Middle-aged SNRs with AGILE

A. Giuliani,
M. Cardillo, G. Piano, M. Tavani

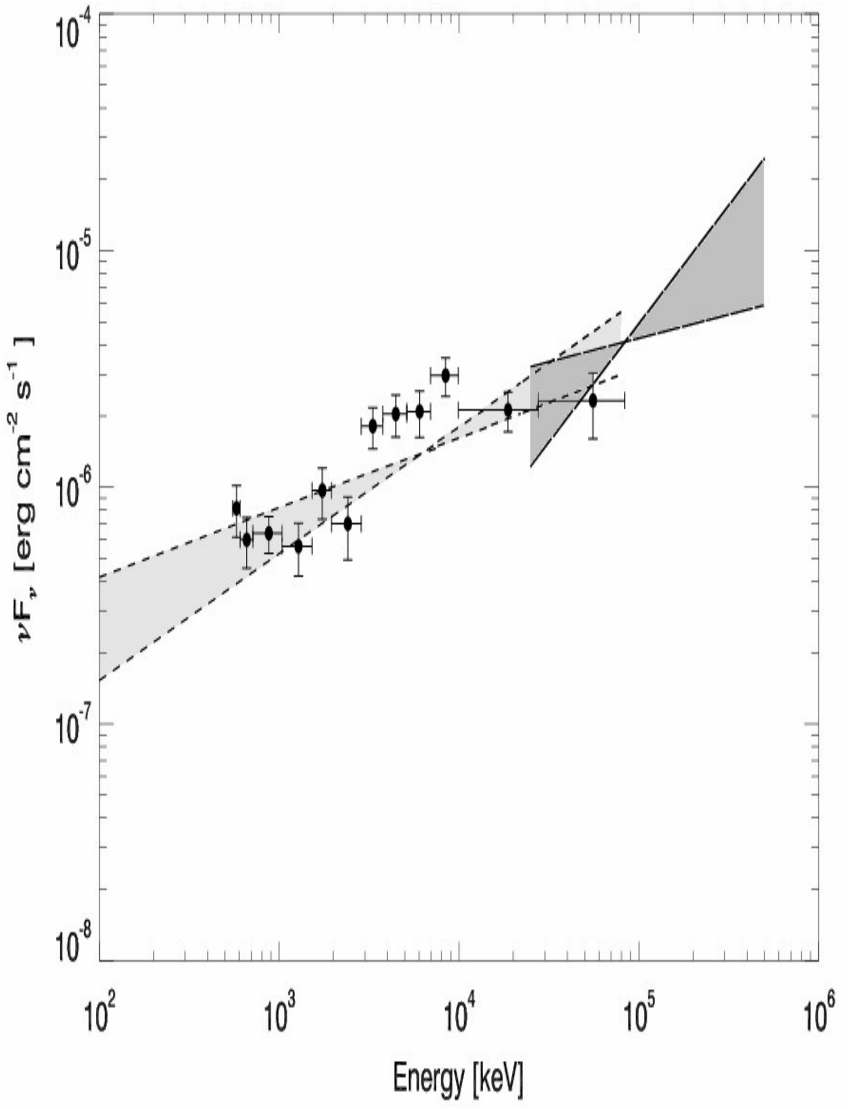
Gamma-ray astronomy below 100 MeV

- ***Last (almost) unexplored window : 10 -100 MeV***

- ***Challenging because of high background flux and strong m.s. suffered by tracks***

- ***AGILE already provided a spectrum below 100 MeV for some “special” sources (GRB 090510, Crab pulsar)***

- ***Thanks to a better knowledge of the instrument is now possible also for “standard” (bright) sources***



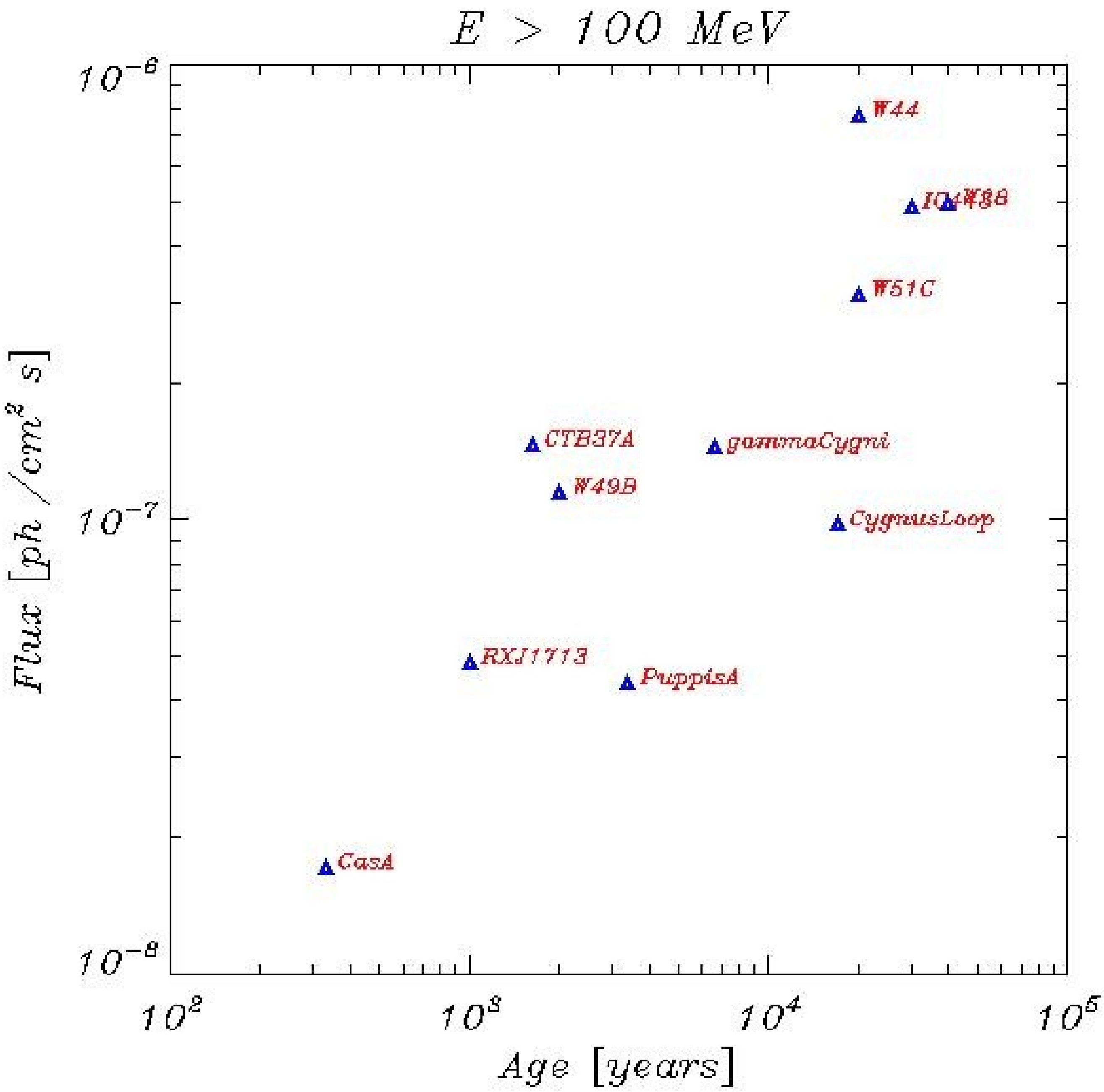
SNRs at “low” energy

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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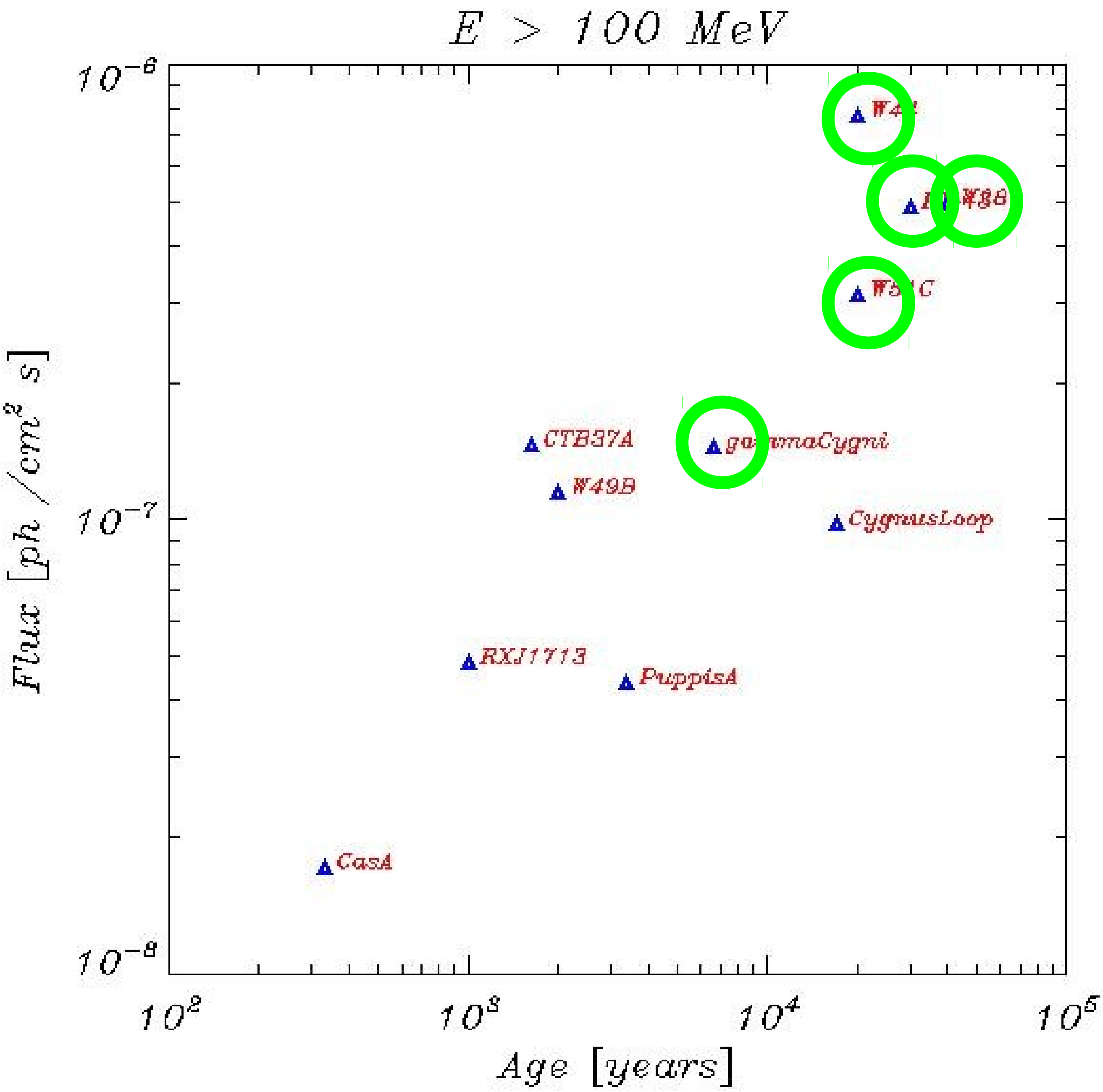
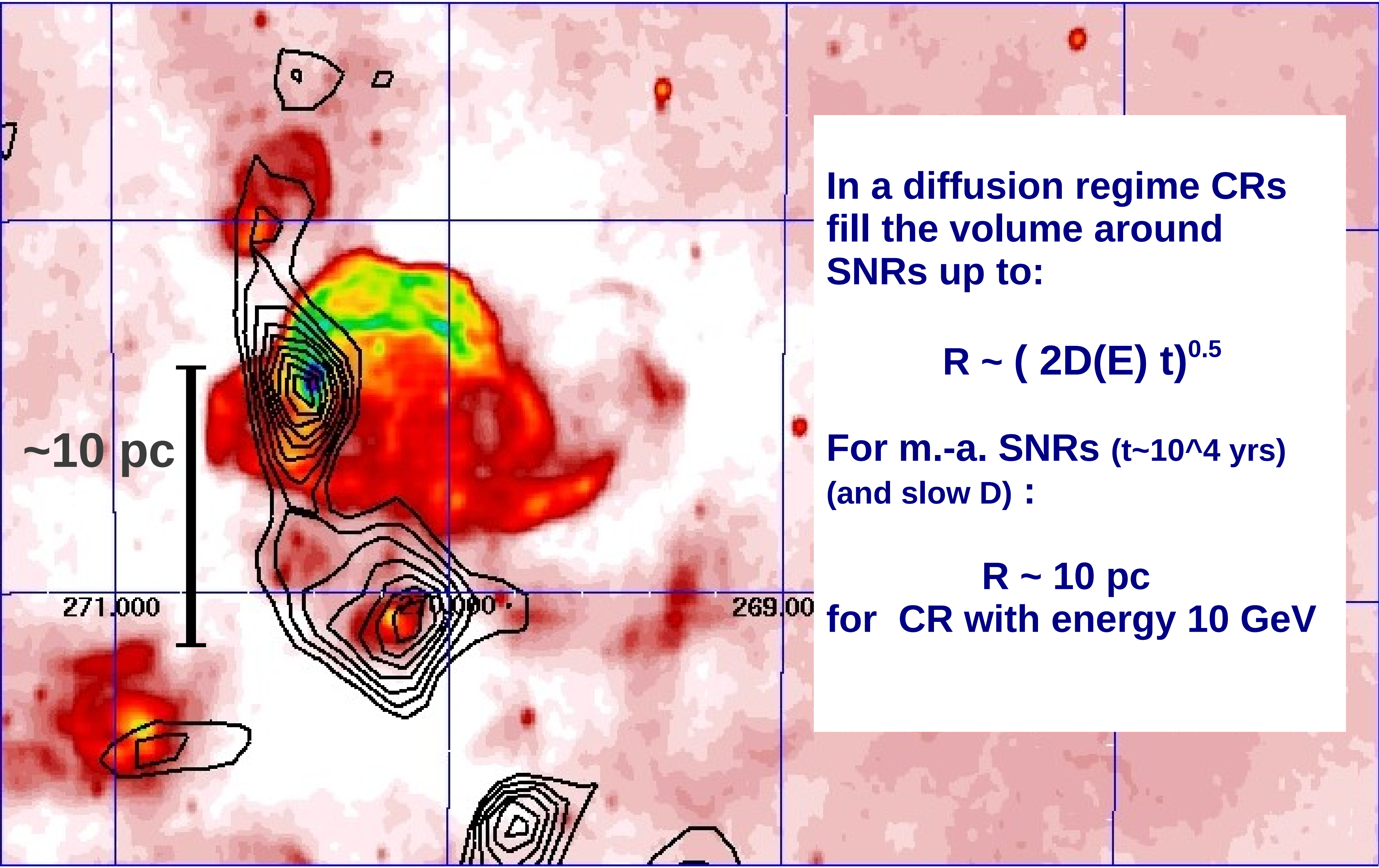


