Supernova Remnants in the H.E.S.S. II era

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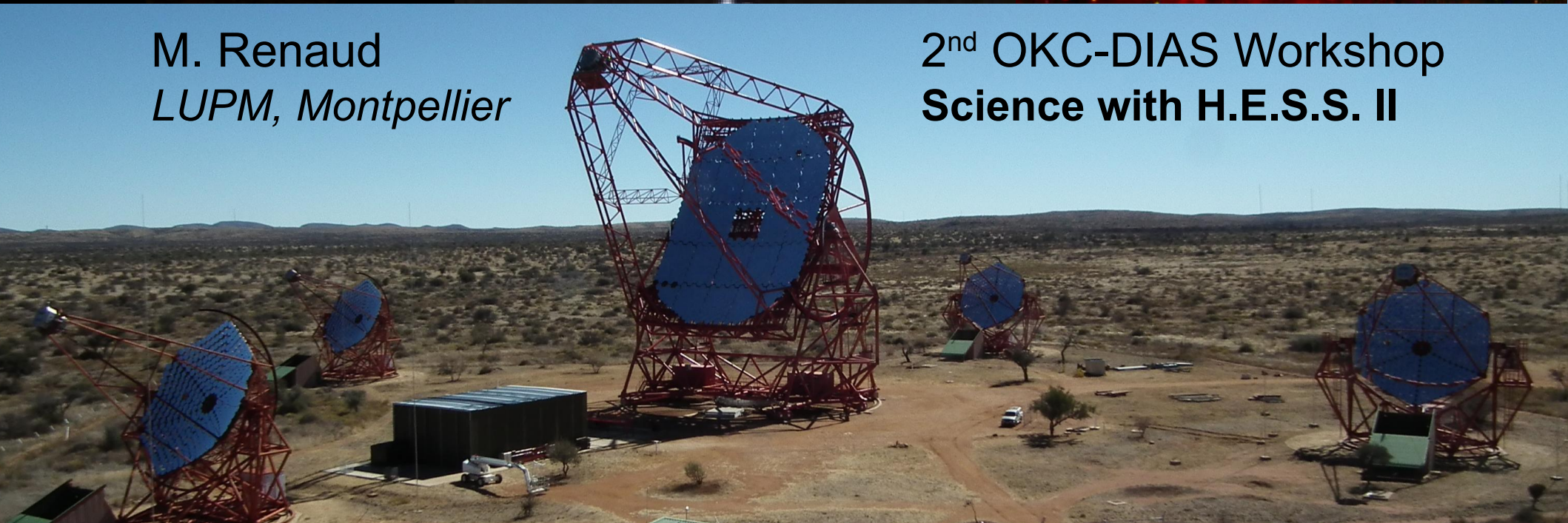
LUPM, Montpellier

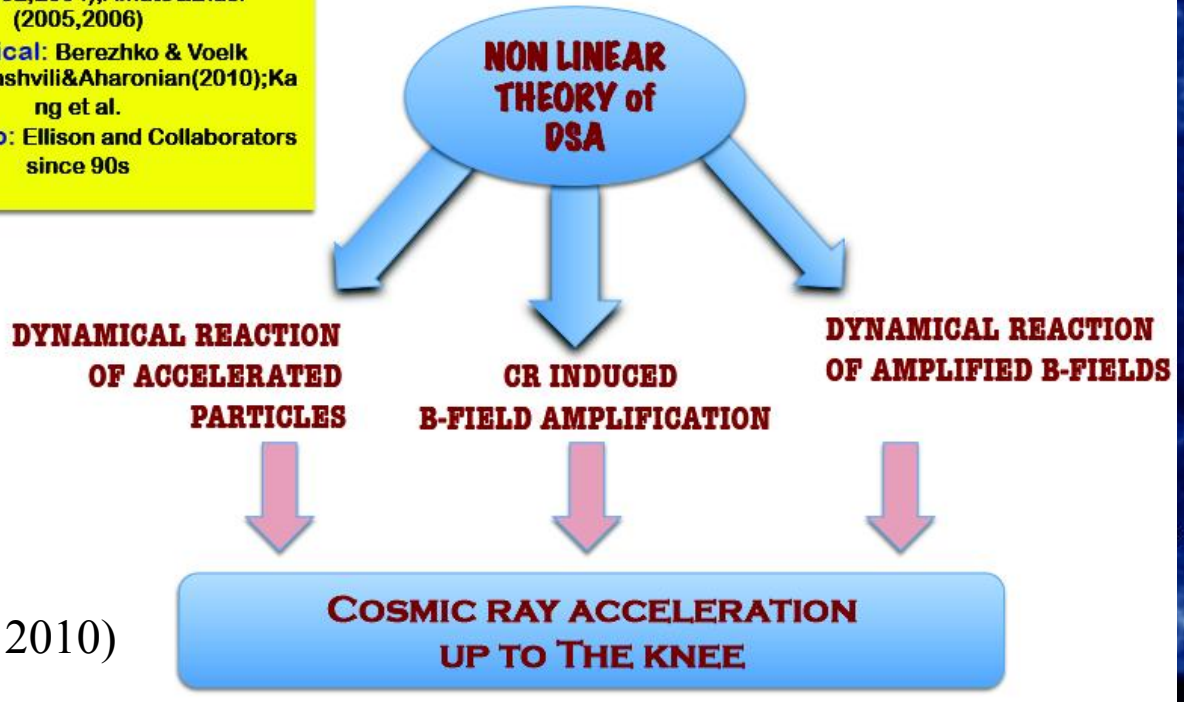
2nd OKC-DIAS Workshop
Science with H.E.S.S. II



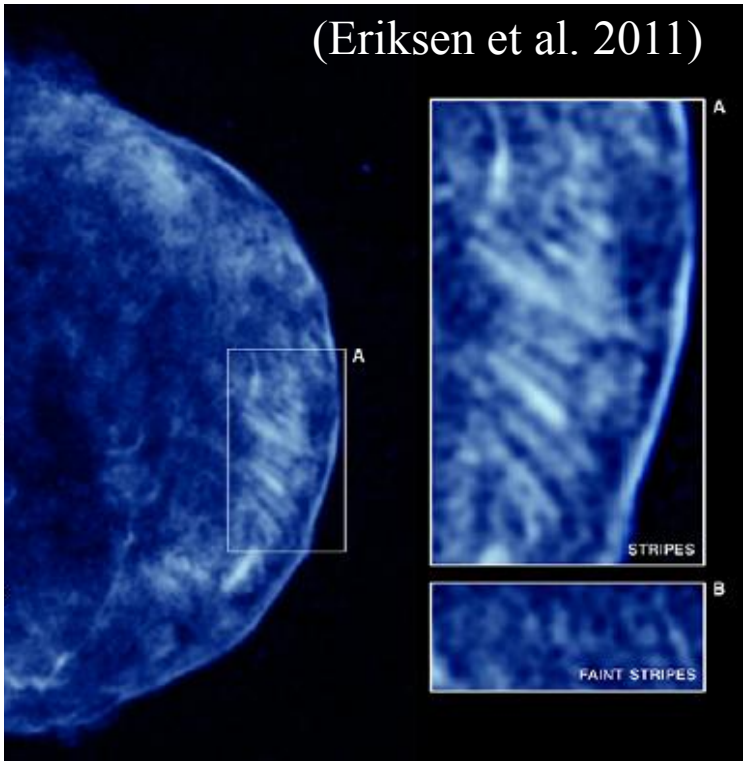
SNRs and the sources of Galactic CRs

Galactic CR luminosity = $L_{CR} \sim 10^{41}$ erg/s → $\eta_{CR} \sim 0.1 \times (R_{SN}/0.03\ \mathrm{yr}^{-1}) \times (10^{51}\ \mathrm{erg}/E_{SN})$

Analytical: Malkov(1997,1999), Blasi(2002,2004),Amato&Blasi (2005,2006)
Numerical: Berezhko & Voelk (1997),Zirakashvili&Aharonian(2010);Kang et al.
MonteCarlo: Ellison and Collaborators since 90s



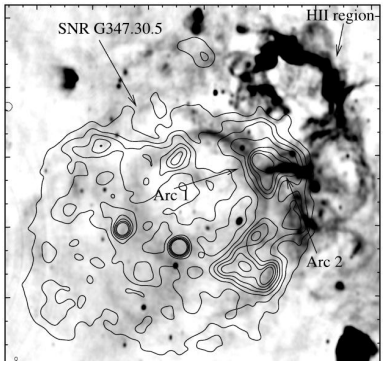
(Blasi 2010)

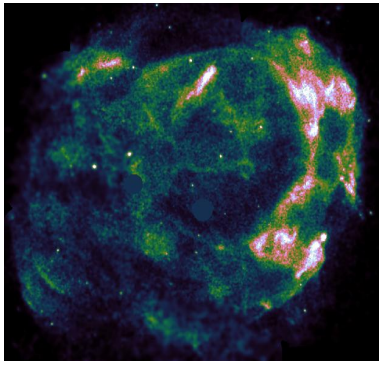


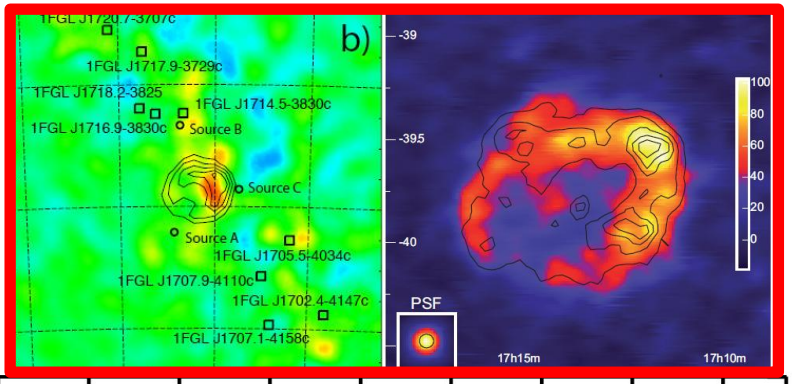
Successes of the NLDSA theory towards the CR origin in SNRs (Helder et al. 2012)

- Reduced heating (larger r, lower T_{down}) & Shock modification (precursor, r_{BW}/r_{CD}, concavity)
- X-ray filaments & knots → B > 100 μG (e.g. Völk et al. 2005, Bamba et al. 2005)
- Maximum energy → $E_{max} \sim E_{knee}$ (Blasi et al. 2007, Eriksen et al. 2011, Bell et al. 2013)
- Balmer-dominated shocks → high P_{CR} (e.g. RCW 86, Helder et al. 2009, 2013)

SNRs at HE/VHE gamma-rays







RX J1713.7-3946

Leptons (SC+IC)

Hadrons ($p\text{-}p \rightarrow \pi^0 \rightarrow 2\gamma$)

100 MeV – 100 TeV gamma-rays

Direct evidence for **GeV – PeV (e,p)** being accelerated at the shock fronts

$E^2\, dN/dE$ (erg cm^{-2} s^{-1})

10^{-10}

10^{-11}

10^{-12}

10^{-13}

(Lazendic et al. 2004; Aharonian et al. 2007, 2011; Tanaka et al. 2008; Acero et al. 2009; Abdo et al. 2011)

Energy (keV)

10^{-5} 10^{0} 10^{5} 10^{10}

SNRs at HE/VHE gamma-rays

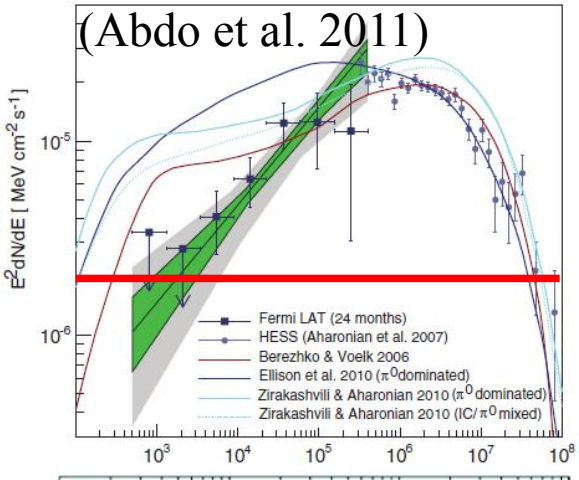
- GeV-hard TeV-bright young SNRs
(RX J1713, Vela Jr, RCW 86, HESS J1731?) :
Leptonic-like shape ⇏ not an efficient CR source

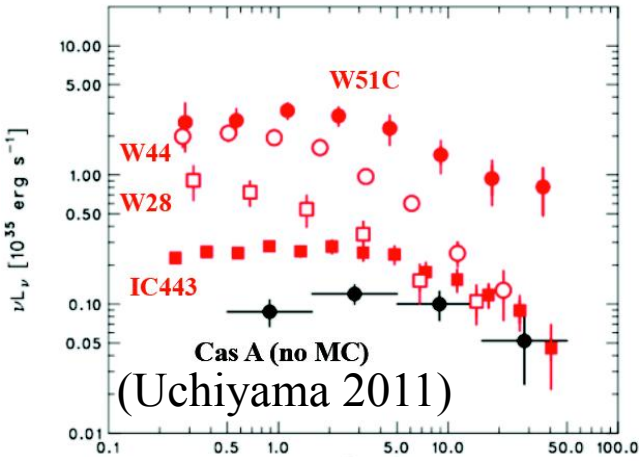
$\eta_{CR} \sim 0.3$, $n = 0.1 cm^{-3}$ still compatible...
→ efficient CR source ≠ hadronic γ-rays

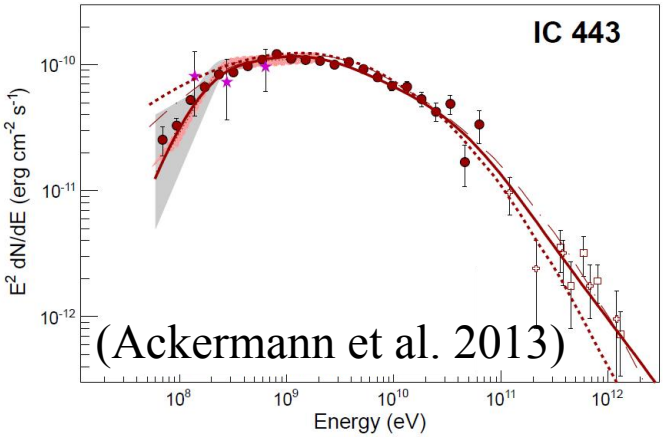
- GeV/TeV-faint « historical » SNRs
(Cas A, Tycho, SN 1006?) :
Hadronic-like shape ⇏ efficient CR source

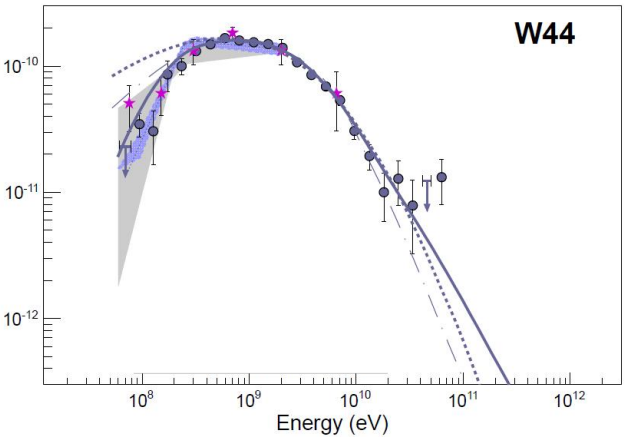
- GeV-bright TeV-soft SNRs, interacting with MCs
(W44, W51C, IC443, W49B...) :
Hadronic-like shape ⇏ efficient CR source...

