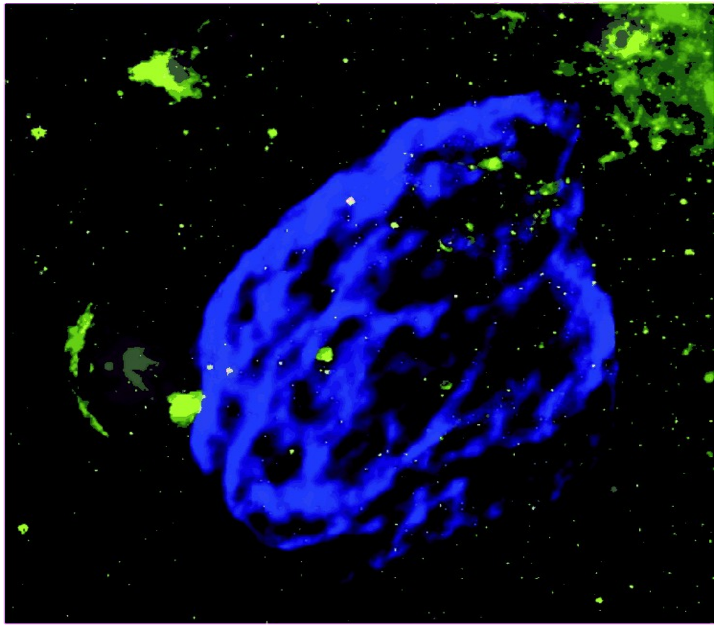
AGILE study of Supernova Remnants

(SNRs @ 100 MeV)



A. Giuliani

for the AGILE Team
INAF / IASF Milan

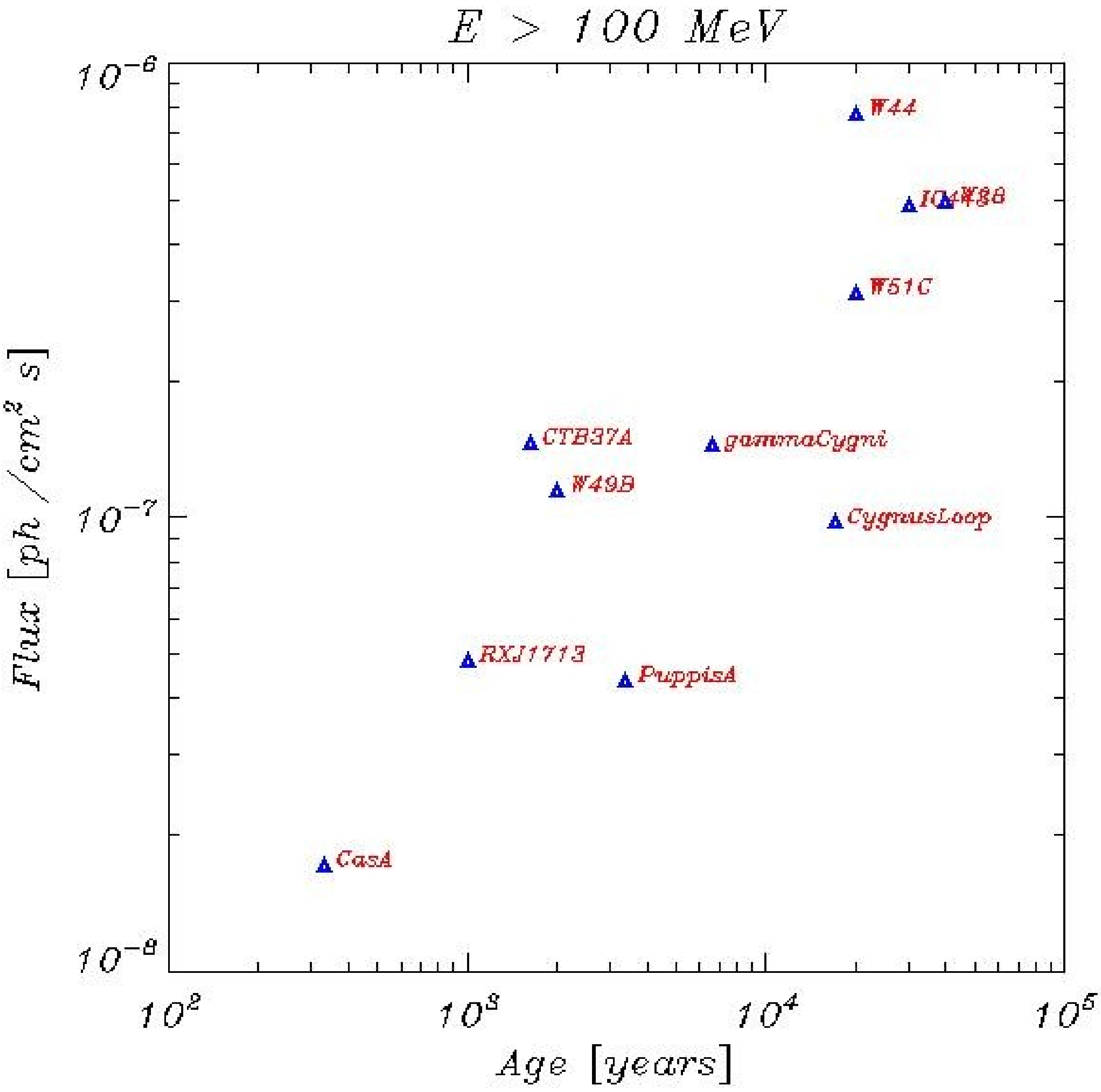
SNRs at "low" energy

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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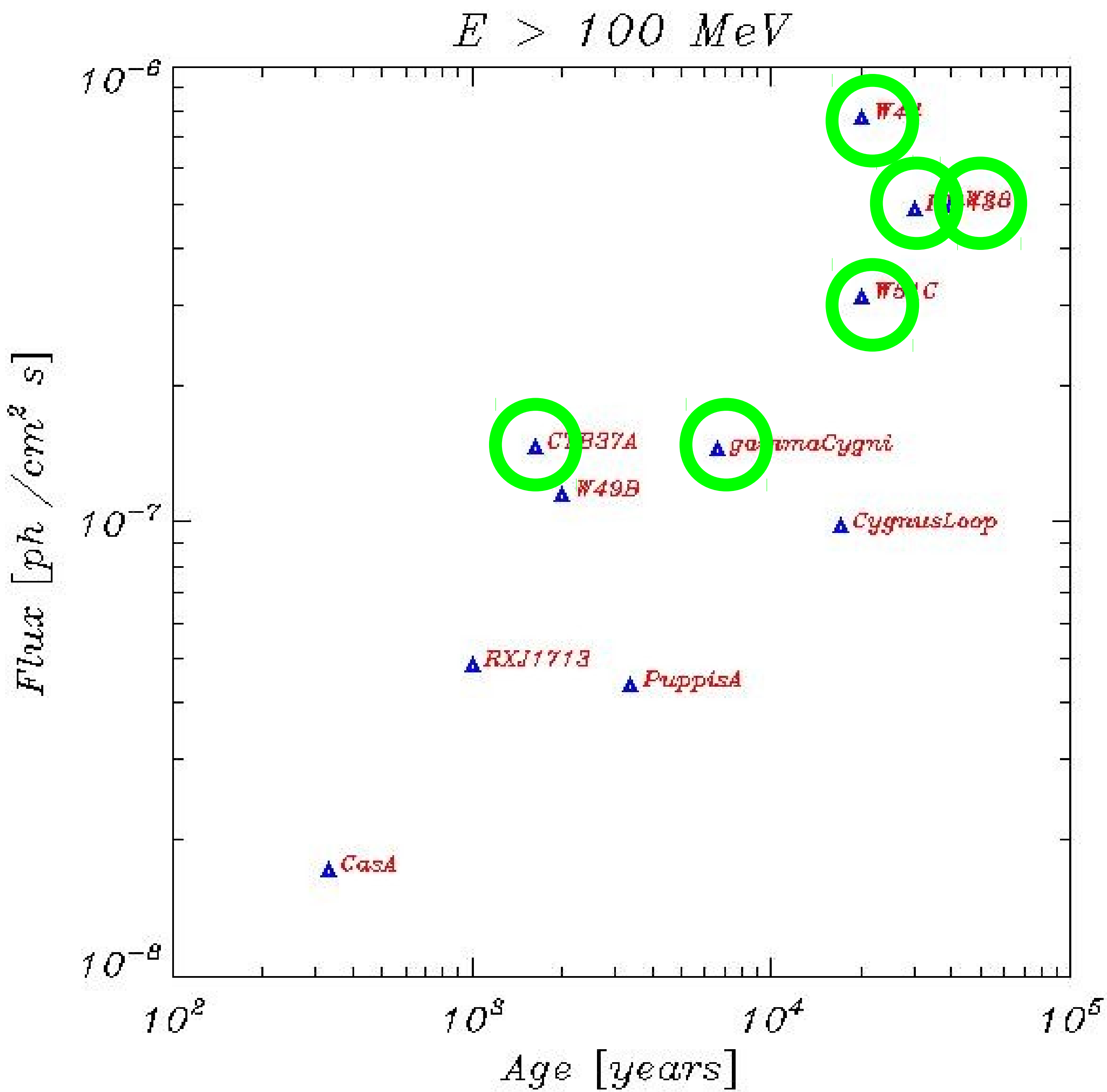
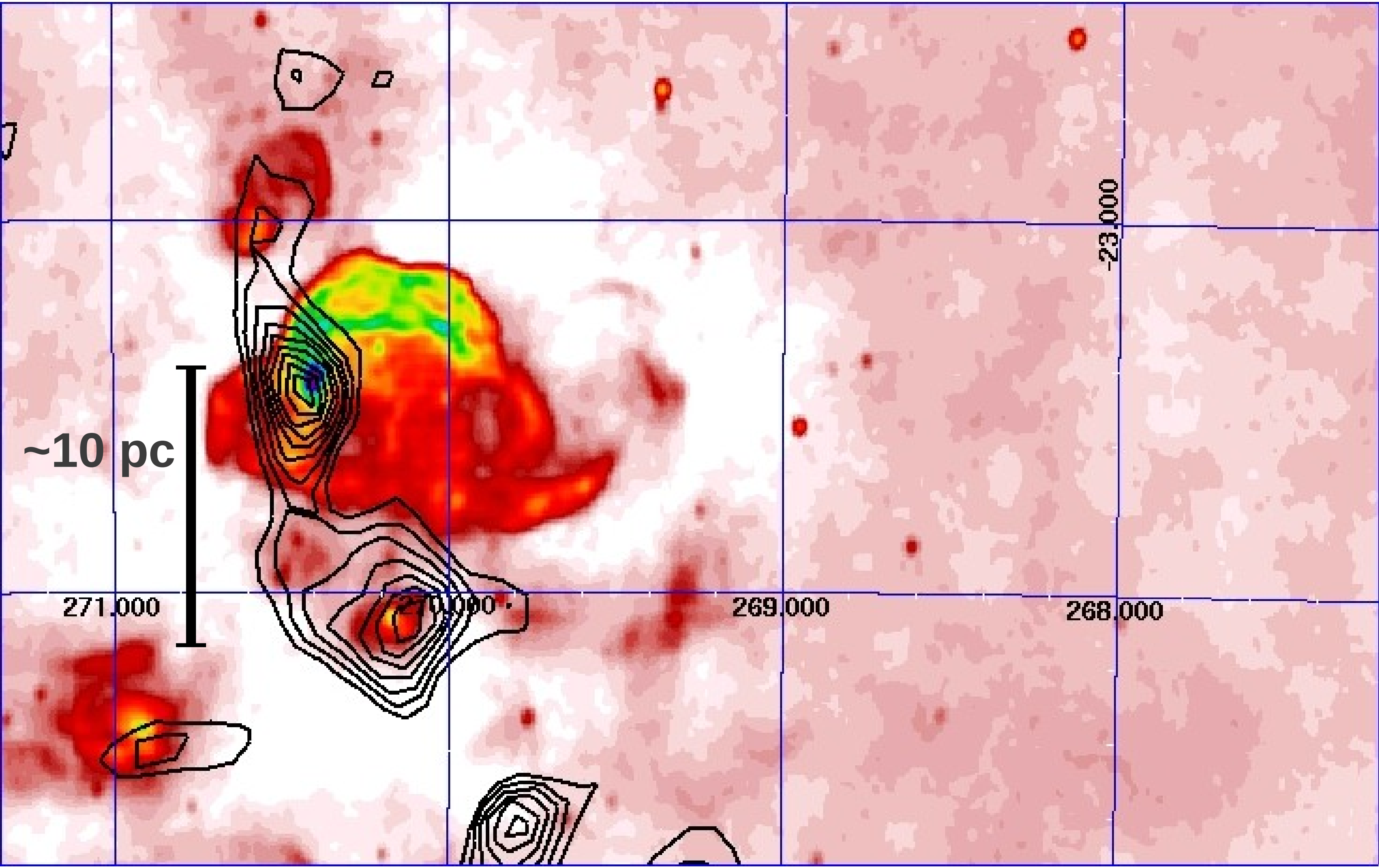


SNRs at “low” energy : diffusion of CRs (W28)