SNRs at “low” energy : diffusion of CRs (W28)



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

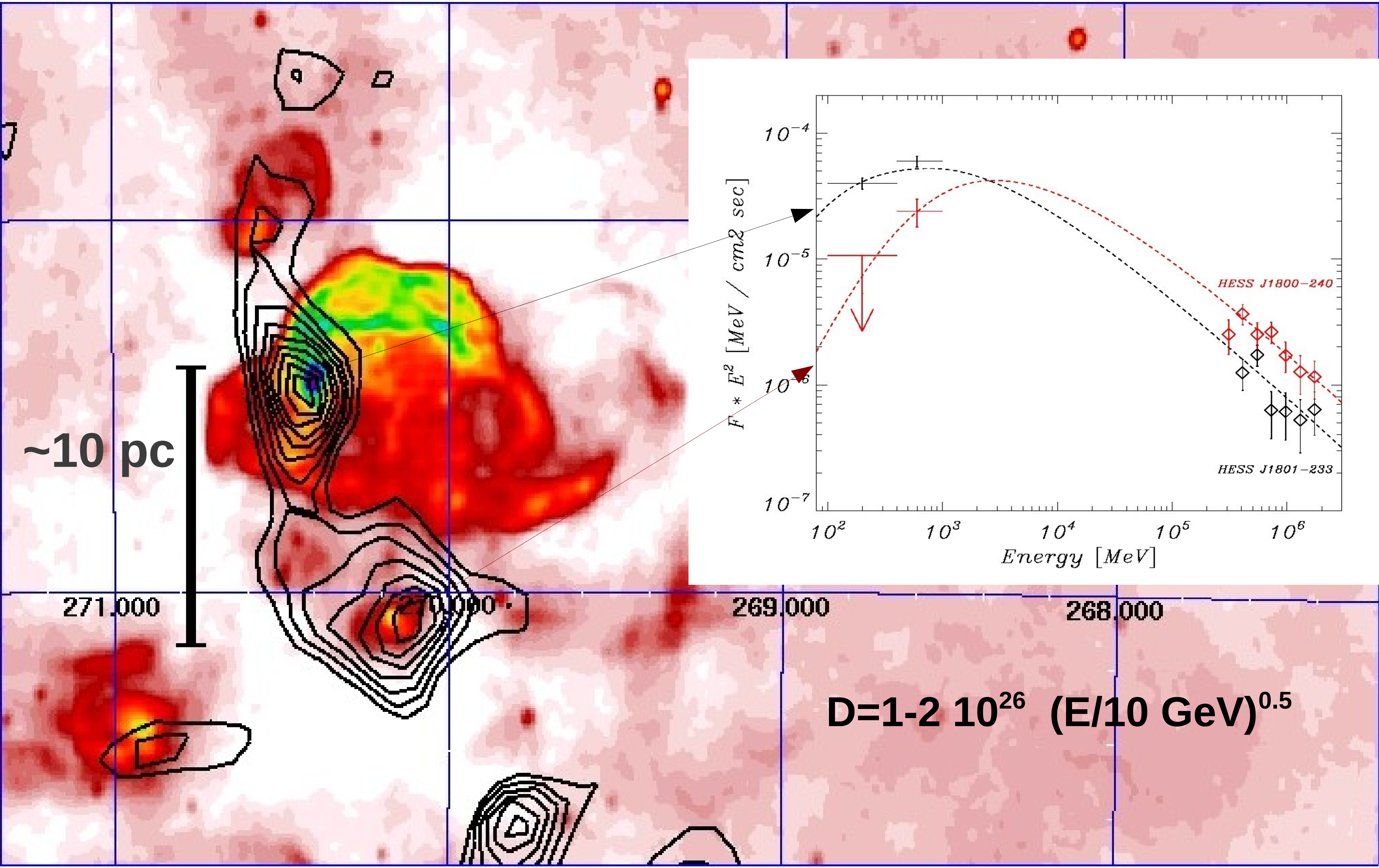
$$R \sim (\ 2D(E)\ t)^{0.5}$$

For m.-a. SNRs (t~10^4 yrs) (and slow D) :

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

for CR with energy 10 GeV

SNRs at “low” energy : diffusion of CRs



$D = 1\text{-}2\ 10^{26}\ (E/10\ \text{GeV})^{0.5}$

SNRs at “low” energy : protons vs electrons

-

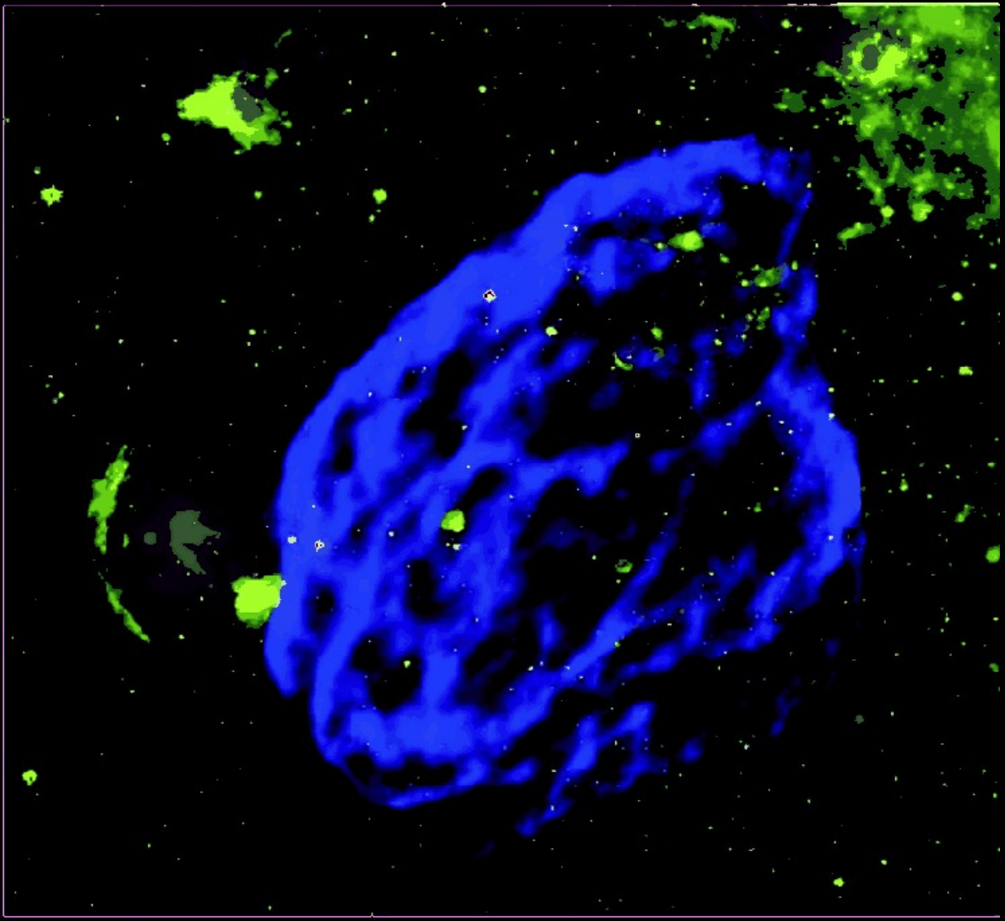
The discrepancies between leptonic and hadronic models are expected to be more evident at low energy (50 -100 MeV)

The Study of SNRs below 100 GeV allows to disentangle between Hadronic vs Leptonic emission.

– > SNR W44

SNR W44

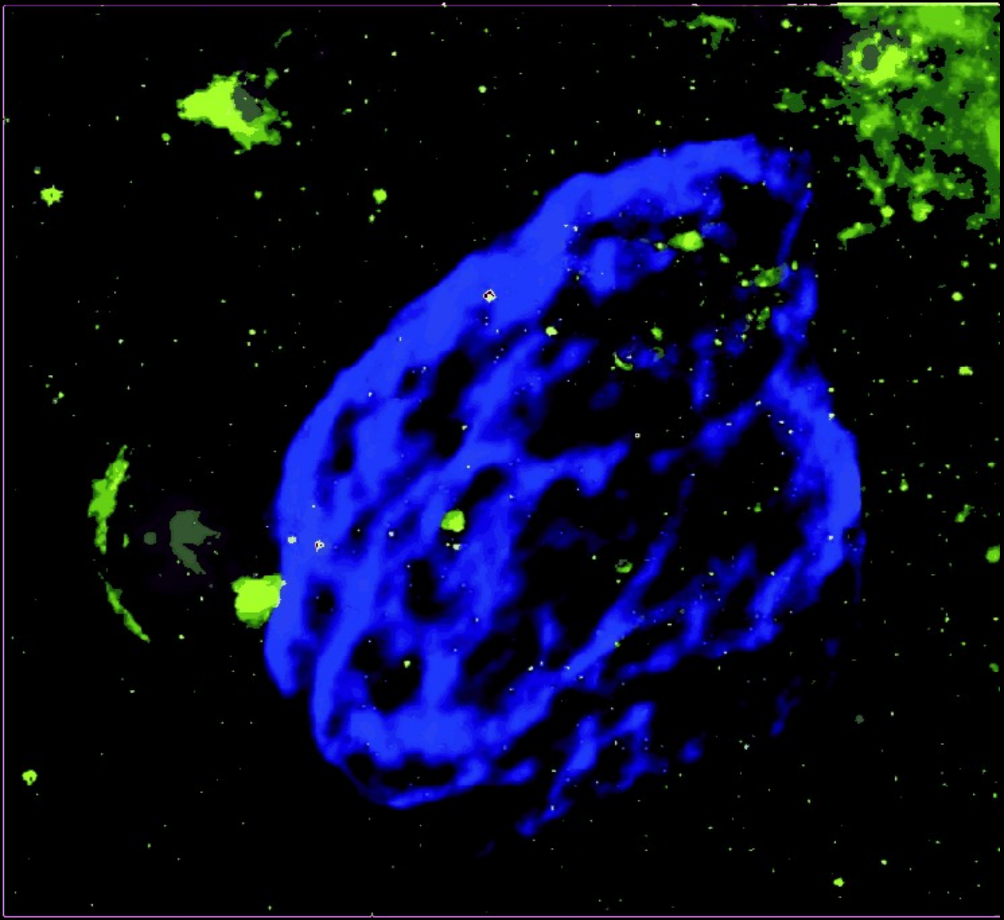
Age : ~ 20000 yr
Distance : ~ 3 Kpc
Type : mixed-morphology



Ideal Laboratory for CRs Study :

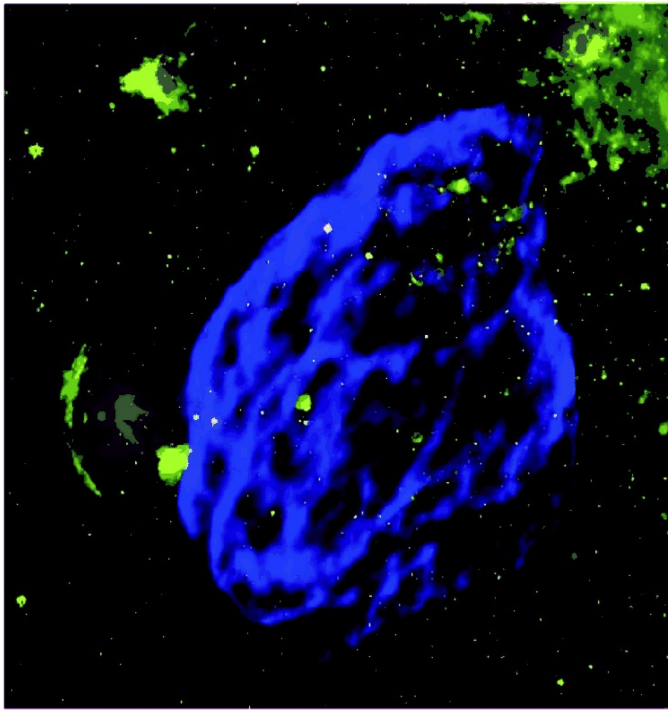
SNR W44

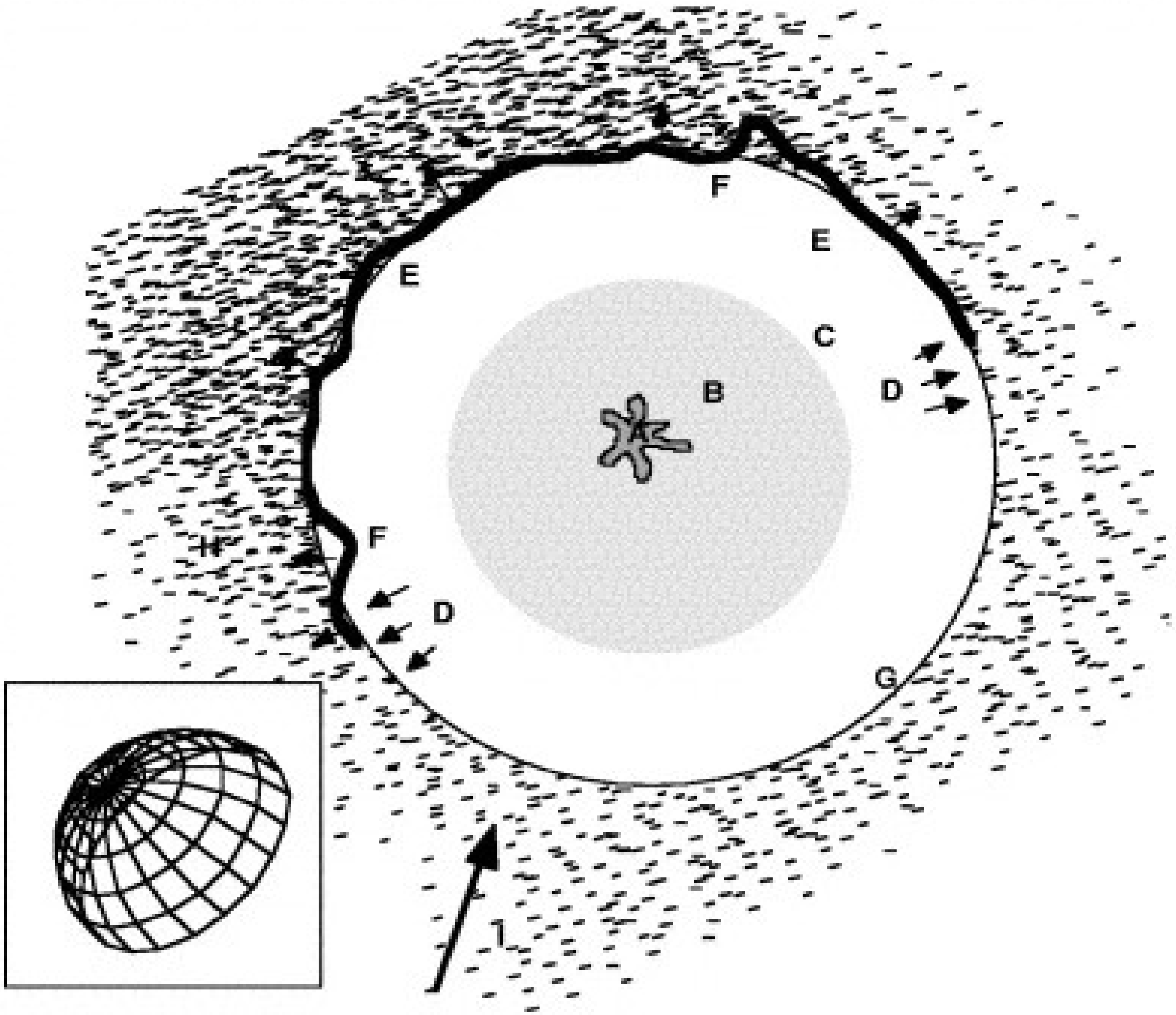
Age : ~ 20000 yr
Distance : ~ 3 Kpc
Type : mixed-morphology



