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Cosmic Ray Electrons and Positrons from Fermi Gamma-Ray Pulsars

“Focus on Indirect Dark Matter Searches”

IPMU – University of Tokyo

Kashiwa, December 11, 2009

1. (as per talk title) contribution to CR e+e- from Fermi gamma-ray pulsars

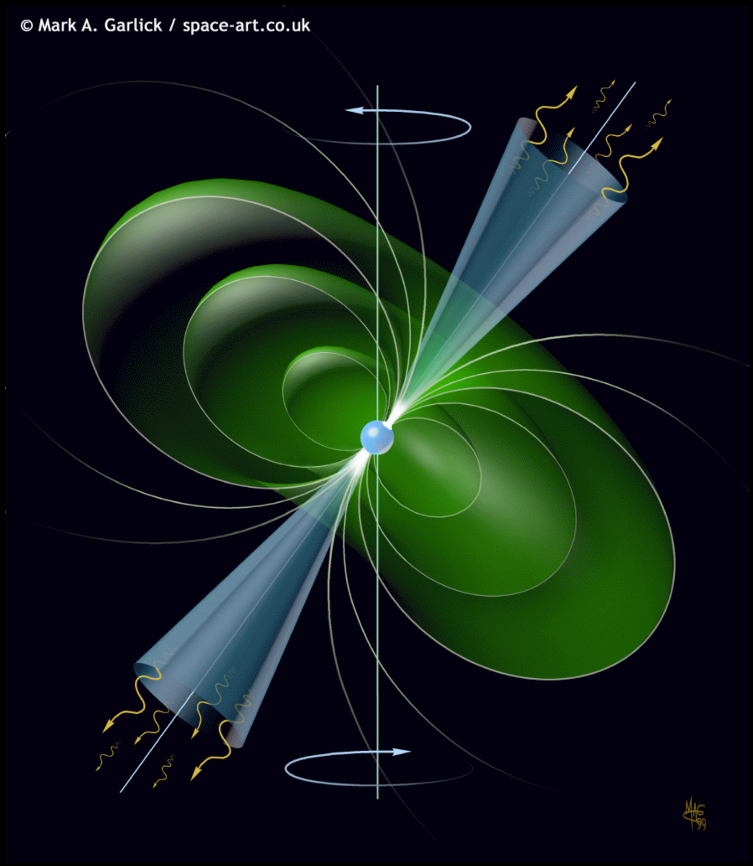
(work in collaboration with UC Santa Cruz undergrad Lev Gendelev and grad Michael Dormody)

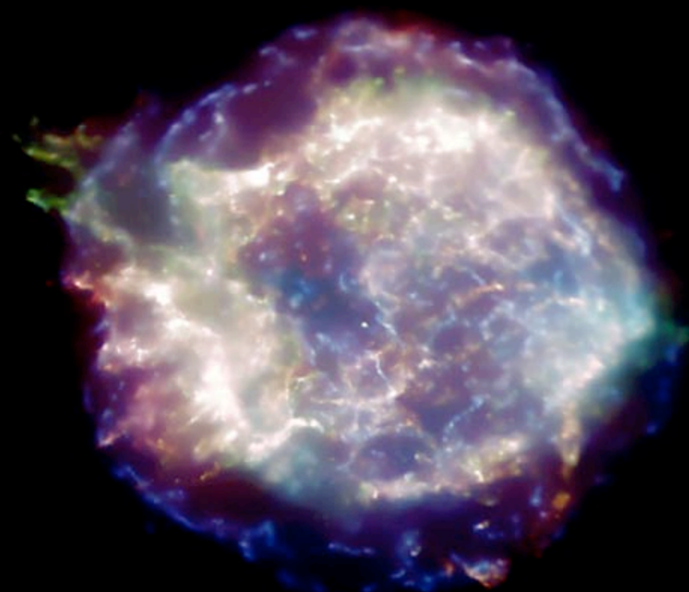
2. some thoughts about the " Fermi haze "

(work in collaboration with UC Santa Cruz grad Tim Linden)

• **Rotation-powered Pulsars can seed e+e- direct pair production**

*(strong rotationally induced **electric fields** in the magnetoshpere accelerate and extract **e-** from stellar surface, which radiate **gamma rays**; gammas cascade produce **e+e- pairs**, escaping the magnetosphere from the polar cap regions)*





• **SNR & PWN shock acceleration**

Propagation of charged species: diffusion equation

$$\frac{\partial f}{\partial t} = \frac{D(\gamma)}{r^2}\frac{\partial}{\partial r}r^2\frac{\partial f}{\partial r} + \frac{\partial (P(\gamma)\ f)}{\partial \gamma} + Q.$$

$f(r,t,\gamma)$ Distribution function

$\gamma = E_{e^\pm}/m_e$

$D(\gamma) \propto \gamma^\delta$

$$P(\gamma) = p_0 + p_1\gamma + p_2\gamma^2$$

0: Coulomb; 1: Brems; 2: IC & Synch

(*) Atoyan, Aharonian, Volk, 1995

Approximate solution to the electron/positron distribution function(*)

(only IC and Synch losses – burst-like injection)

$$f(r,t,\gamma) = \frac{N_0\gamma^{-\alpha}}{\pi^{3/2} r^3}(1 - p_2 t\gamma)^{\alpha-2}\left(\frac{r}{r_{\rm dif}}\right)^3 e^{-(r/r_{\rm dif})^2}$$

$$\gamma < \gamma_{\rm cut} \equiv \gamma_{\rm cut}(t) = (p_2 t)^{-1}$$

$$p_2 = 5.2\times10^{-20}\frac{w_0}{1\ {\rm eV/cm^3}}\ {\rm s^{-1}}$$

Cut-off in Energy → Pulsar Lifetime

$$r_{\rm dif}(\gamma,t) \simeq 2\sqrt{D(\gamma)t\frac{1-(1-\gamma/\gamma_{\rm cut})^{1-\delta}}{(1-\delta)\gamma/\gamma_{\rm cu}}}.$$

Cut-off in Space

(*) Atoyan, Aharonian, Volk, 1995

Main feature of high-energy (10-1000 GeV) e^+e^-:
they lose energy very efficiently

Energy losses ~ **E^2**, via synchrotron and inverse Compton

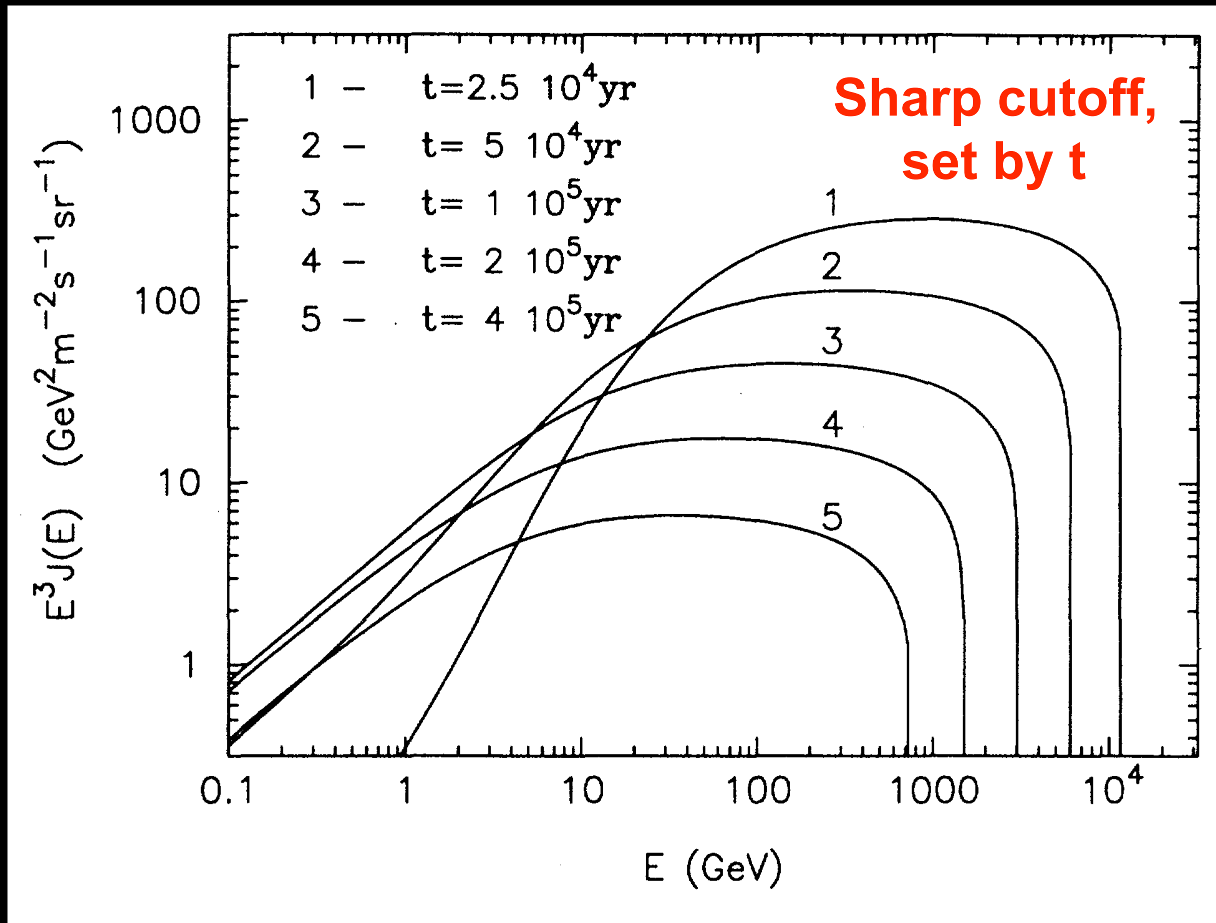
$$\frac{t_{\mathrm{Lifetime}}}{yr} \approx 5\times10^{5}\left(\frac{1\ \mathrm{TeV}}{E}\right)\left[\left(\frac{B}{5\ \mu\mathrm{G}}\right)^{2} + 1.6\times\left(\frac{w}{1\ \mathrm{eV/cm^{3}}}\right)\right]^{-1}$$

In conjunction with conventional diffusion models, this short radiative cooling time limits the sources of high energy electron/positron both in **space and time**

$$\mathrm{dist}_{\mathrm{max}} \approx \sqrt{D_0 \times t} \approx 100\ \text{-}\ 500\ \mathrm{pc} \quad \left[\mathrm{D}_0 \approx 10^{28}\,\mathrm{cm^2/s}\right]$$

Astrophysical sources relevant for energetic e+e- production must be **young** (~10^5 yr) and **nearby** (<kpc)

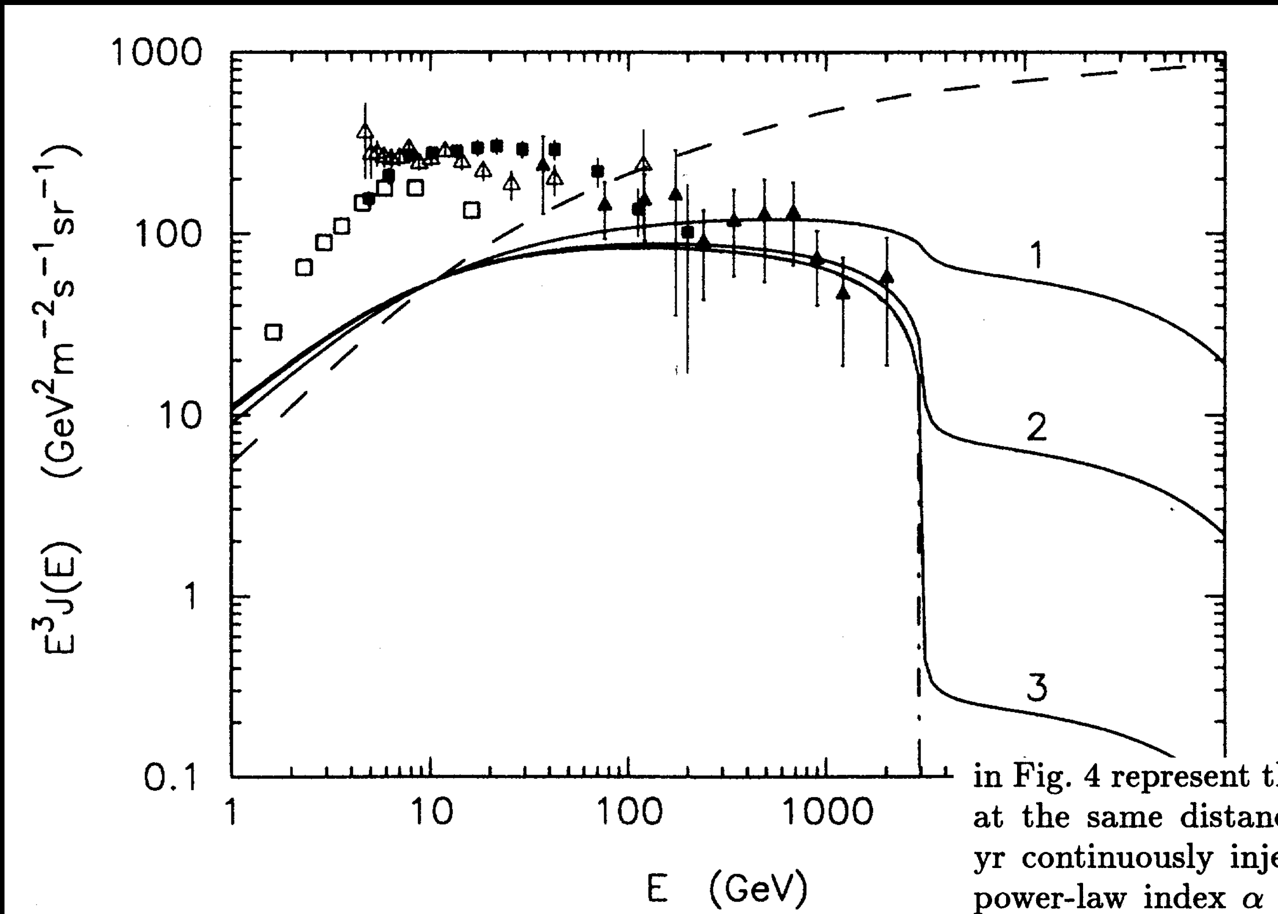
Example of a **burst**-like injection at different **times**,
r = 100 pc, injection power-law: 2.2



Distance sets normalization, and affects spectrum,
($s=r/r_{dif}$, and more distant, more peaked)

