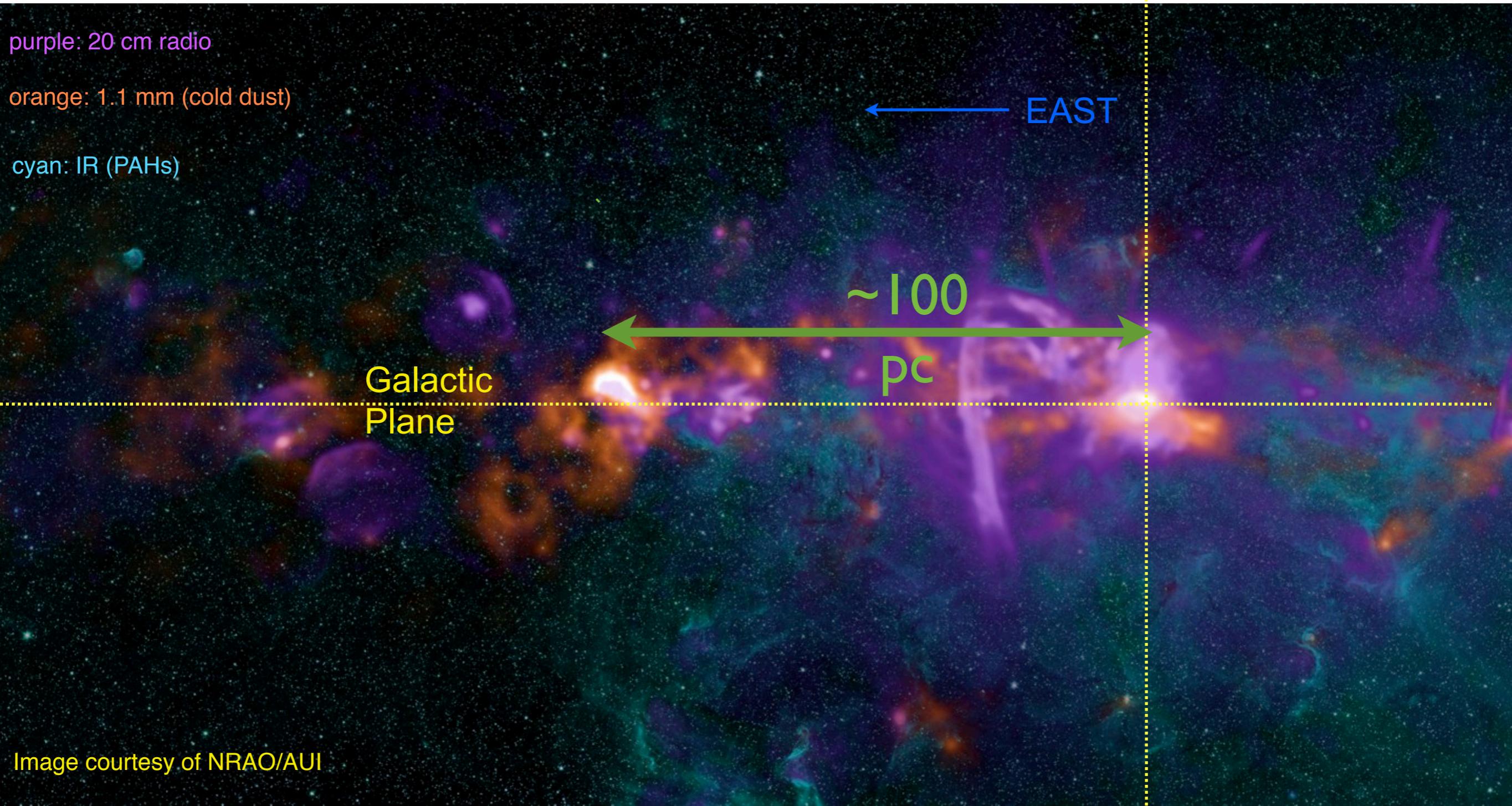
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radio arc

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HII (thermal brems)

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Sgr A complex

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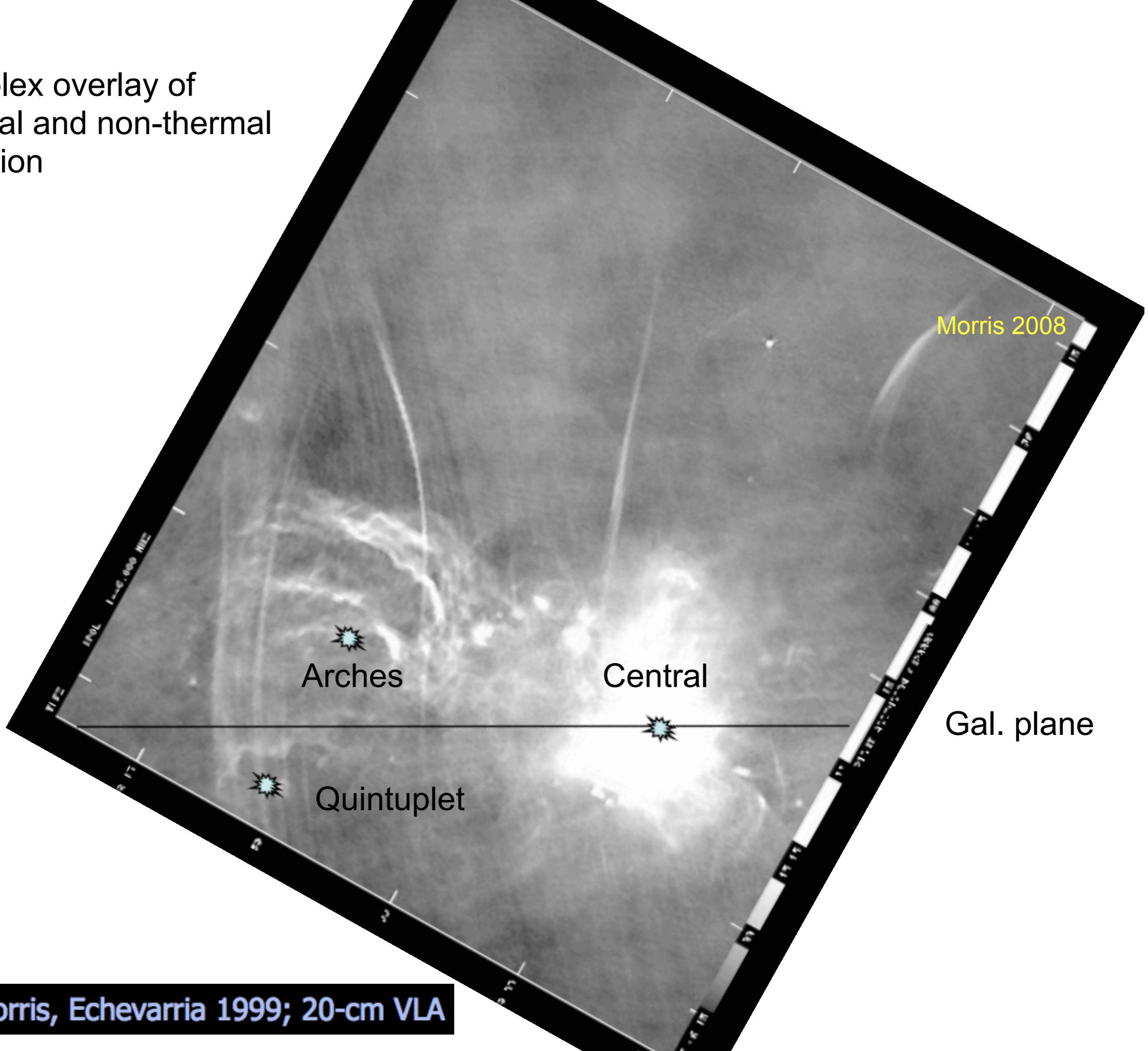
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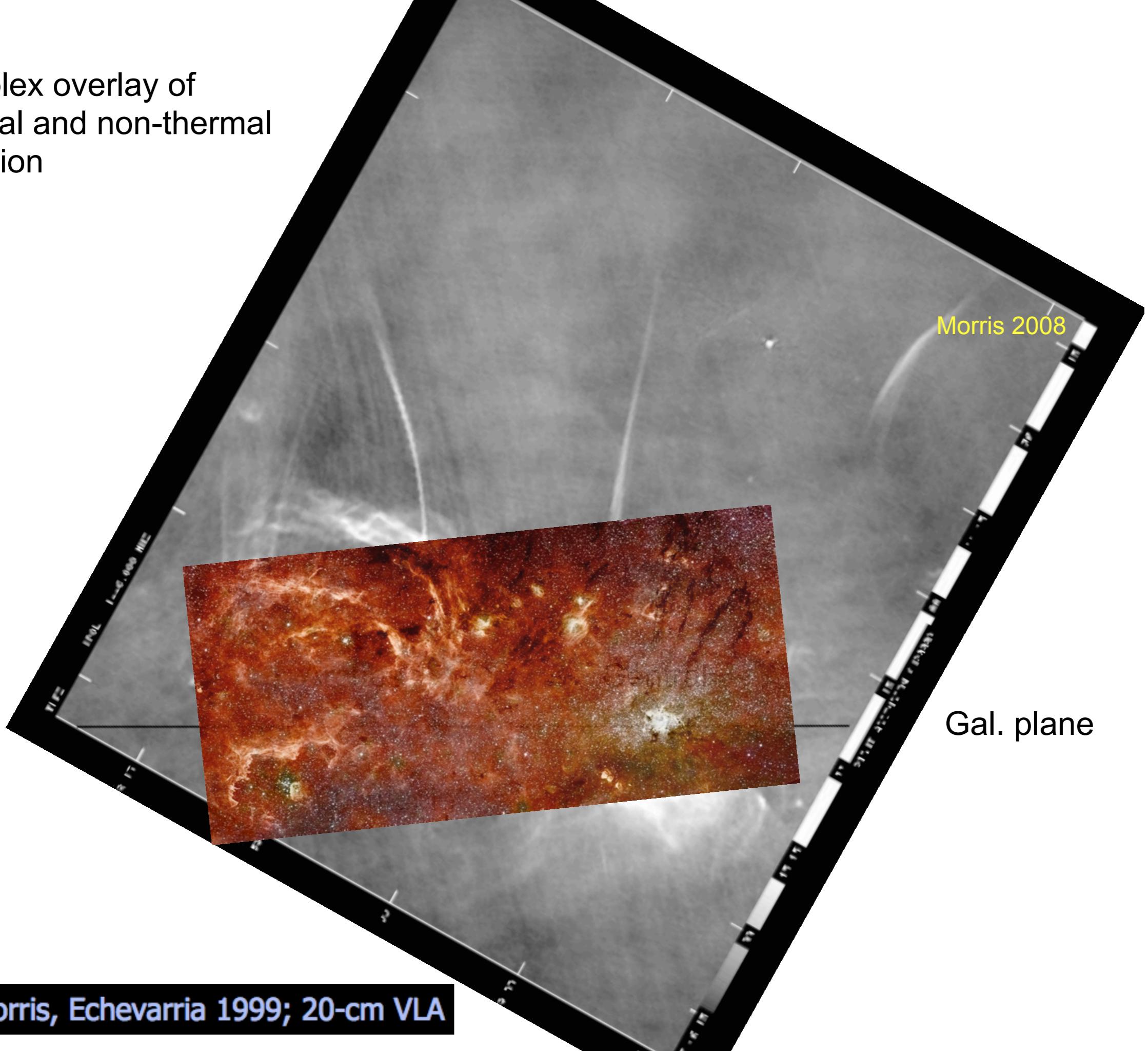
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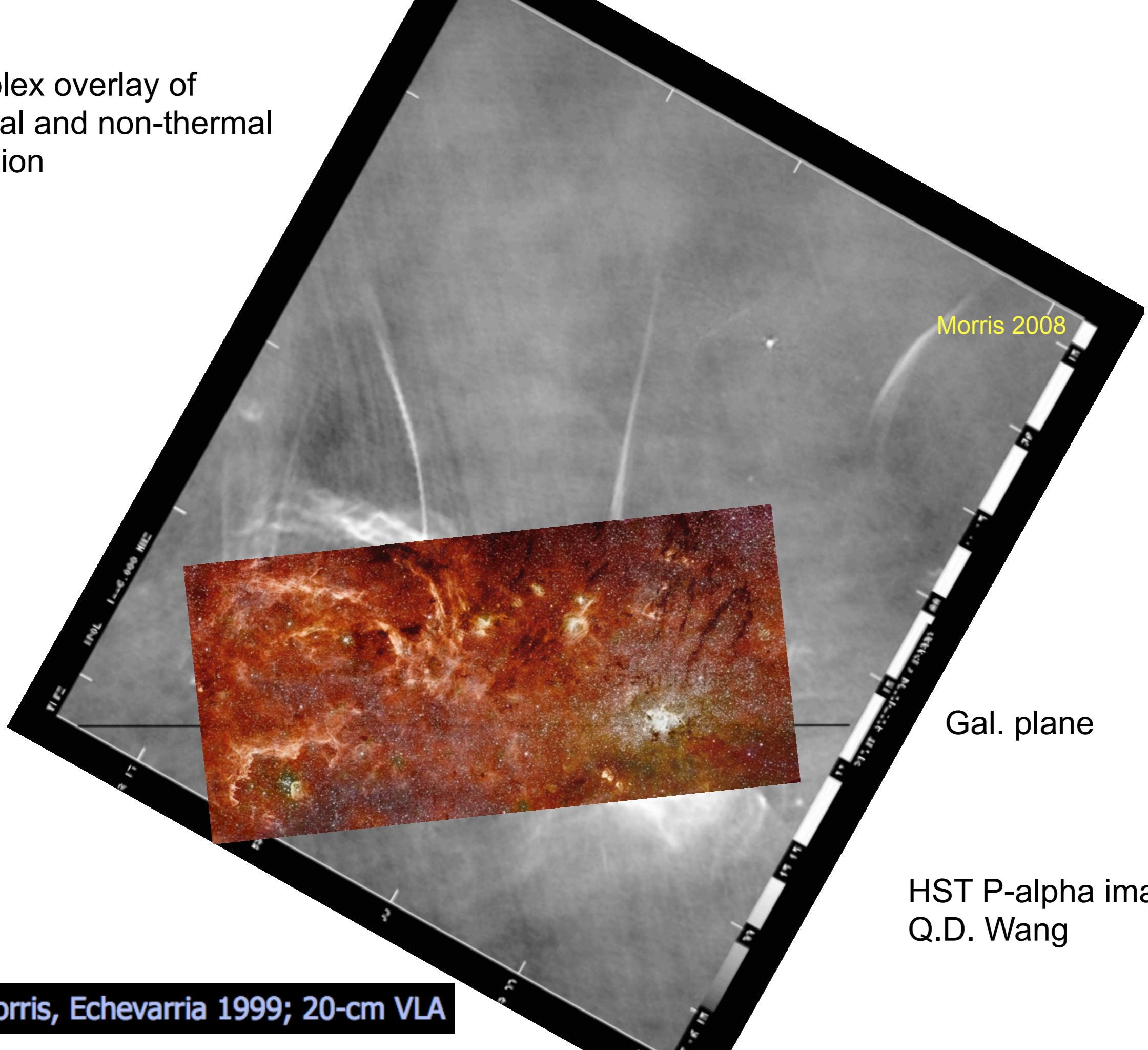
Complex overlay of
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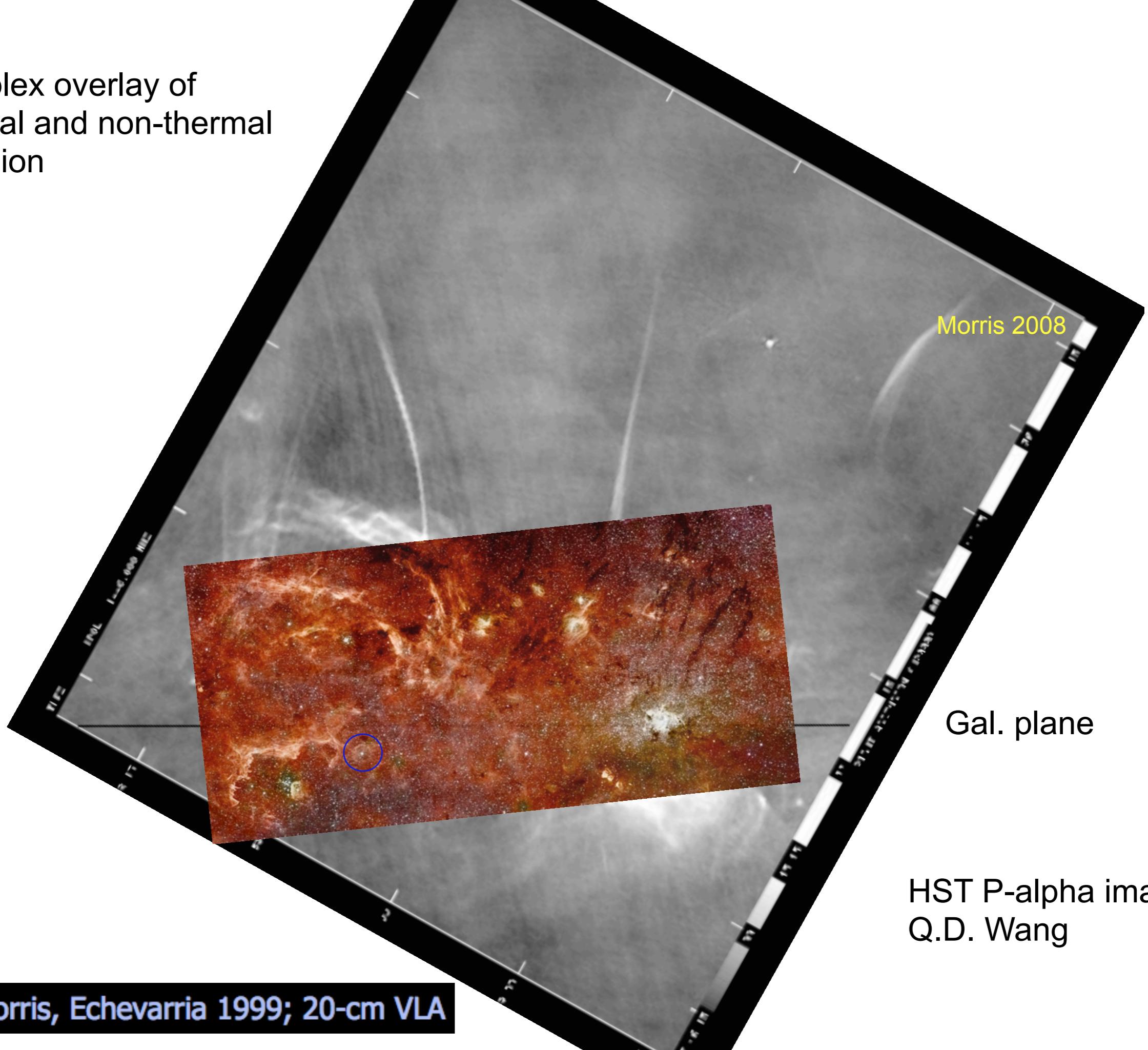
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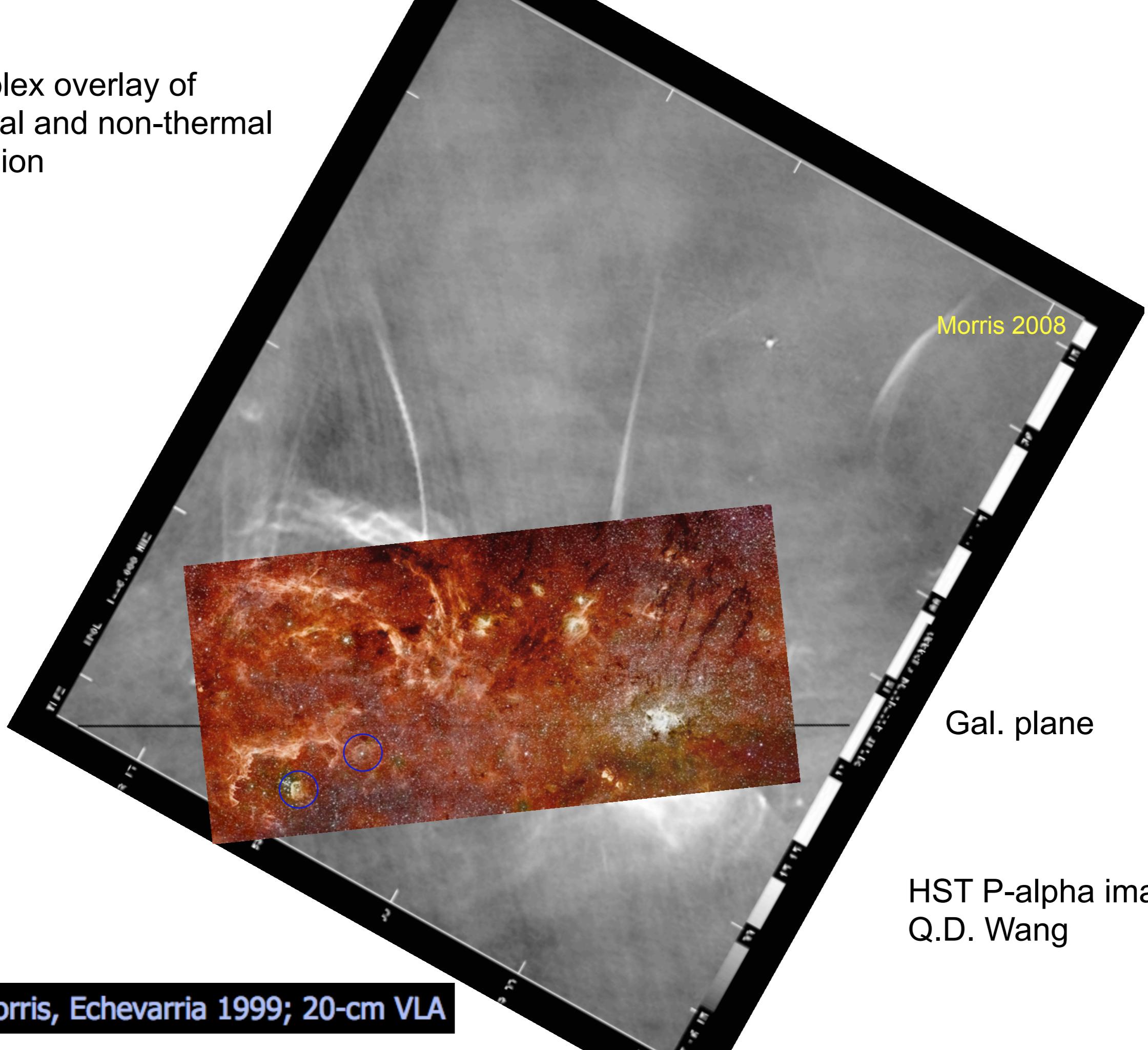
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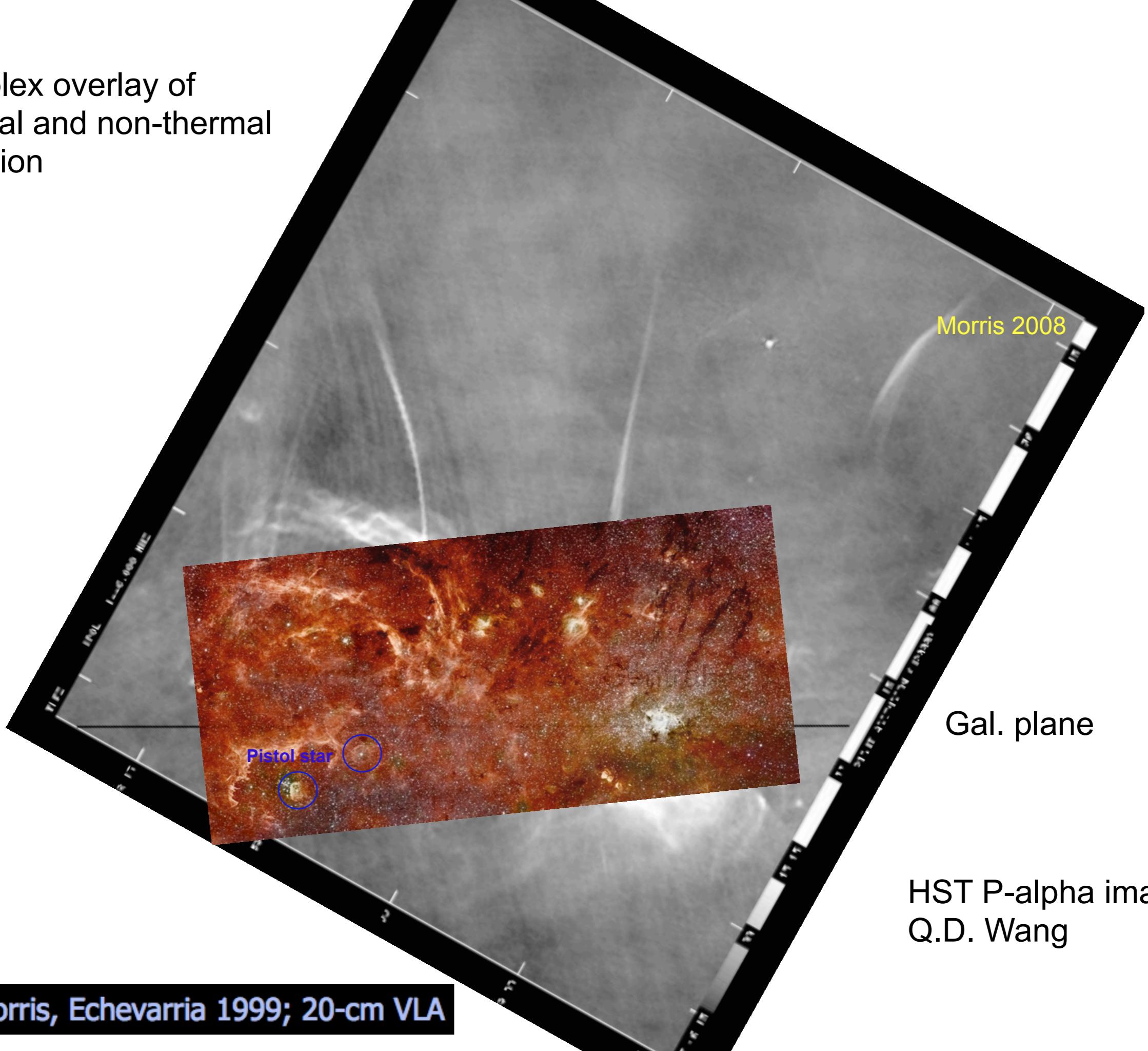
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Exotic/Remarkable Non-Thermal Phenomena of the GC/Inner Galaxy:

- (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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- (Quasi) point-like GeV and TeV γ -ray source coincident with (= radio source coincident with SMBH)
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- Non-Thermal Radio (and X-ray) Flare
- 130 GeV ‘line’
- Few GeV γ -ray ‘line’
- 51 μ m CO ‘line’

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

Energetics

- The (photon) Eddington luminosity of Sgr A* ($4 \times 10^6 M_{\text{Sun}}$):
 $5 \times 10^{44} \text{ erg/s}$
- Socrates (2008) extended the momentum balance argument for L_{Edd} to derive an ‘Eddington limit in cosmic rays’: $L_{\text{Edd}}^{\text{CR}} \sim 10^{-6} L_{\text{Edd}} \Rightarrow 5 \times 10^{38} \text{ erg/s}$ for Sgr A*
- Star formation in the CMZ at a rate $\sim 0.1 M_{\text{Sun}}/\text{yr}$
- This injects mechanical power (supernova explosions, stellar winds) of

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

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

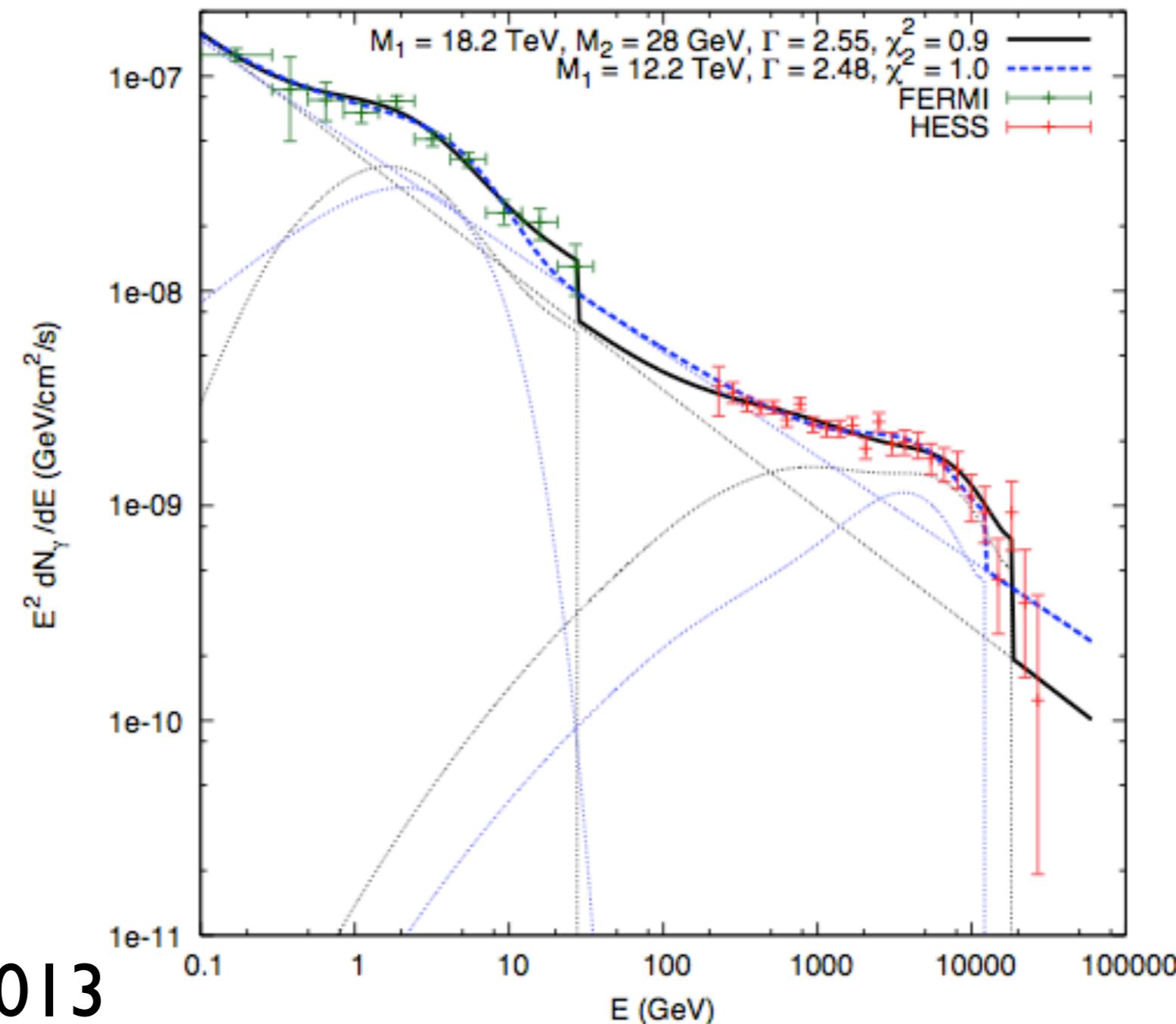
Gamma-ray source coincident with Sgr A*

- Detected by Fermi (\sim GeV) and HESS, MAGIC, VERITAS (\sim 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

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

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

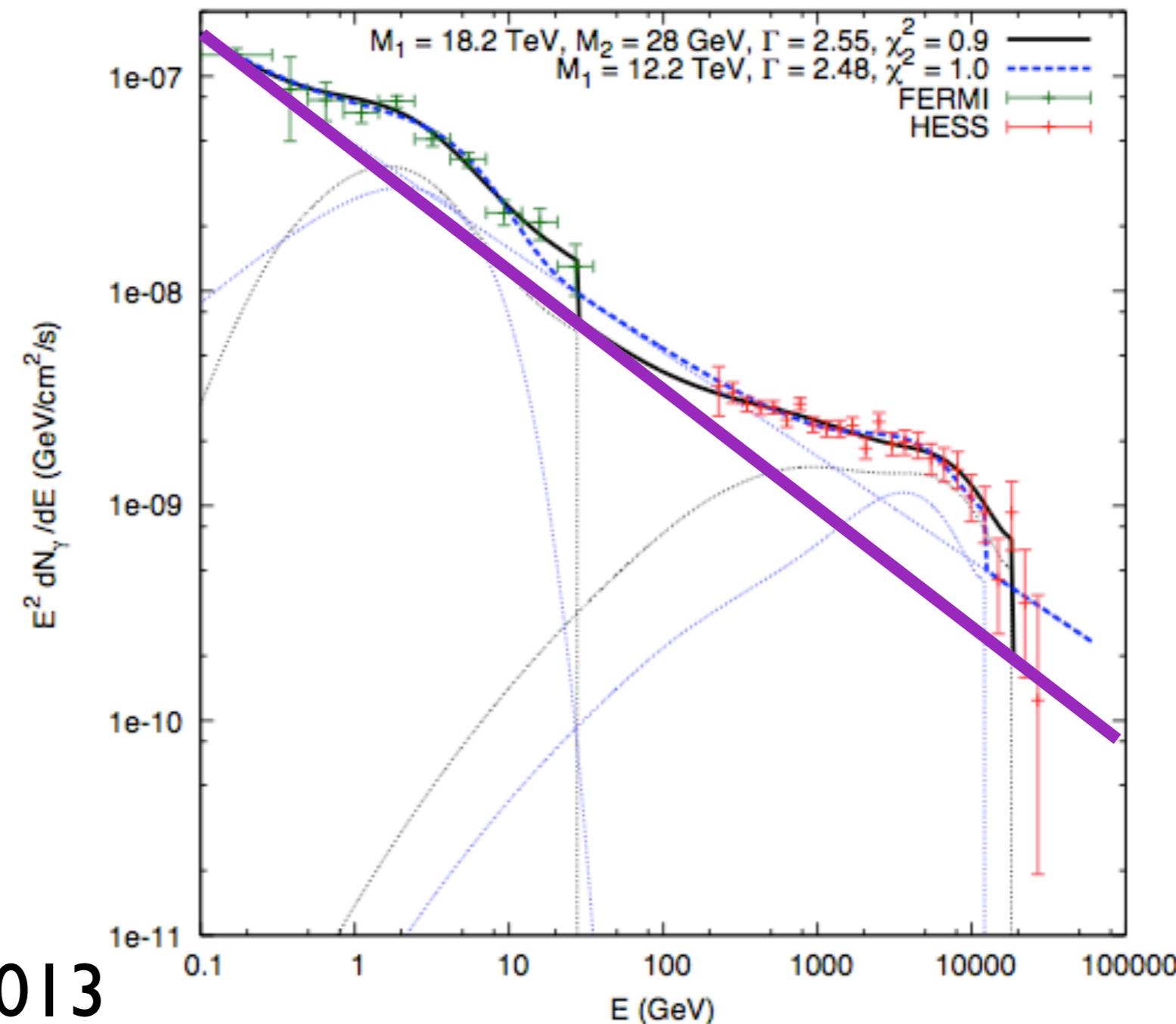
Cases G.4 and G.5 (data set A)



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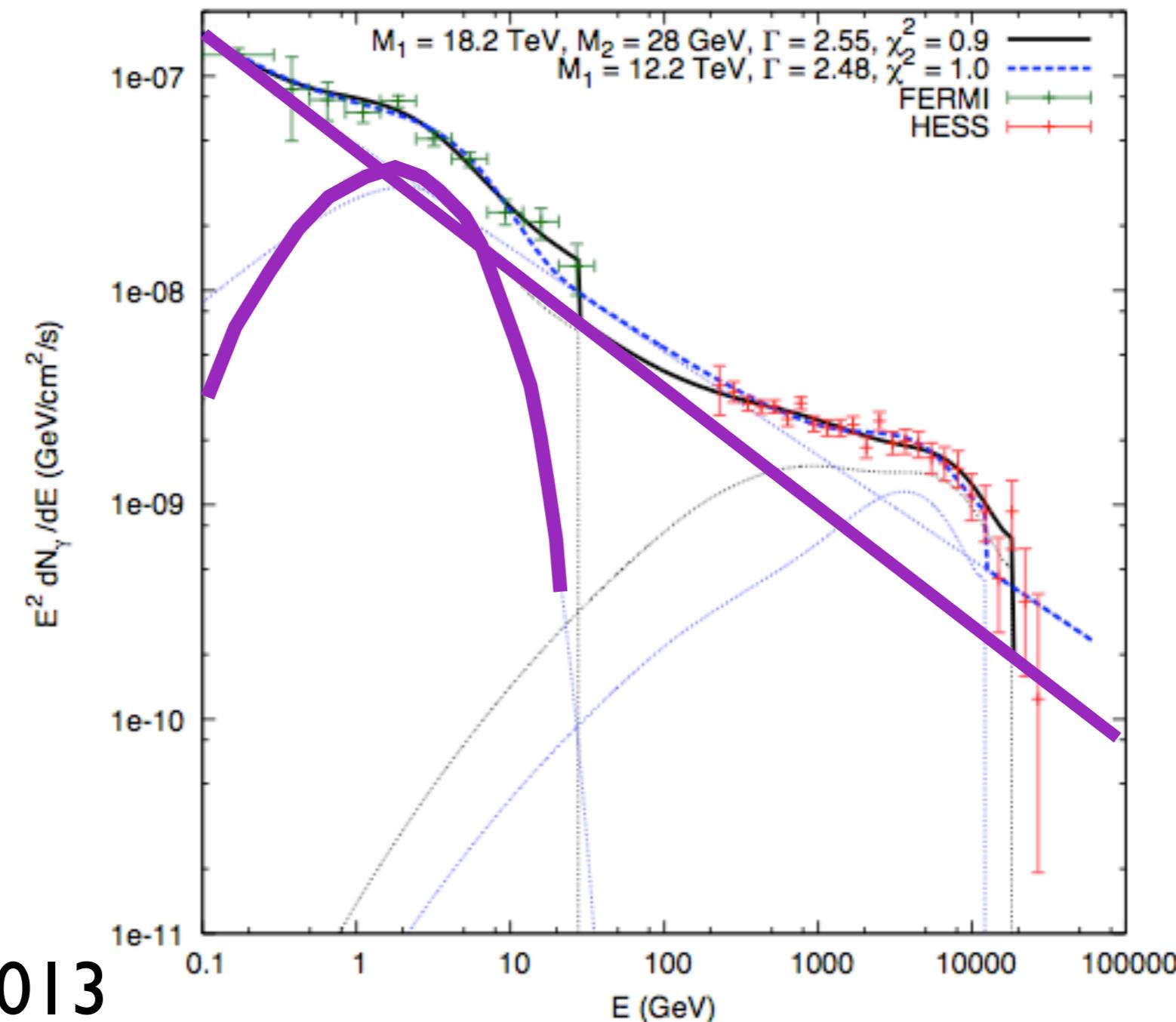
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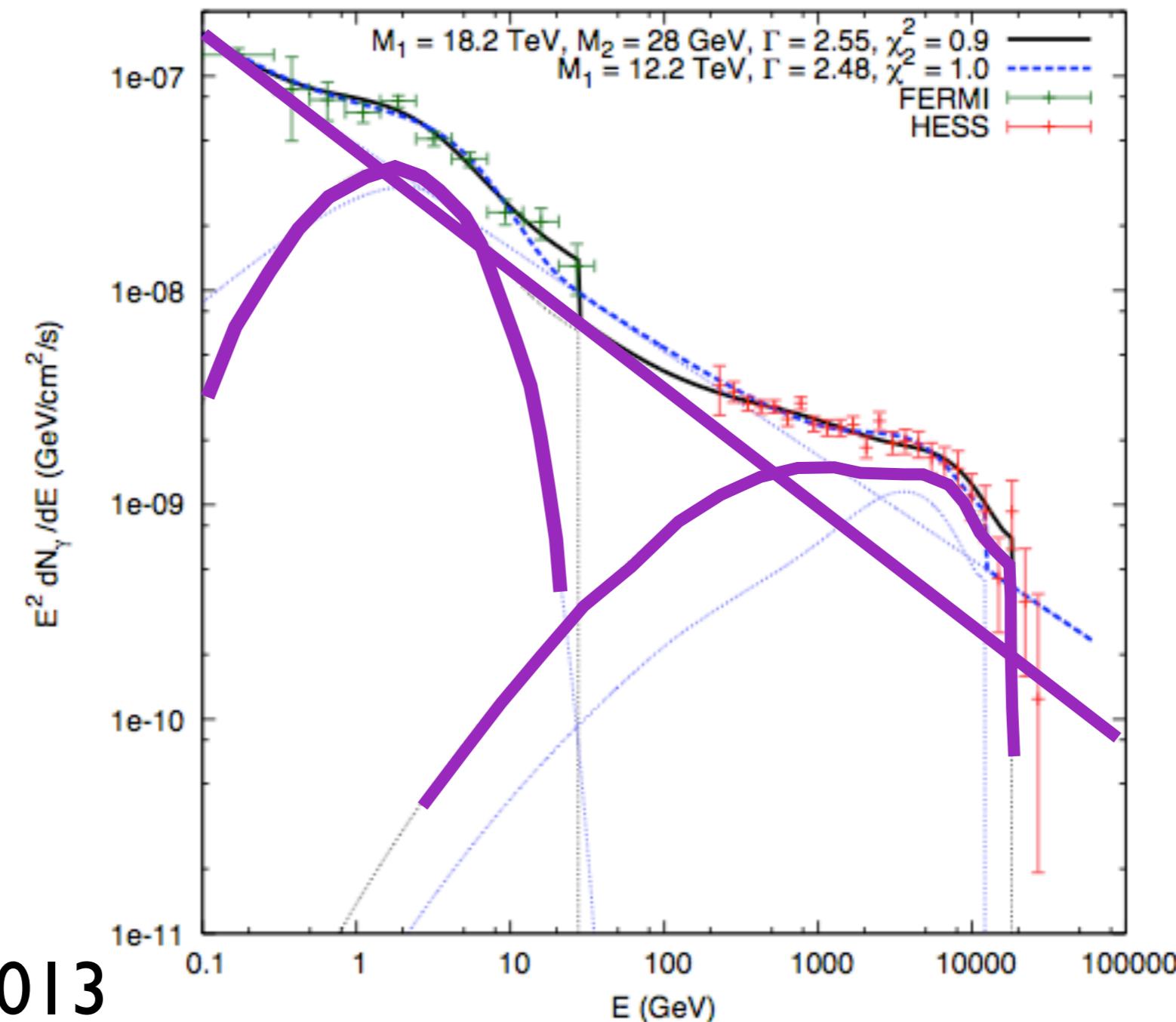
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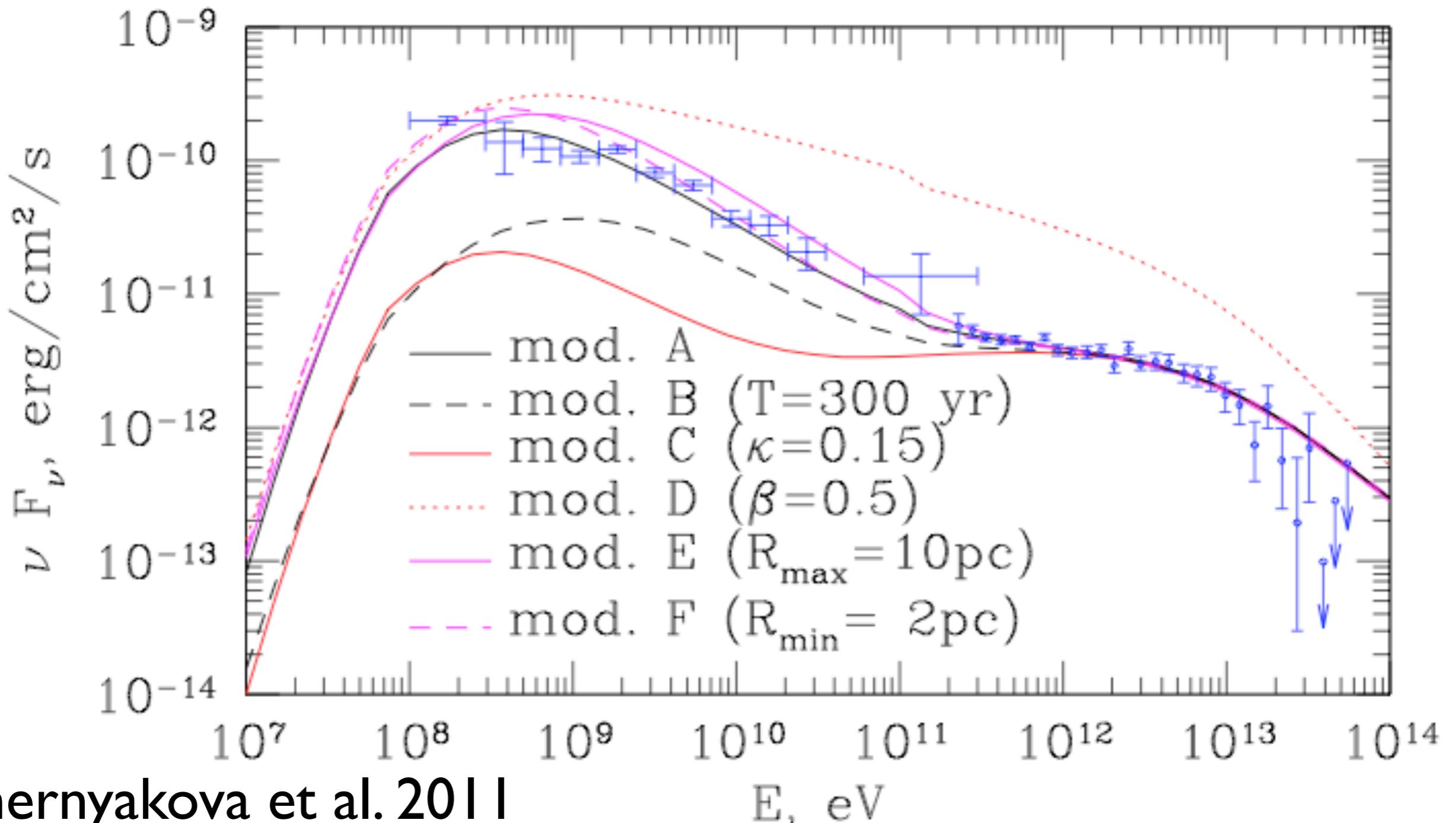
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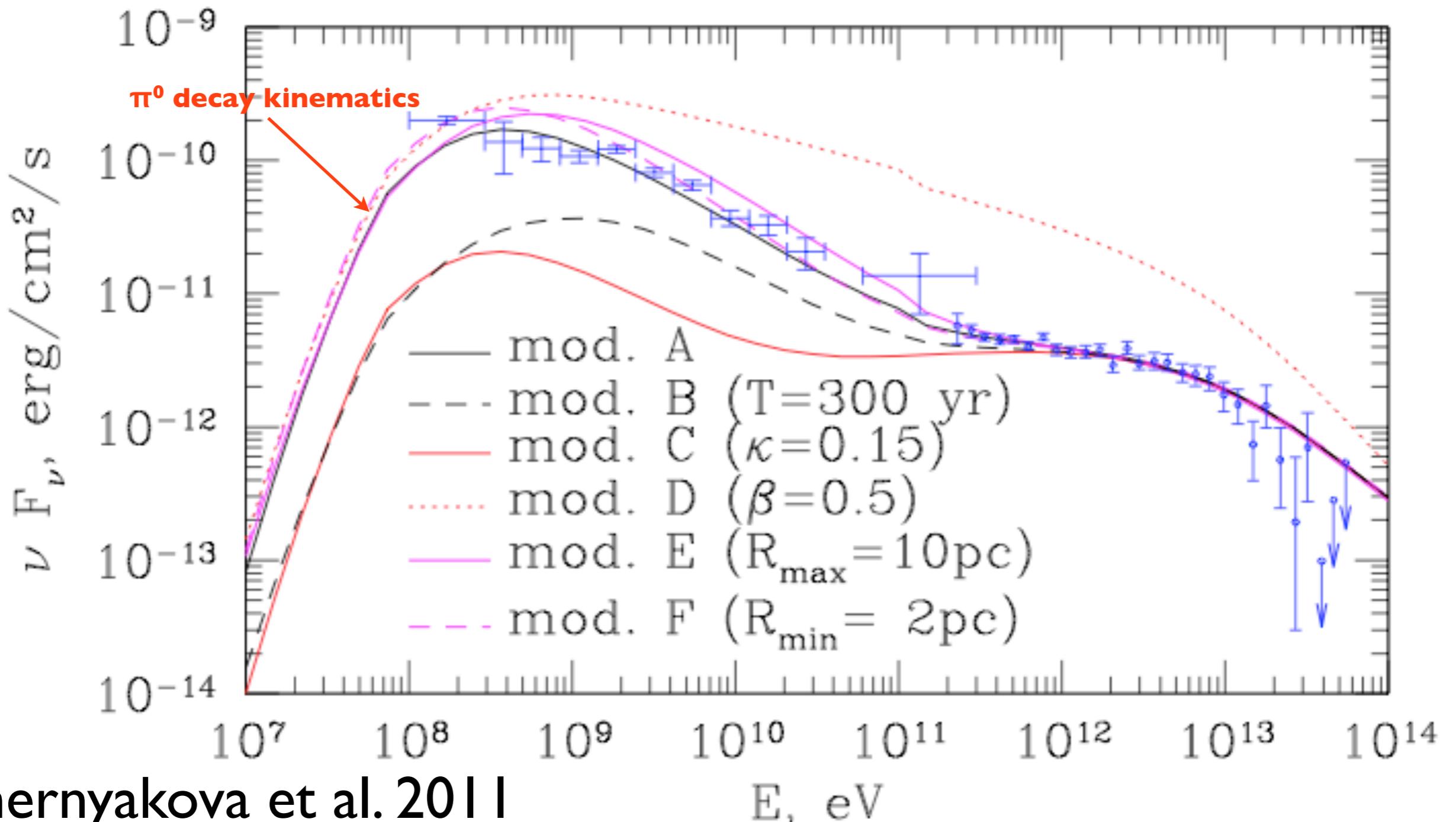
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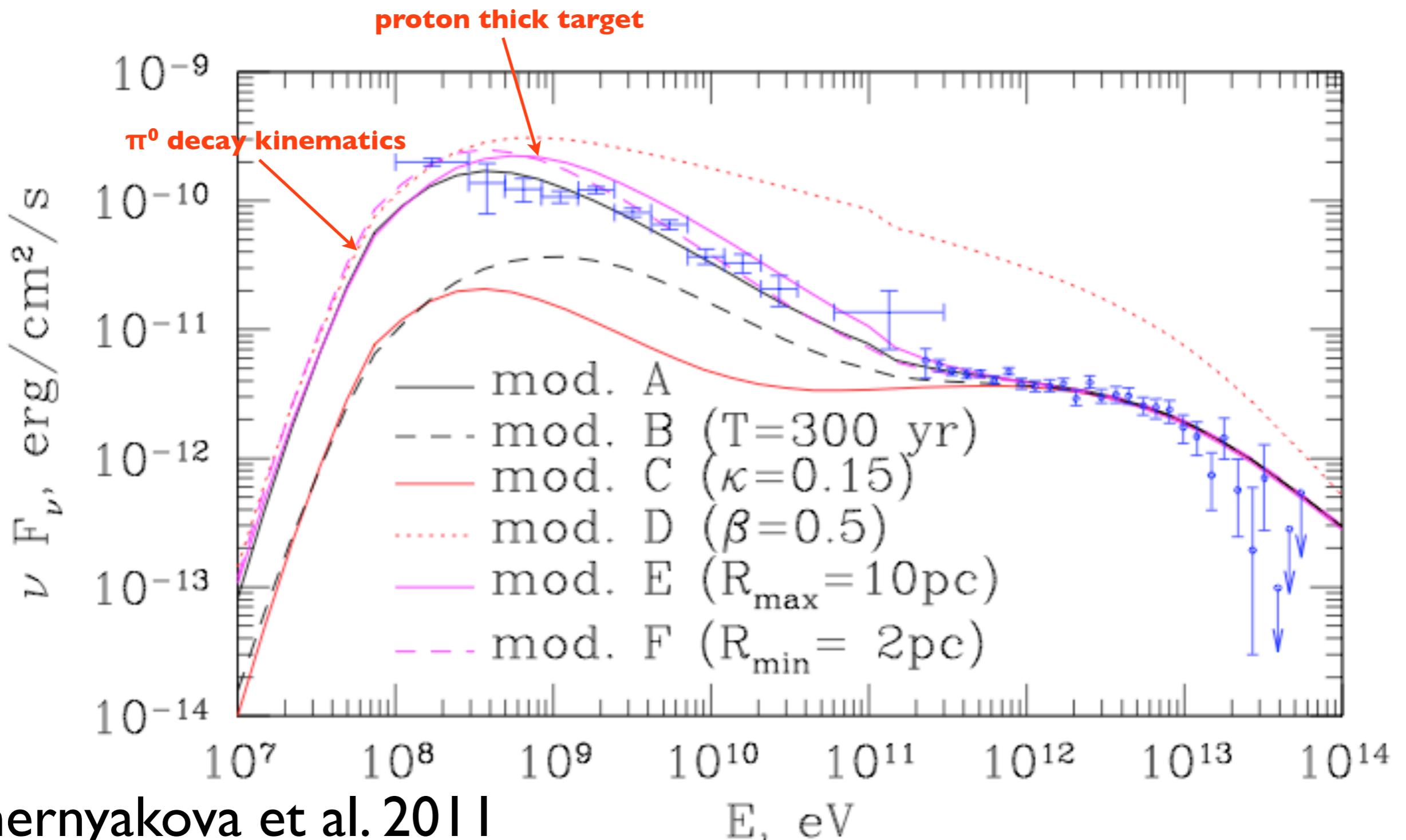
...but ‘astrophysical’ explanations for
the γ -ray spectrum are also credible