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]

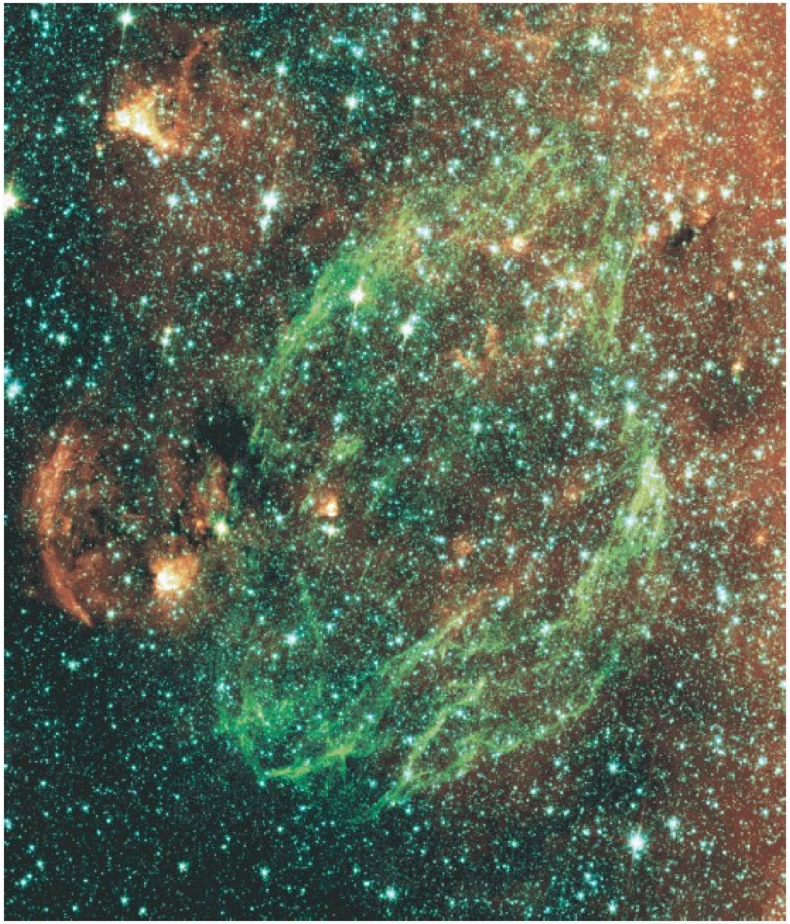




Legend

A	ejecta
B	hot x-ray emitting interior
C	cooler outer region of interior
D	active shell formation in equatorial band
E	cold dense shell, seen in recession in 21 cm, source of radio continuum, gamma rays, bounded by radiative shock
F	corrugation in shell, tangency seen as filament in radio continuum, Hα, OH masers
G	shock with substantial cooling but no shell as yet
H	ambient medium with density gradient, lumpiness which corrugates shell
I	look direction

H_2 and Halpha emission



[Reach et al . 2005]

PLATE 33

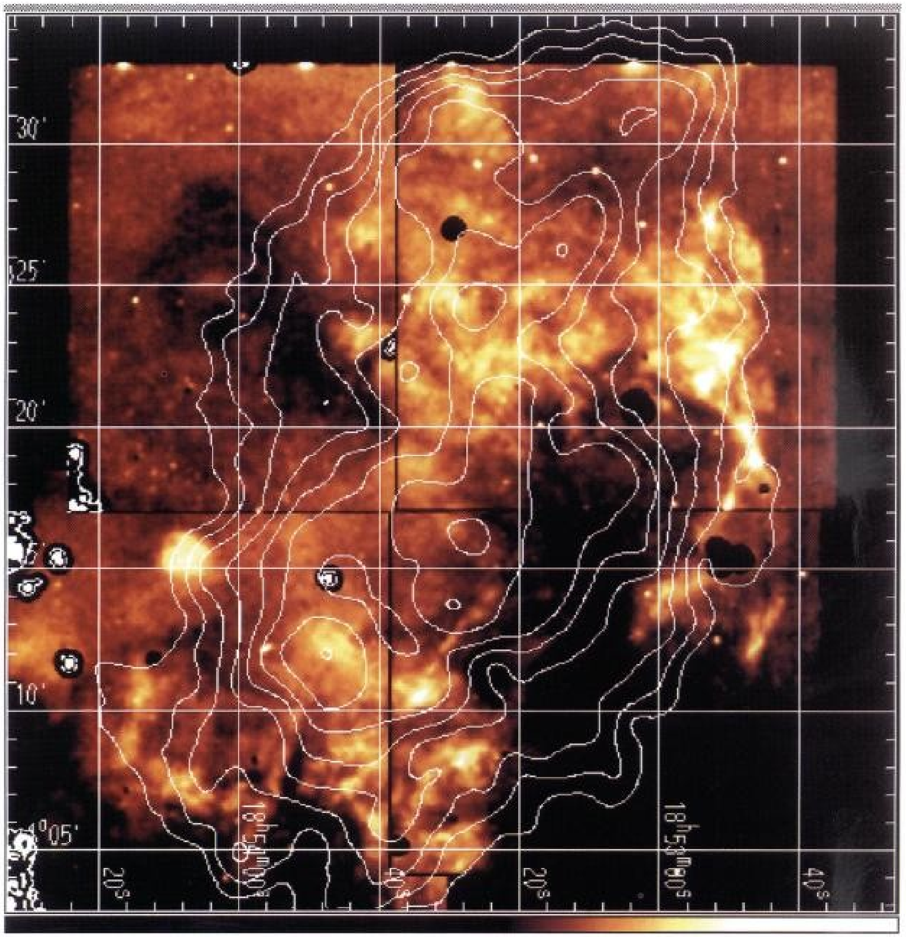
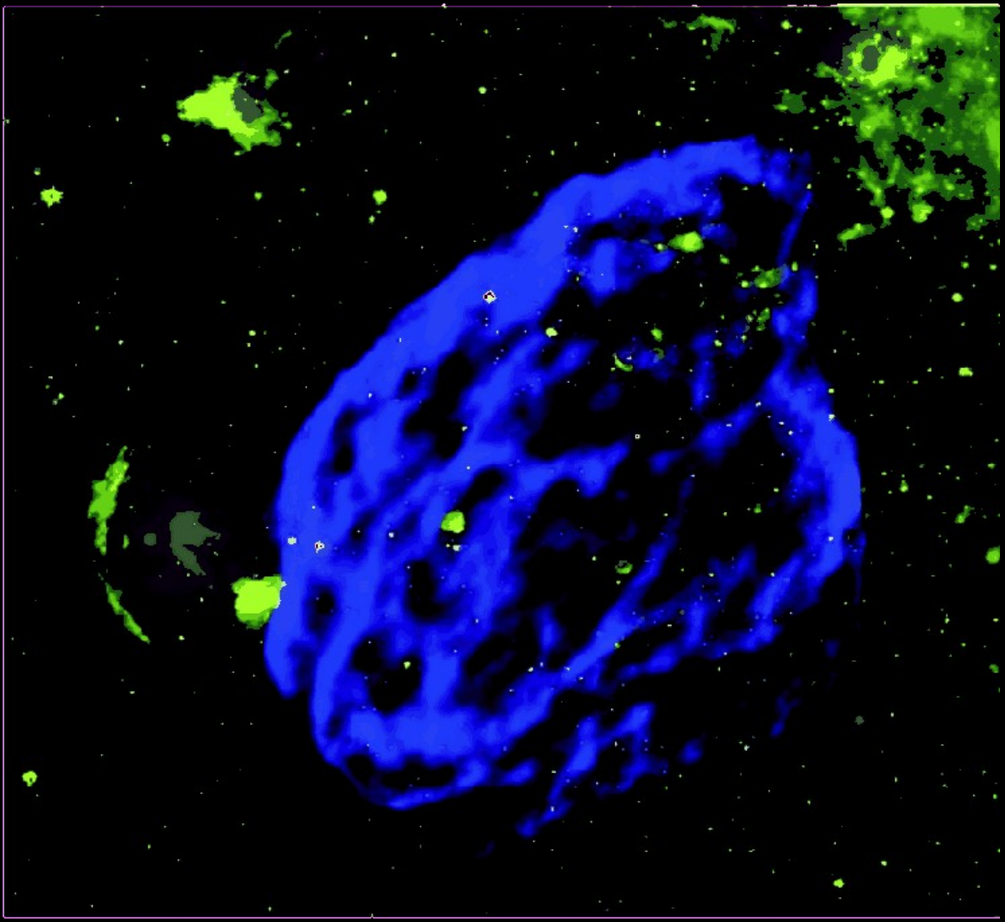


FIG. 4.—Red continuum subtracted Hα image, superposed on PSPC contours

RHO et al. (see 430, 760)



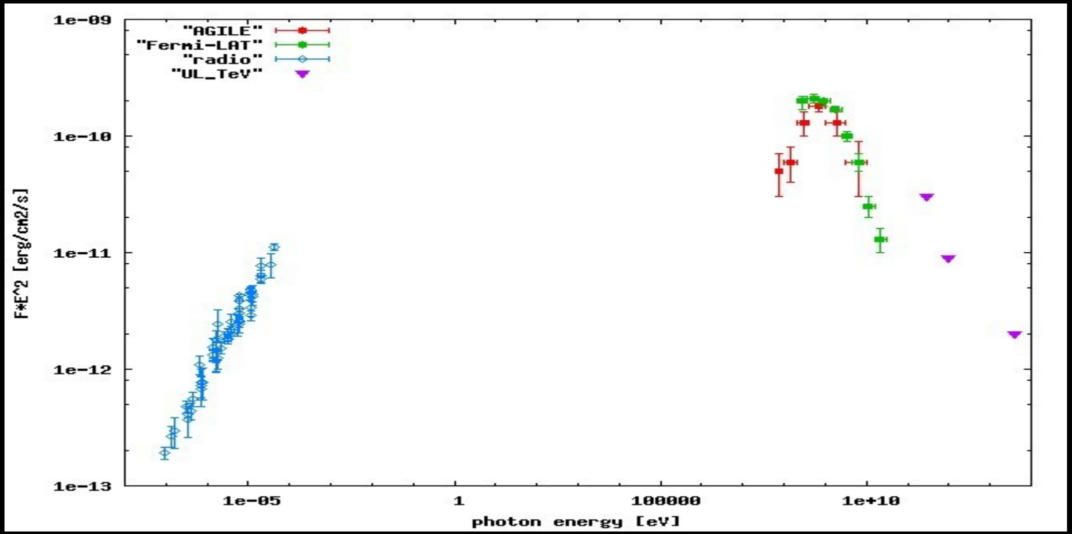
SNR W44

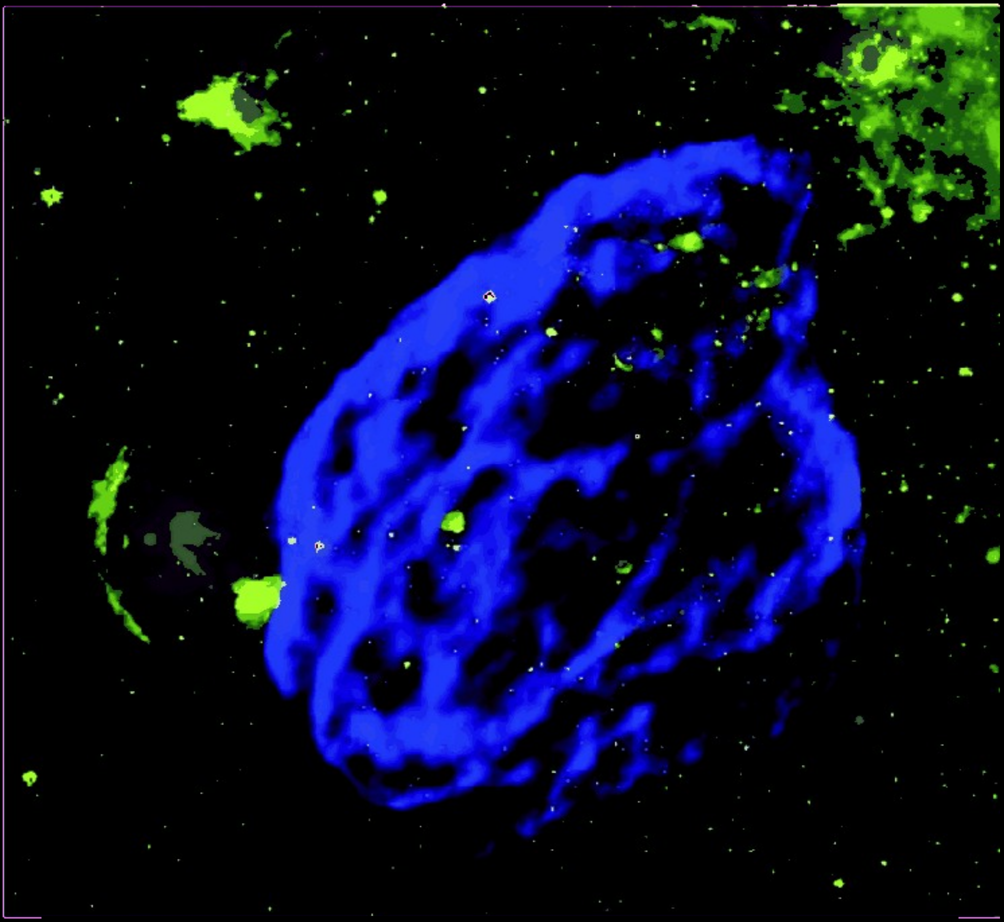
Age : ~ 20000 yr
Distance : ~ 3 Kpc
Type : mixed-morphology

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





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Maser OH (1720 Hz) emission
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2) Strong non-thermal emission in radio e gamma-ray band

