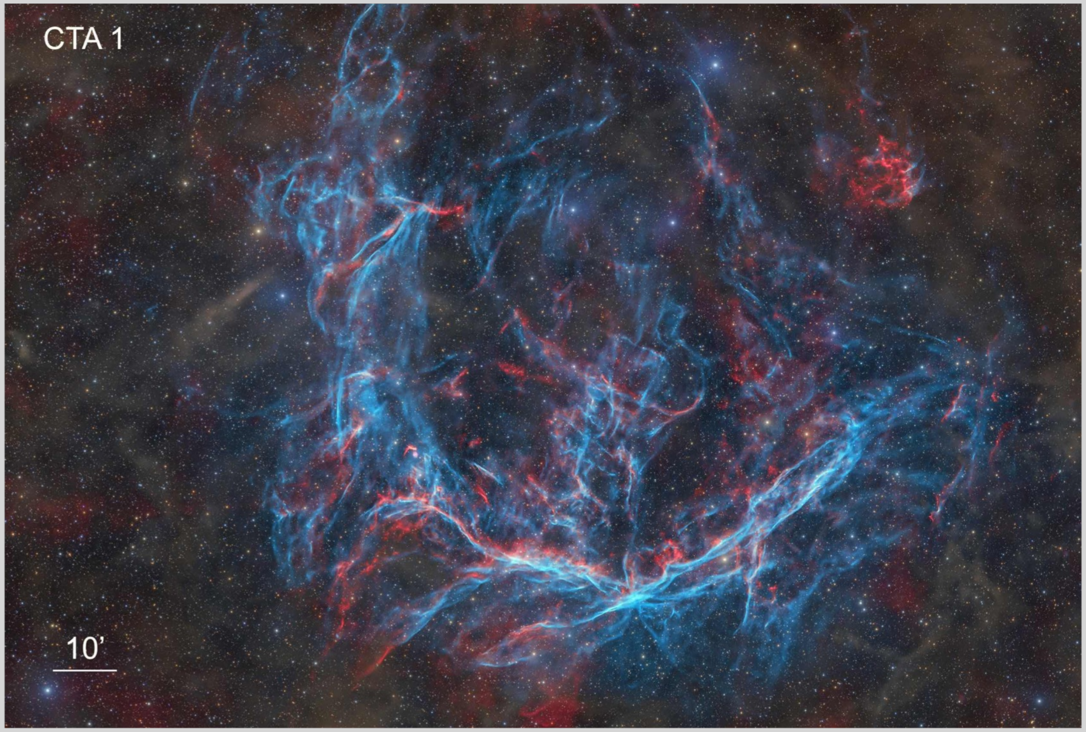
Cosmic Ray $e^{+/-}$ Escaping from CTA 1?



Talk Outline

1) Background
2) CTA 1 System
3) Deep 120 ks XMM Observation
4) Results of Data Analysis
5) Evidence for Particle Escape
6) Preliminary NuSTAR results
7) Conclusions and Future Work

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Optical Image Credit: Fesen et al. 2024

There is a Positron ‘Bump’ in the Cosmic Ray Spectrum Above ~1 GeV

Could this bump be due to positrons from PWNe? Maybe not and it is actually a signature of dark matter? Answering this question requires determining the properties of $e^{+/-}$ escaping from a PWN.

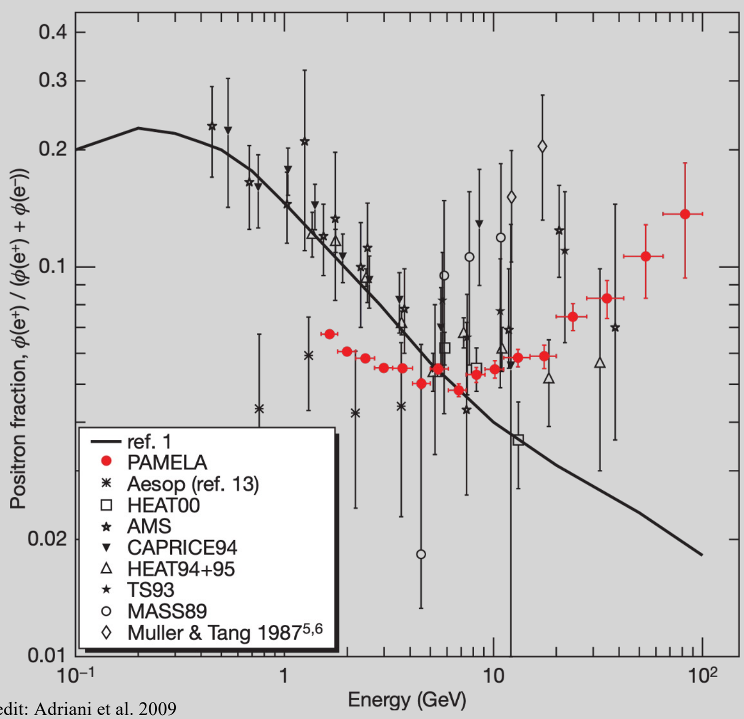

Figure Credit: Adriani et al. 2009

The best targets for a direct measurement are **middle-aged PWNe (Stage 2 below)**. These PWNe are old enough for the particles to no longer be trapped by the PWN magnetic field.

