



**「すざく」(とXMM)による広がったTeVガンマ
線放射VER J2019+368のX線観測(3)
*Suzaku (and XMM) Observation of the extended
TeV gamma-ray source VER J2019+368(3)***

**September 23, 2016@JPS meeting, Miyazaki
Tsunefumi Mizuno (Hiroshima Univ.)**

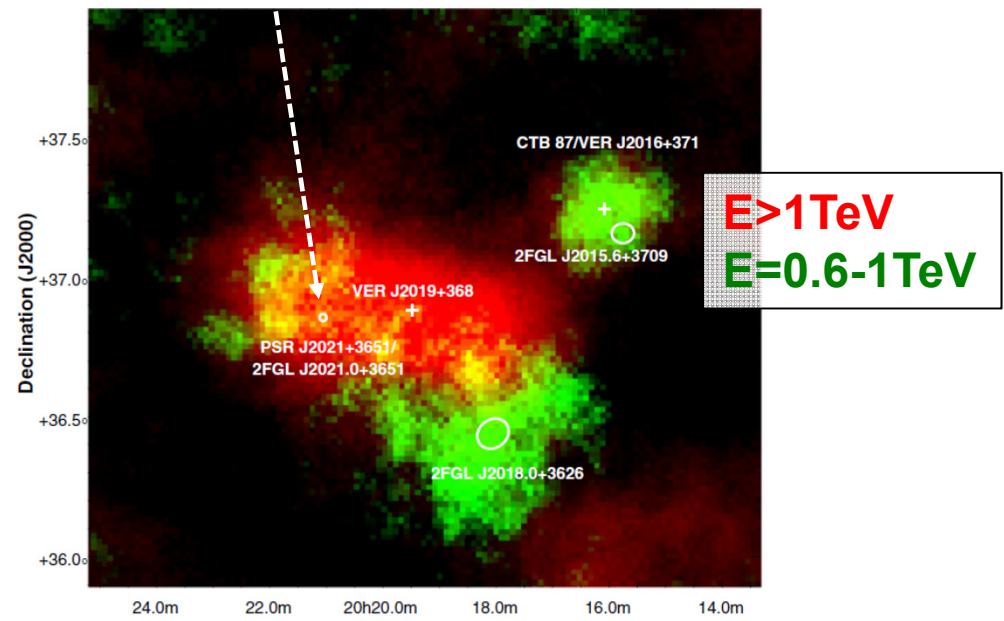
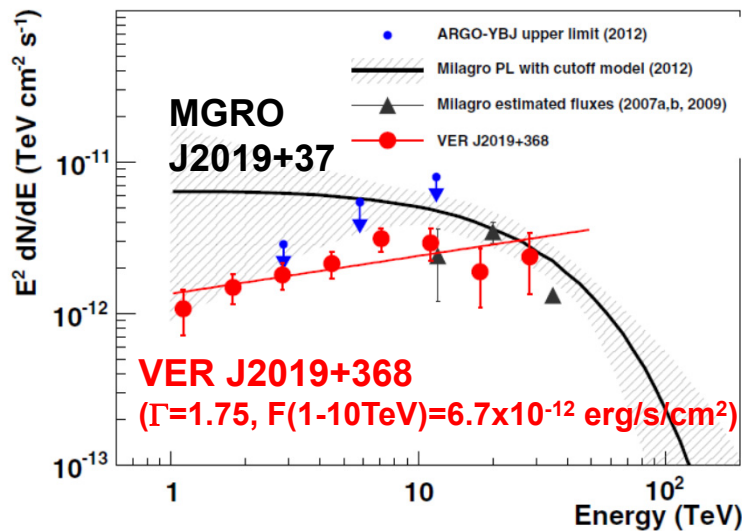
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(based on Mizuno+, submitted)



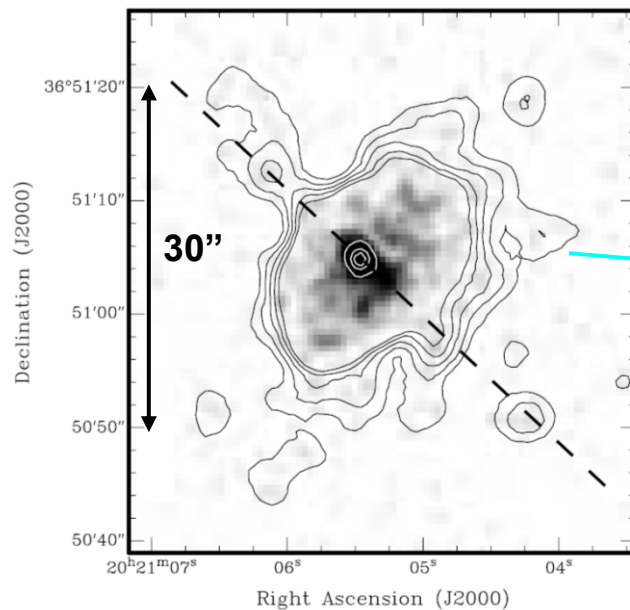
Past Obs. by Milagro & VERITAS

- Milagro reported an extended TeV γ -ray source MGRO J2019+37 in Cygnus-X direction ($\sigma=0.7$ deg)
- It was resolved into multiple sources by VERITAS. The most luminous one, VER J2019+368, has the following properties
 - $\sigma_{\text{major}}=0.34$ deg, positional coincidence with MGRO J2019+37, consistent spectrum in high energy => main contributor
- Possible X-ray counterpart is PSR J2021+3651 & PWN G75.2+0.1

