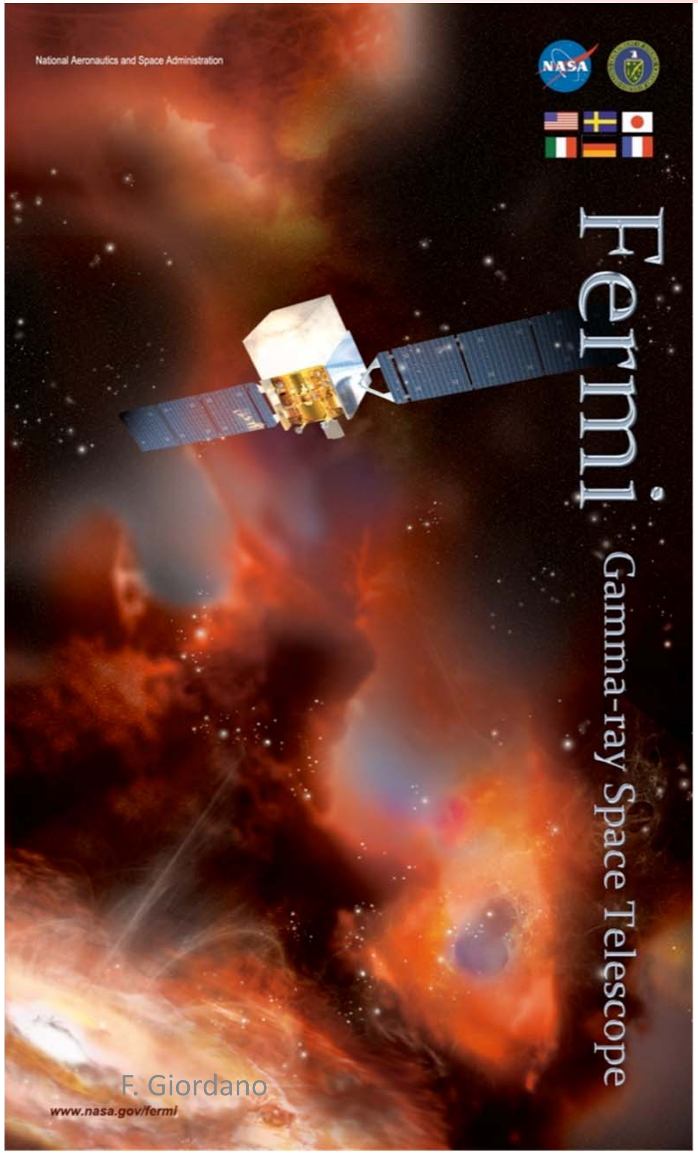
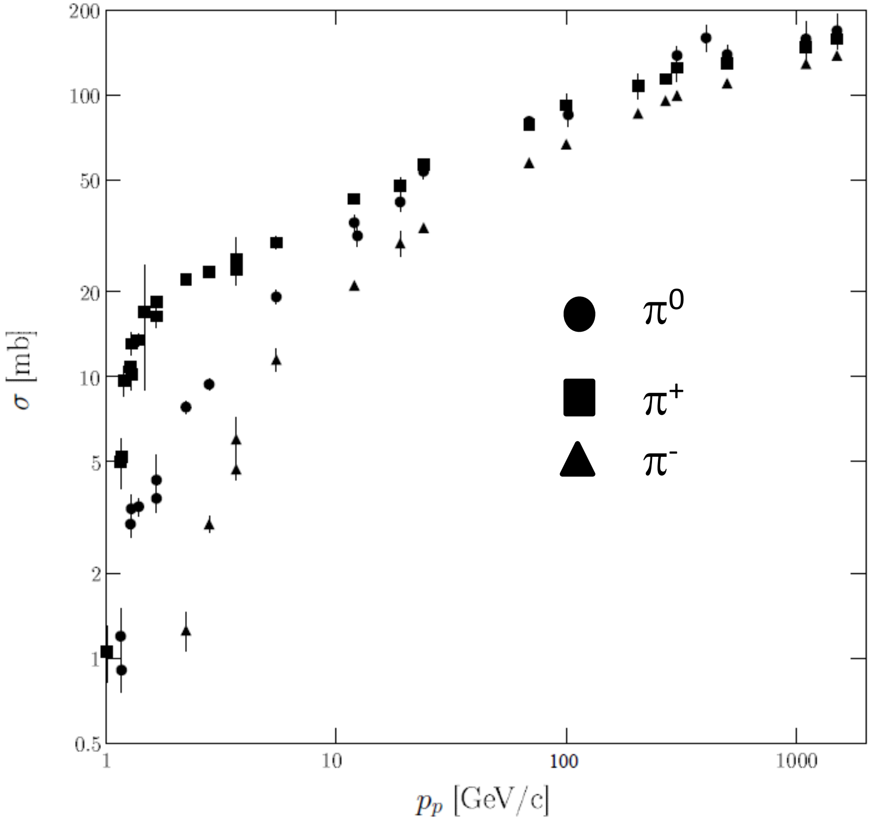


Hadronic accelerators after Fermi

F. Giordano
University and INFN Bari

For the Fermi-LAT Collaboration

Why a γ-ray talk in a ν Conference??



Dermer 1986

$$p + p \rightarrow \pi + X$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

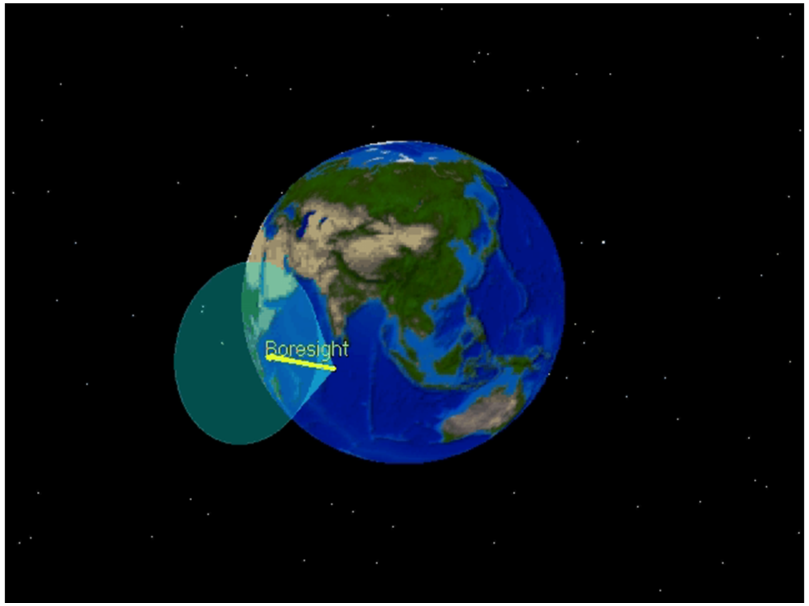
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