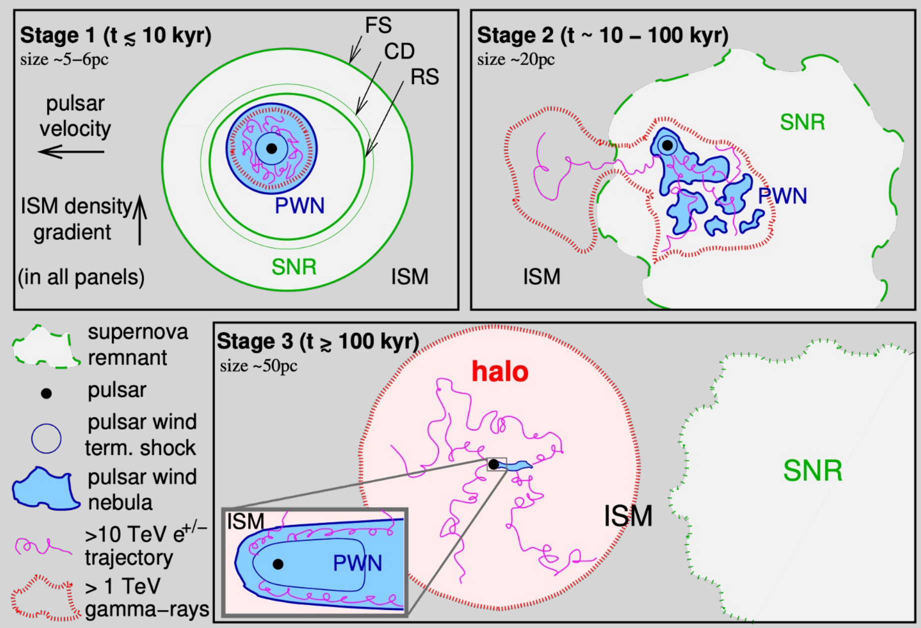

Figure Credit: Giacinti et al. A&A, 636, A113, (2020)

CTA 1 System

SNR and PWN

- ~90 arcminute diameter
- Extended TeV emission **beyond the PWN**
- Thermal throughout the SNR + non-thermal X-rays near the pulsar

PSR J0007+7303

- E dot= 4.5 x 10^{35} erg / s
- τ_{char} = 1.4 x 10^{4} yr
- B = 1.1 x 10^{13} G

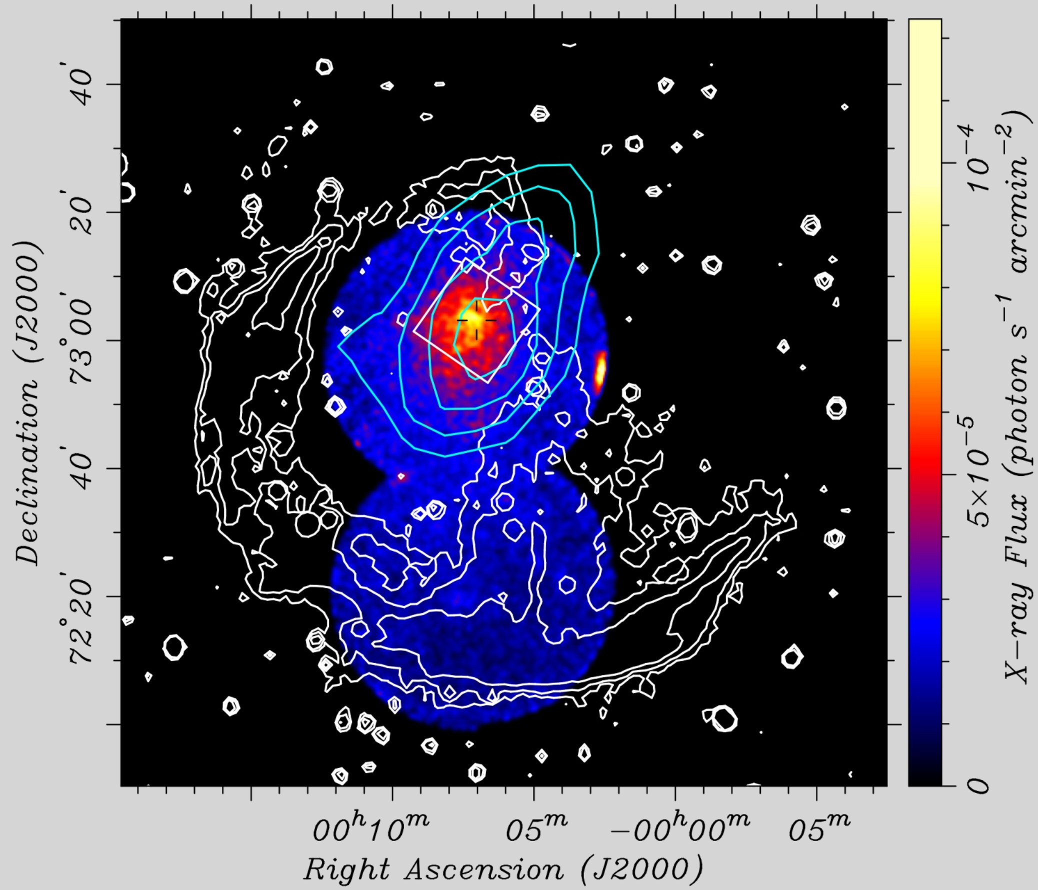

Image Credit: Eric Gotthelf

CTA 1 Pulsar

<u>PSR J0007+7303</u>

- E dot= 4.5×10^{35} erg / s
- $\tau_{char} = 1.4 \times 10^{4}$ yr
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Pulsations discovered by Fermi in 2008.

Soft thermal X-ray pulsations subsequently observed by XMM.

