Science with LST :
the puzzling case of the Boomerang SNR

F. Cassol, 1st VHEGAM meeting, 15-17 January 2024

Introduction

The history of the Boomerang SNR (G106.3+2.7) is pretty long.

It starts in 1990 when it has been discovered as SNR, then MWL data have been added year after year leading to several interpretations or/and hypothesis on its nature and characteristics.

2019 has been pivotal year, when several experiments start to detect VHE and UHE gamma rays emission (up to 570 TeV) inside the SNR, which made it one of the most promising galactic hadronic PeVatron candidate.

Since then, several authors tried to explain the origin of the VHE-UHE emission adding MWL data and/or fitting possible MWL emission models, without any firmly conclusive result yet.

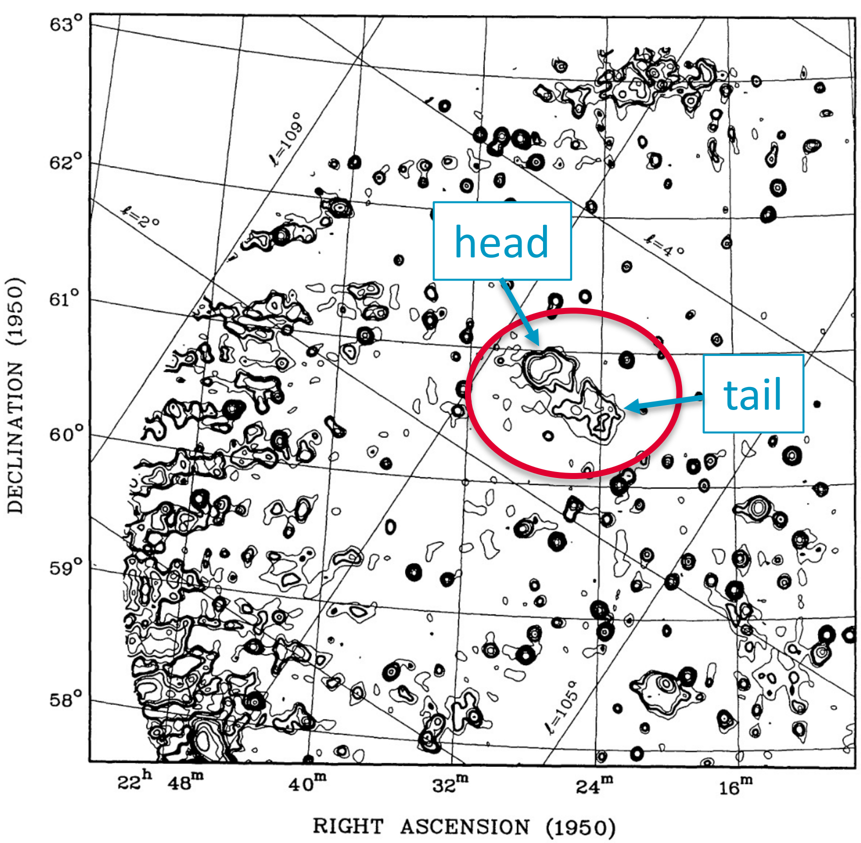
The necessity of improving the knowledge of the VHE emission morphology in order to discriminate among the models makes this SNR a priority target for IACT experiments, which are the only experiments that can guarantee the best angular resolution at E> 1 TeV.

In this talk, we will mainly review the present MWL data and briefly describe the expected results with the ongoing LST and LST+MAGIC observation campaign.

Identified as SNR in radio

Joncas & Higgs (1990)

*W*ith the Dominion Radio Astrophysical Observatory (DRAO) at *408 MHz continuum* defined as a probable SNR composed of two patches: after defined "head" and "tail"
Large angular size : 50' x 18' , i.e. 0.8° x 0.3° → extended source



Source	Description	408-MHz Flux (Jy)
G106.30+2.76	Extended emission area, about 50′ × 18′ in two patches:	8.4±0.5
G106.10+2.73	Fainter SW portion, about 22′ × 18′	3.0±0.6
G106.58+2.86	Brighter NE portion, about 18′ × 12′	4.0±0.2

Using 1420 MHz continuum of Kallas & Reich (1980): spectral index = 0.45 +- 0.05

Image resolution: 3.40'x 3.86', ontours: 70-800 K

Identified as gamma source at E> 100 MeV

Hartman et al. (1999)

In third EGRET catalogue for gamma sources with E> 100 MeV – 20 GeV :

- Angular resolution 5.5º at 100 MeV and 0.5º at 5 GeV
- 95% contour for source position: θ_{95} = 0.46º
- spectral index Γ= 2.24 +- 0.14

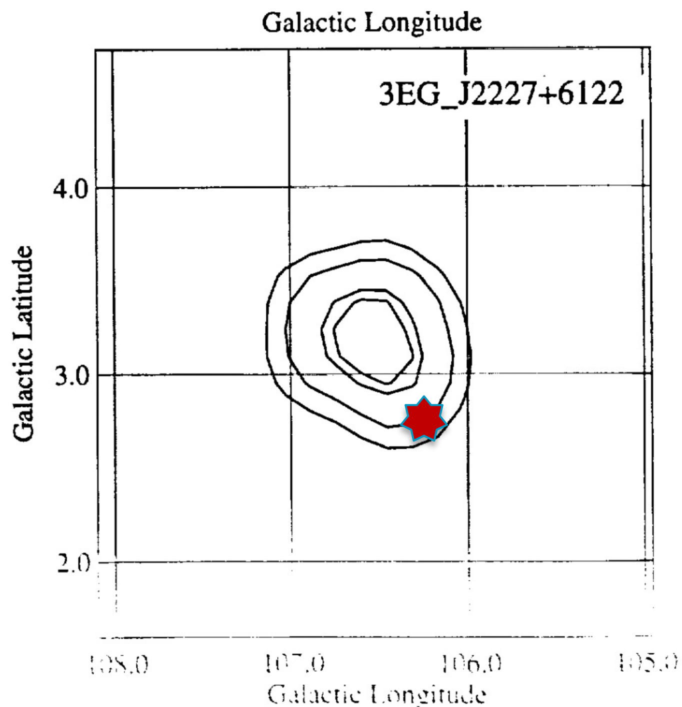
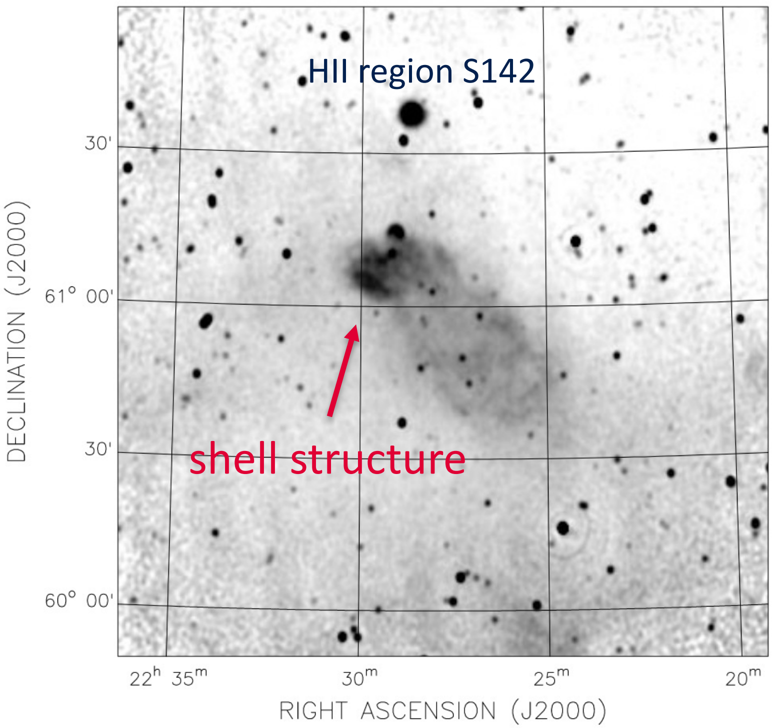


Image: 50%, 68%, 95%, 99% contour for the source position (point source likelihood)

Described as old shell type SNR

Pineault & Joncas (2000)

With DRAO Synthesis Telescope higher radio resolution data: shell type SNR with size 60’x 24’



1420 MHz continuum
Resolution 1.15’x 1.0’, range: 6-9 K

Spectral index of tail is a bit steeper than head: Unrelated object?

TABLE 2

INTEGRATED FLUX DENSITIES AND SPECTRAL INDICES

Object	S_{1420}	S_{408}	α_{int}	α_{TT}
Head	2.3 (0.3)	4.7 (0.3)	0.56 (0.10)	0.49 (0.05)
Tail	2.6 (0.4)	5.7 (0.2)	0.63 (0.11)	0.70 (0.07)
Whole	4.9 (0.6)	10.5 (0.3)	0.61 (0.09)	0.57 (0.04)

NOTE.—Errors shown in parentheses.

Identified as shell type old SNR

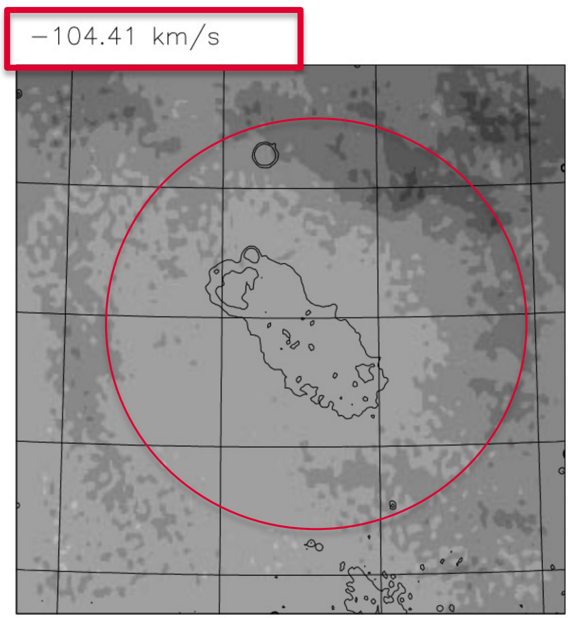
Pineault & Joncas 2000

They associate the SNR to a low density cavity in HI at v_{LSR}= -105 km/s → distance = 12 kpc

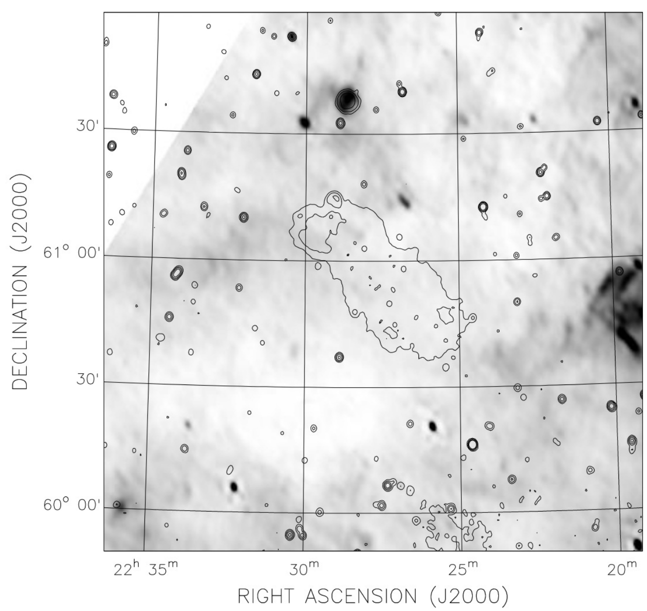
With HIRES data, no correlation infrared images → no warmed dust

From surface brightness-diameter (L=7 x 10^{-22} W Hz^{-1} cm^{-2} s^{-1} at 1 GHz) → maximum diameter = 165 pc → maximum distance = 11.5 kpc

They deduce an old SNR in the late stage of it is isothermal evolution → age 1.25 x 10^5 yrs



HI emission, range



IR image, 61 μm, resolution ~1'.15

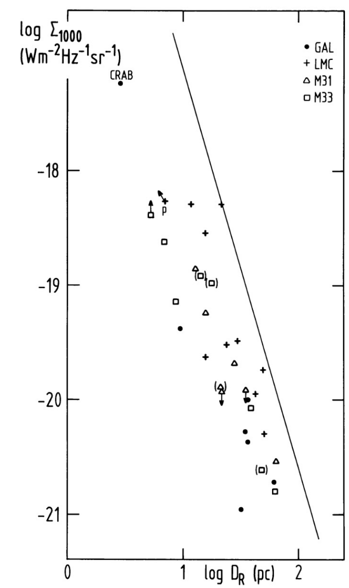


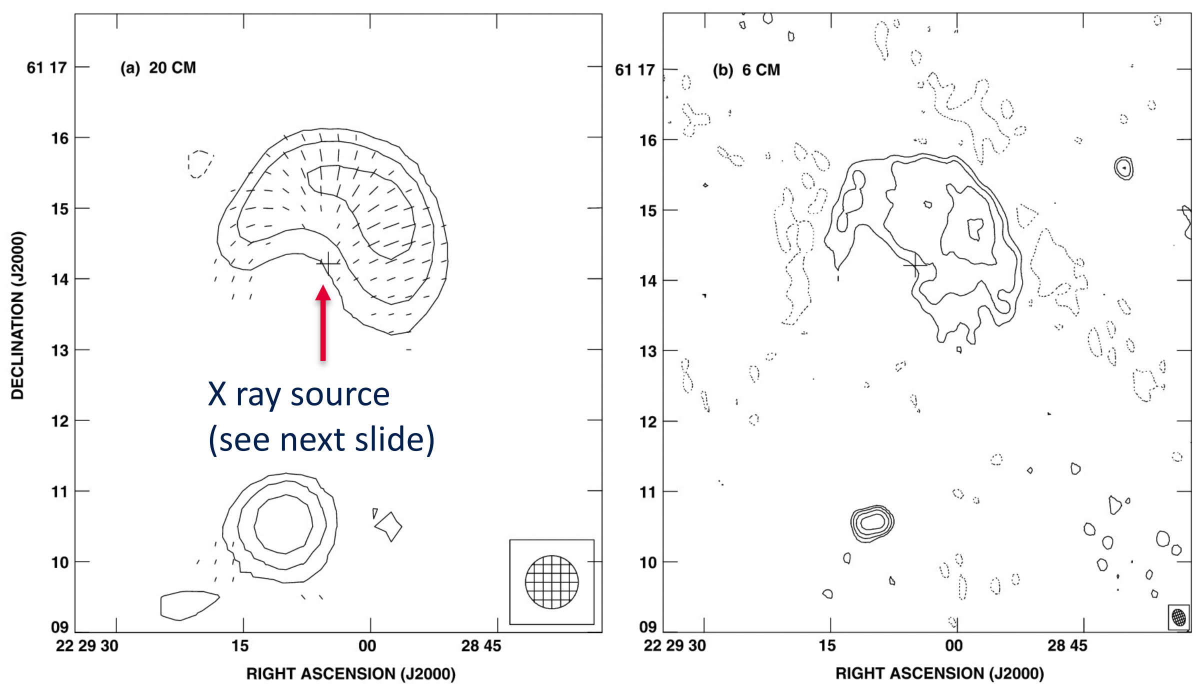
Fig. 7b. Σ_R-D_R diagram for the SNRs with measured [S II] lines. The line of maximum observable diameter from Fig. 1 is shown