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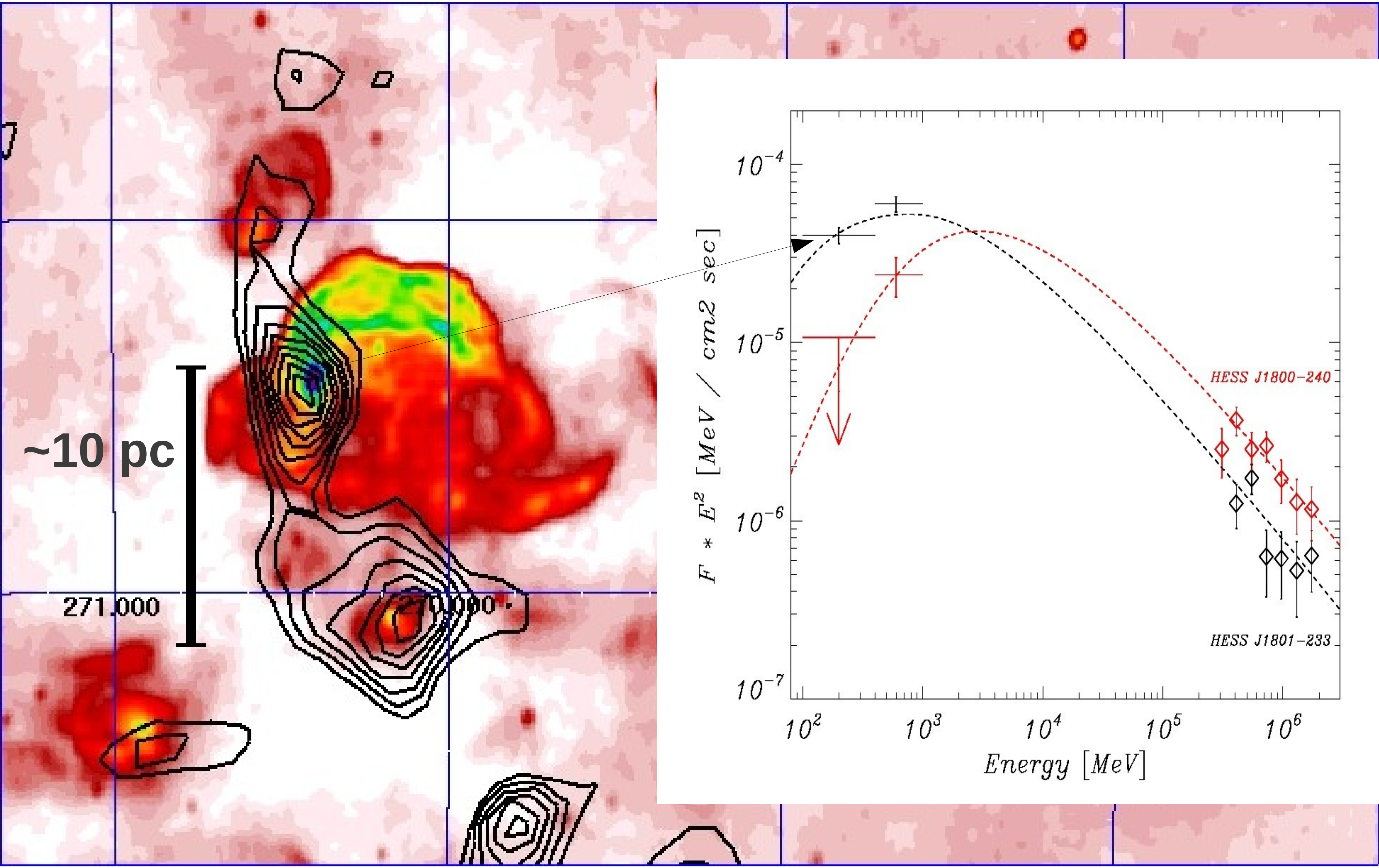
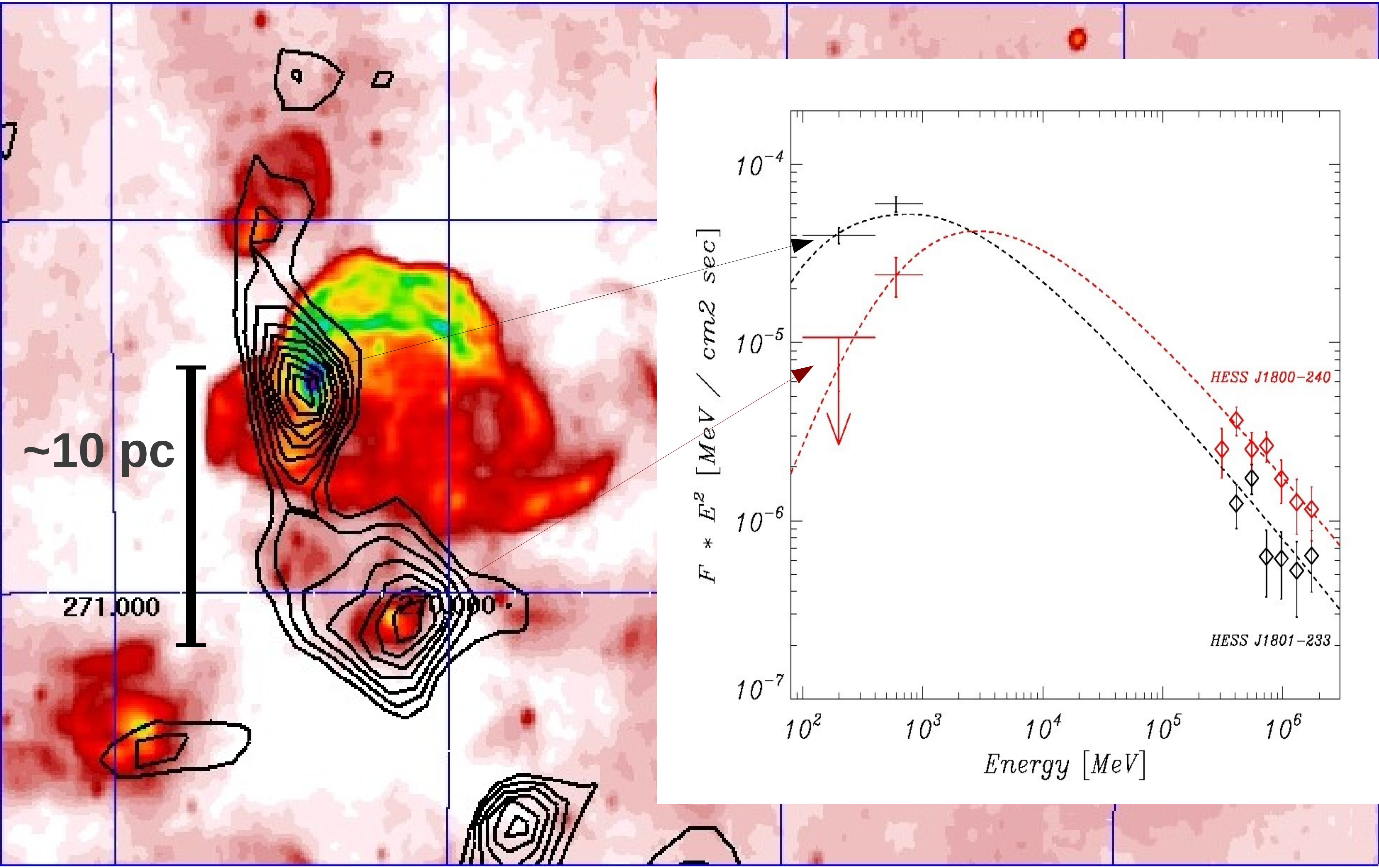
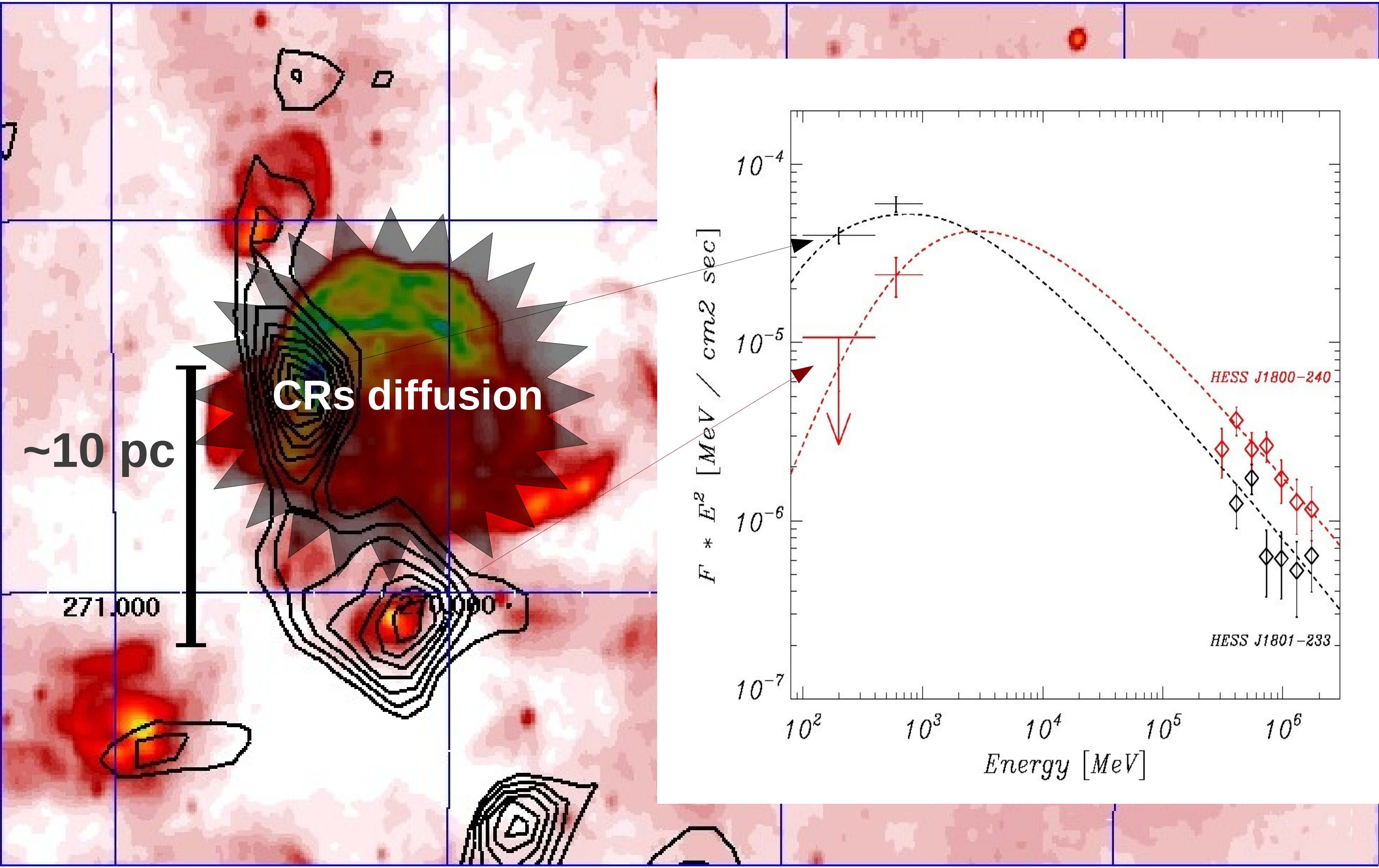


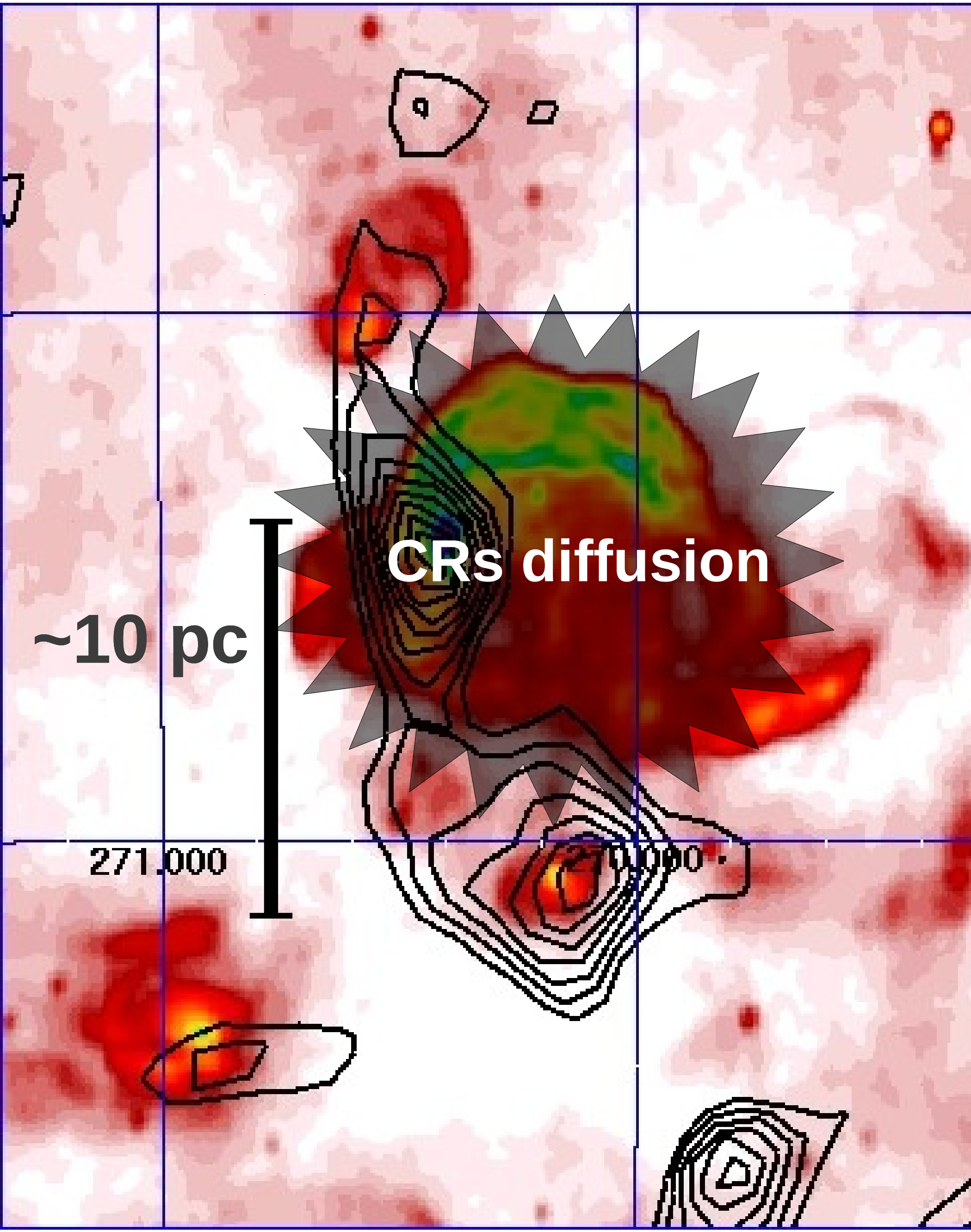
SNRs at “low” energy : diffusion of CRs



SNRs at “low” energy : diffusion of CRs



SNRs at "low" energy : diffusion of CRs



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

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

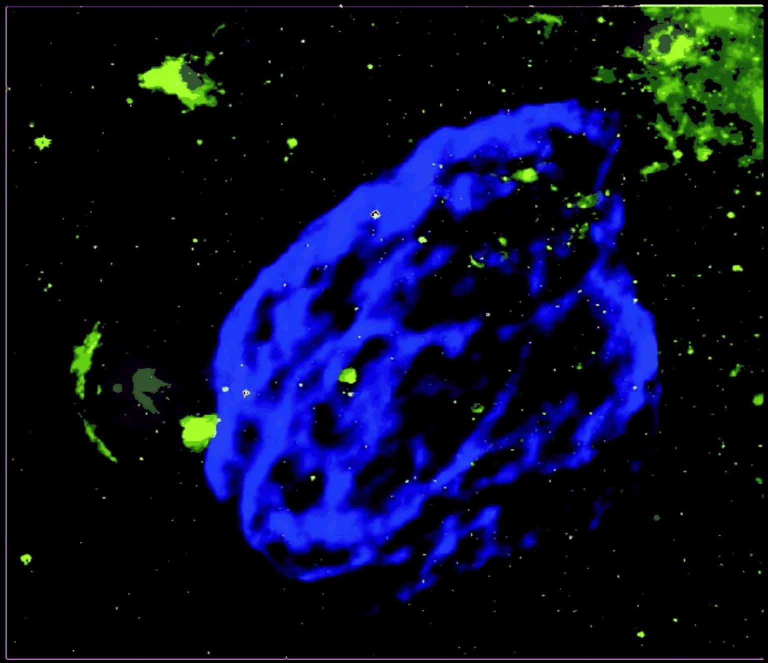
For middle-aged SNRs (10^4 yrs) **and slow D** (~ 1-2 10^{26} $(E/10\ \mathrm{GeV})^{0.5}$) **:**

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

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

SNR W44

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

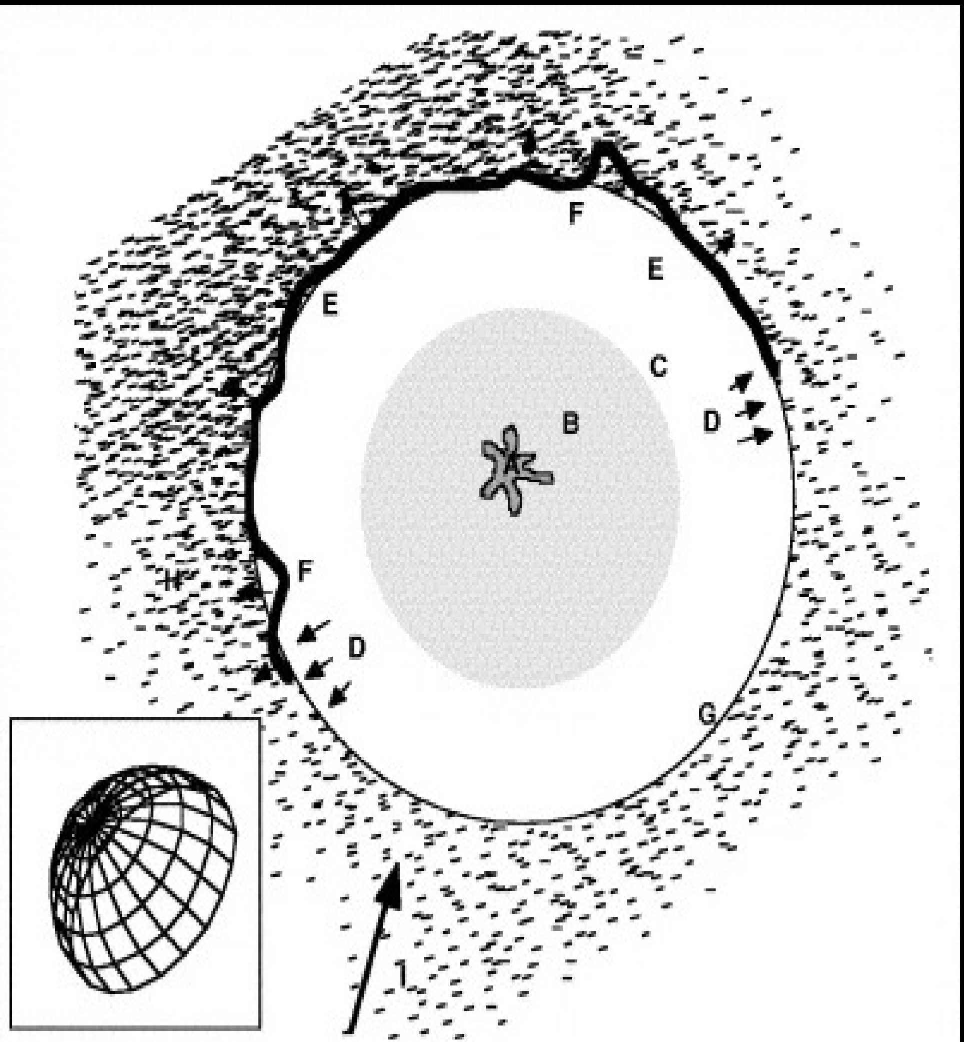


Ideal Laboratory for CRs Study :

SNR W44

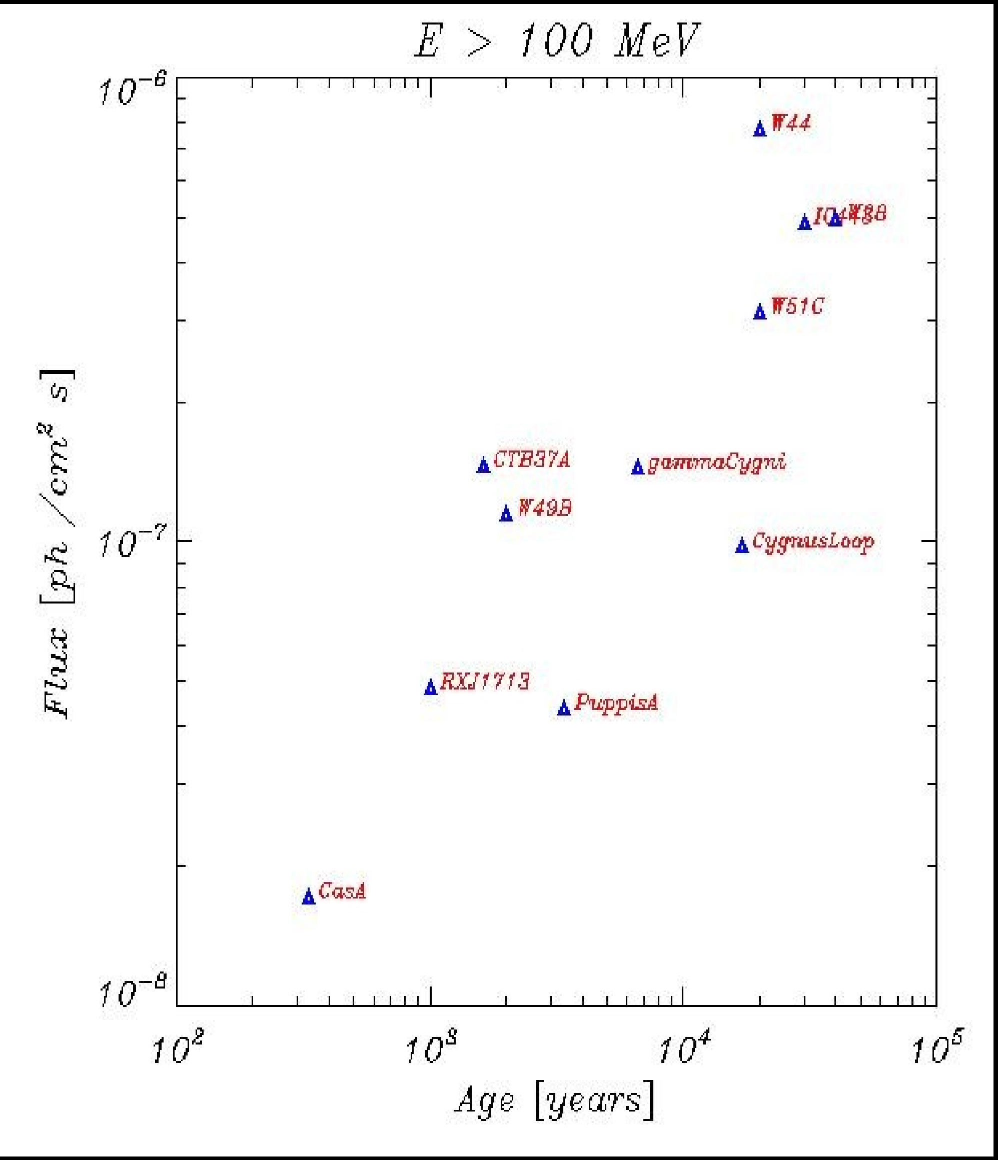
Age : ~ 20000 yr
Distance : ~ 3 Kpc
Type : mixed-morphology

