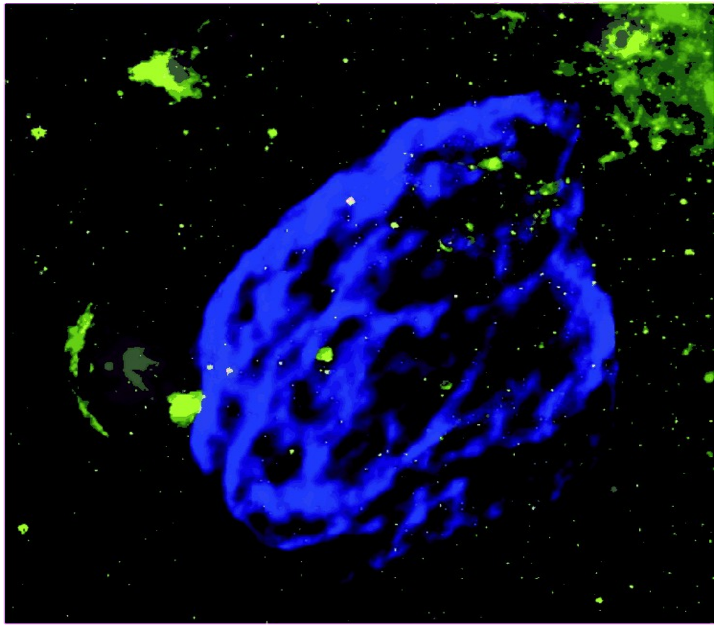
AGILE study of Supernova Remnants

(SNRs @ 100 MeV)



A. Giuliani

for the AGILE Team
INAF / IASF Milan

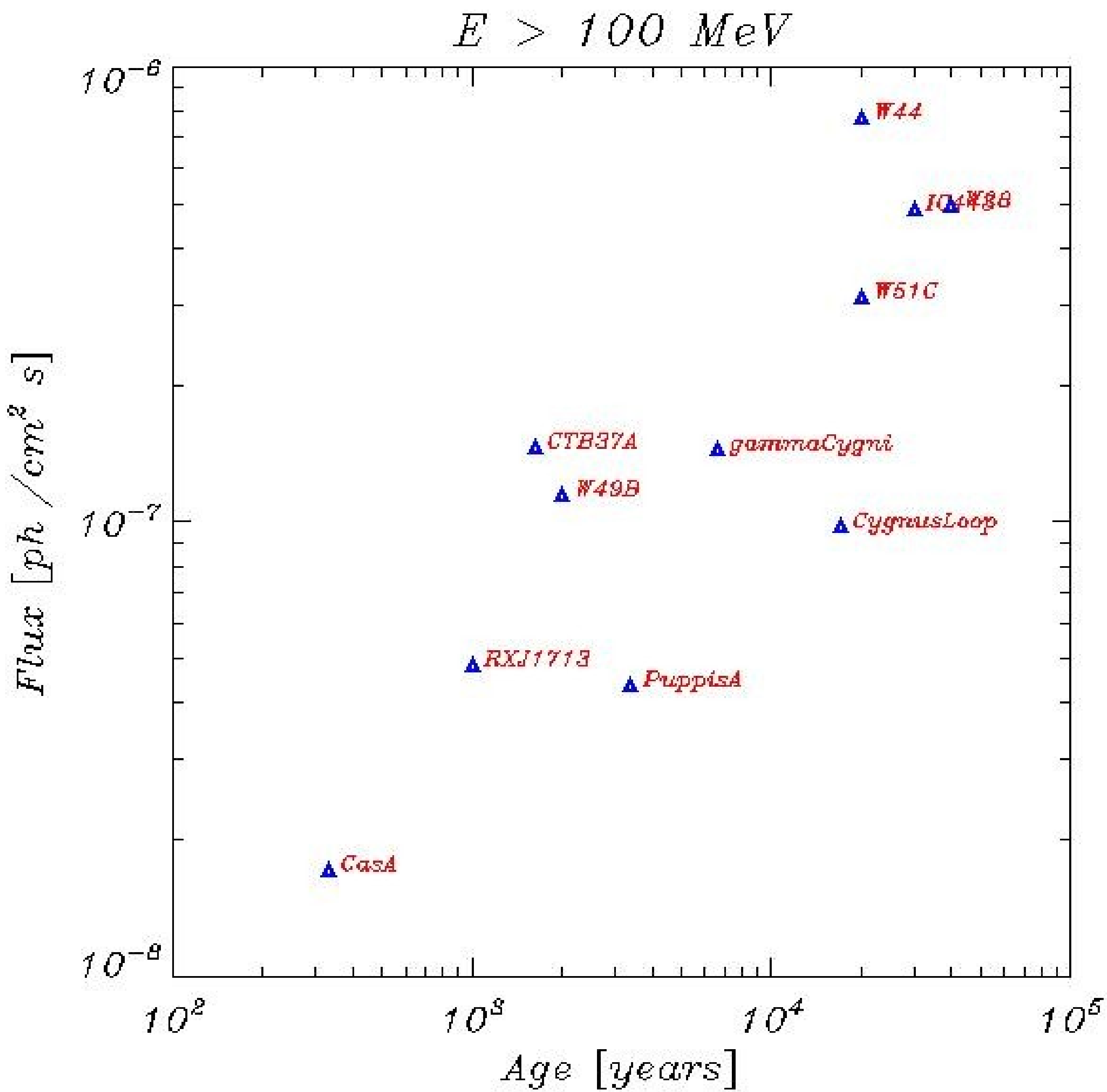
SNRs at “low” energy

At 100 MeV , Middle-aged SNRs are brighter.

High energy CR (~10 TeV) are injected earlier, and travel faster.

Ratio between TeV CRs and GeV CRs is larger in young SNRs

AGILE SNRs are in average older than TeV or Fermi SNRs.



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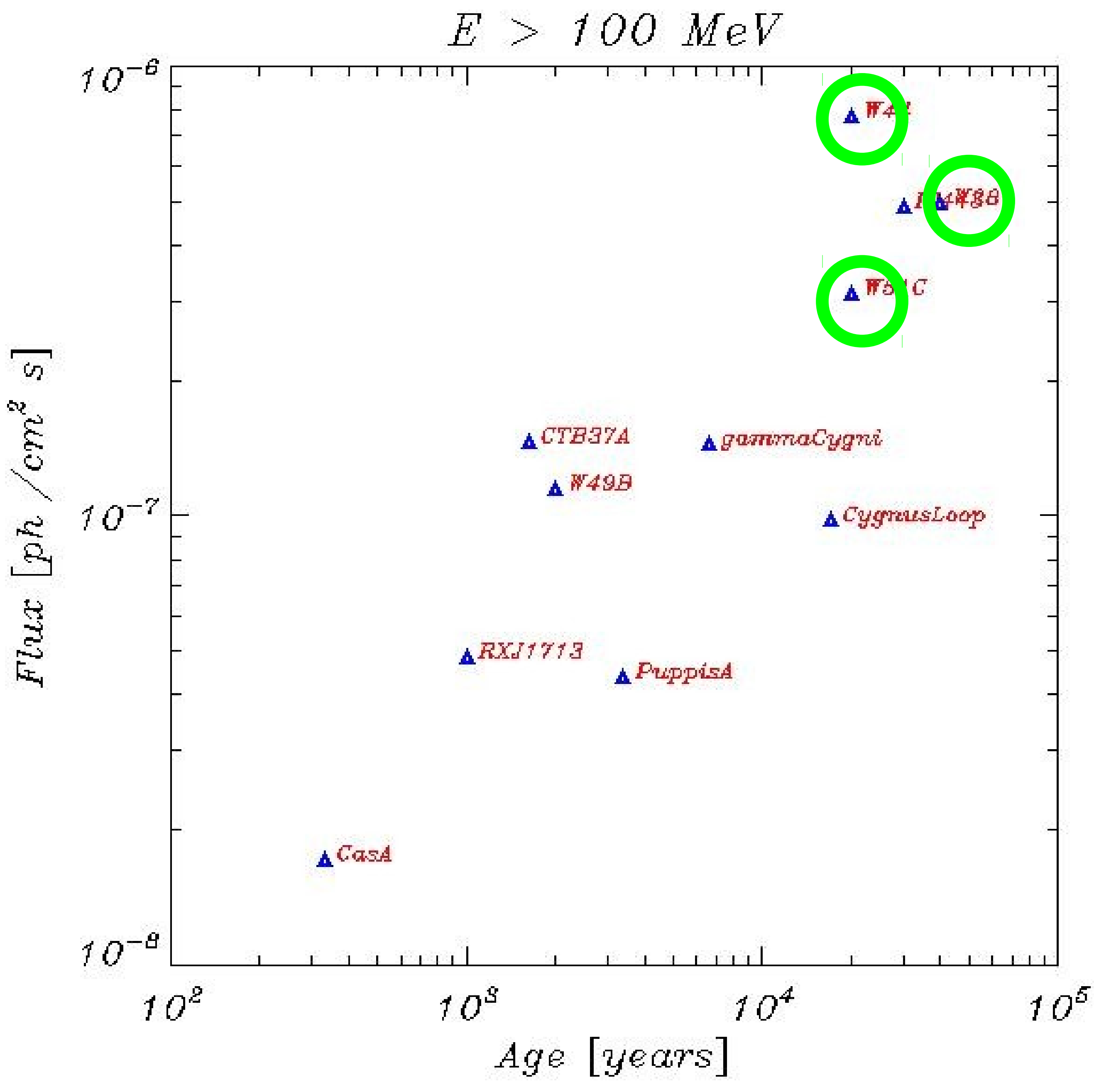
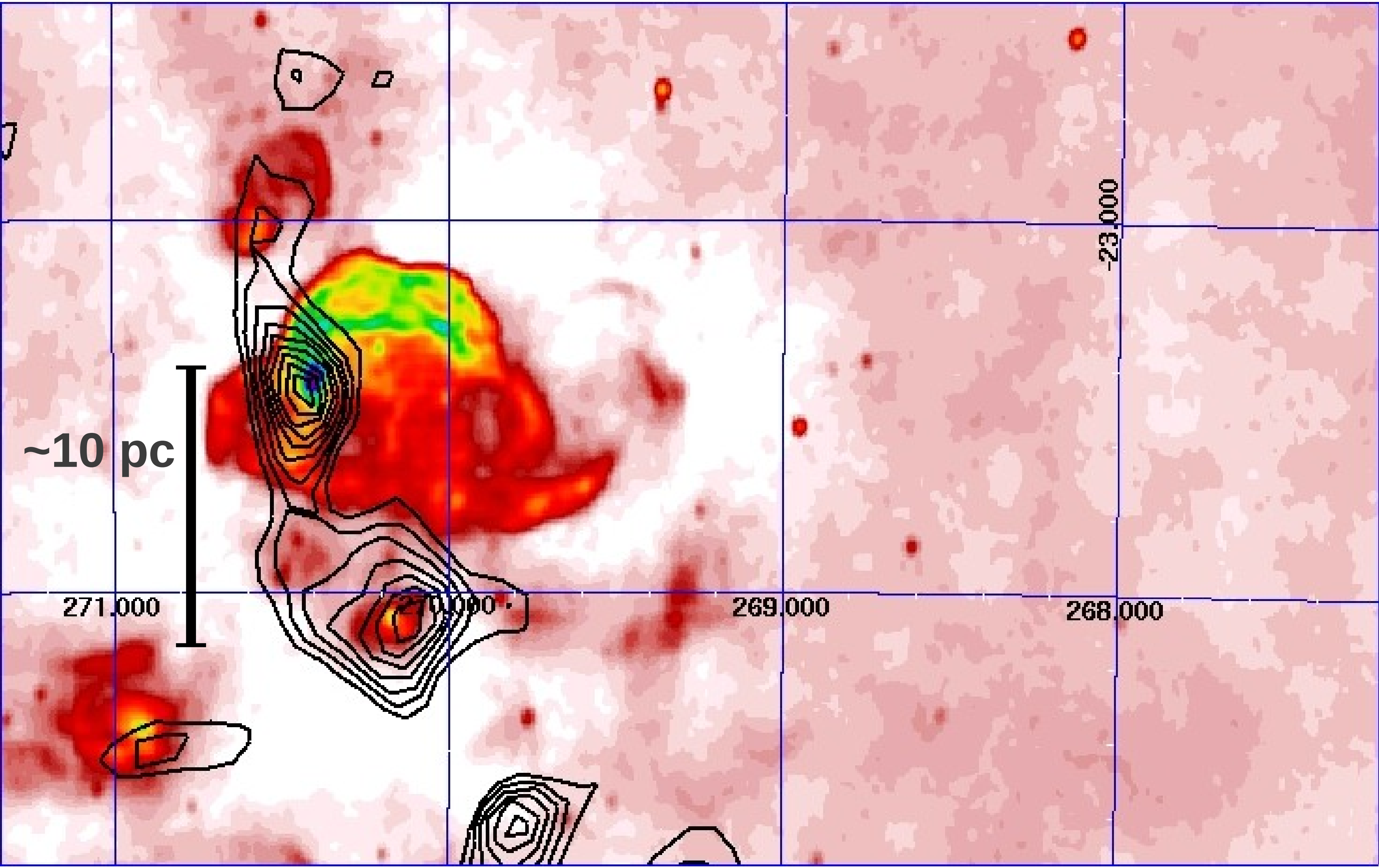


SNRs at “low” energy : diffusion of CRs (W28)



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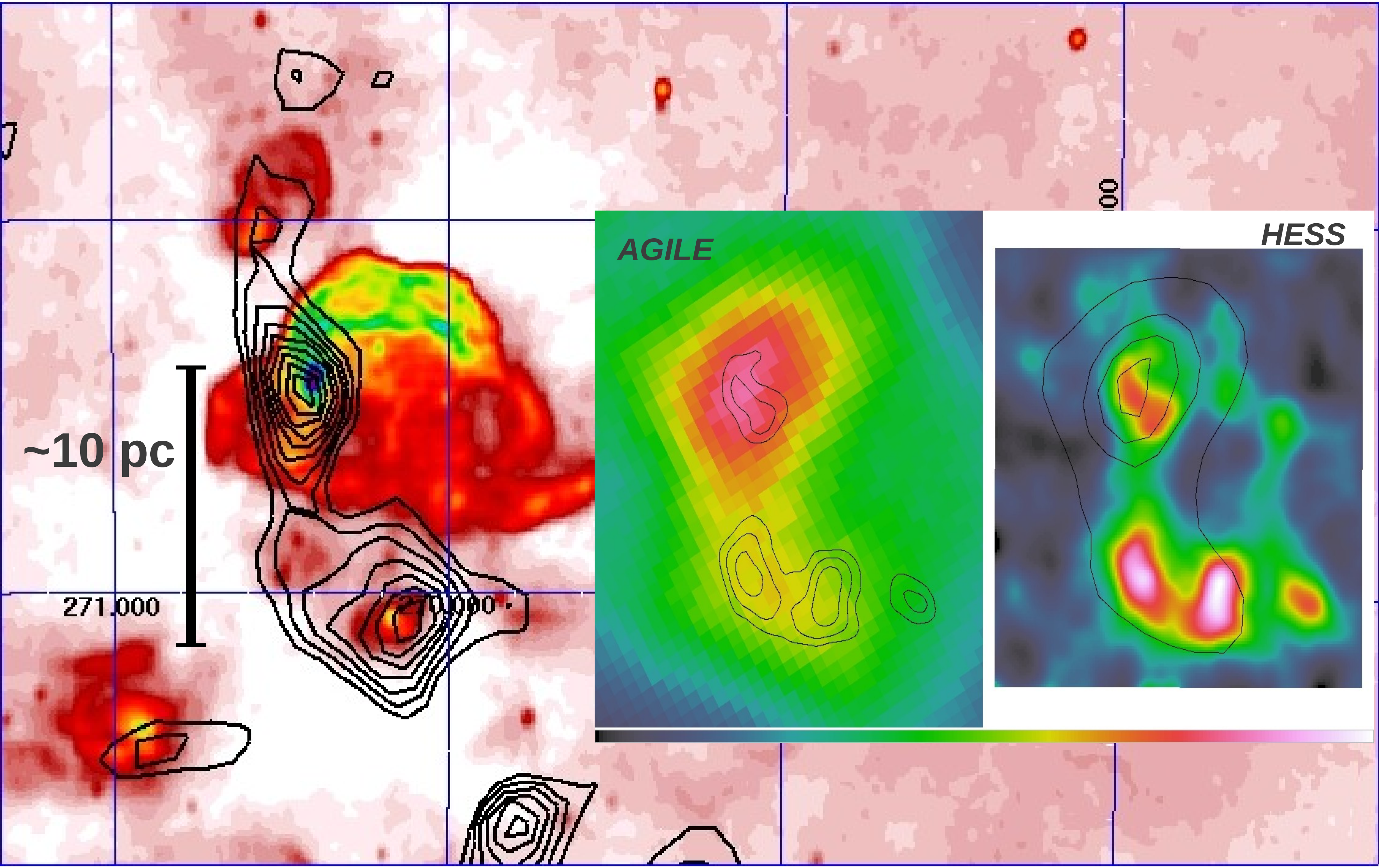
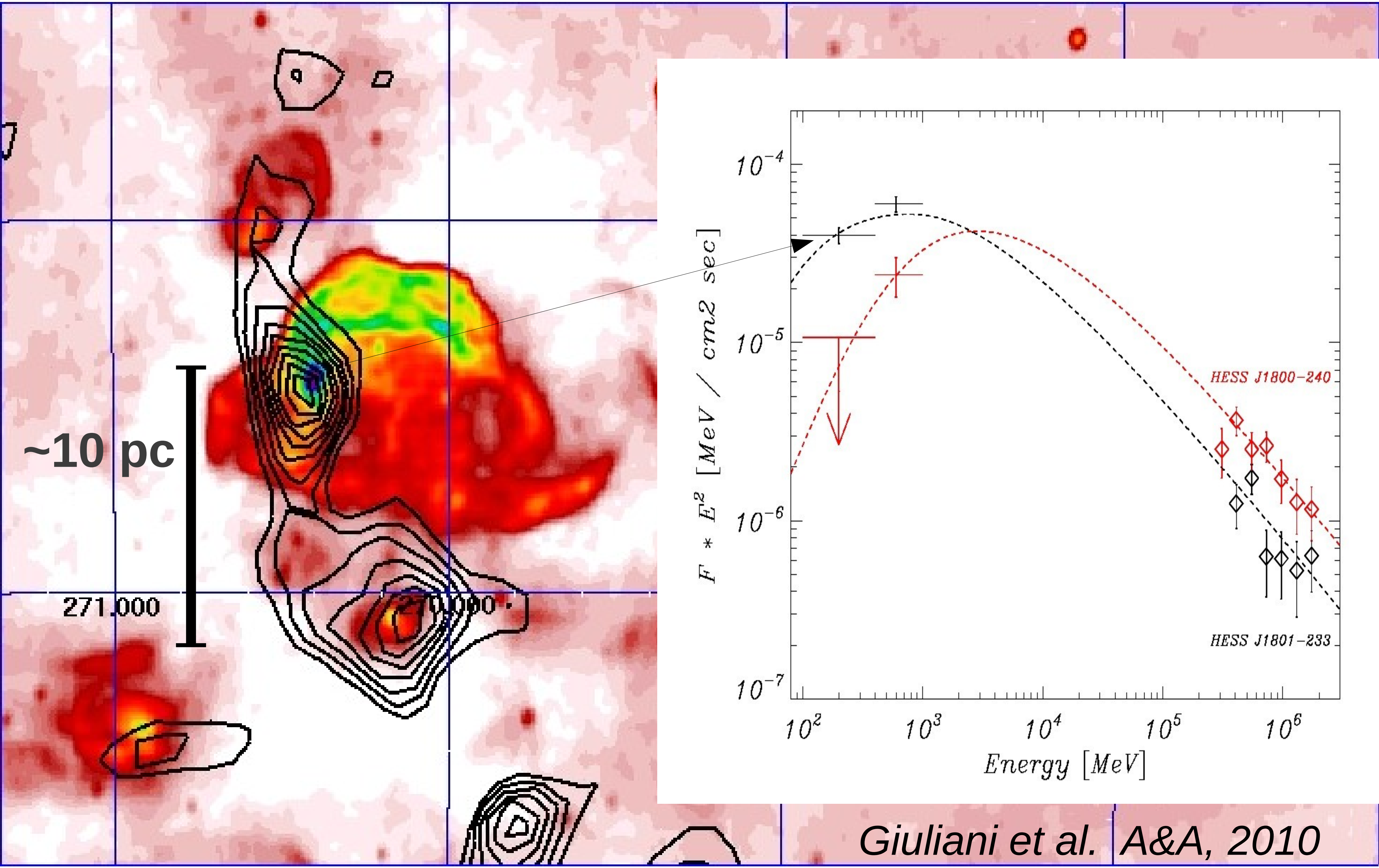
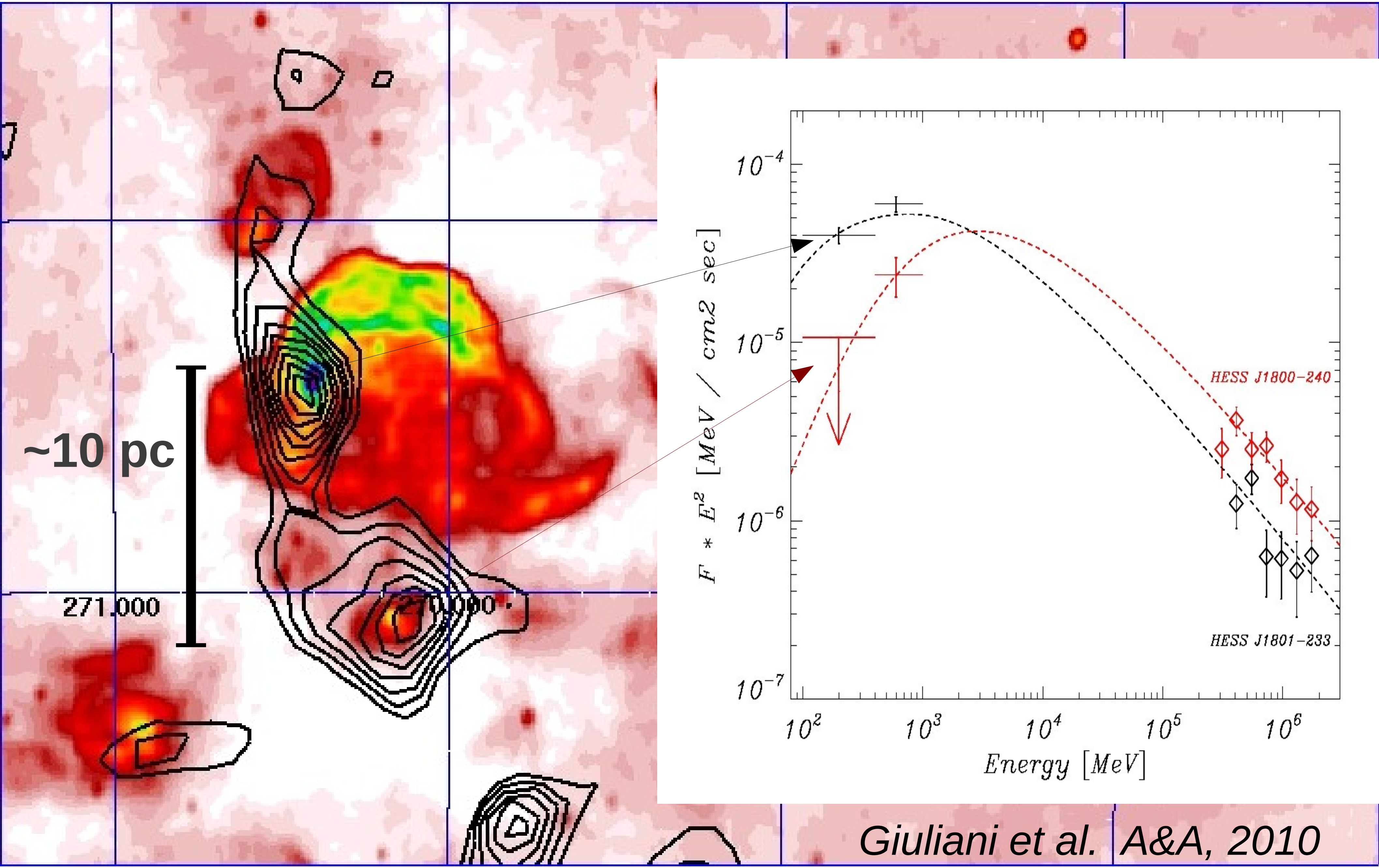