Berkhuijsen (1986)

‘head’ discovered in polarized radio

Halpern et al. (2001a)

Searching in EGRET region with Very Large Array (VLA) and other telescopes, they find a radio polarized shell (100’’) with 25-30% polarization and index $\alpha \approx 0$ (flat spectrum)
→ pulsar and PWN hypothesis

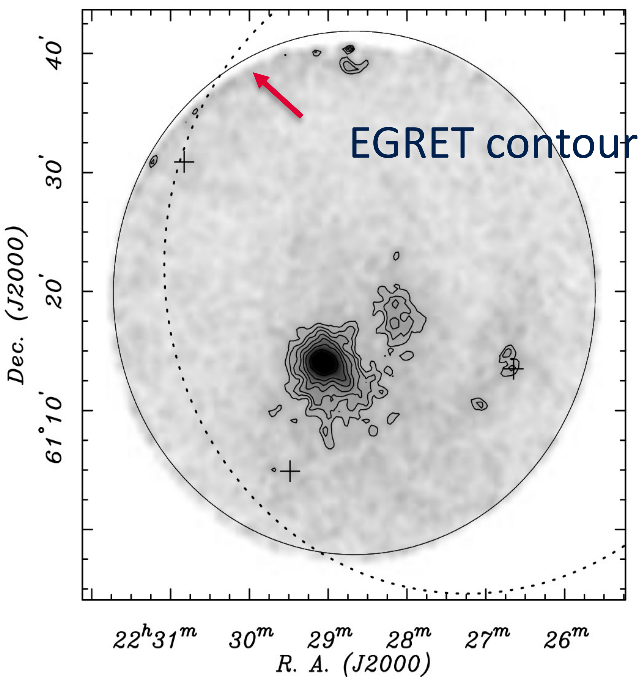


‘head’ discovered in X-rays

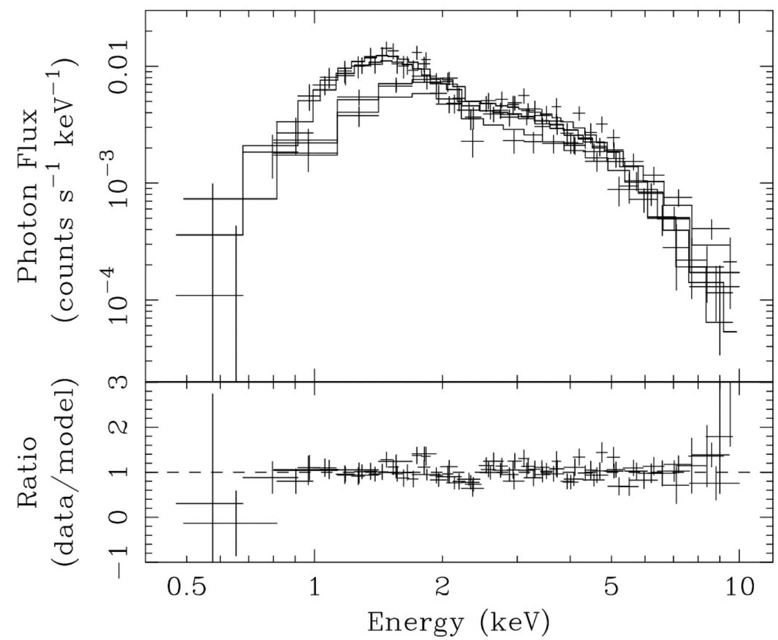
Halpern et al. (2001a)

Searching in EGRET region with ROSAT HRI, they find dense X-ray emission in correlation with polarized radio source.

→ From X-ray absorption, assuming a power law spectrum, they estimate a column density $N_H = 6.3 \times 10^{21}\ cm^{-2}$, close to the total 21 cm galactic column density $8.4 \times 10^{21}\ cm^{-2}$, which suggests a source “at least 2 kpc distant and possibly much farther” → they assume a fiducial distance of 3 kpc, which will be used by several successive works



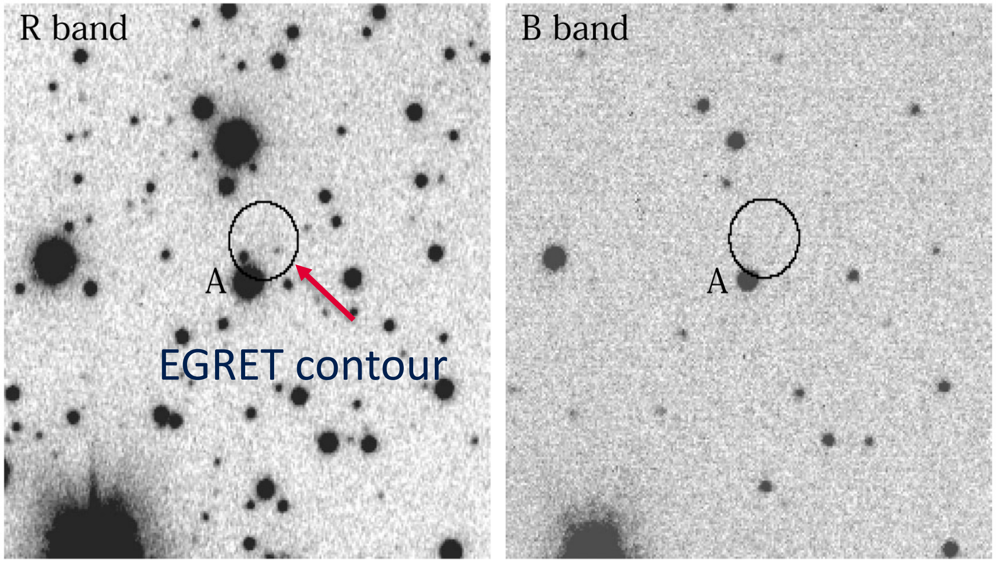
Power law spectrum, fitted index $\Gamma = 1.51 \pm 0.14$



No optical or Hα emission

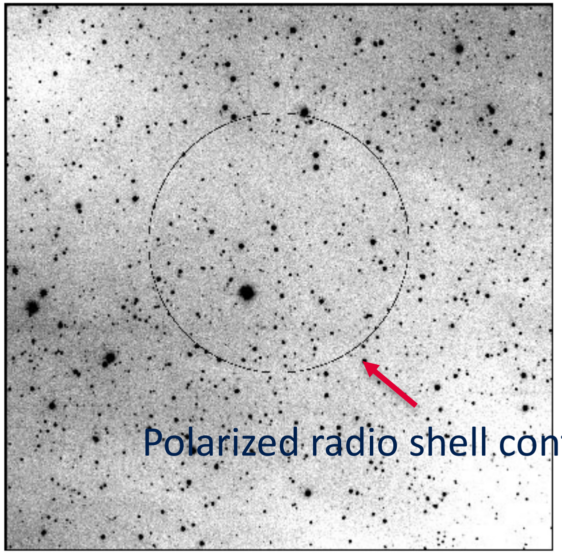
Halpern et al. (2001a)

No optical image for R < 21.3 and B <24



KPNO 2.1 m telescope

No Hα emission



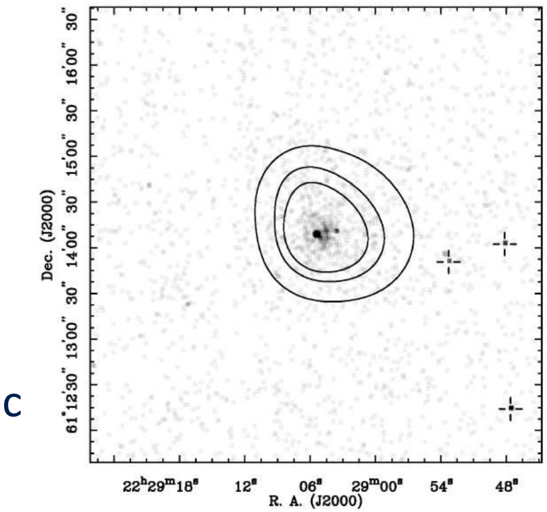
MDM 2.4 m telescope at 6563 Å

Powerful pulsar detection in X-ray

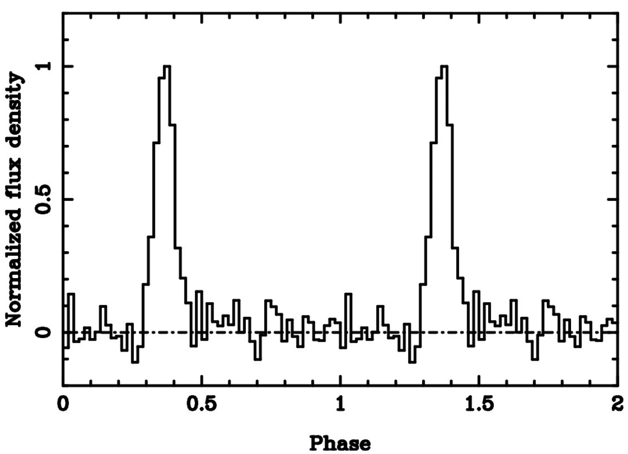
Halpern et al. (2001b)

With Chandra ACIS–I, ASCA and the radio telescope at Jodrell Bank, a powerful pulsar is discovered in the head

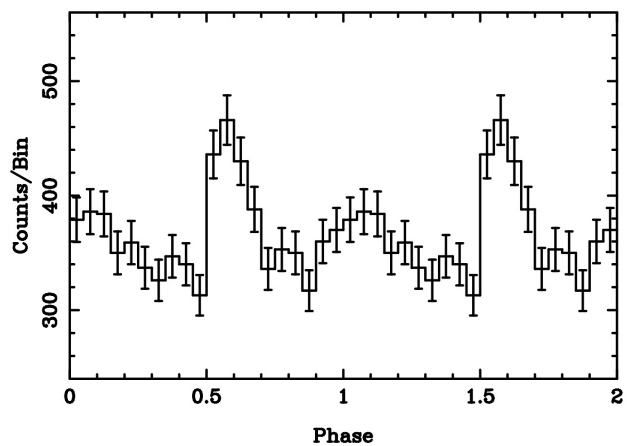
- Period : P = 51.6 ms
- High spin down luminosity : $\dot{E}$= 2.2 x 10^{37} ergs s^{-1}
- Characteristic age : τ_c= 10.460 year
- P derivative : $\dot{P}$ = (7.8 +- 0.03) x 10^{-14} s s^{-1}
- High radio dispersion measure : DM = n_ed = 200 +- 10 cm^{-3} pc → d = 12 kpc , but they prefer to keep 3 kpc from X-ray absorption (→ to be studied again with better n_e data?)



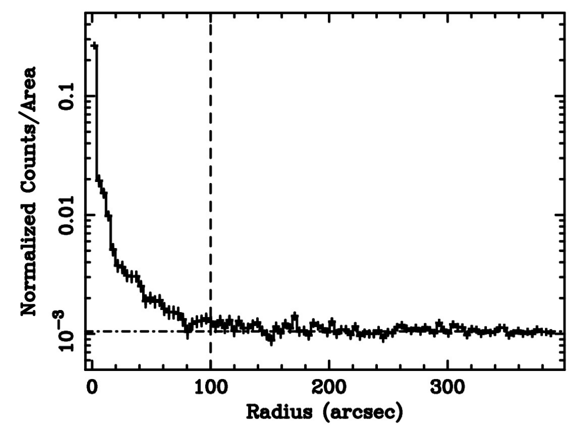
X-ray (2-10 keV) image (pixel 2'')



