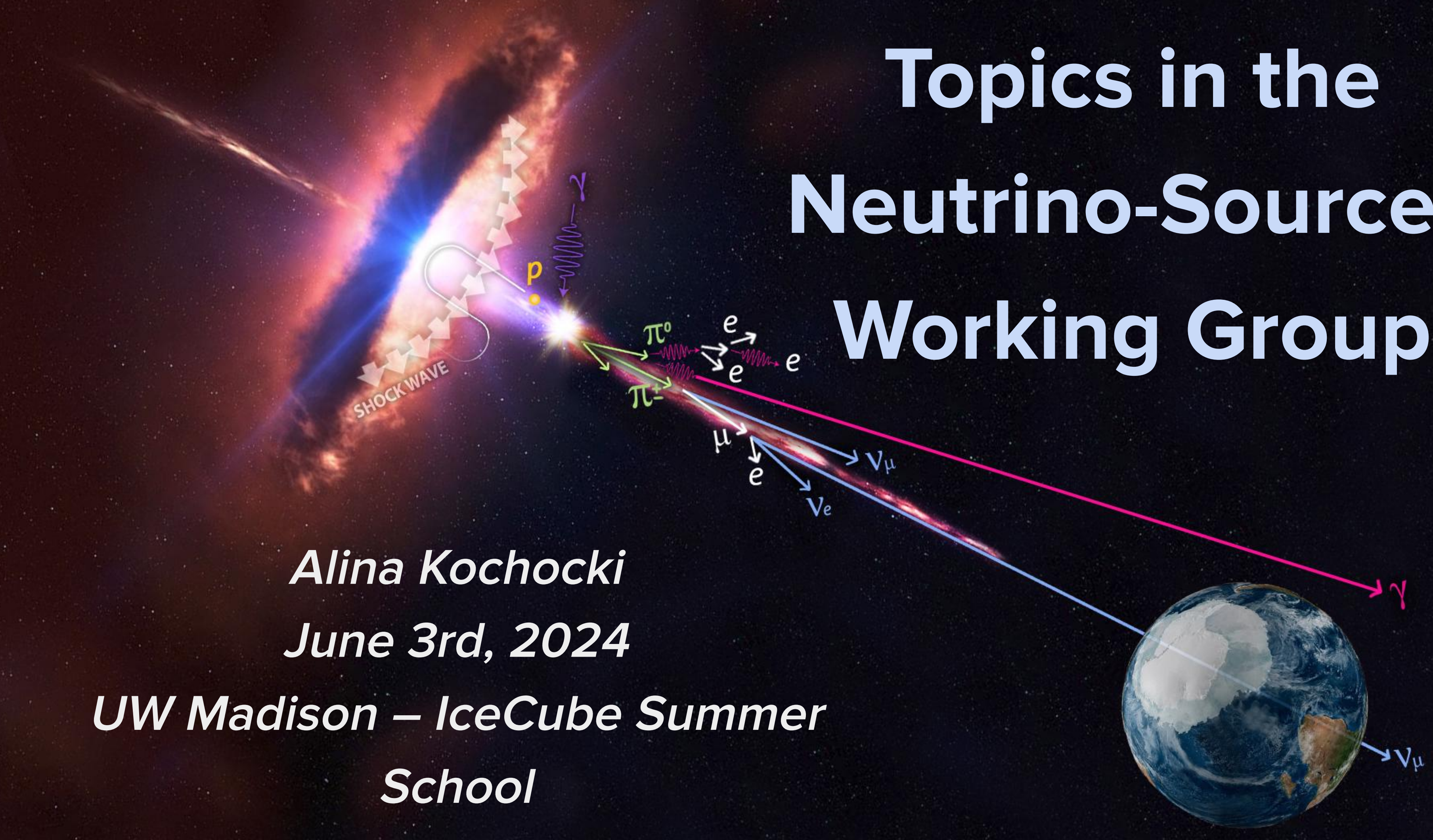
Topics in the Neutrino-Sources Working Group



Alina Kochocki

June 3rd, 2024

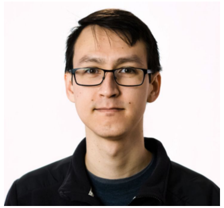
UW Madison – IceCube Summer School

Introduction to the Working Group

Interested in astrophysical sources of neutrinos, both extragalactic and galactic, and the implications of our measurements for the astrophysical and multimessenger communities