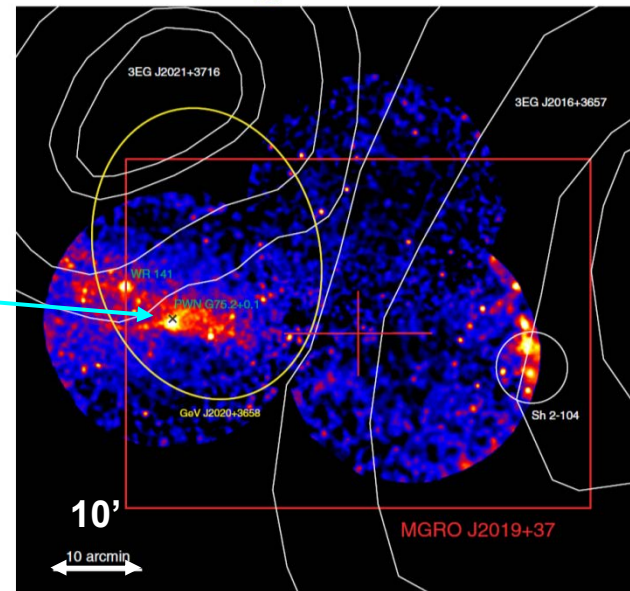


Past Obs. in X-Rays

- Possible X-ray counterpart is PSR J2021+3651 & PWN G75.2+0.1
 - PSR J2021+3651: young and energetic puldar ($\tau=17.2$ kyr, $dE_{rot}/dt=3.4 \times 10^{36}$ erg/s)
 - Chandra revealed a $\sim 20'' \times 10''$ pulsar wind nebula (PWN G75.2+0.1)
 - XMM reported faint emission of $5' - 10'$ length in east and west




Hessels+04, ApJ 612, 389



Zabalza+10, J. of Mod. Phys. D. 19, 811



Issues of the PSR/PWN Scenario

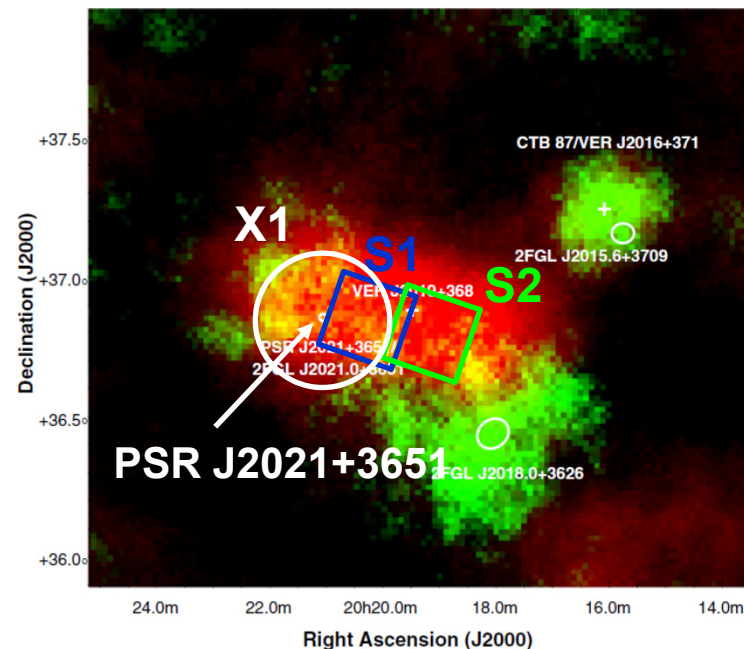
- Possible X-ray counterpart is PSR J2021+3651 & PWN G75.2+0.1
 - PSR J2021+3651: $\tau=17.2$ kyr, $dE_{\text{rot}}/dt=3.4 \times 10^{36}$ erg/s
 - PWN G75.2+0.1: revealed by Chandra and found to extend out 5'-10' in length in east and west by XMM
 - Several issues of the PSR/PWN scenario have been pointed out (e.g., Abdo+09, ApJ 799, 1059; Parades+09, A&A507, 241)
 - Large dispersion measure (370 pc/cm³) and rotation measure (524 rad/m²) indicate large distance to the source ($d > 10$ kpc).
 - γ -ray luminosity of PSR too high compared to dE_{rot}/dt
 - Source size (~ 90 pc for 0.5 deg at 10 kpc) too large for high-energy electrons to propagate before cooling
 - X-rays from only small portion of TeV emission
- 
- Detailed study of the PWN properties (spectrum, morphology) and search for unknown extended emission by Suzaku-XIS



X-ray Obs. of VER J2019+368

- Two Suzaku observations conducted in 2014 November
 - S1 covers region of the PSR/PWN and TeV centroid
 - S2 covers the west part of VER J2019+368, in which no strong X-ray sources has been reported
- Also analyzed archival XMM data to complement Suzaku observations

