Multi-Messenger Observations

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Journée P2I, Orsay
27 November, 2024

Illustration by Sandbox Studio, Chicago with Abigail Malate

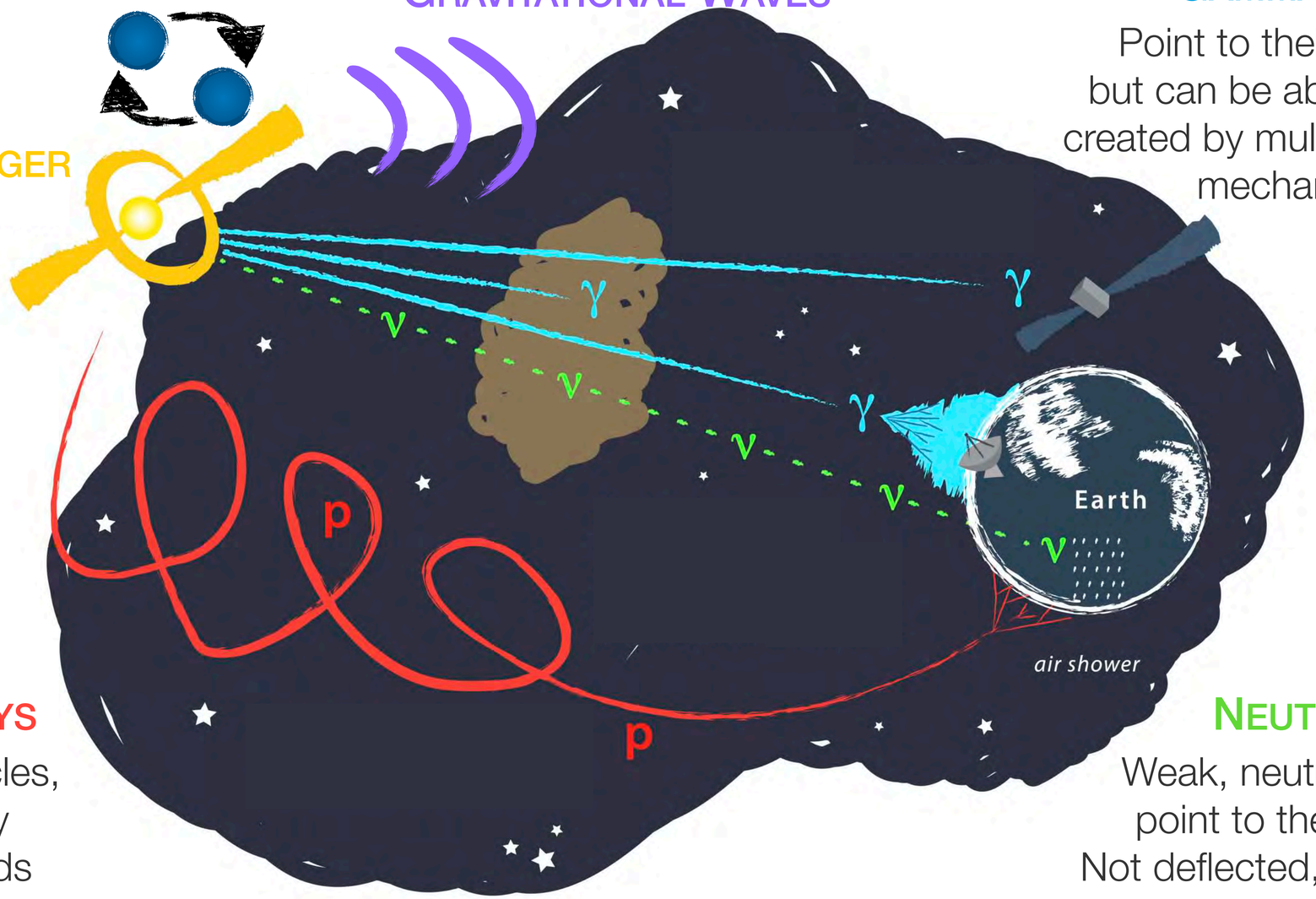
Multi-messenger astrophysics

Gravitational Waves

Gamma Rays

Point to their sources,
but can be absorbed and
created by multiple emission
mechanisms

Multi-messenger source



Cosmic Rays

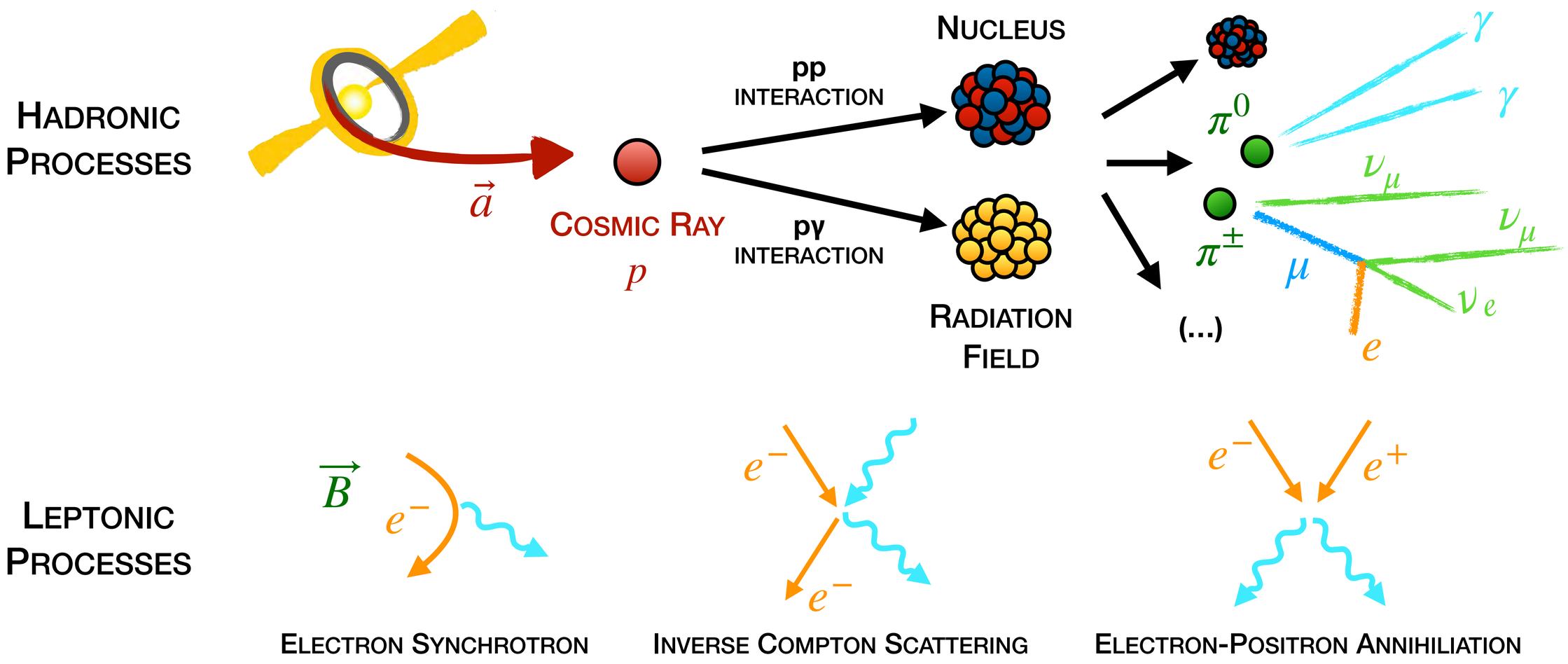
Charged particles,
deflected by
magnetic fields

