Electron Spectrum of the Dragonfly Pulsar Wind Nebula from X-ray to TeV

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Michigan Technological University

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For the HAWC Collaboration
ICRC 2019

NSF

Dragonfly Nebula

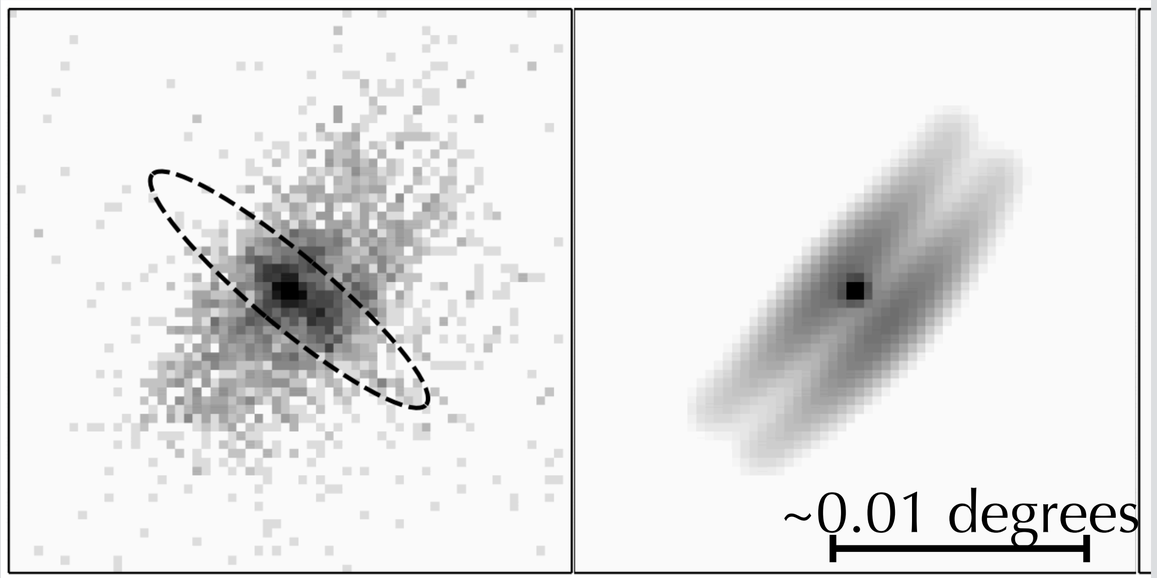
Powered by spin-down of
PSR J2021+3651

$$P = 103.7 \text{ ms}$$
$$\dot{E} = 3.6 \cdot 10^{36} \text{ erg s}^{-1}$$
$$\tau_c = 17.2 \text{ kyr}$$
$$B_{surf} = 3.2 \cdot 10^{12} \text{ G}$$

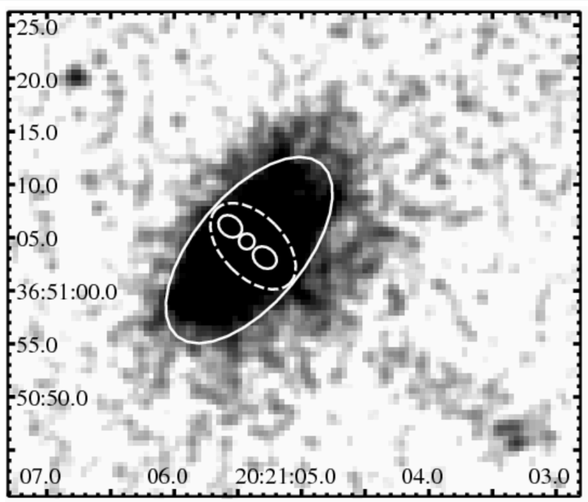
Pulsar discovered in 2002 by Arecibo
Mallory S. E. Roberts *et al* 2002 *ApJ* **577** L19