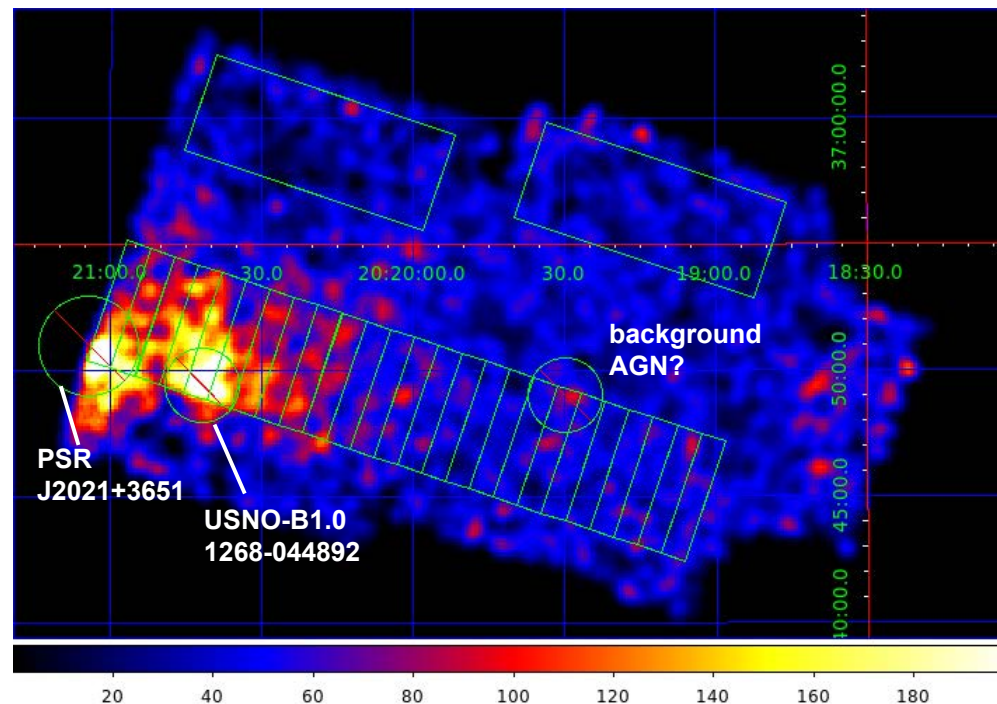
Position	RA (deg)	DEC (deg)	Net exp. (ks)
Suzaku, S1	305.06	36.87	35.0
Suzaku, S2	304.79	36.83	35.7
XMM, X1	305.27	36.85	127.0





XIS Image (soft band)

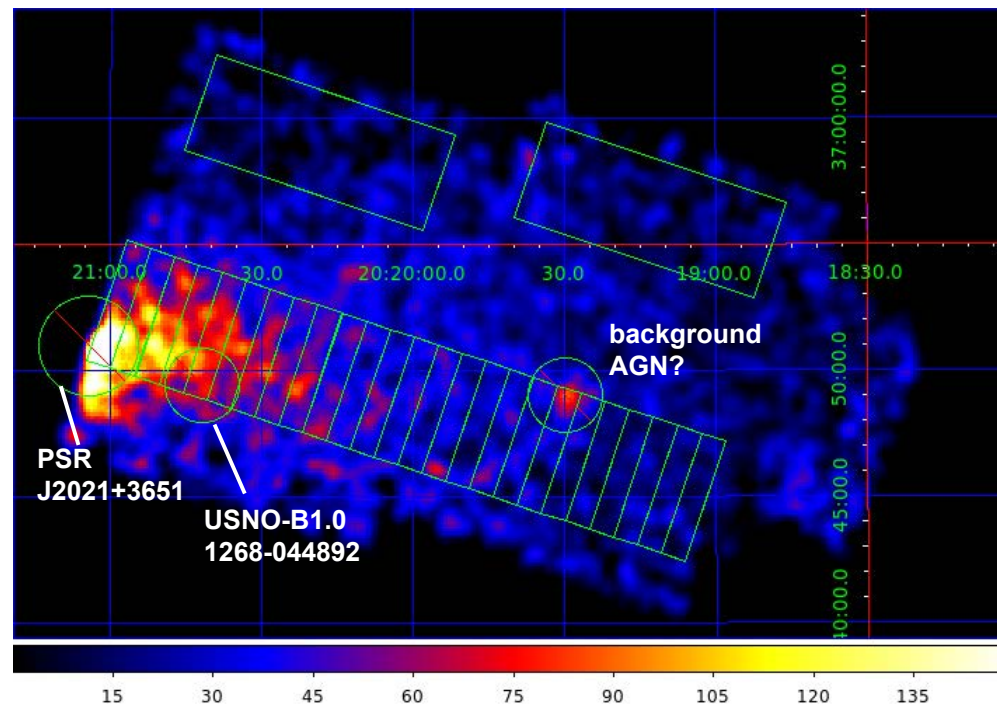
- Soft band (0.7-2 keV) intensity map (XIS3, in unit of photos/s/cm²/sr, NXB subtracted)
- PWN clearly detected in S1
- No extended emission detected in S2 (see slide #8)





XIS Image (hard band)

- Hard band (2-10 keV) intensity map (nxb subtracted)
- PWN clearly detected in S1
- No obvious extended emission in S2
- Size of PWN similar to that in soft band

