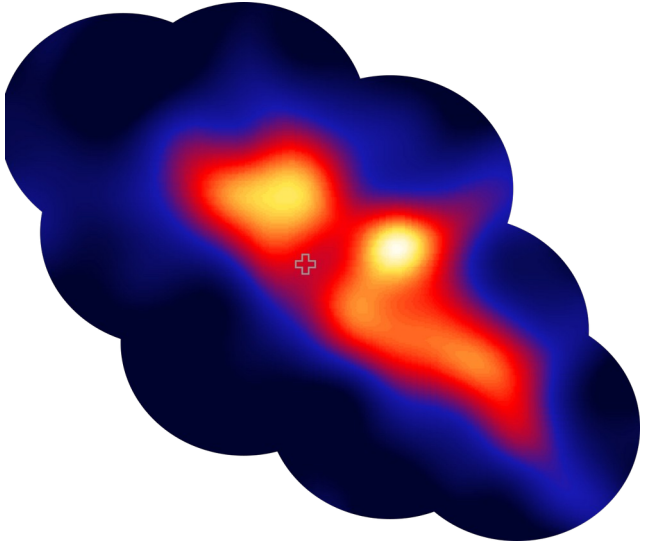
MAGIC observations of the putative PeVatron SNR G106.7+2.7 in the proximity of the Boomerang PWN

Marcel Strzys[a], Tomohiko Oka[b], Takayuki Saito[a], Hidetoshi Kubo[a]
for the MAGIC Collaboration

a) ICRR, The University of Tokyo, b) Kyoto University

TeVPa Conference, Kingston, Canada

10th August 2022

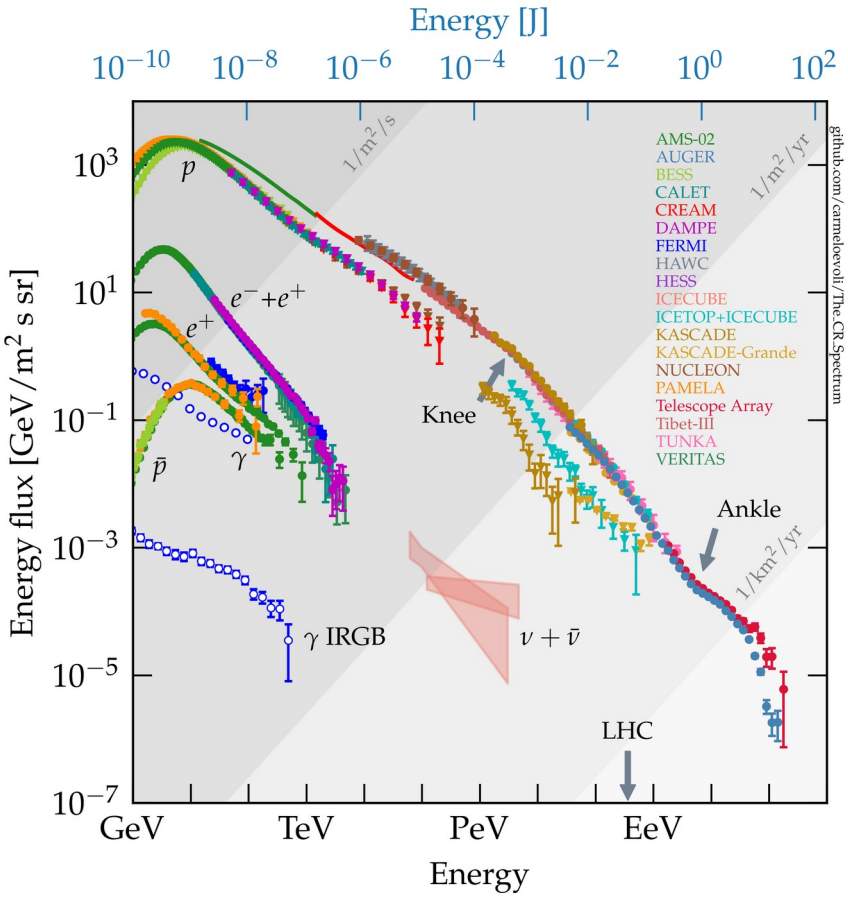


The strange case of PeVatrons

- So far unclear what is the maximum energy of the Galactic CR component; up to the CR knee?
- Recent observations of air shower arrays (e.g. LHAASO) provide list of PeVatron candidates
- Still, no conclusive evidence of hadronic PeV accelerator

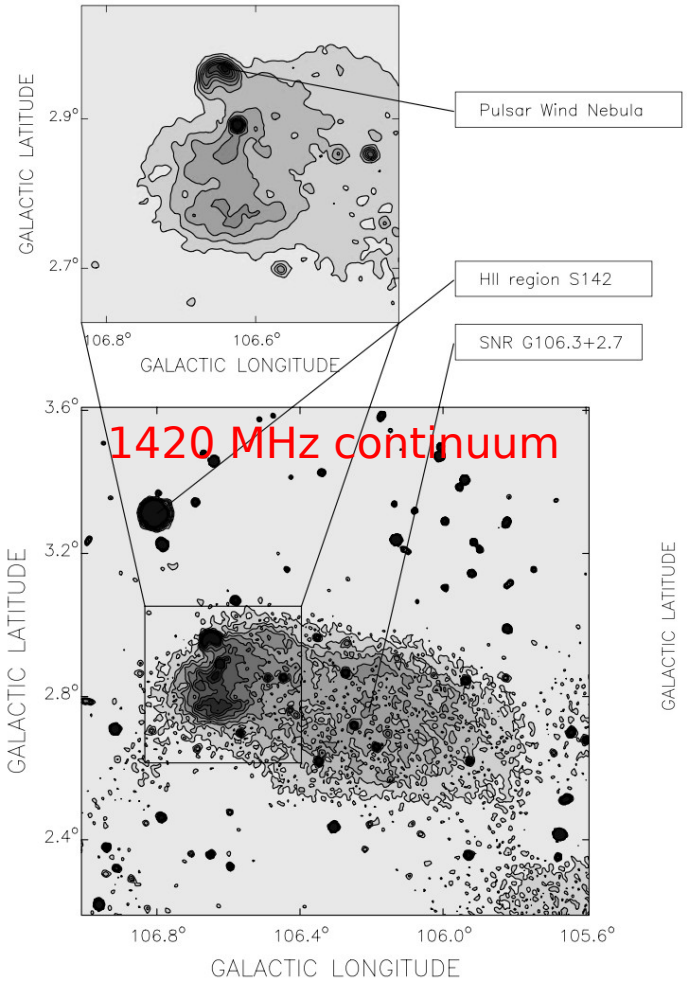
Source	Possible Association	Reference
HESS J1745-290	Sagittarius A*/Galactic center	[39]
Crab/LHAASO J0534+2202	PSR J0534+2200	[26,28,41,107]
LHAASO J1825-1326/2HWC J1825-134	PSR J1826-1334/PSR J1826-1256	[28,134]
LHAASO J1839-0545/2HWC 1837-065	PSR J1837-0034/PSRJ1838-0537	[28,40]
LHAASO J1843-0338/2HWC 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]