...But recent detection of the « π^0 bump » → smoking-gun of the hadronic signal!
(Giuliani et al. 2011,
Ackermann et al. 2013)

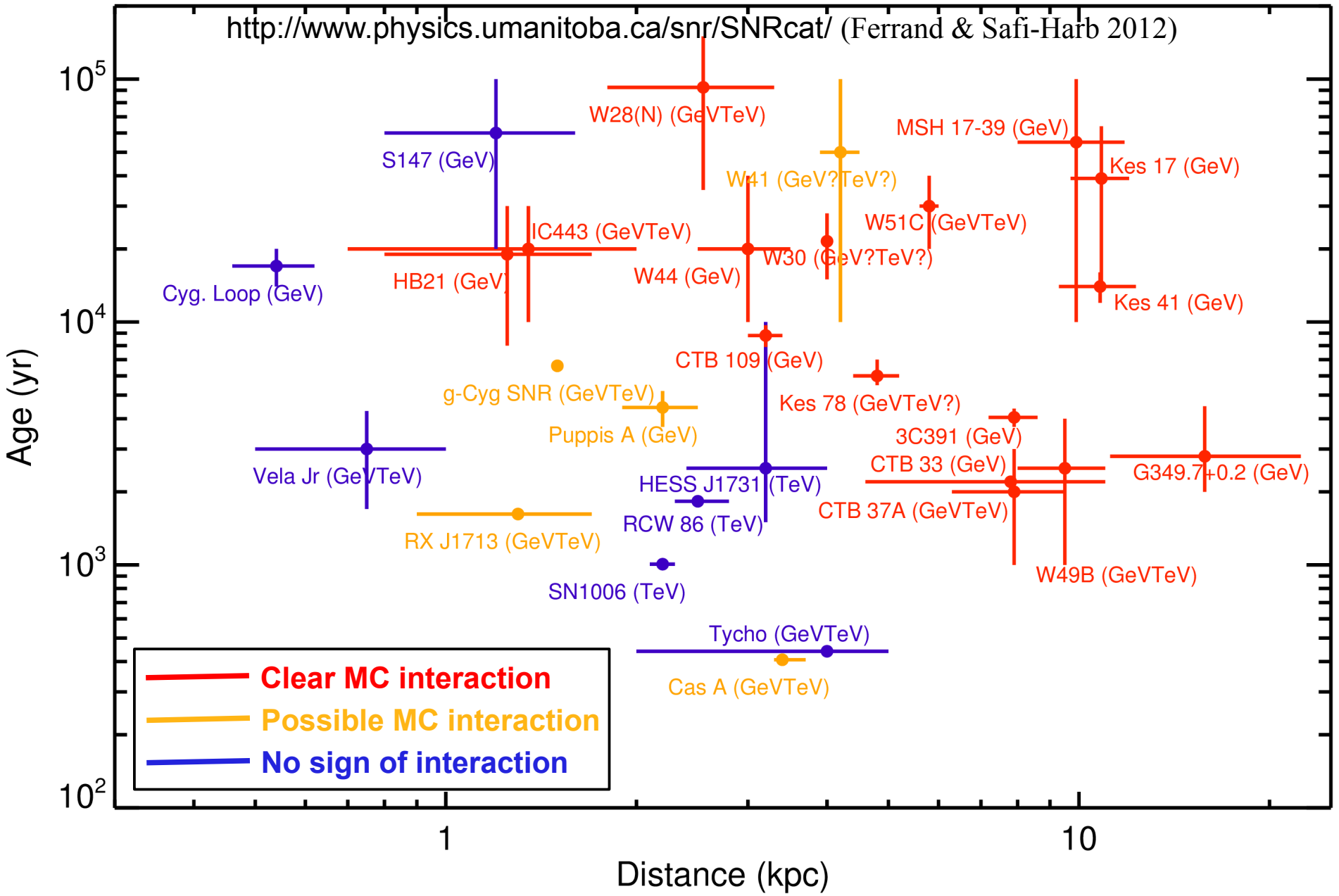








SNRs at HE/VHE gamma-rays



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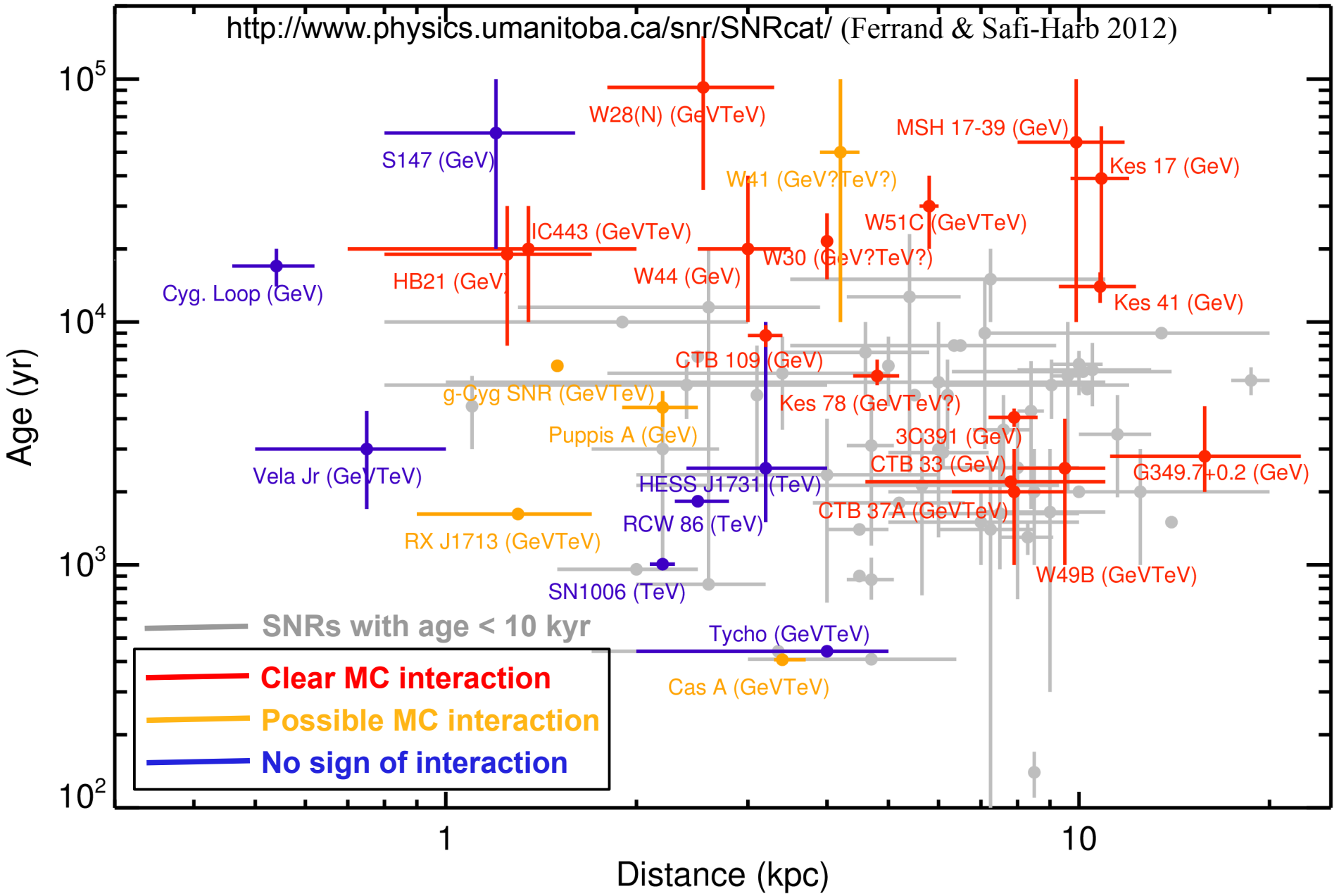

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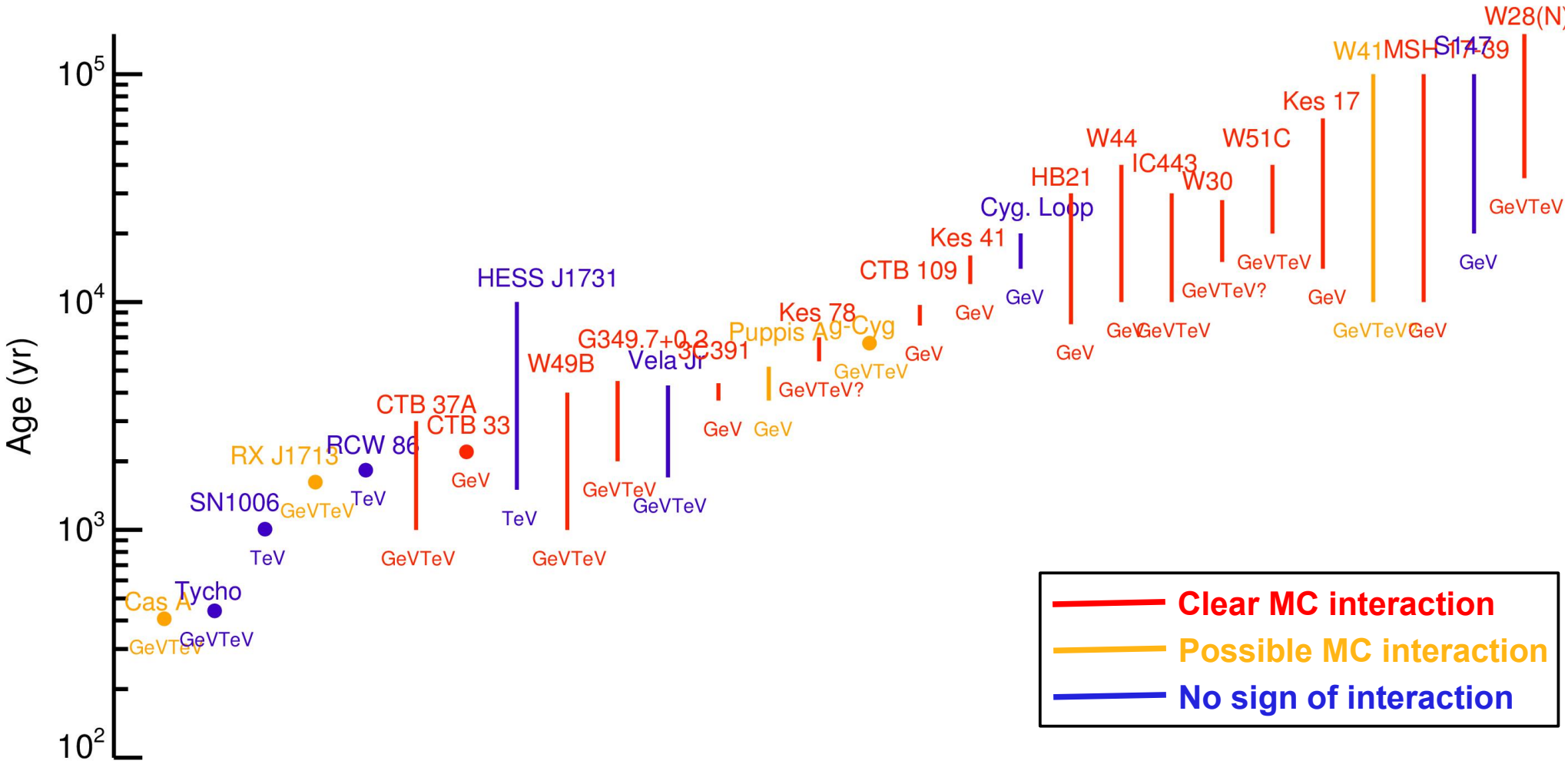

Emission towards *SNRs in « isolation »*, with clear shell-type morphology
→ naturally associated with SNR shells

Emission towards *SNRs in crowded fields*, with no clear shell-type morphology
→ identification more difficult, sometimes doubtful

SNRs at HE/VHE gamma-rays

Several statistical studies of gamma-ray emitting SNRs have been carried out

γ-ray-bright Supernova Remnants					
Coordinates	SNR	Age(kyr)	α_{GeV}	α_{TeV}	Refs.
6.4−0.1	W28 North	35–45	2.09±0.08	2.66±0.27	[14, 31–34]
	W28 A,B,C	35–45	2.19±0.14	2.50±0.20	[14, 31, 32]
8.7−0.1	W30	10–50	2.4±0.07	2.72±0.06	[14, 35–38]
31.9+0.0	3C 391	4	2.33±0.11		[35]
34.7−0.4	W44	15	2.06±0.03		[14, 39]
43.3−0.2	W49B	1–4	2.18±0.04	3.1±0.3	[40]
49.2−0.7	W51C	10–20	1.7±0.3		[14, 41–43]
106.3+2.7		10		2.29±0.33	[14, 34, 44]
119.5−2.1	Cas A	0.330	2.01±0.1	2.3±0.2	[14, 45–47]
120.1+1.4	Tycho	0.438	2.3±0.1	1.95±0.50	[14, 48, 49]
189.1+3.0	IC443	30	1.93±0.03	3.05±0.40	[14, 34, 43, 50–54]
205.5+0.5	Monoceros	30–150		2.53±0.26	[14, 34, 55]
266.2−1.2	Vela Jr.	0.6–4		2.24±0.04	[56, 57]
315.4+2.3	RCW 86	1.825		2.41±0.16	[58]
327.6+14.6	SN1006 NE	1.004		2.54±0.15	[59]
	SN1006 SW	1.004		2.34±0.22	[59]
347.3−0.5	RX J1713.7-3946	1.6	1.5±0.1	2.04±0.04	[4, 60–63]
348.5+0.1	CTB 37A	1.617	2.19±0.07	2.30±0.13	[14, 35, 64]
348.7+0.3	CTB 37B	2.7–4.9		2.65±0.19	[64]
349.7+0.2		2.8	2.10±0.11		[35]
353.6−0.7	HESS J1731-347	27		2.26±0.10	[65, 66]
Other possible candidates					
0.0+0.0	SGR A East	8	∼2.2		[14, 36, 67]
12.8−0.0	HESS J1813-178	0.3–25		2.09±0.08	[36, 38]
21.5−0.9	HESS J1833-105	0.8–1		2.08±0.22	[68]
23.3−0.3	W41	60–100		2.45±0.16	[14, 36, 38, 69]
27.8+0.6		35–55			[34]
28.8+1.5		32			[34]
29.7−0.3	Kes 75	0.7–0.8		2.26±0.15	[68]
35.6−0.4	HESS J1858+020	30		2.2±0.1	[66, 70]
40.5−0.5	HESS J1908+063	20–40		2.08±0.10	[14, 68, 71]
54.1+0.3		2.9		2.3±0.3	[72]
65.1+0.6	0FGL J1954.4+2838	4–14			[38, 43, 73]
78.2+2.1	γ Cygni	5			[14, 34, 74]
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296.4−9.45?	HESS J1507-662	1?		2.24±0.16	[75, 76]
338.3+0.0	HESS J1640+465	20–40		2.42±0.14	[36]
343.0−0.6	RCW 114	20			[34]
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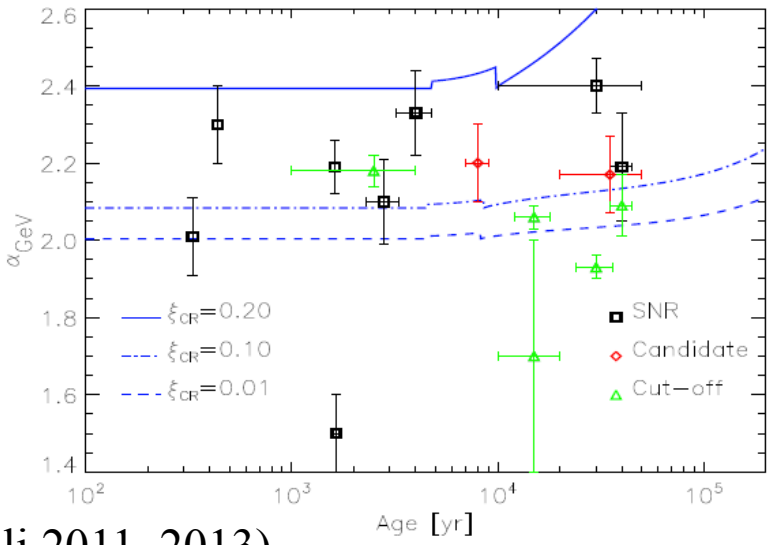
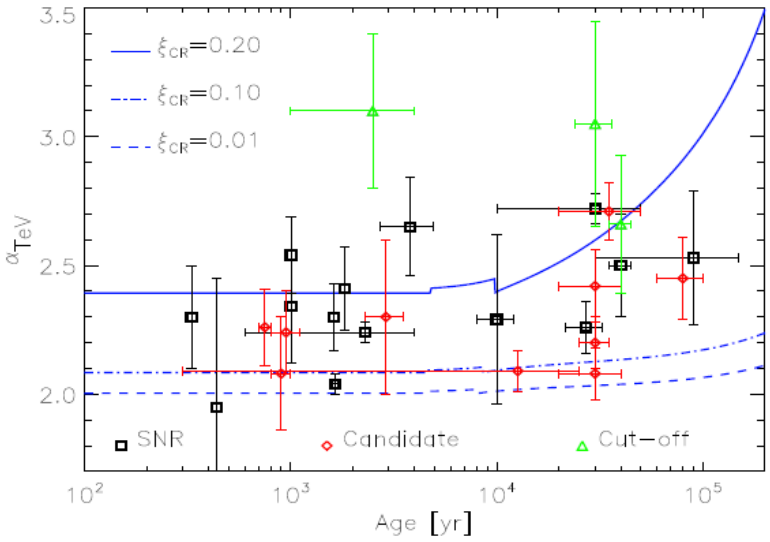


(Caprioli 2011, 2013)



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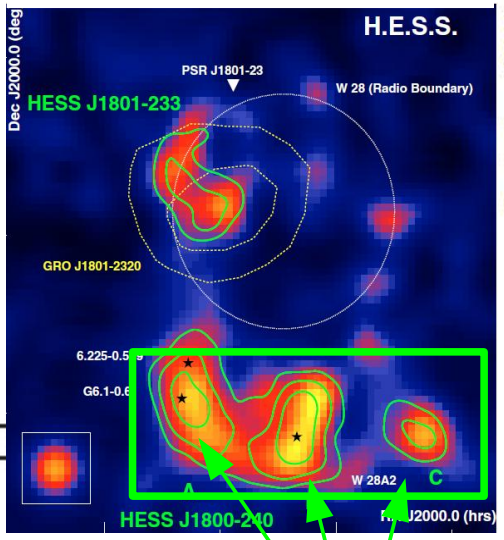
«Confused» PWNe

Others PWN candidates

(Aharonian et al. 2008)



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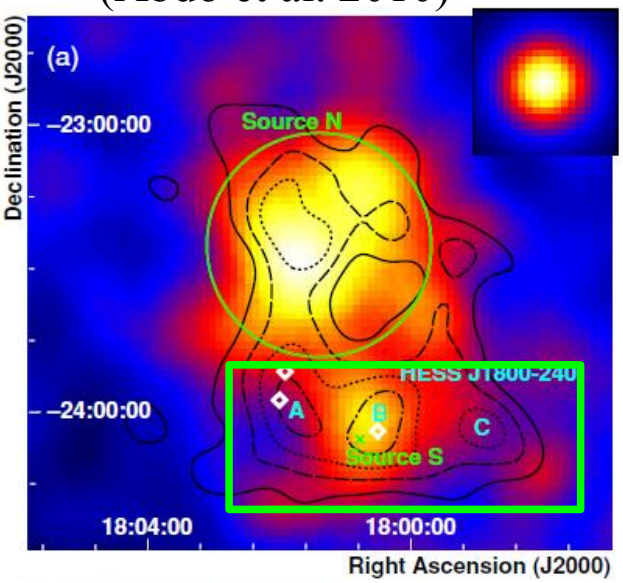

Cosmic-rays which have diffused from W28?
Other local sources (HII regions, SNRs)?