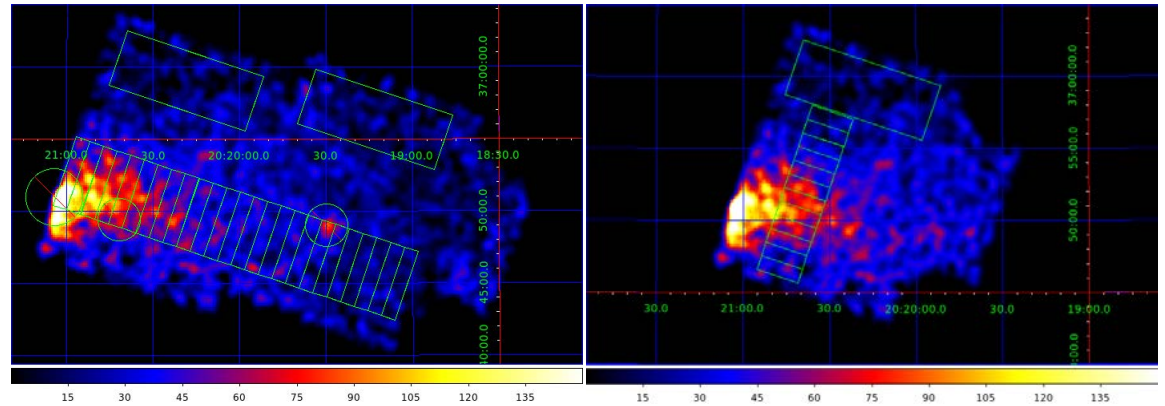




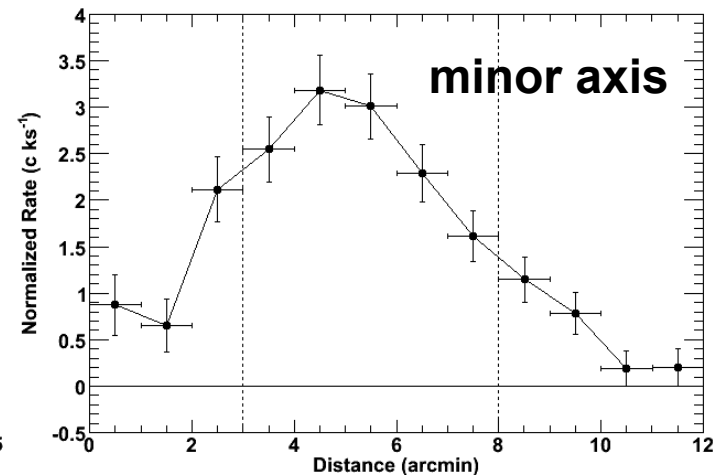
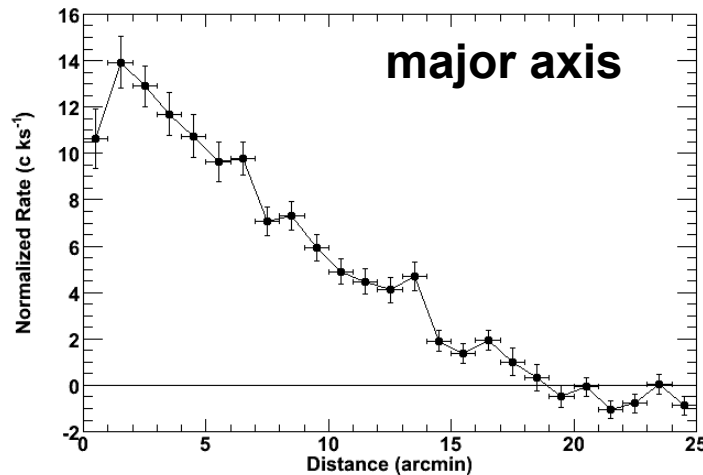
PWN-West Morphology

- Source regions: 25 rectangles of 1' x 5' and 10 rectangles of 1' x 3' along the major axis and minor axis, respectively

- PWN-west emission is detected at least 15' x 10' for the first time
- No significant emission beyond the TeV emission peak



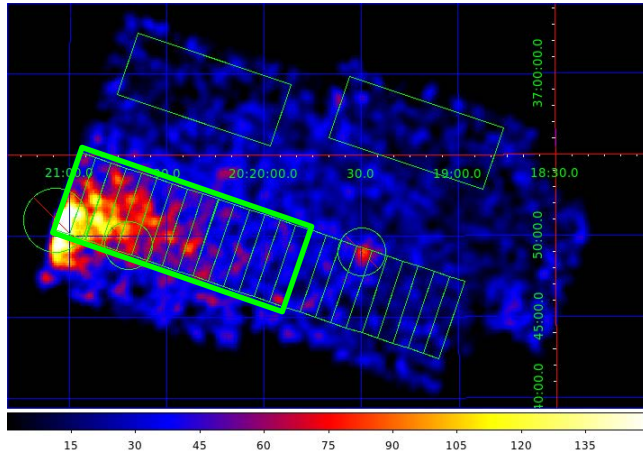
Count rate profiles (2-10 keV), vignetting corrected





PWN-West Spectrum (1)