Radio pulse profile a 1412 MHz



X-ray pulse in the 0.8–10 keV

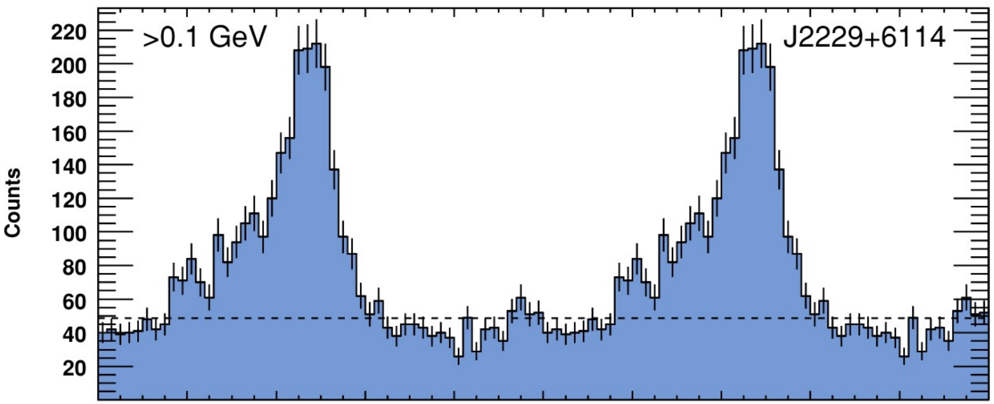


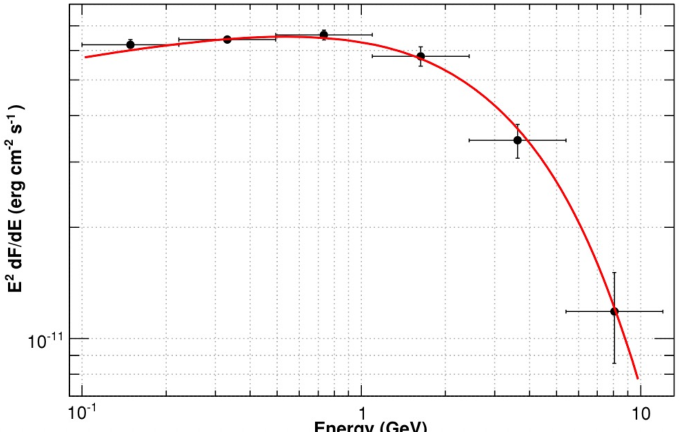
X-ray radial profile

Pulsar detection in GeV by Fermi

Abdo et al. 2009b

Phase-averaged spectrum: Cut off = 3.6 GeV, Γ ~ 1.85

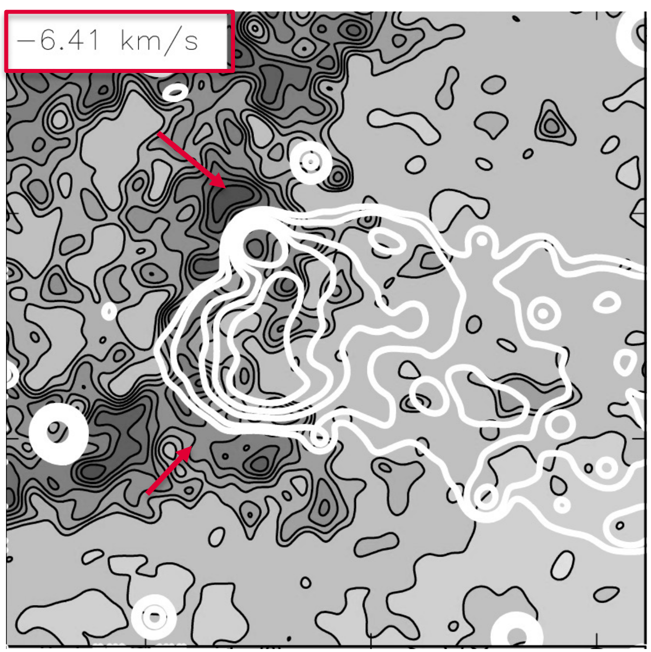




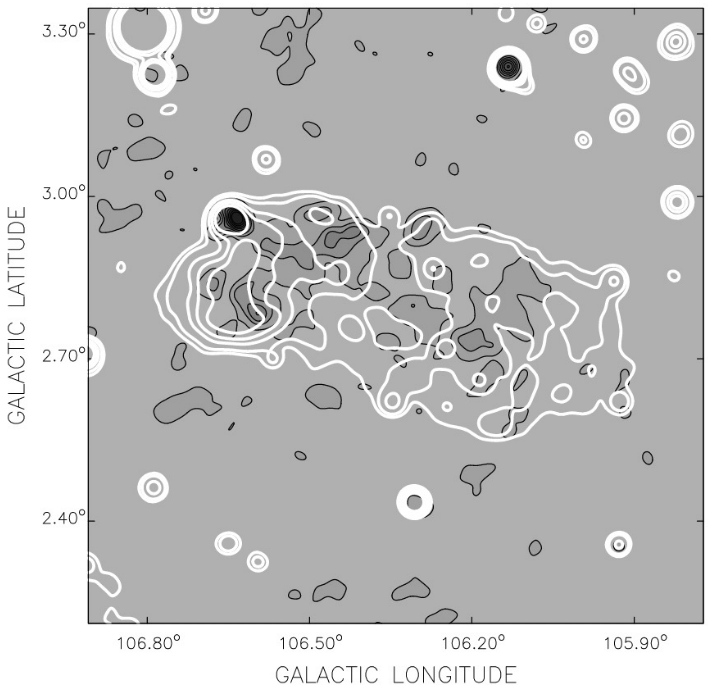
SNR connected to molecular cloud

Kothes et al. (2001)

From the Canadian Galactic Plane Survey (CGPS), they correlate the shape of HI cloud to PWN and head at v_{LSR} = -6.41 km/s → distance = 0.8 kpc
They see also high polarization zones (70%) on the SNR : low de-polarisation → d < 2 kpc
→ SNR length 14 pc, width 6 pc and PWN 0.8 pc wide



HI (grey) and radio continuum 1420 HZ (white)

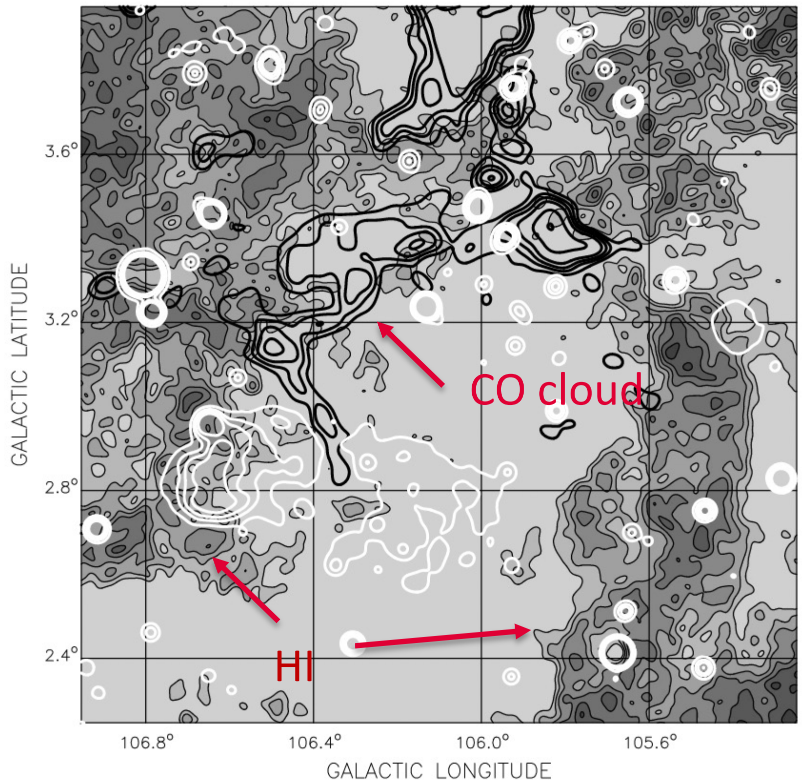


Polarization map (100 to 500 mK in steps of 50 mK)

SNR connected to molecular cloud

Kothes et al. (2001)

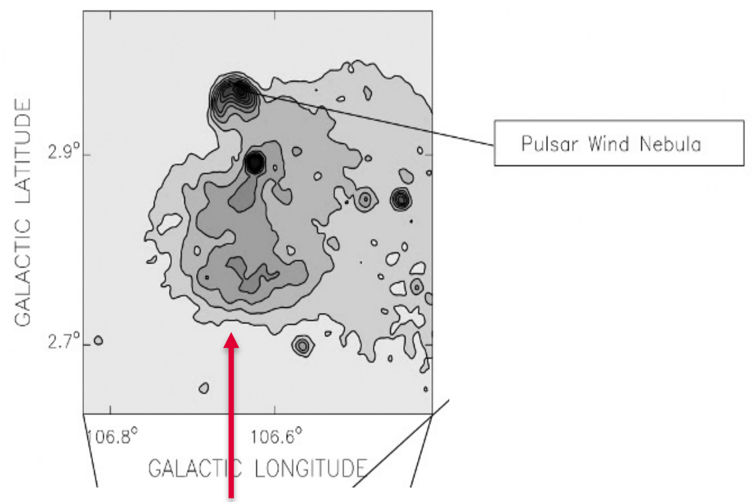
Molecular cloud data ^{12}CO (115 GHz) from the Five College Radio Astronomy Observatory (FRAO)



HI (grey) and CO (black) average emission at v_{kin}=[-5.6,-7.2], radio continuum 1420 HZ (white)

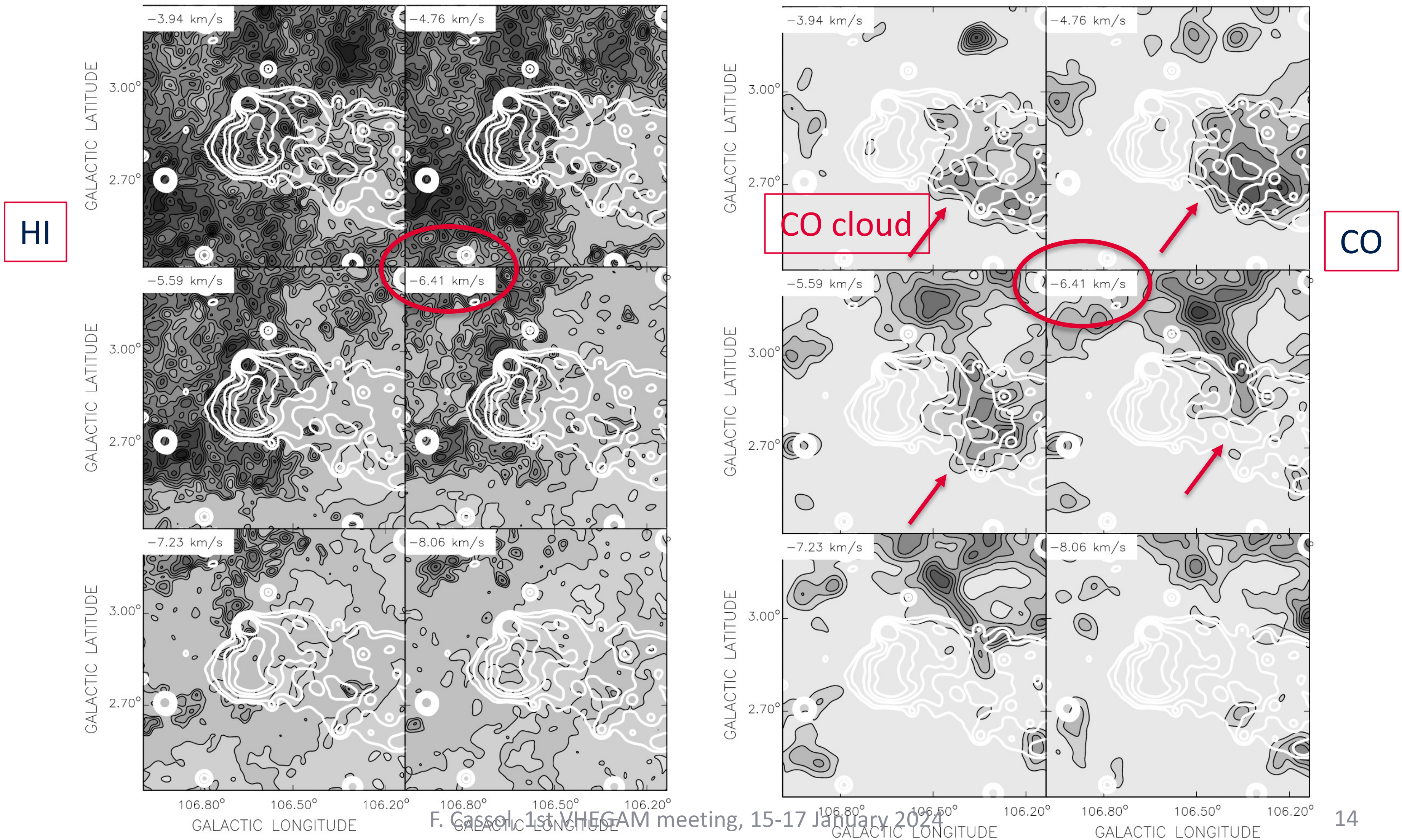
The head interact with HI dense material and the tail outbreaks in a low density bubble.

The explosion was close to the present pulsar position.



SNR connected to molecular cloud

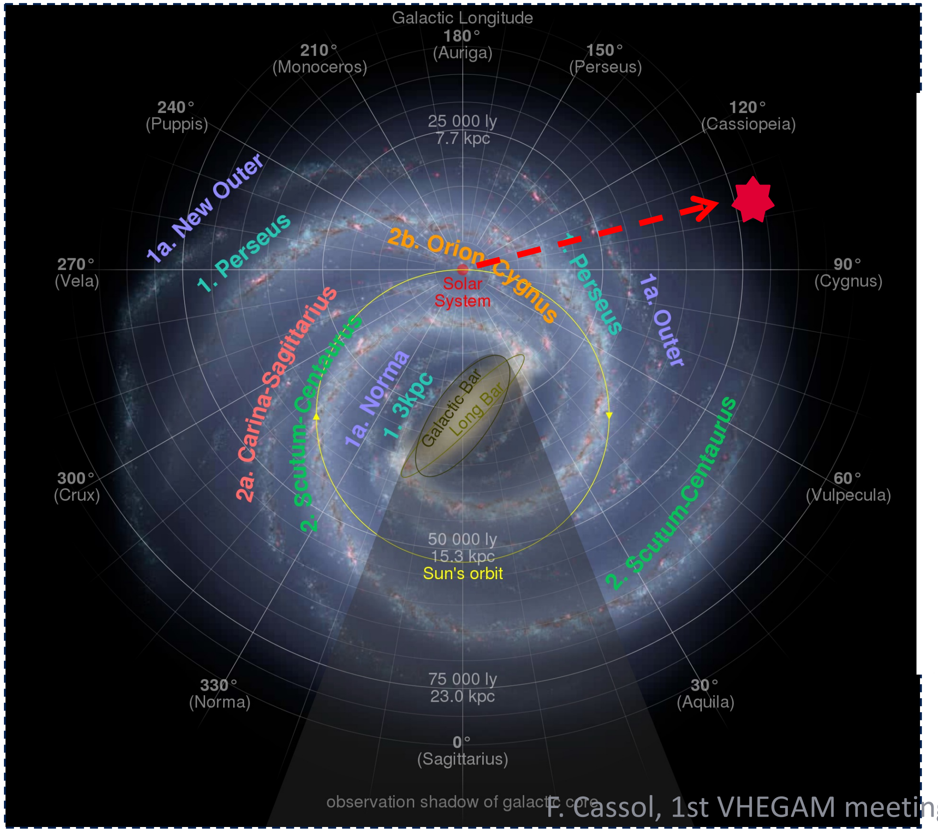
Kothes et al. (2001)

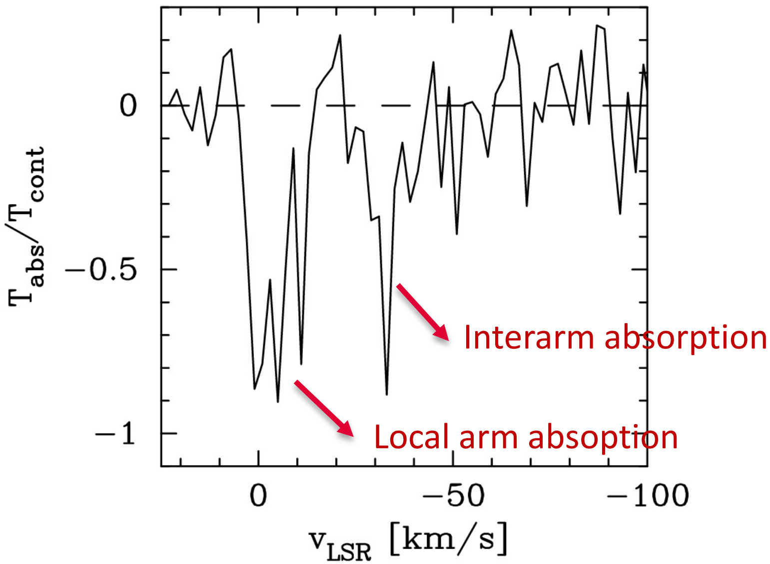


PWN distance from absorption of polarized emission

Kothes et al. (2004)

Determination of the kinematic distance based on absorption of linearly polarized radio continuum emission by HI :
No evidence of Perseus arm absorption → Boomerang in the local arm → distance < 3 Kpc



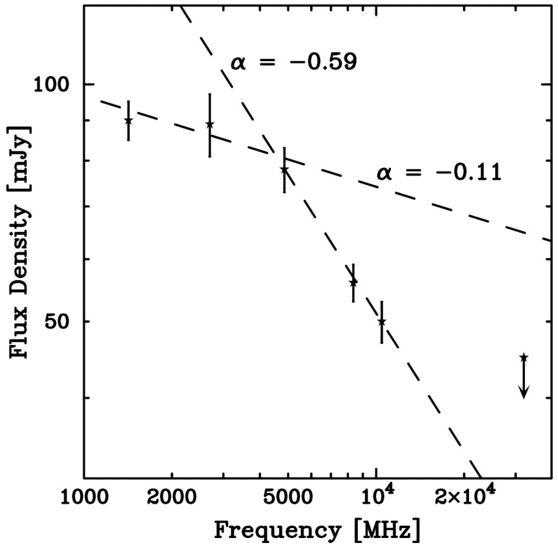


Estimation of PWN age

Kothes et al. (2006a)

With Effelsberg 100 m radio telescope, radio data at high frequency show a spectral break in the border of PWN at 4.3 GHz, if this is interpreted as a cooling break (e.g. the frequency at which the electrons have lost they energy during the age of the PWN) → they estimate PWN age is 3900 yrs and B=2.6 mG (based on the evolution of B and the energy content of the pulsar)

→ The radio luminosity is very low because the original nebula has been washed out by the reverse shock and the present PWN is a second ones with less energy than the original ones.