(*) Atoyan, Aharonian, Volk, 1995

The effects of a **non-burst-like** injection

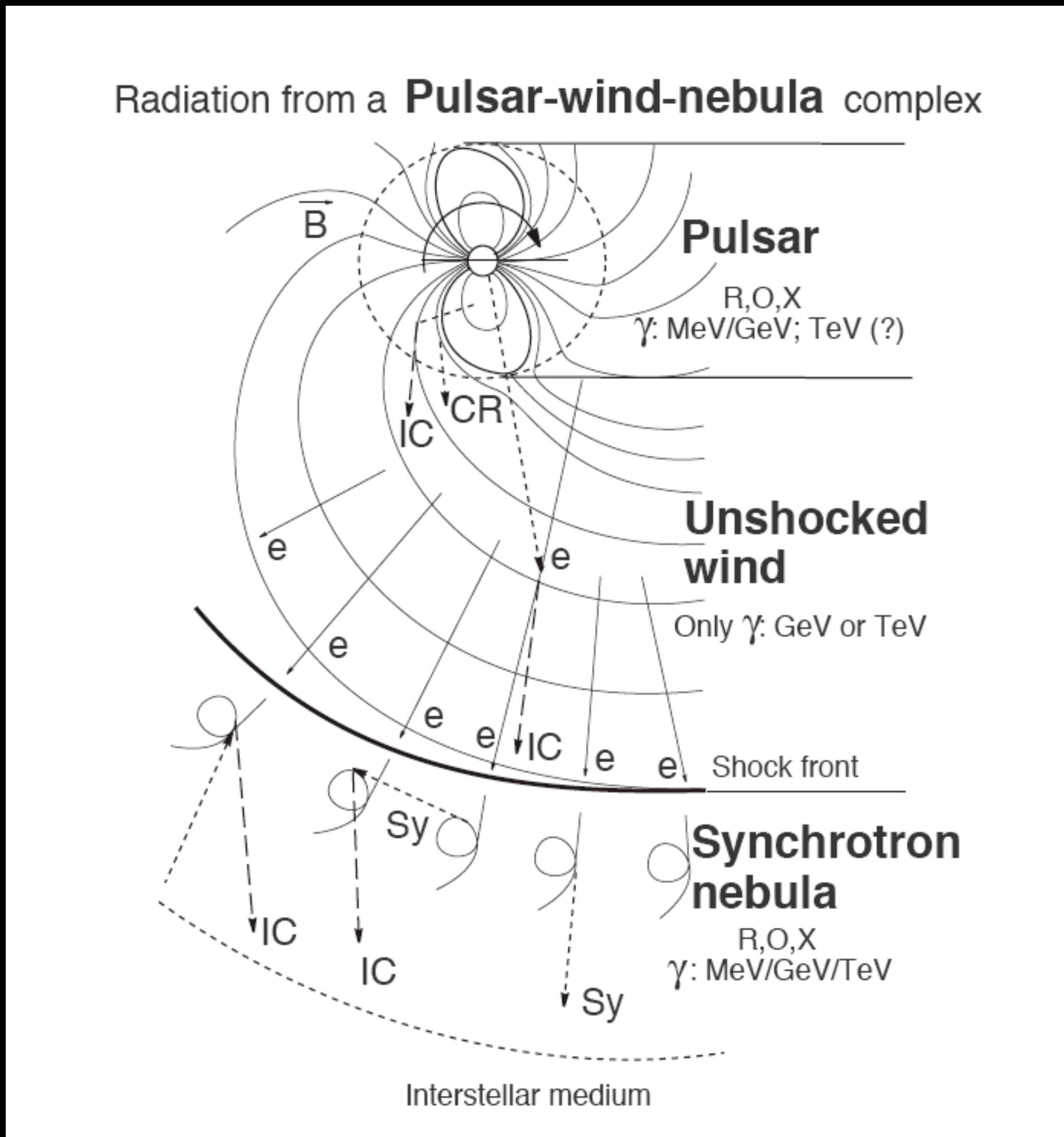


in Fig. 4 represent the fluxes of electrons from the source at the same distance $r = 100$ pc and of age $t = 10^5$ yr continuously injecting relativistic electrons with the power-law index $\alpha = 2.2$ into ISM, but with the total luminosity varying in time during $0 \leq \tau \leq t$ as

$$L_e(\tau) = \frac{L_0}{(1 + \tau/\tau_*)^k} \tag{24}$$

for three different values of the characteristic "decay" time τ_*: $\tau_*/t = 0.1$ (curve 1), $\tau_*/t = 0.01$ (curve 2), $\tau_*/t = 0.001$ (curve 3). This kind of time-dependent in-

(*) Atoyan, Aharonian, Volk, 1995



(*) Aharonian and Bogovalov, 2002

Electromagnetic
processes
and **emission**
in a pulsar
environment

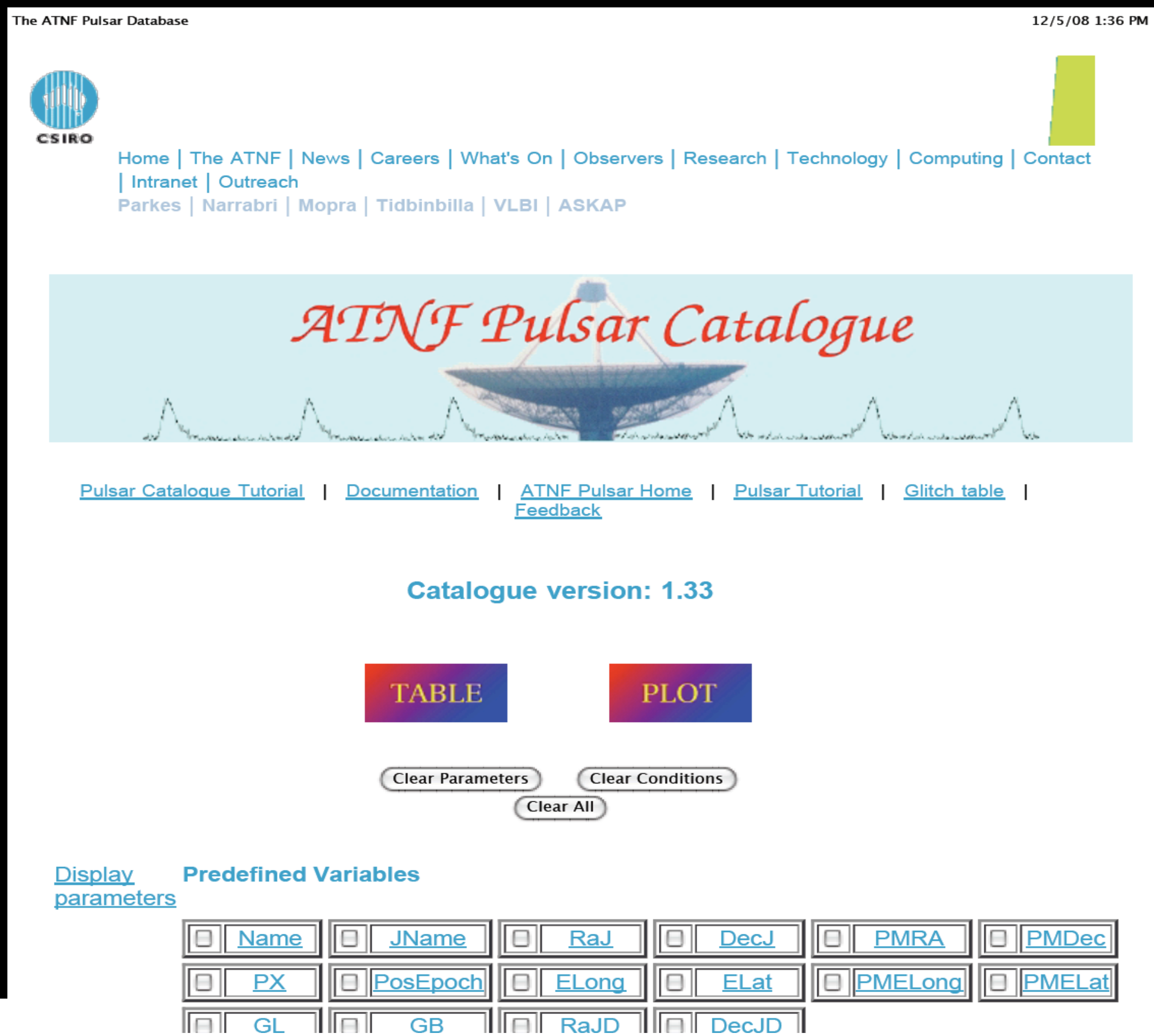
Multi-Wavelength
observations help:

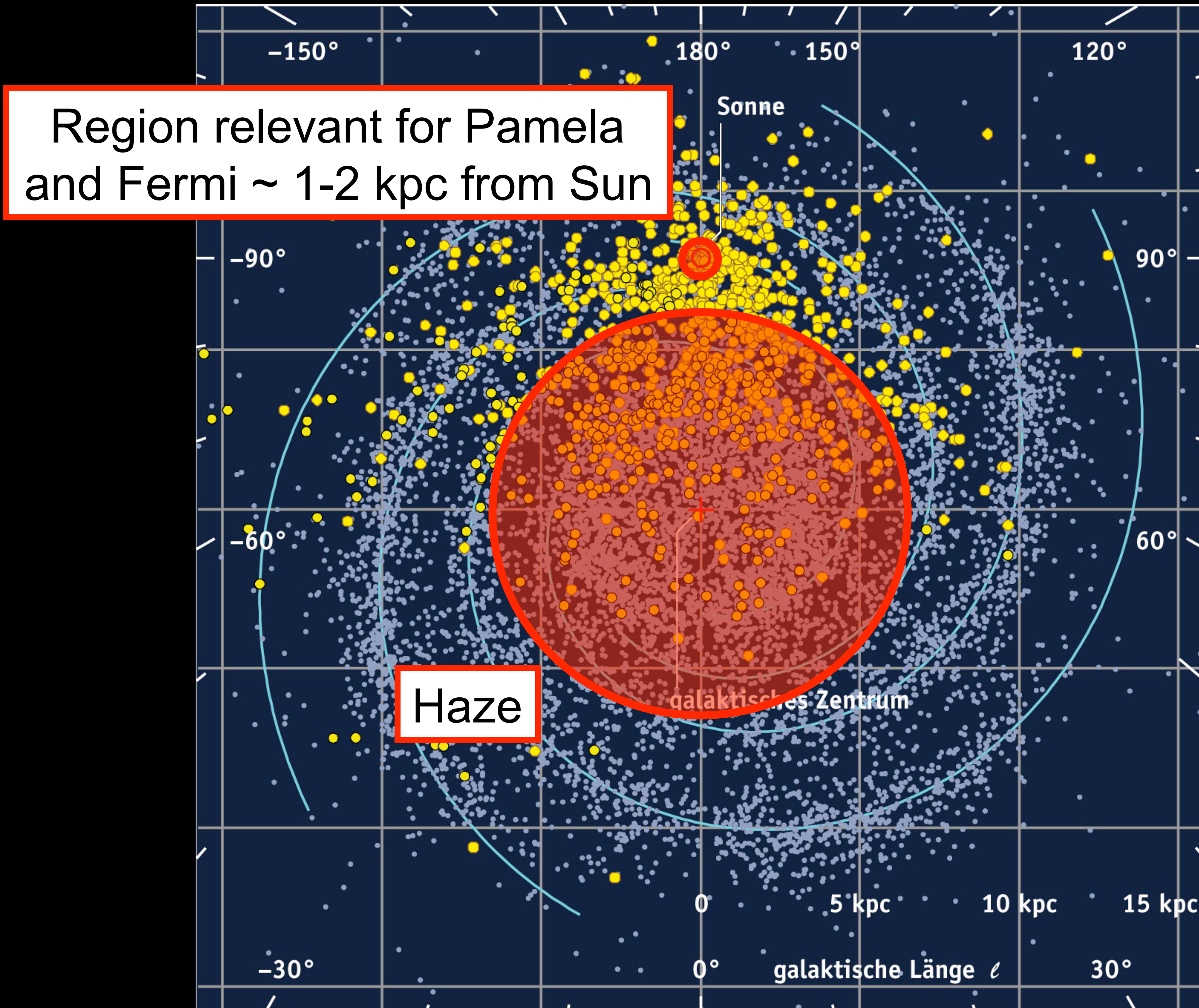
(i) set the scale of
the **total power**
in relativistic e+e-

(ii) understand the
e+e- **spectrum**

examples:
- HESS J1825-137
- Vela X (HESS)
- Geminga (Milagro)

An **asset** of the pulsar scenario: pulsars **exist**, detailed **catalogues**, very **accurate** data





Atlas of known (yellow) and predicted galactic radio pulsars

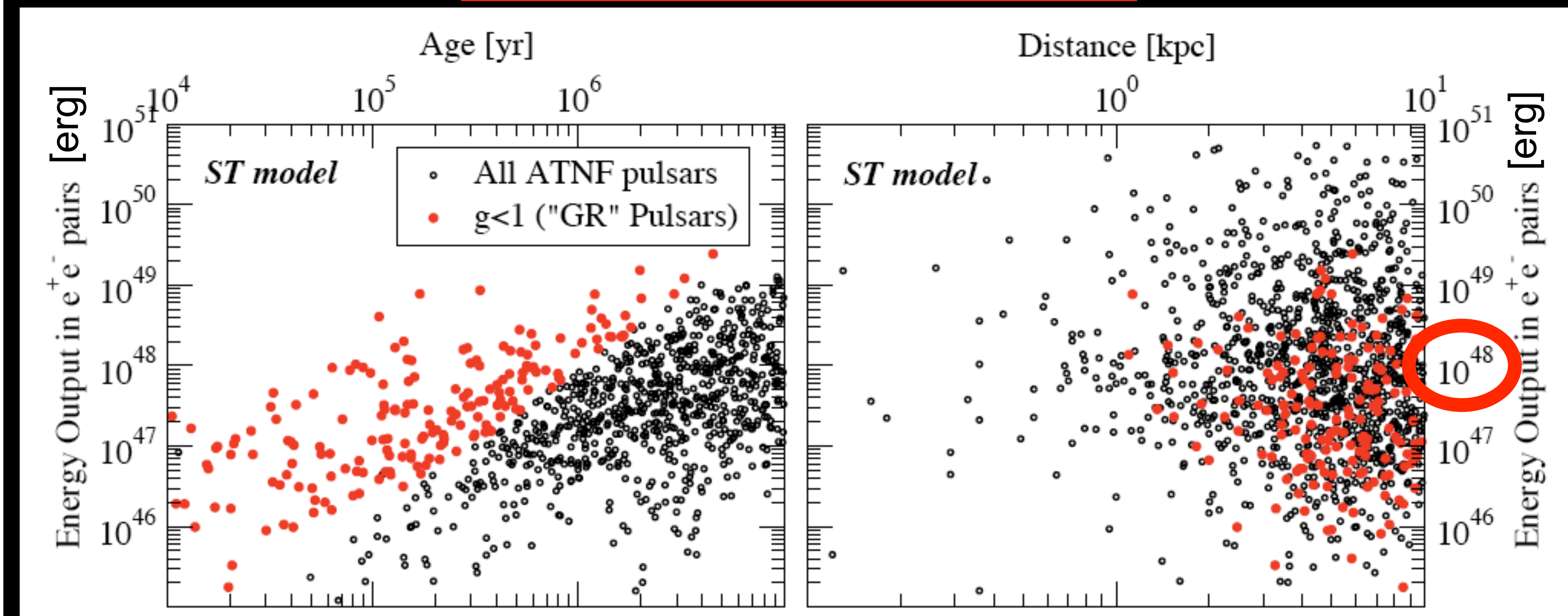
Not all pulsars are **gamma-ray** (and e+e-) pulsars

E.g., in the outer gap model, **pair** production sets in if

$$\boxed{E_x E_\gamma > m_e^2}$$

This condition depends on **magnetic field** intensity and period

$$\boxed{g = 5.5\, P^{26/21}\, B_{12}^{-4/7} < 1.}$$



Profumo, 0812.4457

Role of **Fermi** to assess the **origin** of high-energy **CRE**:

1. Accurate CRE **Spectral Information** (probably not conclusive by itself)

2. **Local** CRE **source** ? → Compare the **Inverse Compton** and **Bremss**. emis. predicted from the measured CRE spectrum with diffuse **gamma-ray data**

3. **Anisotropy**: search for excess CRE from bright nearby **pulsars**
   (problem: pulsar proper motion !!
   also ongoing: East-West asymmetry search !!)

