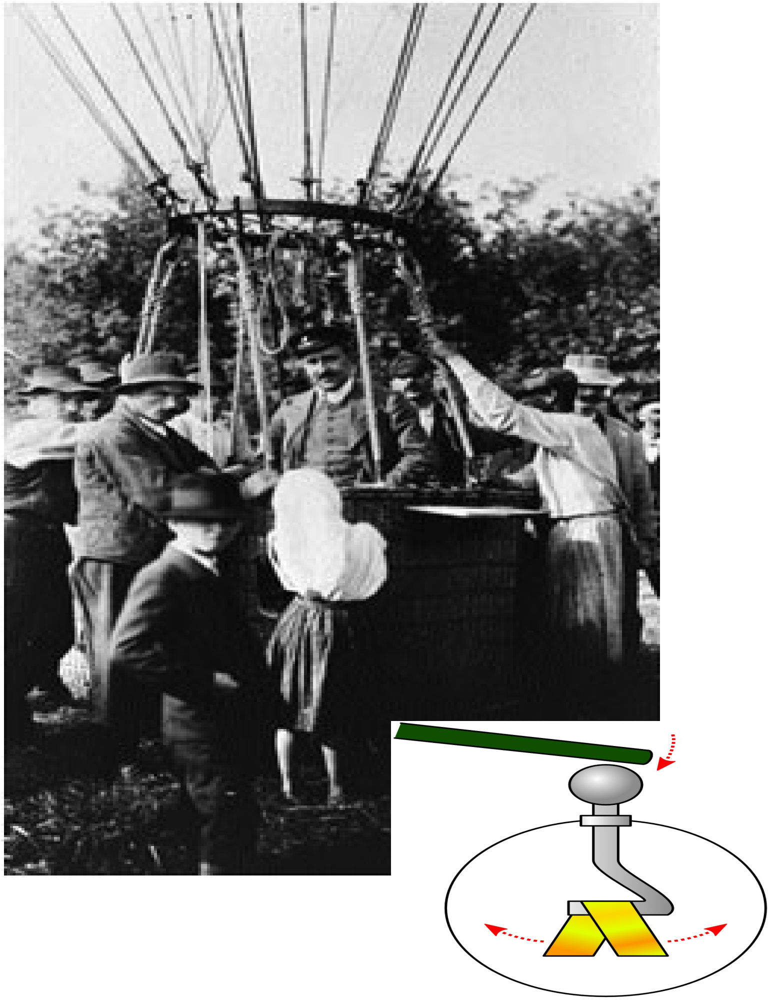
Supernova Remnants, molecular clouds and gamma rays

One century in one slide

1912 : Discovery of CRs



One century in one slide

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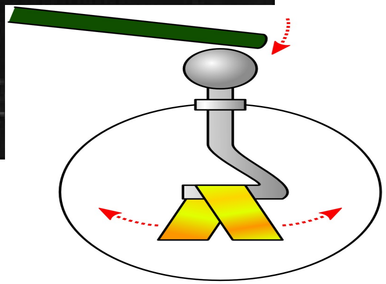
- Radio obs. of relativistic electrons



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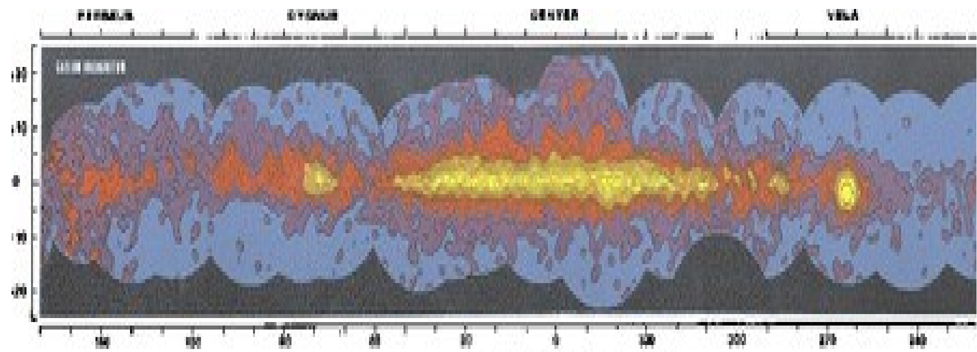
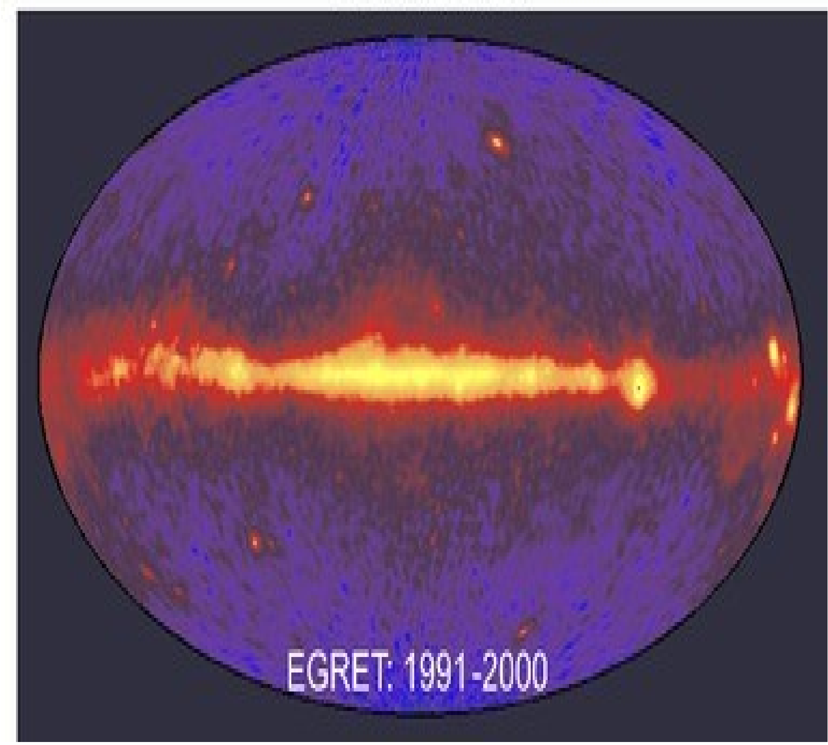


COS-B: 1975-82



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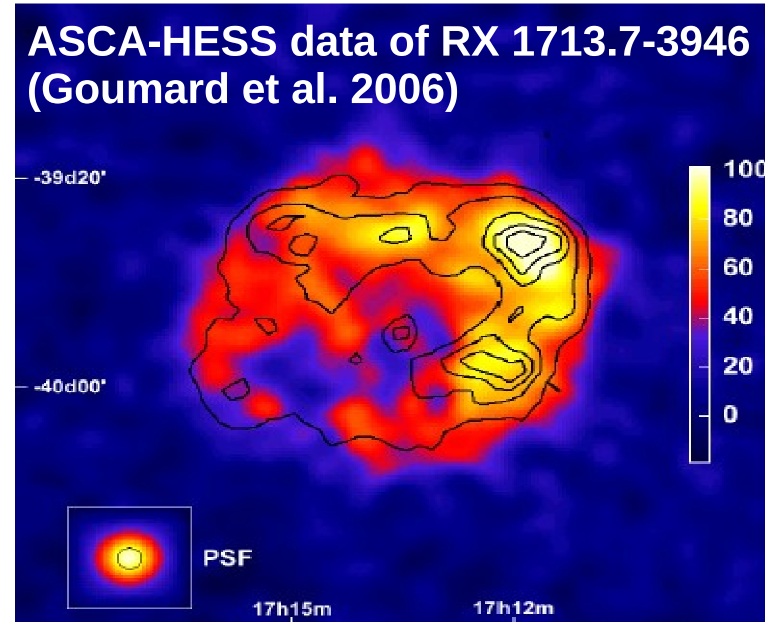

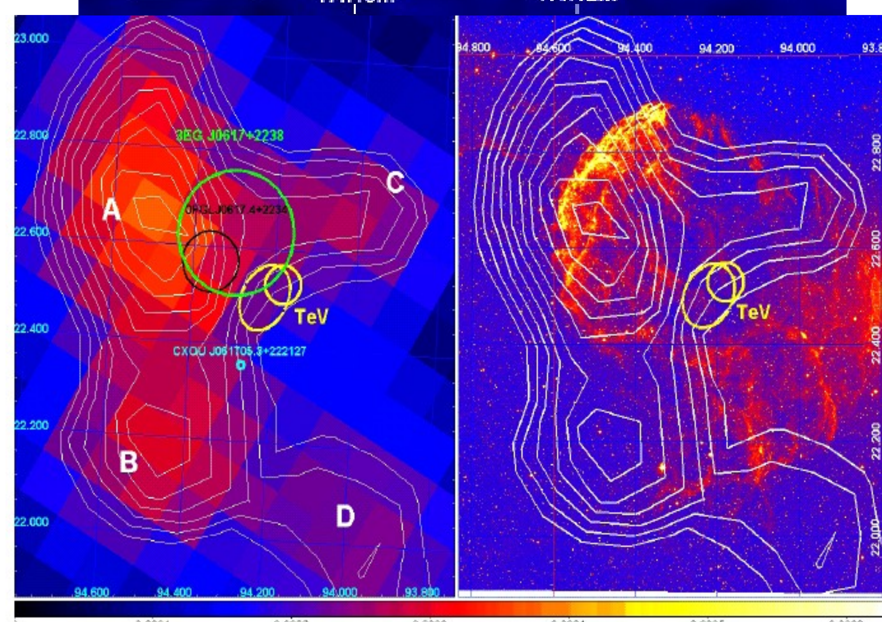

Tavani et al. 2010 ApJ L.

One century in one slide

1912 : Discovery of CRs

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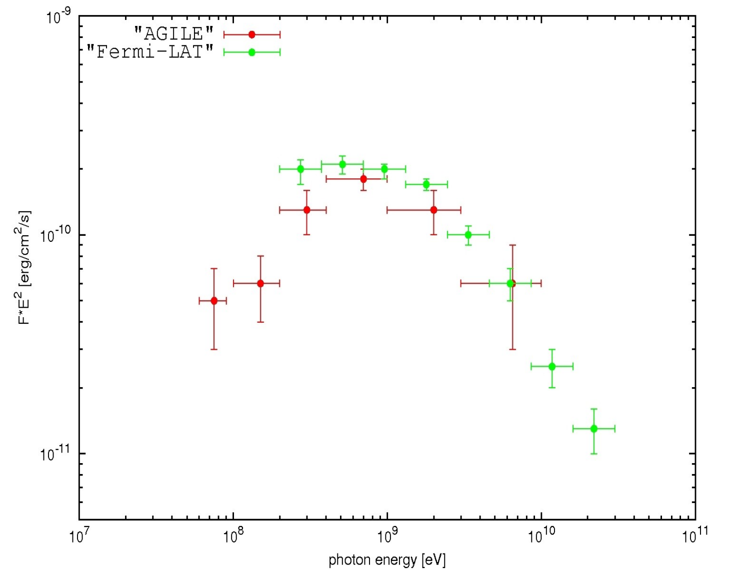
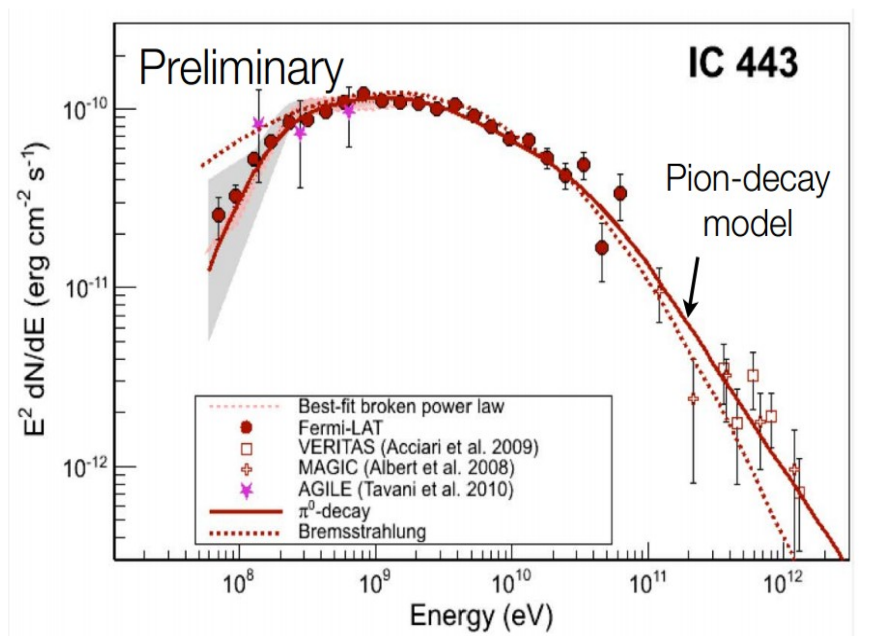
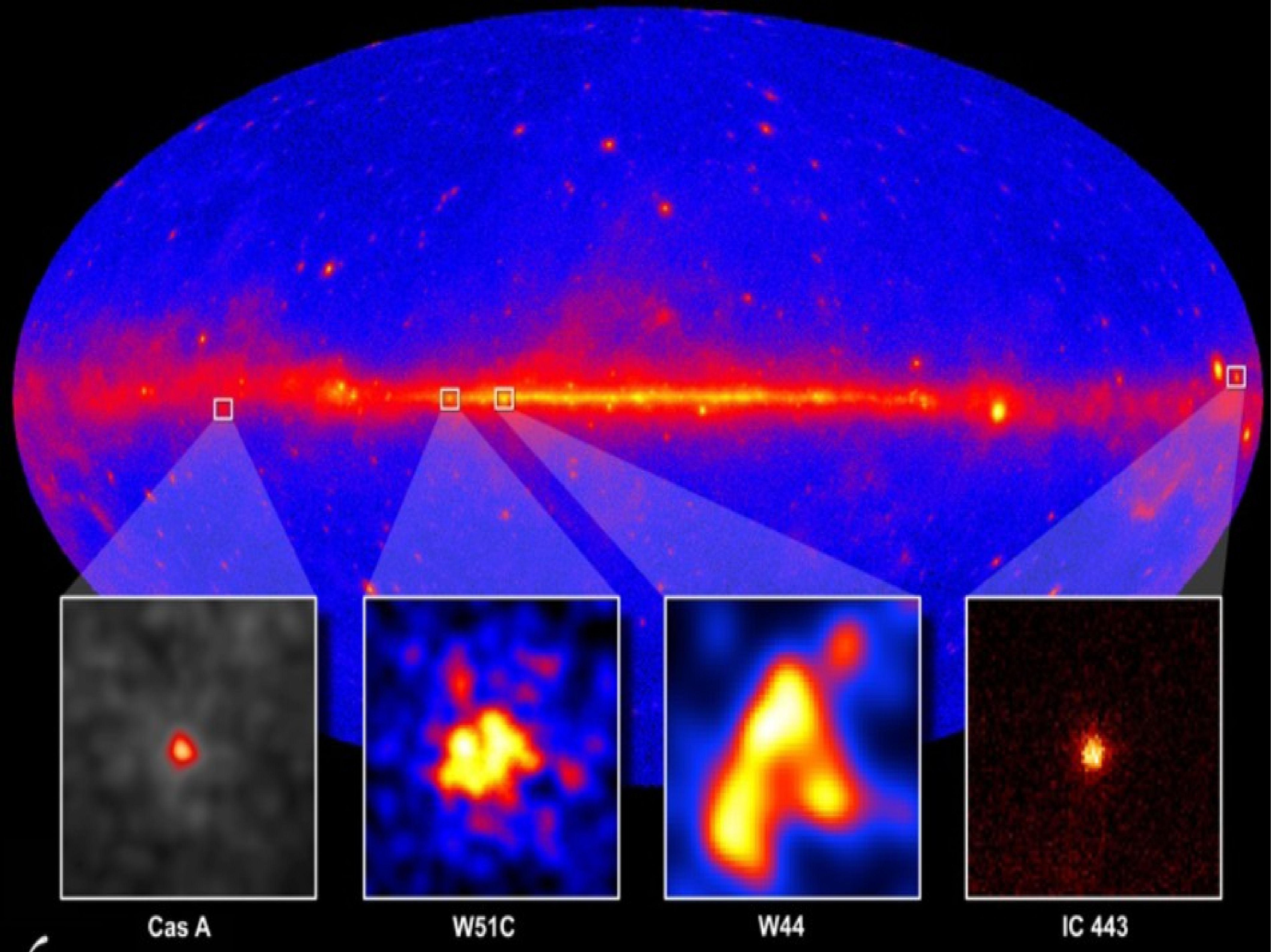
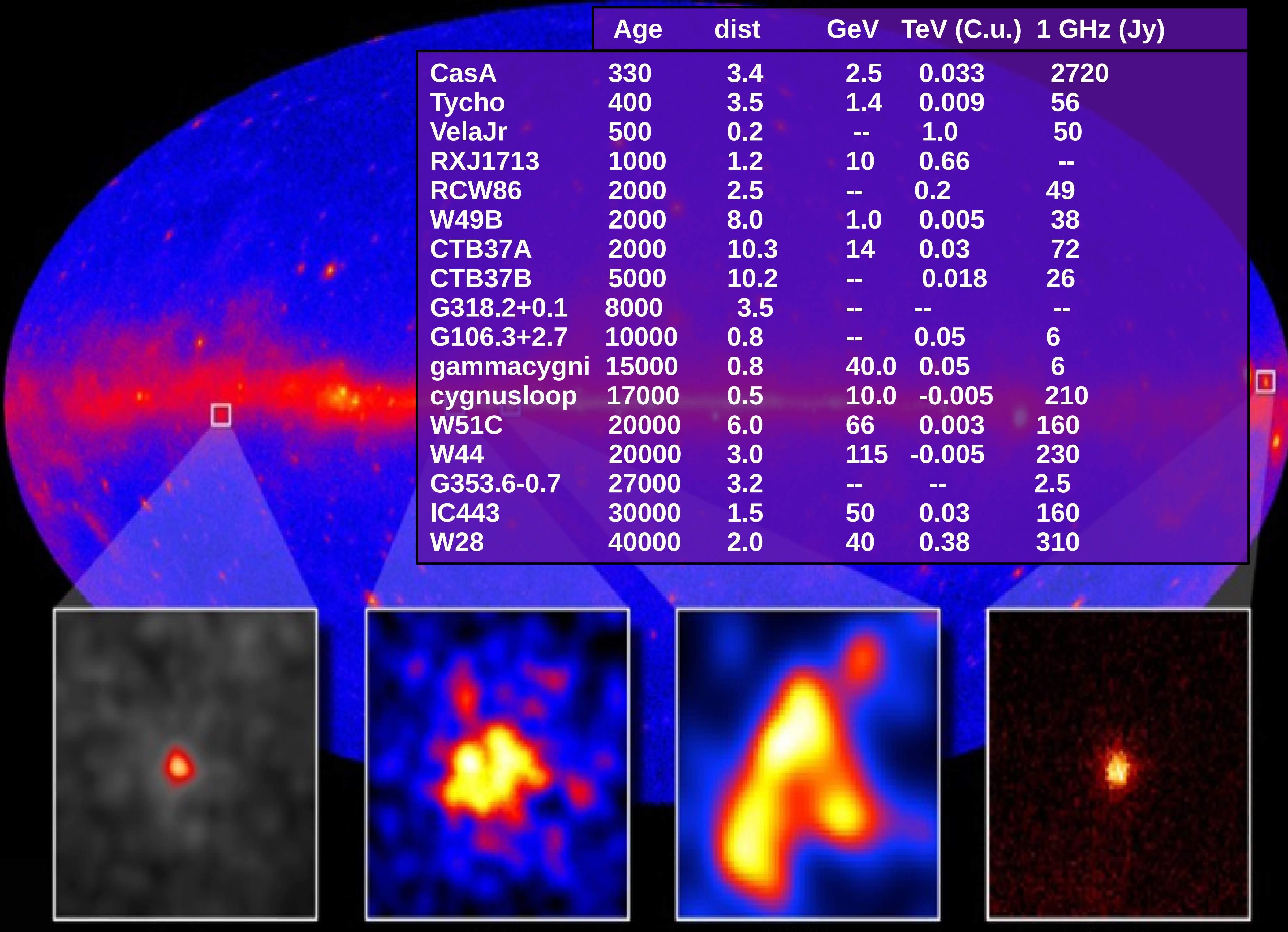
10s : Clear identification of emission from π^0 decay





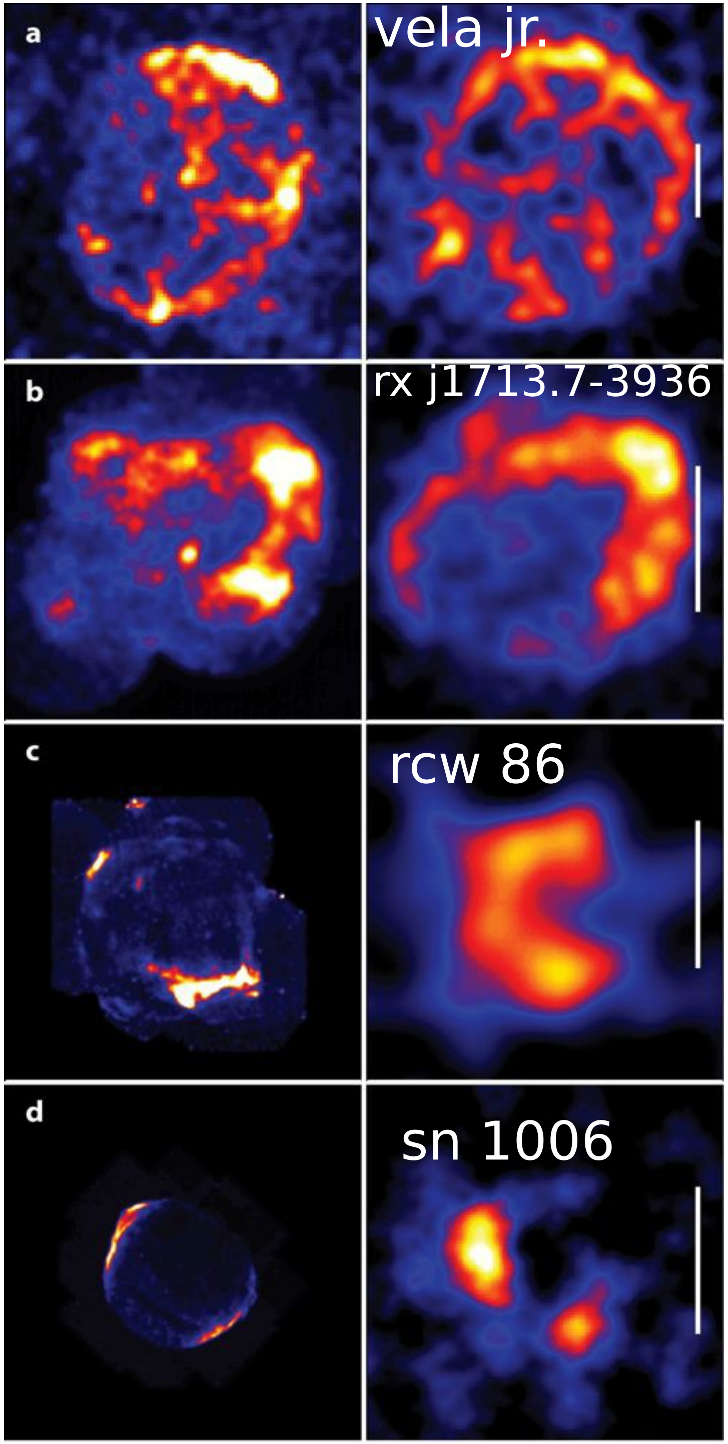

Cas A
W51C
W44
IC 443



	Age	dist	GeV	TeV (C.u.)	1 GHz (Jy)
CasA	330	3.4	2.5	0.033	2720
Tycho	400	3.5	1.4	0.009	56
VelaJr	500	0.2	--	1.0	50
RXJ1713	1000	1.2	10	0.66	--
RCW86	2000	2.5	--	0.2	49
W49B	2000	8.0	1.0	0.005	38
CTB37A	2000	10.3	14	0.03	72
CTB37B	5000	10.2	--	0.018	26
G318.2+0.1	8000	3.5	--	--	--
G106.3+2.7	10000	0.8	--	0.05	6
gammacygni	15000	0.8	40.0	0.05	6
cygnusloop	17000	0.5	10.0	-0.005	210
W51C	20000	6.0	66	0.003	160
W44	20000	3.0	115	-0.005	230
G353.6-0.7	27000	3.2	--	--	2.5
IC443	30000	1.5	50	0.03	160
W28	40000	2.0	40	0.38	310

