MAGIC
Major Atmospheric
Gamma Imaging
Cerenkov Telescopes

ICRR
Institute for Cosmic Ray Research
University of Tokyo

MAGIC Observations of the putative PeVatron SNR G106.3+2.7 in the proximity of the Boomerang PWN

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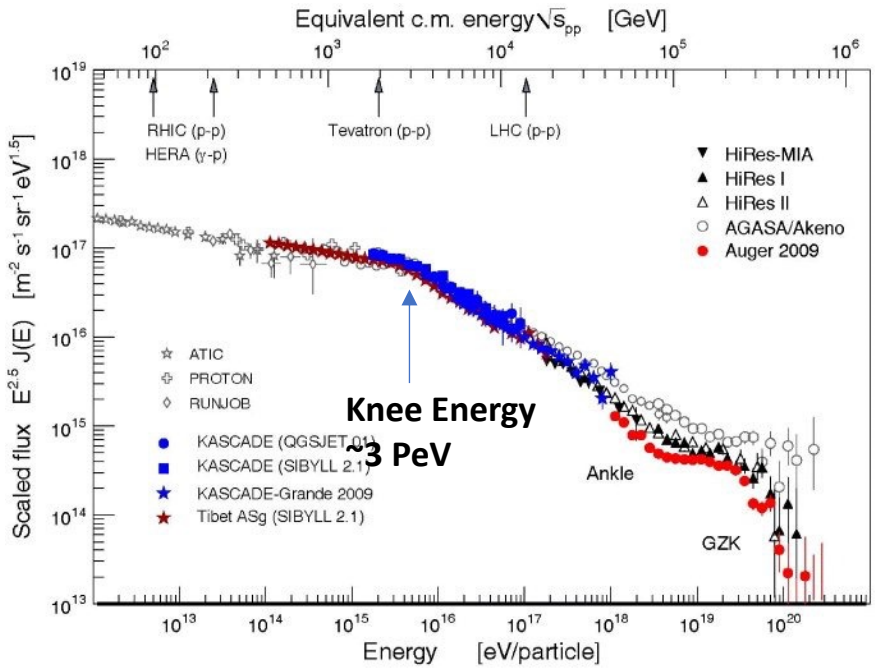
On behalf of the MAGIC collaboration

a) ICRR, b) Kyoto univerisity

PeVatron Candidate



LHAASO

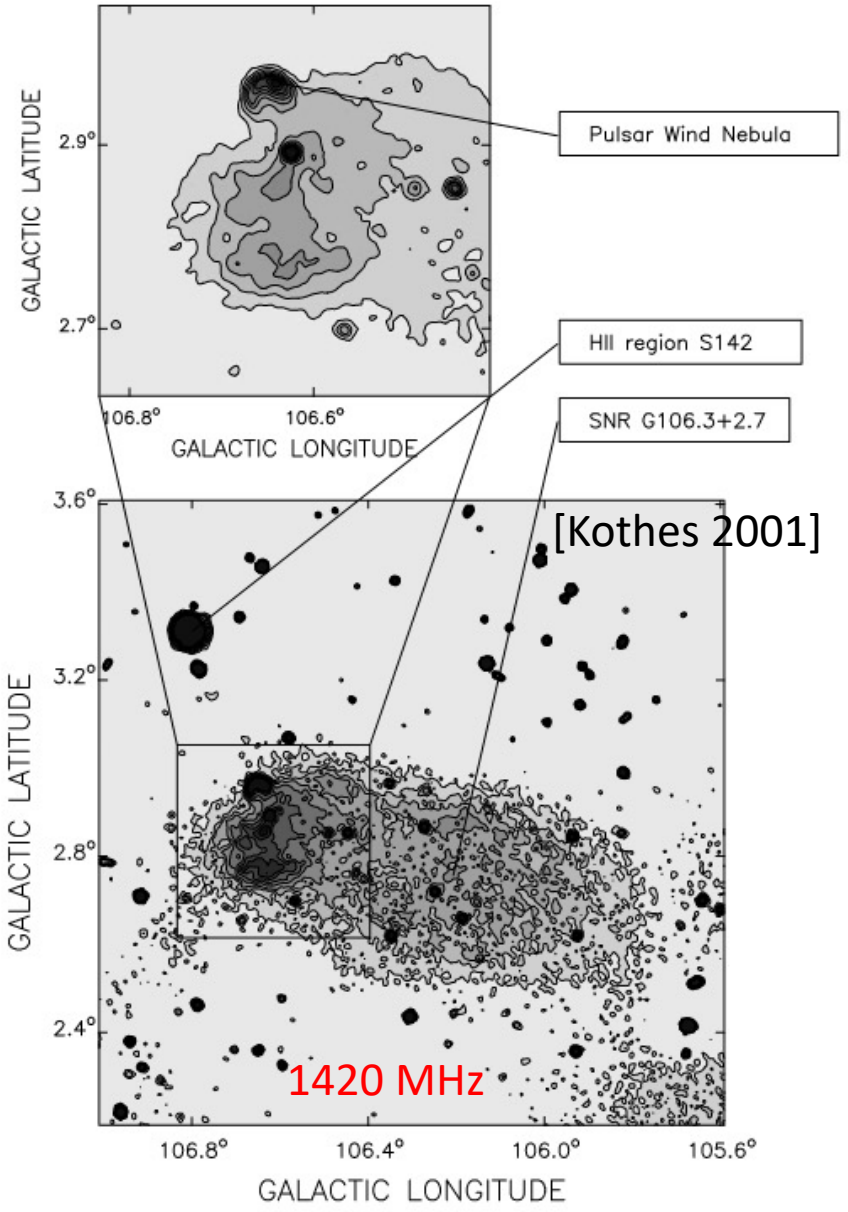
- We don't know which objects are **PaVatrons**, i.e. galactic sources accelerating hardons to the knee energy.
- Recent progress in air shower arrays (e.g. LHAASO) enlarged the list of PeVatron candidate substantially.
- Still, definitive evidence of hadronic PeV accelerators has not been found.

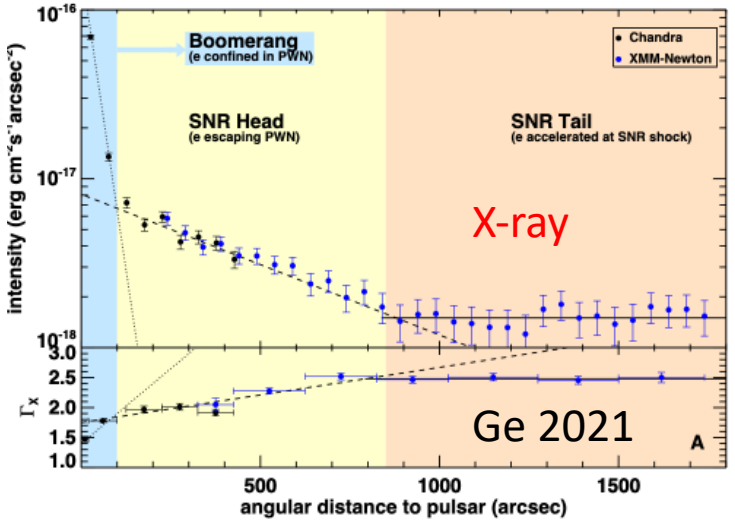
Table 1. List of known Galactic pevatrons as of May 2021. This list is likely to be lengthened soon due to active ongoing detection campaigns.

