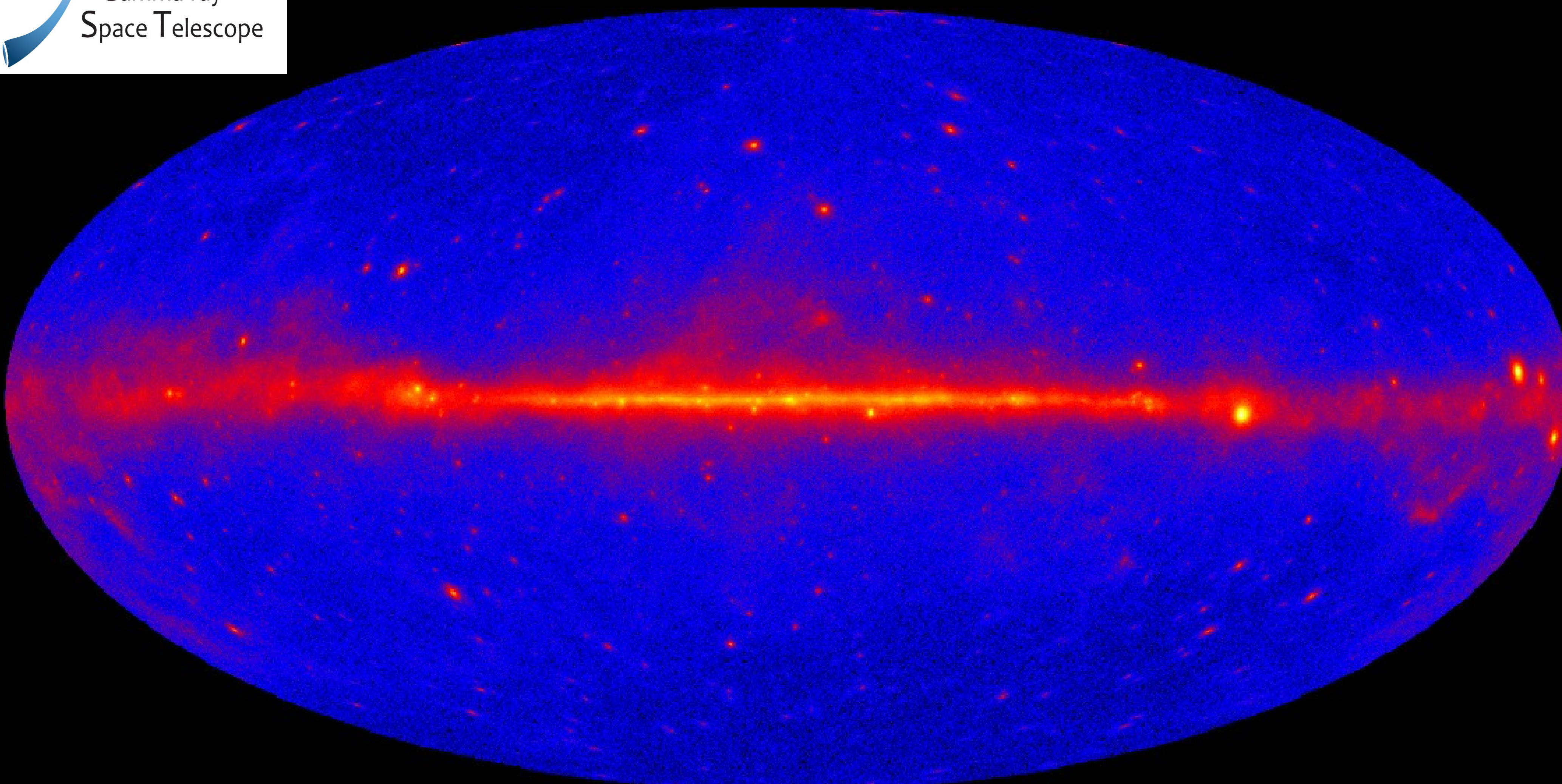
Interstellar gamma-rays: new insight from Fermi-LAT

Andy Strong

on behalf of Fermi-LAT collaboration

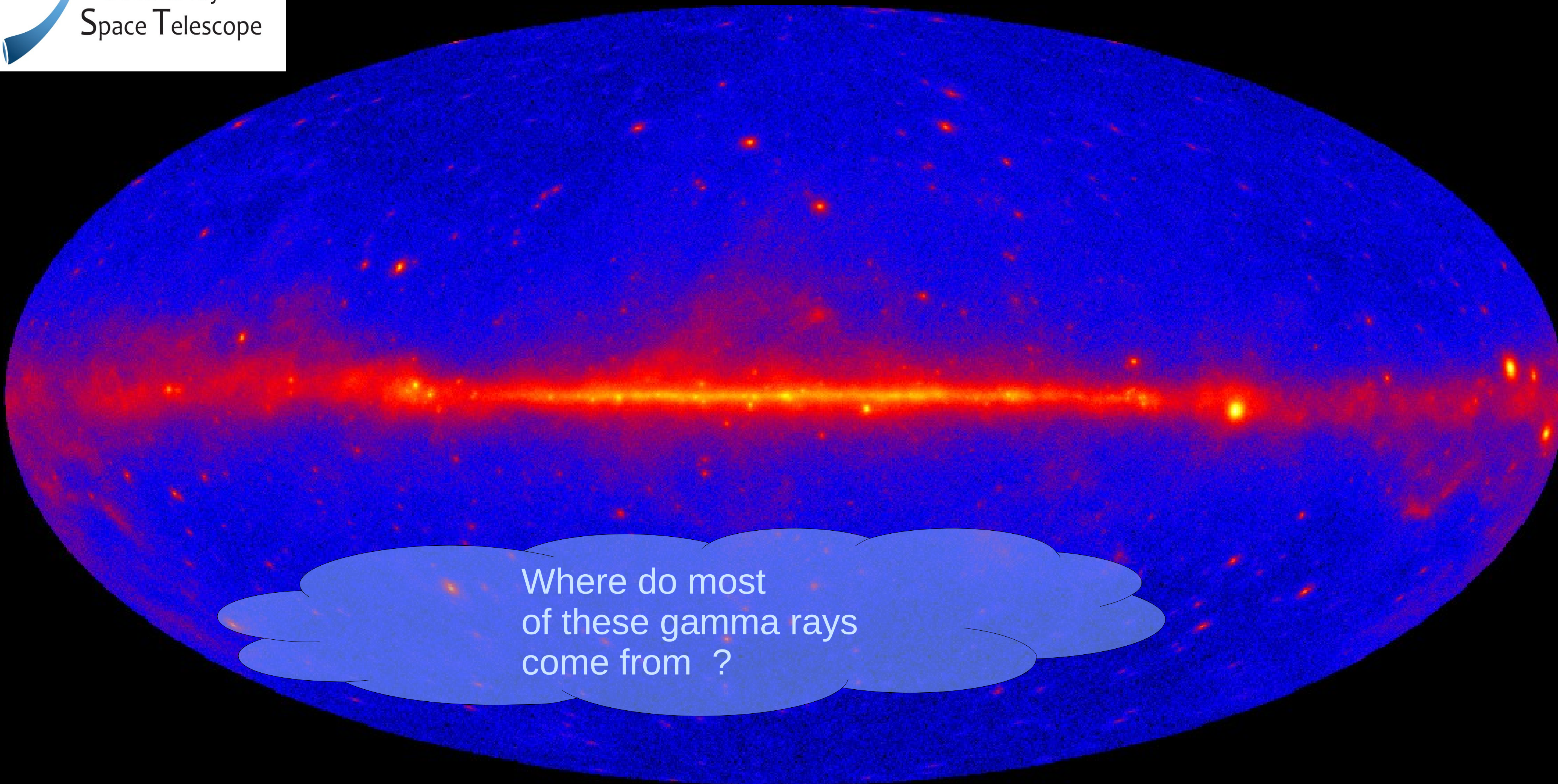
Cosmic-Ray Backgrounds in Dark Matter Searches,
Alba Nova, Stockholm 25-27 Jan 2010

Fermi
Gamma-ray Space Telescope

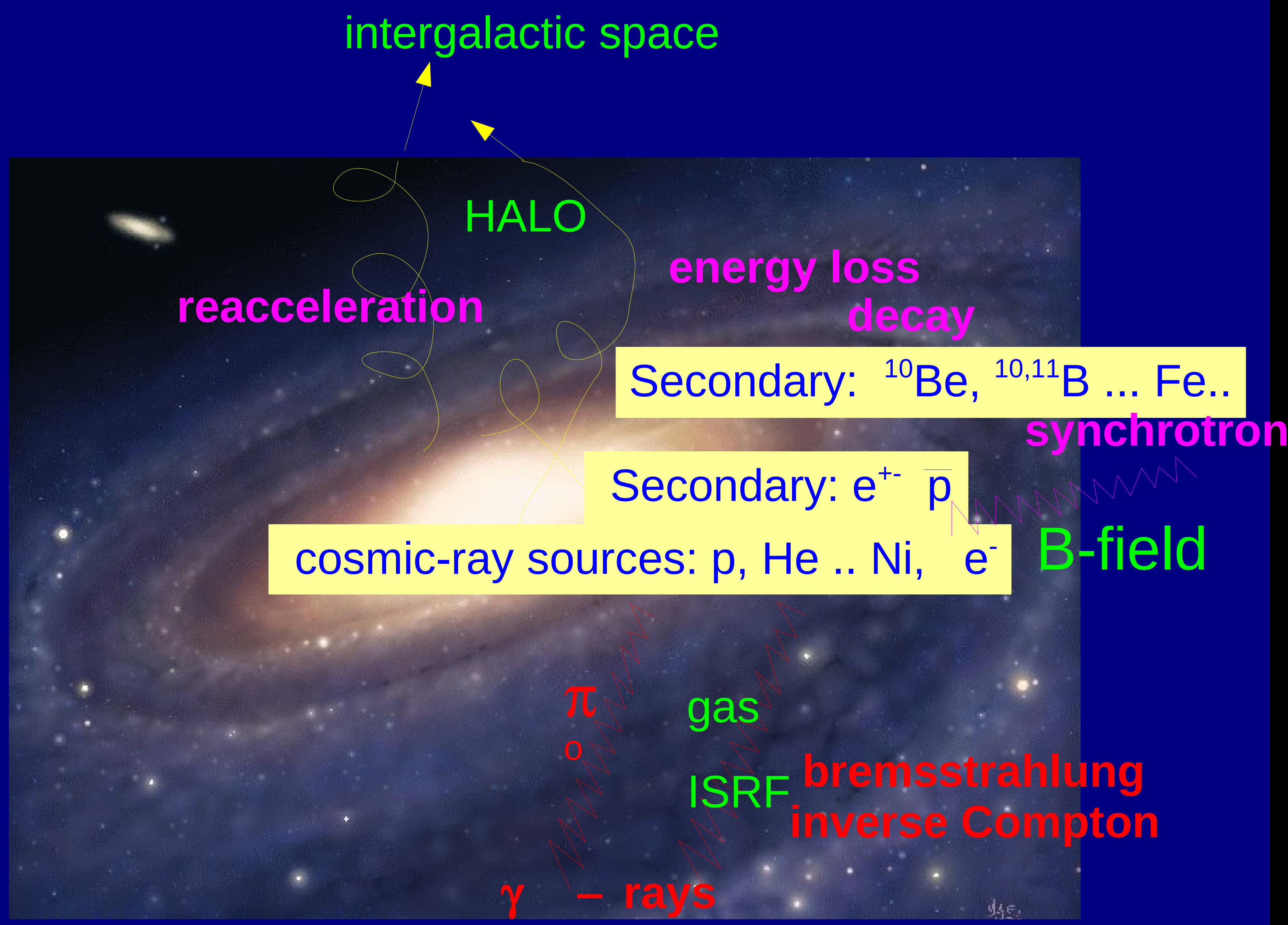


1st year skymap

Fermi
Gamma-ray Space Telescope



Where do most
of these gamma rays
come from ?



intergalactic space
HALO
energy loss
decay
reacceleration
Secondary: ^{10}Be, ^{10,11}B ... Fe..
synchrotron
Secondary: e^{+-} $\bar{p}$
B-field
cosmic-ray sources: p, He .. Ni, e^{-}
π^{o}
gas
ISRF
bremsstrahlung
inverse Compton
γ – rays

Since Fermi's Launch the diffuse emission studies have evolved......
I trace here the stages.

First Fermi results on diffuse Galactic emission: announced earlier this year.

Intermediate Galactic latitudes $10^{o} < |b| < 20^{o}$

Motivation: the gamma rays come from a 'local' region: within 1 kpc

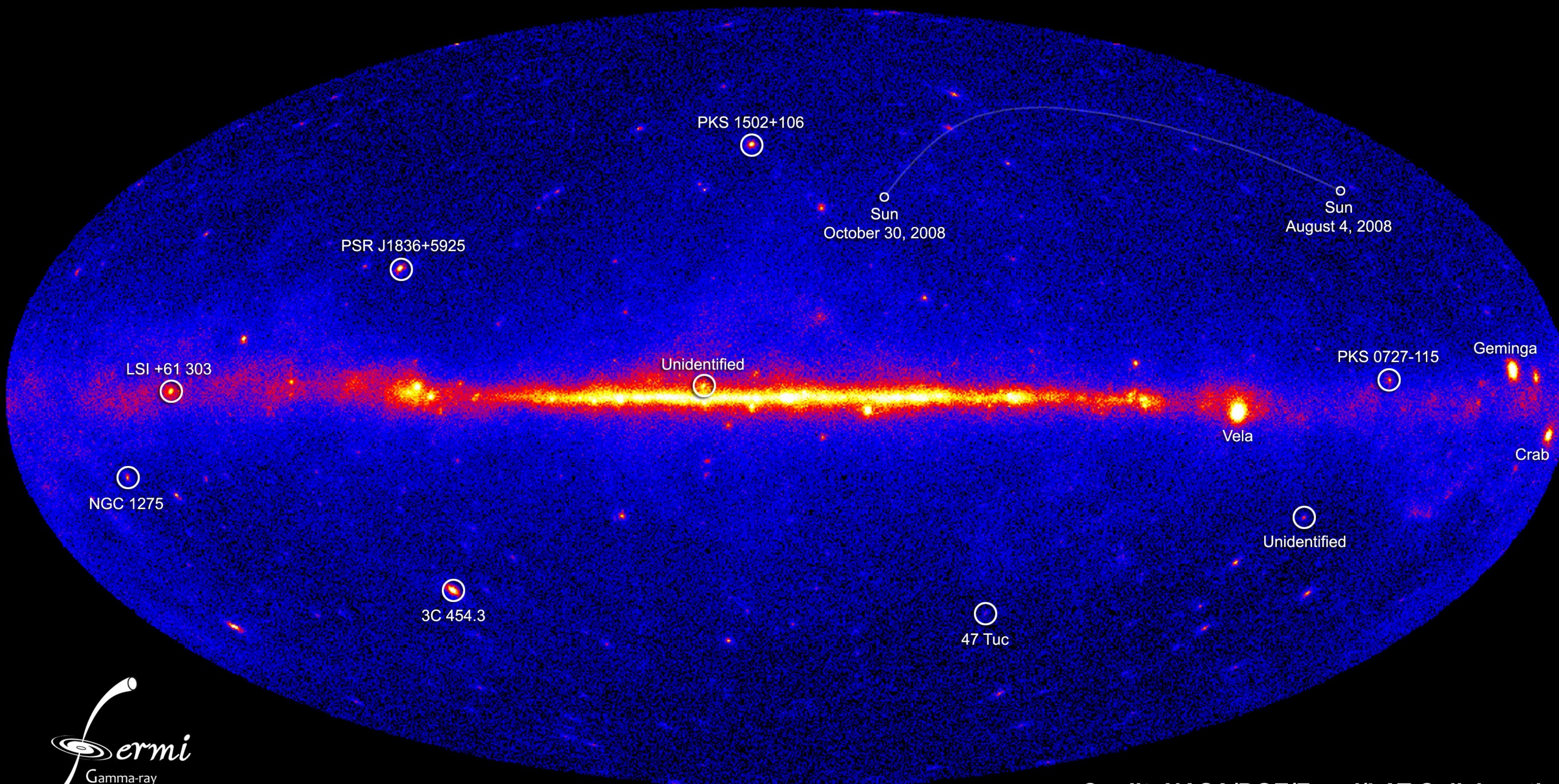
-> cosmic rays should be similar to those observed directly near the Sun

-> model should be reliable, should agree with observed gamma rays

This was *not* the case for EGRET -

found the notorious ' GeV excess ' relative to the expected emission

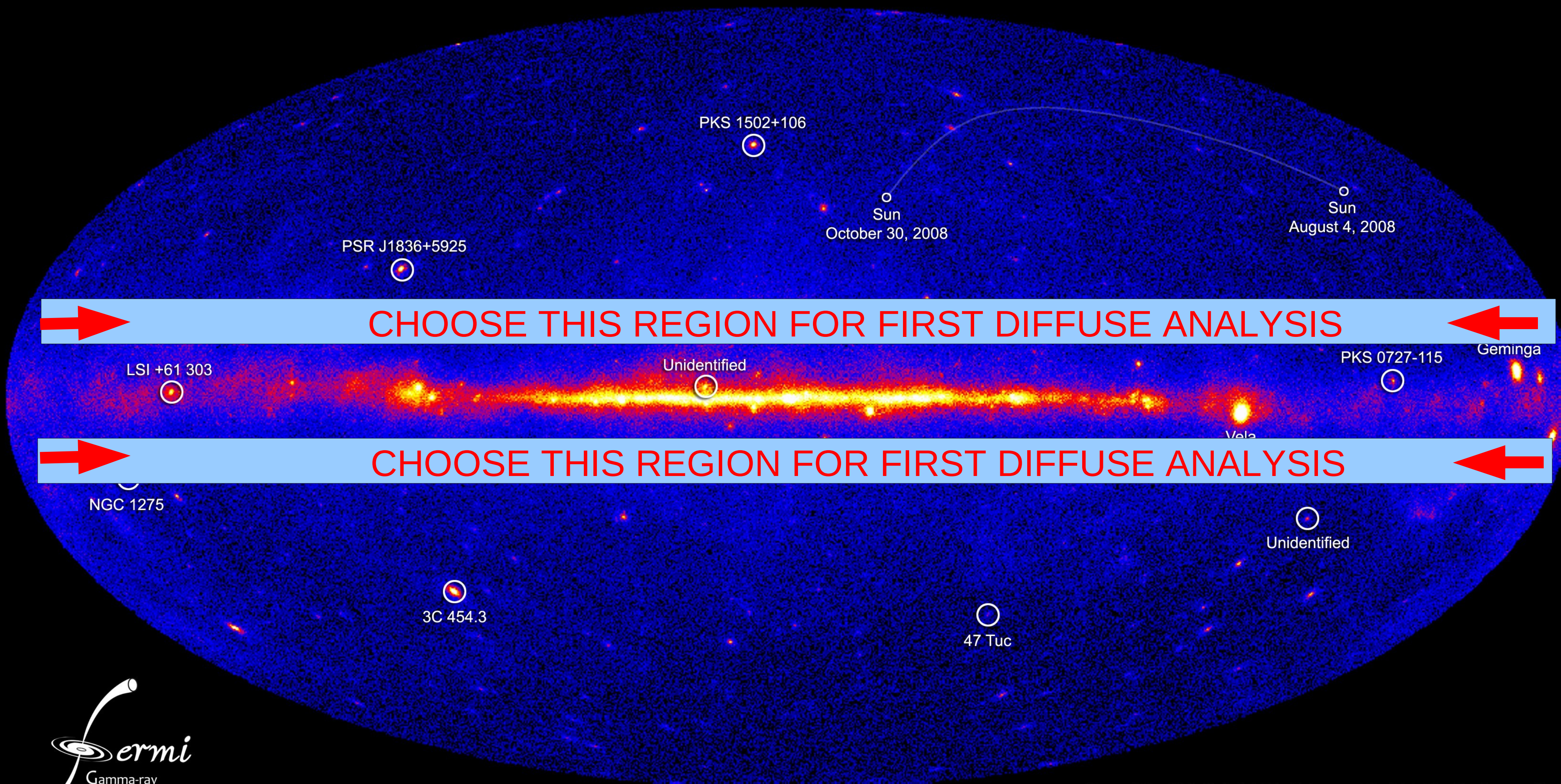
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Fermi
Gamma-ray
Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

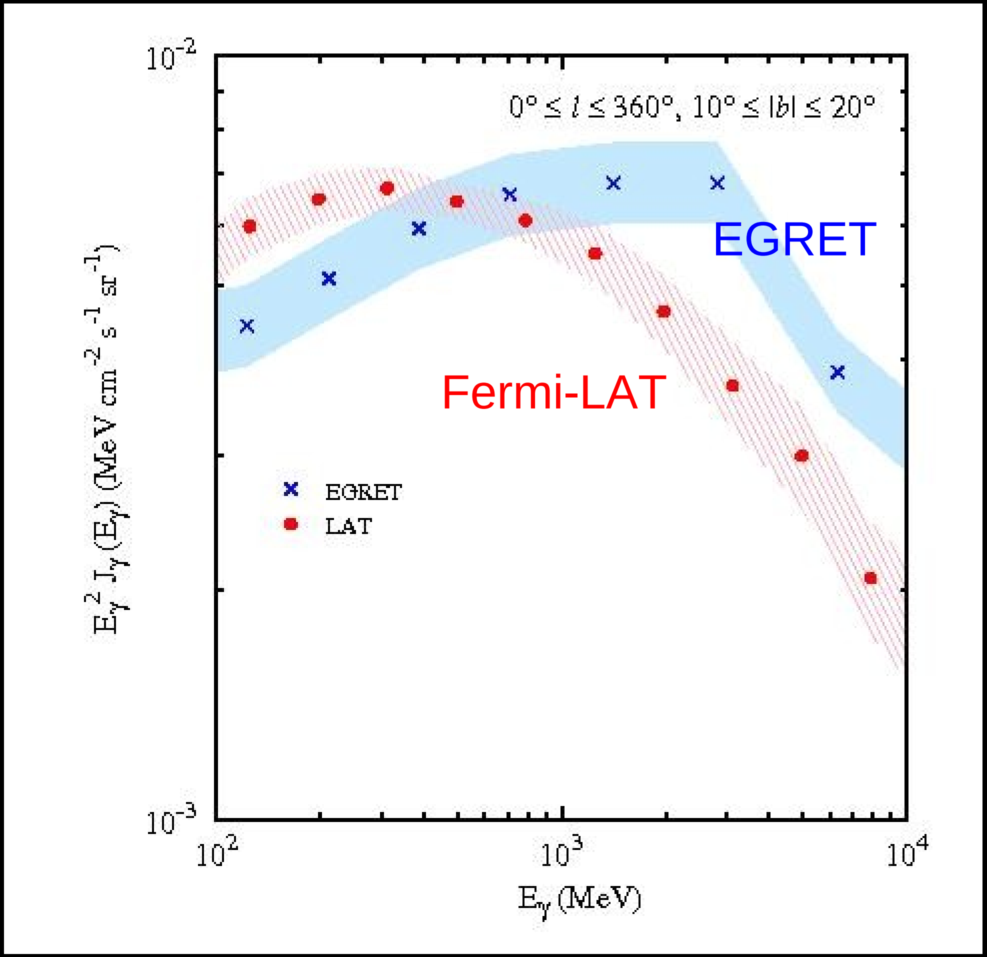
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Fermi Gamma-ray Space Telescope

Credit: NASA/DOE/Fermi/LAT Collaboration

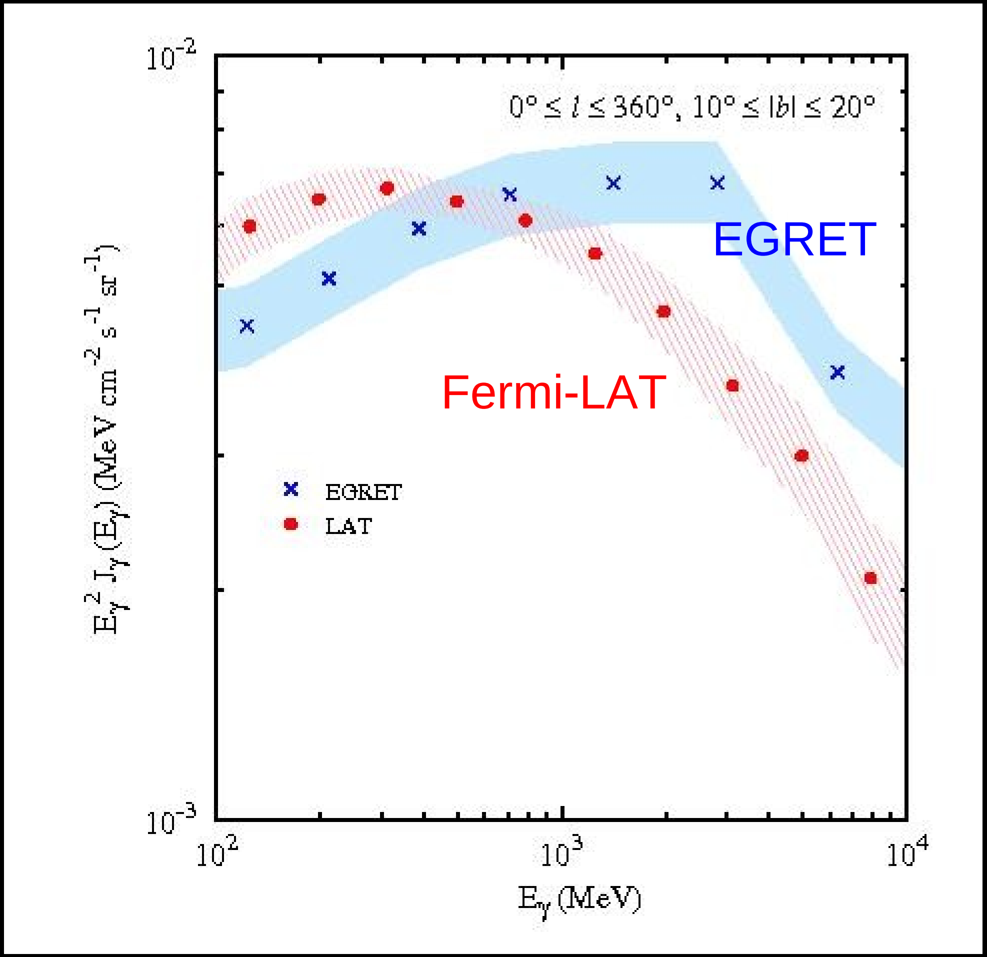
The EGRET GeV excess disappeared !



The two experiments have different instrumental backgrounds,
so this comparison is not exact, but *the difference is not mainly attributable to this.*

Abdo et al. (2009) PRL 103, 251101

The EGRET GeV excess disappeared !



so back to the drawing-board for a lot of models based on it !