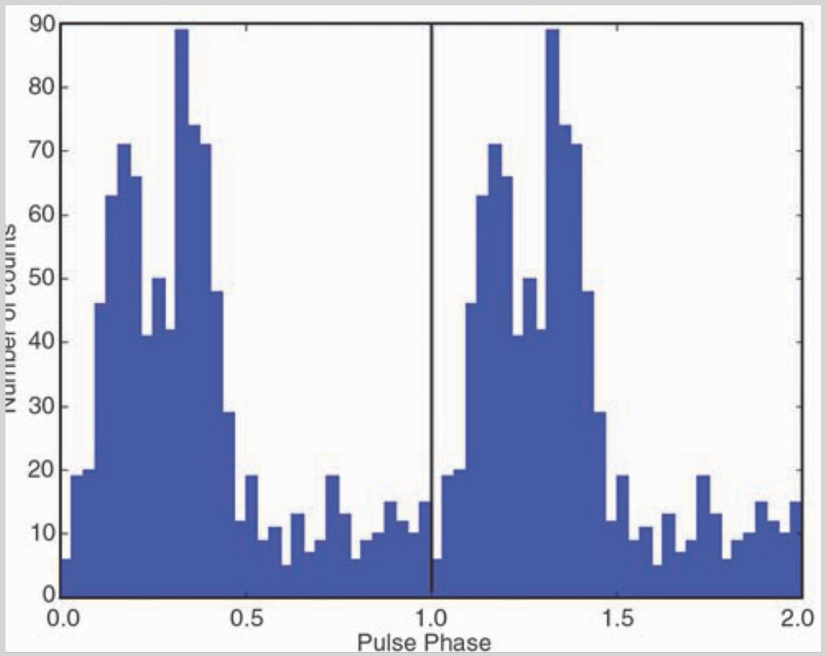

Figure: Abdo et al. 2008

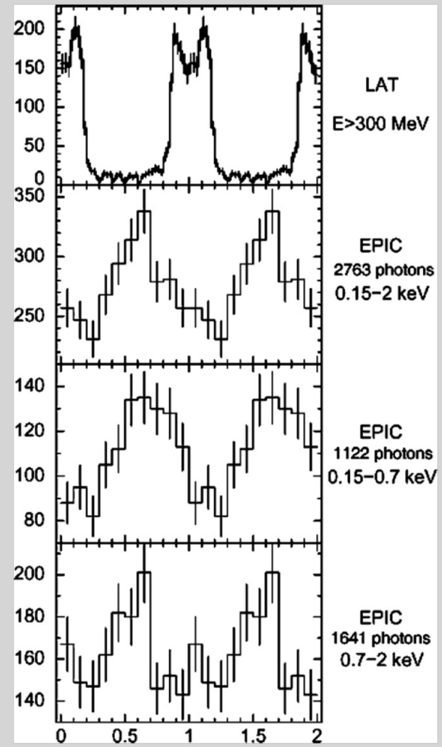

Figure: Caraveo et al. 2010

CTA 1 TeV Emission

LHAASO Detection

- 1LHAASO J0007+7303u ,
detected by both KM2A and WCDA

- One of 43 LHAASO sources in the 1st catalog with clear UHE emission > 100 TeV (4 σ)

PSR J0007+7303

- E dot= 4.5 x 10^{35} erg / s (ATNF 105th)
- τ_{char} = 1.4 x 10^{4} yr (ATNF 98th)
- B = 1.1 x 10^{13} G (ATNF 89th)

$$E_\gamma^{IC} \approx 0.32 E_{e,10}^2 \text{ TeV},$$

$$\dot{E}(t) = \dot{E}_0 \left(1 + \frac{t}{\tau_{\rm sd}}\right)^{-\frac{p+1}{p-1}}$$