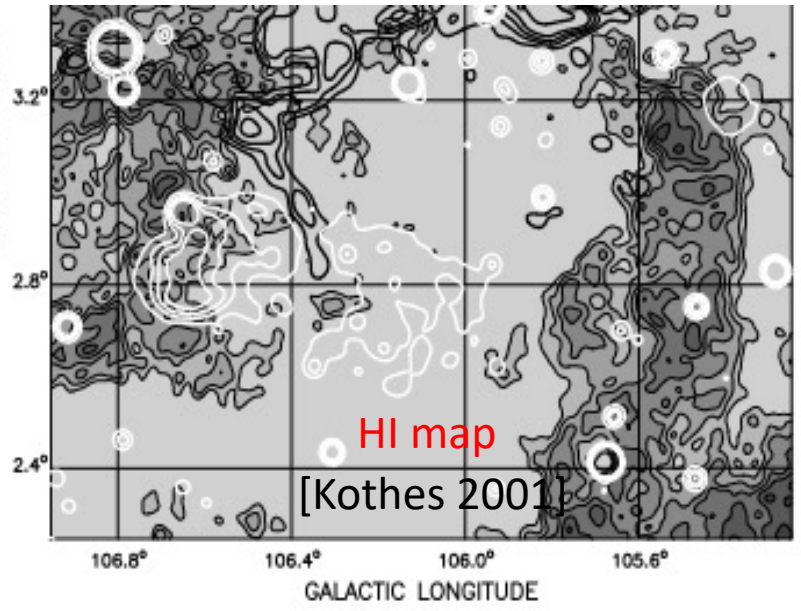
Source	Possible Association	Reference
HESS J1745-290	Sagittarius A*/Galactic center	[39]
Crab/LHAASO J0534+2202	PSR J0534+2200	[26,28,41,107]
LHAASO J1825-1326/2HWC J1825-134	PSR J1826-1334/PSR J1826-1256	[28,134]
LHAASO J1839-0545/2HWC 1837-065	PSR J1837-0034/PSRJ1838-0537	[28,40]
LHAASO J1843-0338/2HWC J1844-032	SNR G.28.6-0.1	[28,40]
LHAASO J1849-0003	PSR J1849-0001/W43	[28]
LHAASO J1908+0621/MGRO 1908+06/ 2HWC 1908+063	SNR G40.5-0.5/PSR 1907+0602/PSR 1907+0631	[28,40]
LHAASO J1929+1745	PSR J1928+1746/PSR1930+1852/SNR G54.1+0.3	[28]
LHAASO J1956+2845	PSR J1958+2846/SNR G66.0-0.0	[28]
LHAASO J2018+3651	PSR J2021+3651/Sh 2-104 (HII/YMC)	[28]
HWC J2019+368		[40]
LHAASO J2032+4102/2HWC J2031+415	Cygnus OB2/PSR 2032+4127/SNR G79.8+1.2	[28,135]
LHAASO J2108+5157		[28]
LHAASO J2226+6057	SNR G106.3+2.7/PSR J2229+6114	[28,69]
HESS J1702-420A	SNR G344.7-0.1/PSR J1702-4128	[136,137]

ArXiv 2110.07956, P. Cristofari

SNR G106.3/ Boomerang PWN

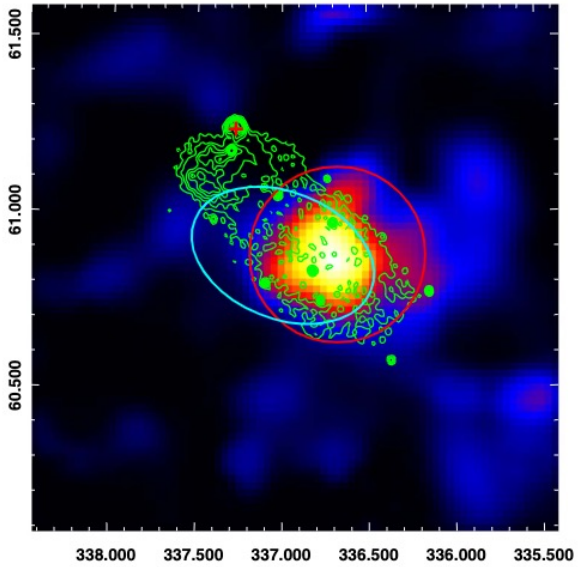




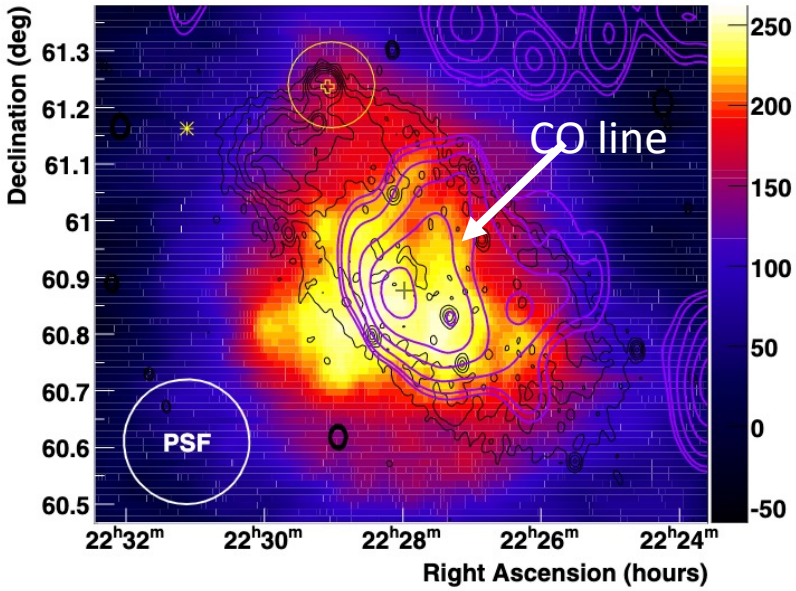


- Comet shape SNR with *head* and *tail* (named by *Joncas & Higgs*, 1990) seen in radio continuum.
- *Head* seems to be colliding with dense molecular cloud
- PWN is at the edge of *head*
- PSR J2229+6114
  - L_{sd} = 2.2 x 10^{37}erg/s
  - T_{sd} = 10 kyr
  - (X-ray absorption shows d = 3 kpc)
- Association with HI and SNR tells
  - distance to SNR G106 is 800 pc.
  - 14 pc long and 6 pc wide
- Non-thermal X-ray shows characteristic profile

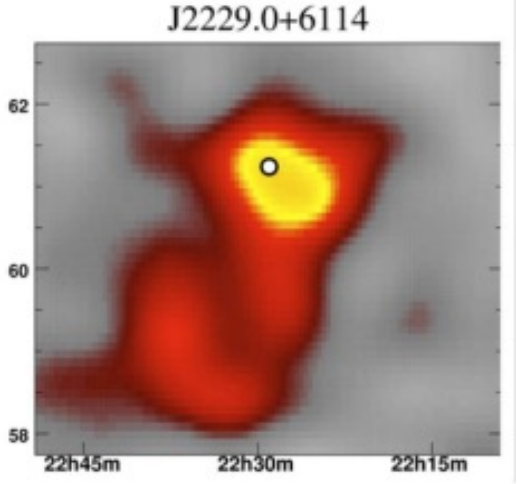
SNR G106.3 in gamma-rays



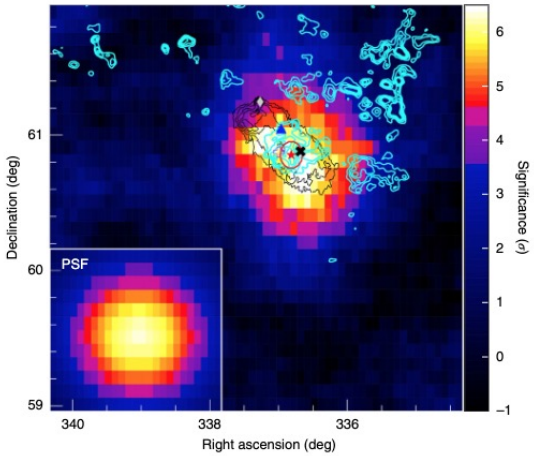
Fermi **>3 GeV** (Xin+ 2019)



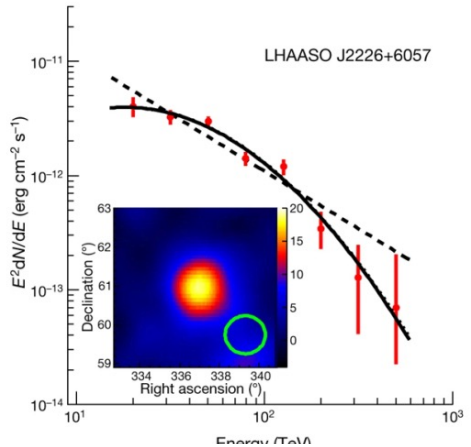
VERITAS **>0.6 TeV** (2009)



Milagro **35 TeV** (2009)



Tibet **10 - 100TeV** (2020)



LHAASO, **30 - 500TeV** (2021)

- The source has been known in TeV community since long
- Extended emission at > 30 TeV is known since 2009
- LHAASO recently detected it up to 500 TeV.