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]

SNR W44



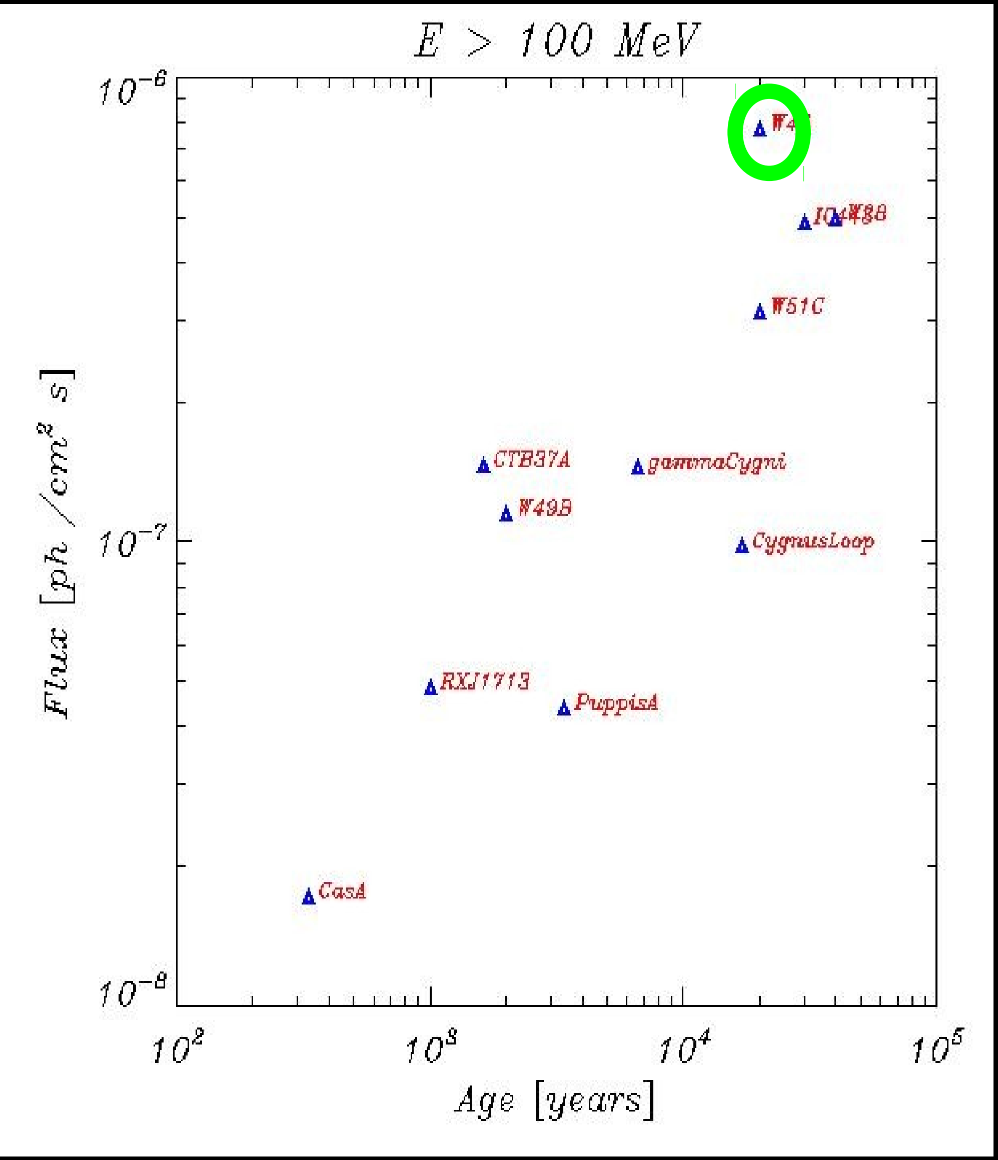
Age : ~ 20000 yr
Distance : ~ 3 Kpc
Type : mixed-morphology

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

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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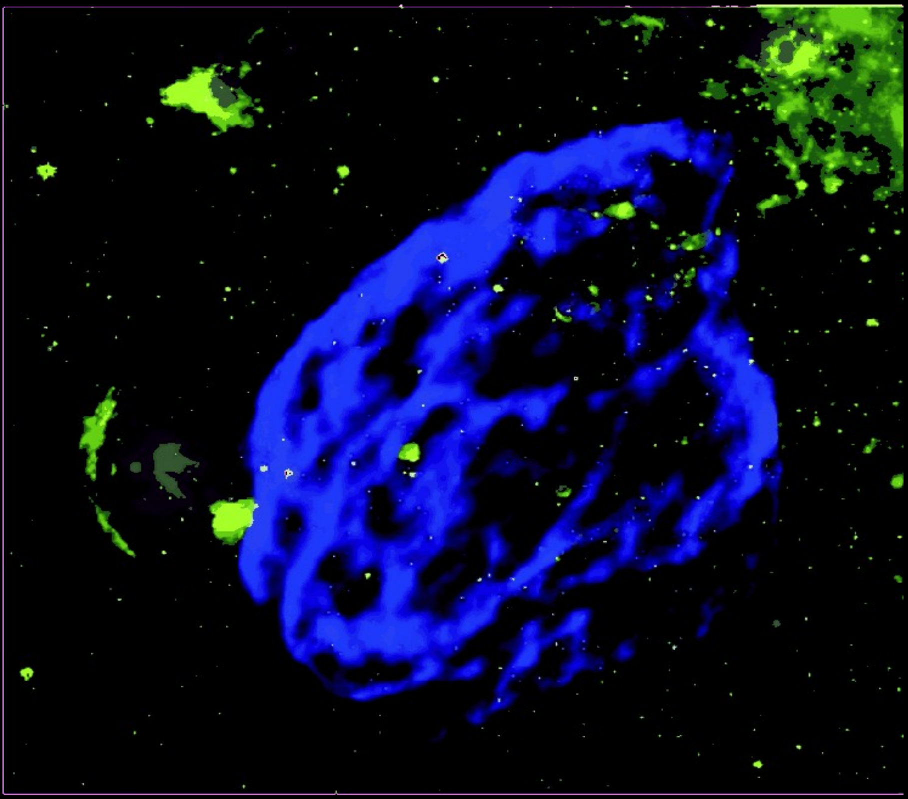

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Maser OH (1720 Hz) emission
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[Claussen et al. 1997, Hoffman et al. 2005]

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

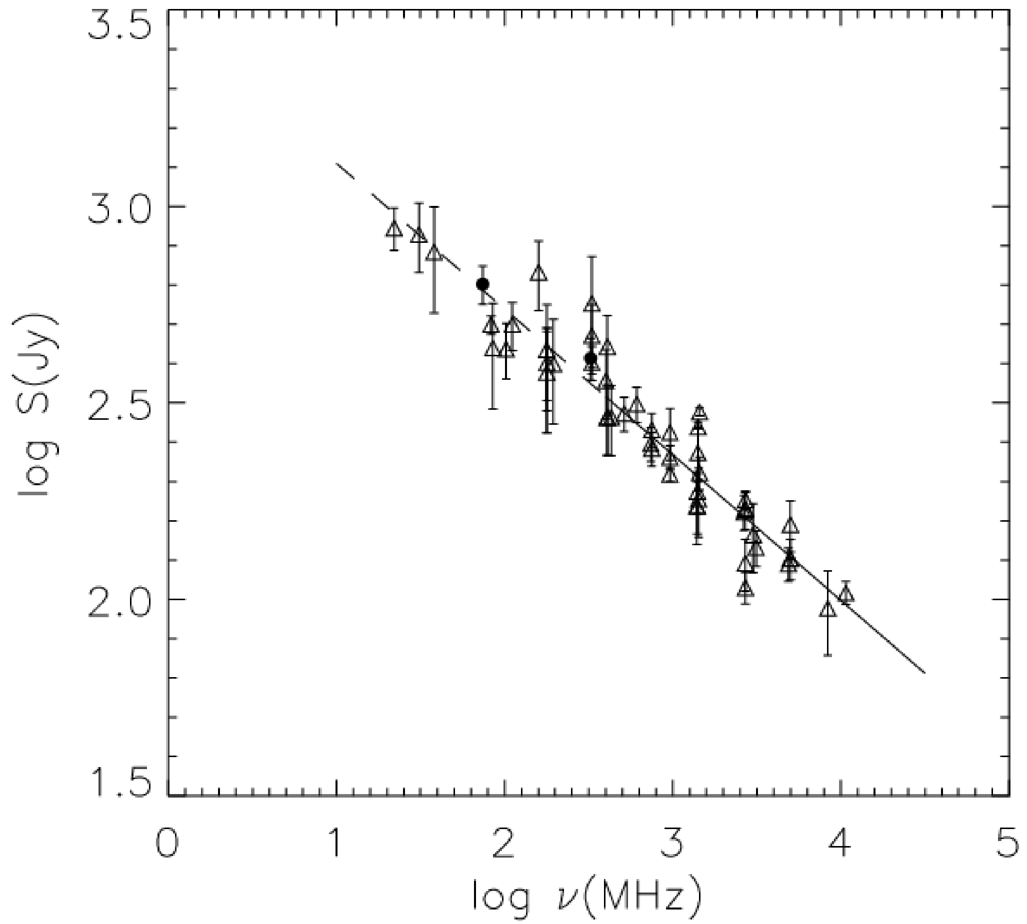
The radio spectrum of W44 is a power-law featurless in the frequency range ~ 10 MHz - 10 GHz (Castelletti et al 2007)

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

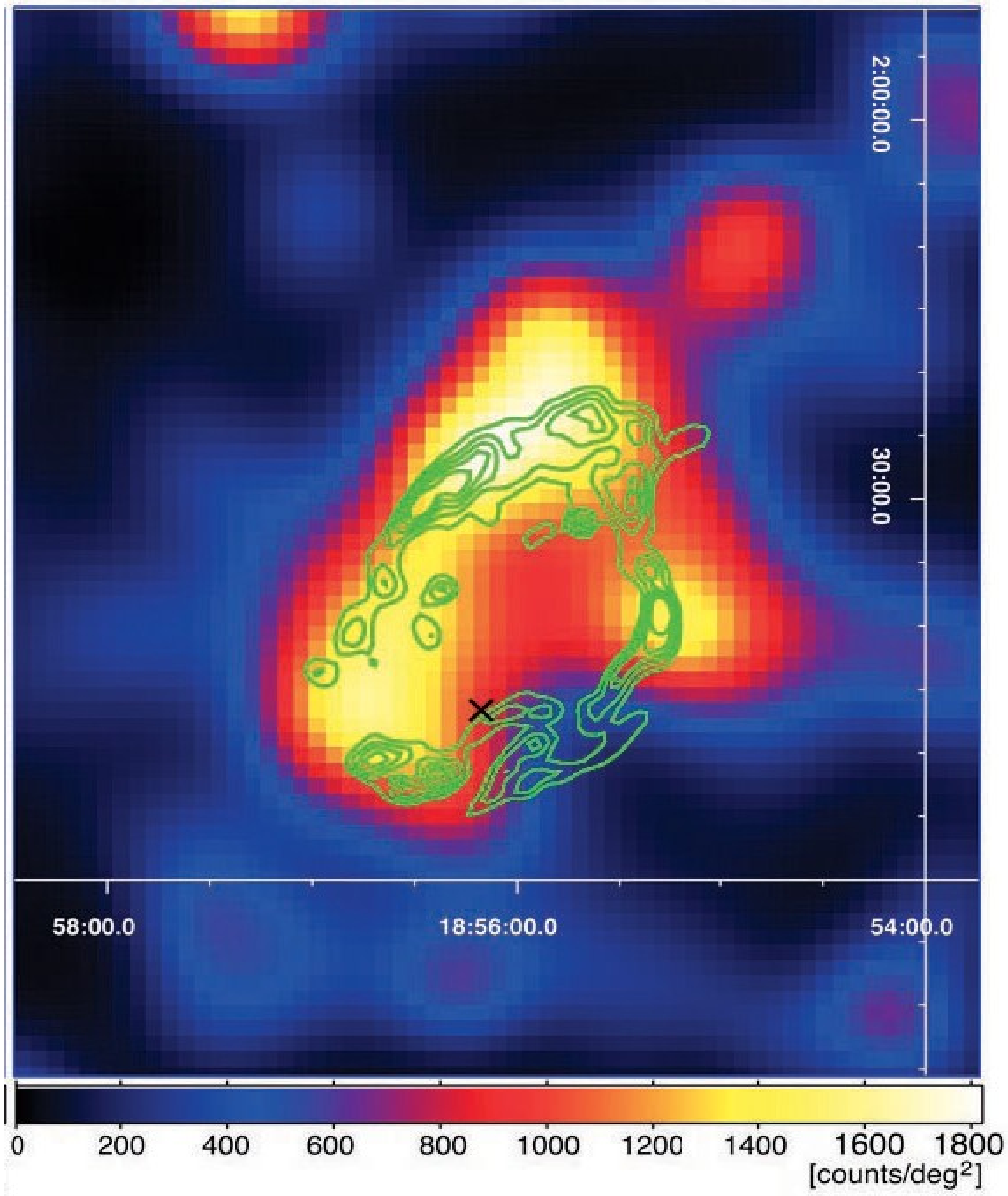
Corresponding to an electrons spectrum :

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

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



Fermi detection of W44



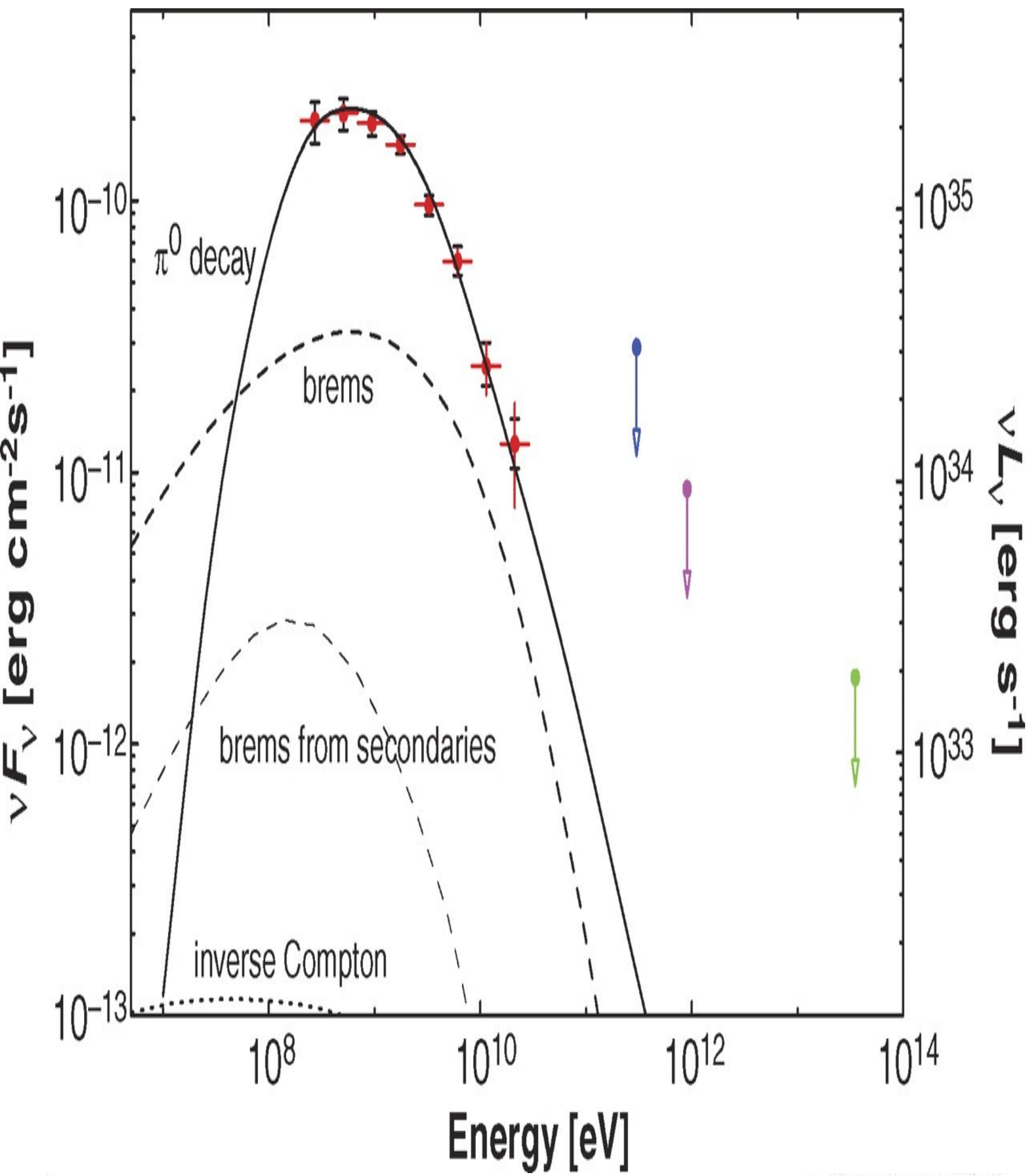
Gamma-ray emission correlated to the shell (enhanced where ISM is more dense)

