

# **Resolving the origin of VHE $\gamma$ -ray emission from the PeVatron candidate SNR G106.3+2.7 using MAGIC telescopes**

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**T. Oka**, T. Saito, H. Kubo, M. Strzys  
for the MAGIC Collaboration

# Boomerang PWN/SNR G106.3+2.7

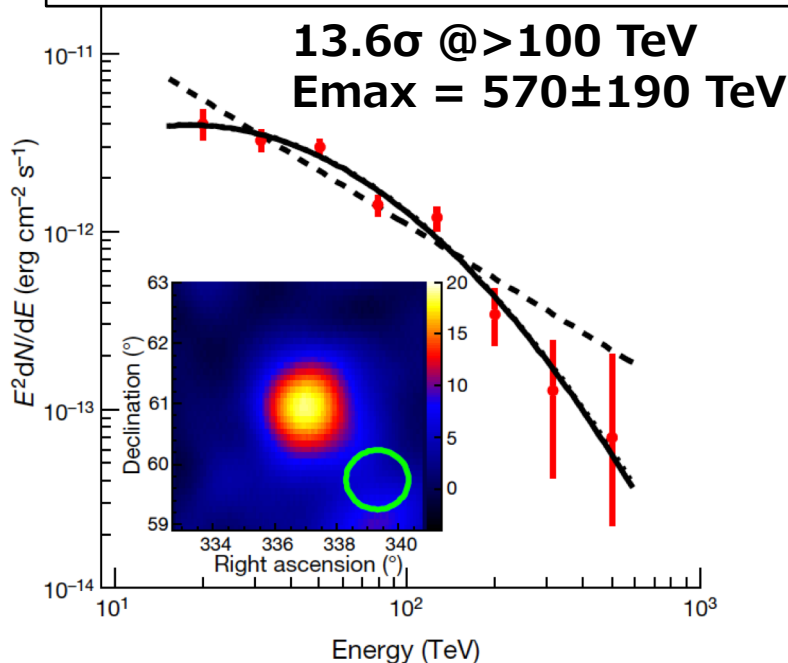
## ☺ One of the PeVatron candidate

- HAWC, TibetASy, and LHAASO detected 100 TeV  $\gamma$ -ray emission [Albert+ 2020; Amenomori+ 2021; Cao+2021]

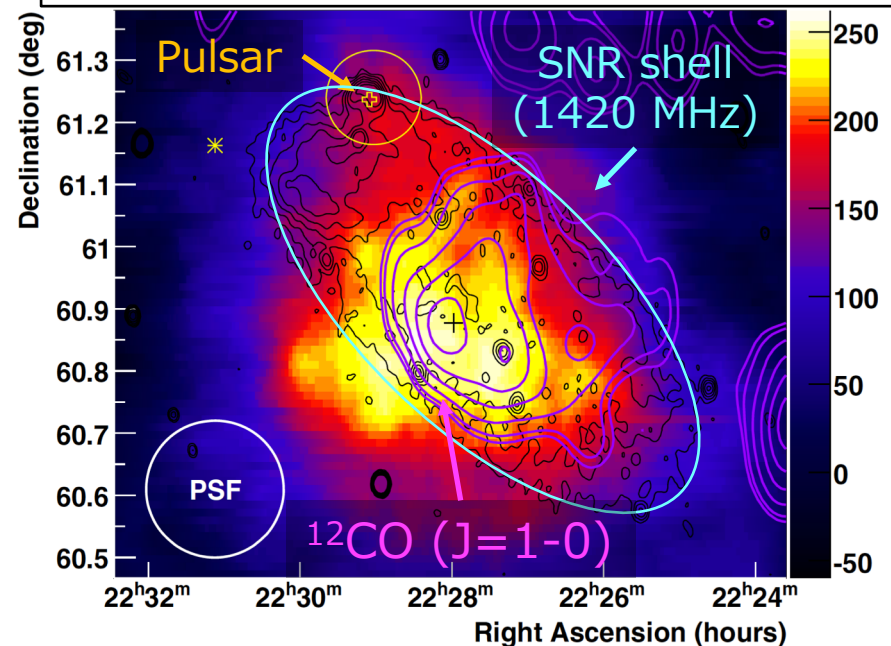
## ☹ PWN & SNR complex (Boomerang PWN & SNR G106.3+2.7)

- age: 4-10 kyr [Halpern+2001, Kothes+2006]
- The origin of the VHE emission is unclear.  
PWN or SNR? hadronic or leptonic?

LHAASO spectrum [Cao+2021]



VERITAS >0.63 TeV [Acciari+2009]



# MAGIC observations

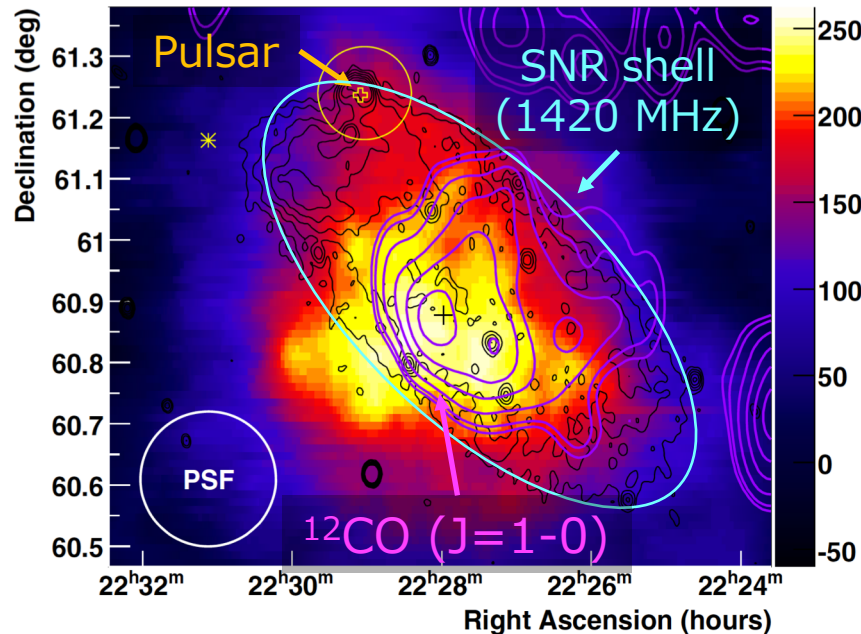
The MAGIC observations were performed with the best angular resolution among the previous  $\gamma$  ray observations in the vicinity of SNR G106.3+2.7.