3) Large angular dimensions

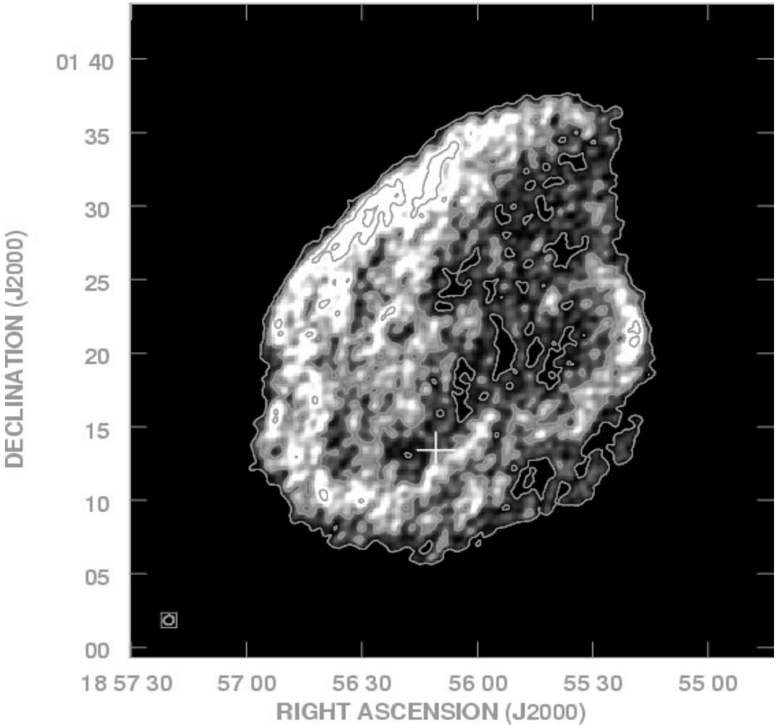
Morphology and spatially resolved spectrum
(in both radio and gamma bands)

Radio Spectrum

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

The spectral slope is alpha = 0.37

(corresponding to an elect. Spec.
F ~ $E^{-1.74}$ particle / cm s MeV)



Gamma-Rays Observations of W44

- No TeV emission detected up to now

  (Upper limits from MAGIC, Veritas and Milagro)

Fermi detection of W44

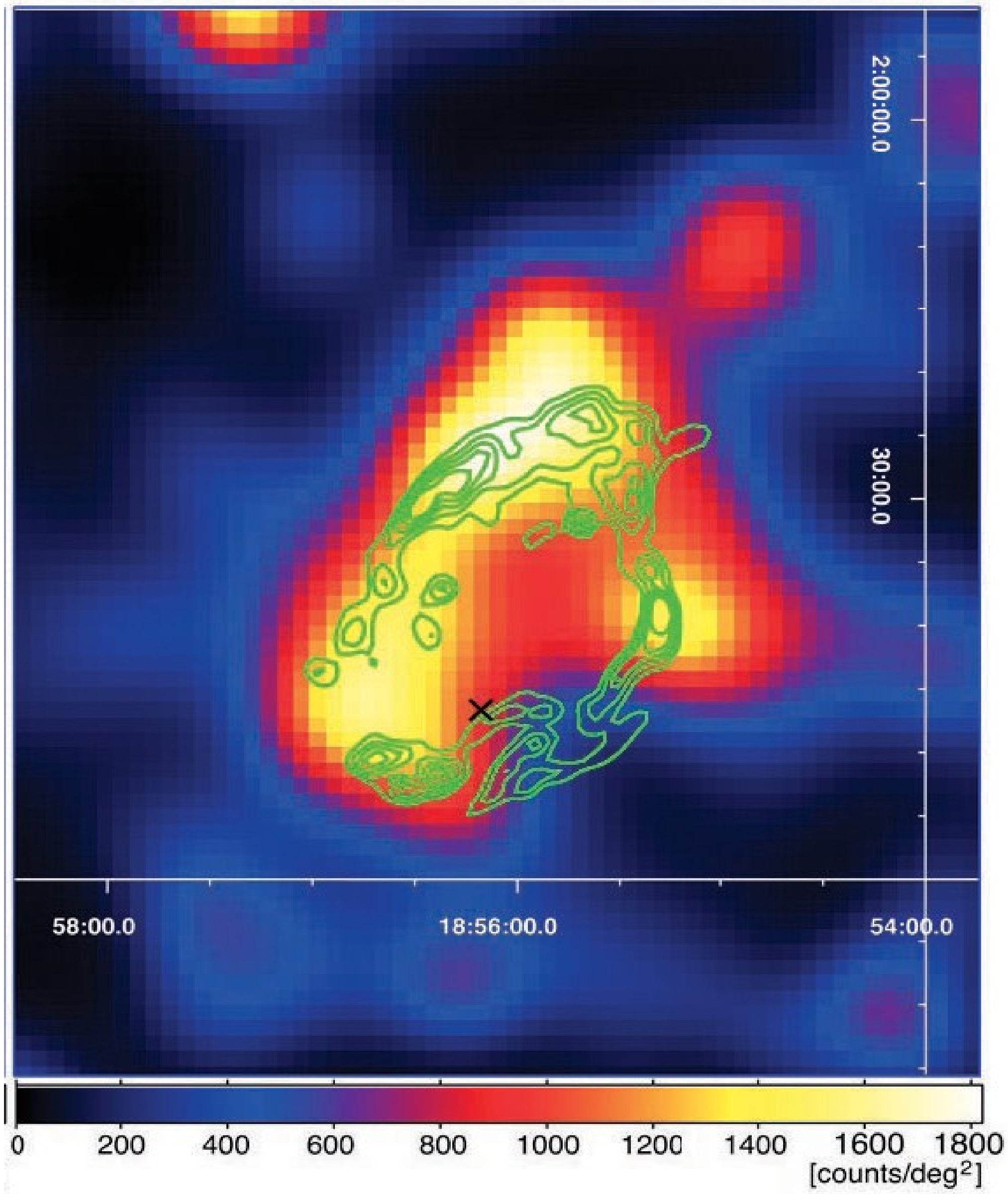


Image for E >2 GeV

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

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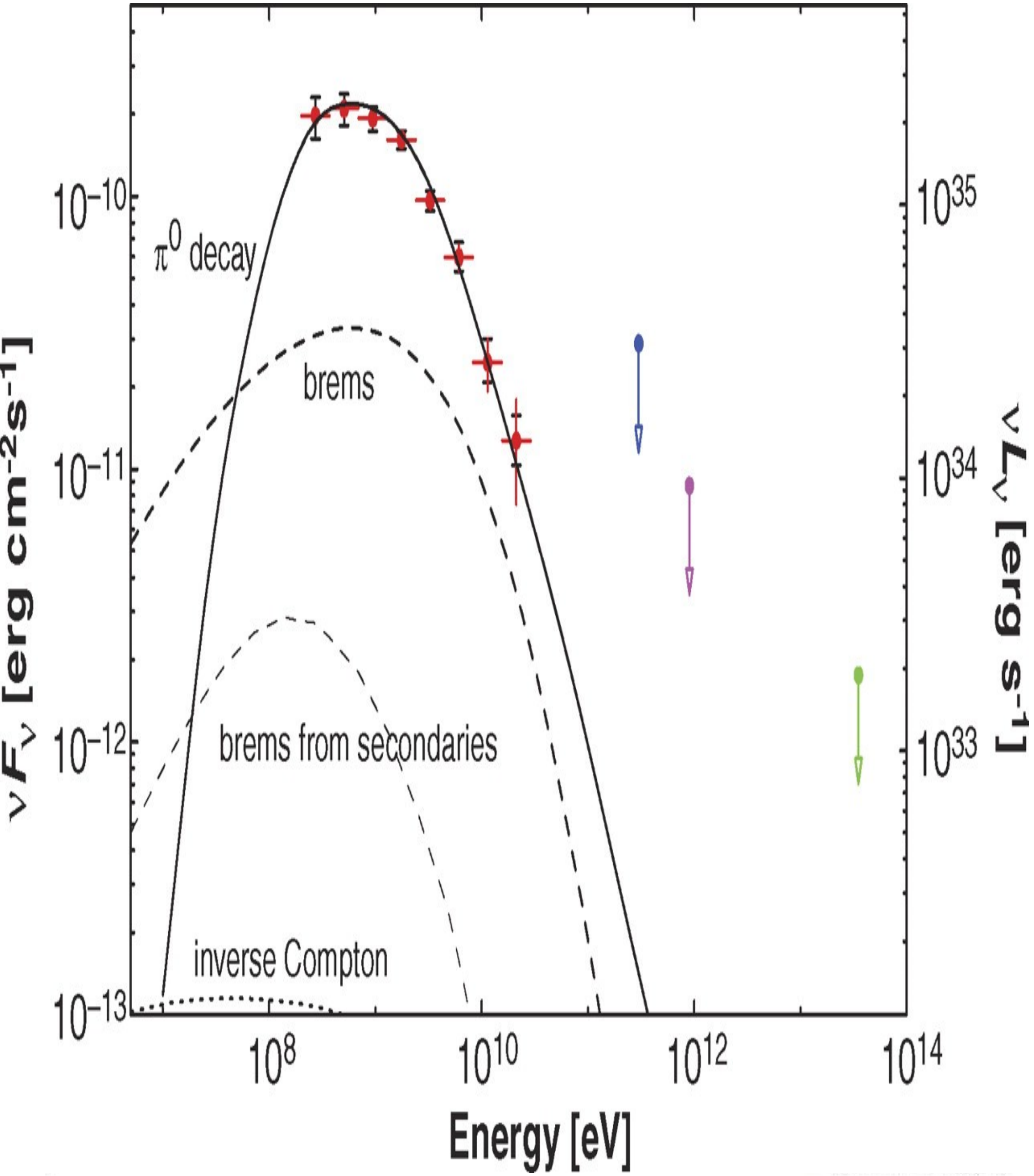

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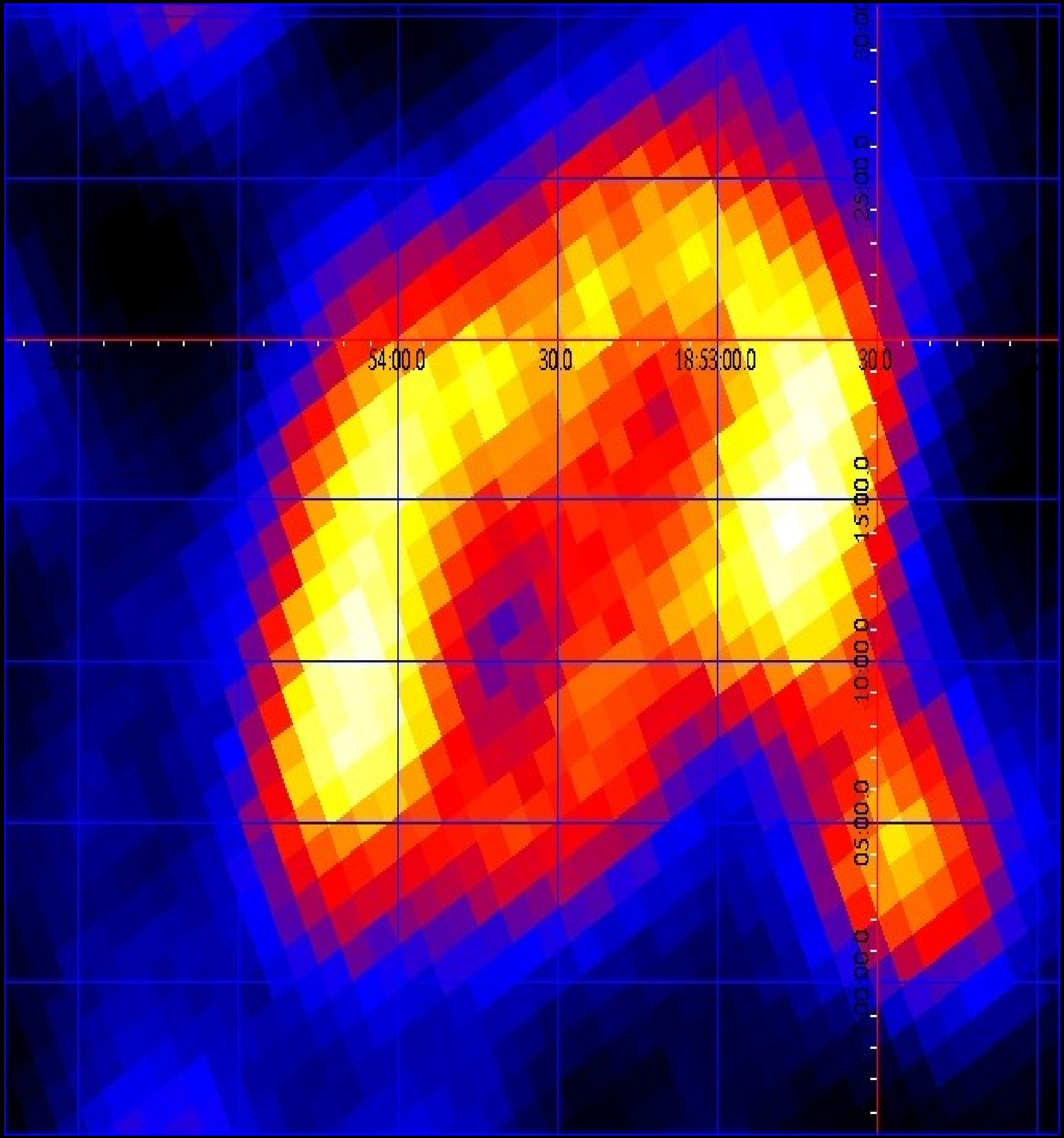
AGILE detection of W44