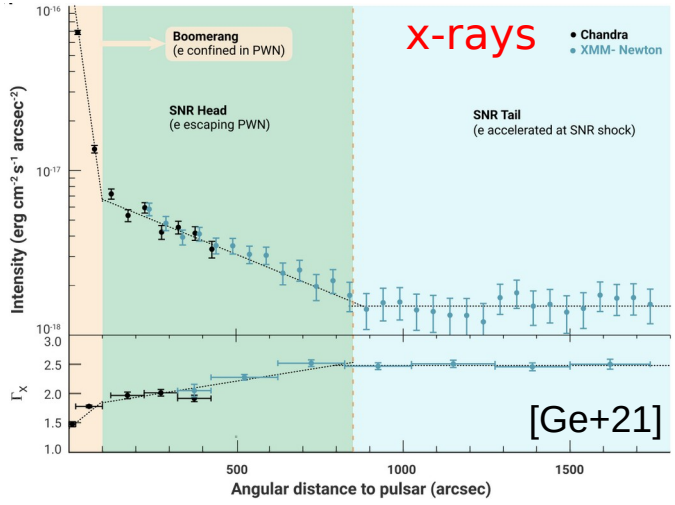
[Cristofari21; arxiv:2110.07956]

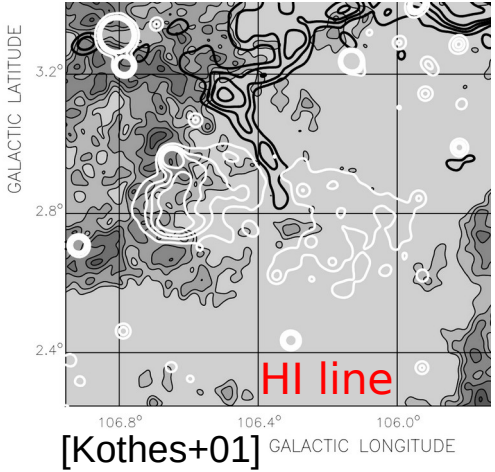


SNR G106.3 & the Boomerang PWN

[Kothes+01]





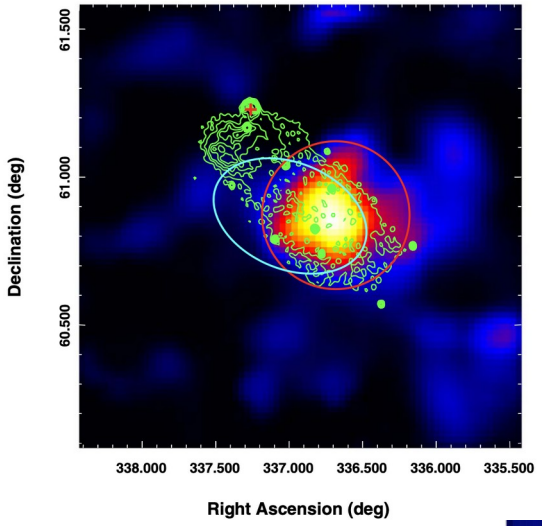


[Kothes+01]

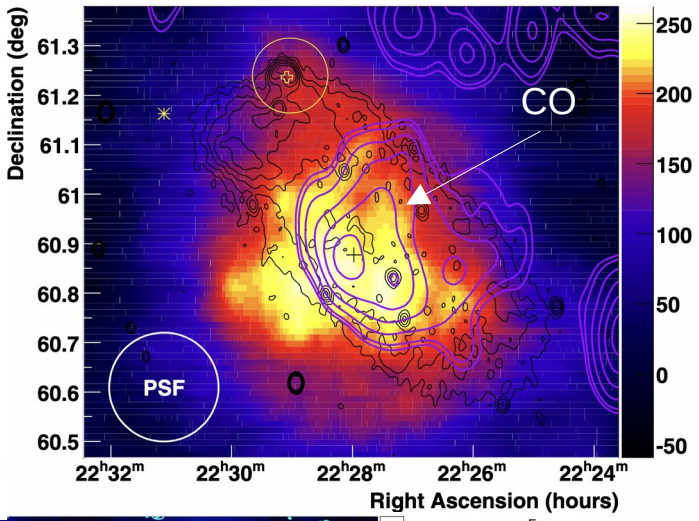
- Comet shape SNR with head and tail (Joncas & Higgs, 1990) seen in radio continuum.
- Head seems to be colliding with dense molecular cloud
- PWN is at the edge of head PSR J2229+6114
  - $L_{sd} = 2.2 \times 10^{37}$erg/s
  - $T_{sd} = 10$kyr
  - d = 3 kpc (X-ray absorption)
- Association of HI with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

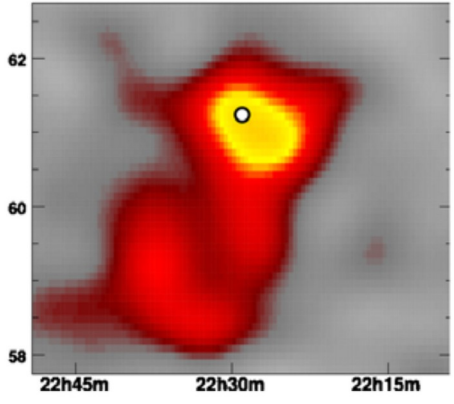
SNR G106.3 in γ rays

> 3 GeV Fermi-LAT (Xin+19)

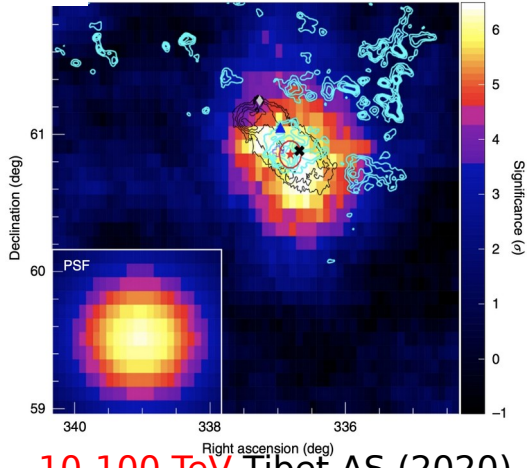


> 0.6 TeV VERITAS (2009)

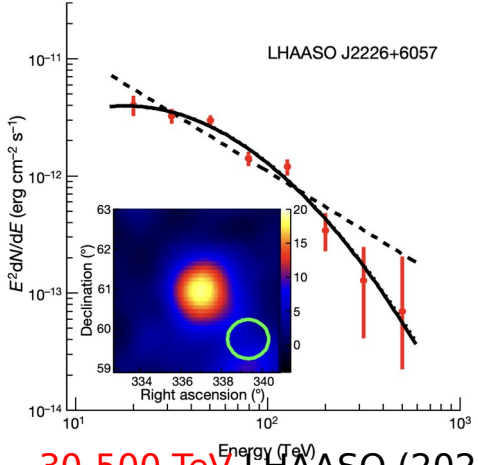




35 TeV Milagro (2009)



10-100 TeV Tibet AS (2020)



30-500 TeV LHAASO (2021)

- Well known γ-ray source
- Emission is extended in the TeV range
- Recent detection up to 500 TeV by LHAASO
  - → Possible PeVatron; but origin not fully determined yet

Objectives for study by MAGIC:

- → Deep study with higher angular resolution

MAGIC observations of SNR G106.3

- Located at La Palma, Canary islands, Spain. 2200m a.s.l.
- Two telescopes with a 17m Ø dish

