Multi-messenger Probe of Galactic PeVatrons

Shuo Zhang, Assistant Professor of Physics

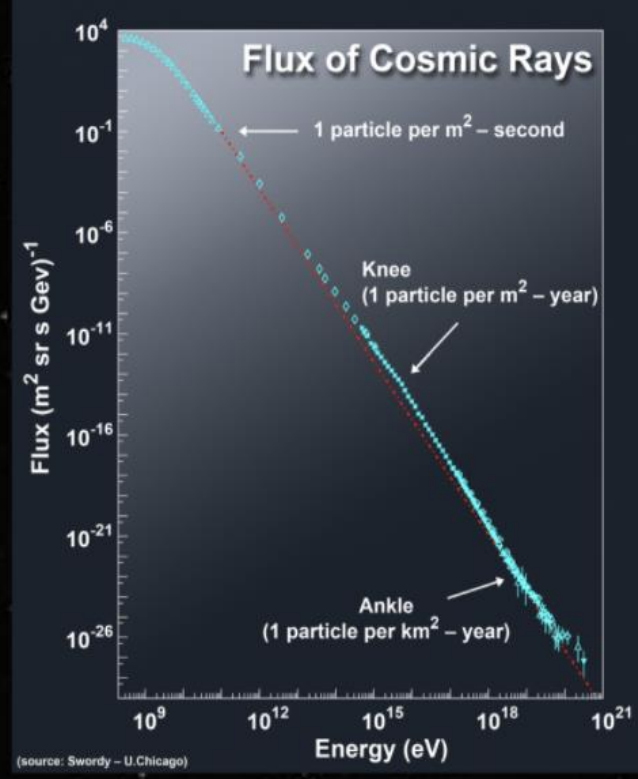
Department of Physics and Astronomy, Michigan State University

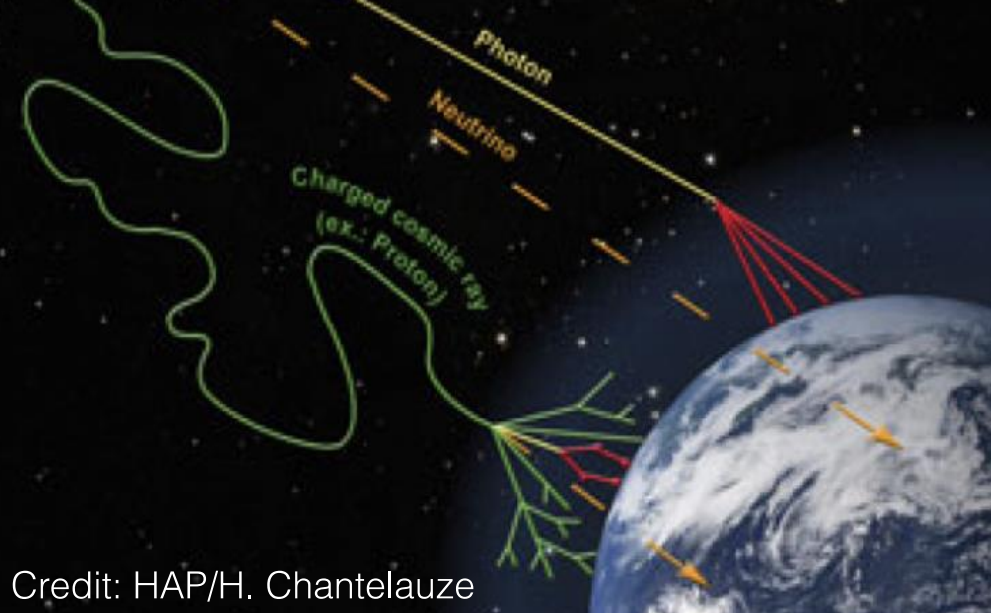
Email: zhan2214@msu.edu

with Steve DiKerby, Tulun Ergin (MSU), Naomi Tsuji, Sunya Takekawa (Kanagawa U.), Kaya Mori, Jooyun Woo (Columbia U.), Fabio Acero (CNRS/IAC), Samar Safi-Harb (Manitoba U.)