SNRs at “low” energy : diffusion of CRs



Giuliani et al. A&A, 2010

SNRs at “low” energy : diffusion of CRs



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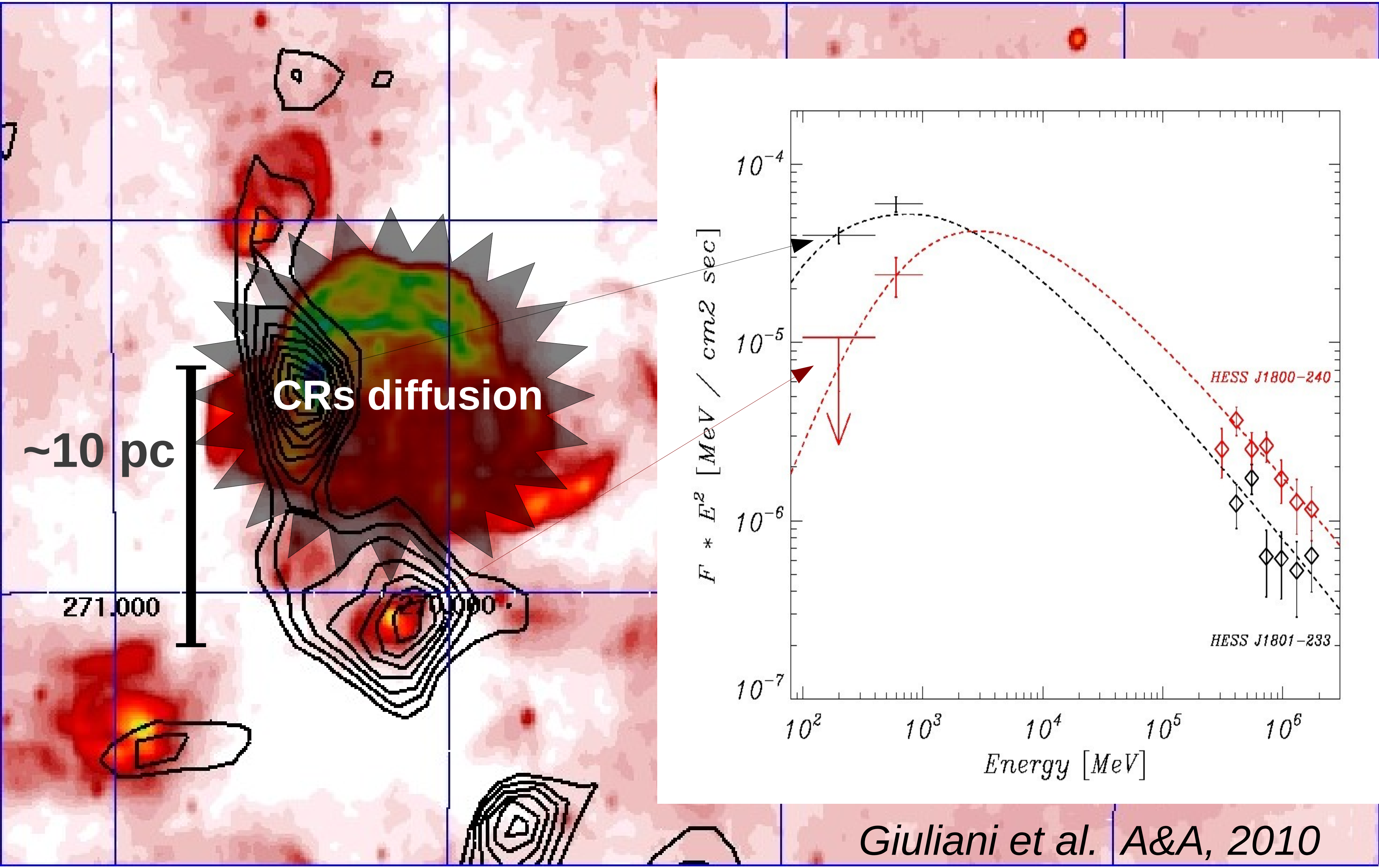
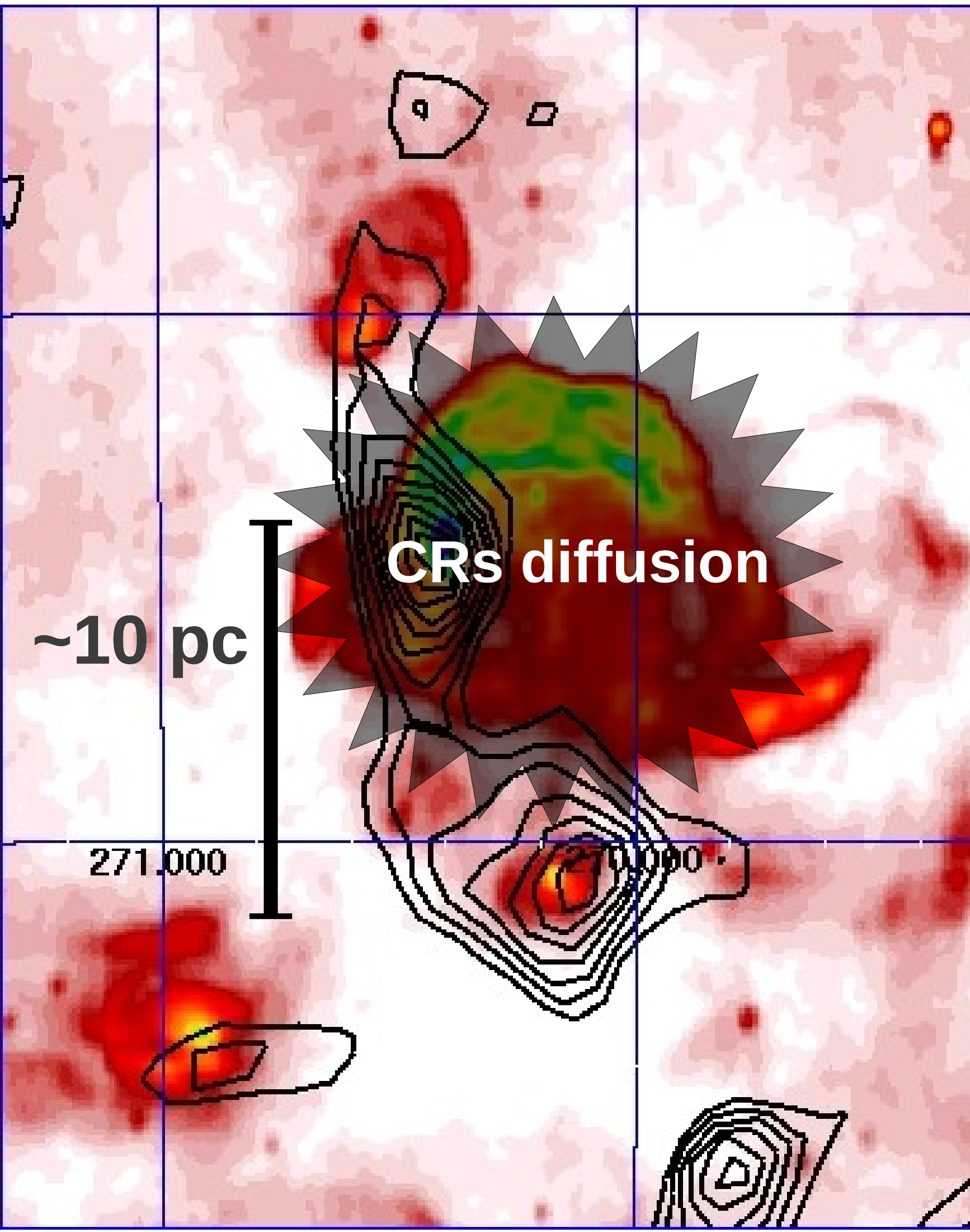


SNRs at “low” energy : diffusion of CRs



In a diffusion regime CRs fill the volume around SNRs up to:

$$R \sim (2D(E)\, t)^{0.5}$$

For middle-aged SNRs (10^4 yrs) **and slow D** (~ 1-2 10^{26} $(E/10\ \mathrm{GeV})^{0.5}$) **:**

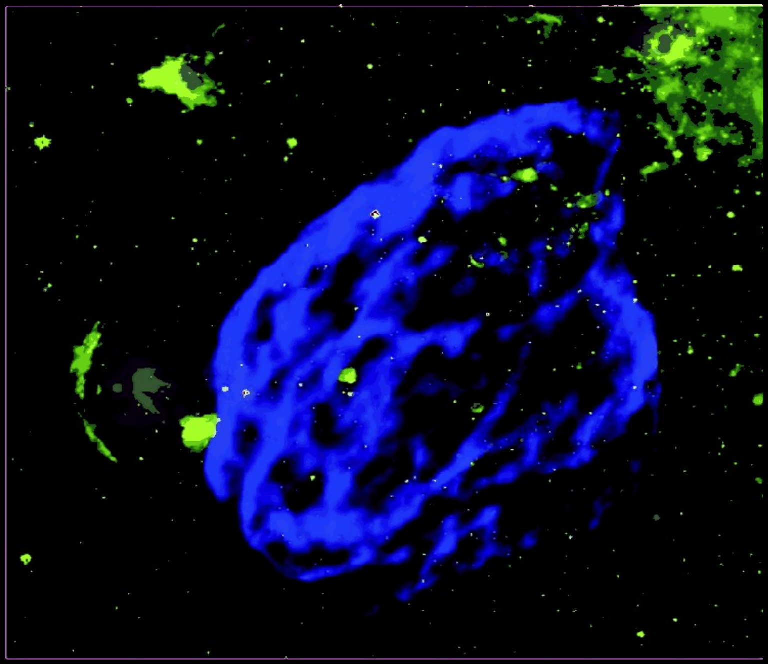
$$R \sim 10\ \mathrm{pc}$$

--> low-energy cutoff in the CRs spectrum @ ~ 10 GeV

Giuliani et al. A&A, 2010

SNR W44

Age : ~ 20000 yr
Distance : ~ 3 Kpc
Type : mixed-morphology



Ideal Laboratory for CRs Study :

SNR W44

Age : ~ 20000 yr
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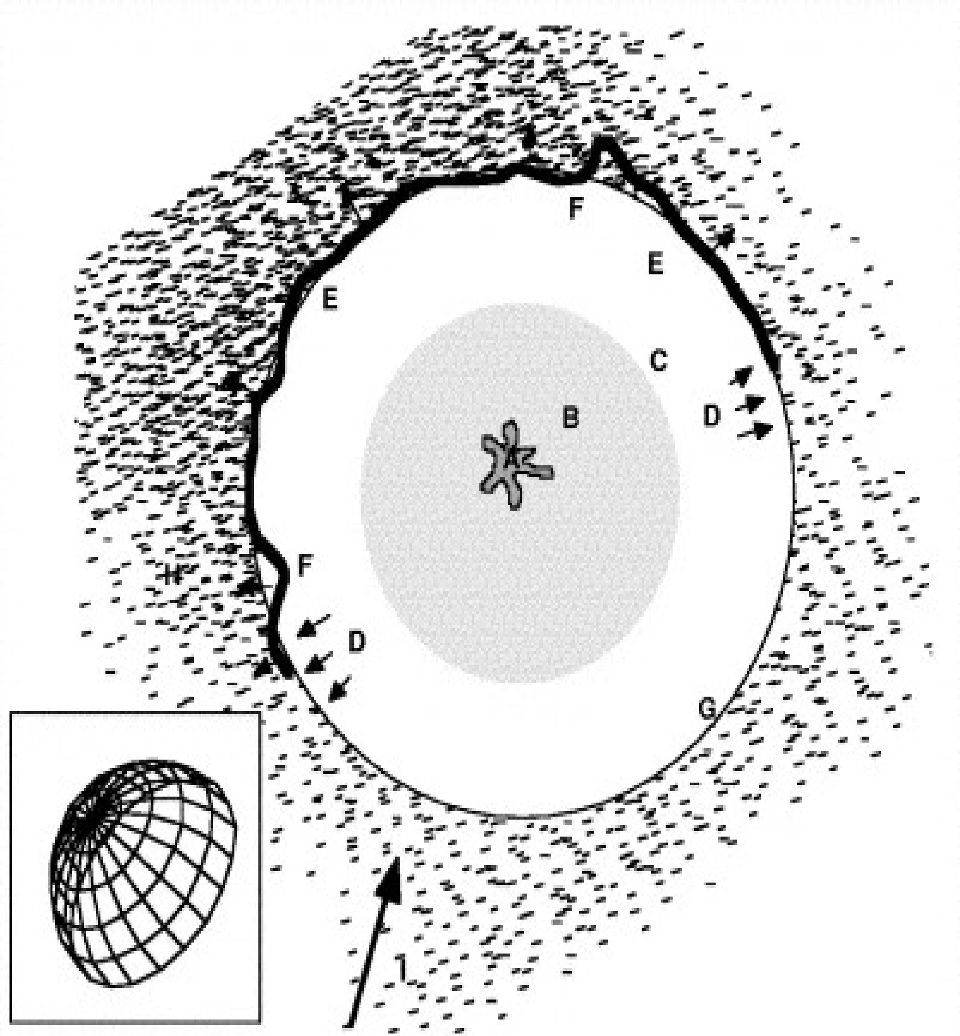
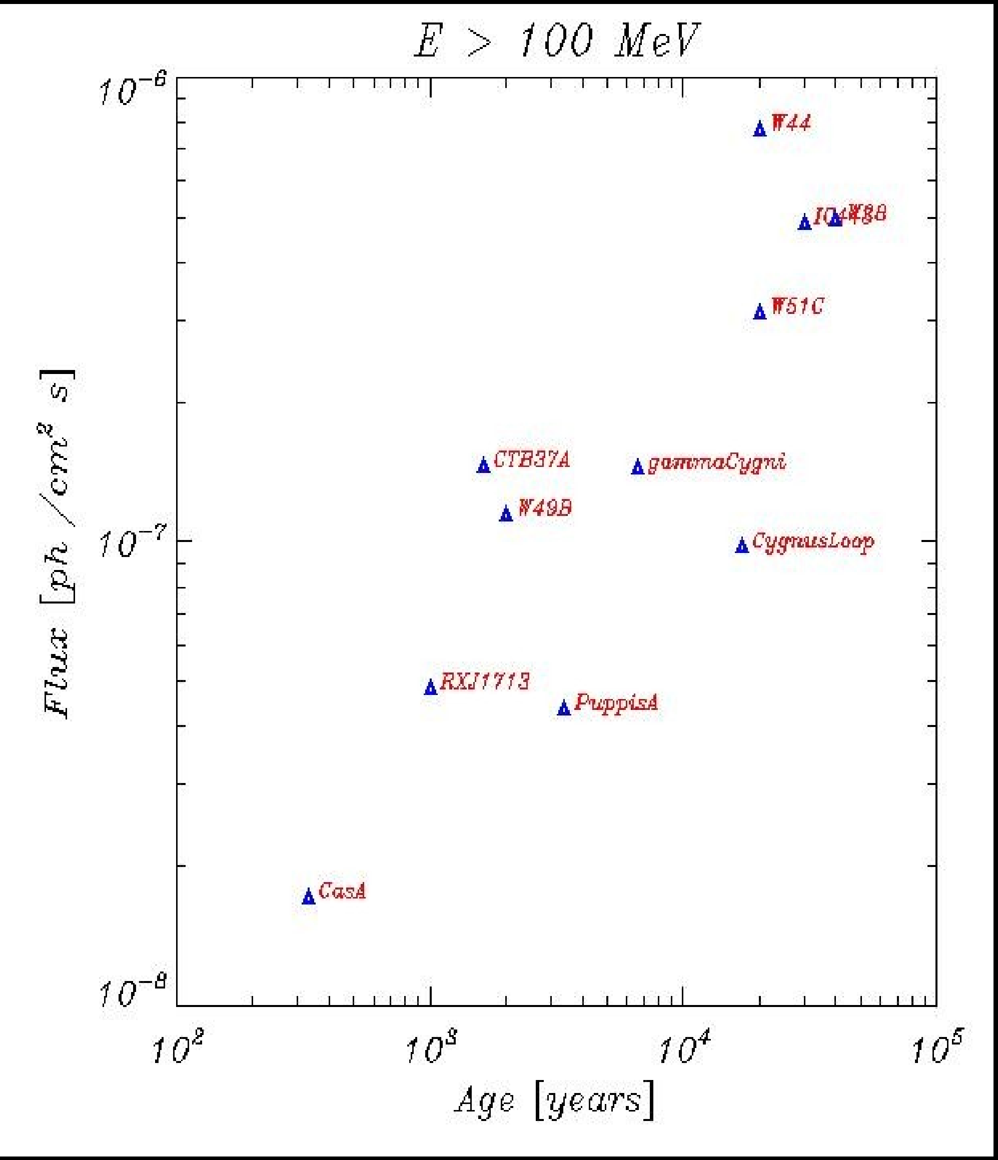
Type : mixed-morphology



1) Expanding in a dense medium
[Reach et al . 2005]

Maser OH (1720 Hz) emission
from SNR-MC interaction
[Claussen et al. 1997, Hoffman et al. 2005]



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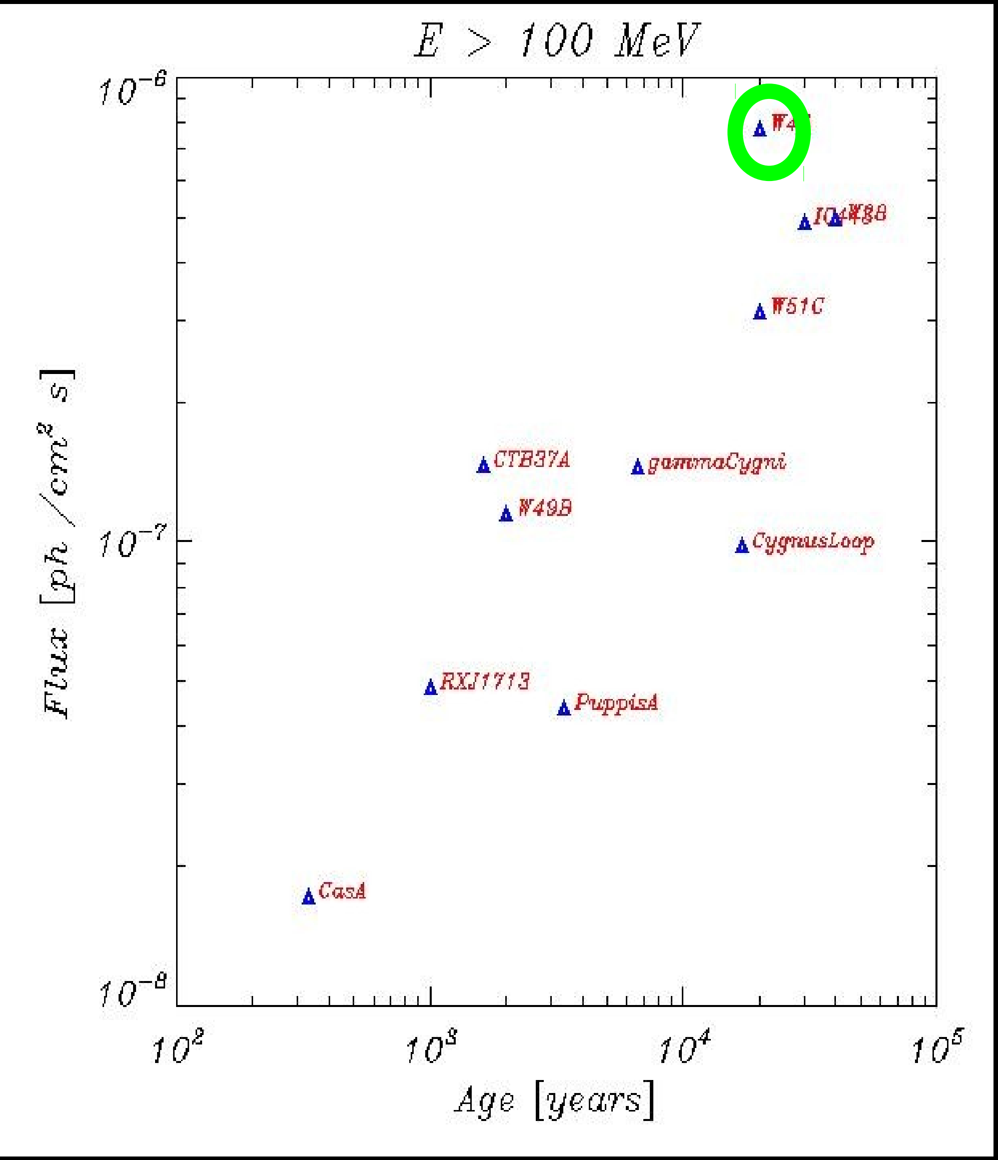
2) Strong non-thermal emission in radio e gamma-ray band