The Fermi mission

The Fermi Large Area Telescope observes the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity

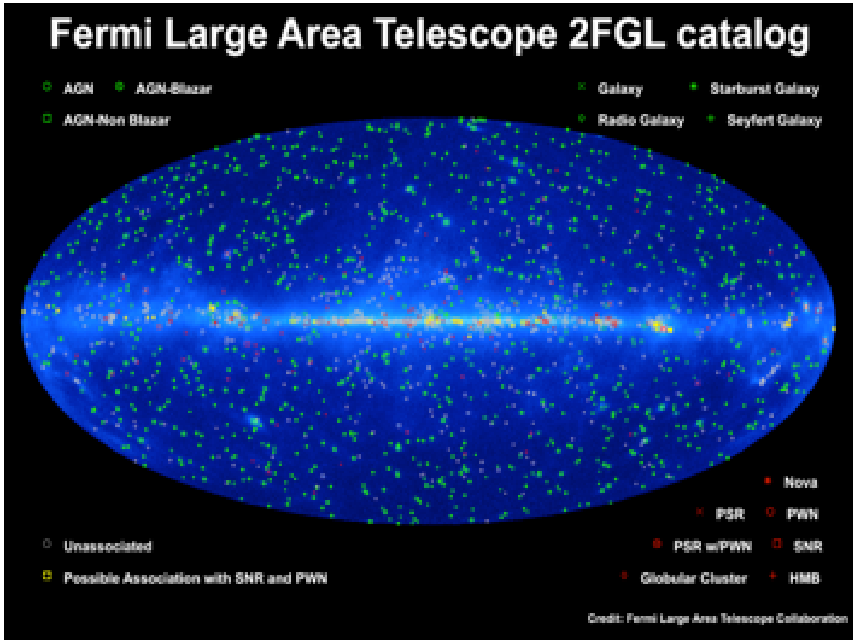
Orbit: 565 km, 25.6° inclination

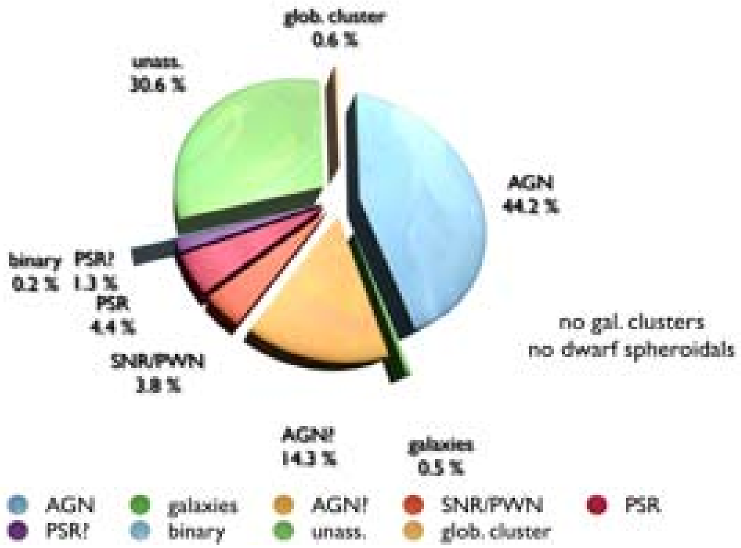
The LAT observes the entire sky every ~3 hrs (2 orbits)