Lisa Schumacher – WG Lead

Ali Kheirandish – WG Lead



Will Luszczak, Data Curator

Sarah Mancina, Tech Lead

Alina Kochocki, Tech Lead

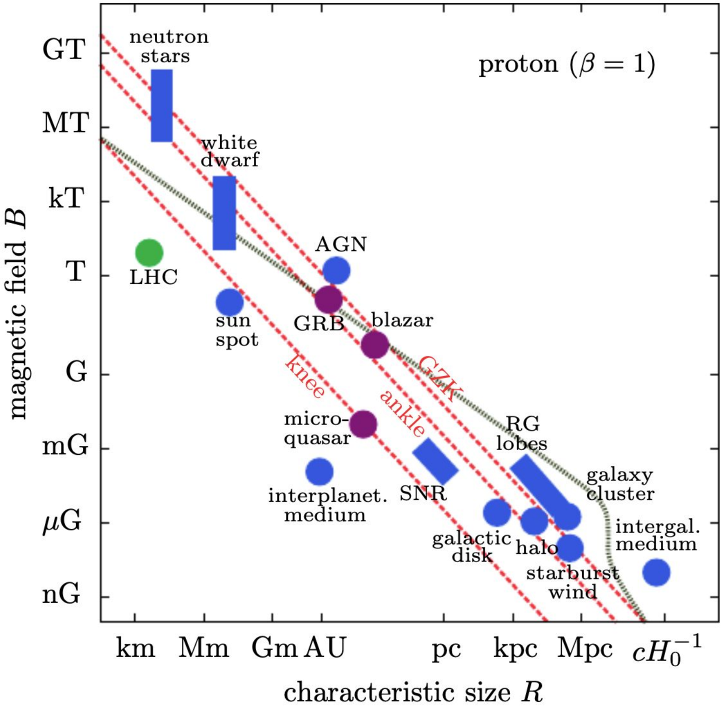
Regular call on Monday, 9 AM CT. Join channel, #nu-sources on slack. See additional administrative information, ongoing analyses: Nu-Sources Wiki. Join the email list: Subscribe to Nu-Sources.

Particle Acceleration in Sources

- Electrons (leptons), protons and charged nuclei (hadrons) exist within astrophysical sources
- Sources of radius (R) and magnetic field strength (B) accelerate charged particles
  - Sustained until escape or gyroradius becomes comparable to region size

$$r_{\text{gyro}} = \frac{\gamma m v_\perp}{|Ze|B} = \frac{\text{Rigidity}}{B}.$$

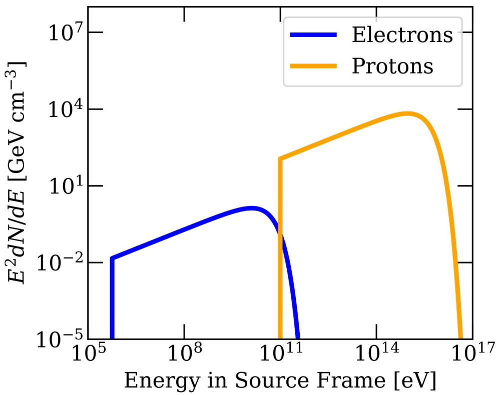
- High-energy neutrinos, photons and cosmic rays (CRs) tell us about the existence of these particle populations, their location, acceleration, variability and interactions… extreme source physics