Only pulsar besides Vela to have
double torus structure in PWN

Chandra measurements 0.5-8 keV

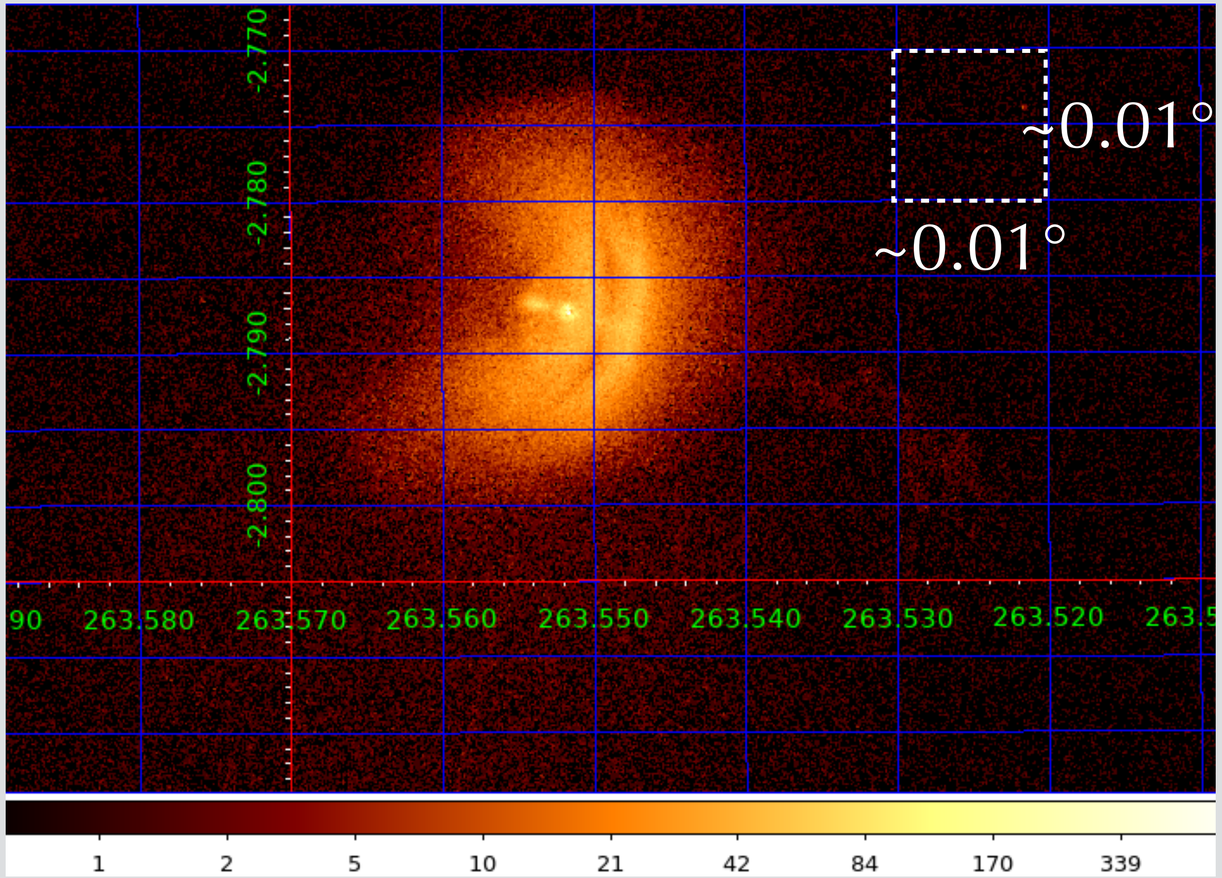


Adam Van Etten *et al* 2008 *ApJ* **680** 1417

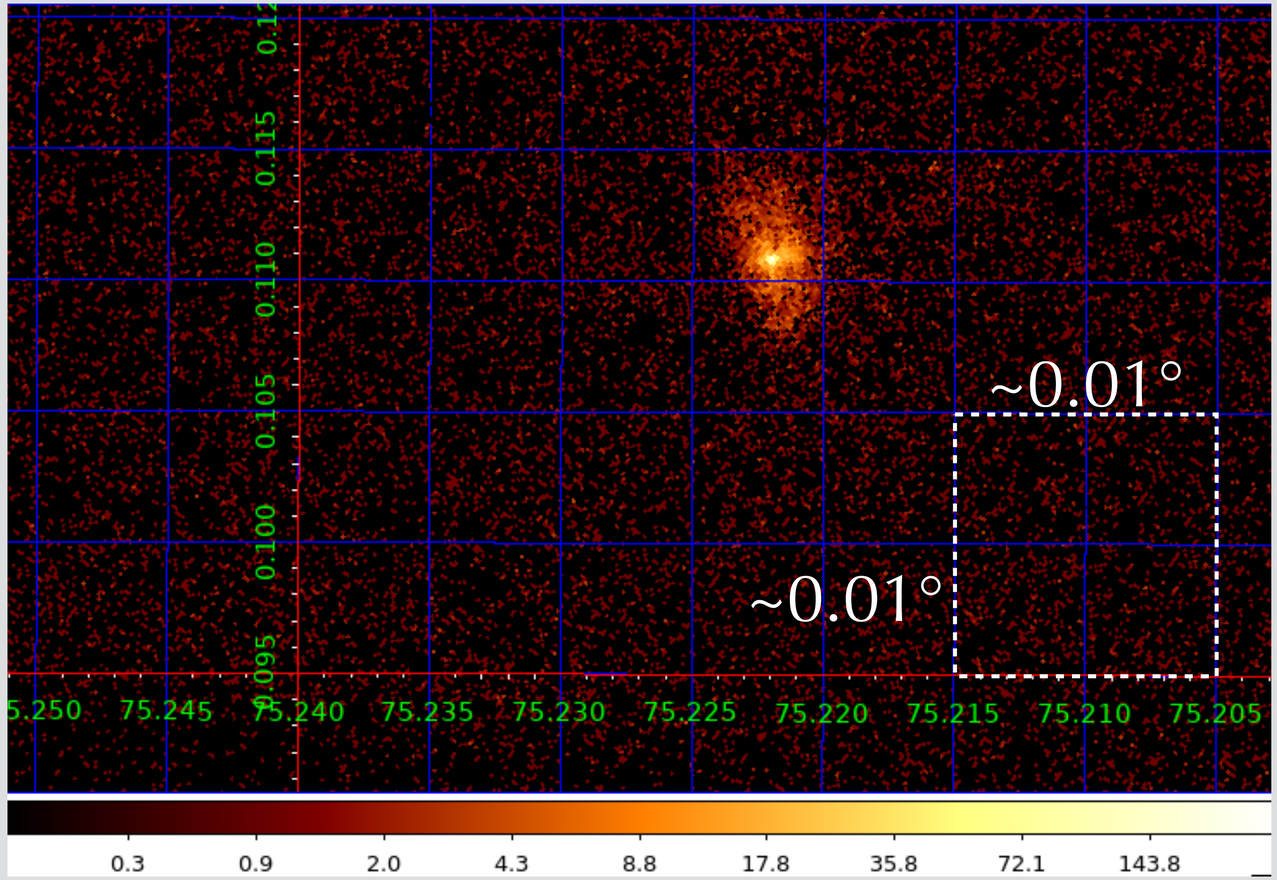


Two Pulsar Wind Nebulae

Vela - 0.294 kpc



Dragonfly - 1.8 kpc



Chandra ACIS Counts map (not the same scale)

42 ks exposure

~0.5 - 8 keV

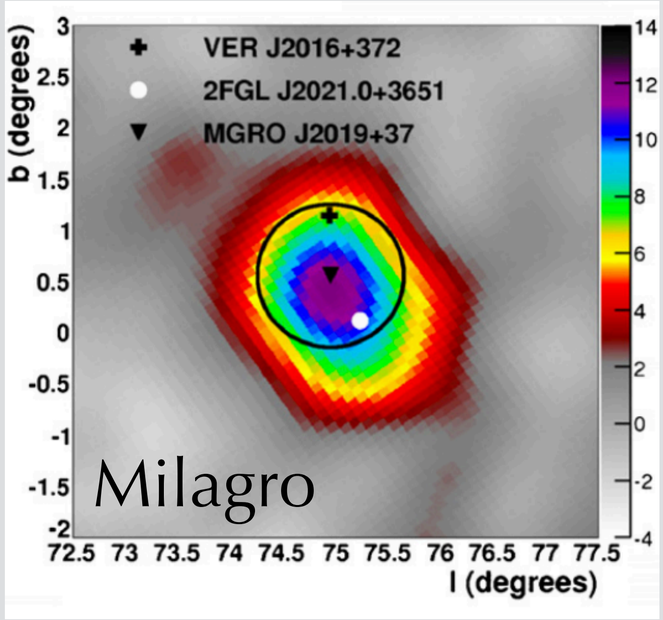
59 ks exposure

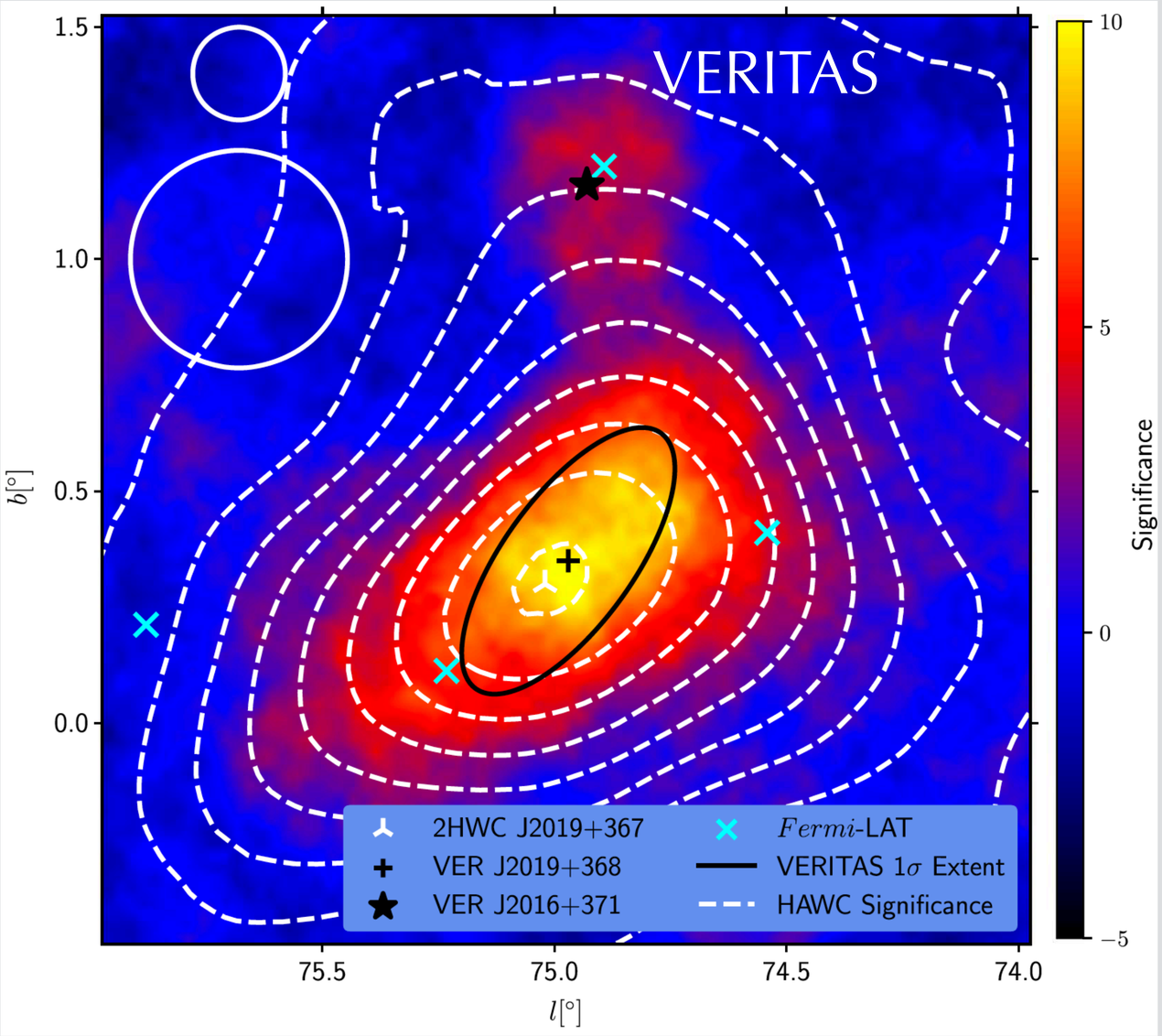
http://asc.harvard.edu/cda/

Brief History of TeV Observations

Milagro finds MGRO J2019+37

VERITAS follows up, resolves 2 sources:
VER J2019+368 & VER J2016+371





A. A. Abdo *et al* 2012 *ApJ* **753** 159
A. U. Abeysekara *et al.* 2017 *ApJ* **843** 40
A. U. Abeysekara *et al* 2018 *ApJ* **861** 134