•**Launch from Cape Canaveral Air Station 11 June 2008 at 12:05PM EDT**

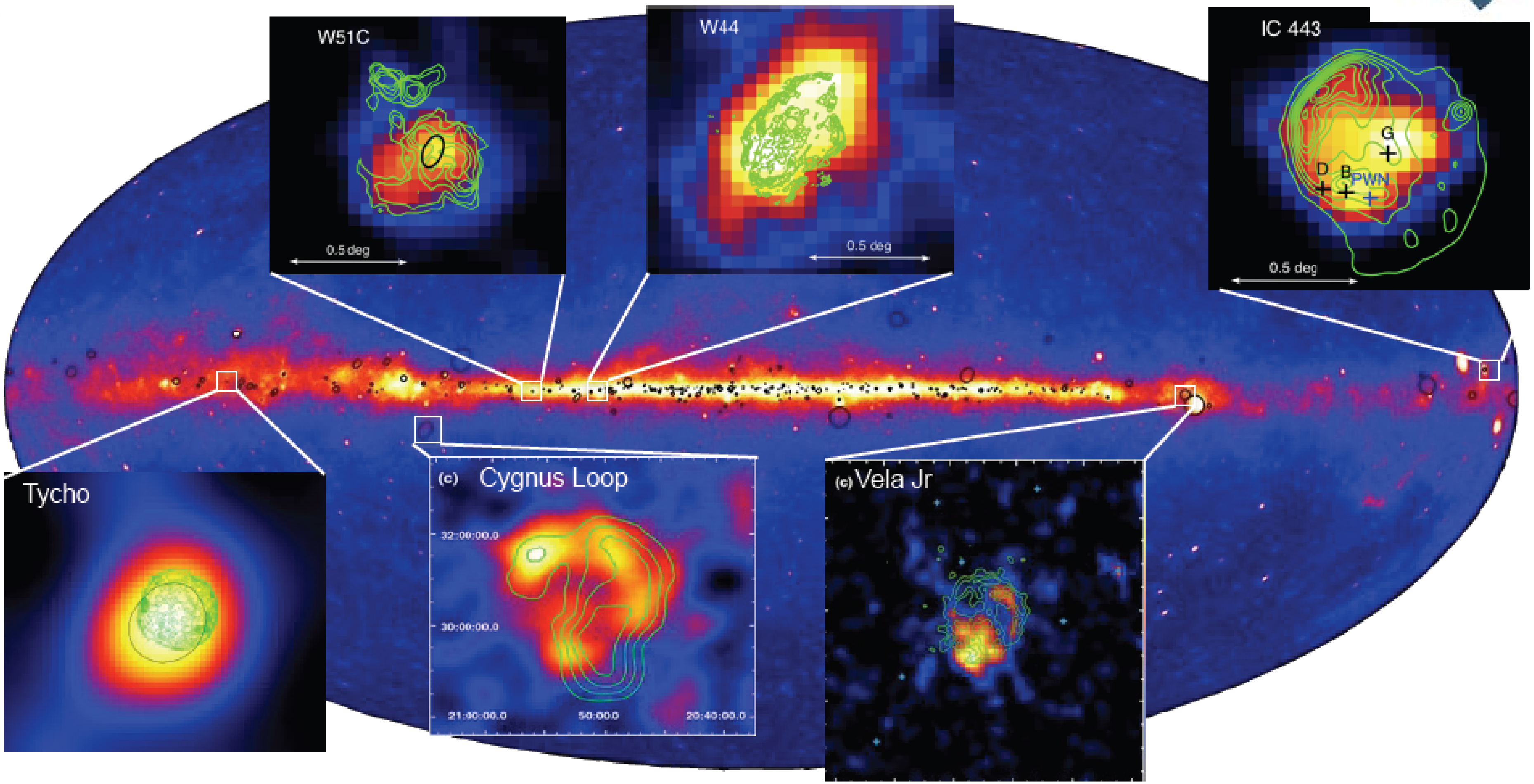
γ-ray Sources





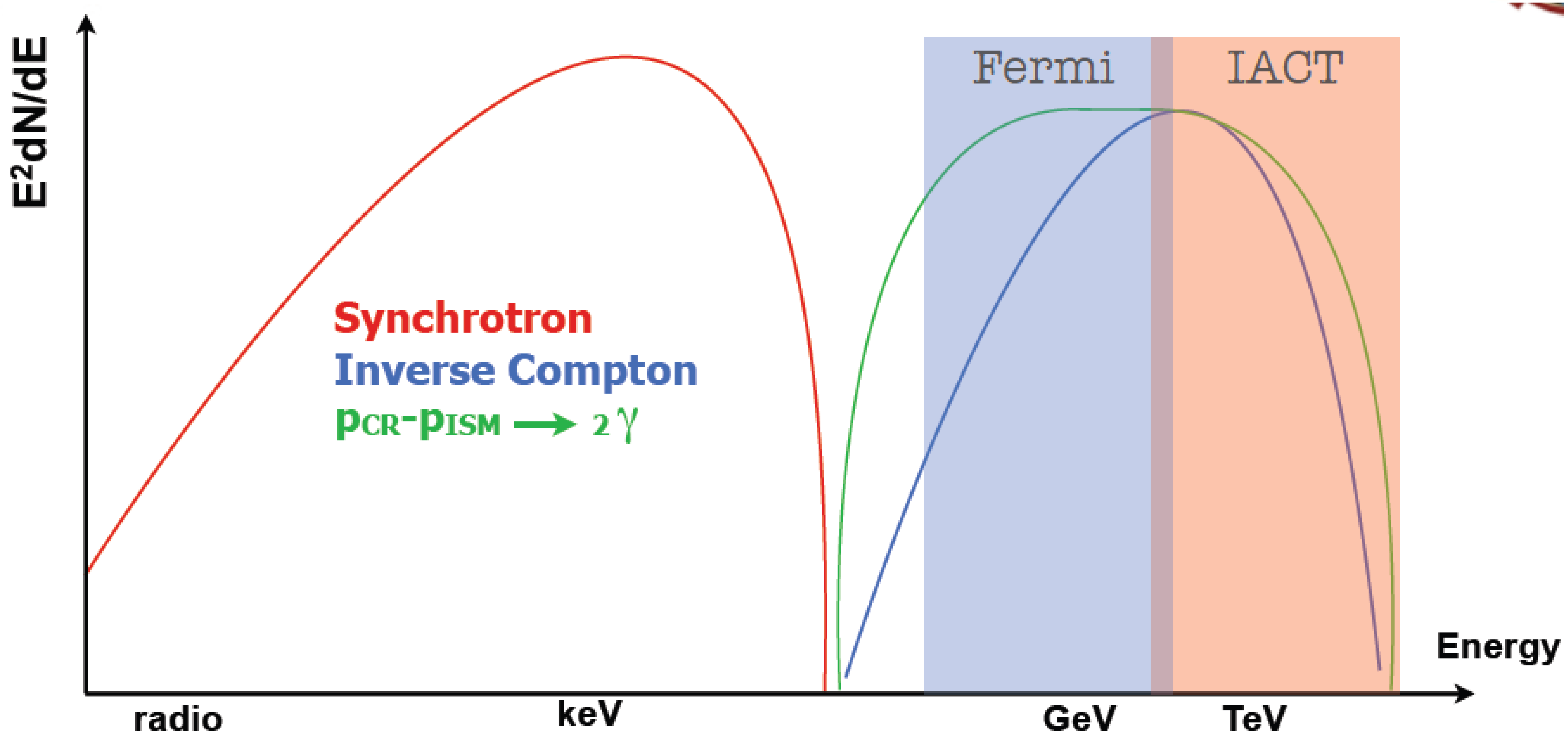
- 1873 sources in the Second Fermi LAT source catalog (2 years of data), 2FGL (Fermi LAT Collab. 2012, ApJS 199, 31)
- Most are Active Galactic Nuclei (2nd LAT AGN Catalog, Fermi LAT Collab. 2011, ApJ 743, 171)
- 1017 AGNs, >95% blazars. Small fraction of non-blazar AGNs, radio galaxies among these
- ~30% of the 2FGL sources have no counterparts at other wavelengths

CRs Sources: Galactic SNRs



12 identified SNRs by Fermi-LAT including:
- 8 interacting with Molecular clouds
- 4 young SNRs (<2,000 yr)

γ-ray emission processes in SNRs



Test the SNR CR acceleration paradigm through SNR's particle radiation:
- Nature of the γ-ray emission, Emax, Energetic SNR CRs
- Time evolution of acceleration, escape, and propagation of CRs
- Effects of the surrounding environment