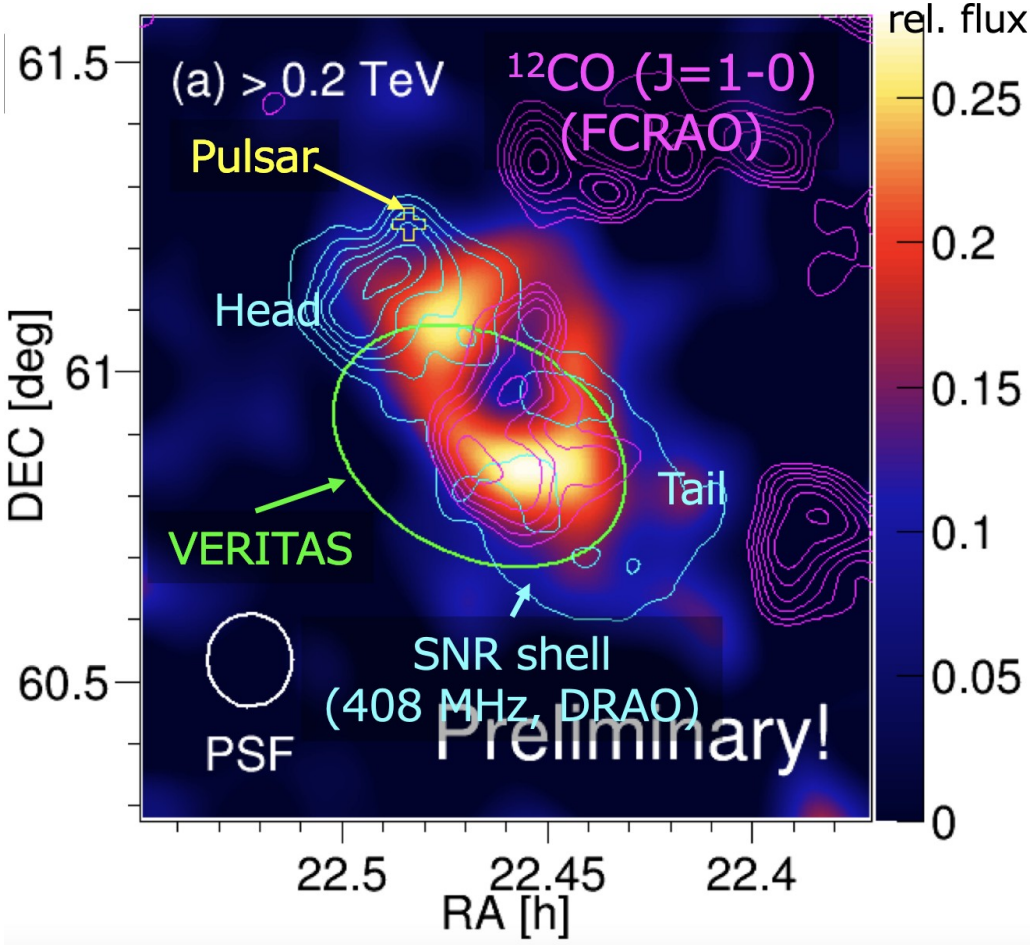
- FoV: Ø 3.5°
- Energy range: 30 GeV - 100 TeV
- Angular resolution (68% cont.):
  - 0.084° > 0.2 TeV
  - 0.072° > 1 TeV
- EnergyResolution: 20% (0.1 - 10 TeV)

[credit: Lea Heckmann]

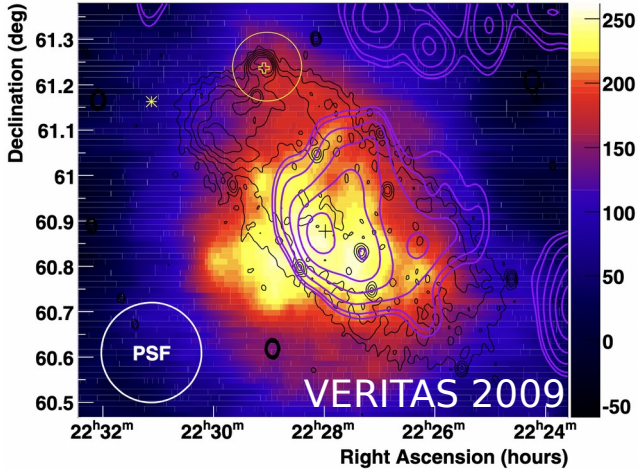
Observations of G106.3+2.7

- Period: May 2017 – Aug. 2019
- Eff. Obs. Time: 122 h
- ZA rage: 30 – 50 °
- Analysys threshold: 0.2 TeV