2 classes of gamma-rays SNRs

1) young SNRs (10^2 - 10^3 yrs) are shell-like object, expanding in a relatively low density medium, with gamma emission morphology typically very nicely correlated with the radio (and often X) shell

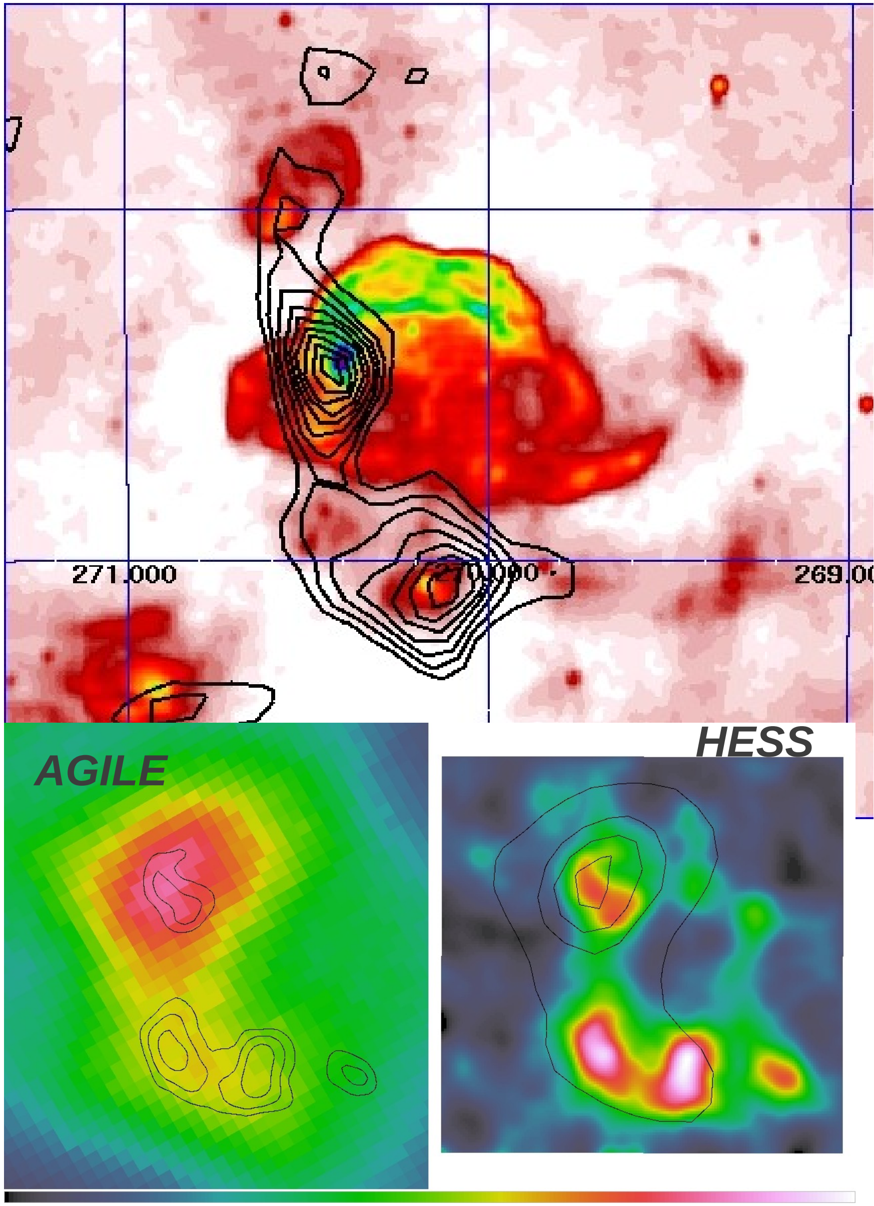


Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

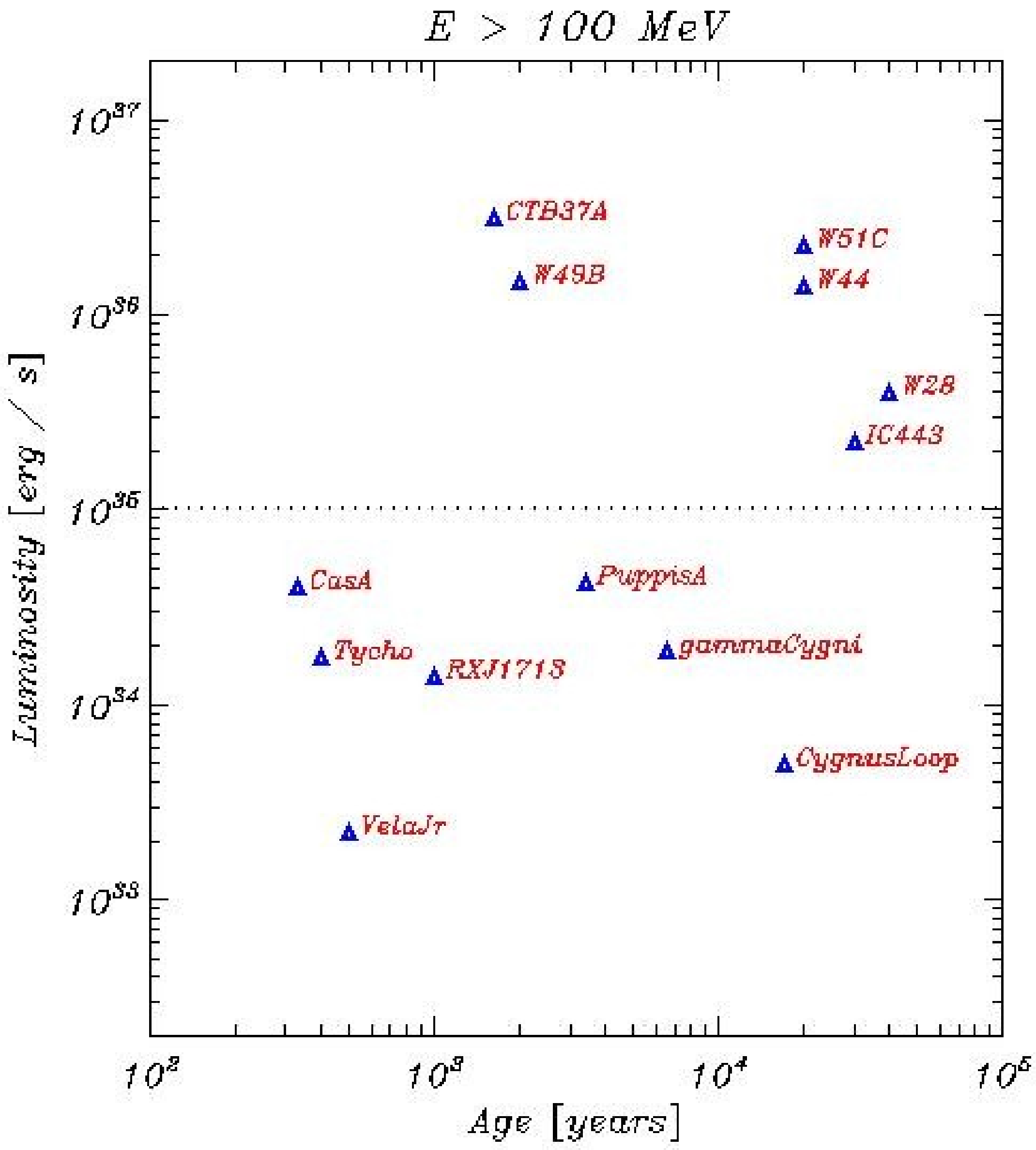
2 classes of gamma-rays SNRs

1) young SNRs (10^2 - 10^3 yrs) are shell-like object, expanding in a relatively low density medium, with gamma emission morphology typically very nicely correlated with the radio (and often X) shell

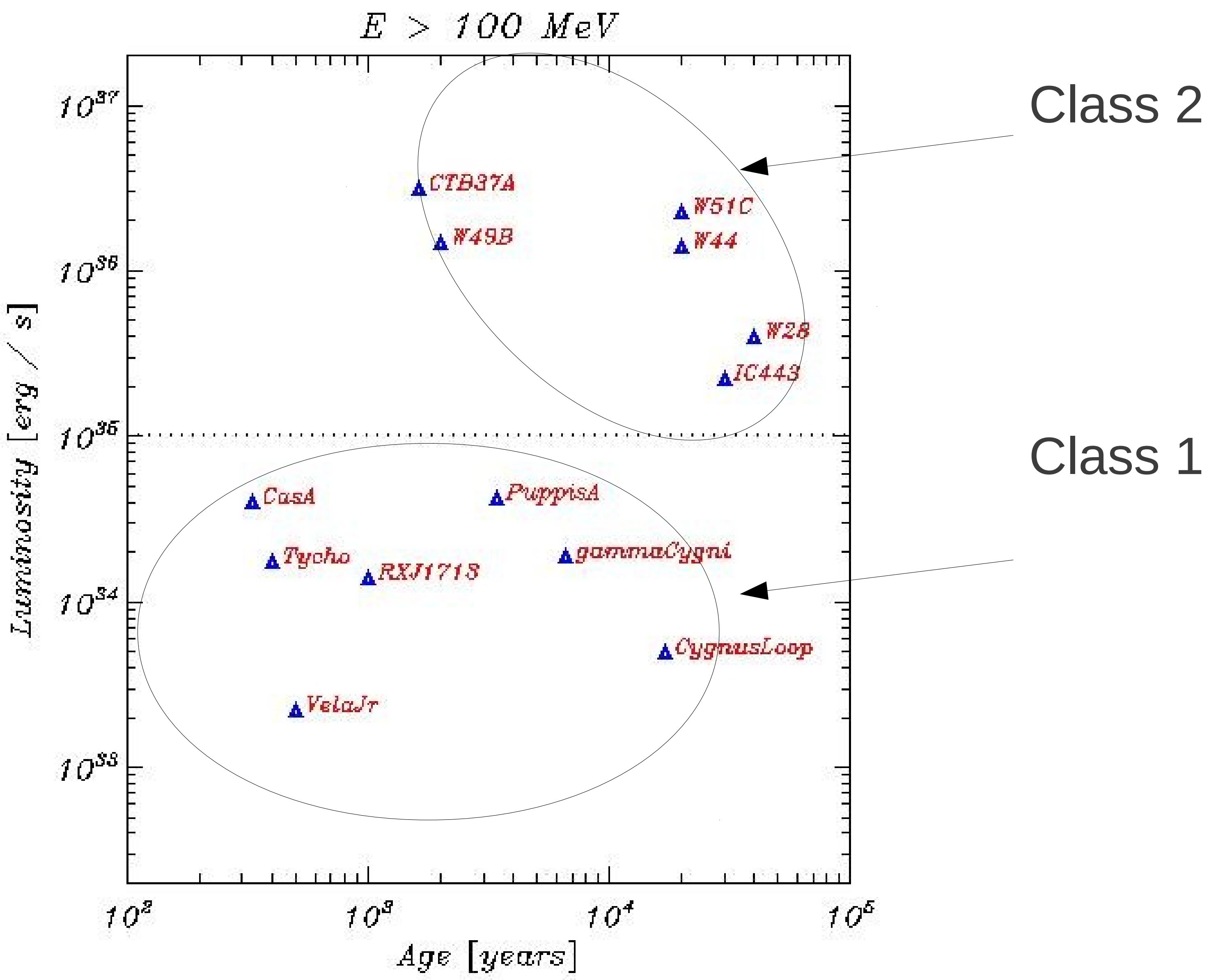
2) middle-aged SNRs (10^3 - 10^4 yrs) are mixed-morphology objects, interacting with giant molecular clouds and with a gamma morphology that correlates with M.C. better than with the radio shell.



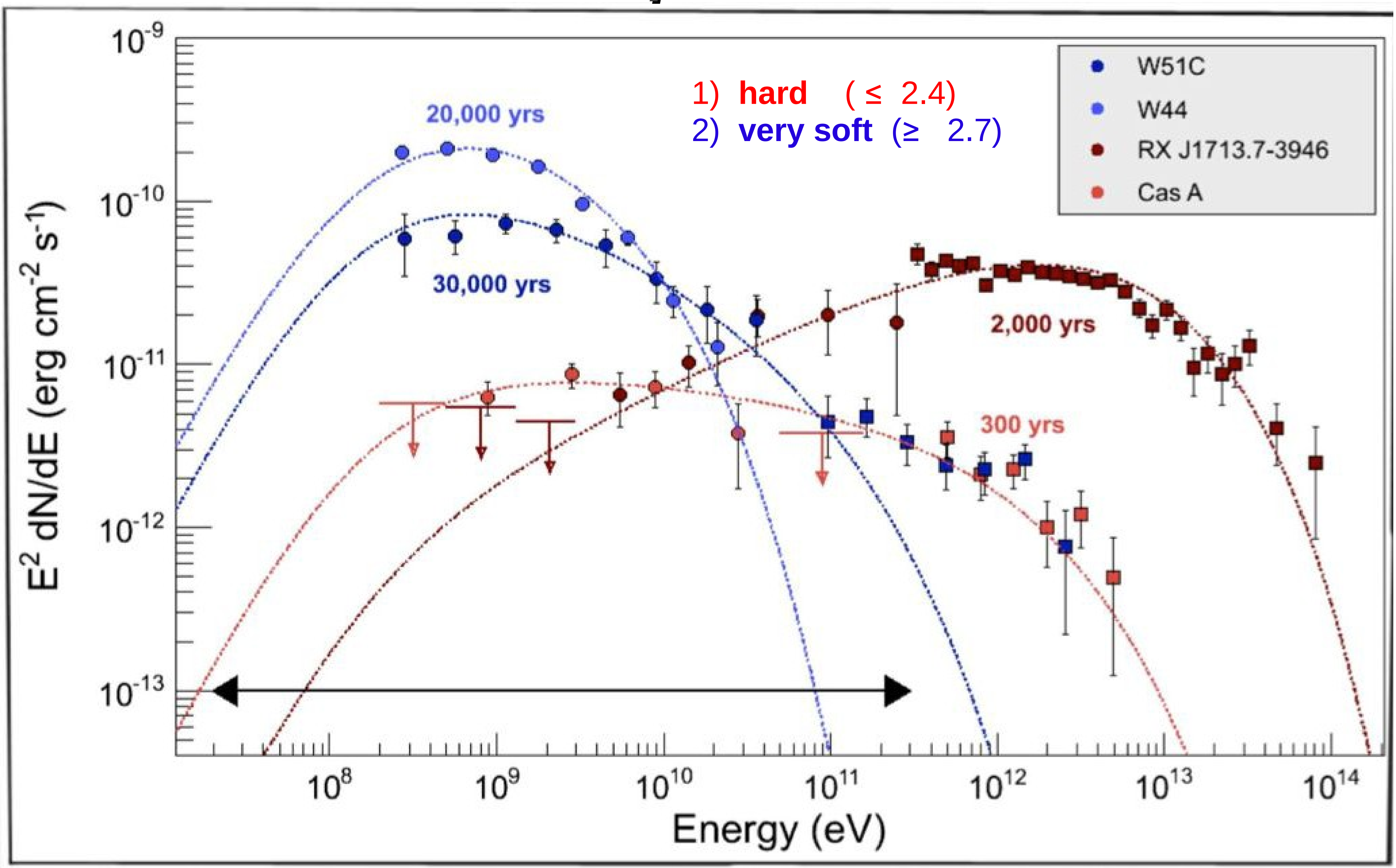
2 classes of gamma-rays SNRs



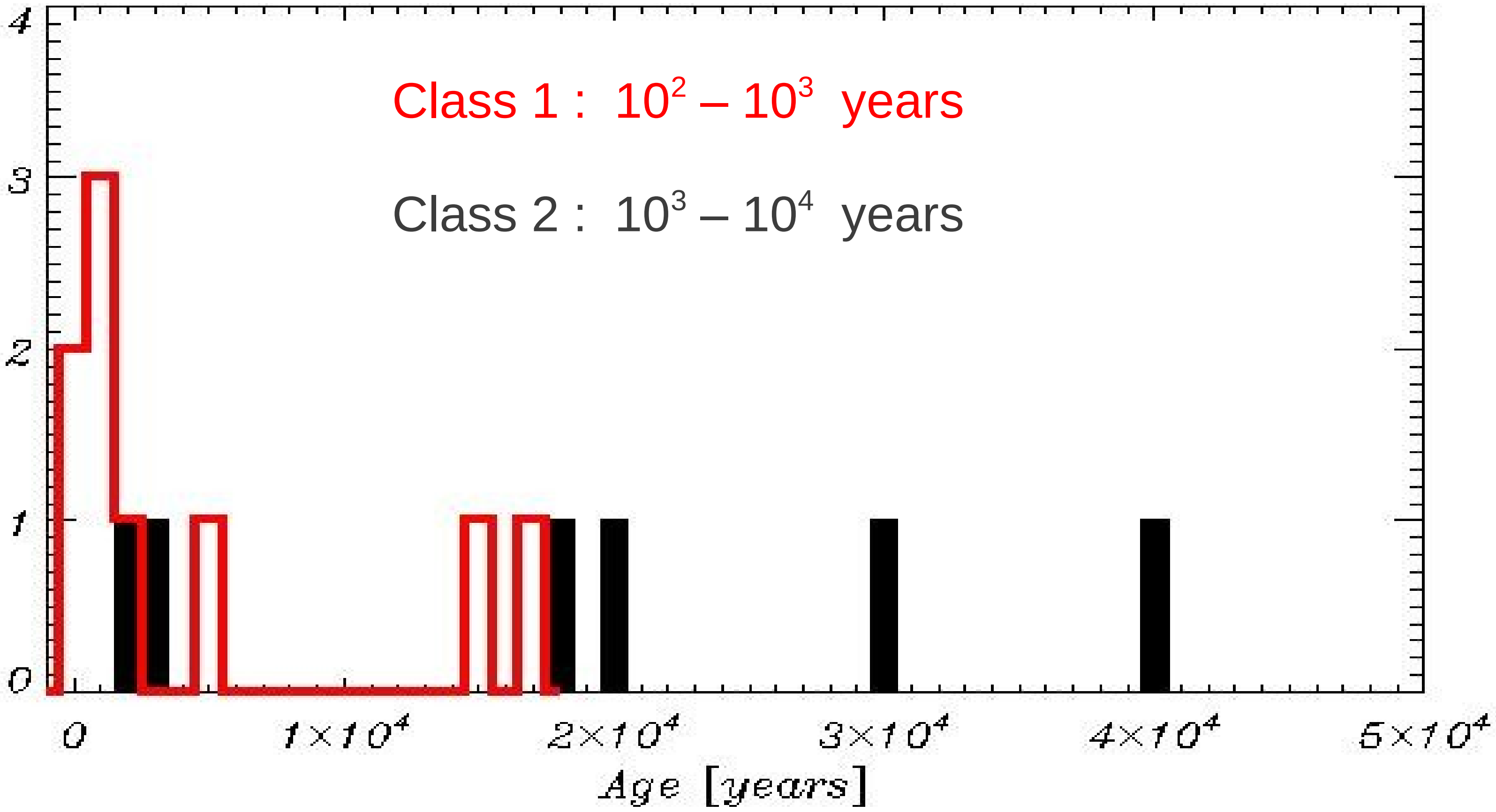
2 classes of gamma-rays SNRs



Different spectrum



Different Ages

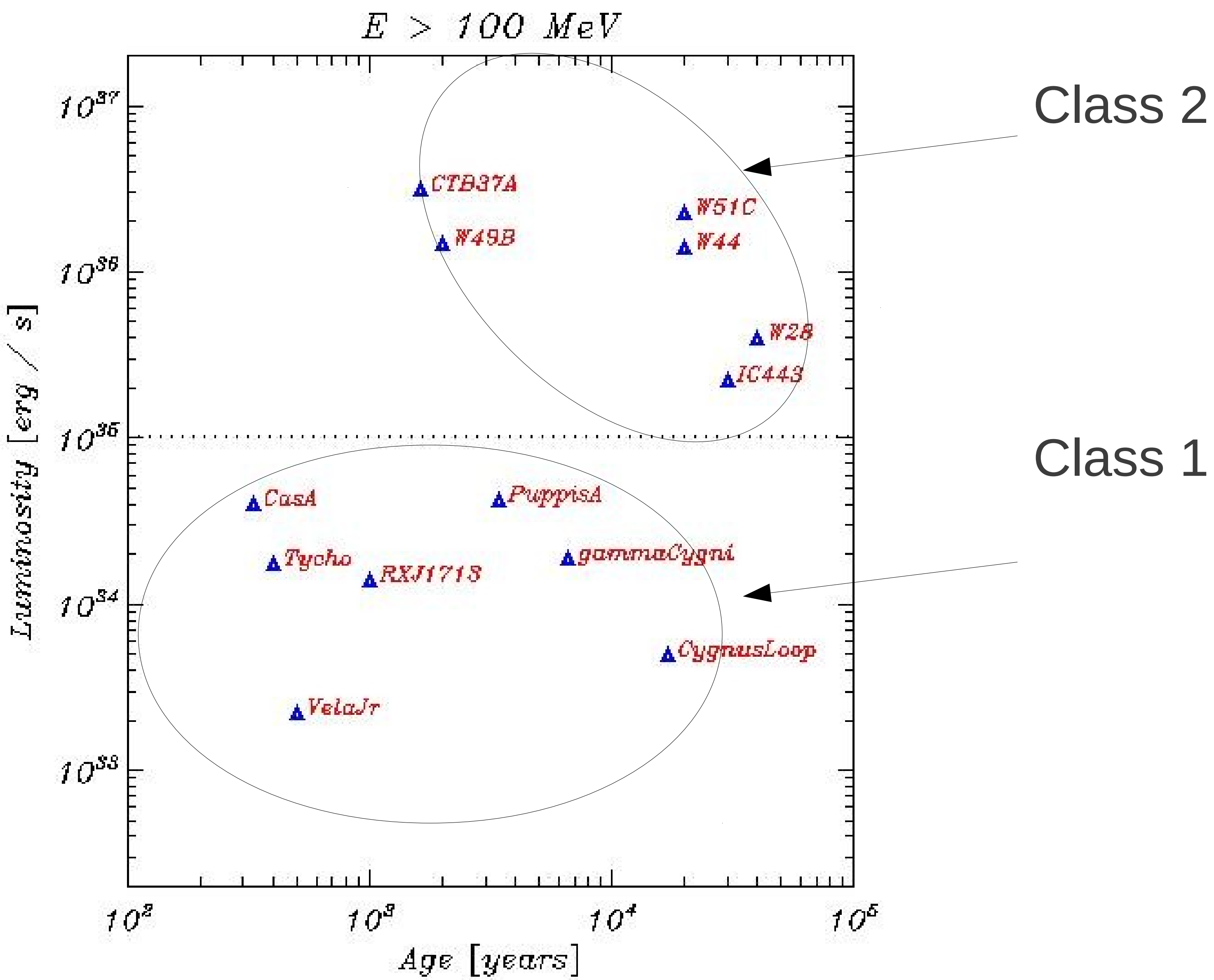


Different frequency (fraction of SNRs gamma-rays loud)