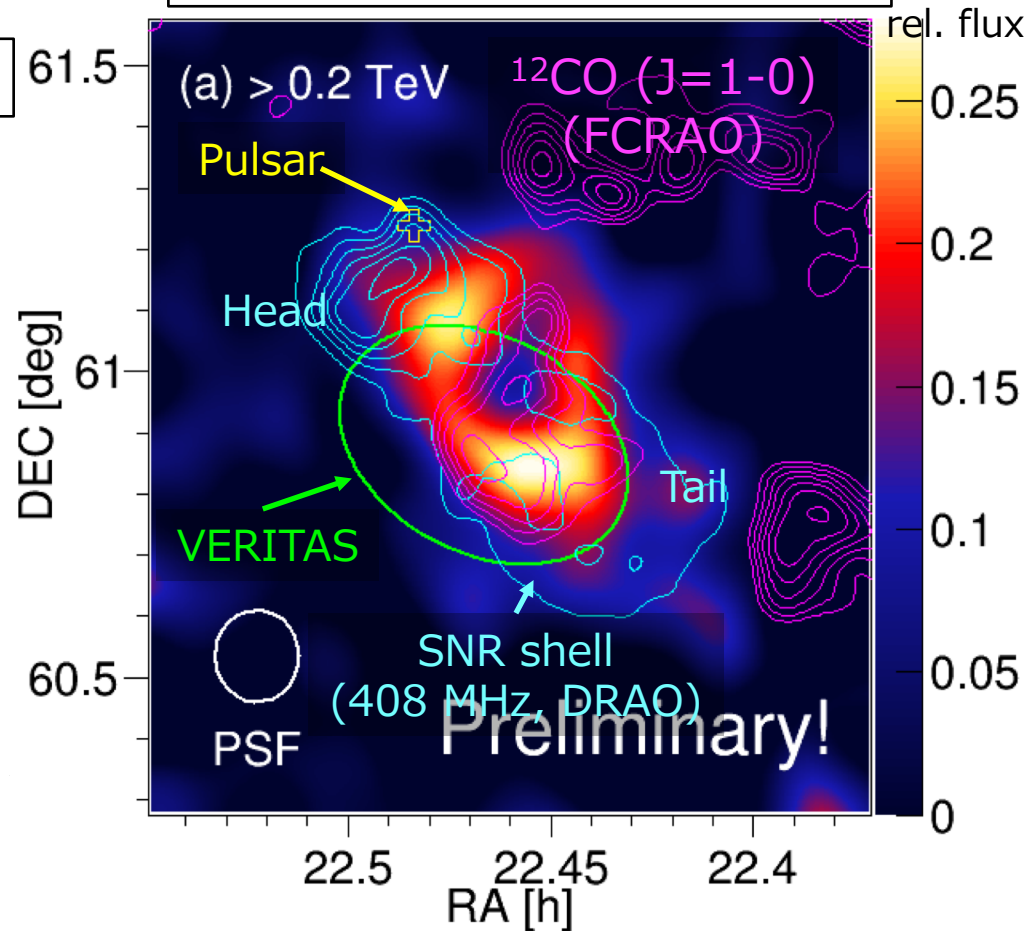
	VERITAS (pre-upgrade) [Acciari+2009]	MAGIC [This work]
Observation period	2008	2017 - 2019
<b>Selected time</b>	<b>33.4 hr</b>	<b>122 hr</b>
Analysis threshold	0.63 TeV	0.2 TeV
<b>68%-containment radius of PSF</b>	<b>0.11°</b>	<b>0.084° (&gt;0.2 TeV) 0.072° (&gt; 1 TeV)</b>

# MAGIC Skymap

VERITAS >0.63 TeV [Acciari+2009]



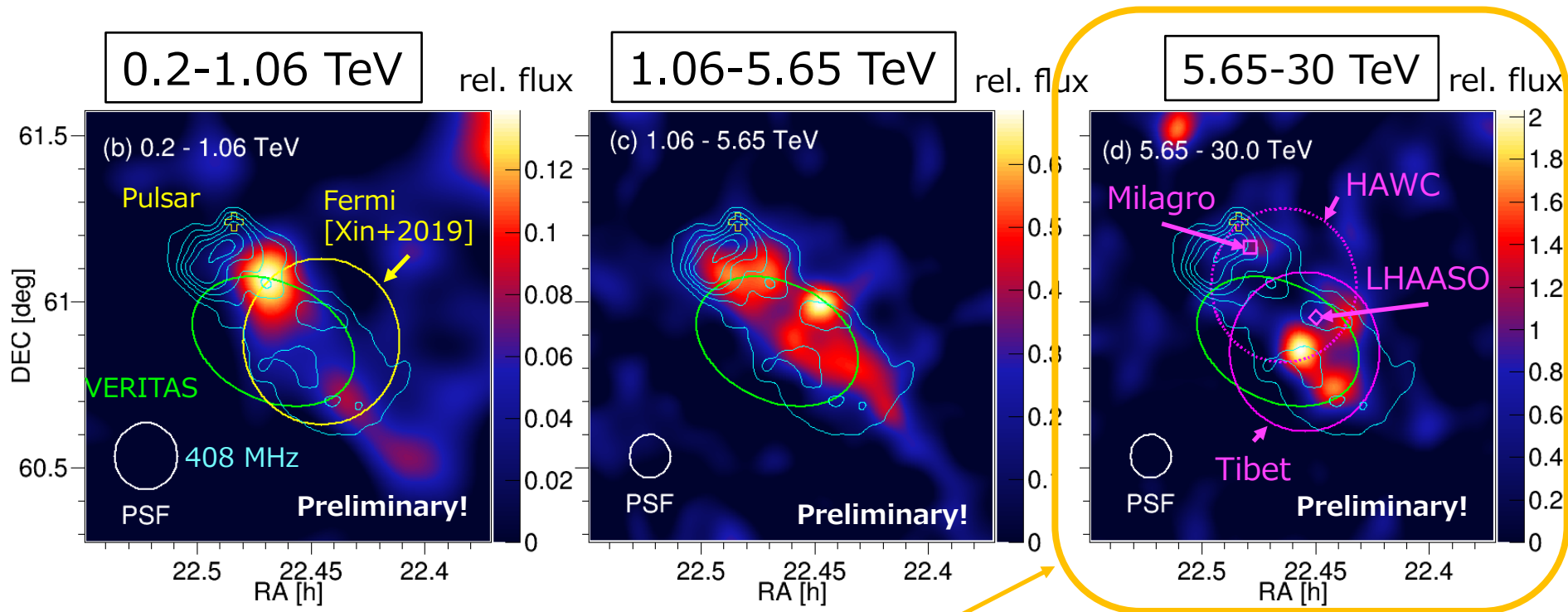
MAGIC >0.2 TeV (This work)