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

Image for E >2 GeV

Abdo 2010, Science, 327

Fermi detection of W44



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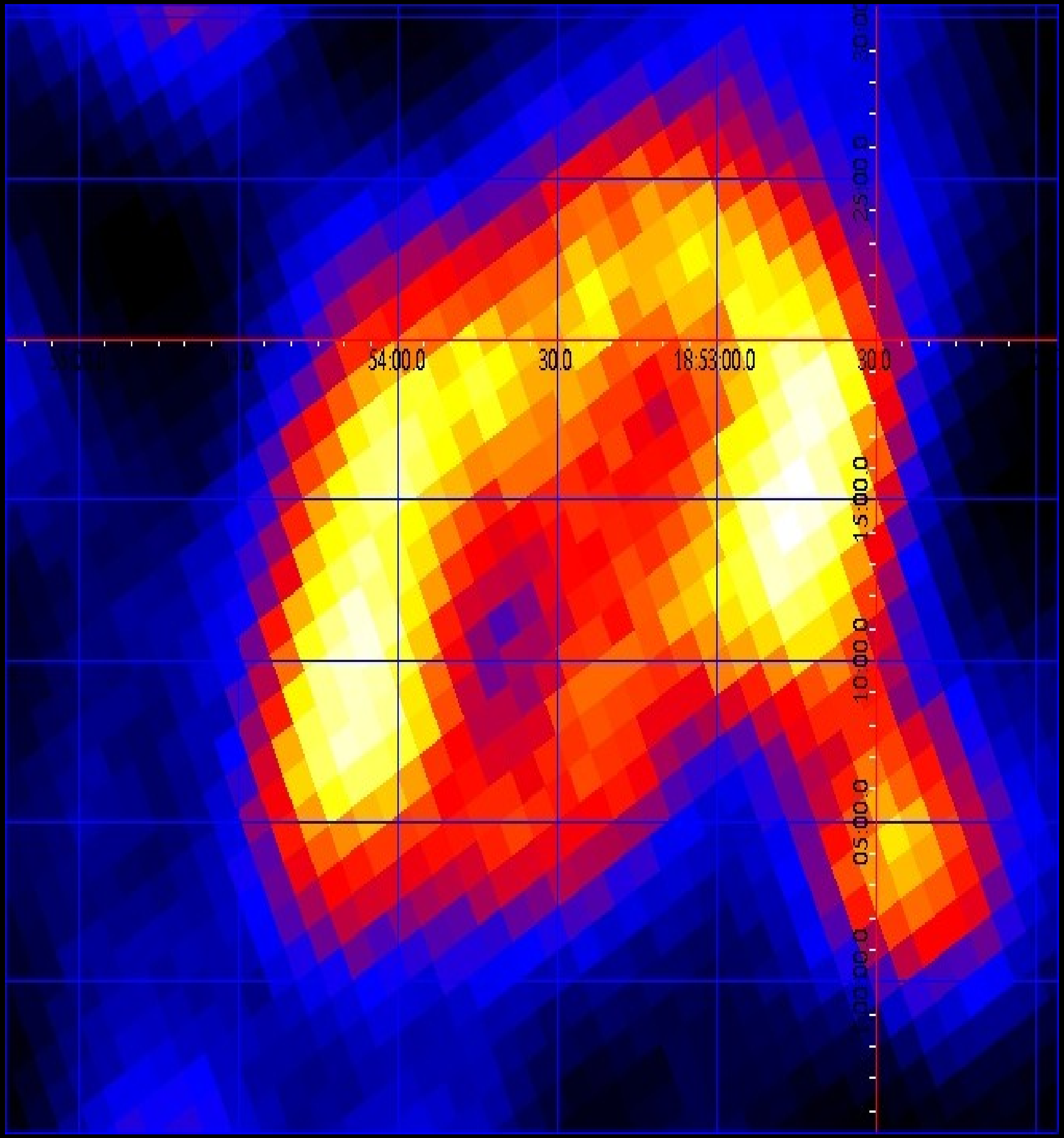
Abdo 2010, Science, 327

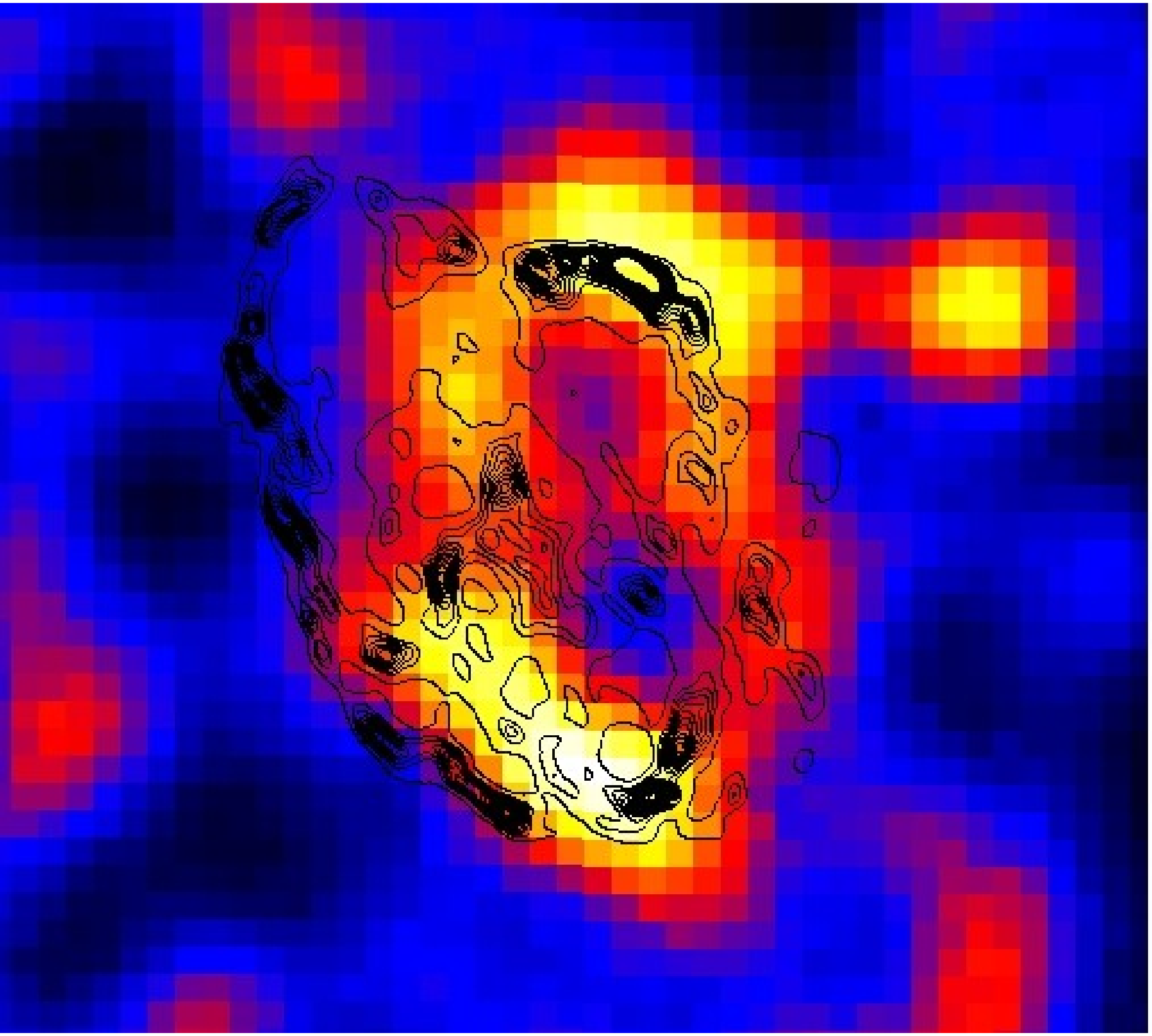
AGILE detection of W44



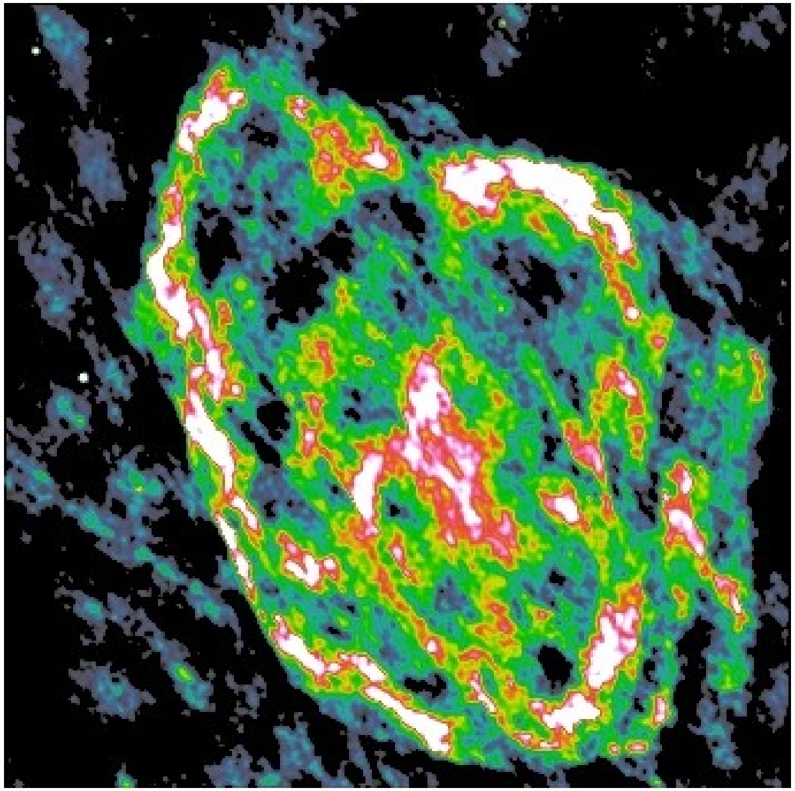
Giuliani et al. ApJ, 2011

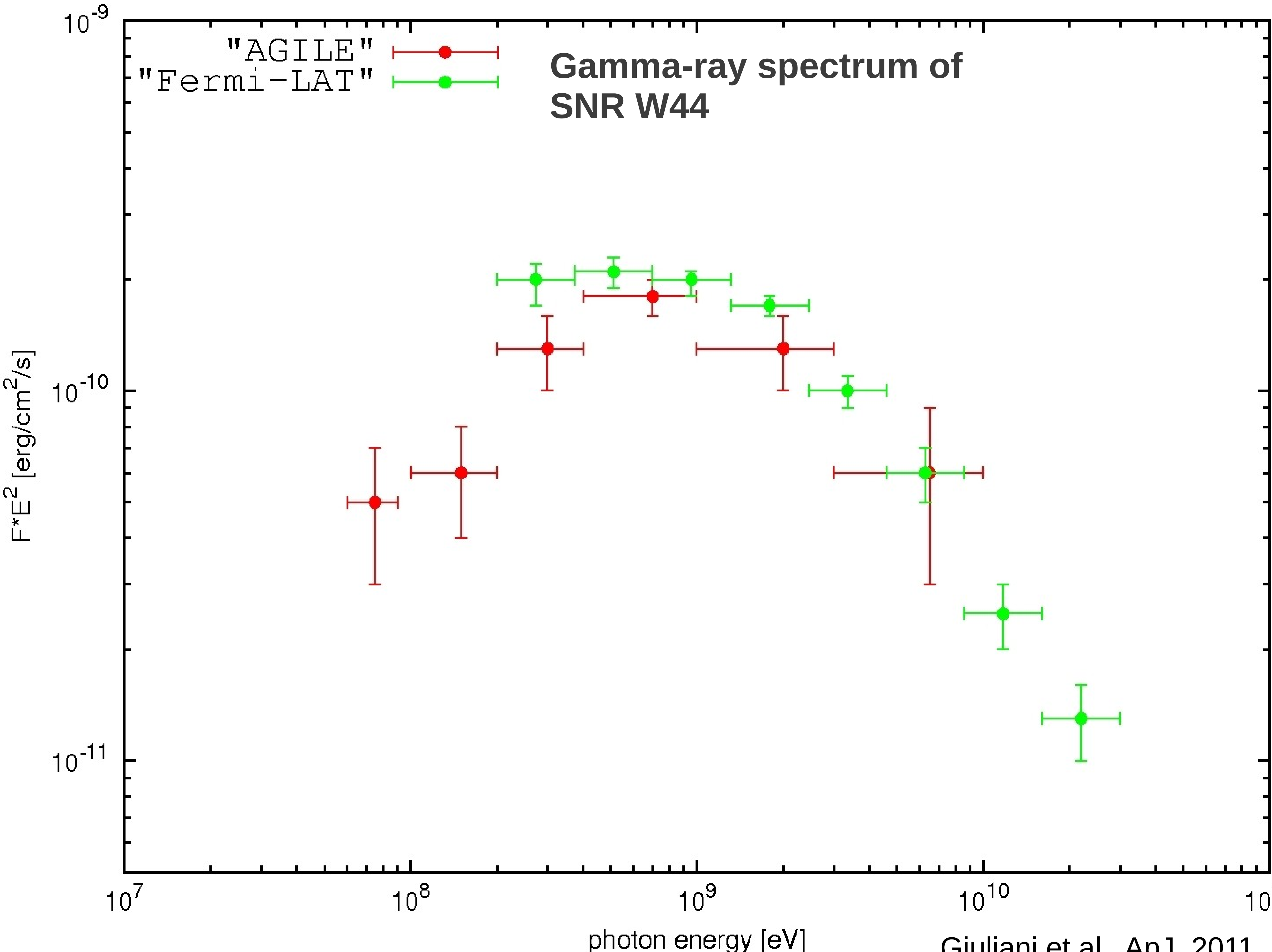
AGILE detection of W44

E > 400 MeV



1.4 Ghz





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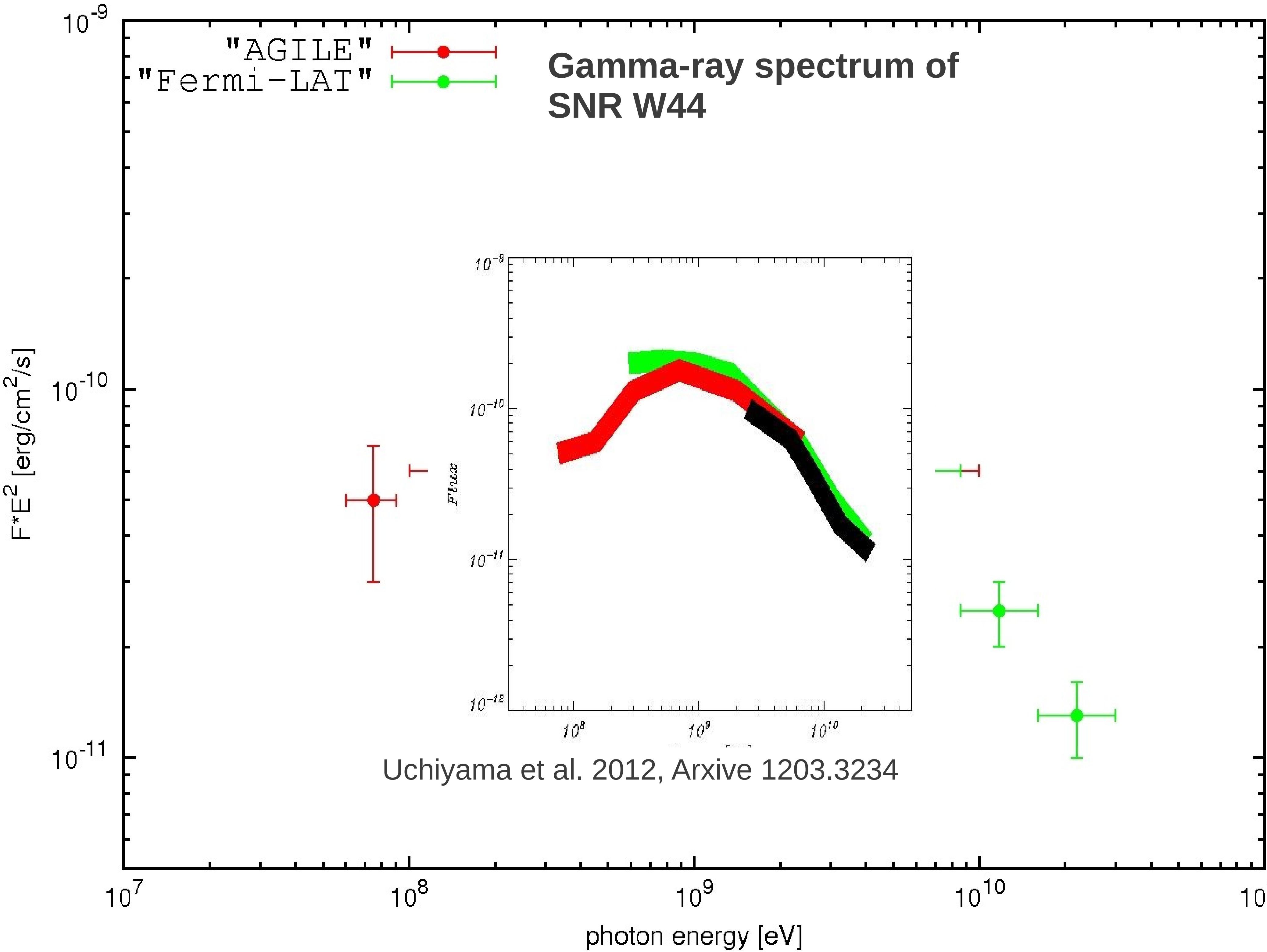
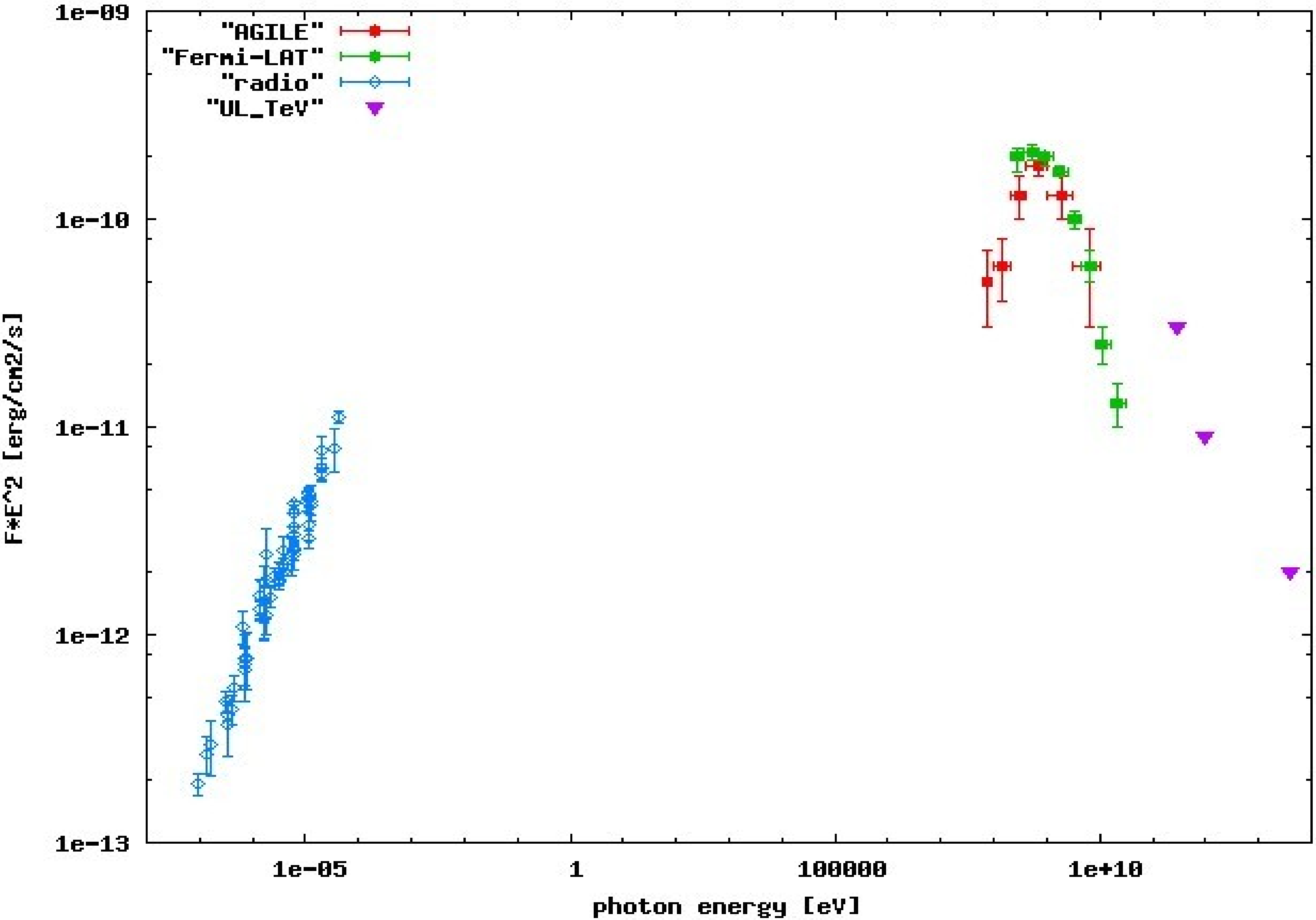