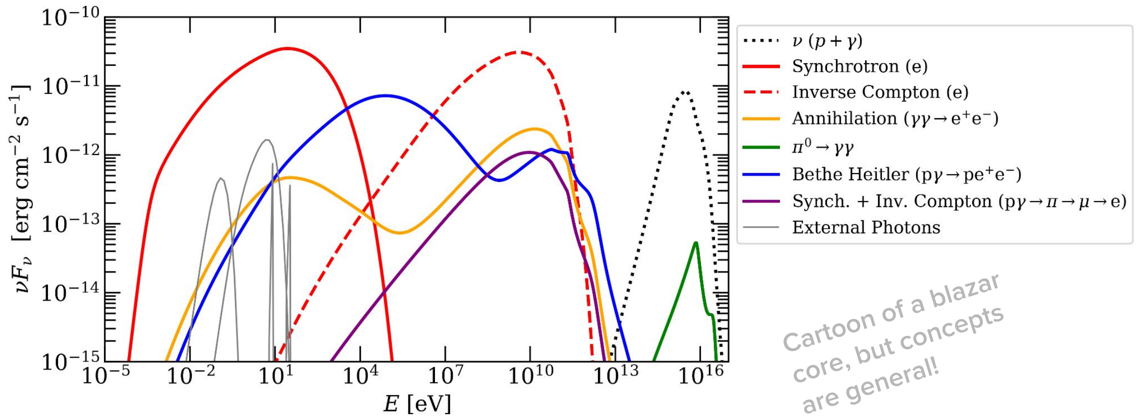


Neutrinos and Cosmic Rays Observed by IceCube: https://arxiv.org/pdf/1701.03731

Cartoon Broadband Energy Distribution

Produced with AM3 Simulation Code,
https://am3.readthedocs.io/en/latest/





Cartoon of a blazar core, but concepts are general!

Energy distributions of electrons and protons exist within a source region of some size and field strength

Electrons produce radiation in magnetic fields (synchrotron), and scatter photons to higher energies (inverse Compton)

Protons can also radiate and produce photons through interactions

Proton collisions can lead to neutrino production

Astrophysical Neutrino Production

- Two common Standard Model mechanisms for neutrino production:

$$p + p \to \pi^0 + \pi^+ + \pi^- + X.$$

$$\pi^+ \to \nu_\mu + \mu^+ \to \nu_\mu + e^+ + \nu_e + \overline{\nu}_\mu,$$
$$\pi^- \to \overline{\nu}_\mu + \mu^- \to \overline{\nu}_\mu + e^- + \overline{\nu}_e + \nu_\mu.$$

Neutrino flavor ratio at the source:

$$(\overline{\nu}_e : \overline{\nu}_\mu : \overline{\nu}_\tau) = (\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$$

Neutrino flavor ratio at Earth:

$$(0.30 : 0.36 : 0.34)$$

$$p + \gamma \to \Delta^+ \to \begin{cases} \pi^+ + n & 1/3 \text{ of time} \\ \pi^0 + p & 2/3 \text{ of time.} \end{cases}$$

Neutrino flavor ratio at the source:

$$(\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 0) \quad (\overline{\nu}_e : \overline{\nu}_\mu : \overline{\nu}_\tau) = (0 : 1 : 0)$$

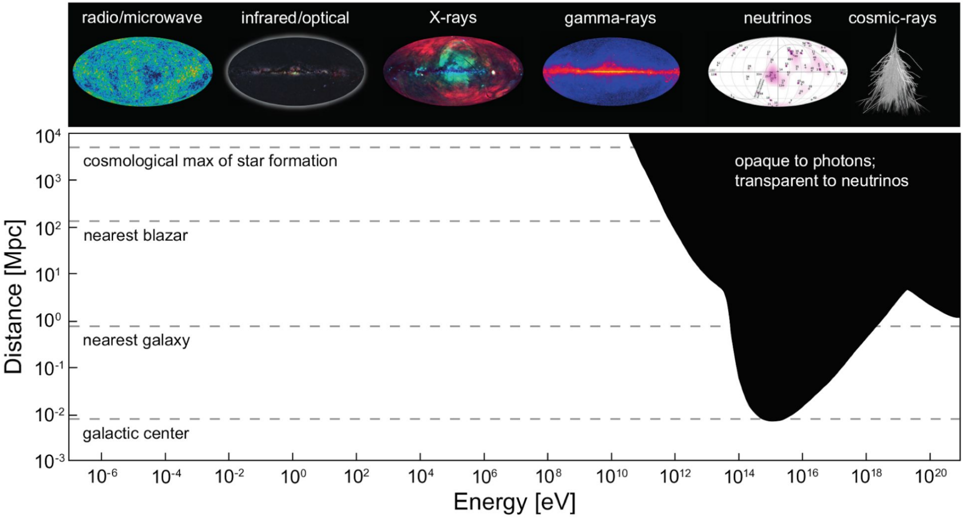
Neutrino flavor ratio at Earth:

$$(0.36 : 0.31 : 0.33)$$

- Both processes are accompanied by gamma-rays from pi-0 decay. pp is likely more relevant in regions with high proton densities. p-gamma is expected to contribute at high neutrino energies (100s of TeV) unless high-energy photons are abundant