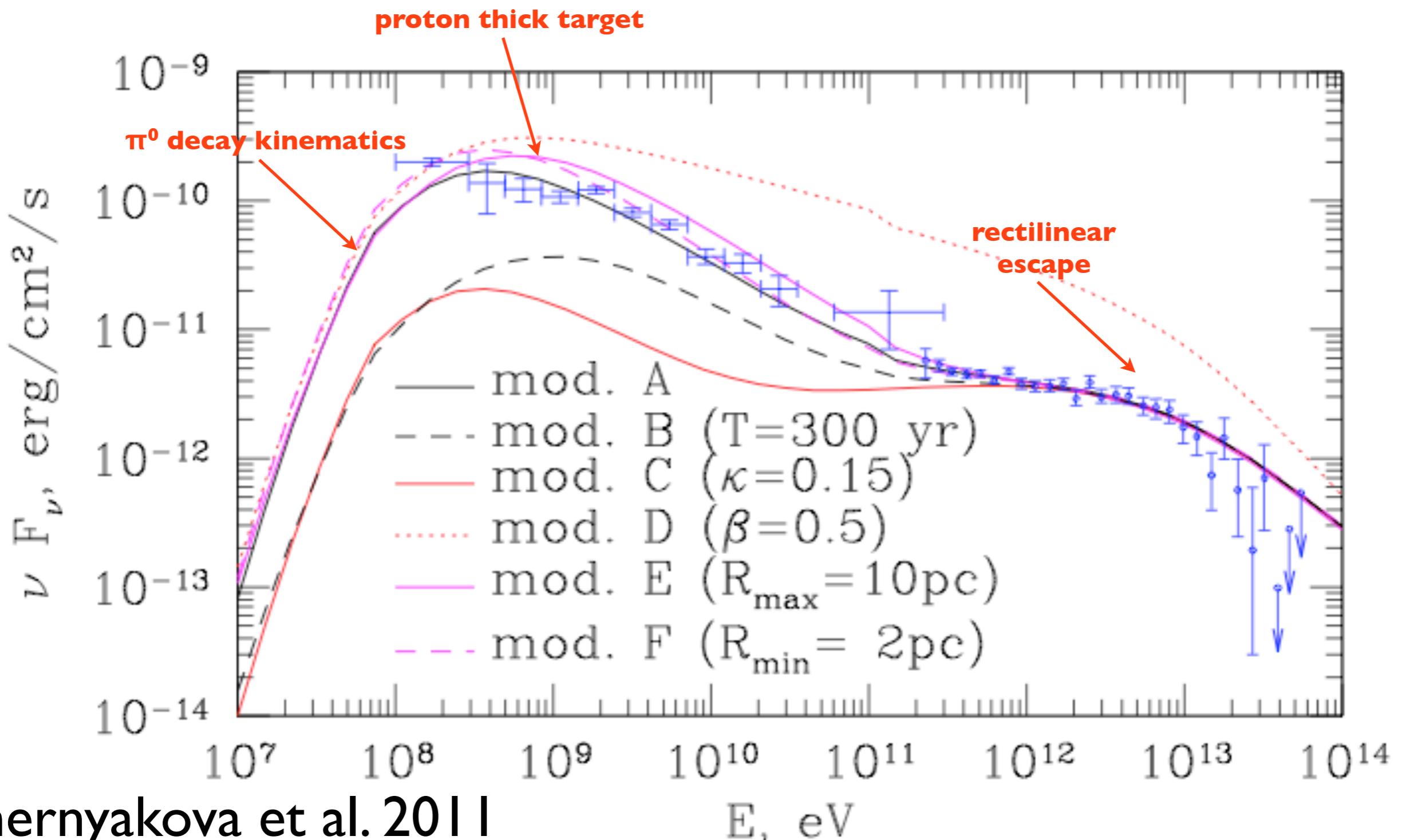
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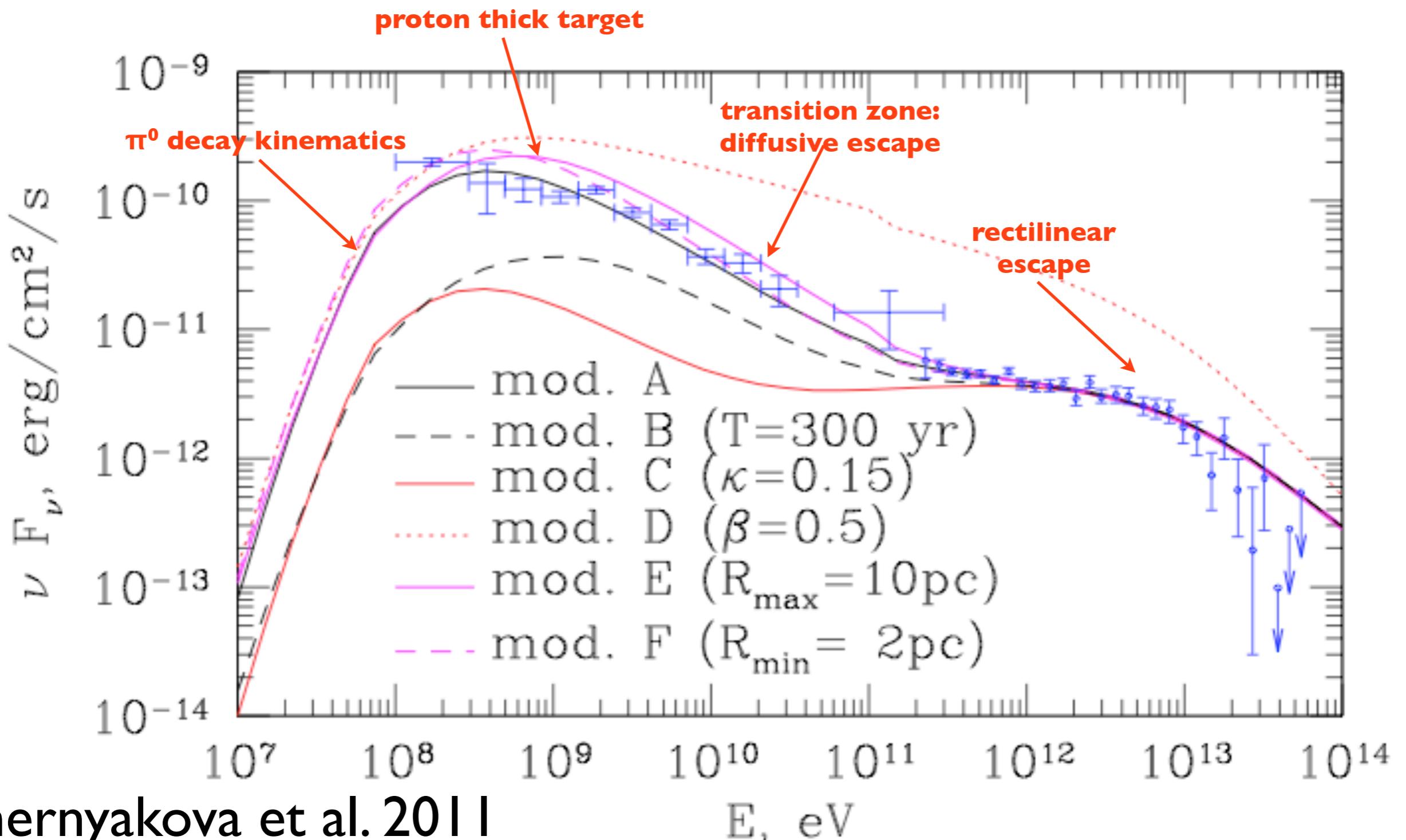
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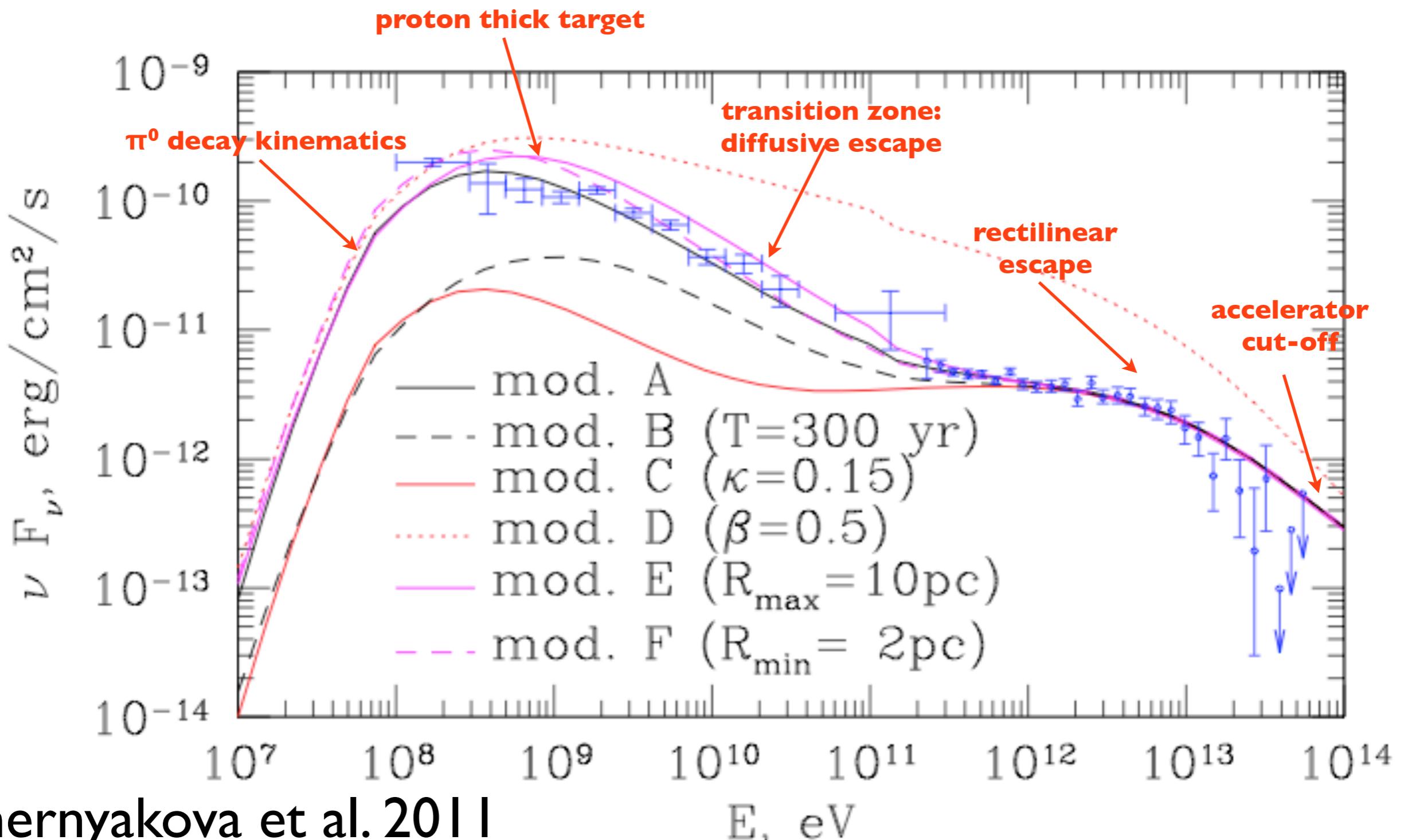
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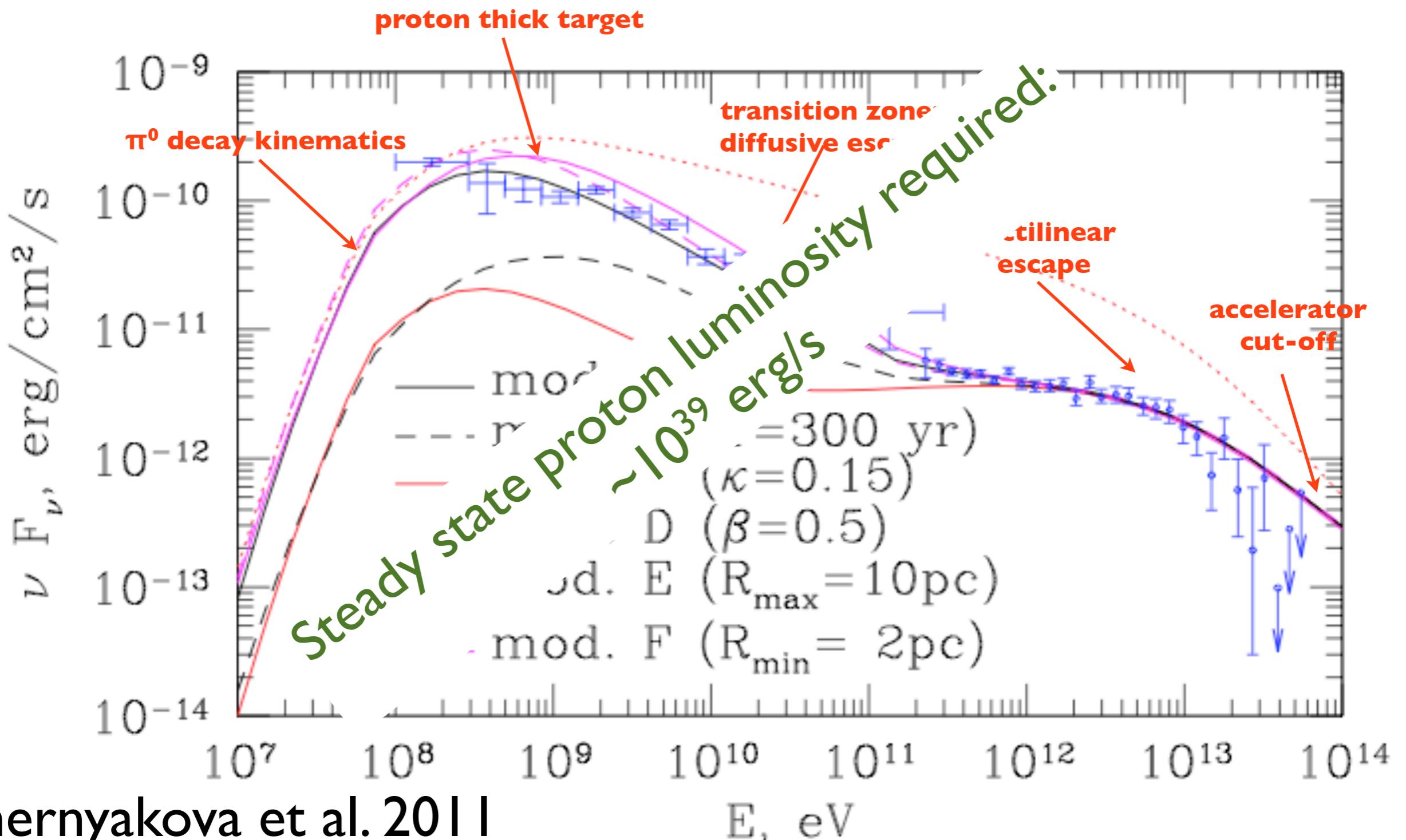
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Wider Scales

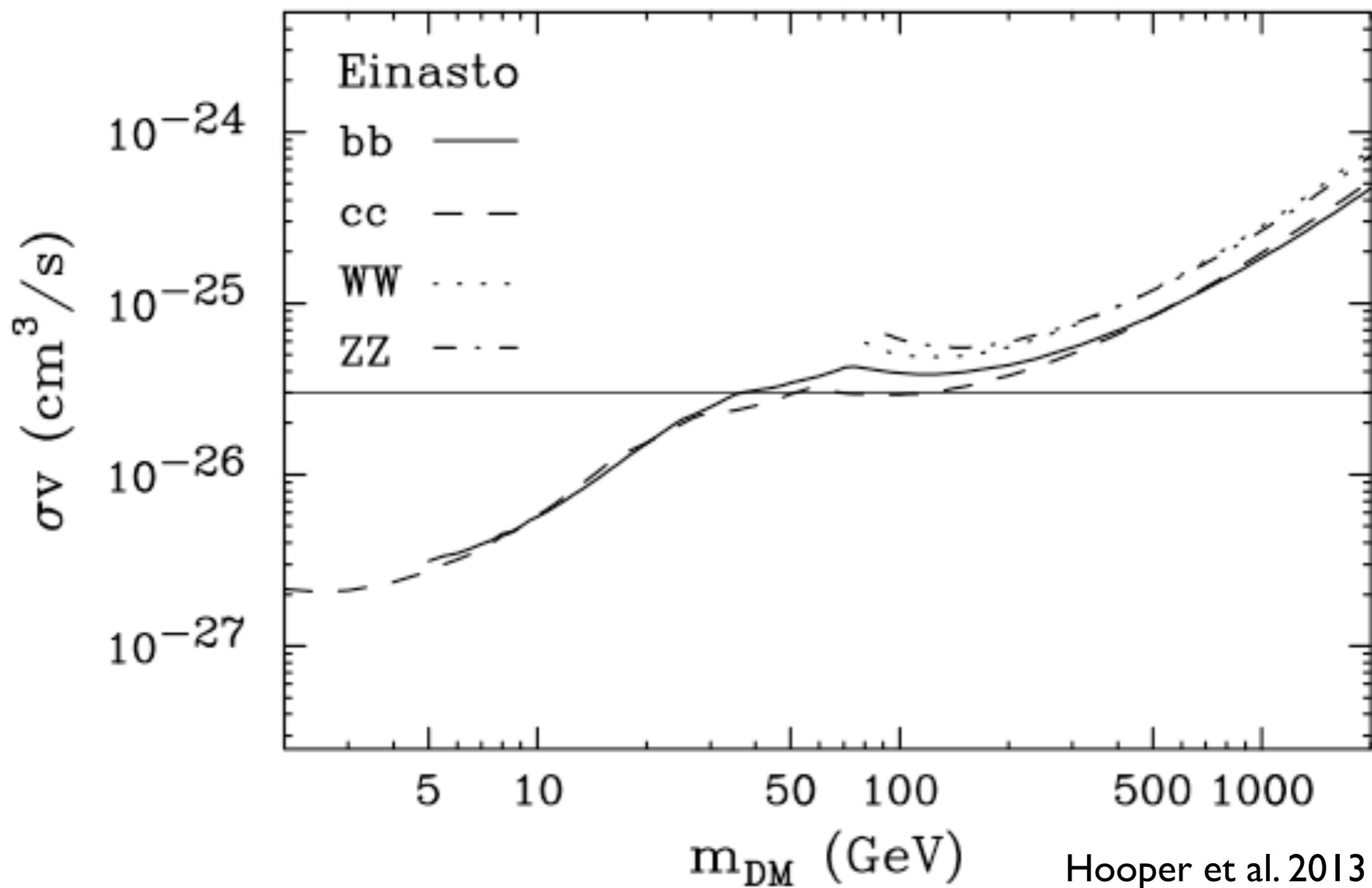
The positron signal remains unexplained

- Gamma-ray constraints (Beacom et al.) imply positrons injected into the ISM with $E_{e^+} < \text{few MeV}$
 - seems difficult to relate to DM annihilation or decay given expected WIMP mass scale
- Power in freshly injected positrons:
 $\sim 10^{43} e^+/s \times \text{few MeV}/e^+ \sim \text{few } 10^{37} \text{ erg/s}$
- ...this is easily supplied by astrophysical sources - but how are the positrons created?