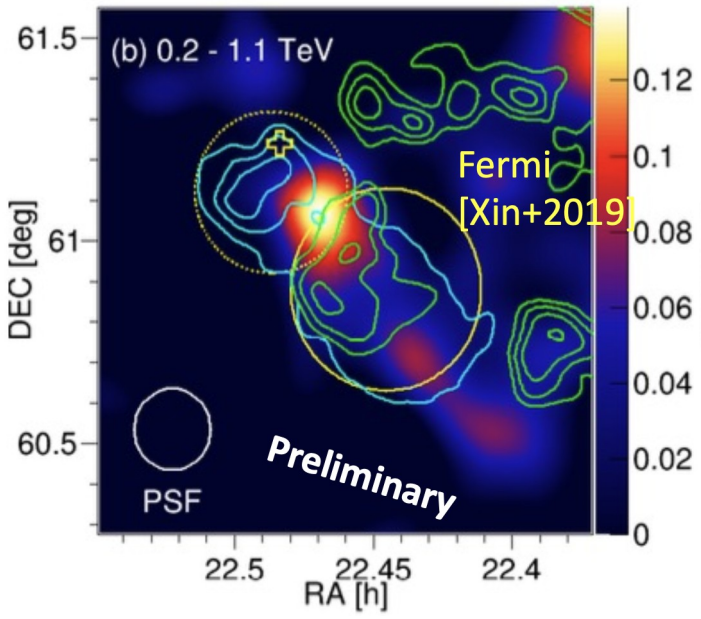
Overall Skymap taken with MAGIC

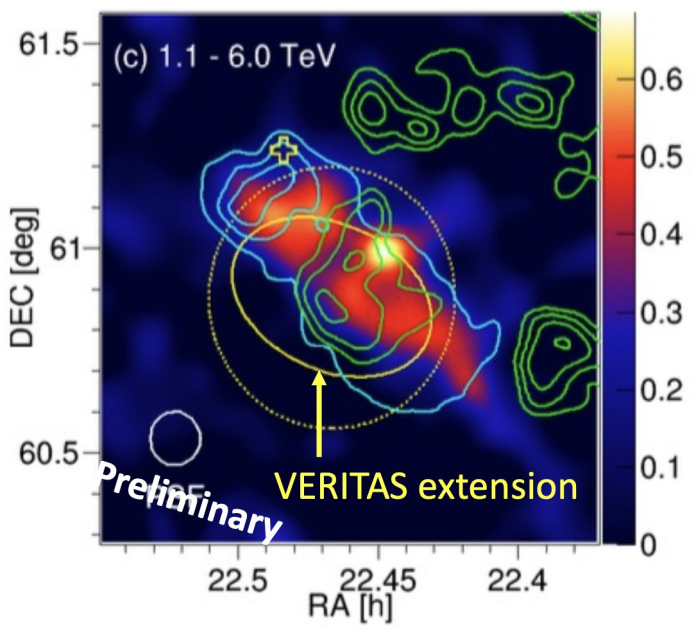


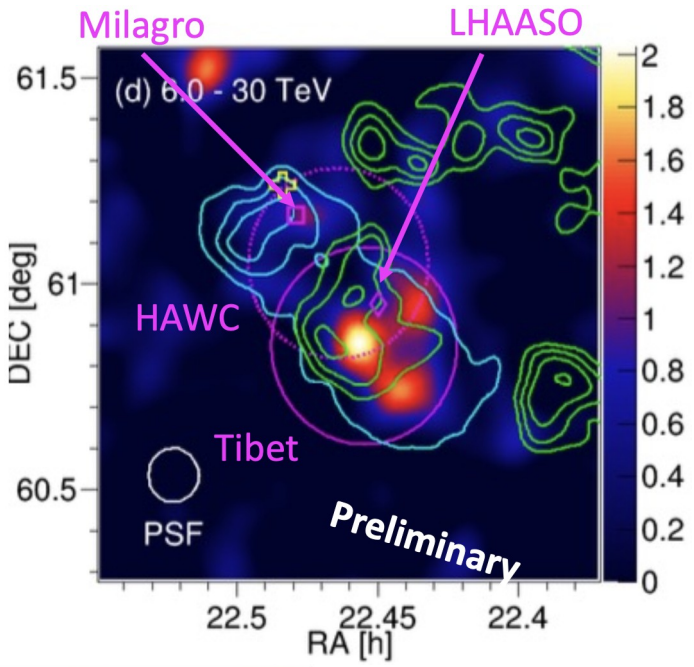
- MAGIC observed extended emission coinciding with radio shell
- MAGIC observes two emission peaks, one towards the head and one towards tail



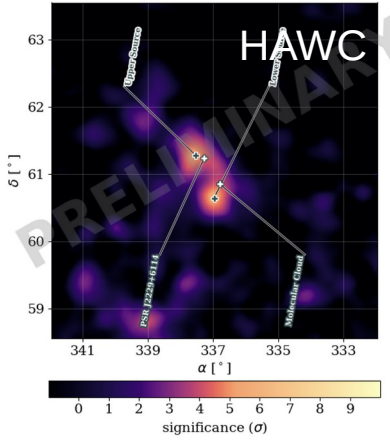
Energy dependent morphology





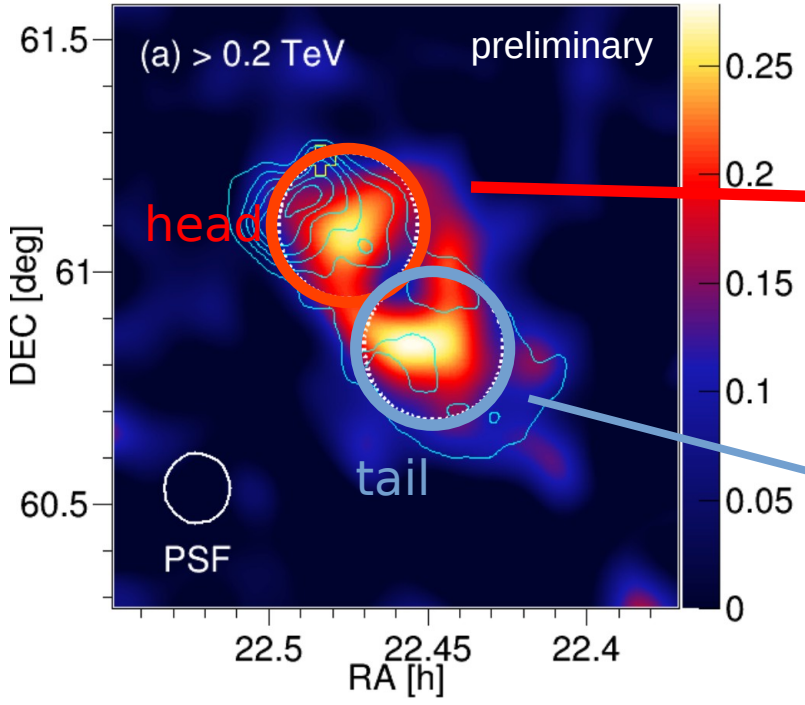


- Morphology changes with energy
- Consistent with previous measurements, emission from head region faints towards higher energies
- Recent result from HAWC also shows similar structure