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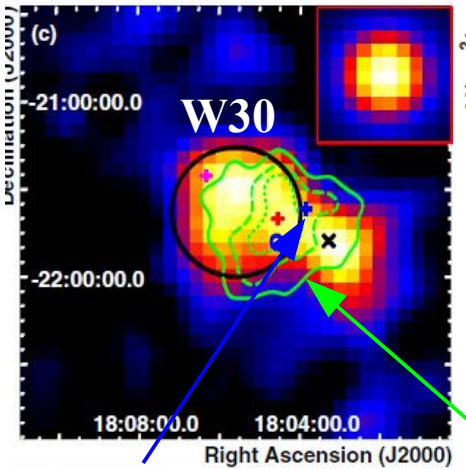
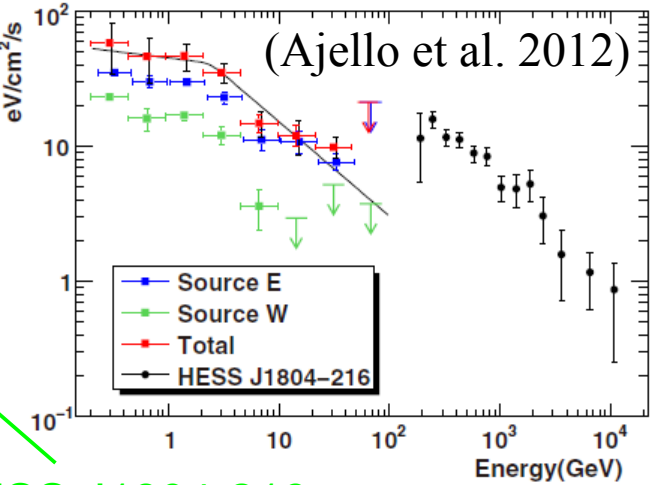
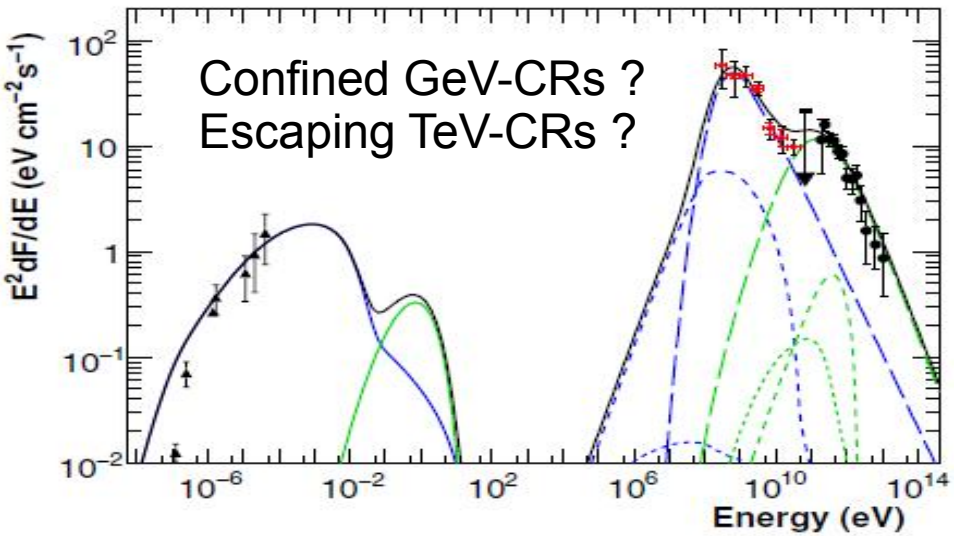




PSR J1803-2137 HESS J1804-216



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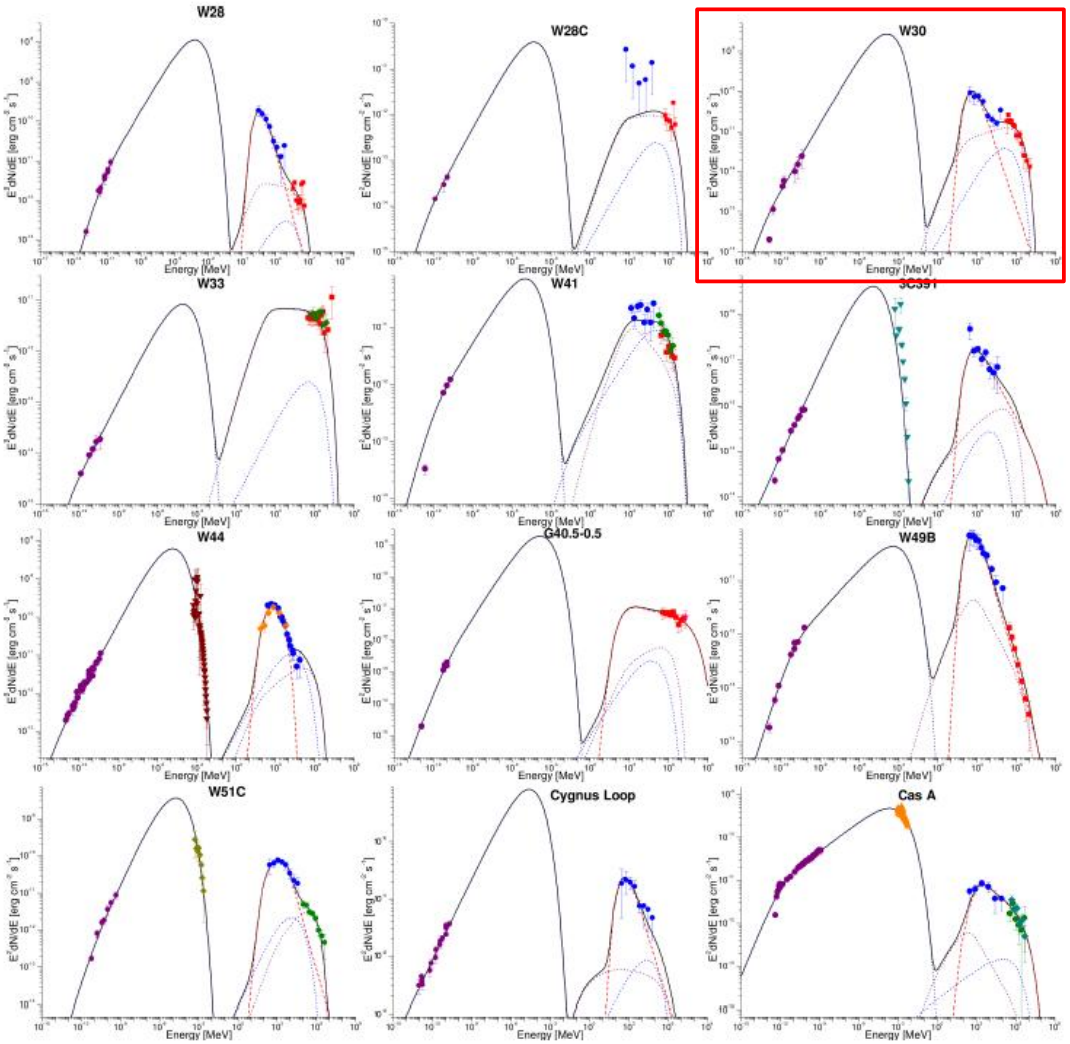
Broad-band modeling of GeV-TeV SNRs (Mandelartz & Tjus 2013)

Table 1: Overview of the supernova remnants studied in this work. The columns of MeV–GeV and GeV–TeV indicated by which process the radiation is dominated in that range assuming the scenario of minimum energy: **B**remsstrahlung, inverse **C**ompton radiation, or **P**ion decay. A hadronical scenario, if possible is indicated in parentheses. The energy column indicates the source of energy that dominates the remnant: **E**lectrons, **M**agnetic field, or **P**rotons. The + in the age column indicates more than one order of magnitude uncertainty up from the presented minimal value, all other ages are averages of the suggested value range.

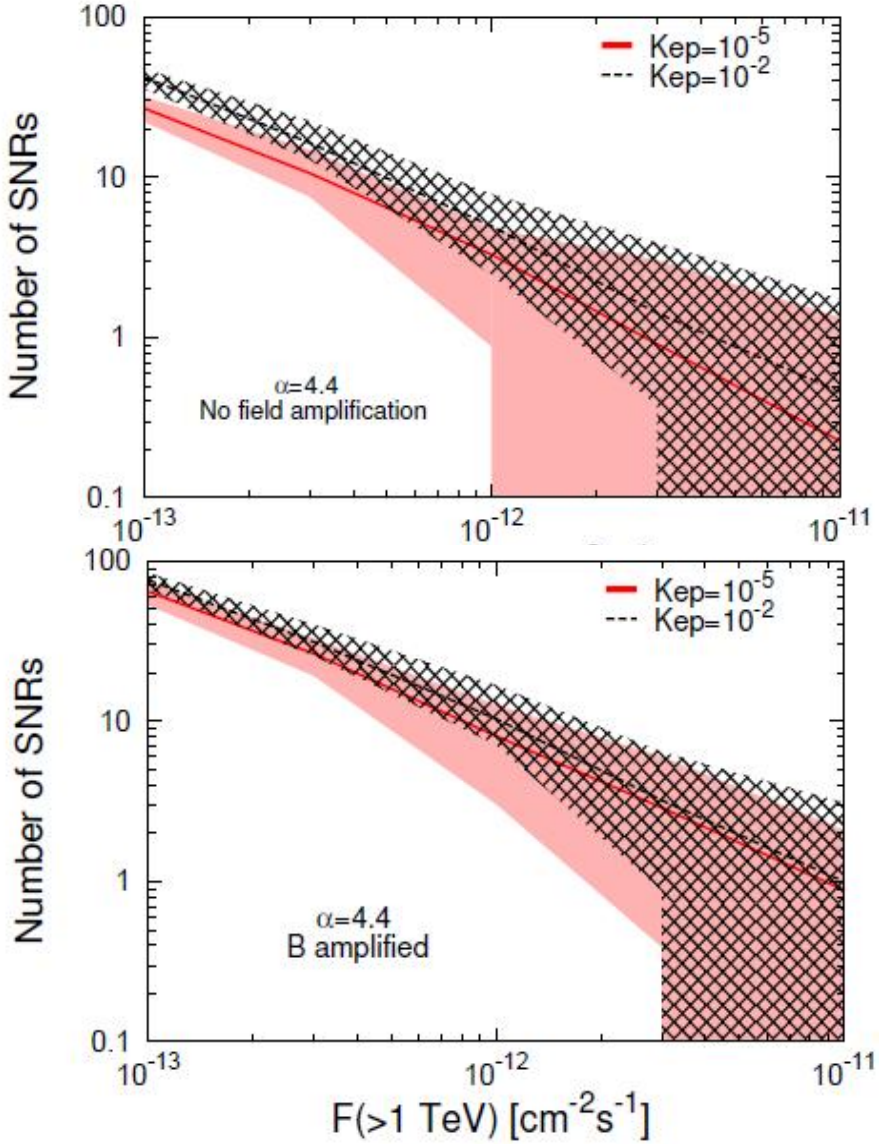
SNR	Dist. [kpc]	Age [yr]	B_{min} [μG]	B_{eq} [μG]	MeV–GeV	GeV–TeV	Energy
W28	1.9	33000+	500	620	P	B(P)	M
W28C	1.9	?	40	40	B(P)	B(P)	M/P
W30	4	25000	100	110	P	B+C	M
W33	4	1200	18	18	B?(P)	B(P)	P
W41	4.2	100000	9	9	B(P)	B(P)	P
3C391	7.2	4000	27	130	P	P	P
W44	3	10000	40	130	P	B	M
G40.5–0.5	3.4	30000	90	159	P	P	M
W49B	10	1000+	100	307	P	P	P
W51C	7.2	26000	120	130	P	B	M
Cygnus Loop	0.58	14000	35	100	P	P	M
Cassiopeia A	3.5	332	37	?	B(P)	C(P)	P
Tycho	3.5	440	45	100	P	P	P
IC443	1.5	3000+	35	40	B	B+P	M
Puppis A	2	4500	33	33	B(P)	B+C(P)	M/P
Vela Jr	1.3	2500	9	9	C(P)	C(P)	P
MSH 11–62	6.2	1300+	10	21	P	–	E+M
RCW 86	2.3	1827	13	13	?	C	P
SN 1006	2.2	1006	29	30	?(P)	C(P)	P
RX J1713.7	3.5	1619?	27	10	C	C	P
CTB 37A	7.9	2000	138	?	P	P/B?	M
CTB 37B	13.2	1750	30	30	C(P)	C(P)	P
G349.7+0.2	18.3	3500	45	>100	P	P	P
G359.1–0.5	7.6	10000+	41	41	B	B	M



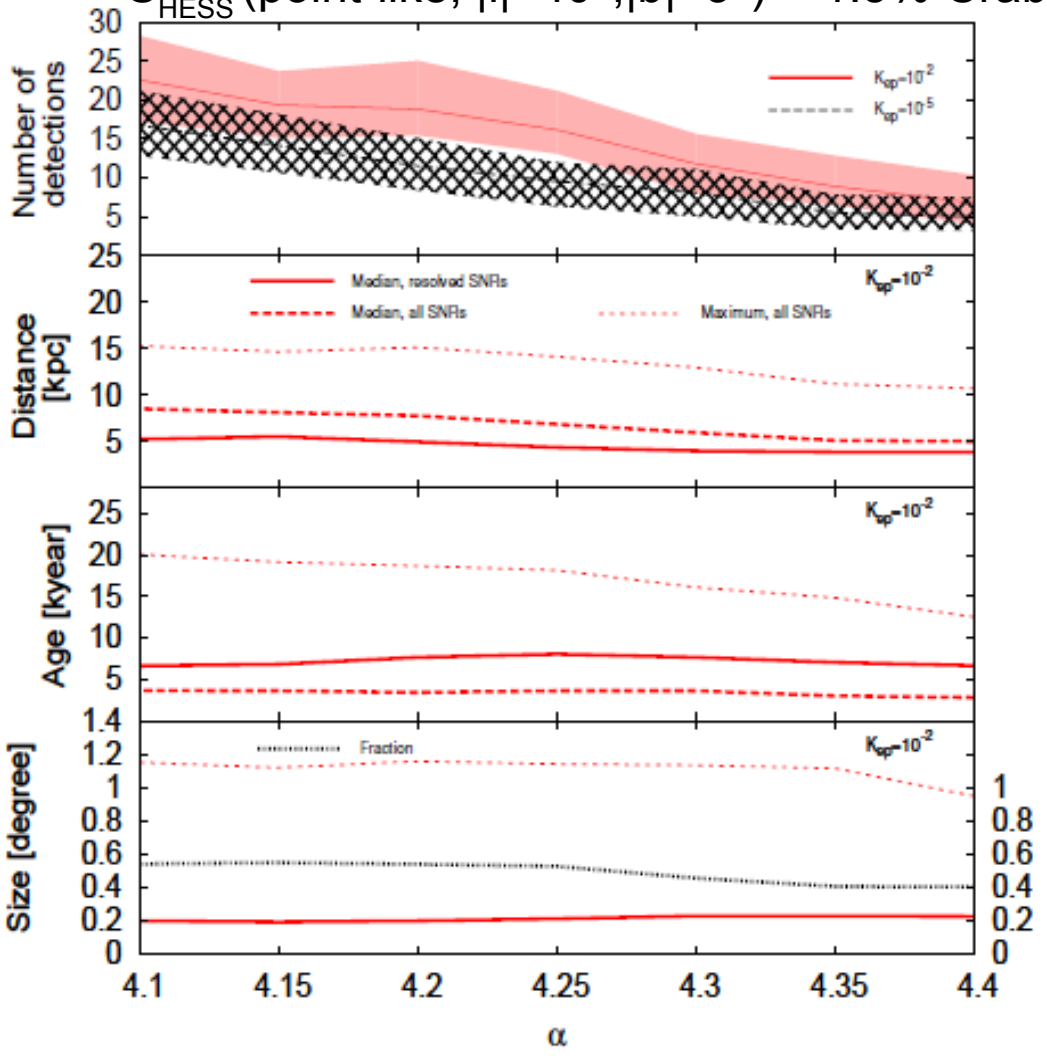
SNRs at HE/VHE gamma-rays

Several statistical studies of gamma-ray emitting SNRs have been carried out

Monte-Carlo simulations of Galactic « isolated » SNRs (Cristofari et al. 2013)

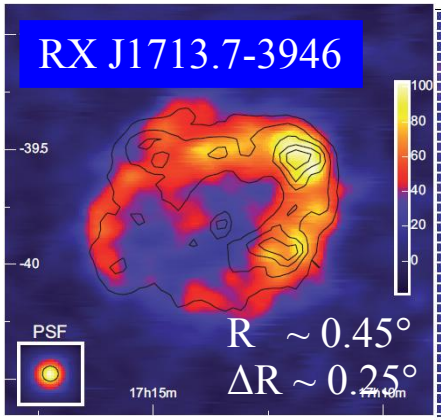


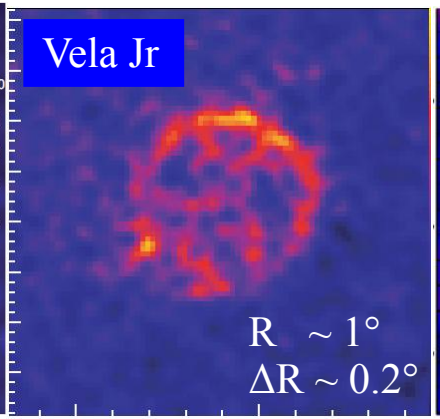
S_{HESS} (point-like, |l|<40°,|b|<3°) = 1.5% Crab

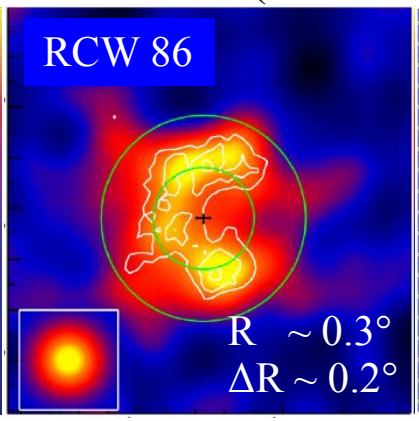


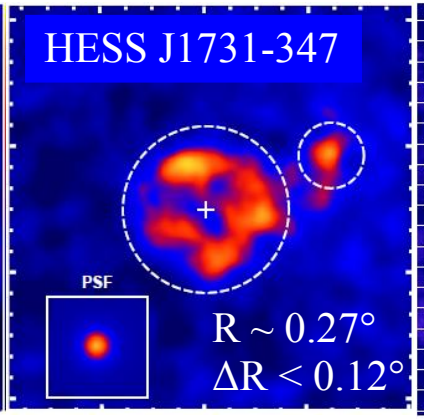
Young, isolated, TeV-bright SNRs

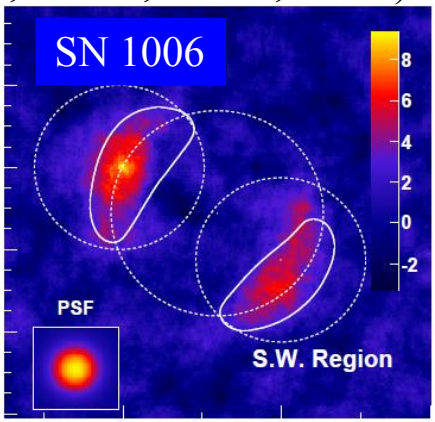
(Aharonian et al. 2006 ; 2007 ; 2009 ; 2011 ; 2012)