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

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See talk by Gabrijela Zaharijas today

Hooper et al.: ~ 10 GeV DM

- Claim: ~ 10 GeV WIMP annihilating to leptons with a weak-scale cross-section $\langle v\sigma \rangle \sim 3 \times 10^{26}$ cm³/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.

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 - spectrum and angular distribution of gamma rays from the Inner Galaxy ($|l| < 20^\circ$)
 - the spectra of diffuse gamma rays
 - the missing mass in the “haze”
 - low-energy signals claimed by/for direct detection experiments DAMA/LIBRA, CoGeNT and CRESST-II.
- See talk by Tracy Slatyer, Thursday*

Hooper et al.: 10 GeV DM

- The DM candidate distributed as $\rho_{\text{DM}} \propto r^{-1.3}$ would release energy in annihilation products at a rate of $3 \times 10^{37} \text{ erg/s}$ within the innermost 150 parsecs around the Galactic Center
- BUT: in the same region star-formation (supernovae, stellar winds) injects $\sim 10^{39} \text{ erg/s}$ in accelerated hadrons and $\sim 10^{38} \text{ erg/s}$ in accelerated leptons (i.e., cosmic ray electrons) - *energetically* this is a good match to Hooper et al.'s putative DM signature.
- On the other hand, it remains undemonstrated that 'conventional' astrophysics can explain the spectral anomalies identified by Hooper et al.

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- On the other hand, it remains undemonstrated that ‘conventional’ astrophysics can explain the spectral anomalies identified by Hooper et al.

However: there *are* strong ‘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....

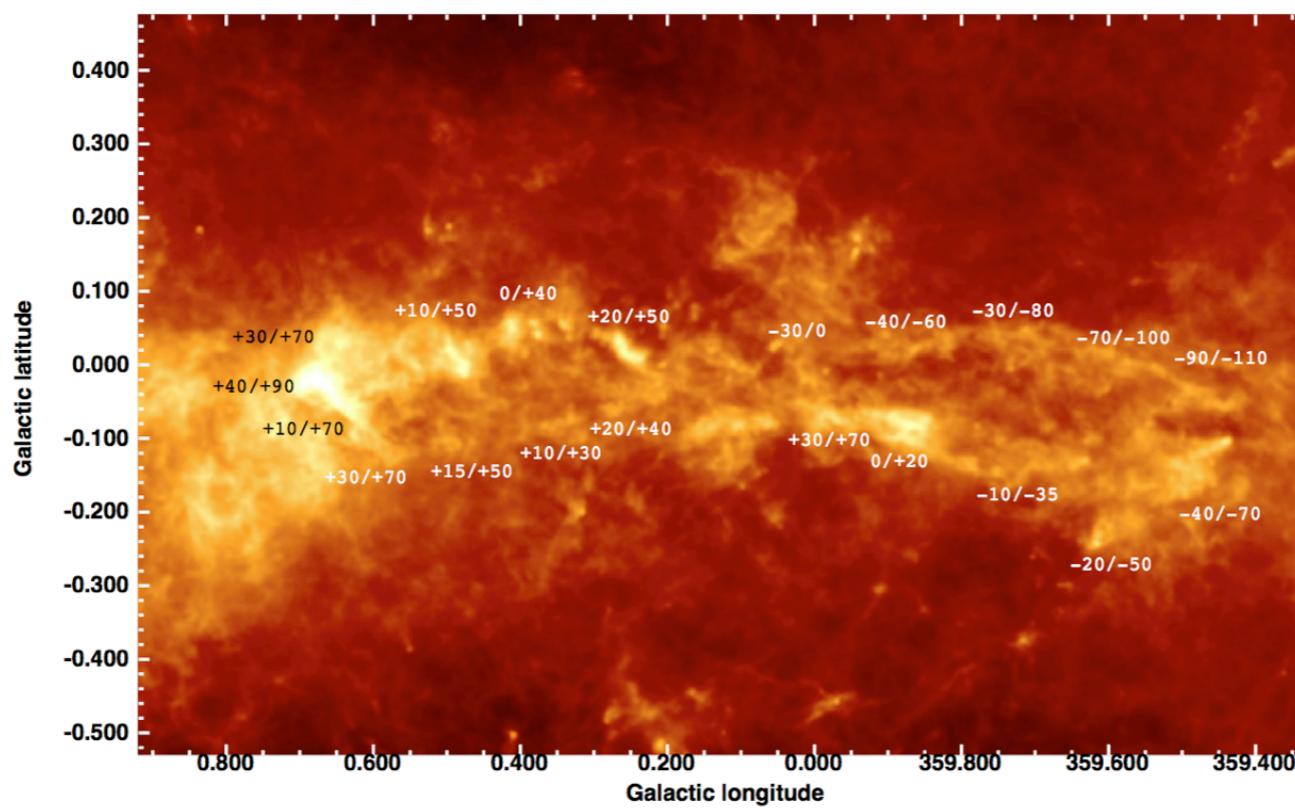
Cosmic Ray Transport on ~ 100 pc scales in the GC

- 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

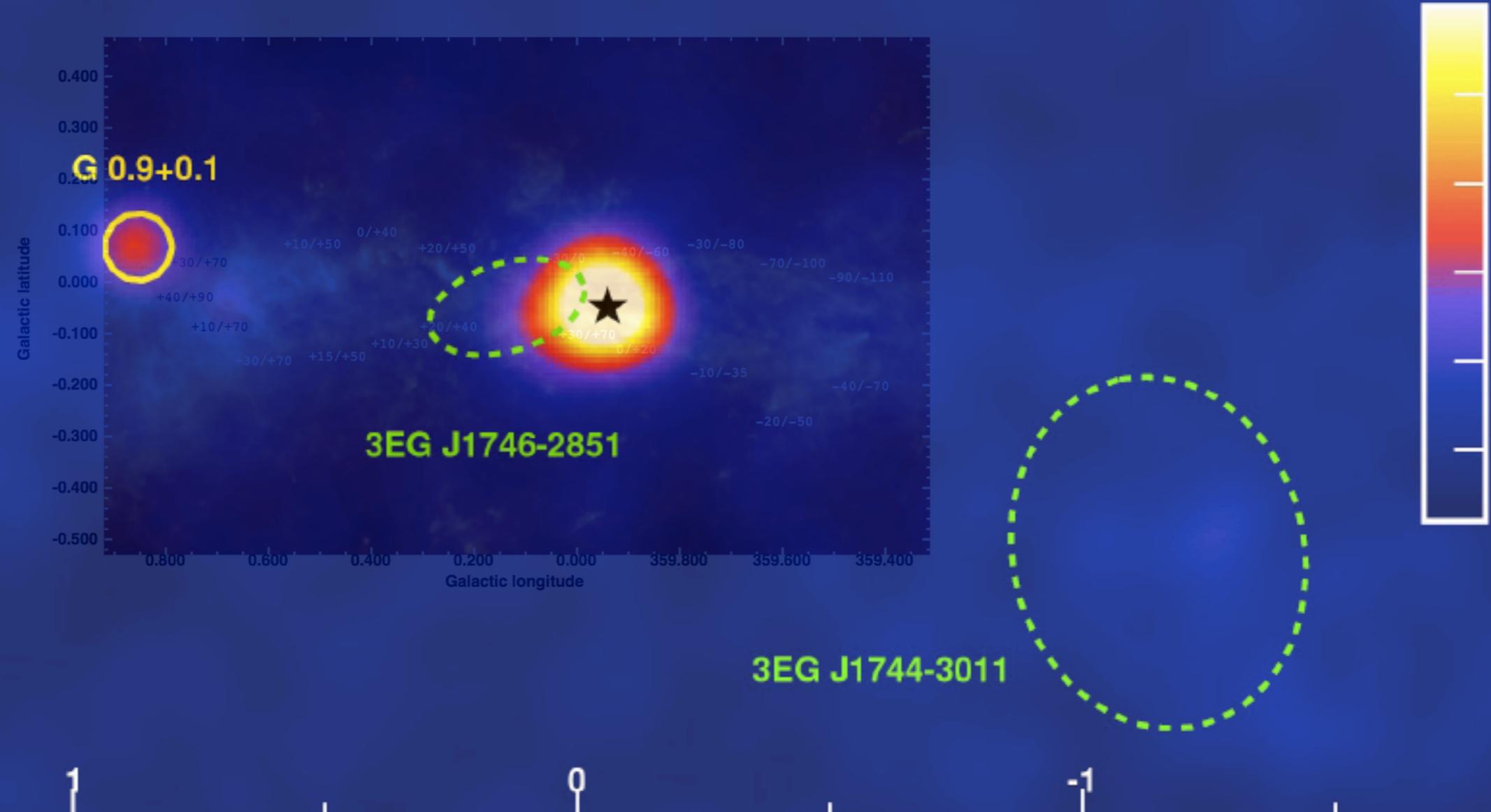
Cosmic Ray Transport in the GC

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

Herschel SPIRE 250 μ m (Molinari et al. 2011)

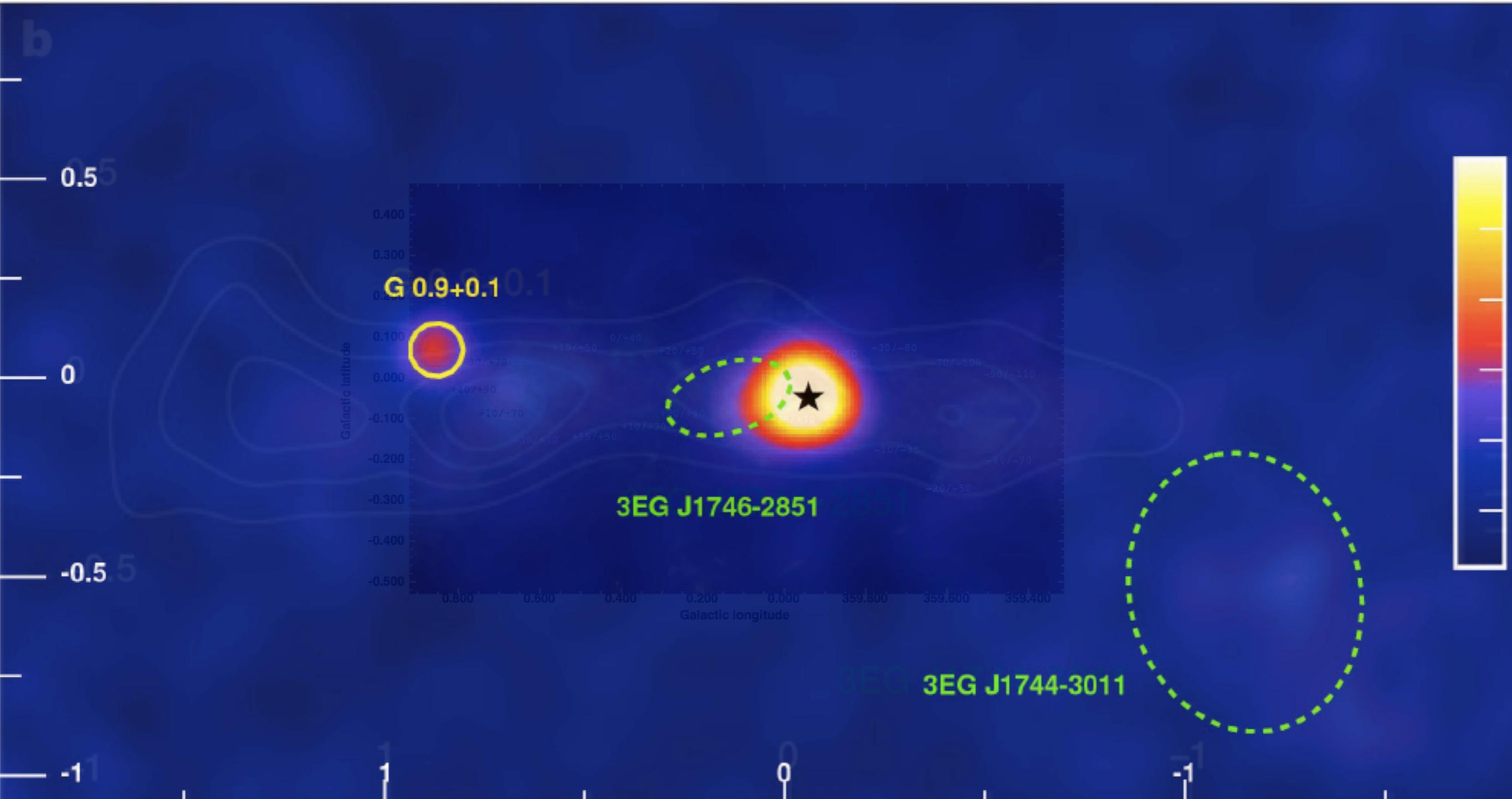


Herschel SPIRE 250 μ m Diffuse γ s in H.E.S.S. data? (Molinari et al. 2011)



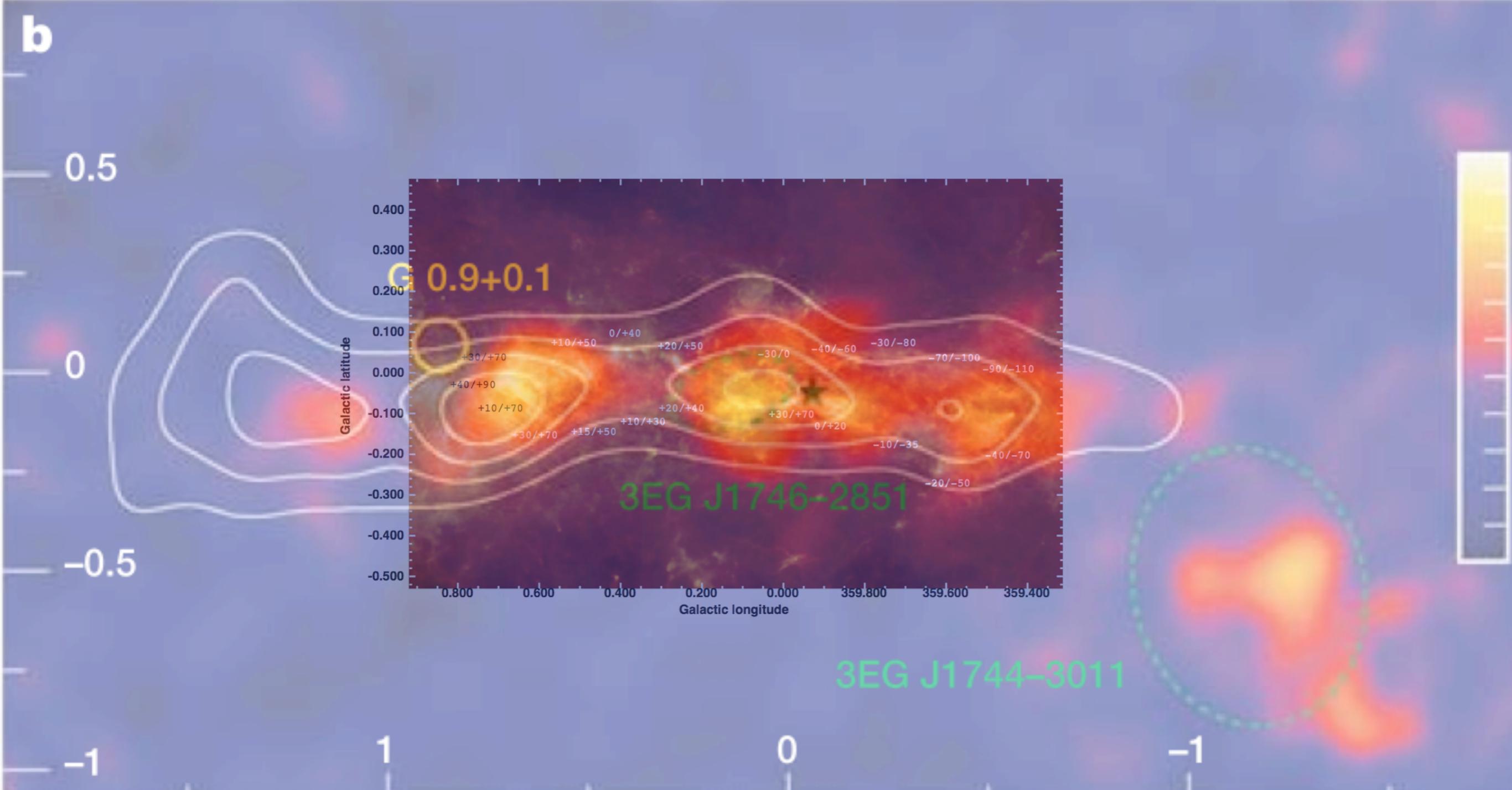
- ▶ 50 hour H.E.S.S. Observation of GC in 2005
- ▶ Need to subtract the two bright sources

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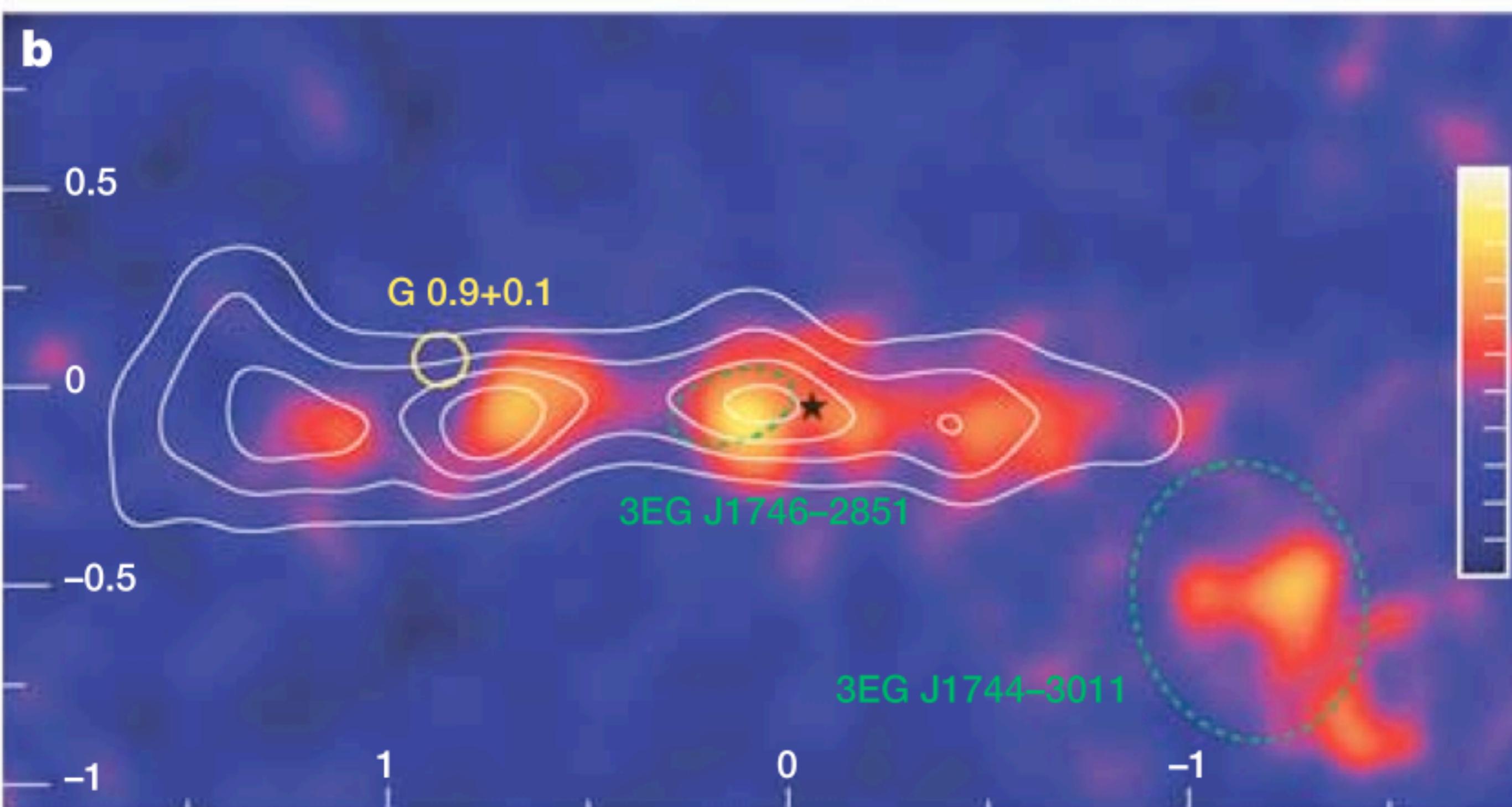
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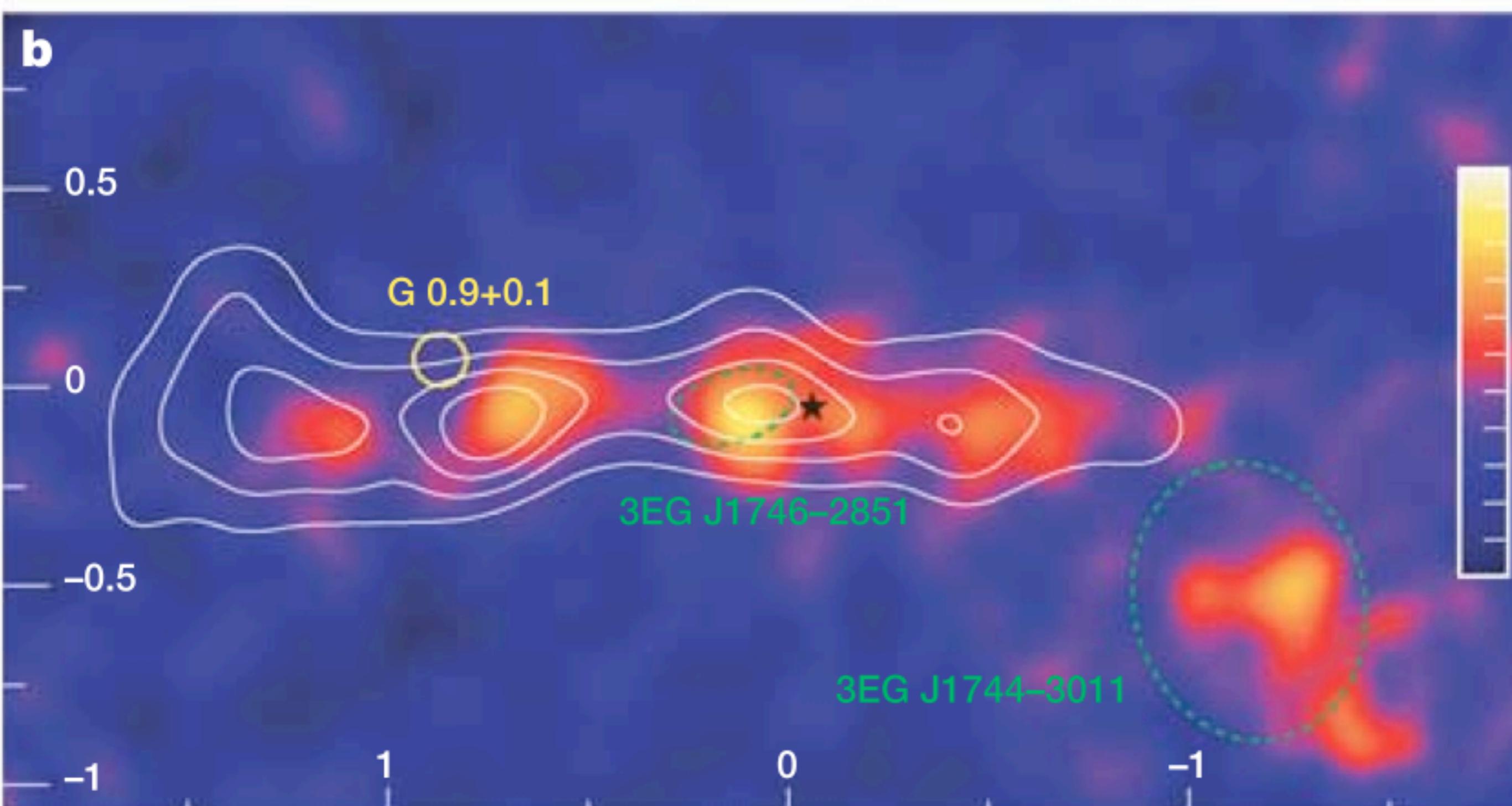
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b