- Procedure of the spectral analysis (15' x 5')
 - 1) subtract the NXB
 - 2) apply vignetting correction in subtracting the BG (GRXE and CXB)
 - 3) calculate the response (arf) assuming linear decrease of the intensity in 0-15'



$$\chi^2/\text{d.o.f.}=211/188$$

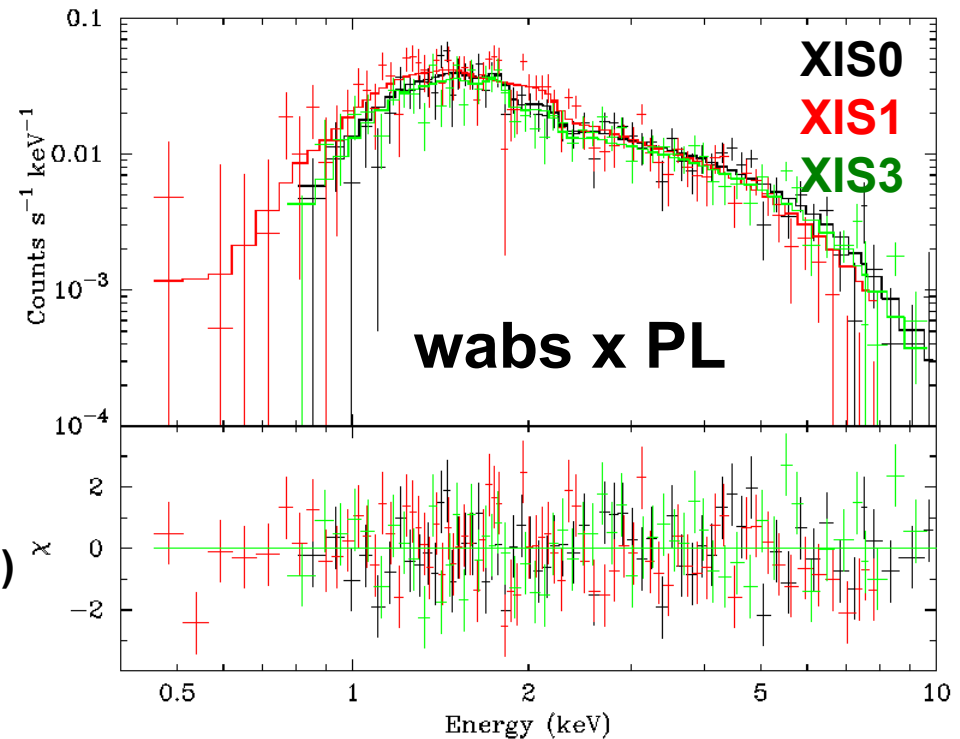
$$N(\text{H})=0.83(+/-0.12)\times 10^{22}, \Gamma=2.05(+/-0.12)$$

$$f(0.5\text{-}2 \text{ keV})=6.04\times 10^{-13} \text{ erg/s/cm}^2$$

$$f(2\text{-}10 \text{ keV})=20.1\times 10^{-13} \text{ erg/s/cm}^2$$

Significantly softer spectrum than that of TeV γ rays ($\Gamma_\gamma \sim 1.75$)

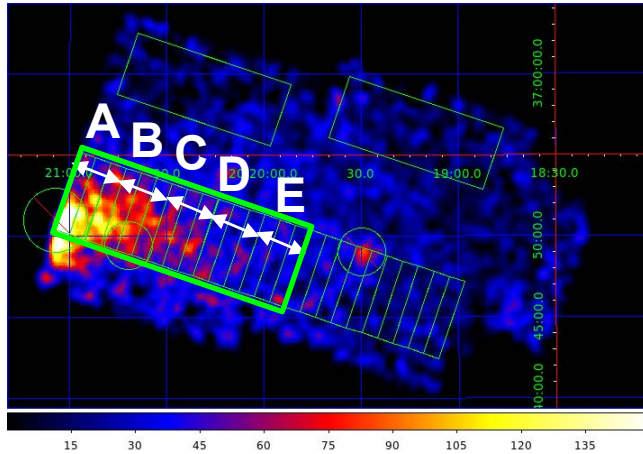
[XMM data indicates PWN-east and west have similar spectra (flux, Γ)]





PWN-West Spectrum (2)

- Procedure of the spectral analysis (15' x 5')
 - 1) subtract the NXB
 - 2) apply vignetting correction in subtracting the BG (GRXE and CXB)
 - 3) calculate the response (arf) assuming linear decrease of the intensity in 0-15'



- No significant spectral change observed
- Absorption of $\sim 0.8 \times 10^{22} \text{ cm}^{-2}$ indicates $d \ll 10 \text{ kpc}$. We adopted $d = 1.8 \text{ kpc}$ estimated by Kirichenko+15

Reg.	N(H)	Γ	f(0.5-2keV) (10^{-13} erg/s/cm 2)	f(2-10keV) (10^{-13} erg/s/cm 2)
A (0'-3')	0.82 (+/-0.21)	2.07 (+/-0.21)	1.96	8.27
B (3'-6')	0.63 (+/-0.16)	1.96 (+/-0.18)	1.68	6.52
C (6'-9')	0.72 (+/-0.17)	2.06 (+/-0.18)	1.22	4.71
D (9'-12')	1.28 (+/-0.36)	2.30 (+/-0.32)	0.57	2.77
E (12'-15')	1.44 (+/-0.51)	2.29 (+/-0.42)	0.30	1.69