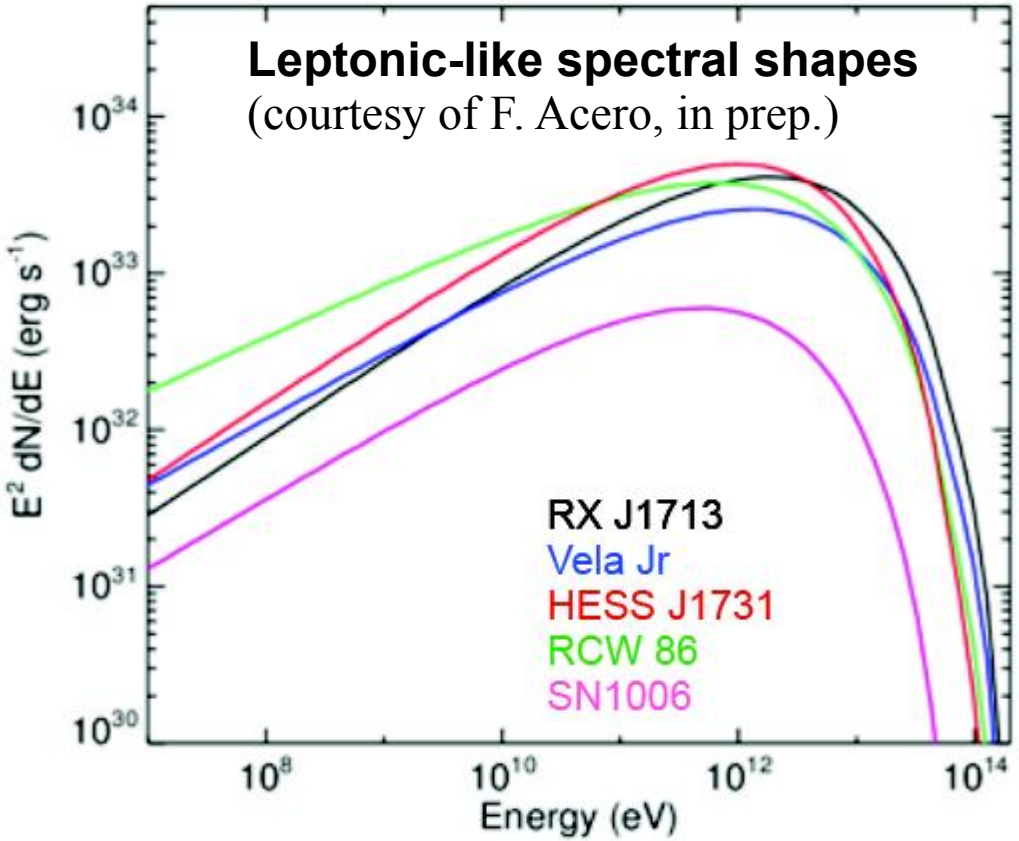












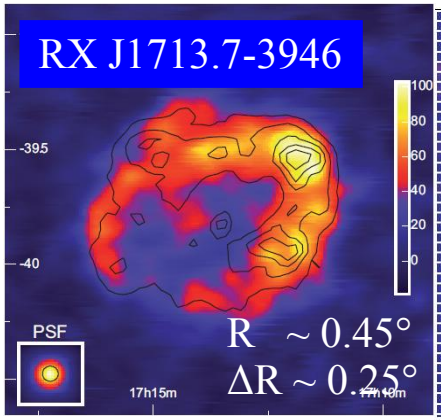
What could H.E.S.S. II bring?

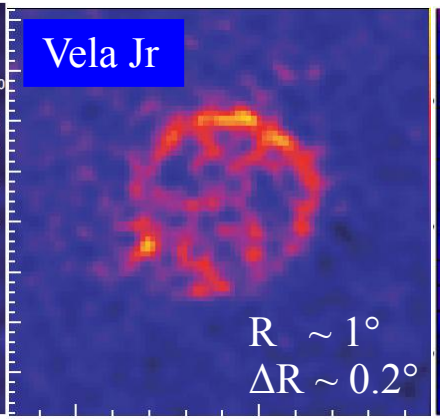
For the brightest SNRs (e.g. J1713)
Improve measurements of the spectral parameters → origin of -ray emission ?

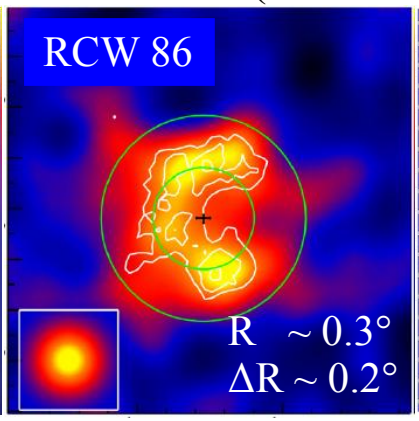
Search for emission in other young SNRs, such as Kepler...

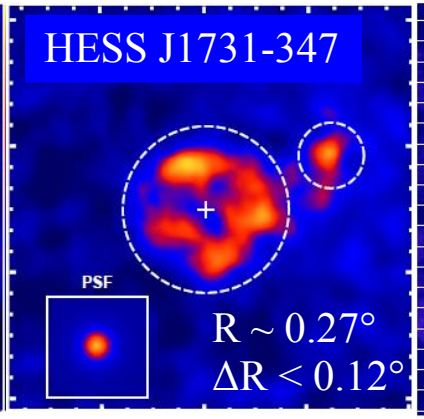
Young, isolated, TeV-bright SNRs

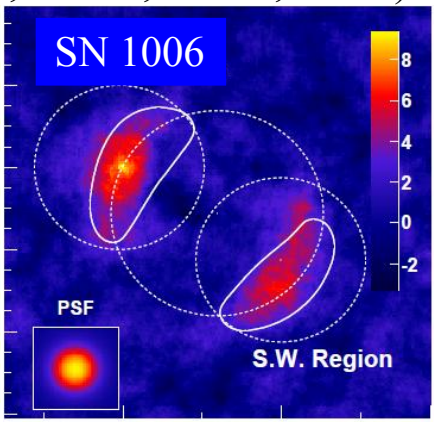
(Aharonian et al. 2006 ; 2007 ; 2009 ; 2011 ; 2012)

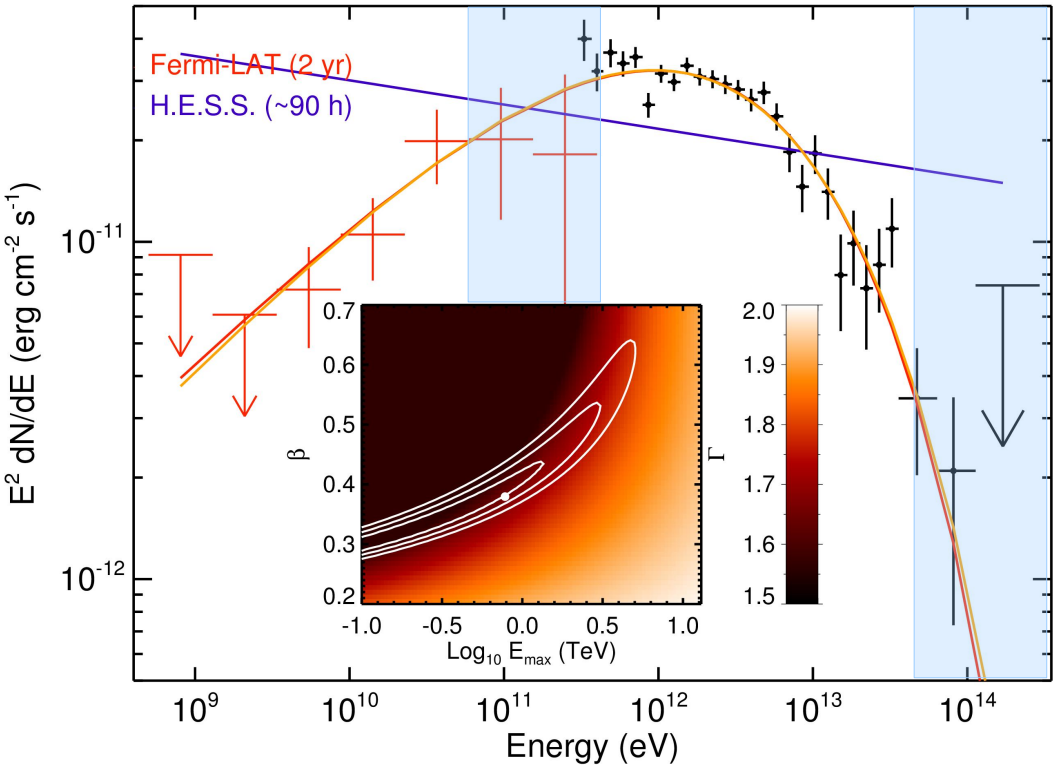












Gamma-ray spectrum in the form :
$dN/dE = N_0 E^{-\Gamma} \exp(-(E/E_c)^{\beta})$

$\pi^0 \rightarrow 2\gamma$, dN_p/dE_p with $\exp(-(E_p/E_{cut}))$ → $\beta = 1/2$
(Kelner et al. 2006)

IC, dN_e/dE_e with $\exp(-(E_e/E_{cut})^{\zeta})$ for $D \alpha p^{\zeta-1}$

Regular B-field → $\beta = 1/2$ for $\zeta = 2$

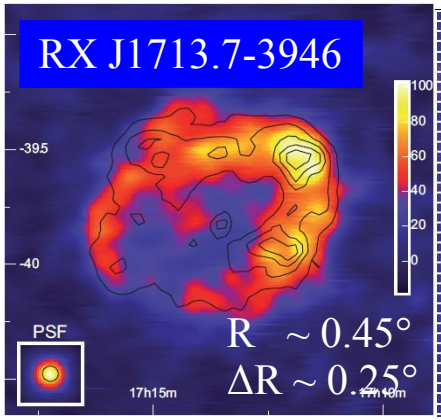
Turbulent B-field → $\beta = 1/3$ for $\zeta = 2$

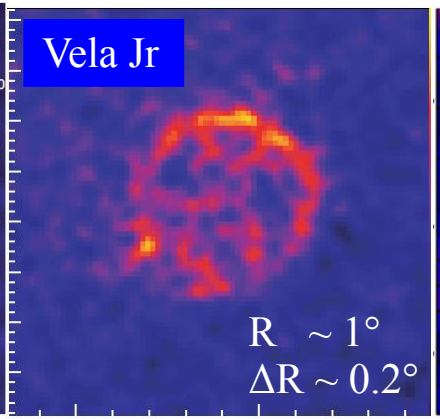
(Zirakashvili & Aharonian 2007, 2010)

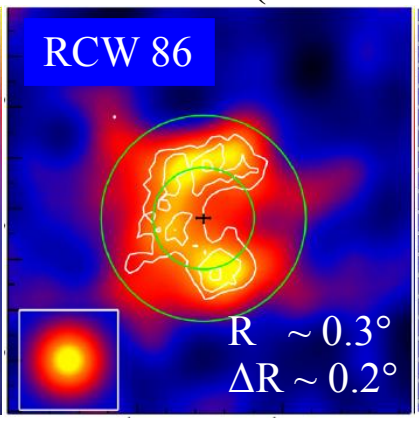
N.B. : increasing the statistics above ~30 TeV could lead to a clear detection → hadrons!

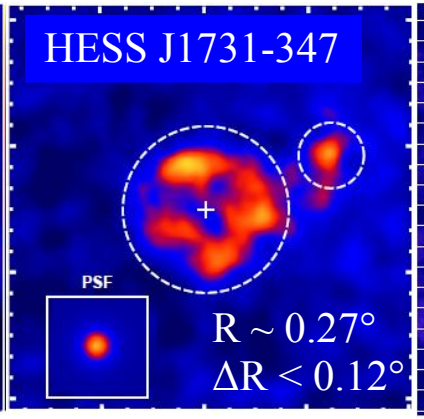
Young, isolated, TeV-bright SNRs

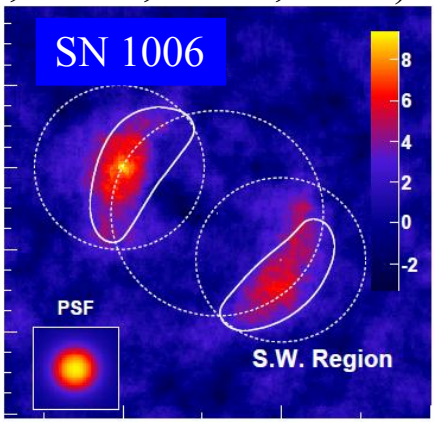
(Aharonian et al. 2006 ; 2007 ; 2009 ; 2011 ; 2012)