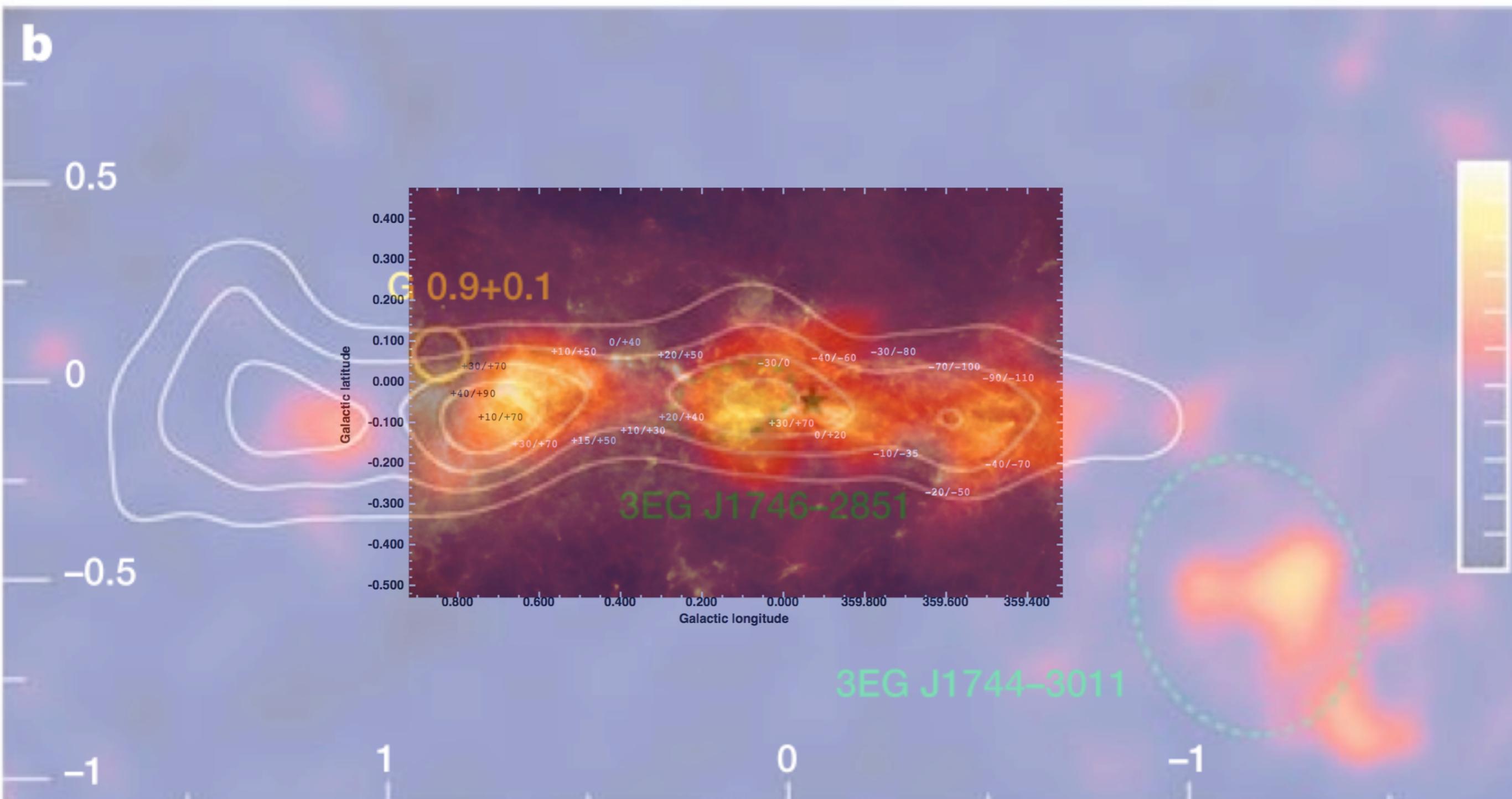


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HESS TeV (Aharonian et al 2006)

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Herschel SPIRE 250 μm (Molinari et al. 2011)

b

0.5

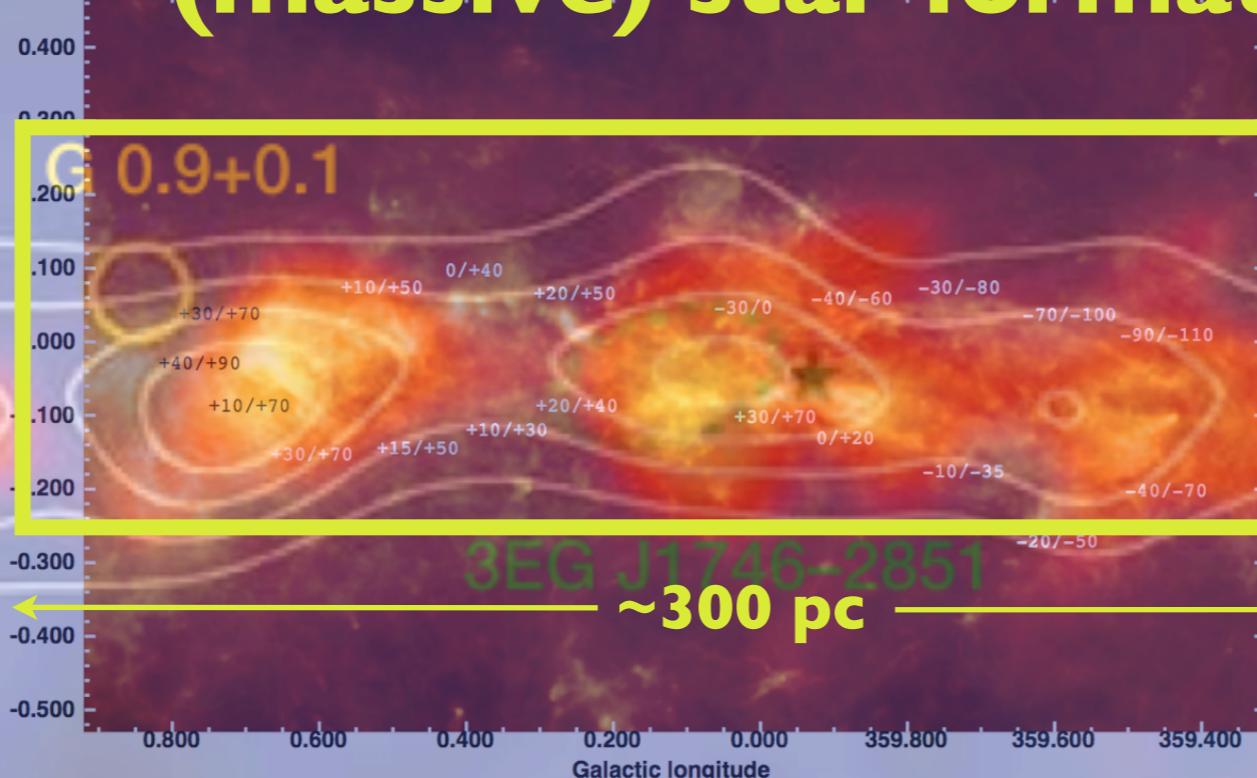
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-0.5

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Galactic latitude

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3EG J1746-2851

~300 pc

3EG J1744-3011

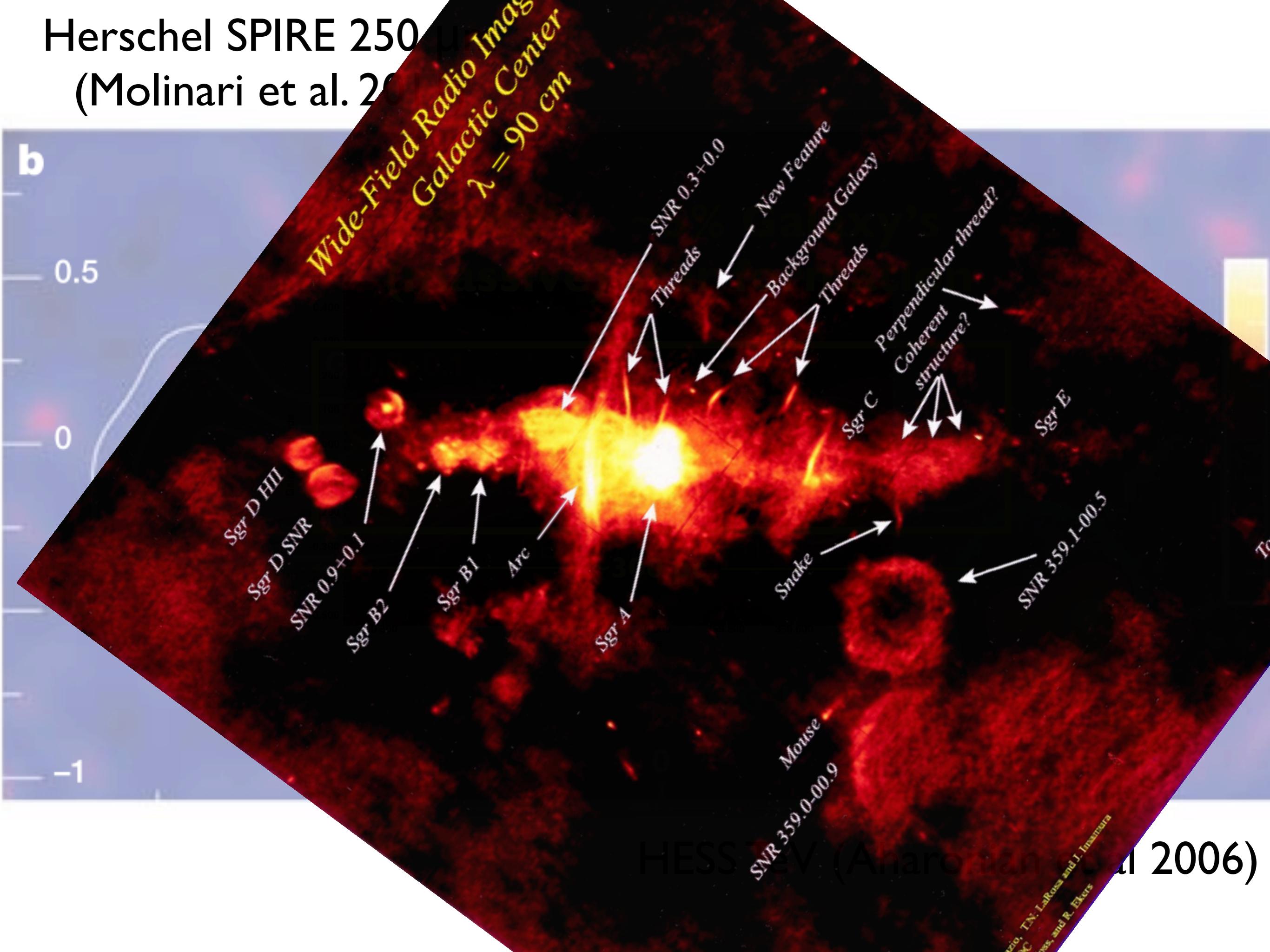
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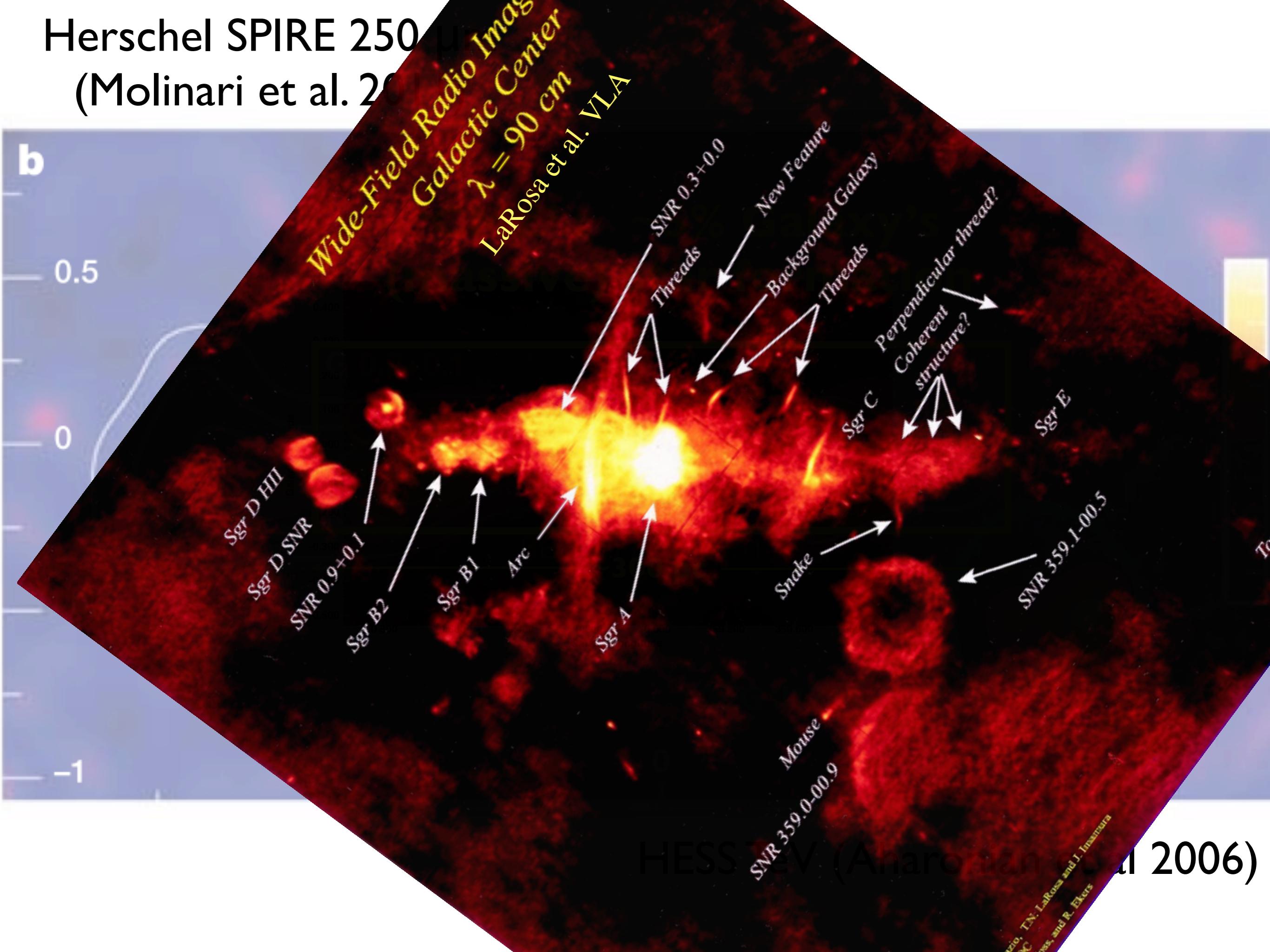
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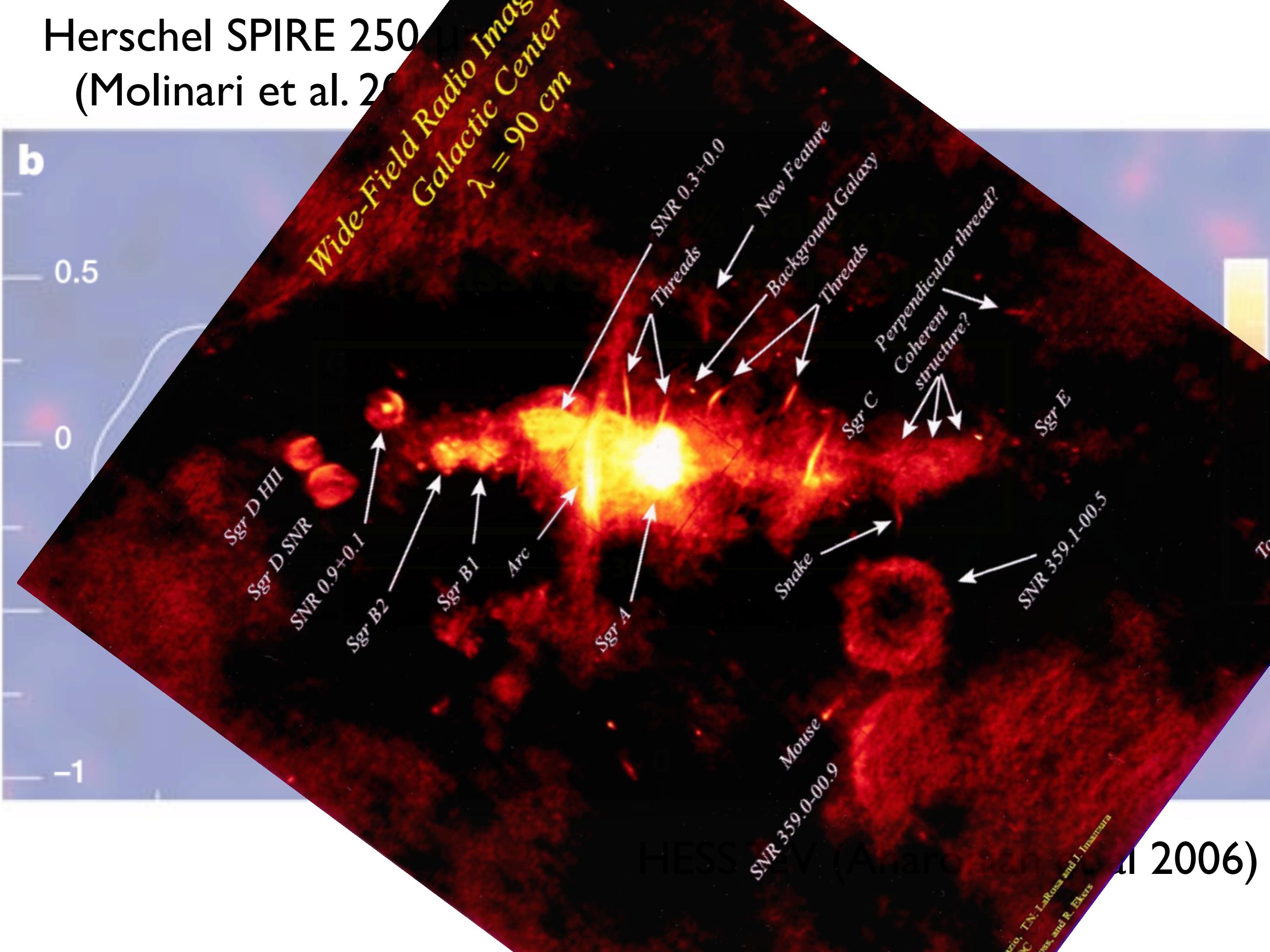
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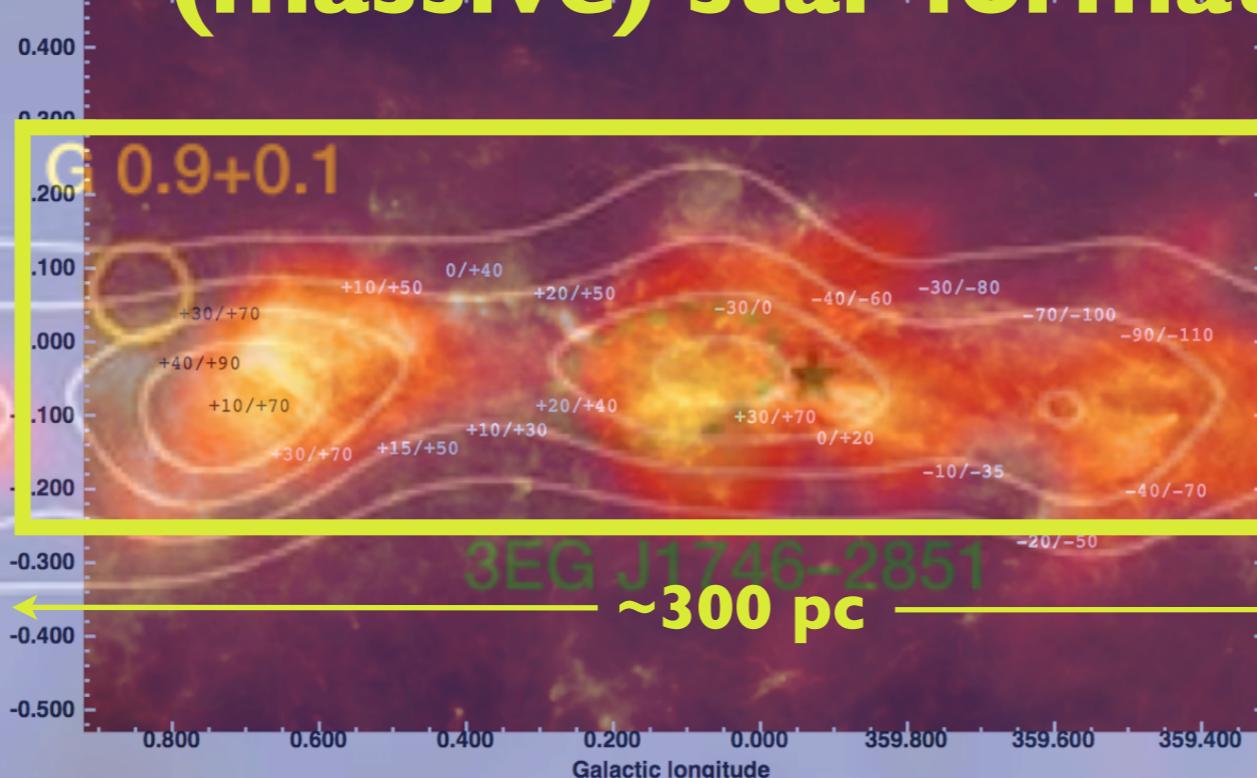
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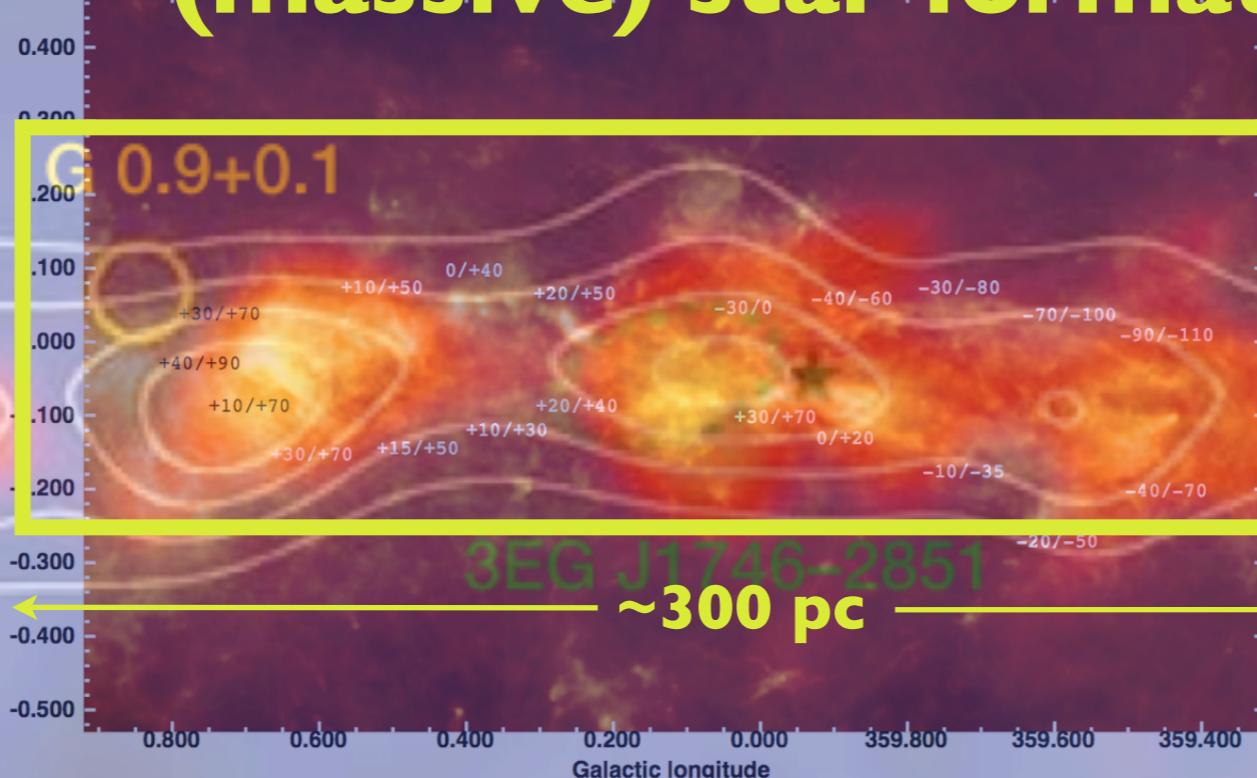
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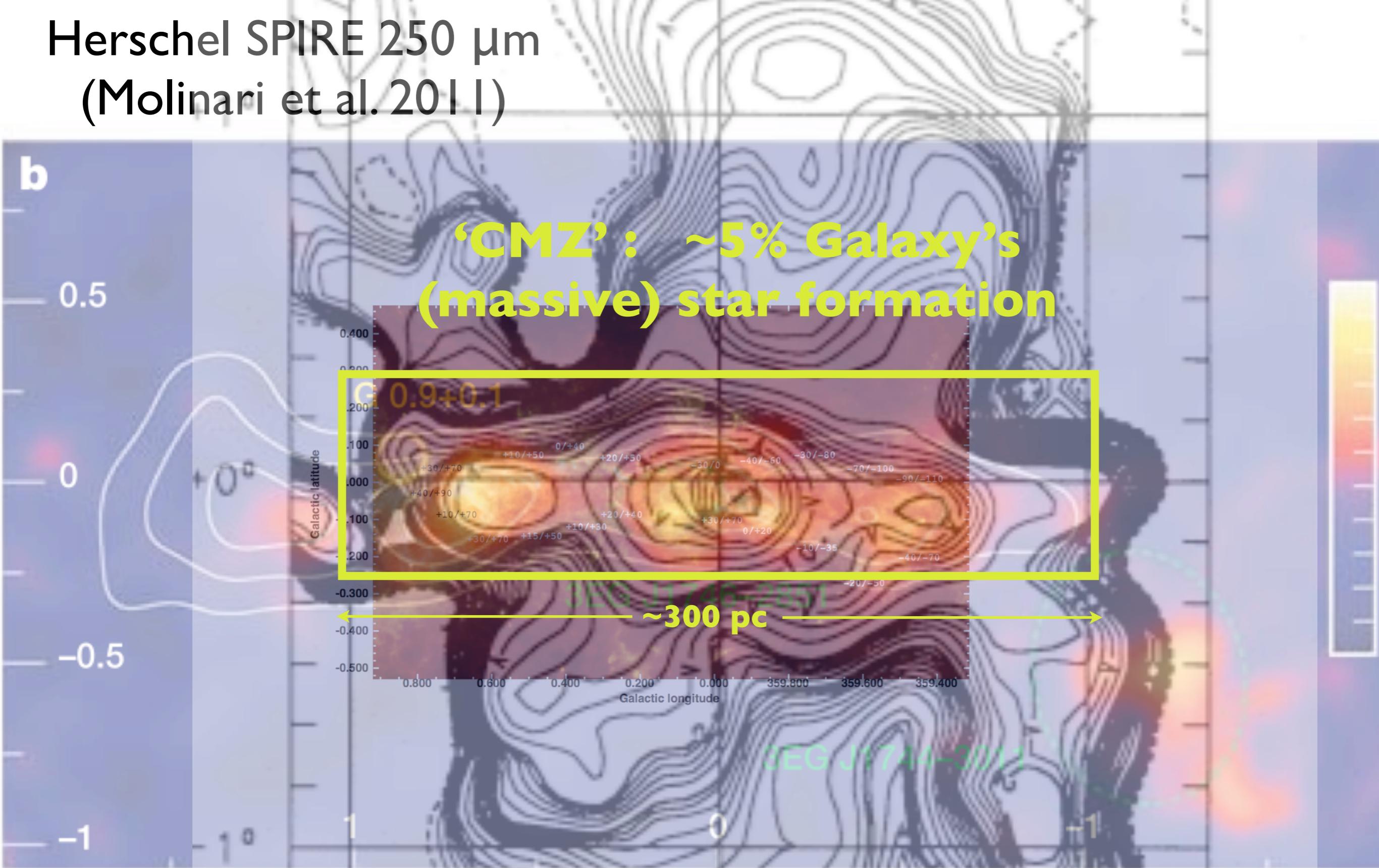
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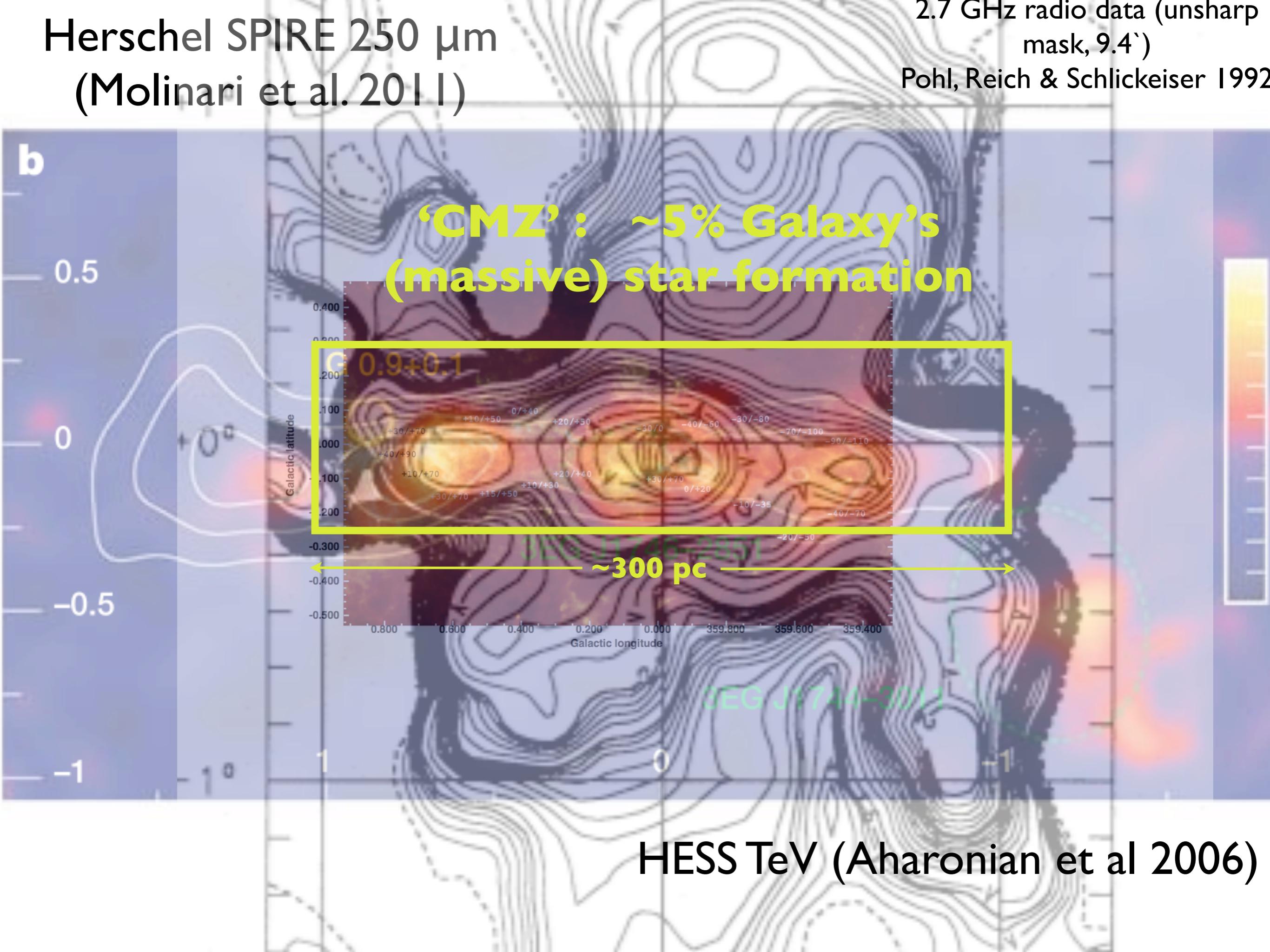