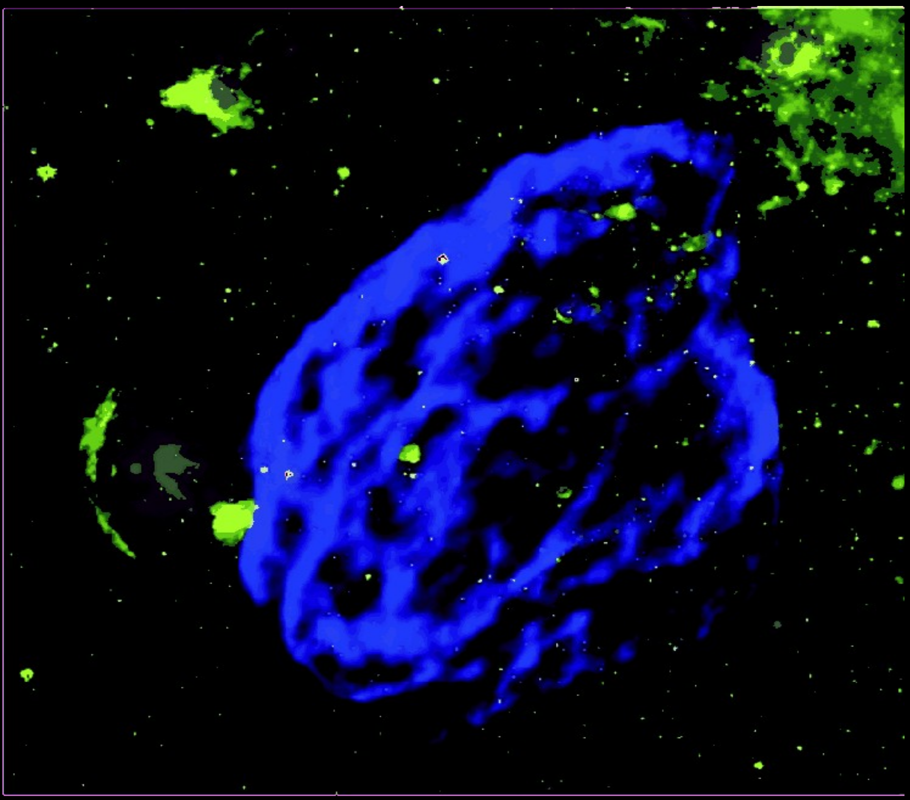
Class 1 : Very common
(All the historical SNRs emit gamma-rays!)

Class 2 : Quite rare
(~ 1 %, only those SNRs close to a GMC)

2 classes of gamma-rays SNRs



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]

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

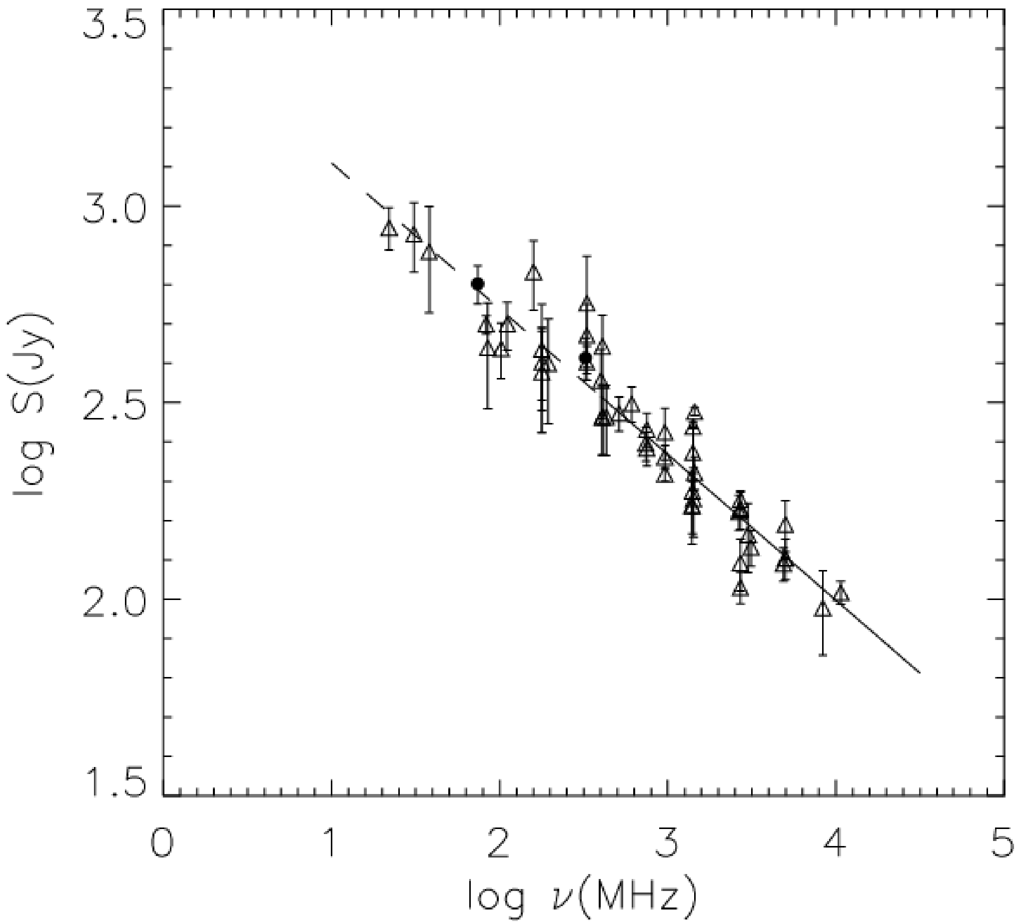
The radio spectrum of W44 is a power-law featurless in the frequency range ~ 10 MHz - 10 GHz (Castelletti et al 2007)

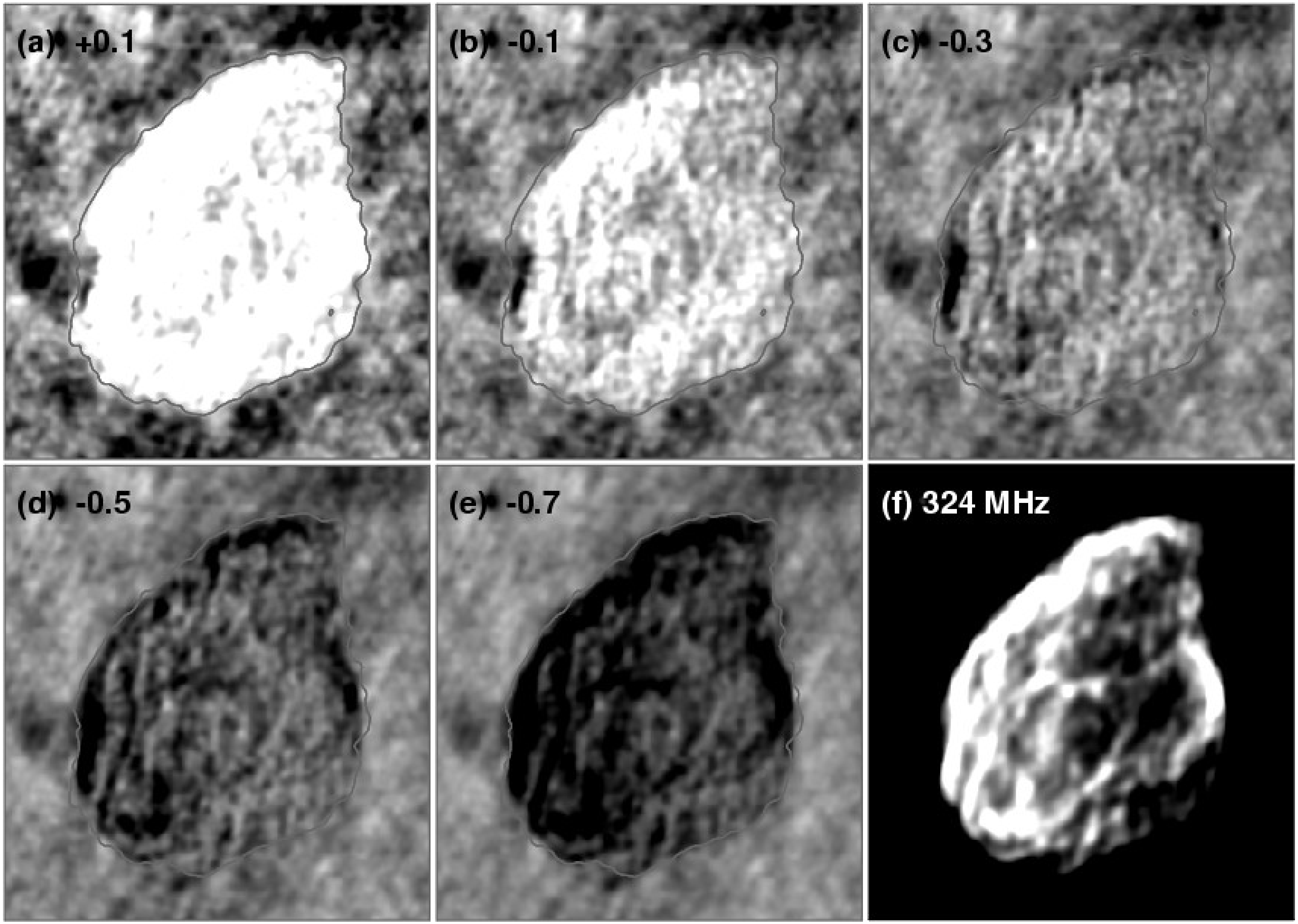
$S\ (Jy) = \nu^{-0.37+-0.02}$

Corresponding to an electrons spectrum :

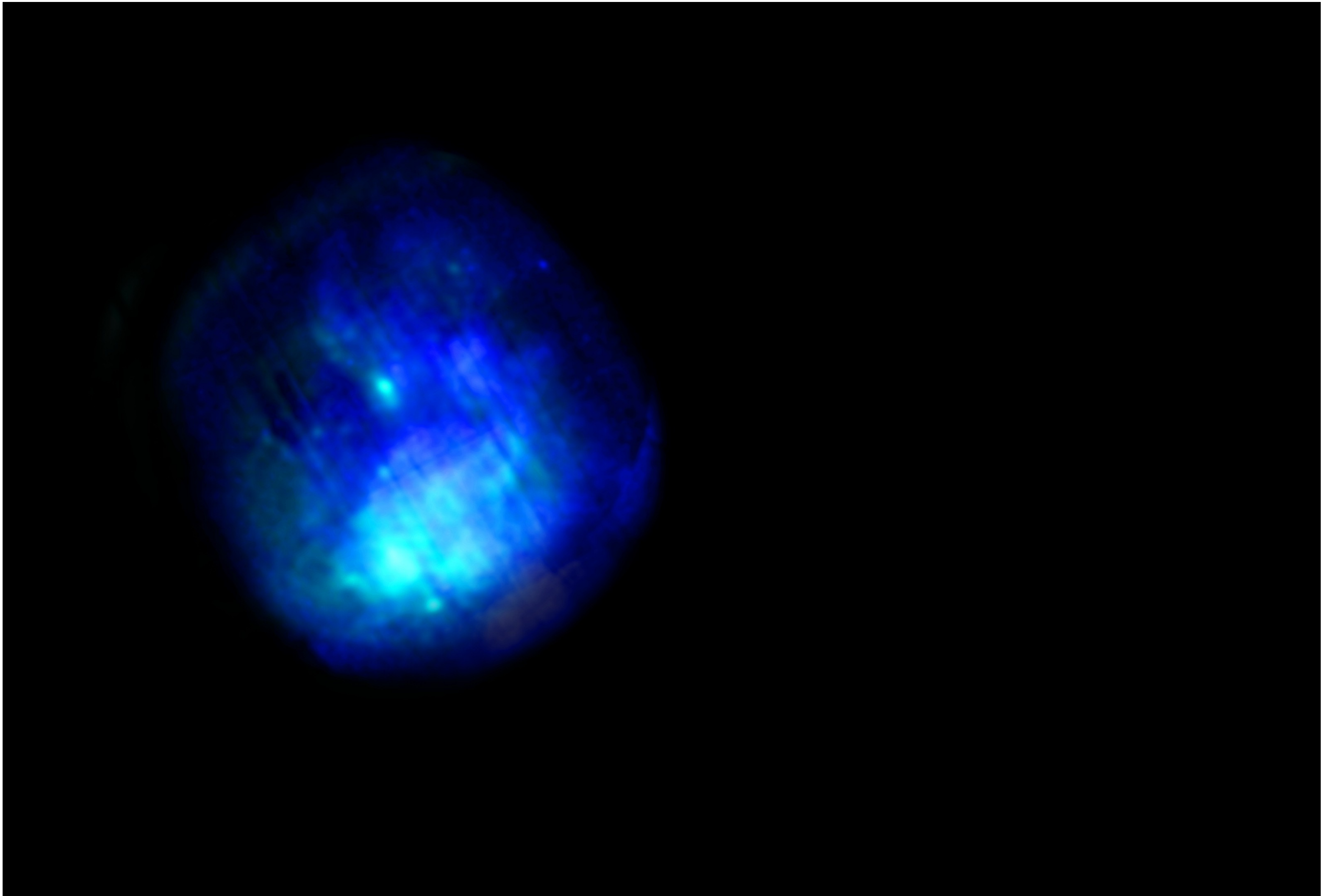
$F \sim E^{-1.74}$ [particles / cm s MeV]

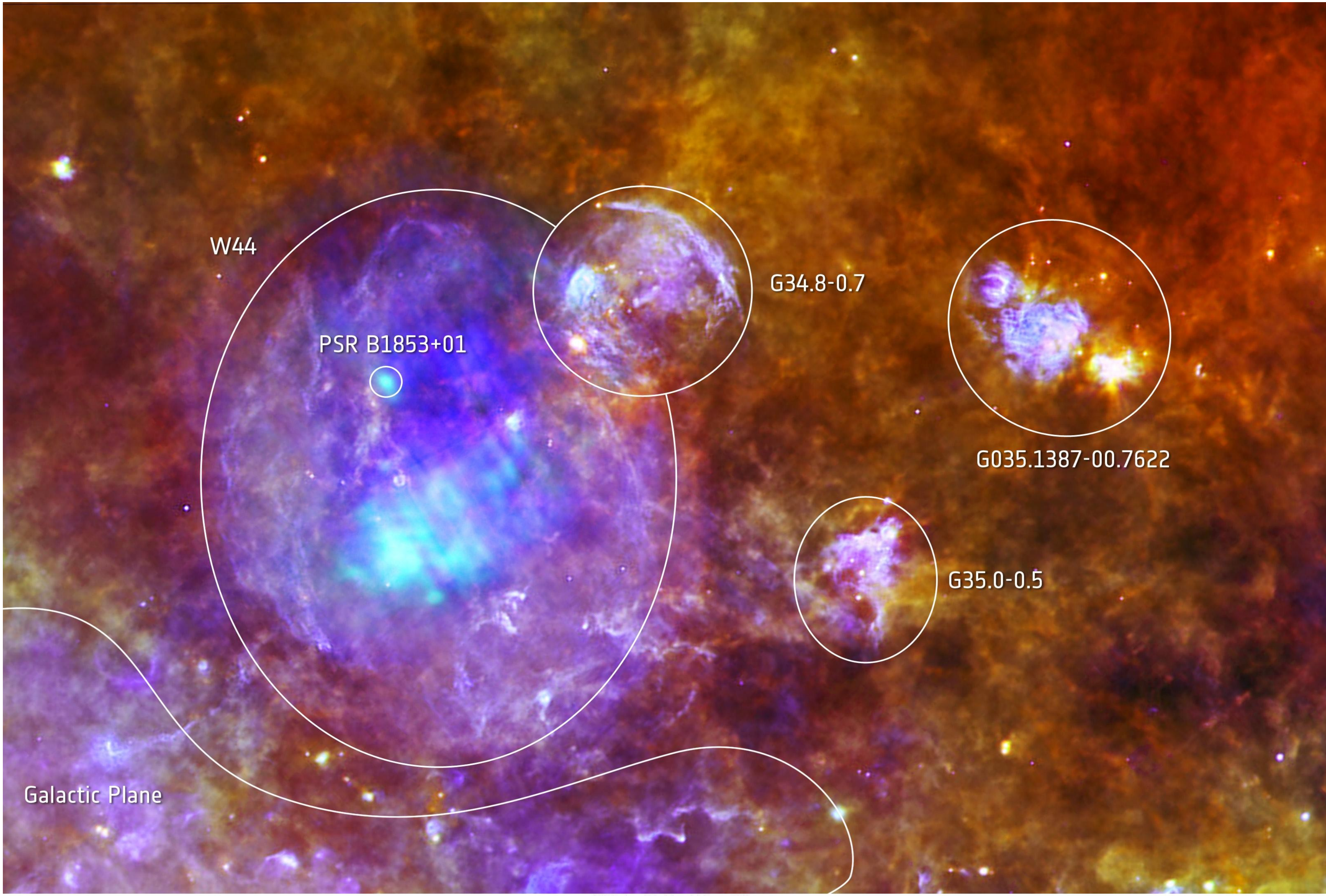
E ~ 300 MeV – 10 GeV (B = 10 uG)
~ 100 MeV – 3 GeV (B = 100 uG)