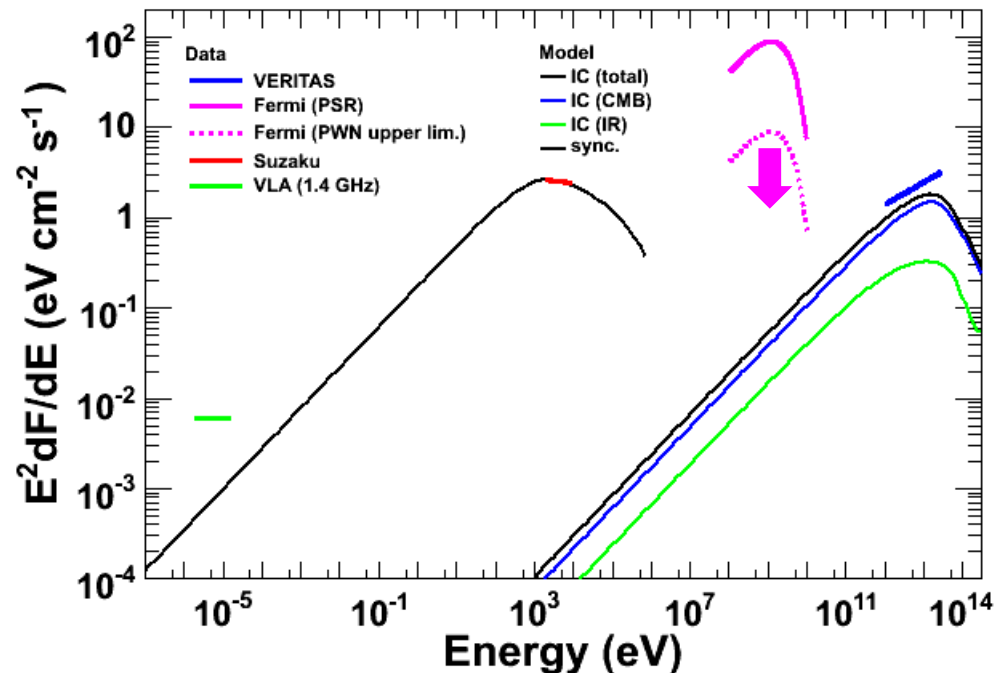


Multiwavelength Spectrum

- $\Gamma_x \sim 2.05$ and $\Gamma_\gamma \sim 1.75$ require a break of electron spectrum at ~ 100 TeV
- If we assume constant injection of electrons into uniform B over the lifetime of pulsar for simplicity, synchrotron break at ~ 80 TeV is expected, consistent with Γ_x and Γ_γ observed

$$E_{\text{bk}} \simeq 80 \text{ TeV} \left(\frac{t_0}{17.2 \text{ kyr}} \right)^{-1} \left(\frac{B}{3 \mu\text{G}} \right)^{-2}$$

- A model assuming $B=3 \mu\text{G}$ and a break at 80 TeV from $\Gamma=2.1$ to 3.1 explains $\sim 70\%$ of TeV emission \Rightarrow X-ray PWN is a main contributor of VER J2019+368
- (The model does not fully account for morphologies in X ray and γ ray. Future observations by CTA is anticipated to reveal the TeV γ -ray properties in more detail)





Particle Transport

- **Absence of spectral softening requires that highest energy electrons (producing 10 keV X-rays) should propagate a distance $\geq 15'$. If advection is the dominant process, this requires**

$$\beta_{\text{adv}} \geq 7.9 \times 10^{-3} \left(\frac{B}{3 \mu\text{G}} \right)^{1.5} \left(\frac{d}{1.8 \text{ kpc}} \right) .$$

- **Alternatively, in the case of energy-independent diffusion (e.g., Porth+15), diffusion coefficient should satisfy**

$$D \geq 2.9 \times 10^{27} \text{ cm}^2 \text{ s}^{-1} \left(\frac{B}{3 \mu\text{G}} \right)^{1.5} \left(\frac{d}{1.8 \text{ kpc}} \right)^2$$

- [In those scenario (under the assumption of uniform B) the absence of X-ray emission beyond the TeV peak position is due to the lower surface brightness of synchrotron X-rays]



Summary

- VER J2019+368 is an extended ($\sigma_{\text{major}}=0.34\text{deg}$) and hard ($\Gamma=1.75$) TeV γ -ray source in Cyg-X direction
- PSR J2021+3651/PWN G75.2+0.1 is a possible counterpart, but several issues are pointed out (distance, morphology)
- We analyzed X-ray data (Suzaku and XMM)
 - PWN-west detected in $15' \times 10'$ with $N(\text{H})=8.2 \times 10^{21} \text{ cm}^{-2}$, $\Gamma=2.05$ (Suzaku)
 - No significant spectral change found (Suzaku)
 - PWN-east shows similar properties (XMM)
- Properties of the system
 - $B \sim 3 \mu\text{G}$ is required (Γ_x and Γ_γ)
 - X-ray PWN is a major contributor of VER J2019+368 (MW spectrum)
 - β_{adv} and D are constrained from X-ray data

Thank you for your Attention



References

- **Abdo+09, ApJ 700, 1059**
- **Abdo+12, ApJ 753, 159**
- **Aharonian+06, A&A 460, 365**
- **Aliu+14, ApJ 788, 78**
- **Bamba+10, ApJ 719, L116**
- **Hessels+04, ApJ 612, 389**
- **Mattana+09, ApJ 694, 12**
- **Parades+09, A&A 507, 241**
- **Porter+08, ApJ 682, 400**
- **Porth+16, MNRAS 460, 4135**
- **Uchiyama+08, PASJ 60, S35**
- **Van Etten+08, ApJ 680, 1417**
- **Zabalza+10, J. of Mod. Phys. D. 19, 811**