Neutrinos

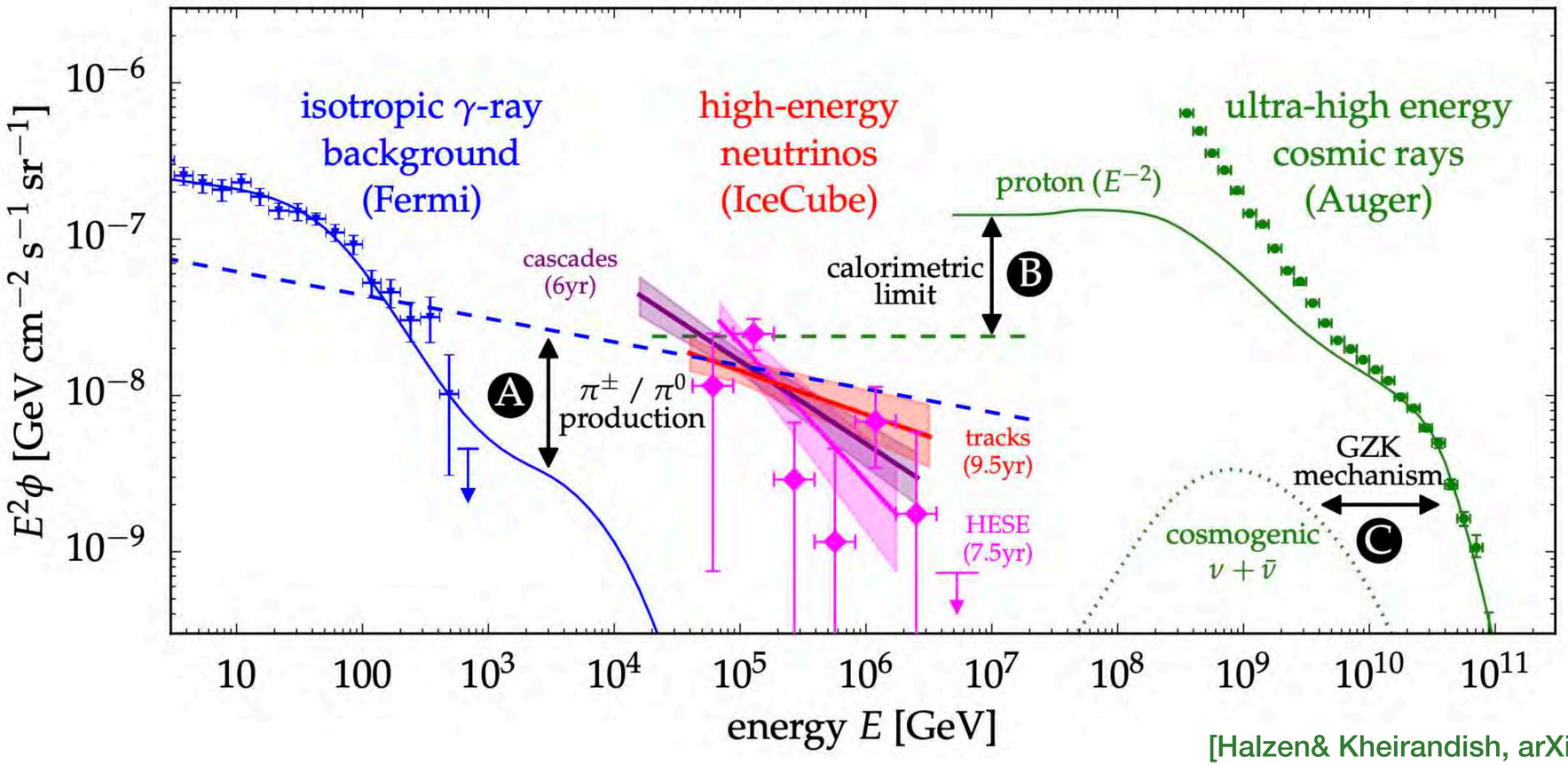
Weak, neutral particles,
point to their sources,
Not deflected, not absorbed