Observing at High Energies

Plot credit: Marek Kowalski



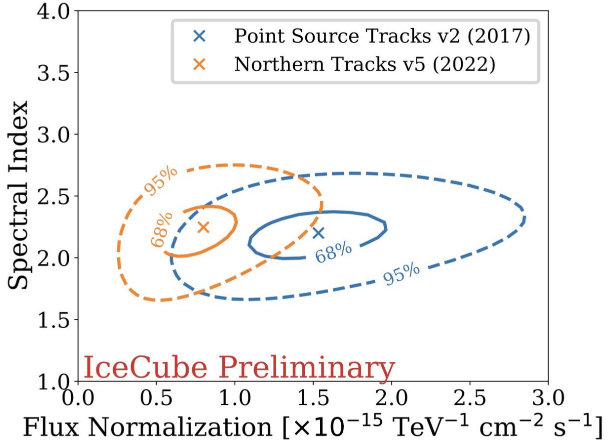
Neutrinos are the ideal messenger for sources in the distant universe beyond 10 TeV… and we are just now entering the discovery phase!

- Galactic magnetic fields deflect CRs (protons and nuclei), poor angular resolution, low statistics
- High-energy gamma rays and neutrinos observed with better directionality
  - Neutrinos indicate protons/hadronic processes
  - Gamma rays can indicate either hadronic/leptonic populations
- Gamma rays beyond 10 TeV attenuated

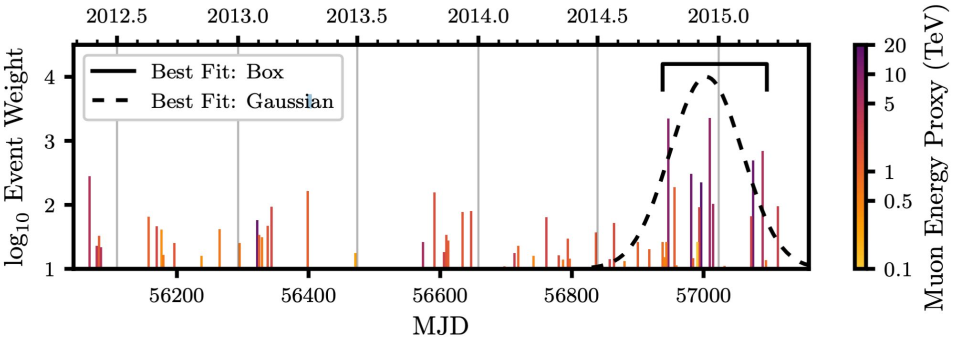
TXS 0506+056 – First Extragalactic Nu Source

- ~300 TeV muon neutrino from blazar, TXS 0506+056 (2017). An Active Galactic Nucleus (AGN) with jet pointed towards Earth
  - 6-month accompanying gamma-ray flare
- Archival search reveals 5-month neutrino flare (September 2014–)
  - No associated gamma-ray flare
- ***A time-variable, blazar AGN. Our high-energy neutrino source class?***
- Smaller excesses from BL Lacs PKS 1424+240, GB6 J1542+6129

TXS 0506+056 with Updated IceCube Data: https://arxiv.org/pdf/2307.14559



A measurement of the neutrino spectrum intensity and shape. TXS 0506+056 is a 'hard' source – more neutrinos at higher energies. A smaller index is 'harder'



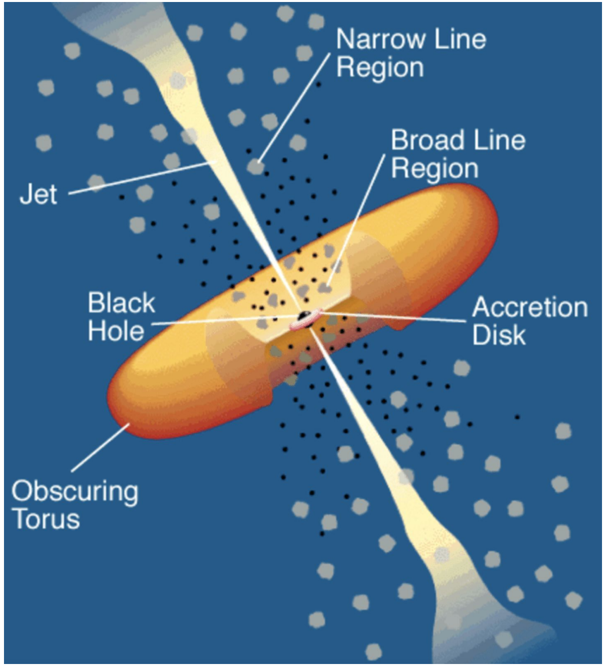
Neutrino Emission from the direction of the blazar TXS 0506+056...: https://arxiv.org/pdf/1807.08794