✓  $\gamma$ -ray emission extends along with radio continuum emissions, named Head & Tail by Joncas & Higgs (1990).



# Energy-dependent morphology



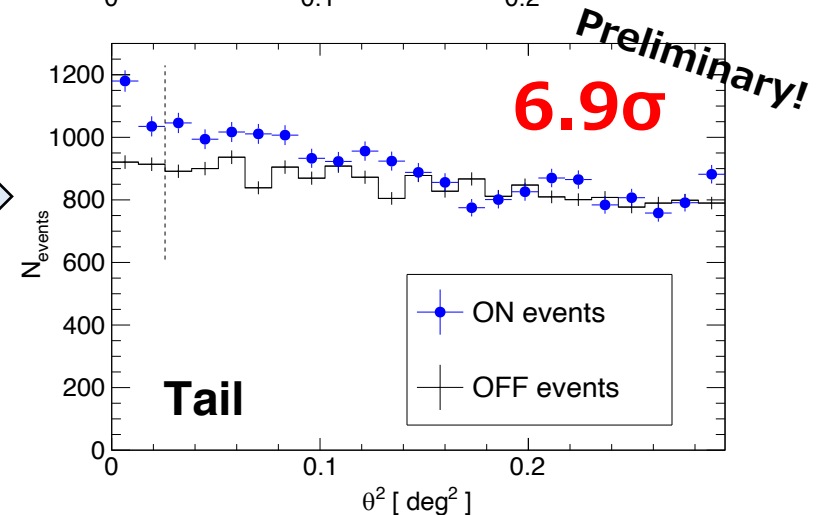
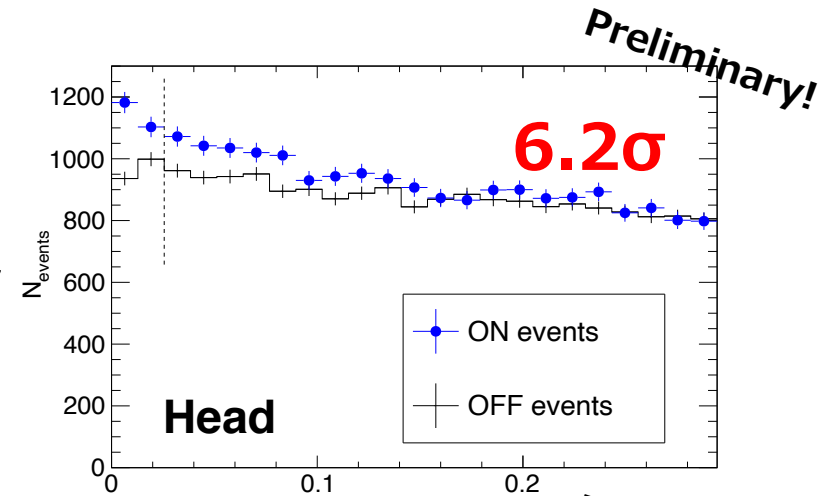
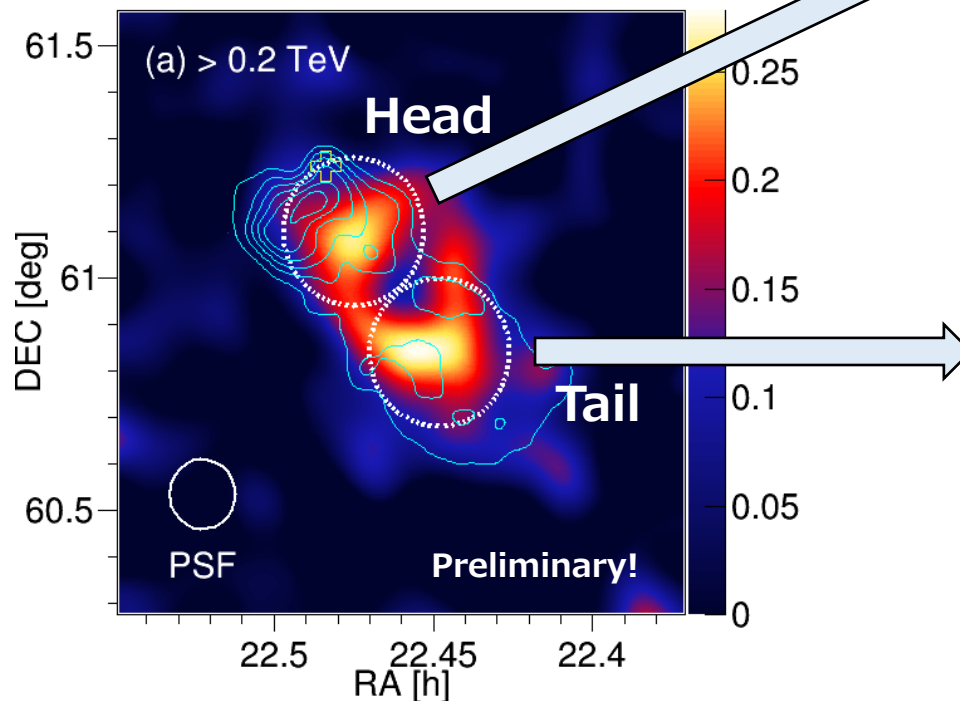
Milagro [Abdo+2009], HAWC [Albert+2020]  
Tibet [Amenomori+2021], LHAASO [Cao+2021]

- ✓ In the highest energy bin,  $\gamma$ -ray emissions are offset from the pulsar position.
- ✓ The position is in good agreement with other experiments

# Two region analysis ( $> 0.2$ TeV)

We analyze the two regions defined in the table below, named MAGIC-Head and Tail.