(a) +0.1
(b) -0.1
(c) -0.3
(d) -0.5
(e) -0.7
(f) 324 MHz

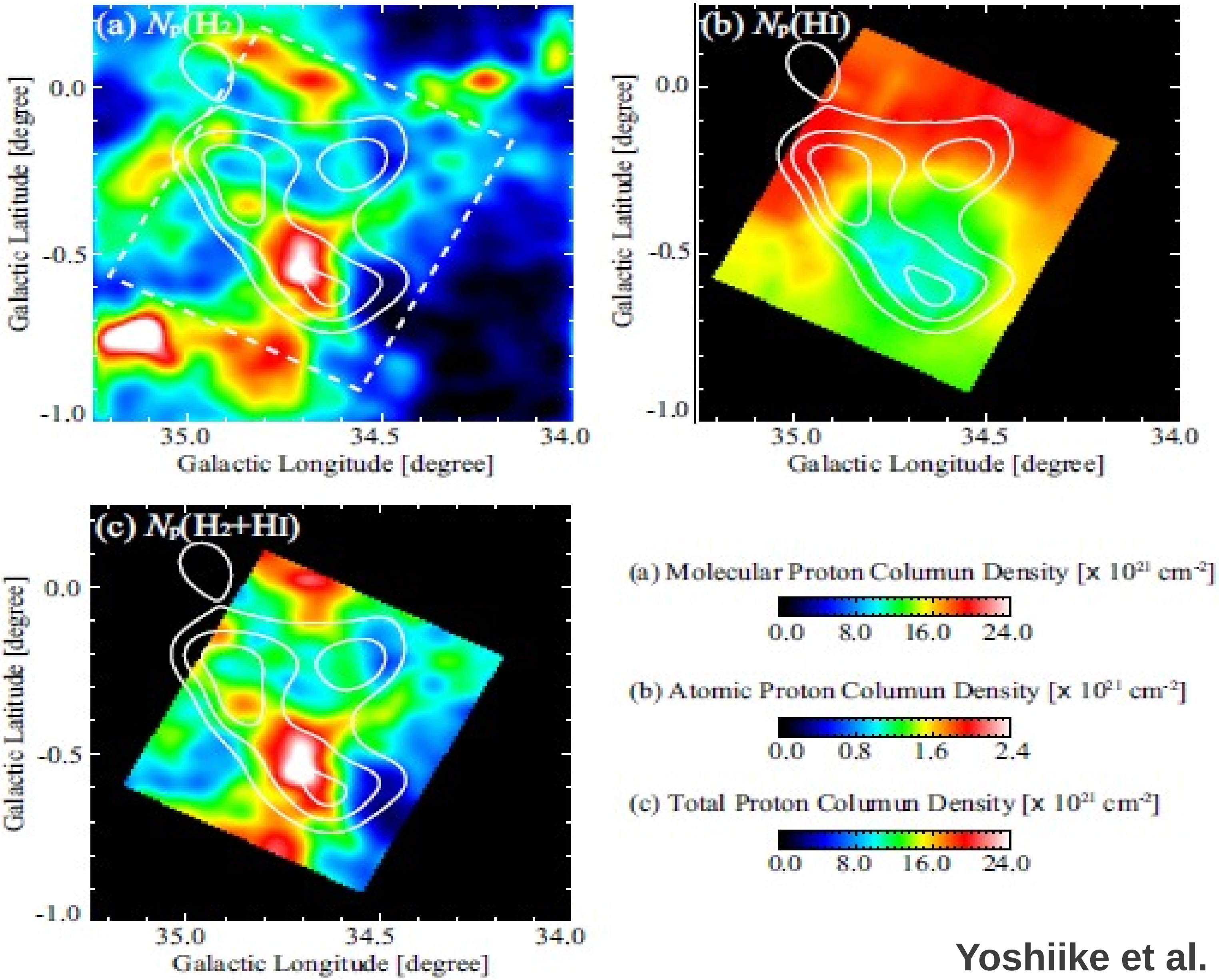




XMM-Newton and Herschel annotated image of W44

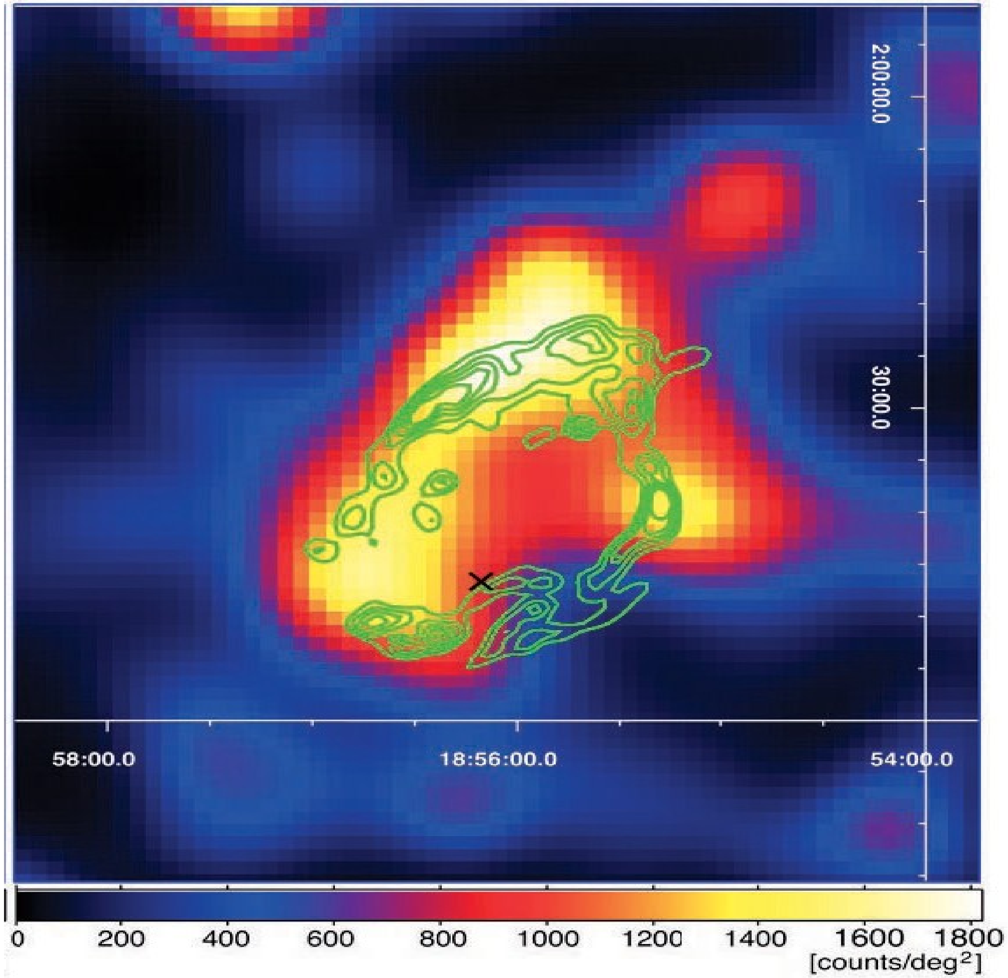
Image courtesy of ESA/PACS/SPIRE/Luong & Motte, HOBYS Key Program consortium; ESA/XMM-Newton

European Space Agency

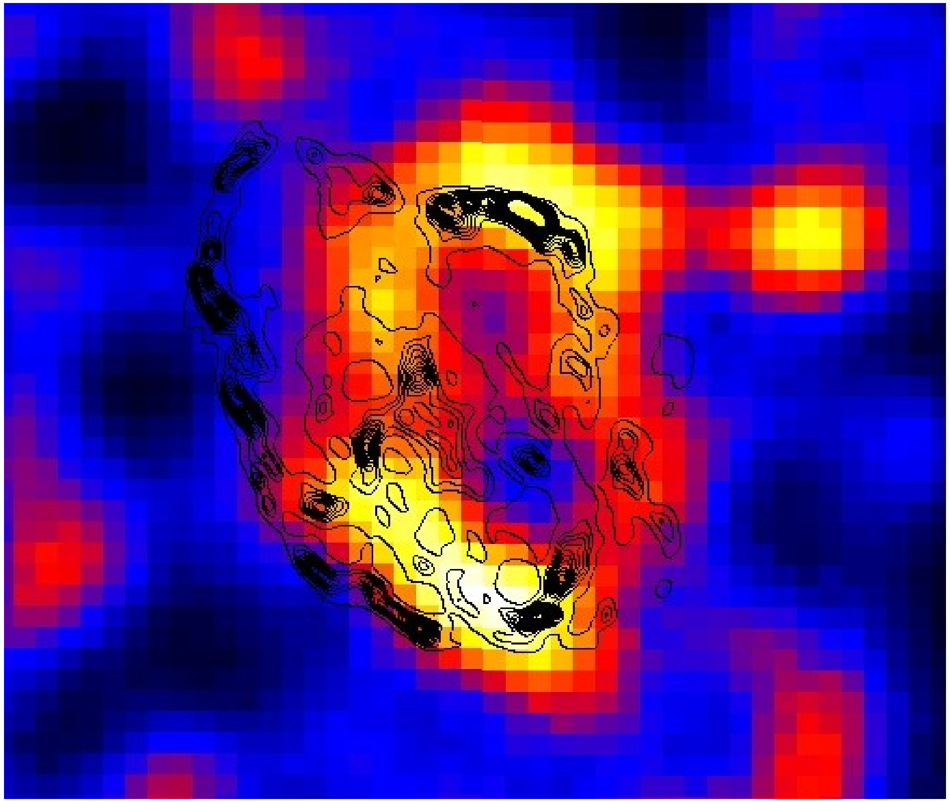


Yoshiike et al. 2013

Fermi and AGILE detection of W44

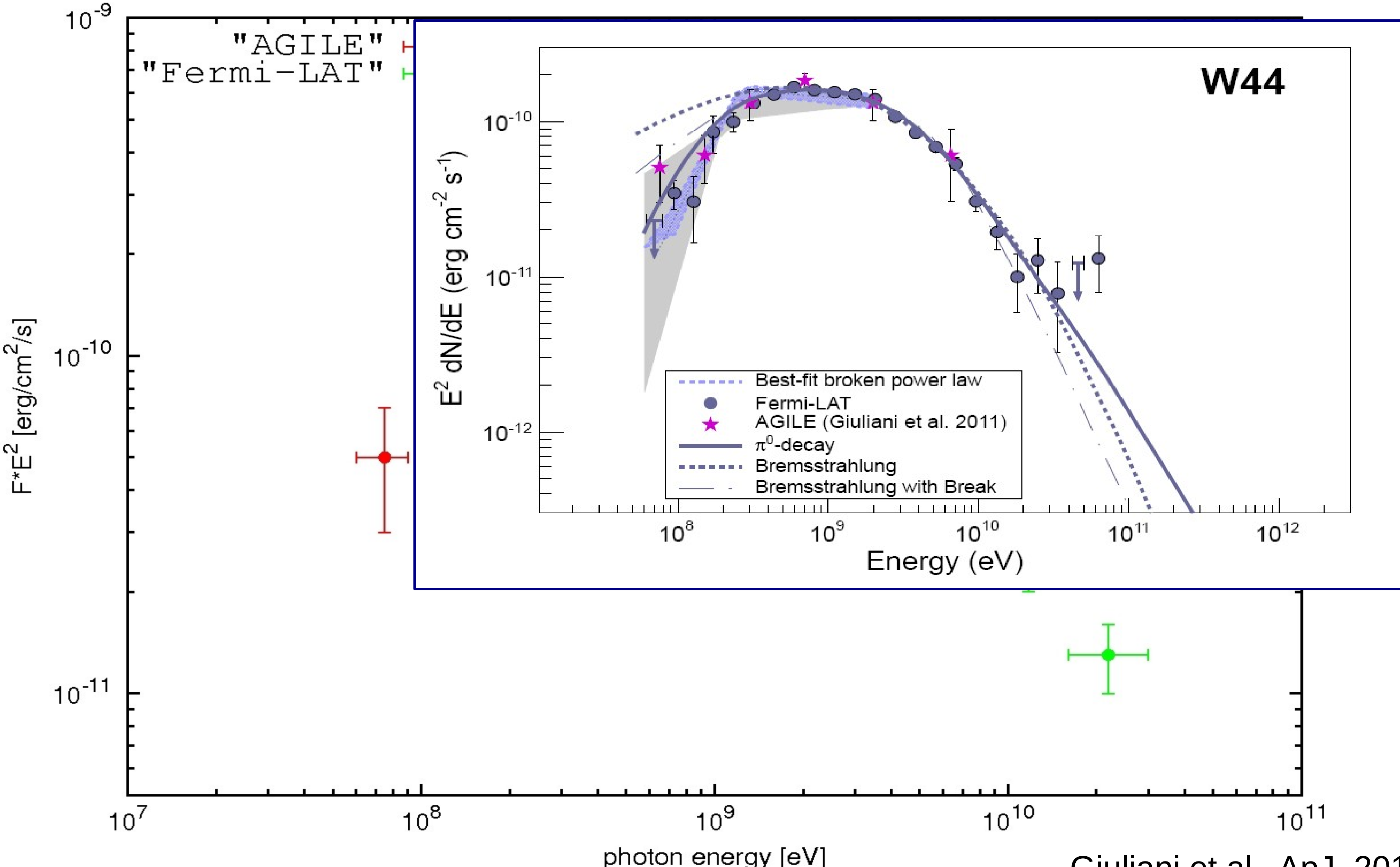


Abdo et al. 2010, Science, 327
Uchiyama et al. 2012, ApJL



Giuliani et al. 2011 ApJL

Giuliani et al. ApJ, 2011

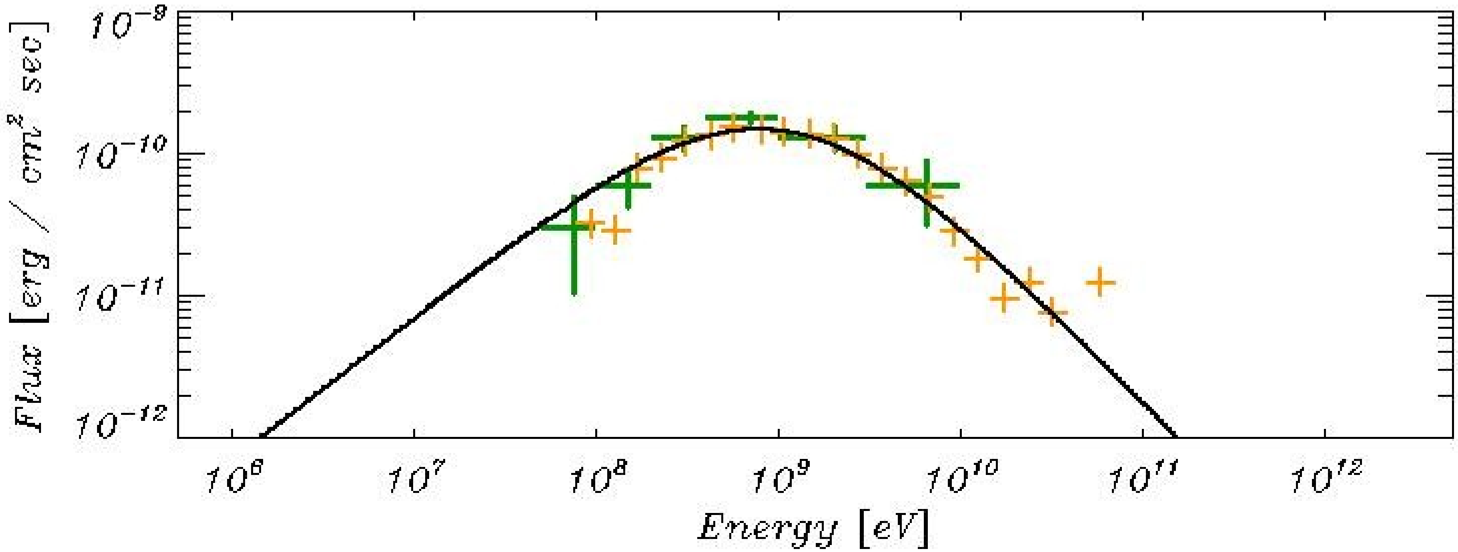


Giuliani et al. ApJ, 2011

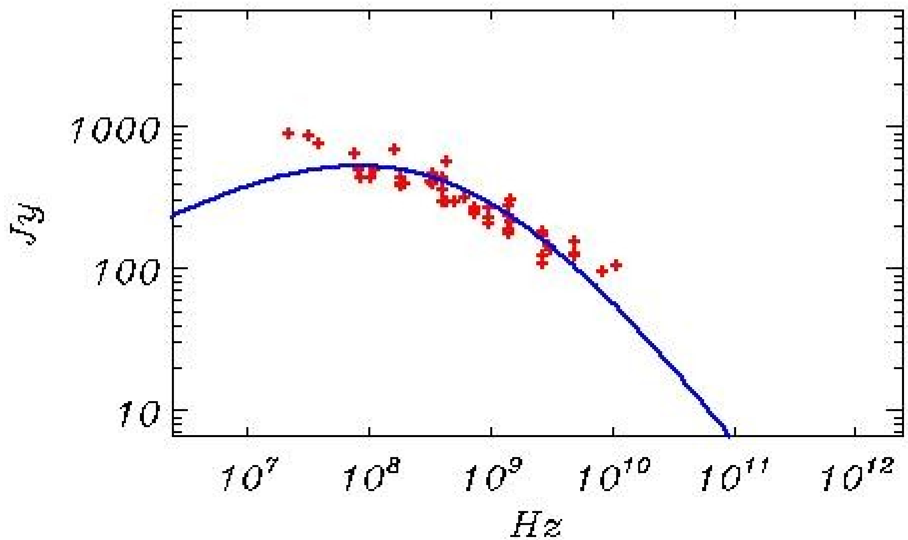
1) ***A single population of electrons cannot fit simultaneously the Gamma-Ray and Radio spectra***

→ ***Protons !***

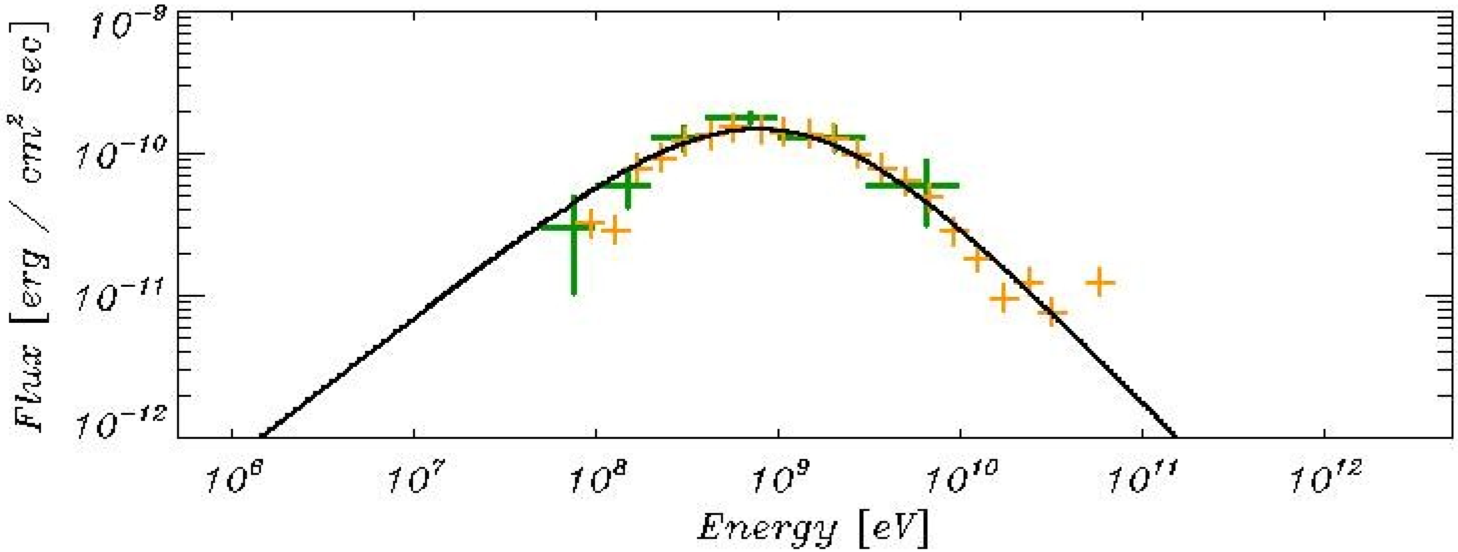
Bremsstrahlung ?



B : 30.0000
n : 300
E_c : 1000.00
kp : 100.000
k : 2.25000e+12
p_1 : 0
p_2 : 3.30000
p : 3.50000
E_{cl} : 3000.00



Bremsstrahlung ?



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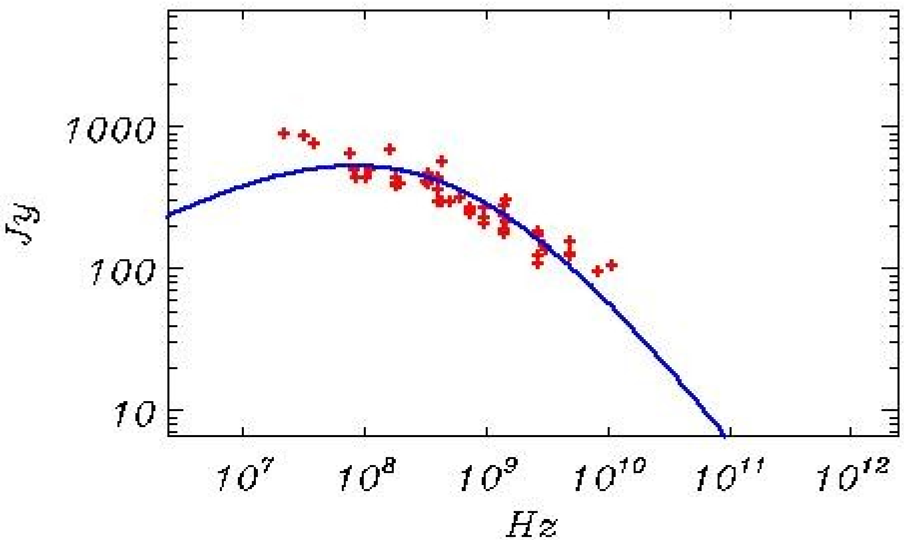

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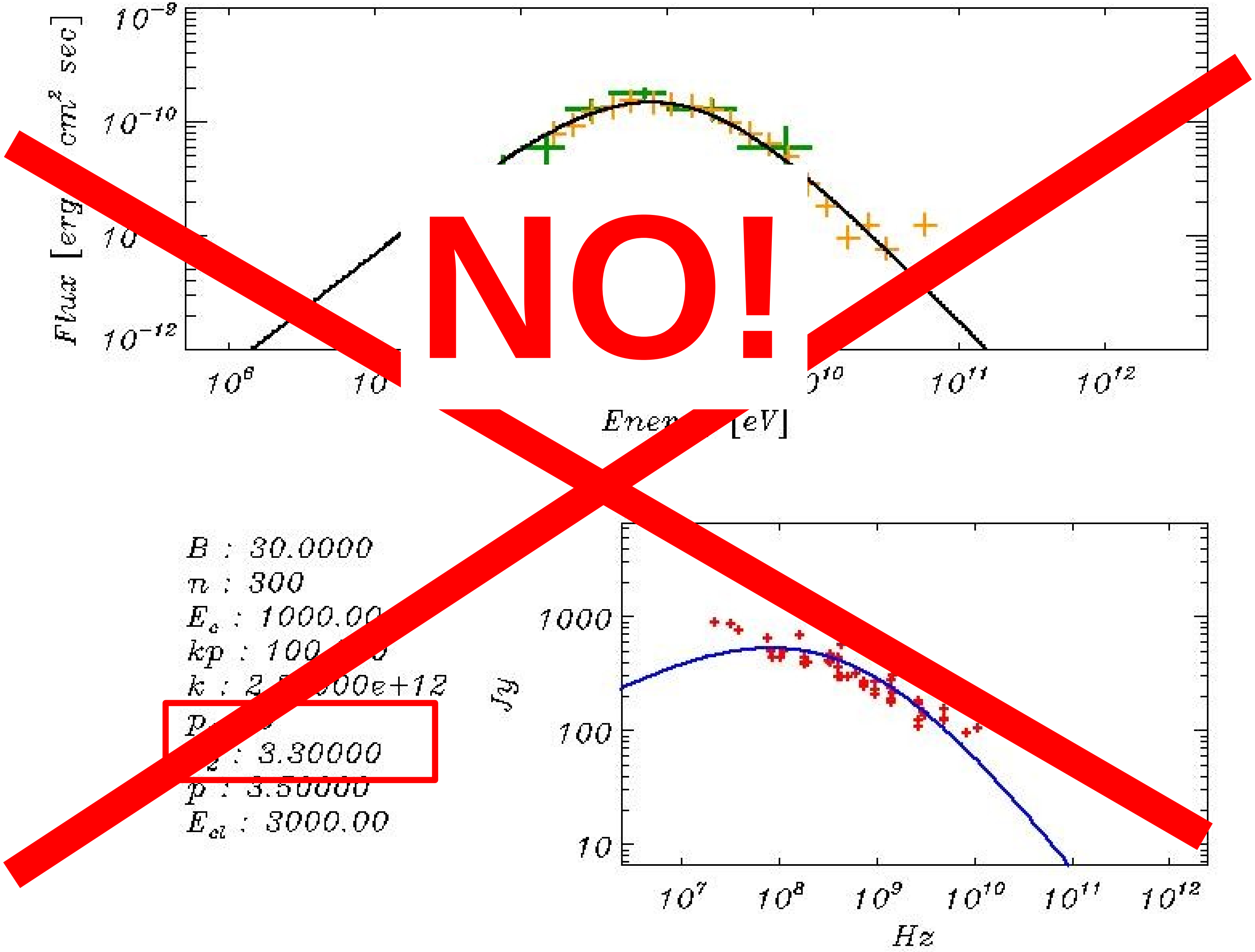
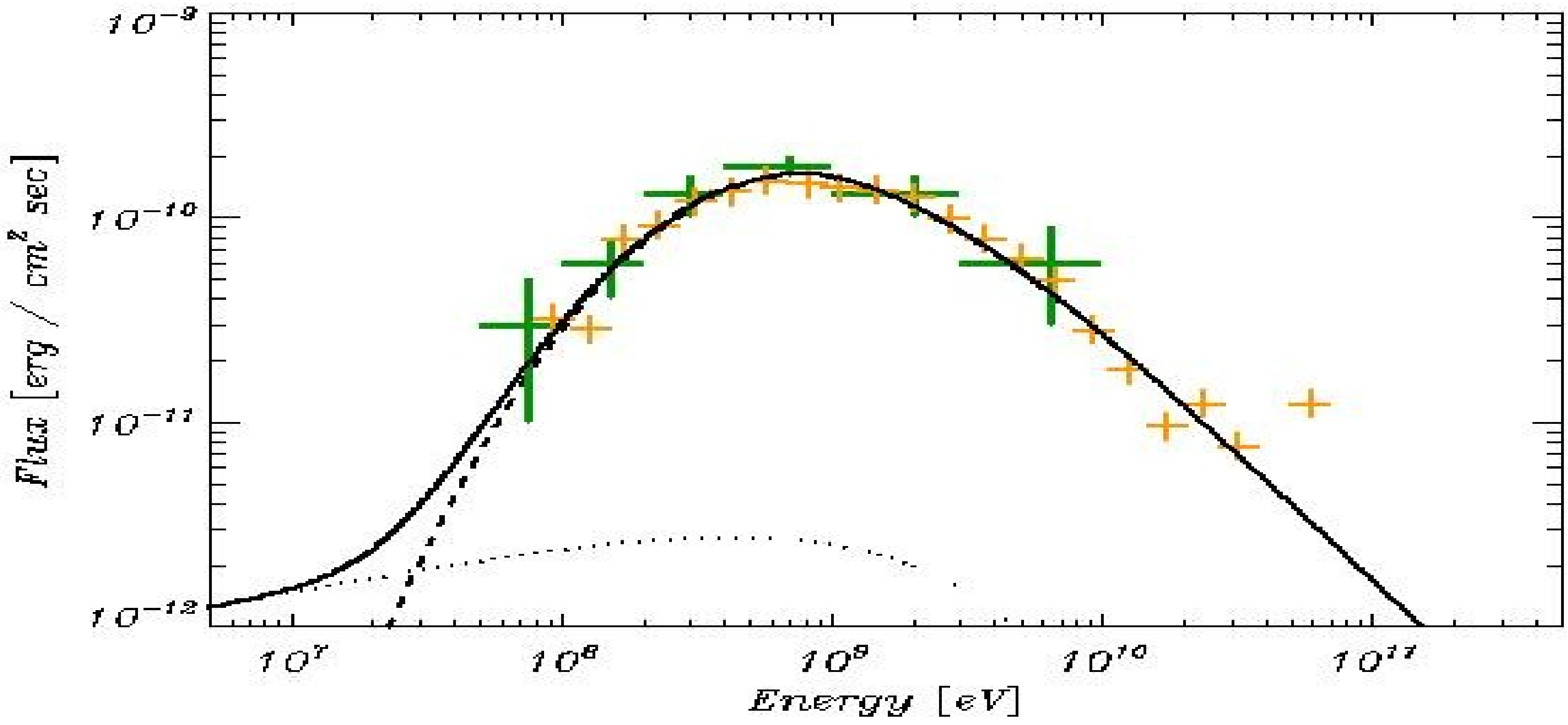