Modelling the gamma-ray sky

main ingredients of GALPROP 'a priori' model

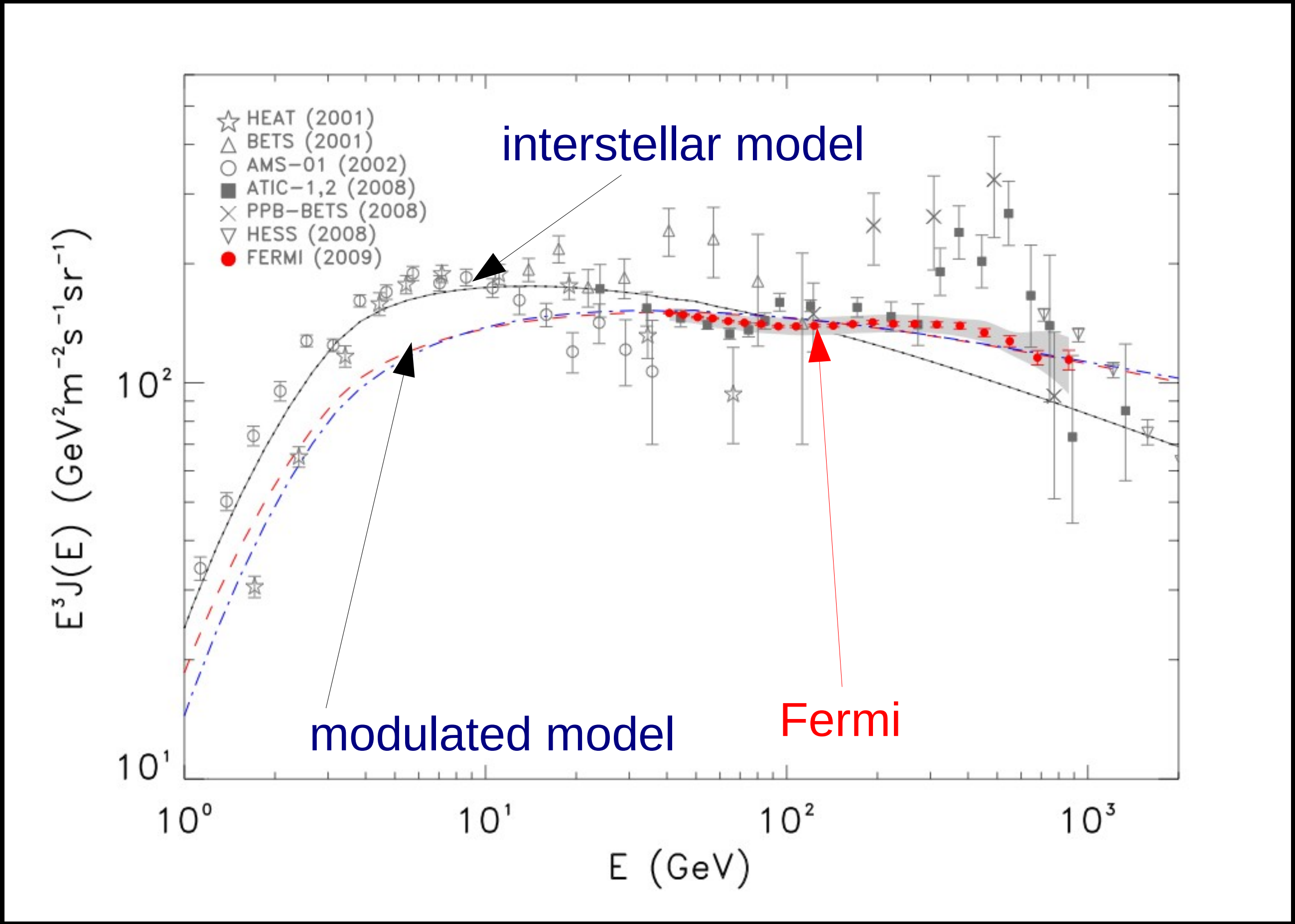
cosmic-ray spectra p , He , e- , e+ (including secondaries)
(NB here using *Fermi-measured* electrons)
cosmic-ray source distribution follows SNR/pulsars

B/C etc for propagation parameters
halo height = 4 kpc (from radioactive nuclei)

Interstellar radiation field
HI, CO surveys
CO-to-H2 conversion a function of position in Galaxy
Fermi 1st year source catalogue

Uses *GALPROP* latest version

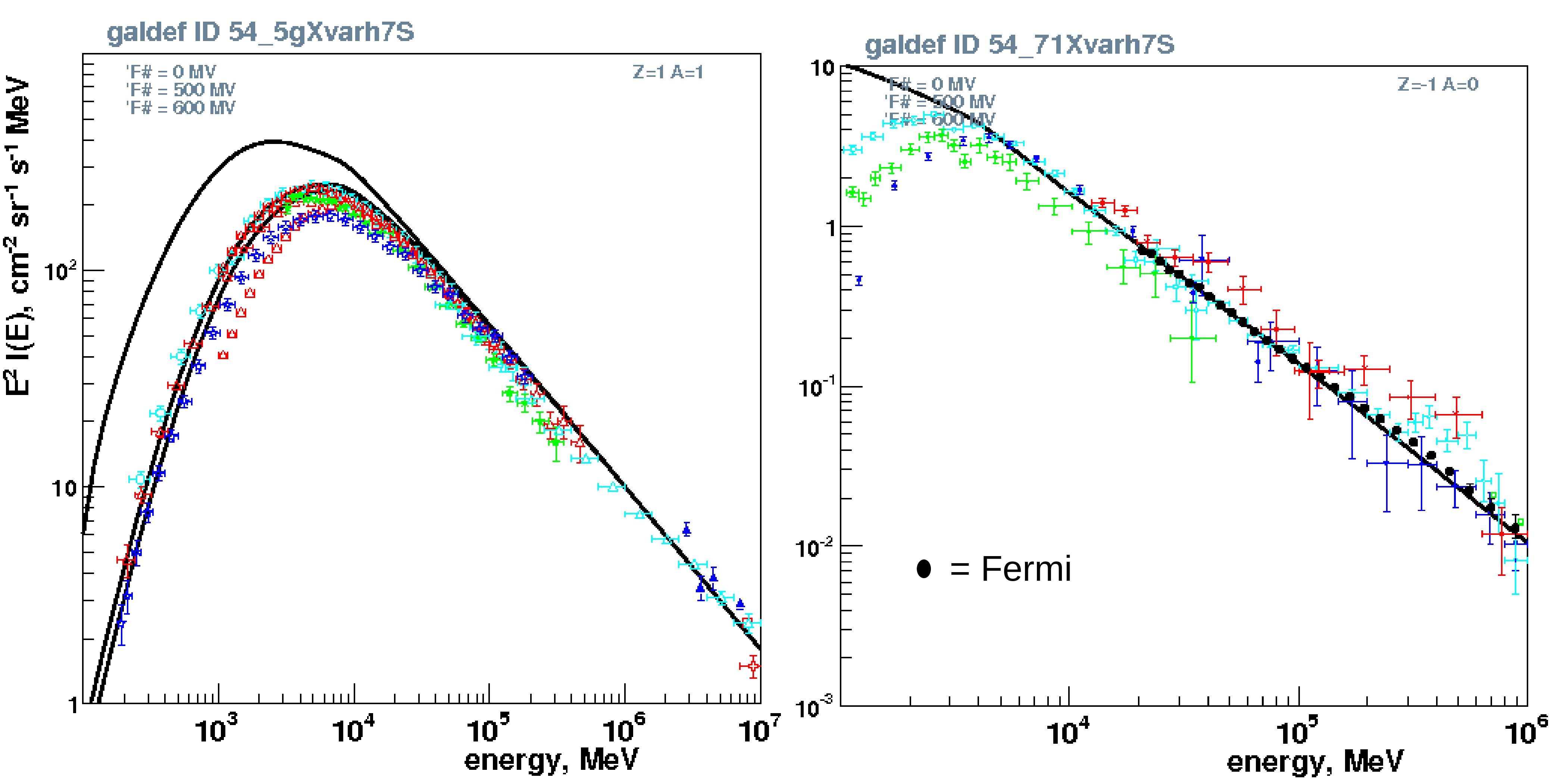
Fermi-LAT electron spectrum



Abdo et al 2009 PRL.102, 181101, Grasso et al 2009 Astropart.Ph. 32, 140

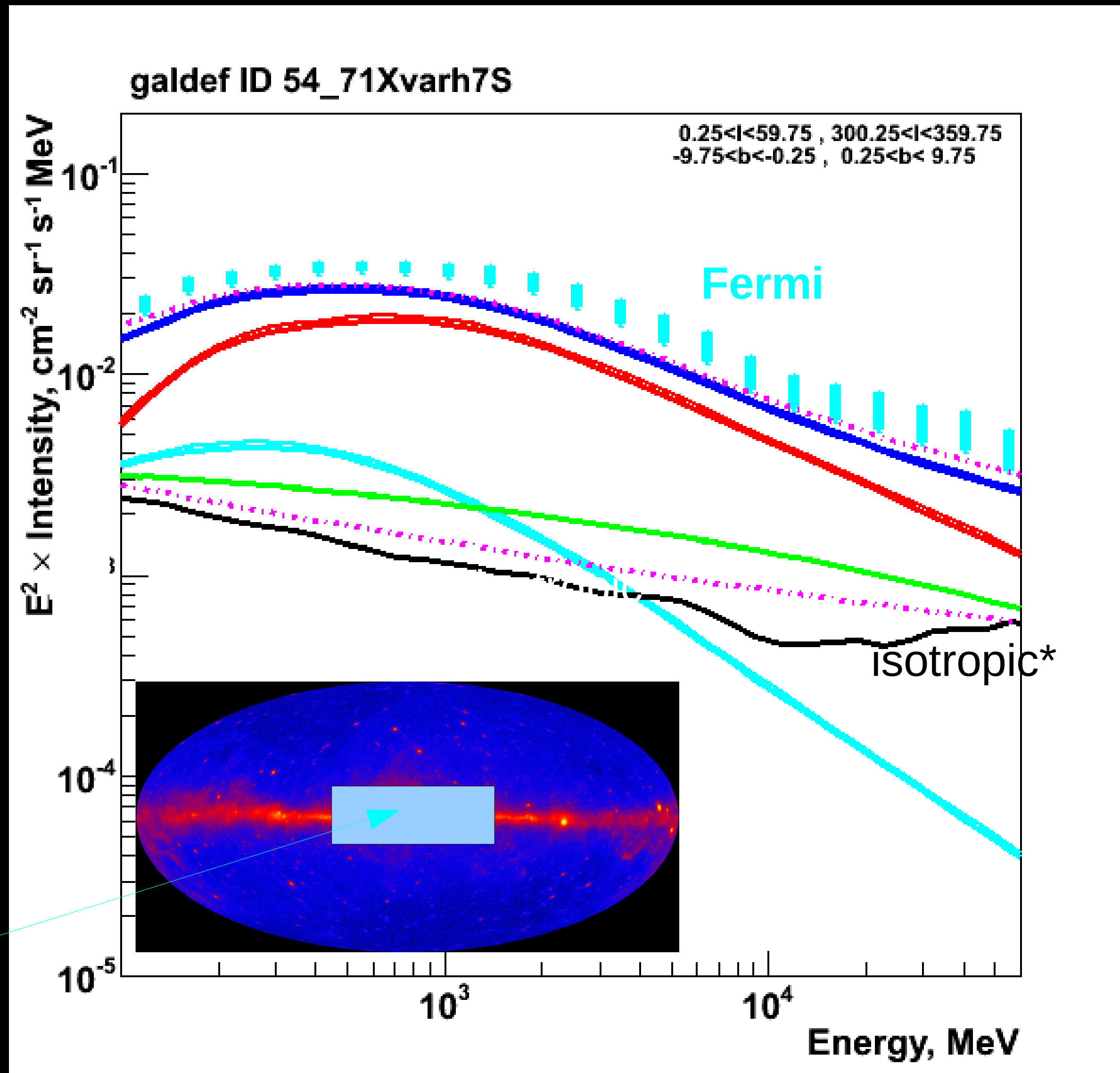
First use a model based on locally-measured cosmic rays

PROTONS **ELECTRONS**



a priori model with Fermi electron spectrum

INNER GALAXY



spectral shape OK

systematically low
need to increase
cosmic rays

pion decay

inverse Compton

LAT bright source list

bremsstrahlung

31st ICRC 2009

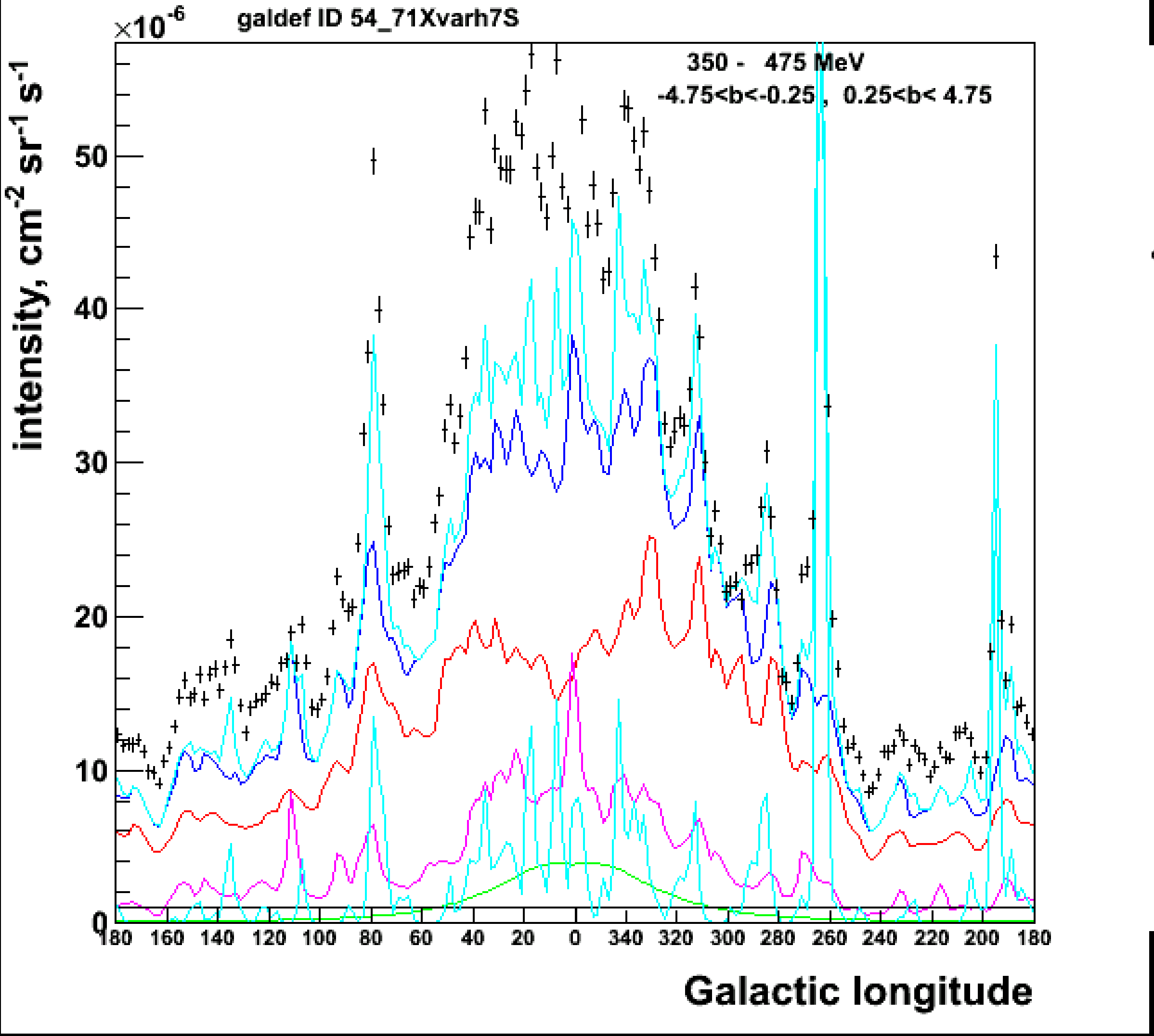
* isotropic = instrumental plus astrophysical backgrounds

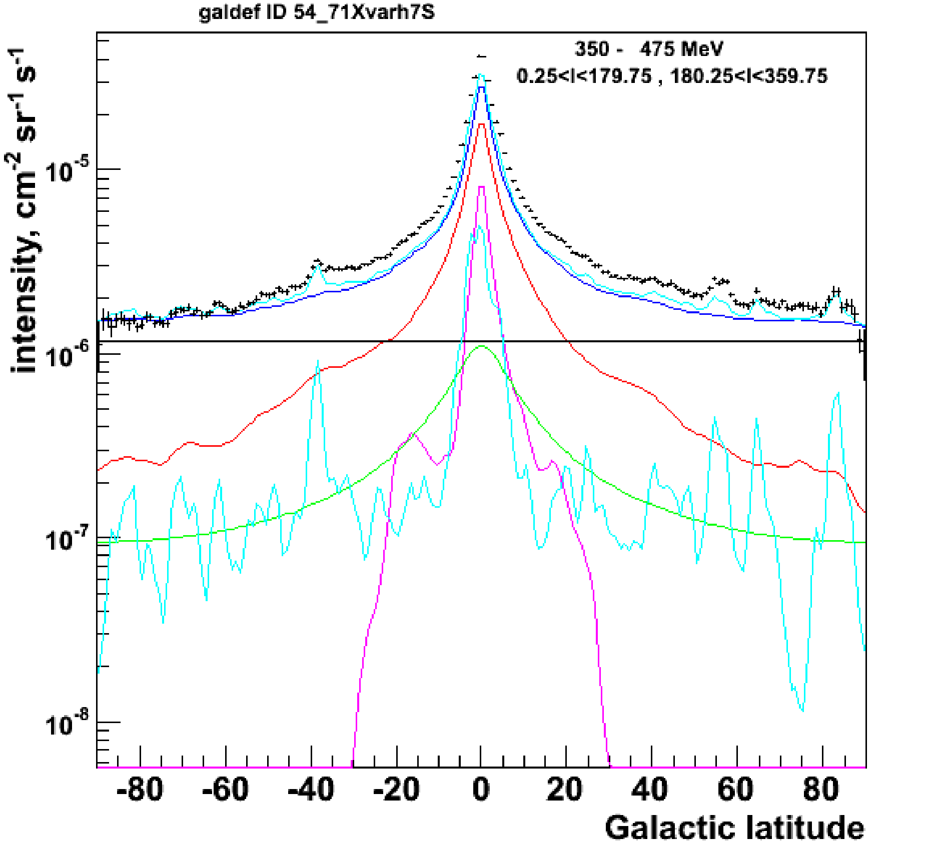
a priori model with Fermi electron spectrum

LONGITUDE PROFILE

LATITUDE PROFILE

400 MeV





generally too low

not bad for an *a priori* model prediction

but generally too low

this means either more CR electrons and/or protons

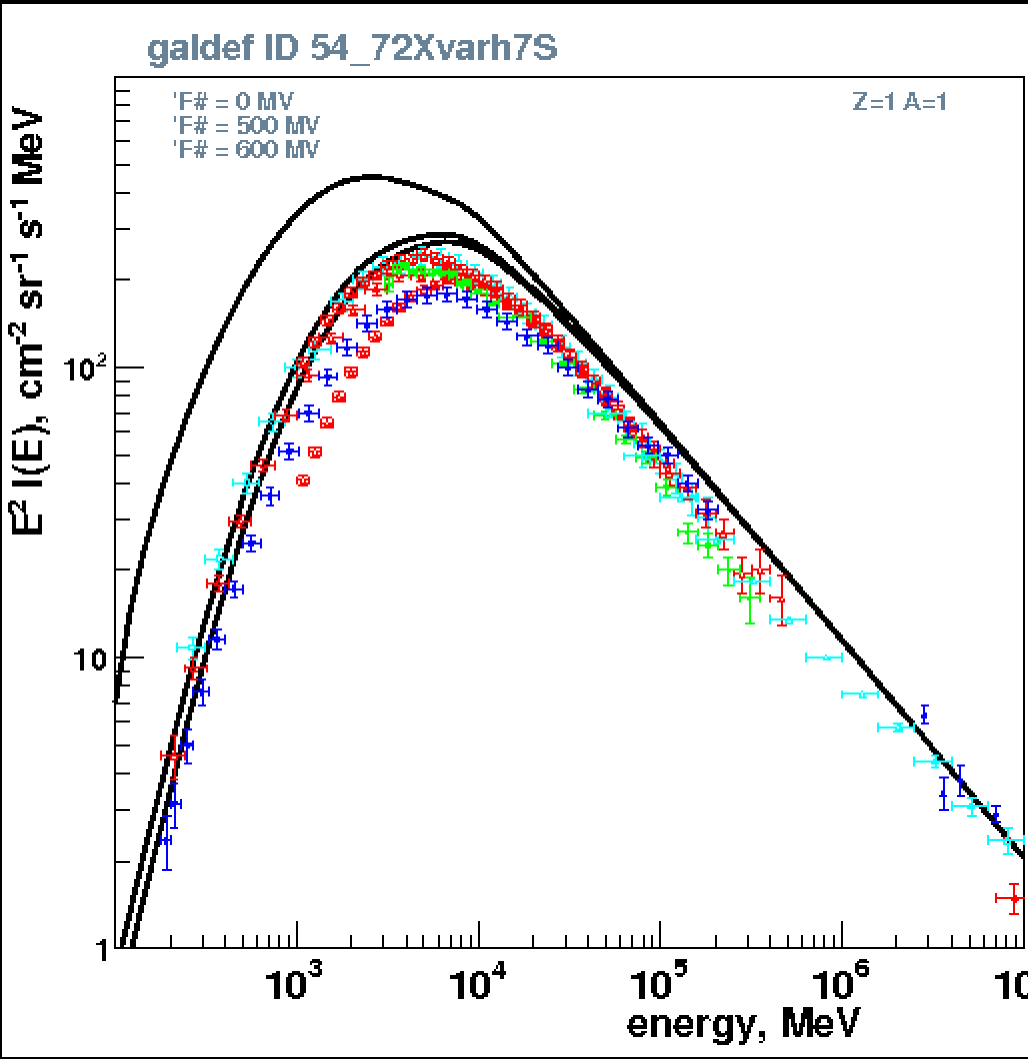
model fitting guides us to a better model:

electrons increased by factor ~2
protons increased by ~15%

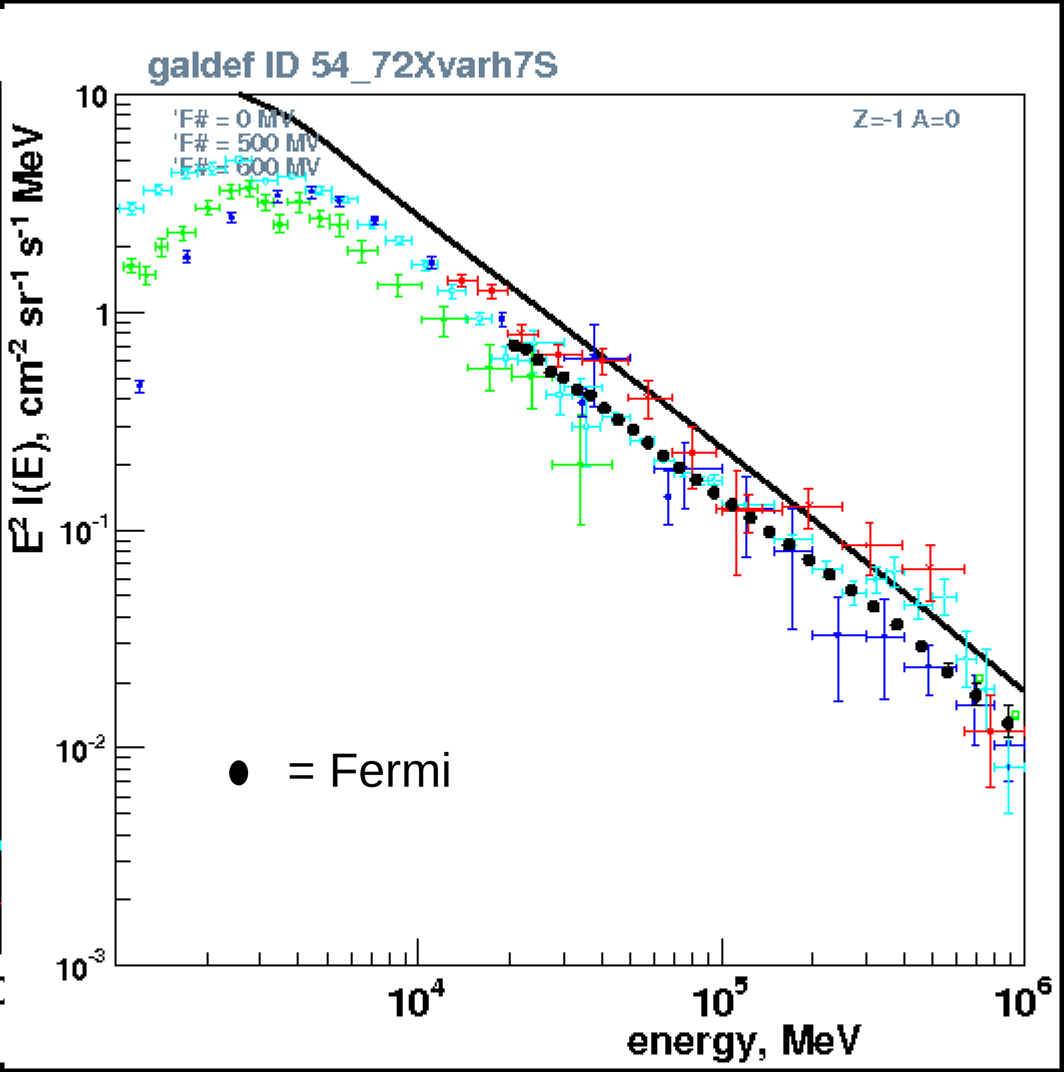
------------->

Improving the model with increased CR

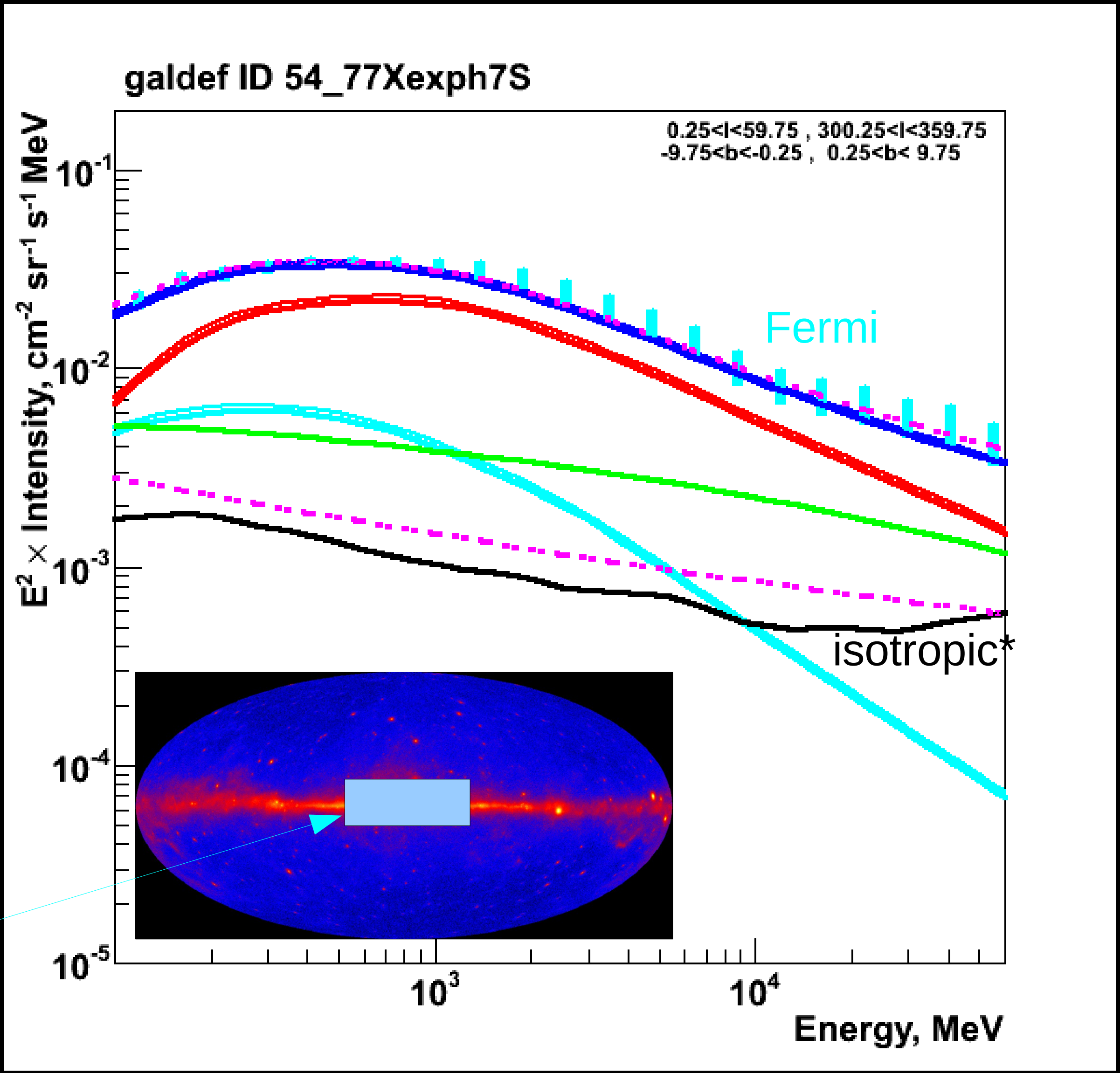
PROTONS



ELECTRONS



model adjusted to Fermi
INNER GALAXY



statistical +systematic errors

pion-decay

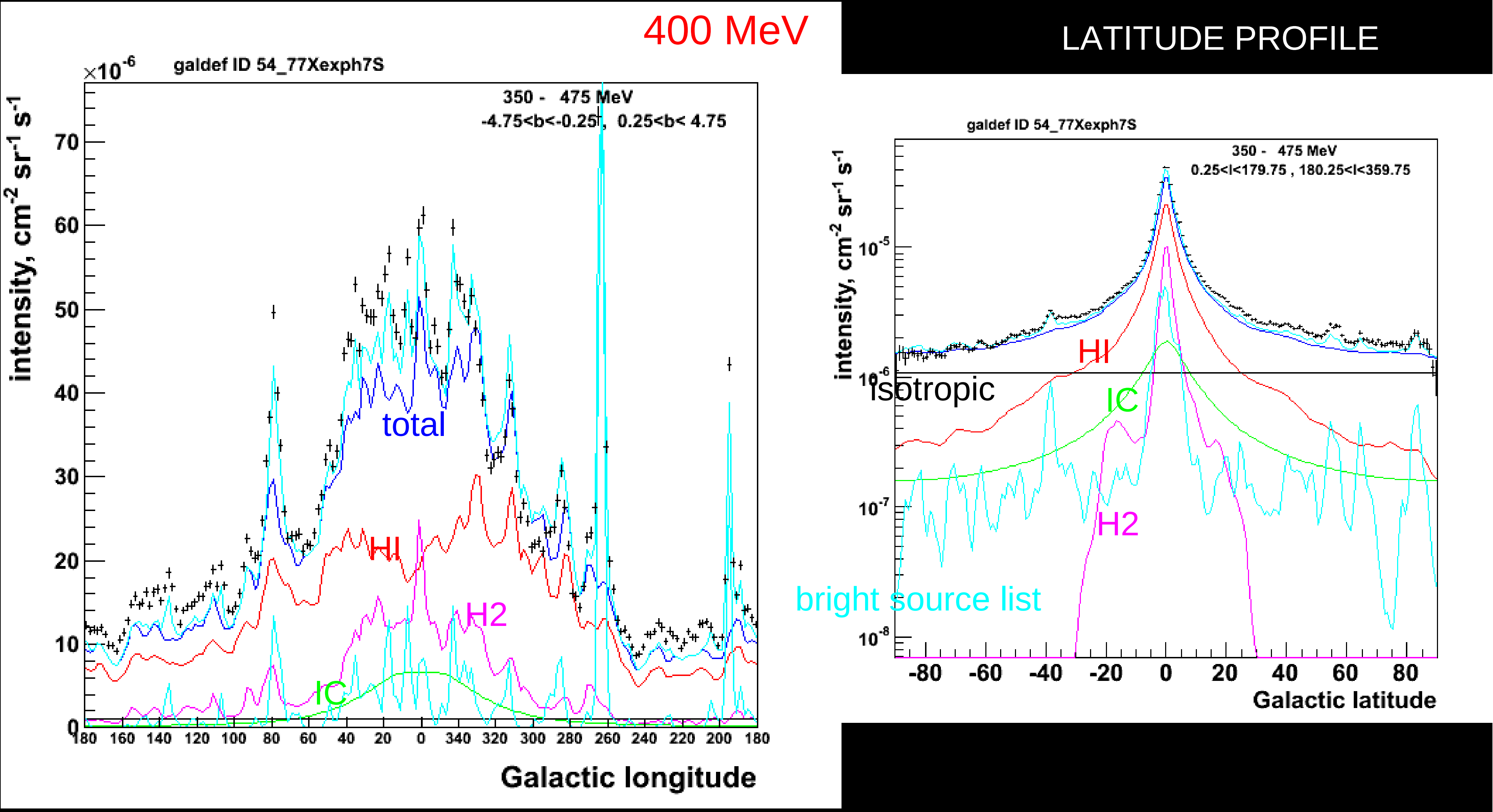
inverse Compton

LAT bright source list

bremsstrahlung

* isotropic = instrumental plus astrophysical backgrounds

Model adjusted to Fermi

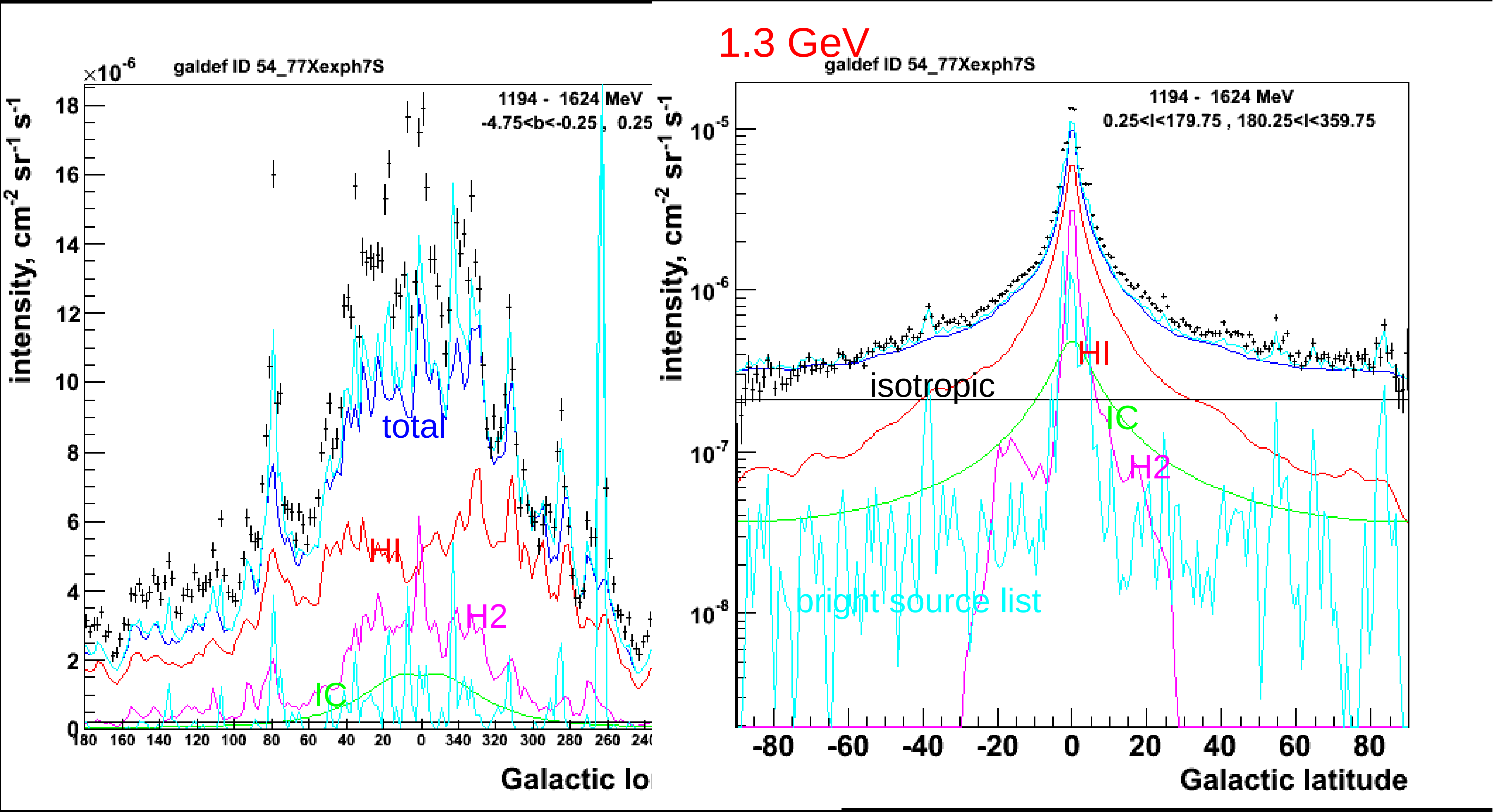


LATITUDE PROFILE

31st ICRC 2009

quite good, latitude fits from plane to poles over 2 decades dynamic range
importance of inverse Compton at high latitudes : gamma-ray halo !

Model adjusted to Fermi



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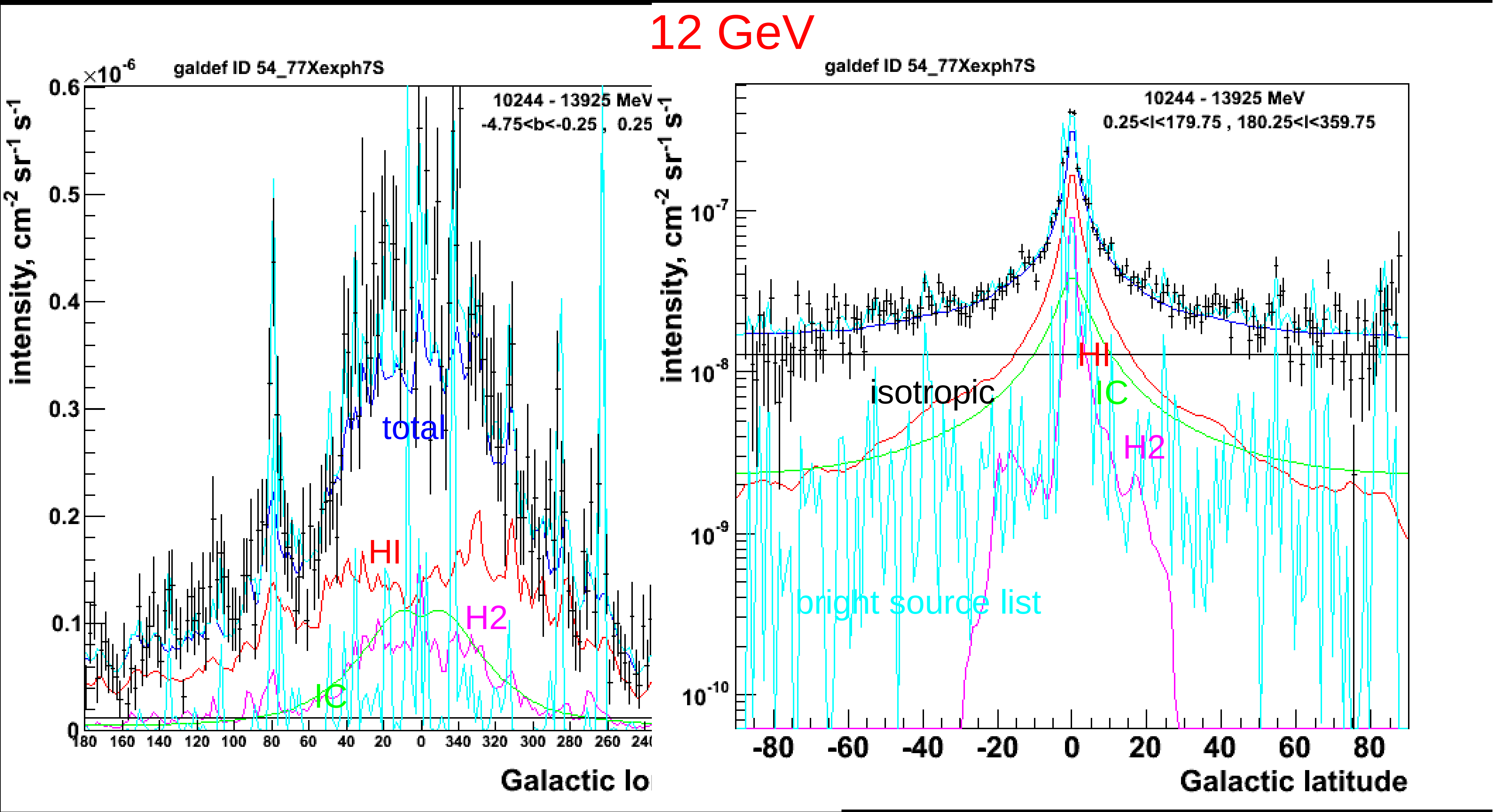

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EARLY CONCLUSIONS

Fermi does *not* confirm EGRET GeV excess

a priori model: agrees with Fermi at **intermediate latitudes**

has correct spectral shape but is rather low in the **inner Galaxy**

generally reasonable fit with **simple scaling** of CR protons, electrons
over the sky and wide energy range

increased protons consistent with local CR data
increased electrons *in*consistent with local CR data (including Fermi-measured)

increased inverse Compton : more electrons OR more ISRF or ..... ?

inverse Compton component at high latitudes : CR halo !

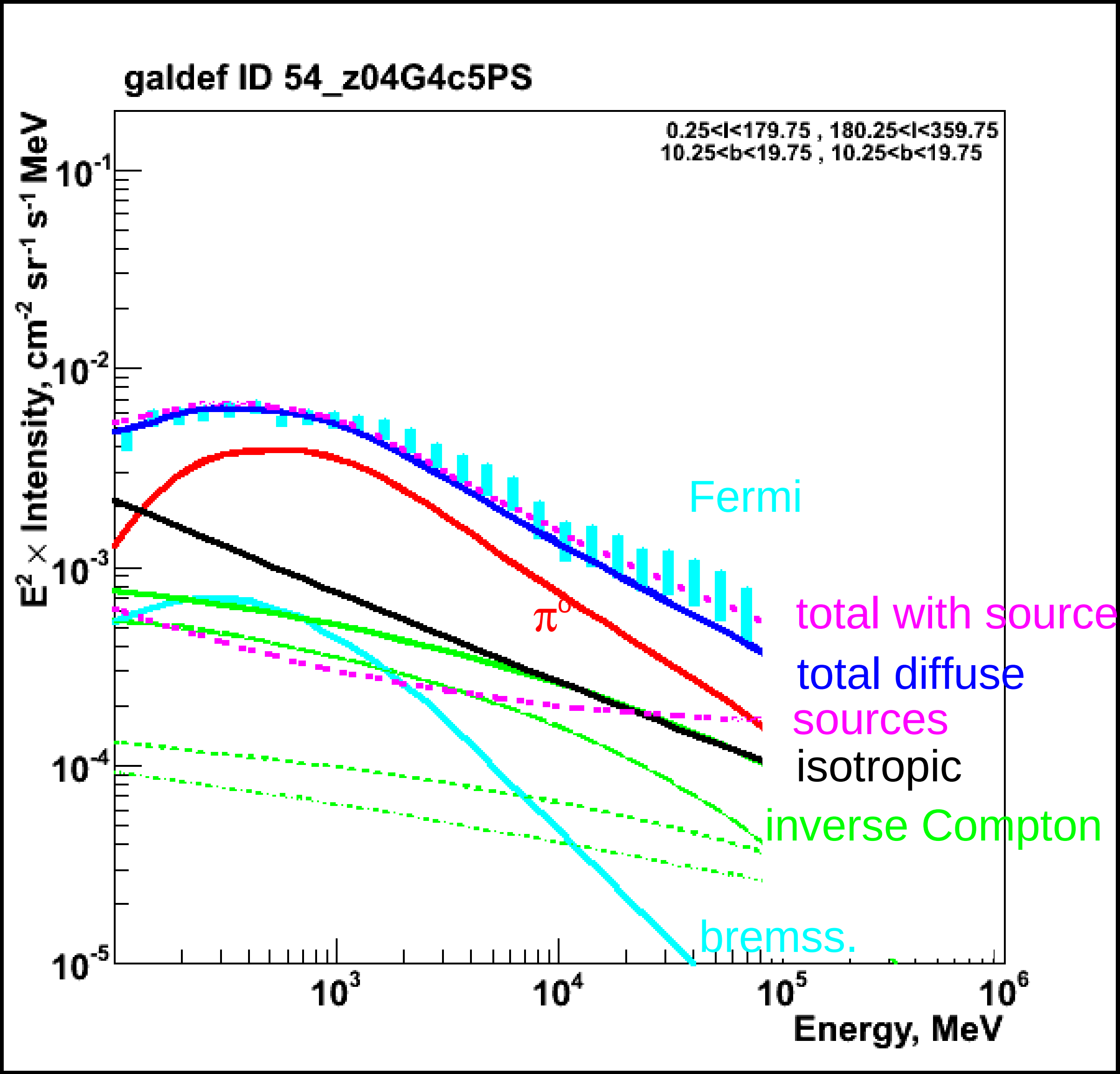
LATEST DIFFUSE EMISSION RESULTS FROM FERMI-LAT

FROM 2009 Fermi Symposium, Washington, 2-5 Nov 2009

New:

- 1 year of data
- low background event class (developed for extragalactic background study)
- Finer fitting to Fermi data: proton, electron spectra scaling by factor 1 – 2
- Improved gas tracer: dust emission

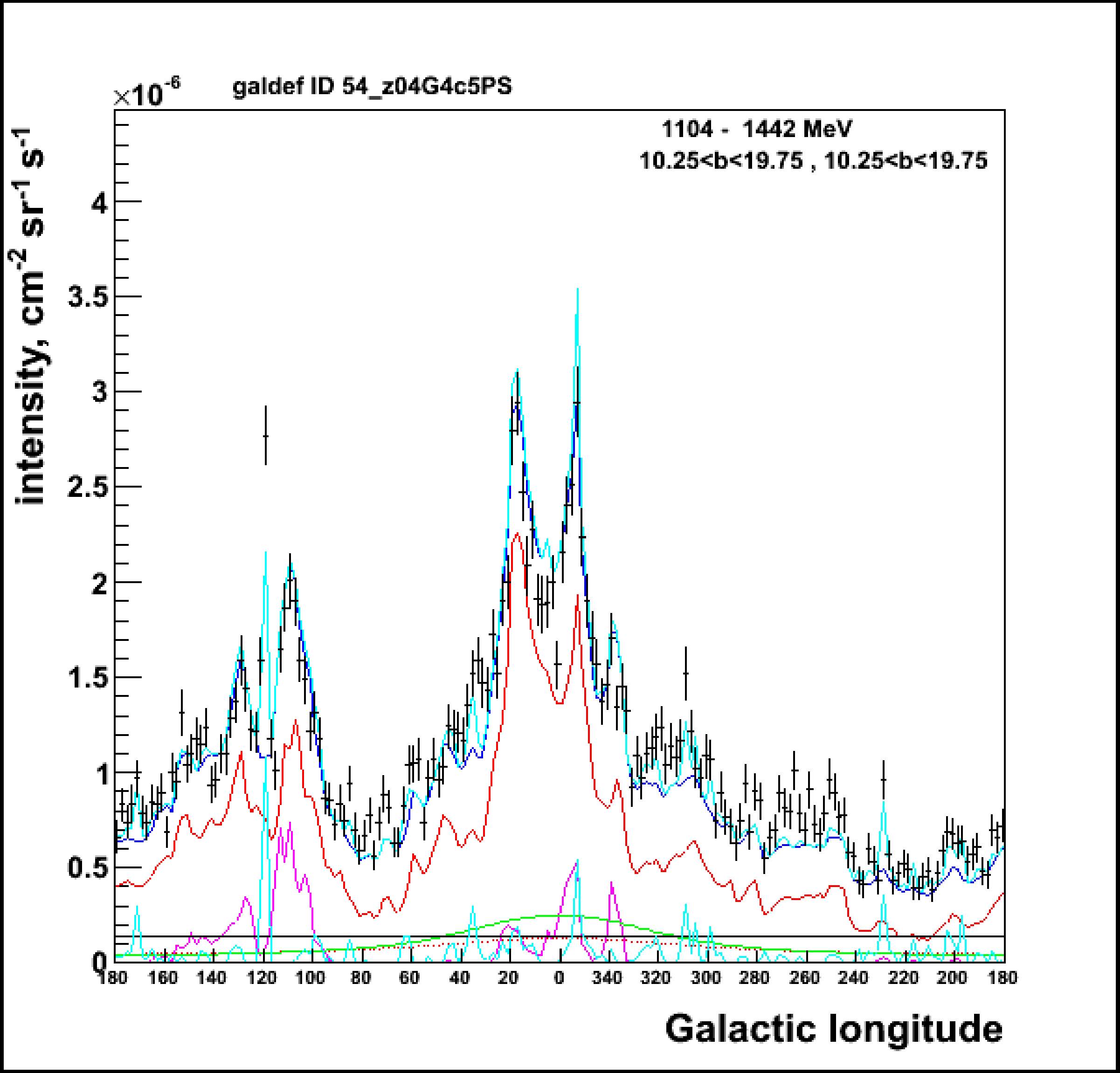
INTERMEDIATE LATITUDES
+10 < b < +20



PRELIMINARY

INTERMEDIATE LATITUDES
+10 < b < +20
1 GeV

total gas traced by dust from IRAS+DIRBE Finkbeiner etal 1999



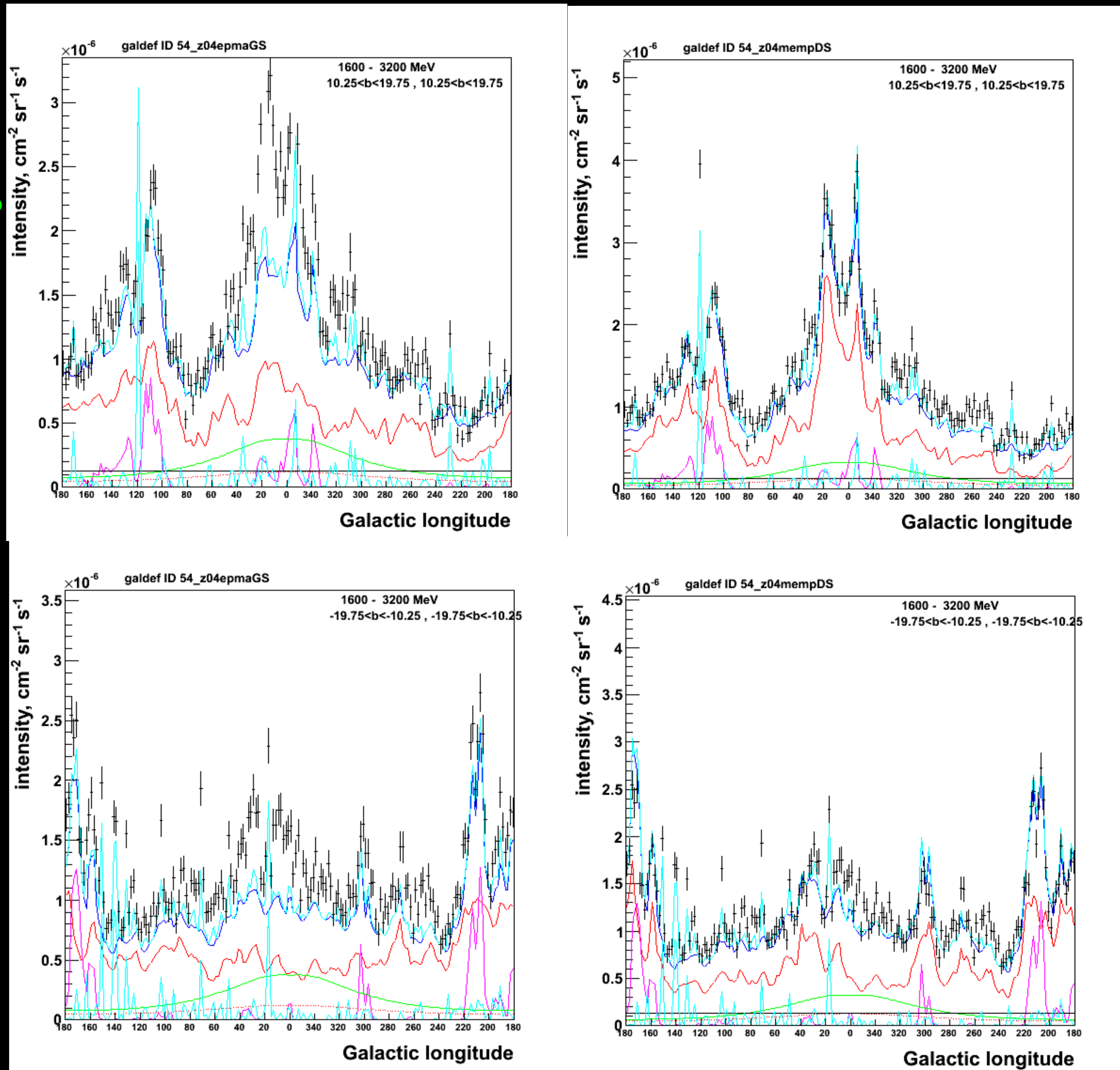
Remarkable agreement. Confirms that dust is a better tracer of local gas than HI+CO (Grenier, Casandjian: found this in EGRET data)

PRELIMINARY

HI, CO tracer of gas | **dust** tracer of gas

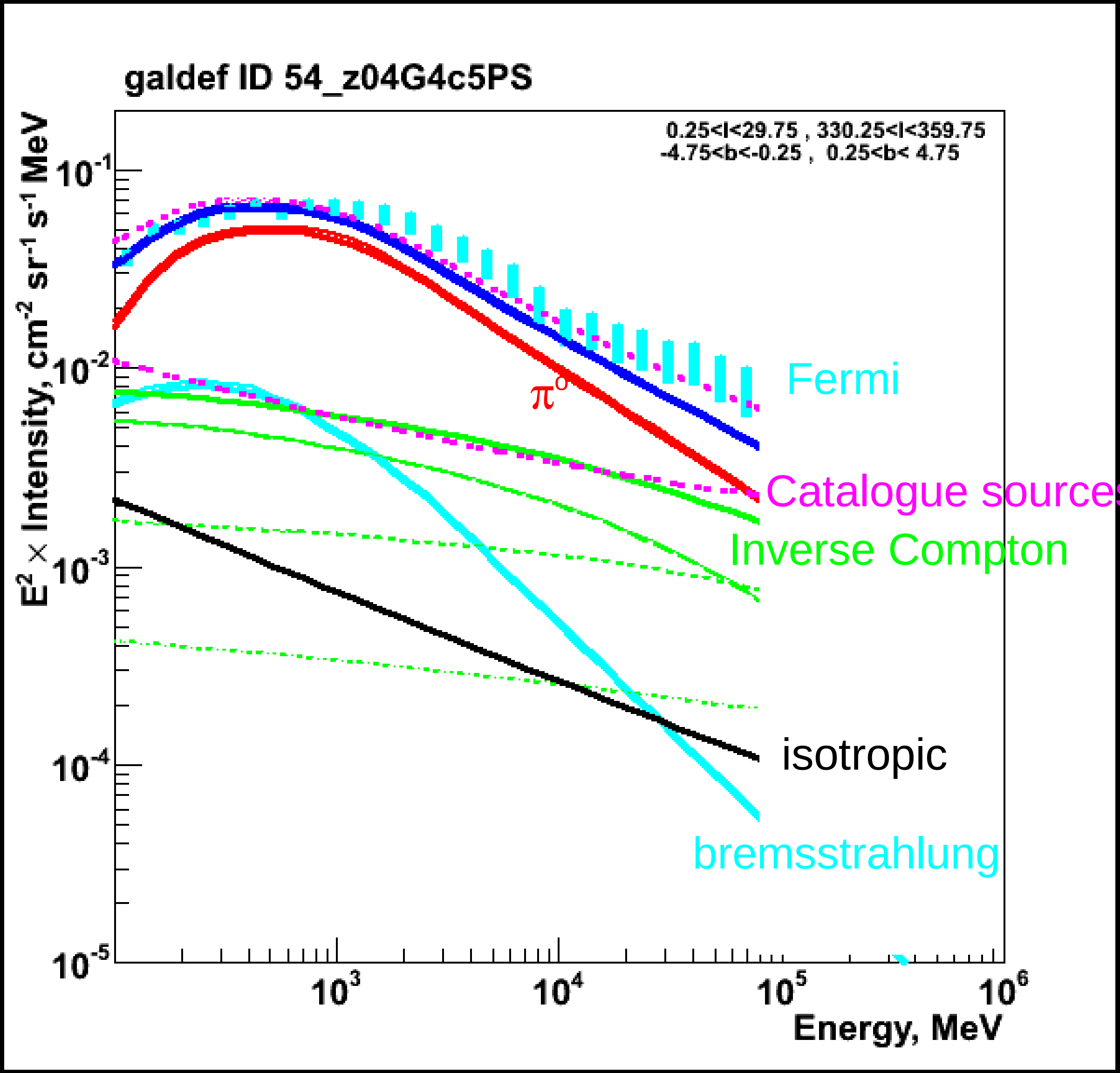
+10° < b <+20°

-20° < b < -10°



Confirms that dust is a better tracer of local gas than HI+CO in these regions !