Giuliani et al. ApJ, 2011

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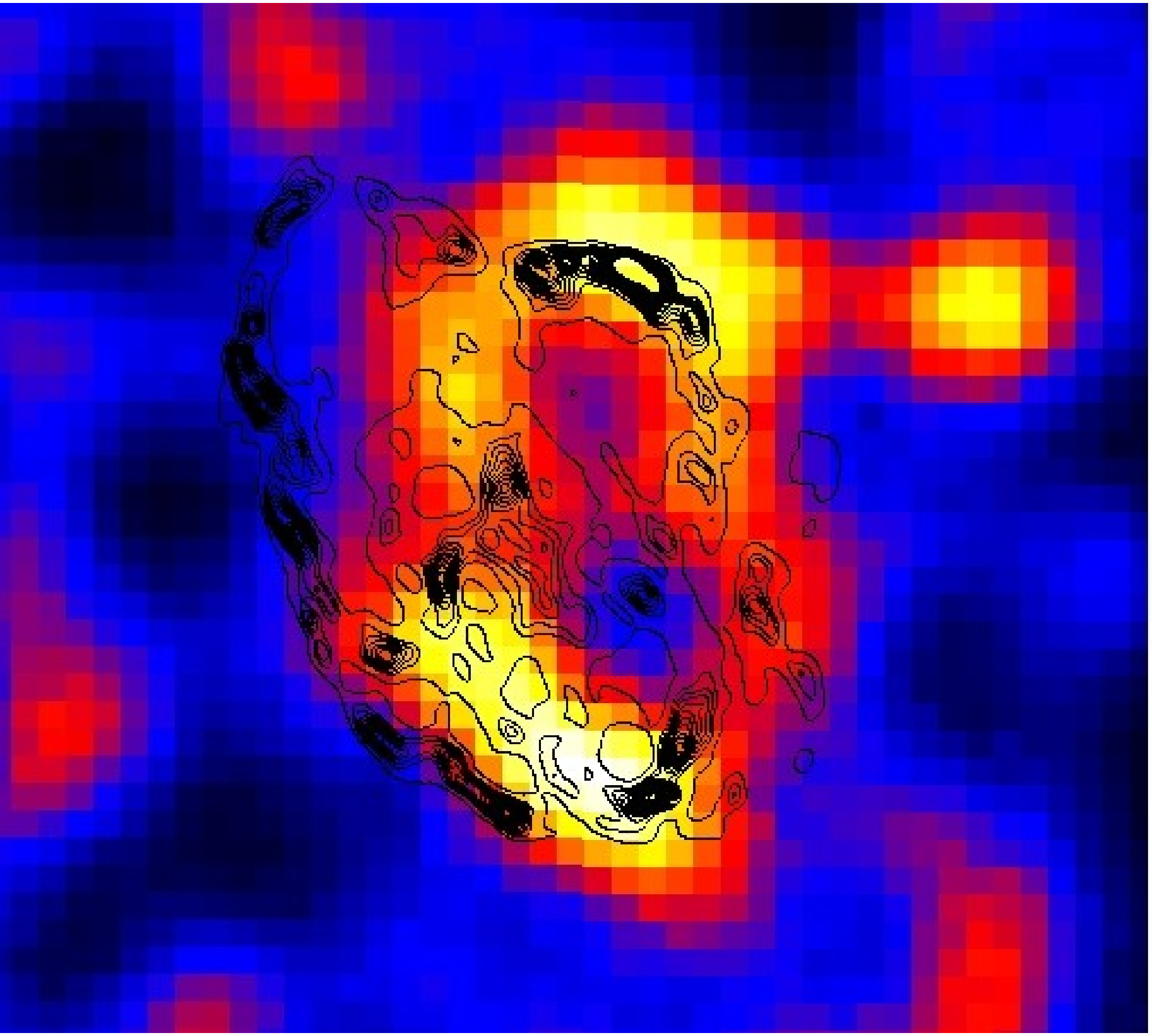
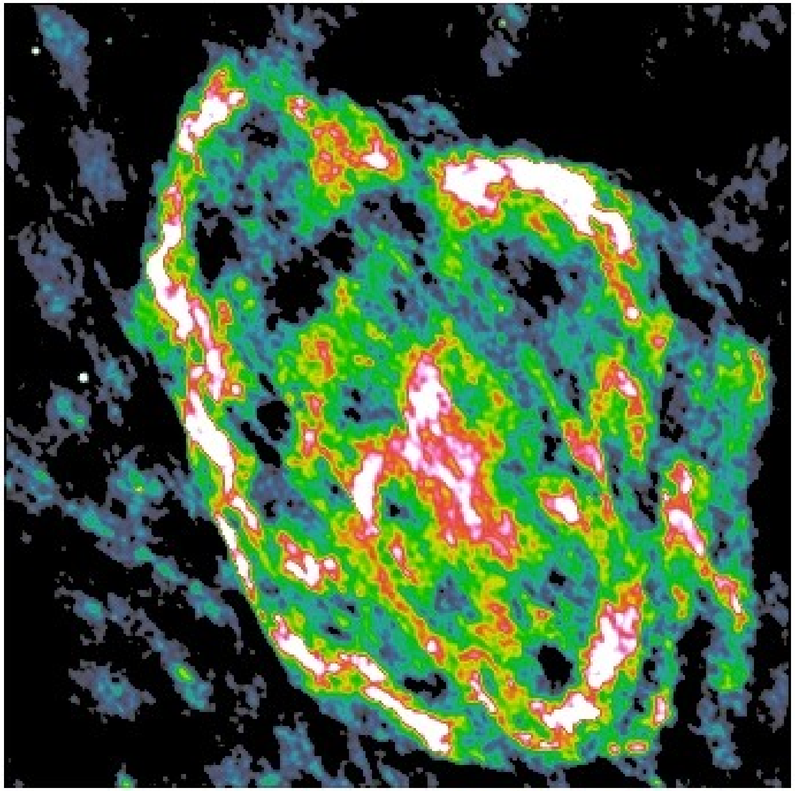
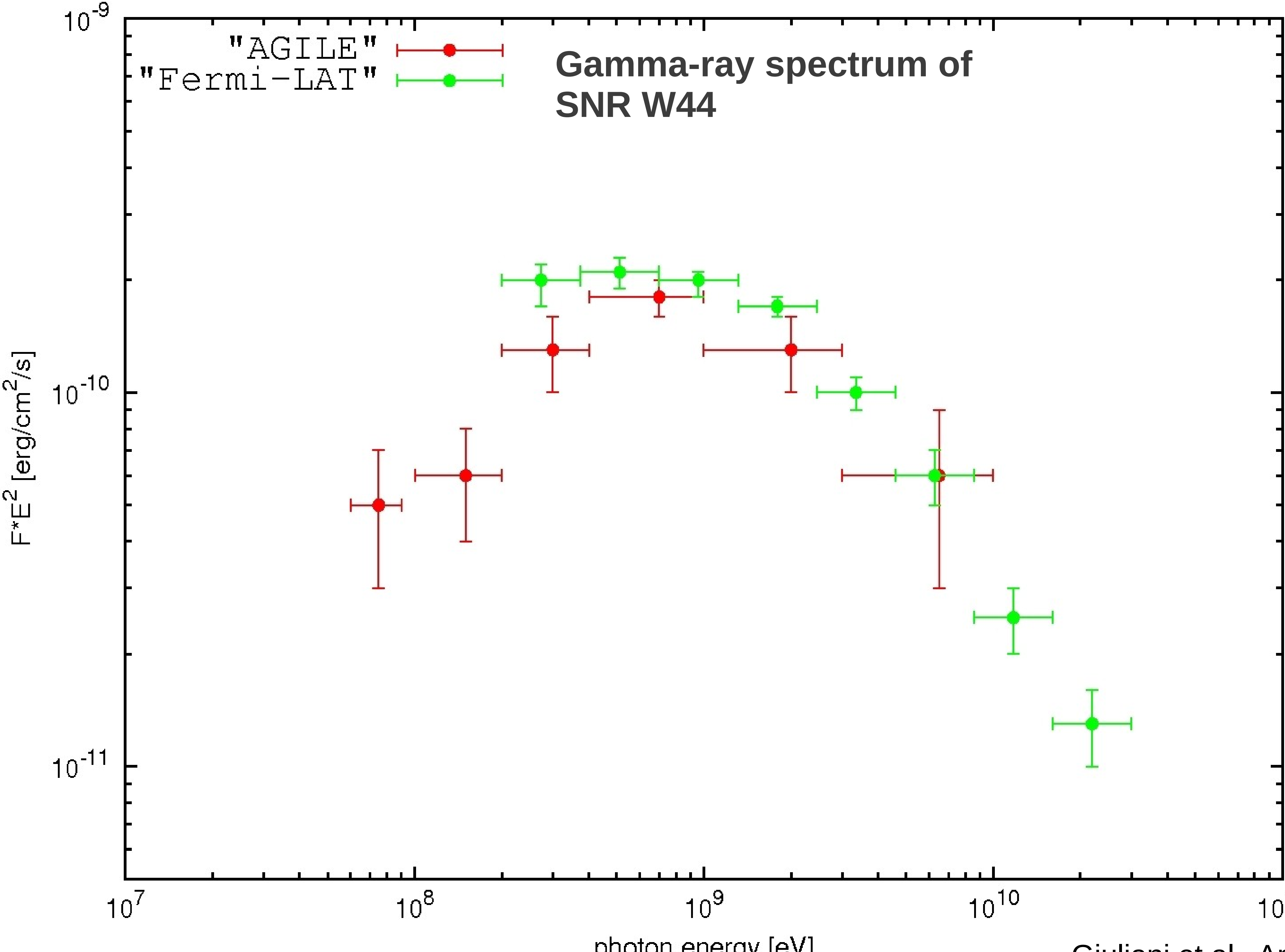


E > 400 MeV



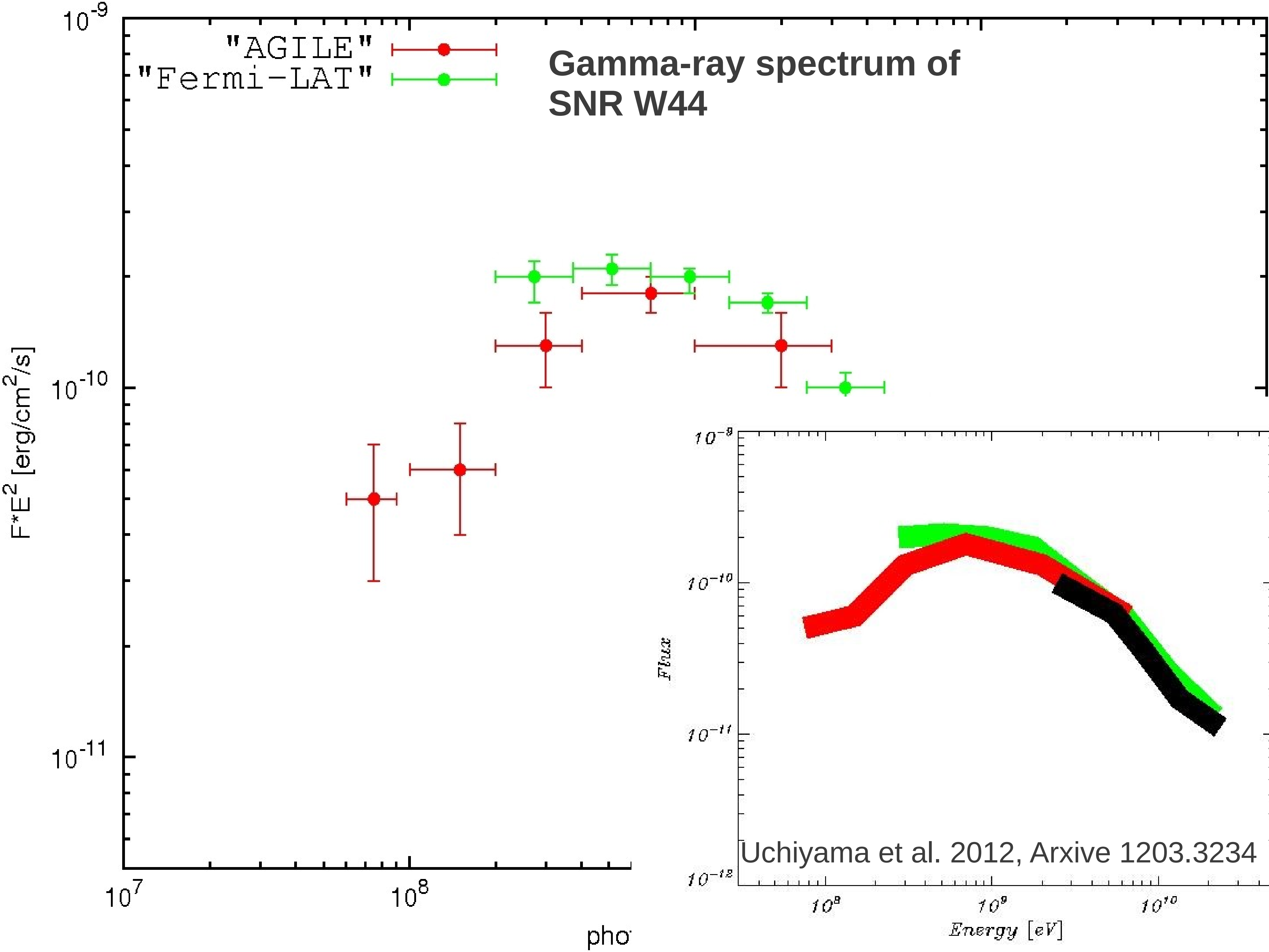
1.4   Ghz

Gamma-ray spectrum of SNR W44

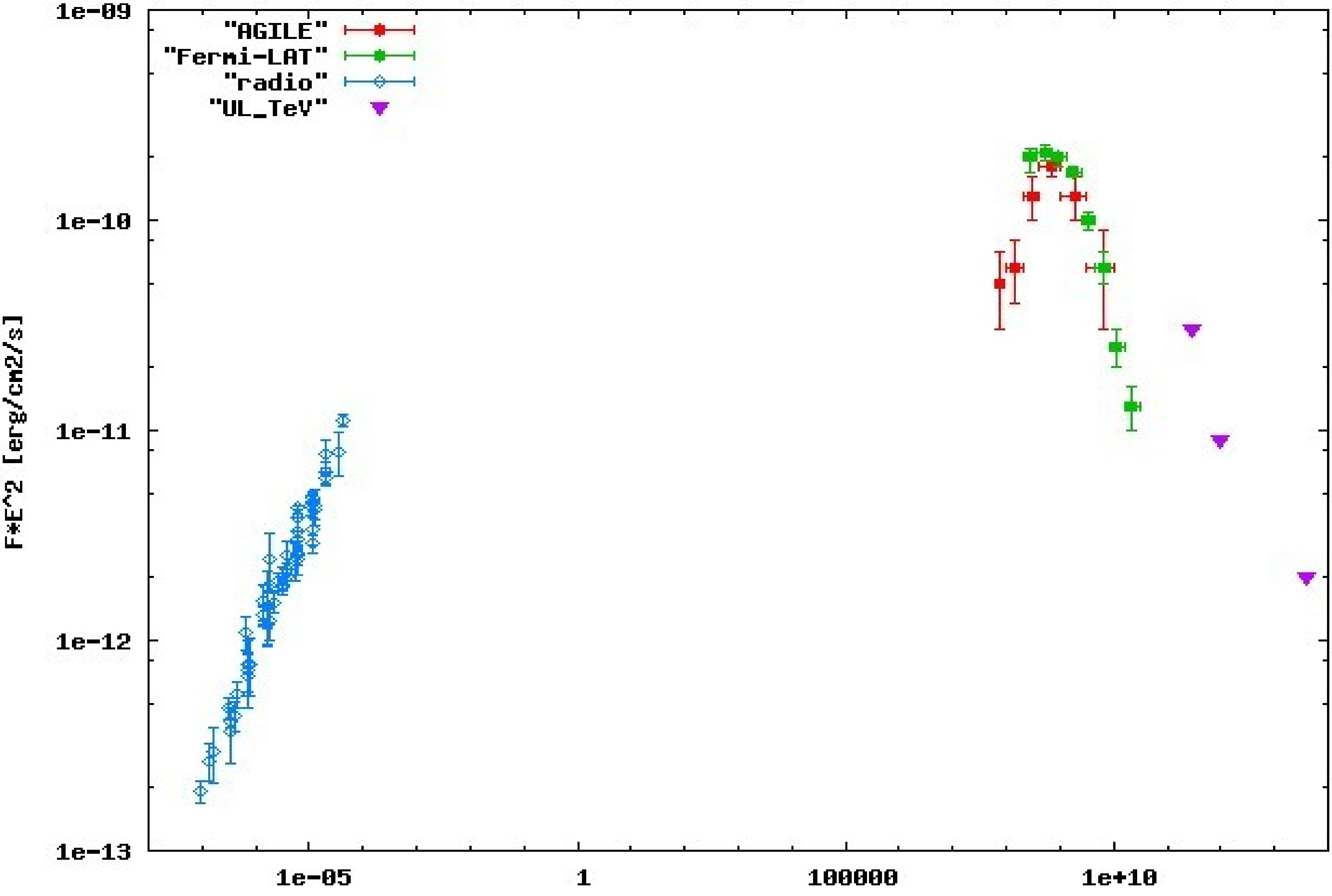


Giuliani et al. Ap

Gamma-ray spectrum of SNR W44



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:

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

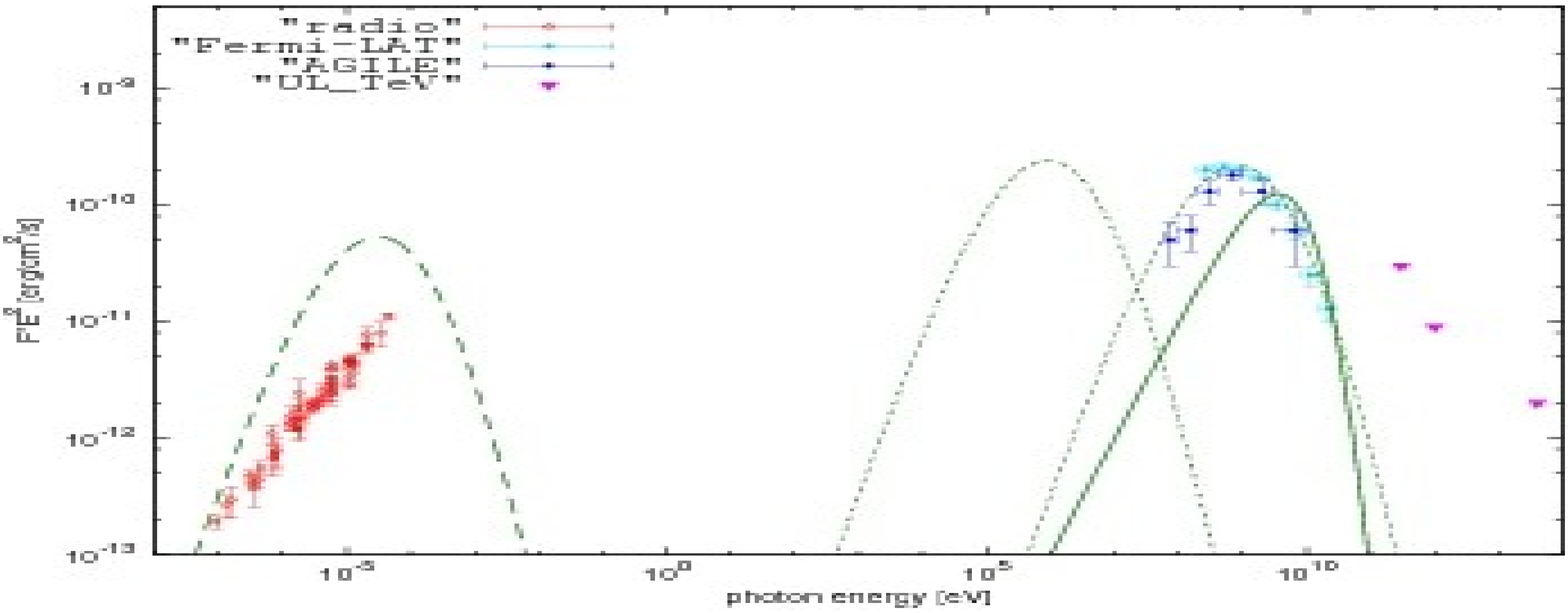
$$F_e(E) = K_e E^{-p} e^{-\frac{E_c}{E}}$$

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

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}

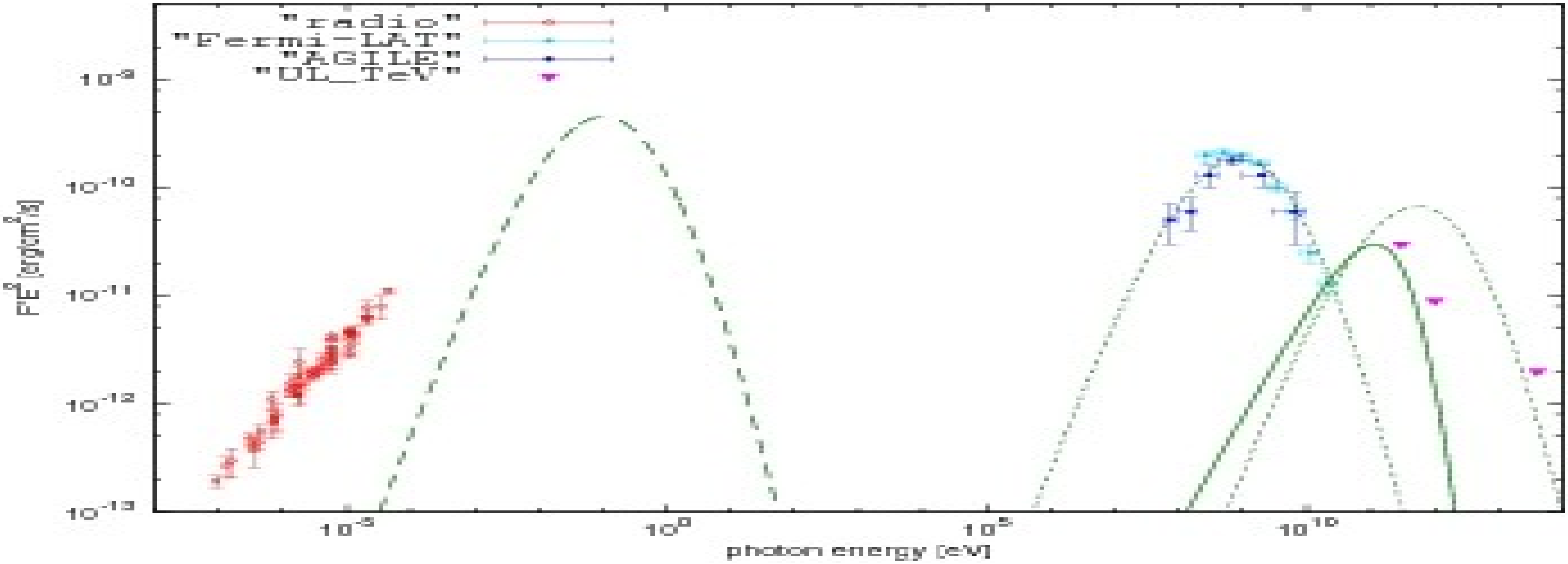
Electrons Spectrum :

p1 = 0

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

= 8
: 22 GeV

Leptonic model : IC, CBR seed photons



Ambient : *B : 10 μG*

n : 1 cm^{-3}

Electrons Spectrum :

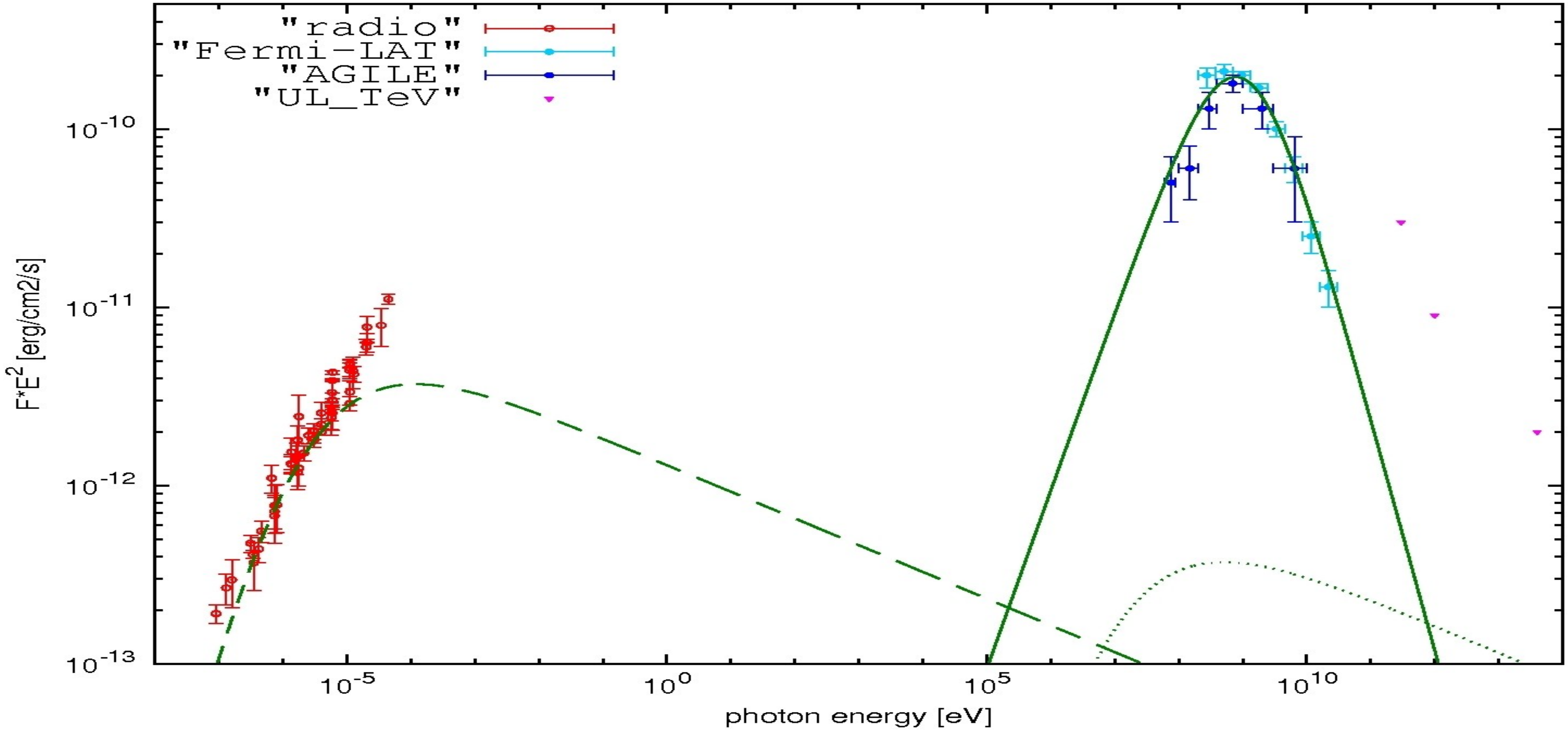
p1 = 0

= 8

: 700 GeV

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

Leptonic model : Bremsstrahlung



Ambient : *B : 20 µG*

n : 300 cm^{-3}

Electrons Spectrum :