"AGILE"
"Fermi-LAT"
Gamma-ray spectrum of
SNR W44
F*E2 [erg/cm2/s]
10-9
10-10
10-11
10^7
10^8
10^9
10^10
photon energy [eV]
Flux
Uchiyama et al. 2012, Arxive 1203.3234



"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:

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

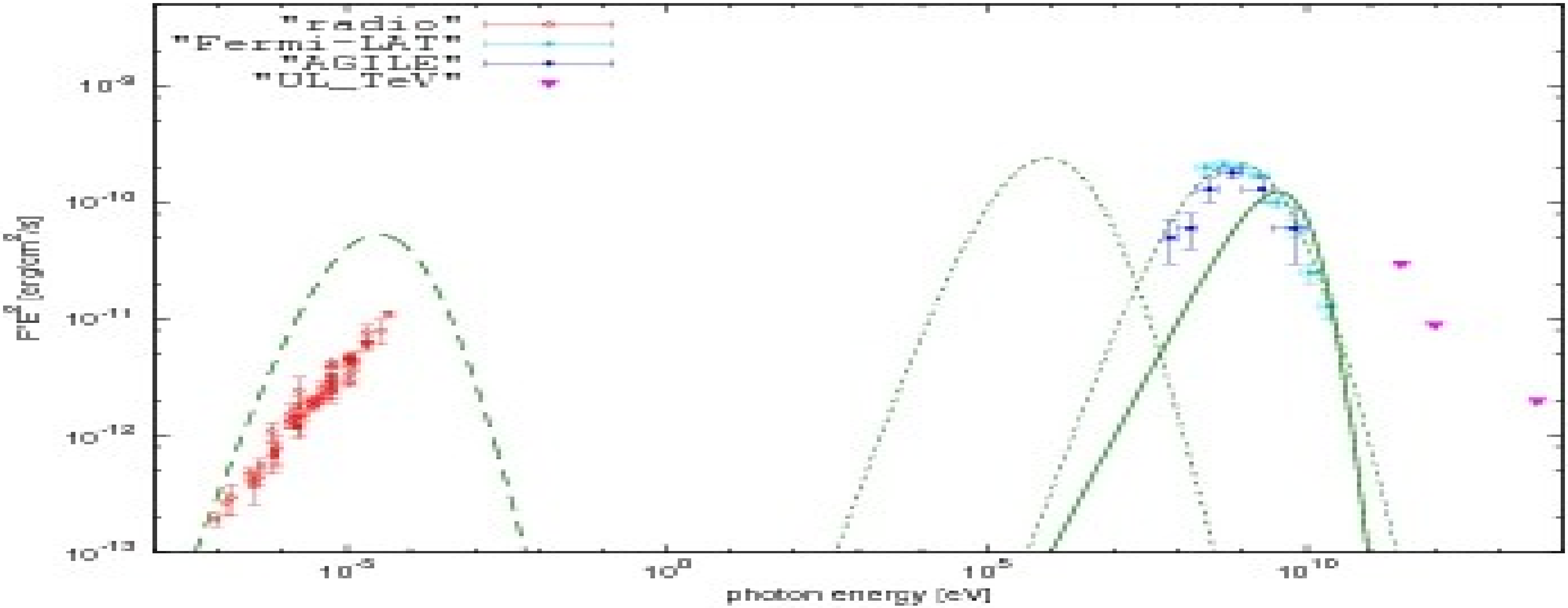
$$F_e(E) = K_e E^{-p} e^{-\frac{E_c}{E}}$$

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

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*

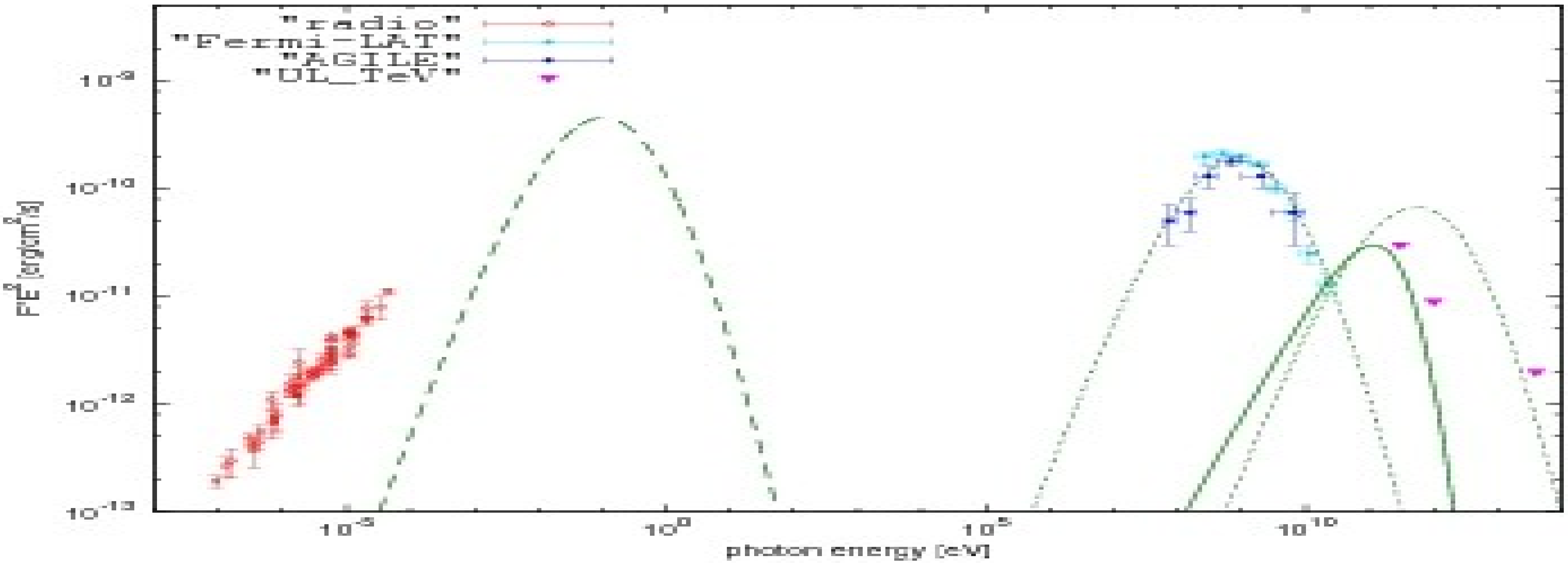
n : 1 cm^{-3}

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 :

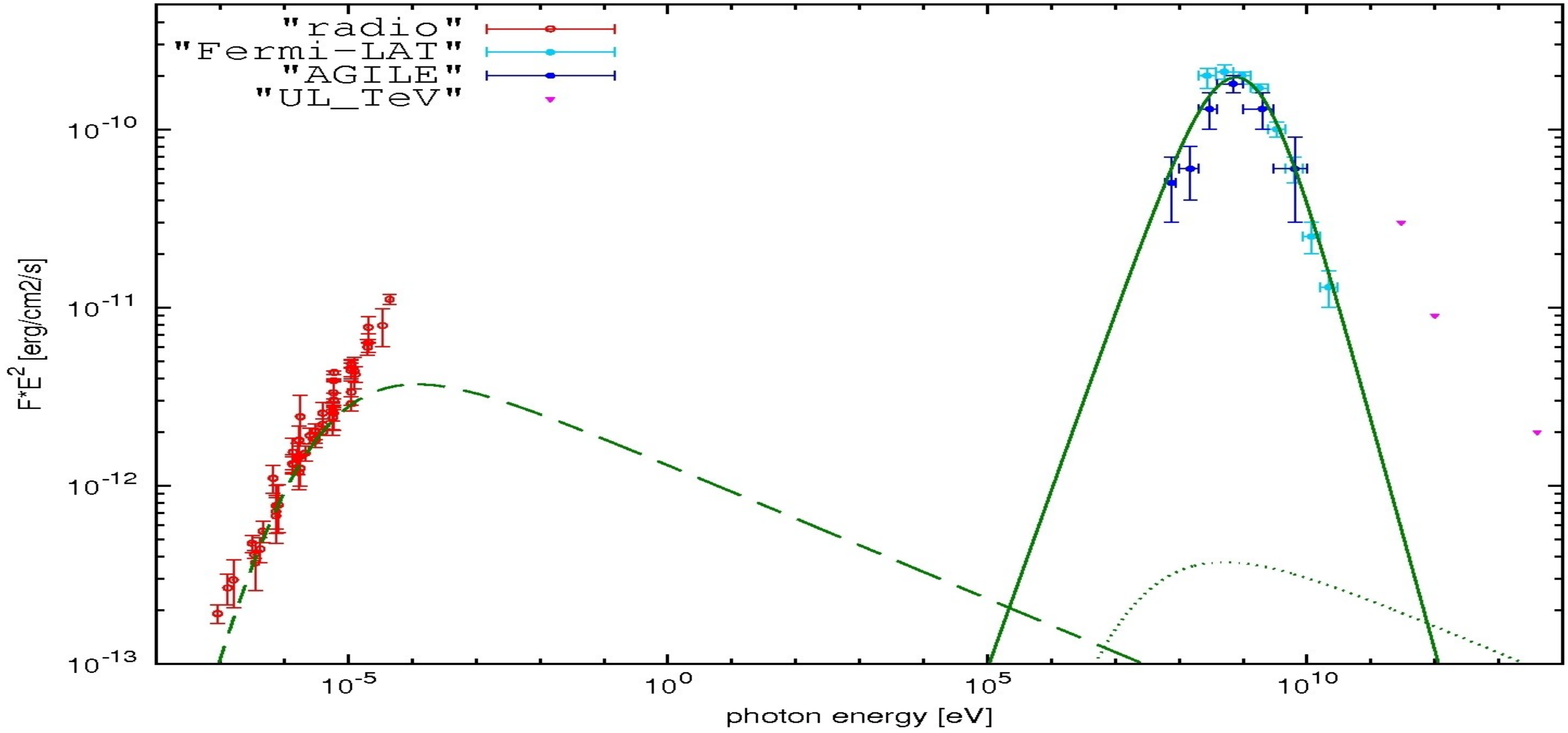
$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1+\frac{E}{E_c}\right)\right)^{p_1-p_2}$$

p1 = 0

p2 = 8

E_c = 700 GeV

Leptonic model : Bremsstrahlung



Ambient : *B : 20 µG*

n : 300 cm^{-3}

Electrons Spectrum :

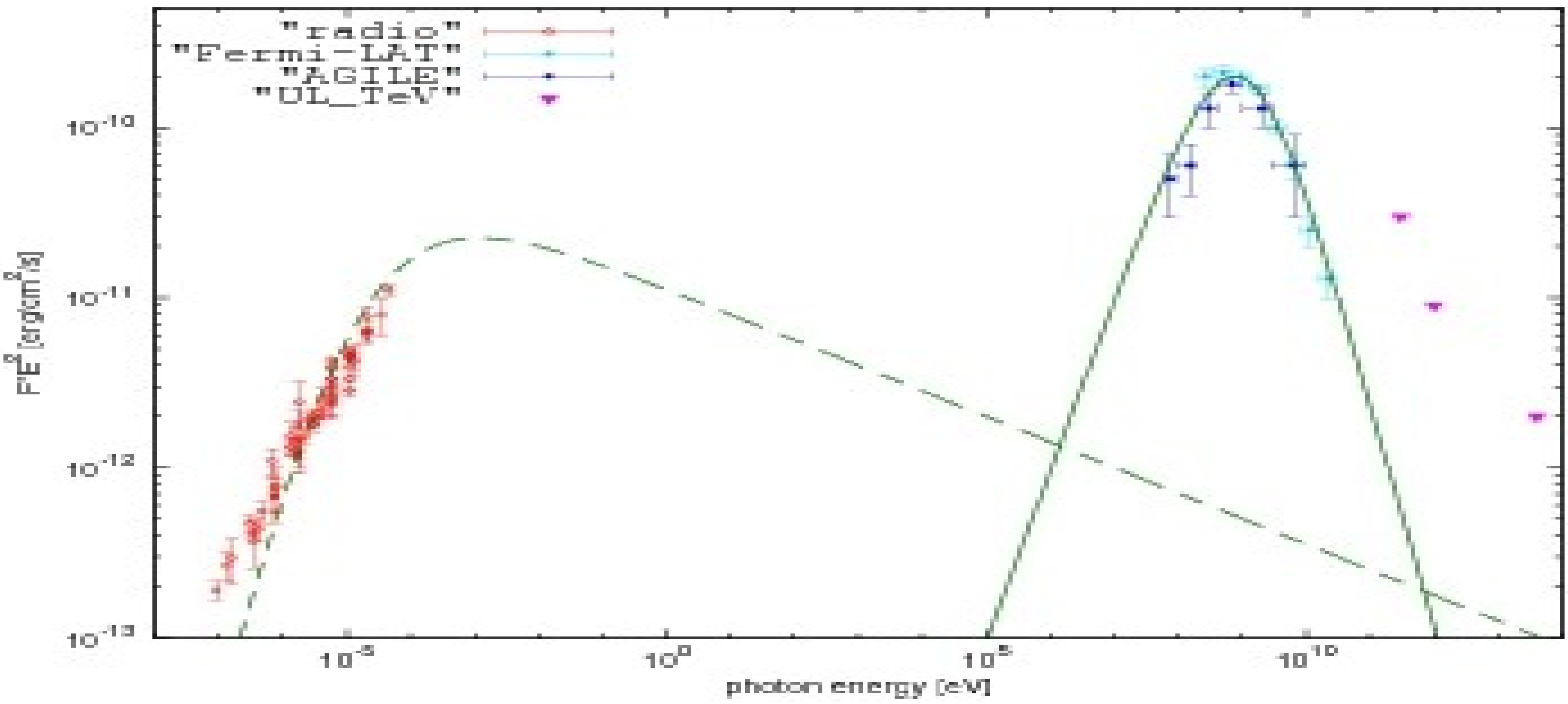
$$F_e(E) = K_e \left(\frac{E}{E_c}\right)^{p_1} \left(\frac{1}{2}\left(1+\frac{E}{E_c}\right)\right)^{p_1-p_2}$$

p1 = 0

p2 = 3.3

E_c = 1 GeV

Leptonic model : Bremsstrahlung, B= 200



Ambient : *B : 200 µG*

n : 5000 cm^{-3}

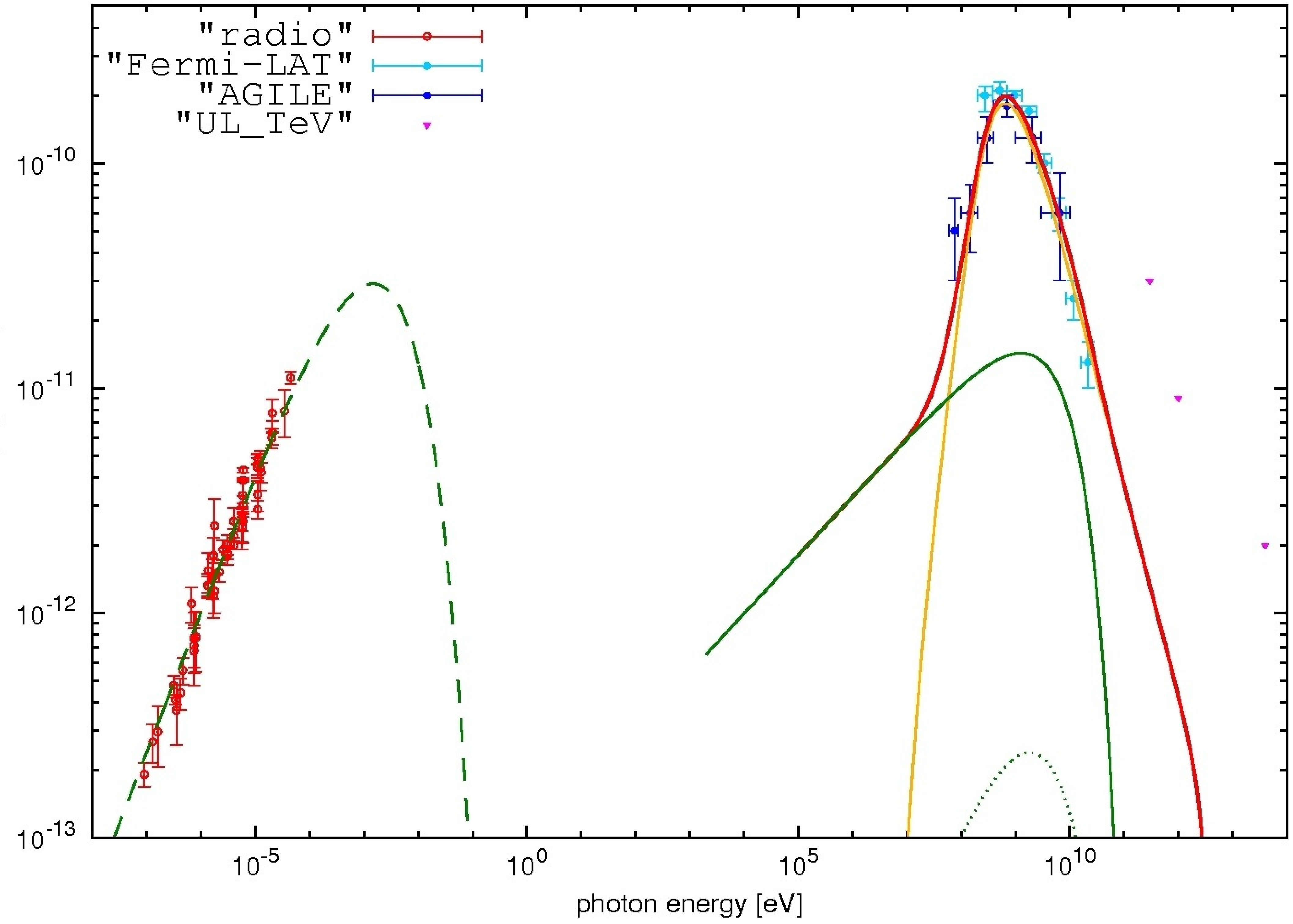
Electrons Spectrum :