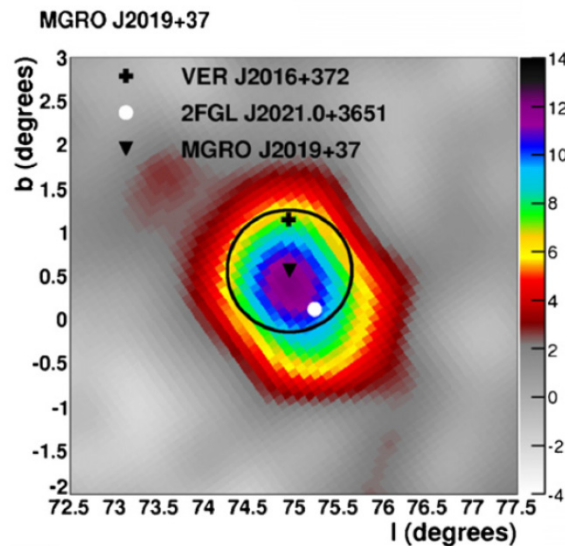


Appendix

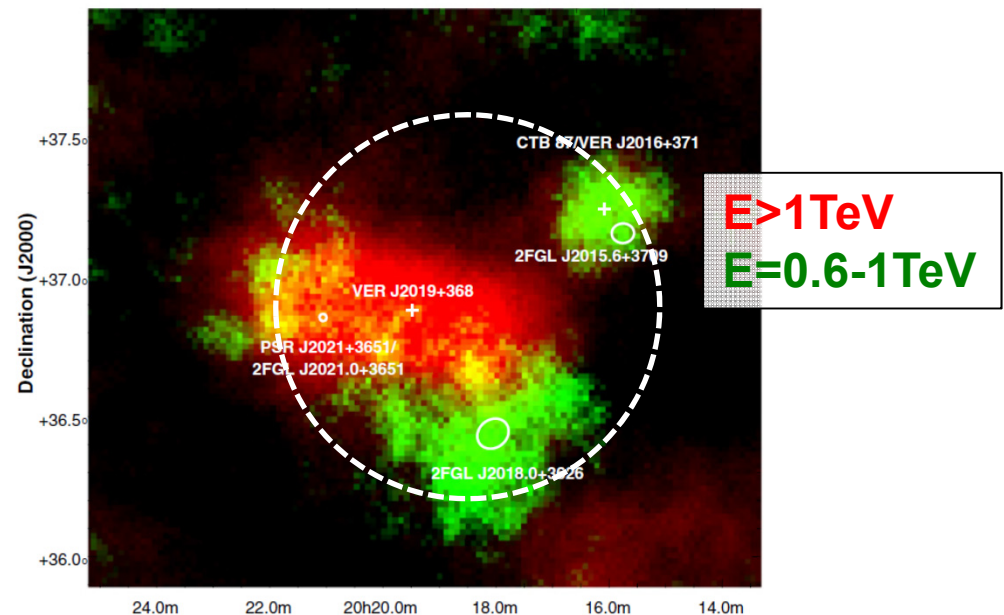


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Abdo+12, ApJ 753, 159

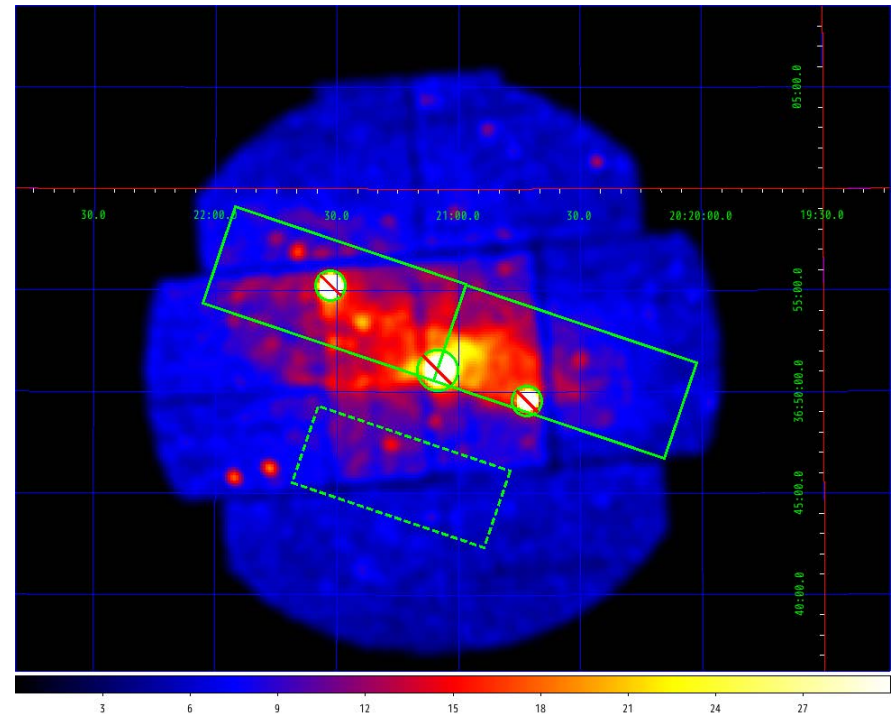


Aliu+14, ApJ 788, 78 Right Ascension (J2000)