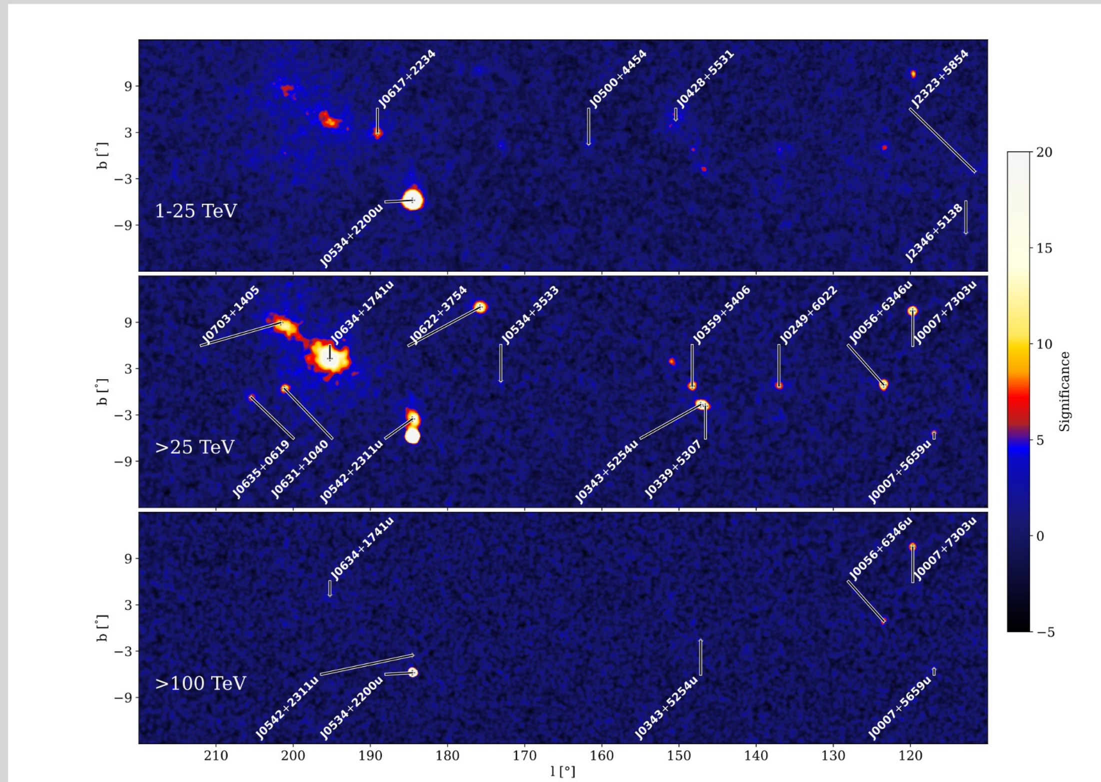

Figure 7. LHAASO significance map within region $115° \leq l \leq 220°$, $|b| \leq 12°$.Top: WCDA (1 TeV < E < 25 TeV) TeV significance map. Middle: KM2A (E > 25 TeV) significance map. Bottom: KM2A (E > 100 TeV) significance map.

Figure from Cao et al. 2023

CTA 1 TeV Emission

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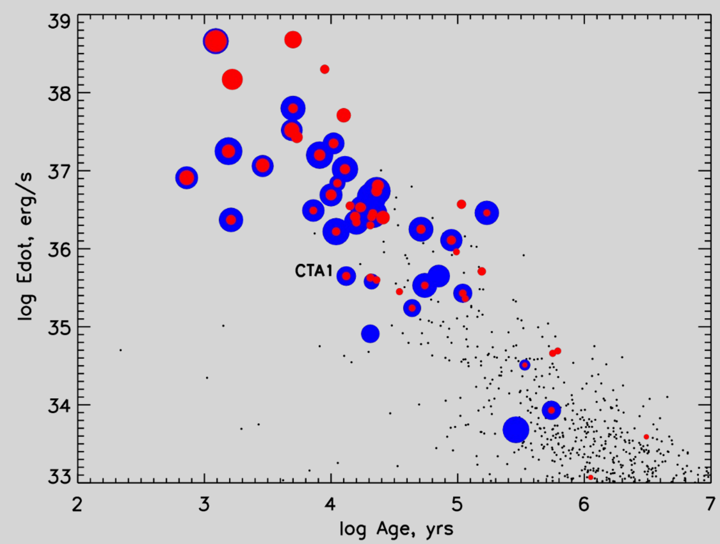


Figure 8. Pulsar spin-down luminosity vs. age, from Kargaltsev & Pavlov (2010), with CTA 1 point indicated. Filled circles: X-ray (red) and TeV (blue) luminosities of PWNe or PWN candidates. Larger circle sizes correspond to higher luminosities in the corresponding waveband. The small black dots denote ATNF catalog pulsars (http://www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005).

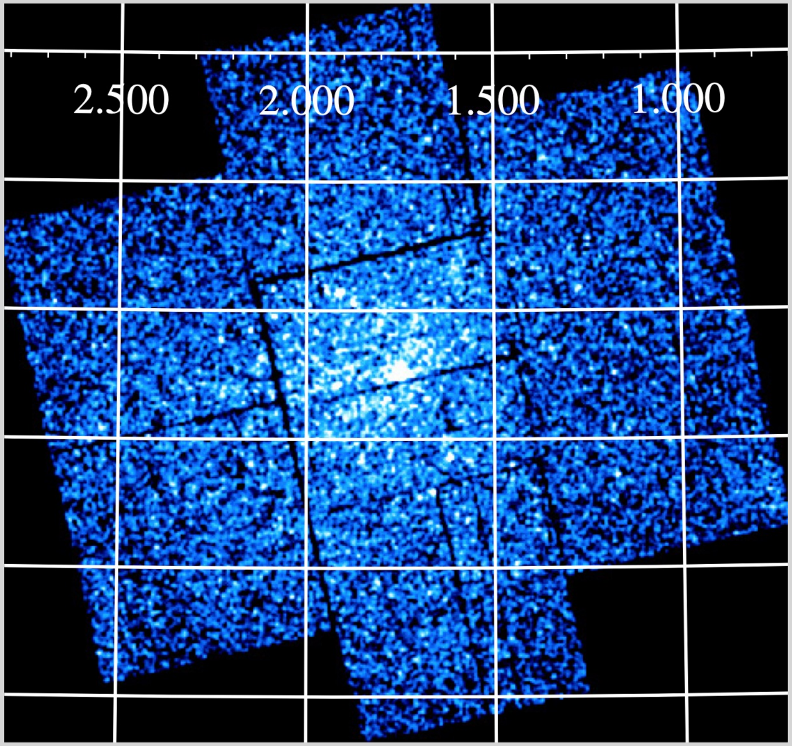
(A color version of this figure is available in the online journal.)