What is a PeVatron?

- PeVatron: a source capable of accelerating particles (e.g. protons, electrons) up to PeV (10^{15} eV) energies — cosmic rays
- Cosmic-ray energy spectrum fit by a broken power-law with a break at a few PeV (the “knee”)
- Below the knee, cosmic-rays are of Galactic origin. But how are they produced? What type of Galactic sources serve as PeVatrons?

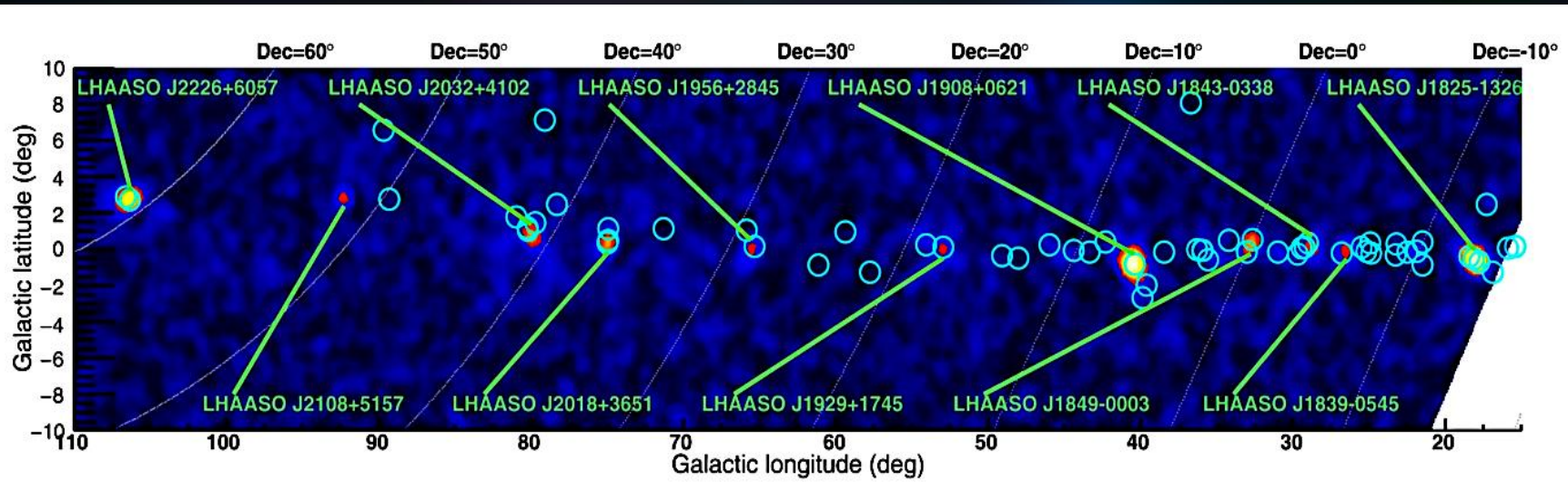




Credit: HAP/H. Chantelauze

Start of a Golden Age for PeVatron Hunting

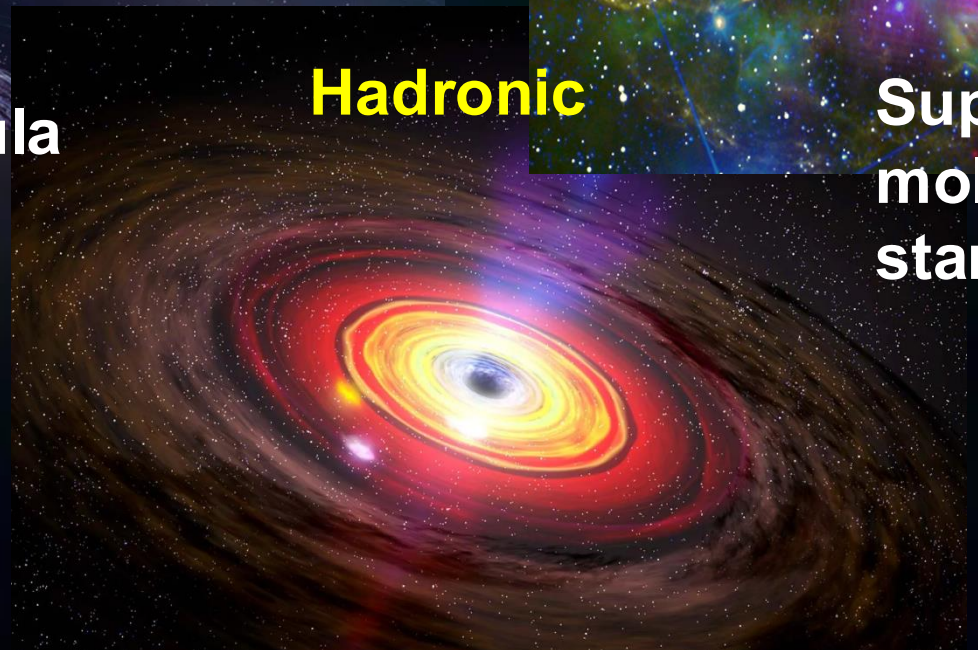