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

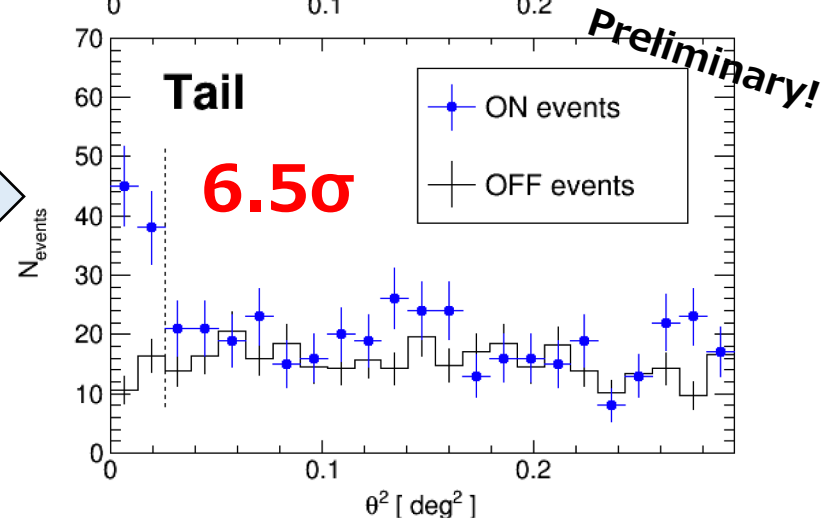
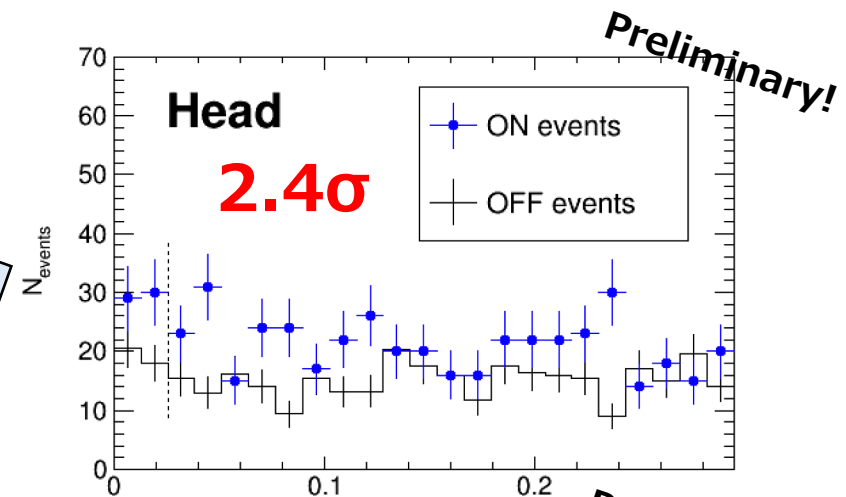
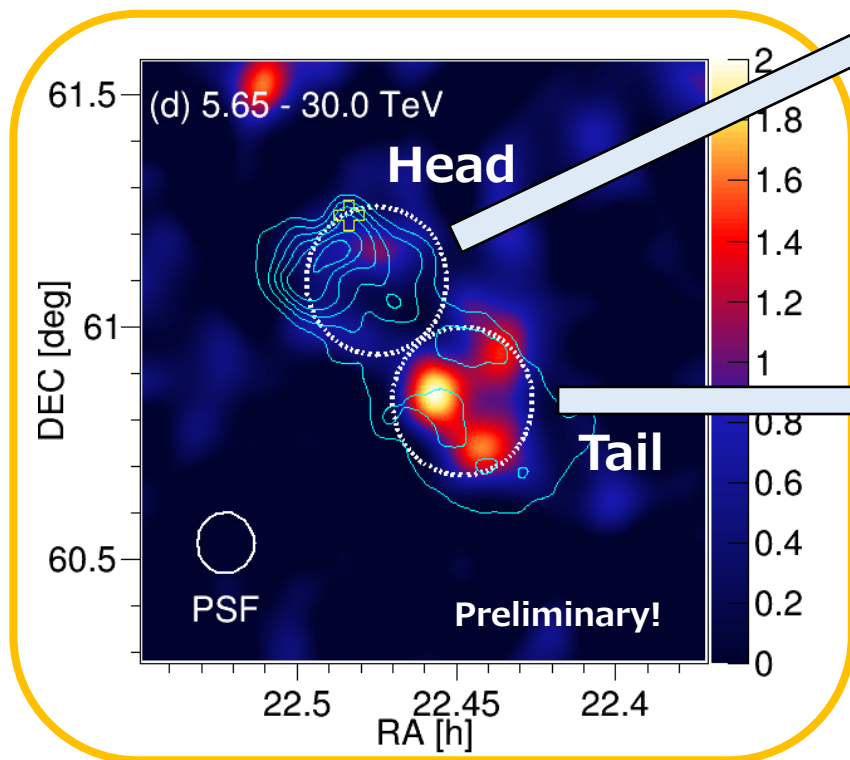


✓ Significant detection at both regions.