Figure from Aliu et al. 2013

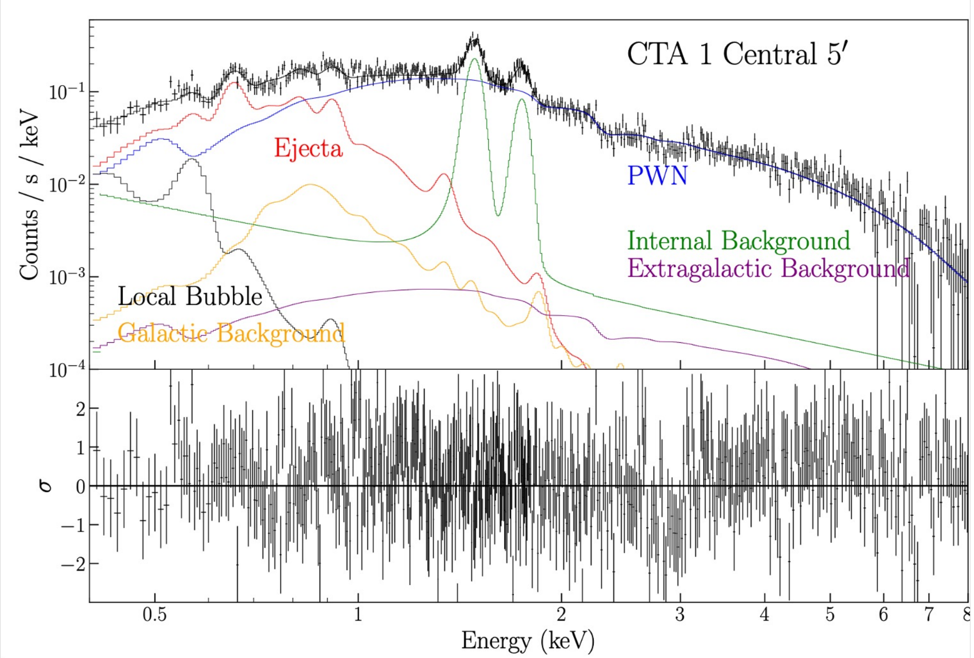
Deep 120 ks XMM Observation

The ~30 arcmin XMM FoV is smaller than the ~90 arcmin SNR; there are no source free regions in this image.

3-8 keV



A detailed extended source spectral analysis is required. This includes carefully modeling various background spectral components (Local Bubble, galactic background, extragalactic background, and internal background).



Non-thermal Surface Brightness Profile

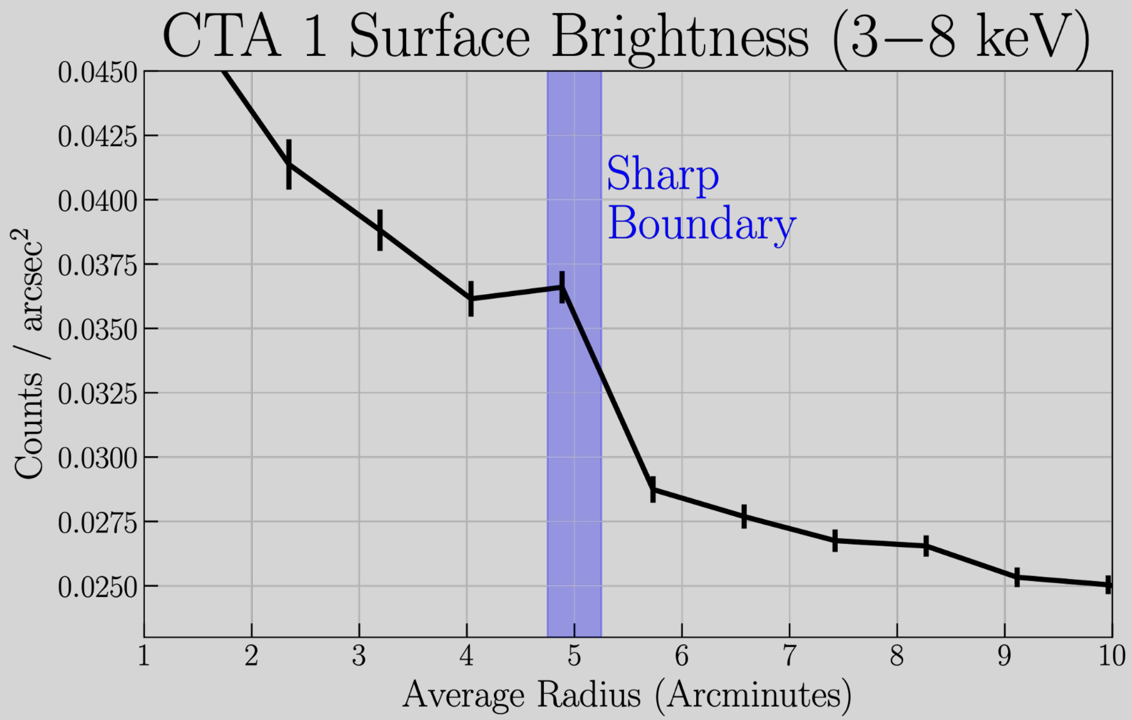
Radial surface brightness of the non-thermal (3 - 8 keV) emission drops off sharply at a radius of 5 arcmin from the pulsar, but remains non-zero, and continues decreasing past this boundary.