- IceCube detected TeV neutrino at 4.5σ from the Galactic Plane (IceCube, 2023 Science)
- LHAASO released the 1st catalogue of 43 UHE sources (Cao+ 2021, Nature; 2023, ApJS)
- These discoveries marked a paradigm shift in high-energy astrophysics from "**Do PeVatrons exist in our galaxy**?" to "**What are the Galactic PeVatrons**?"



Identify individual PeVatrons via Multi-messenger Study

Pulsar wind nebula

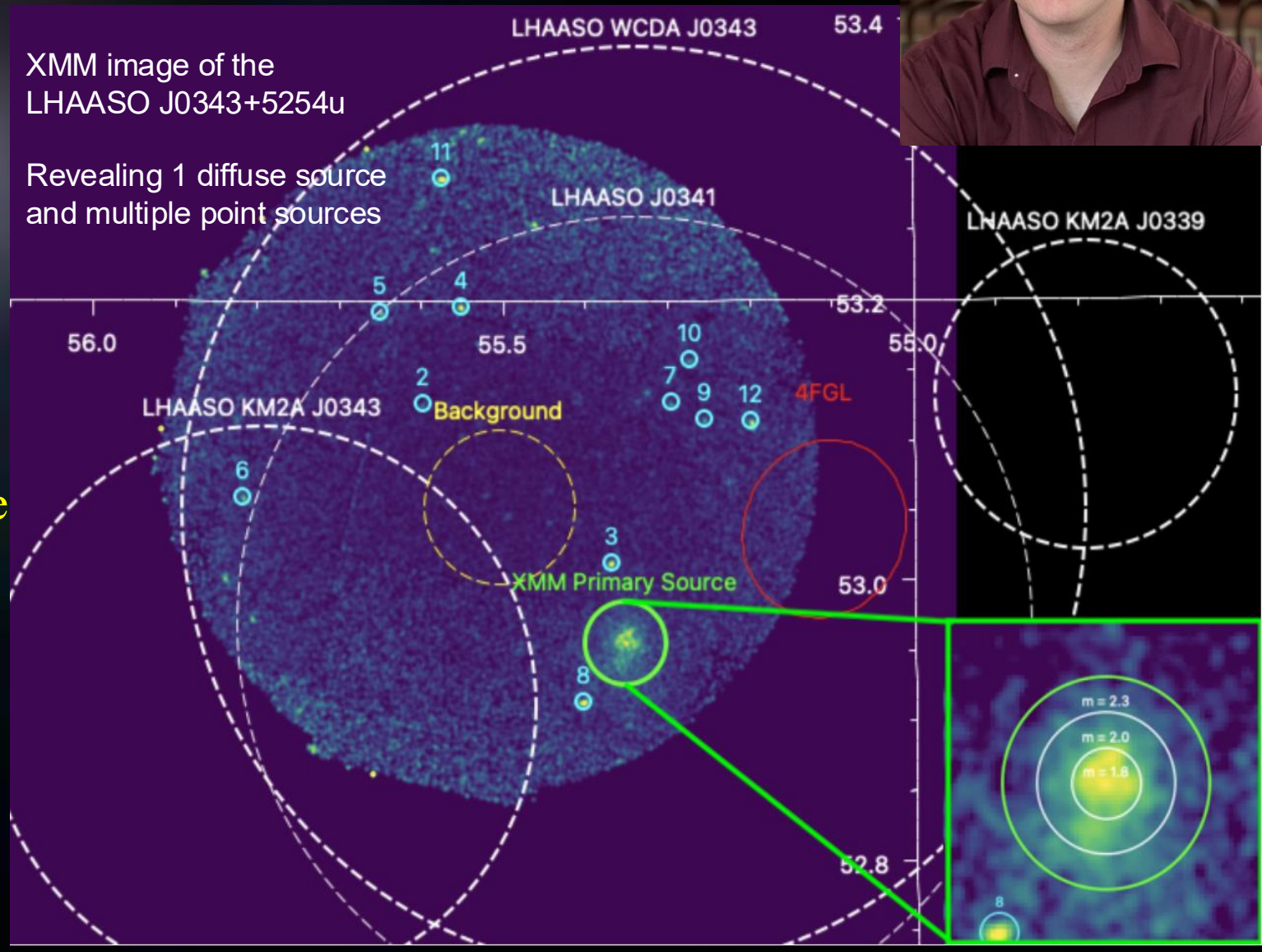
Supernova Remnants and molecular cloud interaction, star-forming regions, etc.