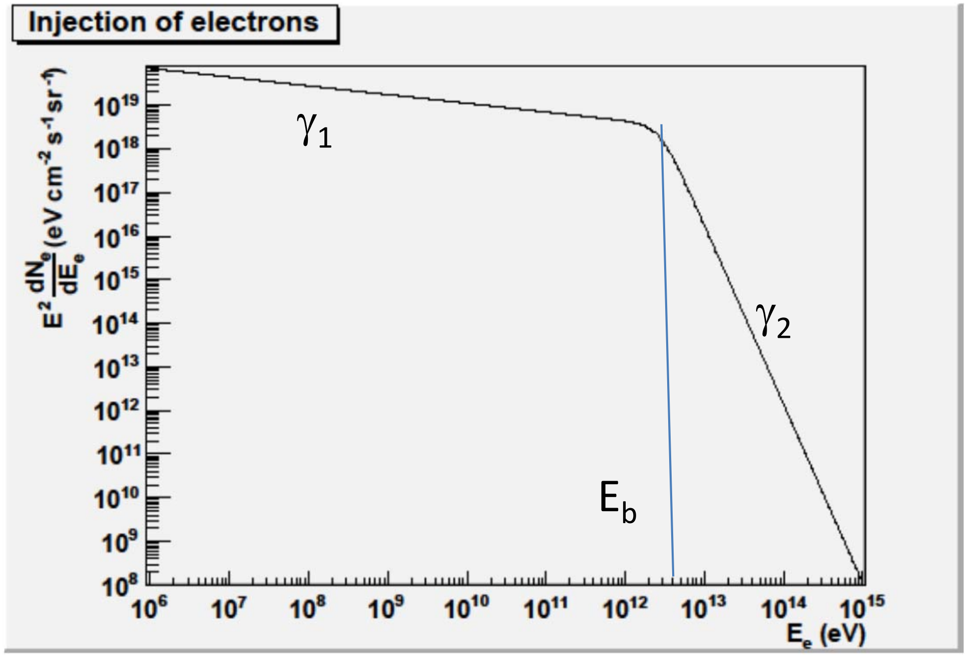
Injection of particles

We are using a **broken power law** to describe the electron population:

$$\frac{dN_e}{dE_e} = A_e \left(\frac{E_e}{E_0}\right)^{-\gamma_{1,e}} \left[1 + \left(\frac{E_e}{E_{b,e}}\right)^{\frac{(\gamma_{2,e}-\gamma_{1,e})}{\gamma_{3,e}}}\right]^{-\gamma_{3,e}} \qquad \left[eV^{-1}cm^{-2}s^{-1}sr^{-1}\right]$$

A_e is the normalization constant;
$E_{b,e}$ is the value of the energy break

From the constant A_e the **acceleration efficiency** can be calculated , starting from a default value of *10^{51} erg* for the total kinetic energy of the explosion.



Non thermal radiation Modeling leptons

The three processes involving electrons and contributing to the production of photon are:

- ***Synchrotron radiation;***
- ***Inverse Compton Radiation;***
- ***Bremsstrahlung***

Synchrotron radiation

[Zirakashvili and Aharonian (2007)]

The **synchrotron emissivity** of electrons per unit volume is determined by:

$$Q_\gamma(\omega) = \frac{\sqrt{3}Be^3}{2\pi m_e c^2} \int \frac{4\pi}{\beta c} \frac{dN_e}{dE_e} R\left(\frac{\omega}{\omega_c}\right) dE_e \qquad [ergcm^{-3}]$$

where

$$R(\omega/\omega_c) = \frac{1.81 \exp(-\omega/\omega_c)}{\sqrt{(\omega_c/\omega)^{2/3} + (3.62/\pi)^2}}. \qquad \text{and} \qquad \omega_c = 1.5\, qBp^2/m^3c^3$$

From the emissivity, the **energy flux**:

$$F_{\gamma,SNR}(\omega) = \frac{Q_\gamma(\omega) V_{SNR}}{d^2} \qquad [eVcm^{-2}]$$

where *d* is the distance of the SNR from the Earth, and V is the SNR Volume

Inverse Compton radiation

[Stuner et al. (1997)]

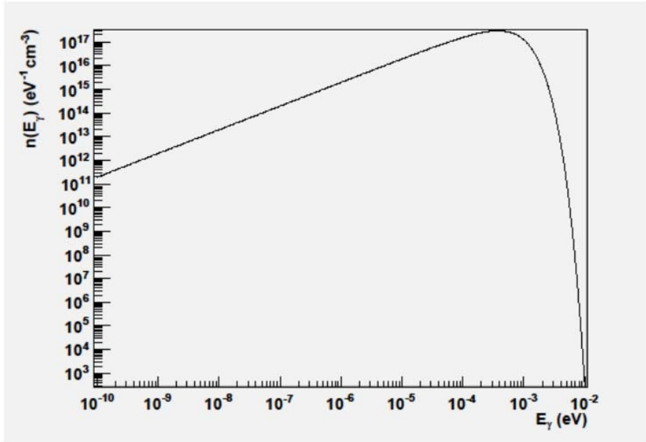
The **Compton scattering emissivity** is calculated using the full Klein-Nishina cross section for relativistic electrons and the number density of the CMB photons as a function of energy.

$$Q_\gamma(E_\gamma)=\int_{E_{e,thresh}}\frac{dN_e}{dE_e}dE_e\int n(E_t)\sigma_{K-N}(E_t,E_e,E_\gamma)dE_t \qquad [eV^{-1}cm^{-3}s^{-1}]$$

where: $$\sigma_{K-N}(E_t,E_e,E_\gamma)=\frac{2\pi r_0^2}{E_tE_e^2}\left[2q\log_e q+1+q-2q^2+\frac{\Gamma^2q^2(1-q)}{2(1+\Gamma q)}\right] \qquad [eV^{-1}cm^2]$$

The CMB defined as

$$n(E_t)=\frac{15U}{(\pi kT)^4}\frac{E_t^2}{\exp\left(\frac{E_t}{kT}\right)-1}$$



Bremsstrahlung radiation

[Baring et al. (2000)]

The **Bremsstrahlung emissivity** can be written in the form:

$$Q_\gamma(\omega) = 4\pi n_H \int \frac{dN_e}{dE_e}\frac{d\sigma}{d\omega} dE_e \qquad [cm^{-3}s^{-1}]$$

where:
- n_H is density of the target (protons);
- ω is the photon energy expressed in units of electron rest mass $m_e c^2$.

The **differential cross-section** is the ultra-relativistic specialization of the Bethe-Heitler formula, obtained in the Born approximation:

$$\frac{d\sigma}{d\omega} = 4\frac{\alpha_f r_0^2}{\omega}\left[1+\left(\frac{\gamma-\omega}{\gamma}\right)^2 - \frac{2}{3}\frac{\gamma-\omega}{\gamma}\right]\left[\log\frac{2\gamma(\gamma-\omega)}{\omega} - \frac{1}{2}\right] \qquad [cm^2]$$

where $\gamma = E_e/m_e c^2$ is the electron Lorentz factor.