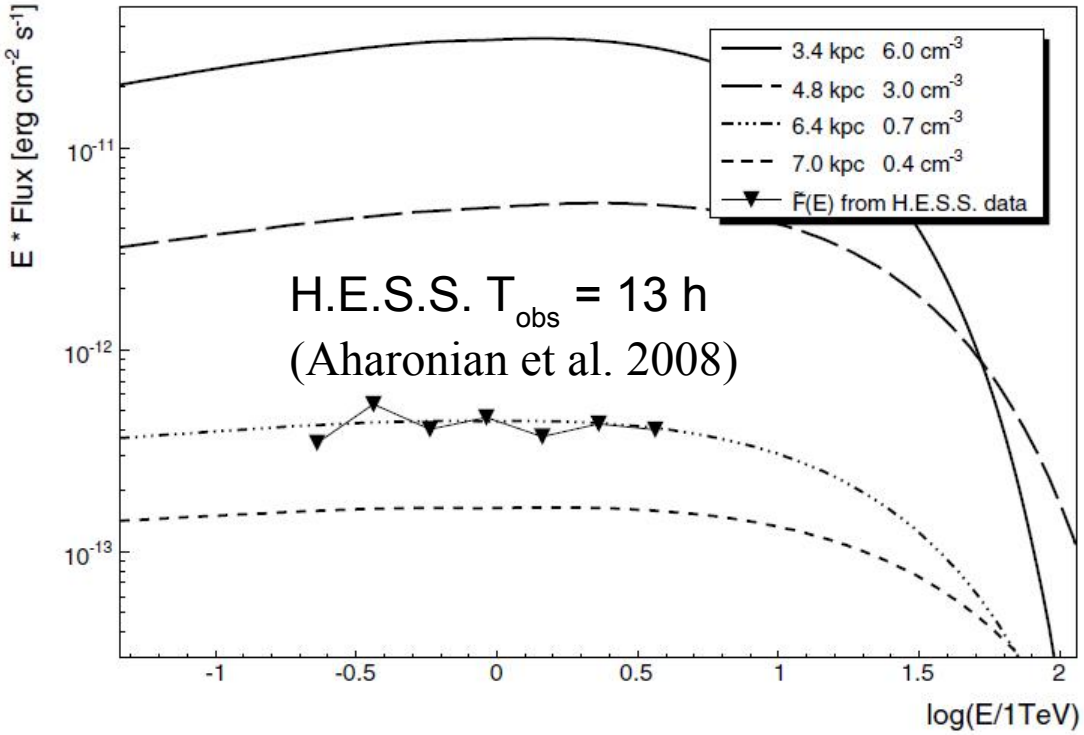




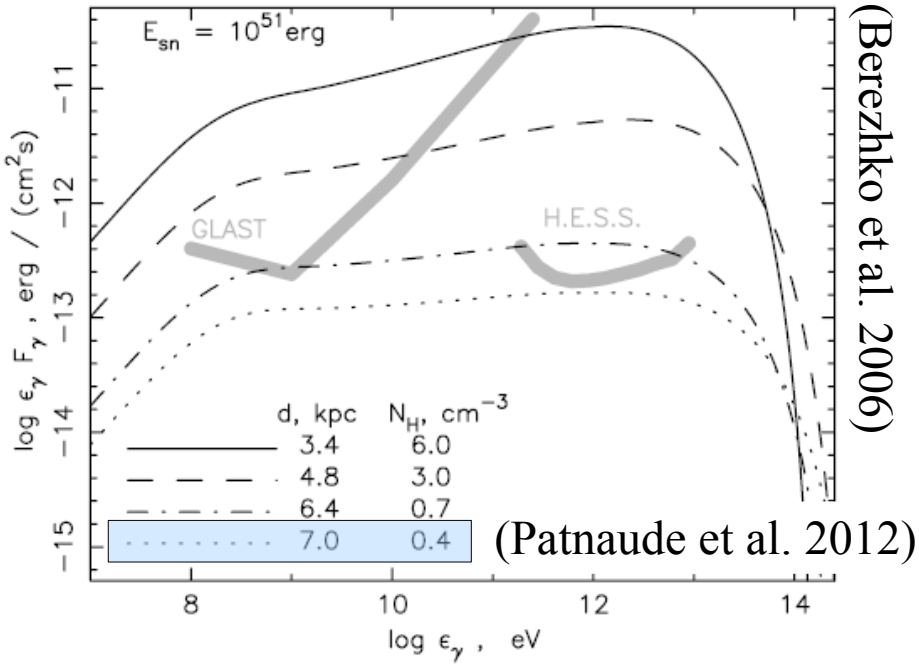




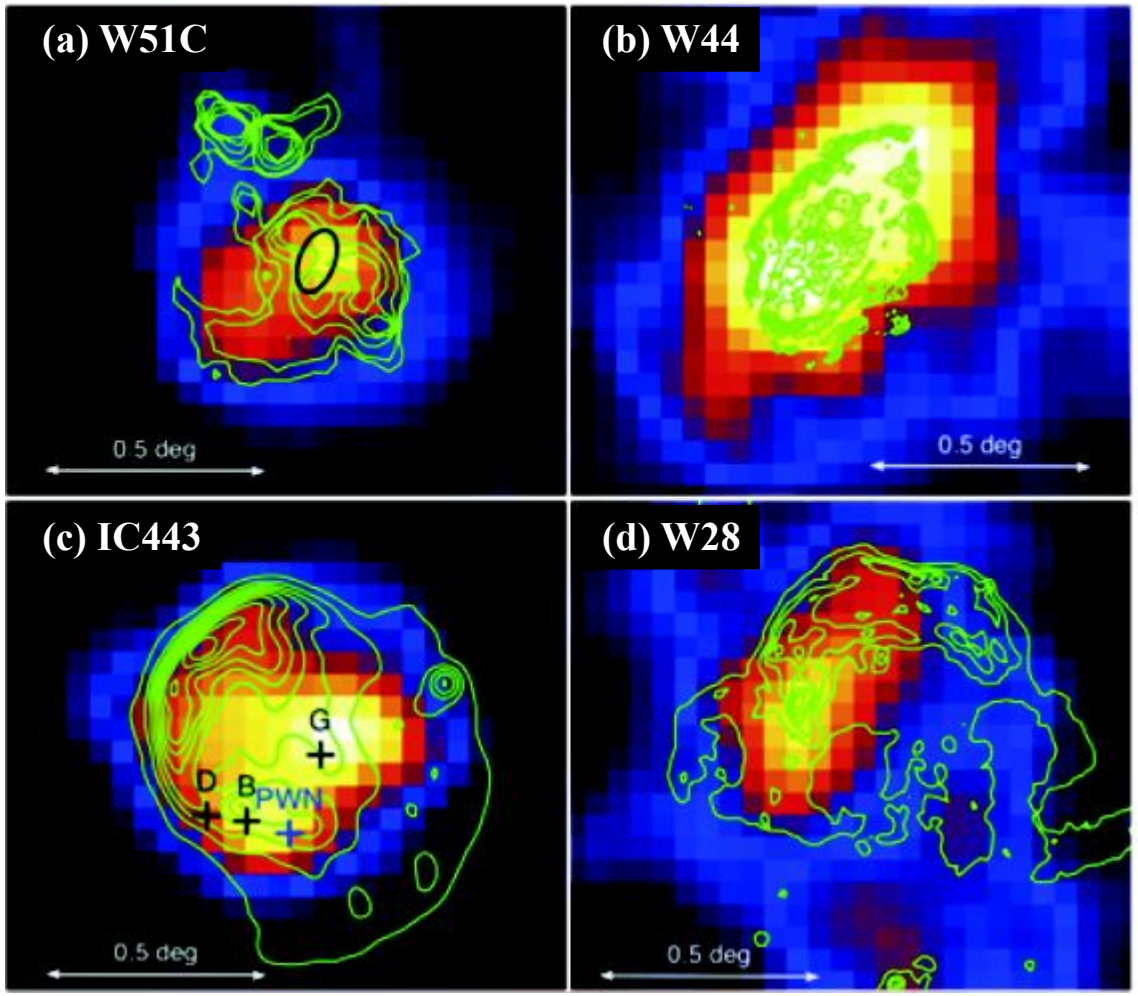




Search for emission from Kepler SNR



Middle-aged, interacting, GeV-bright SNRs



2-10 GeV count maps (Fermi/LAT collab., Uchiyama 2011)

Middle-aged SNRs ~ (1–4)×10^4 yr

Bright at radio wavelengths
Interacting with molecular clouds
(Koo & Moon 1997, Reach et al. 2005, Hewitt et al. 2006 ; 2008)

Extended GeV emission consistent with the size of the radio SNR (except W28)

Extended TeV emission detected by HESS, VERITAS & MAGIC (except W44)
(Albert et al. 2007, Aharonian et al. 2008, Acciari et al. 2009, Fiasson et al. 2009, Aleksic et al. 2012)

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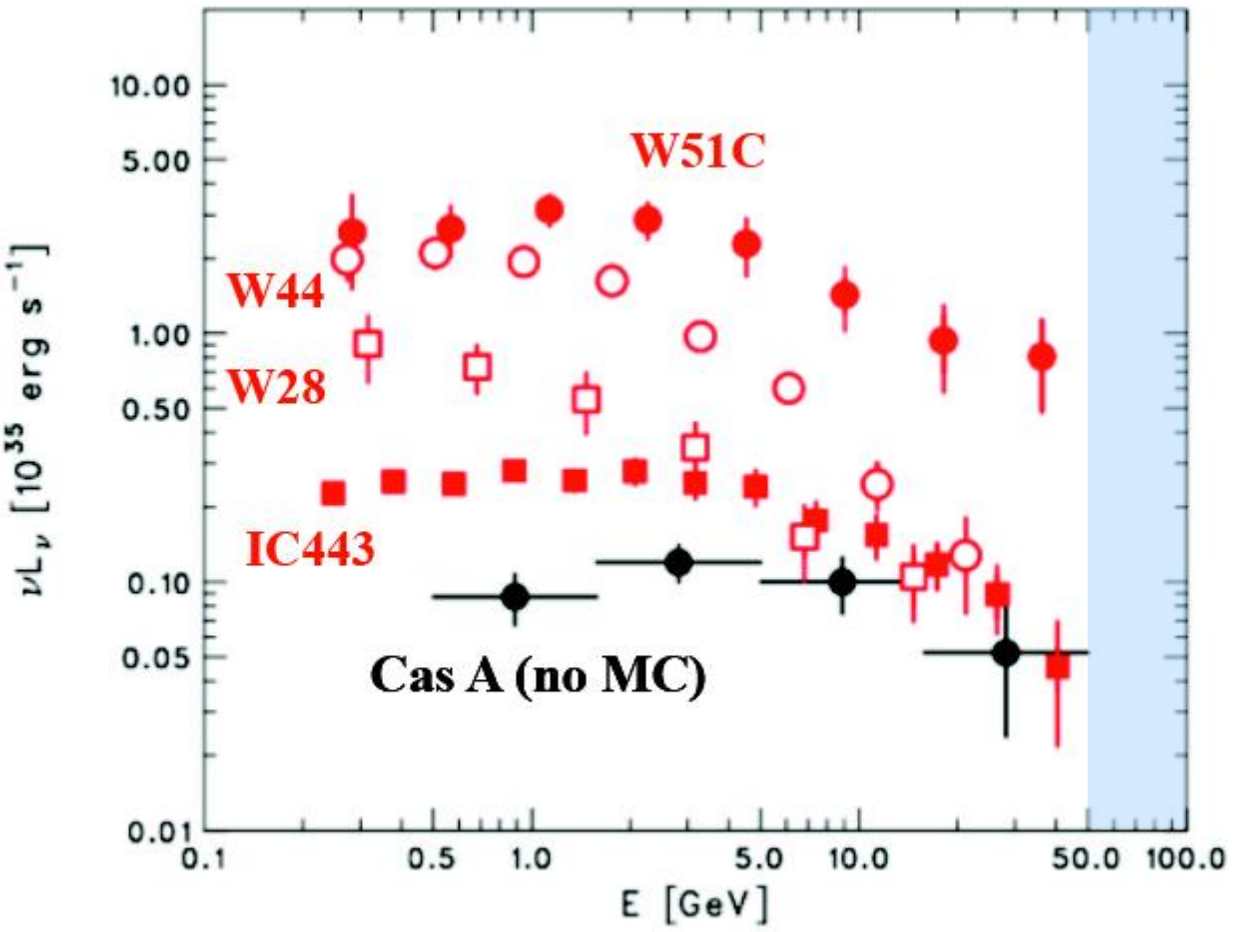

(Fermi/LAT collab., Uchiyama 2011)

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High GeV luminosity up to 10^{36} erg s^{-1}
Spectral steepening in the GeV band
Weak sources in TeV gamma-rays

→ Origin of these breaks at ~GeV?

Middle-aged, interacting, GeV-bright SNRs

Origin of HE spectral breaks

Several scenarios involving acceleration/diffusion effects due to the interaction of a SNR shock with a dense, partially ionized, medium:

1) ion-neutral collisions → Alfven wave damping → reduction of confinement & escape
   → break with $\Delta\Gamma = 1$ at $E_{br} \sim 10\ B_{\mu G}^{2}\ T_{4}^{-0.4}\ n_{0}^{-1}\ n_{i}^{-1/2}$ GeV (Malkov et al. 2011, 2012)

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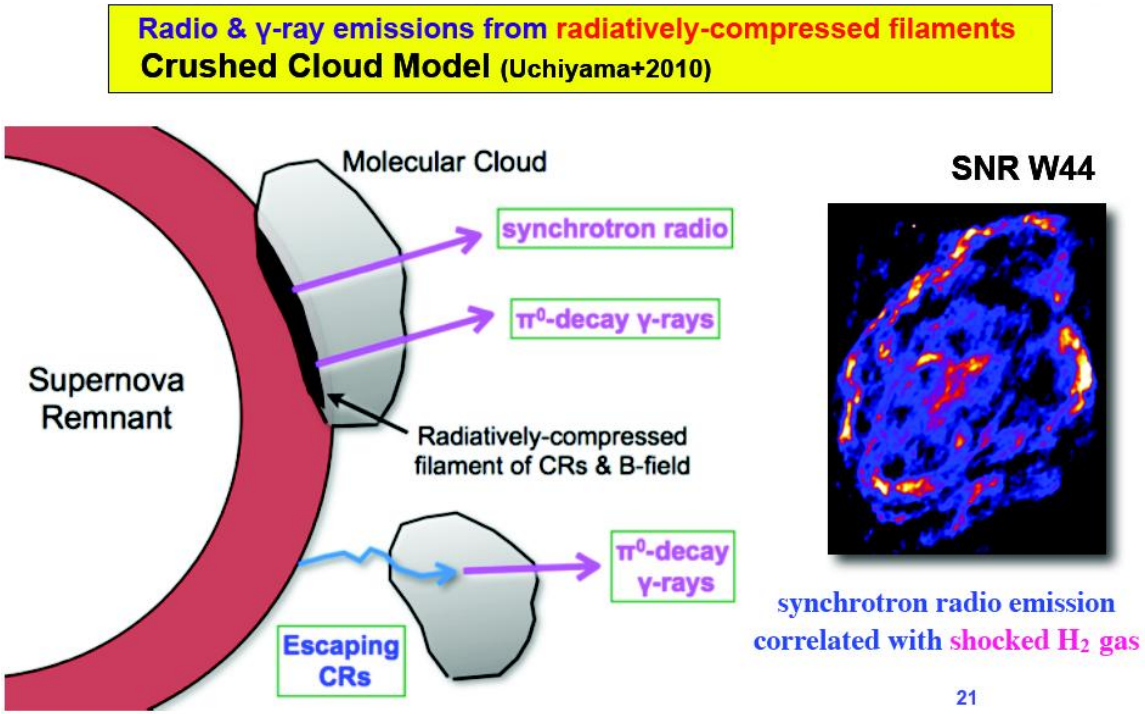
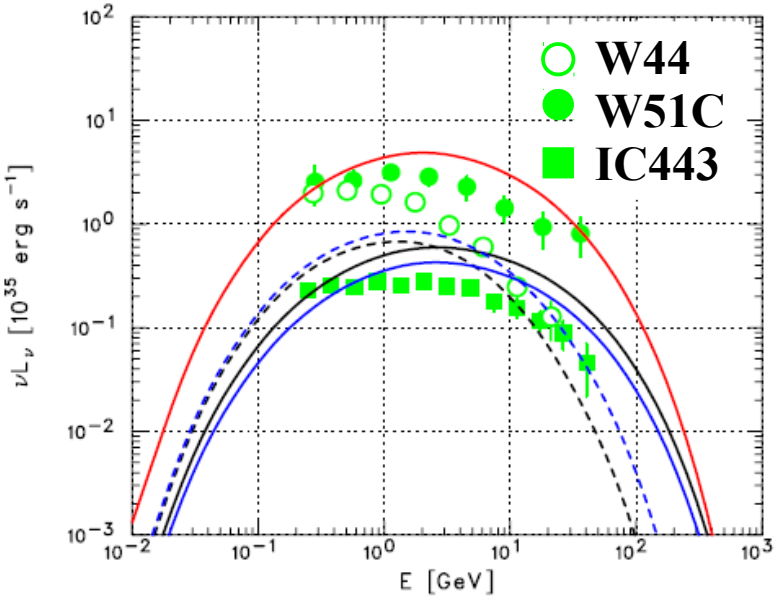
2) Reacceleration of Galactic CRs in crushed clouds (Uchiyama et al. 2010)





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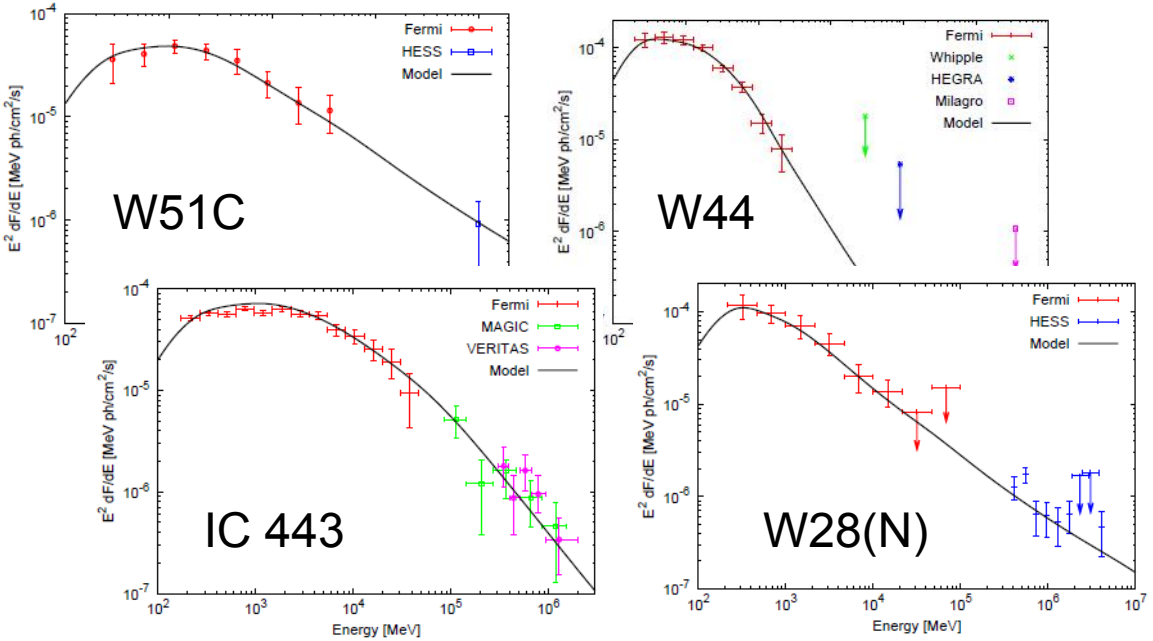

Besides the breaks due to the finiteness of the source and target regions, one break is interpreted as being $E_{p,max}$ when the shock encountered the MC

Good fits... at the expense of several (poorly constrained) parameters related to diffusion and MC properties...

Middle-aged, interacting, GeV-bright SNRs

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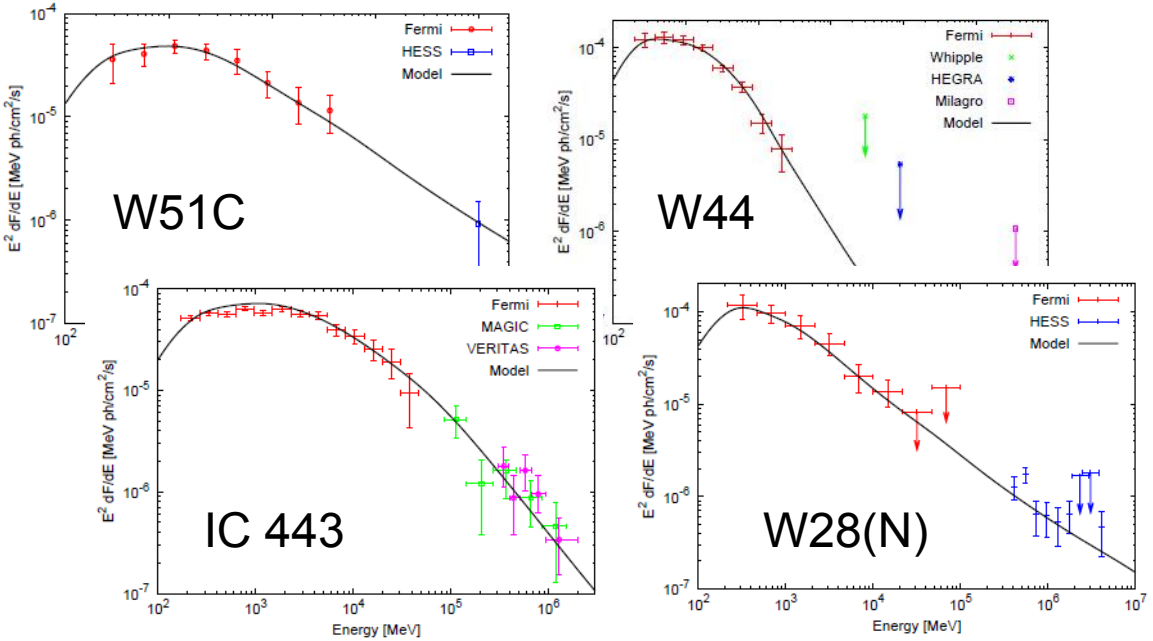
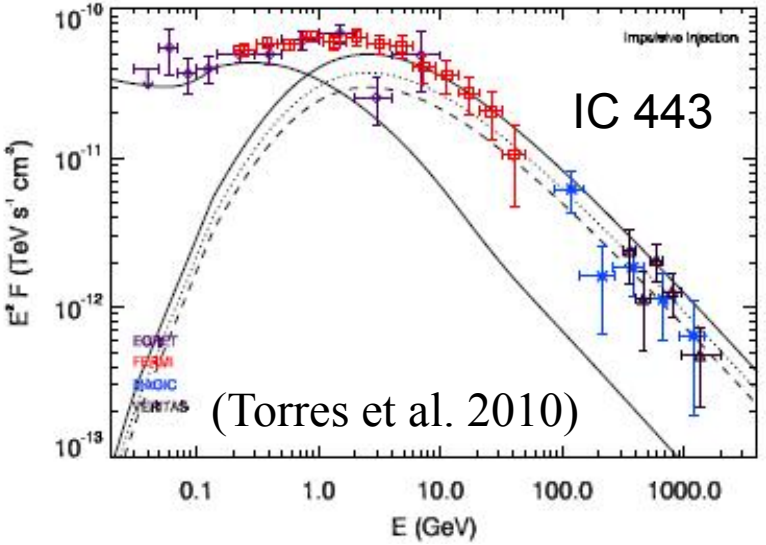
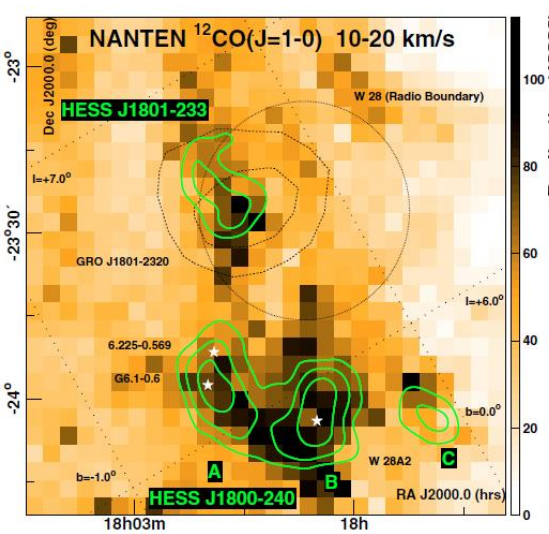