Pion decay !

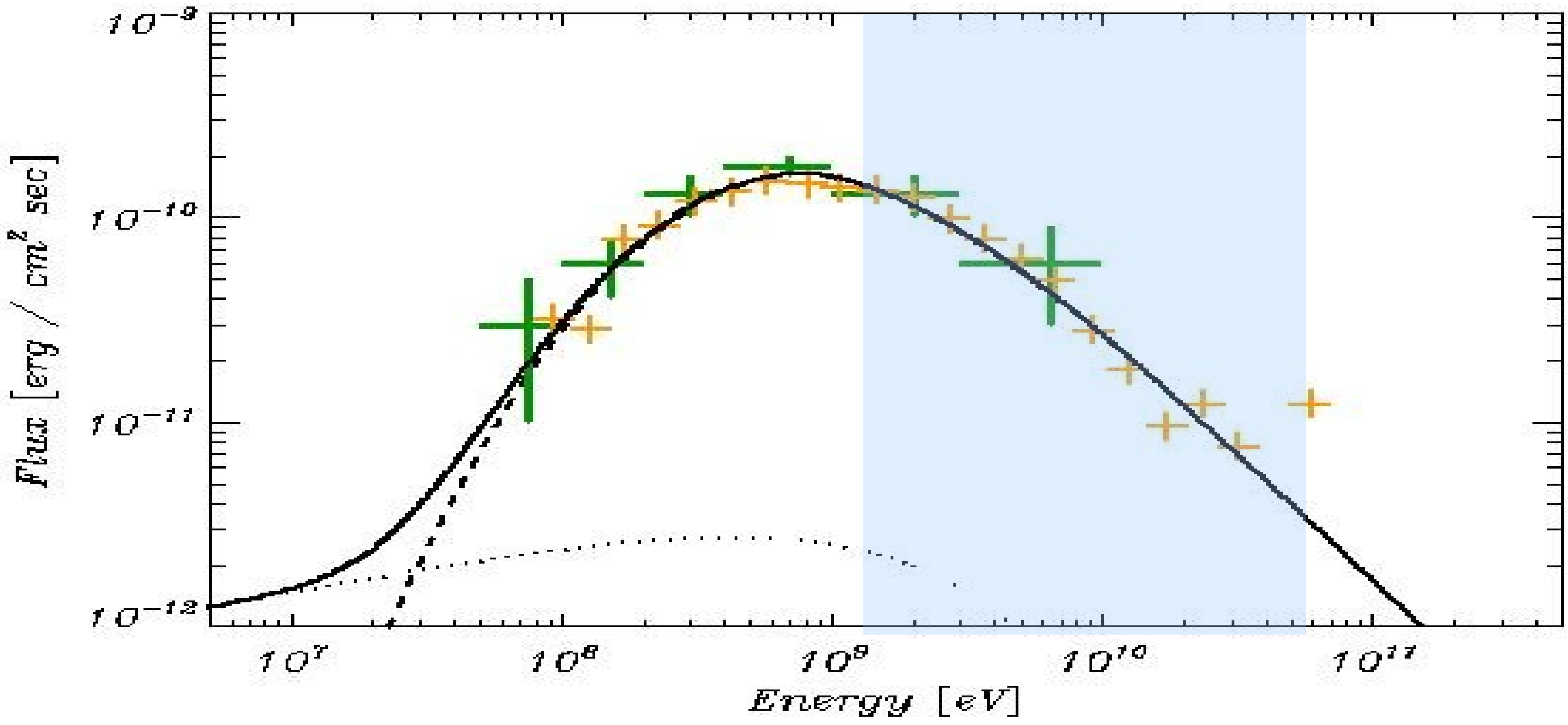


10^{-9}
10^{-10}
10^{-11}
10^{-12}
Flux [erg / cm² sec]
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
Energy [eV]

2) The protons spectrum is very soft for energies greater than ~ 4-5 GeV

Power law with index 3.5 (!!)

At least up to ~ 50 GeV (challenge for CTA)



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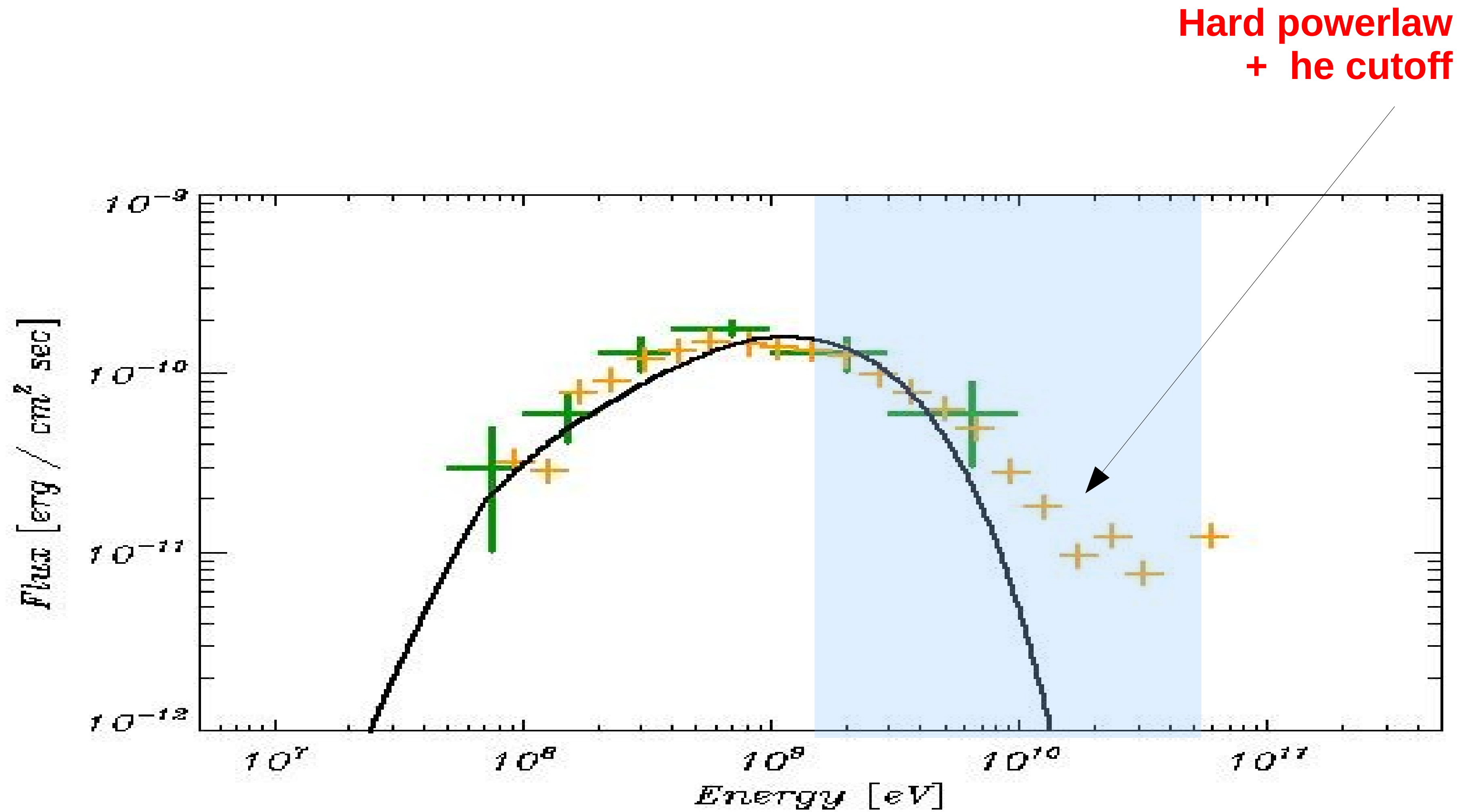

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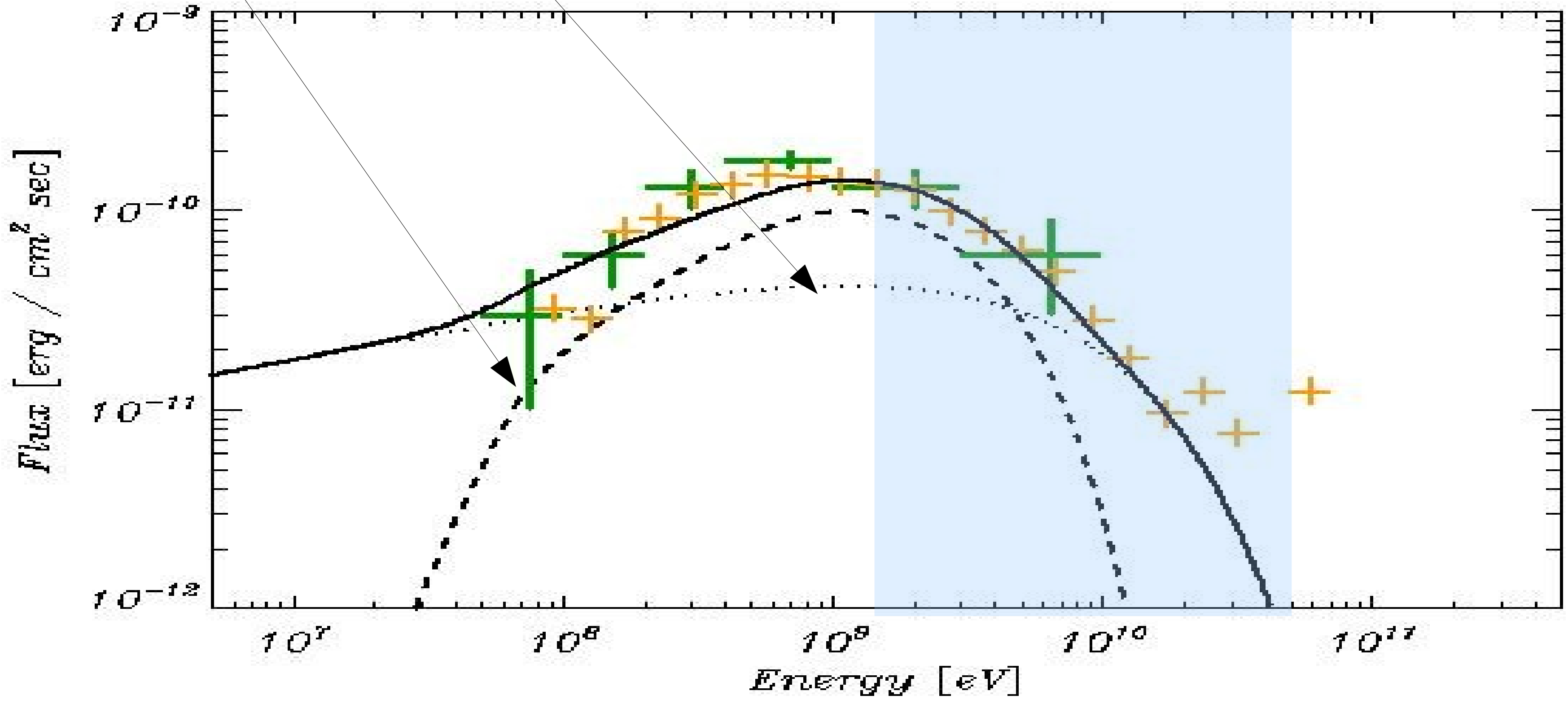
Power law with index 3.5 (!!)

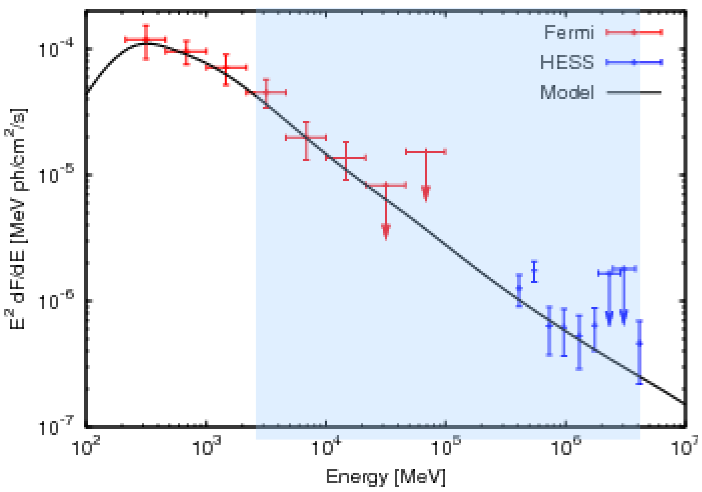
Hard power-lawl + h.e. cutoff for both protons and electrons (see Uchiyama et al. 2011)



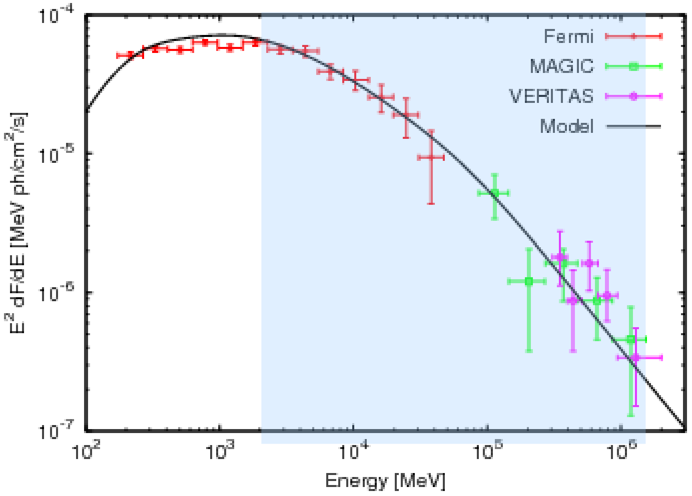
2) The protons spectrum is very soft for energies greater than ~ 4-5 GeV