Non thermal radiation Modeling protons

Kamae et al 2006

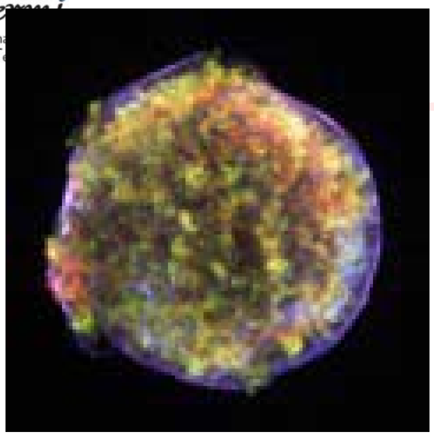
The process we are interested is described by the following:

$$pp \rightarrow \pi^0 + X$$
$$\qquad \hookrightarrow \gamma\gamma$$

The inelastic cross section of π^0 production consists of four contributions:

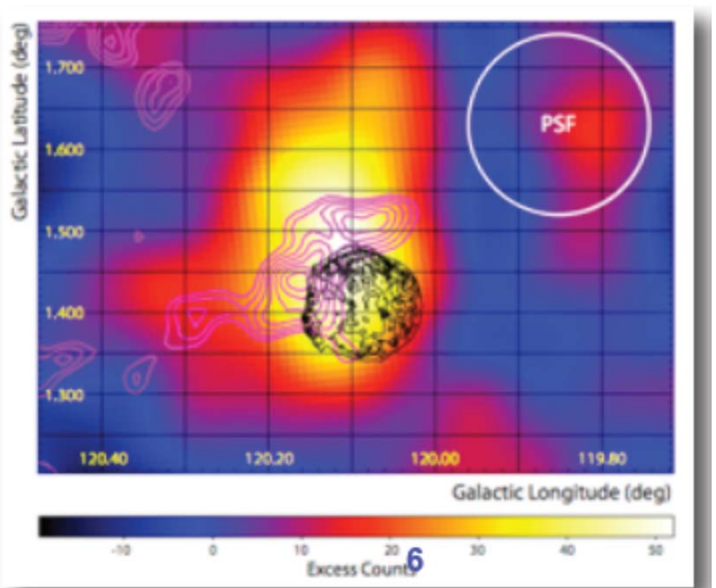
- non diffractive p-p scattering;
- diffractive p-p scattering;
- $\Delta(1232)$ resonance excitation;
- res(1600) resonance excitation.

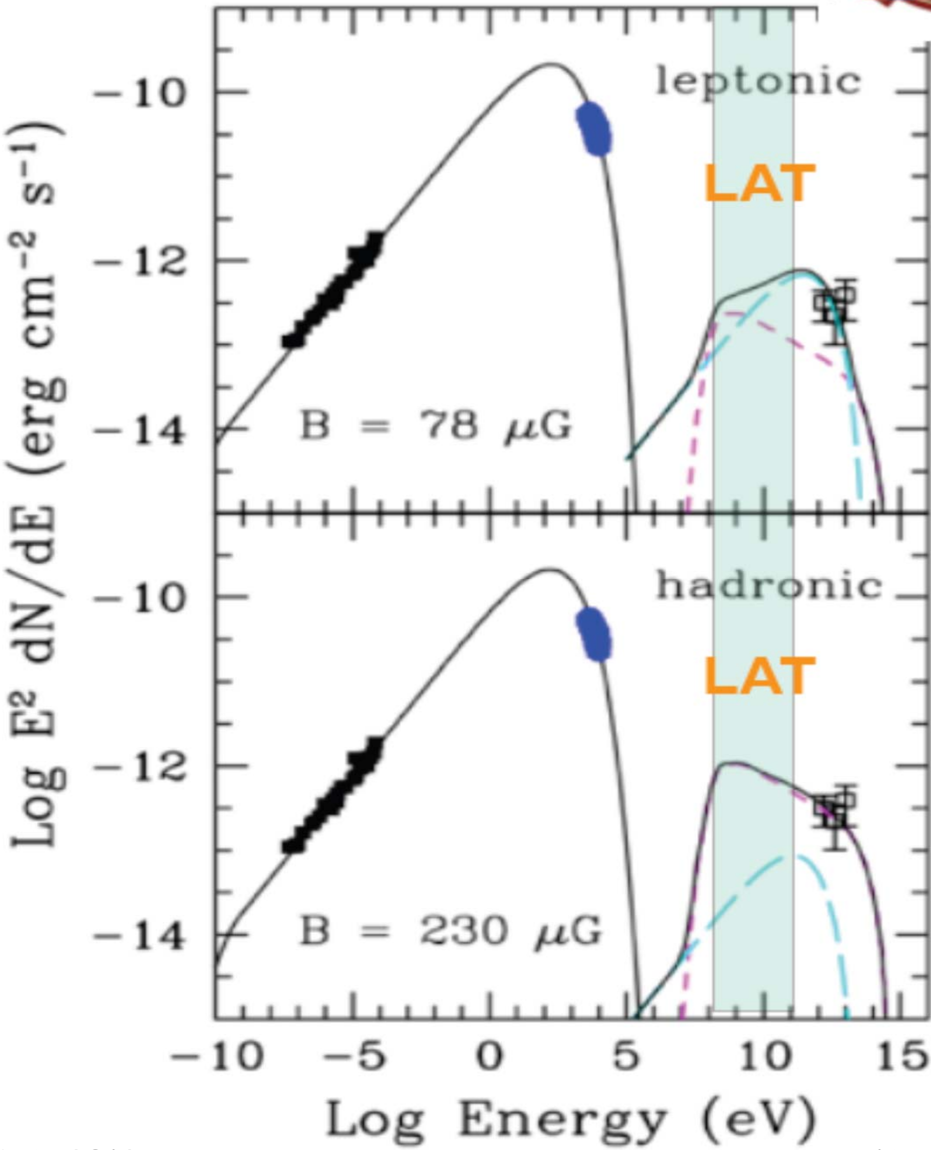
A test case: Tycho



Credit: Chandra

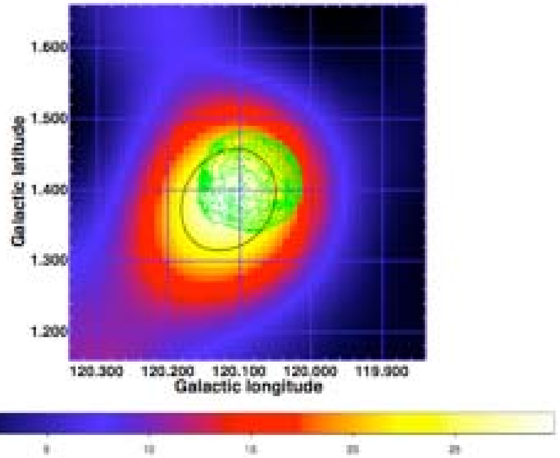
VERITAS Collaboration (2011)