Dedicated analysis of HAWC data resolves HAWC J2019+368 & HAWC J2016+371

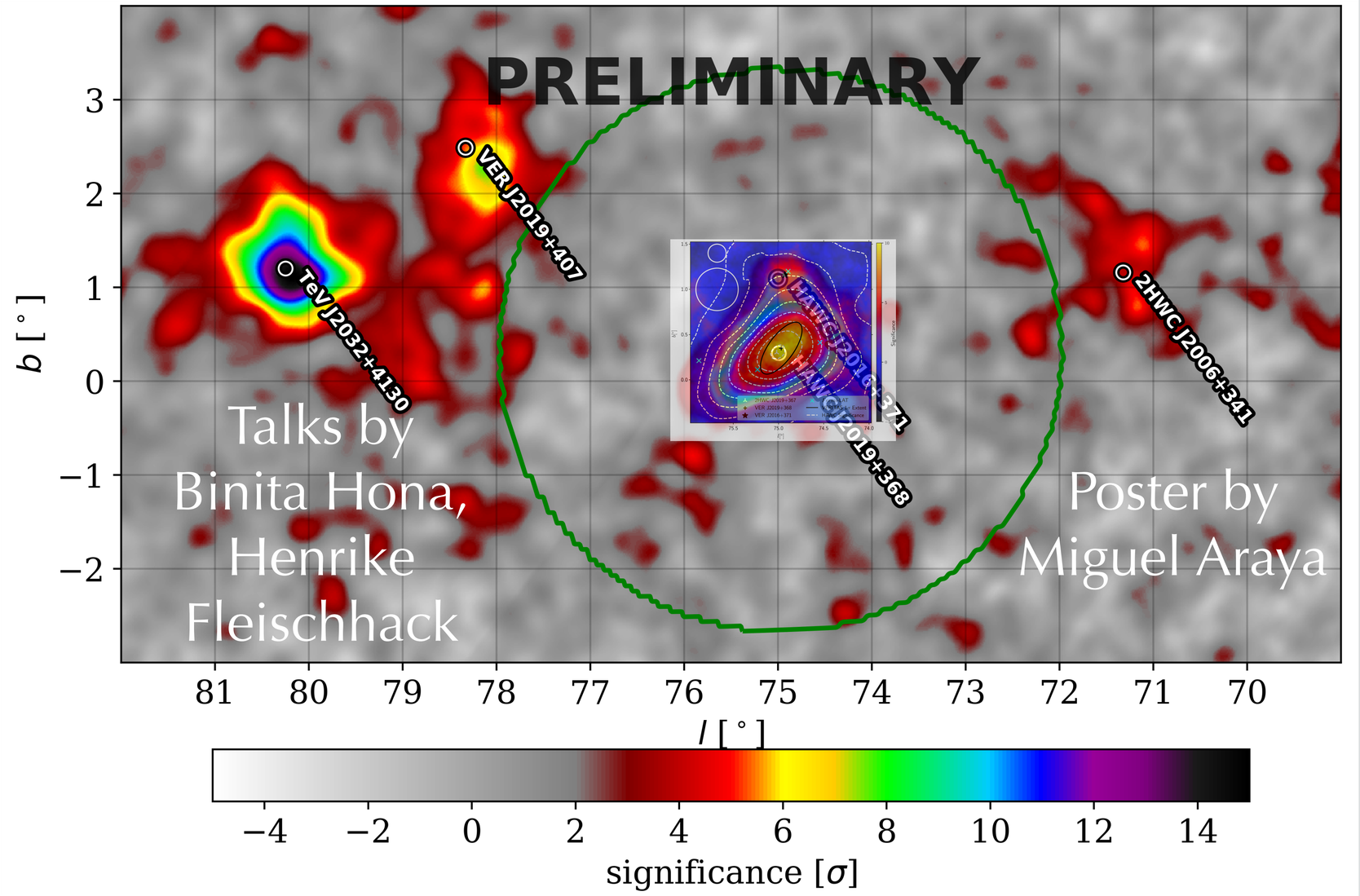
(one source)
VERITAS Morphology

$$a_\sigma = 0.34^\circ \pm 0.02^\circ$$

$$b_\sigma = 0.14^\circ \pm 0.01^\circ$$

Brightest TeV emission not coincident with current pulsar position

E. Aliu *et al* 2014 *ApJ* **788** 78
A. U. Abeysekara *et al* 2018 *ApJ* **861** 134



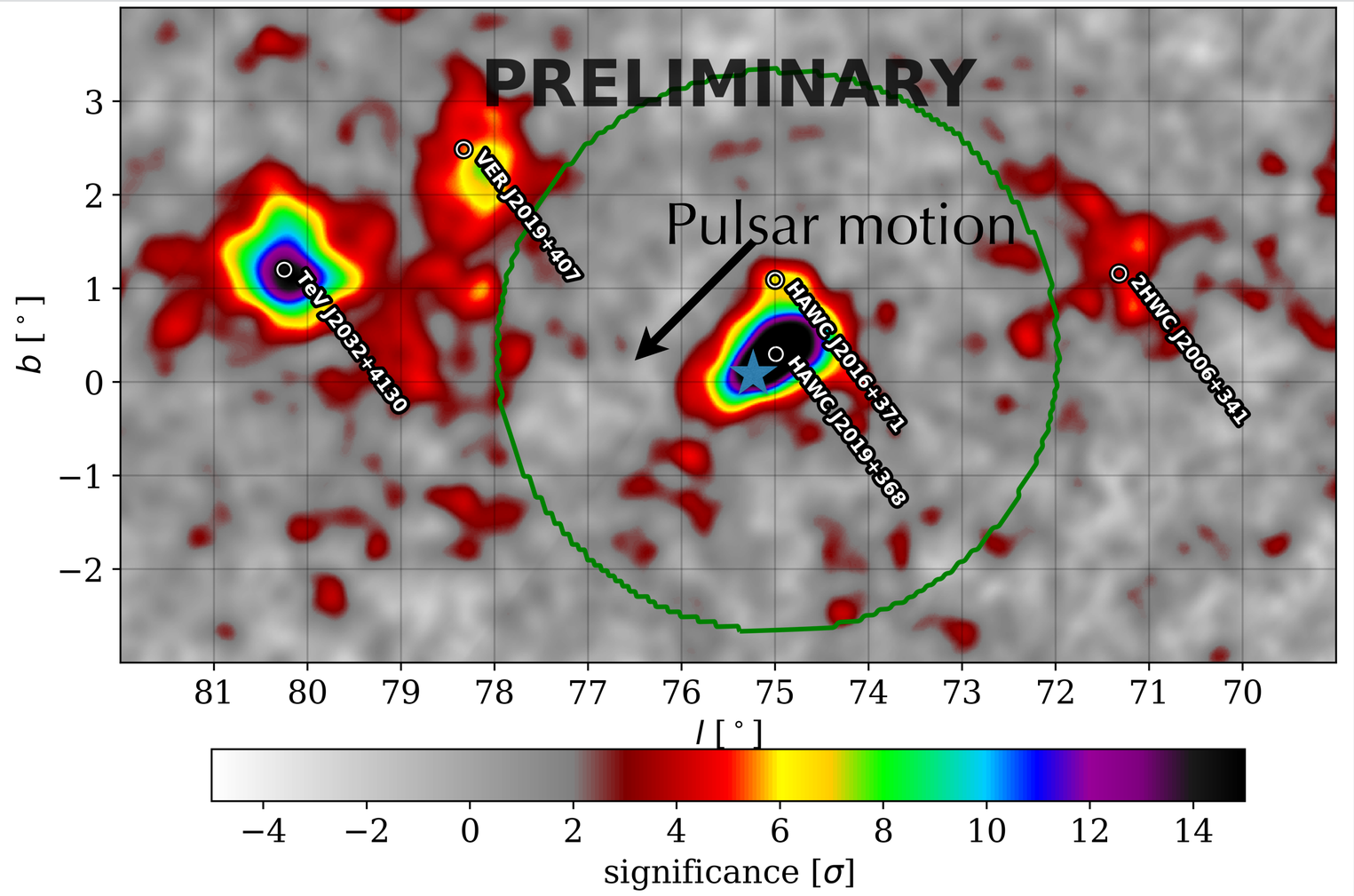
Analysis Details

ROI: 3° centered at l, b = 75°, 0.3°

HAWC J2019+368
- Morphology: Asymmetric Gaussian
- Spectrum: Log Parabola

HAWC J2016+371
- Morphology: Point Source
- Spectrum: Power law

γ-ray background model