Very common for class-2 SNRs

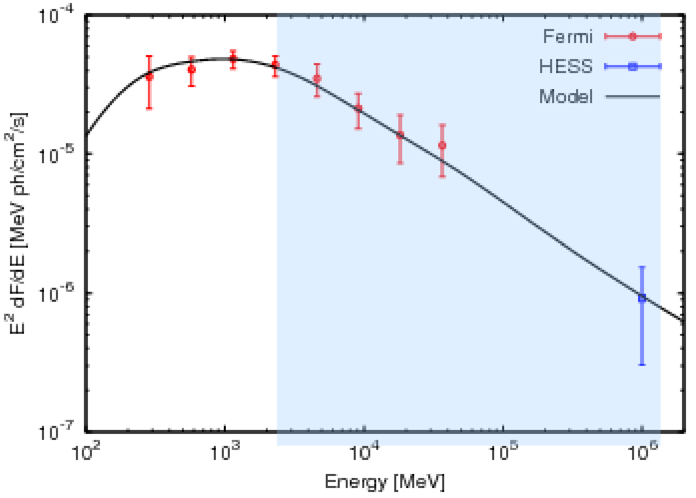
W28



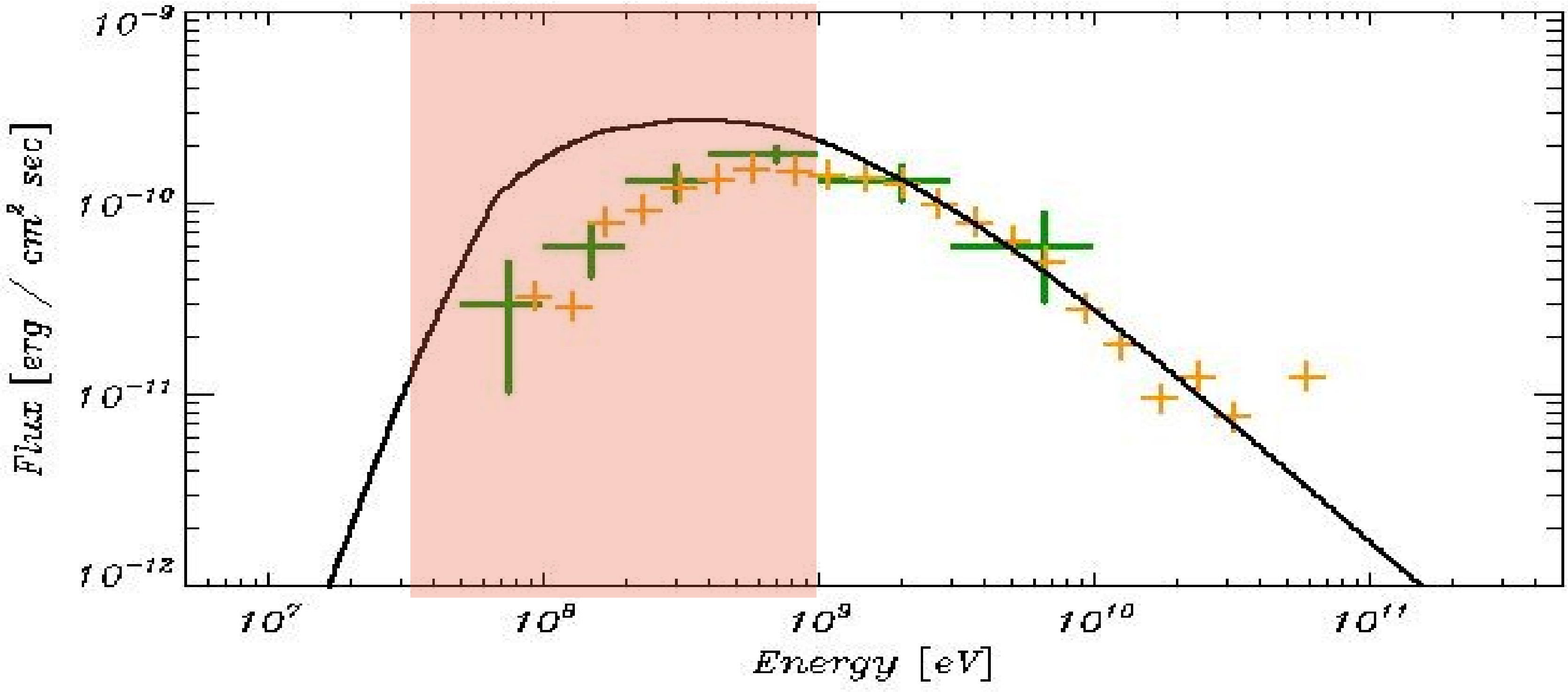
IC 443



W51

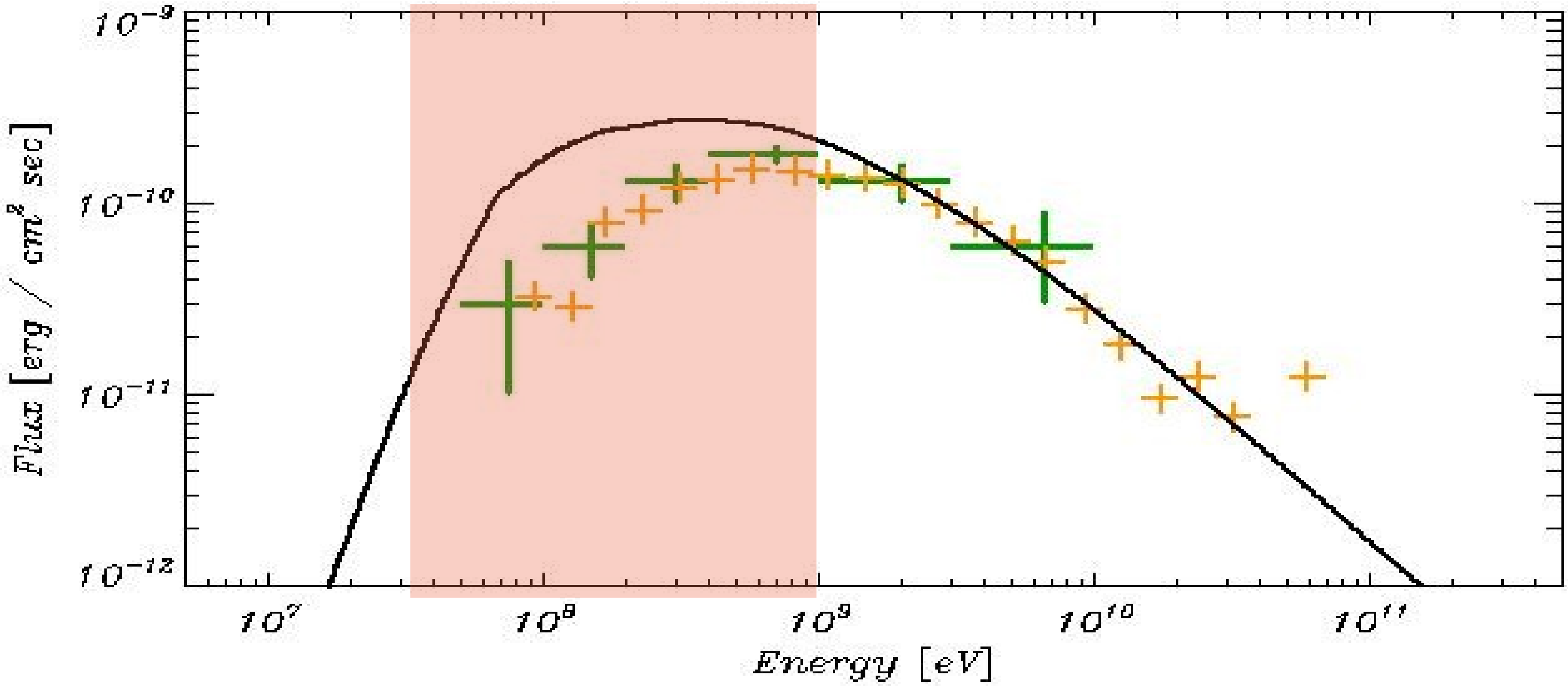


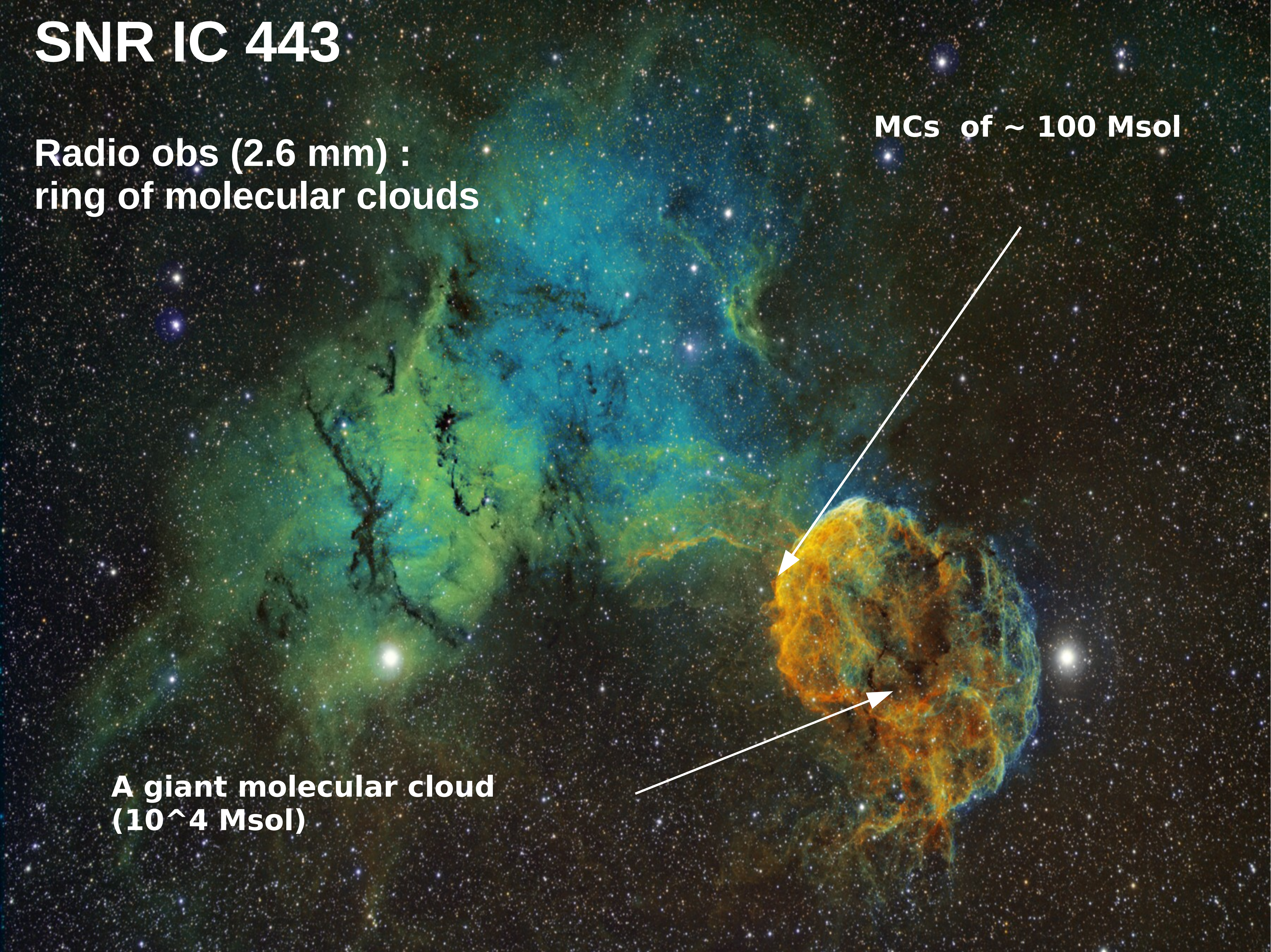
3) A simple power-law overestimate the flux in the low energy part of the spectrum



3) A simple power-law overestimate the flux in the low energy part of the spectrum

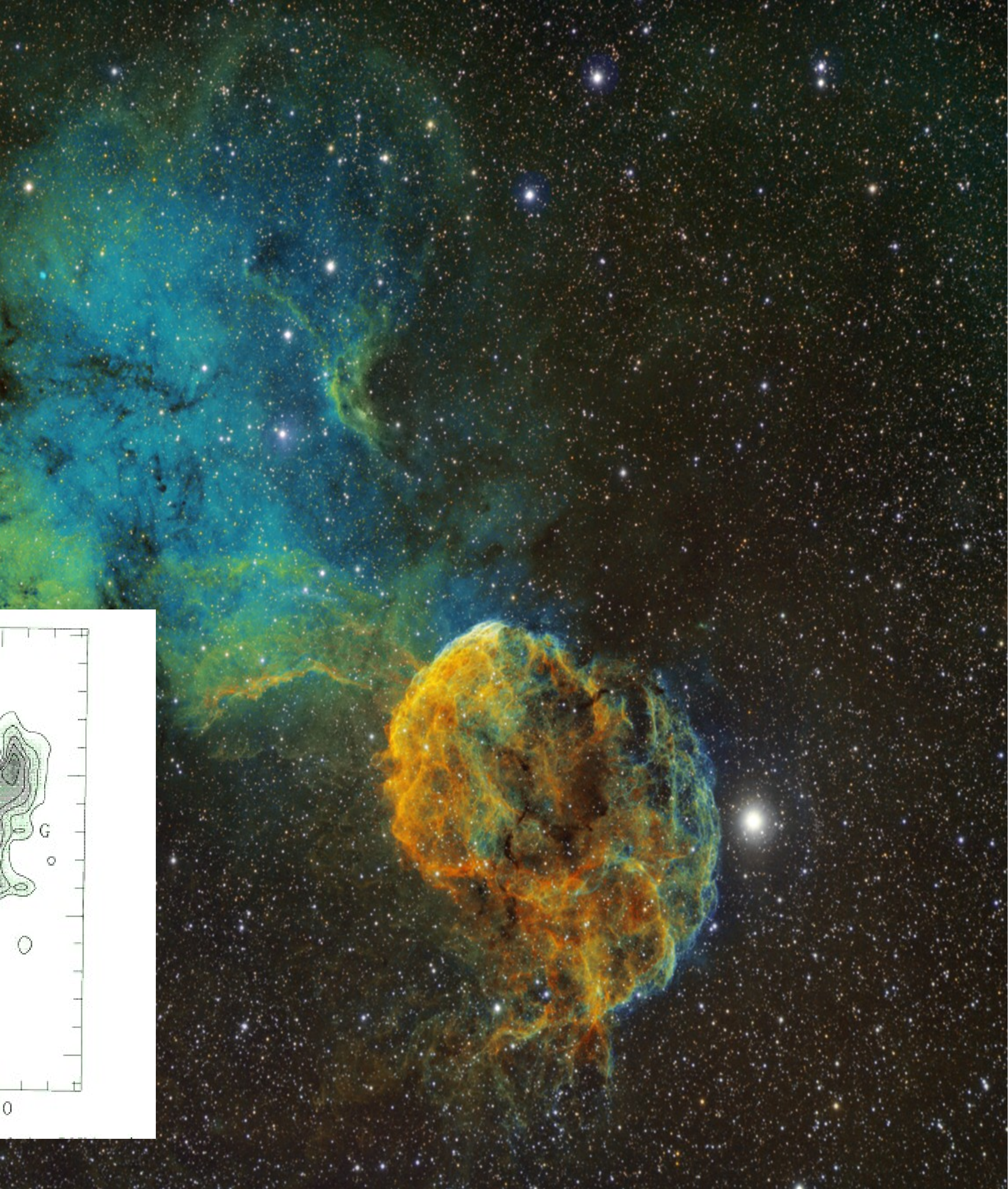
It implies a strong suppression of the proton spectrum below some GeV
(low energy cut off ? , break 3.5→1.8)

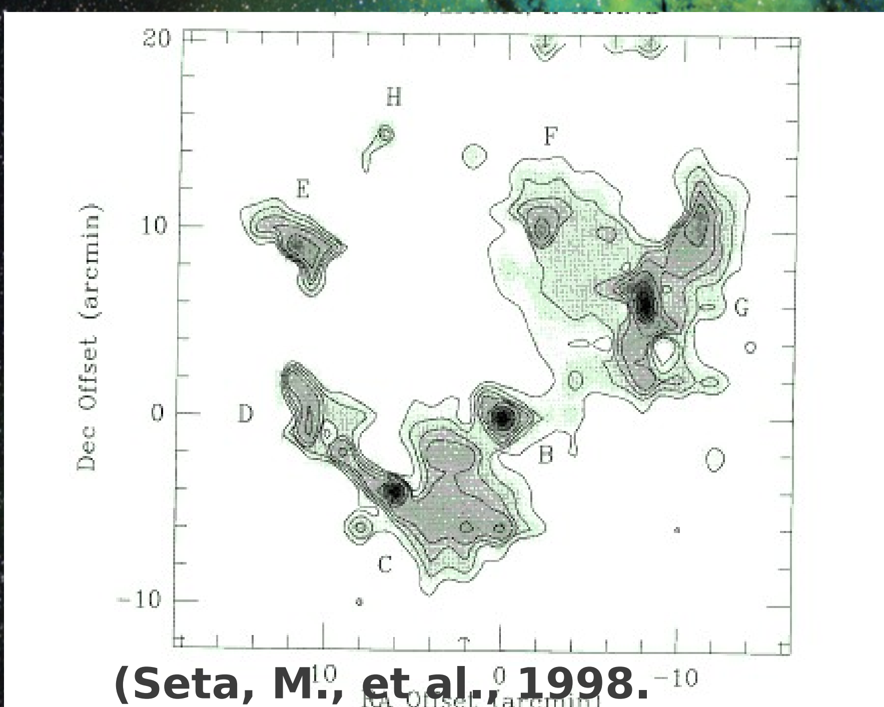



SNR IC 443
Radio obs (2.6 mm) :
ring of molecular clouds
MCs of ~ 100 Msol
A giant molecular cloud
(10^4 Msol)

SNR IC 443

Radio obs (2.6 mm) :
ring of molecular clouds

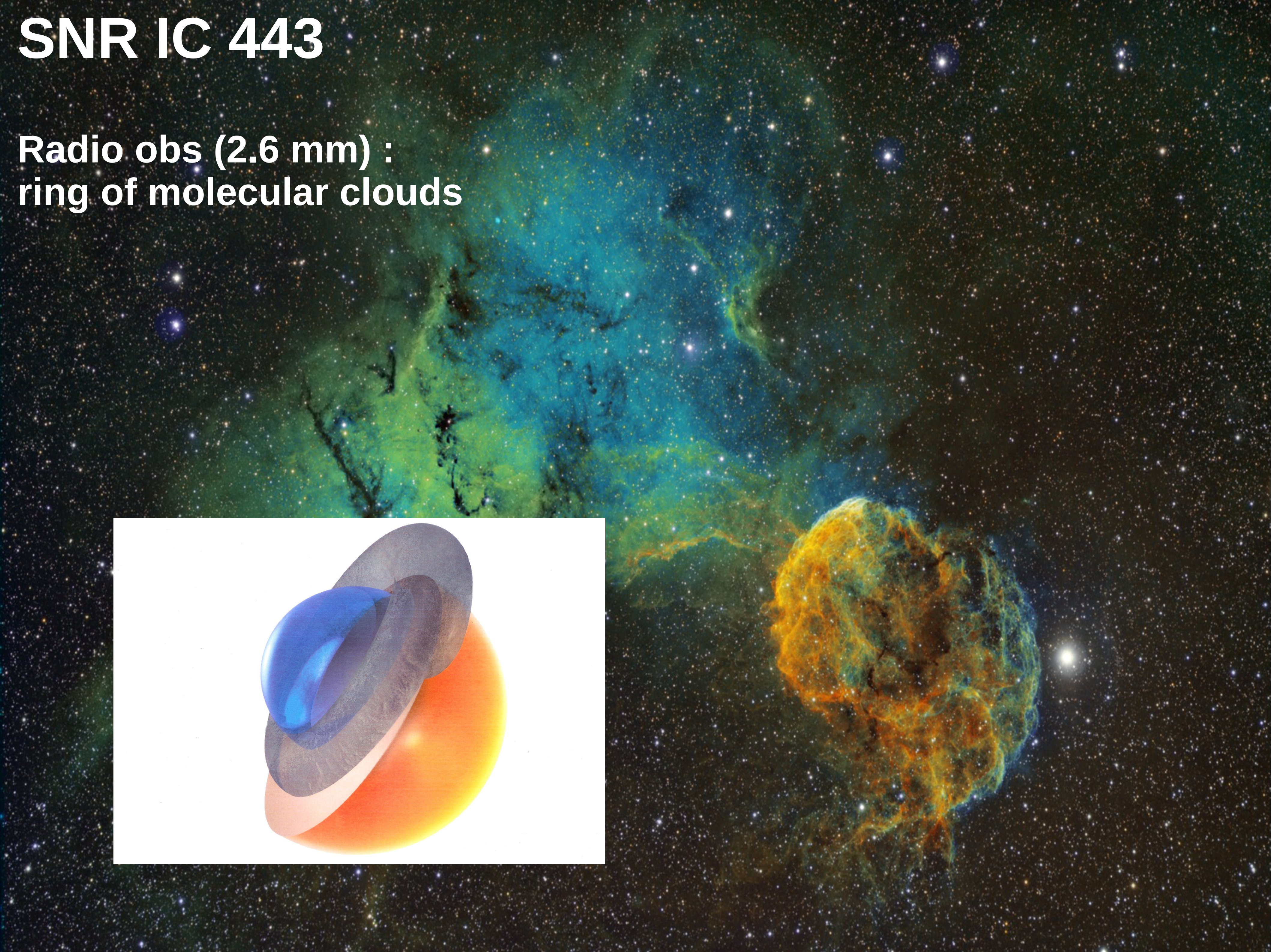


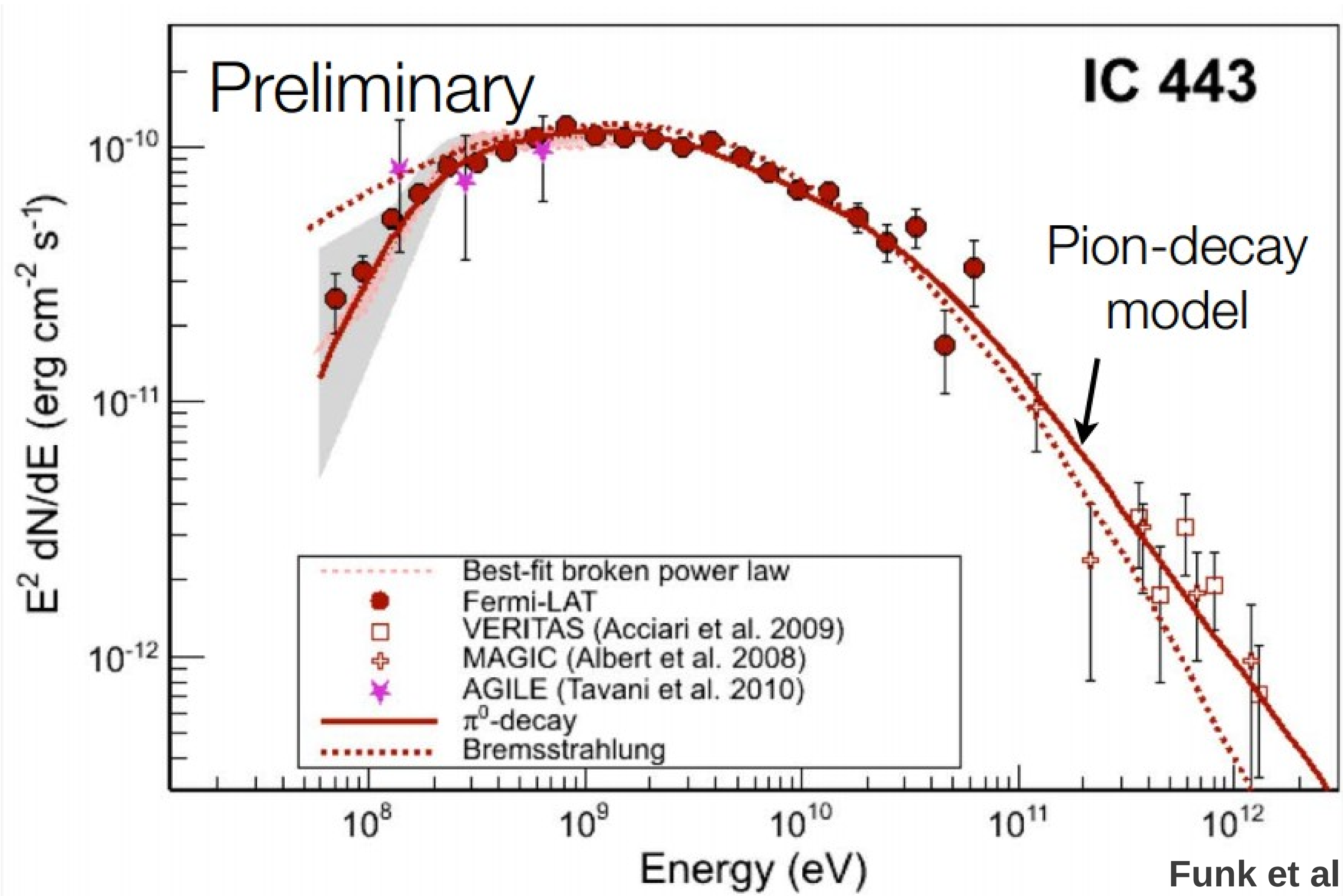


(Seta, M., et al., 1998. ApJ)