- Motivation of MAGIC study -

<u>Observations with higher angular resolution should shed new light on this source.</u>

MAGIC Telescope and G106.3 Observations

Observations of G106.3+2.7

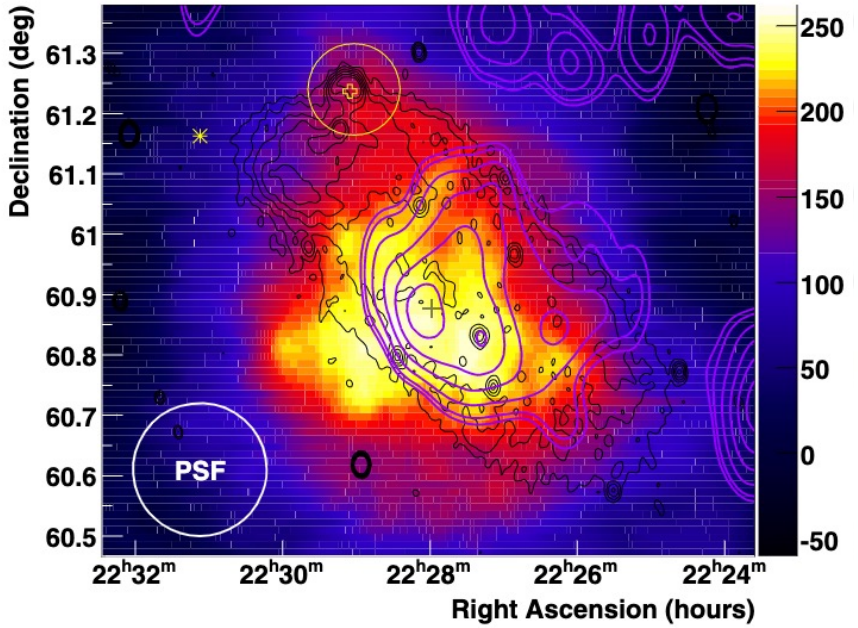
Period: May 2017 - August 2019
Effective Obs. Time: 122 hours
Zenith Angle rage: 30 – 50 degrees
Analysys Threshold Energy: 0.2 TeV

- Located at LaPalma, Canary islands, Spain. 2200m a.s.l.
- Two telescopes with a 17 m diameter dish

- FoV
  - 3.5 degrees
- Energy range
  - from 30 GeV to 50 TeV
- Angular resolution
  - 0.084 degrees > 0.2 TeV
  - 0.072 degrees > 1 TeV
- Energy Resolution
  - ~ 20% from 0.1 to 10 TeV

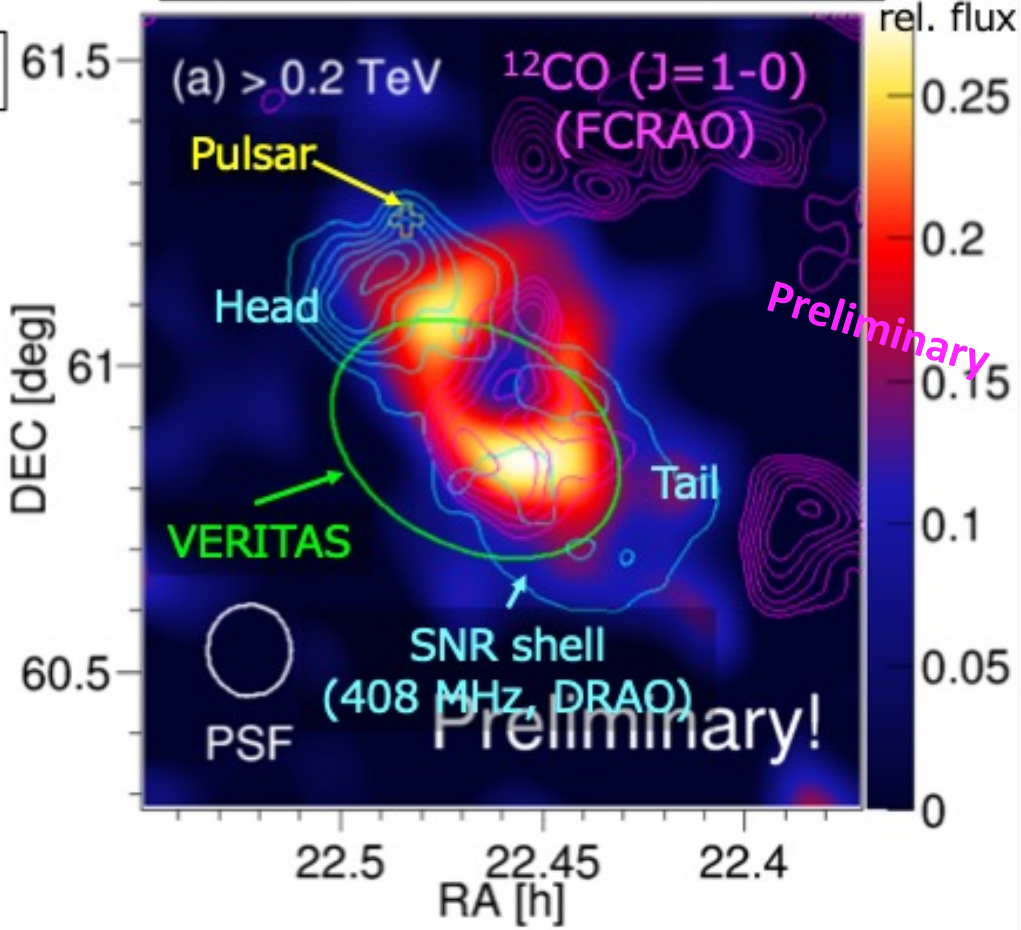
MAGIC Skymap

VERITAS >0.63 TeV [Acciari+2009]



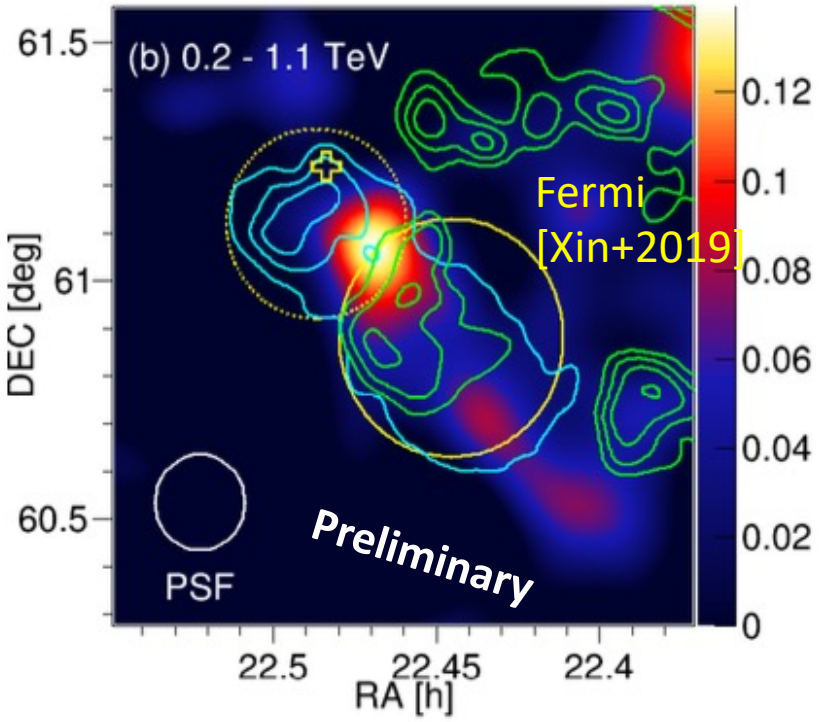
(33.4 hours in 2008)