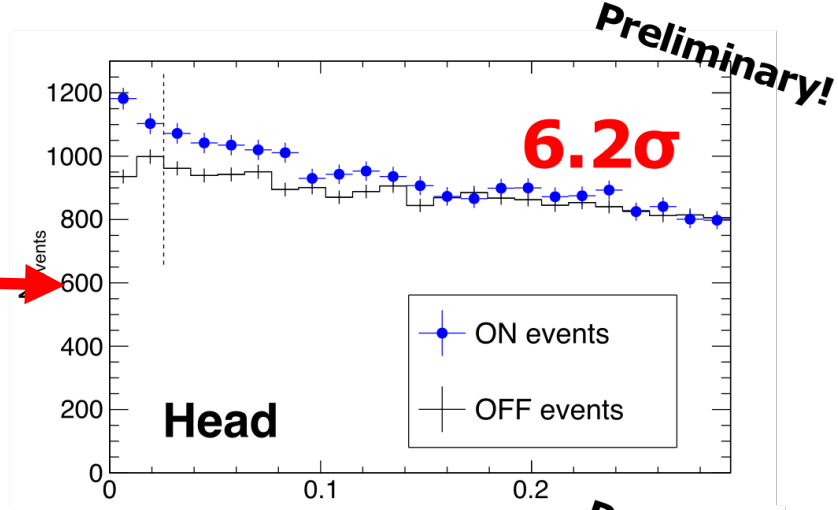


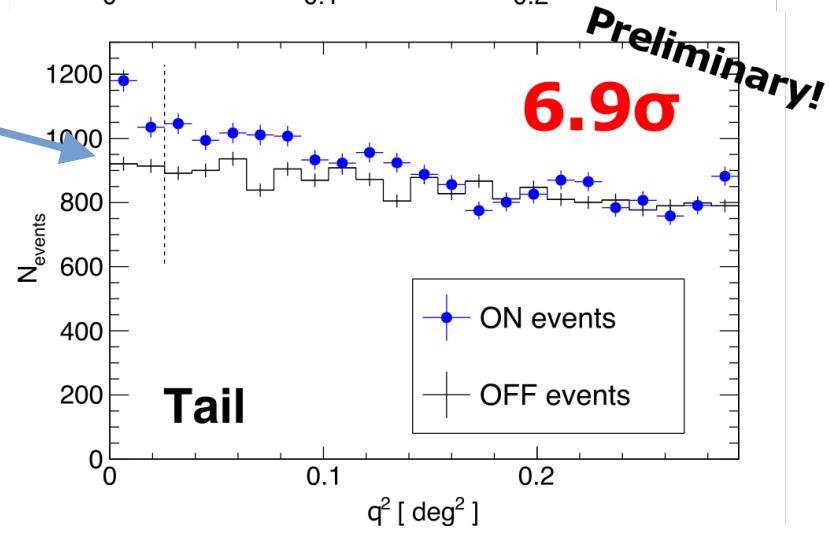
J. Goodman @ gamma 2022

Statistical analysis of the emission regions >0.2 TeV

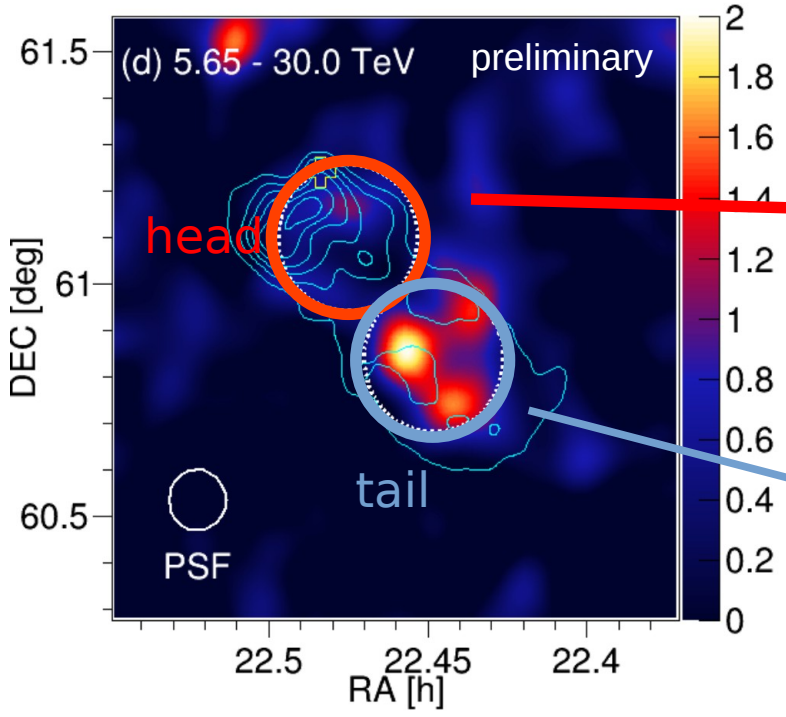


Source	RA	DEC	Radius
head region	337.°13	61.°10	0.°16
tail region	336.°72	60.°84	0.°16