Inner Galaxy
330° < l < 30°, |b|<5°



PRELIMINARY

Inner Galaxy
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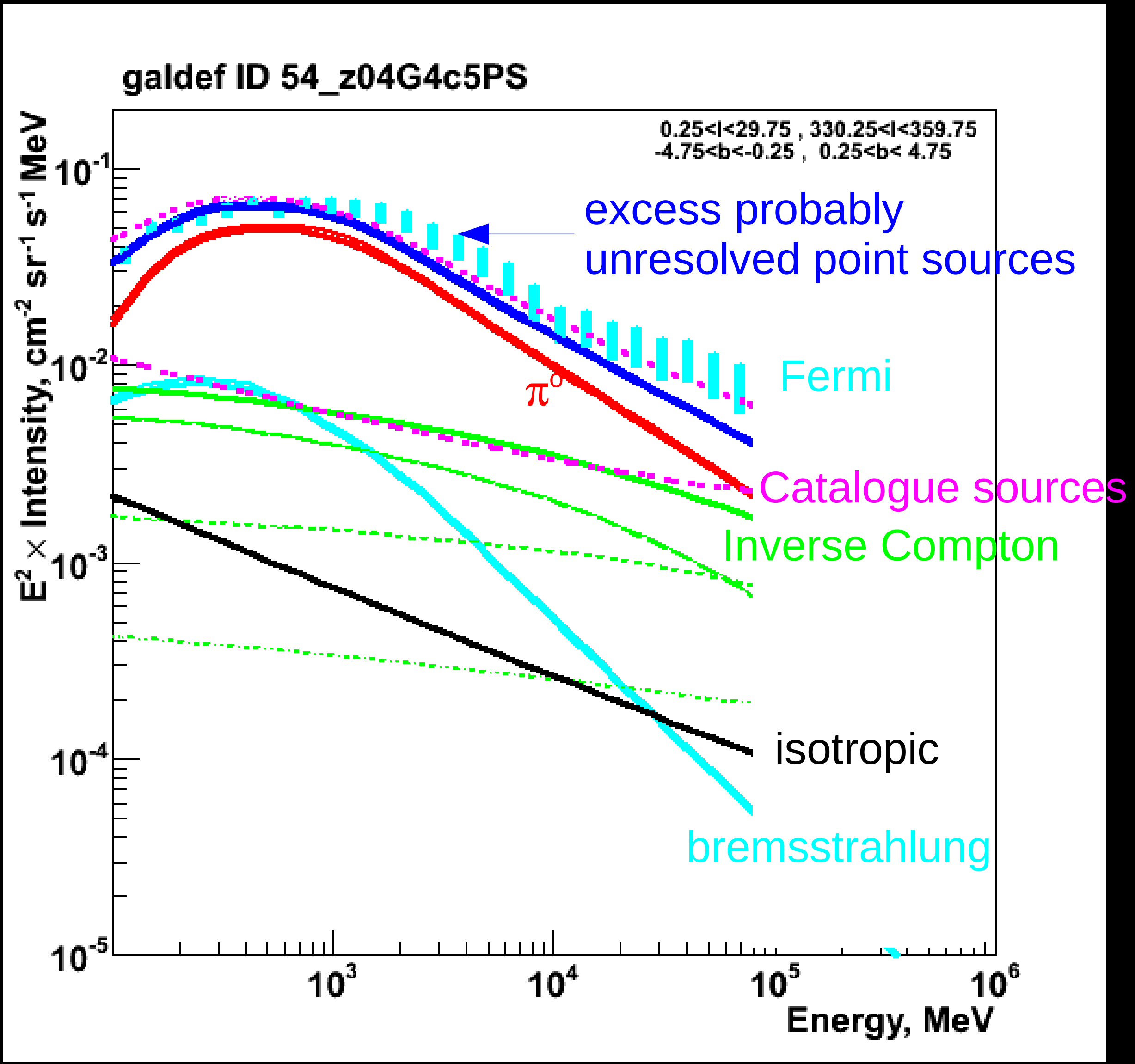
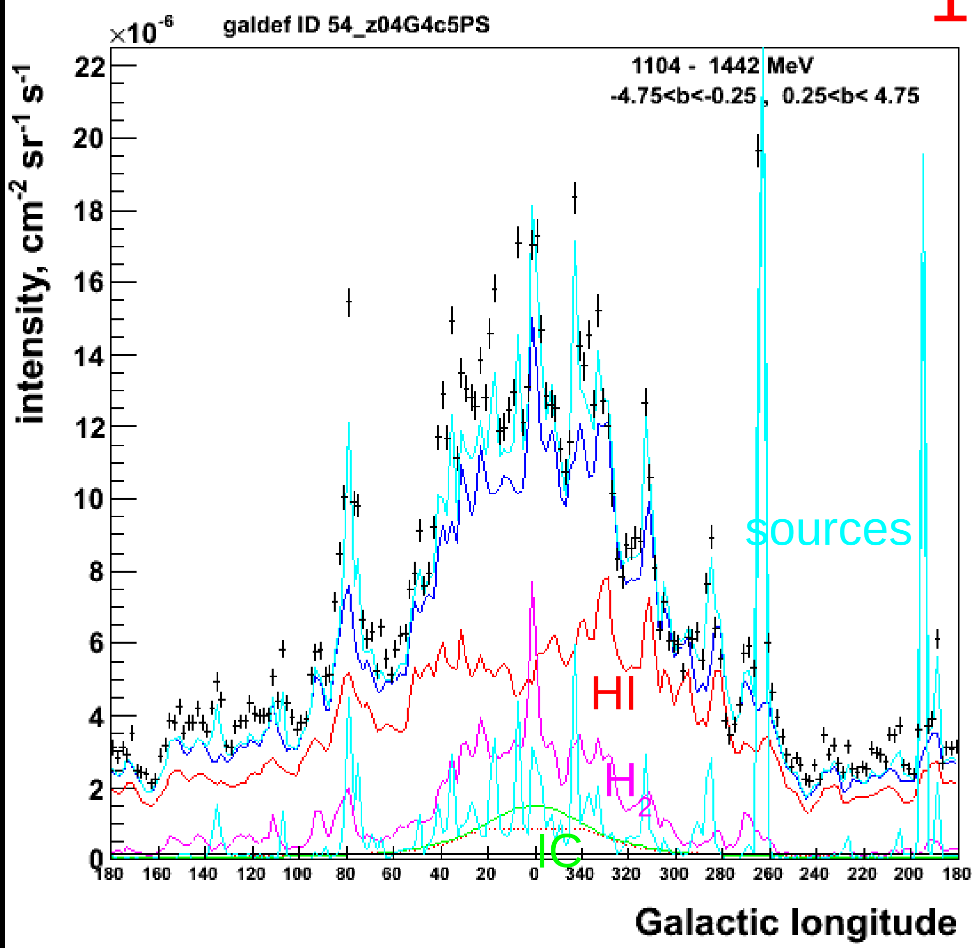


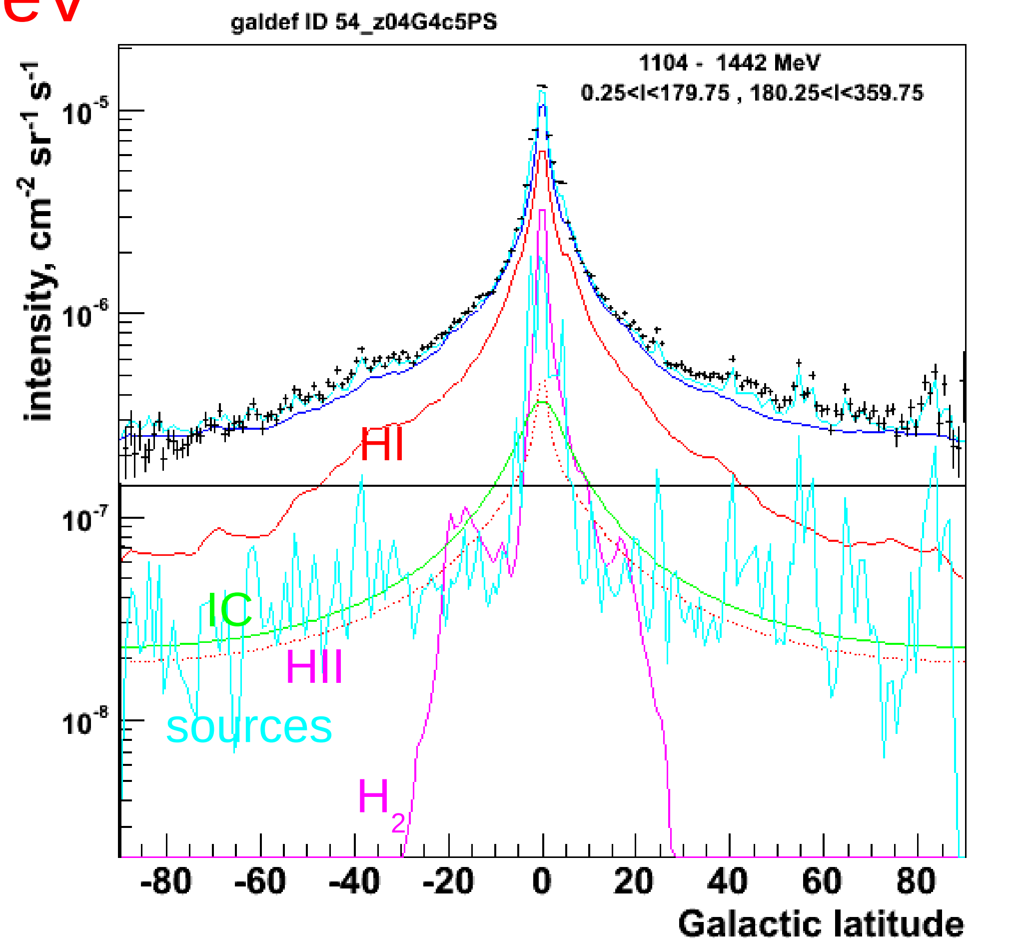
PRELIMINARY

LONGITUDE PROFILE LOW LATITUDES

LATITUDE PROFILE ALL LONGITUDES

1 GeV



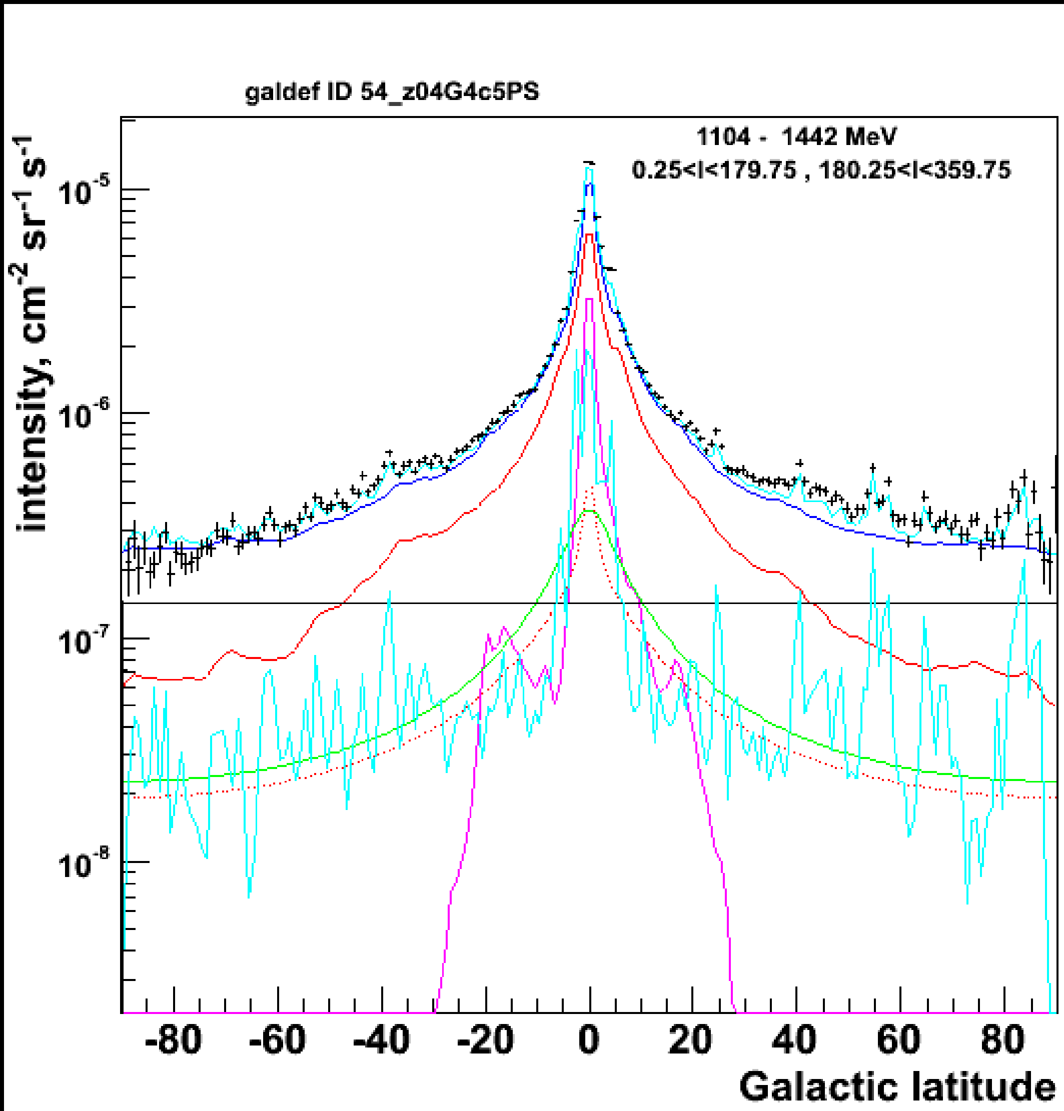


Agrees within 15% over 2 decades of dynamic range

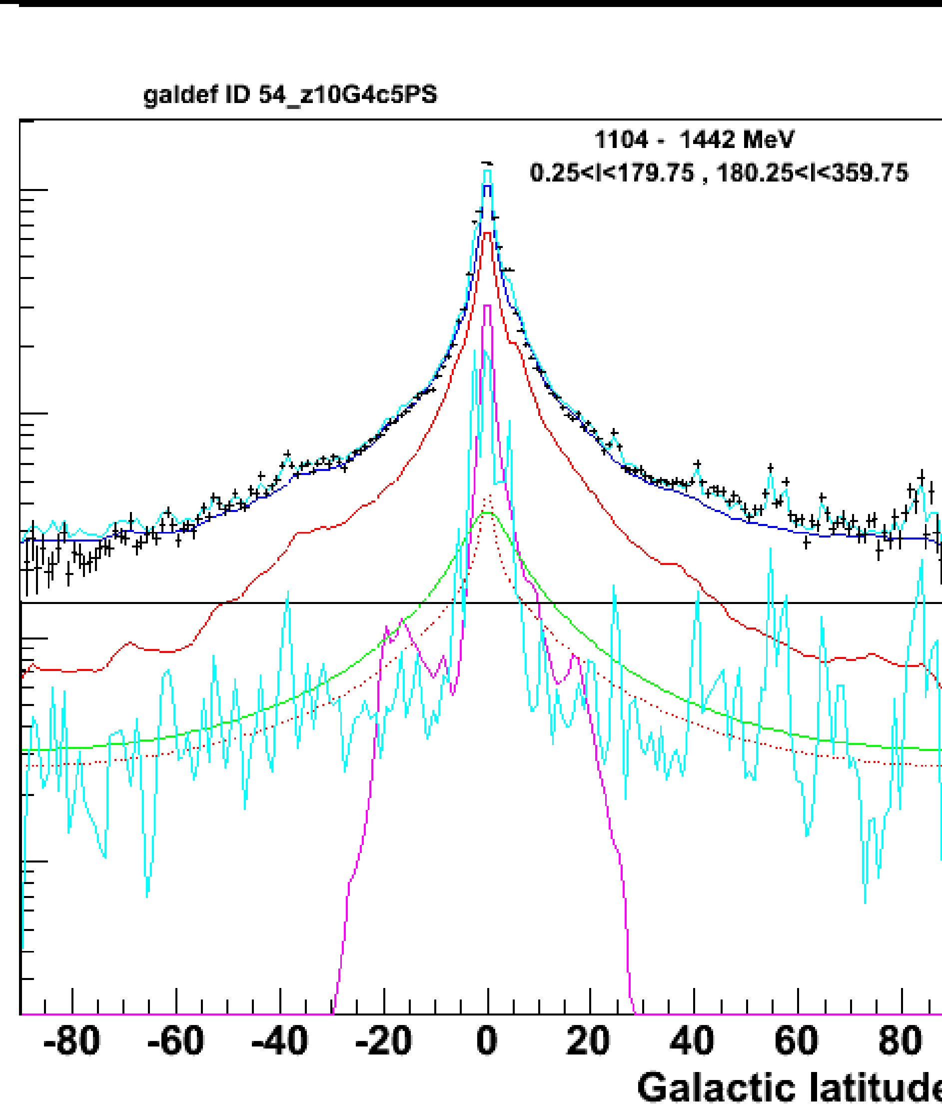
PRELIMINARY

EVIDENCE FOR LARGE COSMIC-RAY HALO

4 kpc halo height



10 kpc halo height



inverse Compton at high latitudes suggests a *large cosmic-ray halo*

PRELIMINARY

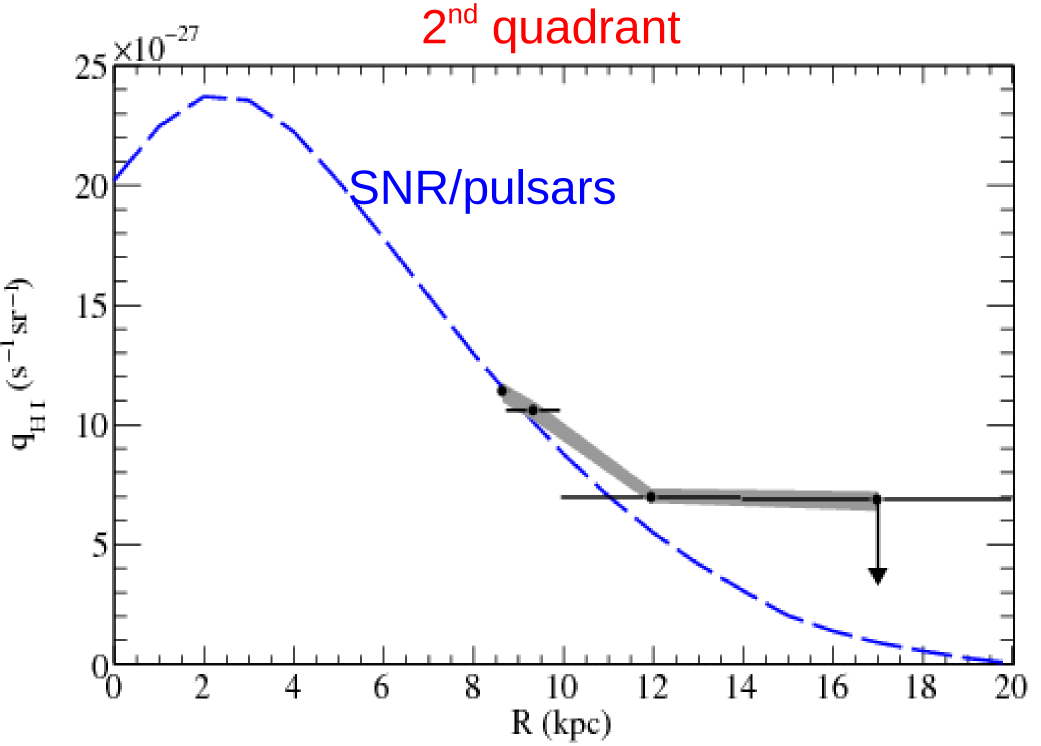
The Astrophysical Journal, 710:133–149, 2010 February 10 doi:10.1088/0004-637X/710/1/133

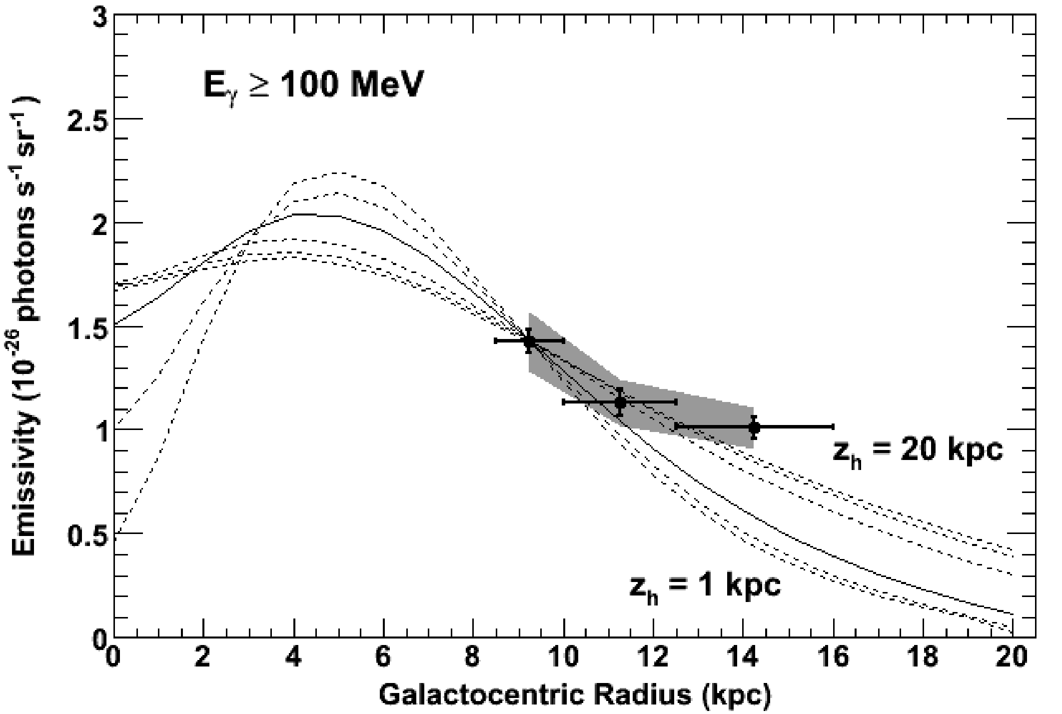
FERMI OBSERVATIONS OF CASSIOPEIA AND CEPHEUS: DIFFUSE GAMMA-RAY EMISSION IN THE OUTER GALAXY

A. A. Abdo[1,2], M. Ackermann[3], M. Ajello[3], L. Baldini[4], J. Ballet[5], G. Barbiellini[6,7], D. Bastieri[8,9], B. M. Baughman[10], K. Bechtol[3], R. Bellazzini[4], B. Berenji[3], E. D. Bloom[3], E. Bonamente[11,12], A. W. Borgland[3], J. Bregeon[4], A. Brez[4], M. Brigida[13,14], P. Bruel[15], T. H. Burnett[16], S. Buson[9], G. A. Caliandro[17], R. A. Cameron[3], P. A. Caraveo[18], J. M. Casandjian[5], C. Cecchi[11,12], Ö. Çelik[19,20,21], A. Chekhtman[1,22], C. C. Cheung[1,2], J. Chiang[3], S. Ciprini[12], R. Claus[3], J. Cohen-Tanugi[23], L. R. Cominsky[24], J. Conrad[25,26,52], C. D. Dermer[1], F. de Palma[13,14], S. W. Digel[3], E. do Couto e Silva[3], P. S. Drell[3], R. Dubois[3], D. Dumora[27,28], C. Farnier[23], C. Favuzzi[13,14], S. J. Fegan[15], W. B. Focke[3], P. Fortin[15], M. Frailis[29], Y. Fukazawa[30], S. Funk[3], P. Fusco[13,14], F. Gargano[14], N. Gehrels[19,31,32], S. Germani[11,12], G. Giavitto[6,7], B. Giebels[15], N. Giglietto[13,14], F. Giordano[13,14], T. Glanzman[3], G. Godfrey[3], I. A. Grenier[5], M.-H. Grondin[27,28], J. E. Grove[1], L. Guillemot[27,28,33], S. Guiriec[34], A. K. Harding[19], M. Hayashida[3], D. Horan[15], R. E. Hughes[10], M. S. Jackson[26,35], G. Jóhannesson[3], A. S. Johnson[3], W. N. Johnson[1], T. Kamae[3], H. Katagiri[30], J. Kataoka[36], N. Kawai[37,38], M. Kerr[16], J. Knödlseder[39], M. Kuss[4], J. Lande[3], L. Latronico[4], M. Lemoine-Goumard[27,28], F. Longo[6,7], F. Loparco[13,14], B. Lott[27,28], M. N. Lovellette[1], P. Lubrano[11,12], A. Makeev[1,22], M. N. Mazziotta[14], J. E. McEnery[19,32], C. Meurer[25,26], P. F. Michelson[3], W. Mitthumsiri[3], T. Mizuno[30], C. Monte[13,14], M. E. Monzani[3], A. Morselli[40], I. V. Moskalenko[3], S. Murgia[3], P. L. Nolan[3], J. P. Norris[41], E. Nuss[23], T. Ohsugi[30], A. Okumura[42], N. Omodei[4], E. Orlando[43], J. F. Ormes[41], D. Paneque[3], V. Pelassa[23], M. Pepe[11,12], M. Pesce-Rollins[4], F. Piron[23], T. A. Porter[44], S. Rainò[13,14], R. Rando[8,9], M. Razzano[4], A. Reimer[3,45], O. Reimer[3,45], T. Reposeur[27,28], A. Y. Rodriguez[17], F. Ryde[26,35], H. F.-W. Sadrozinski[44], D. Sanchez[15], A. Sander[10], P. M. Saz Parkinson[44], C. Sgrò[4], E. J. Siskind[46], P. D. Smith[10], G. Spandre[4], P. Spinelli[13,14], J.-L. Starck[5], M. S. Strickman[1], A. W. Strong[43], D. J. Suson[47], H. Takahashi[30], T. Tanaka[3], J. B. Thayer[3], J. G. Thayer[3], D. J. Thompson[19], L. Tibaldo[5,8,9], D. F. Torres[17,48], G. Tosti[11,12], A. Tramacere[3,49], Y. Uchiyama[3], T. L. Usher[3], V. Vasileiou[20,21], N. Vilchez[39], V. Vitale[40,50], A. P. Waite[3], P. Wang[3], B. L. Winer[10], K. S. Wood[1], T. Ylinen[26,35,51], and M. Ziegler[44]

Gamma-ray distribution in *outer* Galaxy

Gamma-ray emissivity falls off slower than expected for SNR source origin
Large halo will flatten it .... more evidence for large halo