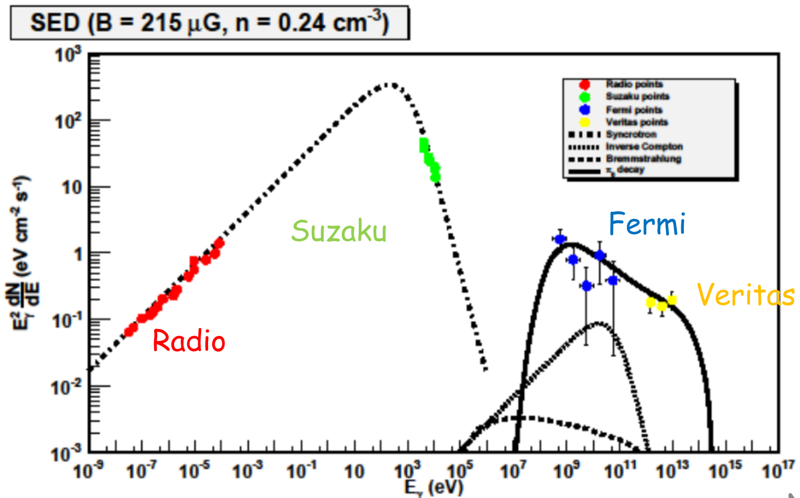


Flux(>1 TeV) ~ 1% Crab
5.0σ detection (post-trial)

Let's start from Young SNRs



- Giordano et al 2012

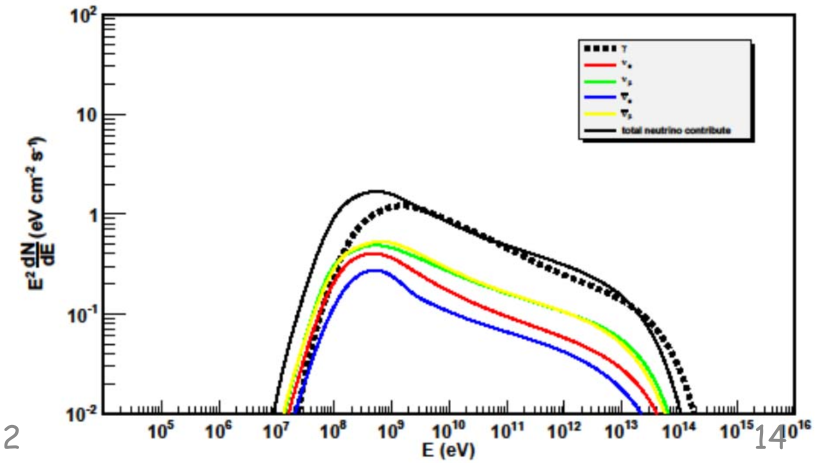


Leptonic not-favoured for:

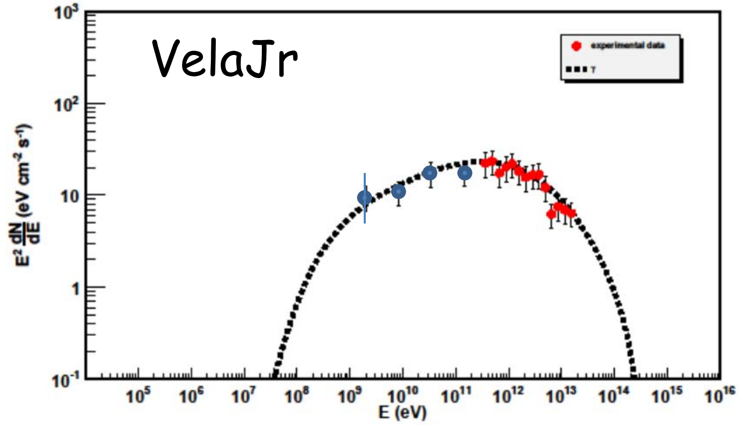
- IC does not fit the data
- Bremss
    - N_e fixed by IC
    - $n_H \uparrow$ up to 10cm^{-3}
    - B $\downarrow$ down to 65uG
- Kep~0.1

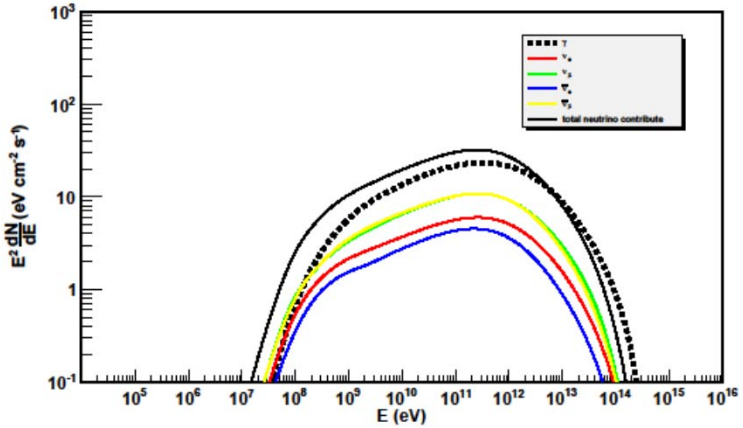
Hadronic:

- index 2.3,
- break@100TeV
- 6-8% acceleration efficiency

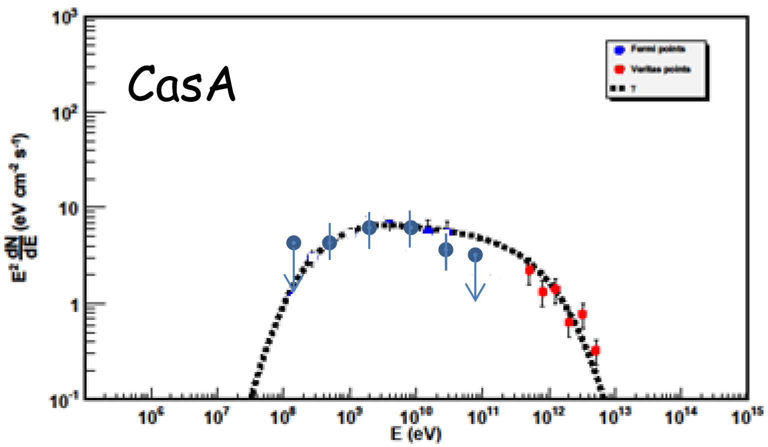


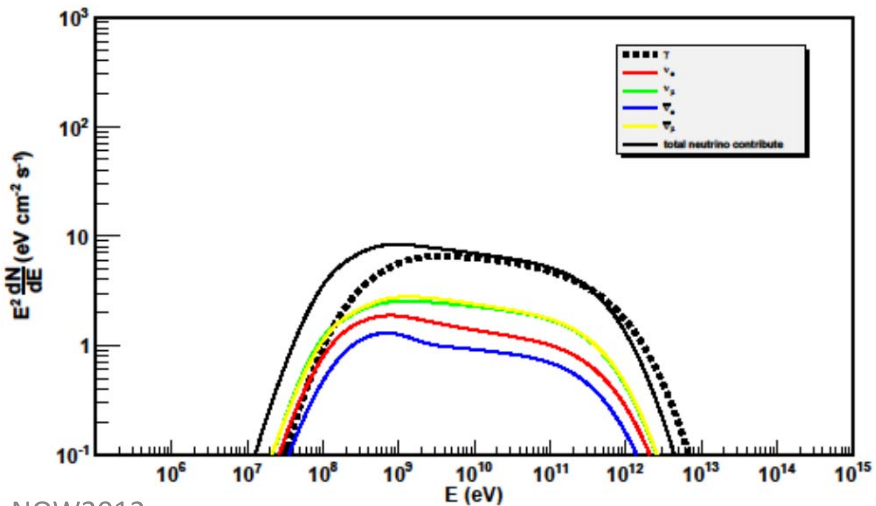
Other young guys…





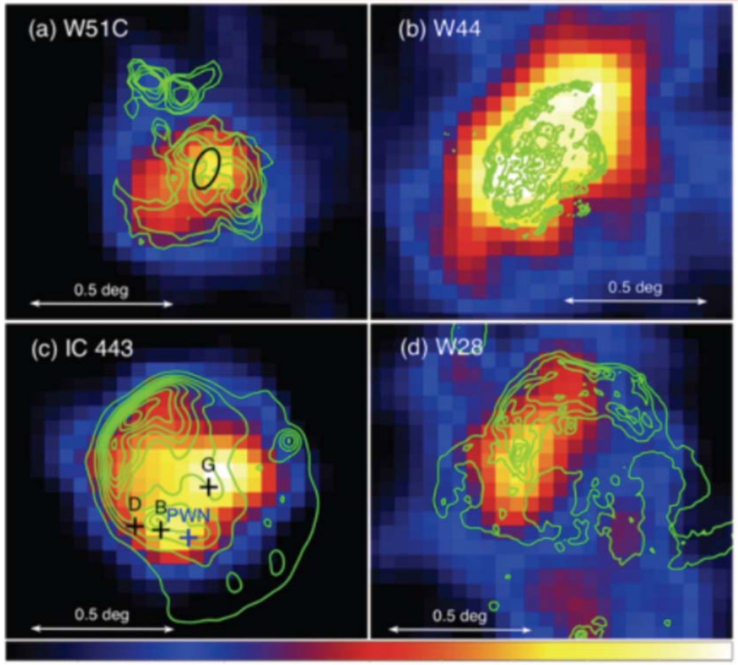
- Tanaka et al 2011 • Aharonian et al 2005





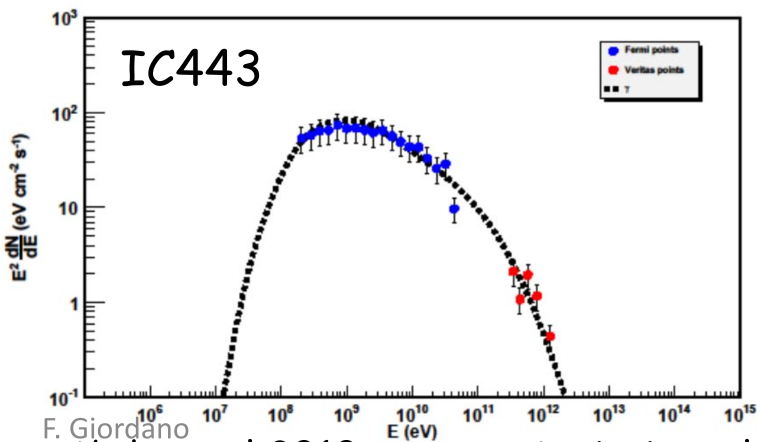
- Abdo et al 2011 • Acciari et al 2010

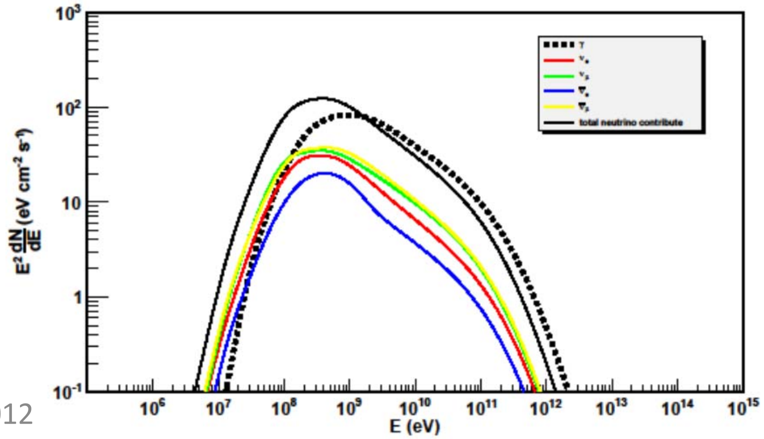
MC Interacting SNRs



Uchiyama et al 2011

- High GeV luminosity up to 10^{36} erg/s
- Assuming e/p ratio less than 10%, the only way to achieve the high luminosity is π^0-decay γ-rays in dense gas (>10 cm^{-3}).
- Spectral break in the GeV band
- GeV Luminosity>>TeV Luminosity