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2.7 GHz radio data (unsharp
mask, 9.4`)

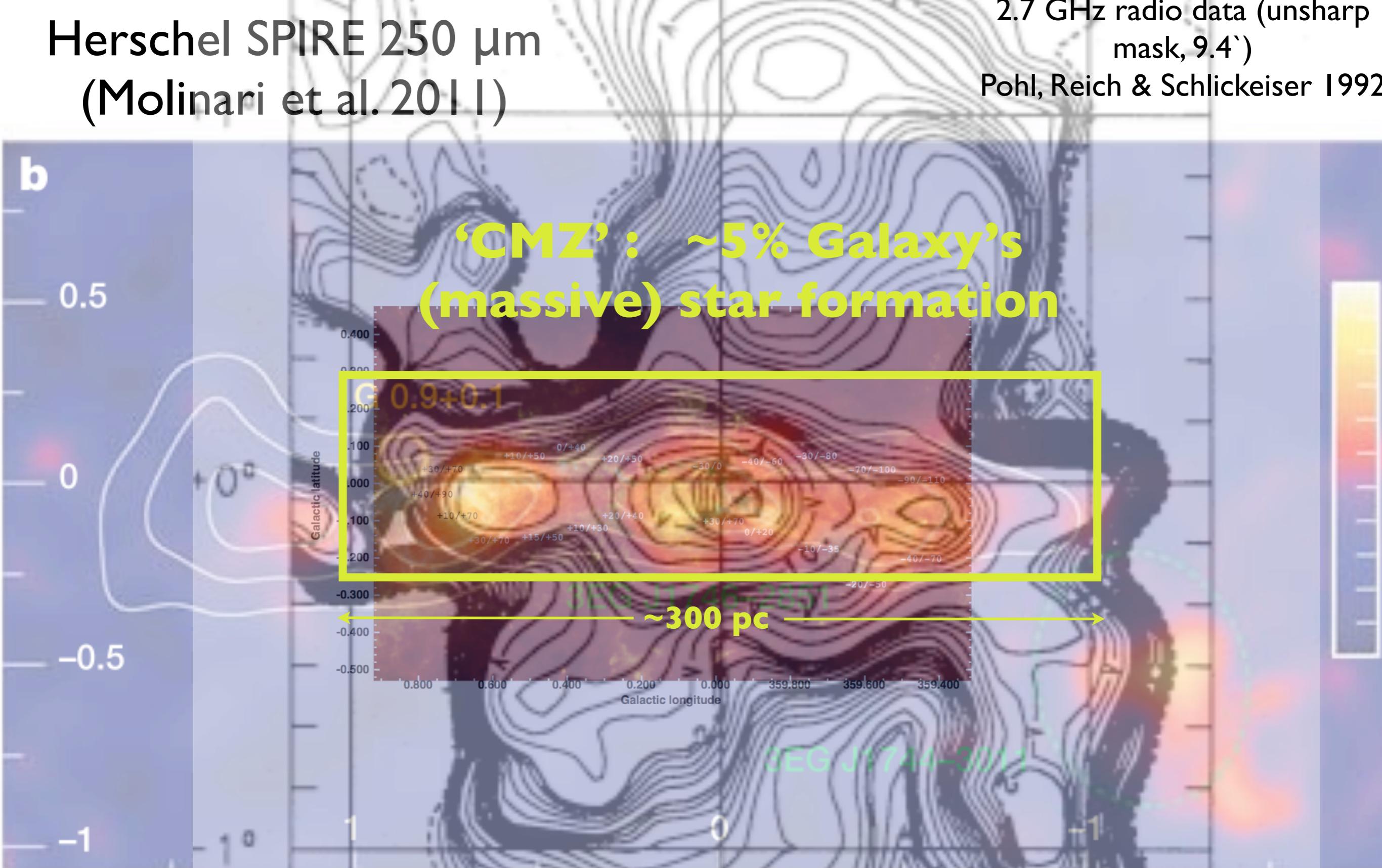
Pohl, Reich & Schlickeiser 1992



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



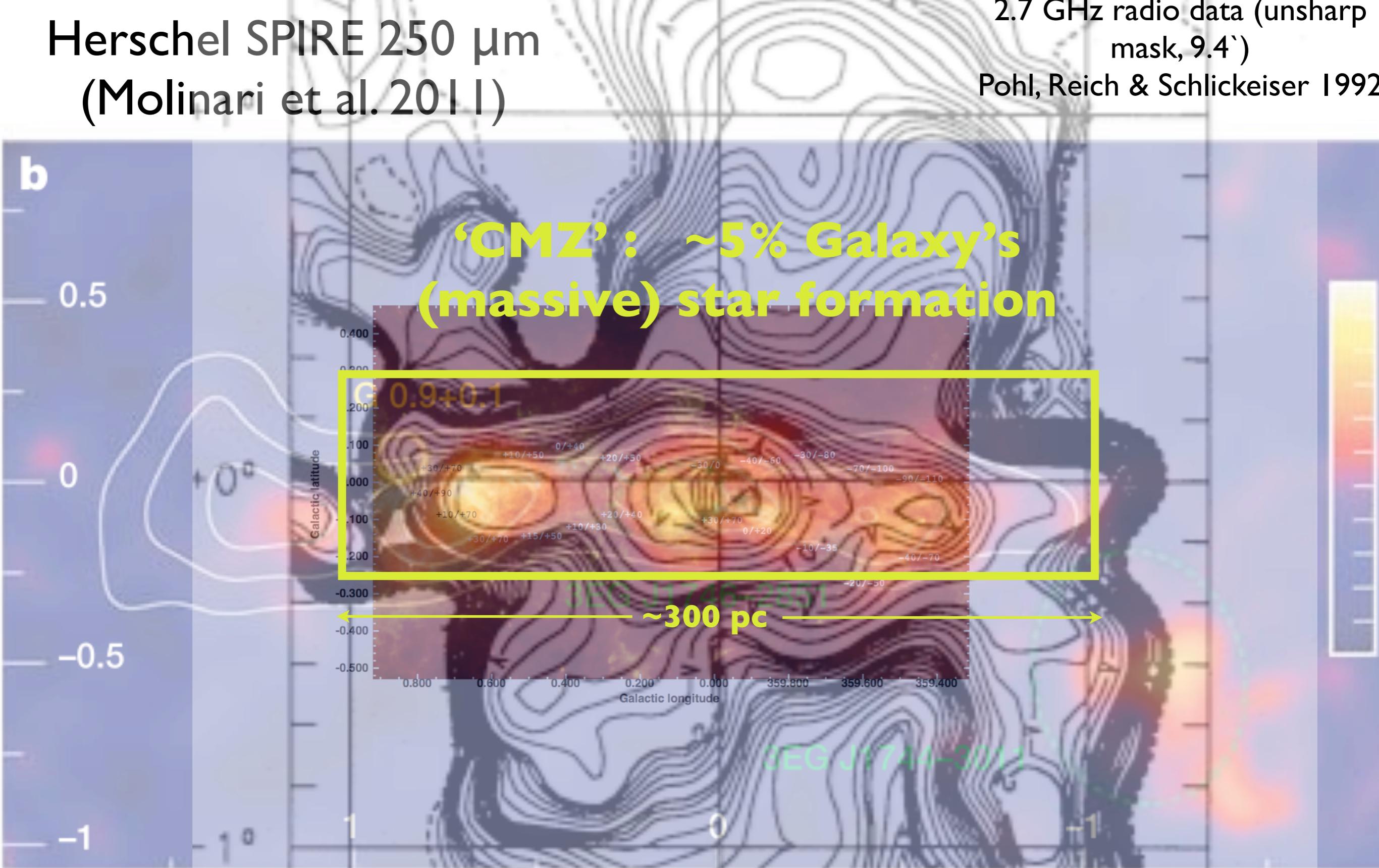
Ring collimates outflow -
outflow ablates cold gas

HESS TeV (Aharonian et al 2006)

Herschel SPIRE 250 μ m (Molinari et al. 2011)

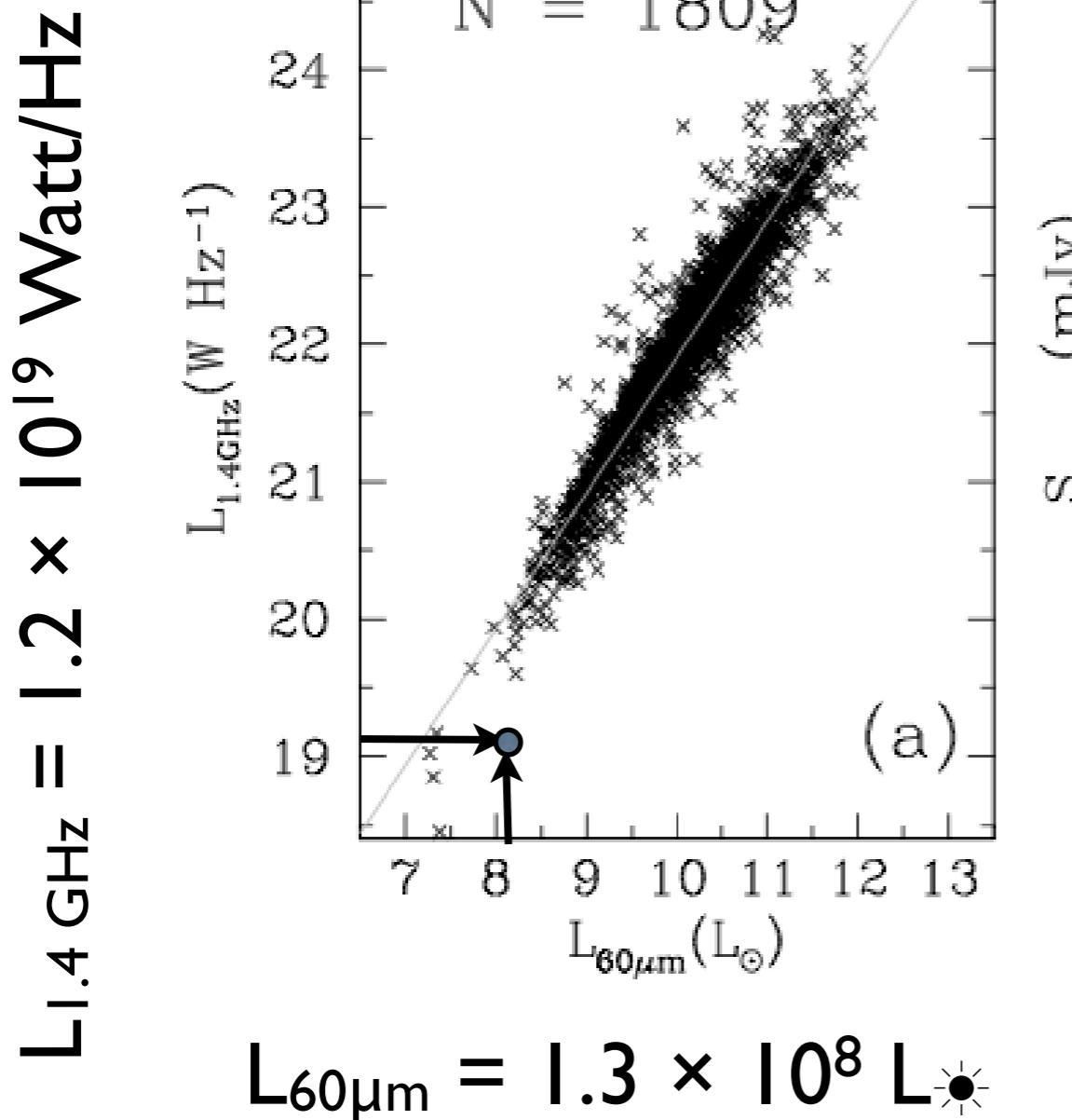
2.7 GHz radio data (unsharp
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Pohl, Reich & Schlickeiser 1992



FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5



RC in deficit wrt expectation
from FIR

HESS system is 1 dex ($> 4\sigma$) off
correlation

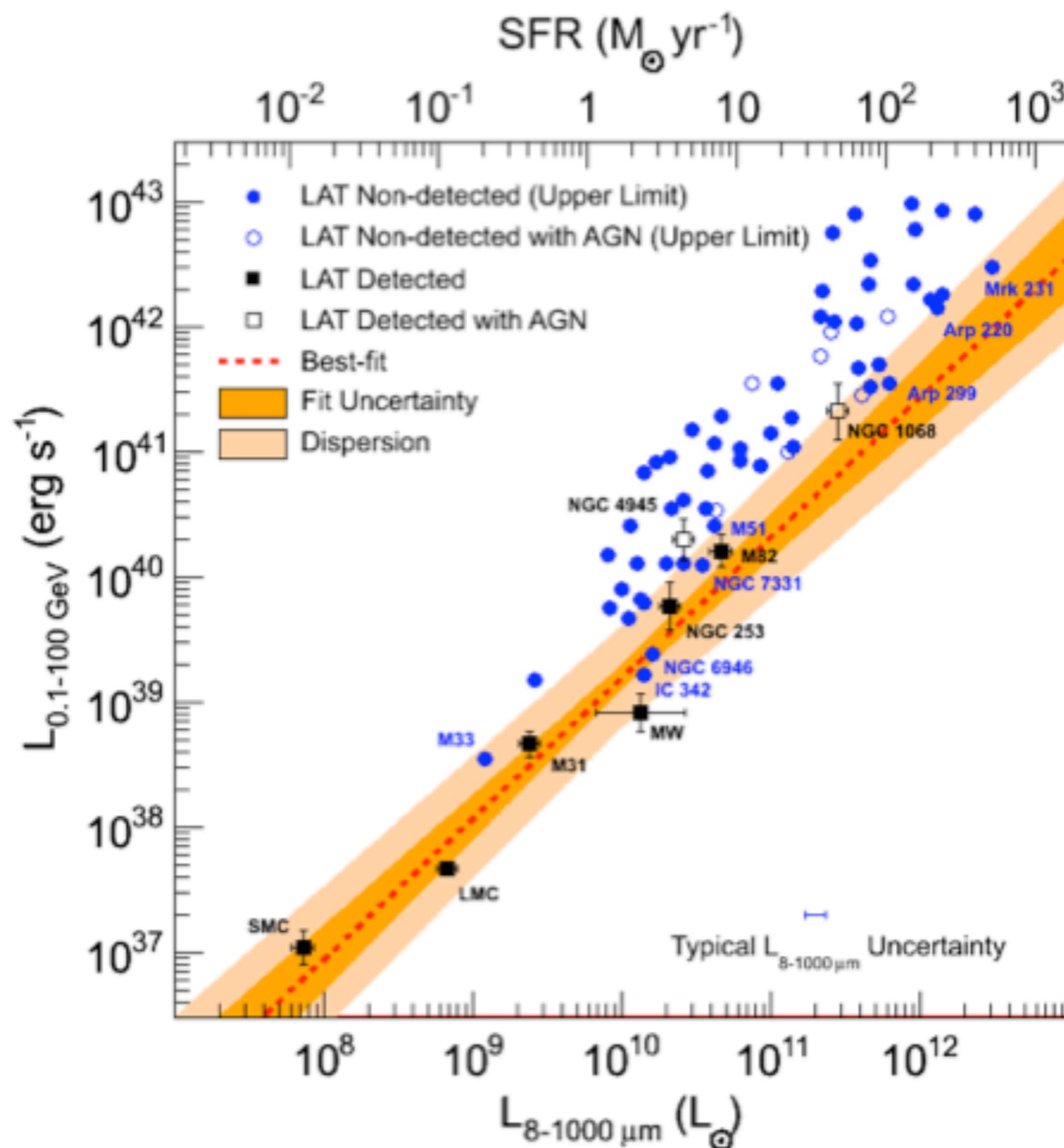
i.e. **GHz RC emission of
HESS region only $\sim 10\%$
expected**

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

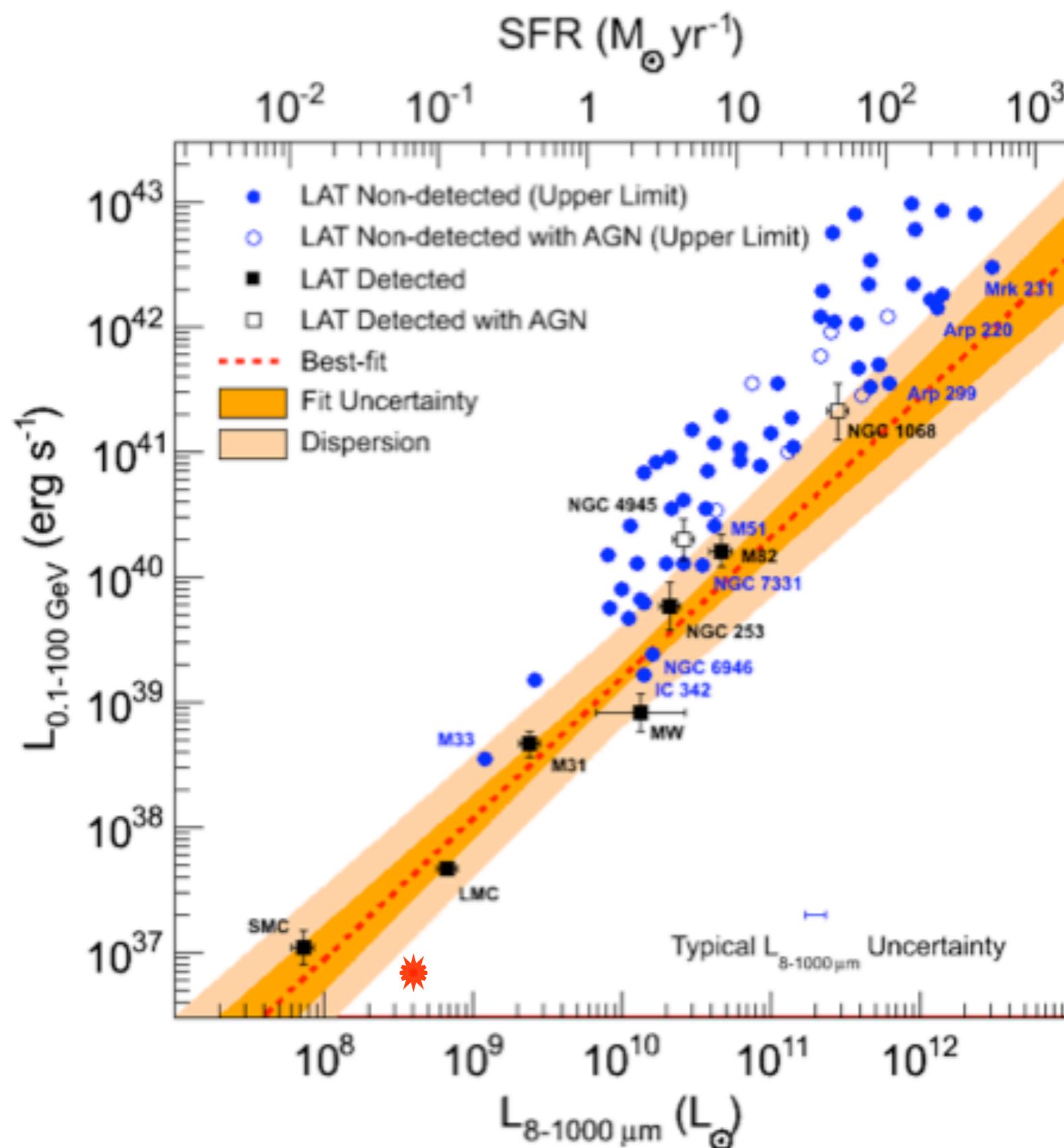
FIR- γ -ray Scaling?