- Morphology: Uniform
- Spectrum: Power law



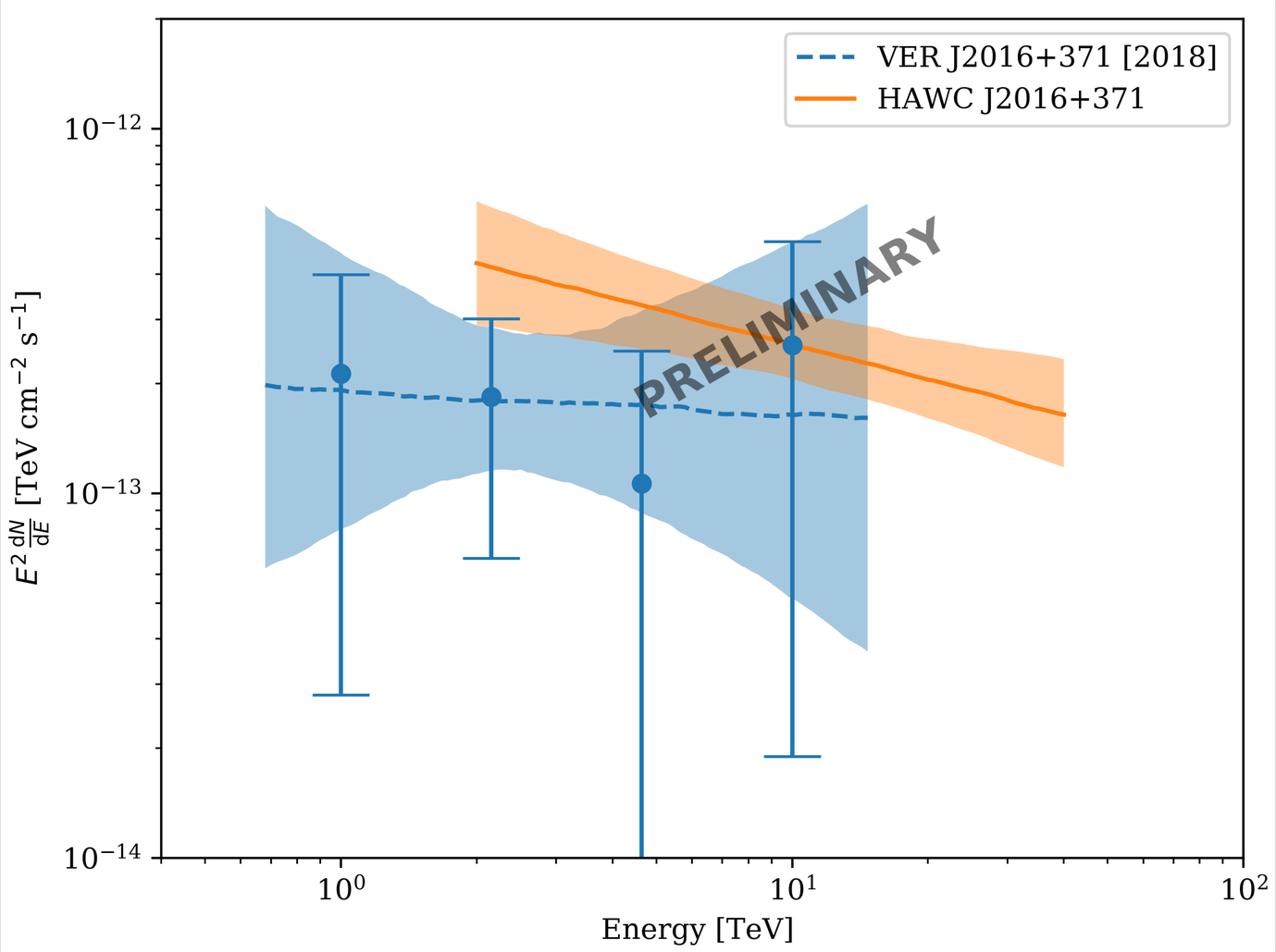
★ Pulsar Location

HAWC data not consistent with two source hypothesis

HAWC J2016+371

Confirmation of VERITAS source

Consistent with interpretation as SNR/PWN CTB 87 + possible contamination from QSO J2015+371 (an AGN)



A. U. Abeysekara *et al* 2018 *ApJ* **861** 134

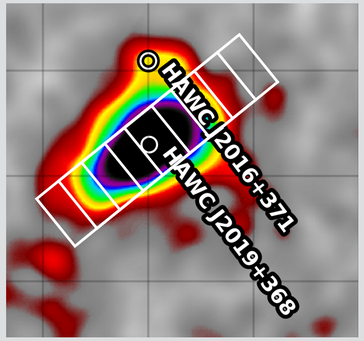
Questions regarding leptonic origin of emission for HAWC J2019+368:

Do we see energy dependent morphology? (cooling electrons & positrons)

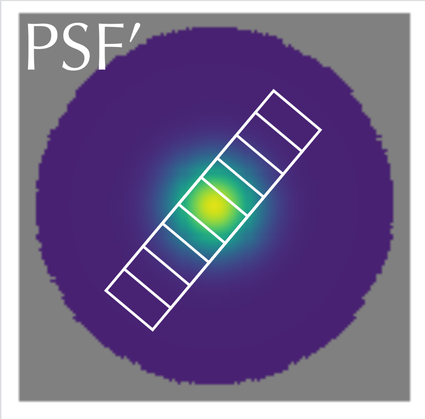
Does the γ-ray spectrum correspond to a realistic distribution of electrons?