There are several **possible explanation**s for this sharp boundary:

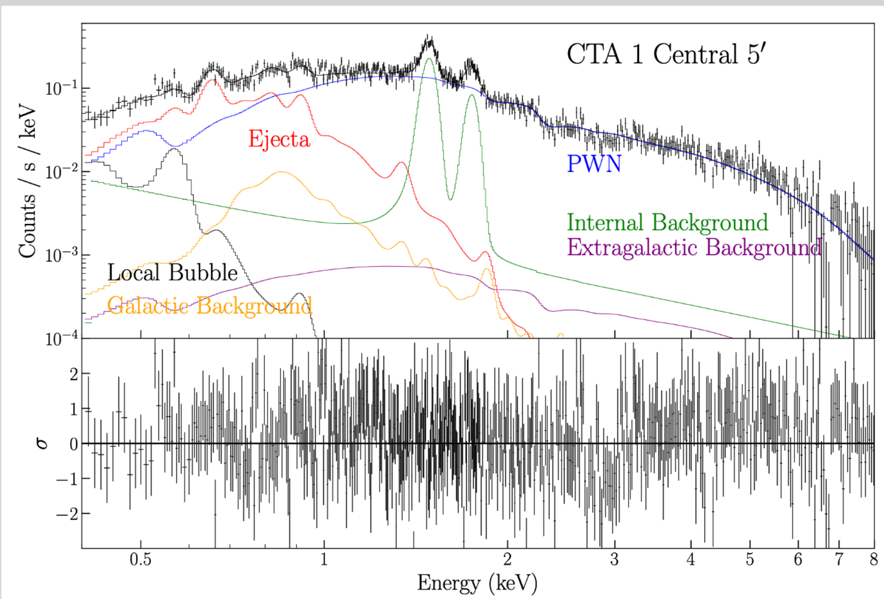
1) It is the real dynamical PWN boundary, and

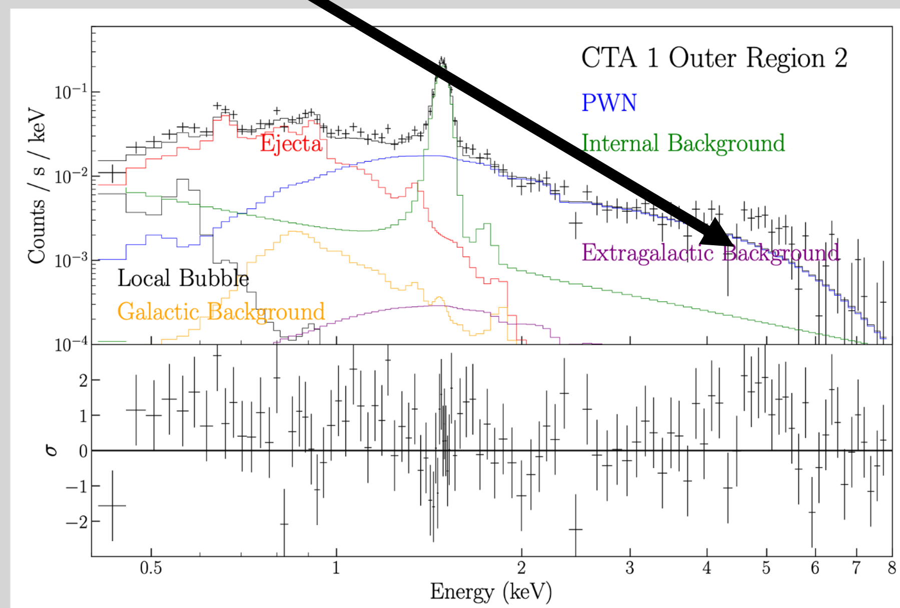
- 1A) The emission beyond this boundary is just **background.**
- 1B) The emission beyond this radius is the direct evidence of **cosmic ray $e^{+/-}$ escape** we have been looking for.

2) **Synchrotron burn-off**, i.e. higher energy particles cool faster, creating different apparent PWN radii in different energy bands



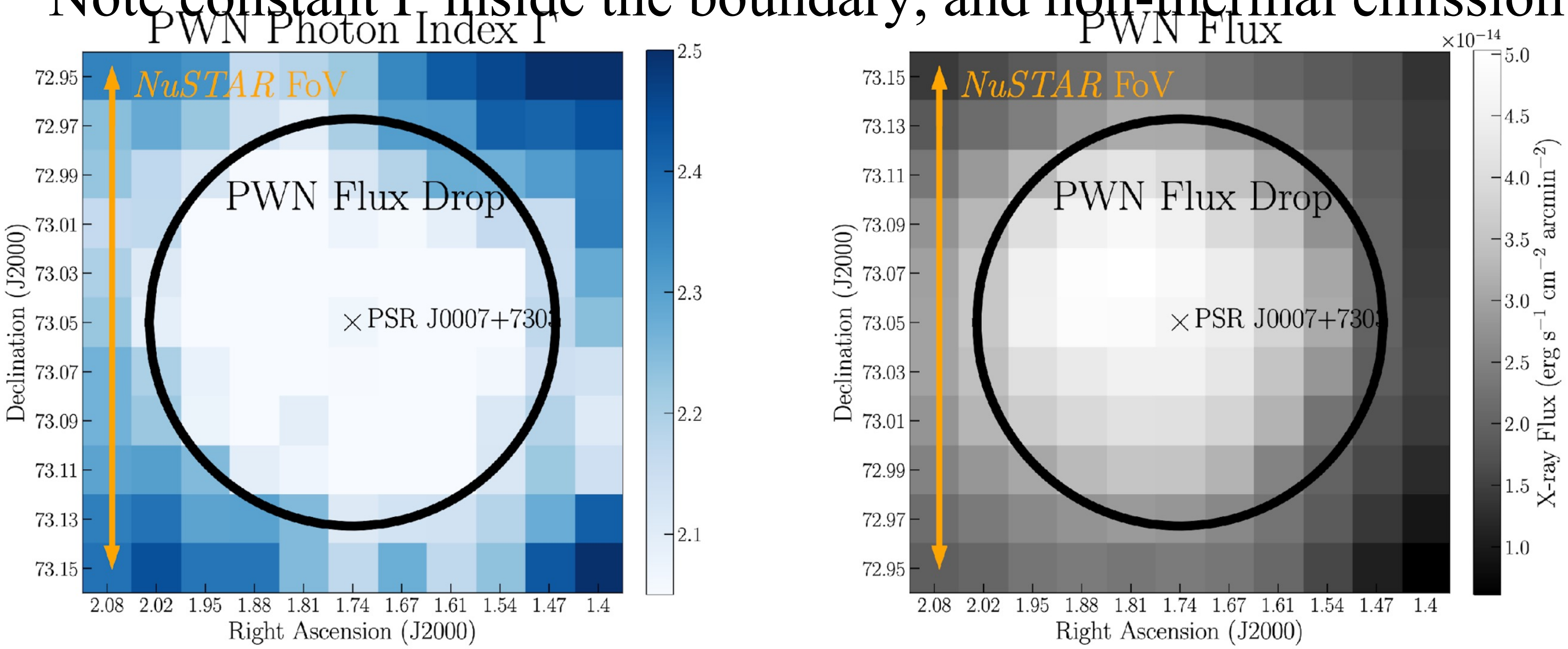
Detailed spectral modeling confirms that the PWN non-thermal emission extends **beyond** this 5 arcmin boundary