Observed over very wide
radio (10 MHz to 10 GHz)
and gamma (50 Mev-50 GeV) bands

SNR W44



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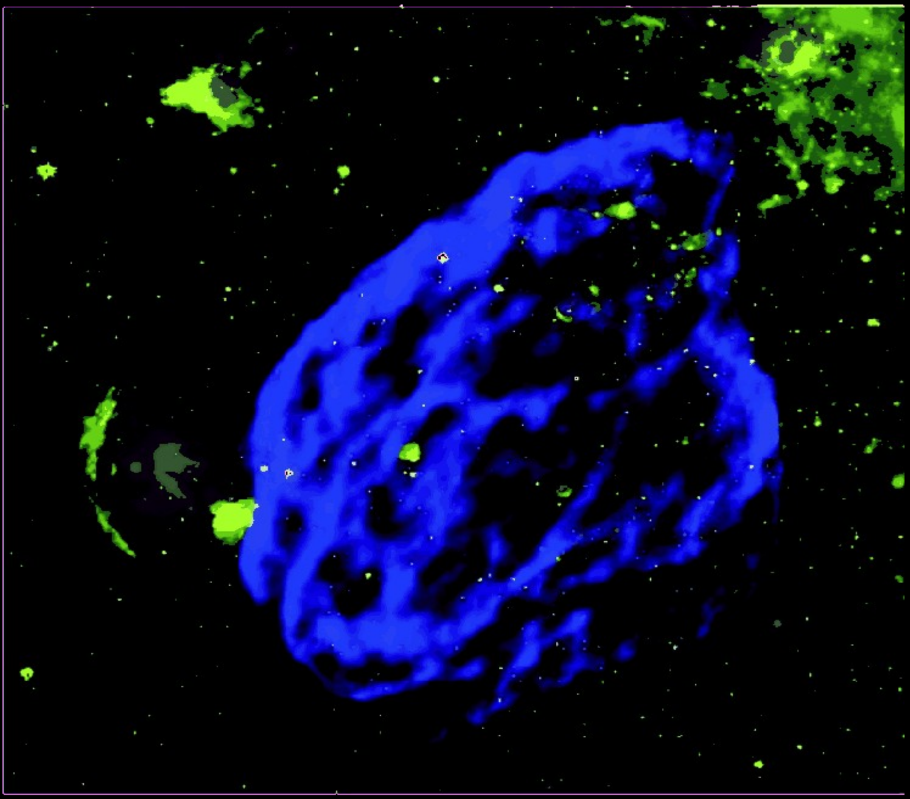

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2) Strong non-thermal emission in radio e gamma-ray band

3) Large angular dimensions

Morphology and spatially resolved spectrum
(in both radio and gamma bands)

Radio Spectrum

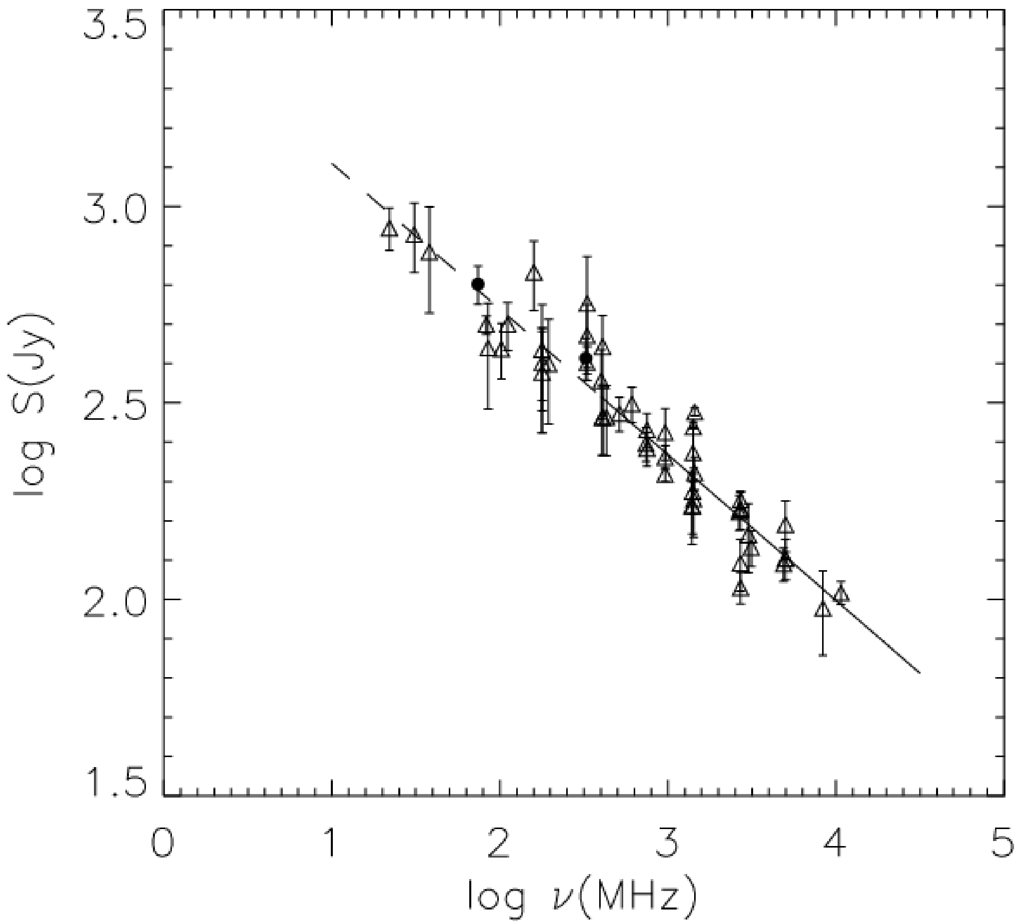
The radio spectrum of W44 is a power-law featurless in the frequency range ~ 10 MHz - 10 GHz (Castelletti et al 2007)

$S\ (Jy) = \nu^{-0.37+-0.02}$

Corresponding to an electrons spectrum :

$F \sim E^{-1.74}$ [particles / cm s MeV]

E ~ 300 MeV – 10 GeV (B = 10 uG)
~ 100 MeV – 3 GeV (B = 100 uG)



Fermi detection of W44

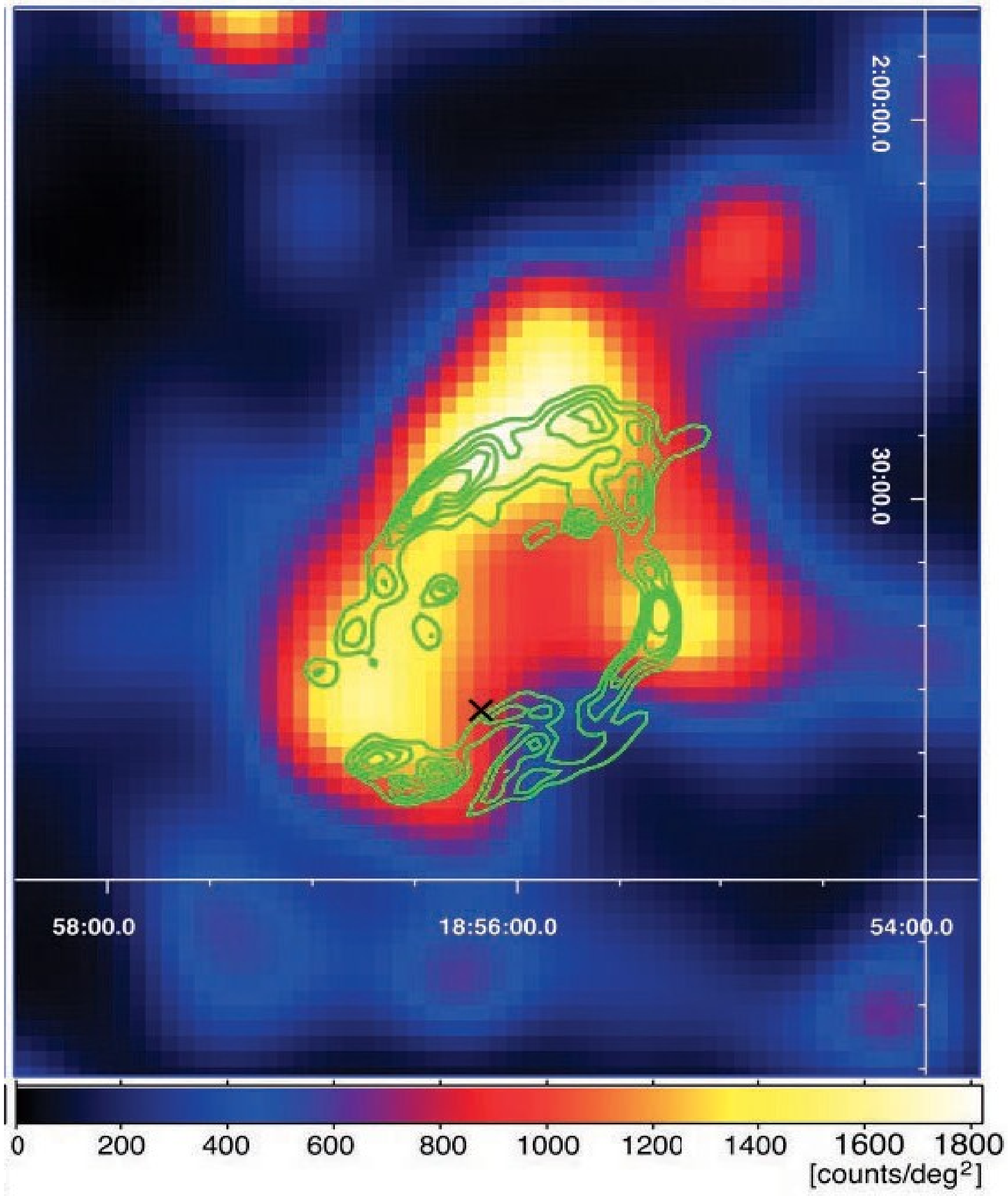


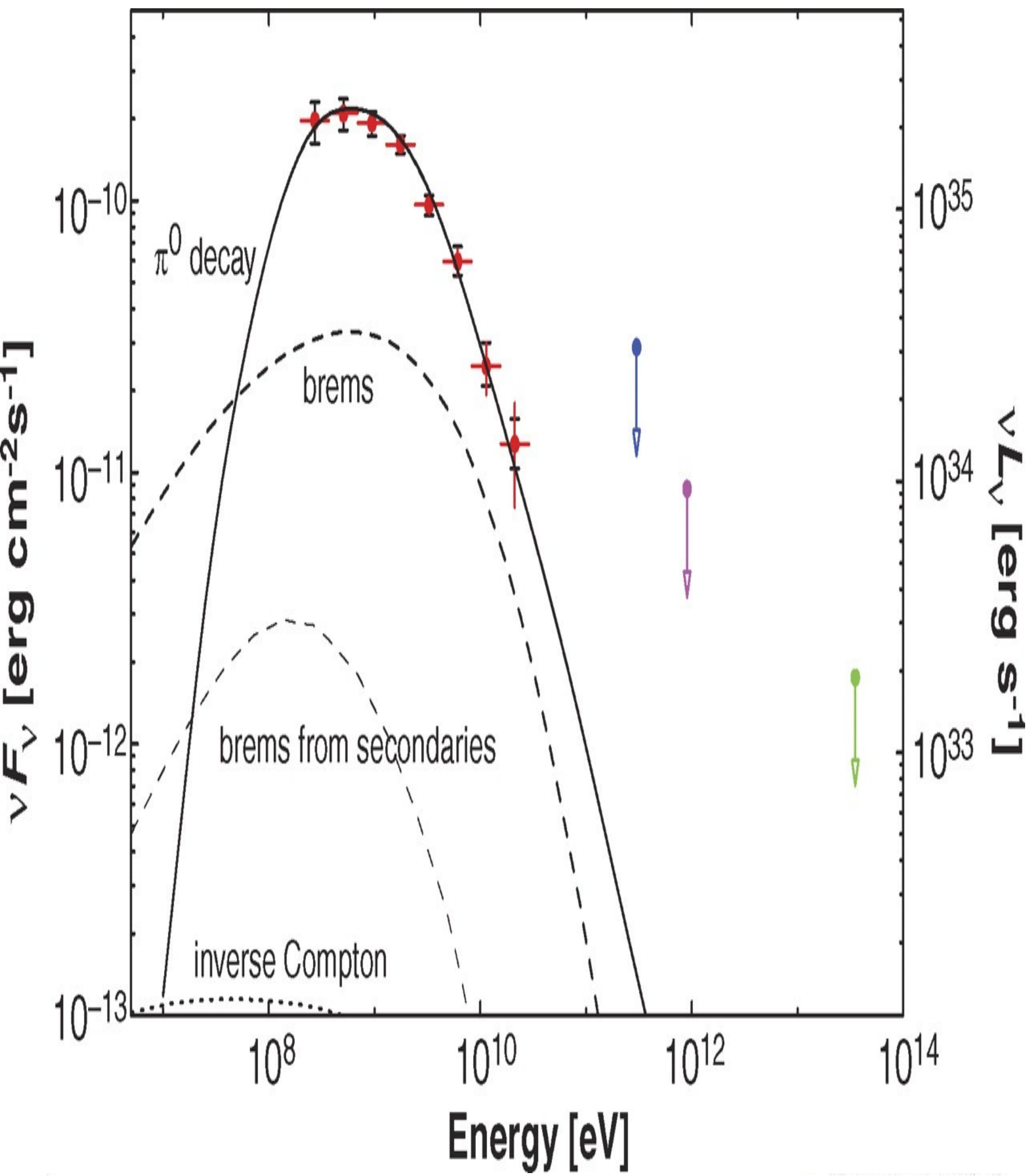
Image for E >2 GeV

Gamma-ray emission correlated to the shell (enhanced where ISM is more dense)

Fermi/LAT measured the spectrum of W44 in the energy band 200 MeV – 50 GeV

Abdo 2010, Science, 327

Fermi detection of W44



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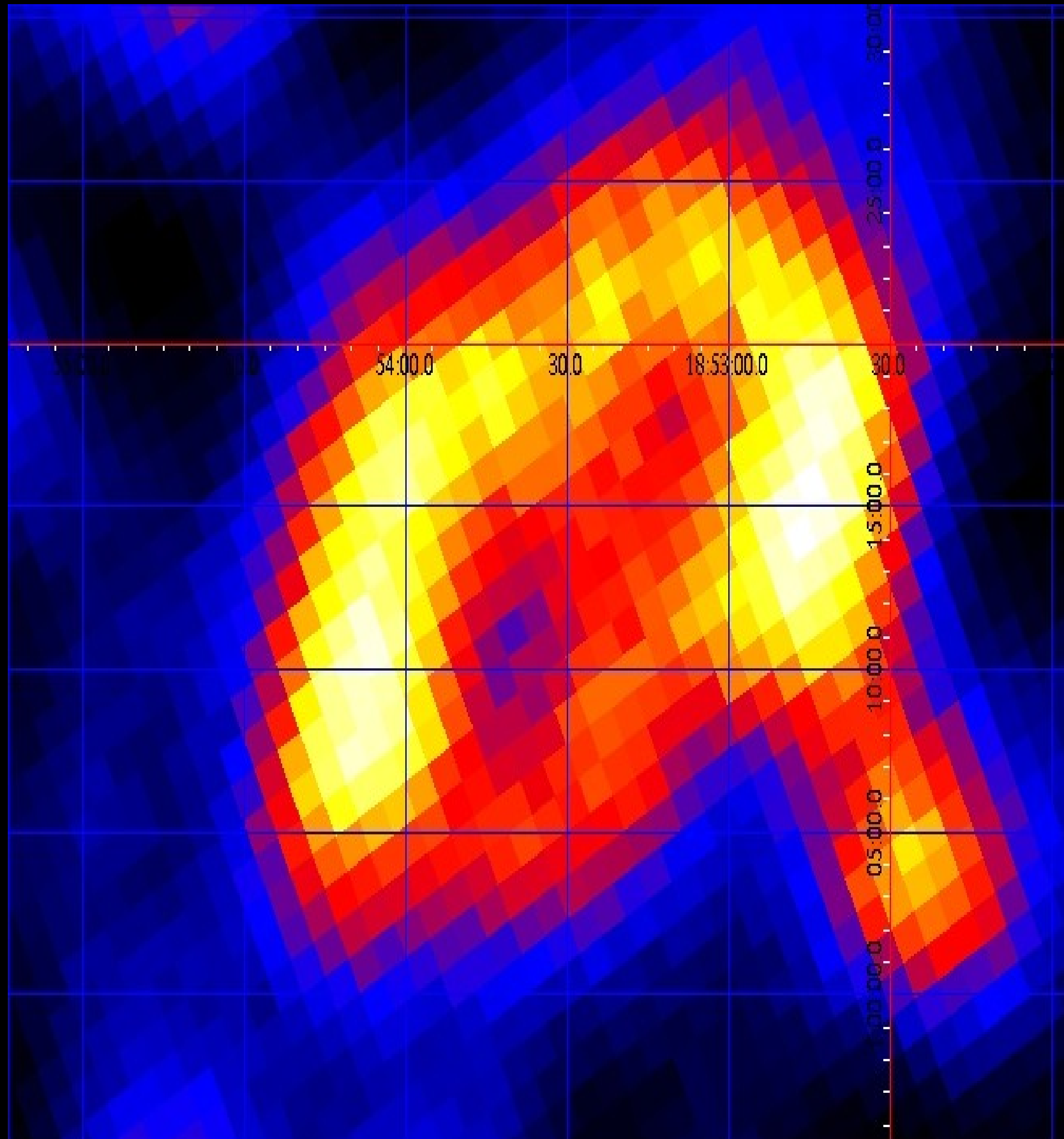
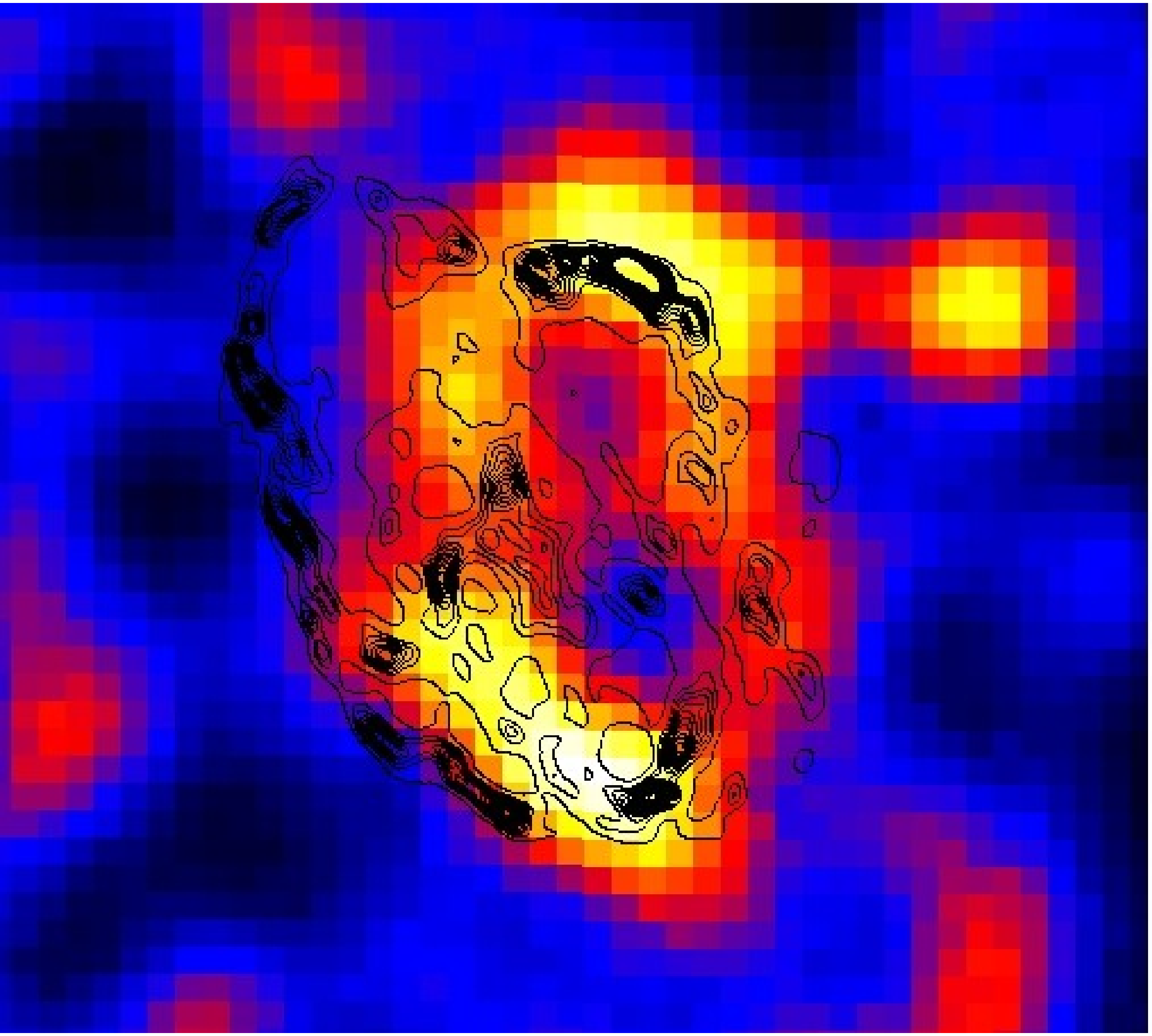