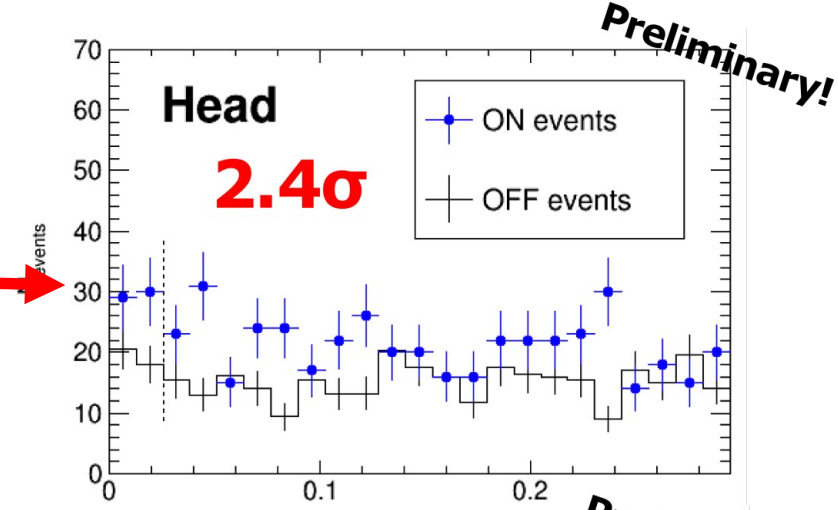


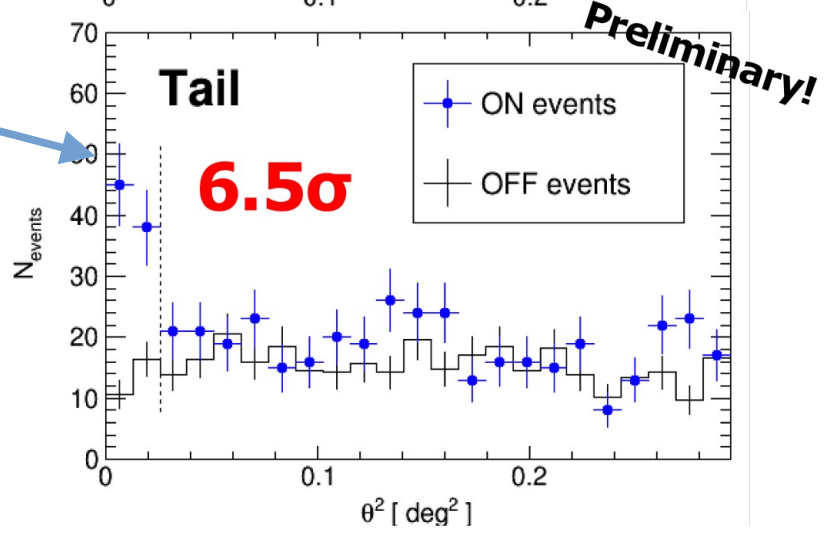


Statistical analysis of the emission regions 6-30 TeV

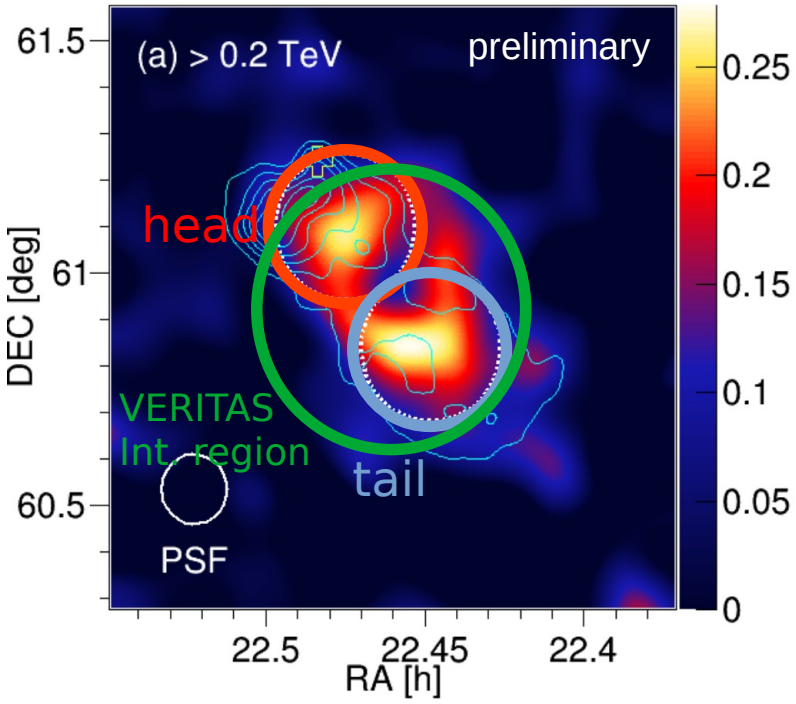


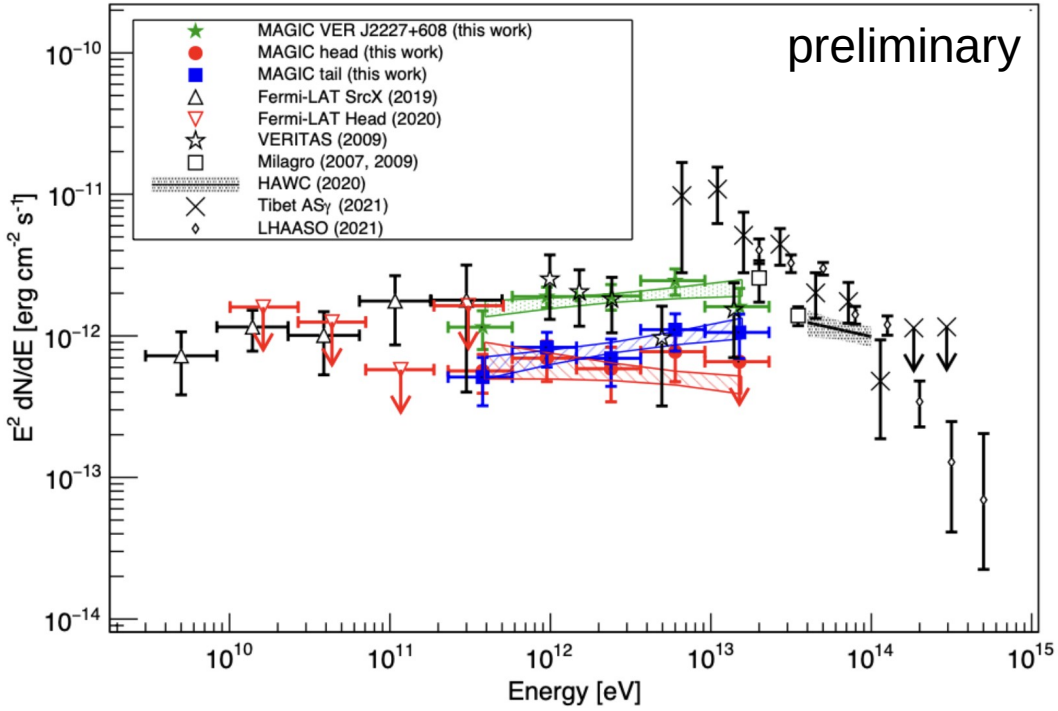
Source	RA	DEC	Radius
head region	337.°13	61.°10	0.°16
tail region	336.°72	60.°84	0.°16





Spectra of the emission regions



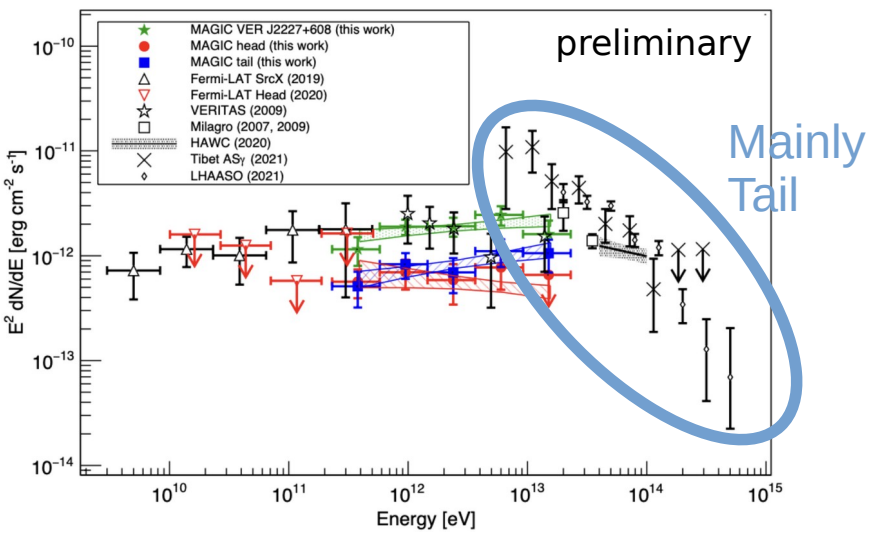


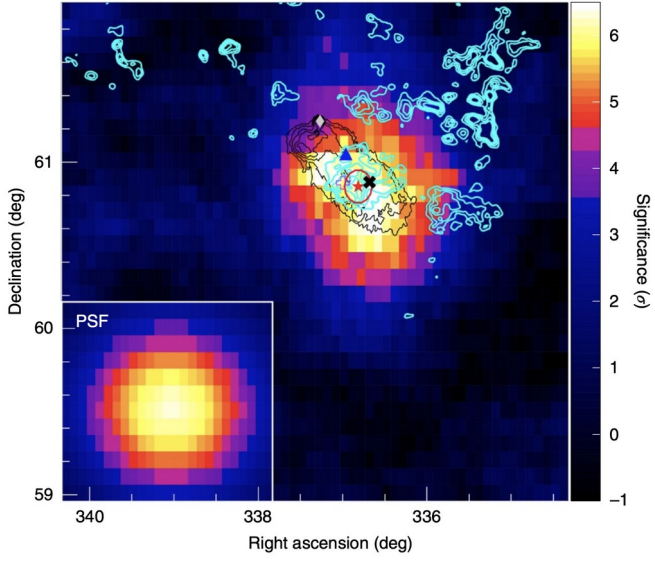
Source	N_0 (10^{-14} cm^{-2} s^{-1} TeV^{-1}) at 3 TeV	Γ	χ^2/ndf
head	$3.8 \pm 0.7_{\text{stat}} \pm 0.7_{\text{sys}}$	$2.12 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}}$	5.5/6
tail	$6.0 \pm 0.7_{\text{stat}} \pm 1.0_{\text{sys}}$	$1.83 \pm 0.10_{\text{stat}} \pm 0.15_{\text{sys}}$	2.6/6
VER J2227+608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

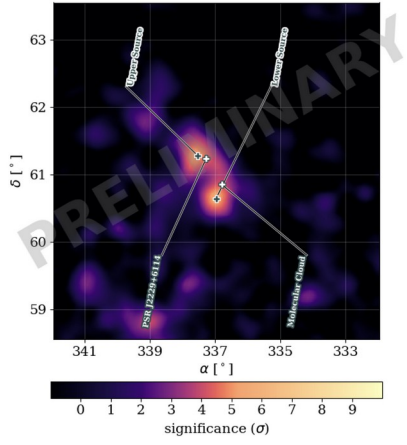
- Consistent with prev. measurements when using same integration region
- Tail slighly harder

Modelling assumptions

- Boomerang PWN and SNR G106.3 are associated.
- They are located at 800 pc with an age of 3 - 10 kyr.
- head and tail emisssion region have different physics conditions
- Emission seen >10 TeV by air shower arrays originates predominantely from tail