Photon Index and Flux Maps

Note constant Γ inside the boundary, and non-thermal emission outside



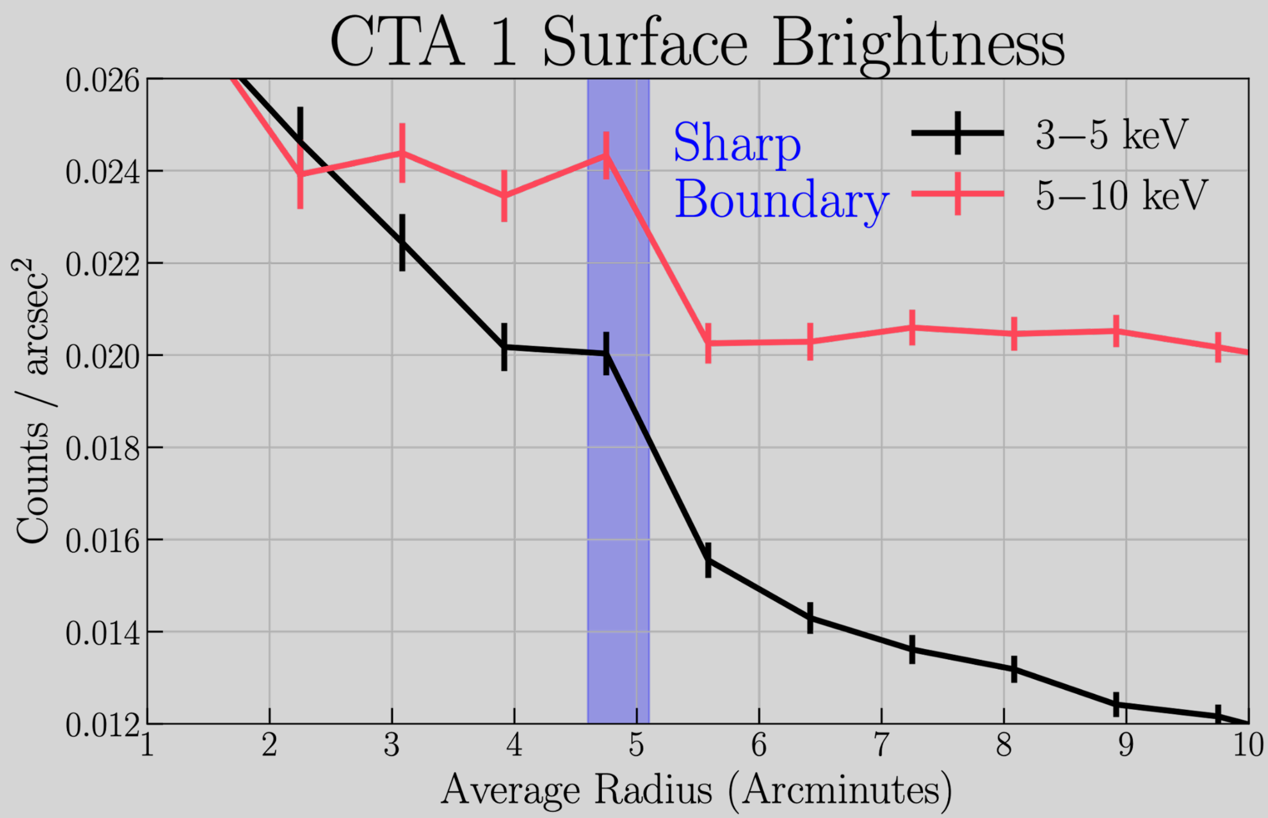
Is this the real dynamical boundary of the PWN in CTA 1?

Two Possibilities:

1: Sharp drop is dynamical boundary, and we are seeing lepton escape

2: Synchrotron burn-off

There is no indication of synchrotron burn-off in existing XMM data, and NuSTAR data would be a good additional test.