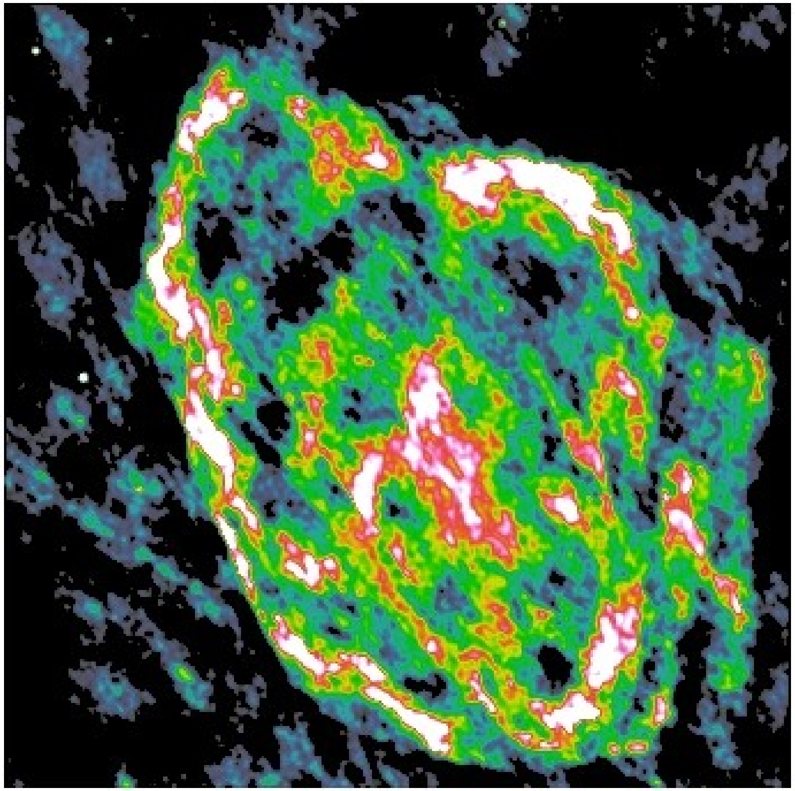
Giuliani et al. ApJ, 2011

AGILE detection of W44

AGILE E > 400 MeV



1.4 Ghz



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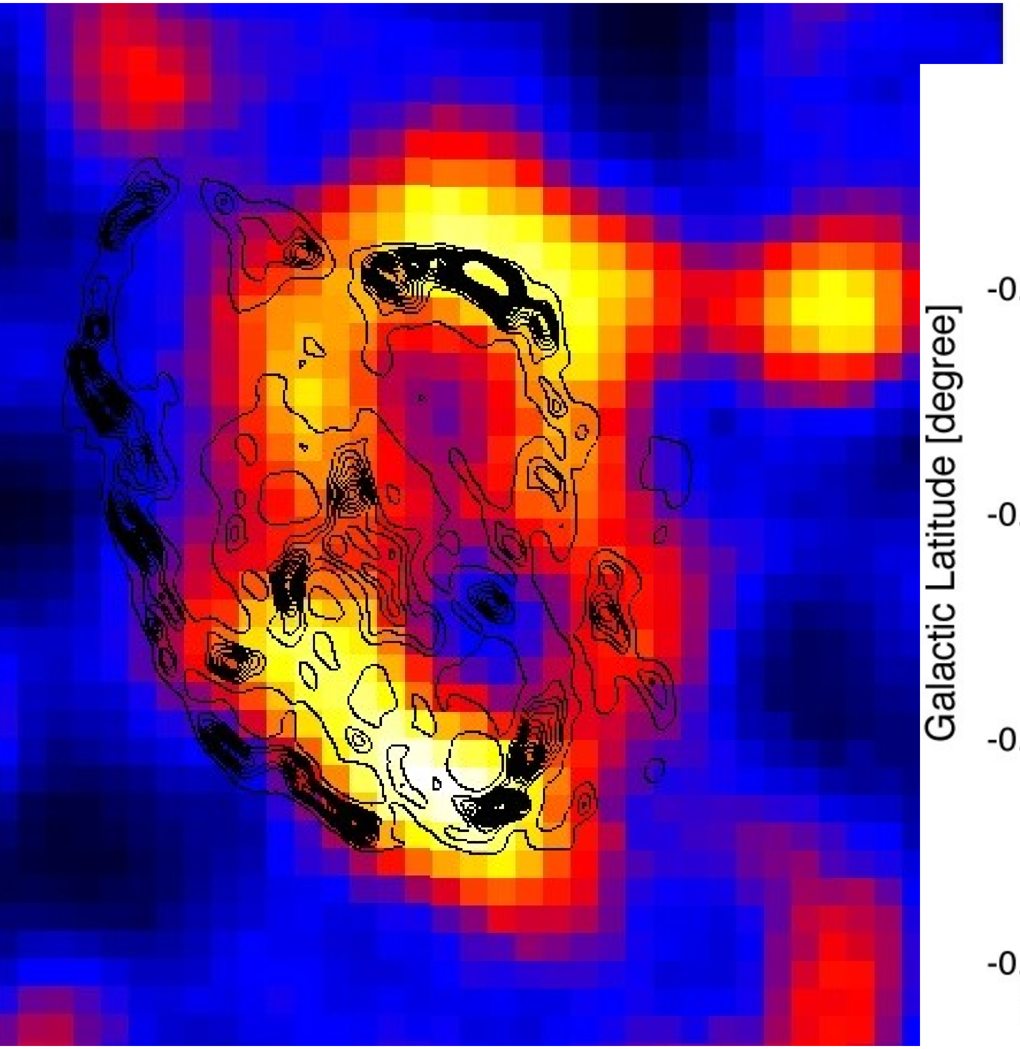
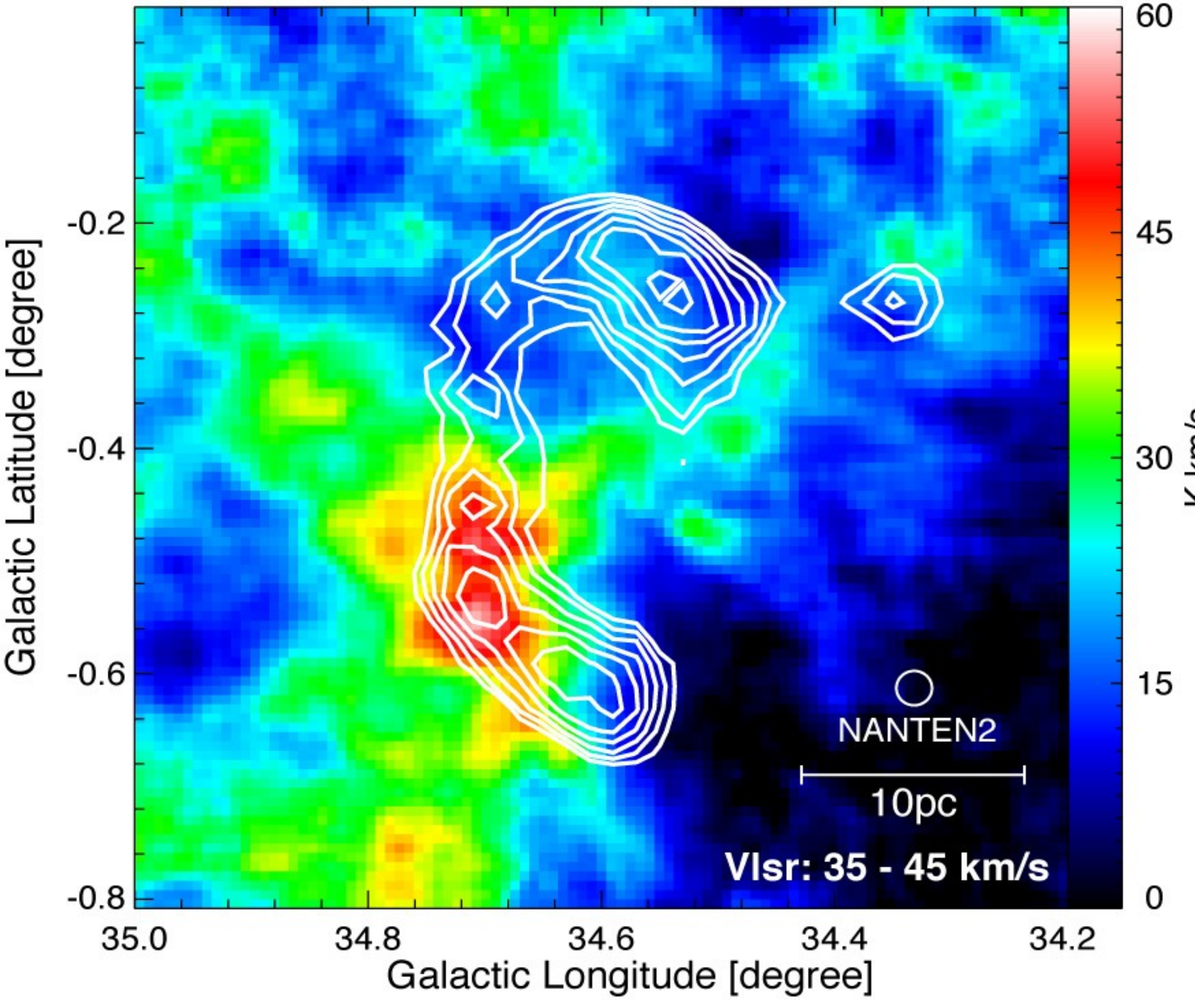
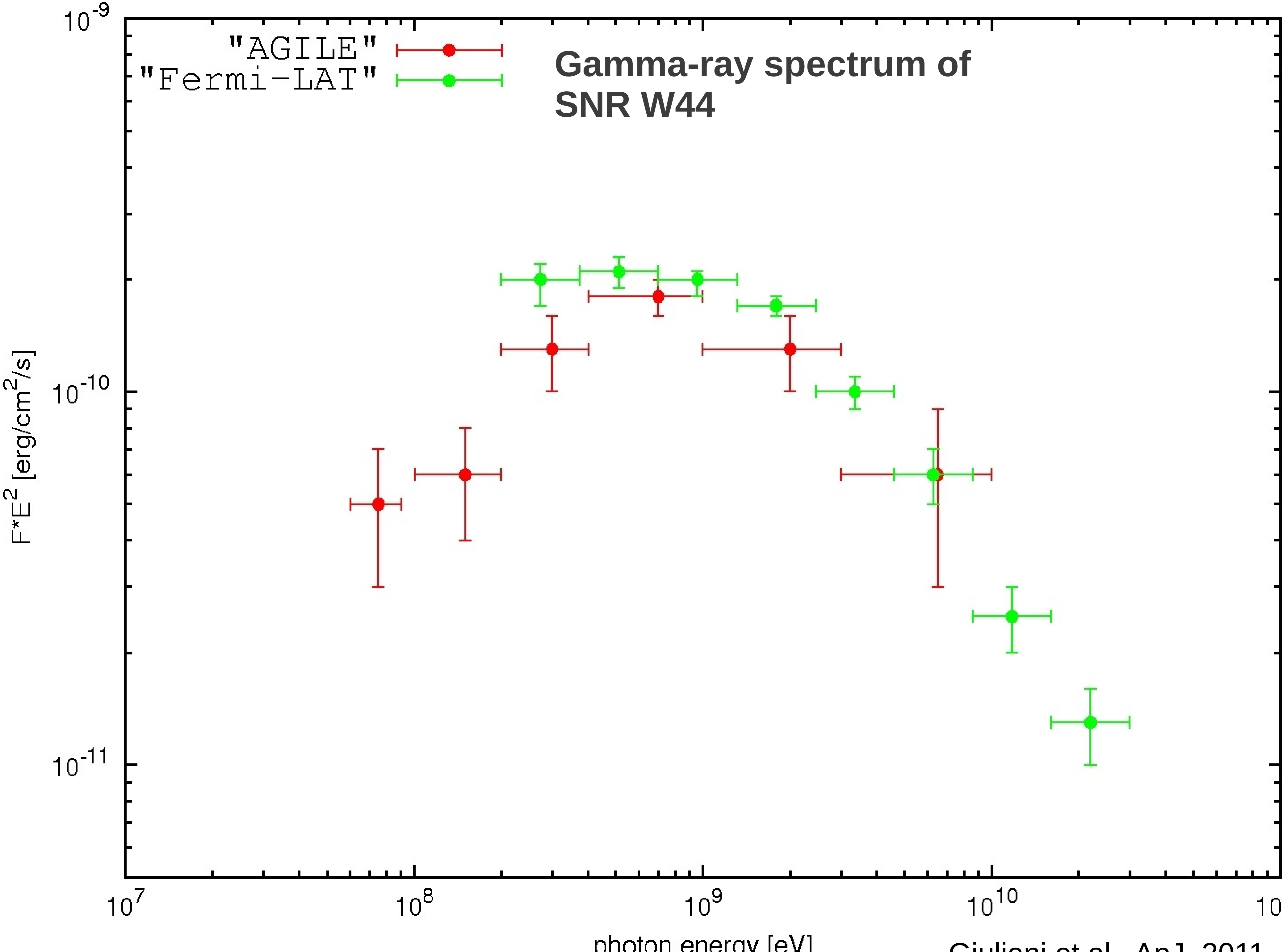
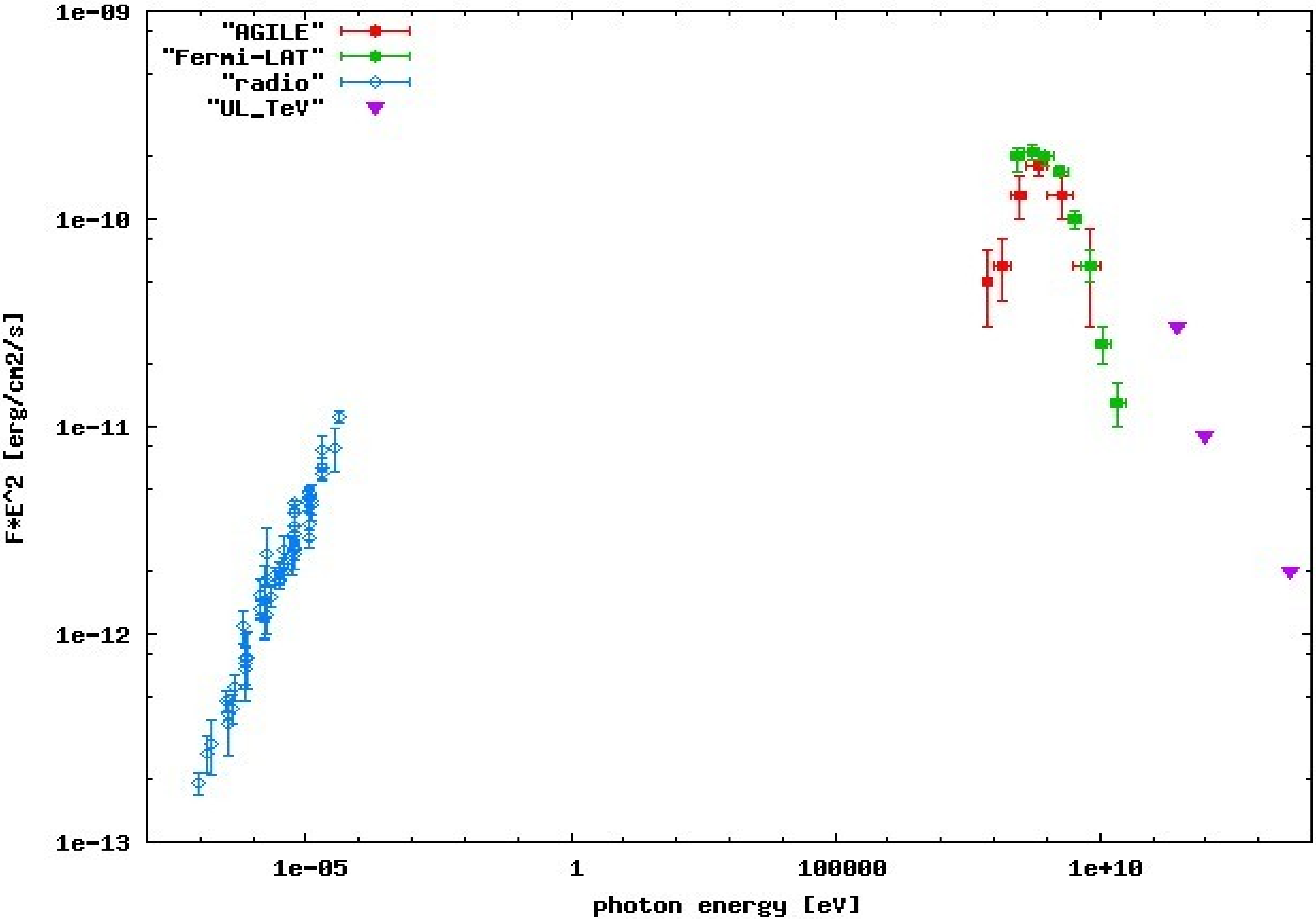


Nanten





Giuliani et al. ApJ, 2011



"AGILE"
"Fermi-LAT"
"radio"
"UL_TeV"
1e-09
1e-10
1e-11
1e-12
1e-13
F*E^2 [erg/cm2/s]
1e-05
1
100000
1e+10
photon energy [eV]

Leptonic models

Electrons energy distribution:

$$F_e(E) = K_e E^{-p} e^{-\frac{E}{E_c}}$$

$$F_e(E) = K_e E^{-p} e^{-\frac{E_c}{E}}$$

$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1 + \frac{E}{E_c}\right)\right)^{p_1 - p_2}$$

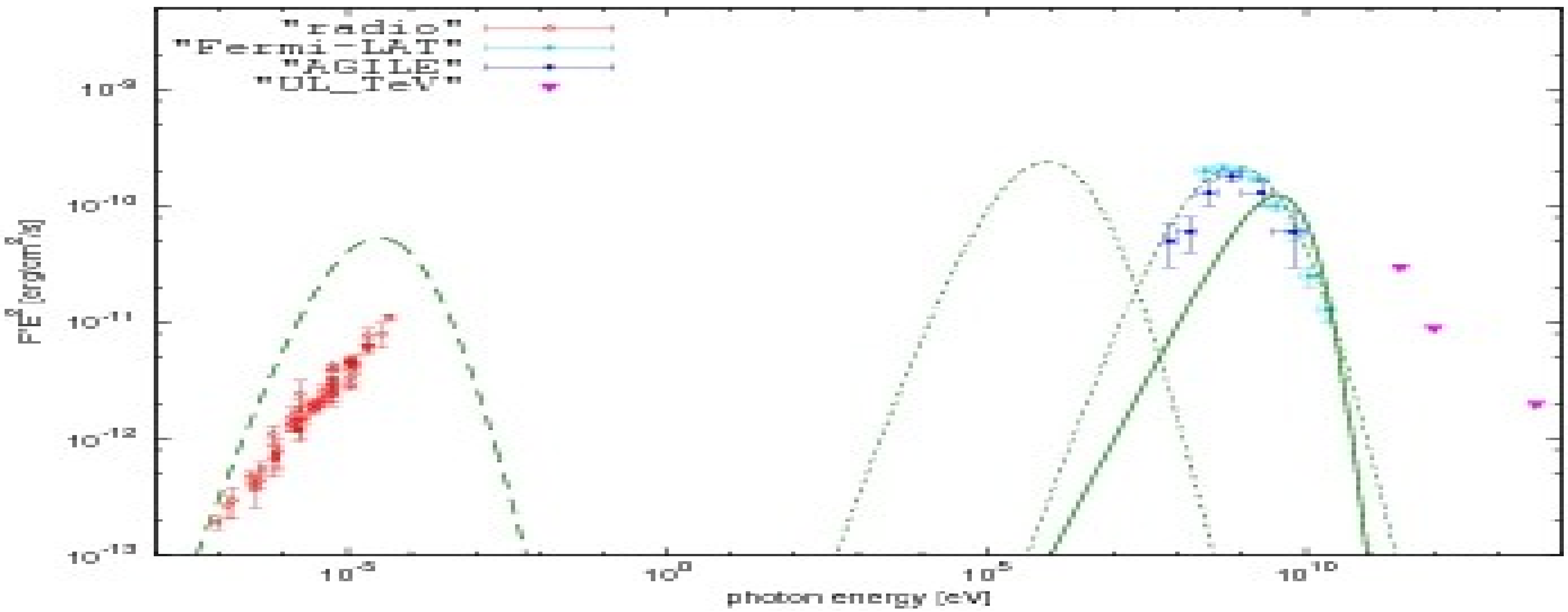
Gamma-rays emission process :

- *Inverse Compton* (B free parameter)

  - on ISRF photons
  - on CMB photons

- *Bremsstrahlung* (B, n free parameters)

Leptonic model : IC, ISRF seed photons



Ambient : *B : 3 μG*

n : 1 cm⁻³

Electrons Spectrum :