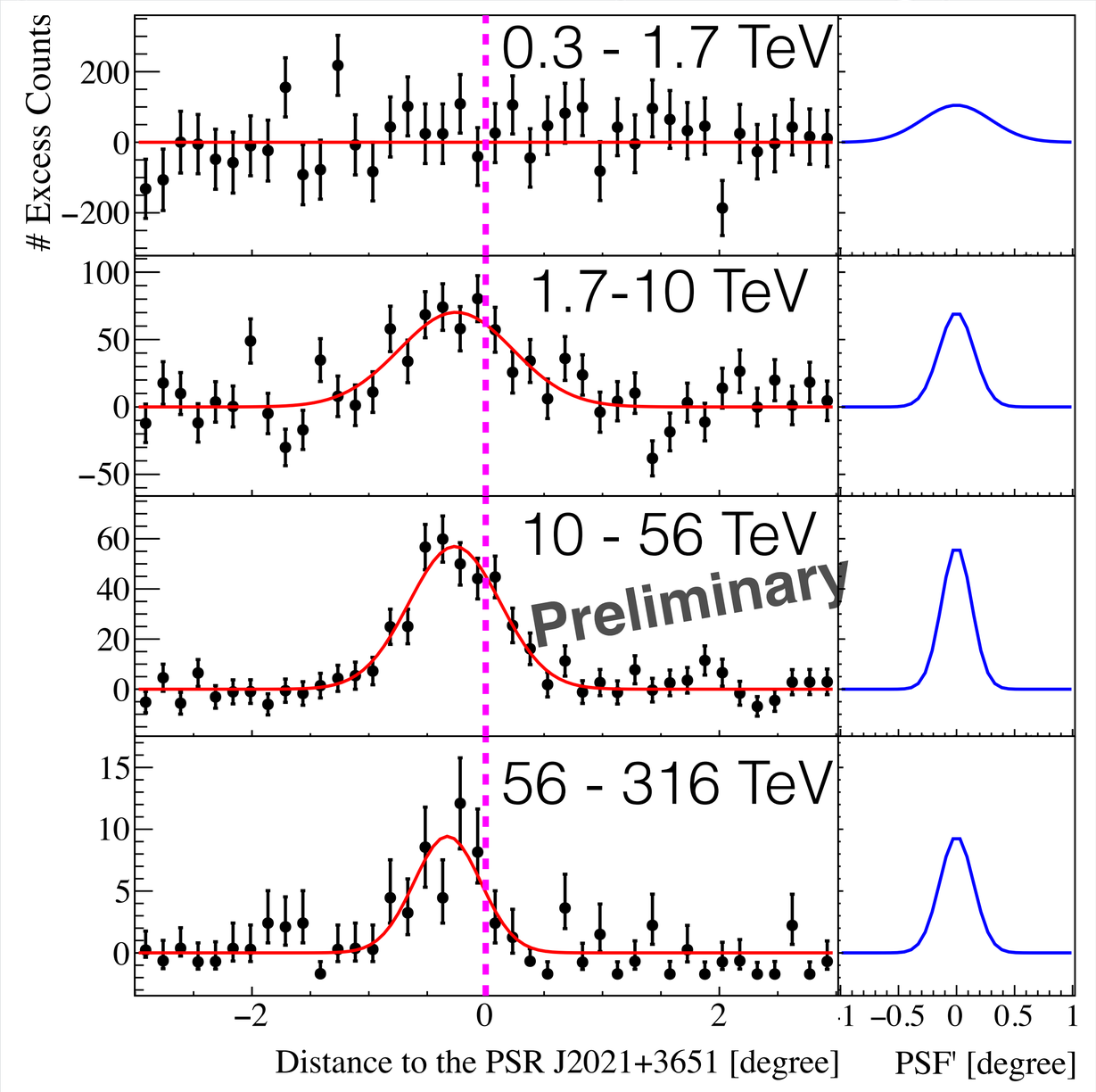
Looking for Energy Dependent Morphology

Longitudinal profile



PSF′ is longitudinal profile through a point source



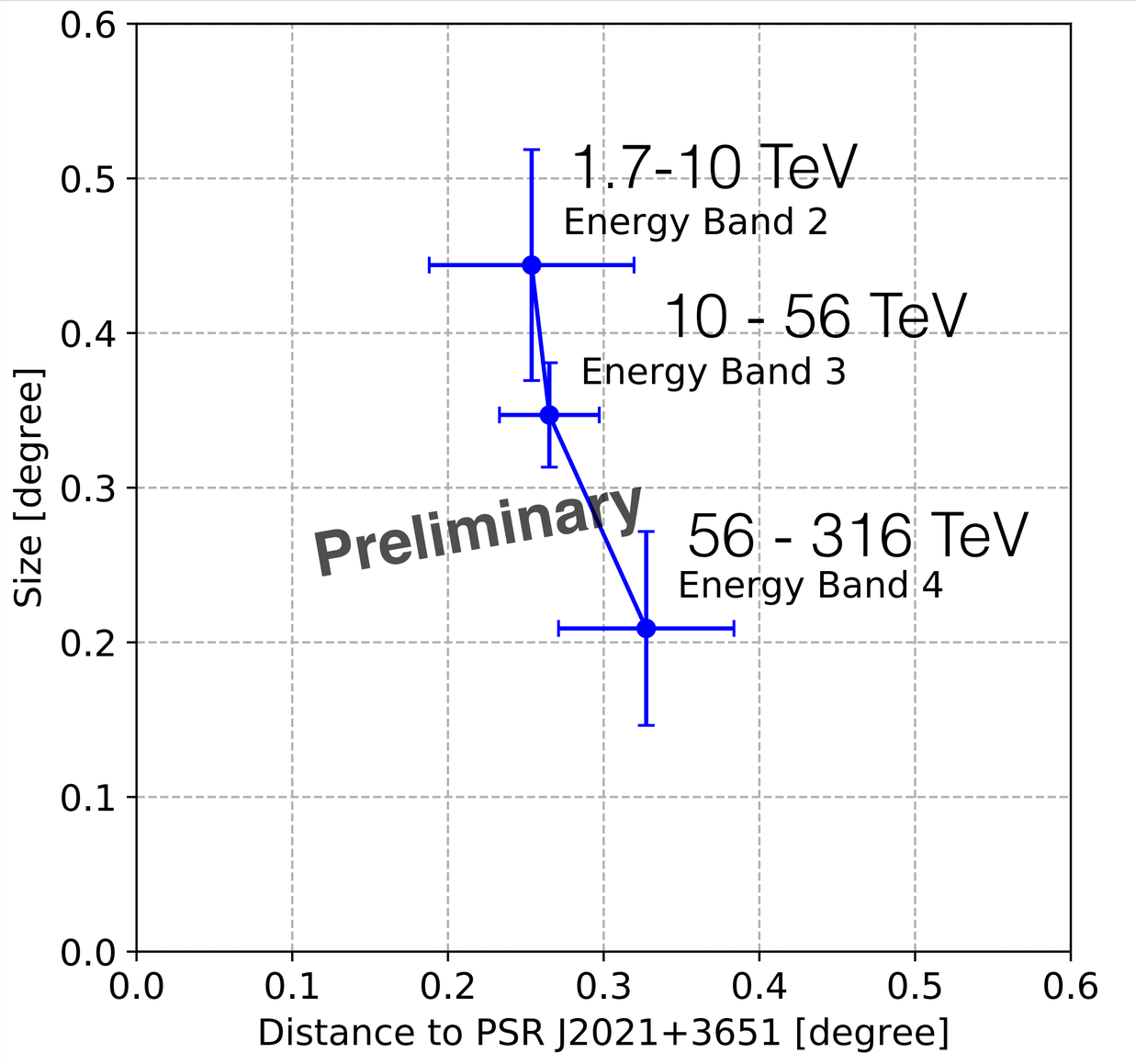


What do we learn?

Width of gaussian fit vs distance from PSR J2021+3651

Centroid in each energy band is consistent

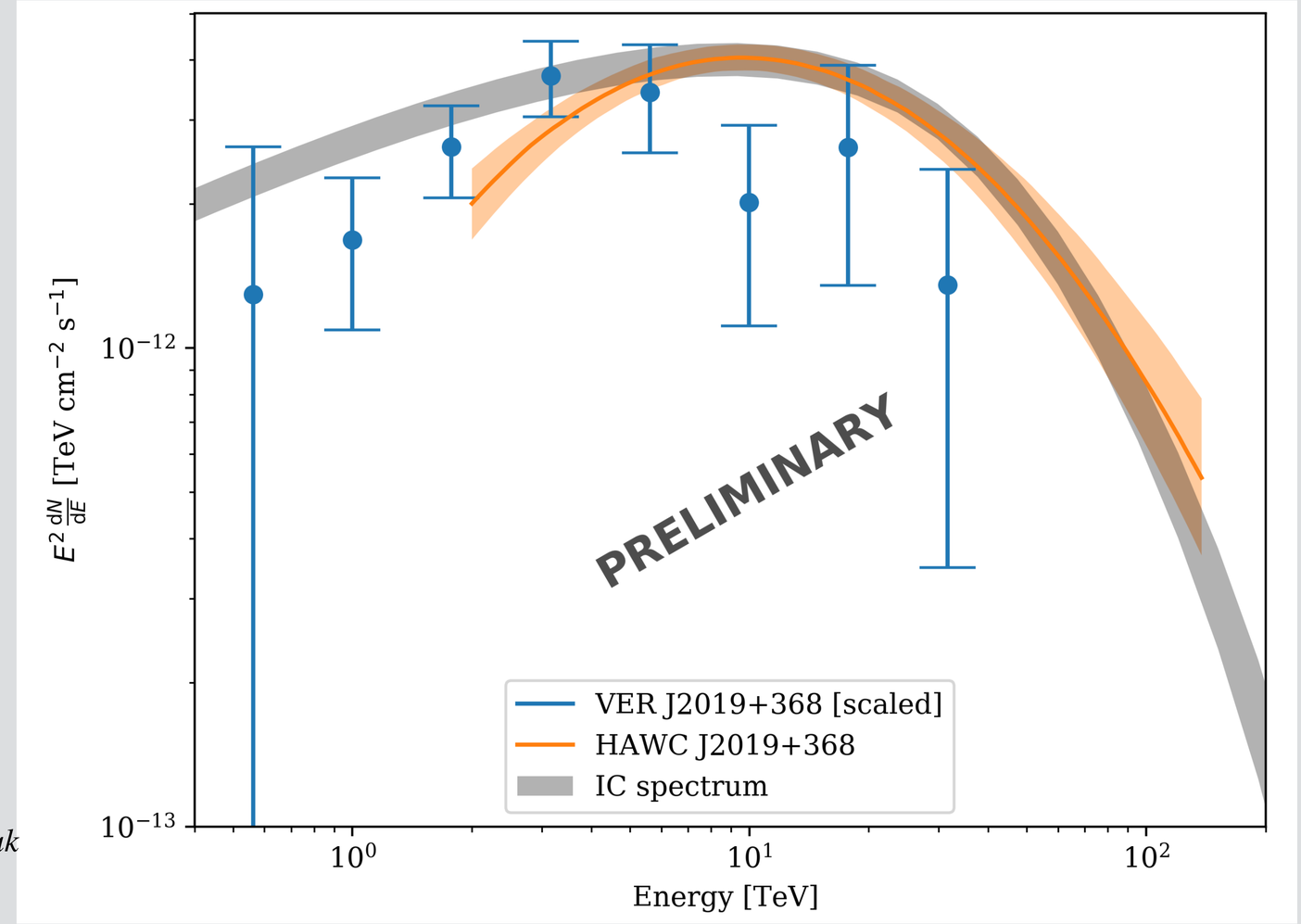
Hints for shrinking size with increasing energy



HAWC J2019+368

HAWC spectrum seems compatible with Inverse Compton emission similar to T. Mizuno *et al* (Fit using `naima`)

~18% of rotational energy in electrons (above 1 MeV)



$$\frac{dN_e}{dE} = exp\left(\frac{-E}{E_{cutoff}}\right)\begin{cases} A\left(\frac{E}{E_p}\right)^{\alpha_1} & E < E_{break} \\ A\left(\frac{E_{break}}{E_p}\right)^{\alpha_1-\alpha_2}\left(\frac{E}{E_p}\right)^{\alpha_2} & E > E_{break} \end{cases}$$

$$\alpha_1 = -2.1 \quad \alpha_2 = -3.1$$

$$E_{break} = 80\,\text{TeV}$$

A. U. Abeysekara *et al* 2018 *ApJ* **861** 134
T. Mizuno et al 2017 ApJ 841 104

Summary & Future work

- Evidence for leptonic origin of emission:
  - Source of energetic electrons (PSR J2021+3651/Dragonfly PWN)
  - Hints of Energy Dependent Morphology in TeV γ-rays
  - HAWC SED consistent with IC emission

Detailed modeling in progress including updated ISRFs and `GAMERA` for particle transport combining X-ray and HAWC observations

More Questions?