Black Holes: X-ray binaries, Microquasar, SMBH…

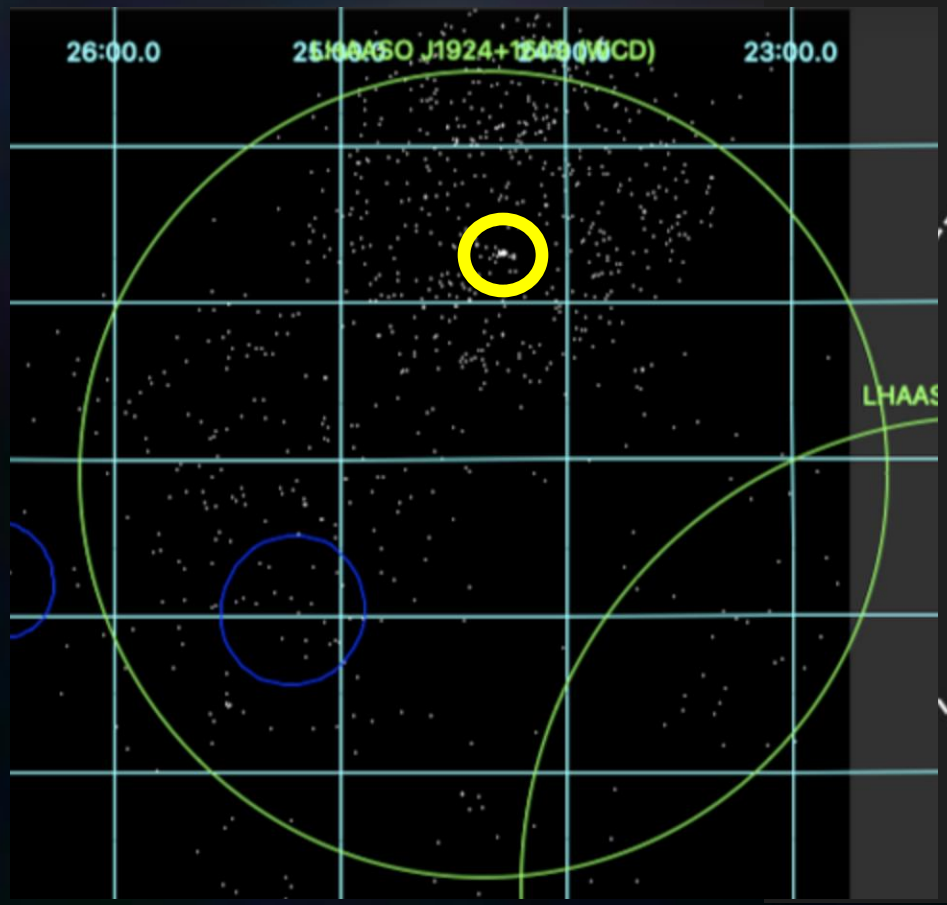
Discovery of a Pulsar Wind Nebula candidate associated with PeVatron LHAASO J0343+5254u using 2024 XMM-Newton observation