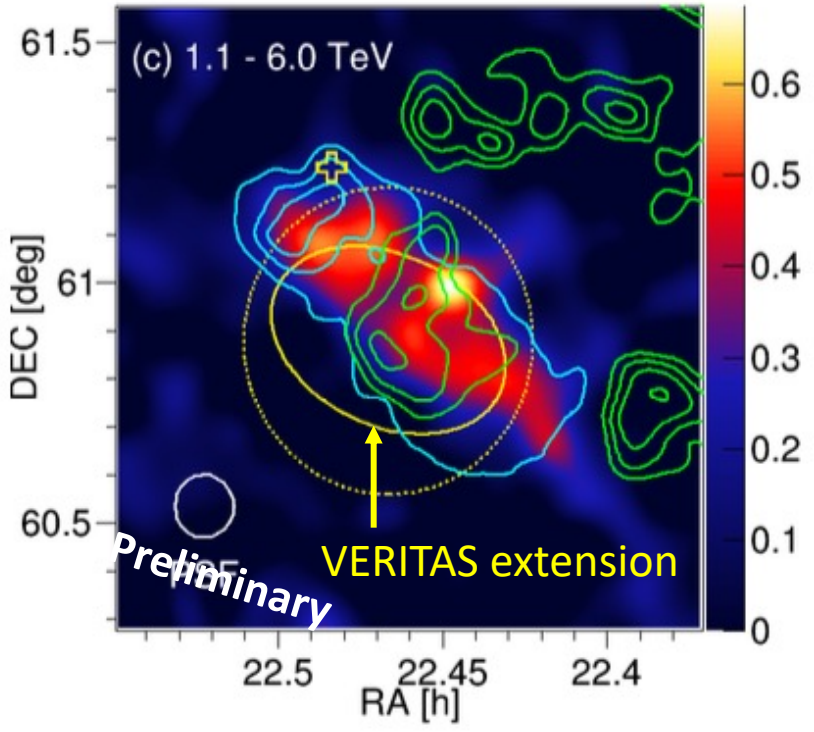
MAGIC >0.2 TeV (This work)

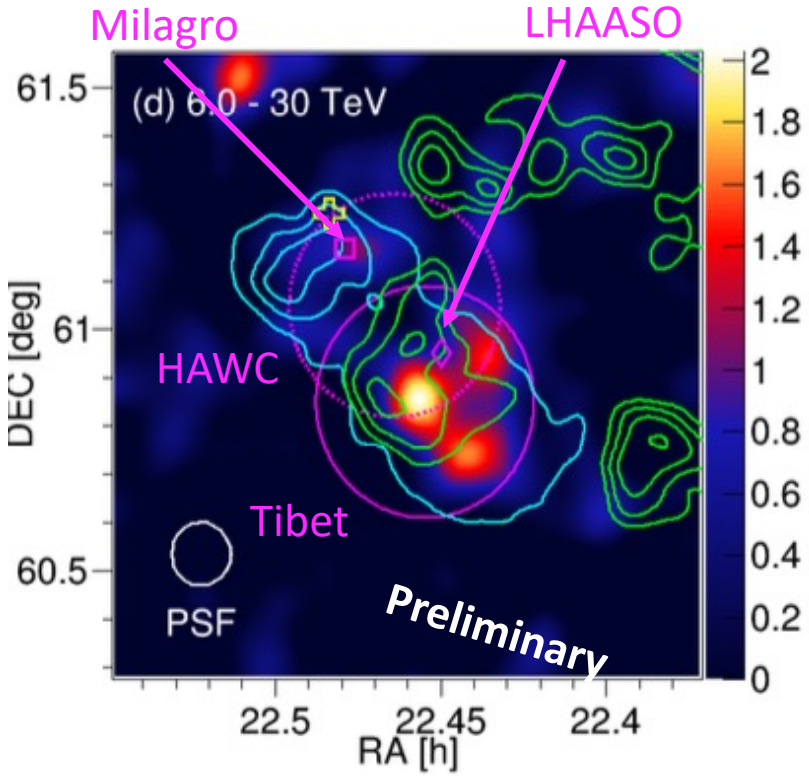


- Gamma-ray emission extends along with the radio continuum emissions.

Energy Dependent Morphology

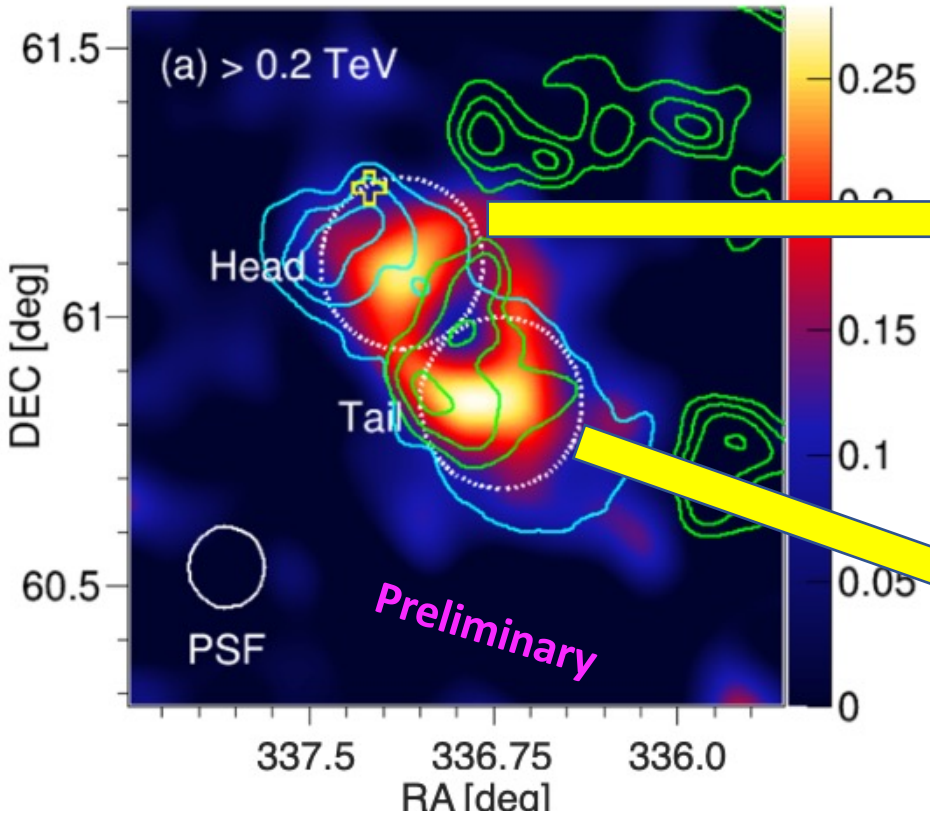


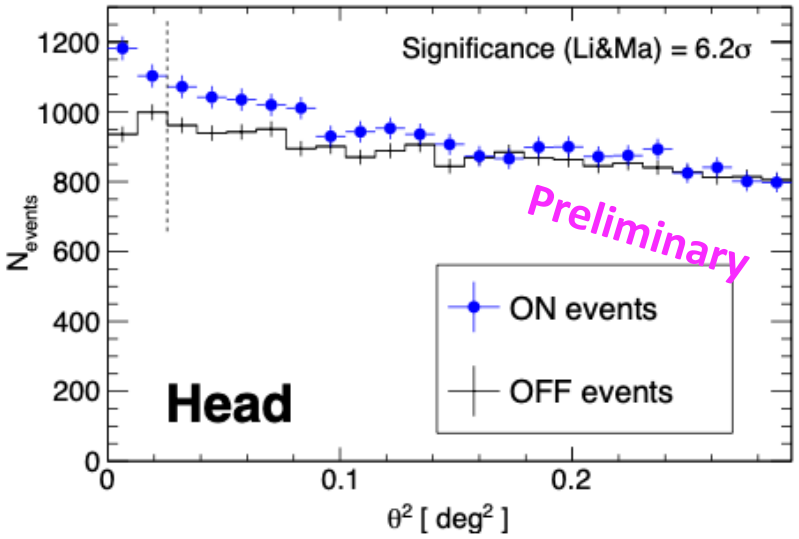


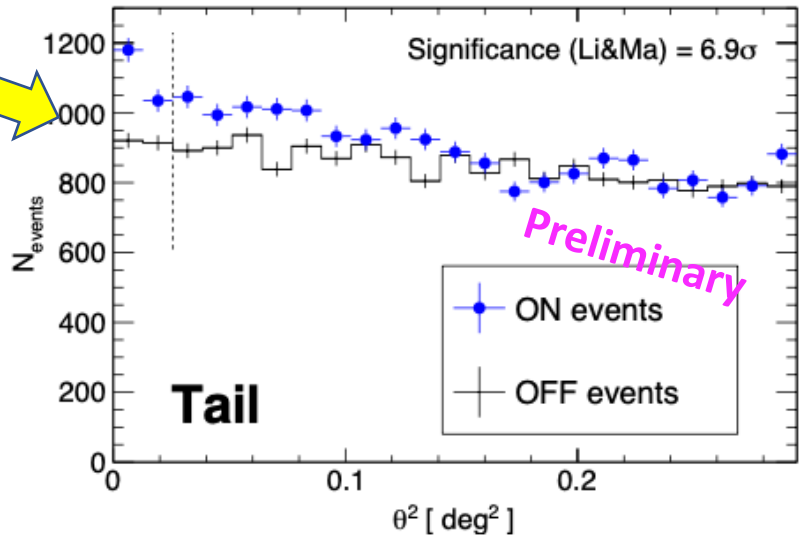


- Morphology changes with energy.
- Consistent with previous measurements.