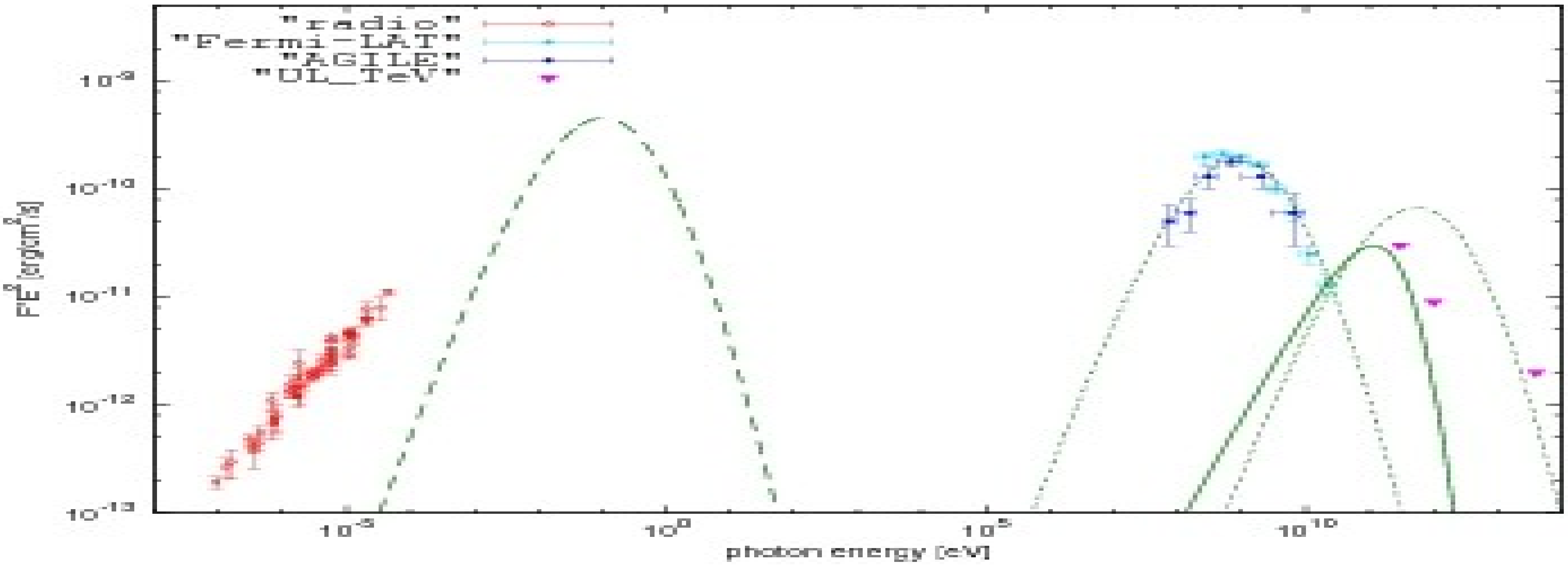
$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1 + \frac{E}{E_c}\right)\right)^{p_1 - p_2}$$

p1 = 0

p2 = 8

E_c = 22 GeV

Leptonic model : IC, CBR seed photons



Ambient : *B : 10 µG*

n : 1 cm^{-3}

Electrons Spectrum :

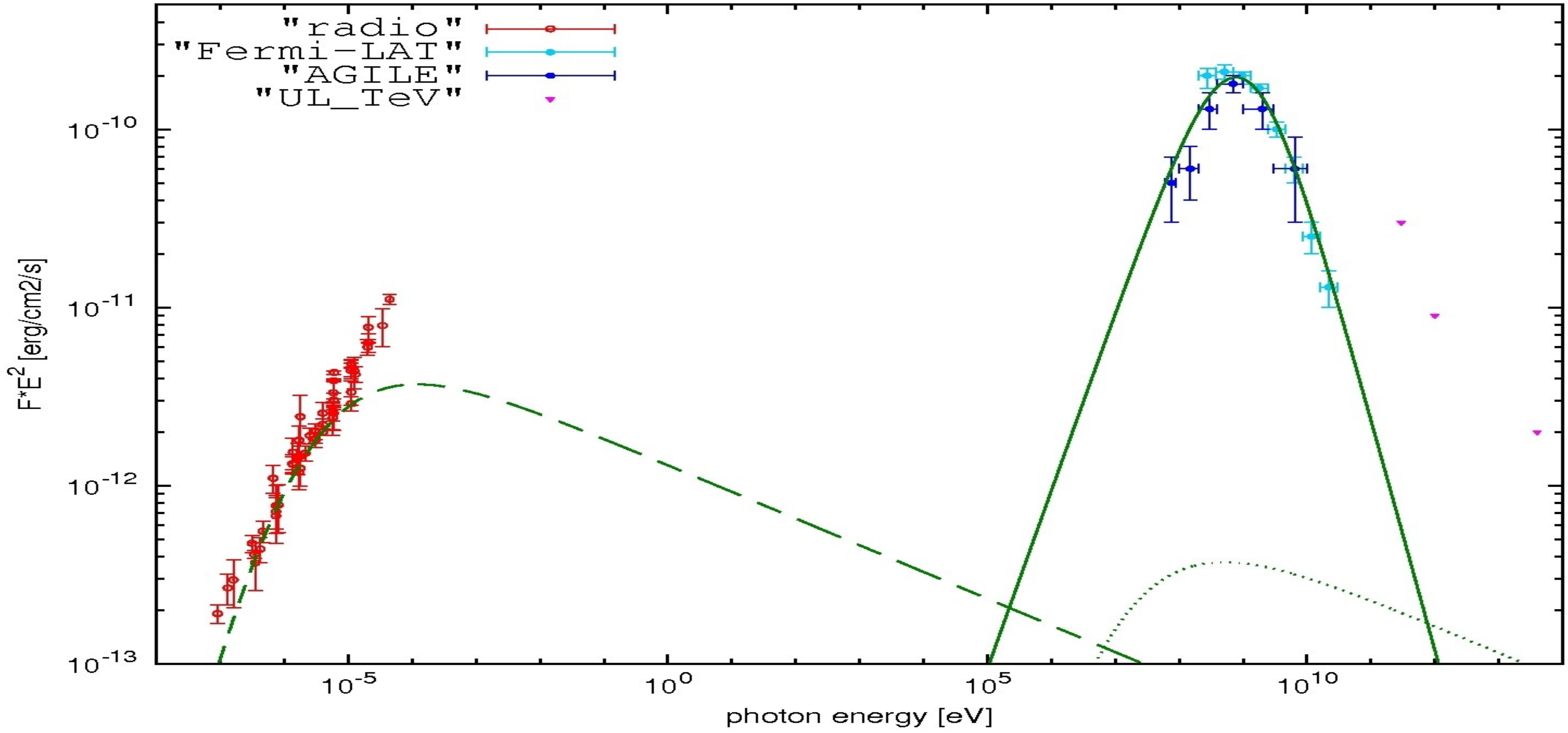
$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1+\frac{E}{E_c}\right)\right)^{p_1-p_2}$$

p1 = 0

p2 = 8

E_c = 700 GeV

Leptonic model : Bremsstrahlung



Ambient : *B : 20 µG*

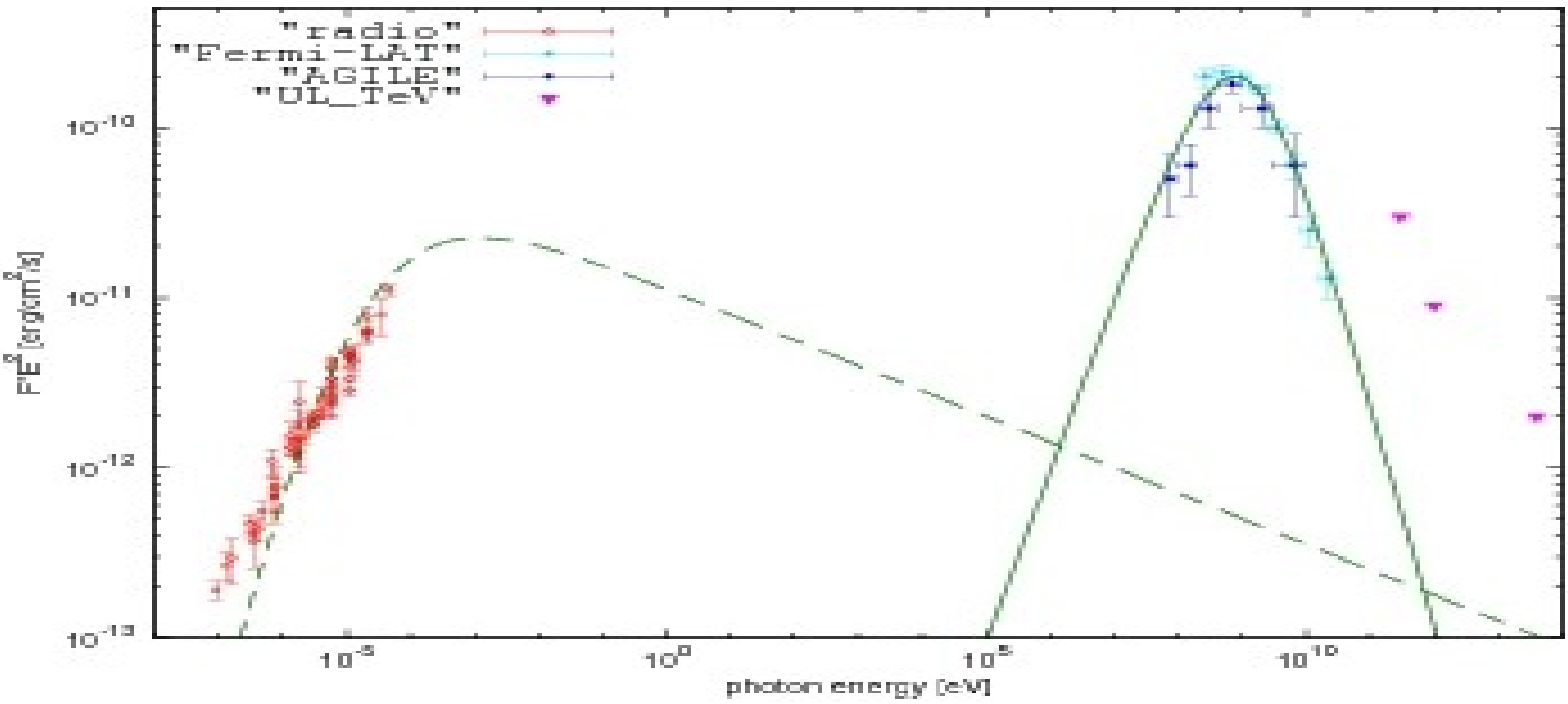
n : 300 cm^{-3}

Electrons Spectrum :

$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1+\frac{E}{E_c}\right)\right)^{p_1-p_2}$$

p1 = 0
p2 = 3.3
E_c = 1 GeV

Leptonic model : Bremsstrahlung, B= 200

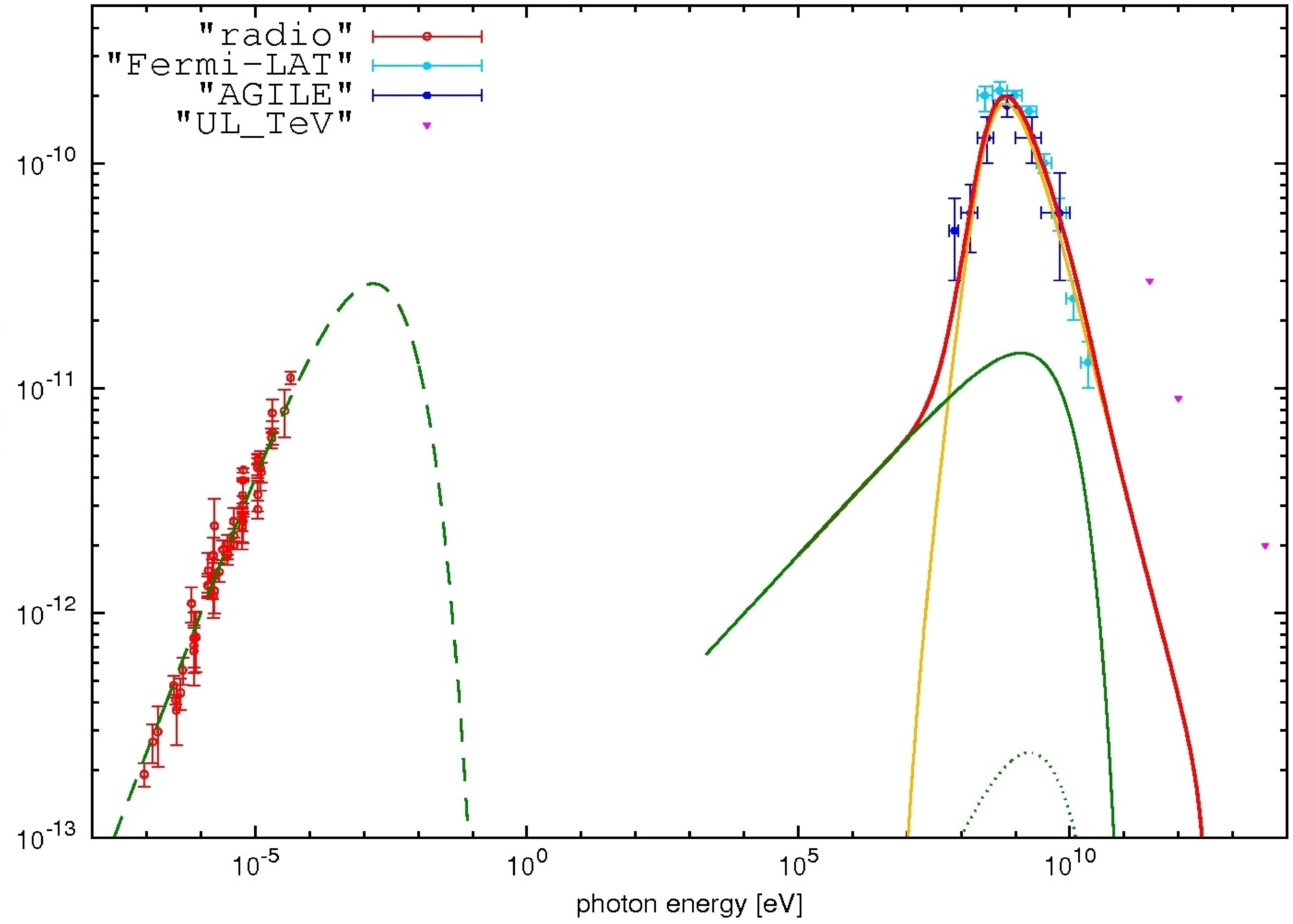


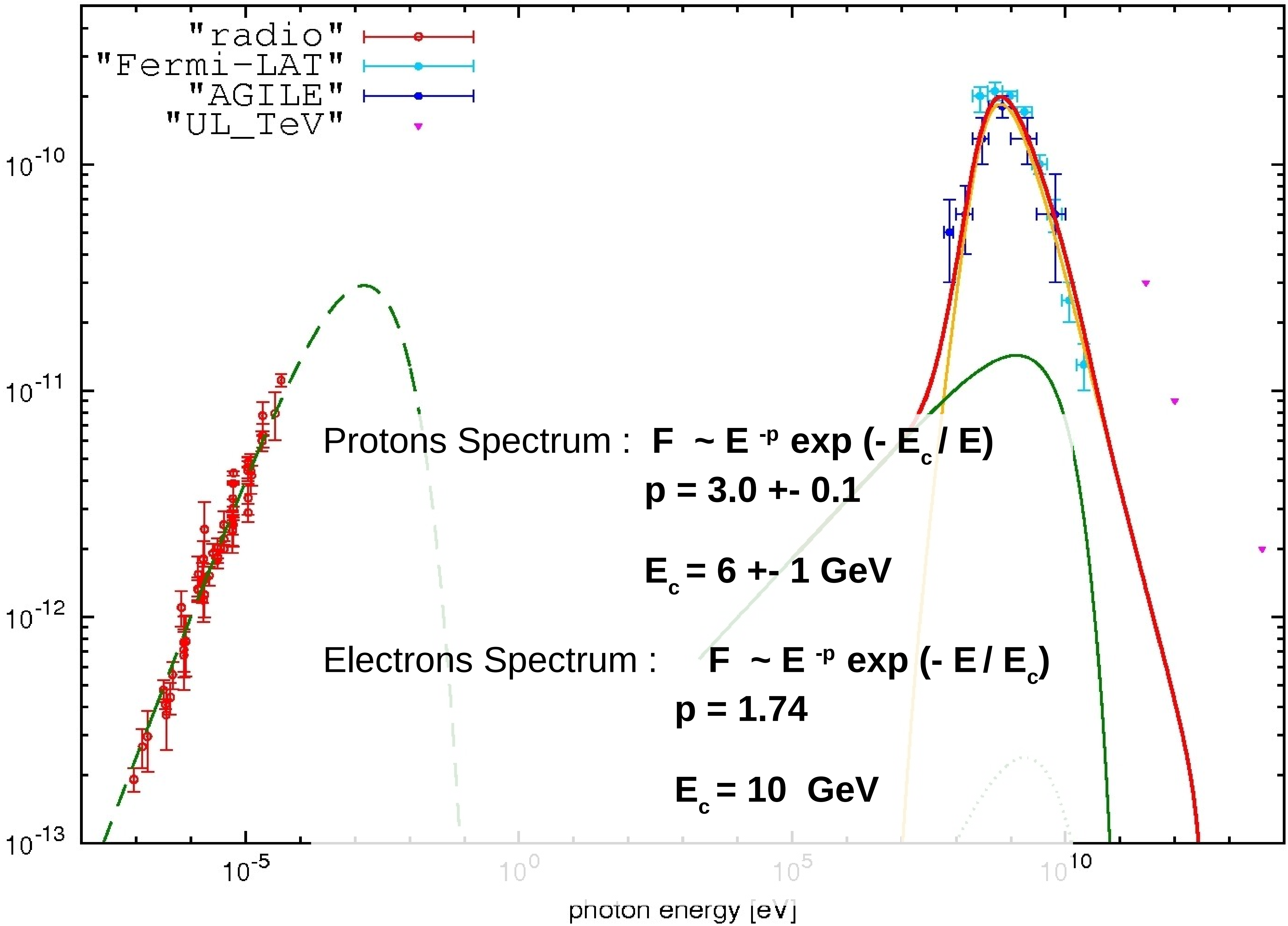
Ambient : *B : 200 µG*
n : 5000 cm^{-3}

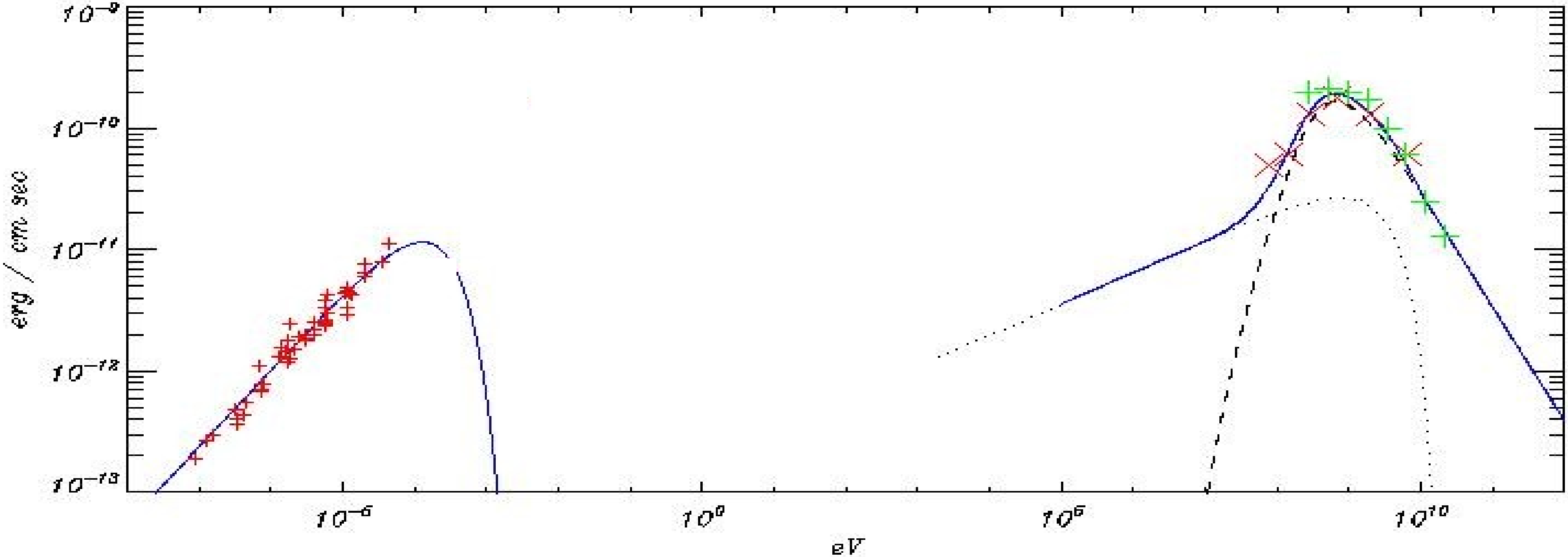
Electrons Spectrum :

$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1 + \frac{E}{E_c}\right)\right)^{p_1 - p_2}$$

p1 = 0
p2 = 8
E_c = 1 GeV


"radio"
"Fermi-LAT"
"AGILE"
"UL_TeV"
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-5}
10^{0}
10^{5}
10^{10}
photon energy [eV]


"radio"
"Fermi-LAT"
"AGILE"
"UL_TeV"
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-5}
10^{0}
10^{5}
10^{10}
photon energy [eV]
Protons Spectrum : $F \sim E^{-p} \exp(-E_c / E)$
$p = 3.0 +- 0.1$
$E_c = 6 +- 1$ GeV
Electrons Spectrum : $F \sim E^{-p} \exp(-E / E_c)$
$p = 1.74$
$E_c = 10$ GeV