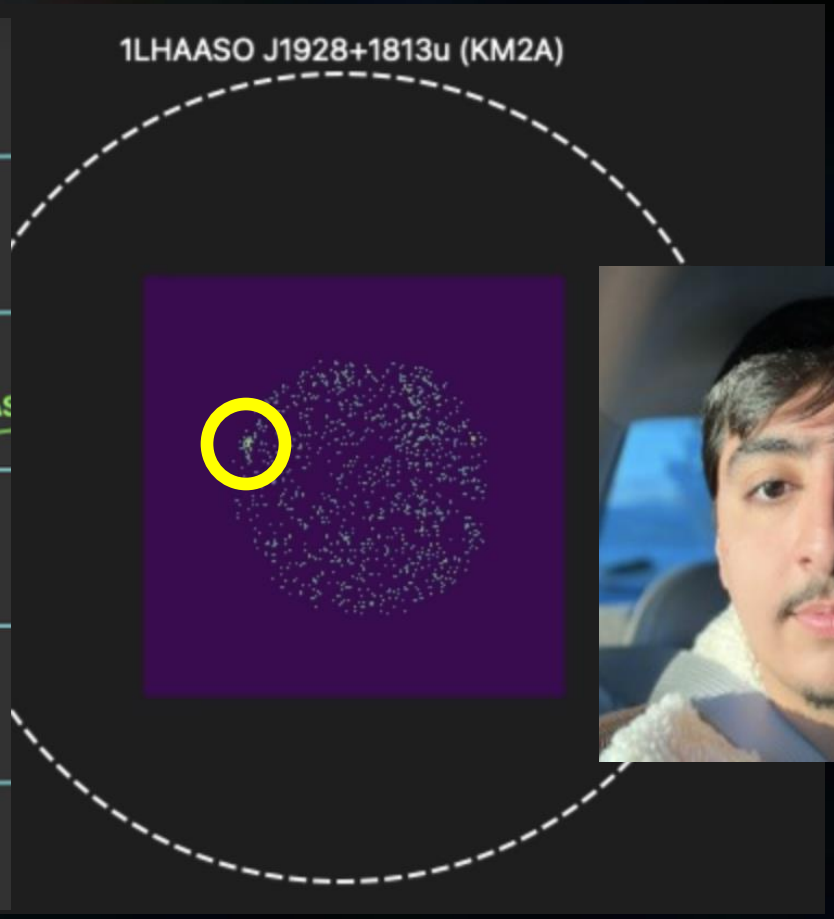
- Detected by LHAASO up to 200 TeV as extended source (0.29 °);
- No low-energy counterpart confirmed before ("dark PeVatron");
- Our XMM-Newton observation in Feb. 2024 led to discovery of a PWN candidate as a likely X-ray counterpart
- Establish this PeVatron as a PWN driven leptonic cosmic ray source



DiKerby, Zhang et al., ApJ, 983 21 (2025)

Swift ToO Follow-up of more LHAASO PeVatrons





Quick Look at Swift ToO Observations of LHAASO PeVatrons obtained in Sep-Oct 2024: some result in positive X-ray detection.