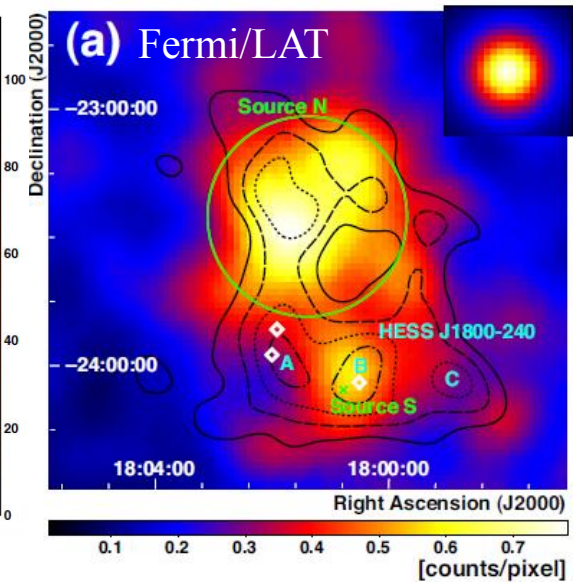
MC illuminated by CRs that have escaped a nearby SNR



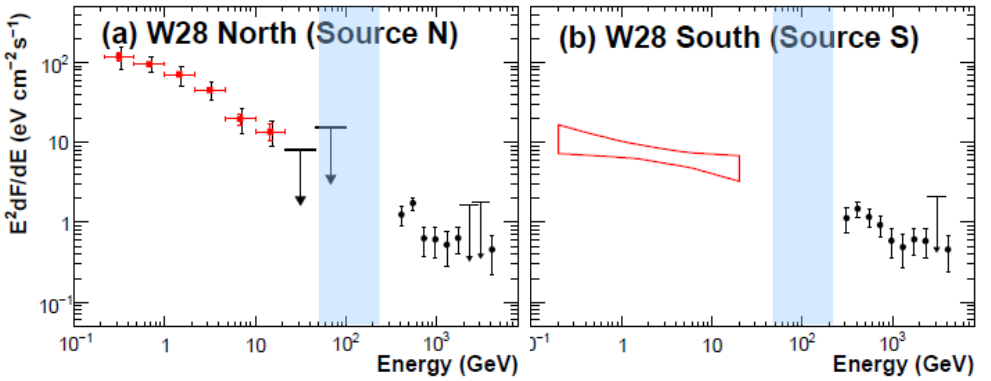
Middle-aged, interacting, GeV-bright SNRs

W28 : SNR/MC interaction and escaping CRs





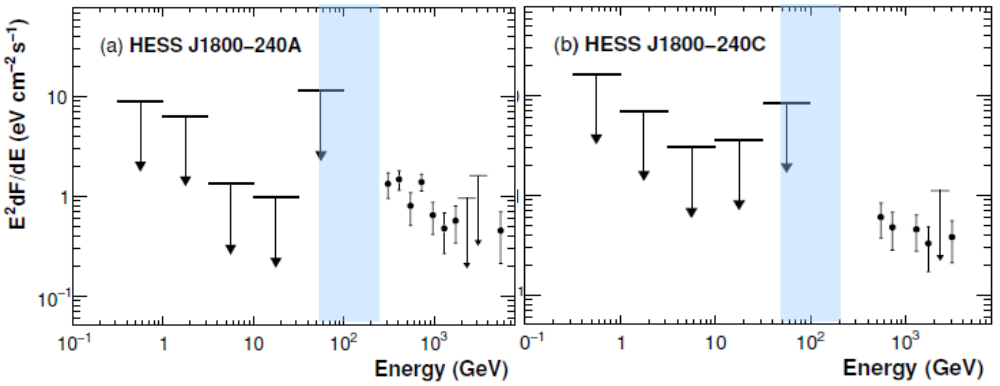
(Aharonian et al. 2008)



(Abdo et al., Giuliani et al. 2010)

HESS J1801-233 **(Source N)** on E rim of W28
Coincident with GeV source
Coincident with CO cloud
1720 MHz OH maser : shock/MC interaction

HESS J1800-240B **(Source S)** outside W28
Coincident with GeV source
Coincident with CO cloud & HII region W28A2
MC illuminated by CRs escaping W28...?



Middle-aged, interacting, GeV-bright SNRs

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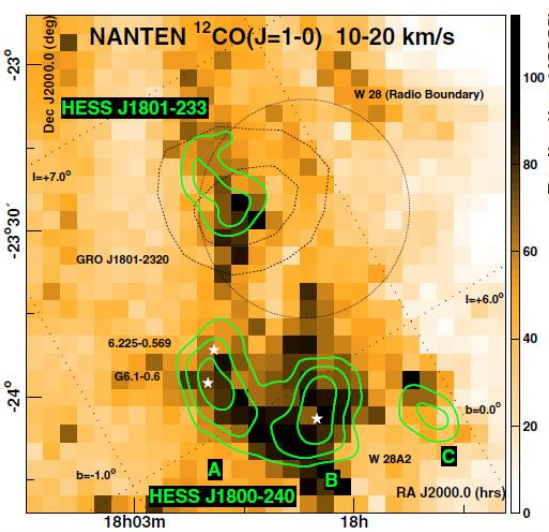
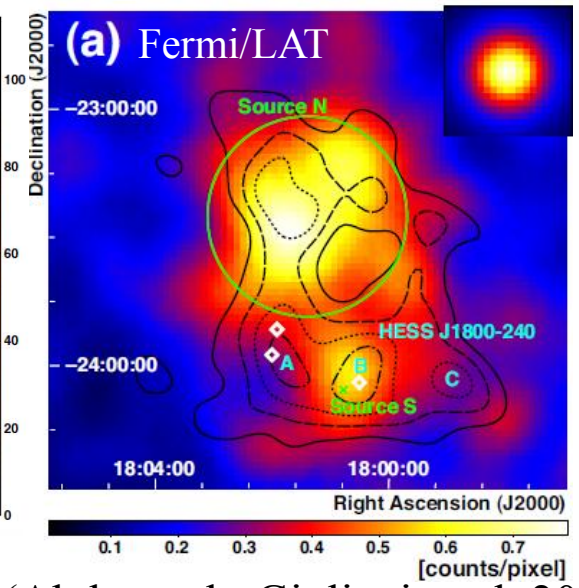
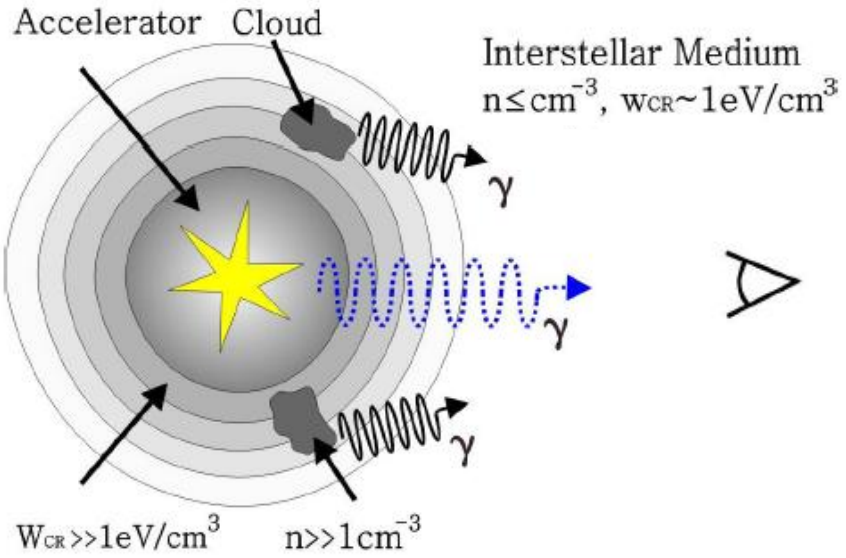




(Aharonian et al. 2008) (Abdo et al., Giuliani et al. 2010)



(Gabici et al. 2007 ; 2009, 2012)

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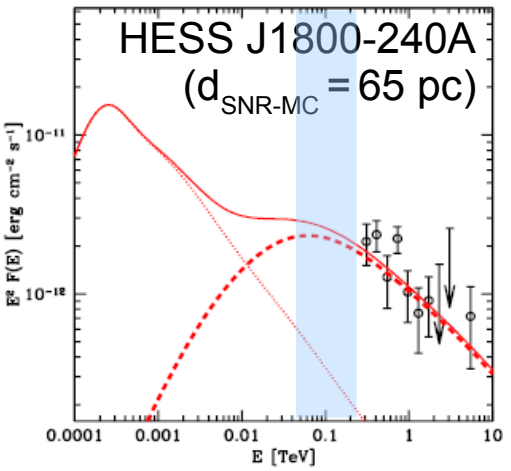
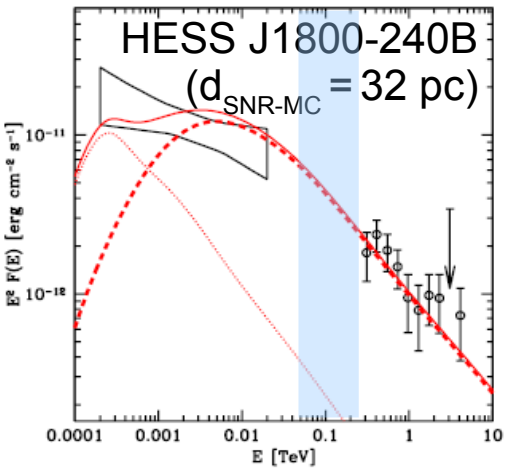
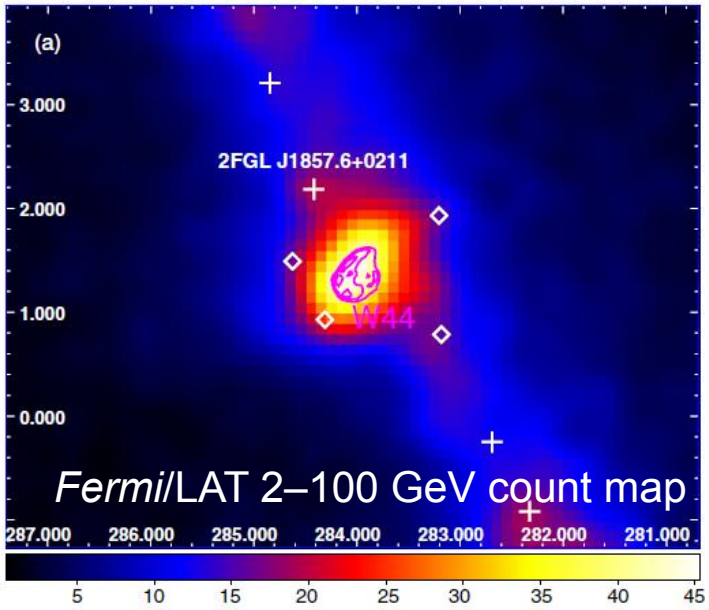


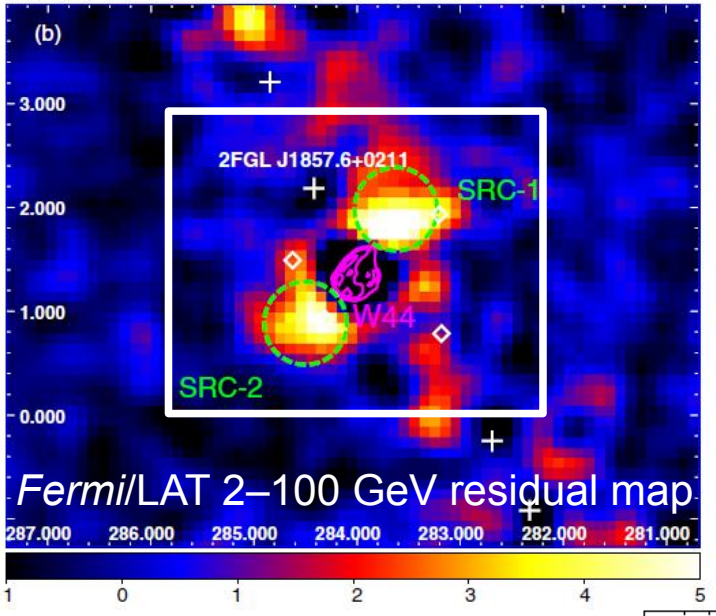


Middle-aged, interacting, GeV-bright SNRs

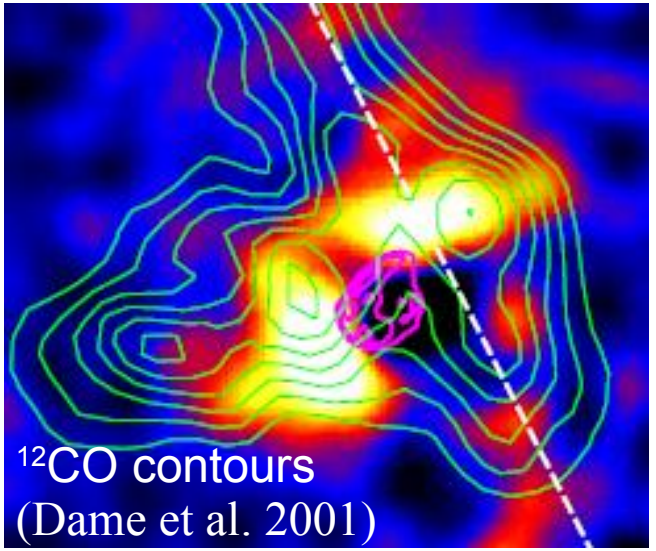
W44 : SNR/MC interaction and escaping CRs



Fermi/LAT 2–100 GeV count map



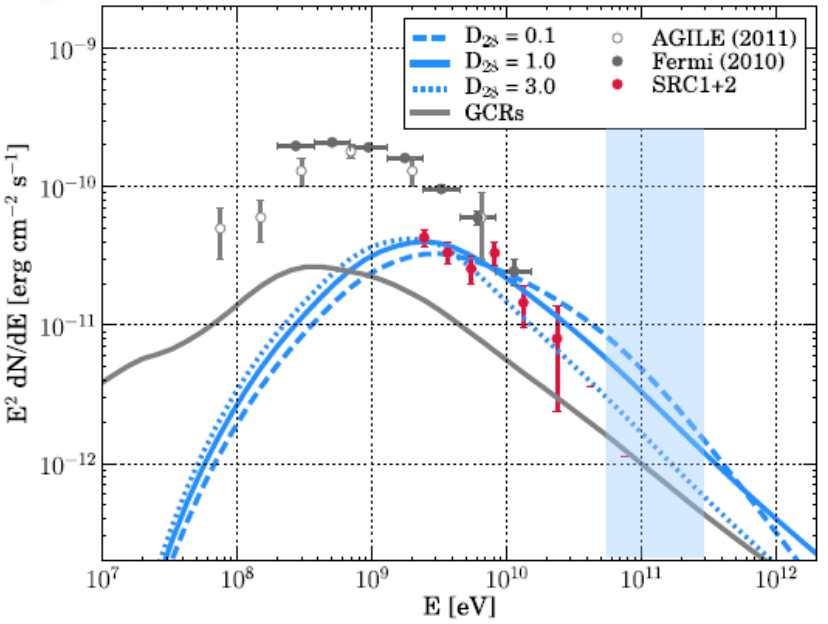
Fermi/LAT 2–100 GeV residual map



High-energy emission detected in the vicinity of W44 (Uchiyama et al. 2012)

Halo of CRs that escaped the SNR, diffused and interacted with the GMC with :
$W_{esc} \sim (0.3–3) \times 10^{50} (M_{GMC}/5\times10^5\ M_{sun})^{-1}$ erg,
depending on D(p) and slope of escaped protons

→ **Observations at E > 50 GeV to constrain the γ-ray spatial distribution as a function of energy**