XMM View of the VER J2019+368 Region

- Advantages of XMM for the study of VER J2019+368
 - Good spatial resolution => reduction/estimation of the point-source contaminations
 - Large FOV => overall property of the PWN

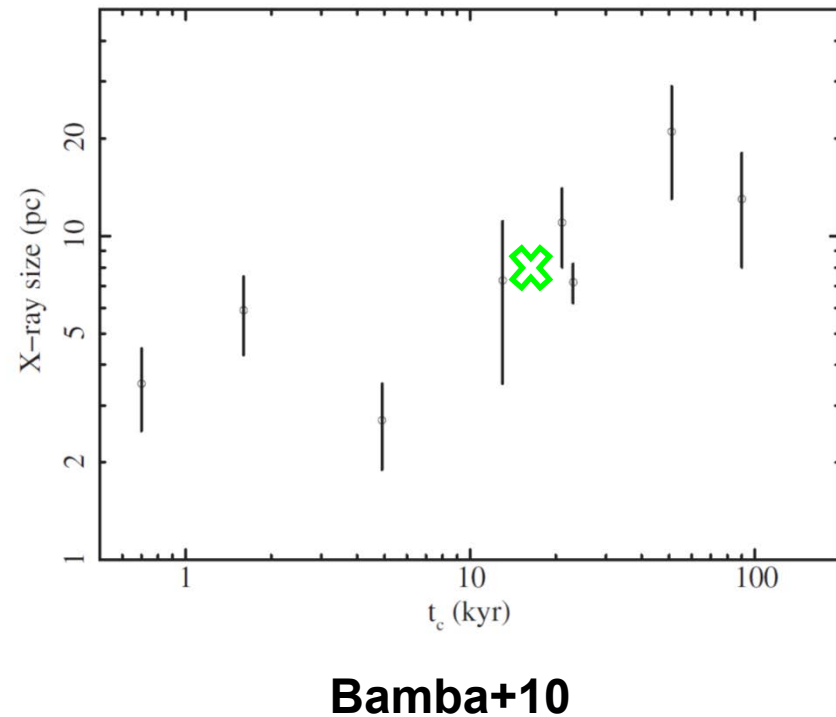
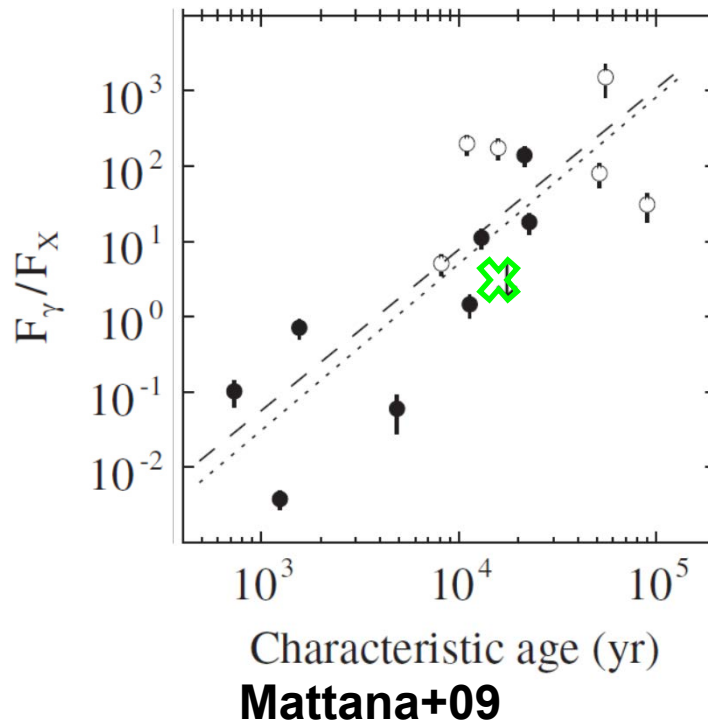


Region	$N(H)$ 10^{22} cm^{-2}	Γ	$f(0.5-2 \text{ keV})$ (erg/s/cm^2),	$f(2-10 \text{ keV})$ (erg/s/cm^2)
West	0.68 ± 0.12	2.11 ± 0.18	~ 4.1	~ 14.1
East	0.47 ± 0.07	1.85 ± 0.13	~ 4.6	~ 16.8



Comparison with Other PWNe (1)

- X-ray PWN and VER J2019+368 show similar properties with those of other PWNe associated with TeV γ rays (F_γ/F_x could be smaller; see next)





Comparison with Other PWNe (2)

- Comparison with the archetype evolved PWN HESS J1825-137 and its extended PWN (Aharonian+06, Uchiyama+09)

Object	P, dP/dt, B_s (G)	characteristic age, dE _{rot} /dt	F(2-10 keV) (unabsorbed; erg/s/cm ²), Γ_x	F(1-10 TeV) (erg/s/cm ²), Γ_γ
VER J2019+368	104 ms, 9.6e-14, 3.2e12	17.2 kyr, 3.4e36 erg/s	~6e-12, ~2.05 (no significant softening)	12e-12, ~1.75
HESS J1825+137	101 ms, 7.5e-14, 2.8e12	21.4 kyr 2.8e36 erg/s	~4.5e-12, ~2 (no significant softening)	~50e-12, ~2.4

VER J2019+368 shows harder spectral index in TeV and smaller F_γ/F_x ratio, indicating weaker magnetic field or younger age