Luigi Tibaldo

Abdo etal (2010) ApJ 710, 133

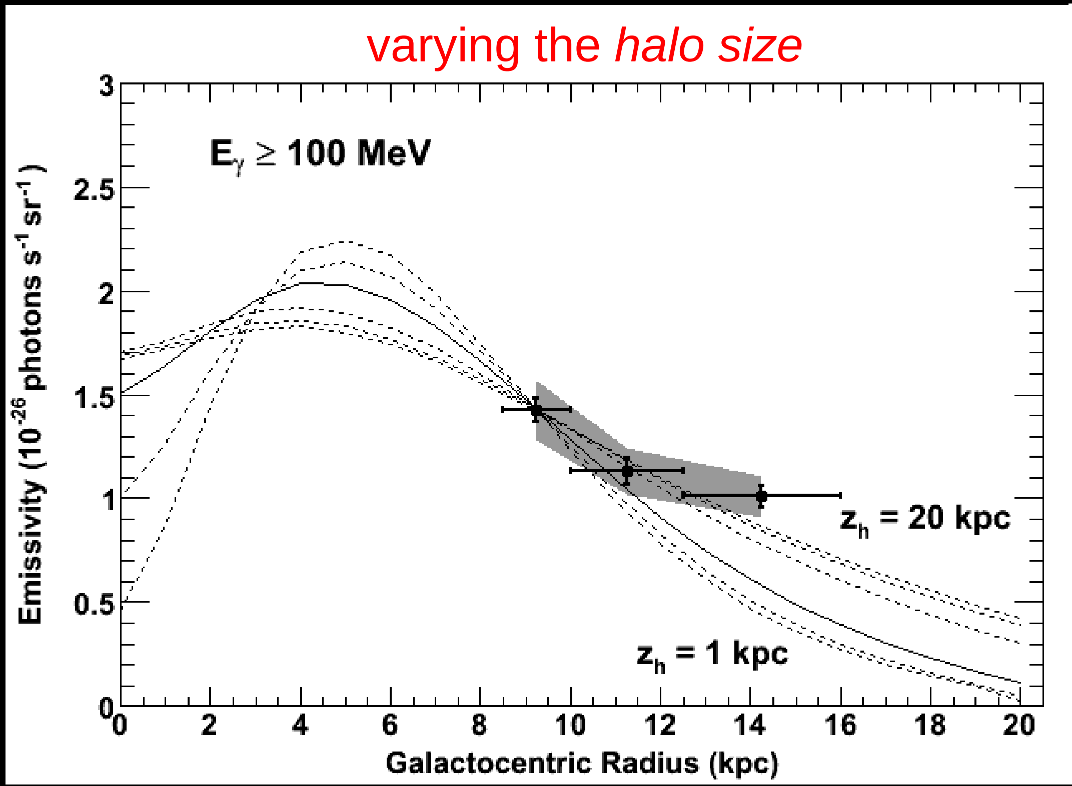
2009 Fermi Symposium

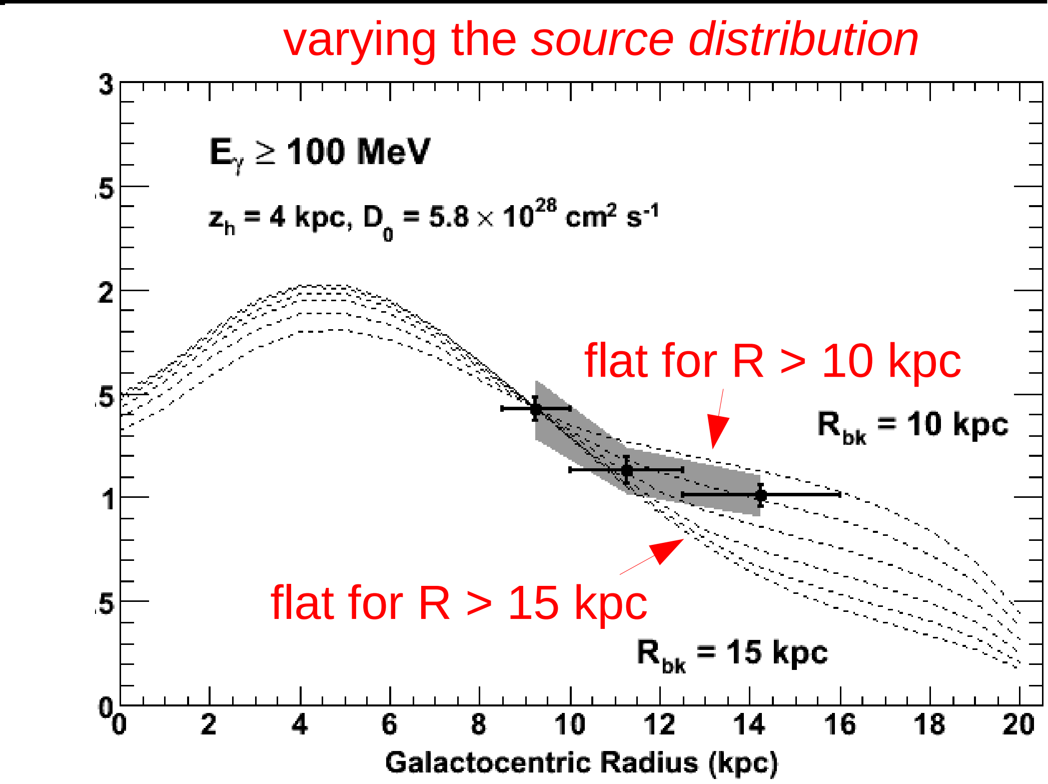
Tsufune Mizuno

PRELIMINARY

Gamma-ray distribution in outer Galaxy

3rd Quadrant

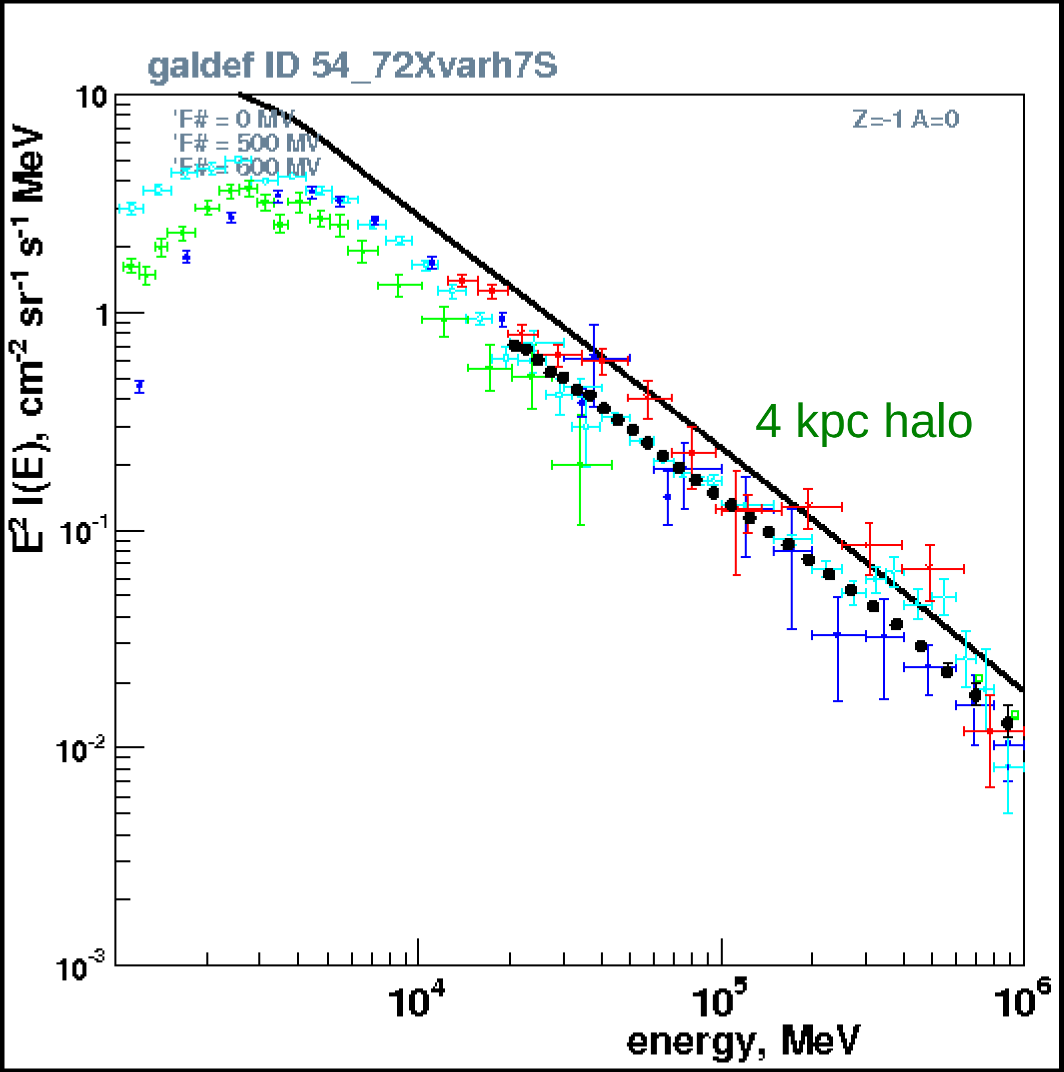




Tsufune Mizuno 2009 Fermi Symposium

PRELIMINARY

BONUS:
Large cosmic-ray halo also reduces the need to increase electron spectrum over Fermi-LAT measurements, to give gamma rays



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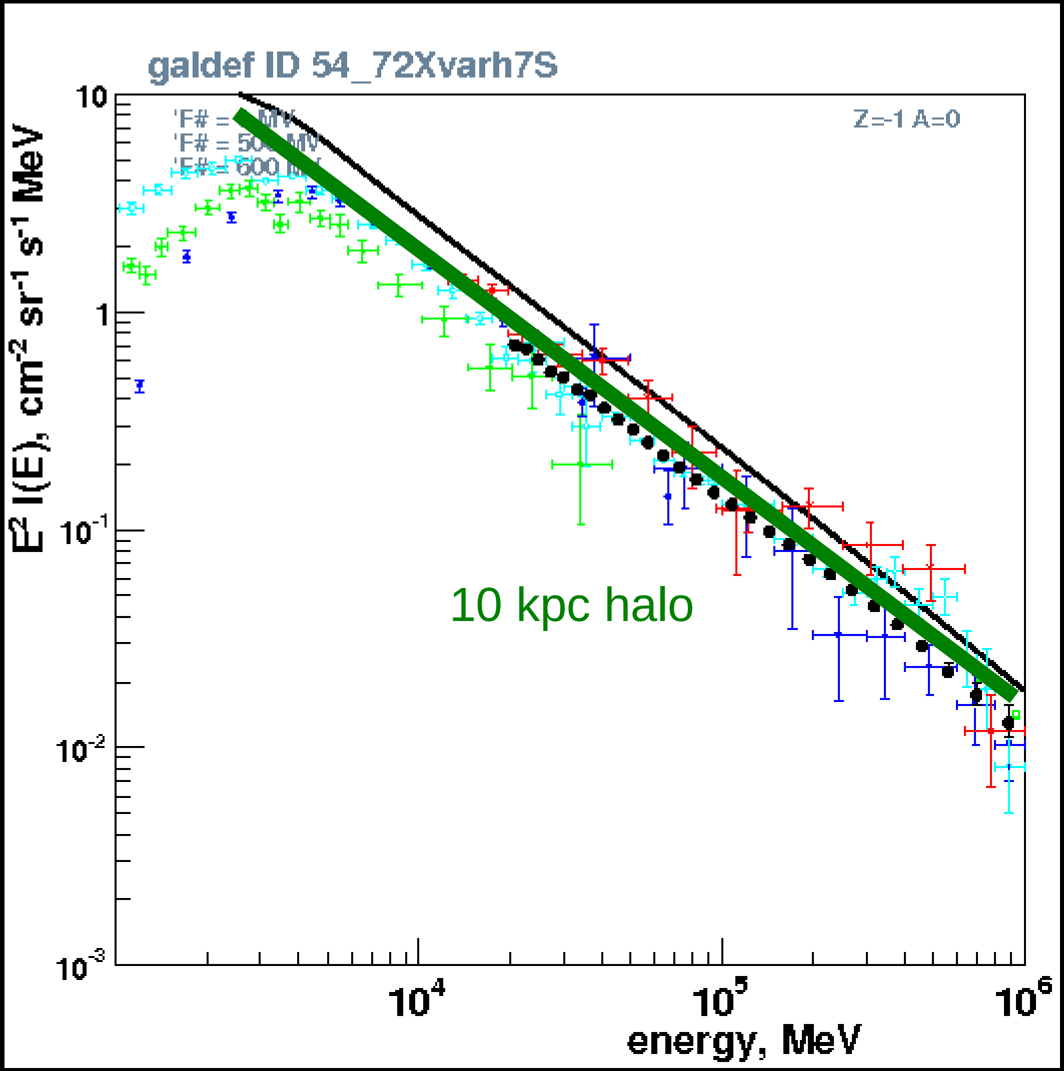
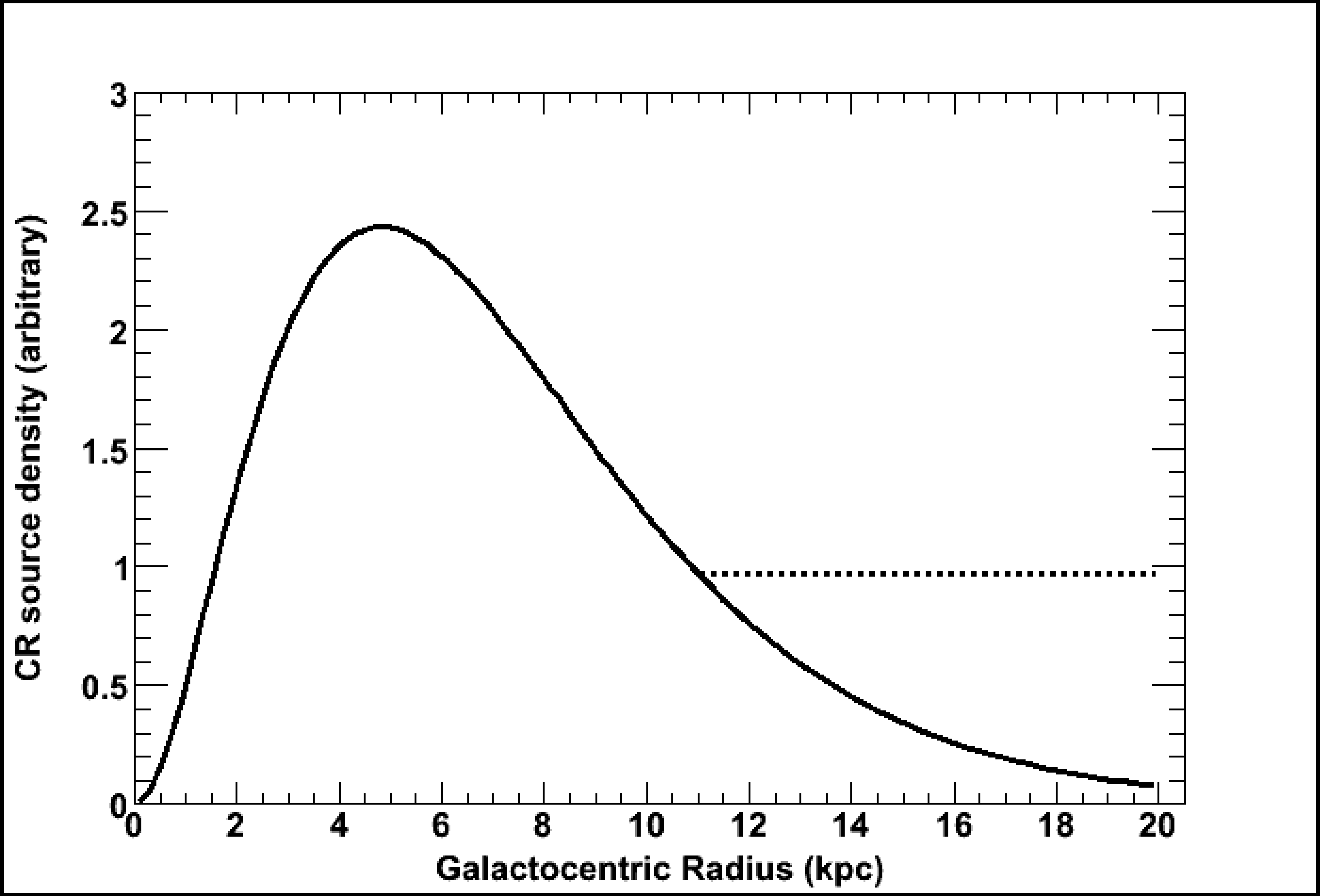
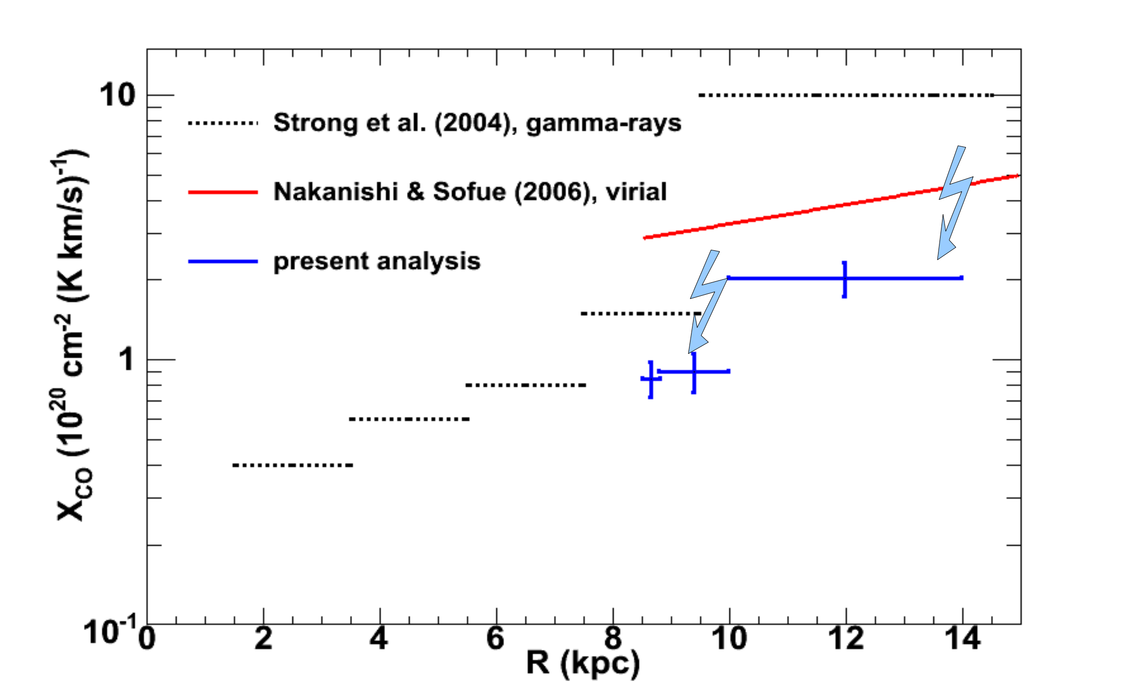


a modified cosmic-ray source distribution
which fits Fermi data without a large halo

but what would be the outer-Galaxy sources ?



Fermi measures molecular gas content of the outer Galaxy



Conversion factor Xco from CO to H_2

Outer Galaxy

Luigi Tibaldo

Abdo etal (2010) ApJ 710, 133

Large Scale Diffuse Emission: FACIT

The diffuse emission model reproduces the data remarkably well with a small amount of adjustment to the Fermi data.

The remaining residuals have many possible origins:
this is where the action and interest is focussed.

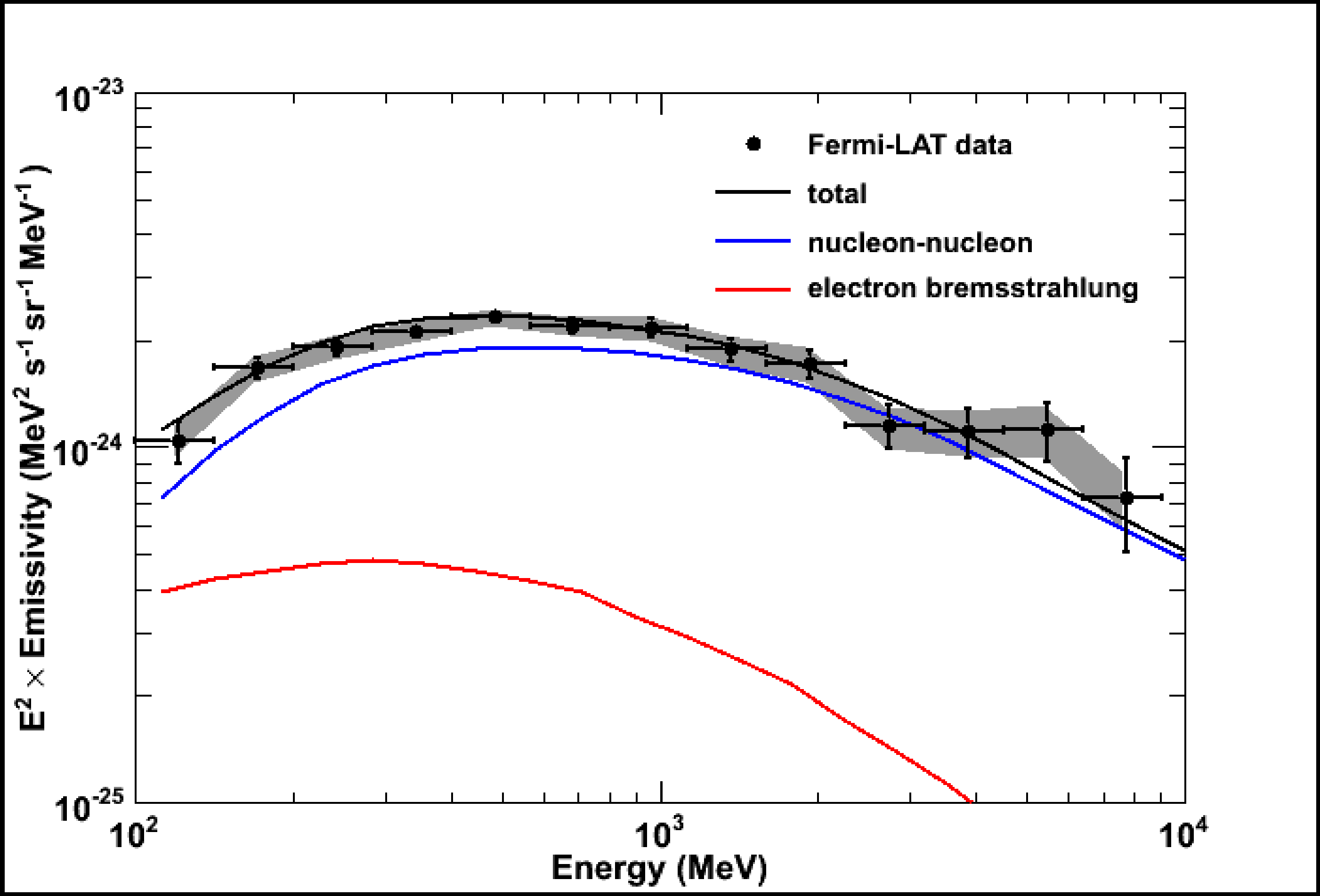
Diffuse Galactic emission and external galaxies: studies with Fermi-LAT

Large-scale Galactic emission
Local HI emissivity
Outer Galaxy
Orion Molecular Clouds
Loop I
Large Magellanic Cloud
Starbursts
Galactic Centre
Extragalactic Background

Source populations contribution to diffuse emission

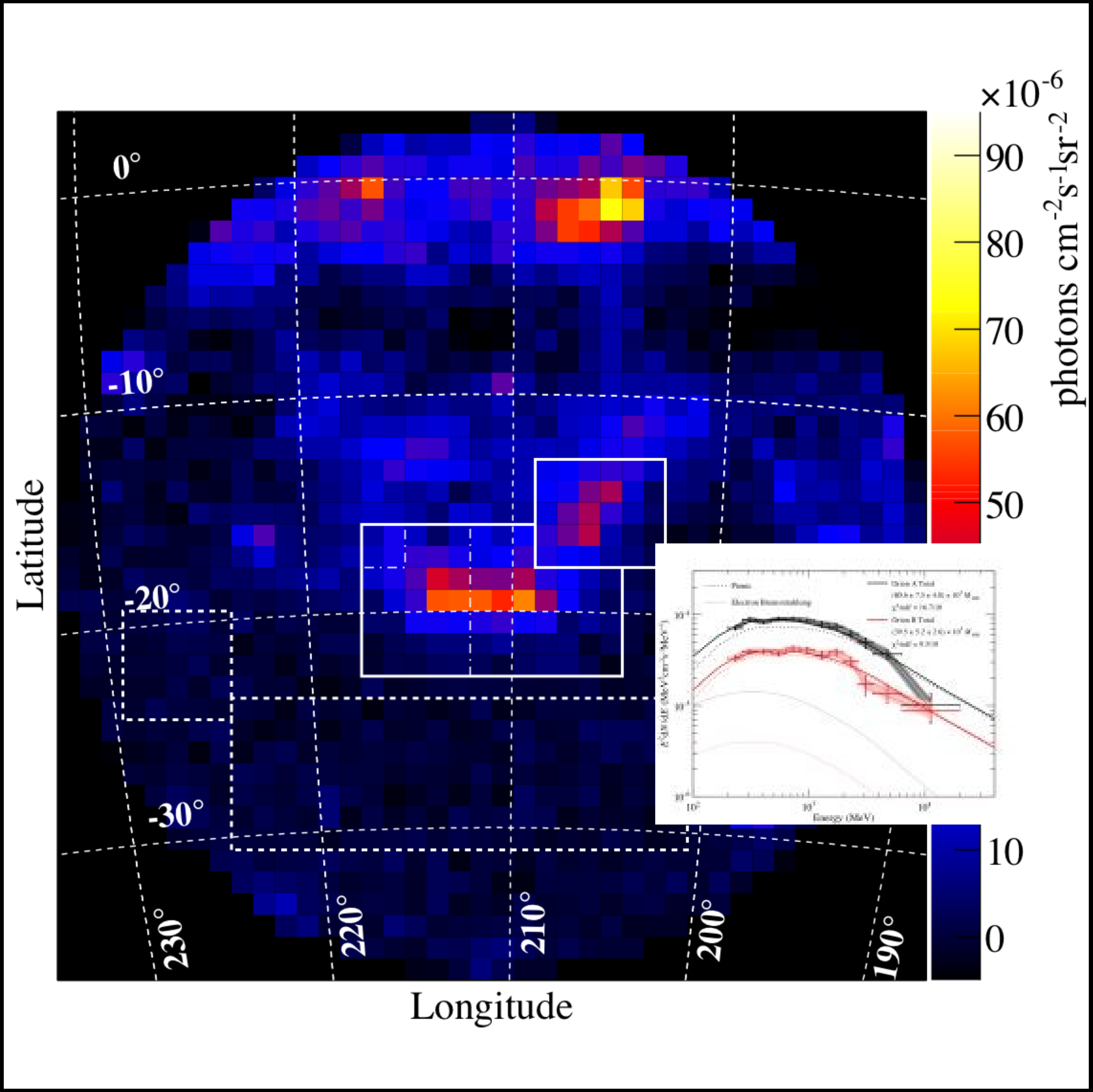
Electrons

Local HI gamma-ray emissivity
Tsufune Mizuno: Abdo et al. ApJ 2009



Agrees well with pion-decay calculation !