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

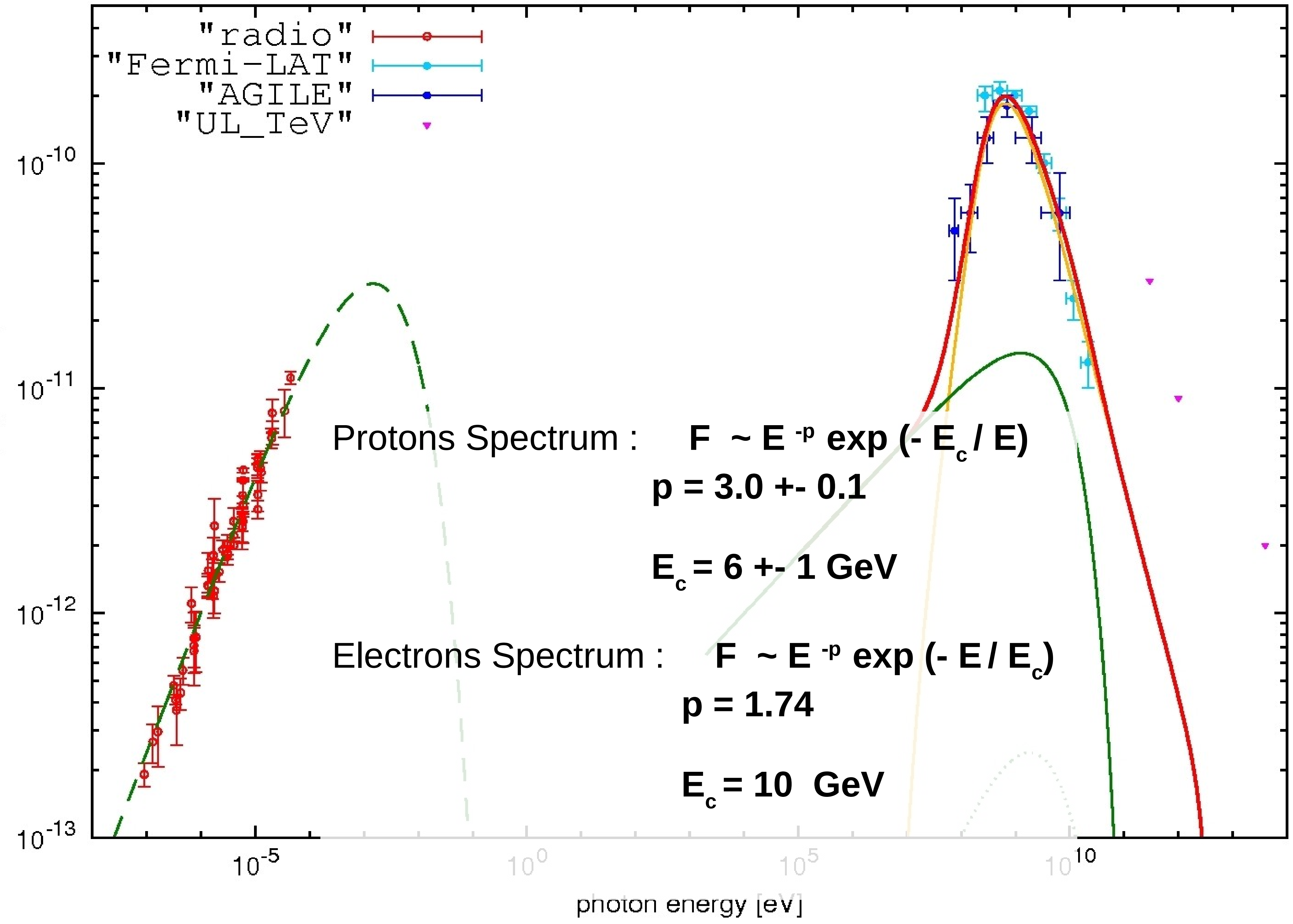
p1 = 0

p2 = 8

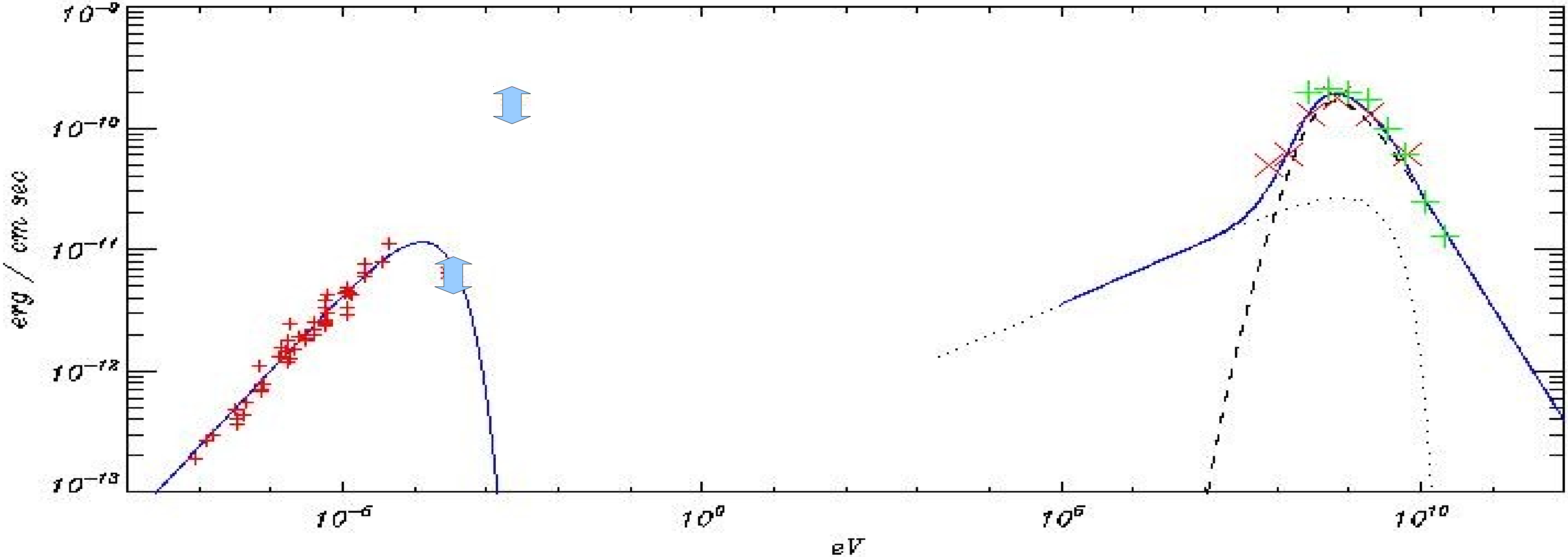
E_c = 1 GeV



"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 ~ E^{-p} exp (- E_c / E)
p = 3.0 +- 0.1
E_c = 6 +- 1 GeV
Electrons Spectrum : F ~ E^{-p} exp (- E / E_c)
p = 1.74
E_c = 10 GeV