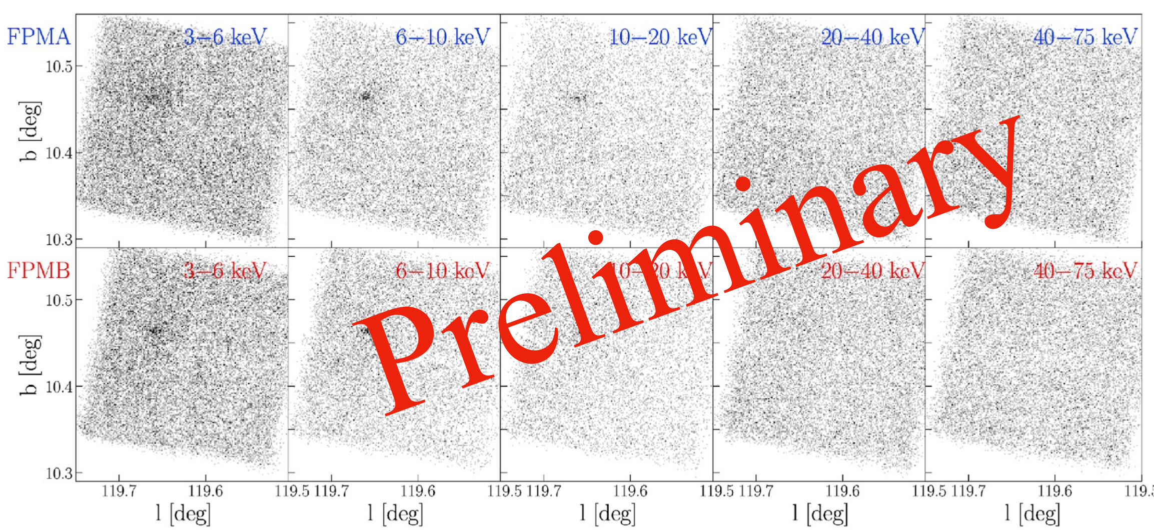


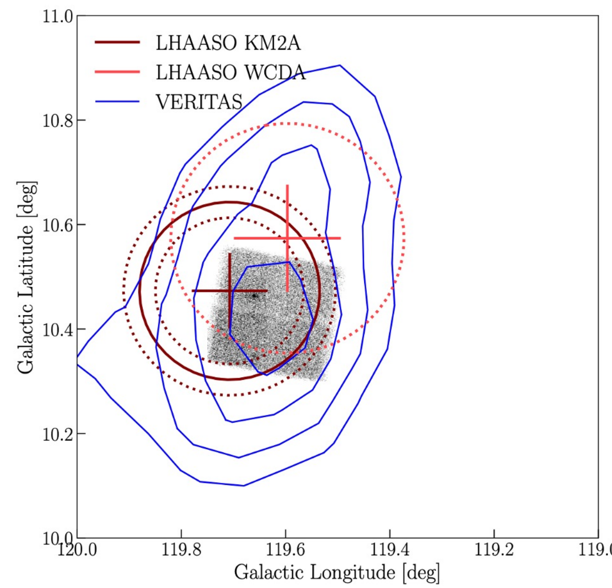
NuSTAR Observation of CTA 1

- We obtained a deep 160 ks NuSTAR observation.
- Preliminary results are a suggestive of particles caught in the act of escaping.
- This is a not a simple analysis; it requires a detailed understanding of the NuSTAR PSF and roll/energy dependent background.
- VERITAS has obtained and continues to collect complementary gamma-ray data

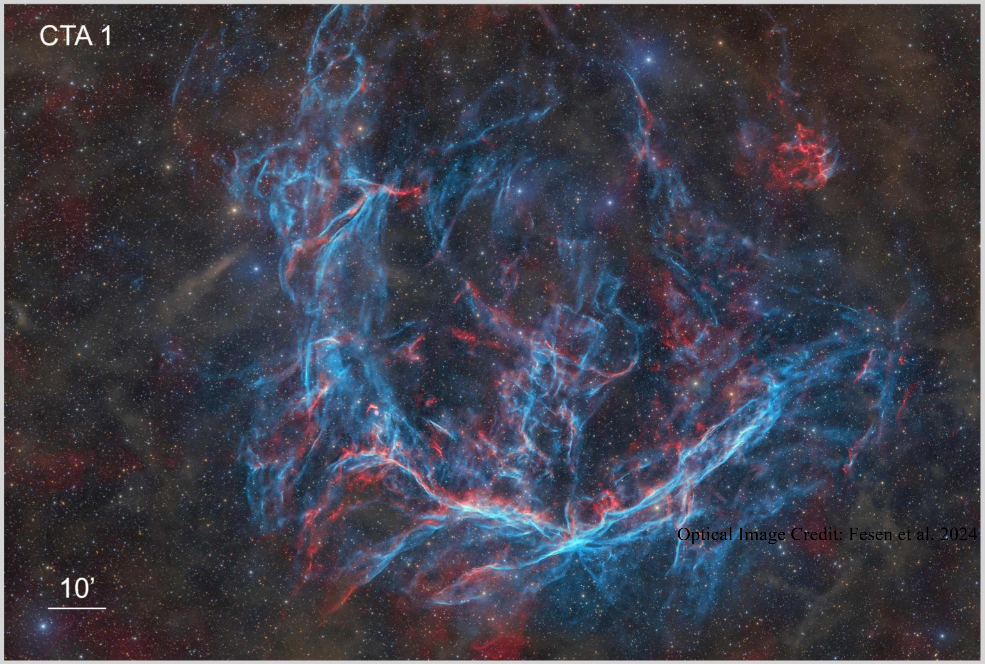
NuSTAR Proposal Collaborators

Joseph Gelfand (NYU Abu Dhabi)
Eric Gotthelf (Columbia University)
Kaya Mori (Columbia University)
Pat Slane (CfA)





Conclusions



- Discovered a sharp boundary surrounding the PWN in CTA 1
- Boundary radius is apparently energy independent
- There is a constant photon index inside the boundary
- Direct evidence of high energy $e^{+/-}$ escaping from a PWN

Future Work

- SED Modeling (Time dependent one-zone PWN