Middle-aged, interacting, GeV-bright SNRs

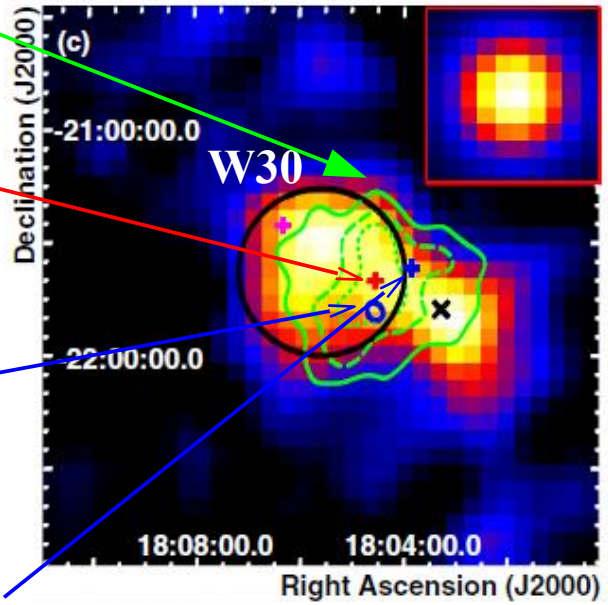
W30 : Origin of the HE/VHE emission

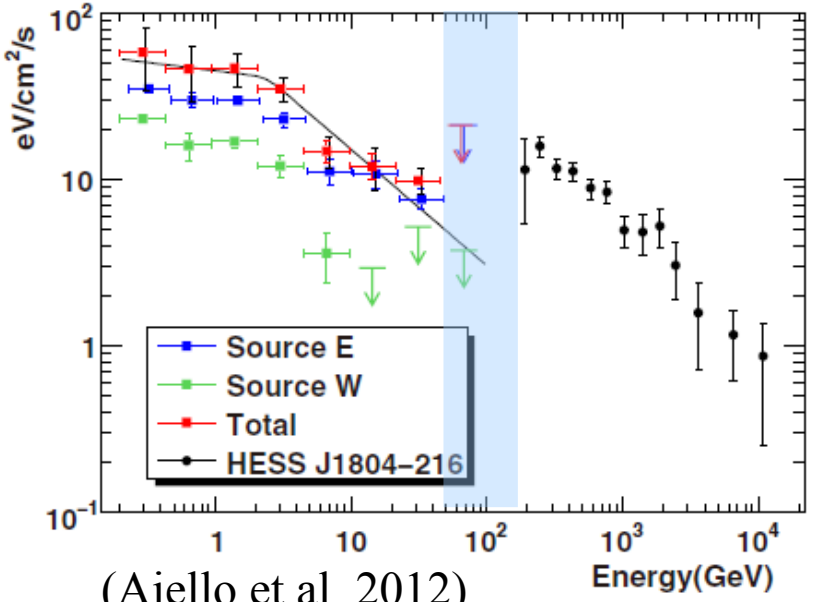
HESS J1804-216
(Aharonian et al. 2006)

Suzaku J1804-2140
(Bamba et al. 2007
Kargaltsev et al. 2007a
Lin et al. 2013)

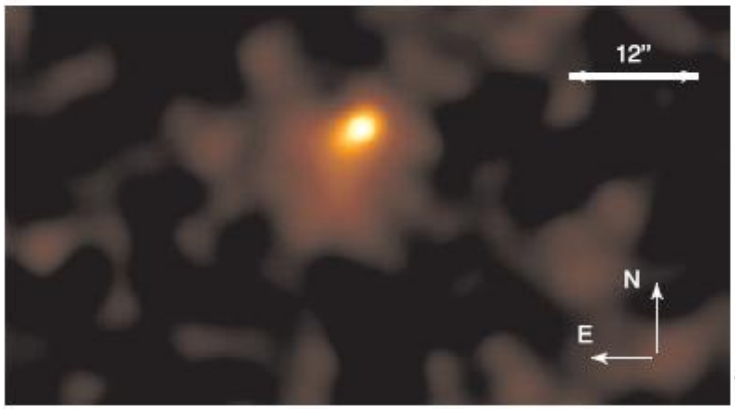
SNR G8.31-0.09
(Brogan et al. 2006)

PSR J1803-2137
Young Vela-like PSR
$\dot{E} = 2.2\times10^{36}$ erg/s
τ = 16 kyr
d = 3.8 ± 0.4 kpc

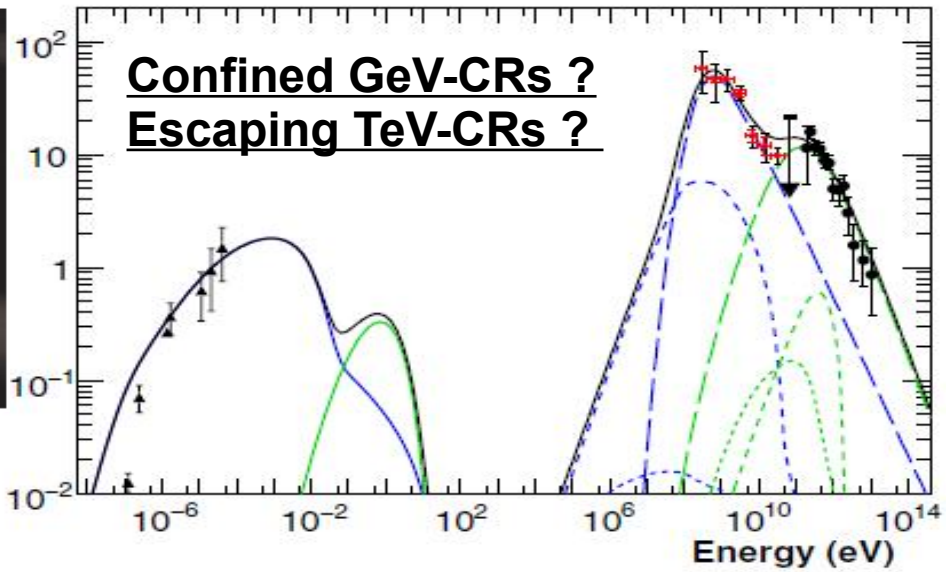




(Ajello et al. 2012)

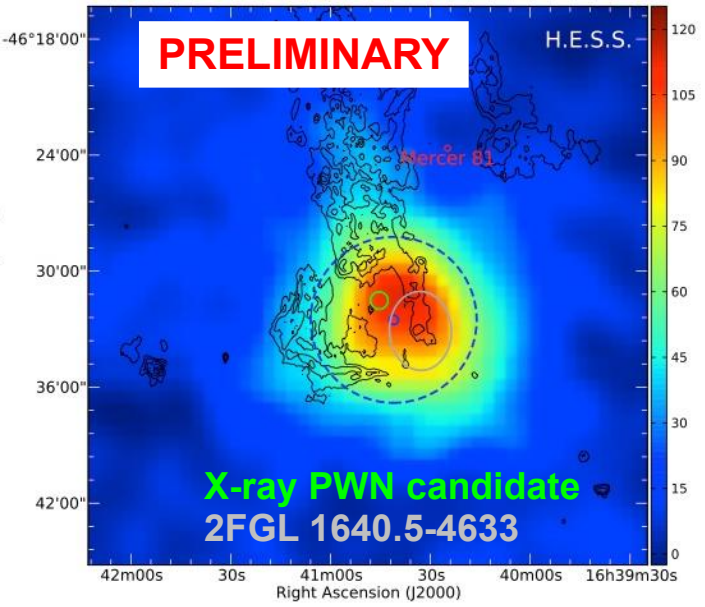


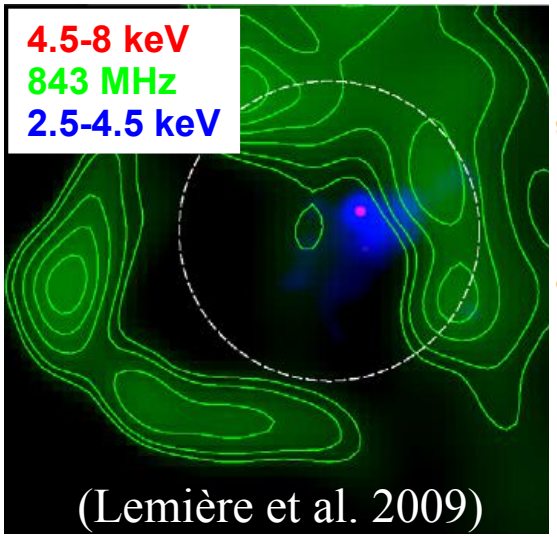
« relic » VHE PWN ?
(Kargaltsev et al. 2007b)

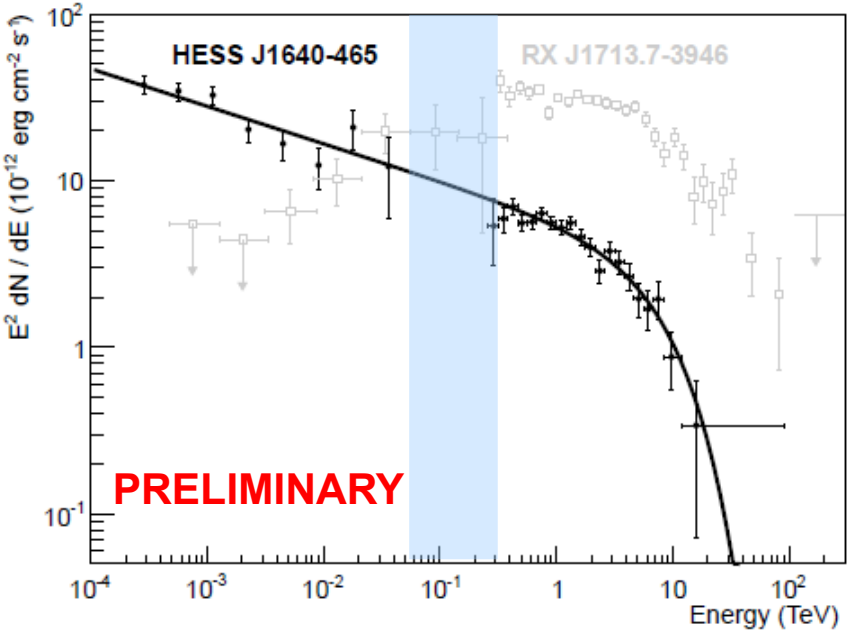


Middle-aged, interacting, GeV-bright SNRs

HESS J1640-465 : Origin of the HE/VHE emission







Originally discovered in the H.E.S.S. Galactic Plane Survey (Aharonian et al. 2006) toward SNR G338.3-0.0 which hosts a X-ray PSR/PWN candidate (Funk et al. 2007, Lemière et al. 2009)

Fermi/LAT data revealed emission coincident with HESS J1640-465 with no evidence for a cutoff at ~1–10 GeV, reminiscent of pulsars (Slane et al. 2010)

If HE/VHE emissions are of the same origin → PWN scenario « spectrally » disfavored
→ **New TeV SNR with $W_p n_H \sim 4\times10^{52}\ d^2_{10kpc}$ erg cm^{-3}** (H.E.S.S. Collaboration, in prep.)

SNRs with H.E.S.S. II

Isolated, « clean » SNRs

- Precise spectral measurements in the brightest TeV SNRs (RX J1713-3946)
- Search for gamma-ray emission from young SNRs (Kepler)

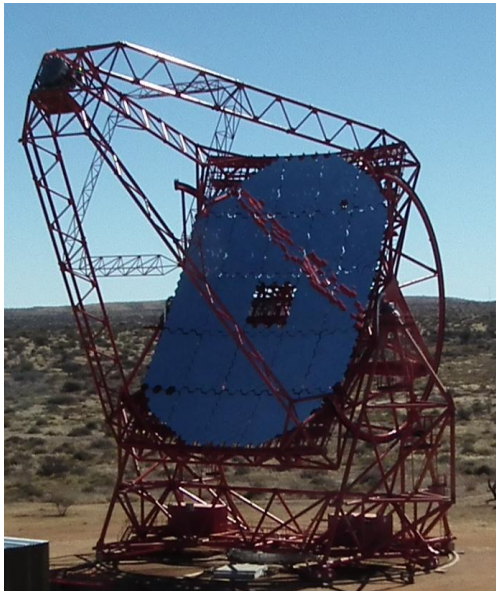
Interacting, « crowded » SNRs

- Origin of the GeV spectral breaks (W28, W44)
- Constraints on diffusion properties of CRs escaping & interacting with MCs (W28, W44)
- Revealing the nature of several VHE sources (W30, HESS J1640-465)

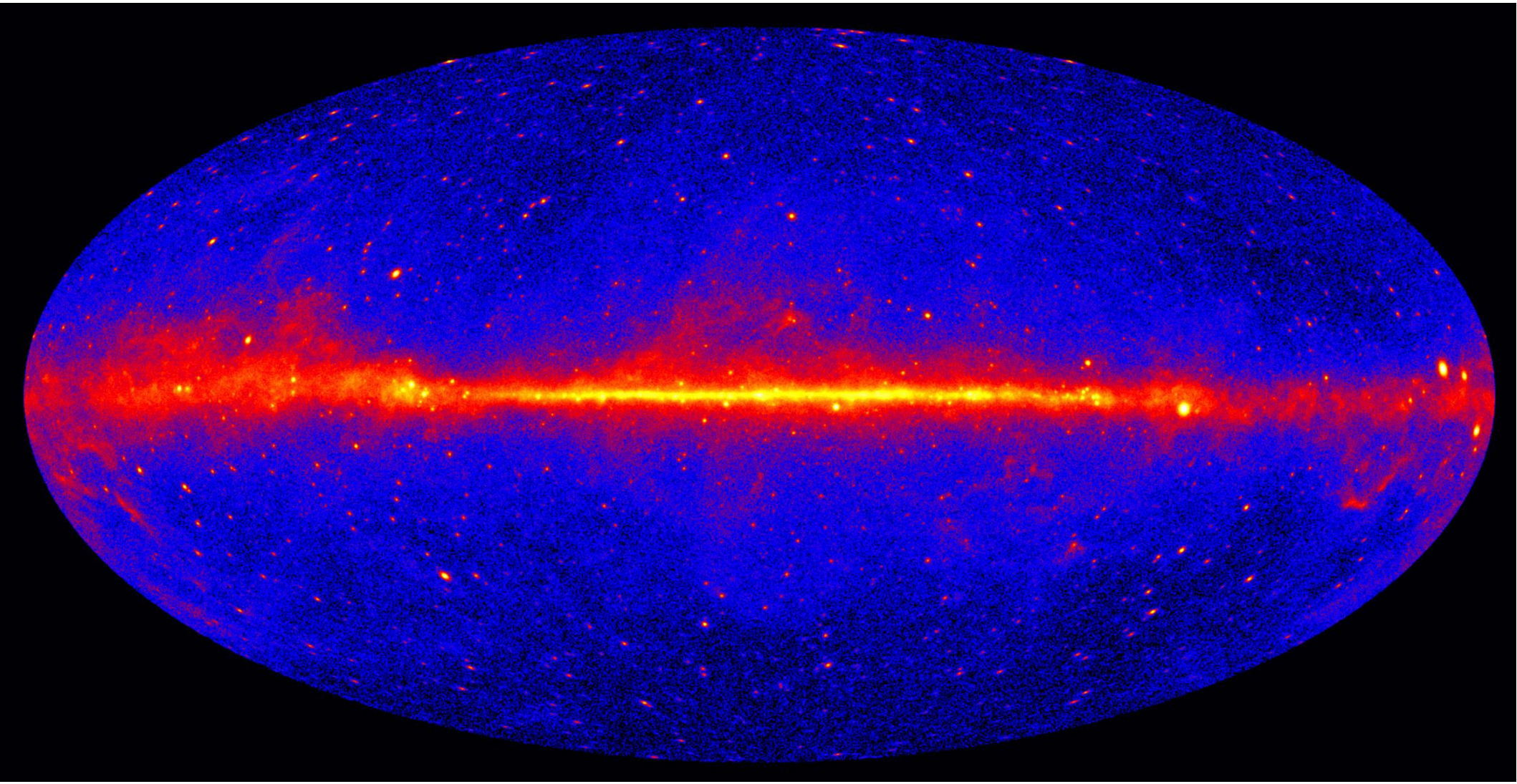
1FHL (E > 10 GeV) source catalog recently released (2013arXiv1306.6772T)

Table 5. Potential Associations for Sources Near SNRs

1FHL Name	2FGL Name	SNR Name	PWN Name	TeV Name	Common Name
J1111.5−6038	J1112.1−6040	G291.0−00.1	G291.0−0.1	...	...
J1552.6−5610	J1552.8−5609	G326.3−01.8	...	...	Kes 25
J1640.5−4634	J1640.5−4633	G338.3−00.0	G338.3−0.0	HESS J1640−465	...
J1717.9−3725	J1718.1−3725	G350.1−00.3	...	...	...
J1745.6−2900	J1745.6−2858	G000.0+00.0	G359.98−0.05	...	Sgr A East
J1834.6−0703	J1834.7−0705c	G024.7+00.6	...	...	...