# Two region analysis (5.65-30 TeV)

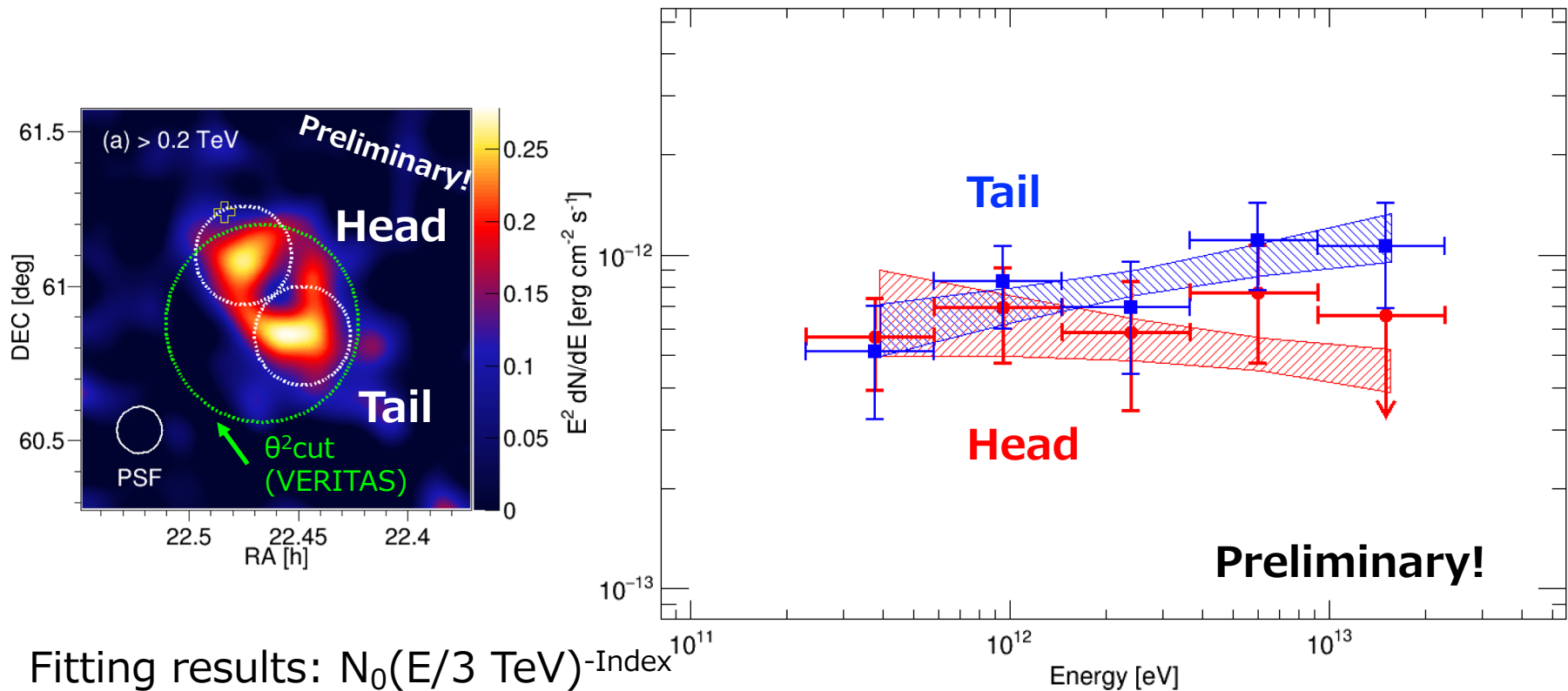
We analyze the two regions defined in the table below, named MAGIC-Head and Tail.