4. Discovery and improved understanding of **gamma-ray pulsars**, guaranteed sources of e+e-

The Fermi First **Pulsar Catalogue**

- Includes high-confidence (>) pulsed sources in the first **6-months** of data

- **16 gamma-ray selected** (majority from blind-search campaign)

- **24 radio-selected** (via ephermerides, and of which 8 millisecond)

- **6 pre-Fermi GR pulsars**

The First Fermi Large Area Telescope Catalog of Gamma-ray Pulsars

A. A. Abdo[2,3], M. Ackermann[4], M. Ajello[4], W. B. Atwood[5], M. Axelsson[6,7], L. Baldini[8], J. Ballet[9], G. Barbiellini[10,11], M. G. Baring[12], D. Bastieri[13,14], B. M. Baughman[15], K. Bechtol[4], R. Bellazzini[8], B. Berenji[4], R. D. Blandford[4], E. D. Bloom[4], E. Bonamente[16,17], A. W. Borgland[4], J. Bregeon[8], A. Brez[8], M. Brigida[18,19], P. Bruel[20], T. H. Burnett[21], S. Buson[14], G. A. Caliandro[18,19,1], R. A. Cameron[4], F. Camilo[22], P. A. Caraveo[23], J. M. Casandjian[9], C. Cecchi[16,17], Ö. Çelik[24,25,26], E. Charles[4], A. Chekhtman[2,27], C. C. Cheung[24], J. Chiang[4], S. Ciprini[16,17], R. Claus[4], I. Cognard[28], J. Cohen-Tanugi[29], L. R. Cominsky[30], J. Conrad[31,7,32], R. Corbet[24,26], S. Cutini[33], P. R. den Hartog[4], C. D. Dermer[2], A. de Angelis[34], A. de Luca[23,35], F. de Palma[18,19], S. W. Digel[4], M. Dormody[5], E. do Couto e Silva[4], P. S. Drell[4], R. Dubois[4], D. Dumora[36,37], C. Espinoza[38], C. Farnier[29], C. Favuzzi[18,19], S. J. Fegan[20], E. C. Ferrara[24,1], W. B. Focke[4], P. Fortin[20], M. Frailis[34], P. C. C. Freire[39], Y. Fukazawa[40], S. Funk[4], P. Fusco[18,19], F. Gargano[19], D. Gasparrini[33], N. Gehrels[24,41], S. Germani[16,17], G. Giavitto[42], B. Giebels[20], N. Giglietto[18,19], P. Giommi[33], F. Giordano[18,19], T. Glanzman[4], G. Godfrey[4], E. V. Gotthelf[22], I. A. Grenier[9], M.-H. Grondin[36,37], J. E. Grove[2], L. Guillemot[36,37], S. Guiriec[43], C. Gwon[2], Y. Hanabata[40], A. K. Harding[24], M. Hayashida[4], E. Hays[24], R. E. Hughes[15], M. S. Jackson[31,7,44], G. Jóhannesson[4], A. S. Johnson[4], R. P. Johnson[5], T. J. Johnson[24,41], W. N. Johnson[2], S. Johnston[45], T. Kamae[4], G. Kanbach[46], V. M. Kaspi[47], H. Katagiri[40], J. Kataoka[48,49], N. Kawai[48,50], M. Kerr[21], J. Knödlseder[51], M. L. Kocian[4], M. Kramer[38,52], M. Kuss[8], J. Lande[4], L. Latronico[8], M. Lemoine-Goumard[36,37], M. Livingstone[47], F. Longo[10,11], F. Loparco[18,19], B. Lott[36,37], M. N. Lovellette[2], P. Lubrano[16,17], A. G. Lyne[38], G. M. Madejski[4], A. Makeev[2,27], R. N. Manchester[45], M. Marelli[23], M. N. Mazziotta[19], W. McConville[24,41], J. E. McEnery[24], S. McGlynn[44,7], C. Meurer[31,7], P. F. Michelson[4], T. Mineo[53], W. Mitthumsiri[4], T. Mizuno[40], A. A. Moiseev[25,41], C. Monte[18,19], M. E. Monzani[4], A. Morselli[54], I. V. Moskalenko[4], S. Murgia[4], T. Nakamori[48], P. L. Nolan[4], J. P. Norris[55], A. Noutsos[38], E. Nuss[29], T. Ohsugi[40], N. Omodei[8], E. Orlando[46], J. F. Ormes[55], M. Ozaki[56], D. Paneque[4], J. H. Panetta[4], D. Parent[36,37,1], V. Pelassa[29], M. Pepe[16,17], M. Pesce-Rollins[8], F. Piron[29], T. A. Porter[5], S. Rainò[18,19], R. Rando[13,14], S. M. Ransom[57], P. S. Ray[2], M. Razzano[8], N. Rea[58,59], A. Reimer[60,4],

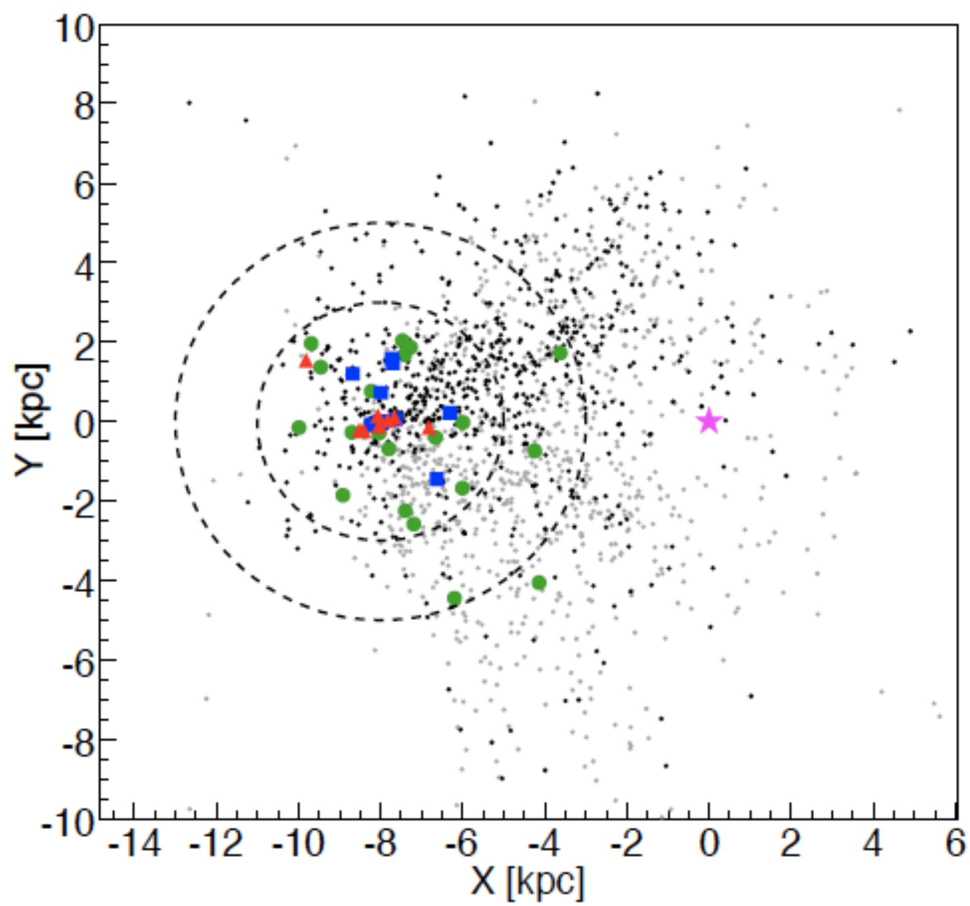


Fig. 3.— Galactic plane pulsar distribution (polar view). The star represents the Galactic center. The two circles centered at the Earth's position have radii of 3 kpc and 5 kpc. For pulsars with different possible distances, the nearer values from Table 5 are used. Note that the millisecond pulsars (MSPs), while having a significantly lower $\dot{E}$ than the other pulsars (see Figure 8), are detectable due to their close proximity. The one exception (PSR J0218+4232) also exhibits a significantly higher $\dot{E}$ than the other MSPs. Blue squares: gamma-ray-selected pulsars. Red triangles: millisecond gamma-ray pulsars. Green circles: all other radio loud gamma-ray pulsars. Black dots: Pulsars for which gamma-ray pulsation searches were conducted using rotational ephemerides. Gray dots: Known pulsars which were not searched for pulsations.

Galactic Center

Gamma-Ray sel

Millisecond P

Other radio-loud

The Issue of **naming** new Pulsars

Fermi-LAT Pulsar **Blind search**

at UC Santa Cruz

(including the "**slug**" pulsar)

1. **Distance** estimates from gamma-ray data
2. Simple + universal PSR **emission** model
3. Estimate of **contribution** to local e+e- flux

The Contribution of Fermi Gamma-Ray Pulsars to the local Flux of Cosmic-Ray Electrons and Positrons

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Abstract. We analyze the contribution of gamma-ray pulsars from the first Fermi-Large Area Telescope (LAT) catalogue to the local flux of electrons and positrons (e^+e^-). We present new distance estimates for all Fermi gamma-ray pulsars, based

Main results:

- gamma-ray pulsar contribution can be **substantial** from **10** of the brightest Fermi pulsars
- **6/10** are blind-search **gamma-ray selected** pulsars
- outline of regions where **radio-pulsars** might contribute without a gamma-ray signal

$$L_\gamma \approx w\dot{E} \approx C \times \left(\frac{\dot{E}}{10^{33}\ \mathrm{ergs}^{-1}}\right)^{1/2} \times 10^{33}\ \mathrm{ergs}^{-1},$$

w : Gamma-Ray **conversion efficiency**

C : constant of O(1) – **fitted** with PSR subset with solid distance determinations

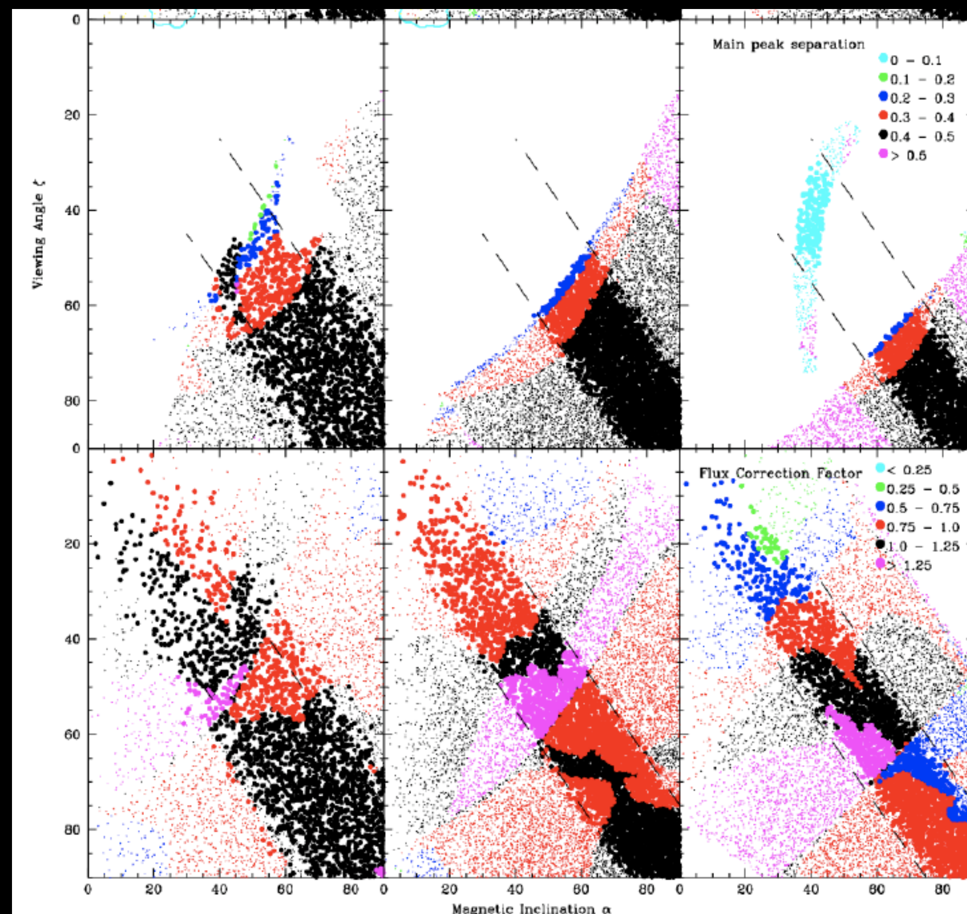
$$L_\gamma = 4\pi f_\Omega D^2 F_\gamma,$$