B : 70.0000

n : 200

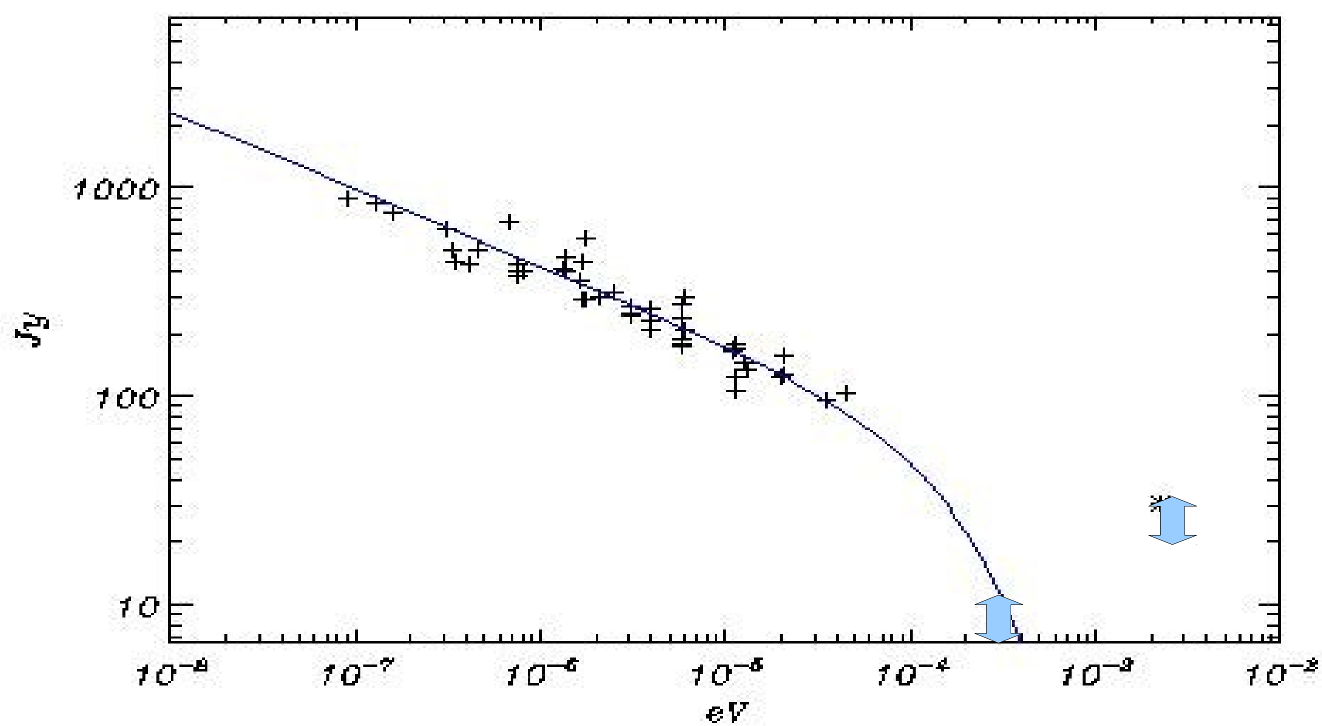
Ec : 7000.00

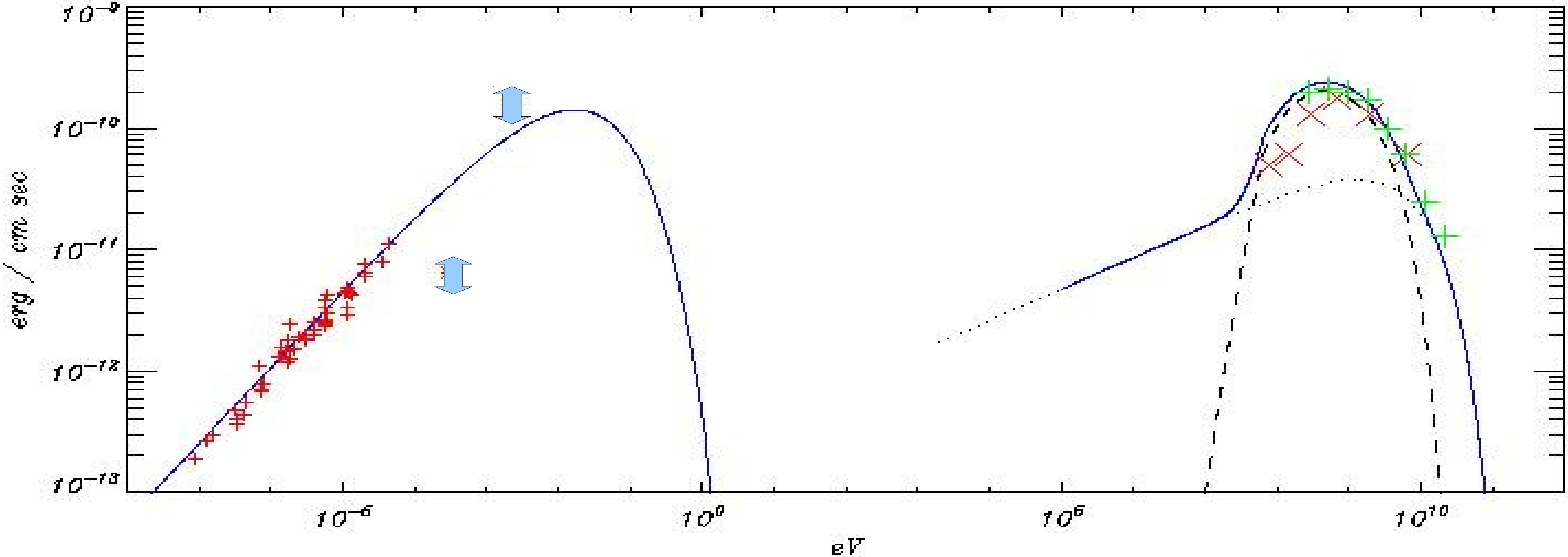
kp : 1.25000e+23

k : 2.01021e+10

p1 : 1.74000

p2 : 12





B : 800.000

n : 7000

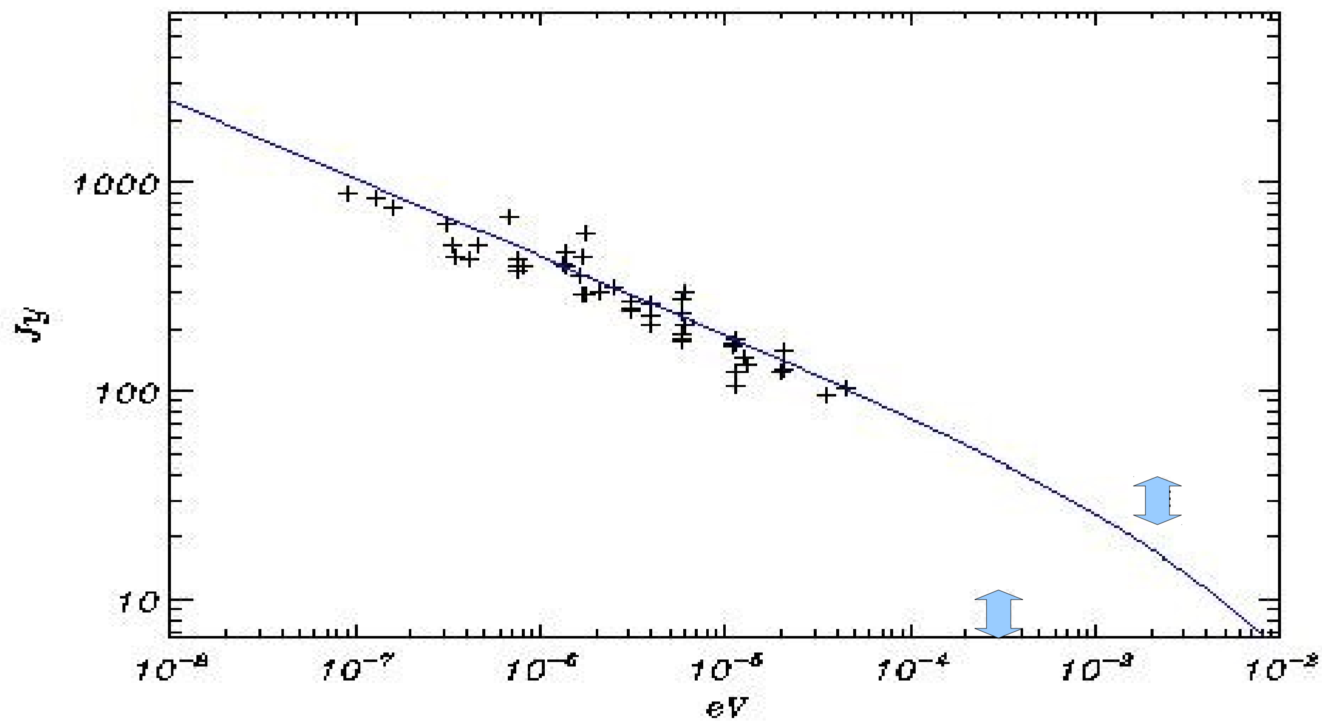
Ec : 15000.0

kp : 4.29752e+16

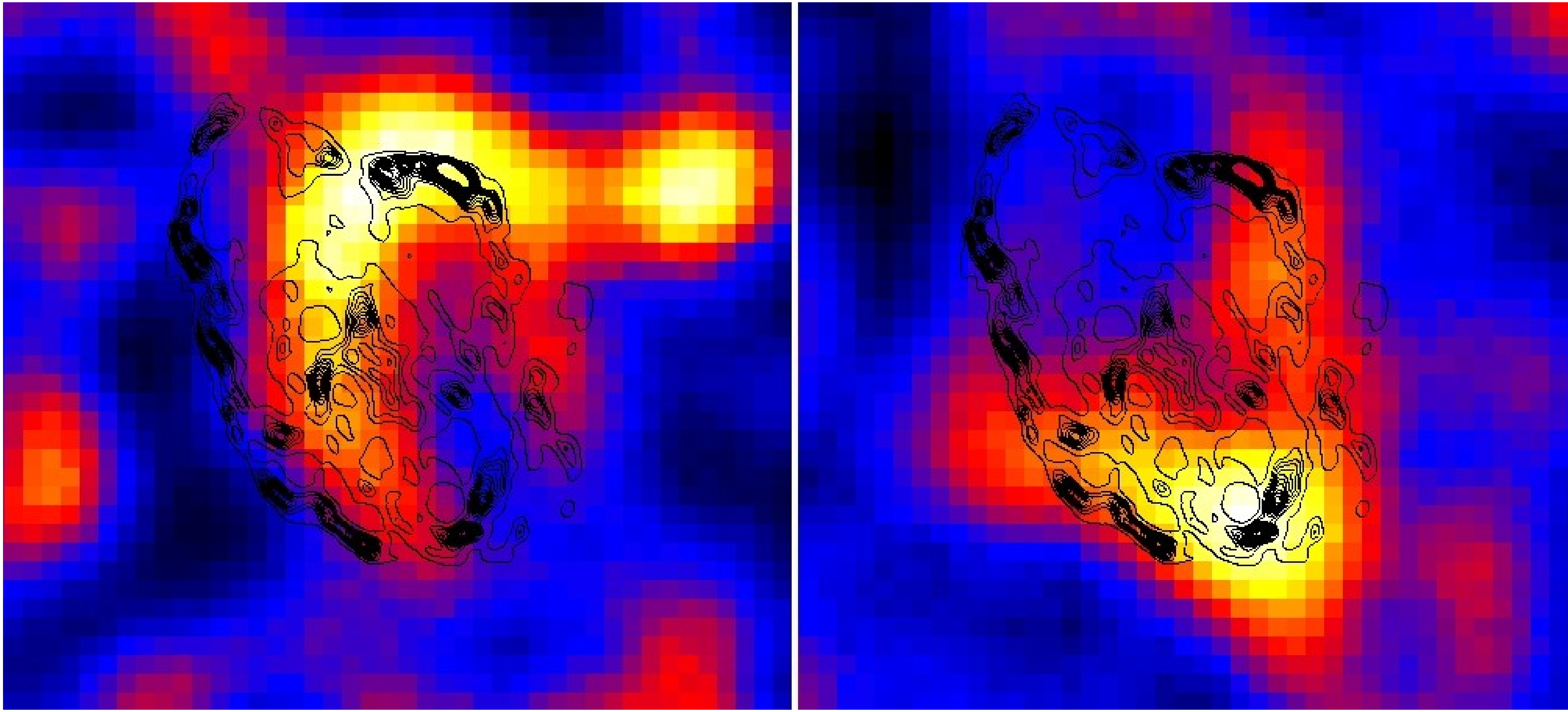
k : 2.01708e+08

p1 : 1.74000

p2 : 12

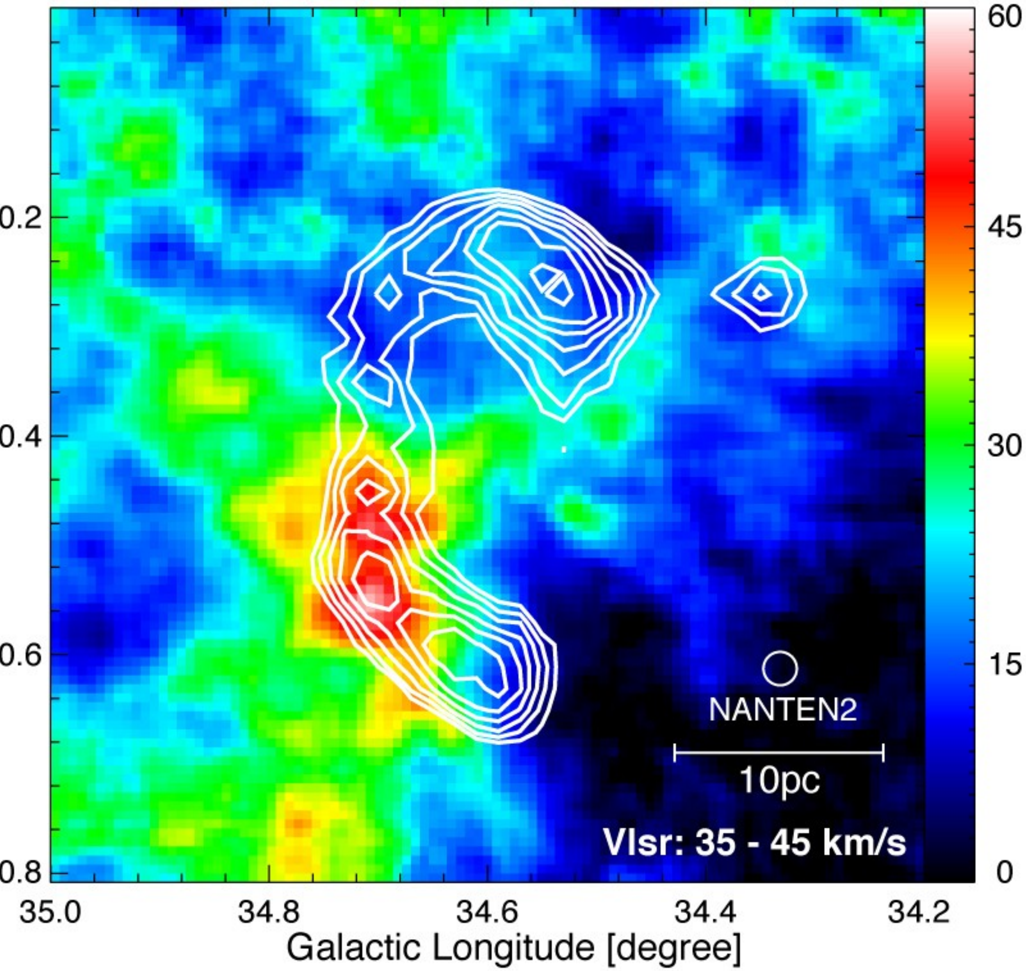


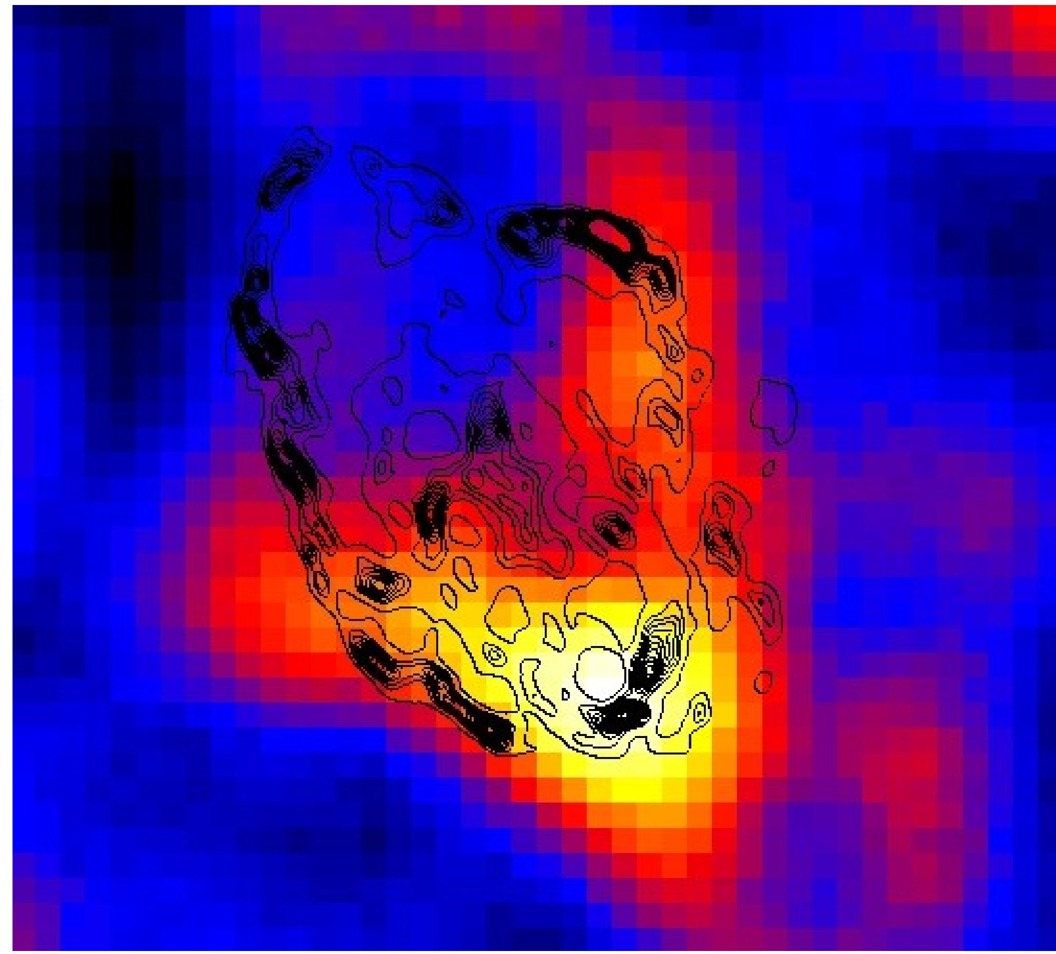
400 MeV < E < 1 GeV **1 GeV < E < 3 GeV**



CO (J 1-->0)

E > 400 MeV



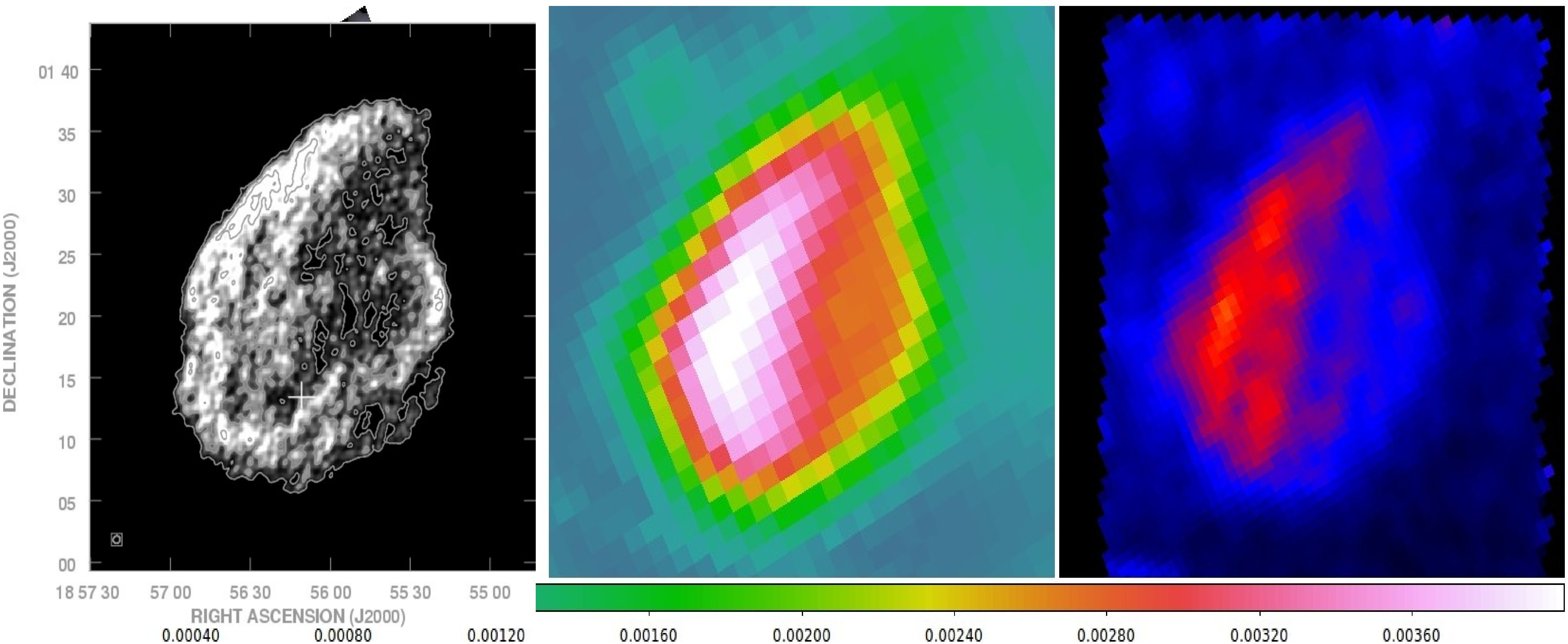


High-Freq. radio map @ Medicina Radiotelescope

74 MHz

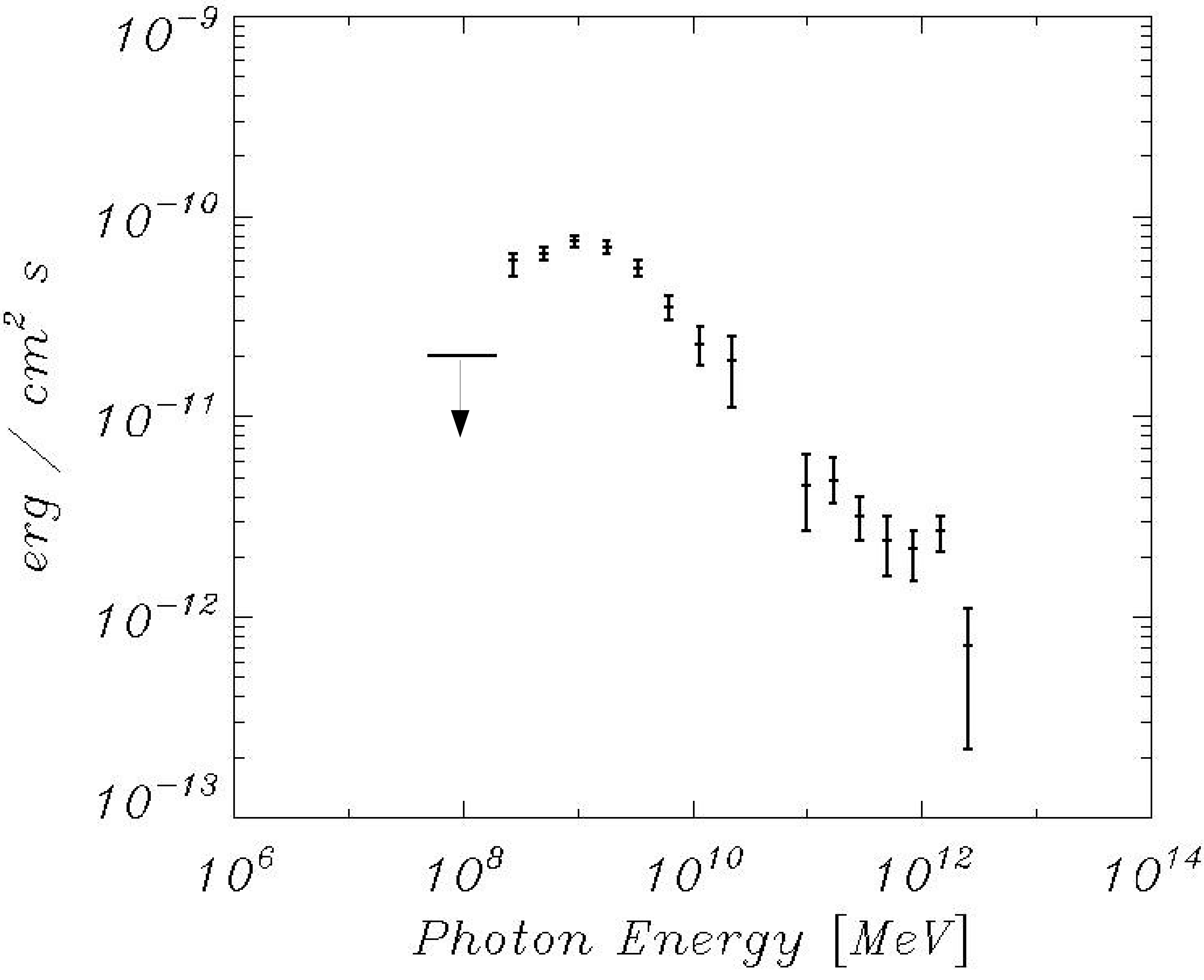
5 GHz

8 GHz

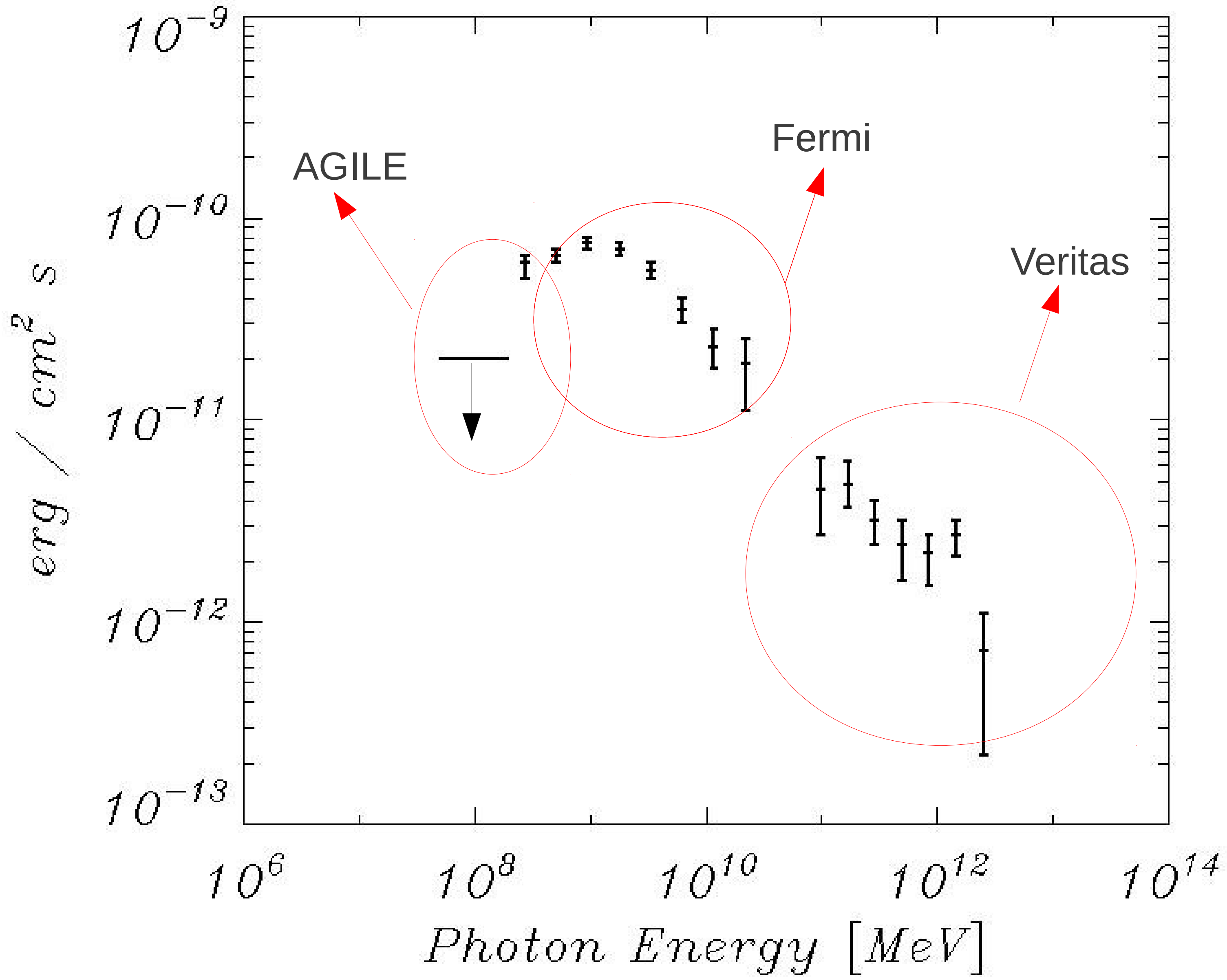


Pellizzoni, Giuliani, et al.