Why so asymmetric?

Particle transport?

Other electron spectral models?

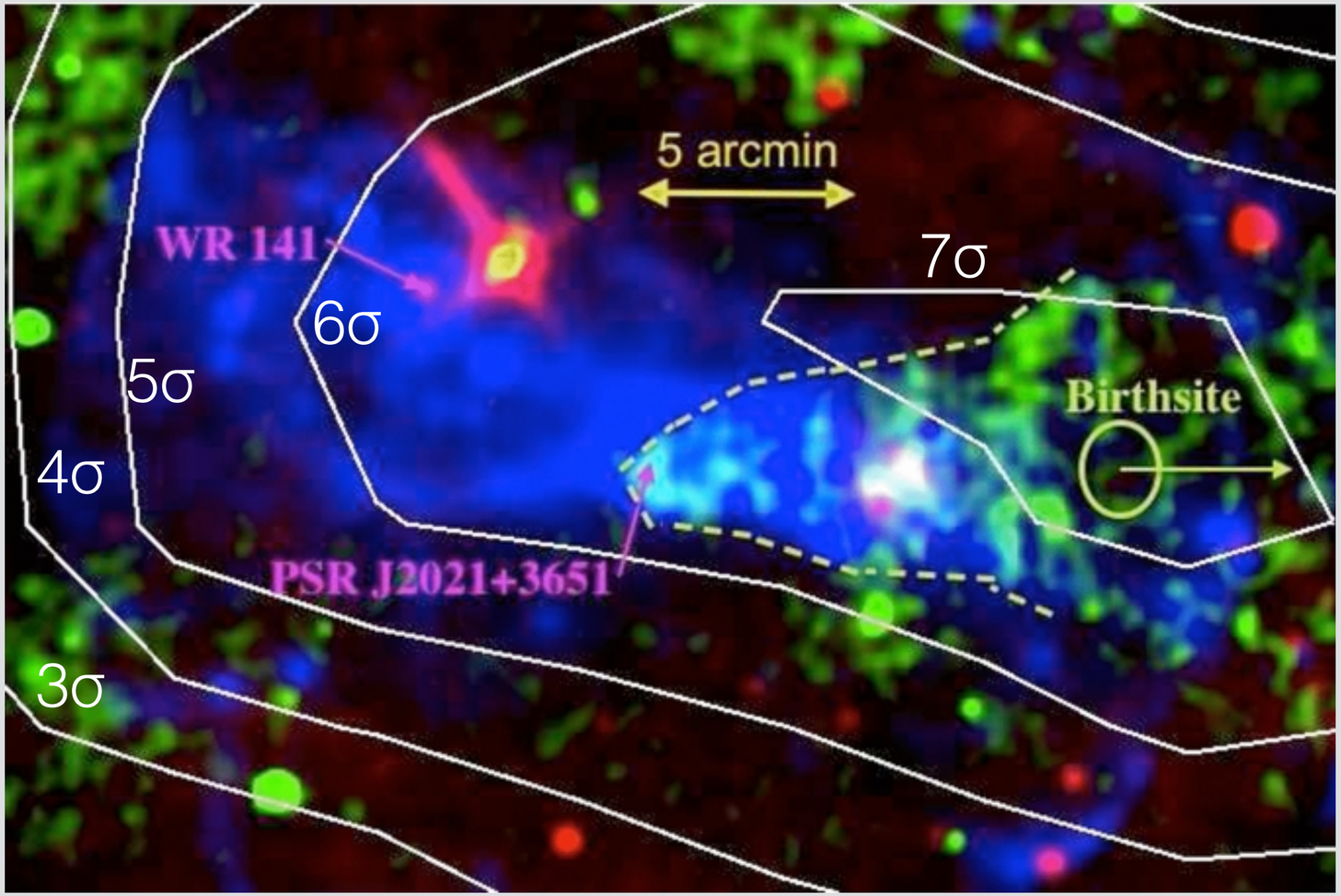
Thank you!

Backup Slides

A Wide Variety of Observations

MSX 8.3 μm (red)
VLA 20 cm (green)
XMM 1-8 keV (blue)

VERITAS (white line)
Radio contour (dashed line)



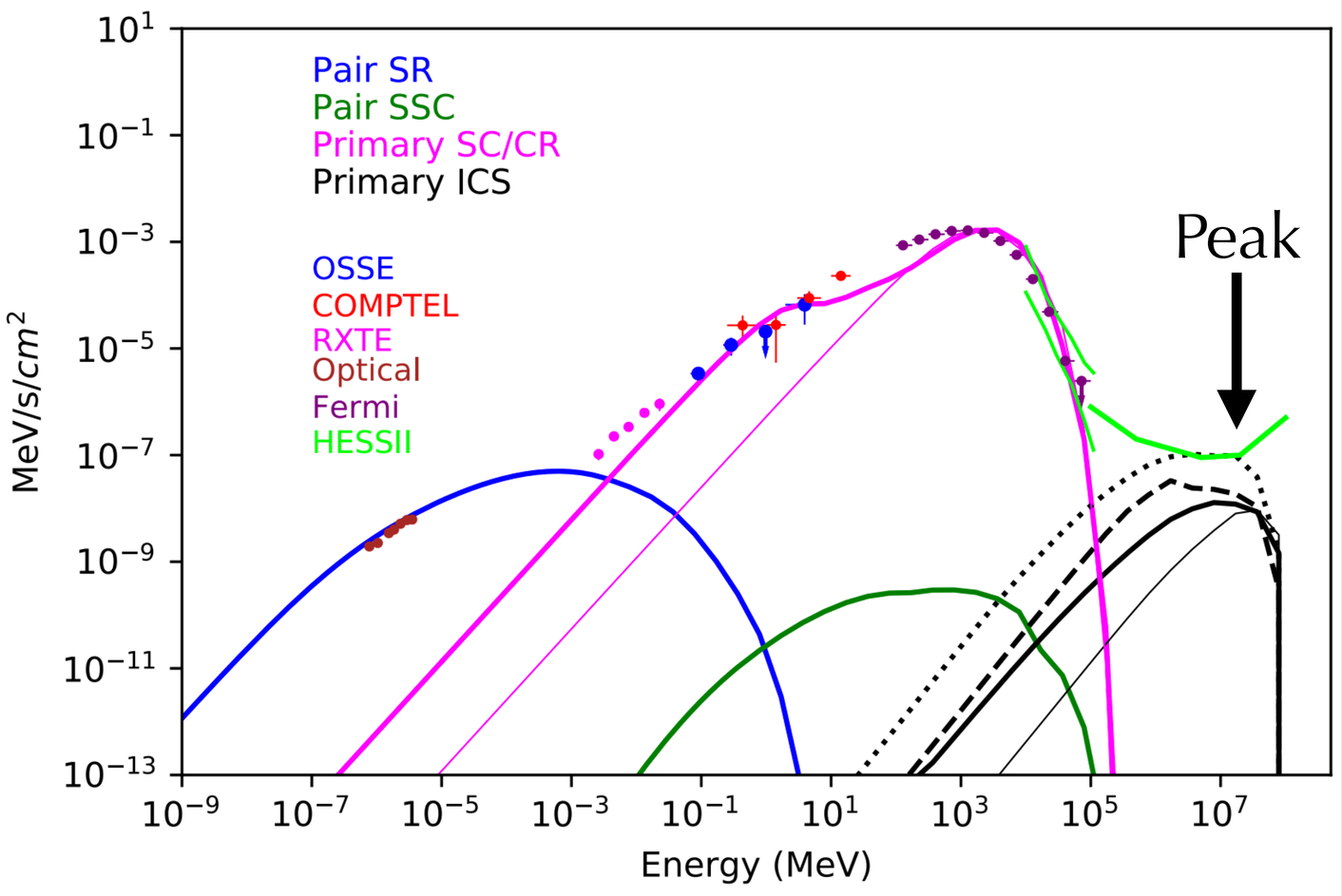
High transverse velocity
≈ 840 km s^{-1}

Assumes 5kpc distance

E. Aliu *et al* 2014 *ApJ* **788** 78

Spectrum of a Pulsar Powered system: Vela

- H.E.S.S. detection of pulsations above 3 TeV
- Injection of 30-60 TeV electrons by pulsar into PWN



Vela is outside HAWC FoV. Why talk about it?