Multi-messenger accelerators

Neutrinos are smoking gun signature of hadronic processes



Multi-messenger interfaces

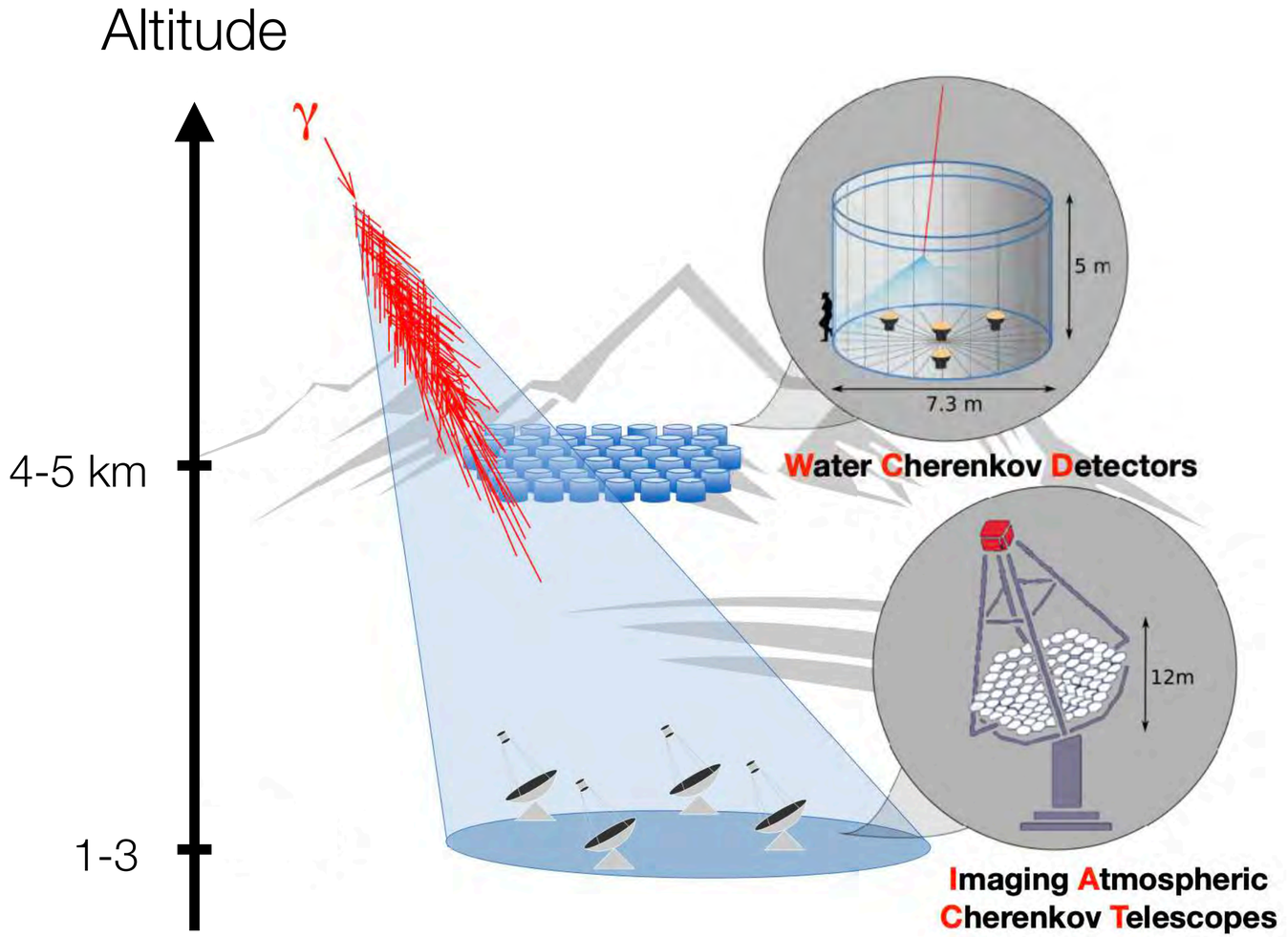


[Halzen& Kheirandish, arXiv/2202.00694]

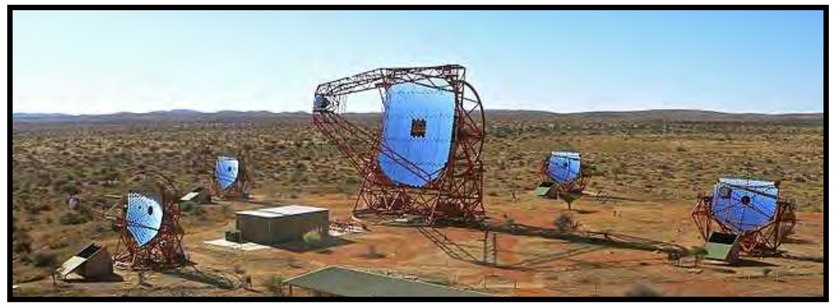
The high intensity of the neutrino flux compared to that of γ-rays and CRs offers many interesting multi-messenger interfaces