Blazars as a Source Class

- Active galactic nuclei are the variable regions around accreting black holes at the centers of galaxies
  - Blazars are a subset of AGN with jets pointed towards Earth. *Only 10% of AGN*
  - Jet emission is relativistically boosted ➔ bright sources in the distant universe

- Correlations with radio-bright and gamma-ray bright blazars suggest contribution < 10% of diffuse flux. The actual neutrino signal is not significant

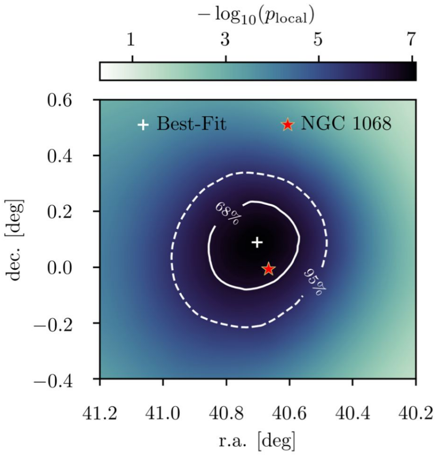
- Many open questions:
  - *How is material fed into the jet? How are particles accelerated? How and where are neutrinos produced along the jet? What is the accompanying multimessenger picture? How to construct a more sensitive neutrino search?*



Unified Schemes for Radio-Loud Active Galactic Nuclei (Urry and Padovani, 1995)

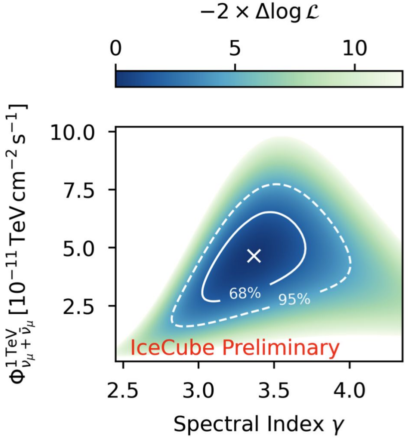
Seyfert, NGC 1068

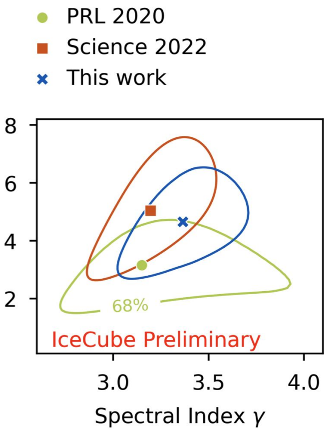
- In 2019, NGC 1068 was observed at 2.9σ significance. Improvements to calibration and detector systematic modeling brought the source to 4.2σ in 2021!
- NGC 1068 is a Seyfert galaxy, an AGN which is dominated by emission from the host galaxy. It features an X-ray bright corona (radiation and plasma around the accretion disk), and a dusty starforming region
- The neutrino spectrum is ‘soft’ corresponding to more low-energy events



Spatial excess around NGC 1068

Evidence for Neutrino... NGC 1068, https://arxiv.org/abs/2211.09972



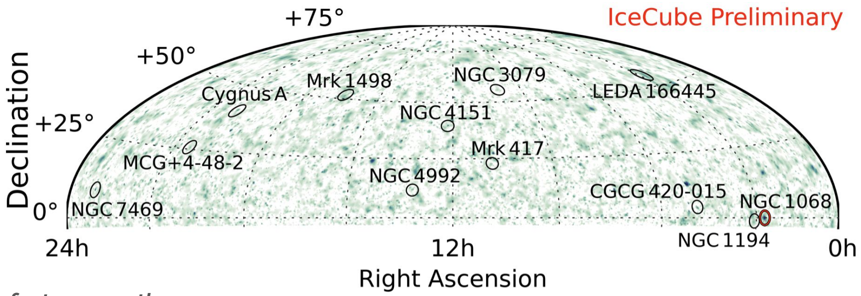


Shape and intensity of neutrino energy spectrum

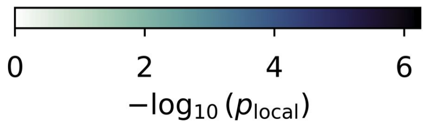
Recent ‘Improved PS-Tracks’ analysis result