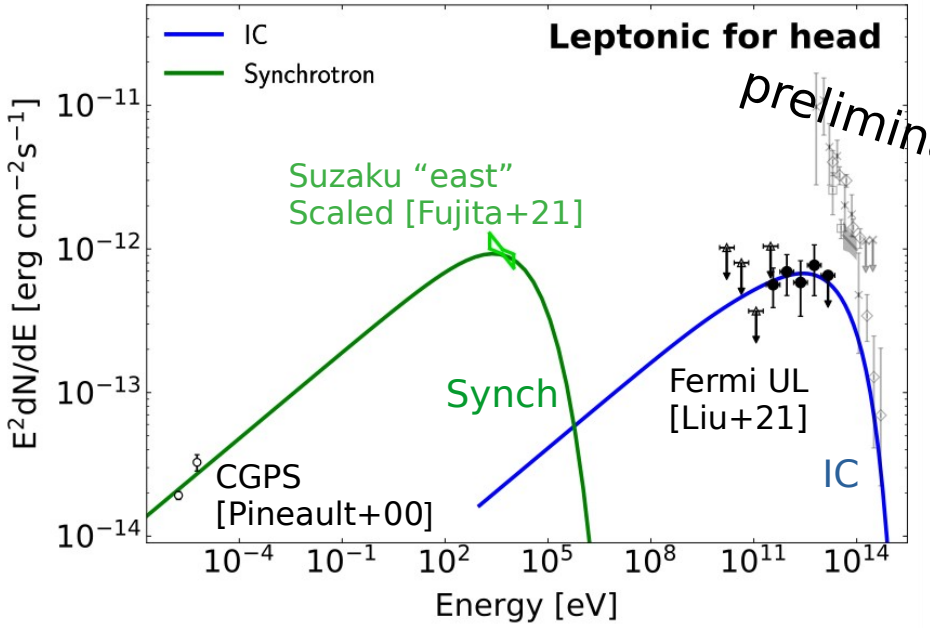


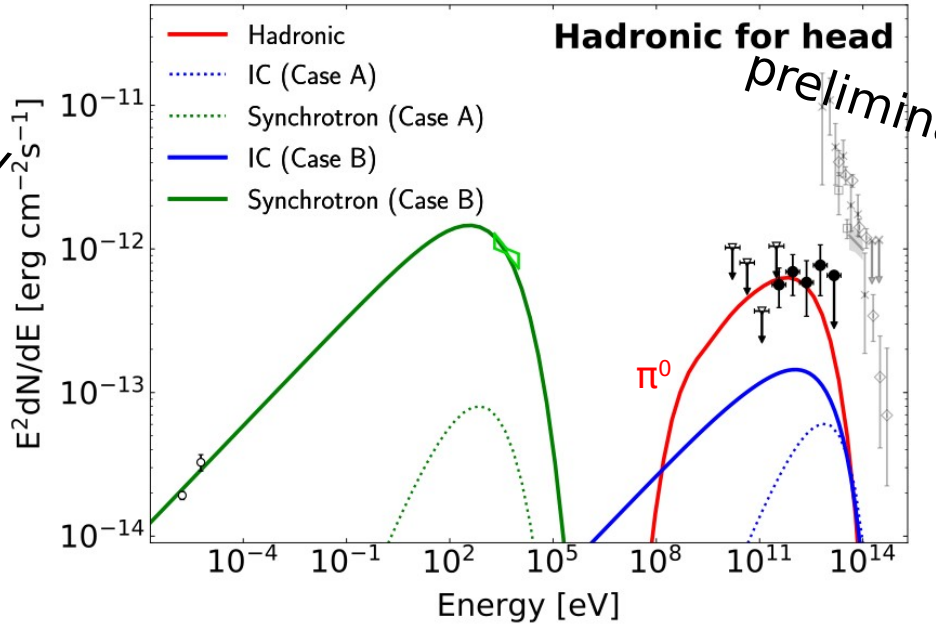




J. Goodman @ gamma 2022

Spectral modelling of head

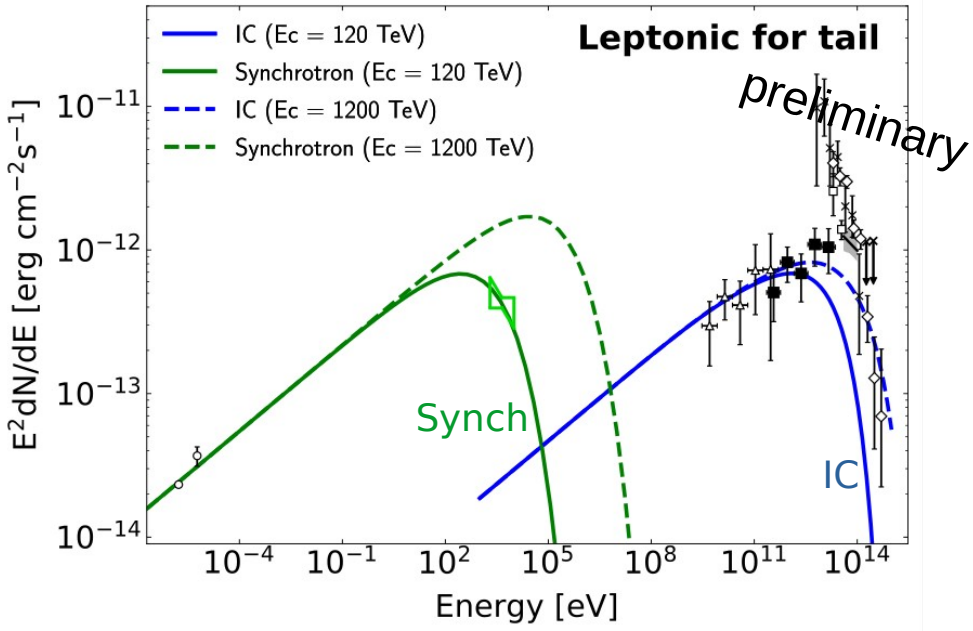


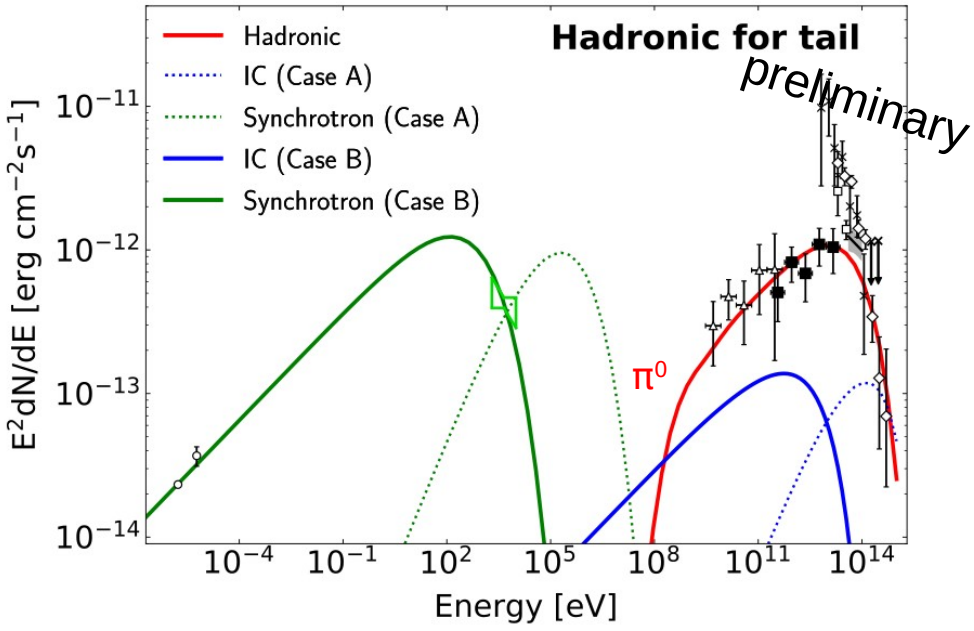


	α_e	$E_{cut,\,e}$	W_e (>1 GeV)	B	α_p	$E_{cut,\,p}$	W_p (>1 GeV)	N_{gas}	
Leptonic	2.6	360 TeV	1.4 ×10^{47} erg	3 μG	-	-	-	-	OK
Hadronic A	1.7	150 TeV	1.0 ×10^{44} erg	3 μG	1.7	150 TeV	1.0 ×10^{46} erg	100 cm^{-3}	Bad
Hadronic B	2.5	60 TeV	1.9 ×10^{46} erg	10 μG	1.7	150 TeV	1.0 ×10^{46} erg	100 cm^{-3}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