Multi-messenger observatories

High-energy gamma-rays



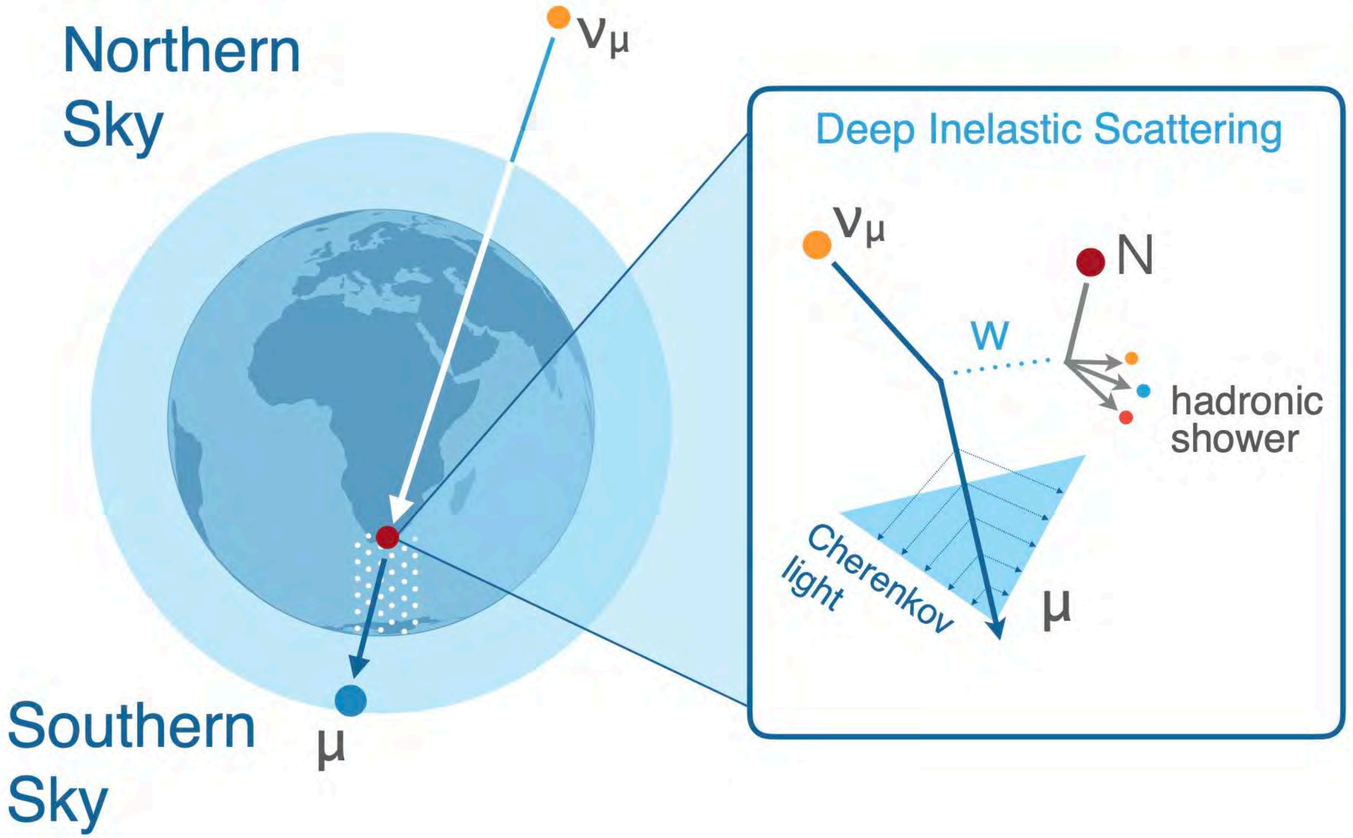
LHASSO (2021)
Daocheng, China (4410 m)