- 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): $L_{\text{GeV}} \sim 10^{-5} L_{\text{TIR}}$ (assuming 10^{50} erg per SN in CRs)
- Given scaling, **GeV emission only ~10% expected, TeV emission of HESS region only about 1% expected,**



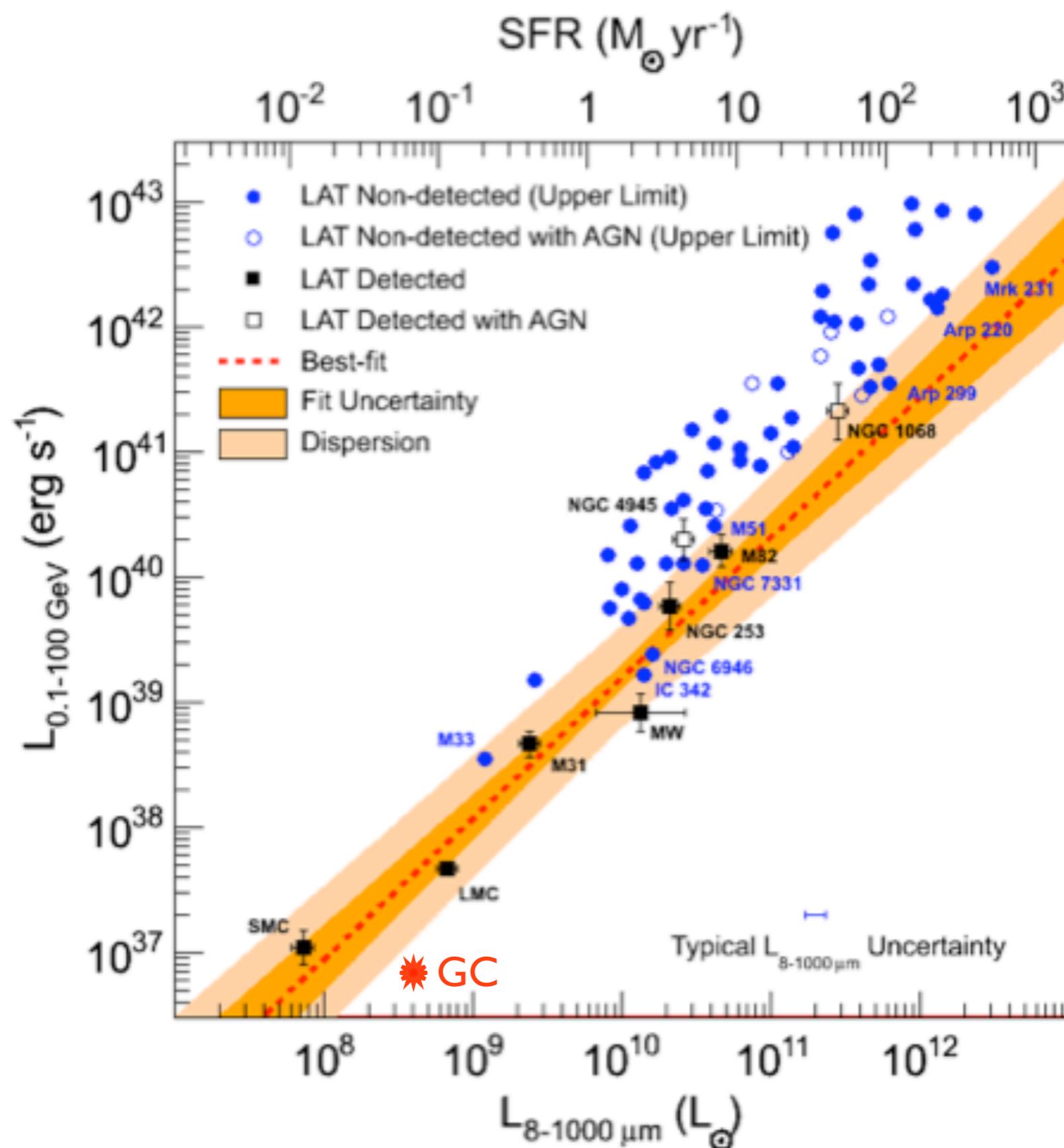
Martin 2011, *Fermi* collab

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



Martin 2011, *Fermi*
collab

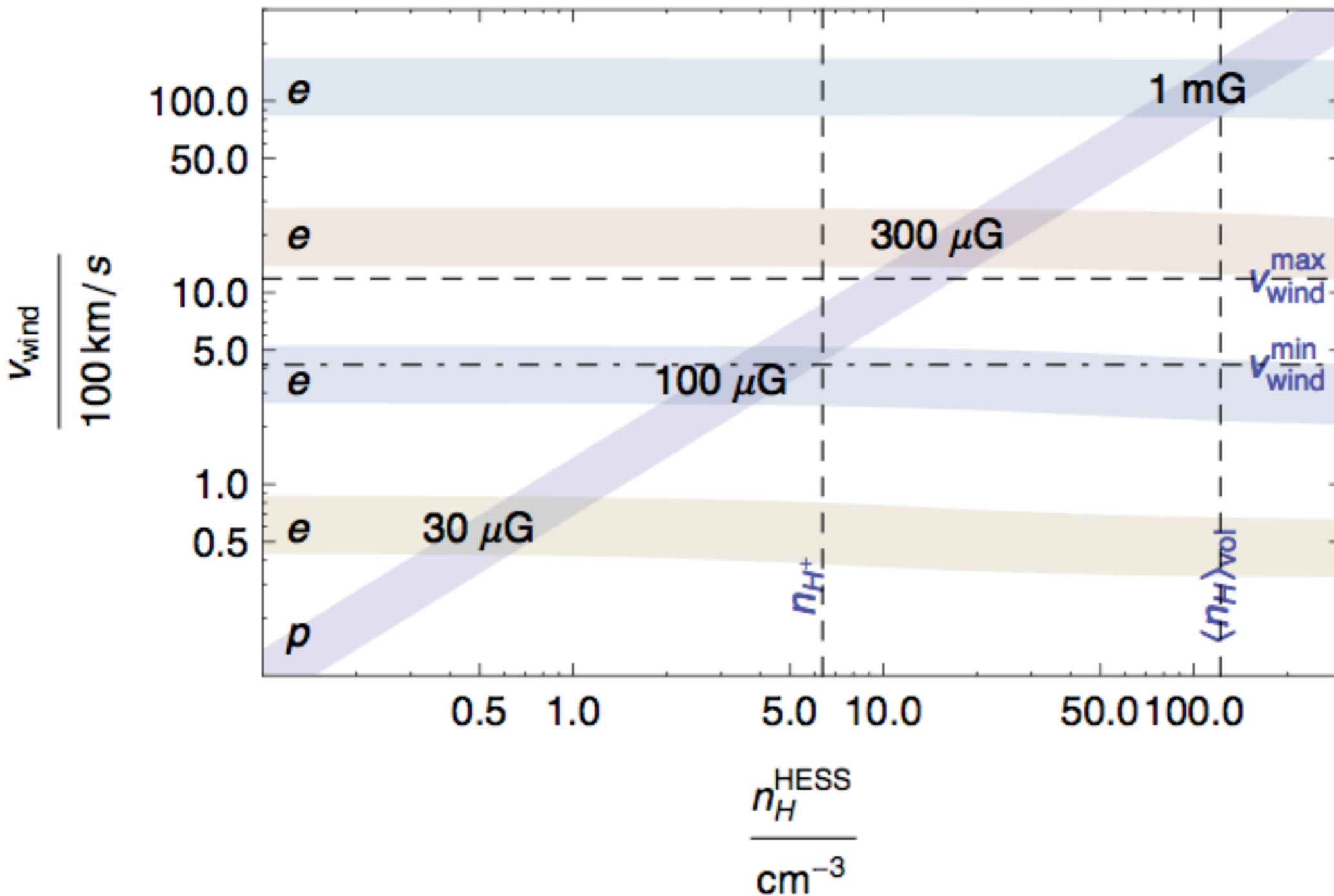
Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).



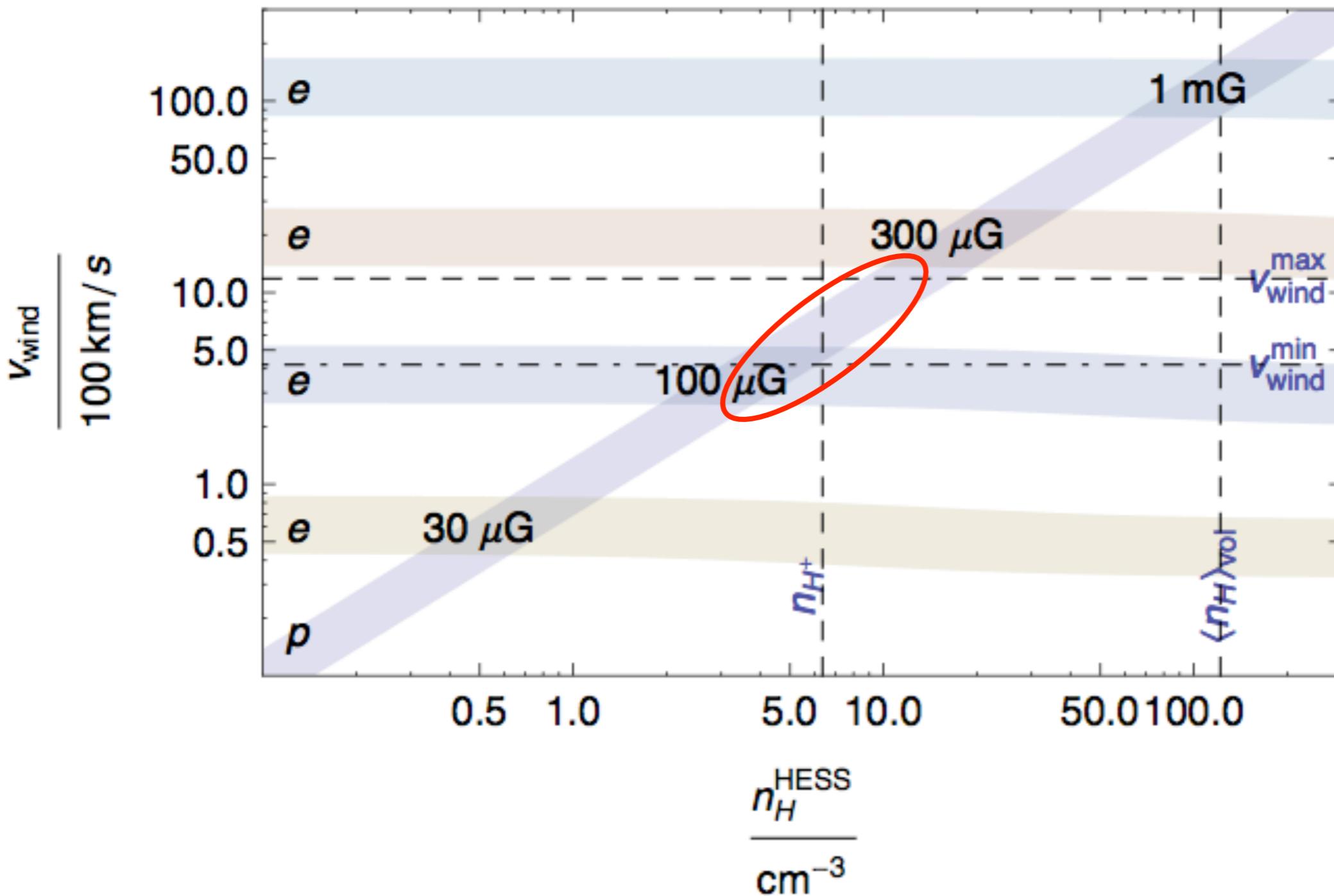
Martin 2011, *Fermi* collab

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

Gas/Wind/Mag. Field

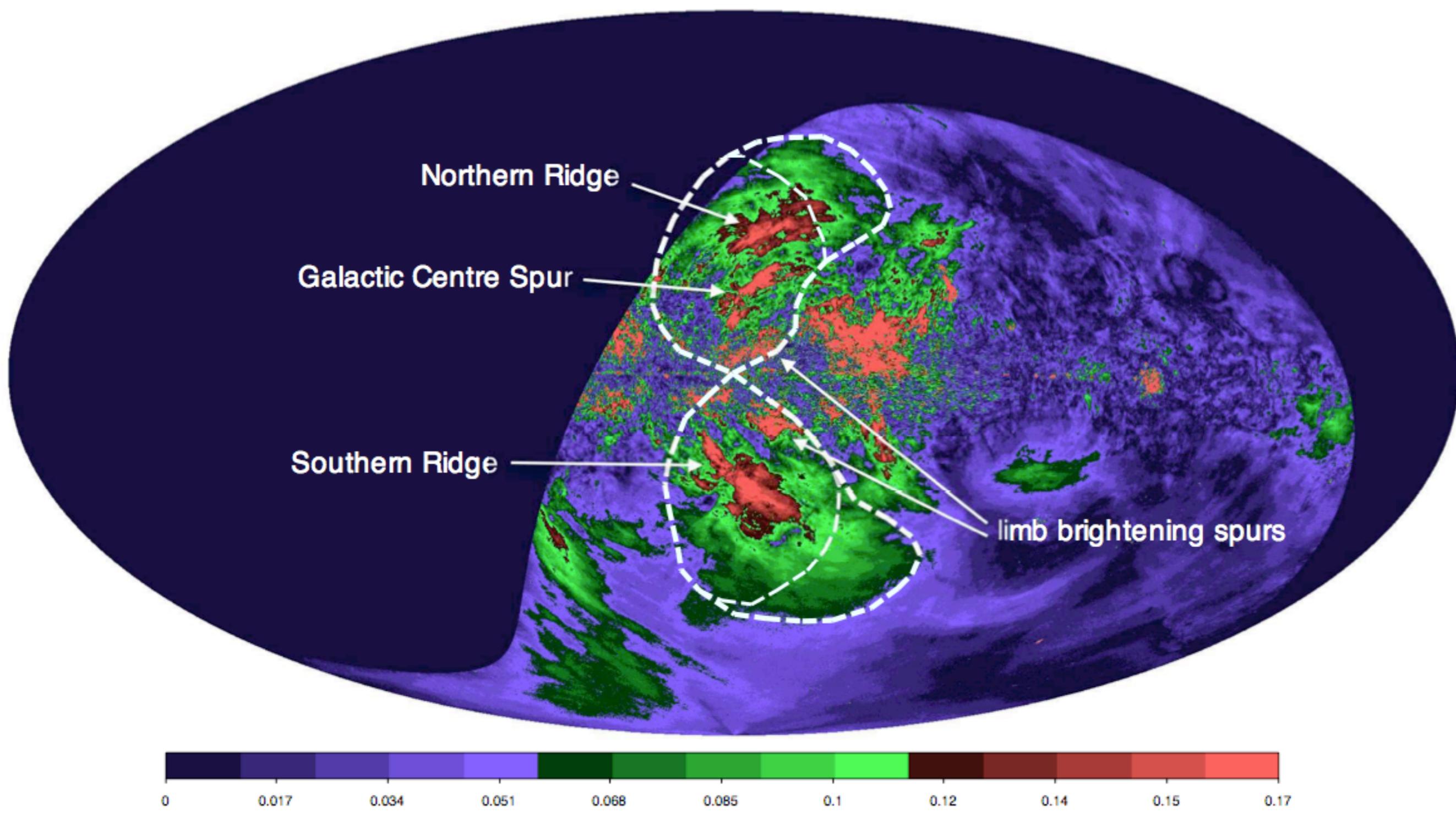


Gas/Wind/Mag. Field



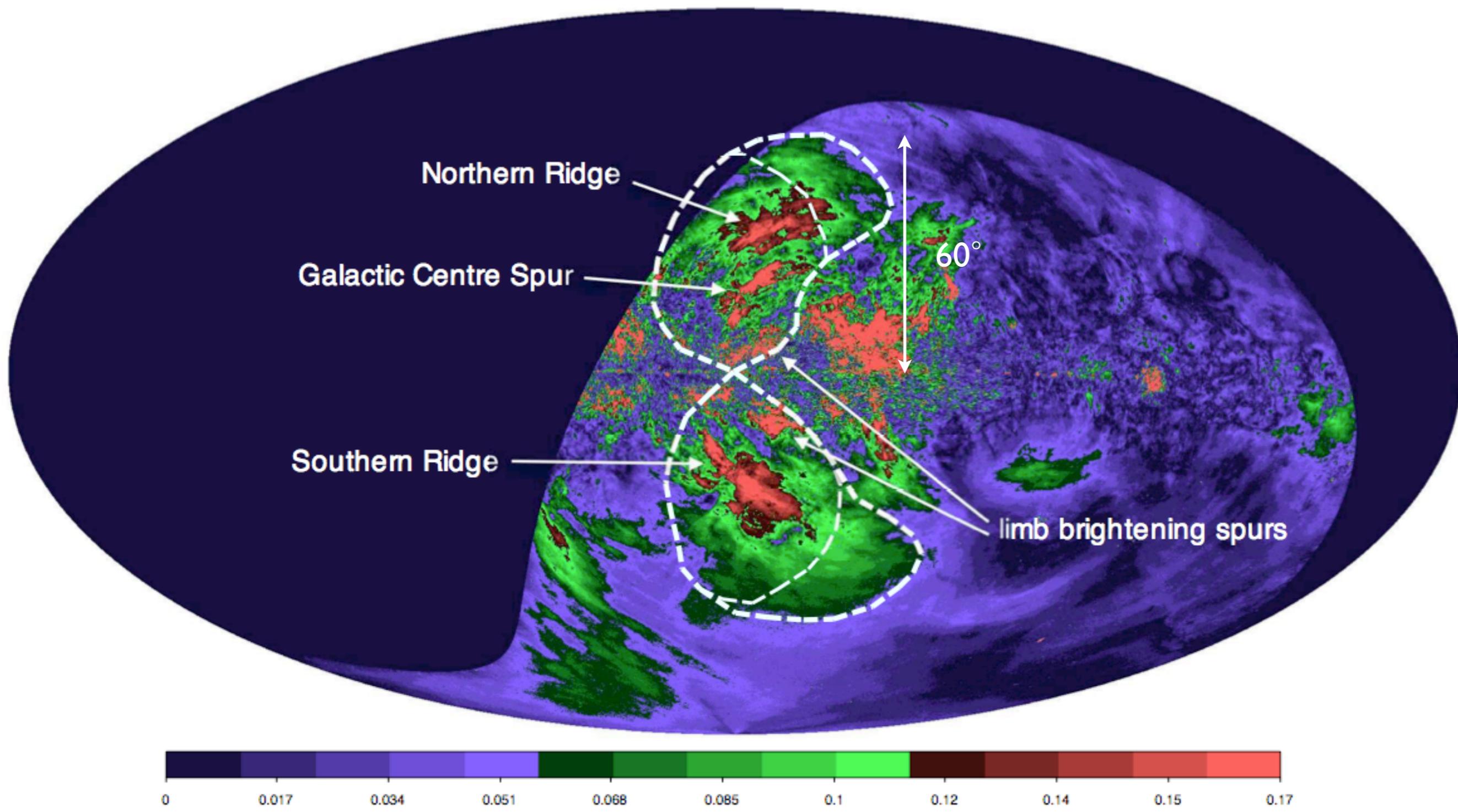
The fate of the
advected cosmic rays?