Two Region Analysis (> 0.2 TeV)

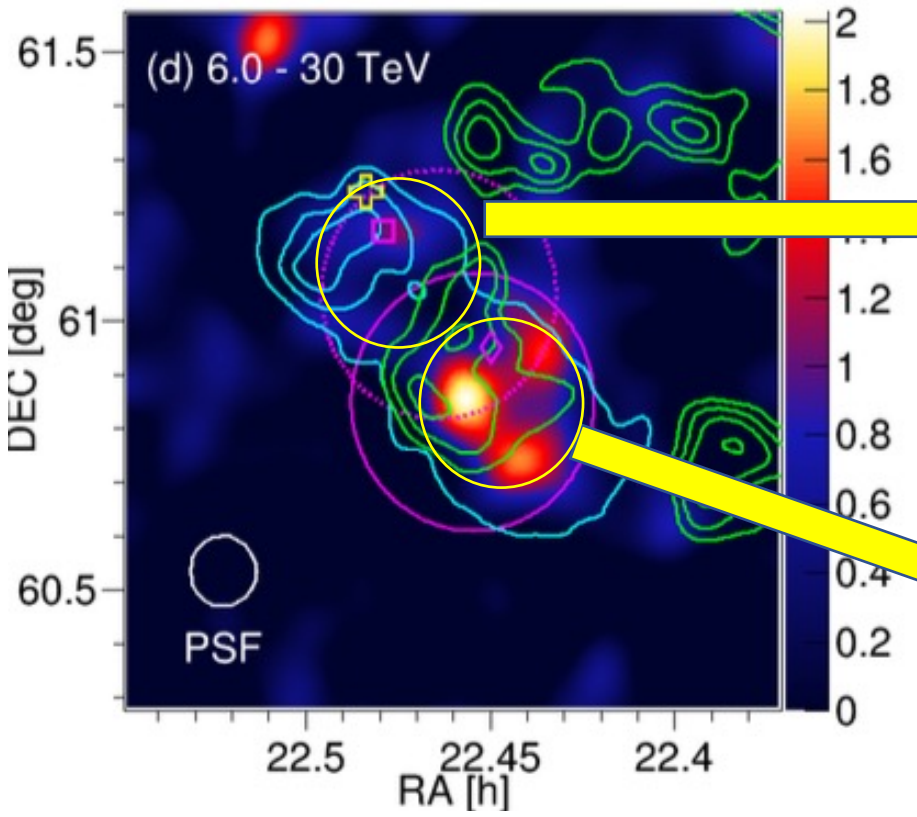


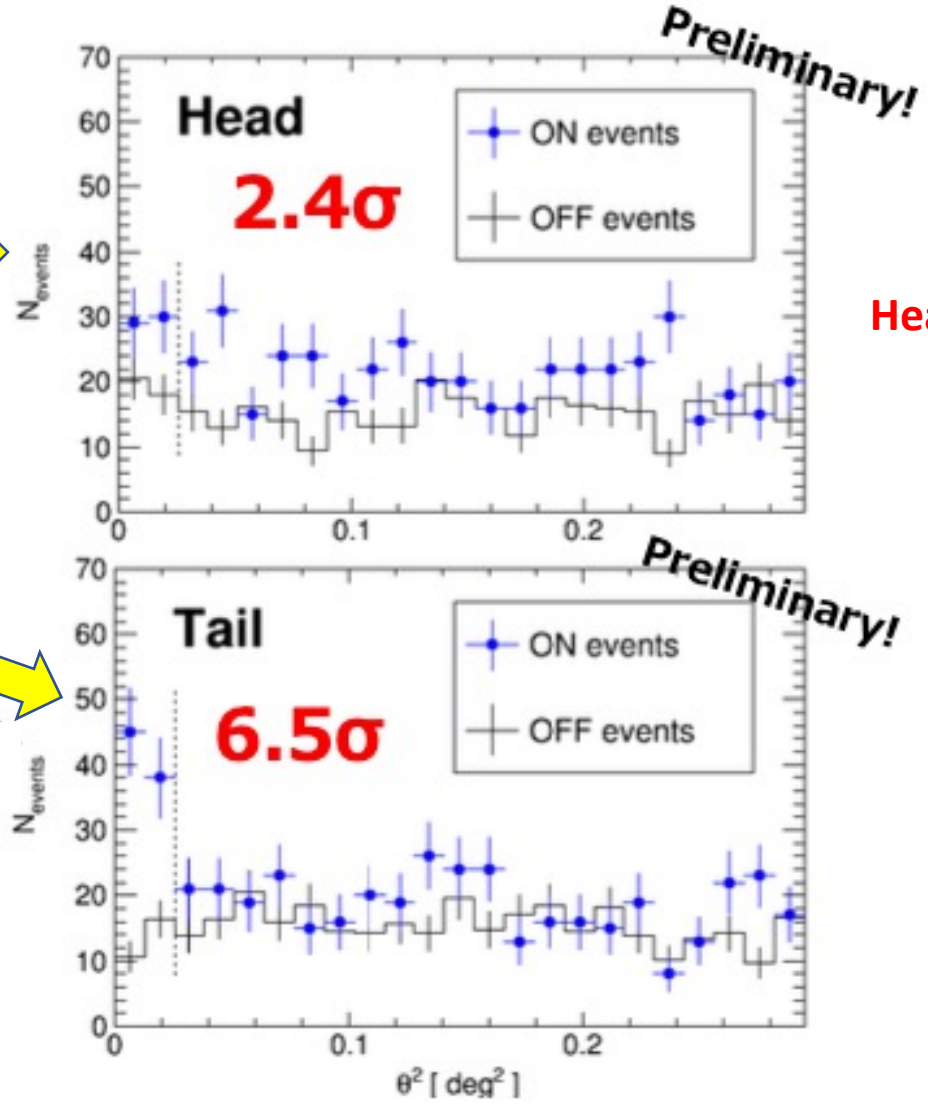




Source	RA	DEC	Radius
Head region	337.°13	61.°10	0.°16
Tail region	336.°72	60.°84	0.°16

Two region analsys (6- 30 TeV)