Harding, A. K., *et al* (2018). The Astrophysical Journal, 869(1), L18.

Pulsars

~1.4 $M_\odot$, ~12 km radius, <1 s rotation period

Diameter of Madison, ~25 km

$$\dot{E} = 10^{29} \rightarrow 10^{38} \text{ erg s}^{-1}$$

Google Maps Distance tool

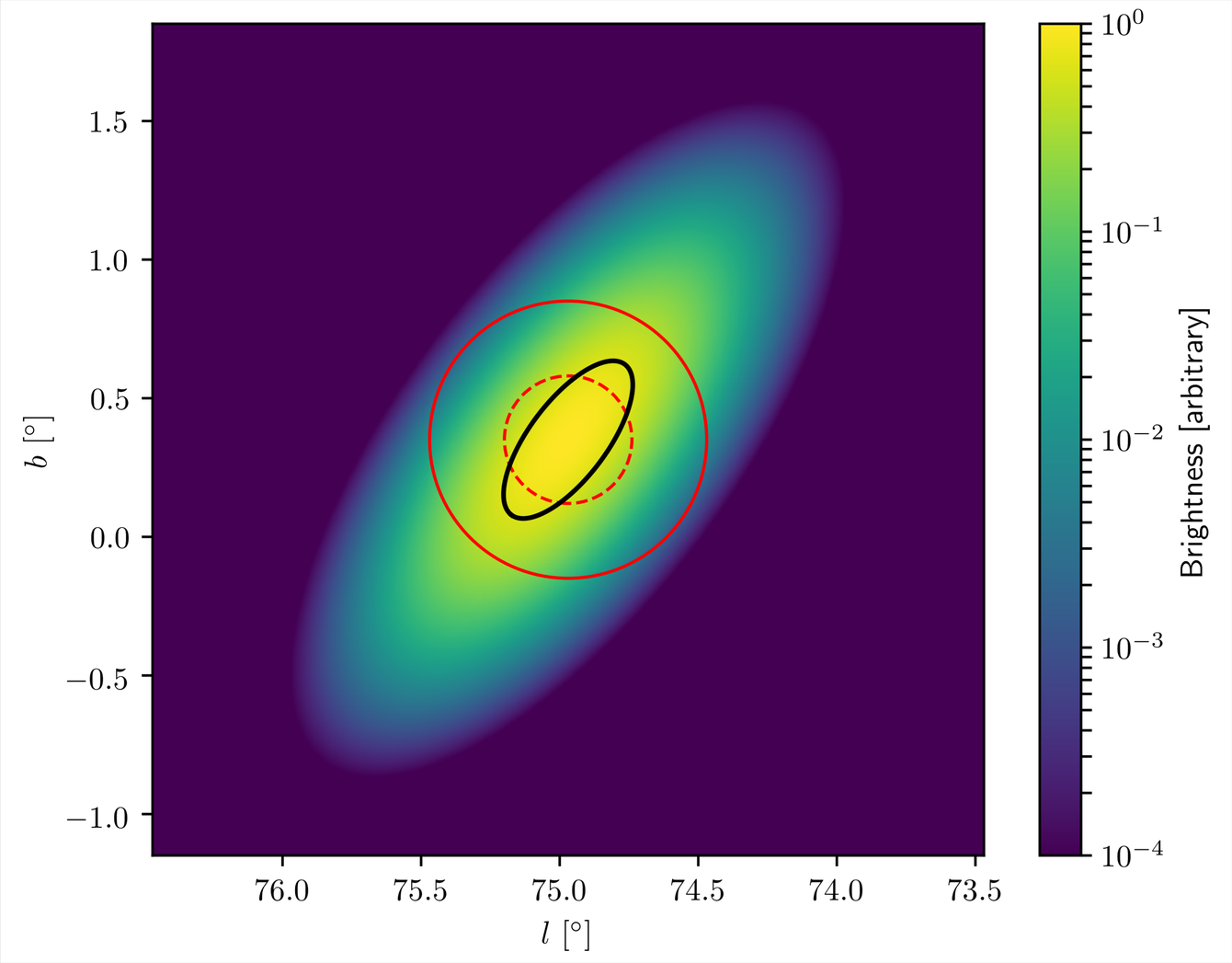
Scaled VERITAS flux?