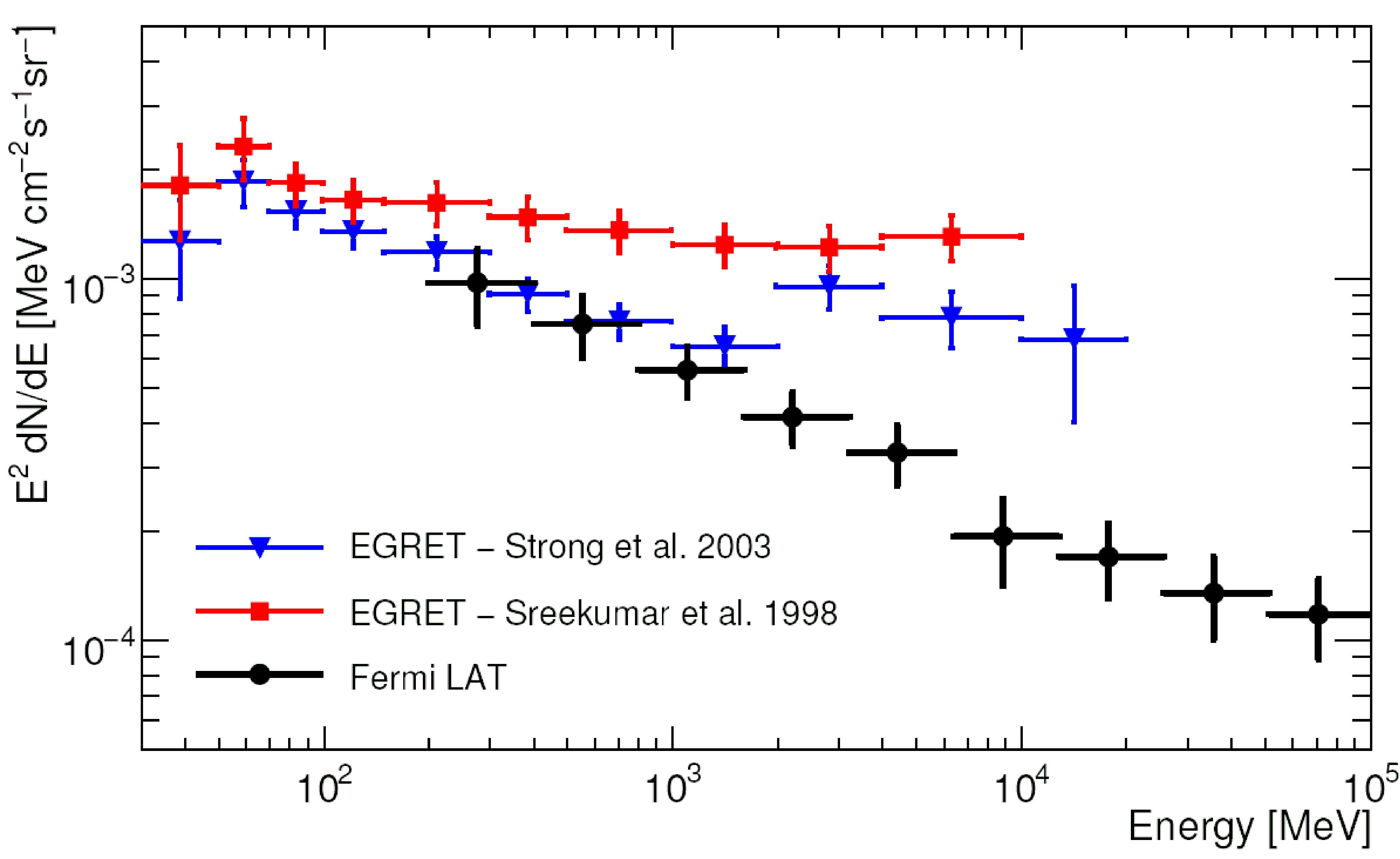
Orion Molecular Clouds as seen by Fermi-LAT >100 MeV



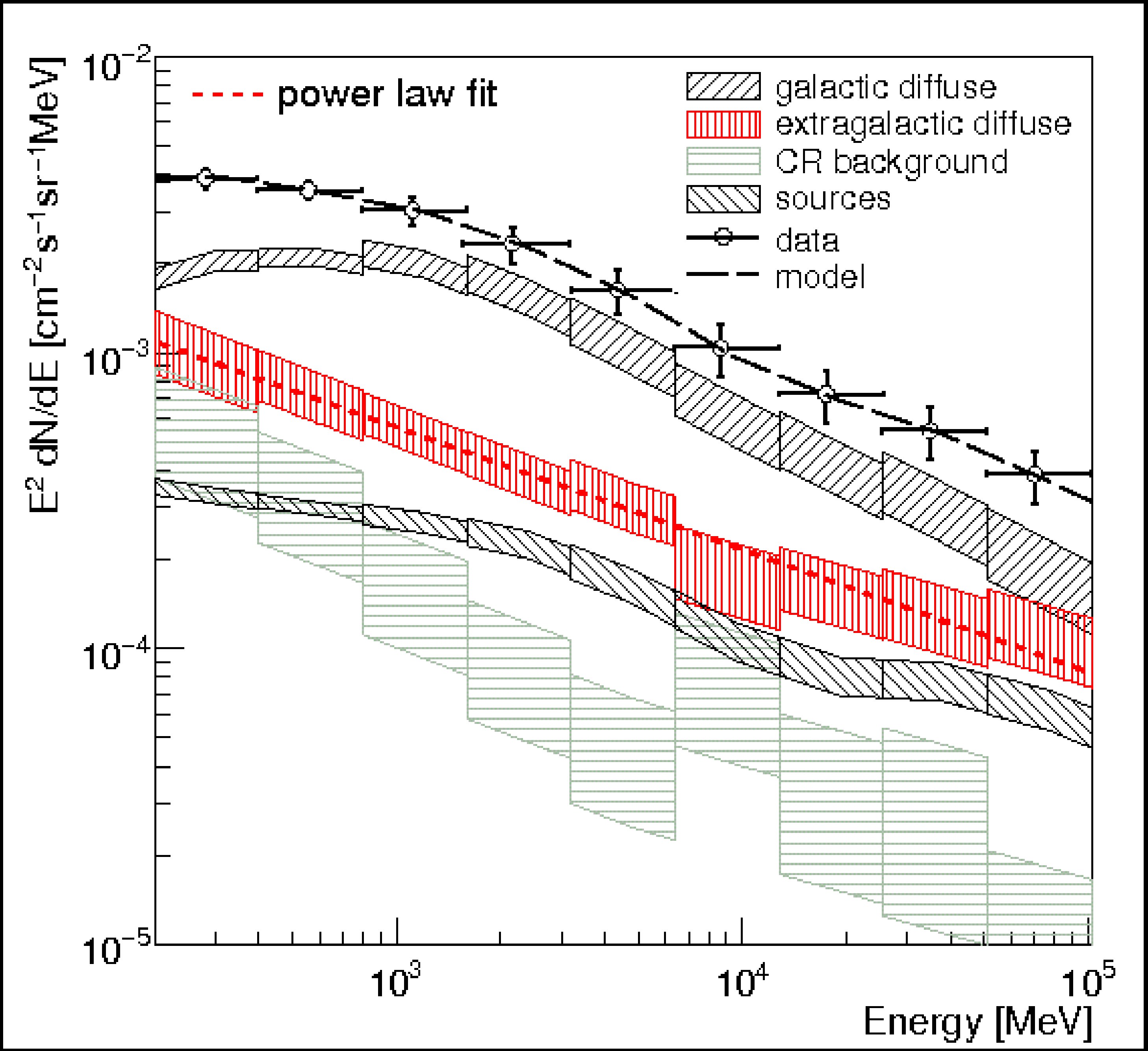
Analysis for H_2-CO relation, cosmic-ray density, cloud masses

Tsufune Mizuno, 2009 Fermi Symposium

Extragalactic (or at least 'isotropic') gamma-ray background

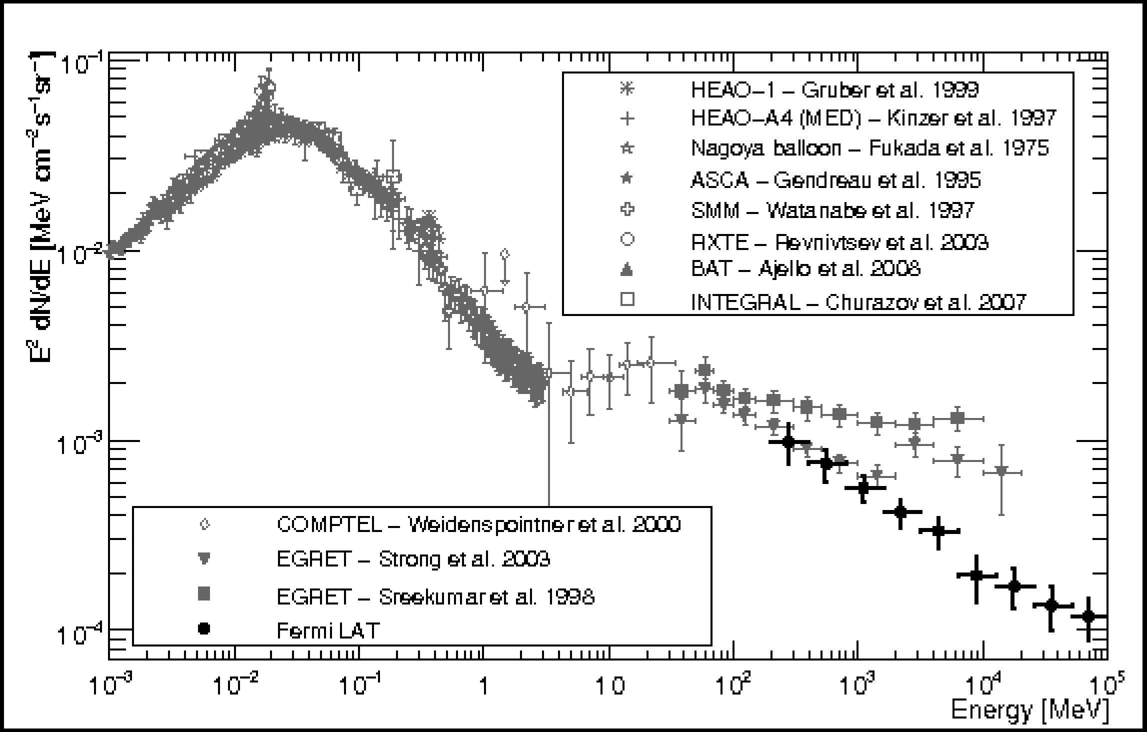


Markus Ackermann, 2009 Fermi Symposium

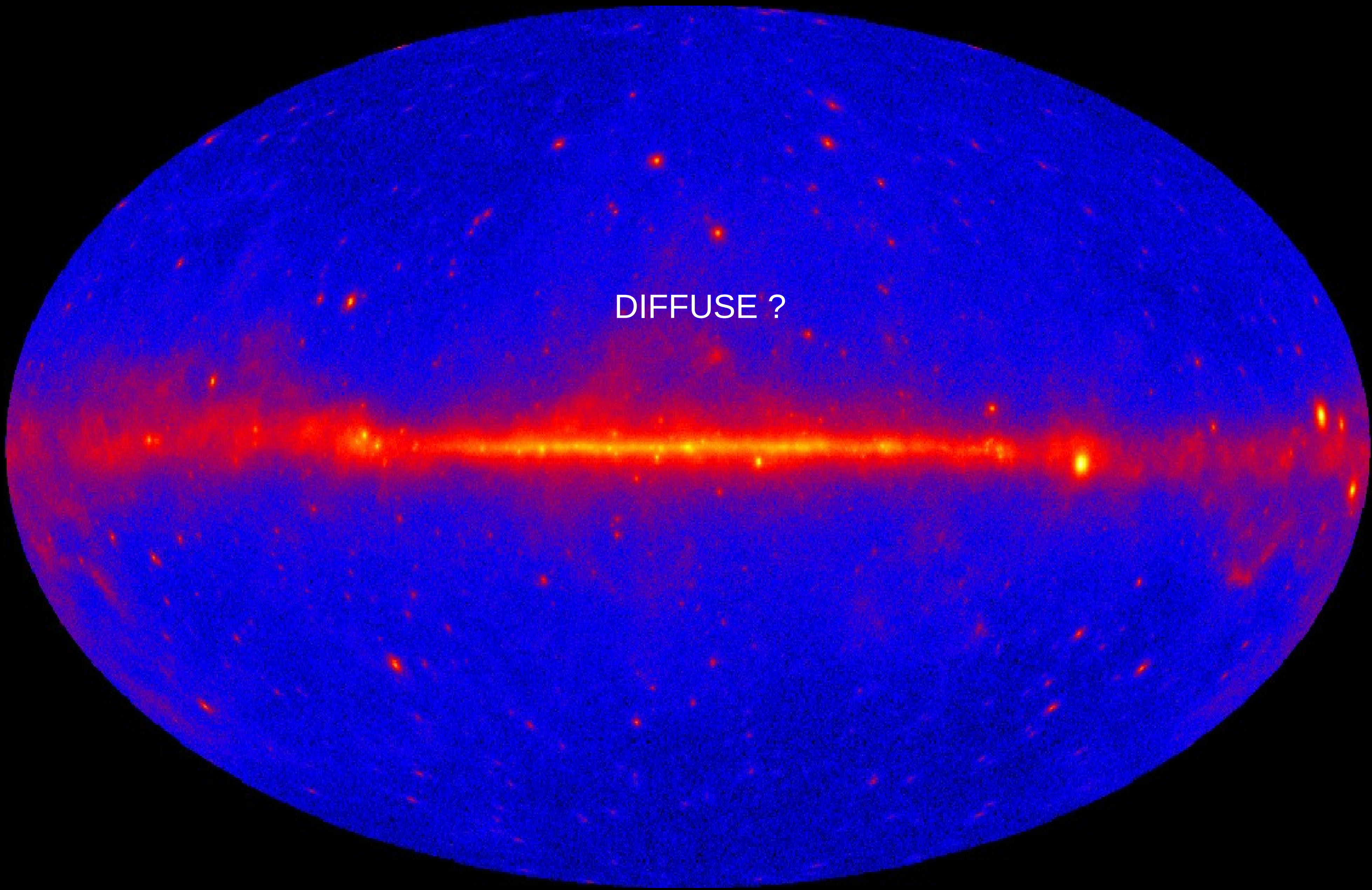


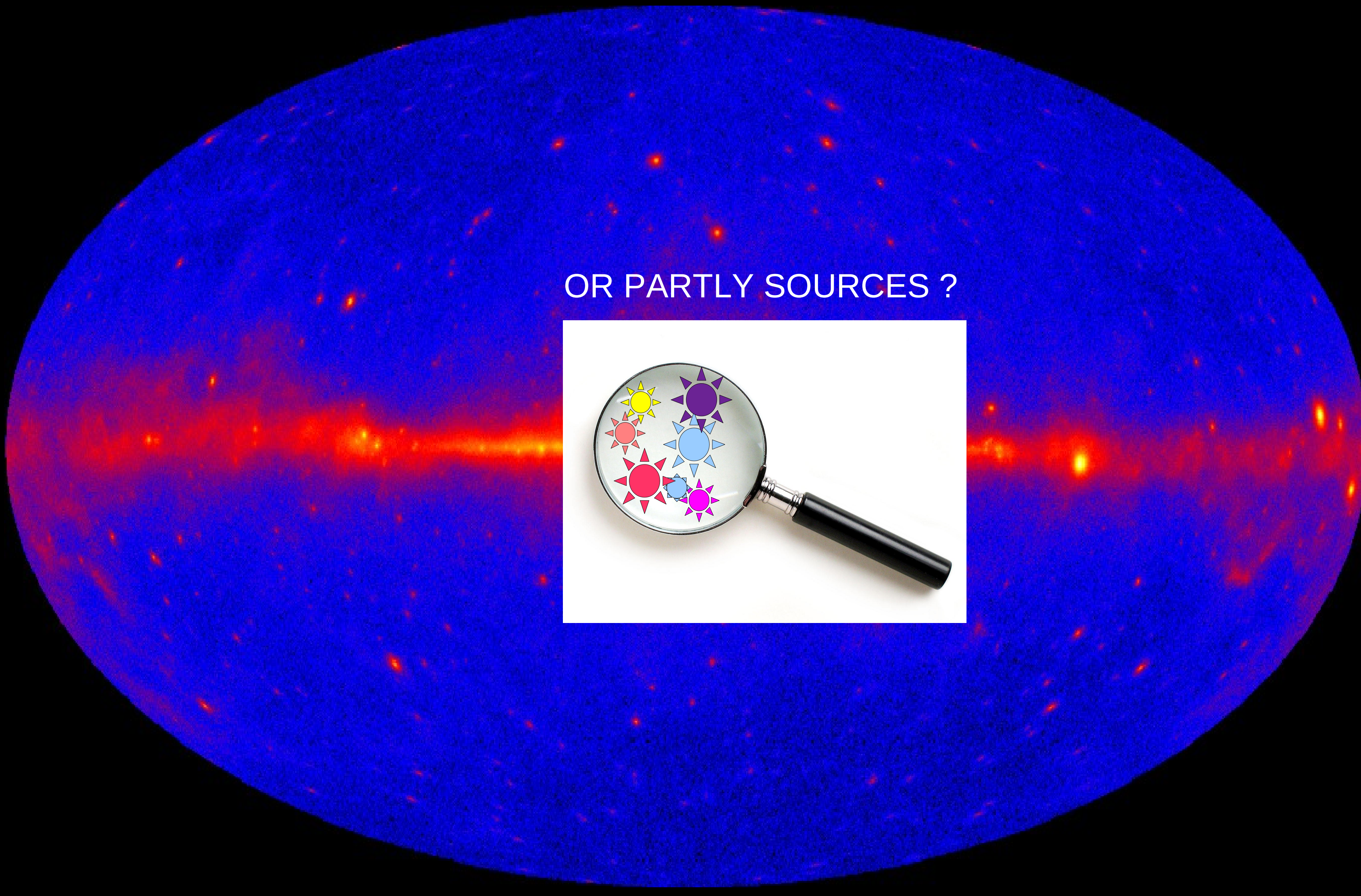
Markus Ackermann, 2009 Fermi Symposium

Extragalactic diffuse background

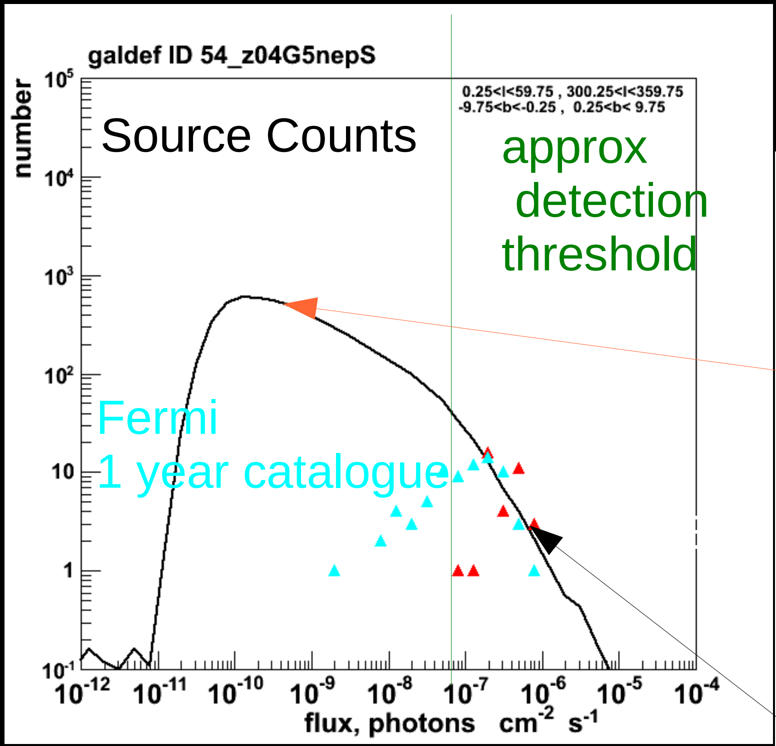


Markus Ackermann, 2009 Fermi Symposium

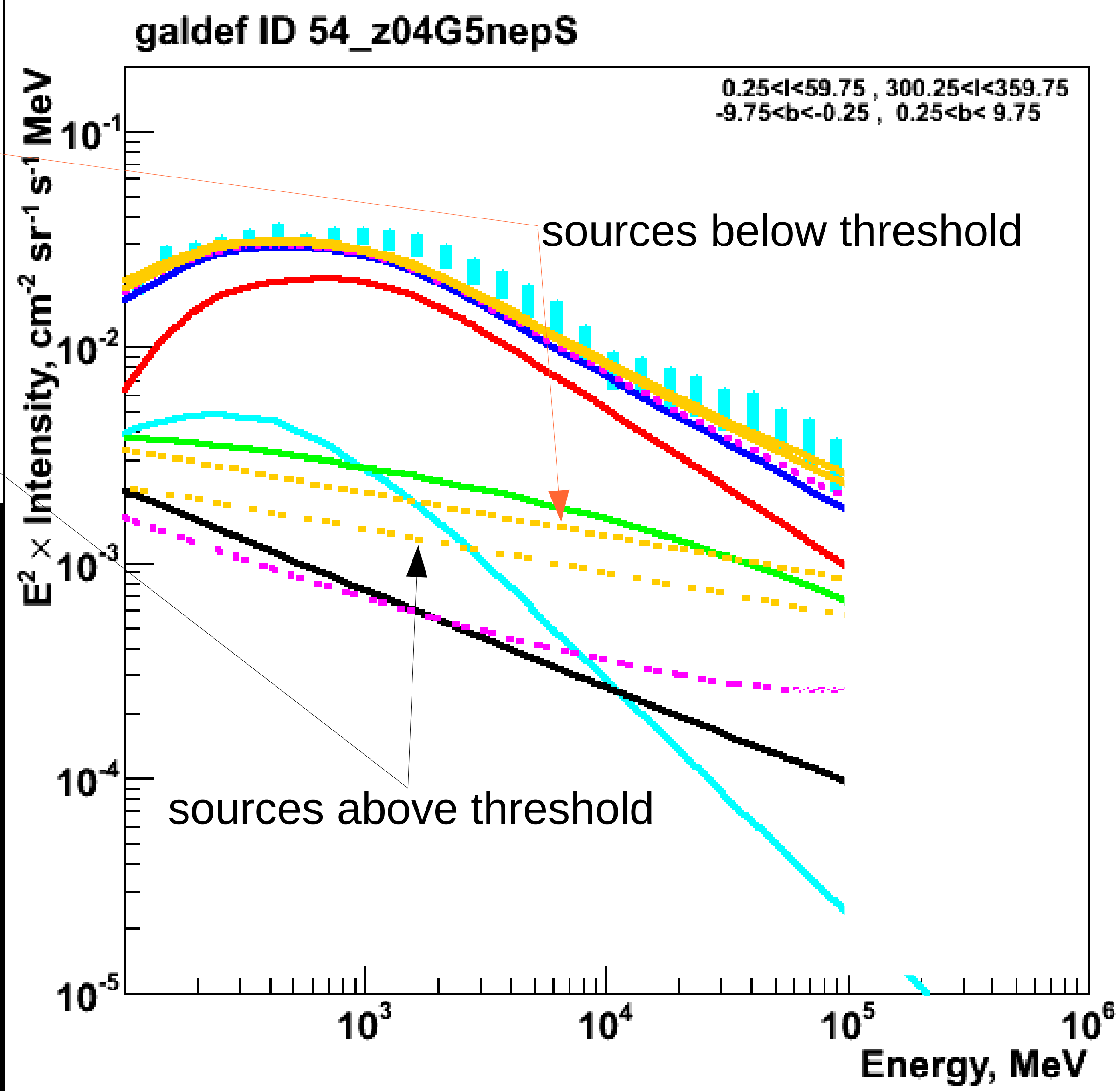

DIFFUSE ?


OR PARTLY SOURCES ?

Source contribution from luminous (pulsars etc) sources



Due to Fermi sensitivity,
unresolved source flux will finally be at percent level

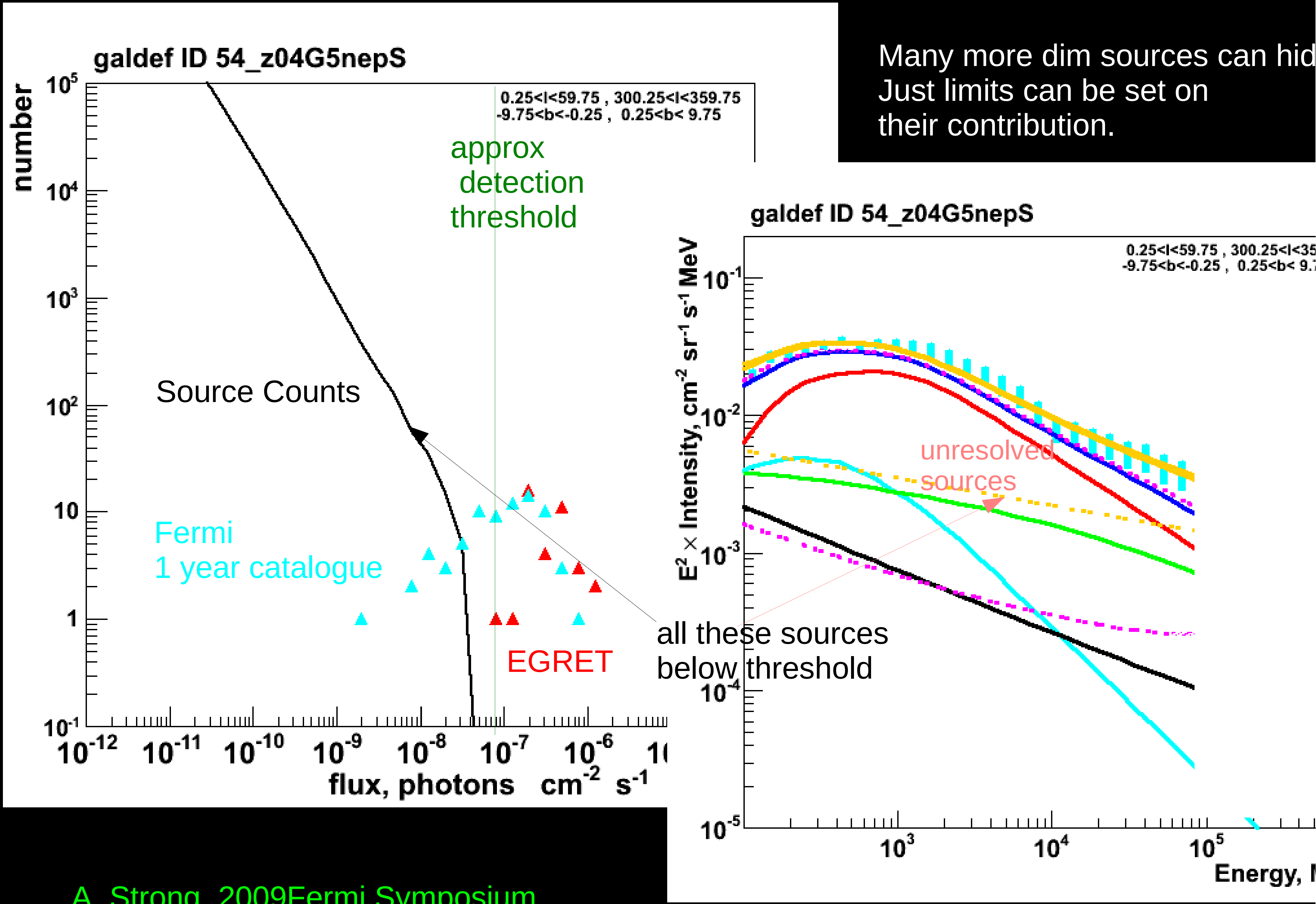


population synthesis
model consistent with
Fermi year 1 Catalogue

A .Strong, 2009 Fermi Symposium

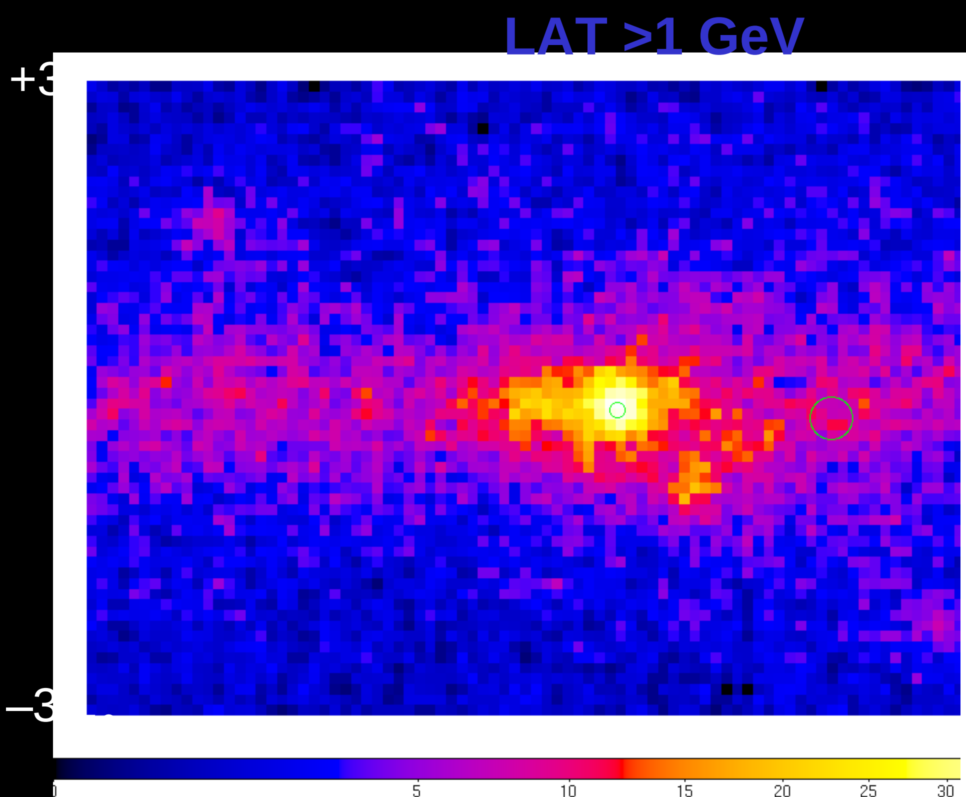
Source contribution from possible low-luminosity sources

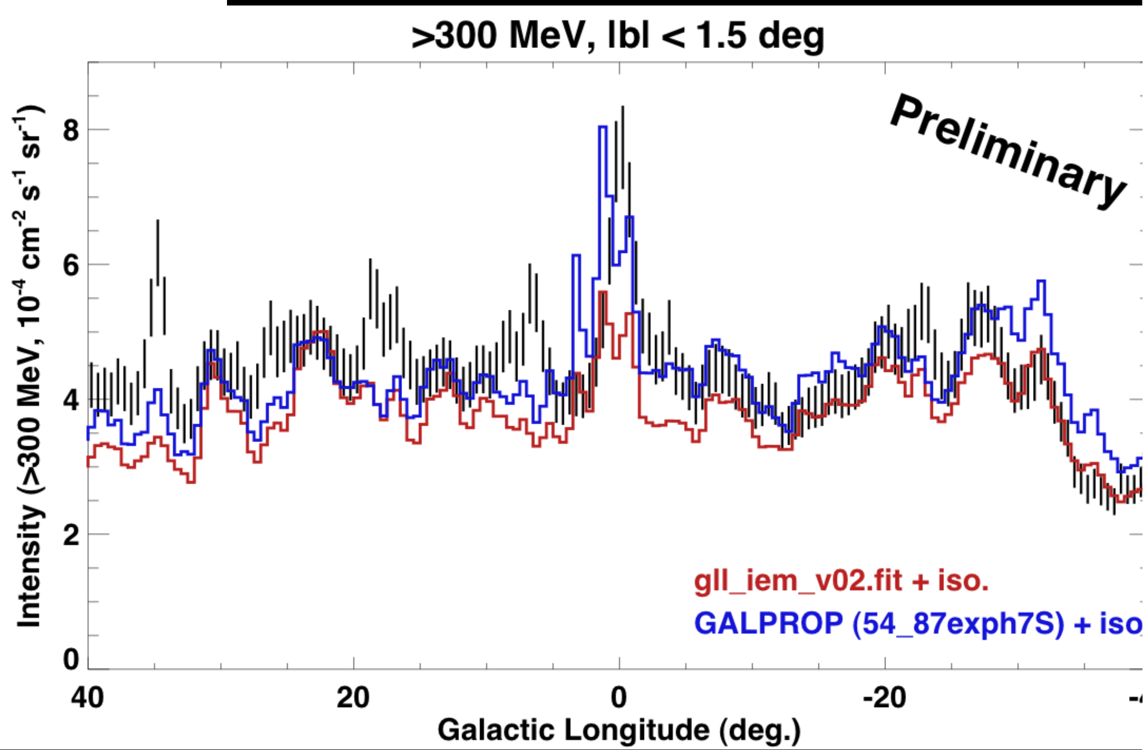
Many more dim sources can hid
Just limits can be set on
their contribution.