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



✓ Tail emission is significant, while Head is not significant

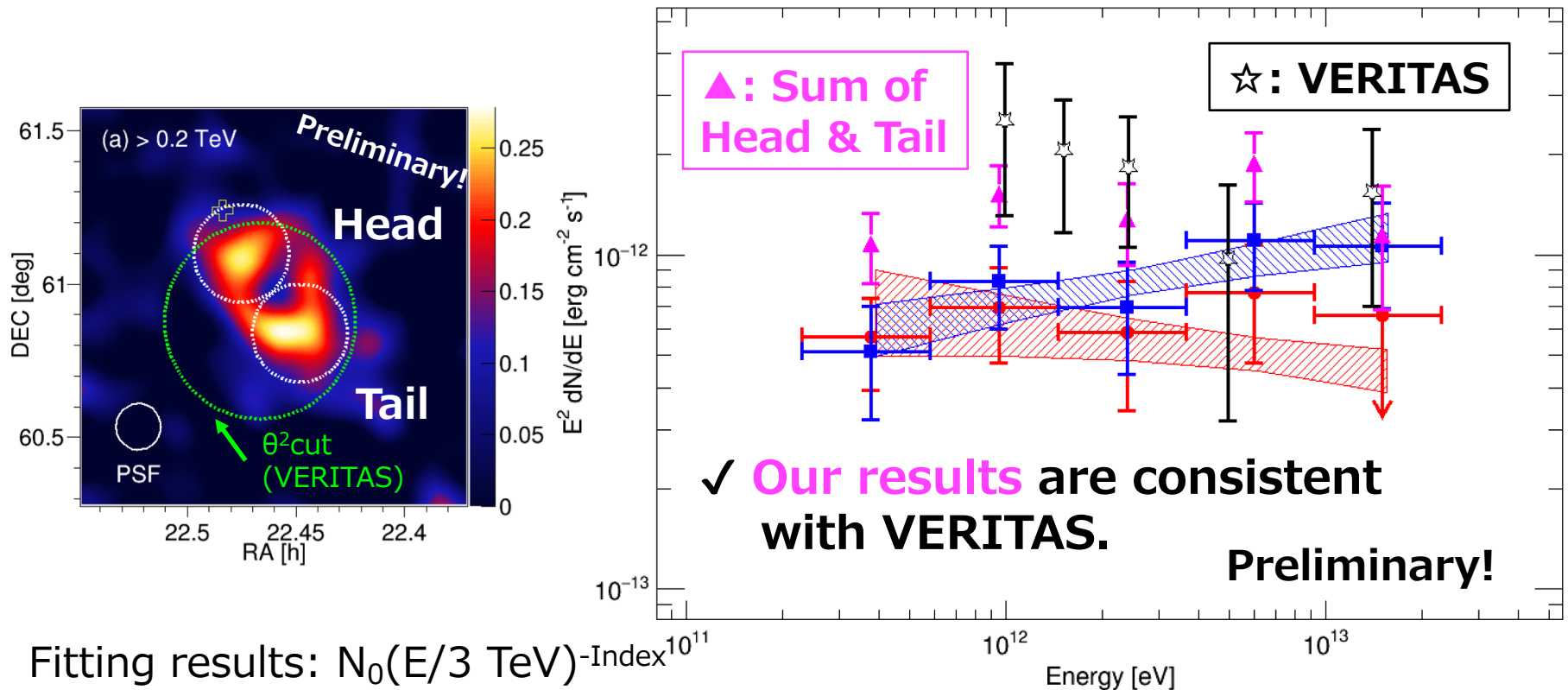
# Spectra of the Two Regions



Source	$N_0@3 \text{ TeV}$ [e-14 /cm $^2$ /s/TeV]	Index
Head	$3.8 \pm 0.7_{\text{stat}} \pm 0.7_{\text{sys}}$	$2.12 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}}$
Tail	$6.0 \pm 0.7_{\text{stat}} \pm 1.0_{\text{sys}}$	$1.83 \pm 0.10_{\text{stat}} \pm 0.15_{\text{sys}}$

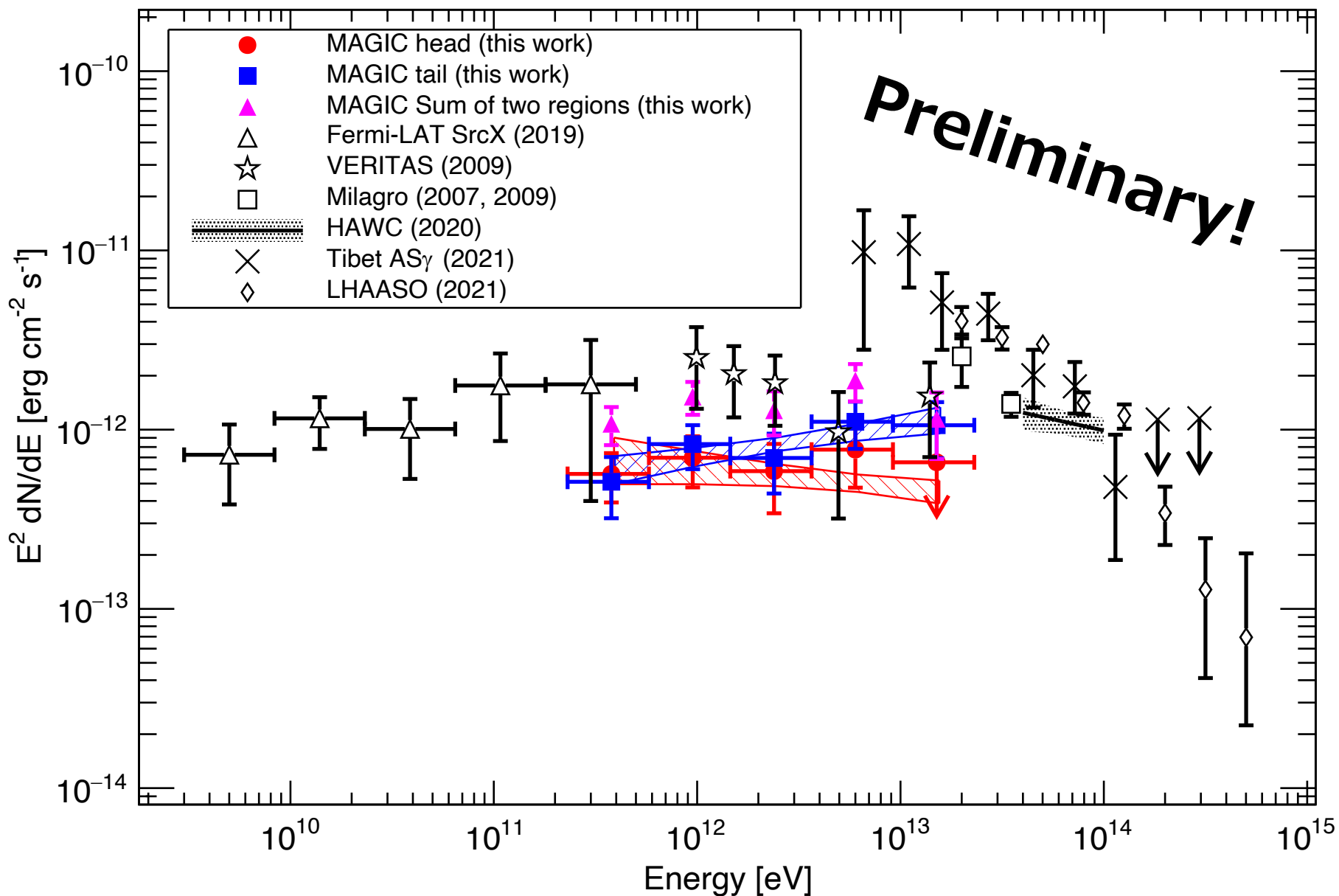
- ✓ The spectra of two regions are very similar  
but at higher energies of  $\sim 10$  TeV, Head has lower flux

# Spectra of the Two Regions



Source	N0 @3 TeV [e-14 /cm2/s/TeV]	Index
Head	$3.8 \pm 0.7_{\text{stat}} \pm 0.7_{\text{sys}}$	$2.12 \pm 0.12_{\text{stat}} \pm 0.15_{\text{sys}}$
Tail	$6.0 \pm 0.7_{\text{stat}} \pm 1.0_{\text{sys}}$	$1.83 \pm 0.10_{\text{stat}} \pm 0.15_{\text{sys}}$
Sum of two regions	$9.8 \pm 0.9_{\text{stat}} \pm 1.2_{\text{sys}}$	-
VERITAS [2009]	$11.5 \pm 2.7_{\text{stat}} \pm 3.5_{\text{sys}}$	$2.3 \pm 0.33_{\text{stat}} \pm 0.30_{\text{sys}}$