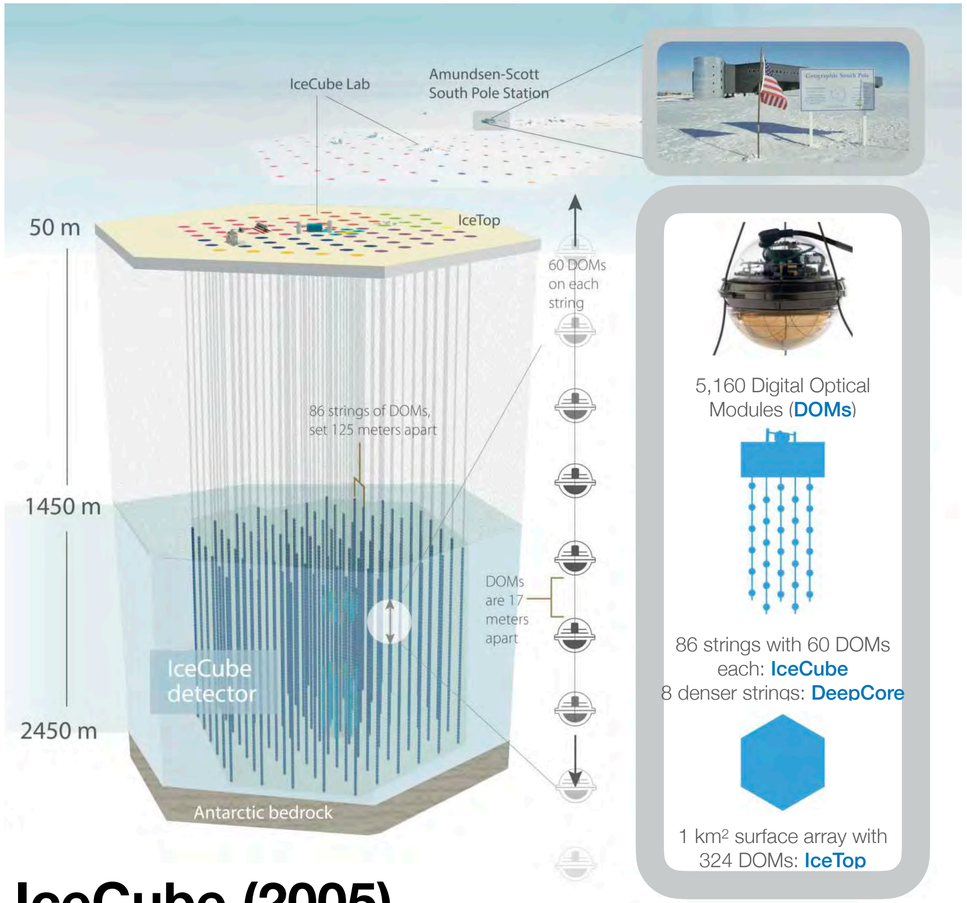


H.E.S.S. (2002)
Khomas Highland, Namibia

Multi-messenger observatories

High-energy neutrinos

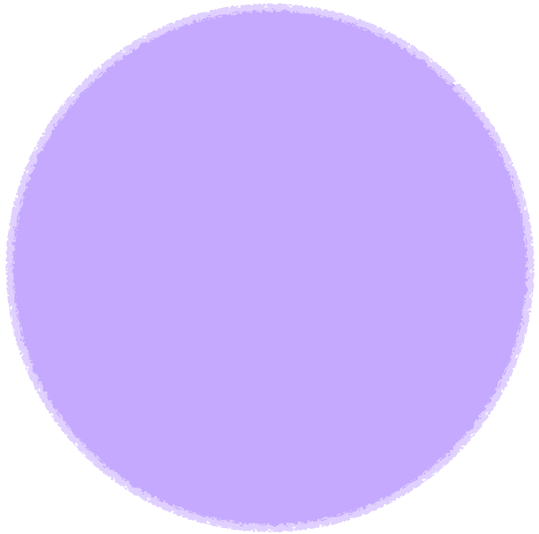




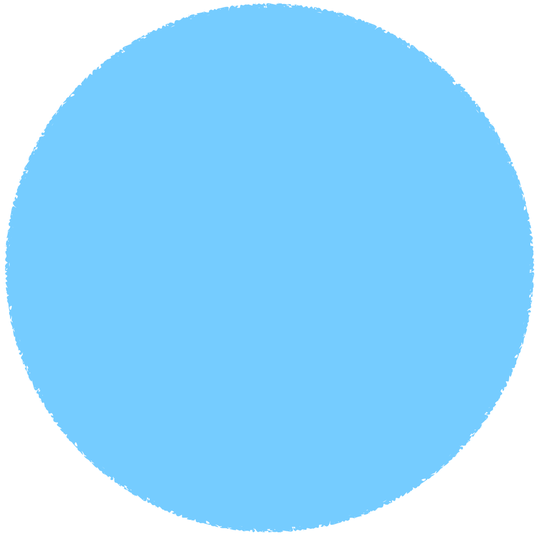
IceCube (2005)
Amundsen-Scott South Pole Station

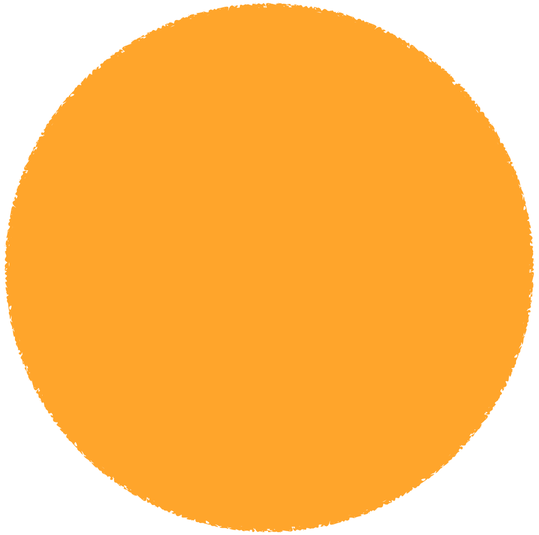
Multi-messenger observations

Gravitational Waves Observations



EM Observations (Radio → γ-ray)