f_Ω: flux correction factor –

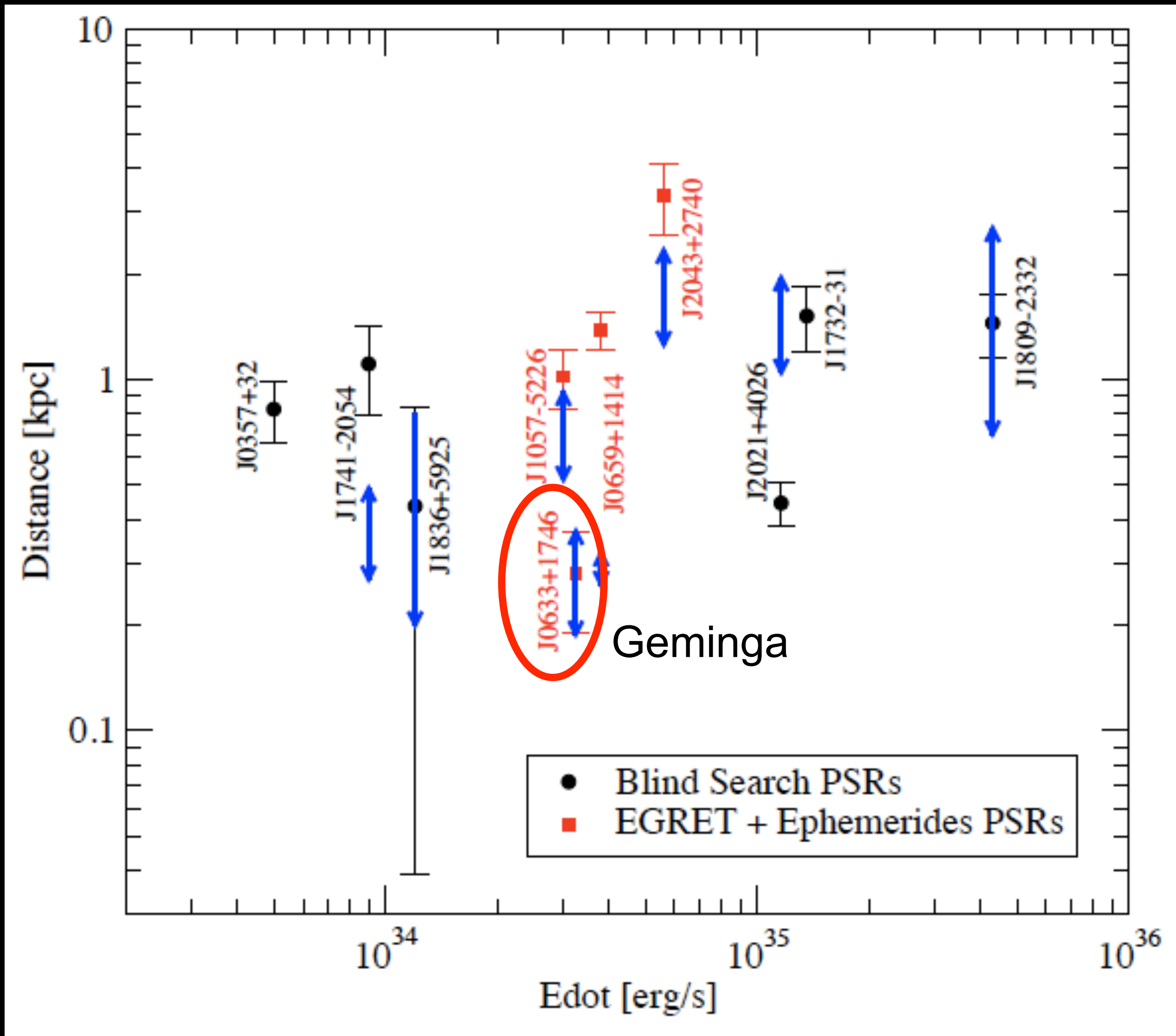
from Watters et al "**Atlas**"

$$f_\Omega = f_\Omega(\alpha, \zeta_E) = \frac{\iint F_\gamma(\alpha,\zeta,\phi)\sin(\zeta)\mathrm{d}\zeta\mathrm{d}\phi}{2\int F_\gamma(\alpha,\zeta_E,\phi)\mathrm{d}\phi}.$$

plus: standard error propagation



Distance Determinations: Results



Contribution to the local e+e- Flux

$$Q(E,t,\vec{r}) = Q_0 \left(\frac{E}{1\ \mathrm{GeV}}\right)^{-\Gamma} \exp[-E/E_{\mathrm{cut}}]\delta(t-t_0)\delta(\vec{r})$$

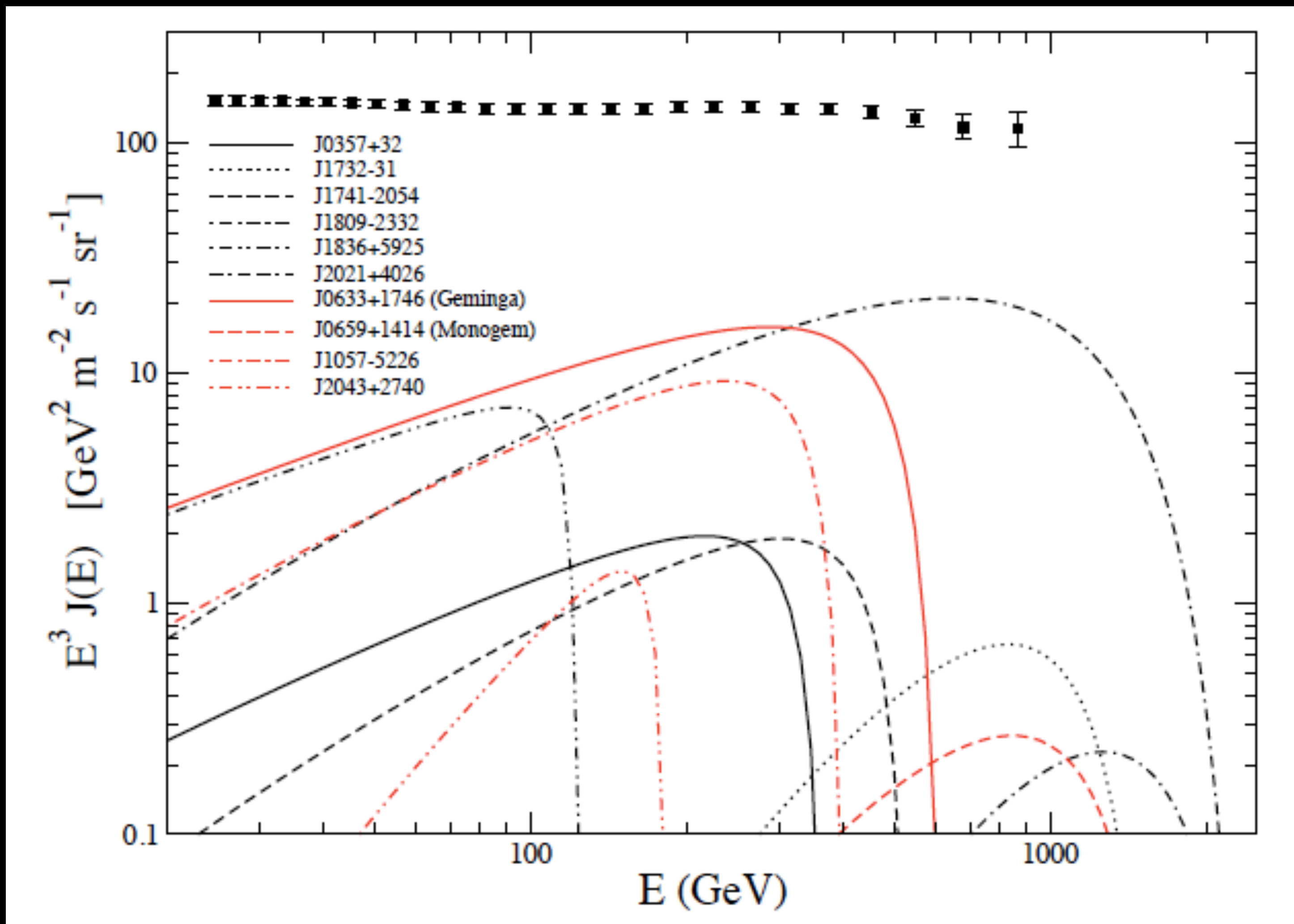
$E_{\mathrm{cut}} = 1\ \mathrm{TeV}$, $\Gamma = 1.7.$

$$\int_{m_e}^{\infty} Q(E)\mathrm{d}E = E_{\mathrm{out}} = \eta \frac{\dot{E}t_{\mathrm{ch}}^2}{\tau}, \quad \text{with } \tau \simeq 10^4 \text{ yr and } \eta = 0.4.$$

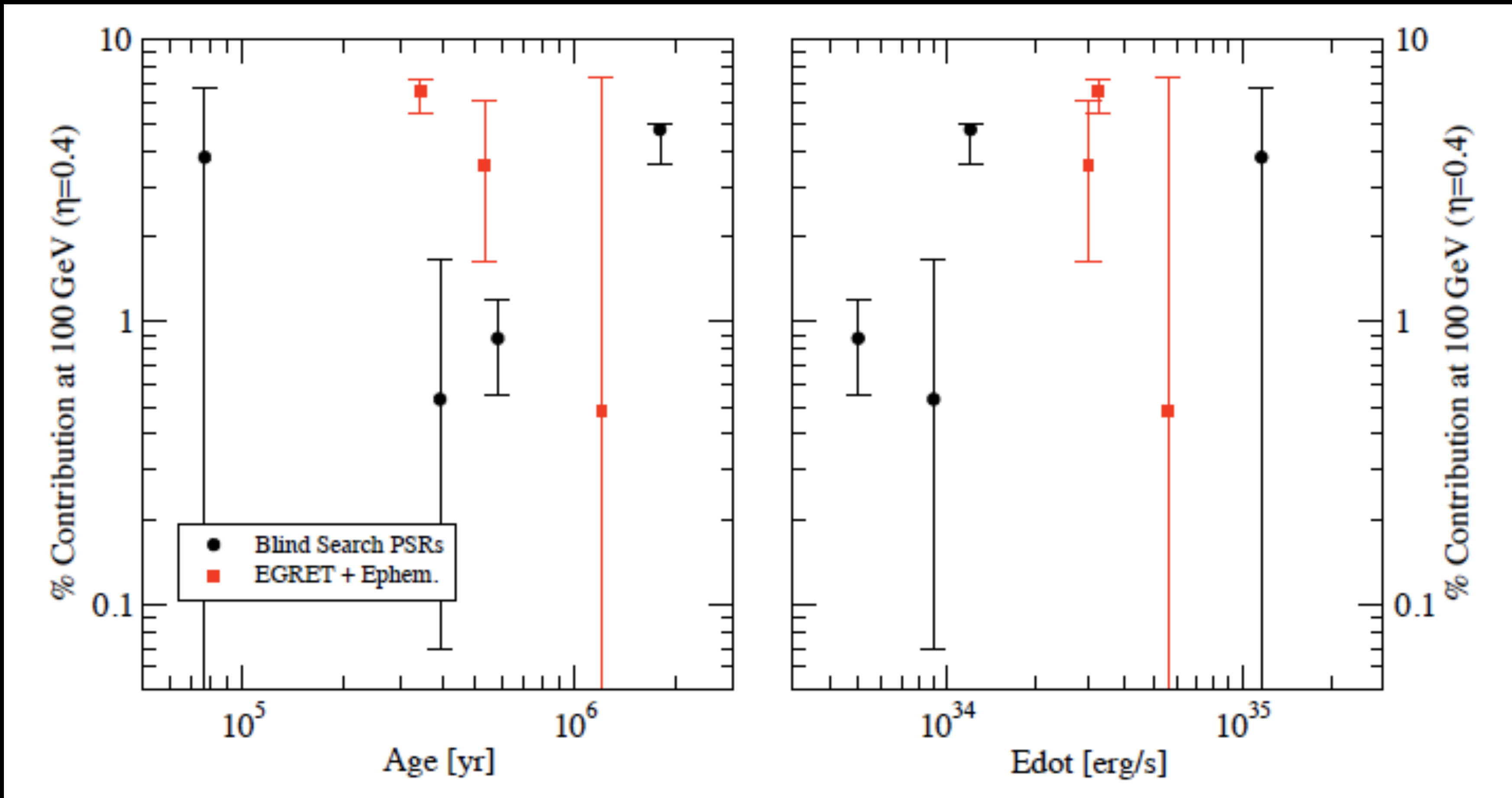
$$\frac{\partial N_e(E,t,\vec{r})}{\partial t} - D(E)\nabla^2 N_e - \frac{\partial}{\partial E}(b(E)N_e) = Q(E,t,\vec{r}),$$

$D(E) = D_0(E/1\ \mathrm{GeV})^{\delta}$ $\quad$ $D_0 = 3.6 \times 10^{28}\ \mathrm{cm}^2/s$ and $\delta = 0.33$