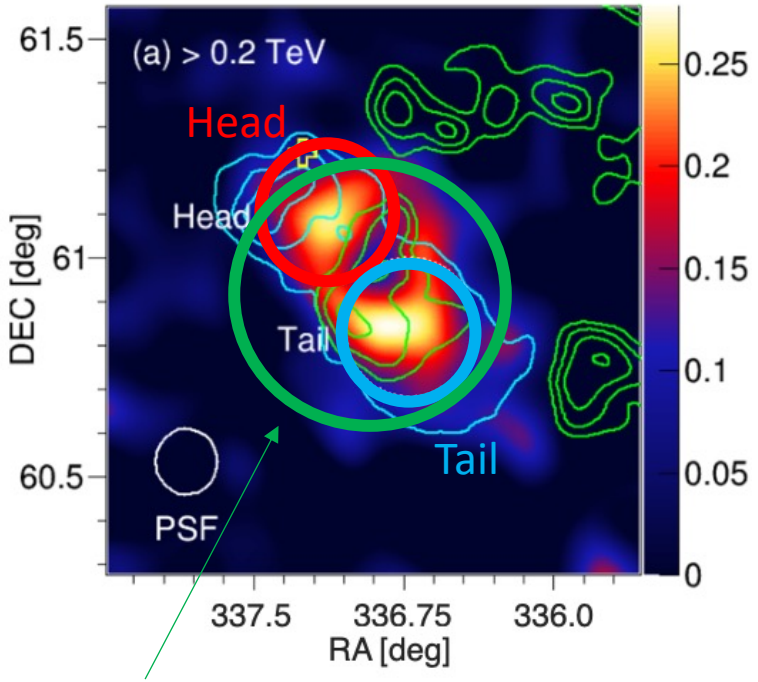


Head is not significant

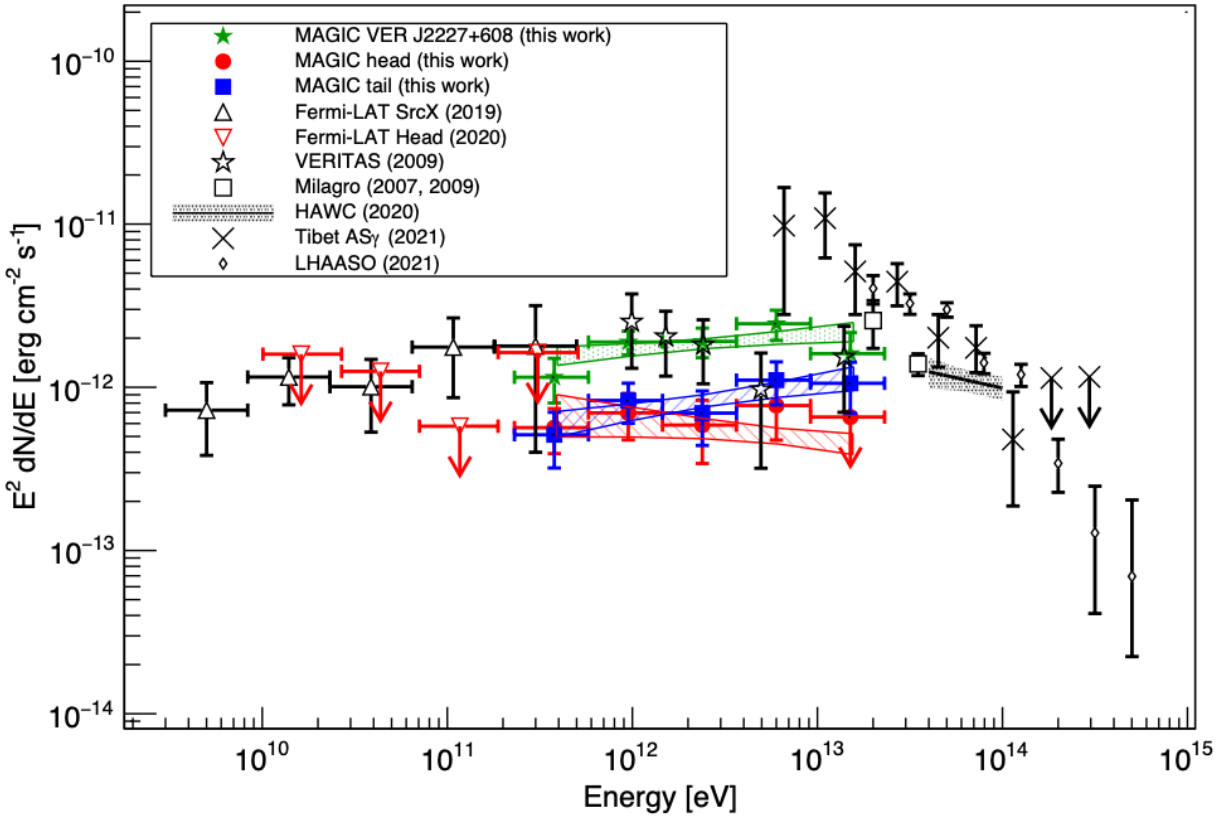
Tail is significant

Source	RA	DEC	Radius
Head region	337.°13	61.°10	0.°16
Tail region	336.°72	60.°84	0.°16

Spectra of the two regions



VERITAS integration region



- Consistent with VERITAS and other previous measurements.
- *Tail* is marginally harder than *head*

Source	N_0 (10^{-14} cm^{-2} s^{-1} TeV^{-1}) at 3 TeV	Γ	χ^2/ndf
Head	$3.8 \pm 0.7_{stat} \pm 0.7_{sys}$	$2.12 \pm 0.12_{stat} \pm 0.15_{sys}$	5.5/6
Tail	$6.0 \pm 0.7_{stat} \pm 1.0_{sys}$	$1.83 \pm 0.10_{stat} \pm 0.15_{sys}$	2.6/6
VER J2227+608 (MAGIC)	$13.1 \pm 1.1_{stat} \pm 2.1_{sys}$	$1.91 \pm 0.07_{stat} \pm 0.15_{sys}$	7.1/6
VER J2227+608 (VERITAS, Acciari et al. 2009)	$11.5 \pm 2.7_{stat} \pm 3.5_{sys}$	$2.3 \pm 0.33_{stat} \pm 0.30_{sys}$	-

Modelling

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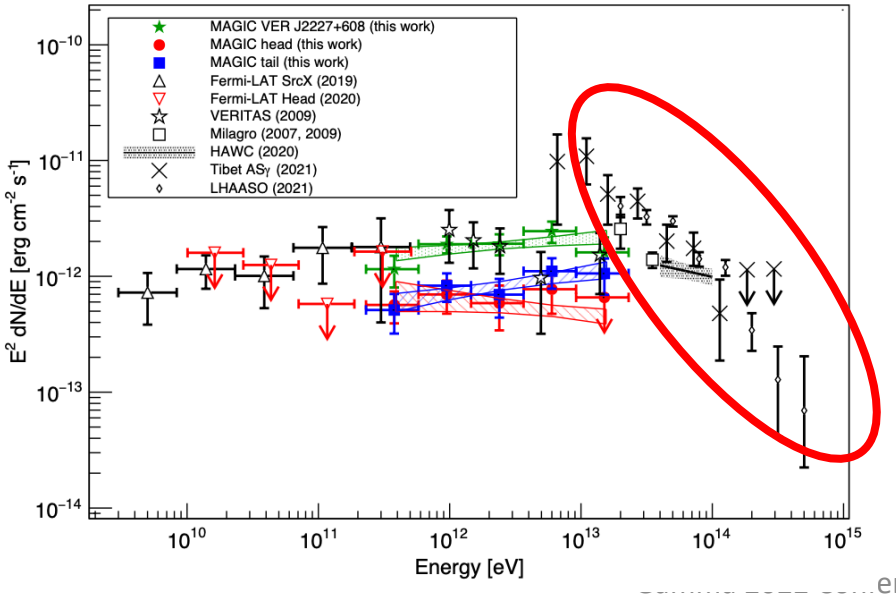
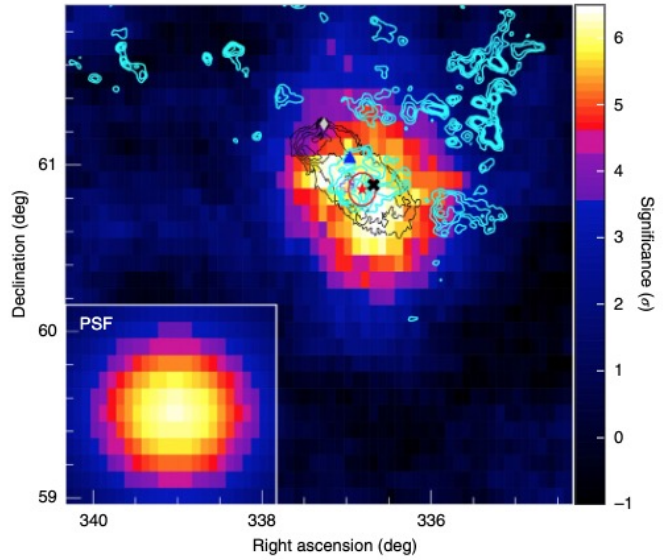
Assumption for modelling and interpretation