The ‘S-PASS Lobes’

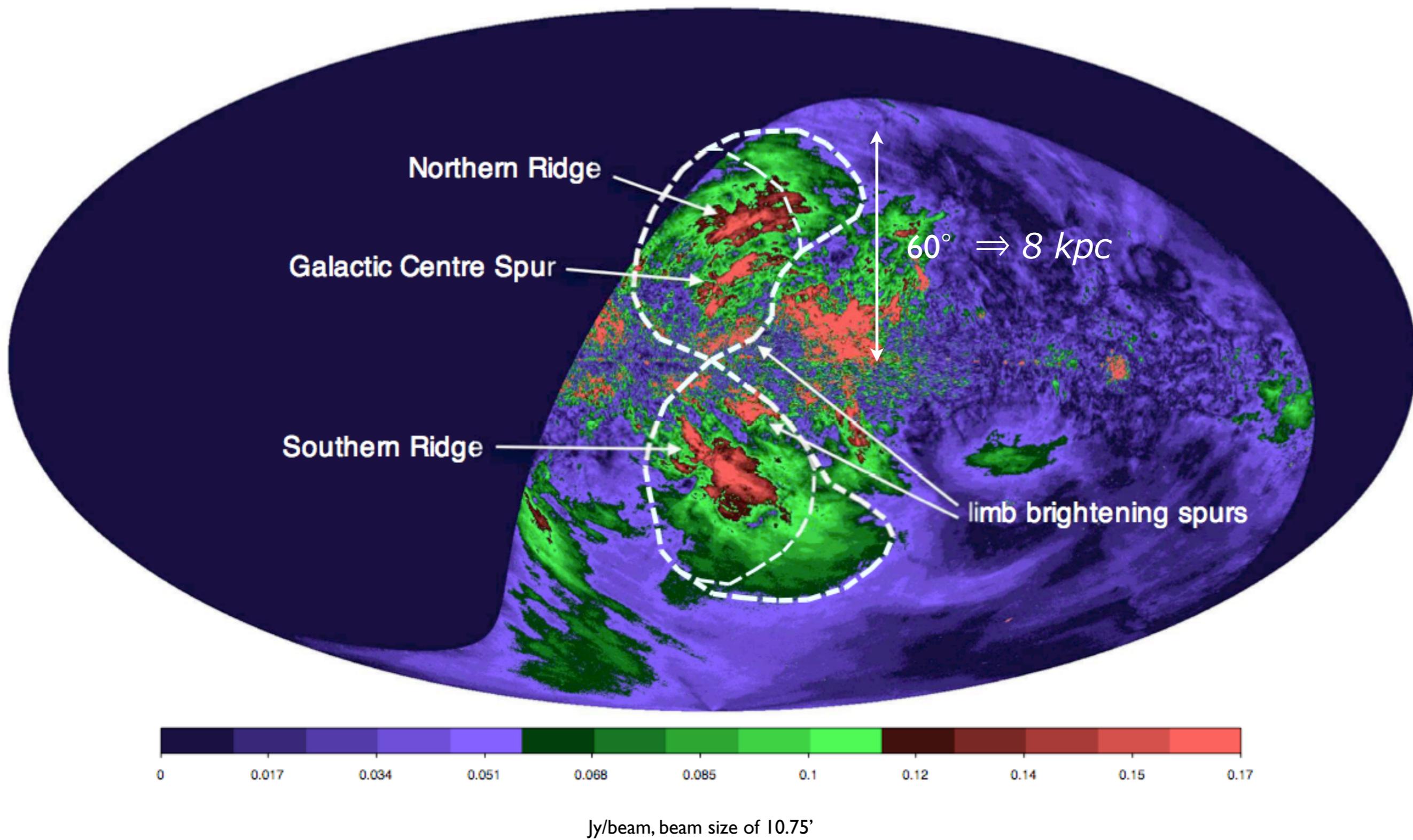


Carretti et al. Nature 2013

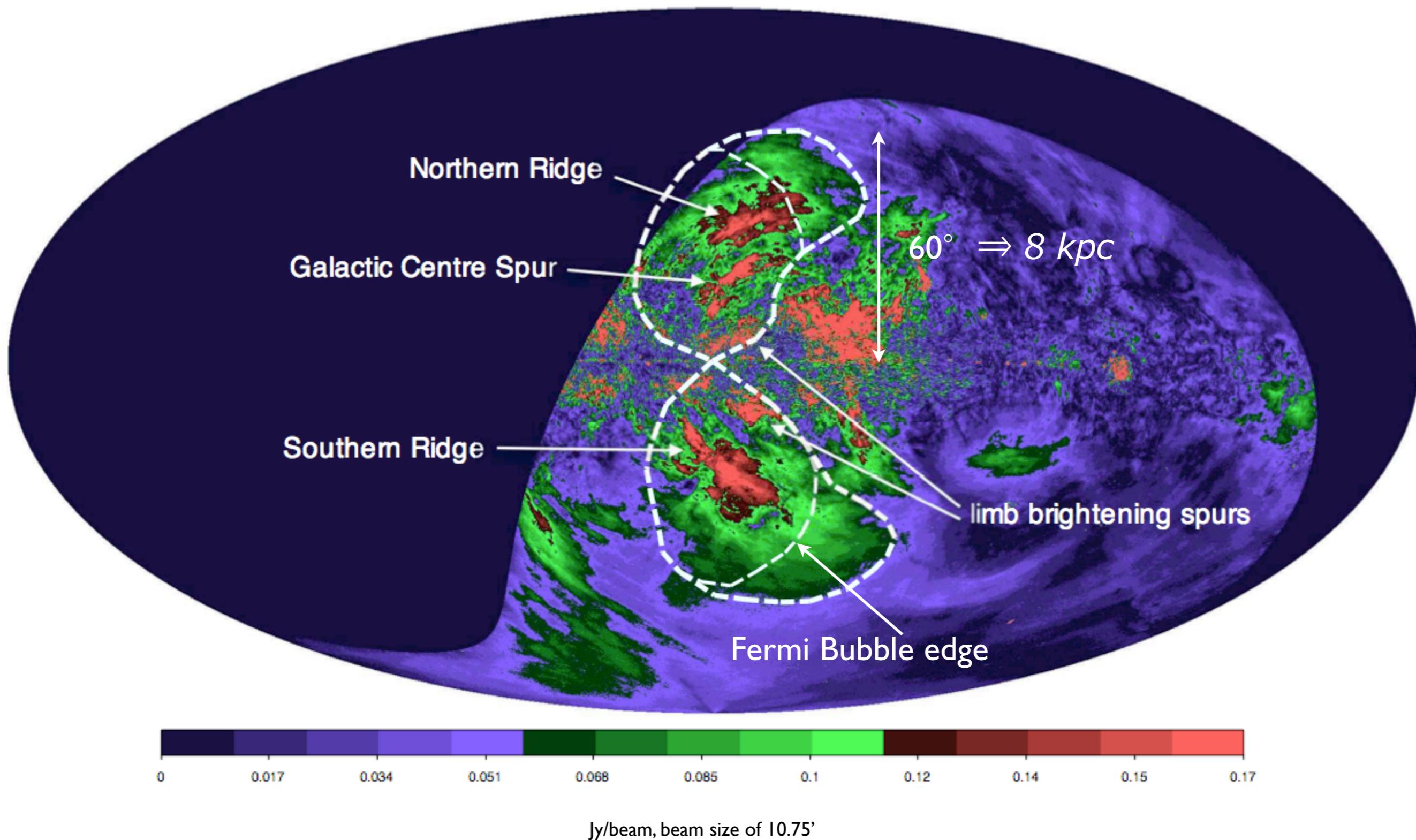
The ‘S-PASS Lobes’



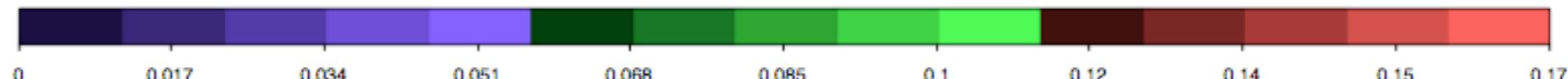
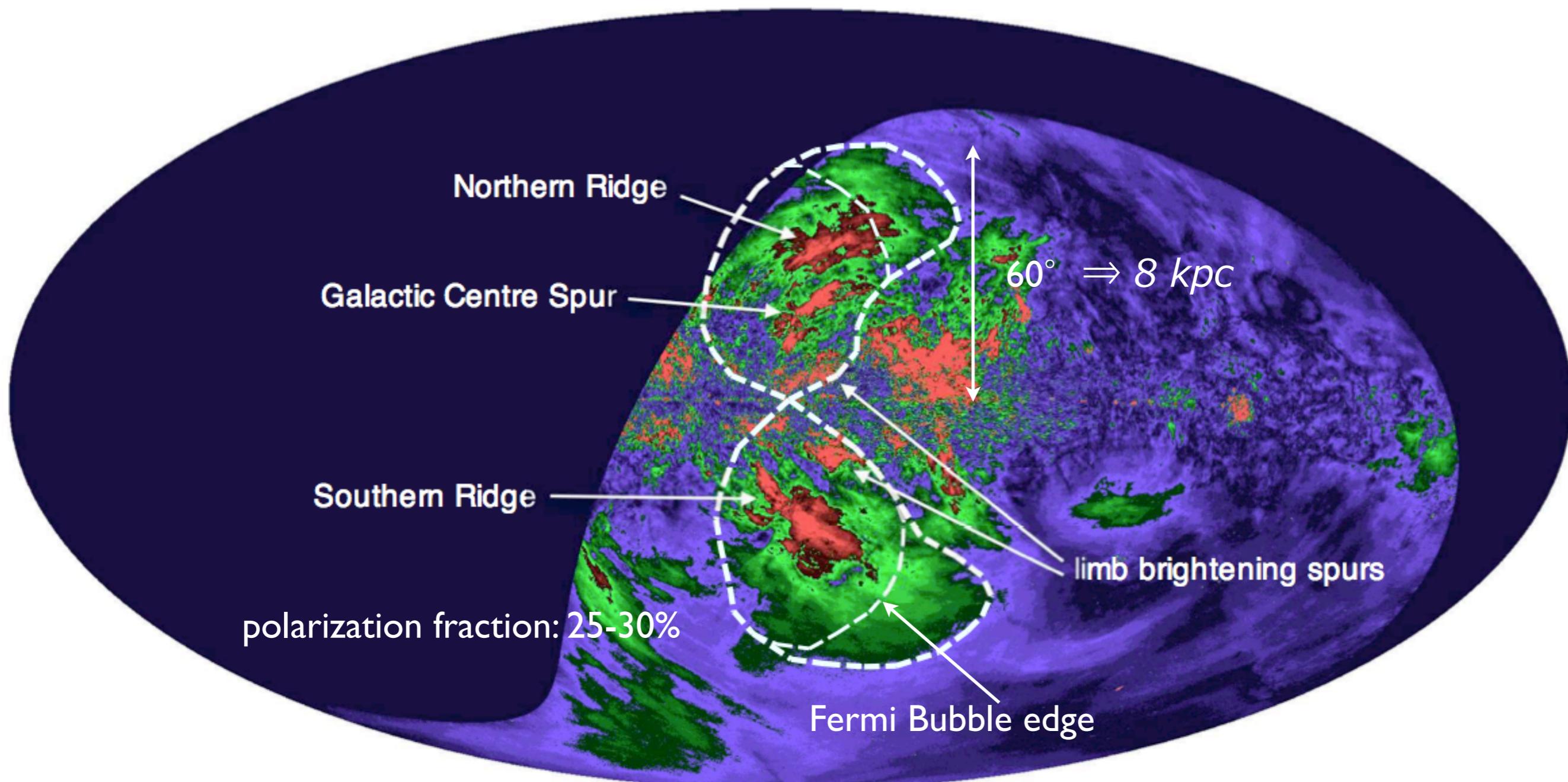
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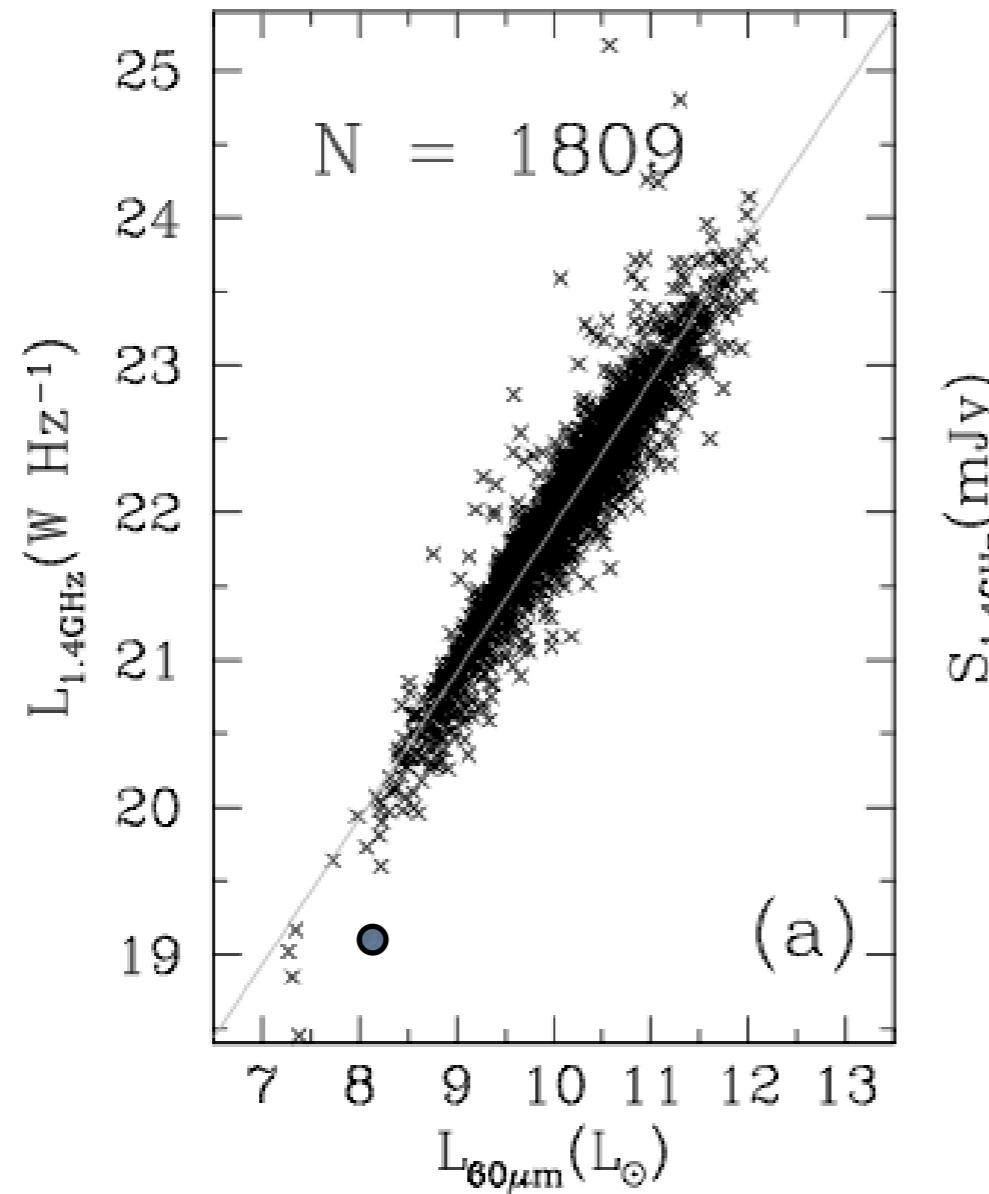


Jy/beam, beam size of 10.75'

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

$$L_{1.4\text{GHz}} = 1.5 \times 10^{20} \text{ Watt/Hz}$$



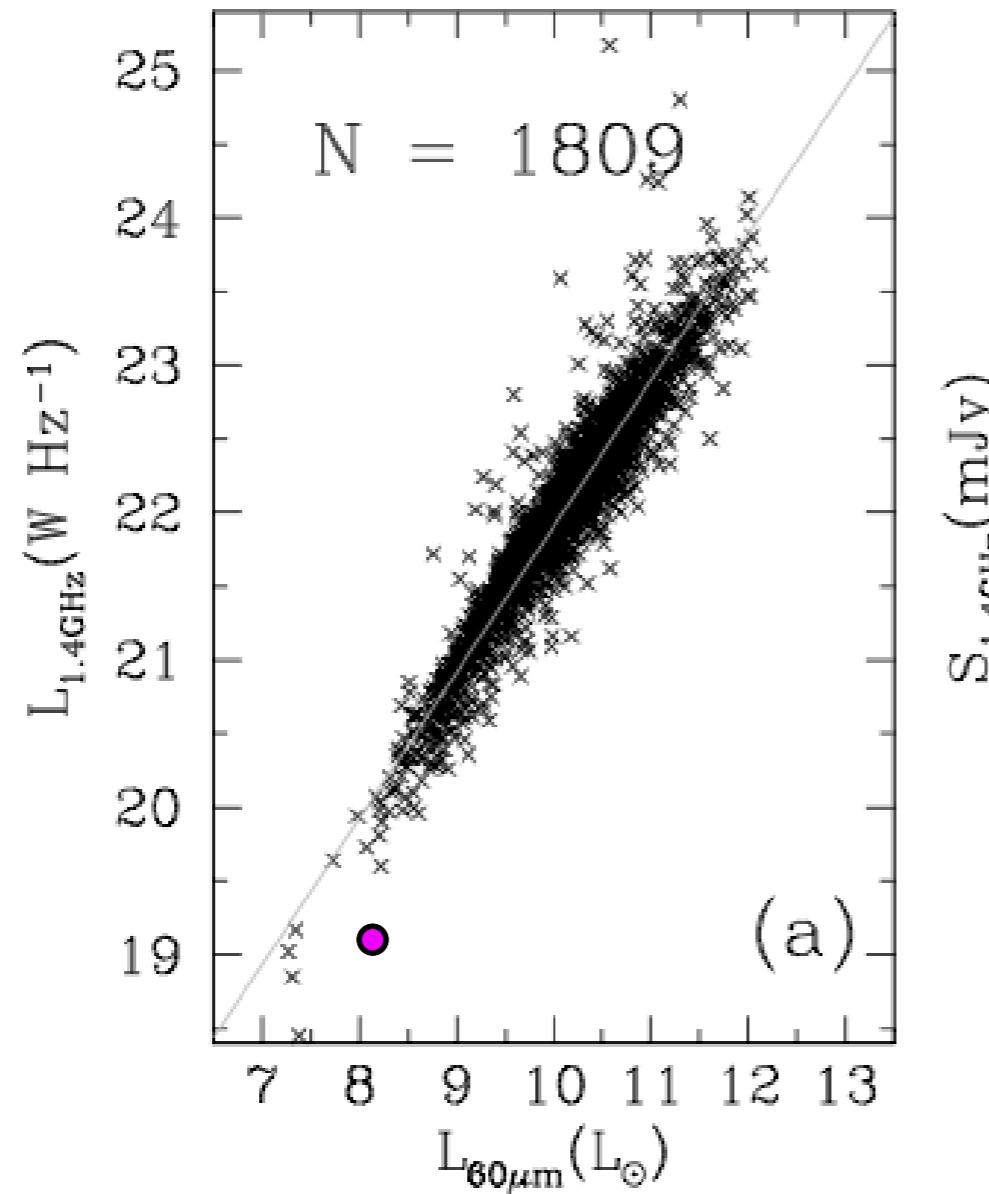
(a)

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

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

$$L_{1.4\text{GHz}} = 1.5 \times 10^{20} \text{ Watt/Hz}$$

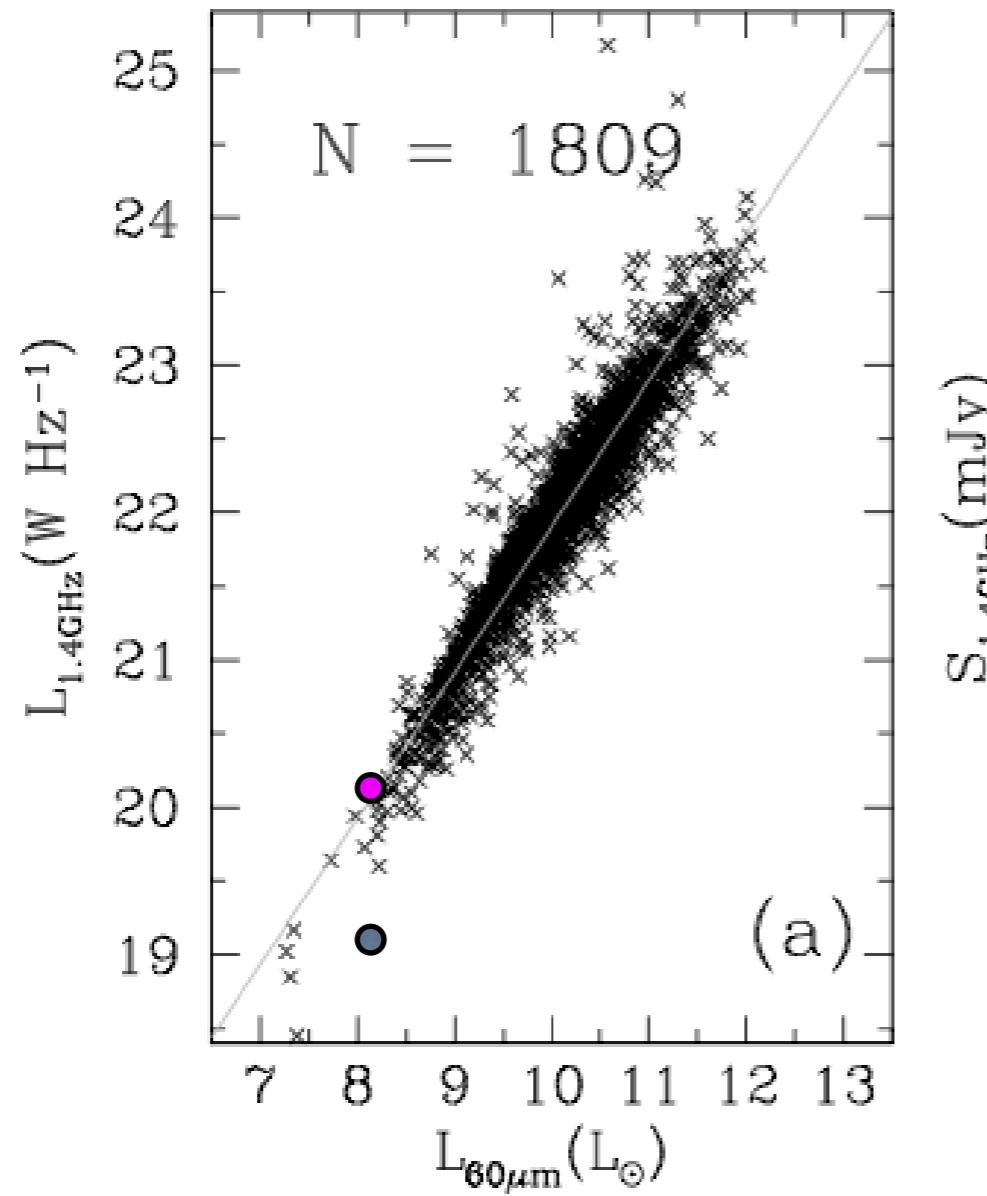


$$L_{60\mu\text{m}} = 1.3 \times 10^8 L_\odot$$

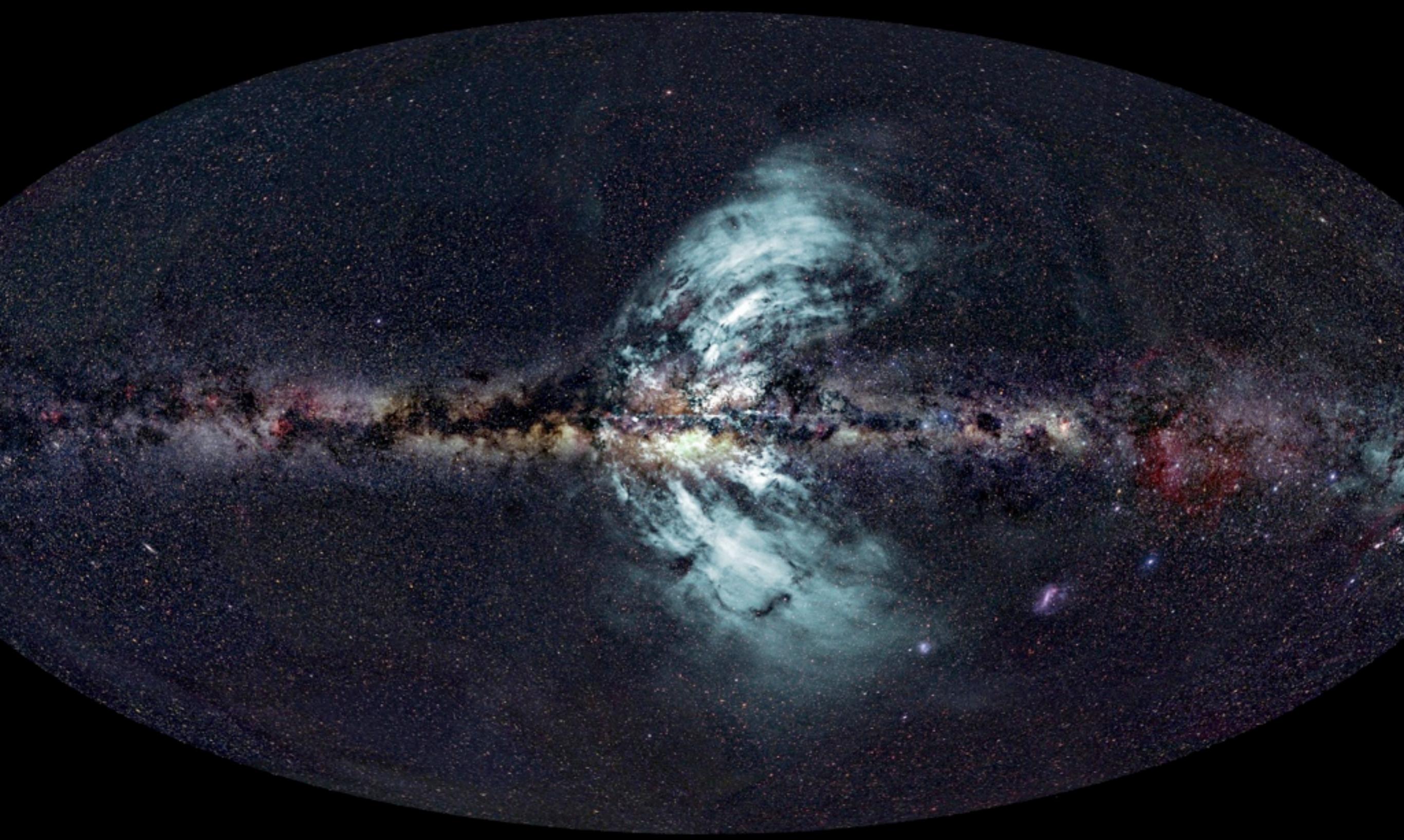
FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5

$$L_{1.4\text{GHz}} = 1.5 \times 10^{20} \text{ Watt/Hz}$$



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



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