Contribution to the local e+e- Flux

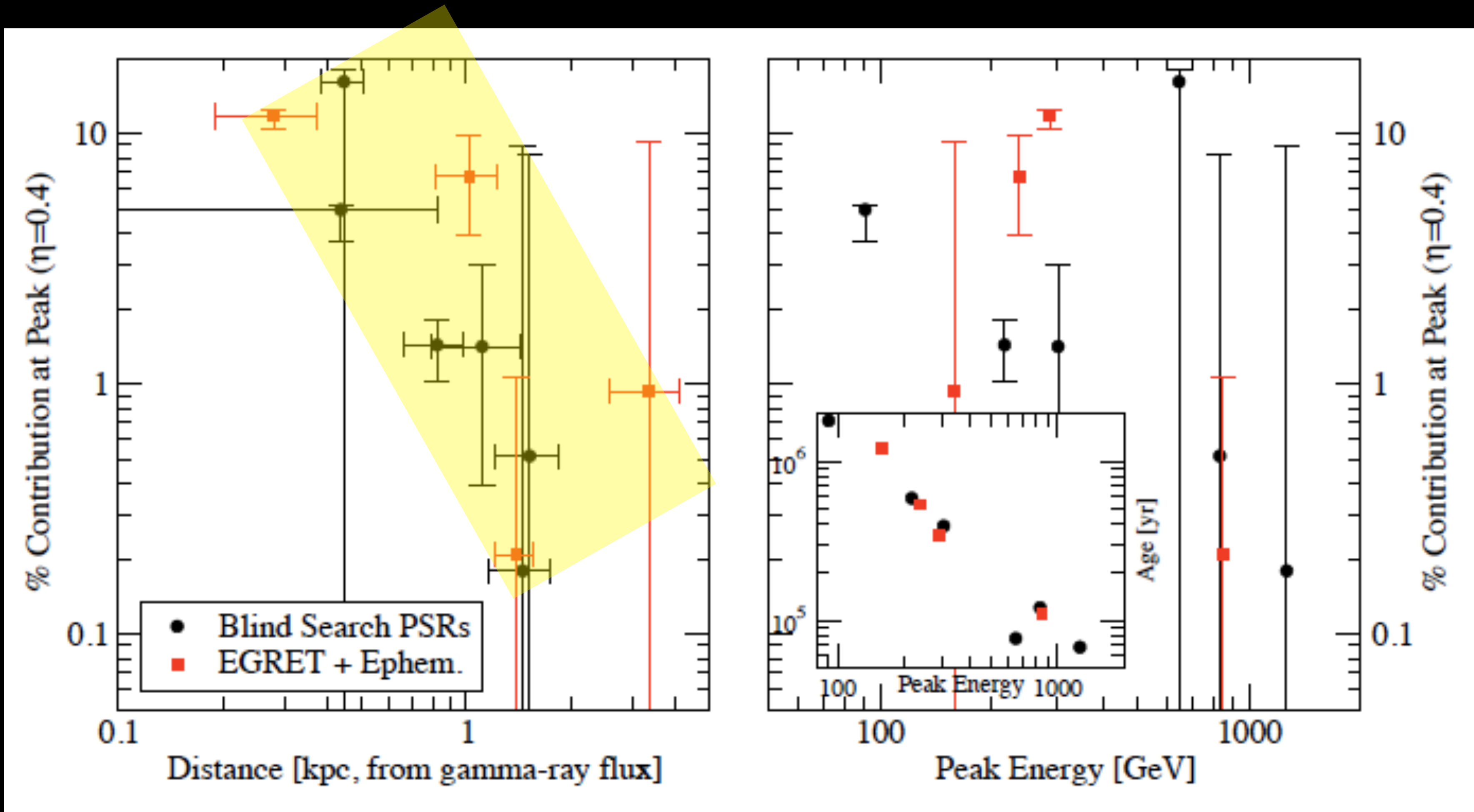


Contribution to the local e+e- Flux – a closer look (1)



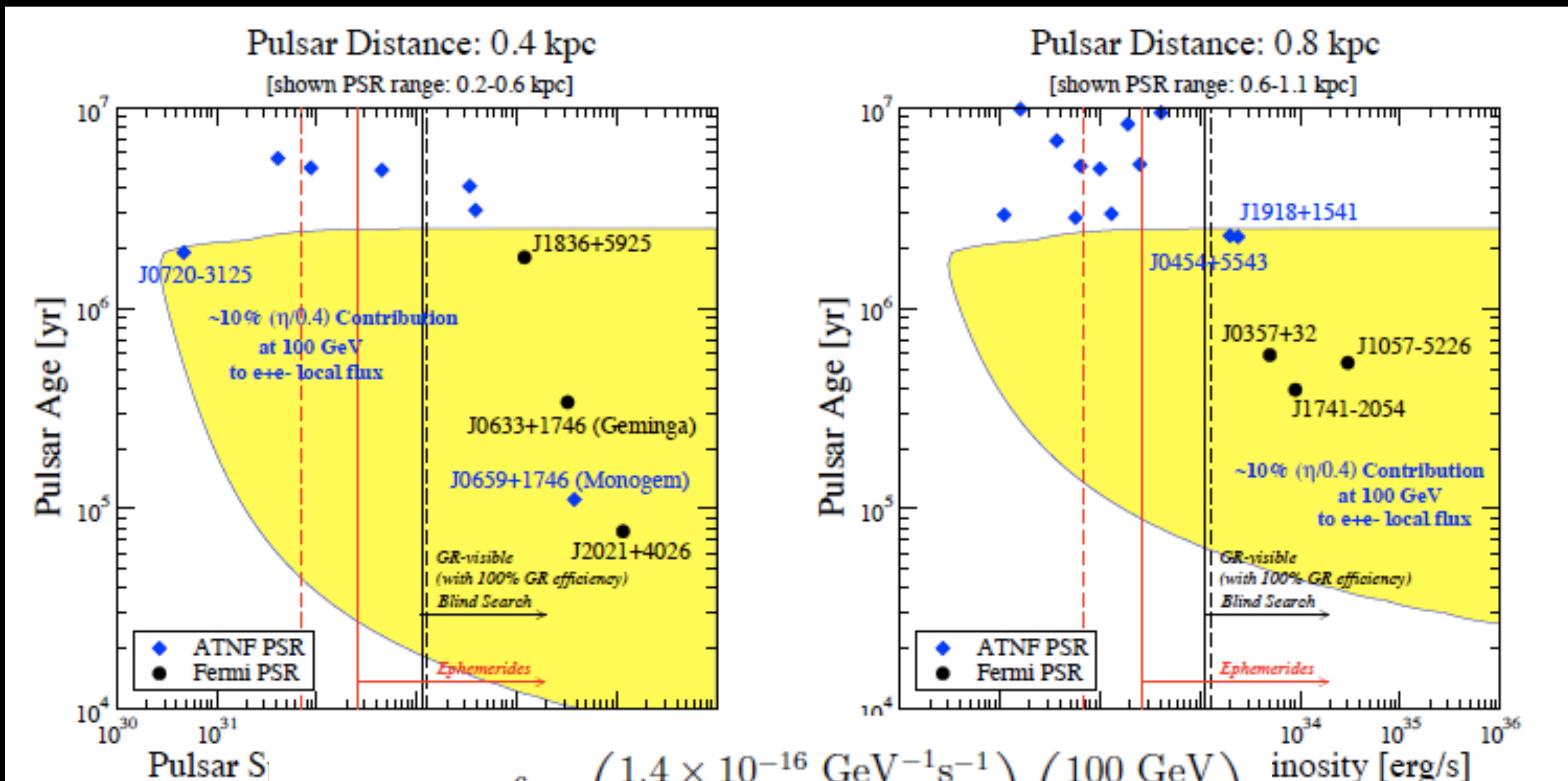
- Rather narrow **age** and **spin-down luminosity** ranges
- **flat contribution** over those ranges

Contribution to the local e+e- Flux – a closer look (2)



- Steeply **declining** contribution **with distance**
- Largest contributions between **100 and 1000 GeV**

Do we expect known **radio pulsar** (~1,500) to be still more important than ~50 **gamma-ray pulsars**?

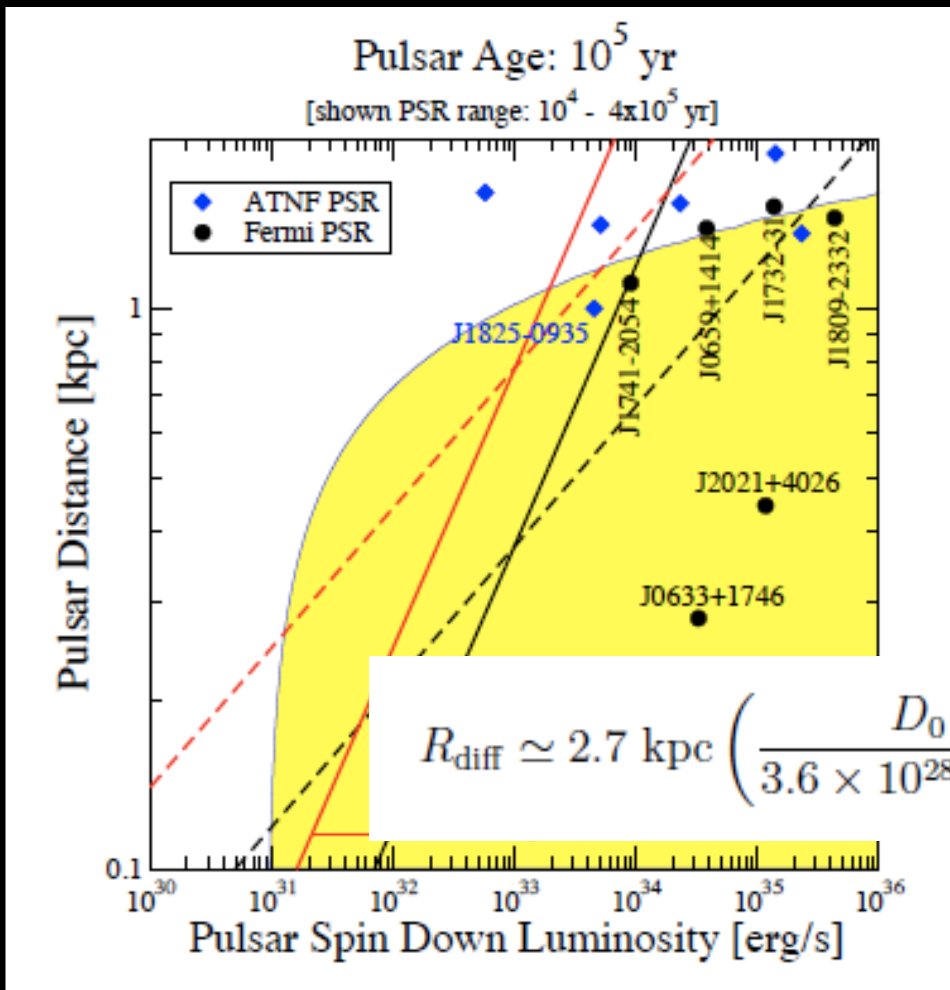


$$t \lesssim 2.3 \times 10^6 \text{ yr} \left(\frac{1.4 \times 10^{-16} \text{ GeV}^{-1}\text{s}^{-1}}{b_0}\right)\left(\frac{100 \text{ GeV}}{E}\right),$$

$$R_{\rm diff} \simeq 0.5 \text{ kpc} \left(\frac{D_0}{3.6 \times 10^{28}\text{cm}^2/\text{s}} \frac{t}{10^5 \text{ yr}}\right)^{1/2} \left(\frac{100 \text{ GeV}}{E}\right)^{\delta/2},$$

$$E \ll E_{\rm max} = (b_0 t)^{-1},$$

Do we expect known **radio pulsar** (~1,500) to be still more important than ~50 **gamma-ray pulsars**?



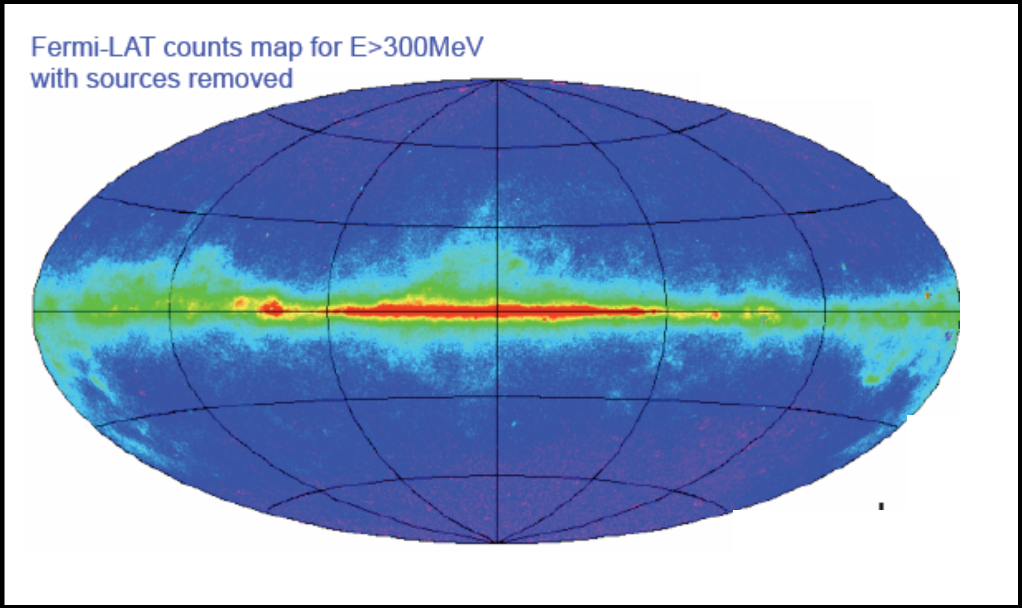
There is parameter space where gamma-ray quiet pulsars could significantly contribute!

$$E/E_{\max} \simeq 1.$$

$$R_{\rm diff} \simeq 2.7\ {\rm kpc} \left(\frac{D_0}{3.6\times10^{28}{\rm cm}^2/{\rm s}}\frac{1.4\times10^{-16}\ {\rm s}}{b_0}\right)^{1/2}\left(\frac{100\ {\rm GeV}}{E}\right)^{1-\delta}.$$

$$N_e \propto \exp[-(r/R_{\rm diff})^2]$$

Some thoughts about the "**Fermi haze**"