B : 70.0000

n : 200

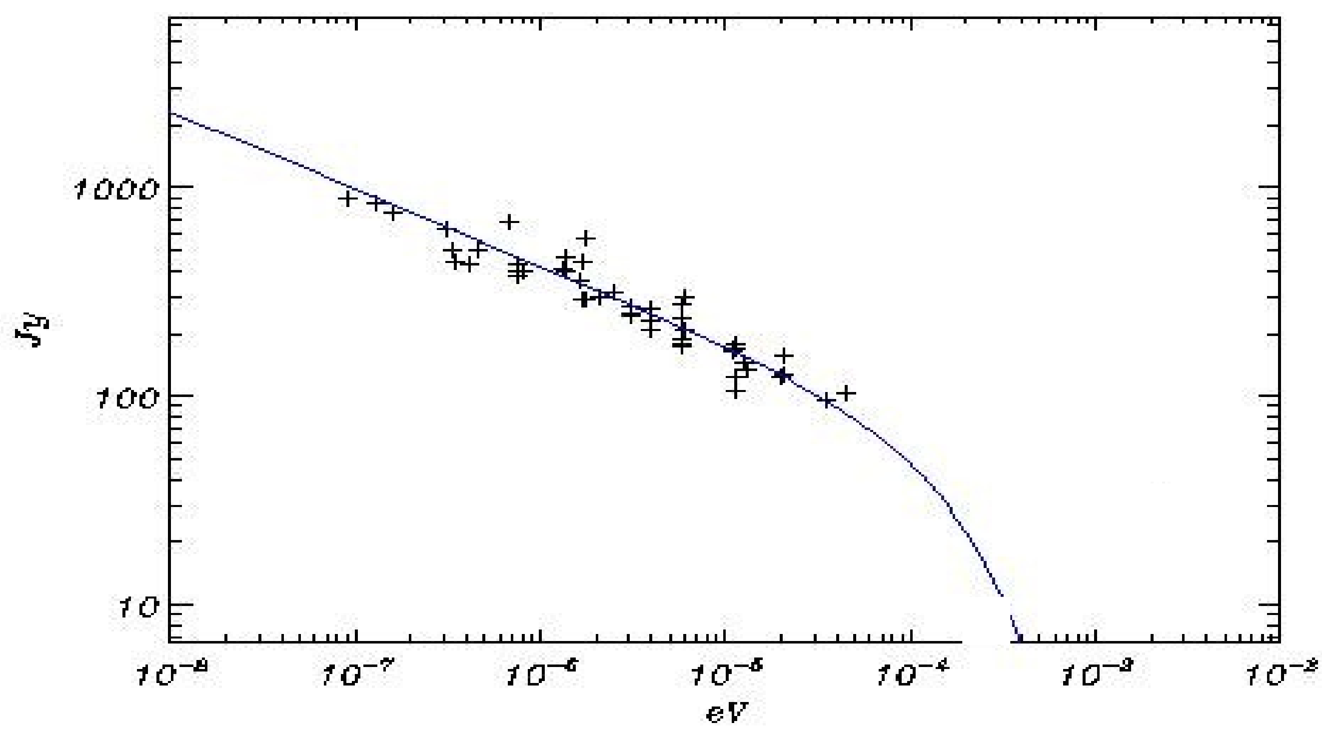
Ec : 7000.00

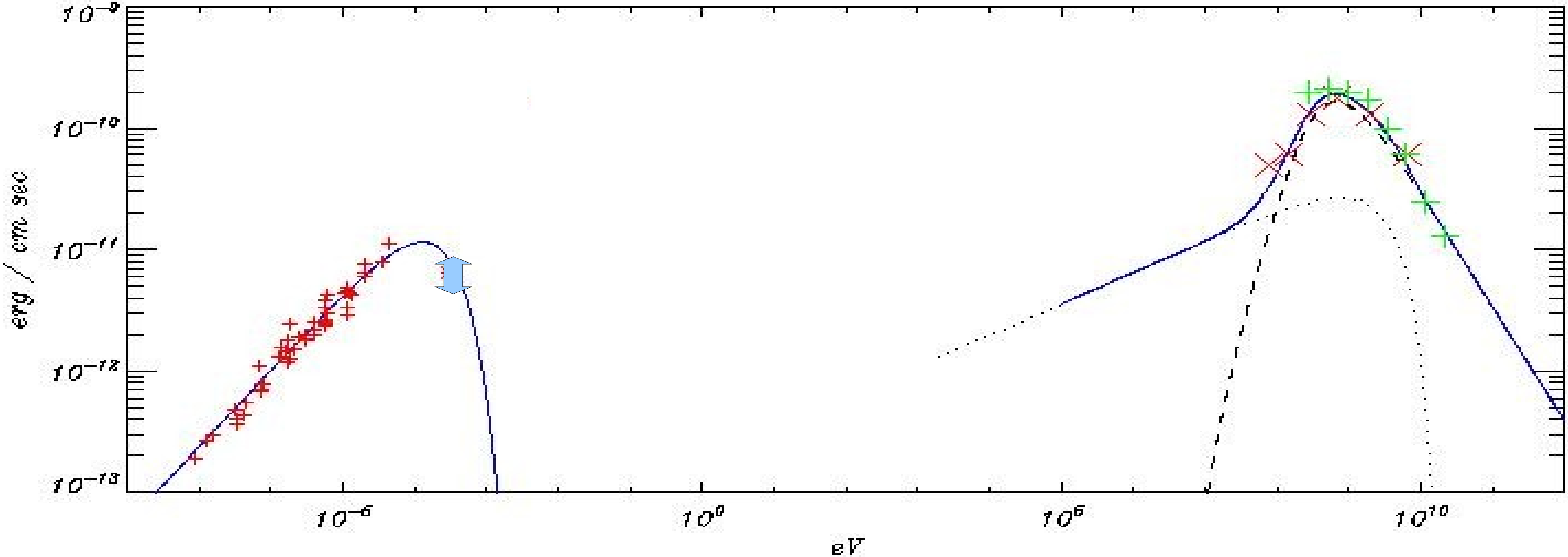
kp : 1.25000e+23

k : 2.01021e+10

p1 : 1.74000

p2 : 12





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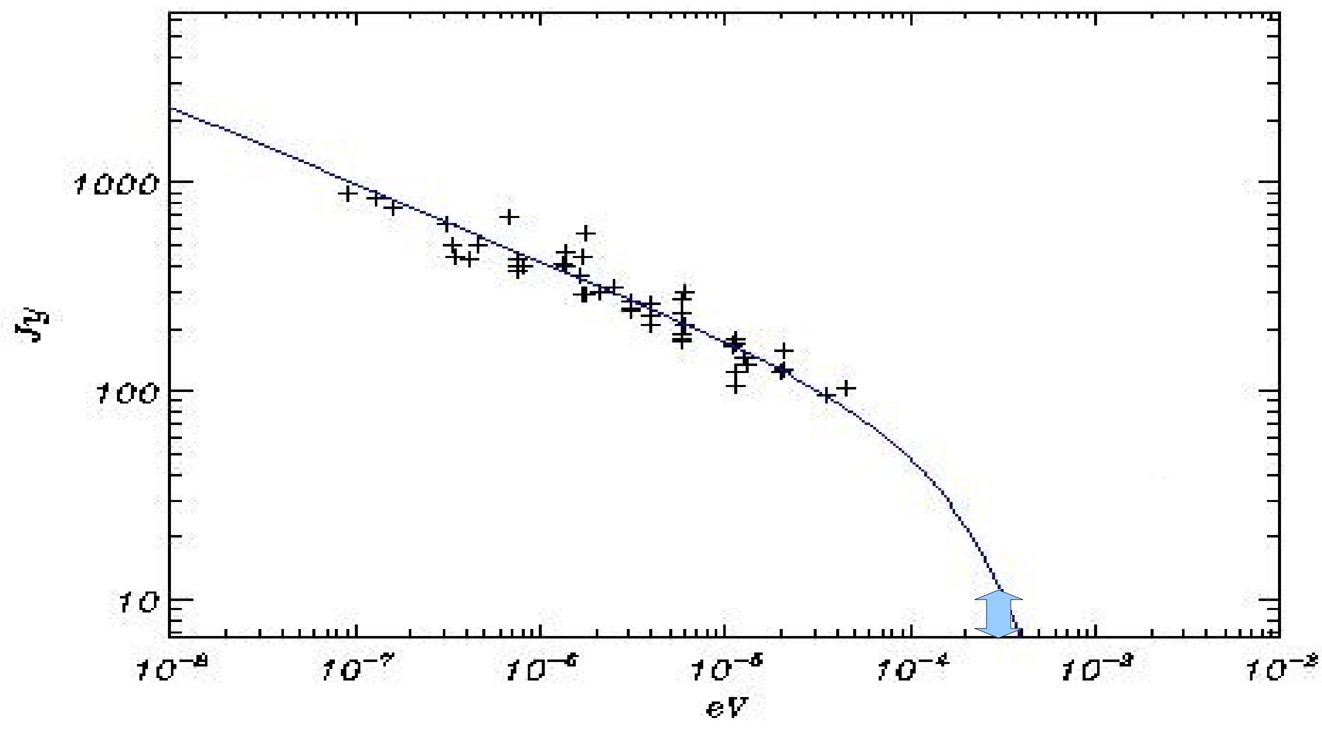
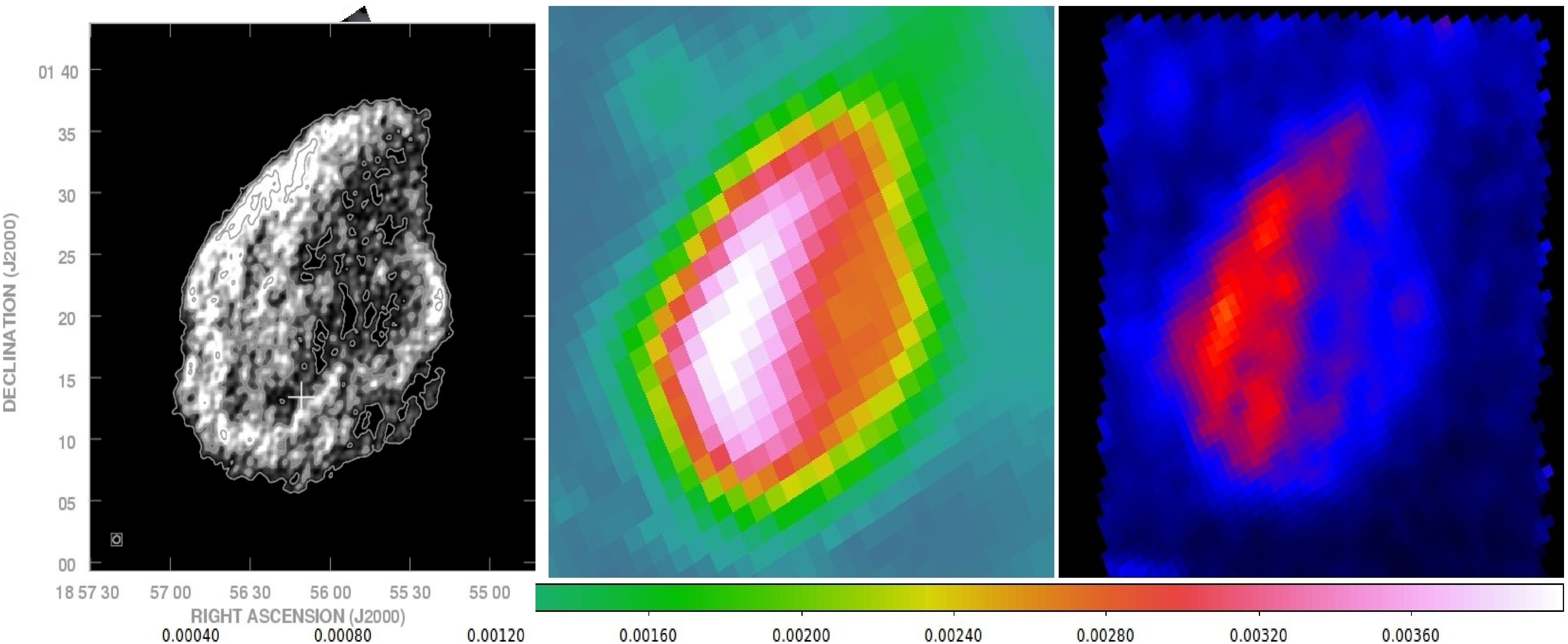
p1 : 1.74000

p2 : 12



High-Freq. radio map @ Medicina Radiotelescope

74 MHz | 5 GHz | 8 GHz



Pellizzoni, Giuliani, et al.

SNR W51C

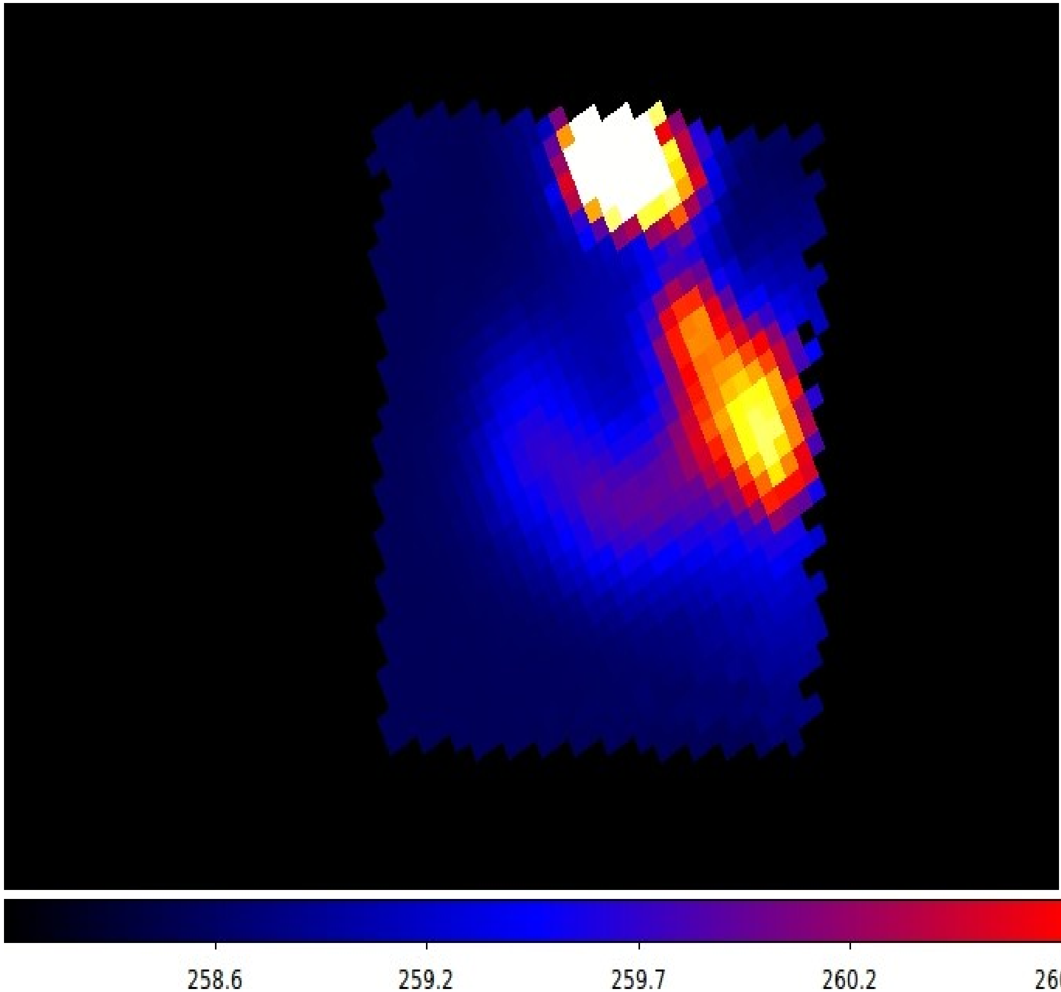
Mixed Morphology

Age : 20 000 yrs

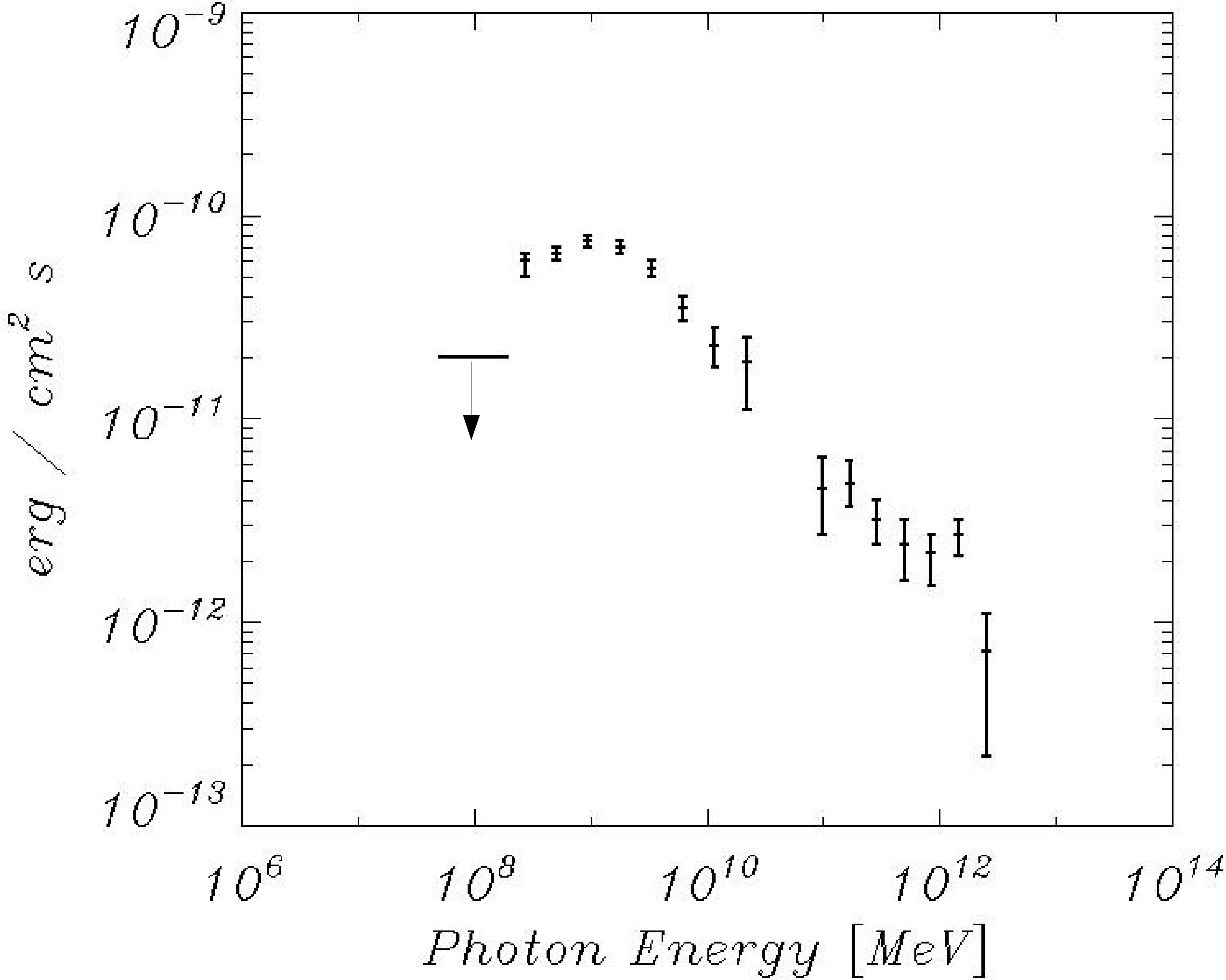
D : 6.0 kpc

Intercting with MCs

OB assoc.