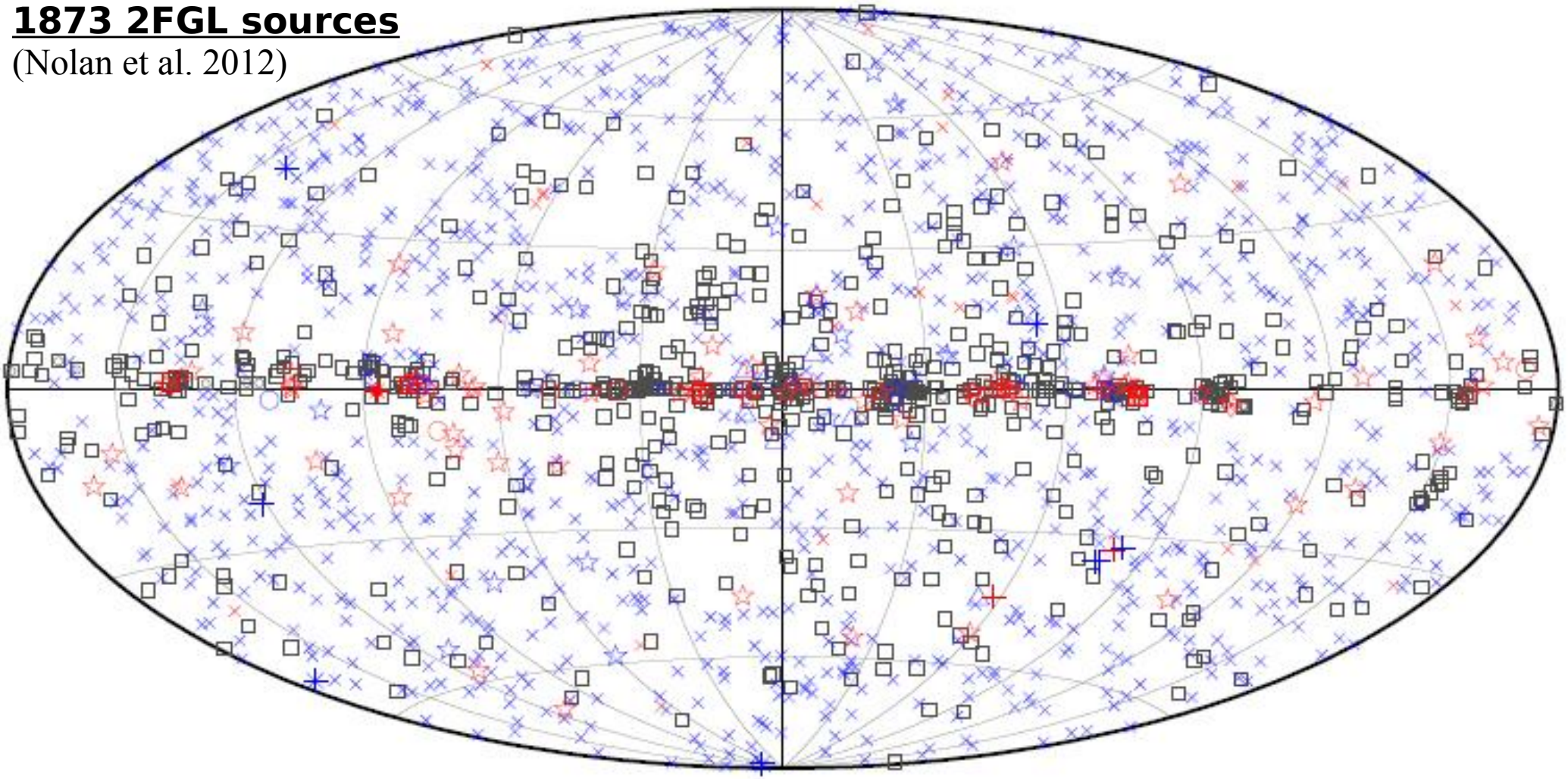
HE sky from *Fermi*/LAT



5-yr all-sky image (E > 1 GeV)

HE sky from *Fermi*/LAT

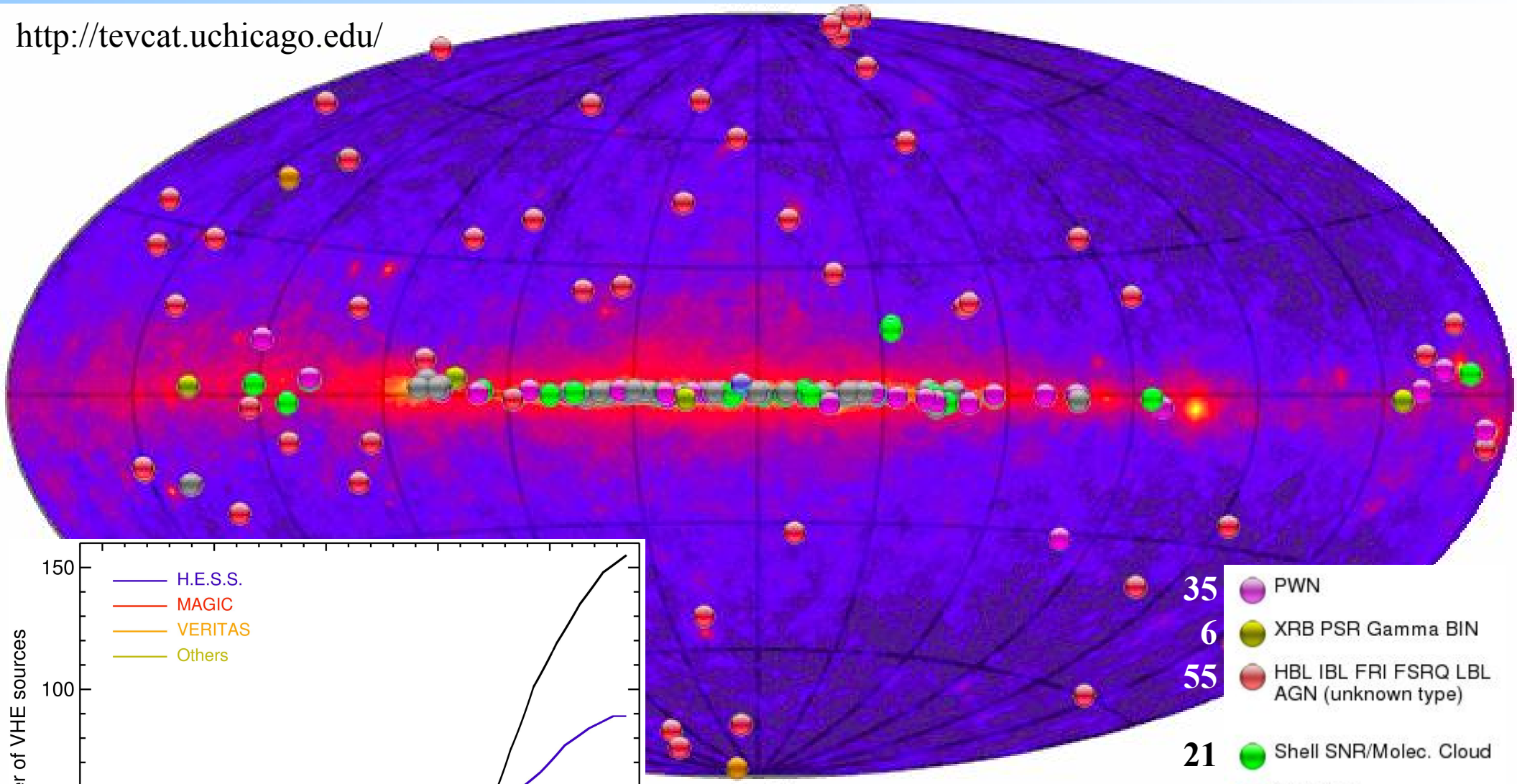
1873 2FGL sources
(Nolan et al. 2012)



No association	Possible association with SNR or PWN	
AGN	Pulsar	Globular cluster
Starburst Gal	PWN	HMB
Galaxy	SNR	Nova

VHE sky from IACTs

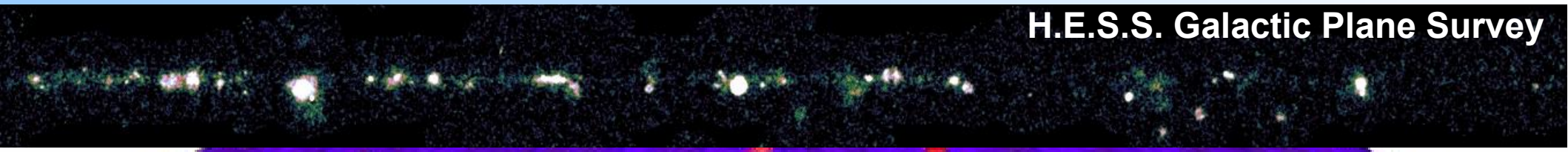
http://tevcat.uchicago.edu/

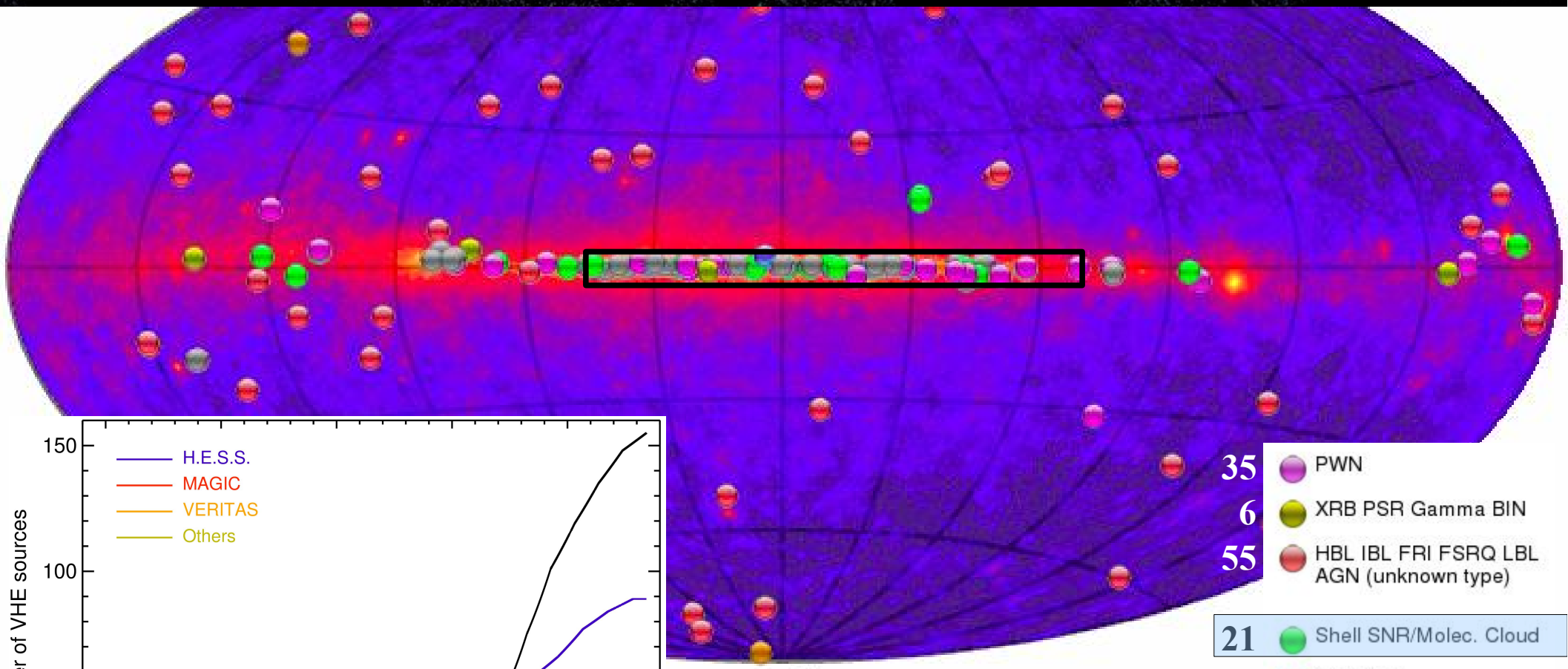


155 sources as of june 2013

35	PWN
6	XRB PSR Gamma BIN
55	HBL IBL FRI FSRQ LBL AGN (unknown type)
21	Shell SNR/Molec. Cloud
2	Starburst
30	DARK UNID Other
6	uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

VHE sky from IACTs





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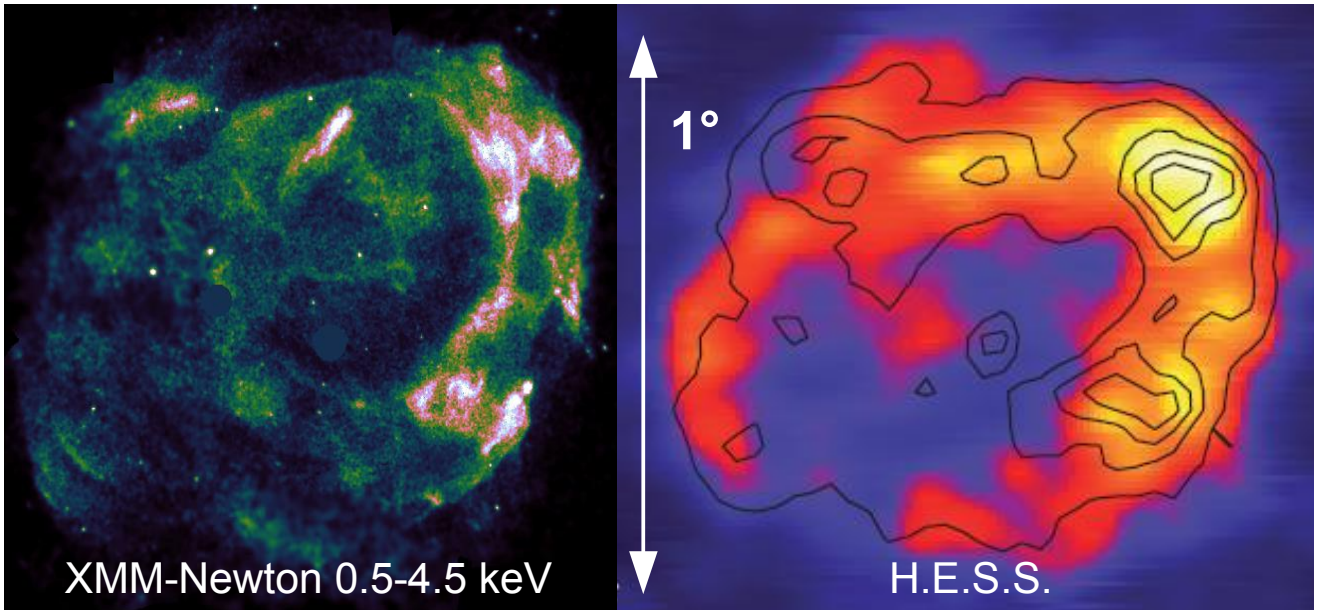
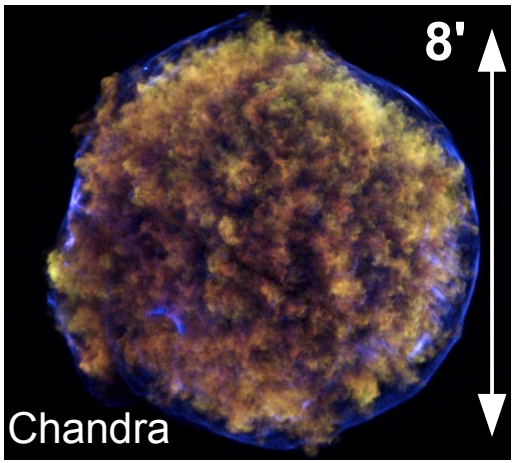
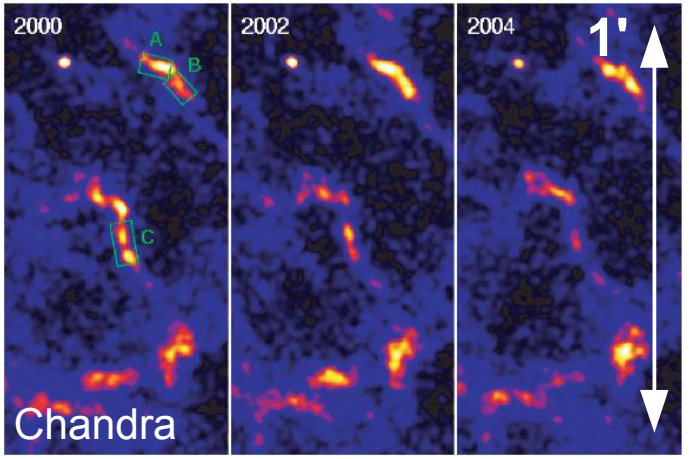
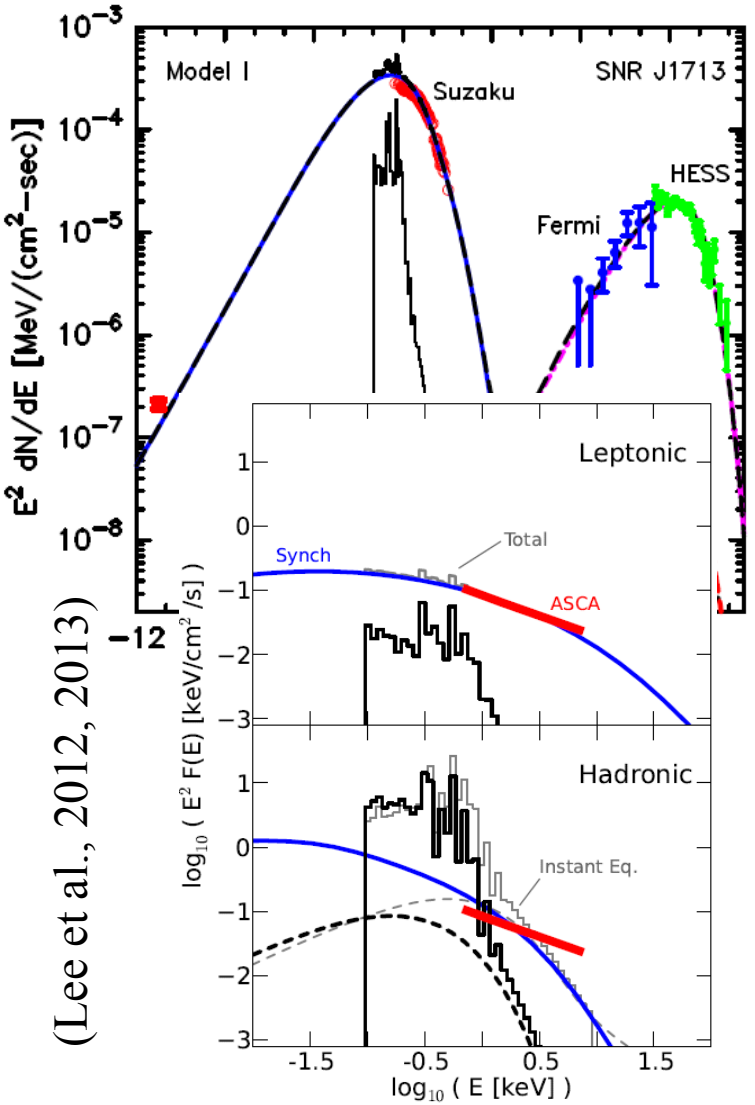
SNRs at HE/VHE gamma-rays









Thermal emission → hydrodynamical conditions
Small-scale structures → B-field → CR acceleration
Nonthermal spectrum → diffusion regime

⟷

Origin of γ-ray emission ↔ E_{max}, ε_{CR}
SNRs ↔ Galactic CR sources ?