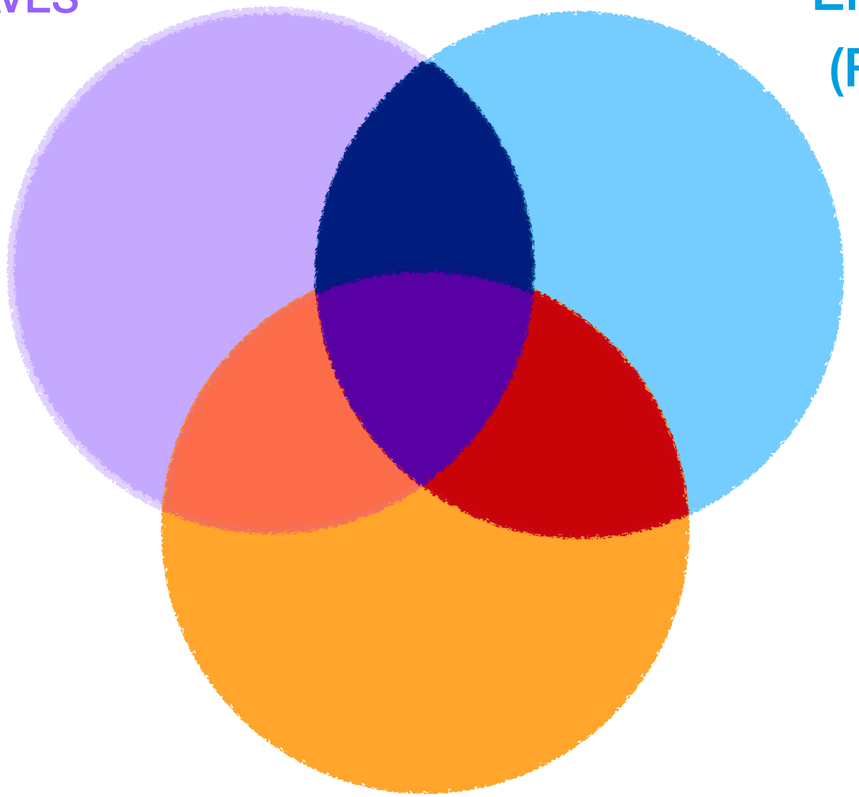


Neutrinos & Cosmic Rays Observations

Multi-messenger observations

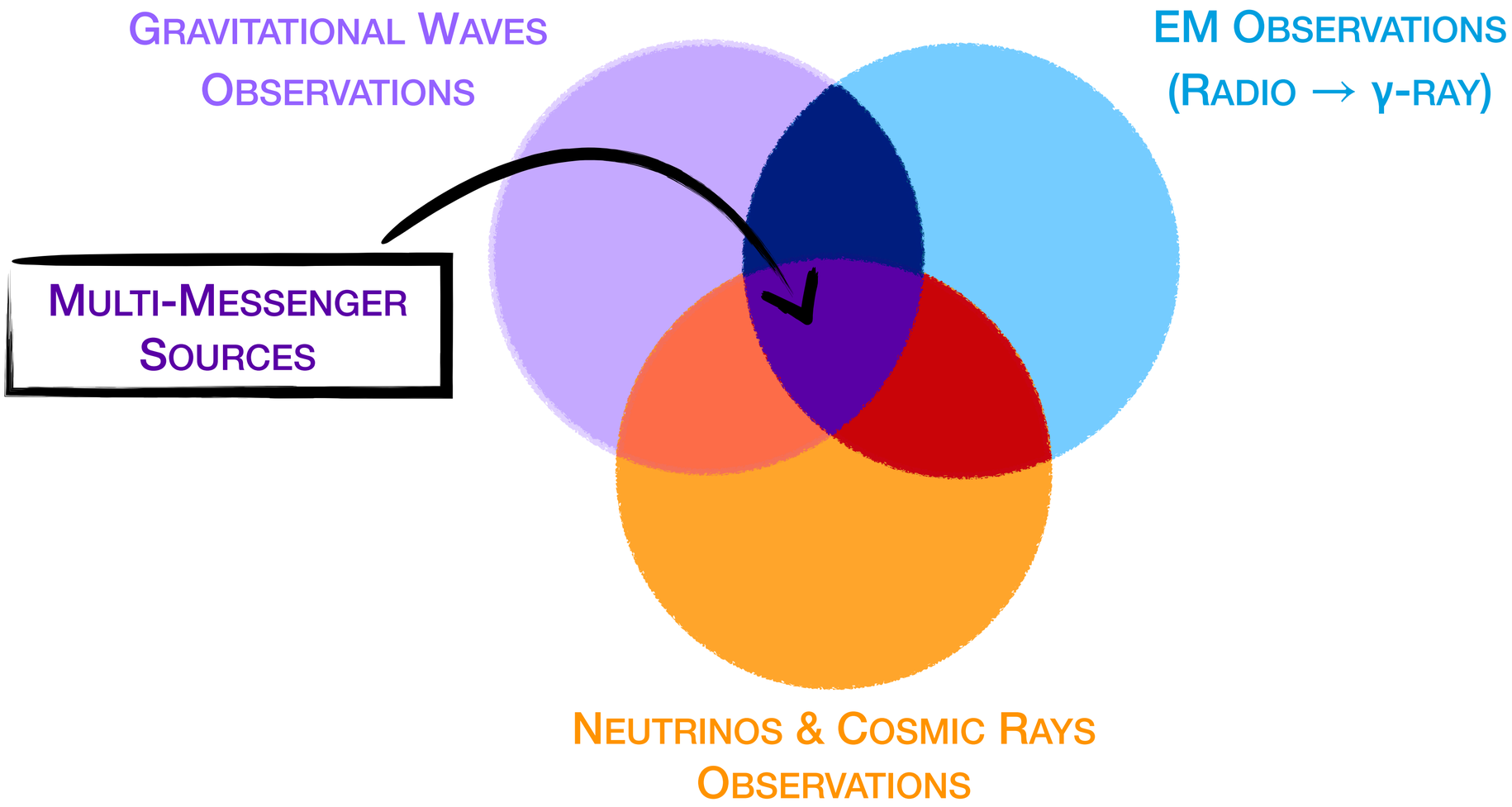
Gravitational Waves Observations

EM Observations (Radio → γ-ray)