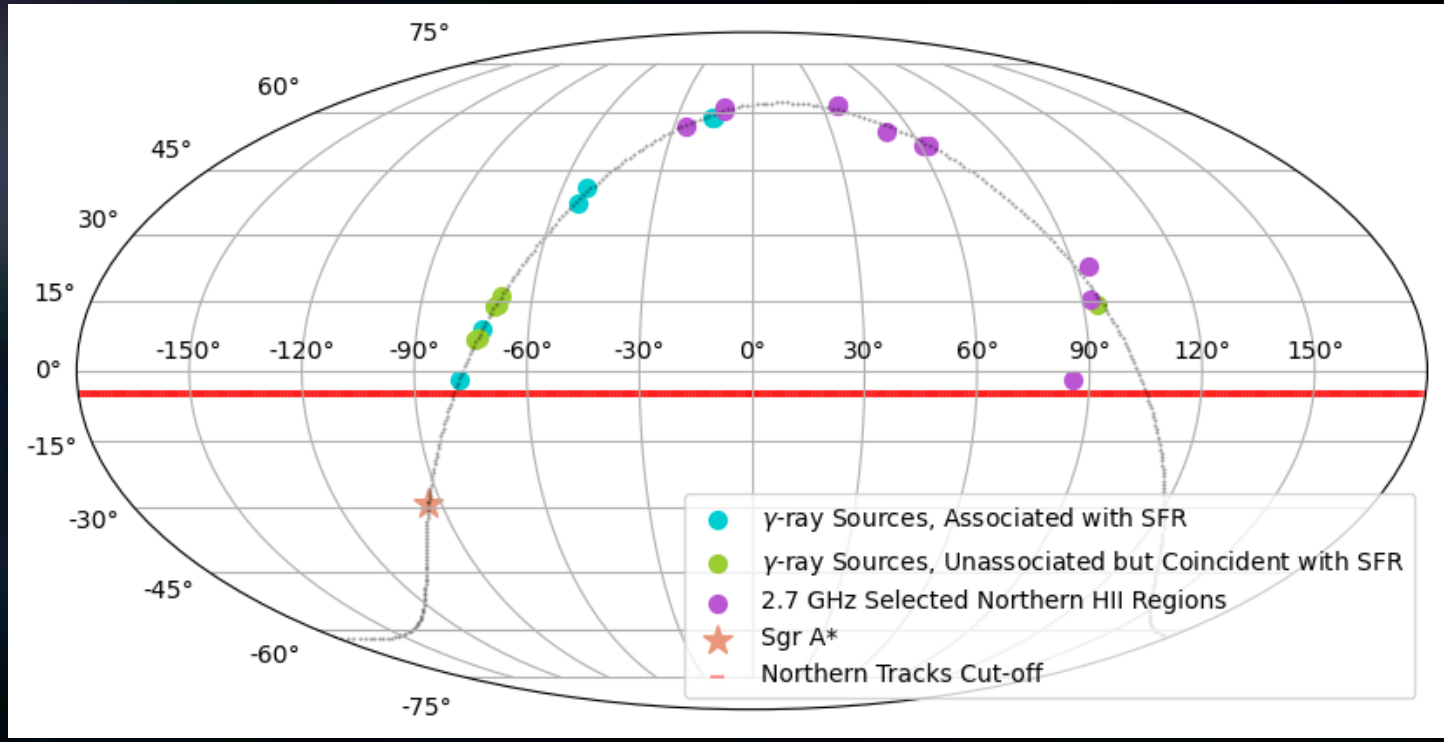
Ella Werre, Shaan Kerim, Amiri Walker, Dikerby, Research Notes of AAS, 9, 89 (2025)

Multi-messenger study on Star Forming Regions as a new PeVatrons class?