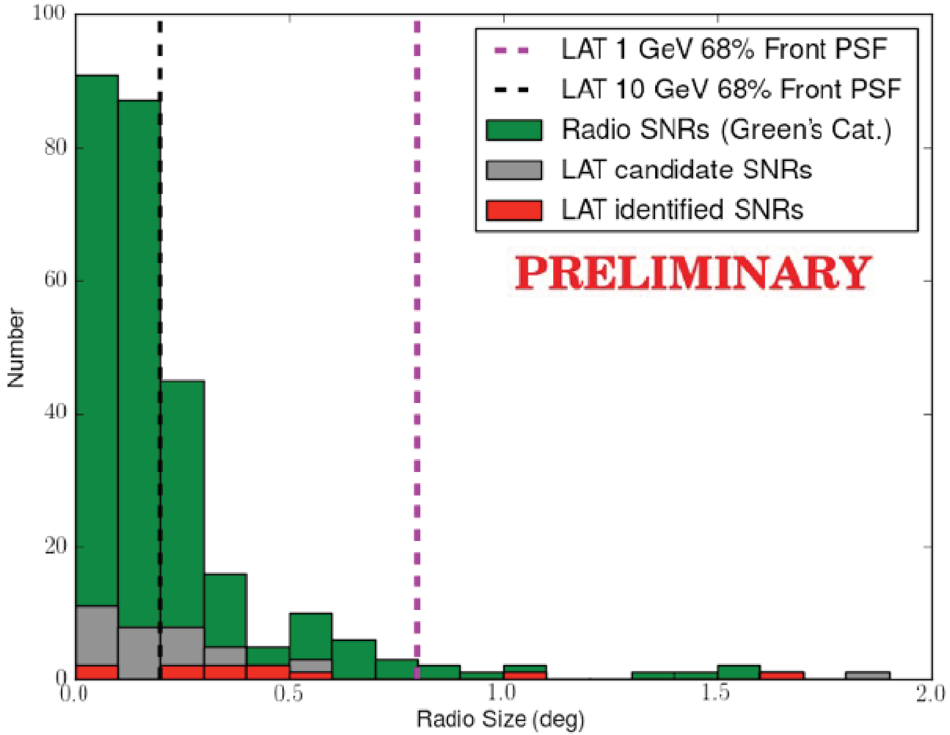


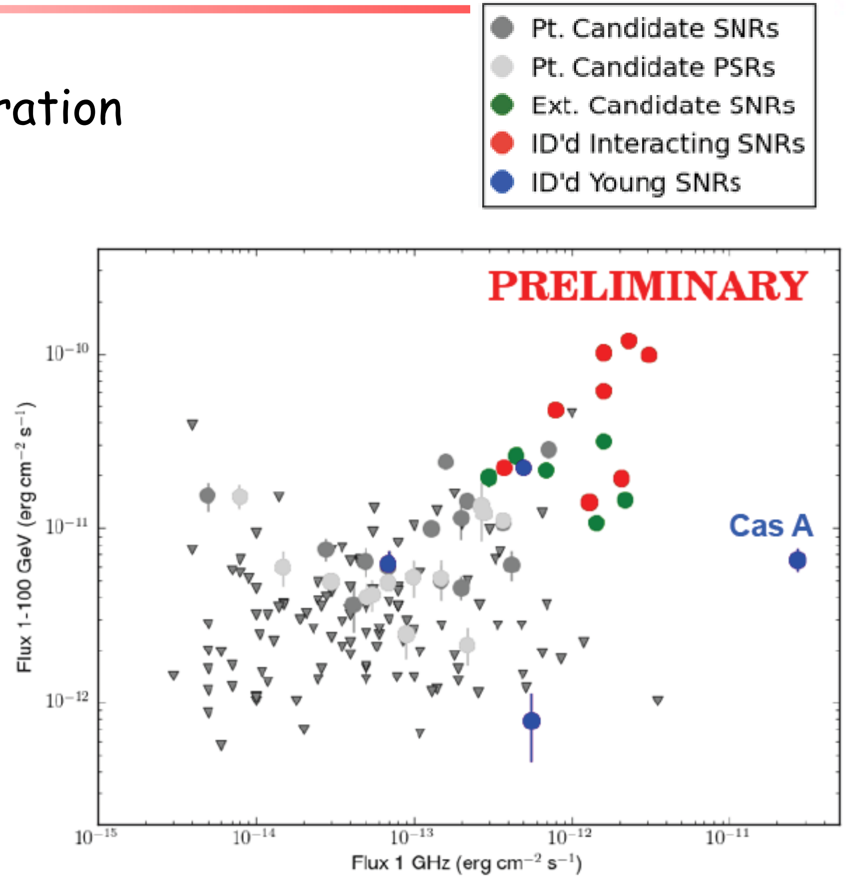


- Abdo et al 2010
- Acciari et al 2009

More sources???

The Fermi-LAT 1st SNR catalog is in preparation

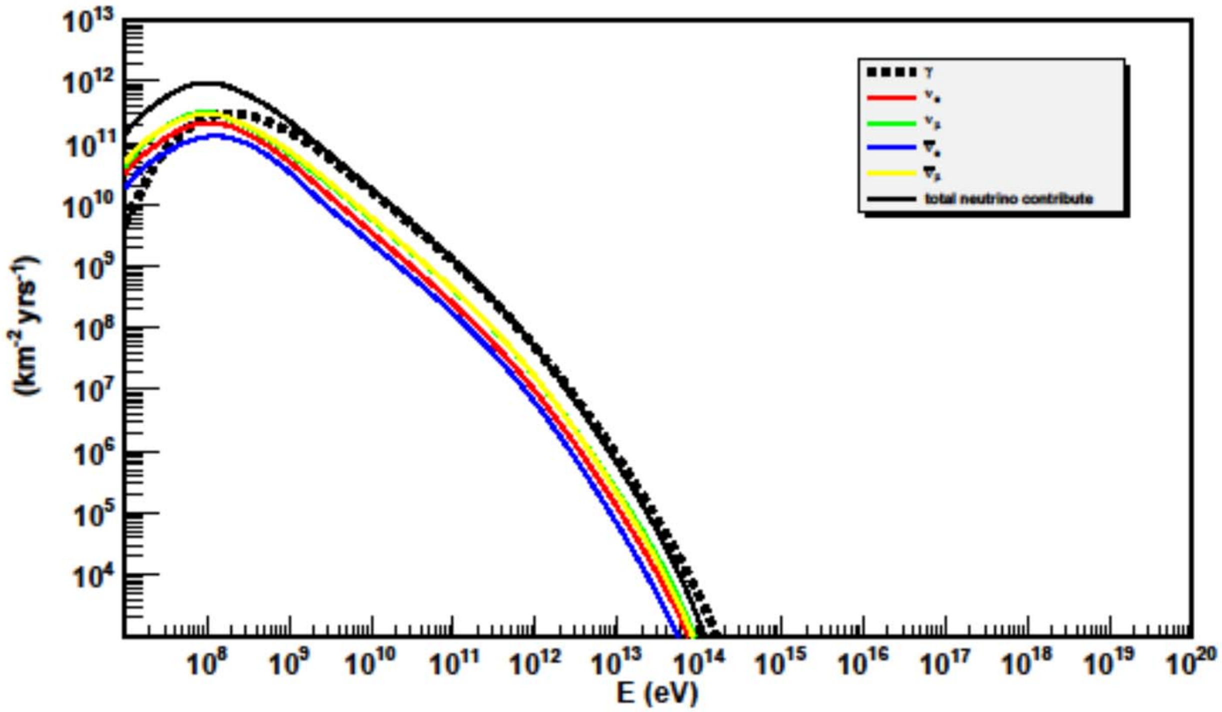




Our results consist of:
15 *extended* SNRs (9 previous ID, 6 new)
30 *point-like* SNRs (3 previous ID, 27new)
7 sources that are *NOT* SNRs (PSRs, AGN, HMB, PWN)

Thanks

Fluxes



γ
ν_e
ν_μ
$\bar{\nu}_e$
$\bar{\nu}_\mu$
total neutrino contribute
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
(km^{-2} yrs^{-1})
10^{8} 10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
E (eV)