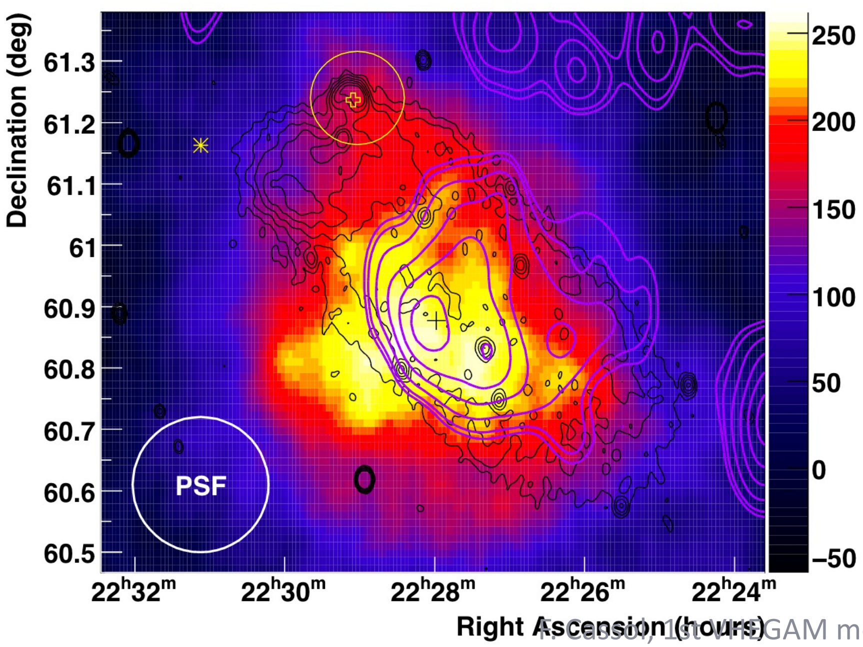


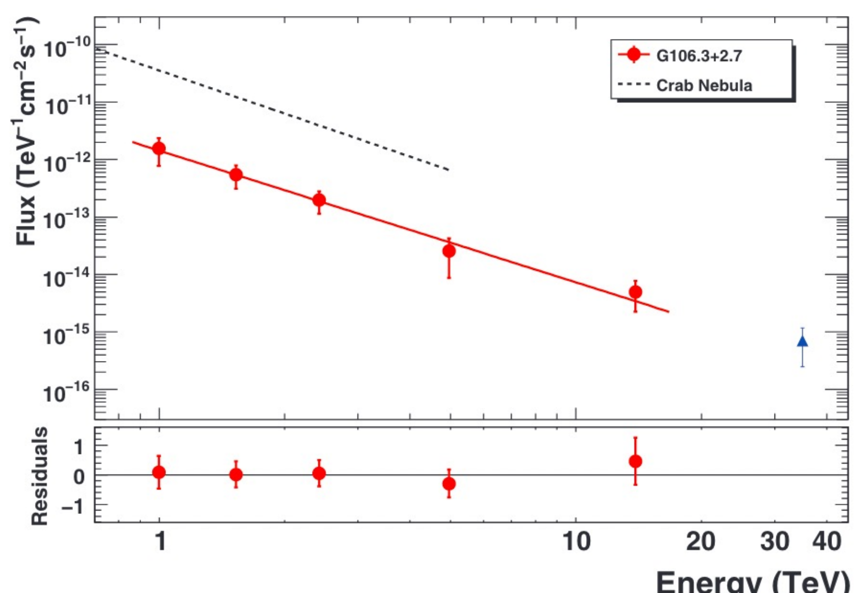
Detection at E > 1 TeV by VERITAS

Acciari et al. 2008

TeV source is displaced of ~ 0.4° from the pulsar, over the CO molecular cloud.
Post trail significance = 6 σ in the peak emission, 3.6 σ in the pulsar location

Observation time : 33.4 h, PSF = 0.11° , E threshold = 630 GeV
Angular size = 0.27° x 0.18°
Flux at 1 TeV ~ 5% of the Crab : 1.11 x 10^{-12} TeV^{-1} s^{-1} cm (integrated in radius of 0.32°)
Power law index : $\Gamma = -2.29$
PS: Other experiments scale the Veritas flux of 1.62 estimating a spillover of 38%





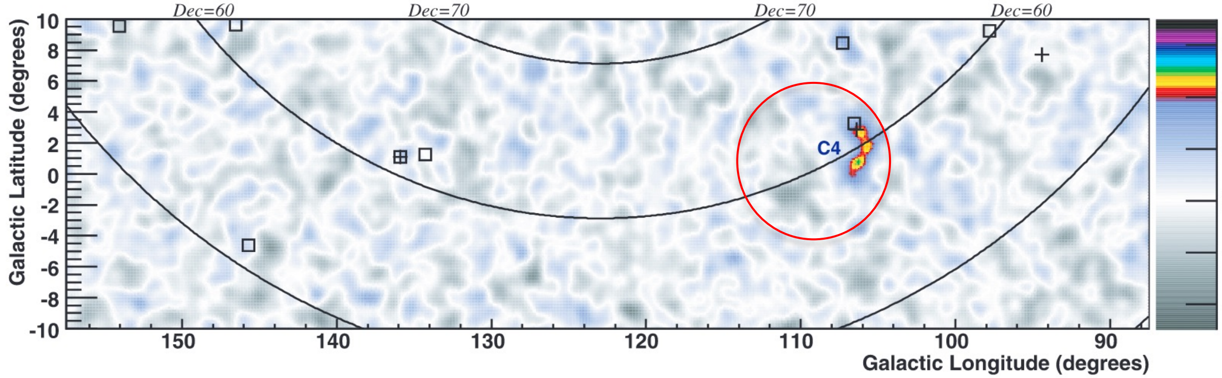
Detection at E > 10 TeV by MILAGRO

Abdo et al. (2007) (2009)

VERITAS detection confirmed but with poor angular resolution

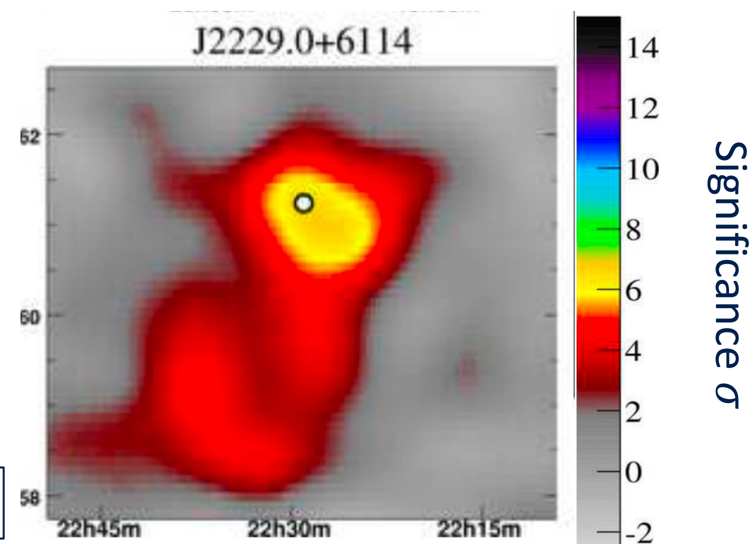
At 20 TeV: C4 source
Flux = 4. x 10^{-15} TeV^{-1} s^{-1} cm^{-2}
angular resol. ~ 1.1°
Diameter ~ 3.4°

TeV gamma ray galactic source survey

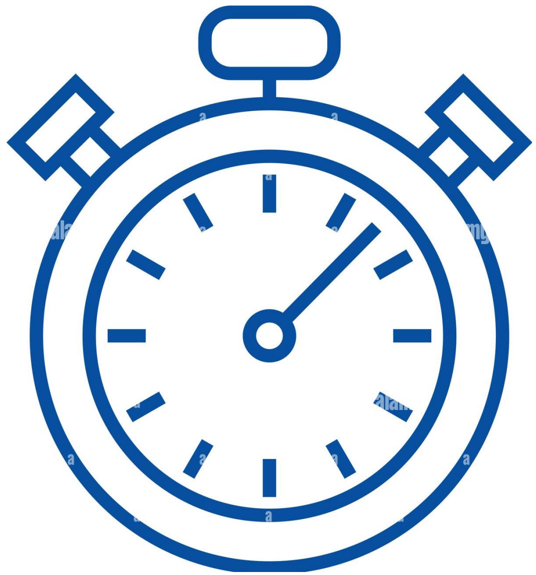


At 35 TeV: Flux = 70.8 x 10^{-17} TeV^{-1} s^{-1} cm^{-2}
Position on the pulsar but with angular resolution > 0.4°-1.0°

White dot = Pulsar Fermi position



No progress for ~ 10 years …



…then, in 2019 starts the promising “PeVatron” phase

Detected > 1 GeV source in the tail by Fermi-LAT

Xin et al. (2019)

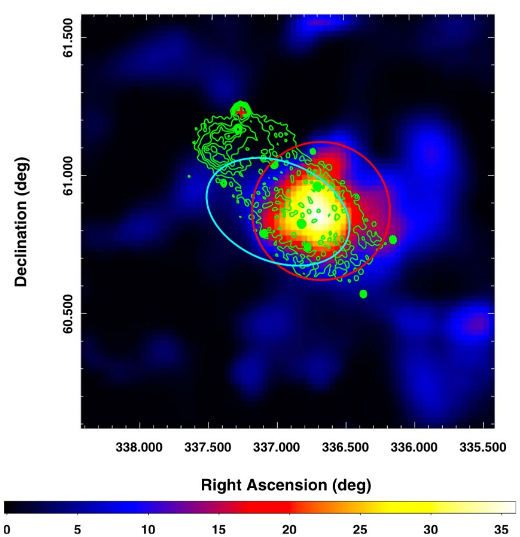
Title = “VER J2227+608: A Hadronic PeVatron Pulsar Wind Nebula?”

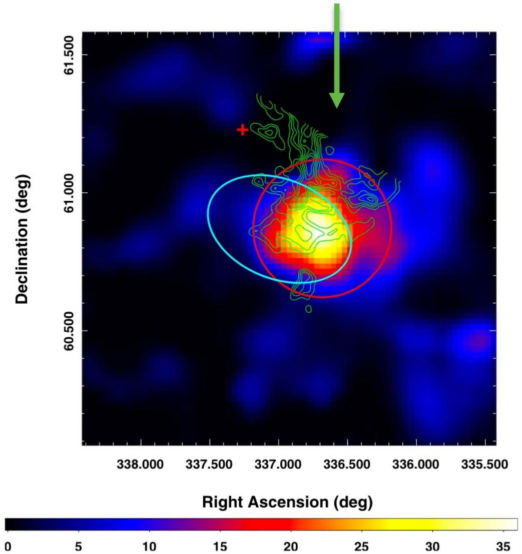
Energy range = 3 - 500 GeV

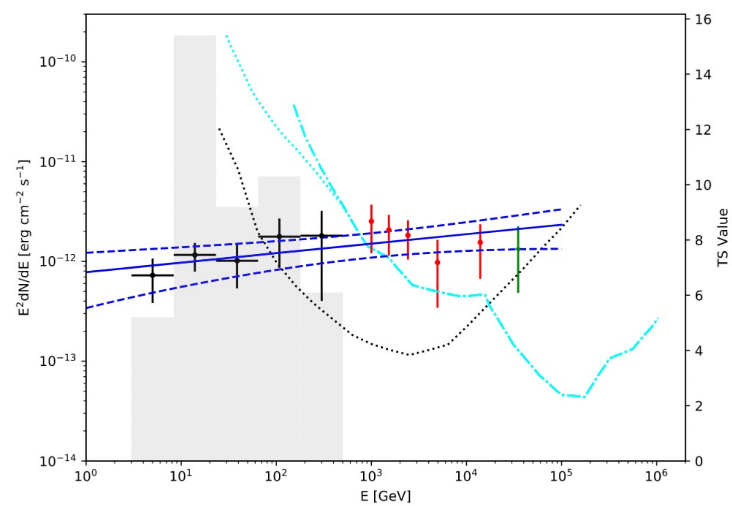
Size = uniform disk 0.25° spatially coincident with the CO molecular cloud

First MWL fit with VHE data from VERITAS and Milagro data: they make the hypothesis that the p/e are accelerated by PWN

CO cloud







Detection at E > 100 TeV by Hawc

Albert et al. (2020)

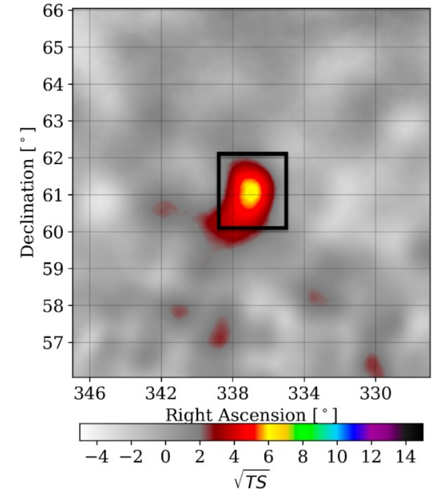
Tittle = “HAWC J2227+610 and its association with G106.3+2.7, a new potential Galactic PeVatron”