SNR W51C

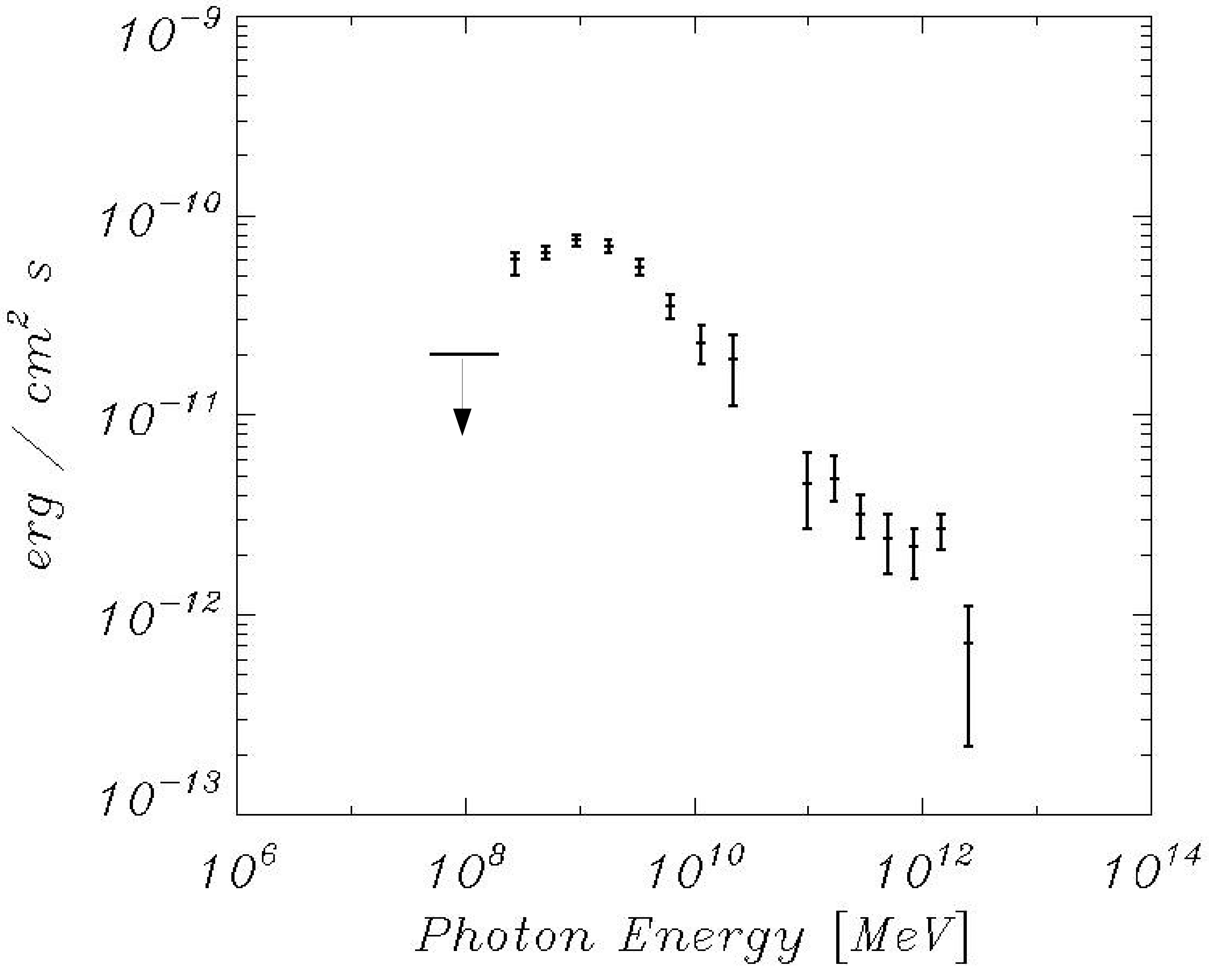

10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
erg / cm^2 s
10^{6}
10^{8}
10^{10}
10^{12}
10^{14}
Photon Energy [MeV]

SNR W51C



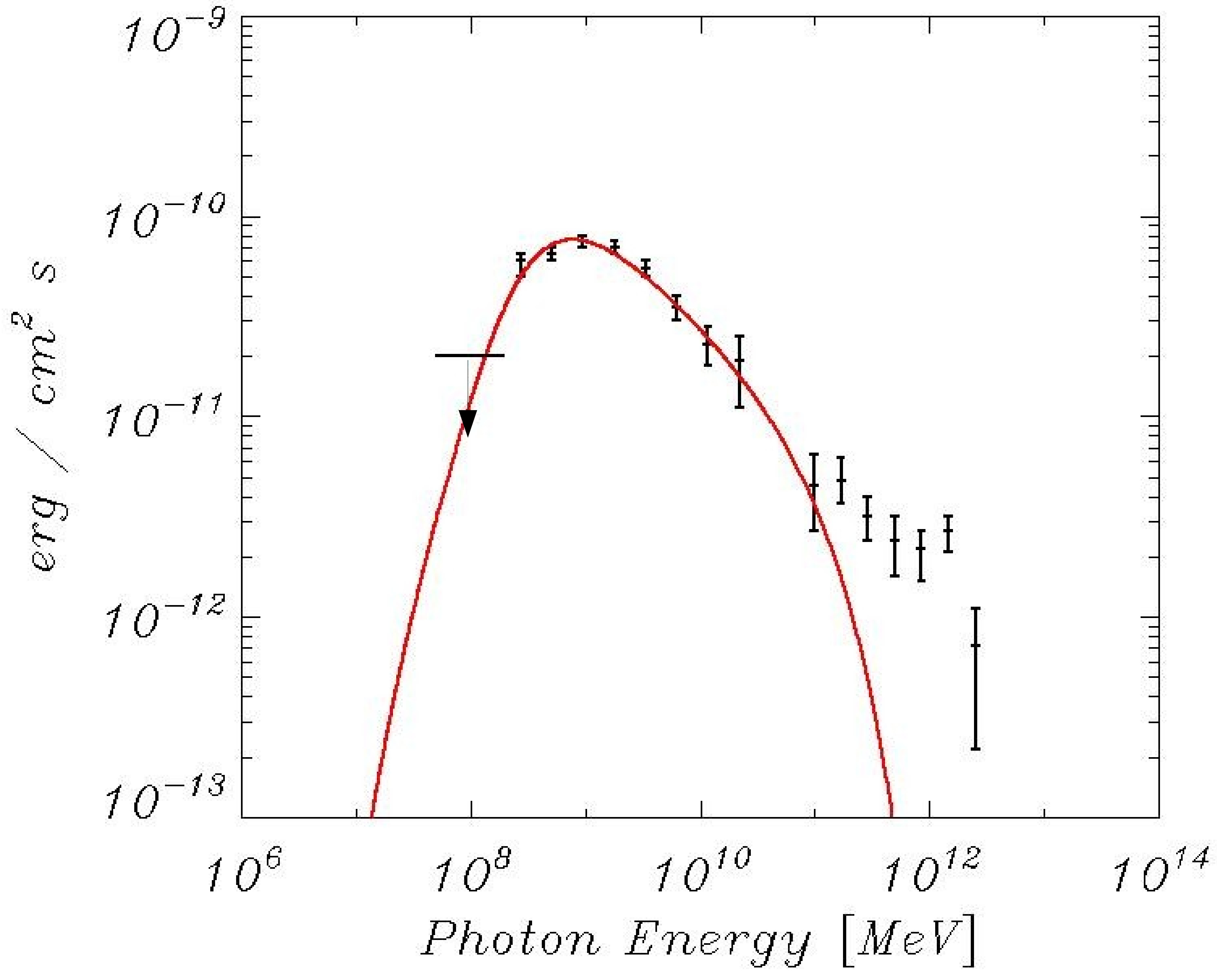
AGILE
Fermi
Veritas
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$erg / cm^2 s$
10^6
10^8
10^{10}
10^{12}
10^{14}
Photon Energy [MeV]

SNR W51C



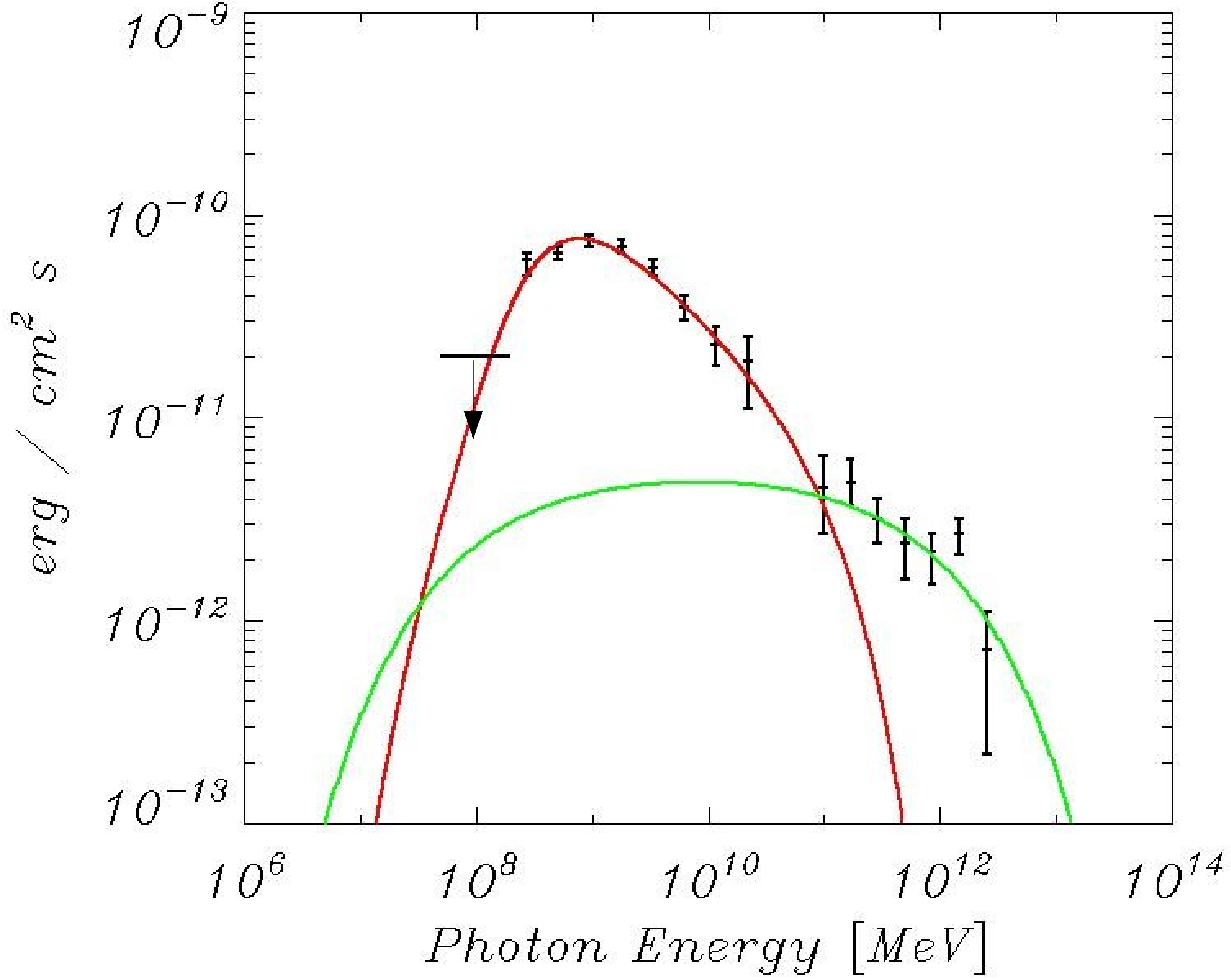
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$erg\ /\ cm^2\ s$
10^6
10^8
10^{10}
10^{12}
10^{14}
$Photon\ Energy\ [MeV]$

SNR W51C



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]

Conlusions

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

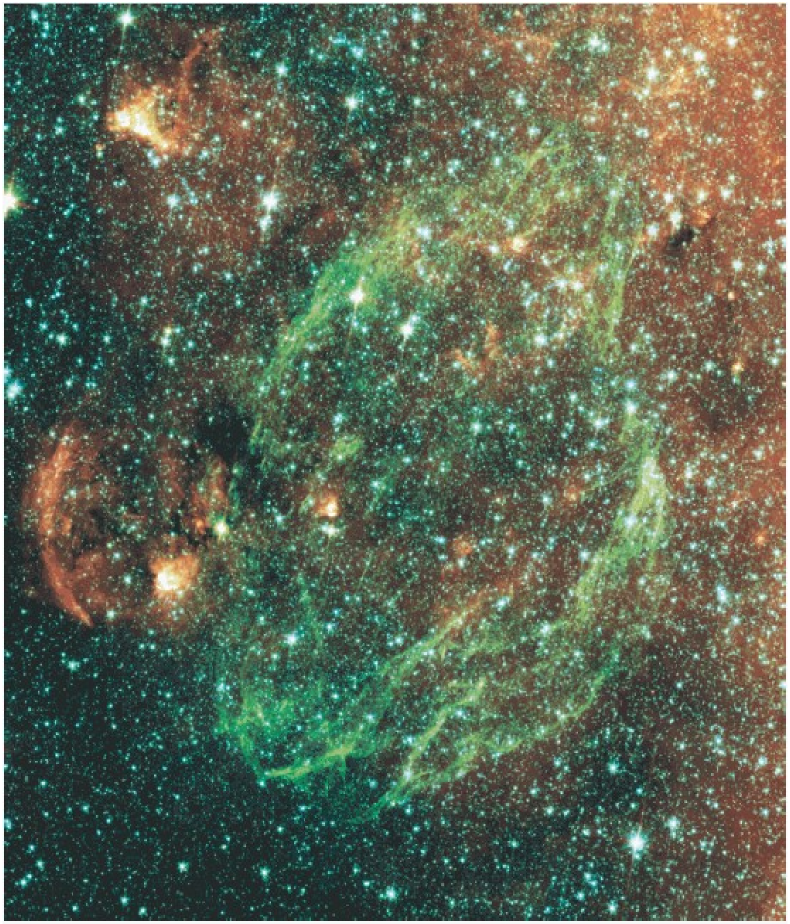
The inferred proton spectrum for W44 has:

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



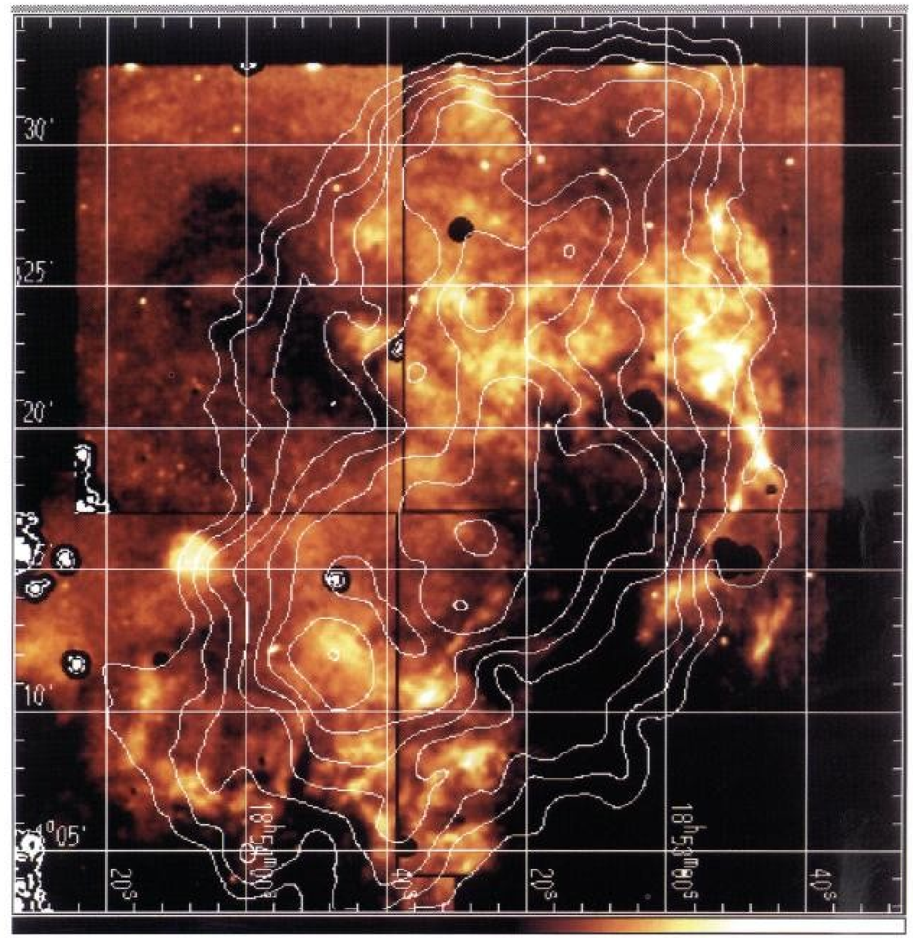


FIG. 4.—Red continuum subtracted Hα image, superposed on PSPC contours

RHO et al. (see 430, 760)

[Reach et al . 2005]