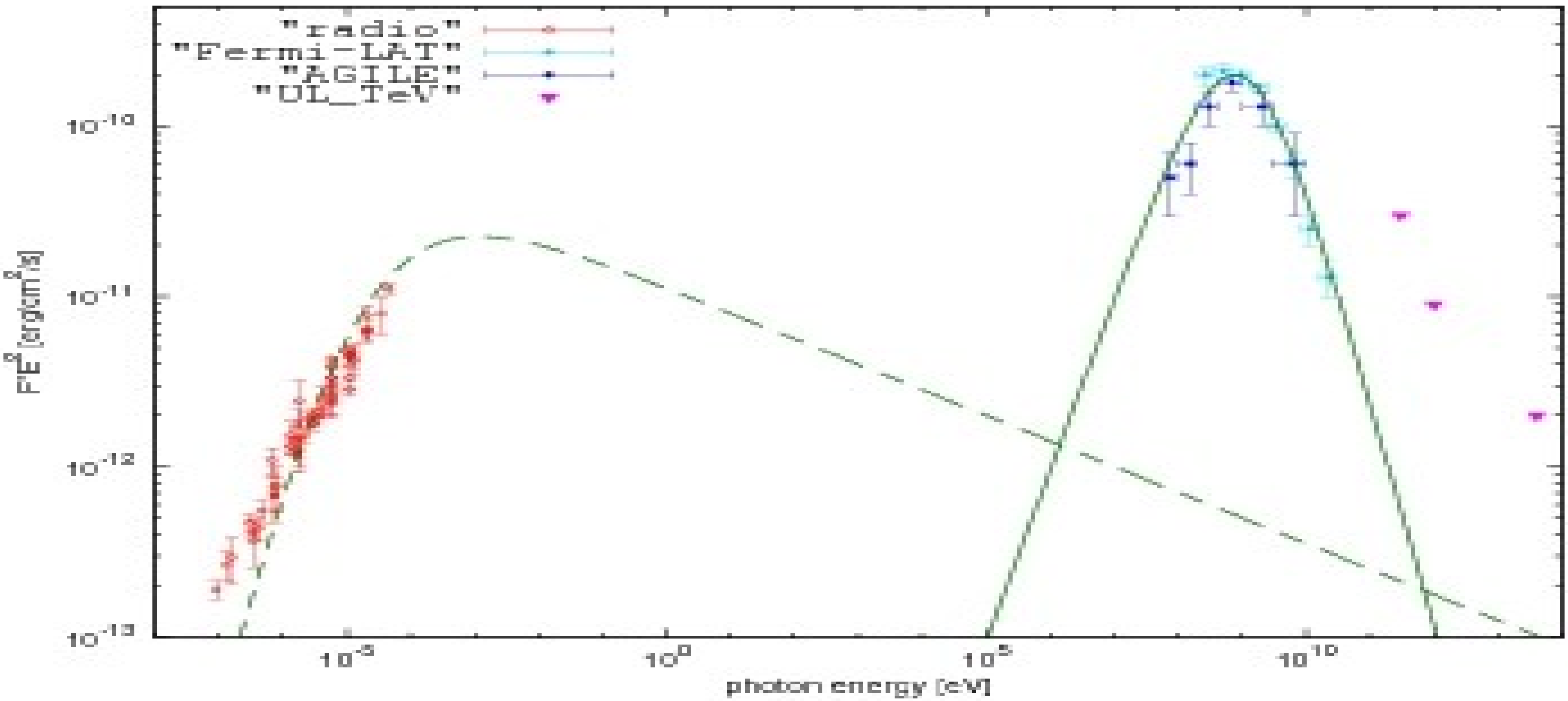
p1 = 0

= 3.3

: 1 GeV

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

Leptonic model : Bremsstrahlung, B= 200



Ambient : *B : 200 µG*

n : 5000 cm^{-3}

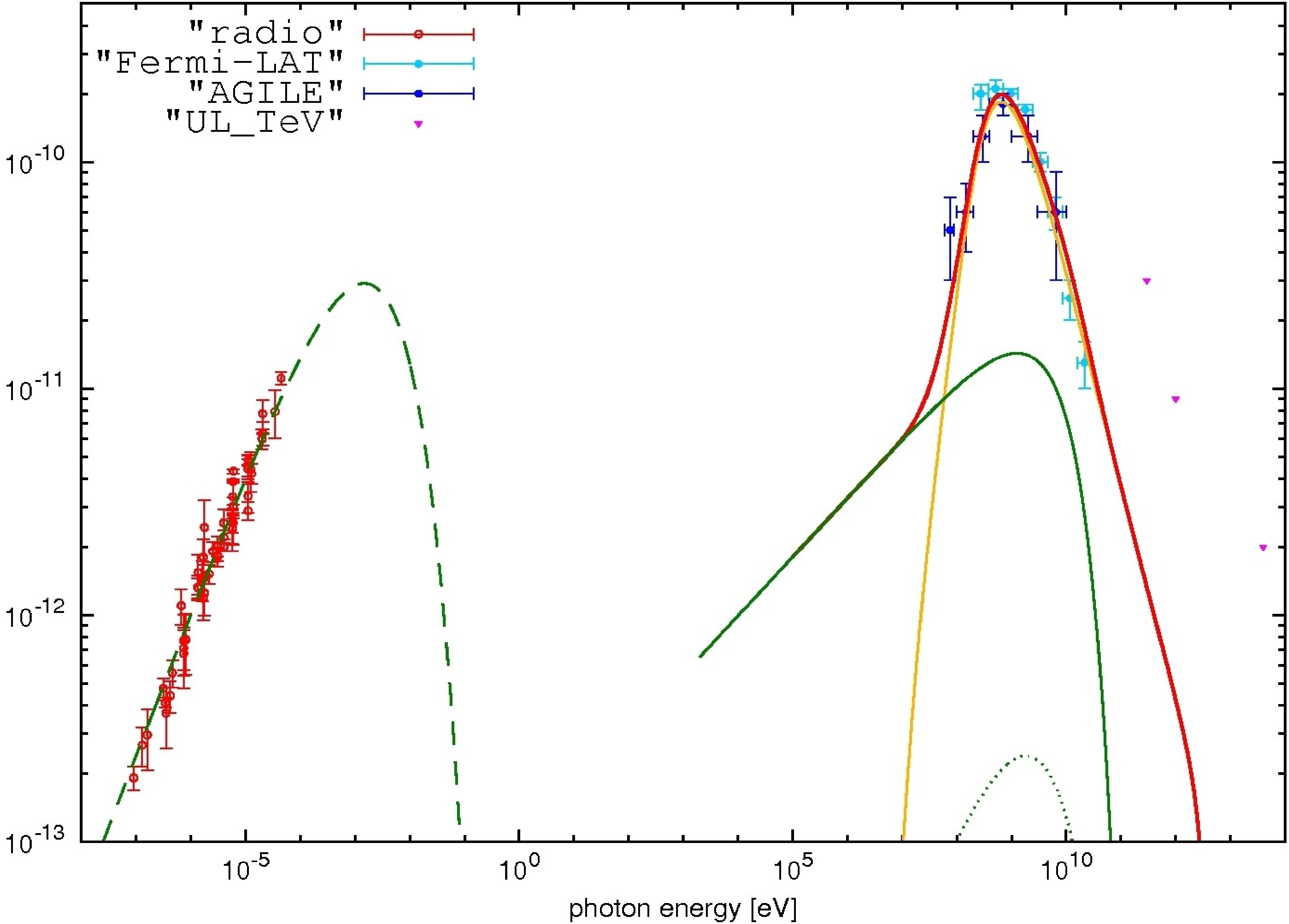
Electrons Spectrum :

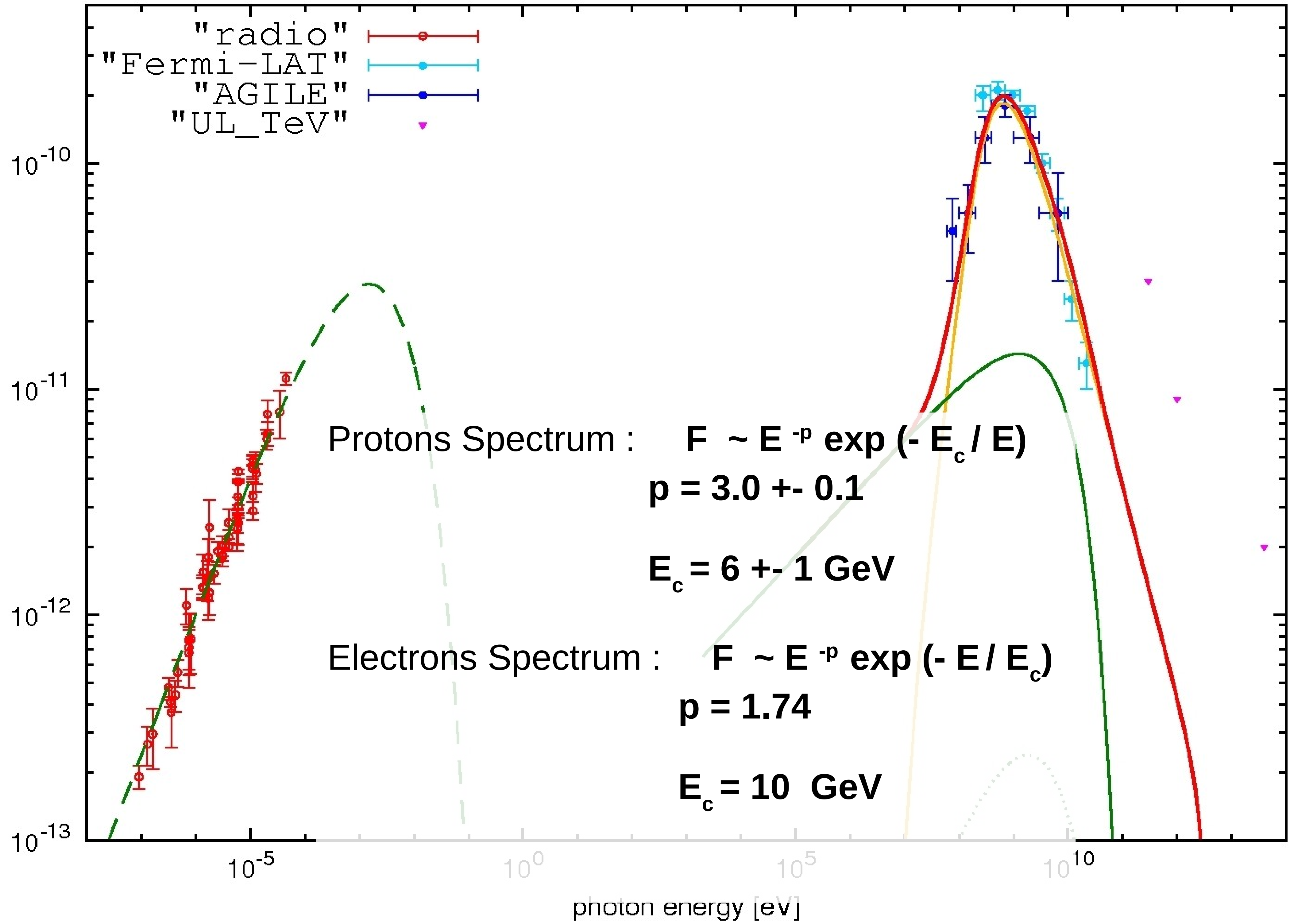
p1 = 0

= 8

: 1 GeV

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


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

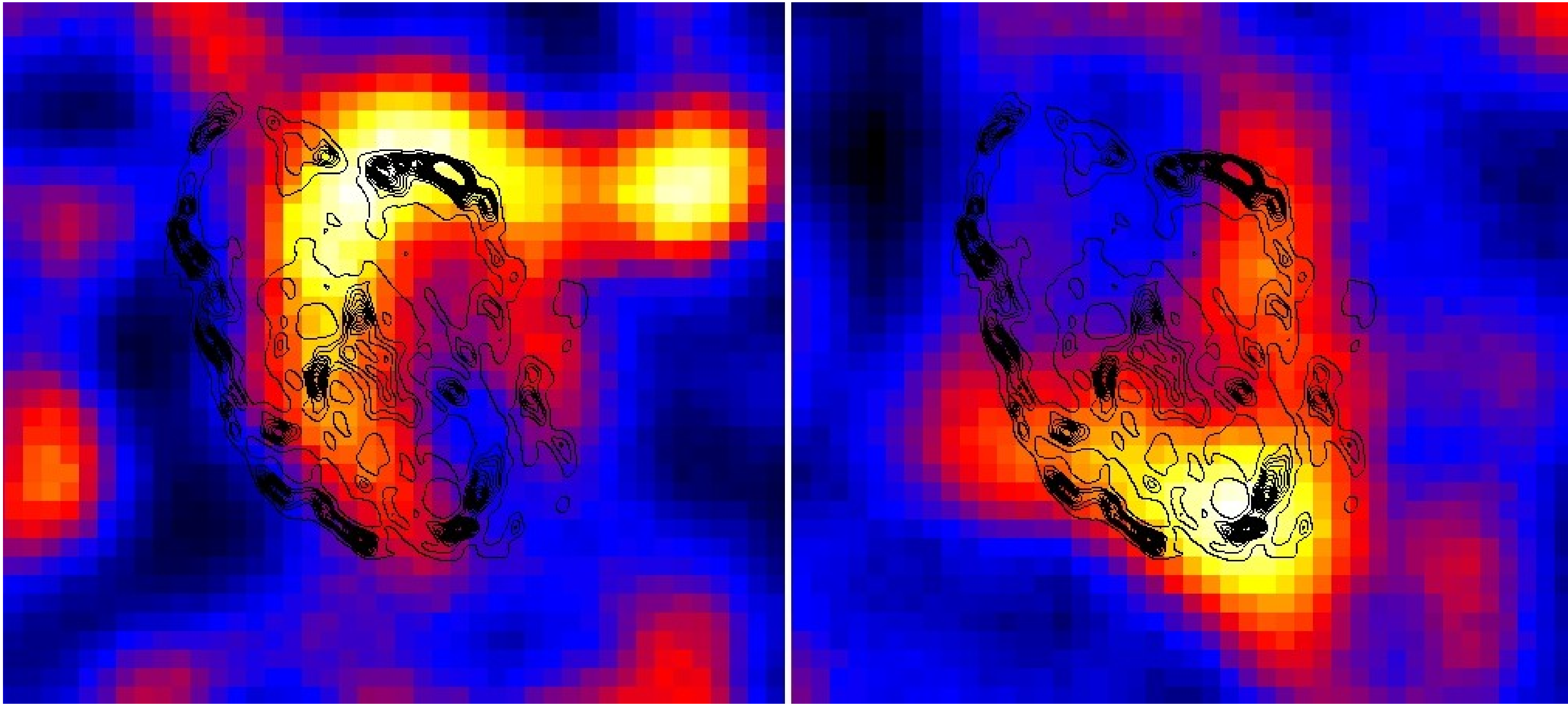
$p = 3.0 \pm 0.1$

$E_c = 6 \pm 1$ GeV

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

$p = 1.74$

$E_c = 10$ GeV



E < 400 MeV

E > 400 MeV

Lesson from W44

W44 is a "smoking gun" proof for the emission in SNRs

Protons are (still) present in the shell of W44

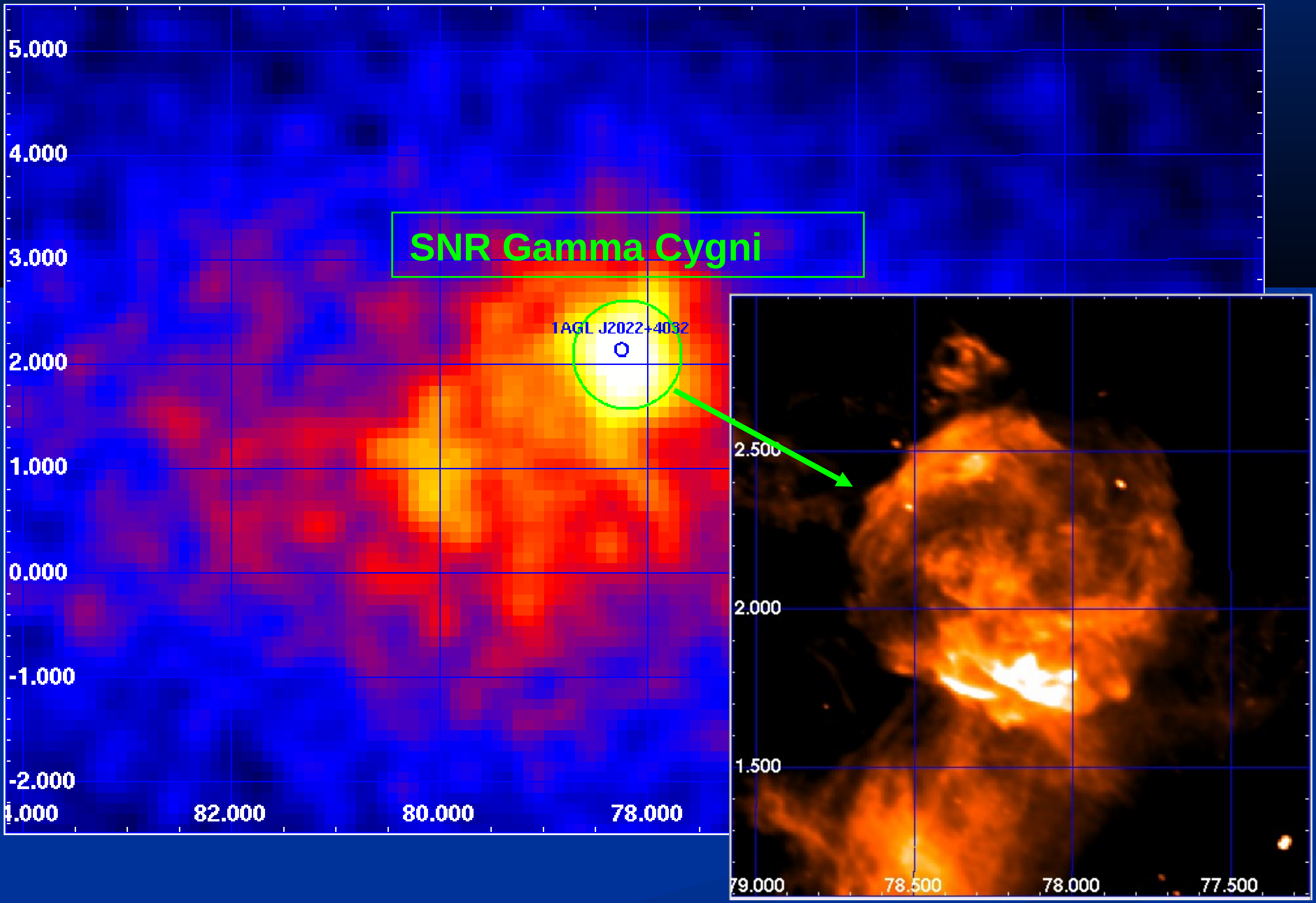
The inferred proton spectrum has:

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

up to ~ 200 GeV

challenging for theoretical models of particles injection

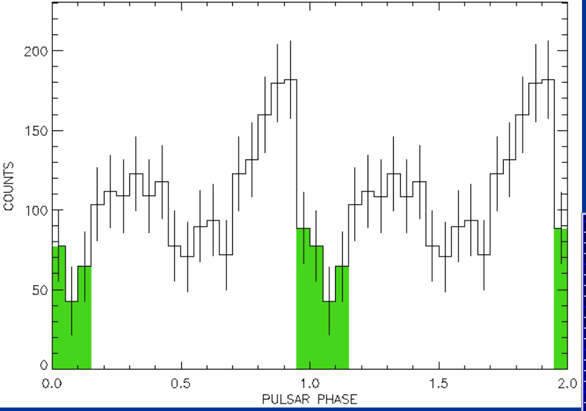
The region of the Supernova Remnant Gamma Cygni (G78.2+2.1)

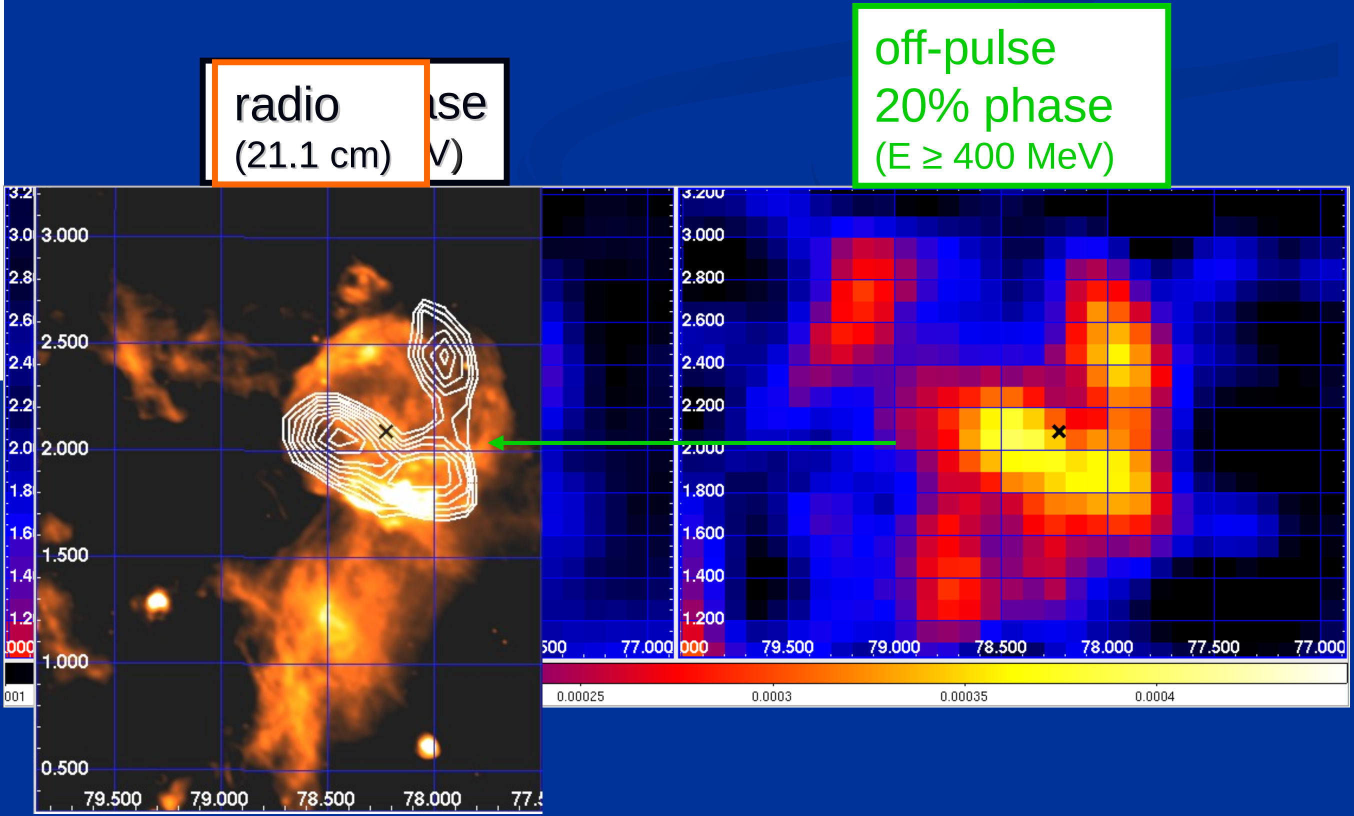


SNR Gamma Cygni (G78.2+2.1)

“subtracting” the pulsar → “off-pulse” analysis

- PSR → peculiar light curve (high unpulsed fraction, not sharp separation between on-peak and off-peak phases)
- several cuts for the off-pulse phase (45%, 20%, 10%)
- better-defined off-pulse phase: $0.95 \leq \Delta\varphi_{\text{off-phase}} \leq 1.15$ (20%)
- AGILE-*GRID* imaging for E ≥ 400 MeV



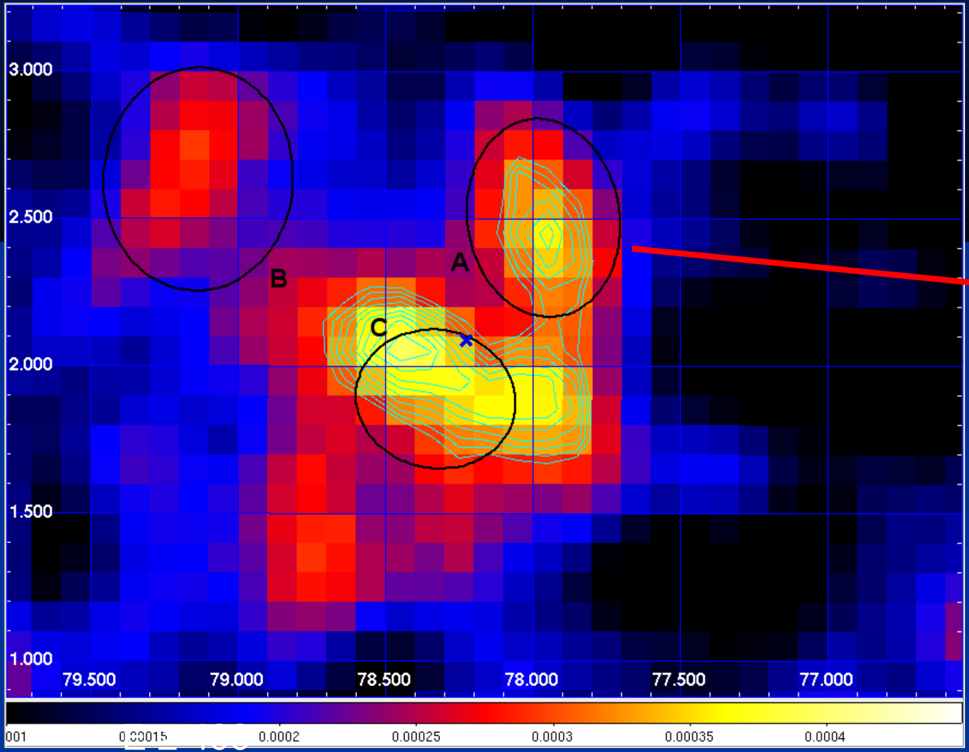

radio
(21.1 cm)

off-pulse
20% phase
(E ≥ 400 MeV)

SNR Gamma Cygni (G78.2+2.1)

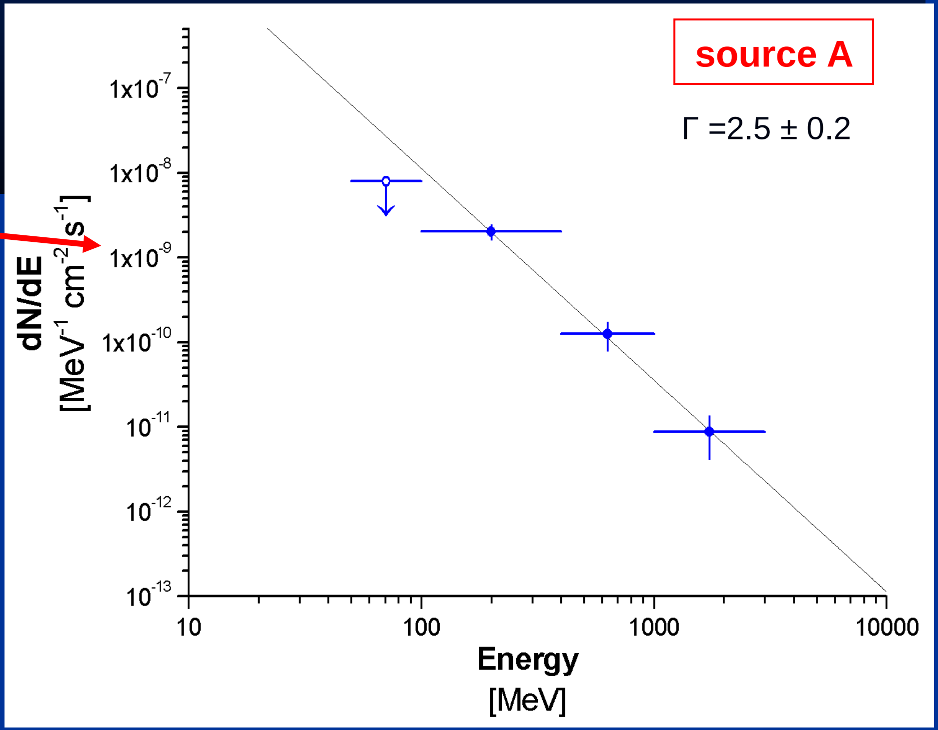
analysis of the “off-pulsed” map above 400 MeV

Multi-source analysis: **3 γ-ray “sources”**



E ≥ 400 MeV

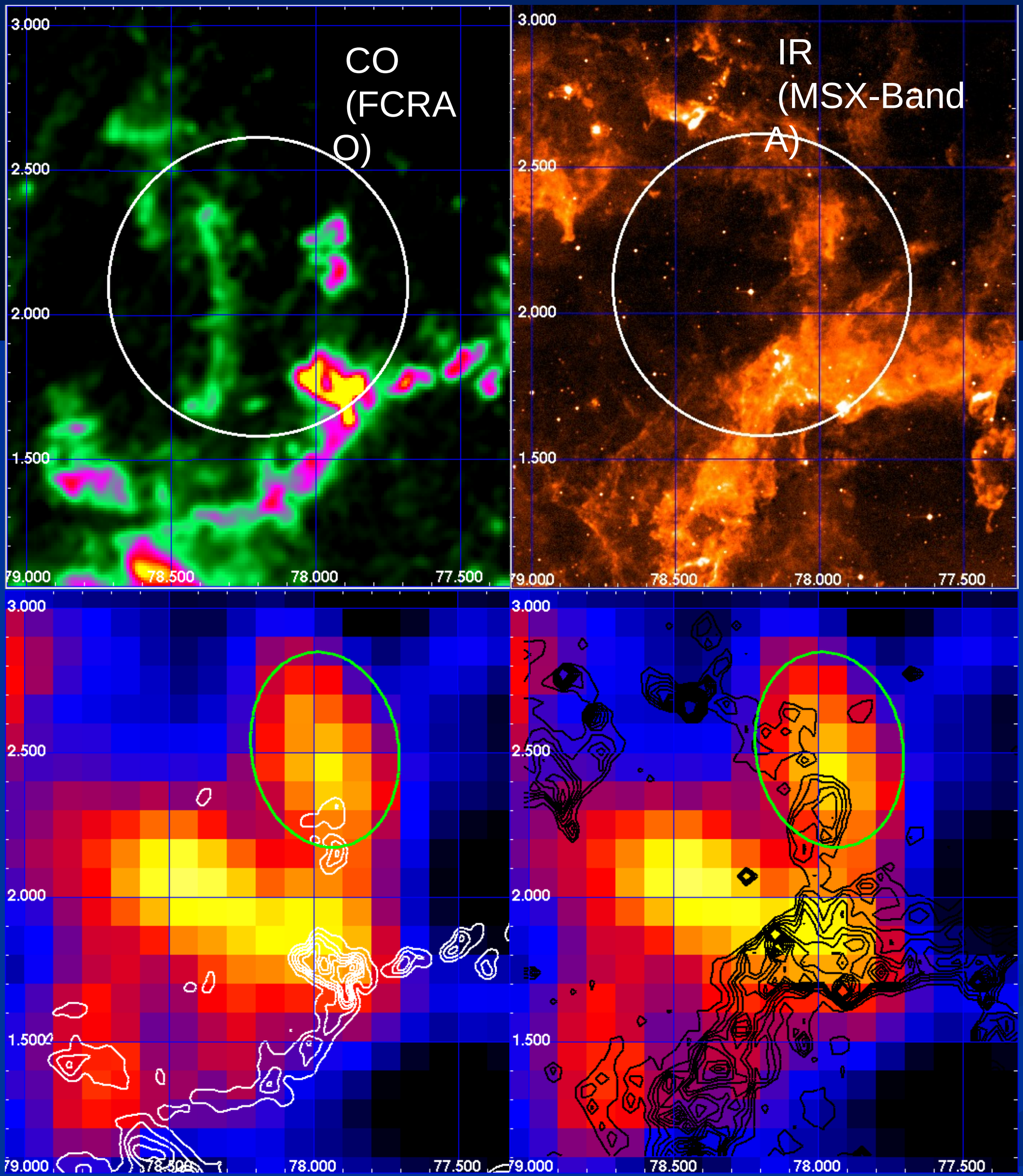
Photon Spectrum



Name	Centroid $(l,\ b)$	$\sqrt{TS}$ [MSLA-σ]	flux [10^{-8} photons cm^{-2} s^{-1}]
source A	(77.96, 2.46)	3.9	13.9 ± 4.0
source B	(79.16, 2.67)	3.7	6.7 ± 2.1
source C	(78.35, 1.93)	5.0	12.7 ± 3.0

SNR Gamma Cygni (G78.2+2.1)

gas distribution



Modeling the γ-ray SED of the source "A"