A. Strong, 2009Fermi Symposium

Galactic Centre Region



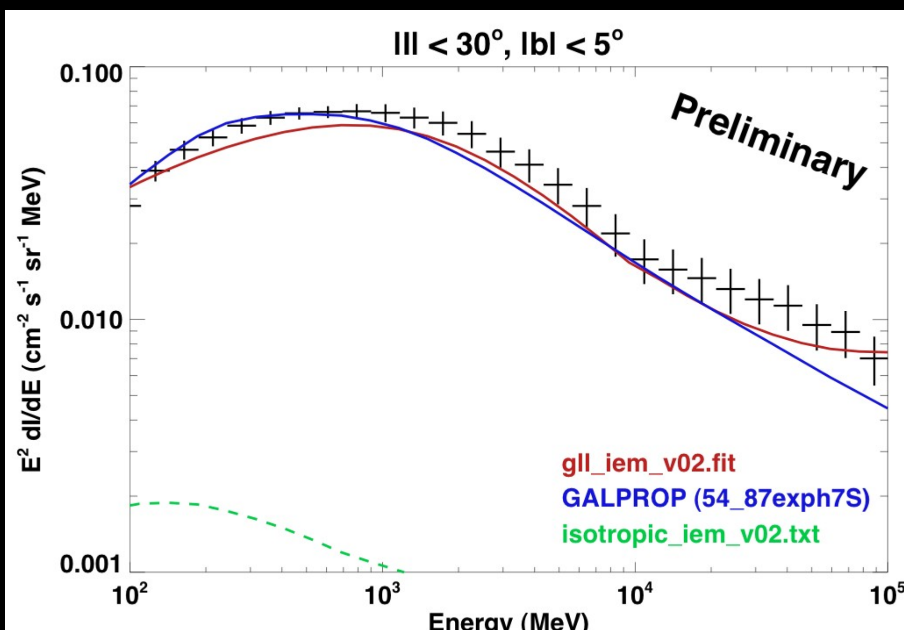


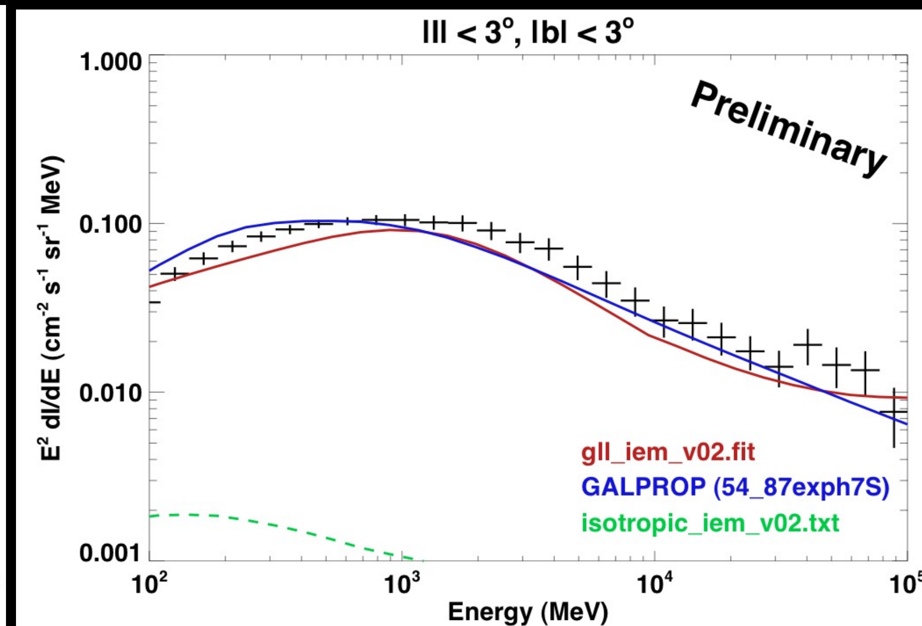
Seth Digel, 2009 Fermi Symposium

Spectral Residuals

Galactic Centre Region

- The all-sky Galactic diffuse emission model released by the LAT team (red curve) somewhat under-predicts the sky intensity in the GC region

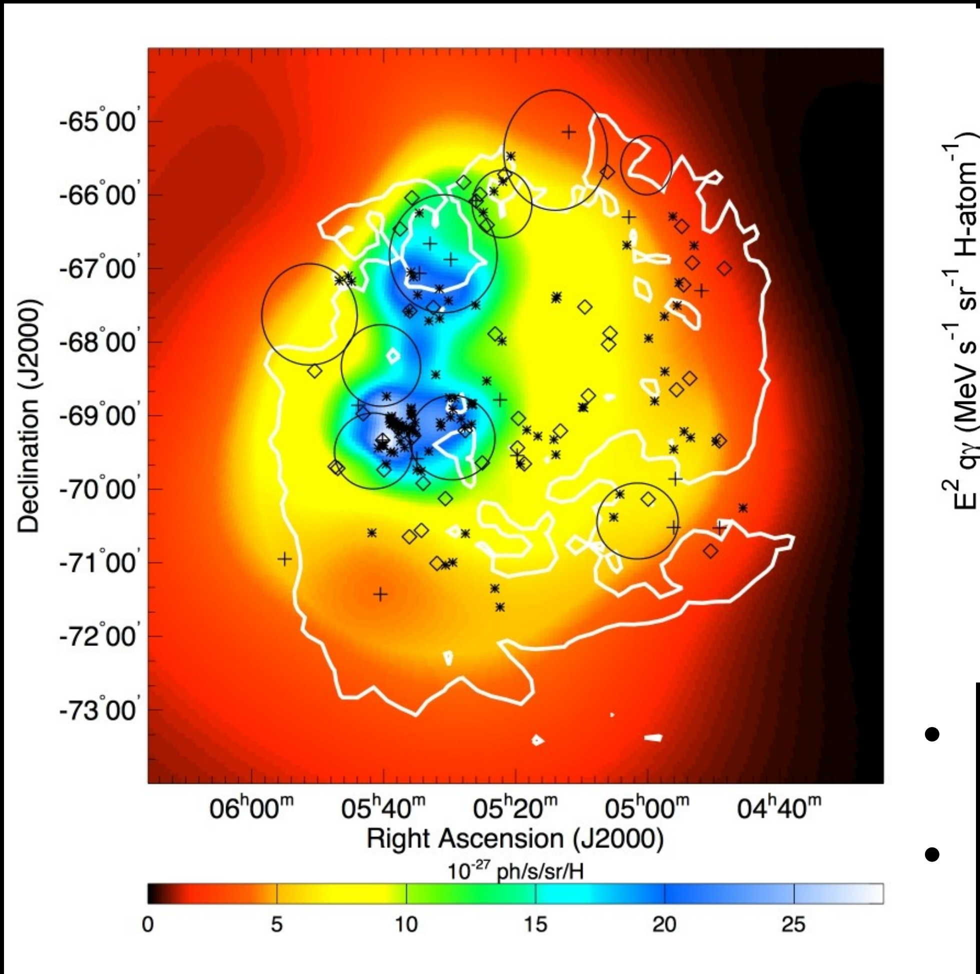




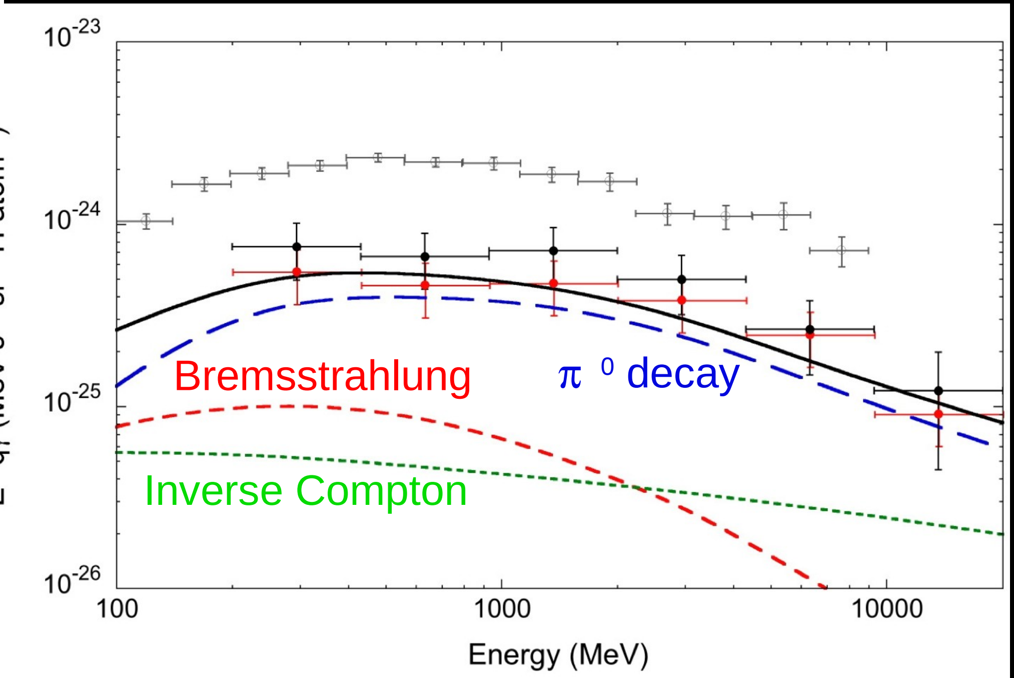
Seth Digel, 2009 Fermi Symposium

Large Magellanic Cloud

LMC emissivity map



Average emissivity spectrum



- **Spectrum consistent with expectations (using local galactic p, e^-, e^+ spectral shapes)**
- **Average cosmic-ray density about 0.2-0.3 times that in solar vicinity (consistent with difference between galactic and LMC SN rate)**

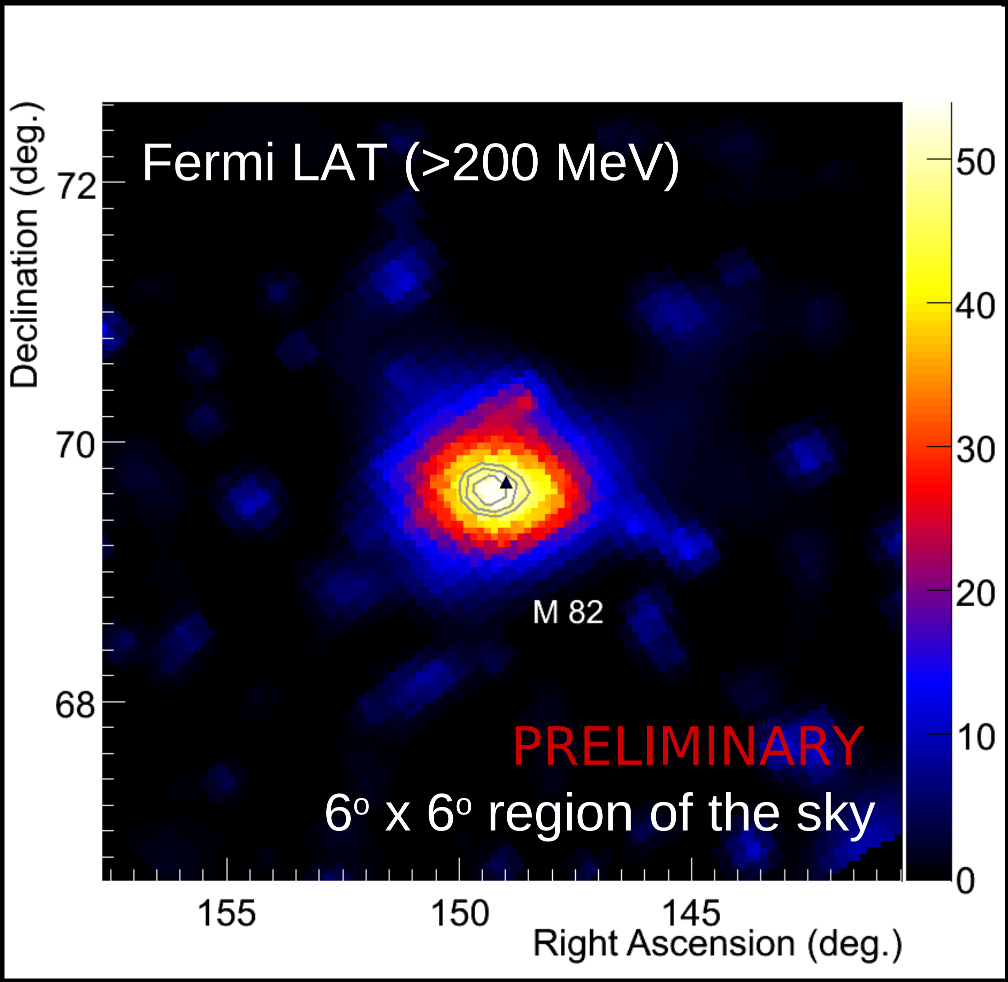
Considerable cosmic-ray density variations

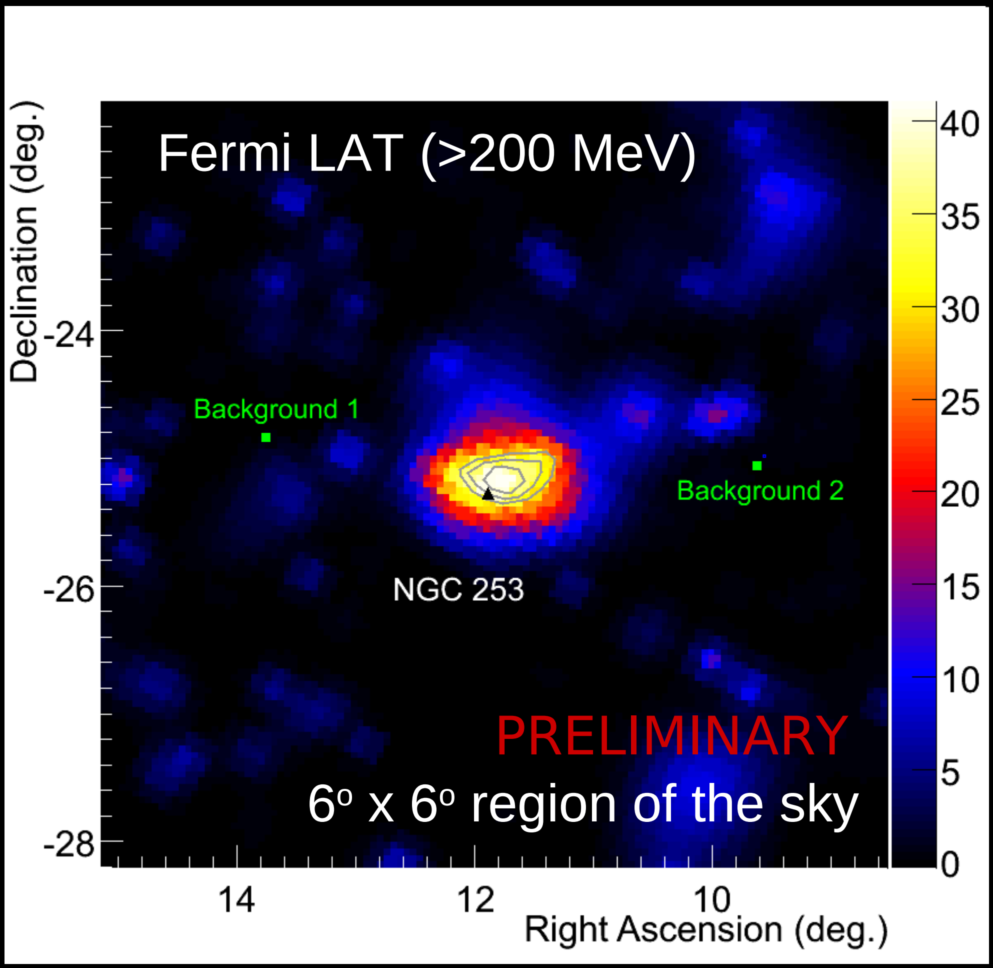
Small GeV proton diffusion length

Jürgen Knödlseder, 2009 Fermi Symposium

Starburst Galaxies

Galactic diffuse, isotropic diffuse, and point sources subtracted





0.68, 0.95, 0.99 confidence level localization contours

Appear as LAT point sources, starburst regions unresolved

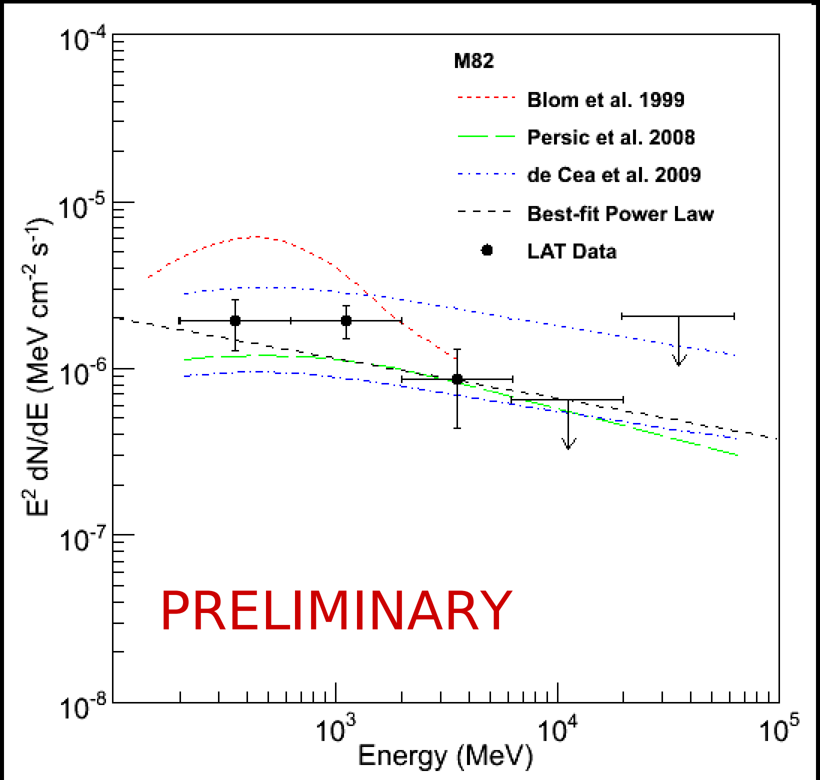
Detection Significance Maps

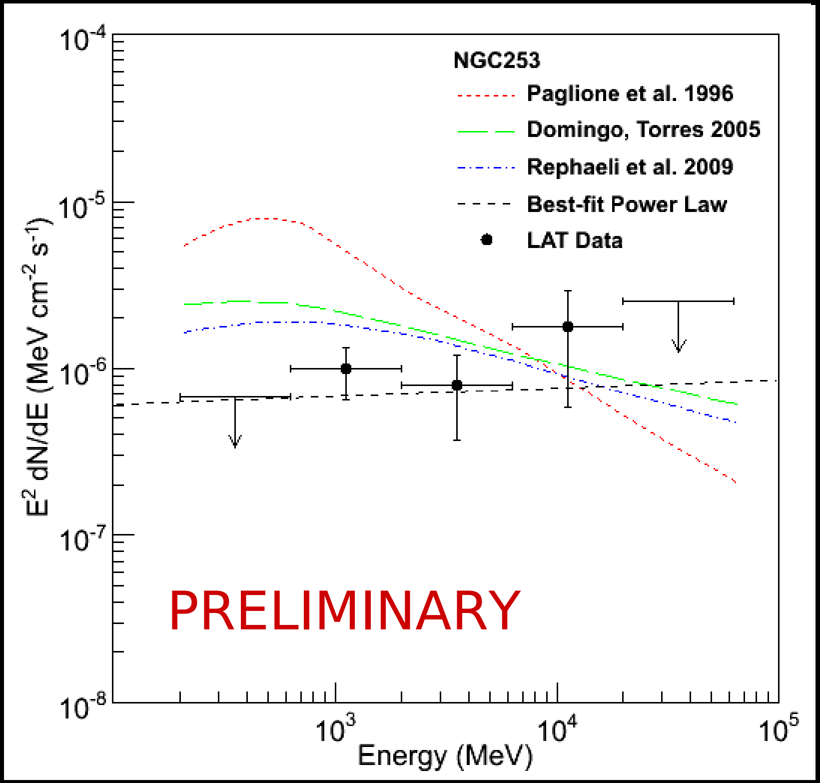
Keith Bechtol, 2009 Fermi Symposium, now Abdo etal (2010) ApJL 709, L152

Starburst Galaxies

Observed integral fluxes consistent with models of diffuse galactic gamma-ray emission

, but data do not yet tightly constrain spectral shapes

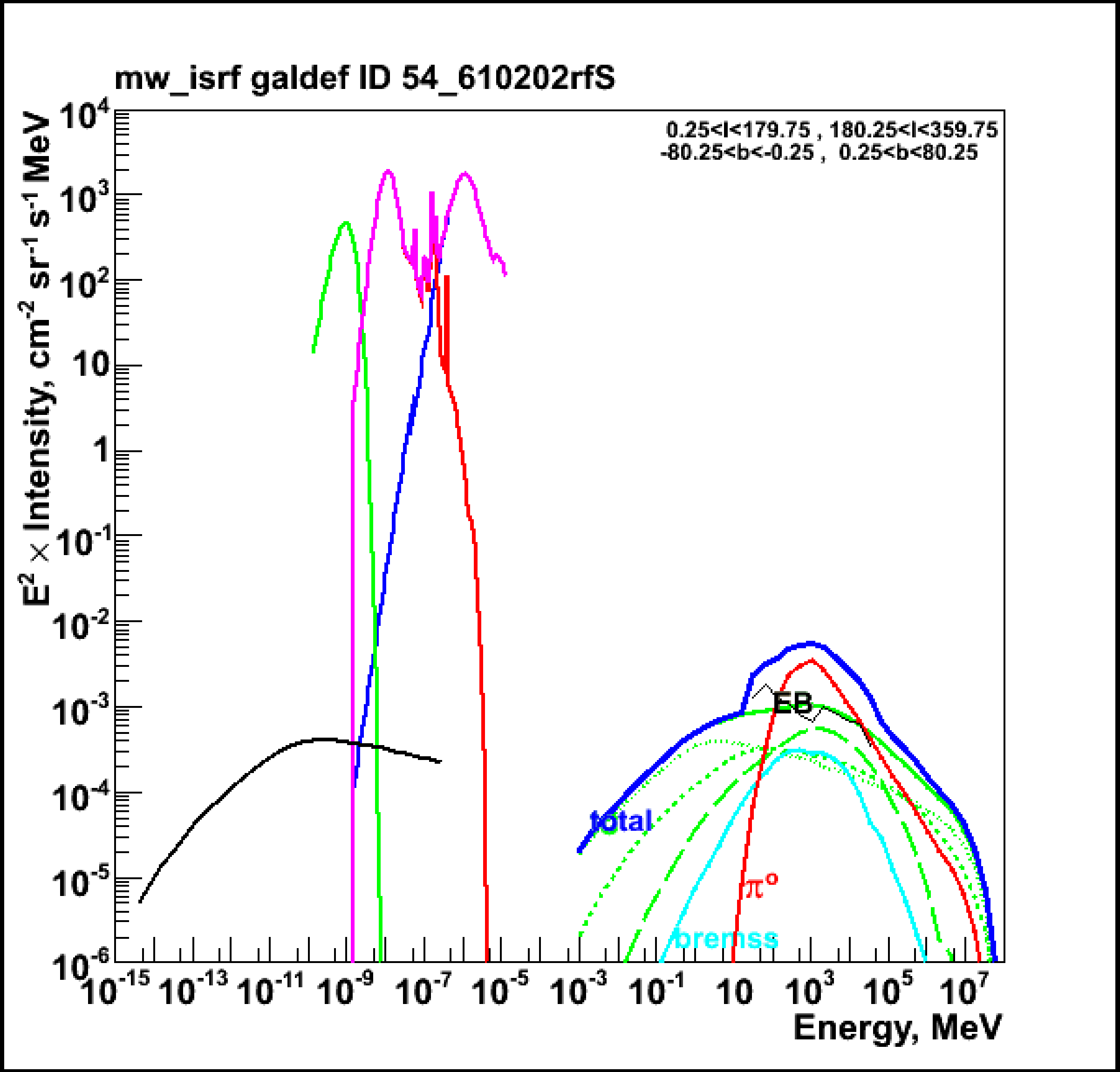




	Flux (>100 MeV) (10^{-8} ph cm^{-2} s^{-1})	Photon Index
M82	$1.6 \pm 0.5_{stat} \pm 0.3_{sys}$	$2.2 \pm 0.2_{stat} \pm 0.05_{sys}$
NGC 253	$0.6 \pm 0.4_{stat} \pm 0.4_{sys}$	1.95 ± 0.4stat $\pm 0.05_{sys}$

Keith Bechtol, 2009 Fermi Symposium, now Abdo etal (2010) ApJL 709, L152

Interstellar radiation over 20 decades of energy

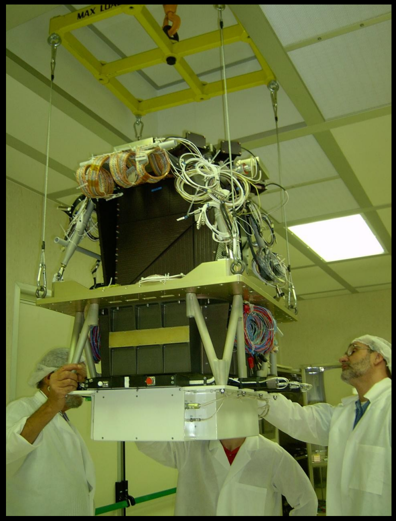


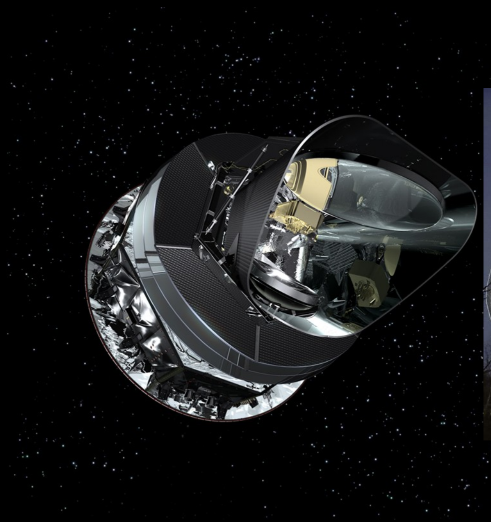
radio CMB IR optical X γ

Outlook

Fermi operational , results coming out fast
The fine data challenges the models.