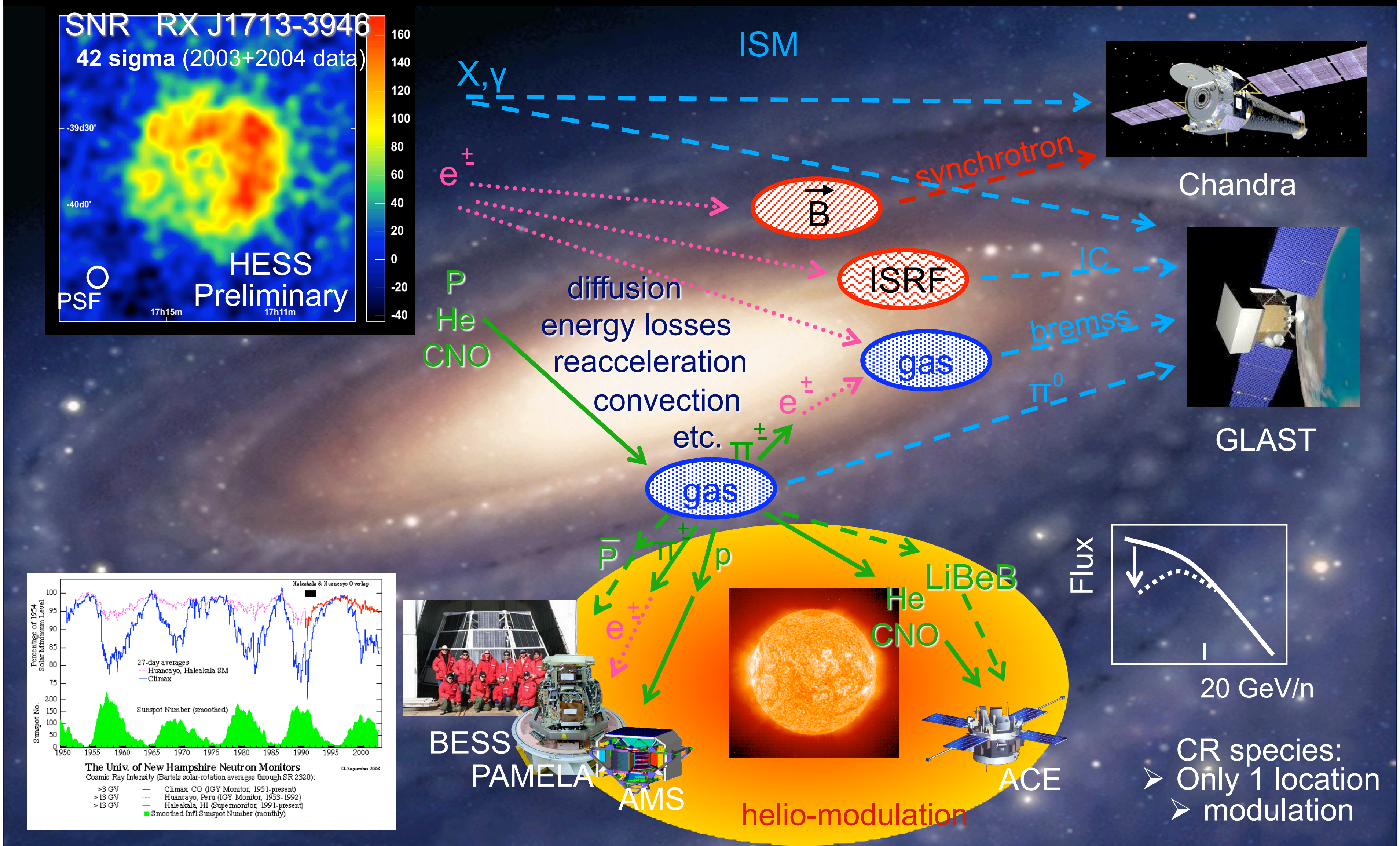
Three main contributions to the **diffuse** gamma-ray **emission**:

- **Galactic** emission
  - Neutral Pions – inelastic hadronic cosmic-ray processes
  - e+e- Radiative Losses: Inverse Compton & Bremsstrahlung

- **Isotropic** emission (extra-galactic + cosmic ray mis-ID)

(*) J-M Casandjian, Fermi Symposium 2009

The standard **full-glory** approach



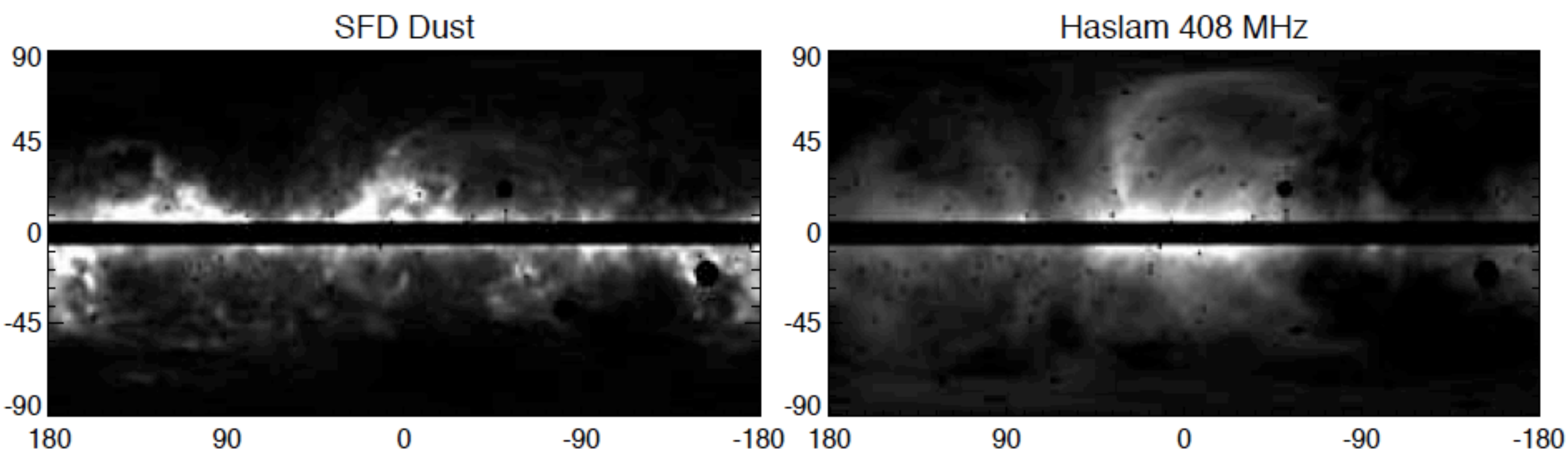
[slide from Igor Moskalenko]

Is there an **excess** gamma-ray diffuse **emission**?

Relevant for: e+e- responsible for the haze, DM annihilation

Dobler et al: simple diagnostic:

fit **spatial templates** to Fermi gamma-ray sky



Dust (far IR 100 μ emission)

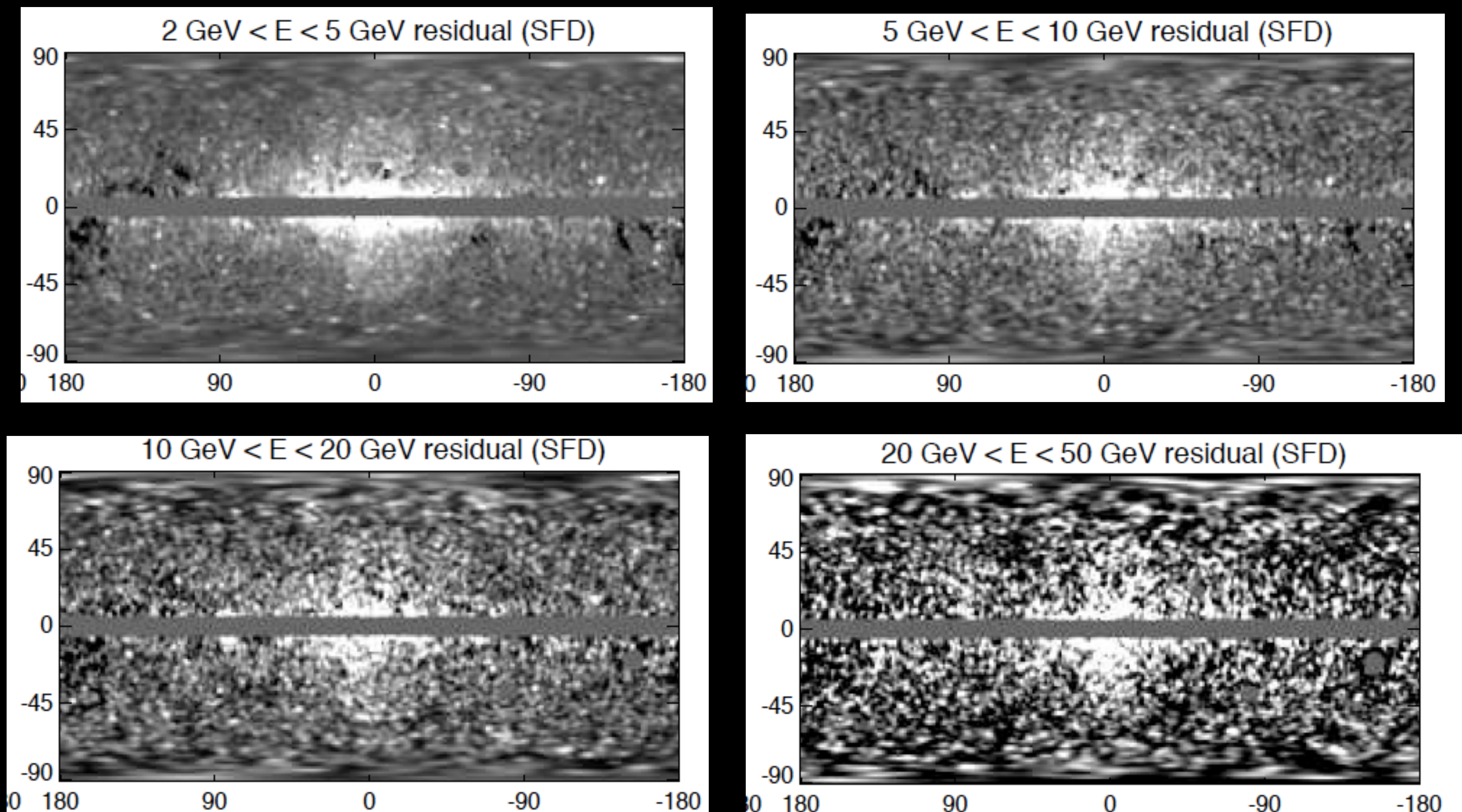
=> ISM Gas => π^0 (no CR sources!)

Synchrotron emission map

=> **IC** emission (same e+e-, but…)

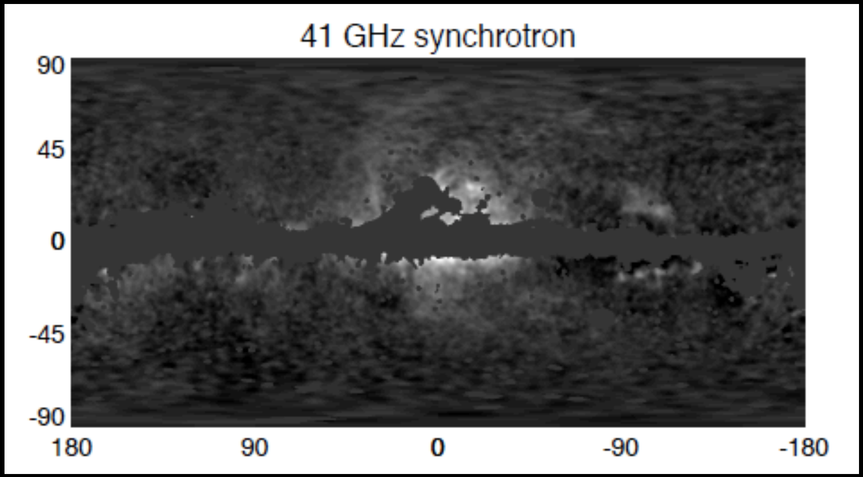
(*) Dobler et al, 0910.4583

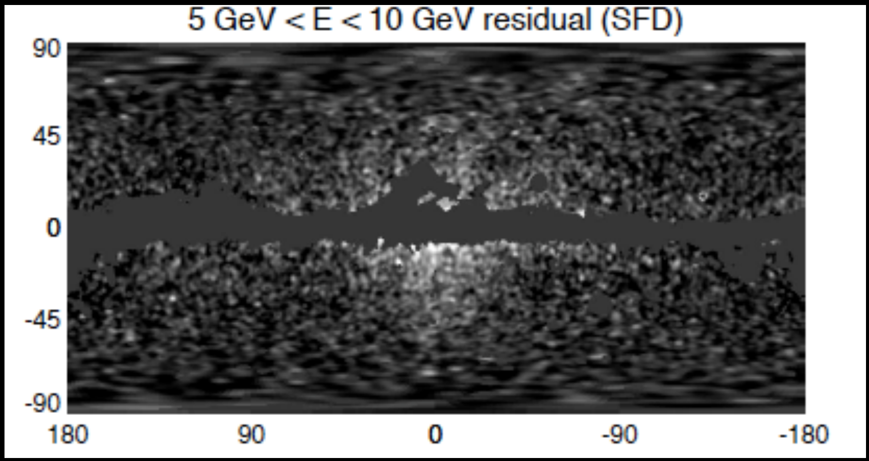
Large **residuals** in a region morphologically comparable to the microwave **WMAP haze** excess



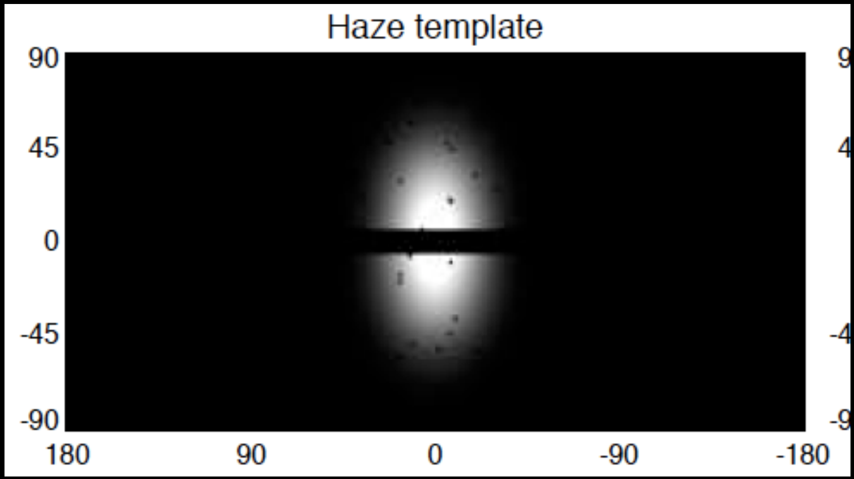
(*) Dobler et al, 0910.4583

The resulting “Fermi haze” has an intriguing **morphology**





Try to fit with a **bi-variate gaussian** additional diffuse component (expected from e.g. e+e- producing WMAP haze, or DM secondaries)



(*) Dobler et al, 0910.4583

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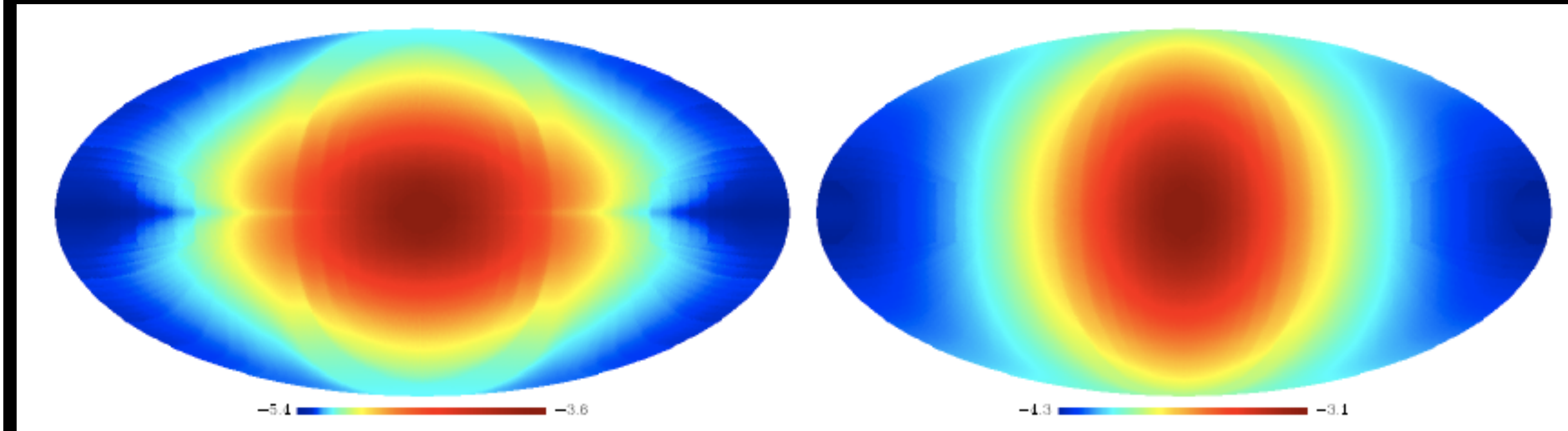