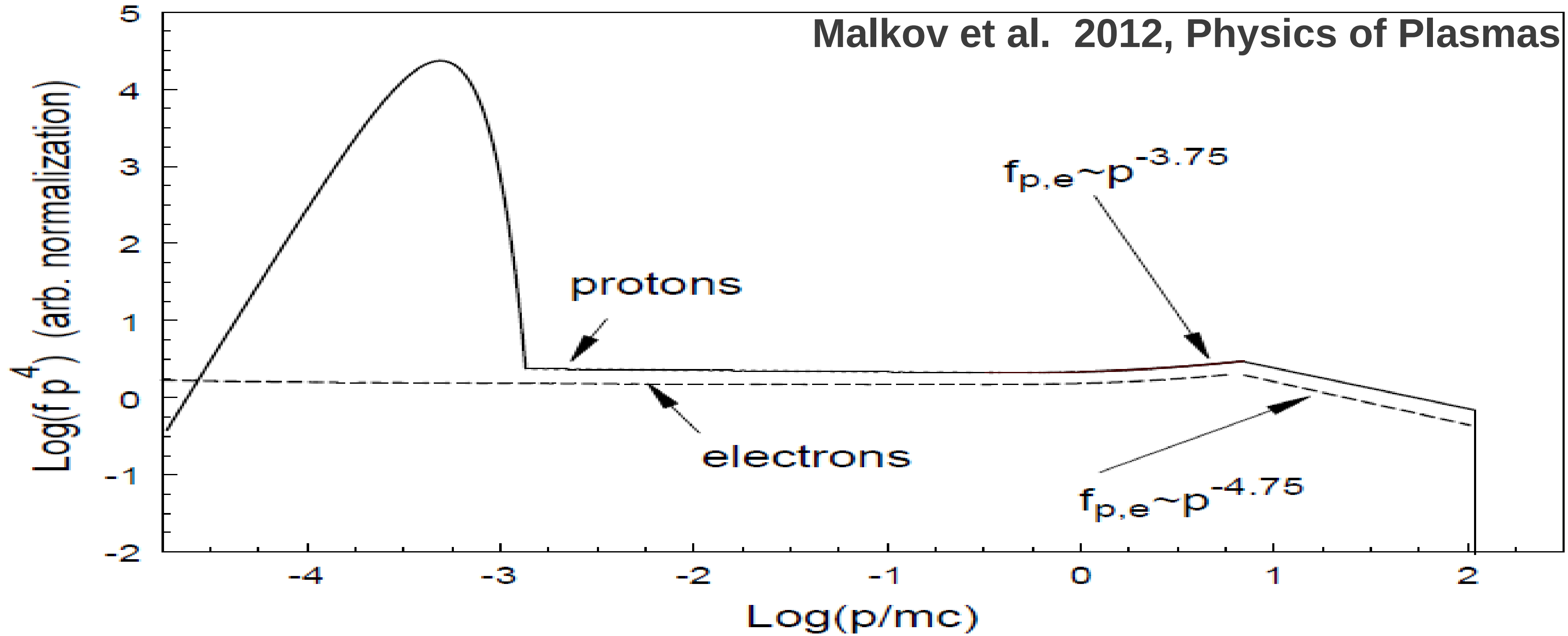
SNR IC 443

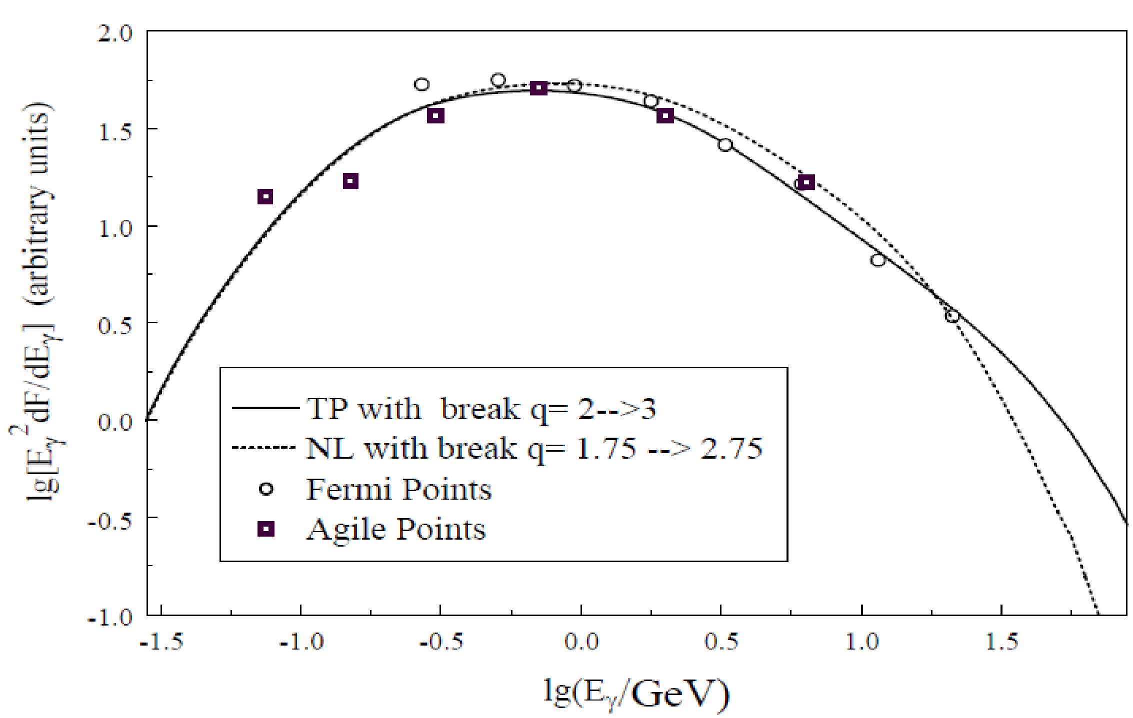
**Radio obs (2.6 mm) :
ring of molecular clouds**





Funk et al. 2013



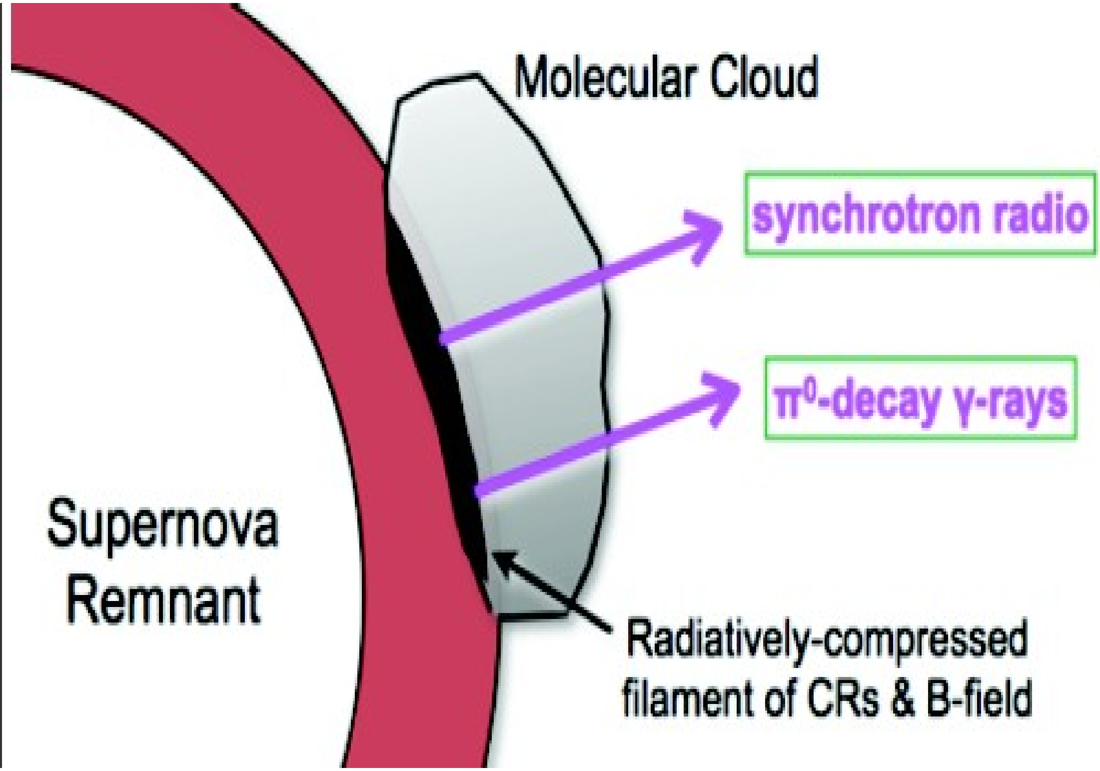


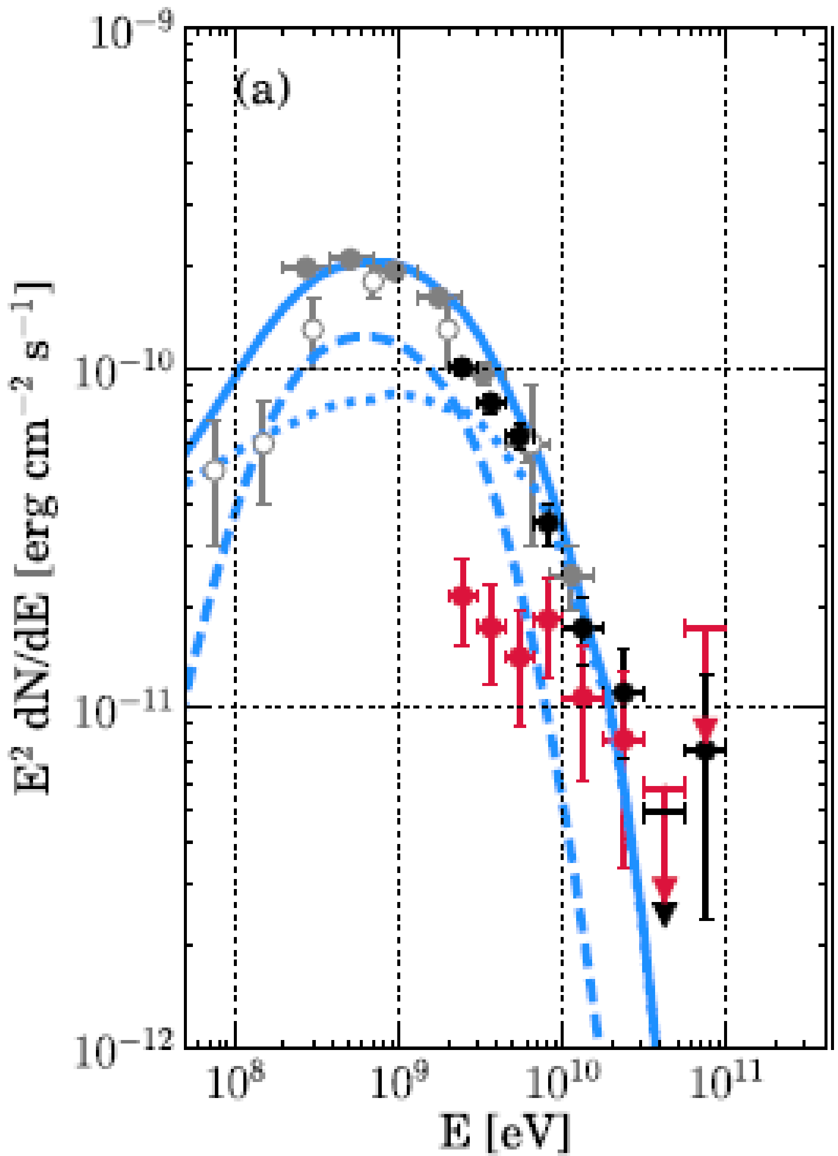
Ion-neutral collisions in the remnant surrounding lead to the steepening of the energy spectrum of accelerated particles by exactly one power.

The spectral break is caused by a partial evanescence of Alfven waves that
confine particles to the accelerator.

Crushed Molecular Clouds

(Uchiyama et al. 2012)

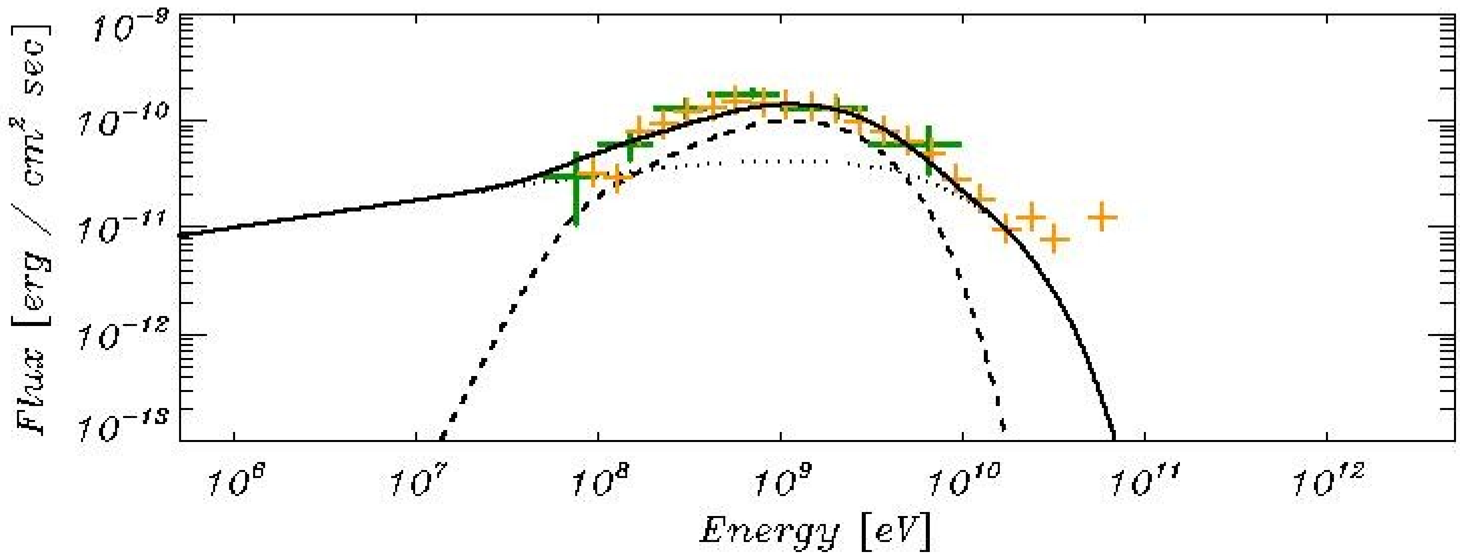




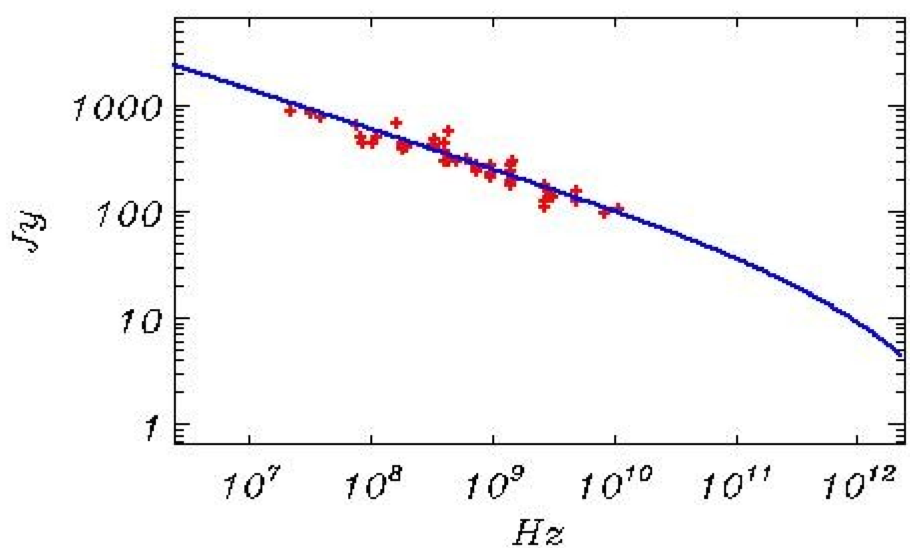
$n_{e,p}(p) = k_{e,p}\ p^{-1.74} \exp(-p/p_c)$

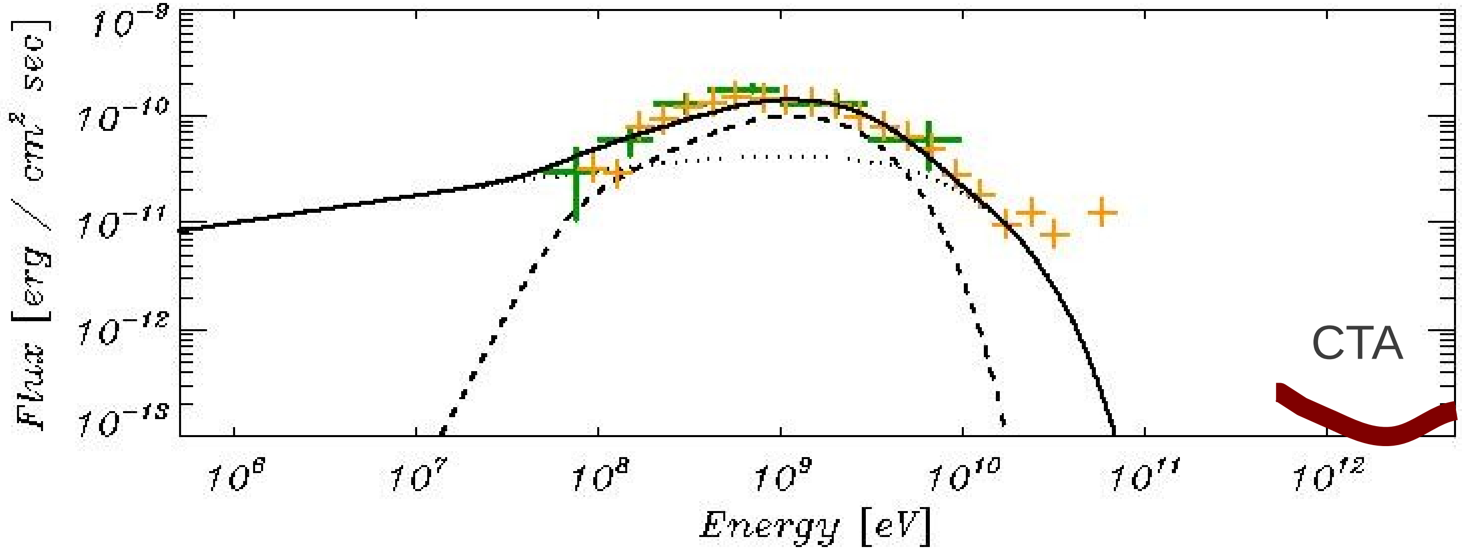
$p_c = 10$ GeV c^{-1}

$n \simeq 7\ 10^3$ cm^{-3}
B $\simeq$ 800 microG



B : 700.000
n : 7000
E_c : 13000.0
kp : 2.68141e+16
k : 2.96758e+08
p_1 : 1.74000
p_2 : 12
p : 1.74000
E_{cl} : 2500.00





B : 700.000
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E_c : 13000.0
kp : 2.68141e+16
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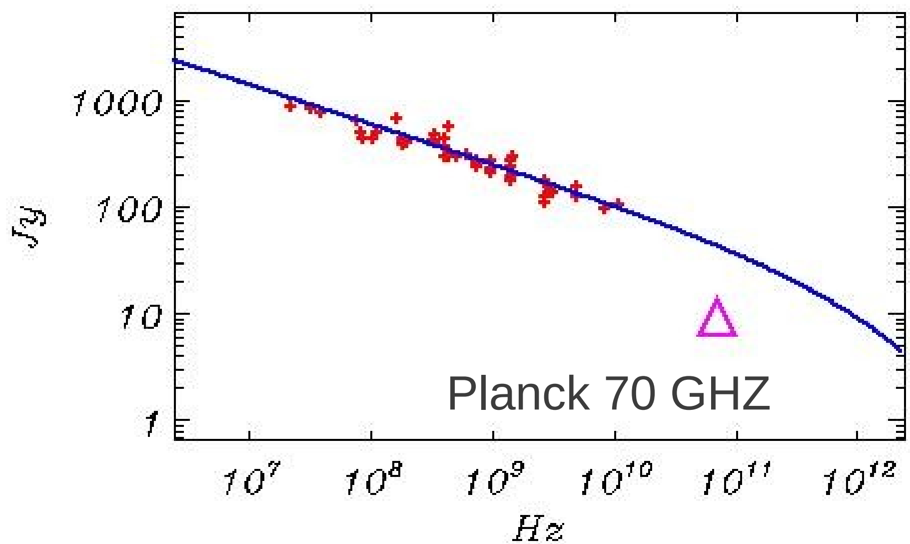
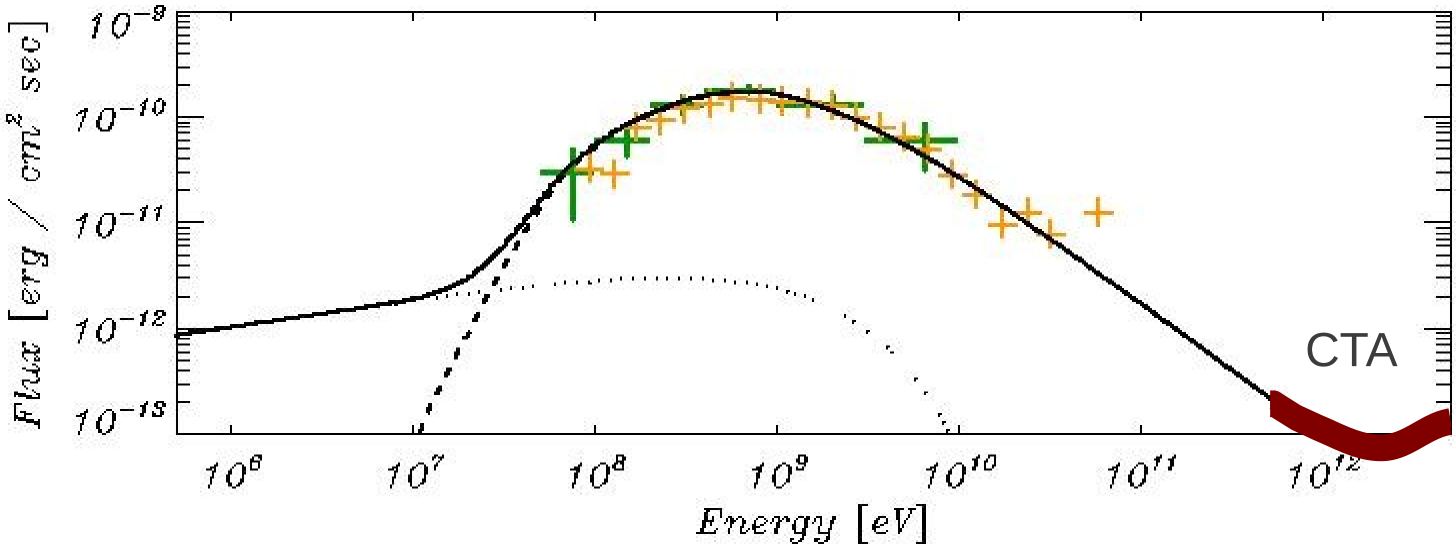
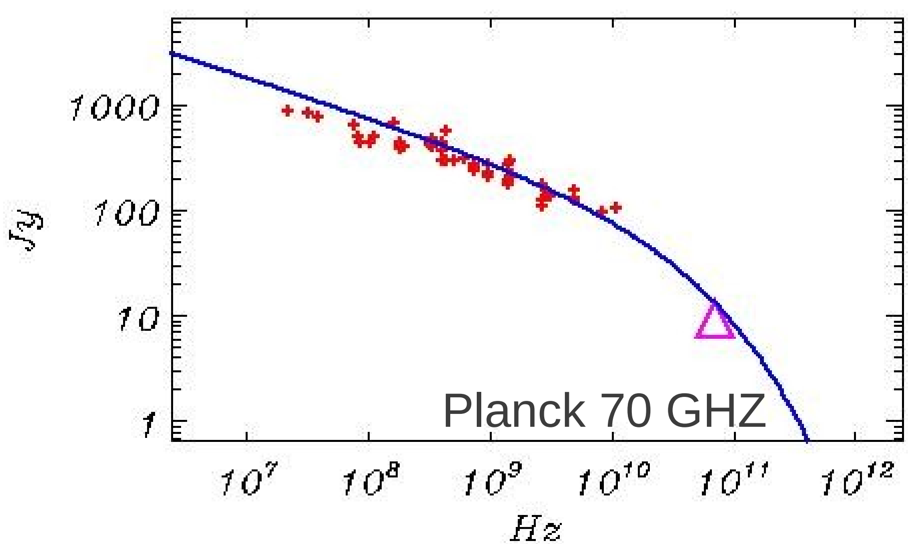
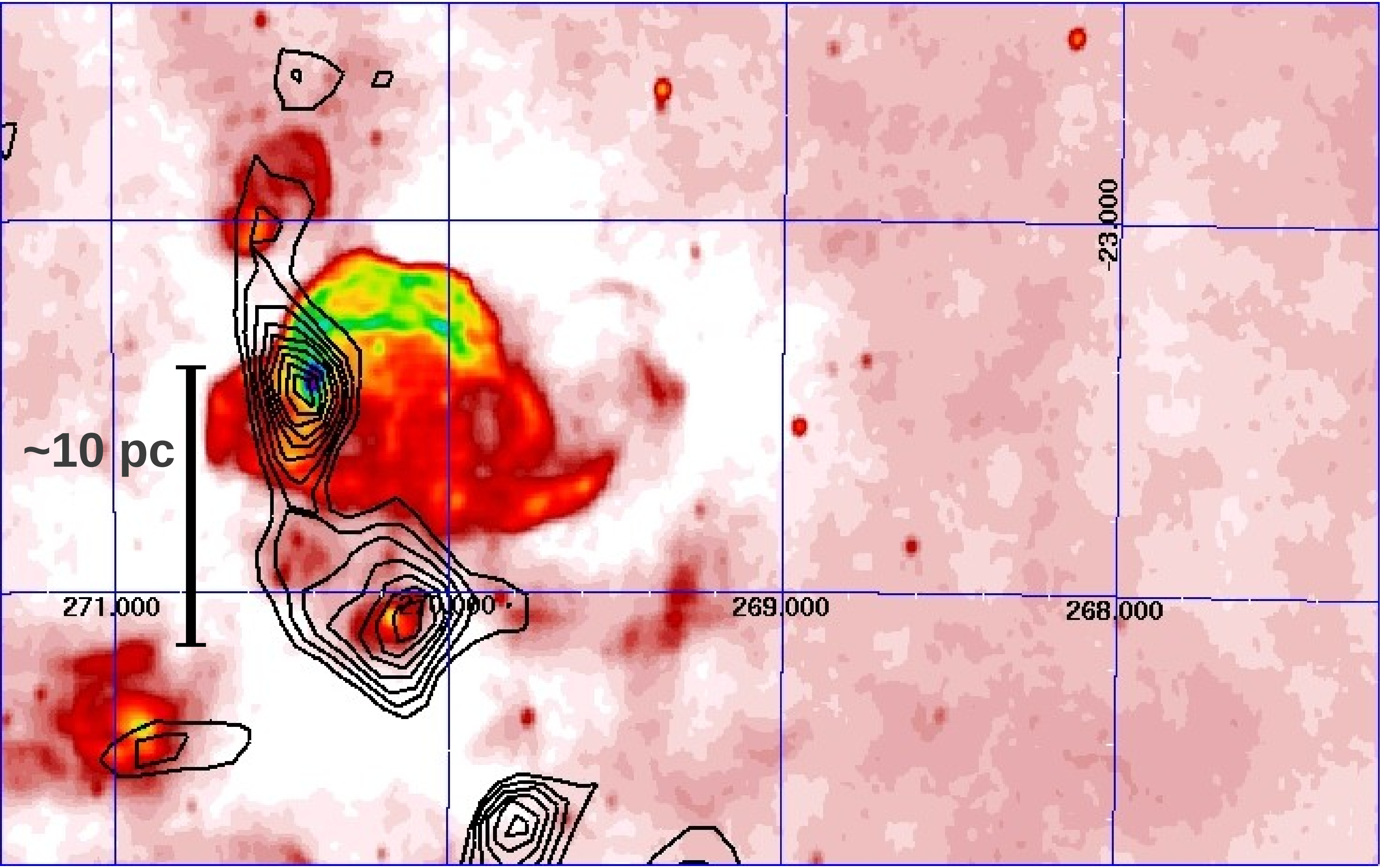