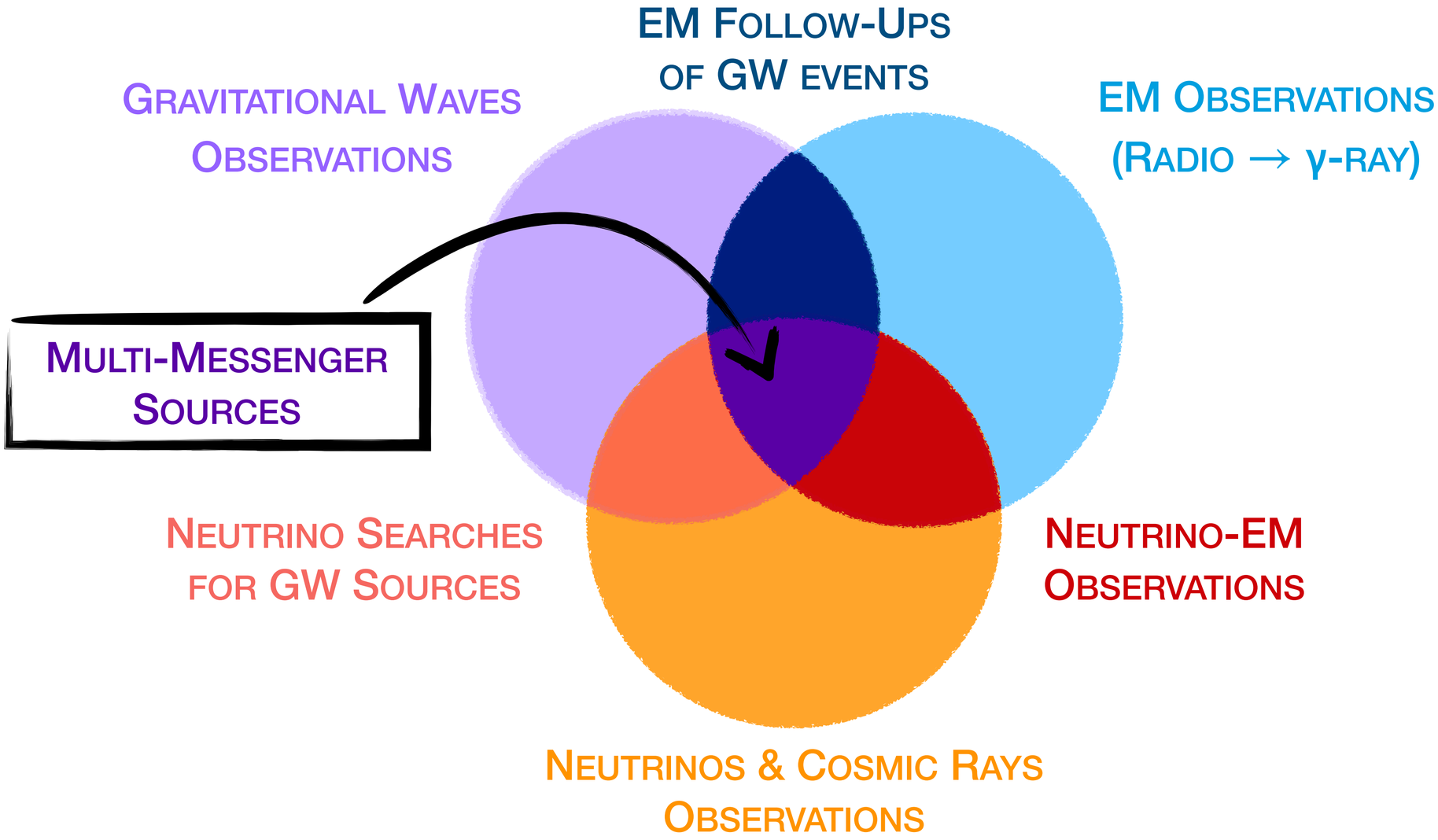


Neutrinos & Cosmic Rays Observations

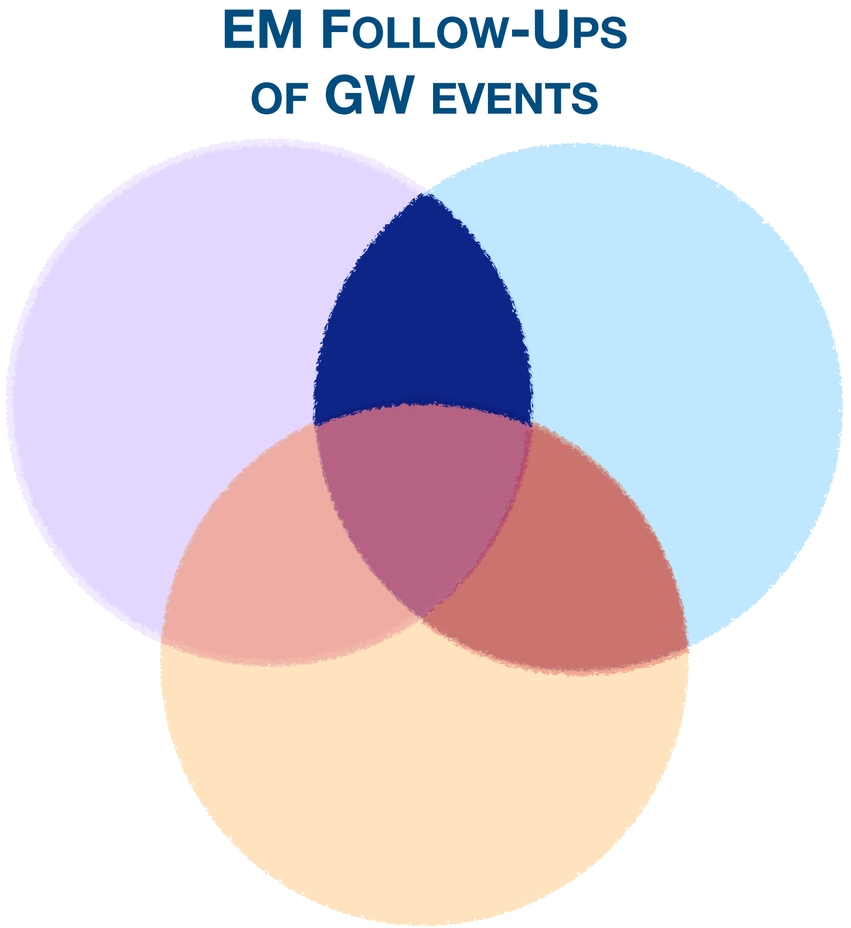
Multi-messenger observations



Multi-messenger observations

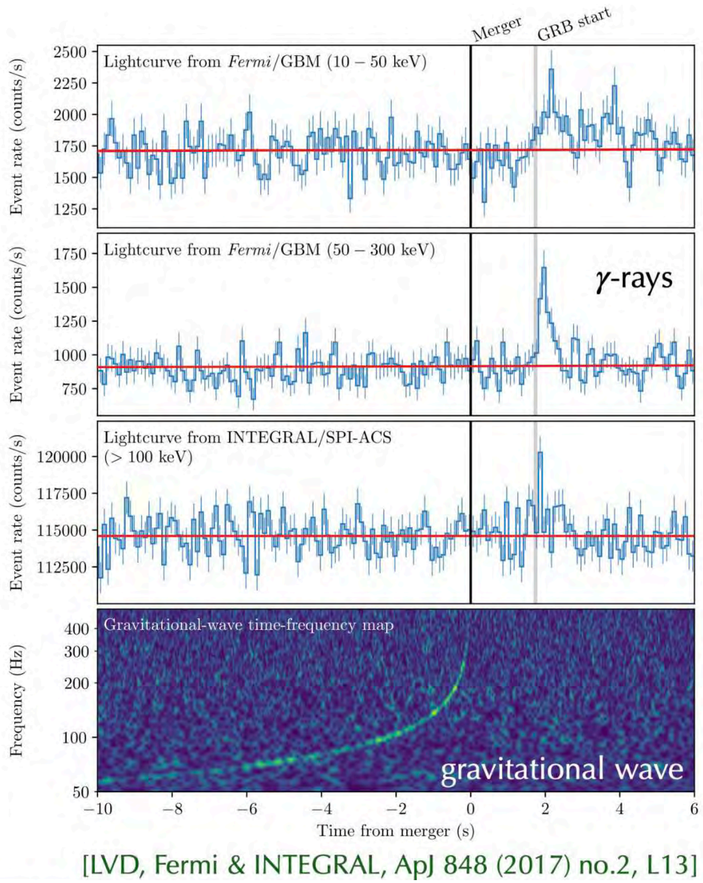


Multi-messenger observations

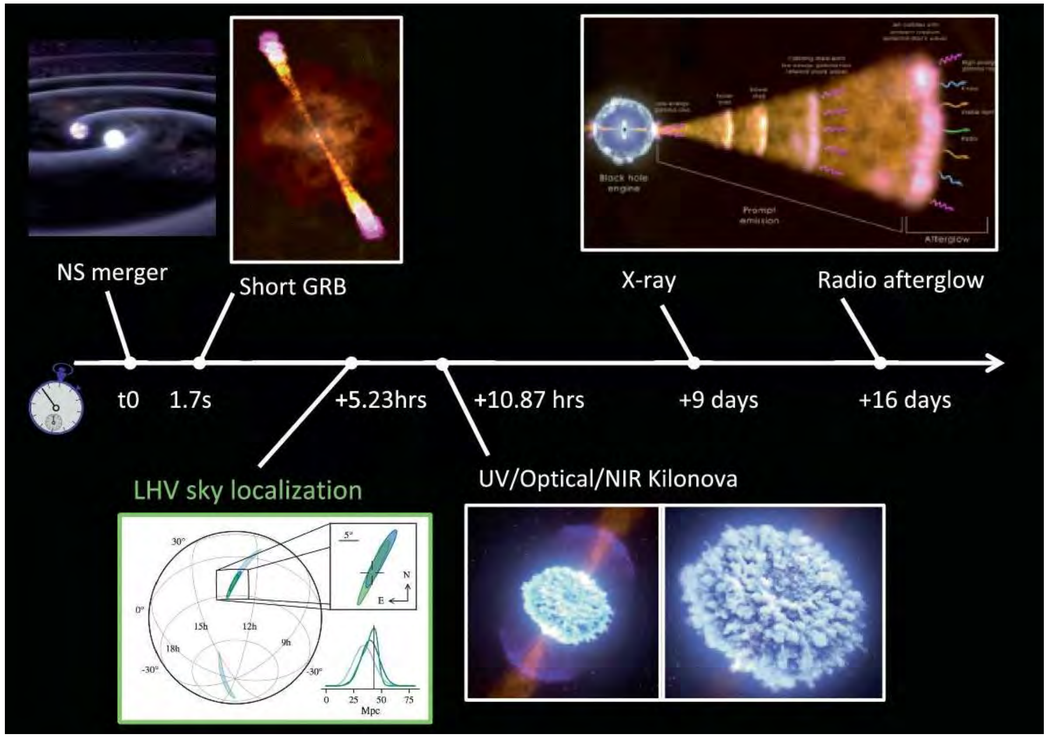


GW 170817 + GRB 170817A