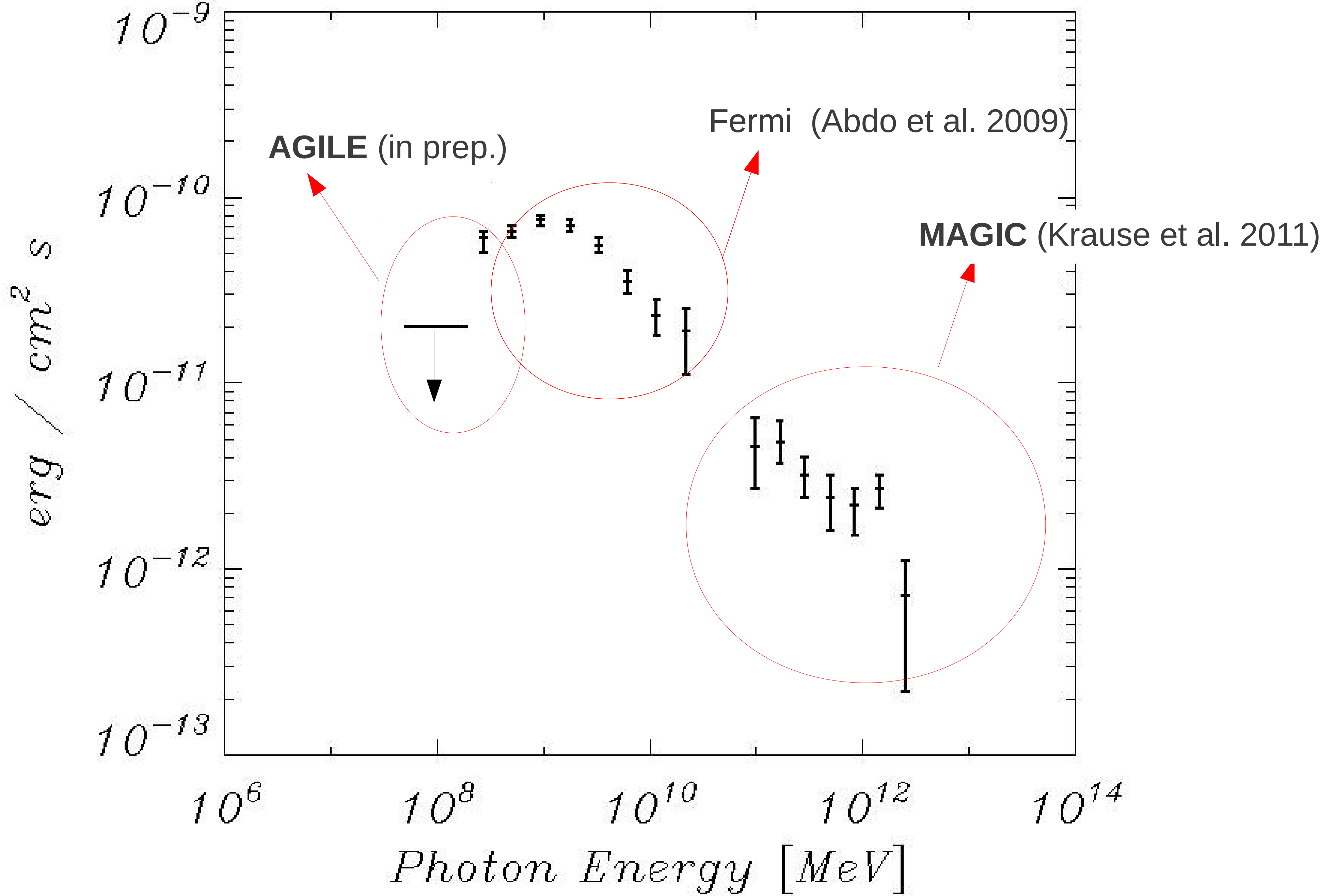


SNR W51C

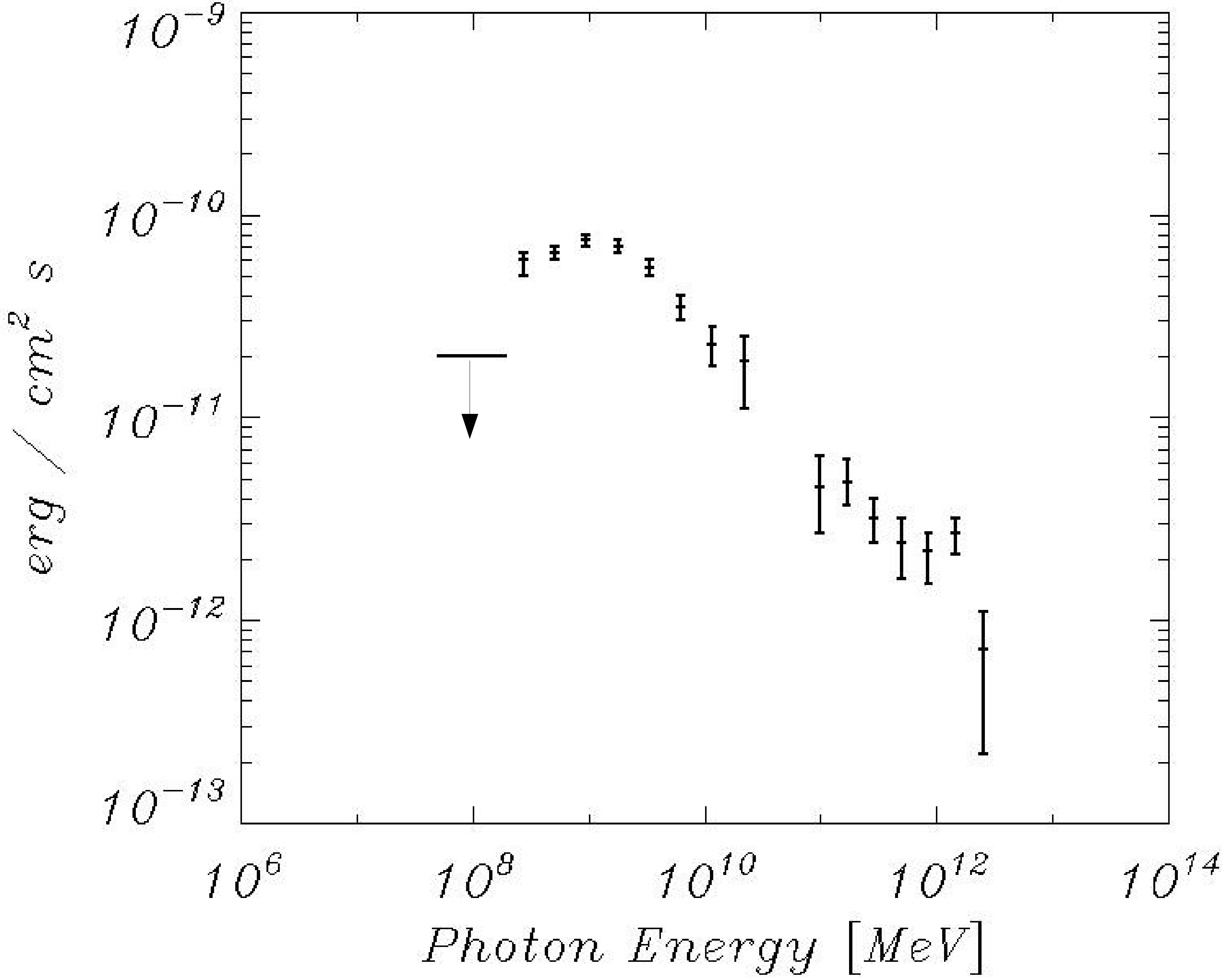


10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$erg\ /\ cm^2\ s$
10^6
10^8
10^{10}
10^{12}
10^{14}
$Photon\ Energy\ [MeV]$

SNR W51C

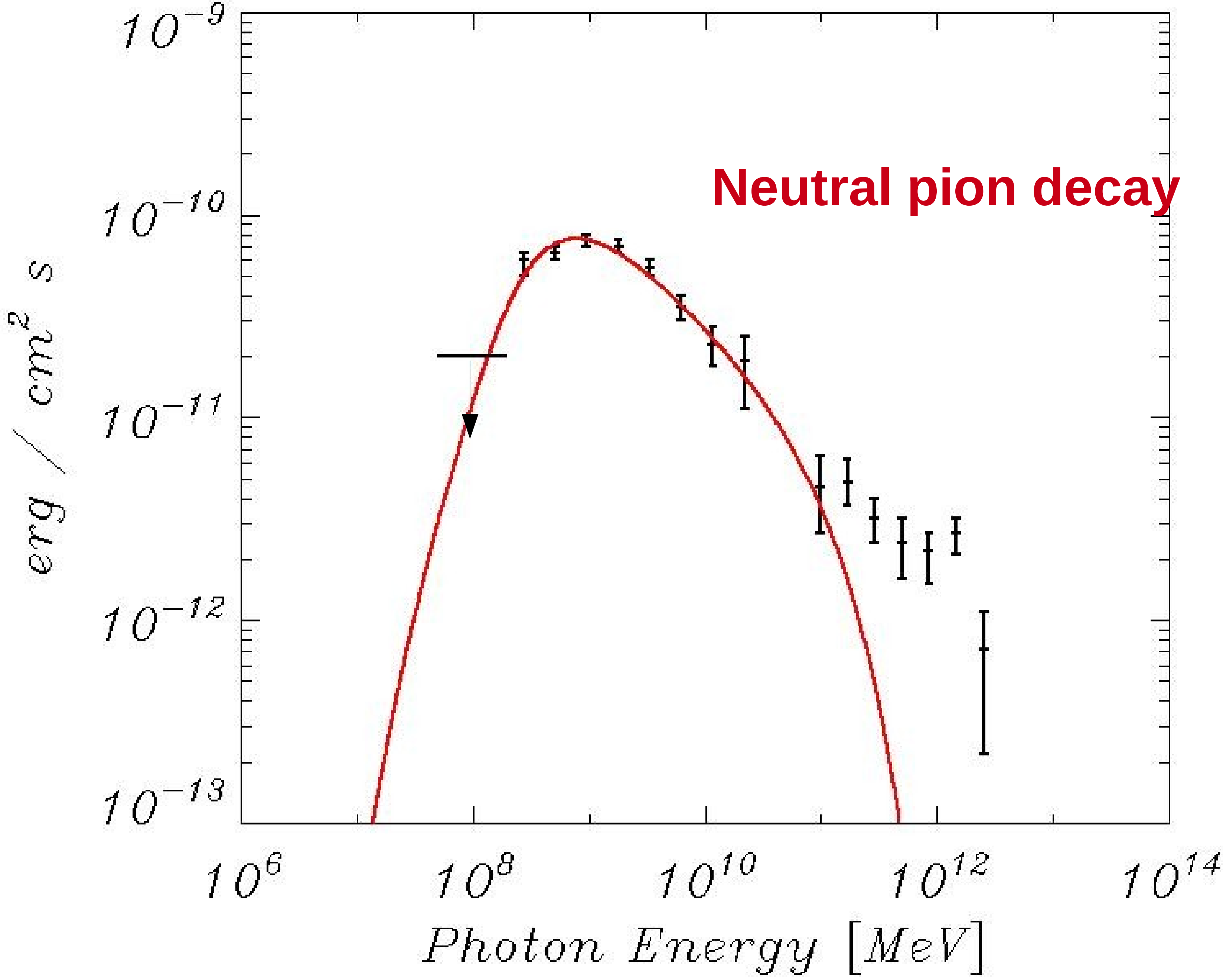

AGILE (in prep.)
Fermi (Abdo et al. 2009)
MAGIC (Krause et al. 2011)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$erg / cm^2 s$
10^6
10^8
10^{10}
10^{12}
10^{14}
Photon Energy [MeV]

SNR W51C



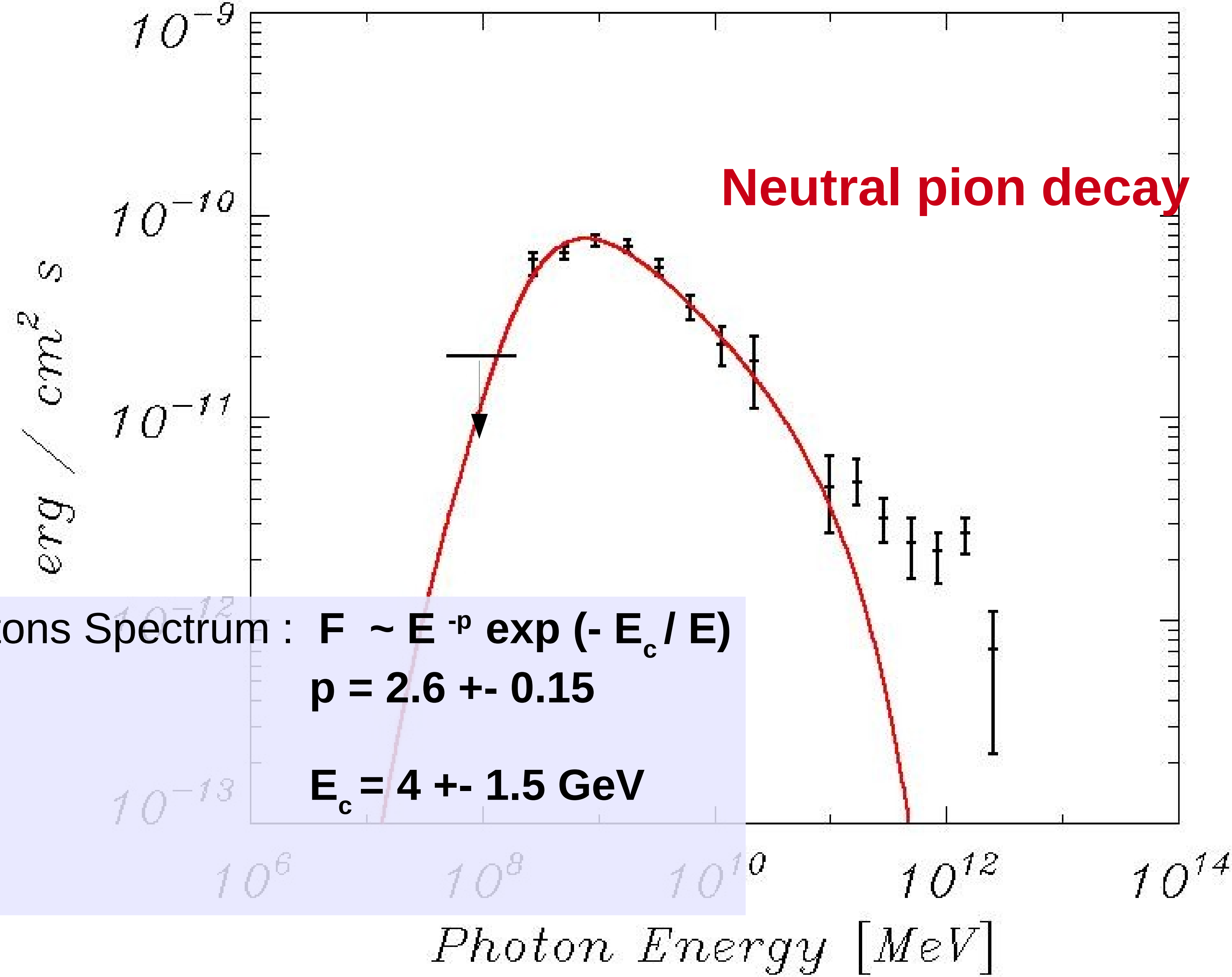
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
erg / cm^2 s
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
Photon Energy [MeV]

SNR W51C



Neutral pion decay
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$erg / cm^2 s$
10^6
10^8
10^{10}
10^{12}
10^{14}
Photon Energy [MeV]

SNR W51C

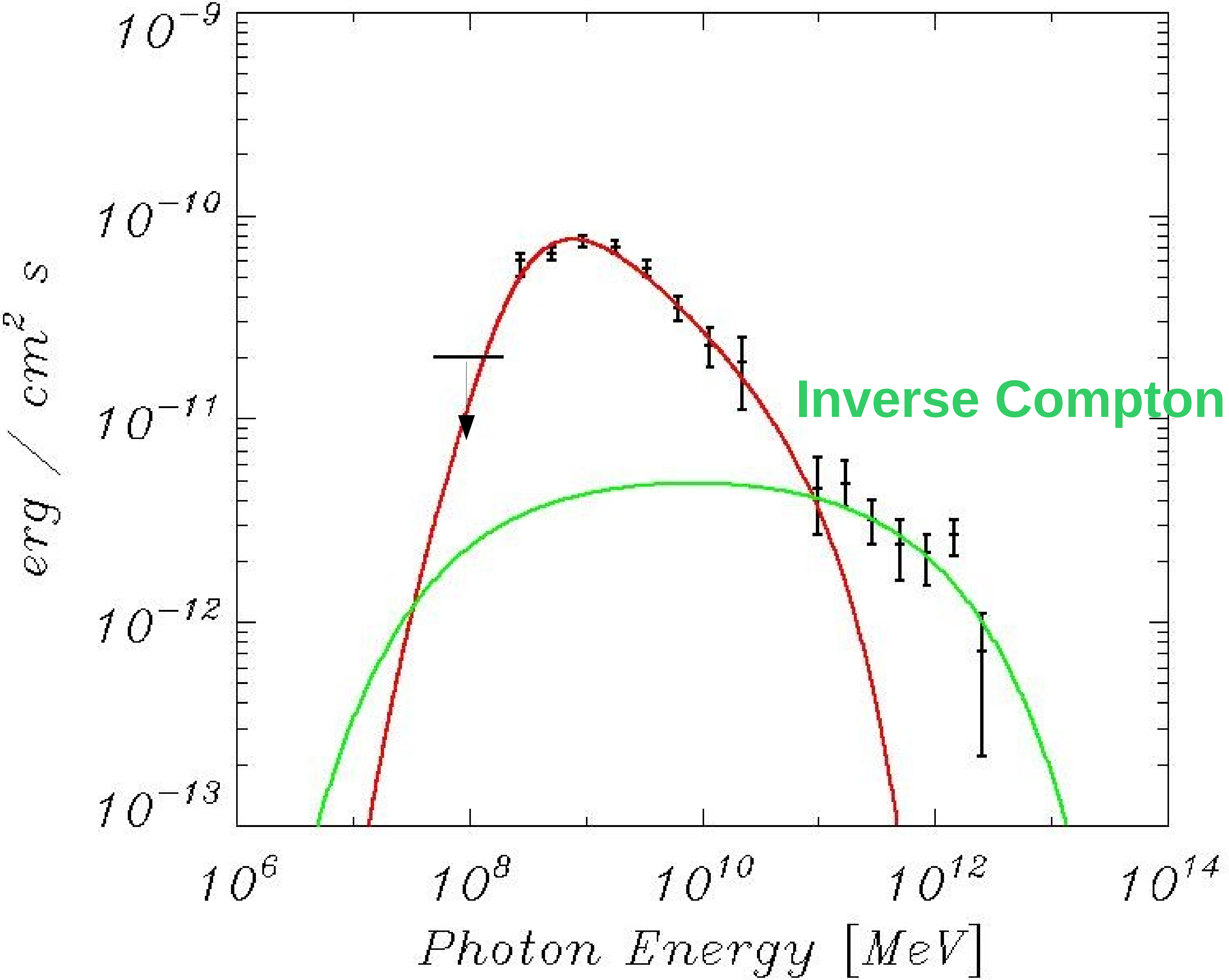


Protons Spectrum : **$F \sim E^{-p} \exp(-E_c / E)$**

$p = 2.6 \pm 0.15$

$E_c = 4 \pm 1.5$ GeV

SNR W51C



Inverse Compton
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
erg / cm^2 s
10^6
10^8
10^{10}
10^{12}
10^{14}
Photon Energy [MeV]

Conlusions

Accelerated protons are present in SNRs (at least in middle-aged SNRs)

The spectrum of middle-aged SNRs show a decrease for energies lower than ~ 1 GeV

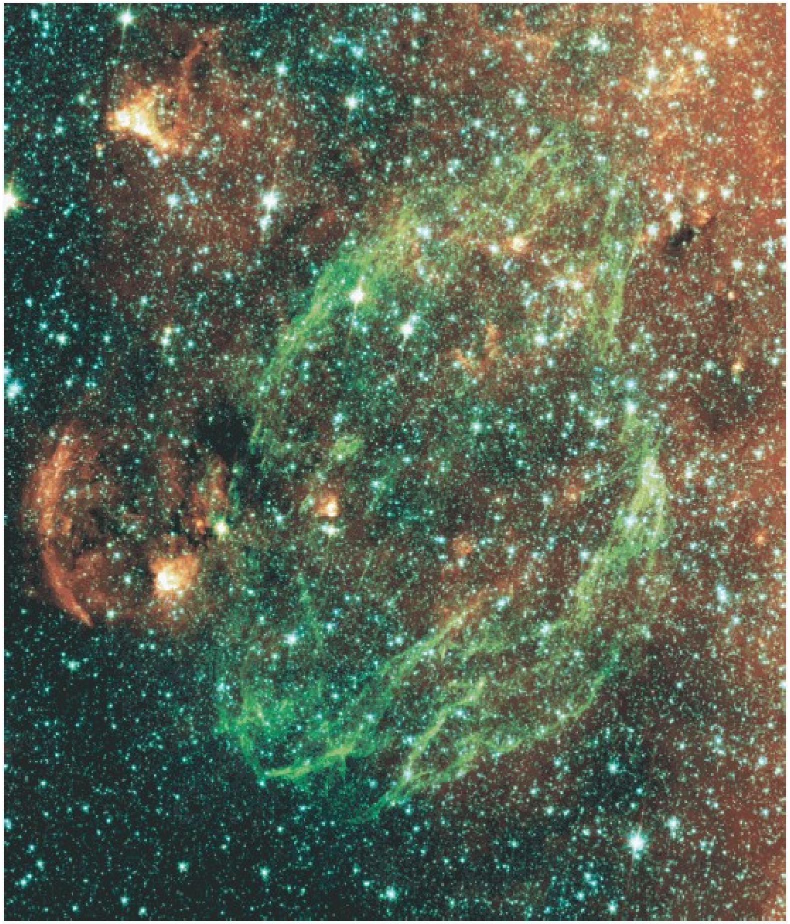
The inferred proton spectrum for W44 has:

spectral index : - 3.0 ± 0.1
I.e. cutoff ~ 6 GeV

challenging for theoretical models of particles injection

Future Radio obs at frequencies > 10 GHz will be crucial for the detection the sync. cut-off.