Essential to exploit synergy between
cosmic-rays - gammas – microwave - radio



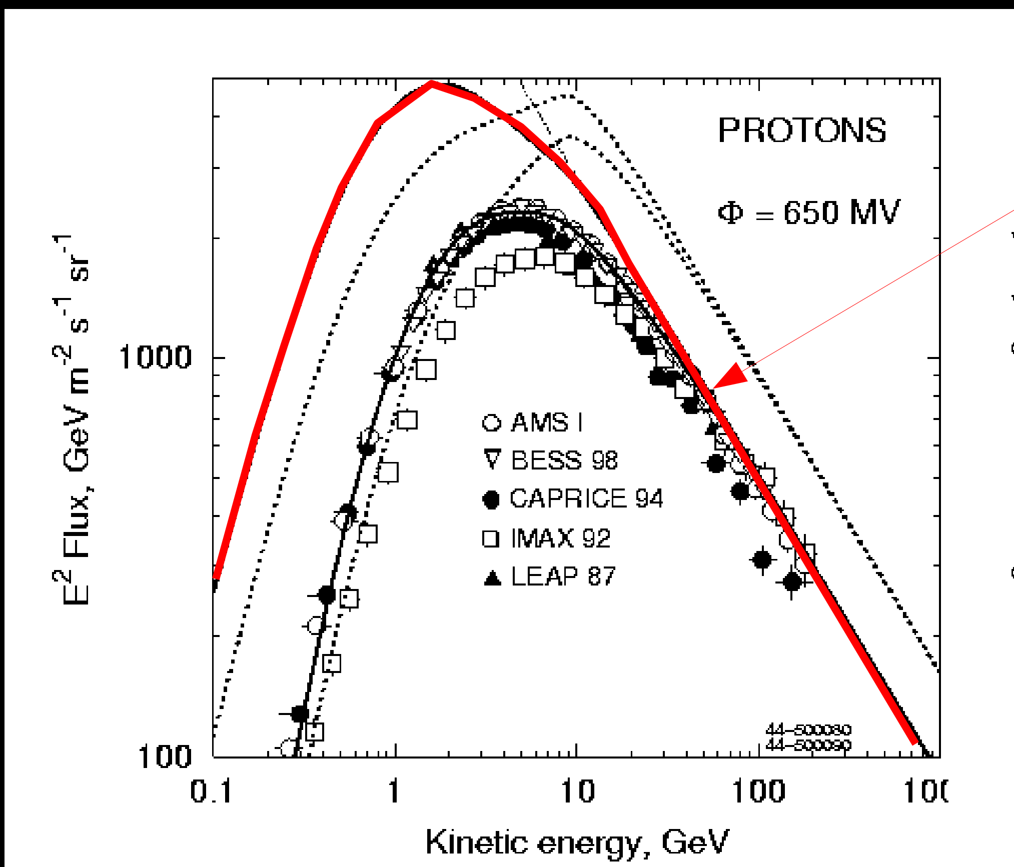


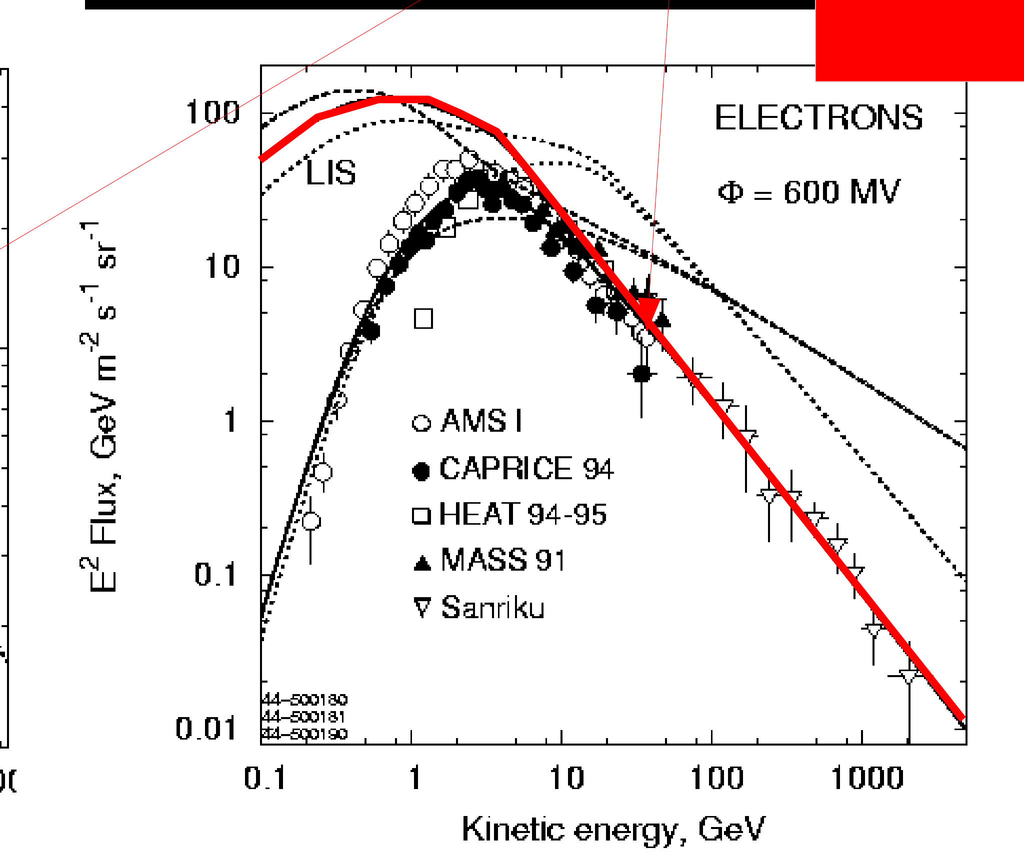

FIN

ADDITIONAL MATERIAL TO BE USED AS REQUIRED IN THE WORKSHOP

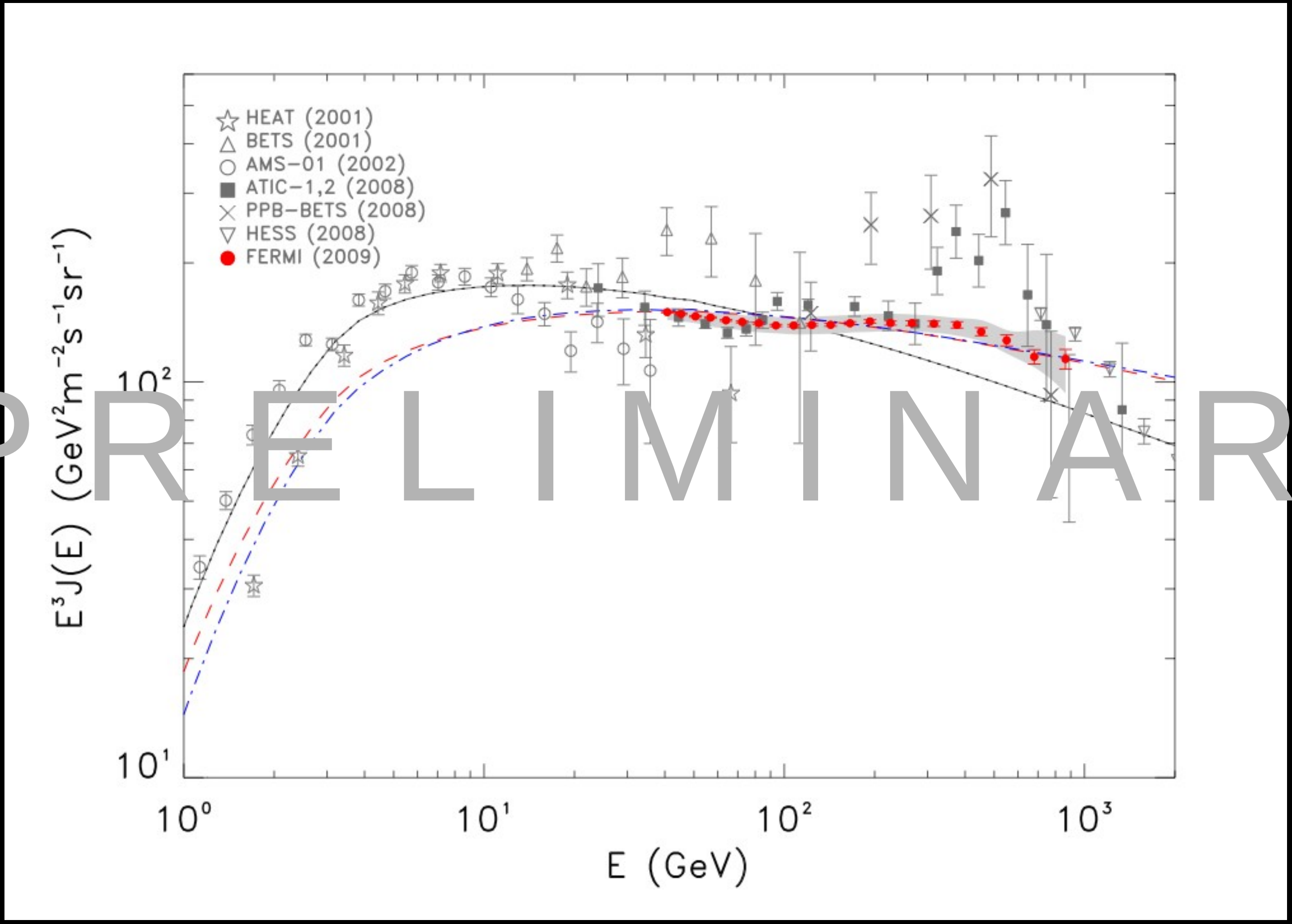
Modelling diffuse Galactic γ - rays:

Conventional model: proton, electron spectra as measured





GALPROP application : models for Fermi electrons
(from John Bregeon's talk)

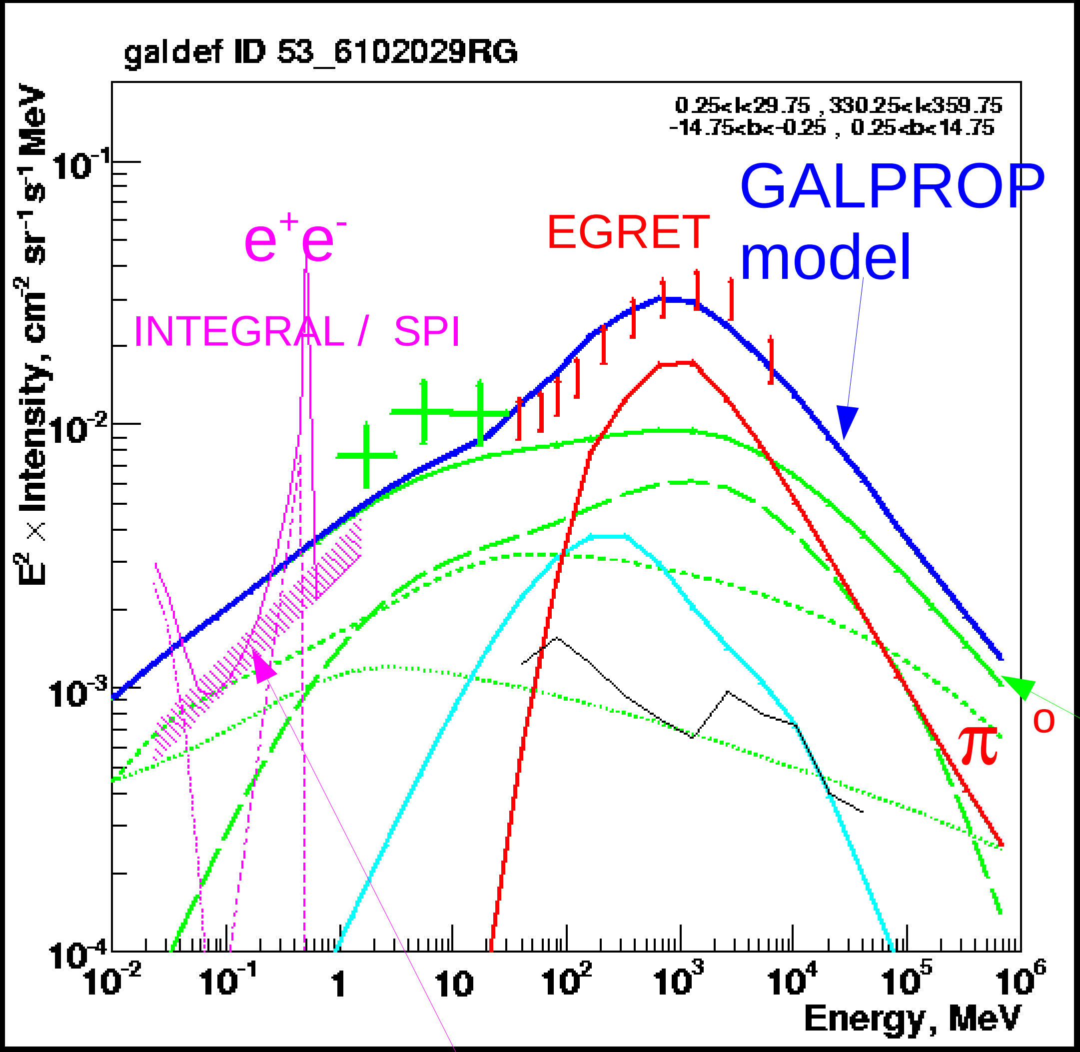


PRELIMINARY

Gamma-rays, inner Galaxy

inverse Compton
from primary electrons, secondary electrons, positrons

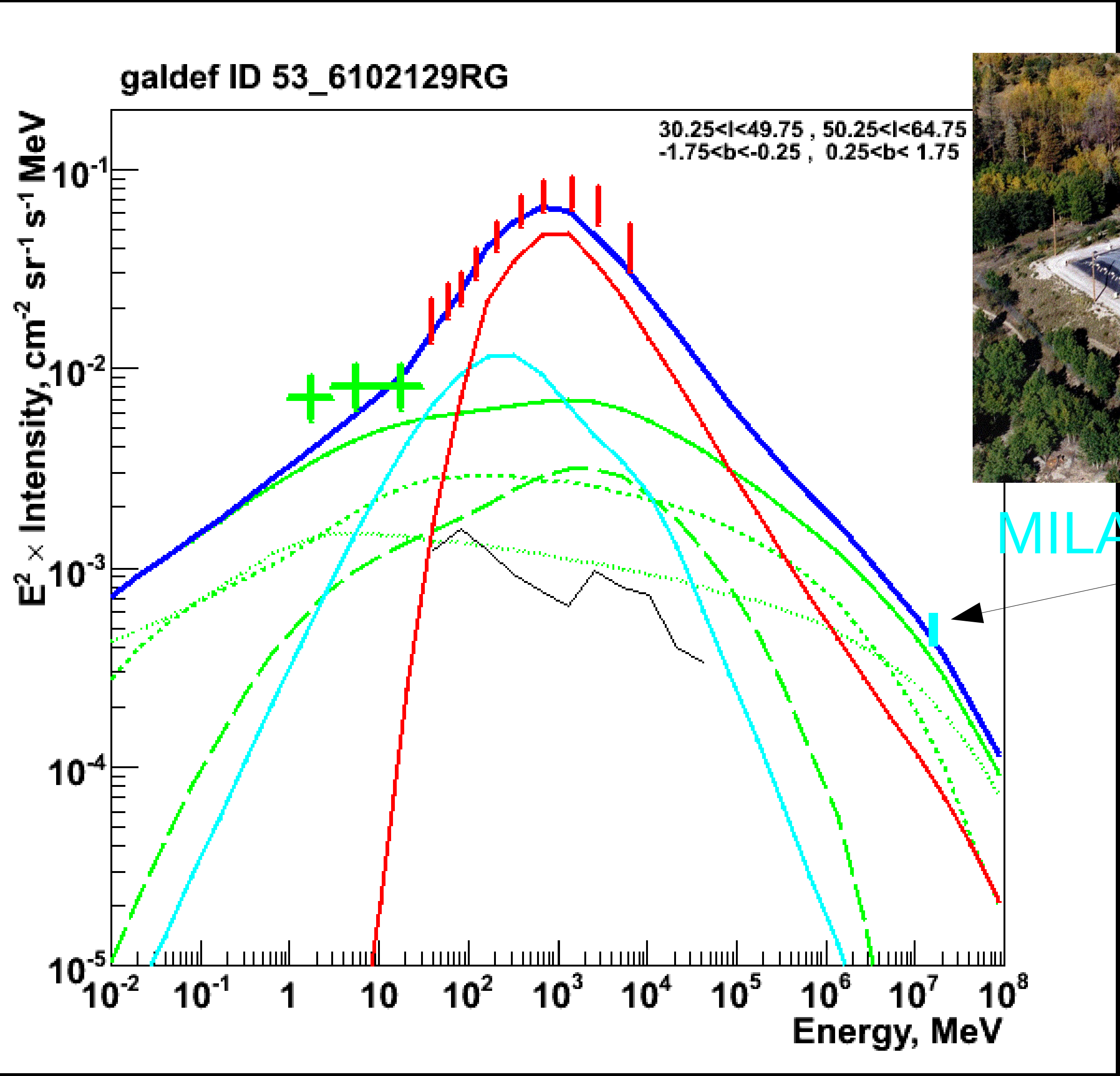
These processes are very relevant down to hard X-rays !



Bouchet et al power-law continuum

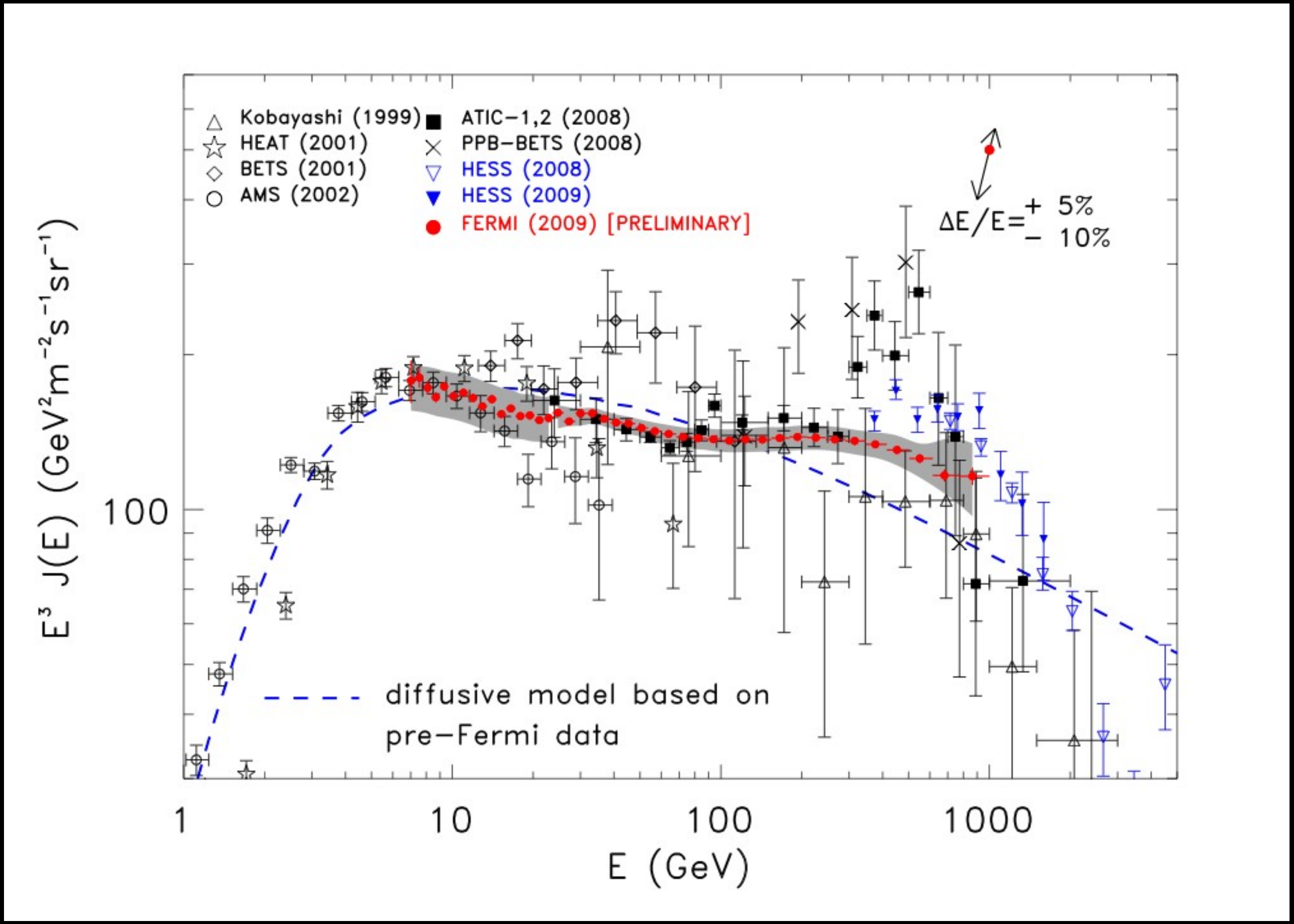
Porter, Moskalenko, Strong, Orlando, Bouchet ApJ 682, 400 and towards the highest energies...

Diffuse Galactic Emission



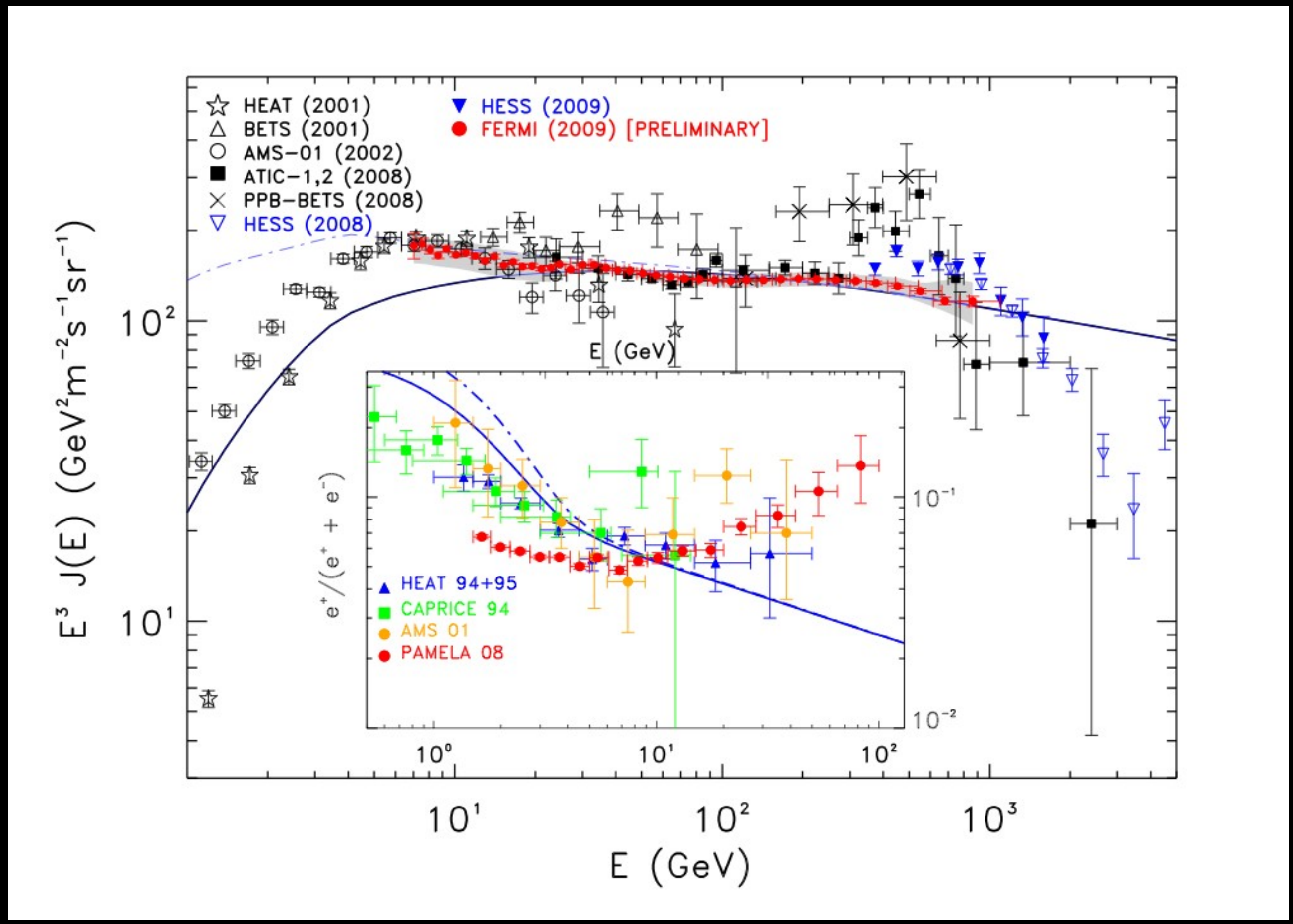
MILAGRO : 15 TeV

Electron spectrum
Extended down to 7 GeV (from 20 GeV)



2009 Fermi Symposium: Melissa Pesce-Rollins, arXiv:0912.3611
PRELIMINARY

Electron spectrum extended down to 7 GeV



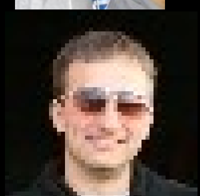
2009 Fermi Symposium: Latronico; Pesce-Rollins; Grasso

Igor Moskalenko (Stanford) :

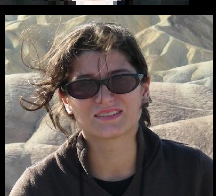
Troy Porter (UCSC):

Gulli Johannesson (Stanford):

Elena Orlando (MPE) :



Seth Digel (Stanford):



Andy Strong (MPE)