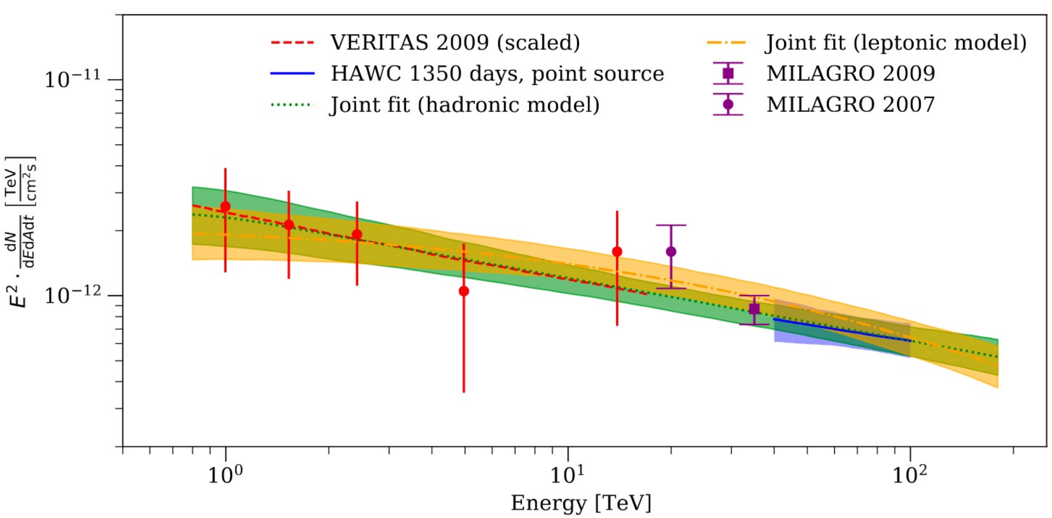
Energy range = 40 - 110 TeV

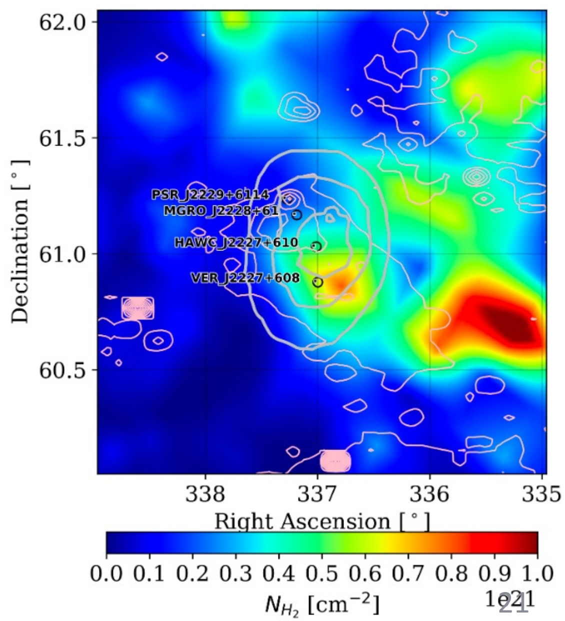
Angular resolution : θ_{68} = 0.2º - 1º

Angular size: σ = 0.232º

→ VHE-UHE fit with leptonic/hadronic models







Detection at E > 100 TeV by Tibet ASγ

Amenomori et al. (2020)

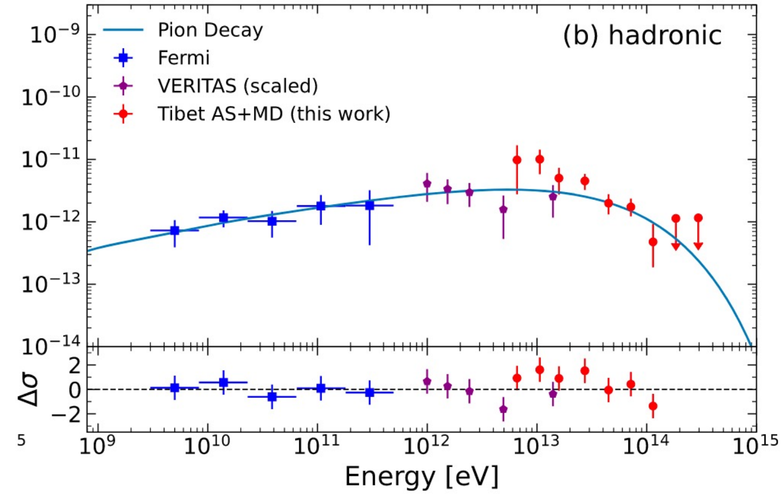
Title= “Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays”

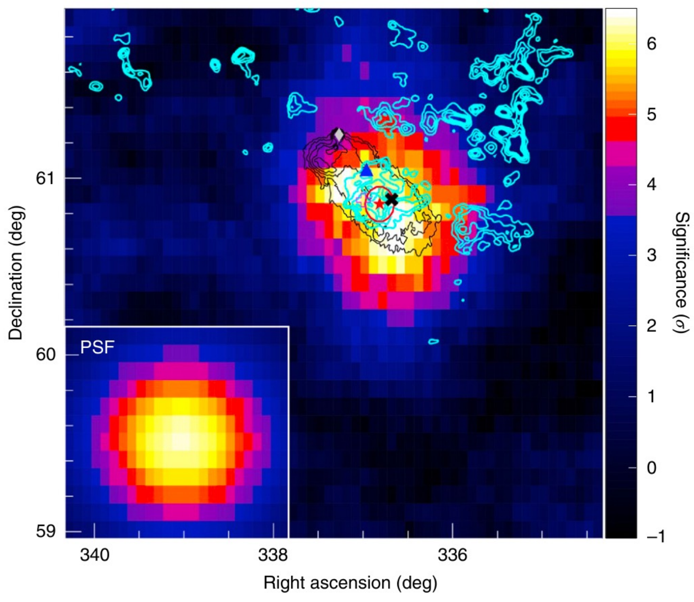
Confirmation of Hawc data

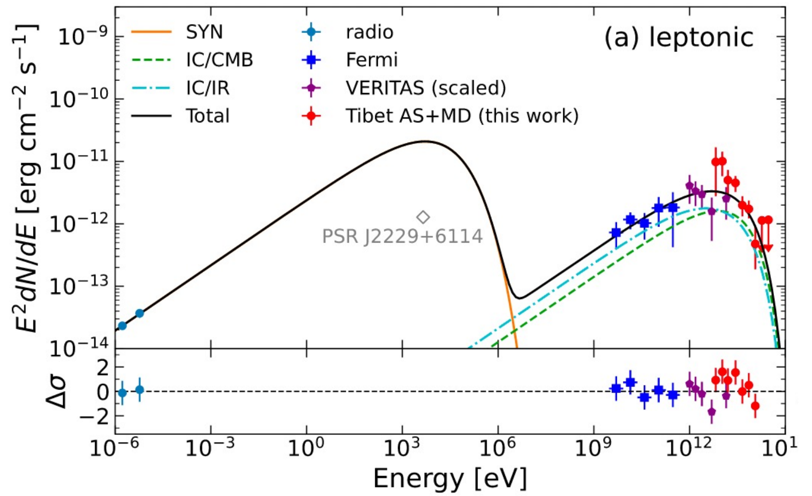
Energy range = 6 - 115 TeV

Angular resolution : θ_{95} = 0.5°/0.2° for 10/100 TeV

→ MWL fits with leptonic/hadronic models







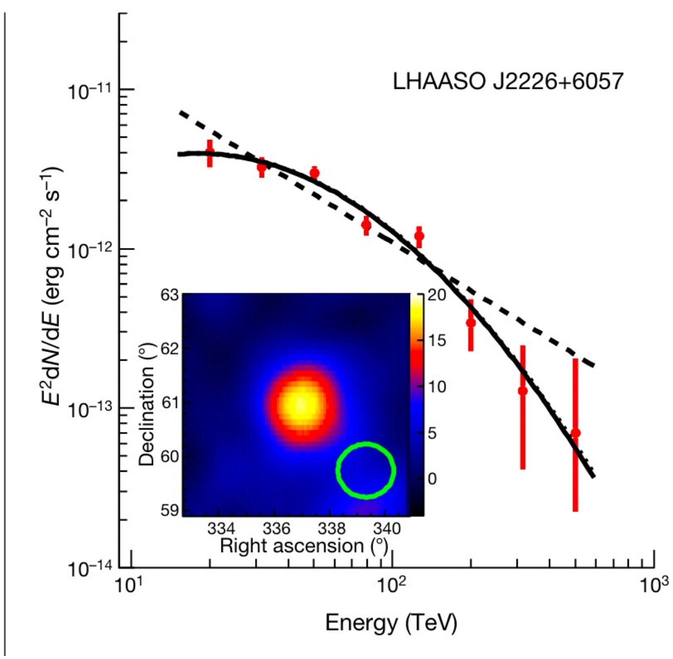
Detection at E > 500 TeV by LAAHSO

Cao et al. (2021)

Title = "Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources"

Energy range ~ 15 - 570 TeV
Angular resolution : θ_{68} = 0.49º - 1º
Log parabola fit

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)



Two instruments:
WCDA (78.000 m^2) for E >1-25 TeV and KM2A (1.3 km^2) for E= 25 TeV –1.6 PeV

WCDA PSF 0.22º/0.3º for E>1/25 TeV

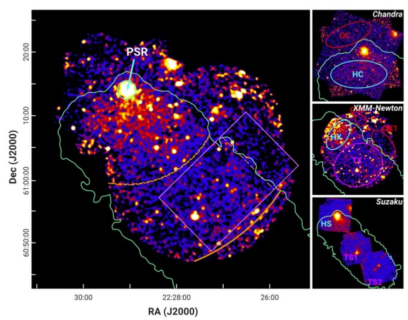
LM2A PSF 0.2º/0.5º for 10/100 TeV and zenith< 0.20º, it depends on zenith

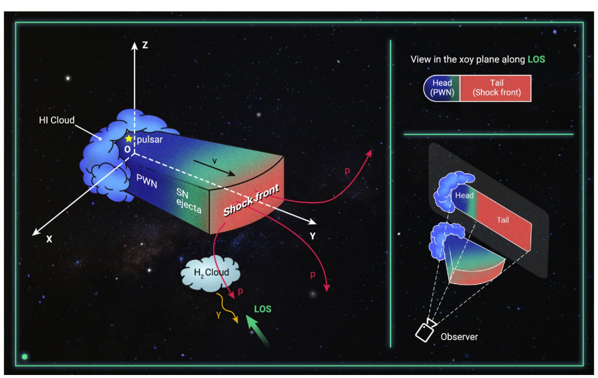
Detection of X-ray in the tail

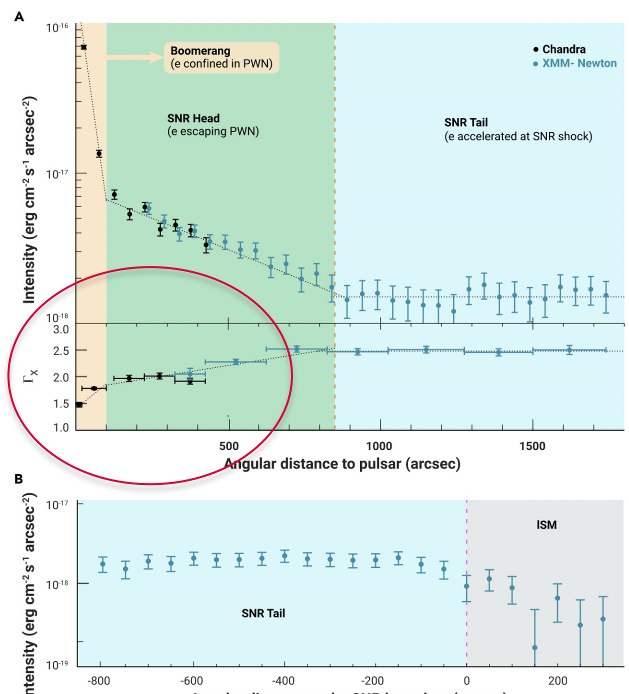
Ge et al. (2021) *(also Fujita et al. (2021))*

Title = "Revealing a peculiar supernova remnant G106.3+2.7 as a petaelectronvolt proton accelerator with X-ray observations"

X-rays flux and index change in head and tail → different origin: from PWN in head, electrons accelerated in situ from tail ?
They suggest a SNR expanding in a low density cavity, still in free expansion, with high shock velocity (> 3000 km/s) in the tail since they do not see spectral break in X-ray







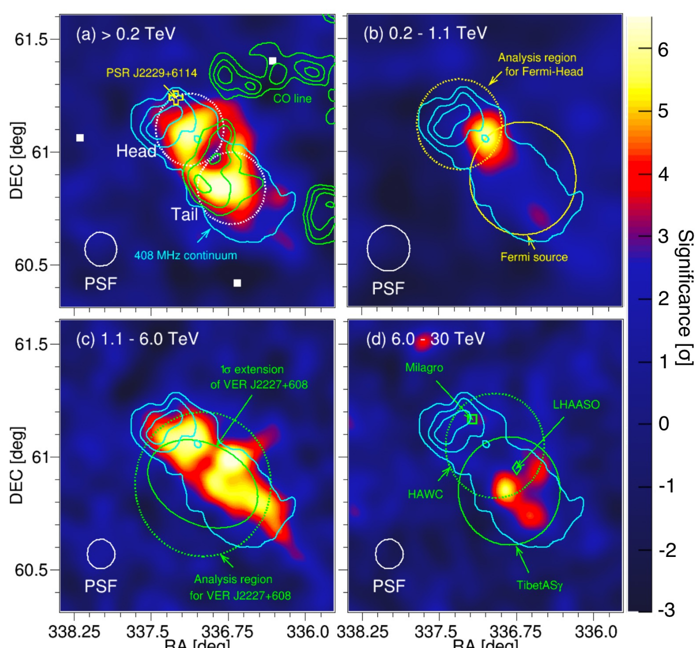
High angular resolution detection by MAGIC

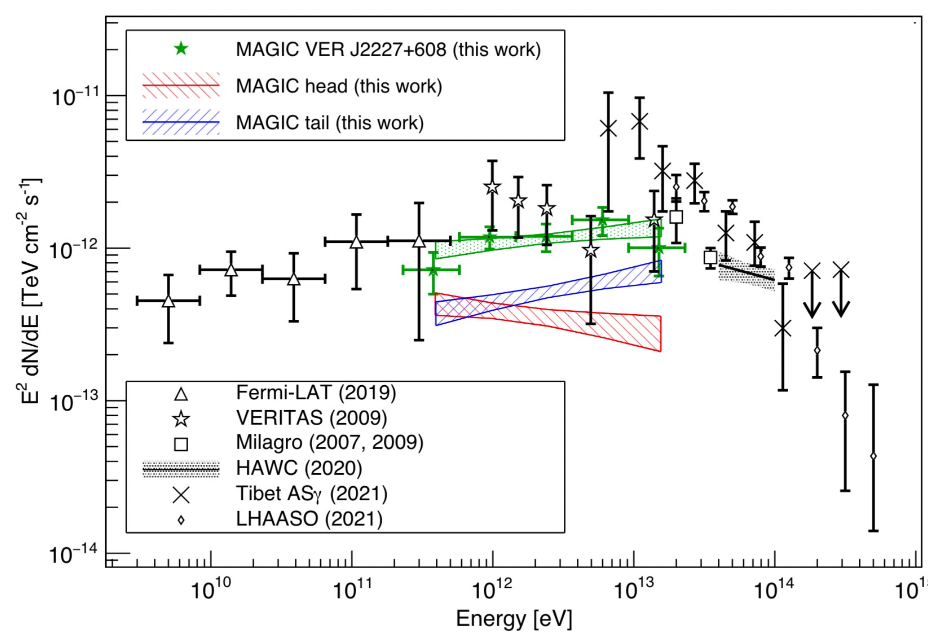
Abe et al. (2022)

Title = “MAGIC observations provide compelling evidence of the hadronic multi-TeV emission from the putative PeVatron SNR G106.3+2.7”

First evidence of energy dependent morphology 0.2-30 TeV energy range
Observation time : 121.1 h, PSF ~ 0.8°-0.1°, E threshold = 200 GeV,

Separated head and tail MWL fit: tail emission explained only with hadronic model → leptonic and hadronic emission from different sites? SNR and far clouds?