Seyferts as a Source Class

- Seyferts are AGN characterized by relatively bright host galaxies
    - Seyferts are the most common class of AGN. *10% of all galaxies*
    - While they feature actively accreting black holes, potential jets are misaligned with Earth. Bright jets are not regularly observed
    - Seyferts are abundant in the local universe
- Seyfert galaxies appear to be emerging as a neutrino source class responsible for a large fraction of the diffuse flux
    - ~3σ excess associated with Seyfert and X-ray bright AGN populations
    - Evidence for emission in both southern and northern hemispheres



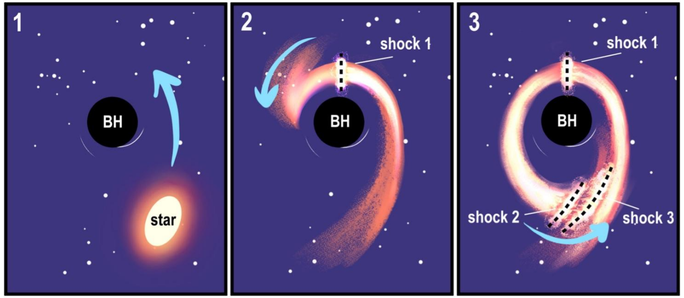
Seyferts recently found to contribute in the North, see 'Improved PS-Tracks' analysis



Is neutrino production driven by coronae around the disk? What do our observations tell us about the corona environment? Are Seyfert neutrino sources variable? Do the jet or starforming regions play a role?

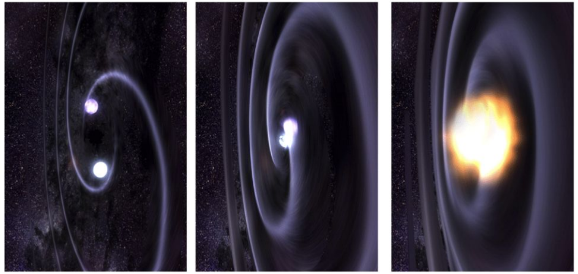
Transient Extragalactic Sources

- Other potential extragalactic sources include classes of transient events:
  - **Tidal Disruption Events (TDEs):** The bound mass of a star is disrupted when passing near the strong gravitational gradient of a supermassive black hole
  - **Gamma-ray Bursts (GRBs):** A massive output of radiative energy, likely linked to the supernovae of massive stars or mergers
  - **Events linked to Gravitational Waves:** The rapid mergers of black hole (BH) + BH, neutron star (NS) + BH or NS + NS, and massive supernovae
- More evidence is needed for these source classes. *How can we construct more sensitive searches? What can our measurements (or upper limits) tell us about the environments of these extreme source regions?*