- Colliding stellar winds and shocs in star-forming regions can accelerate protons/ions into extreme energies (Aharonian+ 2019)

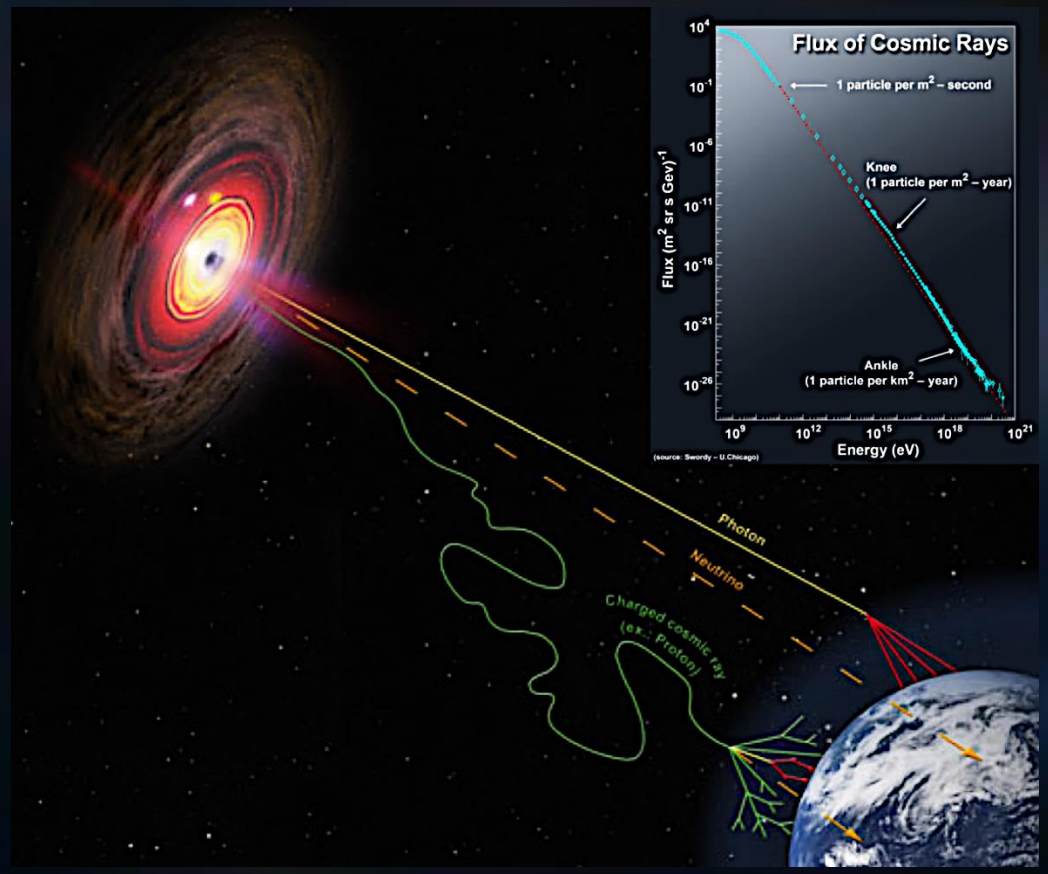
- Recent KM3Net detection of PeV neutrino from the direction of the Orion star-forming region spurs further interest.

- Our MSU IceCube group launched a neutrino search for star forming regions in the Northern sky using the IceCube data.



DiKerby, Sanger-Johnson, Zhang
see talk 230.06 from DiKerby on 6/10/2025

Summary: Start of a Golden Age for PeVatron Hunting



- We rolled out an X-ray follow-up observation campaign to identify PeVatron candidates discovered by LHAASO using XMM and Swift.
- We discovered a PWN candidate associated with the Galactic PeVatron LHAASO J0343+5254u, potentially establishing it to be a PWN-powered leptonic PeVatron.
- We launched a new neutron search for star-forming regions with the IceCube data.

Contact:

Shuo Zhang, Michigan State University, zhan2214@msu.edu