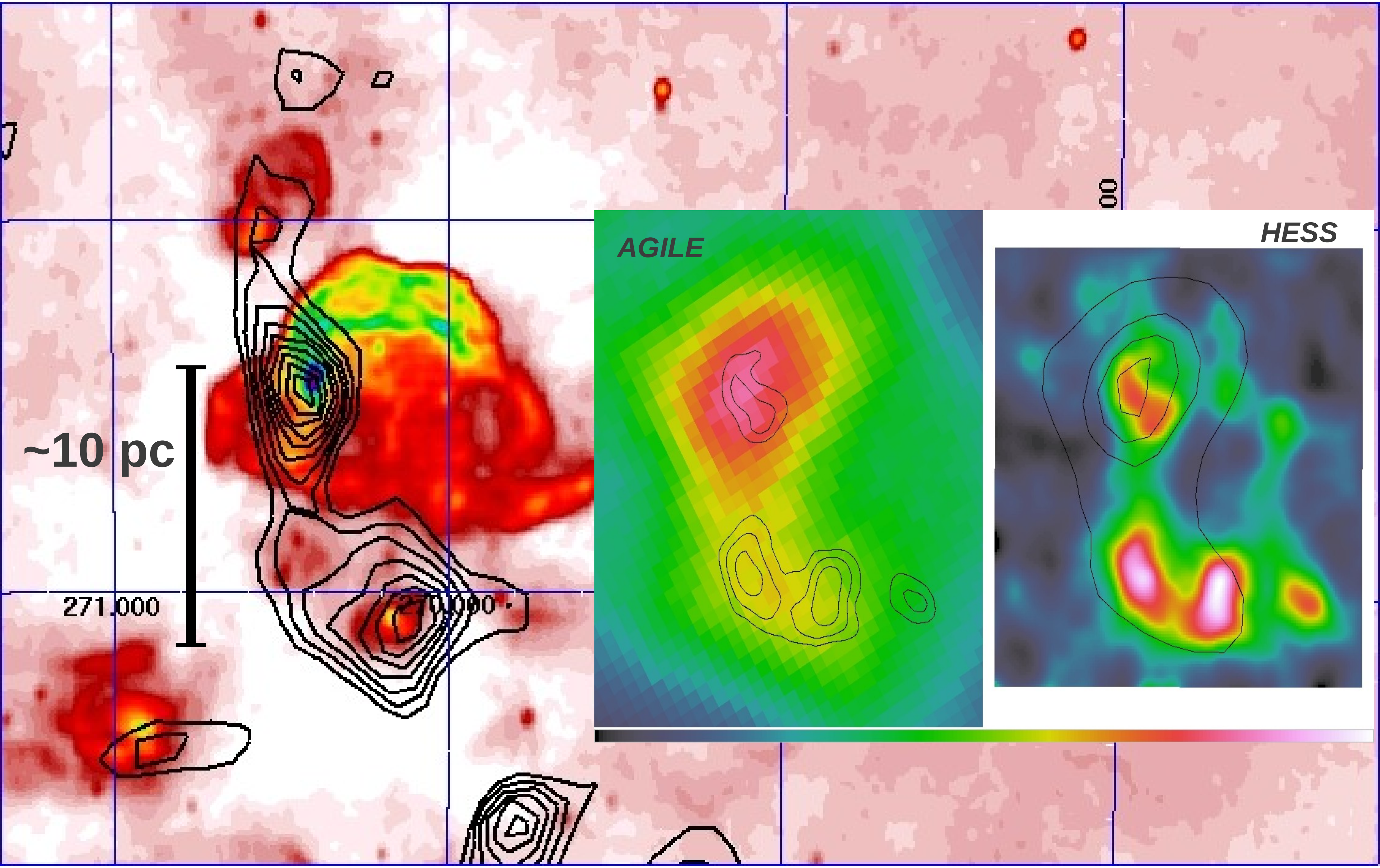
B : 200.000
n : 100
E_c : 3000
kp : 2.41619e+25
k : 2.76314e+10
p_1 : 1.74000
p_2 : 12
p : 3.50000
E_{cl} : 2500.00



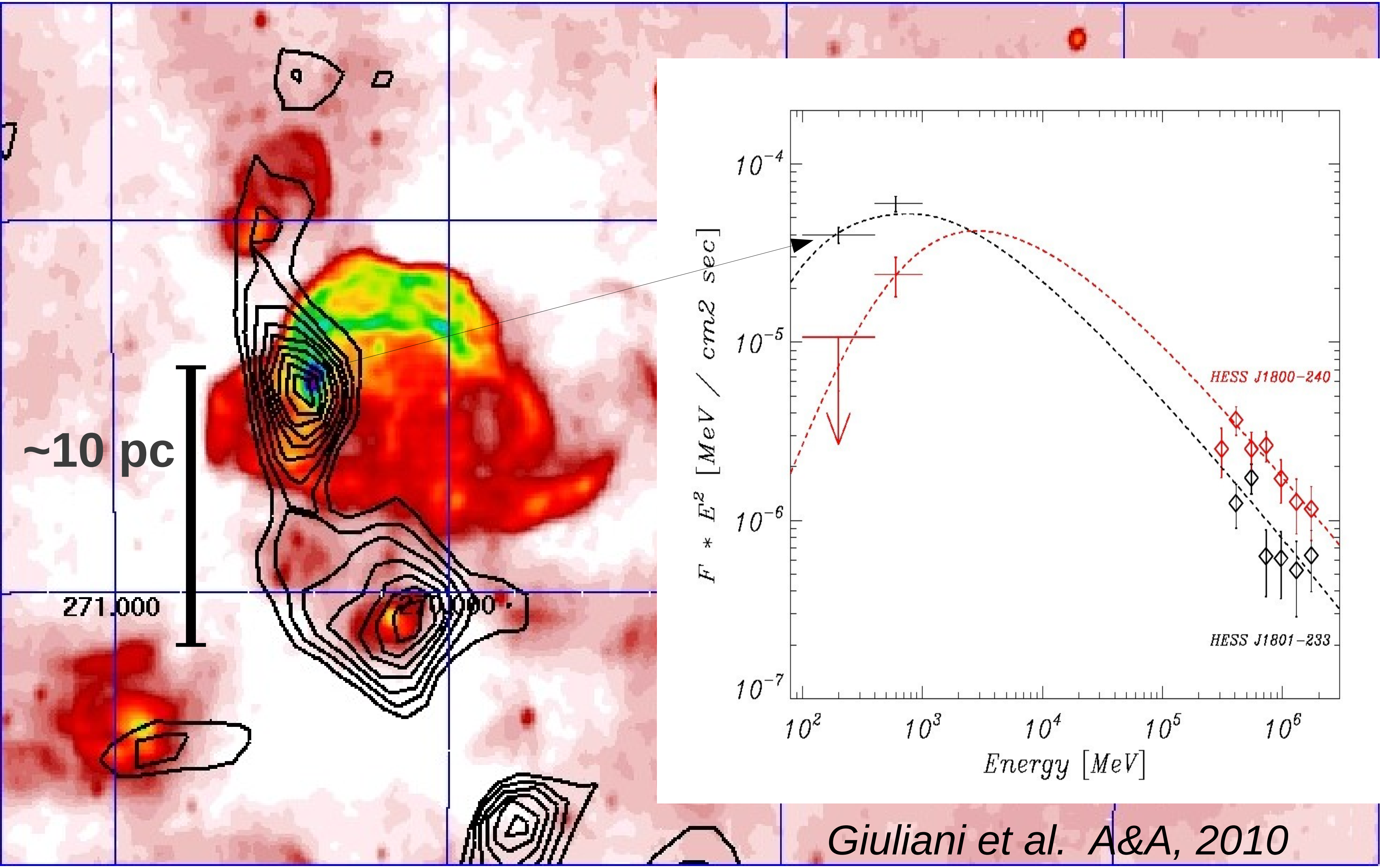
SNRs at “low” energy : diffusion of CRs (W28)



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

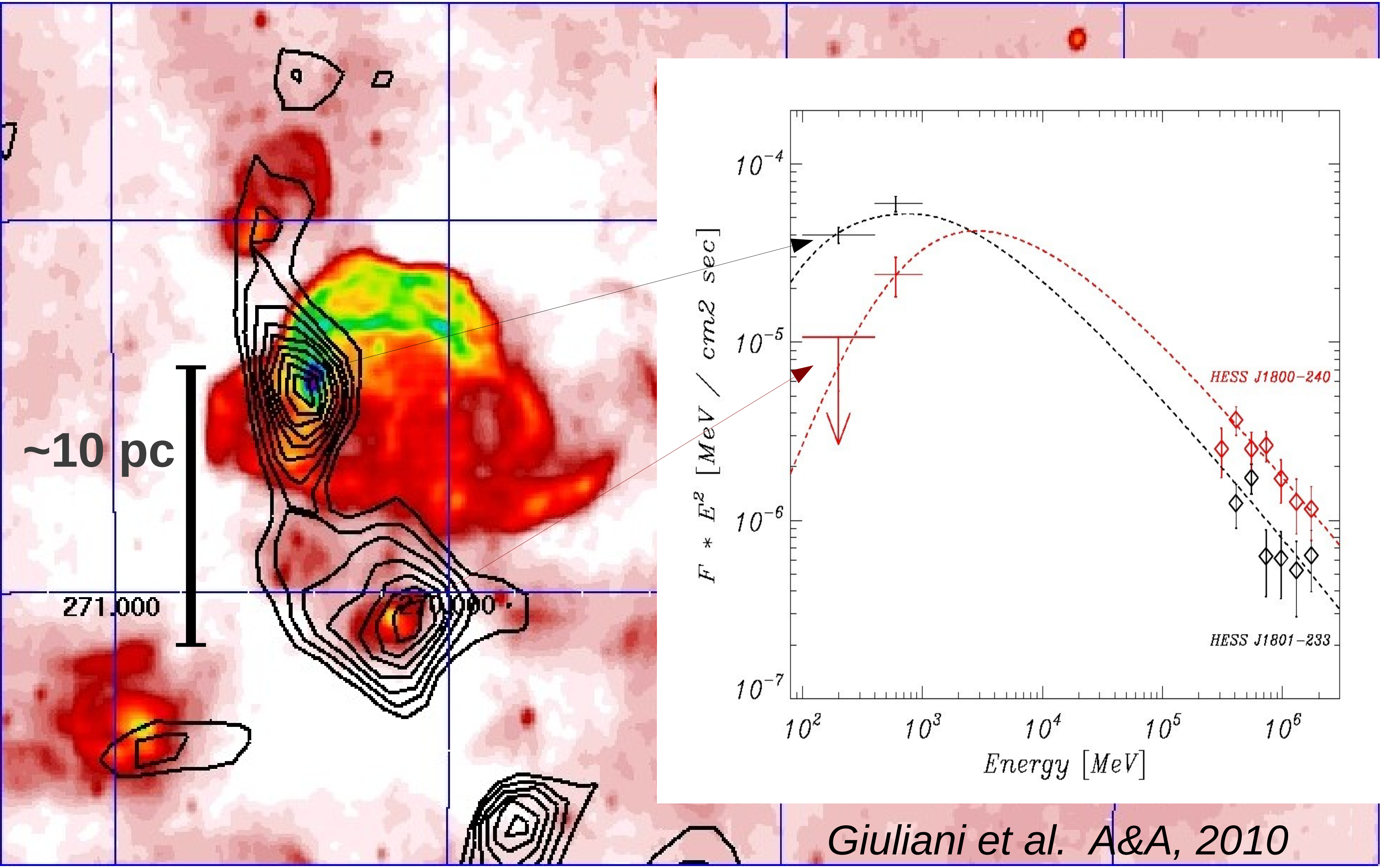


SNRs at “low” energy : diffusion of CRs



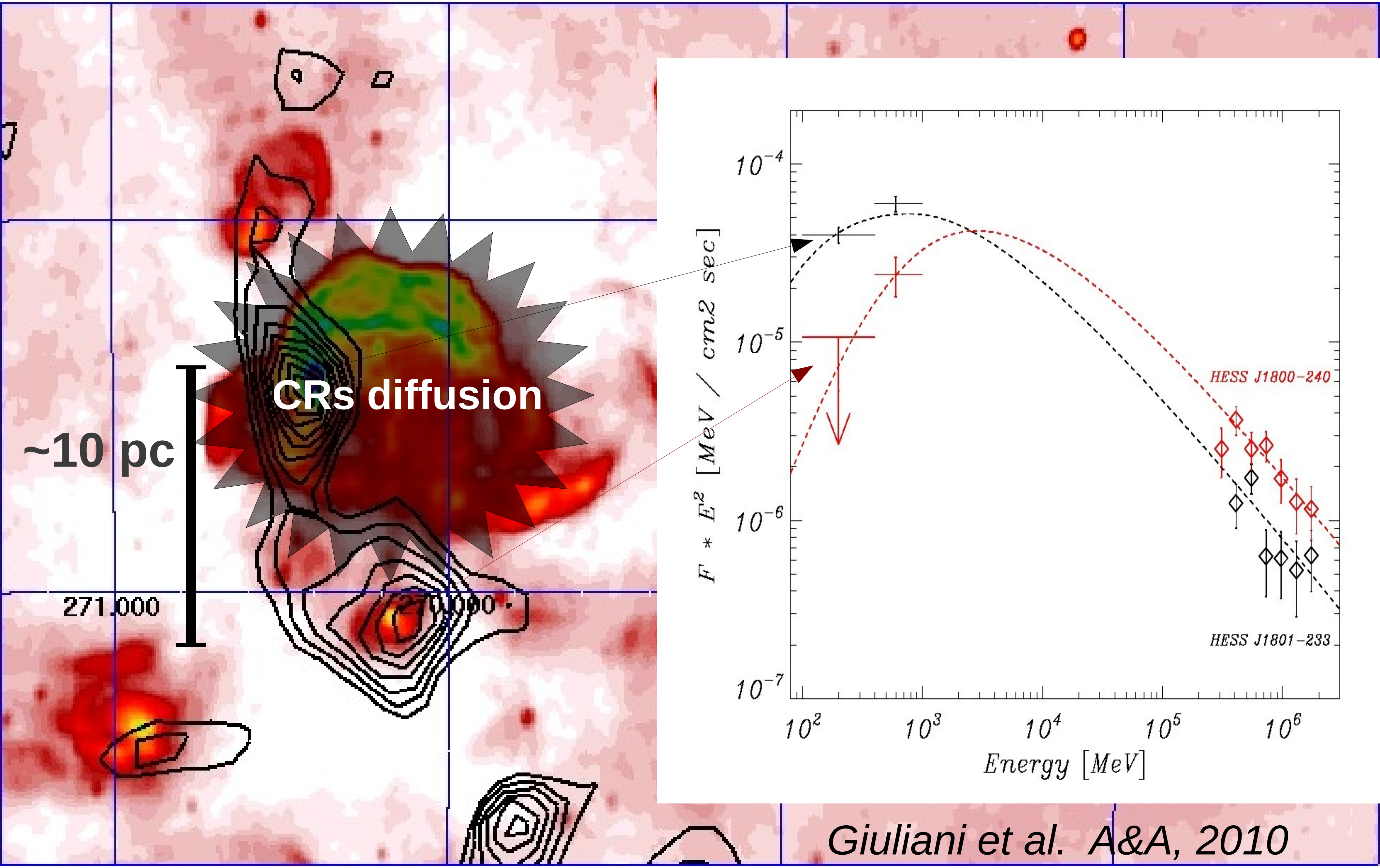
Giuliani et al. A&A, 2010

SNRs at “low” energy : diffusion of CRs



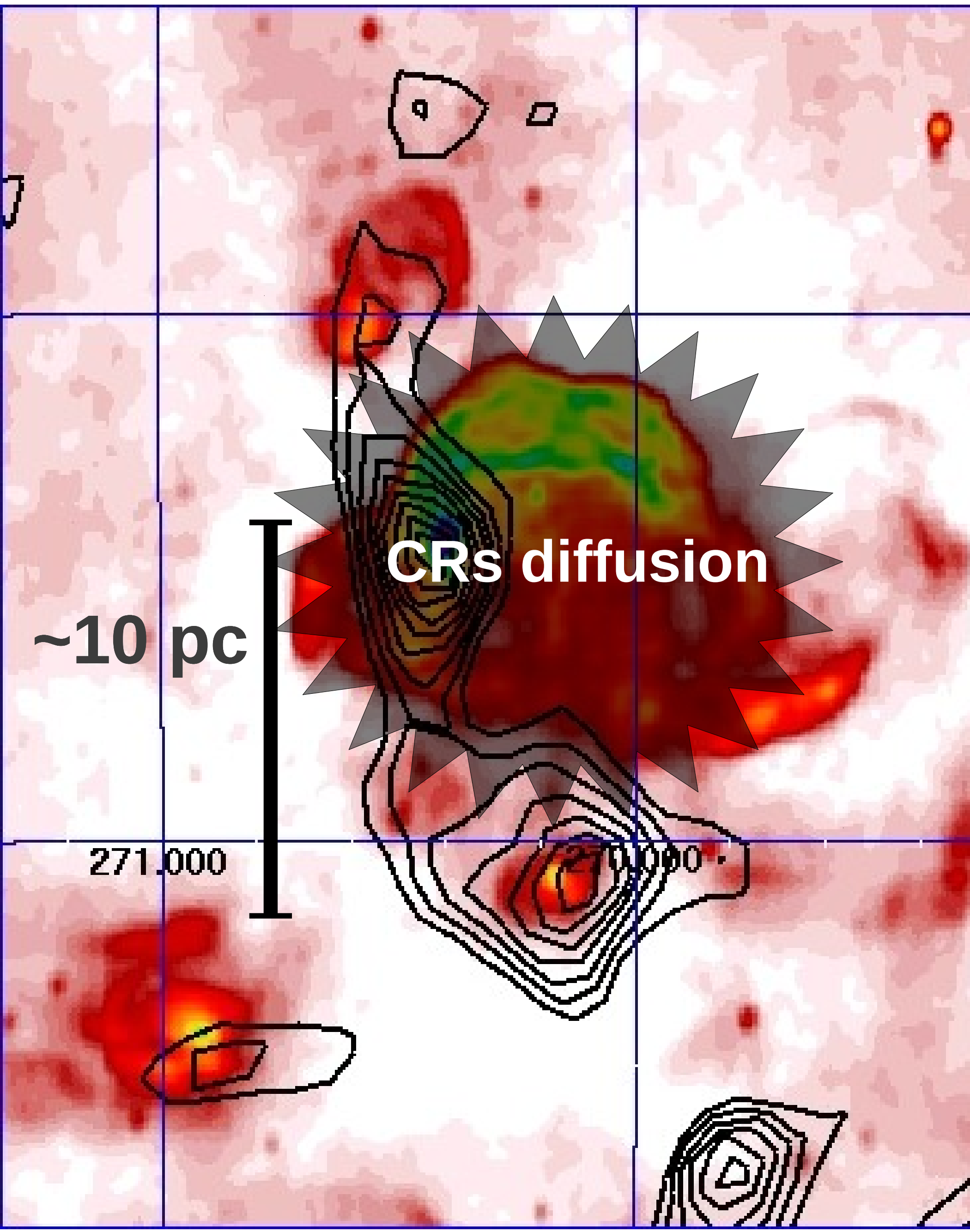
Giuliani et al. A&A, 2010

SNRs at “low” energy : diffusion of CRs



Giuliani et al. A&A, 2010

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 GeV)$^{0.5}$) :

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

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

Giuliani et al. A&A, 2010

Summary

° 2 classes : young and m.a. interacting with mol. clouds

° Protons have been found in SNRs ! (al least in m.a. SNRs...)

° Very soft spectrum with break @ GeV

° Not trivial interpretation of the spectrum

→ Need for new radio and gamma-rays data (CTA, Gamma 400)