H_2 and Halpha emission



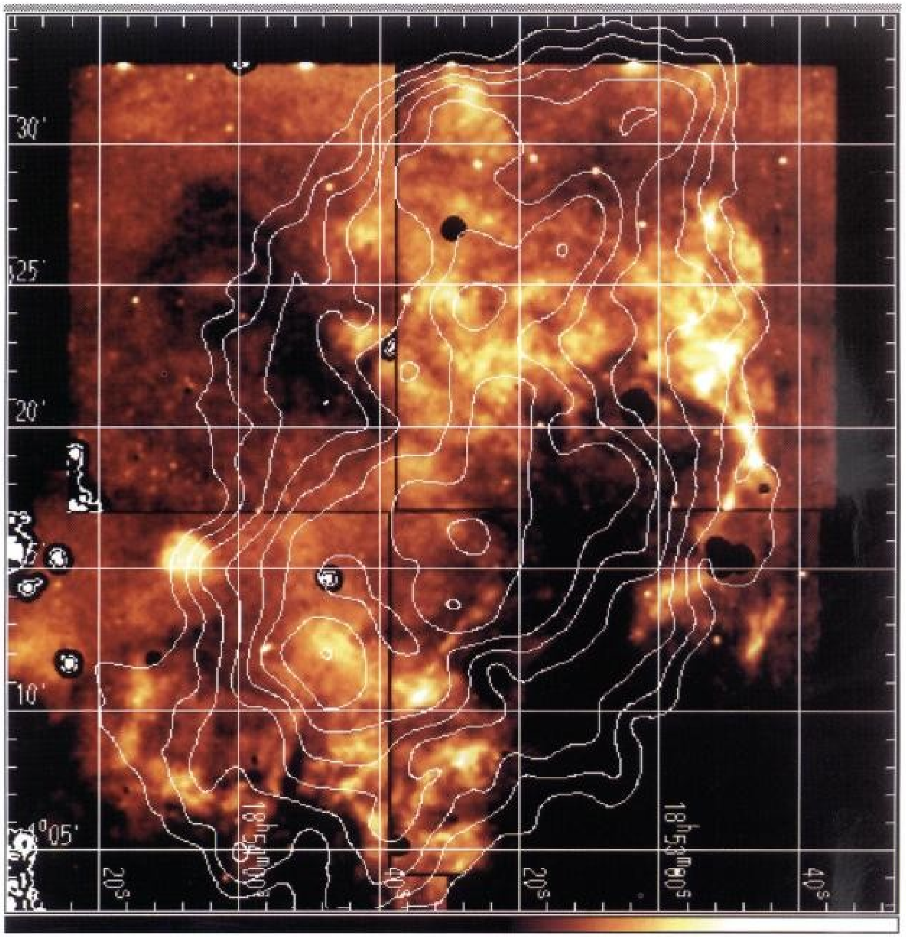
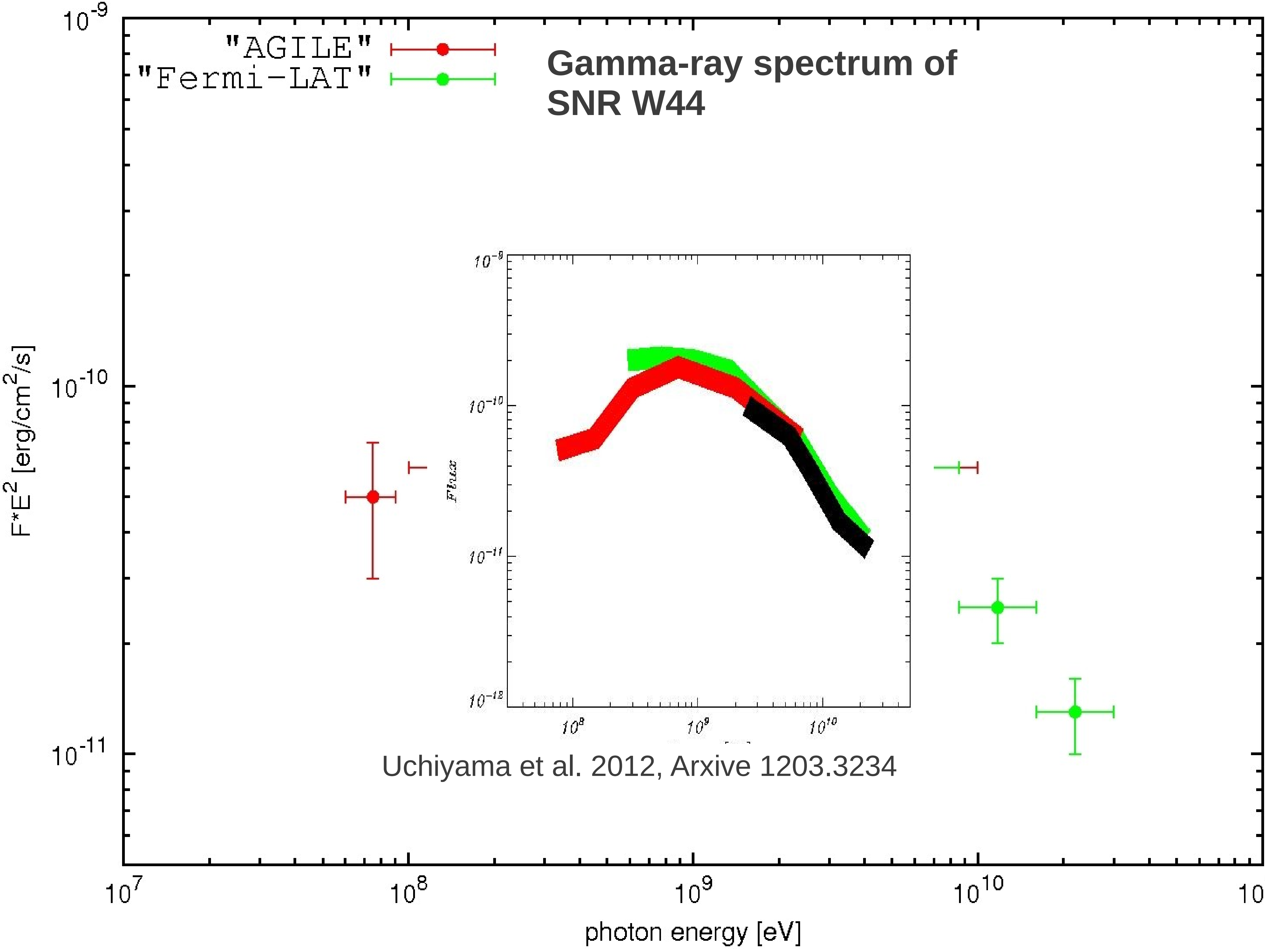
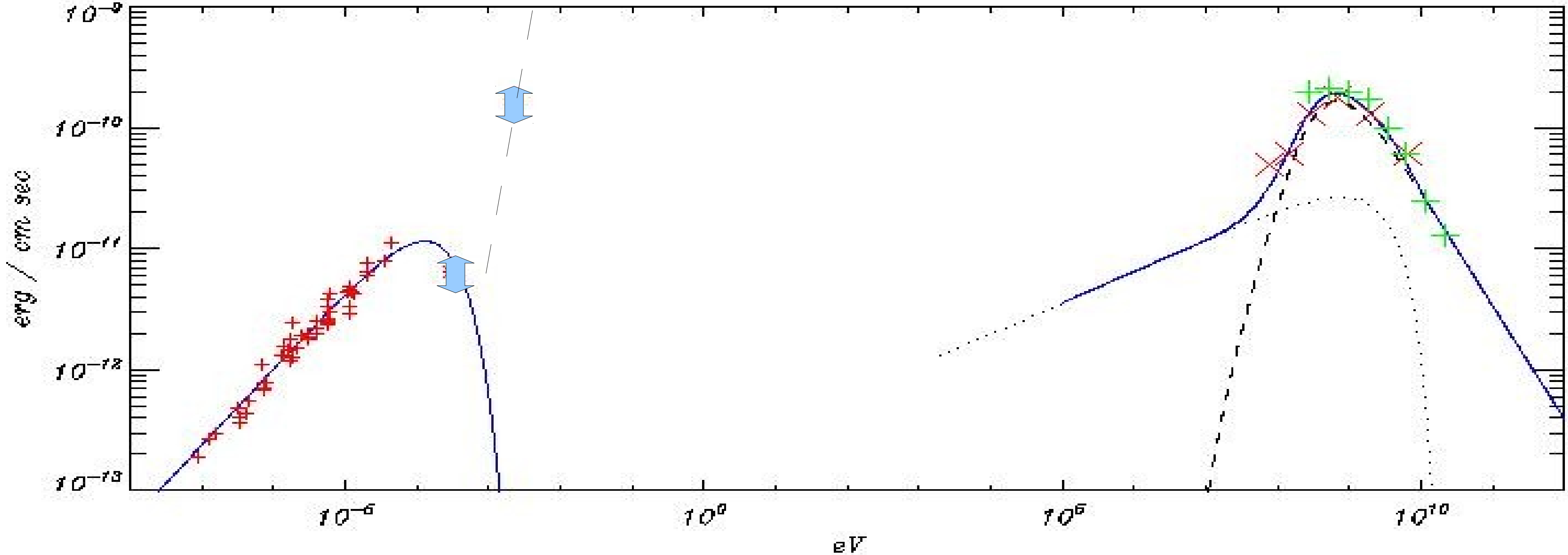


FIG. 4.—Red continuum subtracted Hα image, superposed on PSPC contours

RHO et al. (see 430, 760)

[Reach et al . 2005]


"AGILE"
"Fermi-LAT"
Gamma-ray spectrum of SNR W44
Uchiyama et al. 2012, Arxive 1203.3234
F*E^2 [erg/cm^2/s]
photon energy [eV]
10^-9
10^-10
10^-11
10^7
10^8
10^9
10^10
Flux



B : 70.0000

n : 200

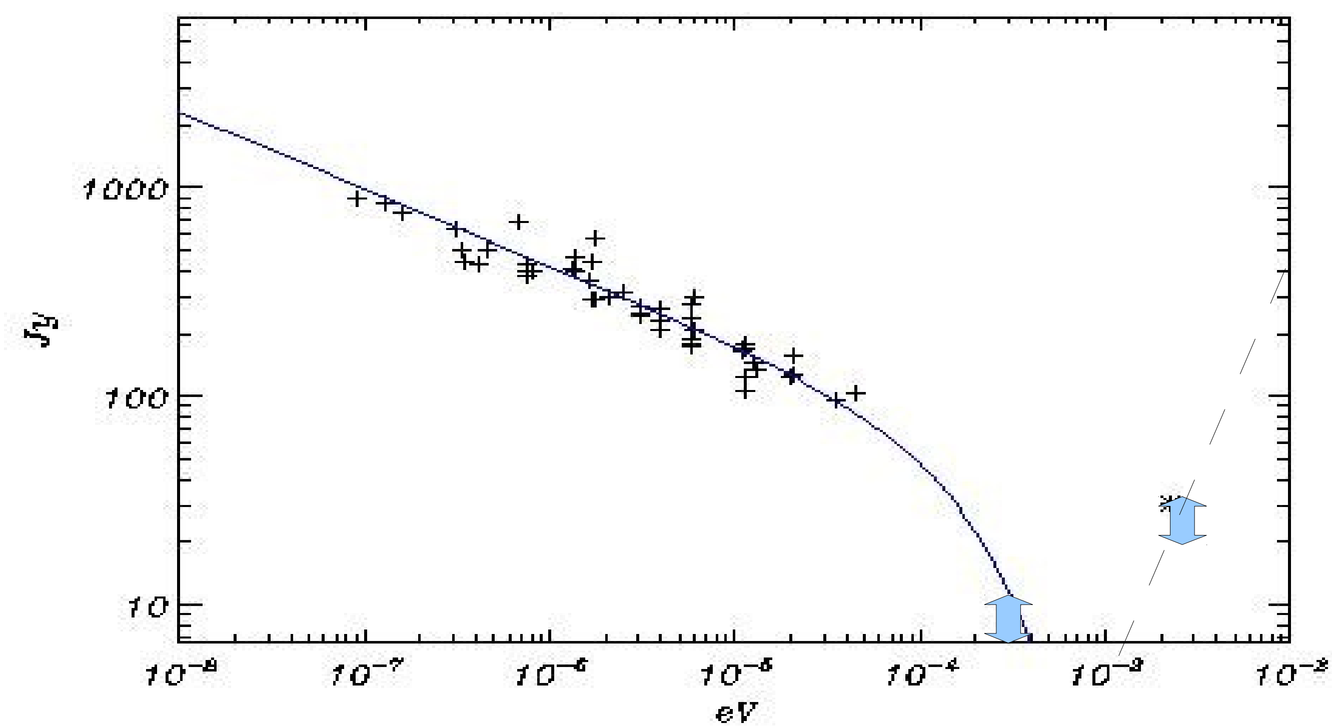
Ec : 7000.00

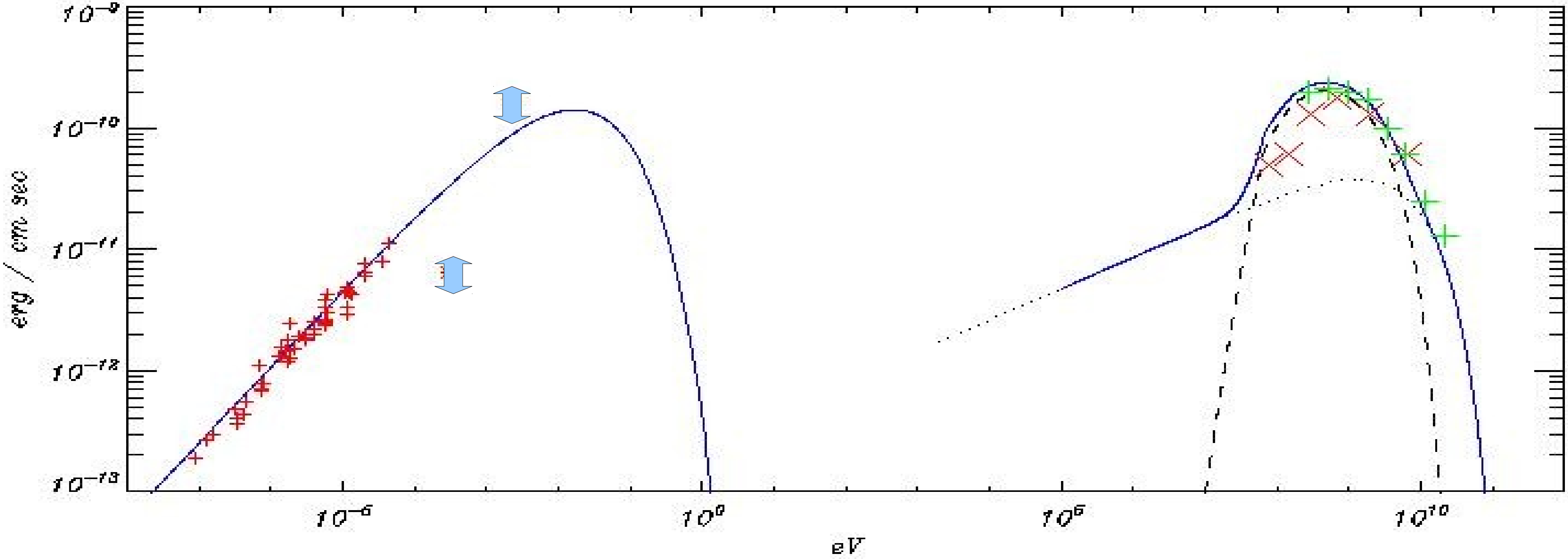
kp : 1.25000e+23

k : 2.01021e+10

p1 : 1.74000

p2 : 12





B : 800.000

n : 7000

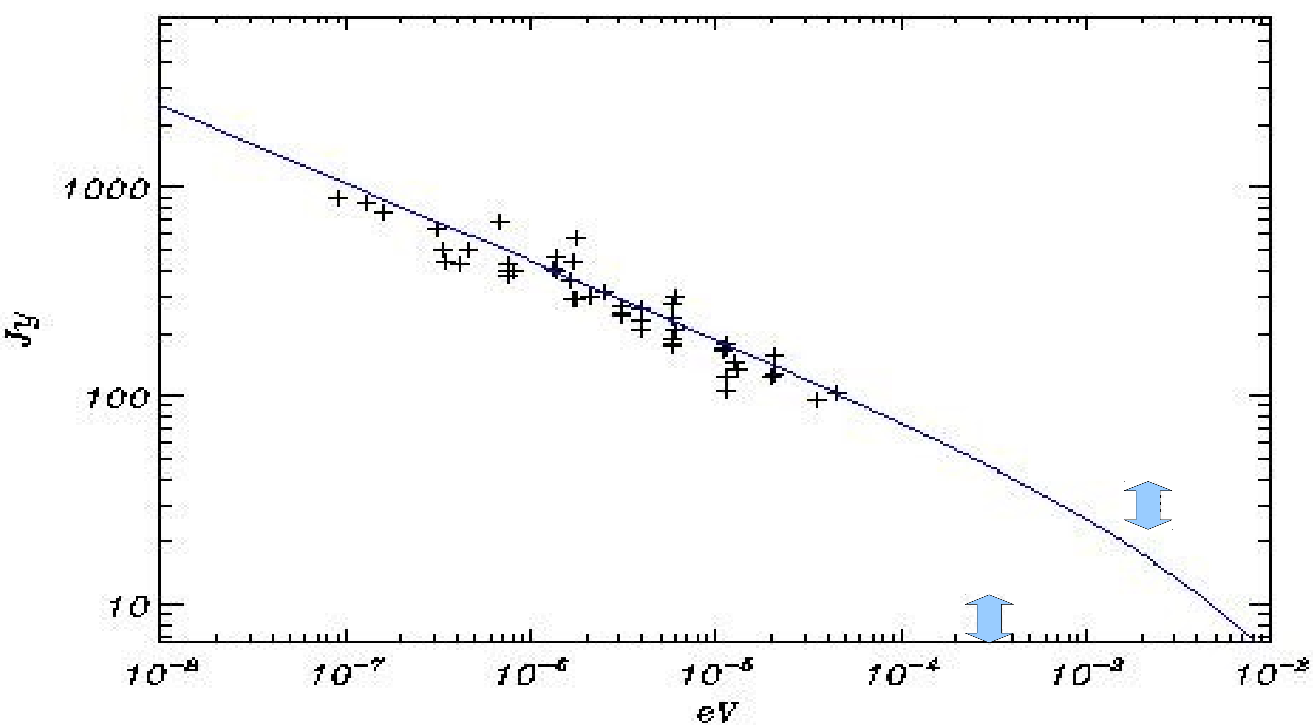
Ec : 15000.0

kp : 4.29752e+16

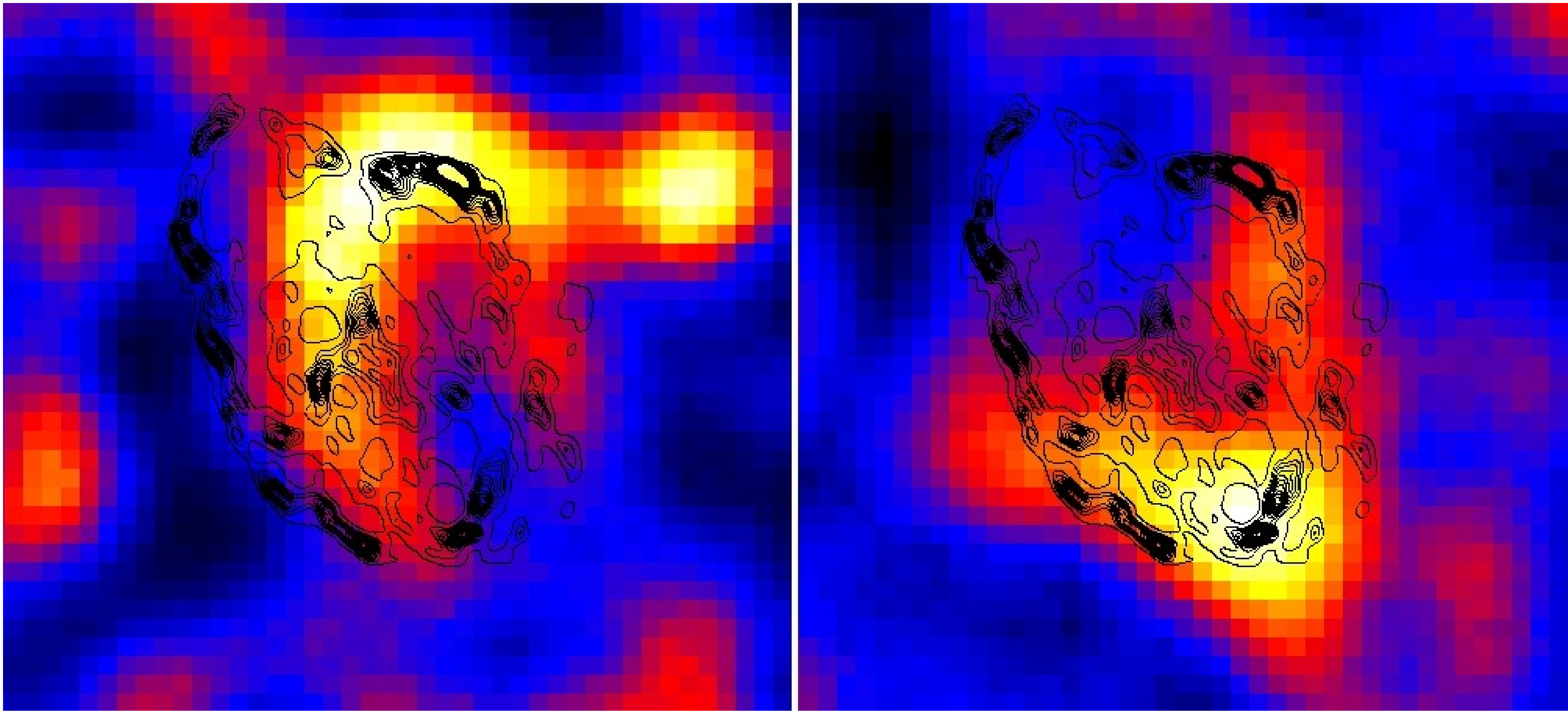
k : 2.01708e+08

p1 : 1.74000

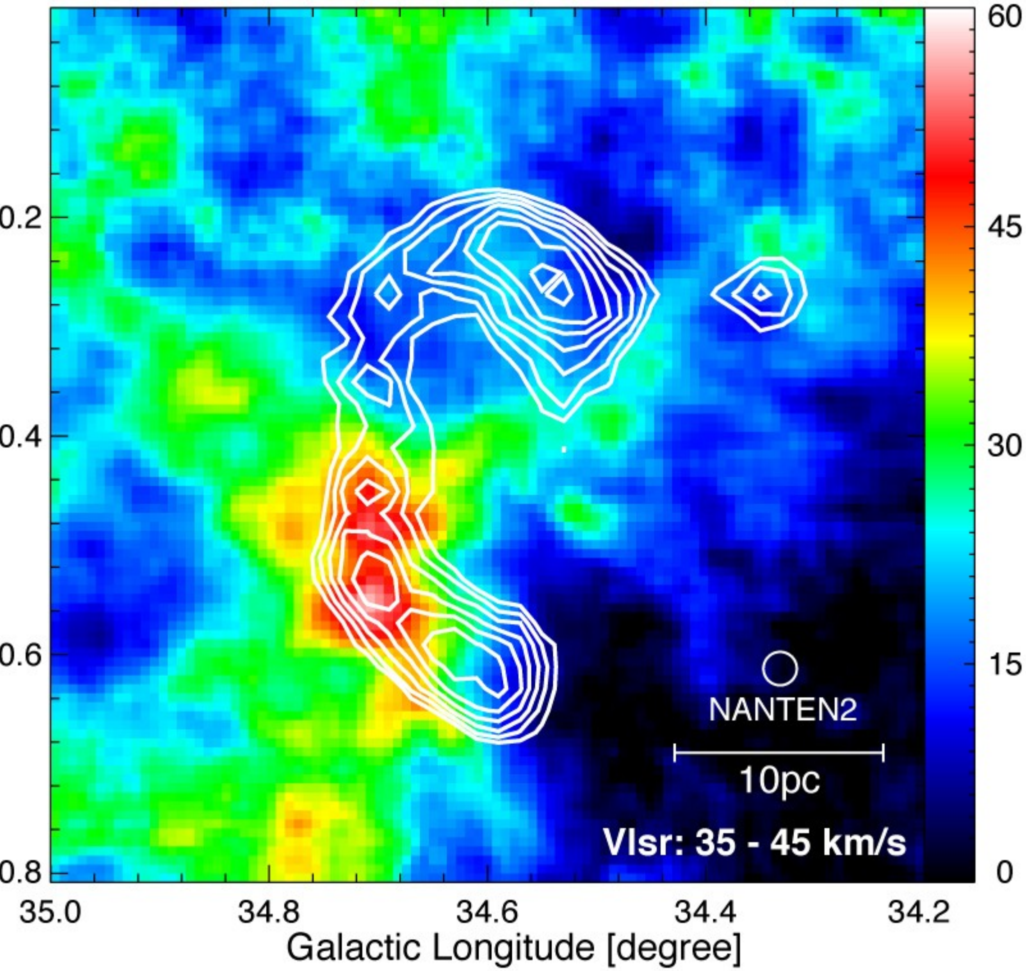
p2 : 12



400 MeV < E < 1 GeV **1 GeV < E < 3 GeV**



CO (J 1-->0)



E > 400 MeV