# Comparison with other experiments

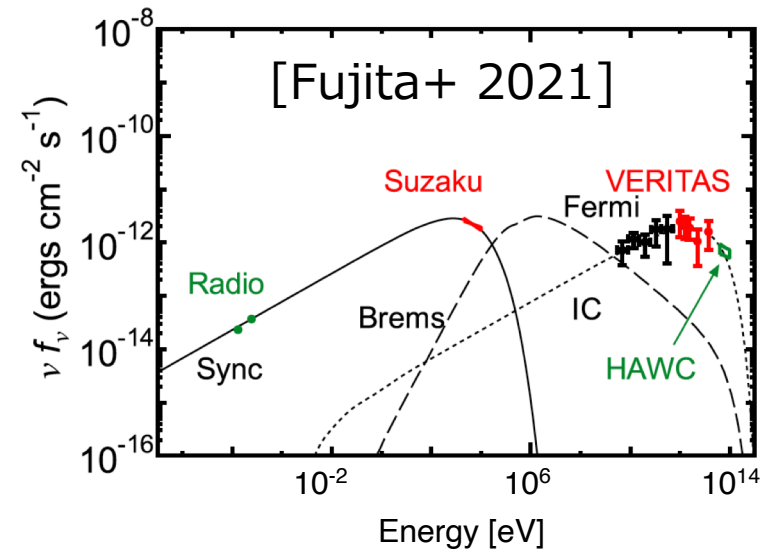
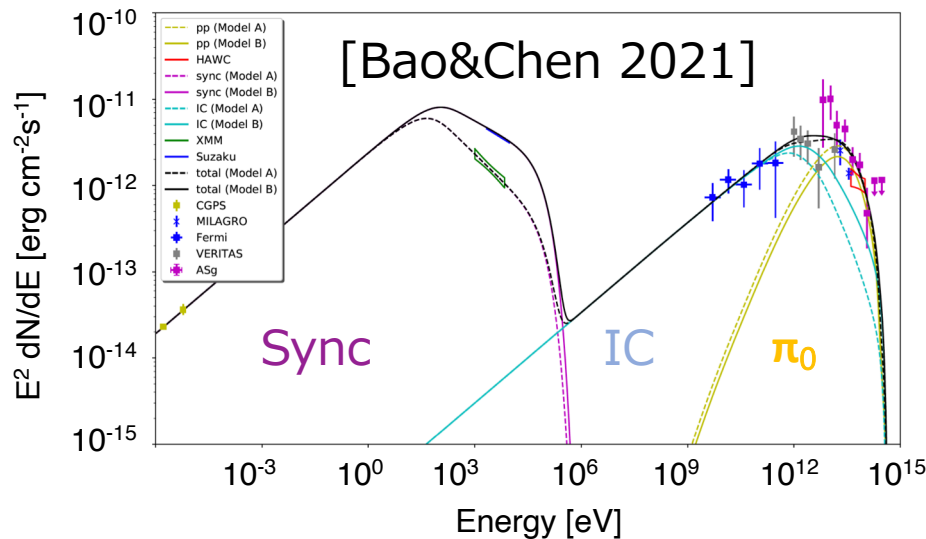




# Interpretation of the VHE emission

## Case 1: the origin of Head and Tail are **same**

- ✓ The extension along with the shell suggests that the gamma-ray emissions originate in the SNR.
- ✓ Various models have been considered for Case 1.
  - Hadronic models can reproduce well the observed spectra  $>10$  TeV.
  - However, there is still a leptonic scenario which can explain MWL SED.

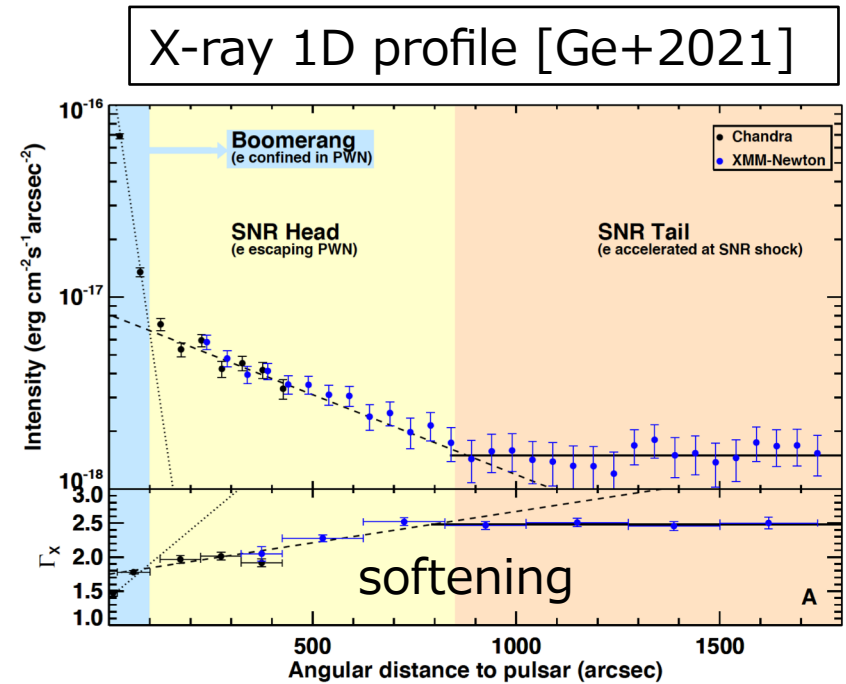
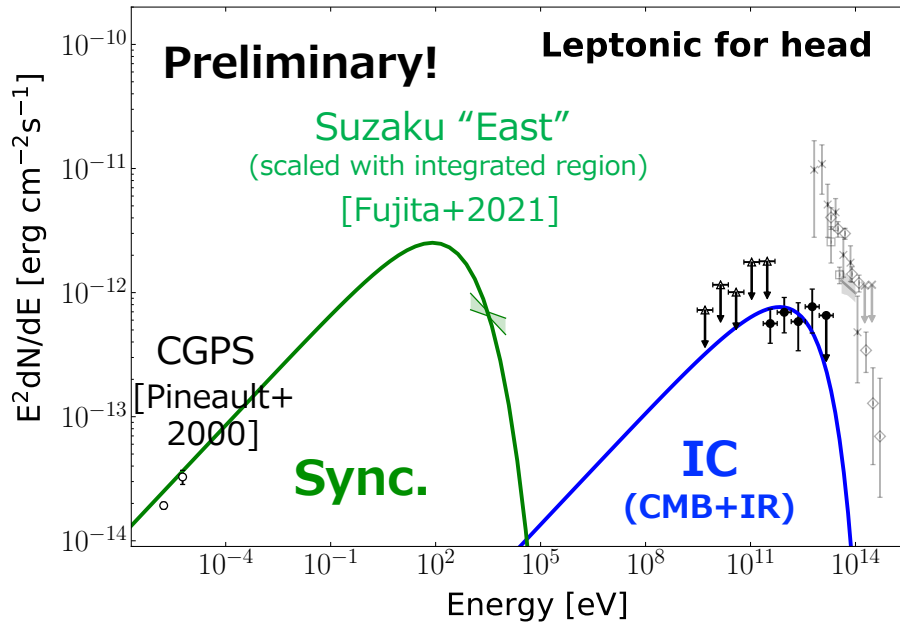