Cartoon of TDE

Credit: Jenni Jormanainen



Credit: NASA

Cartoon of merger event

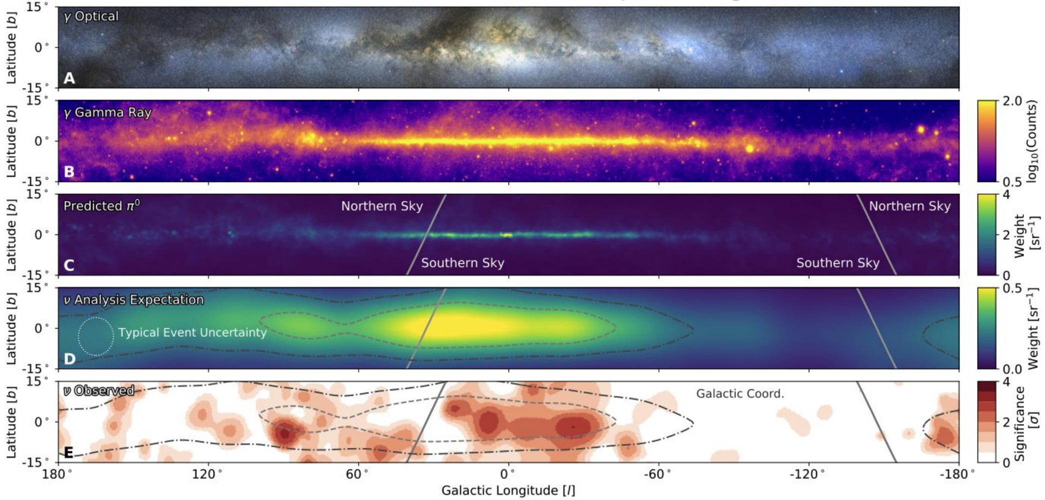
Neutrinos from the Galactic Plane

- In 2022, a correlation between a template of diffuse galactic gamma-rays and neutrinos was observed at 4.5σ

- A *diffuse* galactic neutrino emission is expected from cosmic-ray interactions on gas within the galaxy

- Galactic point sources may also contribute to this excess:
  - X-ray binaries
  - Supernova remnants
  - Pulsar wind nebulae
  - Dense, gaseous regions
  - Magnetars...

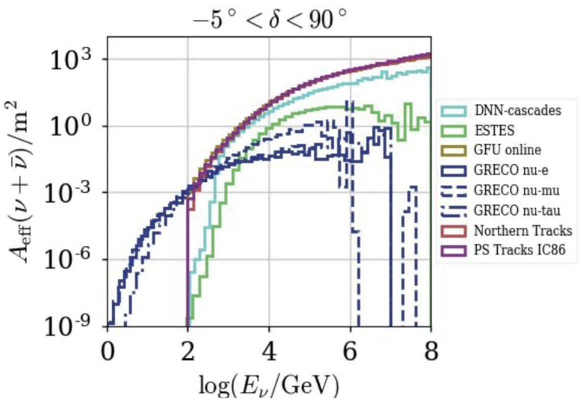
Observation of... Galactic Plane, https://arxiv.org/abs/2307.04427



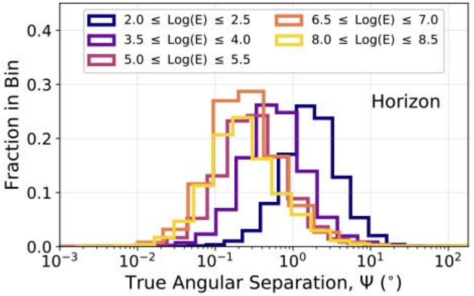
What is the proper model for diffuse, galactic emission? What classes of galactic sources may also contribute? How can we become sensitive to such sources in the north and south? What can we learn about the physics of these source environments?

Technical Considerations

- IceCube searches are limited by:
  - Dominating rate of atmospheric background relative to astrophysical signal
  - Uncertainties related to our detection technique and reconstruction
  - Theoretical predictions are not perfect, and develop in step with observation
- While we are still building evidence in favor of source populations, analyzers should:
  - Consider the impact of selection purity and size, and how to improve
  - Consider observables (direction, energy, time, flavor)
  - Possibly investigate theory to develop informed, maximally sensitive models



The 'effective area' of different selections, the effective face of IceCube to be totally efficient in neutrino detection



Angular resolution – directional uncertainty for reconstructed interactions in PS Tracks

IceCube Data... 2008-2018:https://arxiv.org/pdf/2101.09836

Roadmap of a Nu-Sources Analysis

- Present initial analysis topic on nu-sources call
  - An analysis idea that answers a new question or builds on existing knowledge
- Present status updates on nu-sources call. When analysis concept is finalized, a working group reviewer may be requested
  - Should 'characterize' analysis prior to this stage, sensitivities, signal recovery, overlap with previous works, etc
  - Iterate with working group reviewer to answer questions. Present relevant changes or discussion
- When working group reviewer is satisfied, a collaboration-level reviewer is requested
  - Iterate with both reviewers to finalize analysis details and unblinding plan
- When analysis is near unblinding (perform on real data) contact the nu-sources tech lead to initiate a software reproducibility review
  - Iterate with your software reviewer so proper checks are performed
- Request unblinding from the working group, then on the analysis call
  - Two-week period for collaboration feedback
- Unblind your analysis and present results at the working group and collaboration levels (analysis call)
- Check out the official guideline document: Working Group Procedures
- *Good luck! And always feel comfortable reaching out directly to leads or tech leads for help along the way!*