VERITAS morphology drawn
2014 paper used 0.5° extraction region

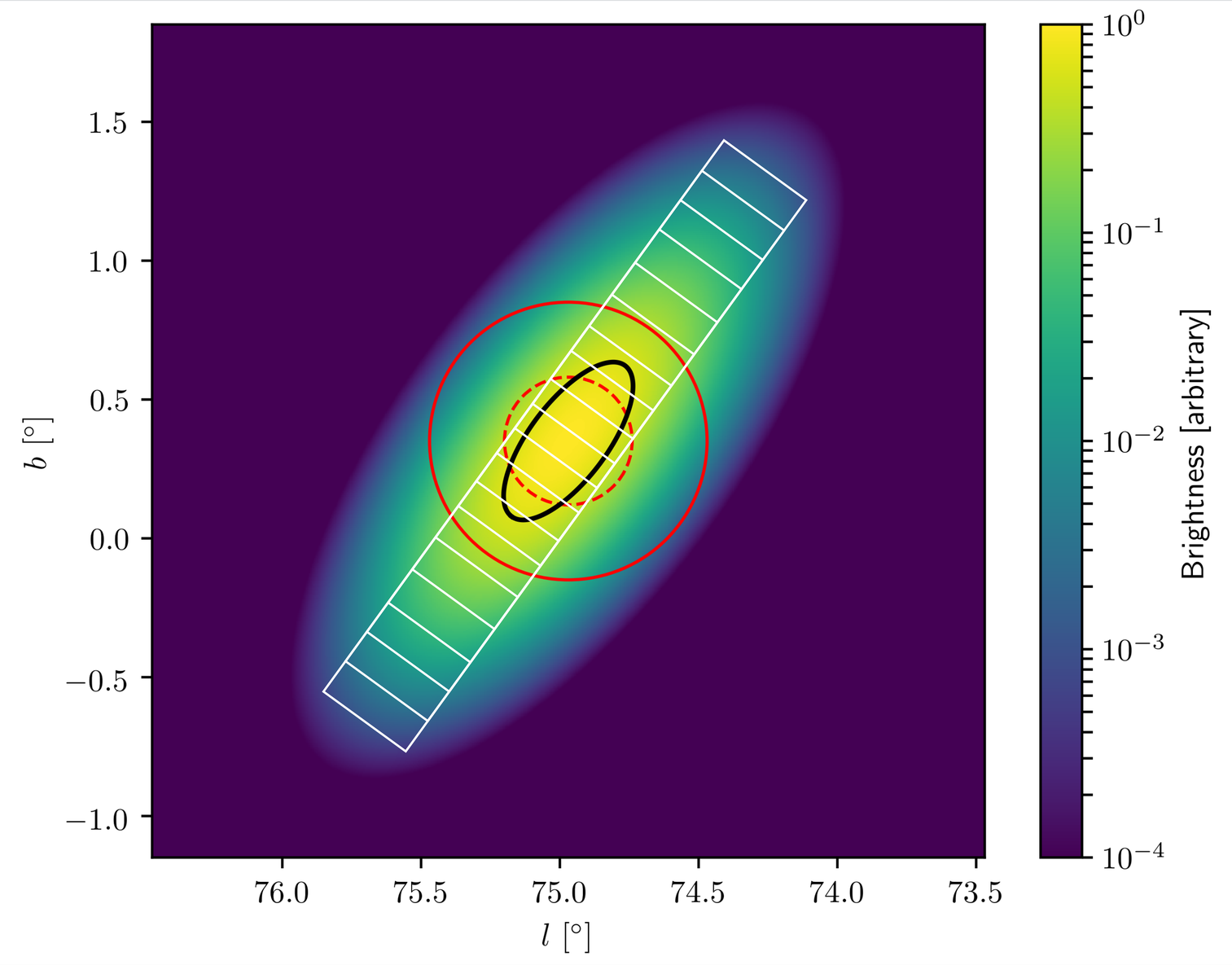
2018 paper used 0.23° extraction region

1σ contour given in black

HAWC fits morphology+ spectrum simultaneously



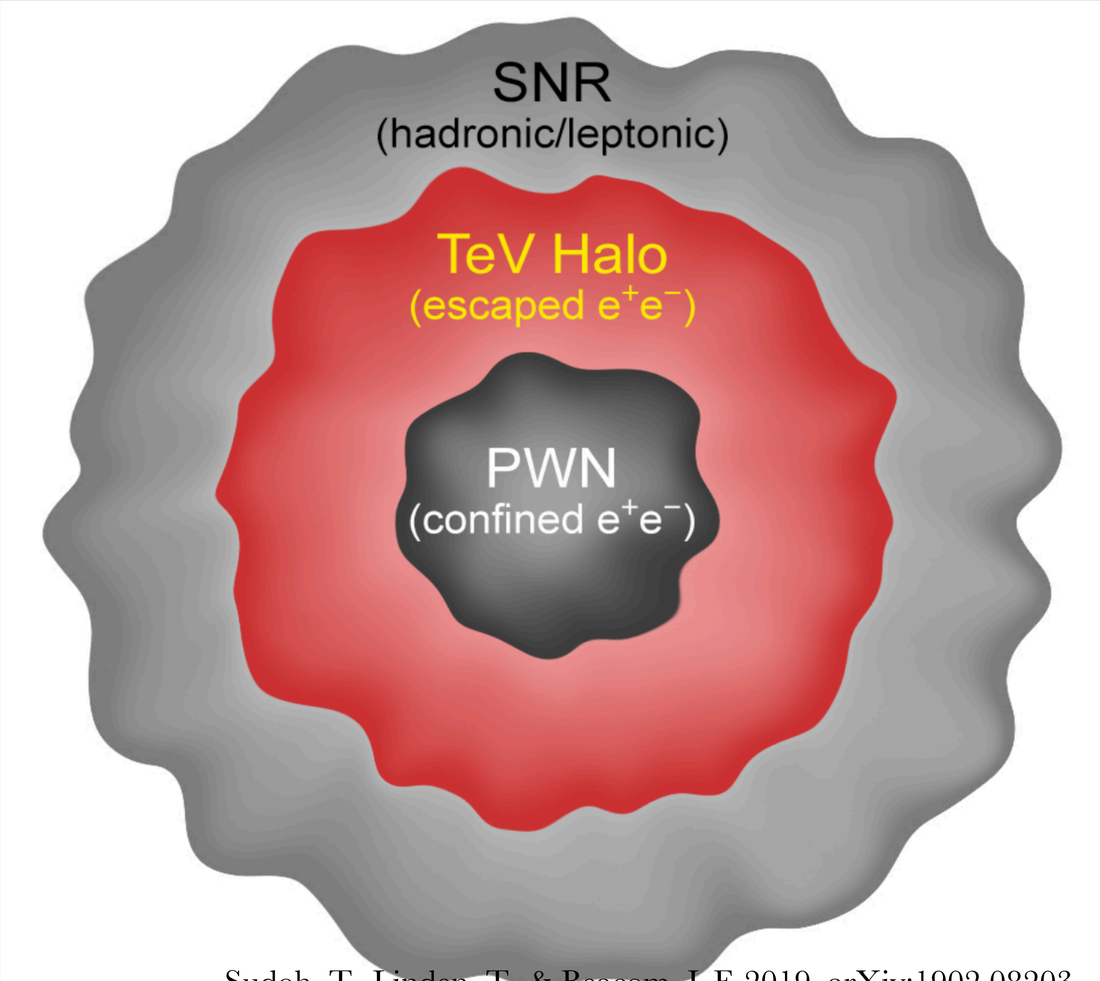
Along the Major axis?



Pulsar Powered Systems?

SNR - Not Powered by the Pulsar
Not Accretion Powered Pulsars

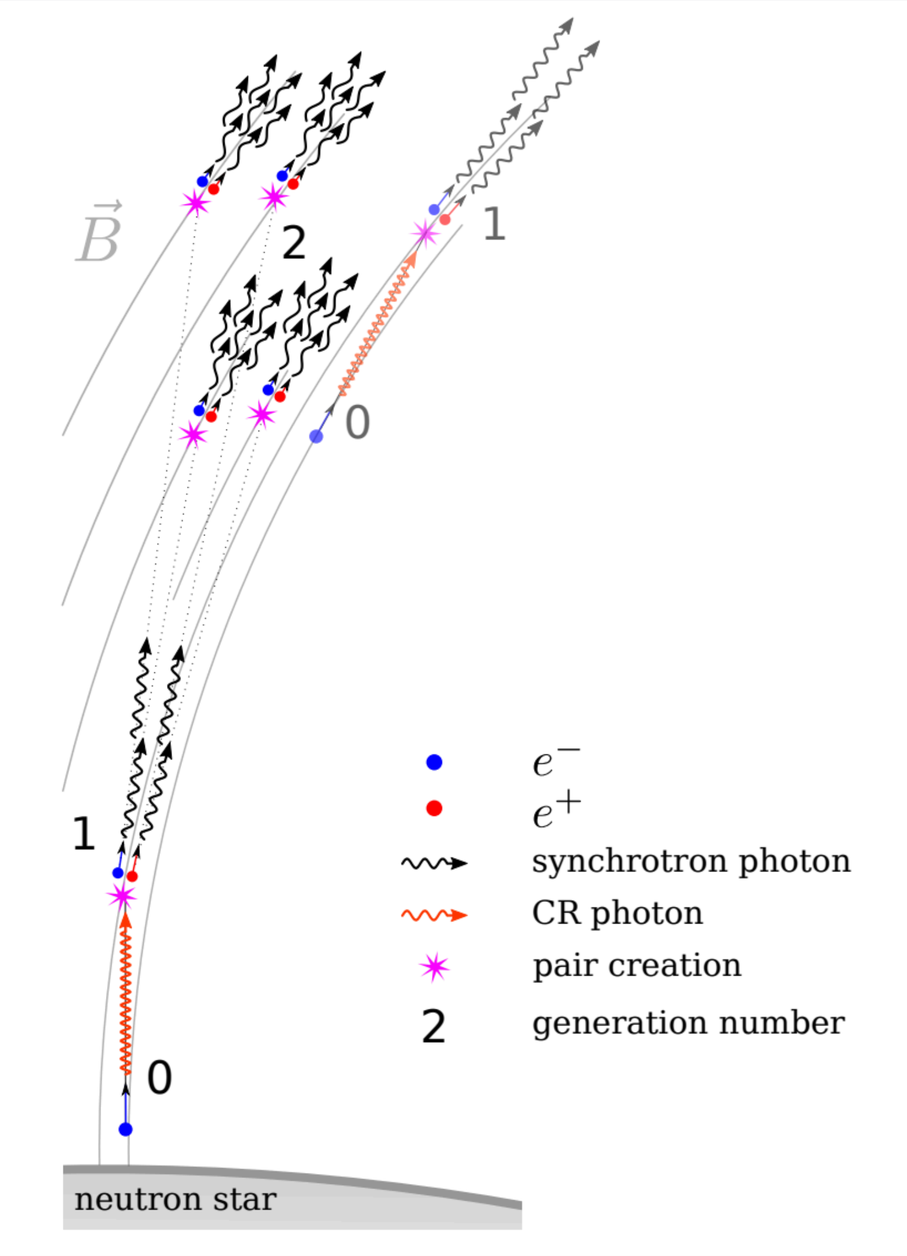
<u>Origin of energetics is Pulsar spin down</u>
Pulsar (and its magnetosphere) — 1 R_L
Pulsar Wind Nebula (PWN) — $O(1)$ pc
TeV Halo *[New]* — 10s pc



Sudoh, T., Linden, T., & Beacom, J. F. 2019, arXiv:1902.08203.

A Sketch of Polar Cap Cascades

1. Primary e^- travels along **B** field
2. Primary e^- emit photon(s)
3. Photon pair-produces
4. $e^\pm$ emit photon(s)
5. Those photon(s) pair-produce
6. Repeat!



Timokhin, A. N., & Harding, A. K. (2015). The Astrophysical Journal, 810(2), 144.