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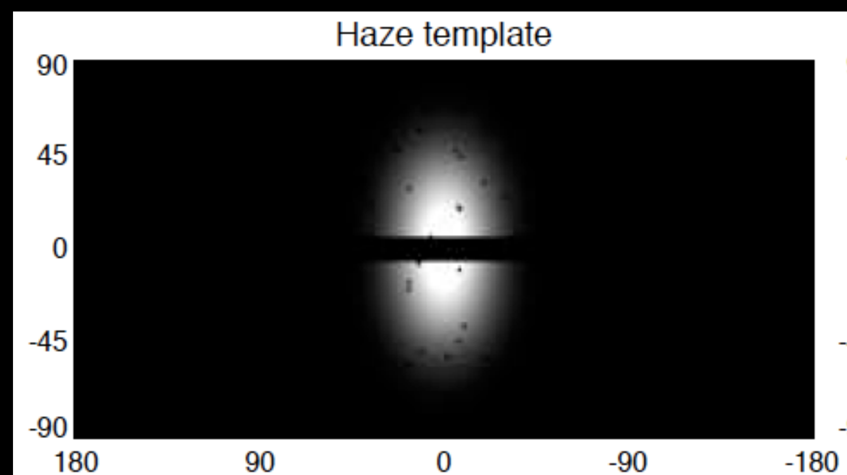
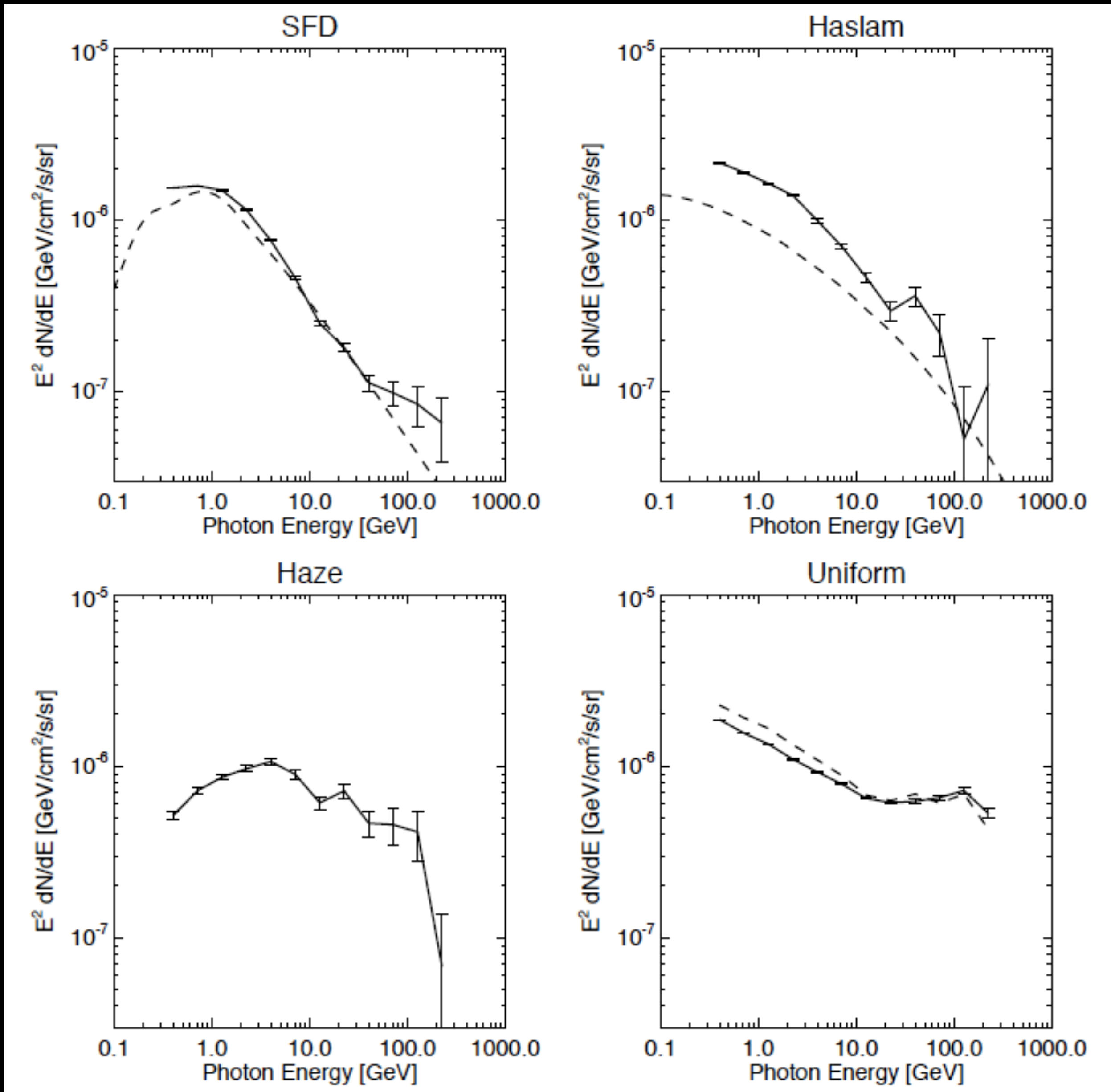


(*) Dobler et al, 0910.4583



Residuals are now at a “noise” level – **satisfactory fit**!

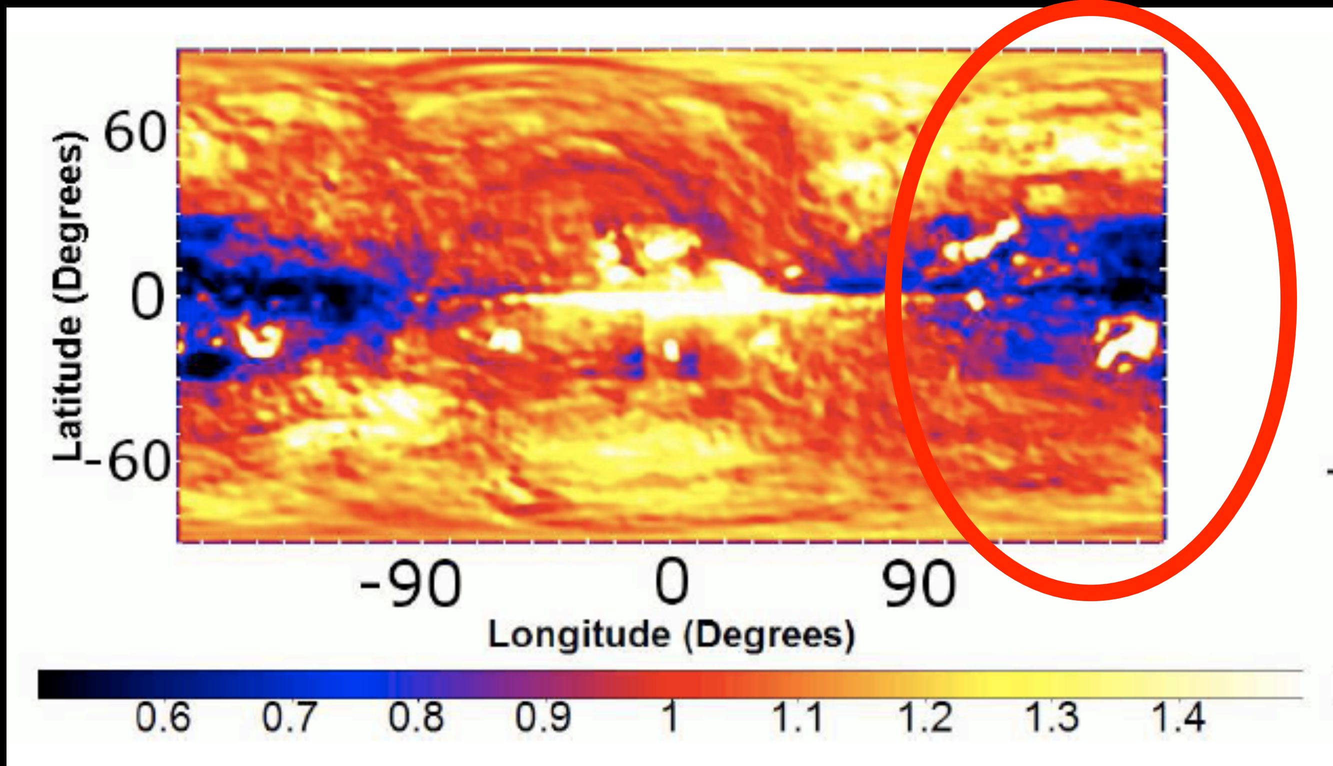
Proceed to use the relative normalization to calculate **spectra**

(*) Dobler et al, 0910.4583

Are **spatial templates** accurate enough to claim a Fermi haze?

Test quantitatively by employing the predictions of the full-glory approach

First template - **First assumption**: gas (dust) traces π^0's



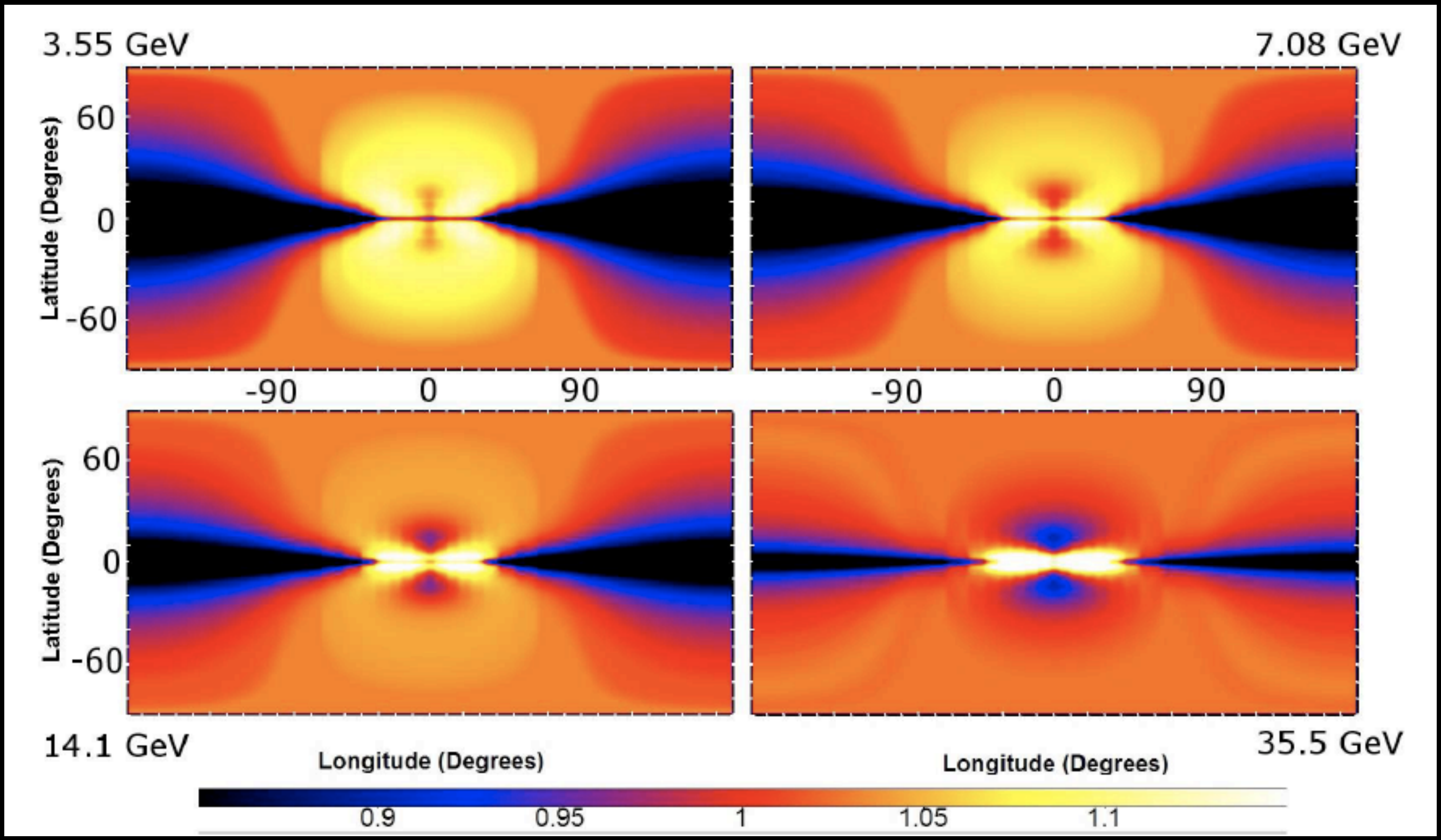
Regions used to **normalize**

Map (norm. to 1) of ratio of π^0's to **ISM** col. dens.

Issue: **cosmic rays sources** live in the haze region!

Second Template - **Second Assumption**: Synchrotron traces IC

Issue: while both are sourced by e+e-, the emissions follow the magnetic field and inter-stellar radiation field energy densities with potentially very **different morphologies**!