## Case 2: the origin of Head and Tail are **different**

→ Discuss in the following pages.

# Interpretation -Head-

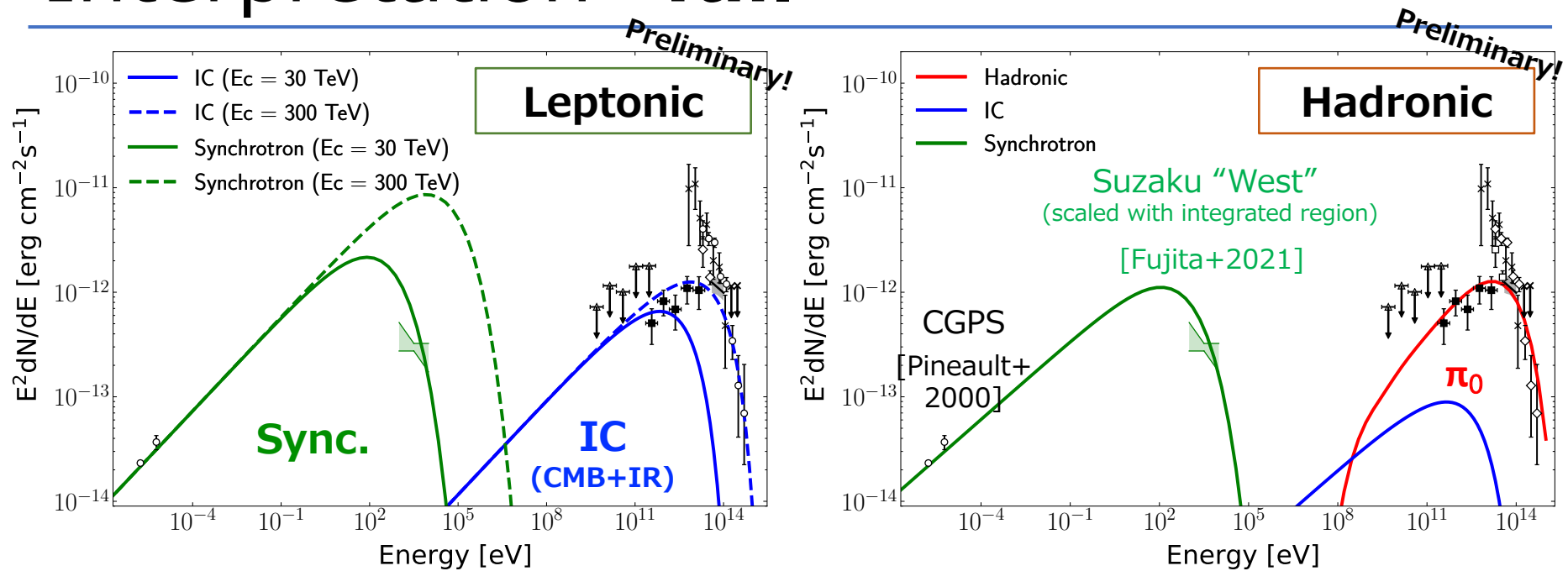
Modeling with naima [Zabalza 2015]



	$\alpha_e$	$E_{\text{cut}, e}$	$W_e (>1 \text{ GeV})$	$B$
Leptonic	2.4	30 TeV	$5.7 \times 10^{46} \text{ erg}$	$6 \mu\text{G}$

- ✓ Leptonic emission can reproduce the MWL spectrum in the head region.
- ✓ X-ray results for the head region (Ge+2021, Fujita+2021) suggest the synchrotron emission originates in the Boomerang PWN.

# Interpretation -Tail-



	$\alpha_e$	$E_{\text{cut, e}}$	$W_e (>1 \text{ GeV})$	B	$\alpha_p$	$E_{\text{cut, p}}$	$W_p (>1 \text{ GeV})$	$N_{\text{gas}}$
Leptonic	2.4	30 TeV (300 TeV)	$4.9 \times 10^{46}$ erg ( $5.0 \times 10^{46}$ erg)	6 $\mu\text{G}$	-	-	-	-
Hadronic	2.5	30 TeV	$1.3 \times 10^{46}$ erg	12 $\mu\text{G}$	1.7	1 PeV	$8.2 \times 10^{45}$ erg	200 cm <sup>-3</sup>

Leptonic: Electrons of SNR-tail can reproduce the MAGIC spectrum  
but if assume gamma-ray  $> 10$  TeV is only from tail, in tension.

Hadronic: Protons escaped from SNR in the past can explain  
PeV energies and the hard index at the middle-aged SNR (4-10 kyr)

# Summary

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- ✓ 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.
- ✓ MAGIC spectra at both regions could be reproduced with IC emission.  
Head: electrons escaped from PWN?  
Tail: SNR? Clouds?  
Once we assume the spectra measured by air shower experiments,  
suggested to be a PeV proton acceleration in SNR.

## Future prospective

For precise discussion at the break energies of Head & Tail, further VHE observations with better angular resolution are required to resolve the head and tail emissions.