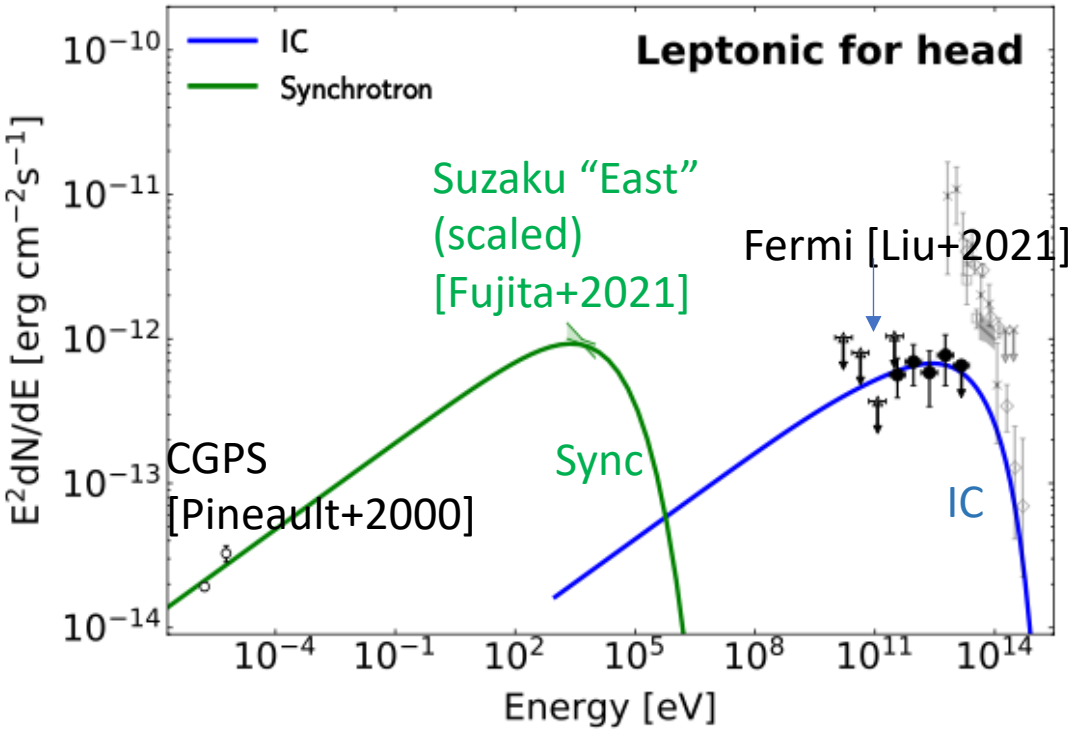
- Boomerang PWN and SNR G106.3 are associated.
- They are located at 800 pc and their age is 3 - 10 kyr.
- Emission at *head* and *tail* are produced in different physics conditions.
- Emission seen above 10 TeV by Air Shower Arrays are **all from *tail***