Finally, most recent data

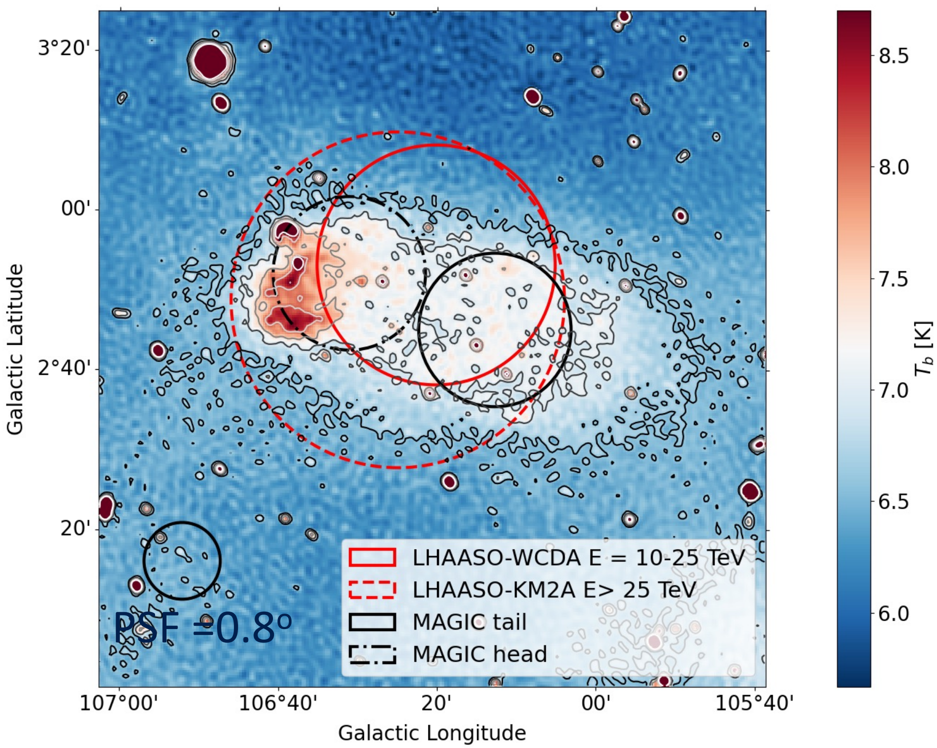
They suggest a diffuse emission in the multi TeV range also in the head region and even outside the SNR …

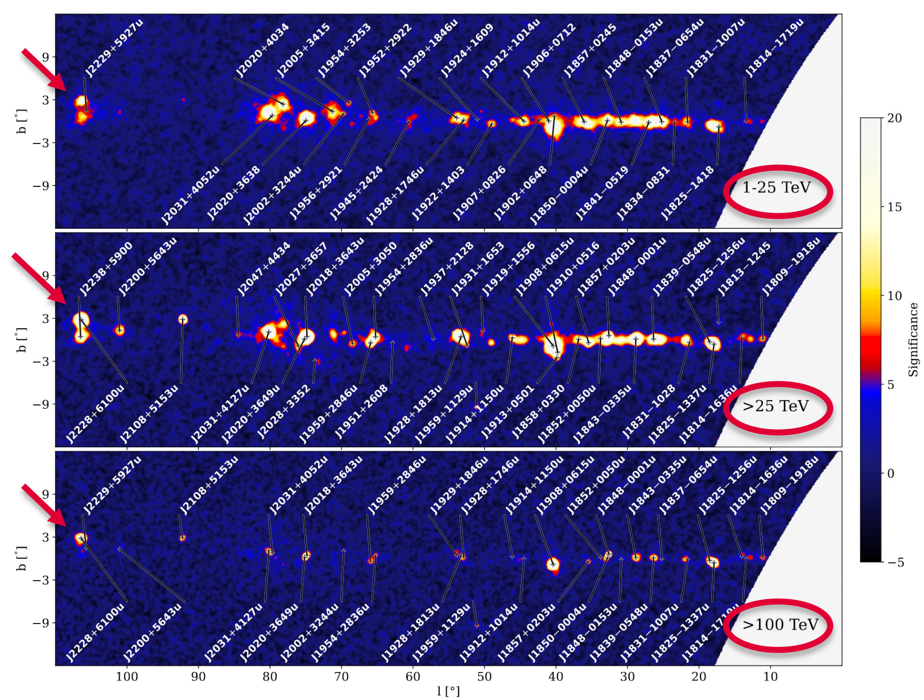
LHAASO Catalogue

Preprint, Cao et al. (2023)

Data from two instruments separates: WCDA for E >1-25 TeV and KM2A for E= 25 TeV –1.6 PeV

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}	Asso.(Sep.[°])
1LHAASO J2228+6100u	KM2A	337.01	61.00	0.04	0.35±0.01	2180.9	4.76±0.14	2.95±0.04	605.2	SNR G106.3+02.7 (0.13)
	WCDA	336.79	61.02	0.05	0.25±0.02	576.0	2.37±0.16	2.26±0.04		





LHAASO Catalogue

Preprint, Cao et al. (2023)

Added a new extended UHE source below SNR G106.3+2.7

Source name	Components	α_{2000}	δ_{2000}	$\sigma_{p,95,stat}$	r_{39}	TS	N_0	Γ	TS_{100}	Asso.(Sep.[°])
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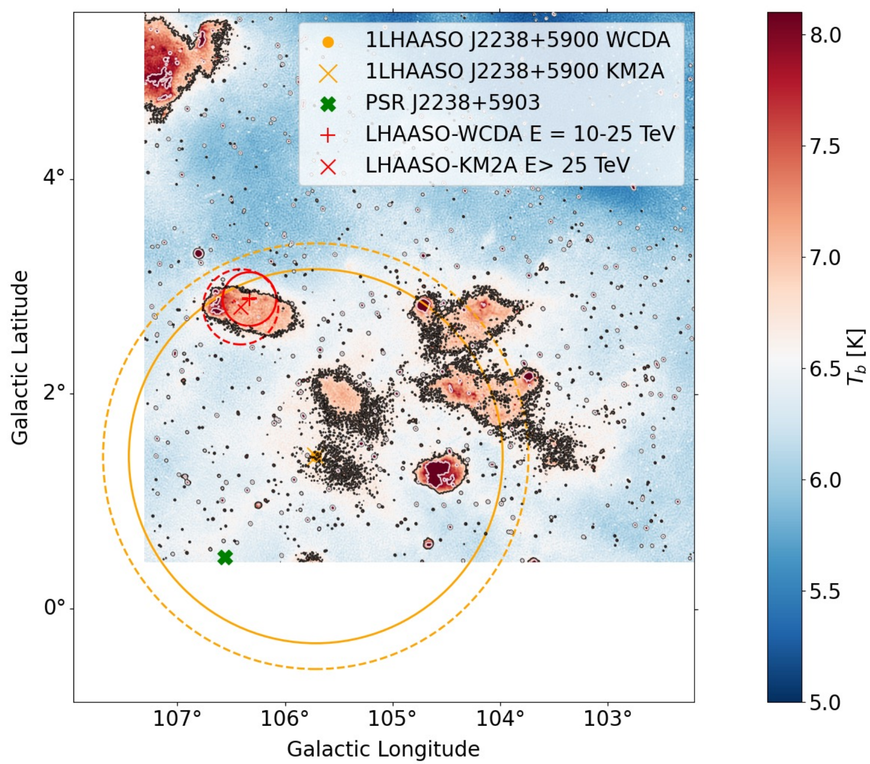
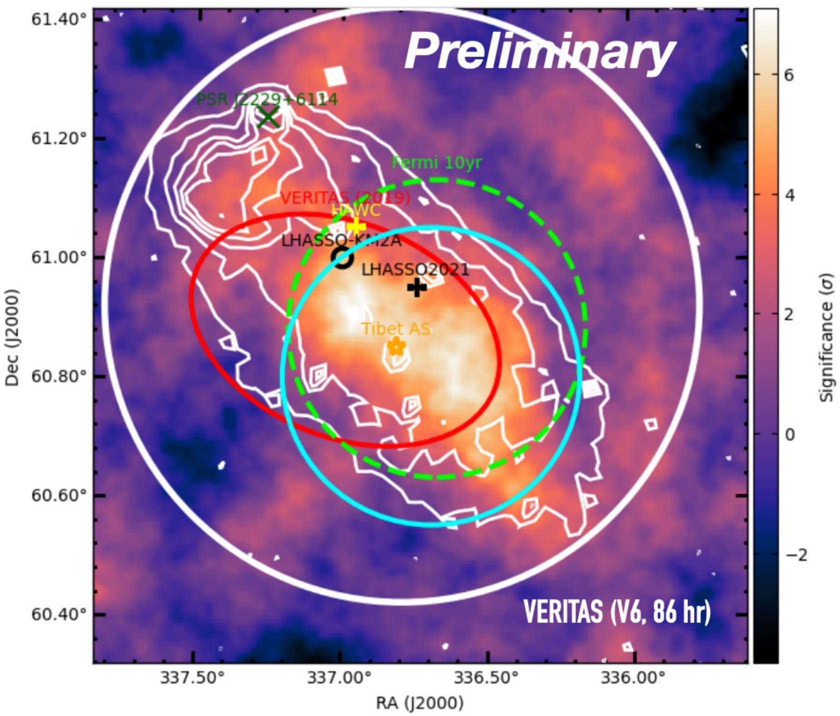
	WCDA	336.79	61.02	0.05	0.25±0.02	576.0	2.37±0.16	2.26±0.04		
1LHAASO J2229+5927u	WCDA	337.26	59.45	0.36	1.98±0.10	228.0	14.90±0.99	2.67±0.05		
New big source	KM2A*	337.88	59.55	0.46	1.74±0.16	163.8	4.43±0.36	3.53±0.11	31.4	

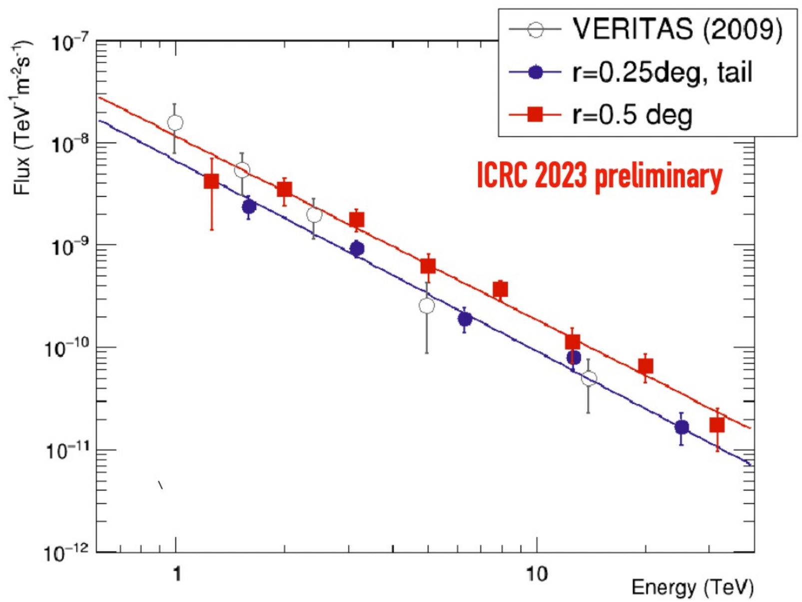


Recent data from VERITAS

ICRC 2023

86 h of observation, PSF~0.1^o , they claim a diffuse emission (~50-60% in tail), possibly related to the new largely extended source 1LHAASO J2229+5927u (LHAASO catalogue)