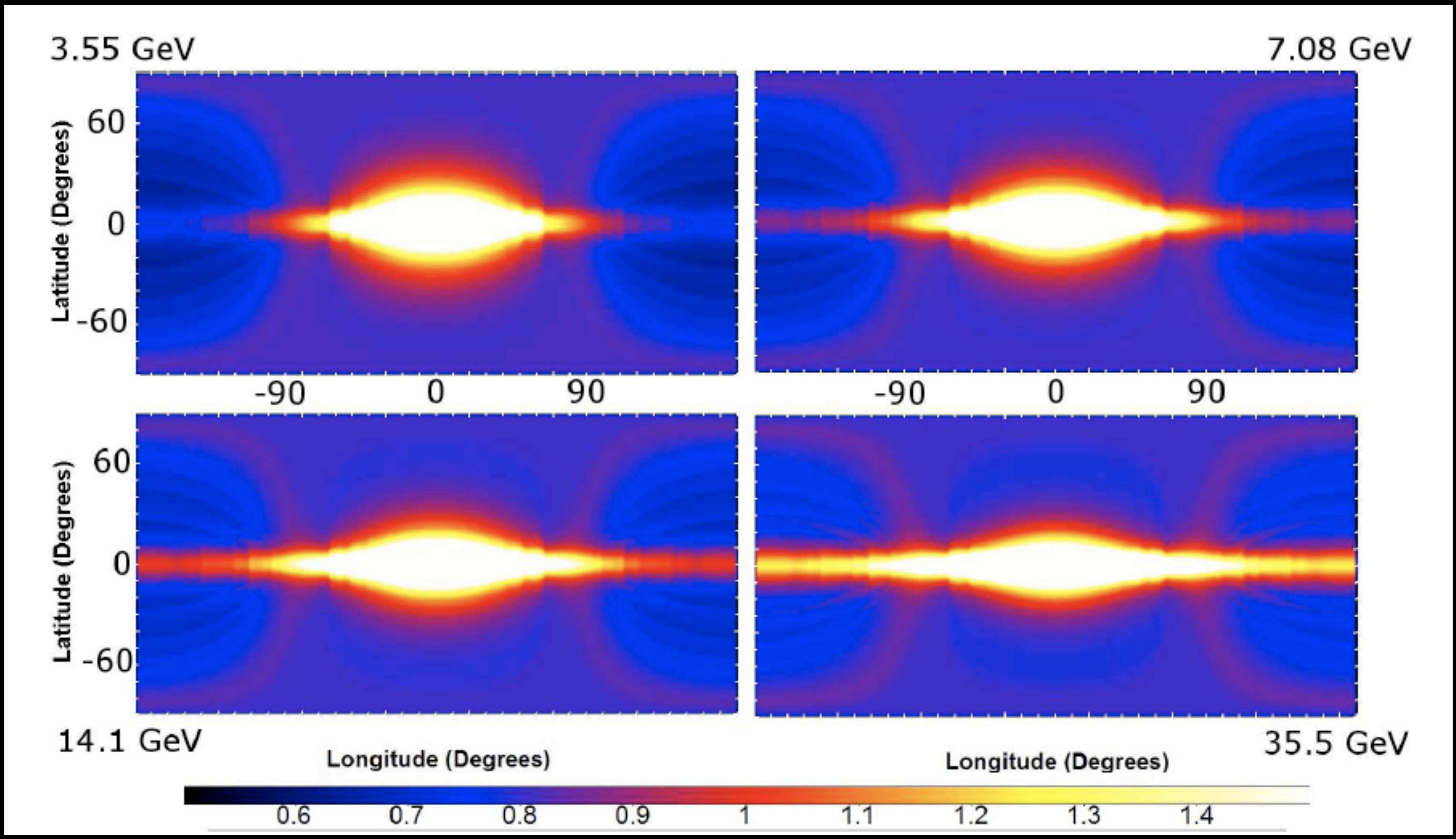


Second Template - **Second Assumption**: Synchrotron traces IC

Try a **constant** magnetic field model

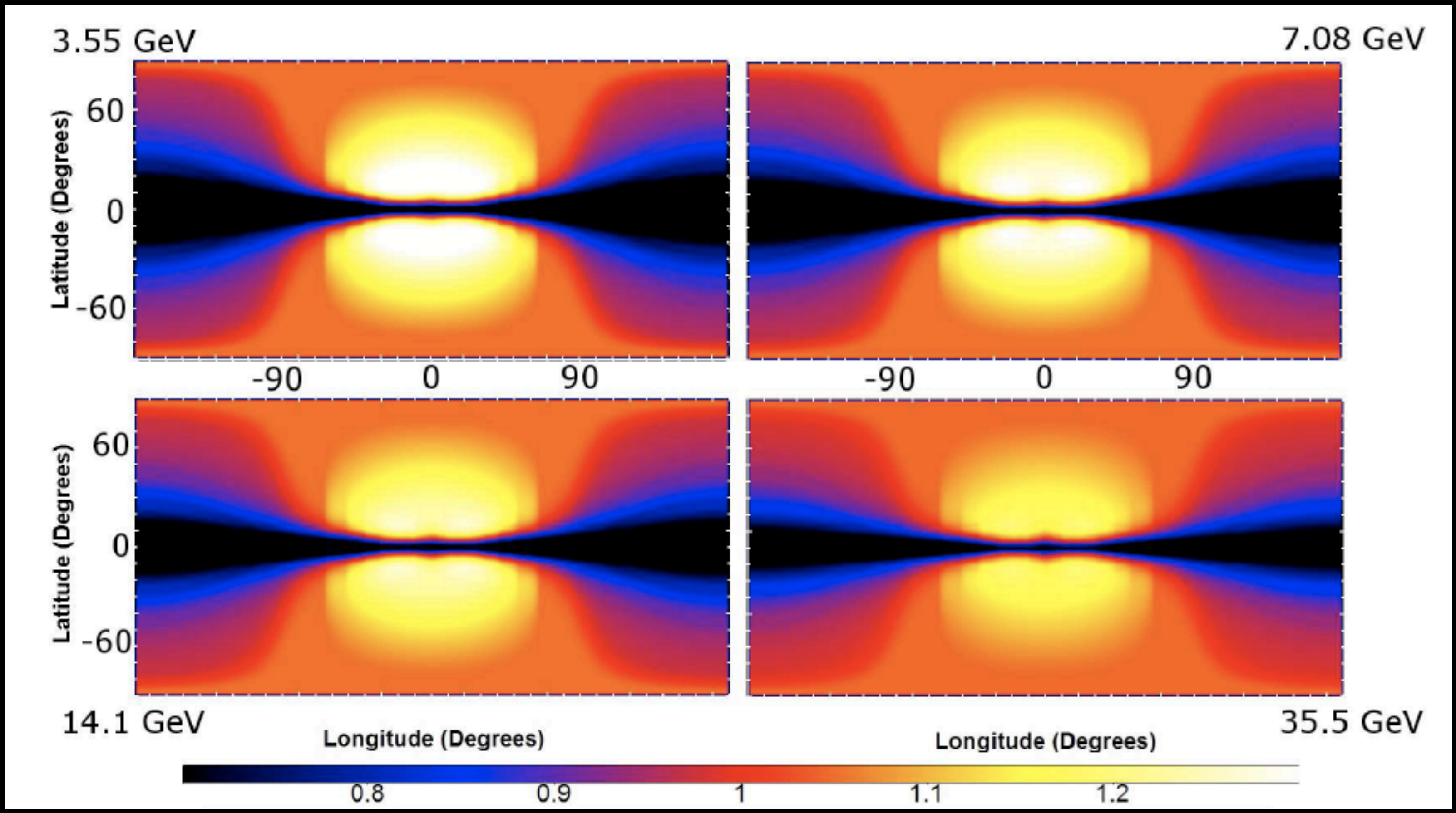
(retaining a detailed **ISRF** model)

again, produce an artificial haze



Second Template - Second Assumption: Synchrotron traces IC

Assuming a "**sharper**" galactic magnetic field model (smaller z scale) one produces again an (energy-dependent) **artificial haze**



Systematic effects in the spatial templates
artificially produce a **haze**
and affect the low-energy determination of an excess

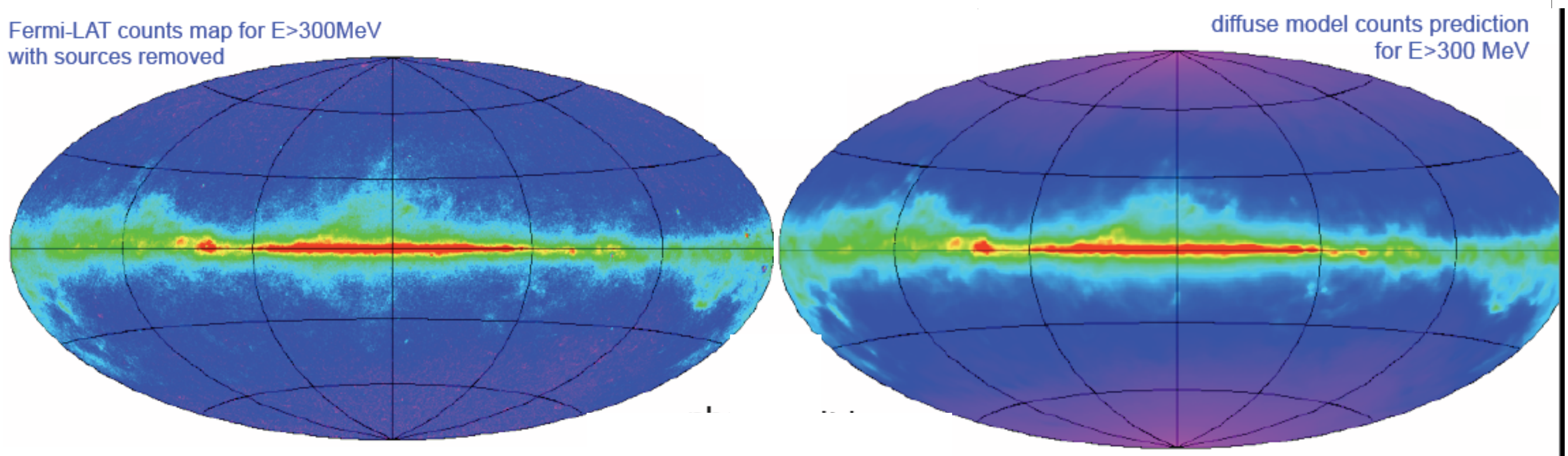
At large energies: very **low statistics** +
very large **cosmic ray** contamination

A **full-glory** galactic cosmic ray simulation is necessary

but is it **sufficient**?!

Fermi gamma-ray sky (source subtracted) and Galprop predictions

(from Casandjian, poster @ Fermi Symposium, 2009)



(*) J-M Casandjian, Fermi Symposium 2009

The **residuals** trace the

polarized synchrotron emission

presumably from the nearby

Loop I (North Polar Spur)

supernova shell (~100 deg!!)

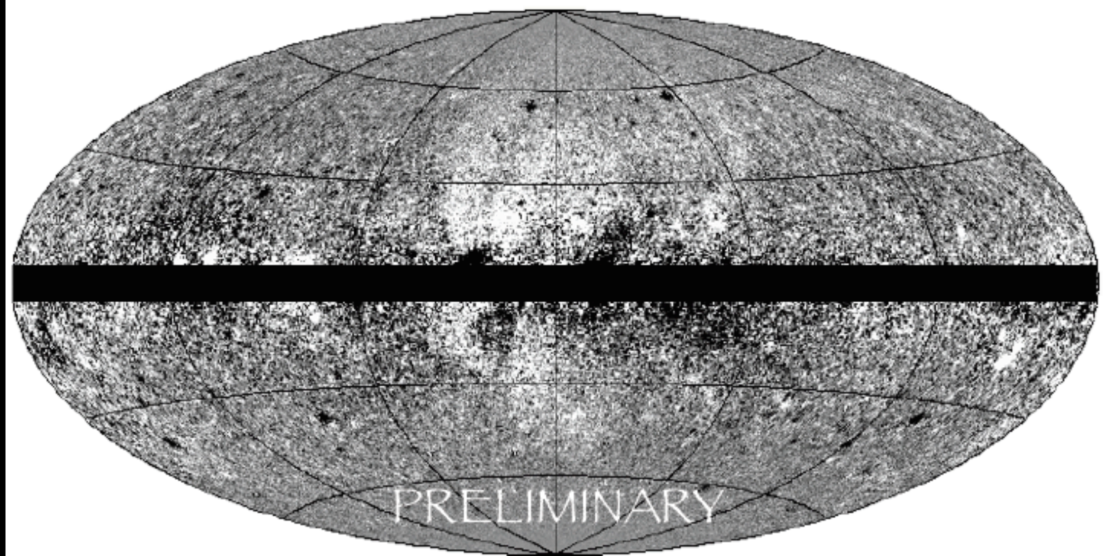
local cosmic ray **structure**

maybe key to understand

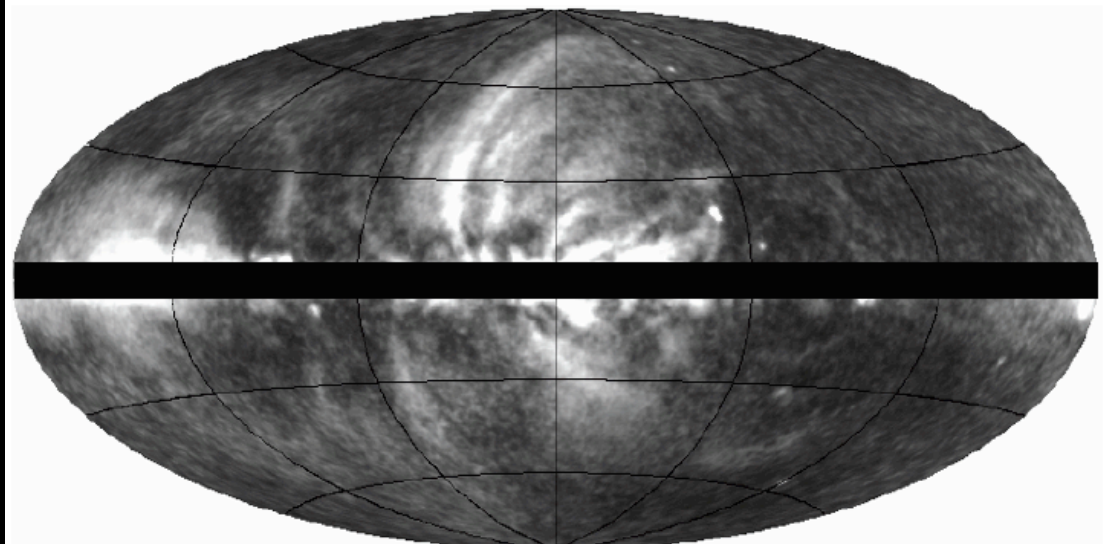
the diffuse emission

beyond galactic cosmic ray

simulations and models



Residual map (data-model) for photons with E>300 MeV


WMAP 23GHz polarized intensity convolved with Fermi-LAT PSF for E>300 MeV

(*) J-M Casandjian, Fermi Symposium 2009

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and they are sometimes not produced by our **favorite sources**…

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A solid prediction: **boredom not in sight for theorists**!

[redacted]