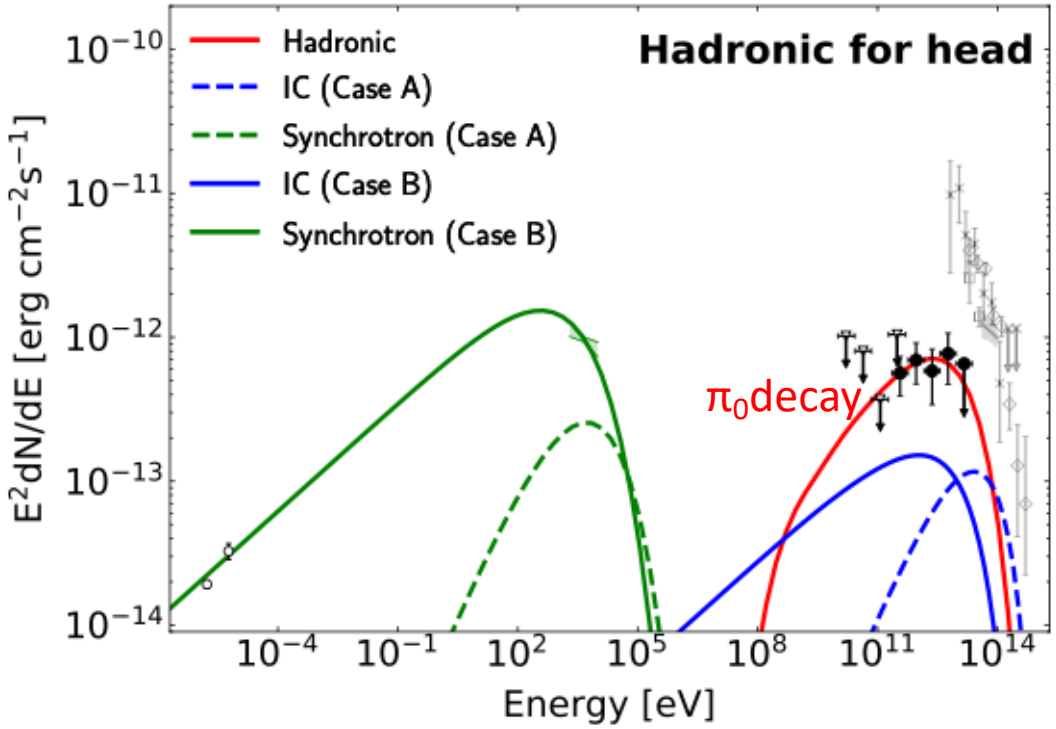


Tail



SED modelling: *head*

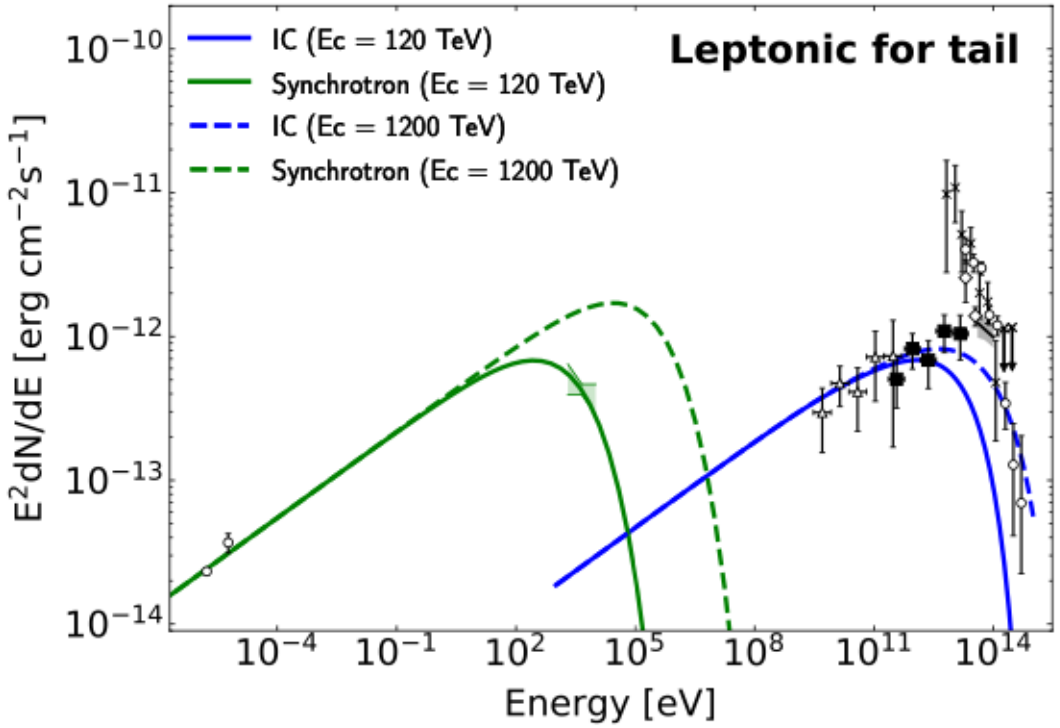


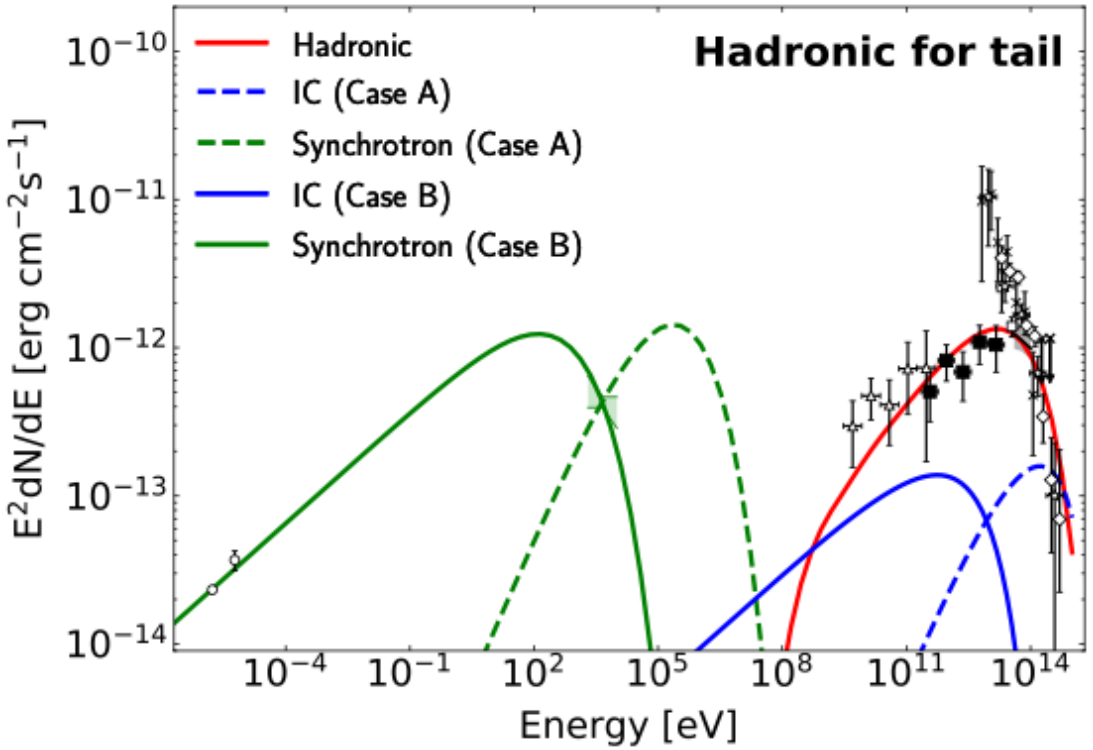


	α_e	$E_{cut,\,e}$	W_e (>1 GeV)	B	α_p	$E_{cut,\,p}$	W_p (>1 GeV)	N_{gas}	
Leptonic	2.6	360 TeV	1.4×10^{47} erg	3 μG	-	-	-	-	**OK**
Hadronic A	1.7	150 TeV	1.0×10^{44} erg	3 μG	1.7	150 TeV	1.0×10^{46} erg	100 cm^{-3}	**Bad**
Hadronic B	2.5	60 TeV	1.9×10^{46} erg	10 μG	1.7	150 TeV	1.0×10^{46} erg	100 cm^{-3}	**OK**

P and e Spectrum: Cutoff Power Law
IC seed photon: CMB and IR (inferred with GALPROP).
Pi production target gas: Inferred from HI and ^{12}CO

SED modelling: *tail*





	α_e	$E_{cut,\,e}$	W_e (>1 GeV)	B	α_p	$E_{cut,\,p}$	W_p (>1 GeV)	N_{gas}	
Leptonic	2.6	120/1200 TeV	1.6×10^{47} erg	3 μG	-	-	-	-	**Bad**
Hadronic A	1.7	1000 TeV	8.7×10^{43} erg	3 μG	1.7	1000 TeV	8.7×10^{45} erg	200 cm^{-3}	**Bad**
Hadronic B	2.5	35 TeV	2.0×10^{46} erg	10 μG	1.7	1000 TeV	8.7×10^{45} erg	200 cm^{-3}	**OK**

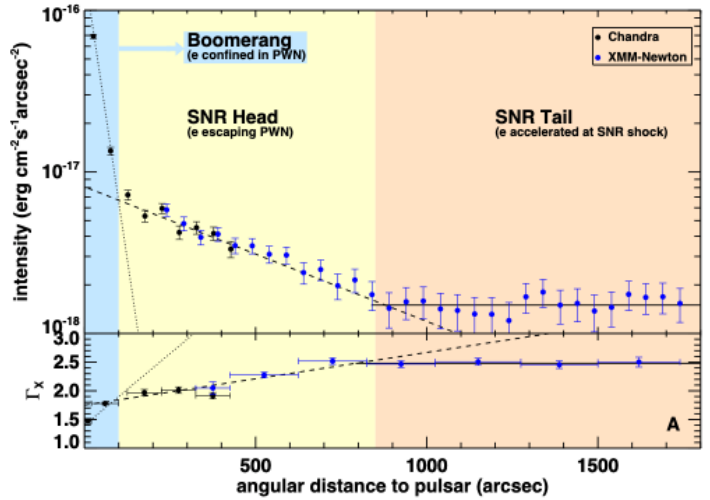
P and e Spectrum: Cutoff Power Law
IC seed photon: CMB and IR (inferred with GALPLOP).
Pi production target gas: Inferred from HI and ^{12}CO

Interpretation

head

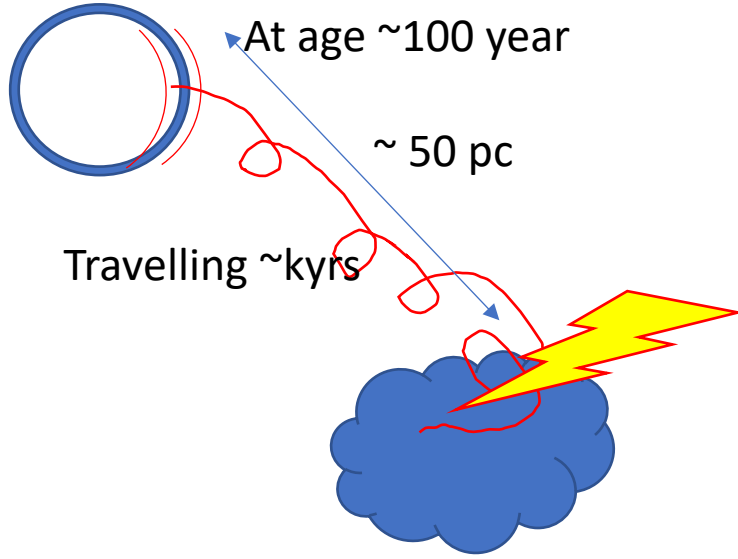
- **Leptonic**
  - Electrons may be provided by the PWN
  - Synchrotron Cooling time at 360 TeV is ~4 kyr
  - Spin Down power 2.2 x 10^{37}erg/s and age 3 kyr suggests the total enegy release of 2.2 x 10^{48} erg.
  - W_e=1.4 ×10^{47} erg

- **Hadronic**
  - Protons are accelerated in SNR shell up to 150 TeV
  - +Electrons from PWN



tail

- **Hadronic**
  - Protons were accelerated up to 1 PeV when the SNR was younger, escaped the shock, and are colliding with the cloud now.
  - Diffusion length for O(100 TeV) protons after 5-10 kyr is 40-60 pc, larger than the SNR
  - The spectral index (1.7) harder than 2.0 can also be explained.
  - Spatial coincidence may be by chance?



Summary

- ✓ SNR G106.3+2.7/Boomerang PWN is a PeVatron candidate.
- ✓ MAGIC has detected extended gamma-ray emission spatially coincided with the SNR radio morphology.
- ✓ At higher energies (5.65-30 TeV), MAGIC-tail emission is significant, while the *head* is not significant.
- ✓ Assuming that the emission > 10 TeV measured by Air Shower experiments are all from *tail*,
  head: electrons escaped from PWN?
  tail: Protons accelerated in the past up to PeV and colliding with cloud later?

<u>Future prospective</u>

For precise discussion at the break energies of *head* & *tail*, further VHE observations with better angular resolution at 10 – 100 TeV are required to resolve the *head* and *tail* emissions.