Index =. 1.86±0.10, compatible with other data

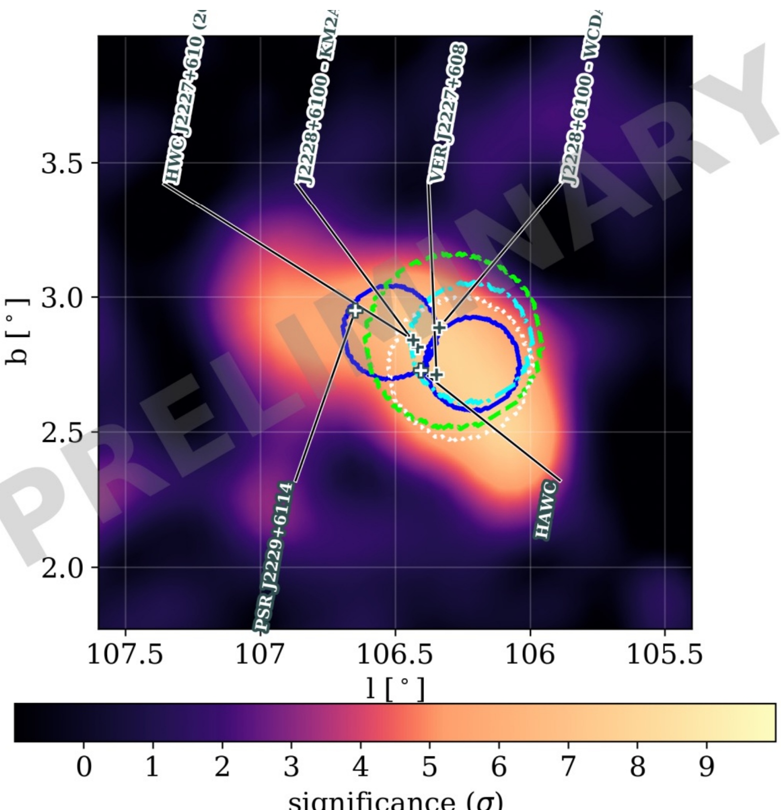
Recent data from HAWC VHE

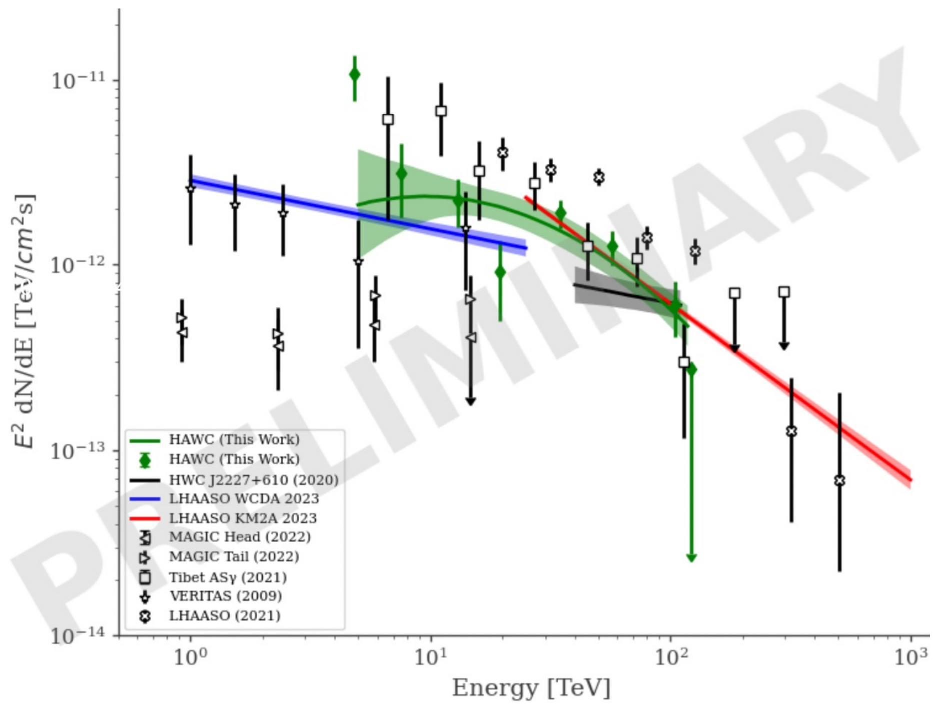
ICRC 2023

Energy range 300 GeV – 100 TeV

New data reconstruction using using artificial Neural Net algorithm

They see also an elongated emission, but without giving details on the energy morphology dependence





Interpretation of all these data?

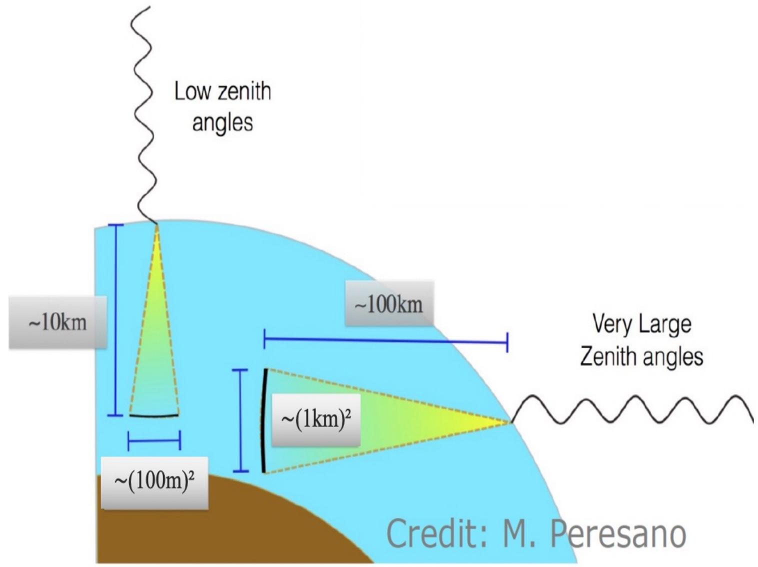
Many different interpretation and hypothesis have been proposed, but none is completing convincing, principally due the following fundamental uncertainties :

- Distance/size of the SNR : 0.8 – 10 kpc ?
- Age of SNR (< 10.400 yrs) and PWN (original or new ones as suggested by Kothes)?
- Precise morphology of the VHE-UHE emission, which could help to define the sites of photon production sites and their spatial spectral dependency

Concerning this last point, IACTs achieve the best angular resolution at VHE, which is ~ 0.1-0.8 deg and difficult to improve further

→ Before the CTA-North era, LST and MAGIC can improve the present morphology knowledge increasing the signal to noise ratio over the map thanks to higher data statistics.

This can be obtained with a reasonable time increasing the detector effective area using Large Zenith Angle observations

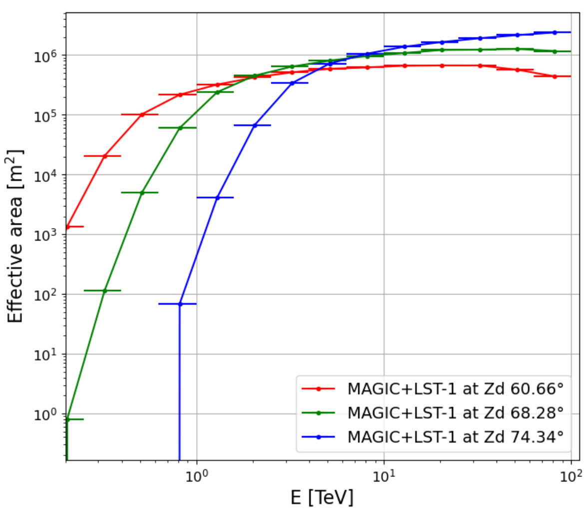


What LST can do?

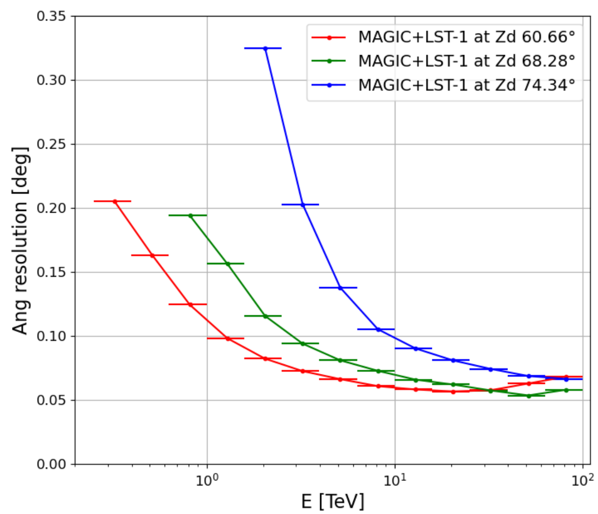
Observe SNR 103.6+2.3 at LZA at zenith = 60-75 deg :

The effective area strongly increase with zenith at VHE
The angular resolution is expected to be < 0.1° for highest energies
The energy resolution is also expected to be better than 15% for highest energies at all zd

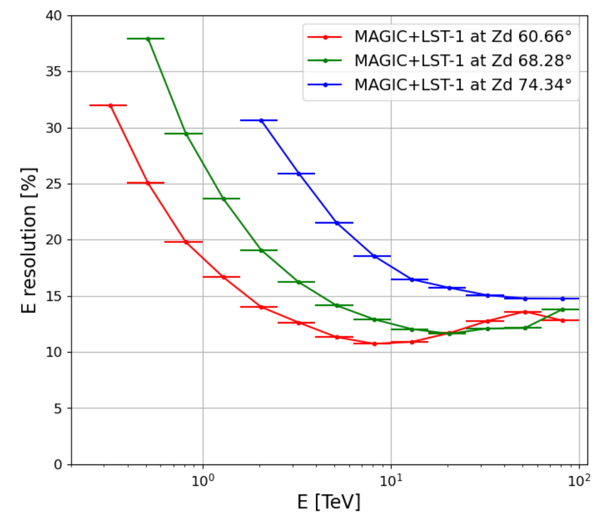
Effective area vs zenith



Angular resolution vs zenith



Energy resolution vs zenith

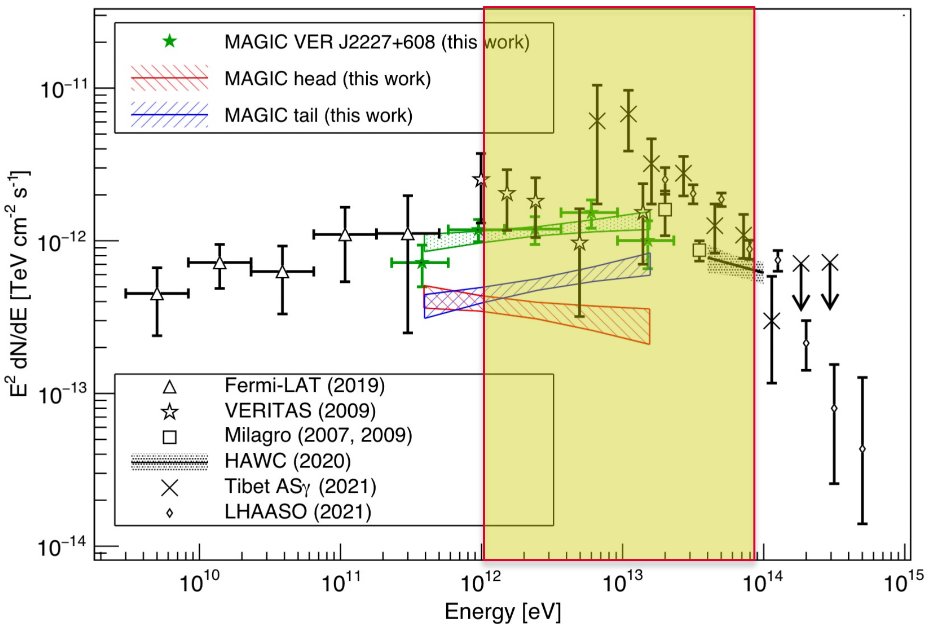


G. Emery

MC simulation of MAGIC+LST stereo data reconstructed with magic-cta-pipe

What LST can do?

With 120 h observation, if we assume the MAGIC tail flux, at zenith = 68° we expect at least 4 bins in energy with significance > 5 σ bins for 1-100 TeV in the case of LST and >> 5 σ in the case of MAGIC+LST, this should permit a much more precise energy dependent morphology (considering also a joint analysis with 121 h MAGIC data at low zenith angle)



A multi-years campaign with LST and MAGIC+LST started in 2022 and first results are very promising and confirm MC expectations.

All interested people are welcome to join the project!

References 1/2

- *Joncas, G., & Higgs, L. A. 1990, A&AS, 82, 113*
- *Kallas, E., & Reich, W. 1980, A&AS, 42, 227*
- *Fürst et al. 1990, A&AS, 85, 691*
- *Pineault S. & Joncas E. 2020, Astr. J. 120, 3218*
- *Hartman R. C. et al. 1999, ApJ, 123, 79*
- *Halpern J.P. et al. 2001a, ApJ, 547, 323*
- *Halpern J.P. et al. 2001b, ApJ, 552, 125*
- *Kothes R. et al. 2001, ApJ, 560, 236*
- *Kothes R. et al. 2004 ApJ, 607, 855*
- *Kothes R. et al. 2006a ApJ, 638, 225*
- *Kothes R. et al. 2006b A&A, 457, 1081*
- *Abdo A. A. et al. 2007 ApJ, 664, 91*
- *Abdo A. A. et al. 2009a ApJ, 700, 127*
- *Acciari V. A. et al. 2009 ApJ 703, 6*

References 2/2

- *Abdo A. A. et al. 2009b, ApJ, 706, 1331*
- *Albert A. et al 2020, ApJ, 896, 29*
- *Amenomori M. et al. 2021 Nature Astronomy, 5, 460*
- *Cao Z. et al. 2021 Nature, 594, 33*
- *Ge C. et al. 2021 The Innovation 2, 10018*
- *Fang K. et al. 2022 Phys. Rev. Lett. 129*
- *Abe H. et al. 2022 A&A, 671, A12*

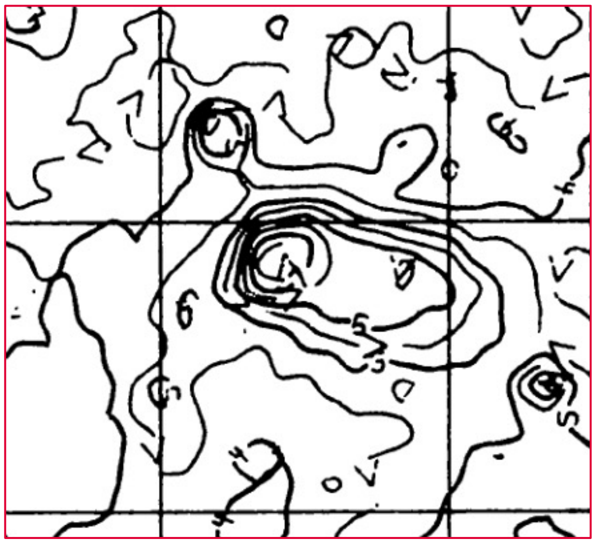
THANK!