- P and e Spectrum:
  Power Law + CutOff
- IC seed photon:
  CMB and IR (inferred with GALPLOP)
- π^0 target gas:
  based on HI and ^{12}CO

Spectral modelling of 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:
  Power Law + CutOff
- IC seed photon:
  CMB and IR (inferred with GALPLOP)
- π^0 target gas:
  based on HI and ^{12}CO

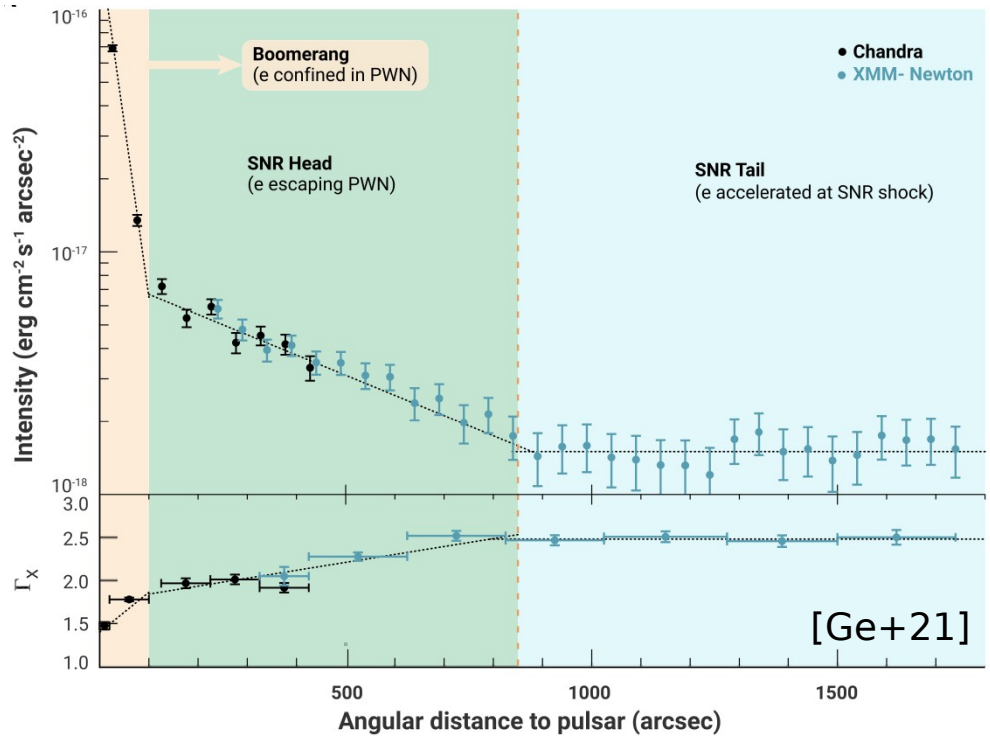
Interpretation

Head:

- Leptonic
  - Electrons may originate from PWN
  - Synchrotron Cooling time at 360 TeV is ~4 kyr
  - Spin Down power 2.2 x 10^{37} erg/s and age 3 kyr

    => total energy release of 2.2x 10^{48} erg.
  - W_e=1.4 ×10^{47} erg

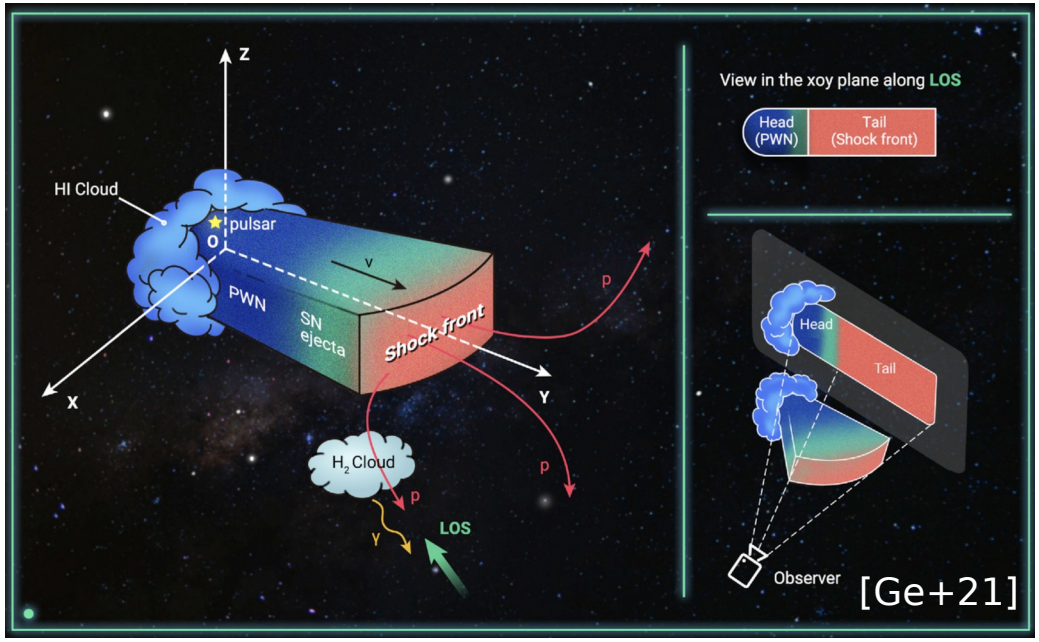
- Hadronic
  - Protons are accelerated in SNR shell up to 150 TeV



Interpretation

Tail:

- Hadronic
  - Protons accelerated up to 1 PeV when the SNR was young, escaped the shock, and interaction with MC
  - Diffusion length for O(100 TeV) protons:
    after 5-10 kyr is 40-60 pc > r_{SNR}
  - The spectral index (1.7) harder than 2.0 may result from diffusion
  - Spatial coincidence may be by chance?



Summary

- SNR G106.3+2.7 among most promising PeVatron candidate
- MAGIC detected extended γ-ray emission spatially coinciding with SNR radio morphology
- At HE (5.65-30 TeV), MAGIC-*tail* emission is significant, whereas *head* faints
- If emission > 10 TeV measured by Air Shower experiments mainly originates from *tail*:
  - *head*: electrons escaped from PWN?
  - *tail: p*rotons accelerated in the past and interacting with cloud?

Future prospective

Resolving head and tail at energies of 10 – 100 TeV crucial for preciser modelling; sensitive CO observation needed for testing escape scenario