Backup slides

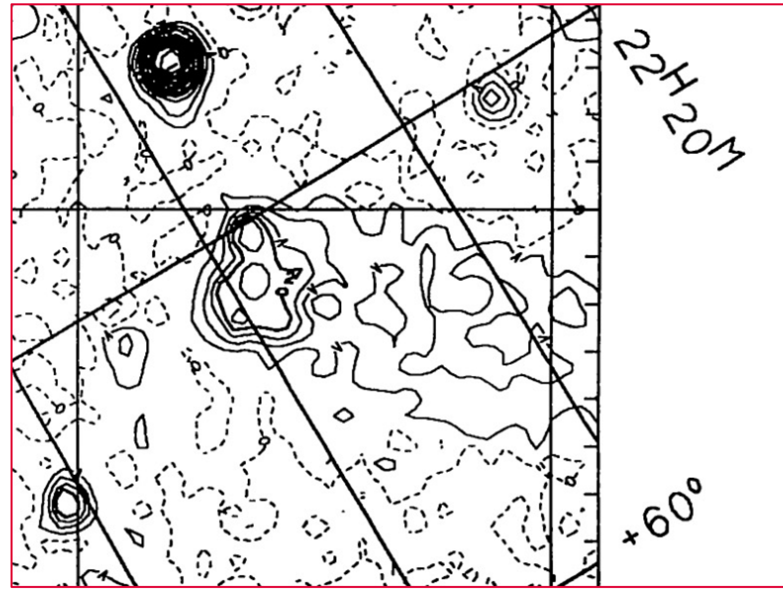
Clearly Identified as SNR (2000)

- Low surface brightness
- 7%–10% classified as “composite” remnants showing plerionic cores accompanied by shells with steeper radio indices (alpha=0.4-0.7)
- The absence of any shell or halo of fast-moving ejecta in the Crab Nebula, 3C 58, and other plerionic remnants may be simply the result of a low ambient density which precludes the formation of a detectable shock
- IR? Devo cercare in https://irsa.ipac.caltech.edu/cgi-bin/bgServices/nph-bgExec sembrerebbe che ci sia poco
- E\` definite nel green catalogue come un composite con dubbio

Other very old radio images



1420 MHz continuum
Kallas & Reich (1980)

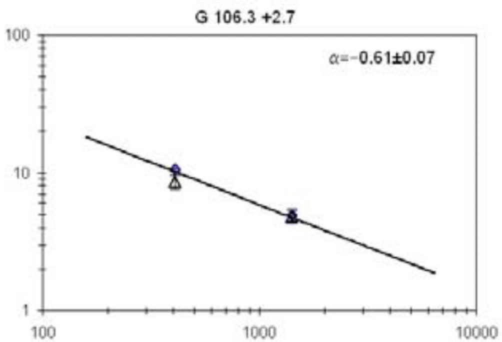


2695 MHz continuum (11 cm)
Fürst et al. 1990

In SNR catalogue of CGPS

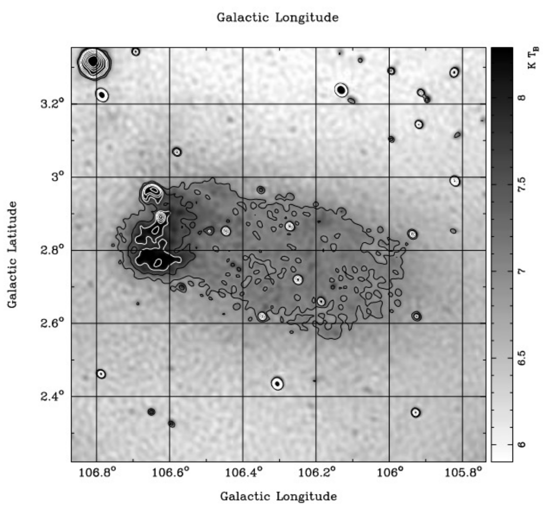
Kothes et al. (2006b)

In Canadian Galactic Plane Survey at 408 MHz (*S*=8.6±1.0 Jy) and 1420 MHz (*S*=4.8±0.5 Jy)

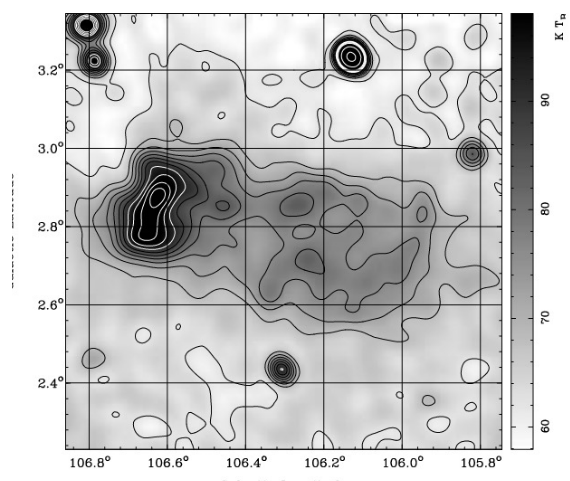


Index α= -0.61

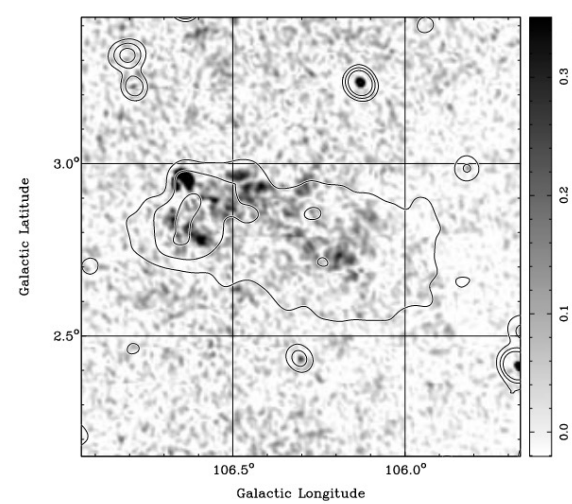
1420 kHz, resolution 1’



408 kHz, , resolution 3’



Polarisation map



Low luminosity

Kothes et al. (2006a)

Comparison with other SNR assuming the distance of 0.8 kpc

TABLE 4

CHARACTERISTICS OF PULSAR-PWN PAIRS FOR WHICH THE ROTATIONAL ENERGY LOSS RATE $\dot{E}$ IS LARGER THAN 10^{37} ergs s^{-1}

Pulsar	SNR	d (kpc)	$\dot{E}$ (10^{37} ergs s^{-1})	Sd^2 (Jy kpc^2)	References
J0537-6910	N157B	49.4	48	6833	1
B0531+21	Crab Nebula	2.0	46	4160	2
B0540-69	SNR 0540-693	49.4	15	220	3
J0205+6449	3C 58	3.2	2.7	338	2
J2229+6114	G106.3+2.7	0.8	2.2	0.061	4
B1509-58	G320.4-1.2	5.2	1.8	54	5
J1617-5055	RCW 103?	3.3	1.6	?	2
J1124-5916	G292.0+1.8	6.2	1.2	215	6
J1930+1852[a]	G54.1+0.3	>5.0 (9.0)	1.2	>12.5 (40.5)	7

NOTES.—Listed are the distance d, $\dot{E}$ and the luminosity of the PWN Sd^2 at 1 GHz. The values for $\dot{E}$ were taken from the ATNF Pulsar Catalogue (http://www.atnf.csiro.au/research/pulsar/psrcat/).

[a] Lu et al. (2002) derived that the distance to G54.1+0.3 is halfway to the edge of the Galaxy. They used a distance of 10 kpc to the Galactic edge in the direction of G54.1+0.3, which is in fact the distance back to the same galactocentric radius as the Sun after crossing the inner Galaxy. Using a diameter of 30 kpc for the Milky Way gives the results listed in the brackets.

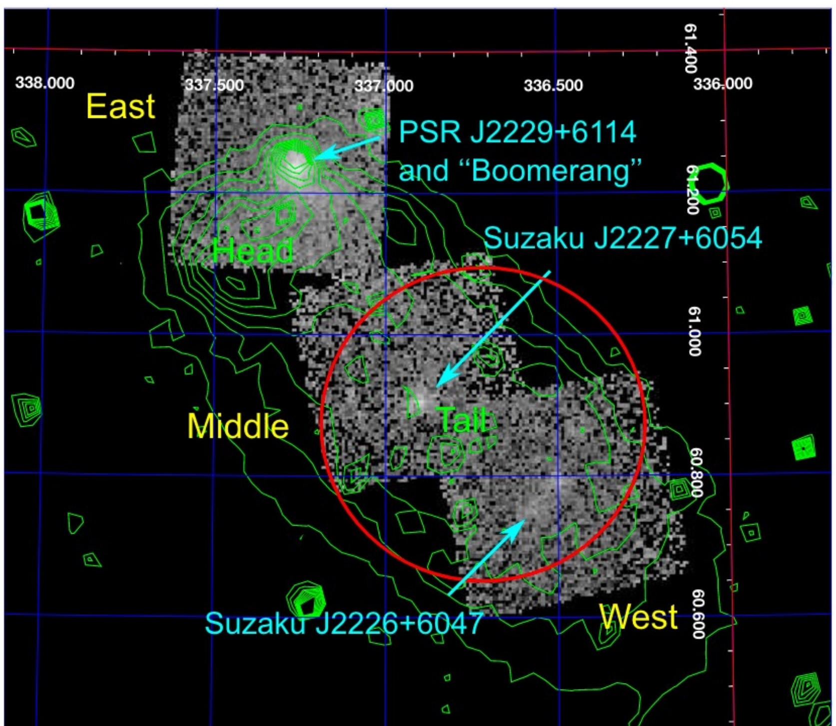
REFERENCES.—For the distance and the PWN flux densities S: (1) Lazendic et al. 2000; (2) Green 2004; (3) Manchester et al. 1993; (4) Kothes et al. 2001; (5) Gaensler et al. 2002; (6) Gaensler & Wallace 2003, Lu et al. 2002.

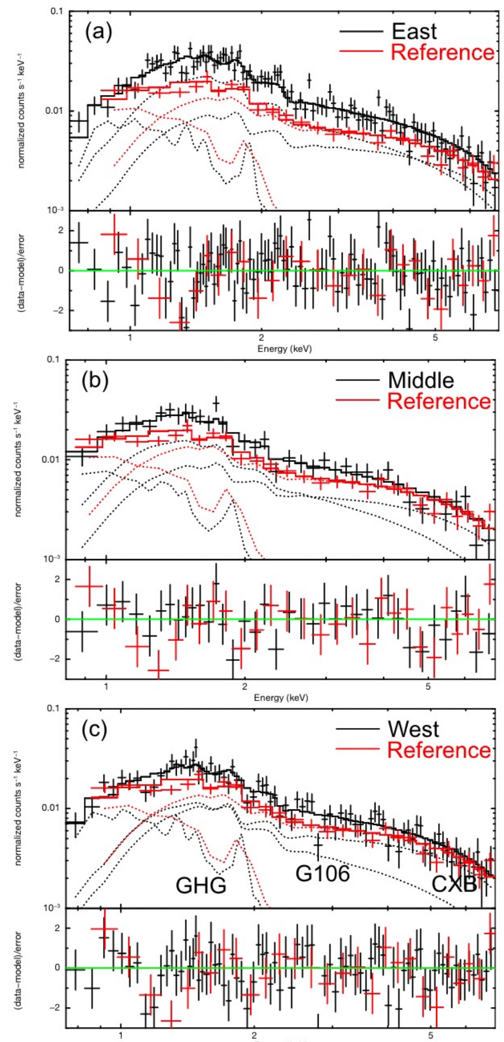
First X-ray on tail

Fujita et al. (2021)

E range = 1 - 10 keV

Diffuse X-ray, peaked at the PWN as radio, with constant index over the SNR





Detection at E > 10 GeV not from pulsar

Fang et al. (2022)

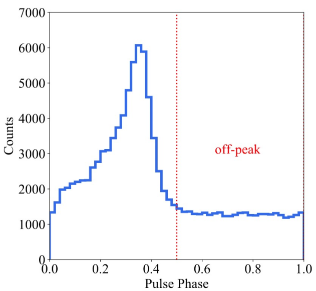
Title = “Evidence for PeV Proton Acceleration from Fermi-LAT Observation of SNR G106.3+2.7”

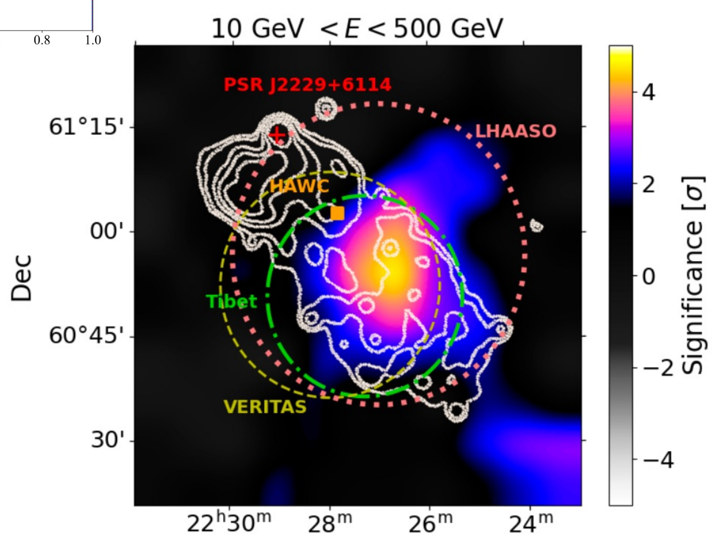
Energy range = 0.1 - 500 GeV, only radiation out of phase with the pulsar

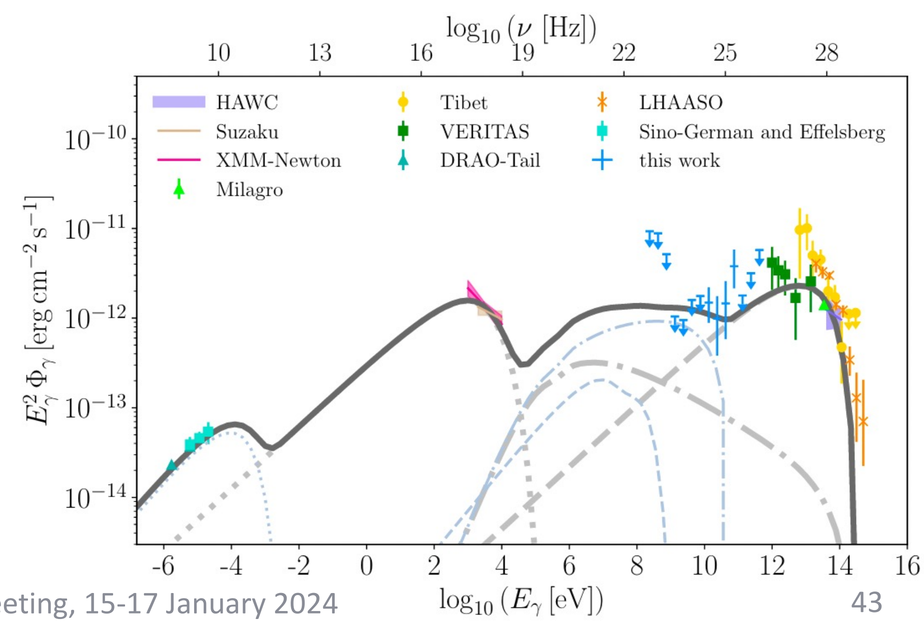
No tail source below 10 GeV

Above 10 GeV: Gaussian size = σ = 0.20° but compatible with a point source model, PSF < 0.2°

MWL fit : leptonic model, two leptonic populations, hybrid model favoured







MAGIC MWL fit

Abe et al. (2022)