The dawn of multi-messenger astrophysics



[LVD, Fermi & INTEGRAL, ApJ 848 (2017) no.2, L13]



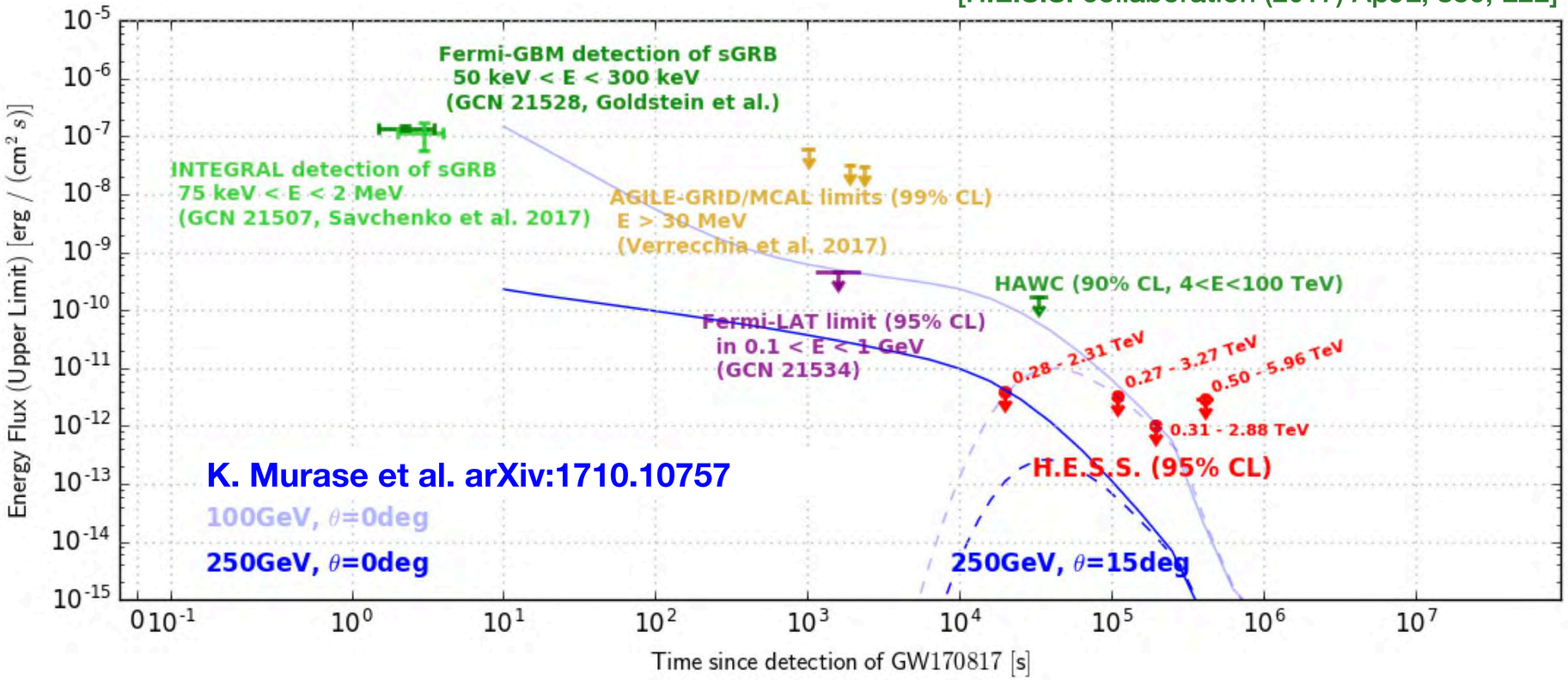
[M. Branchesi, (2023) Springer Proceedings in Physics, vol 287]

MM and MW observations provided the first observational evidence that binary neutron-star mergers power short GRBs

GW 170817 + GRB 170817A

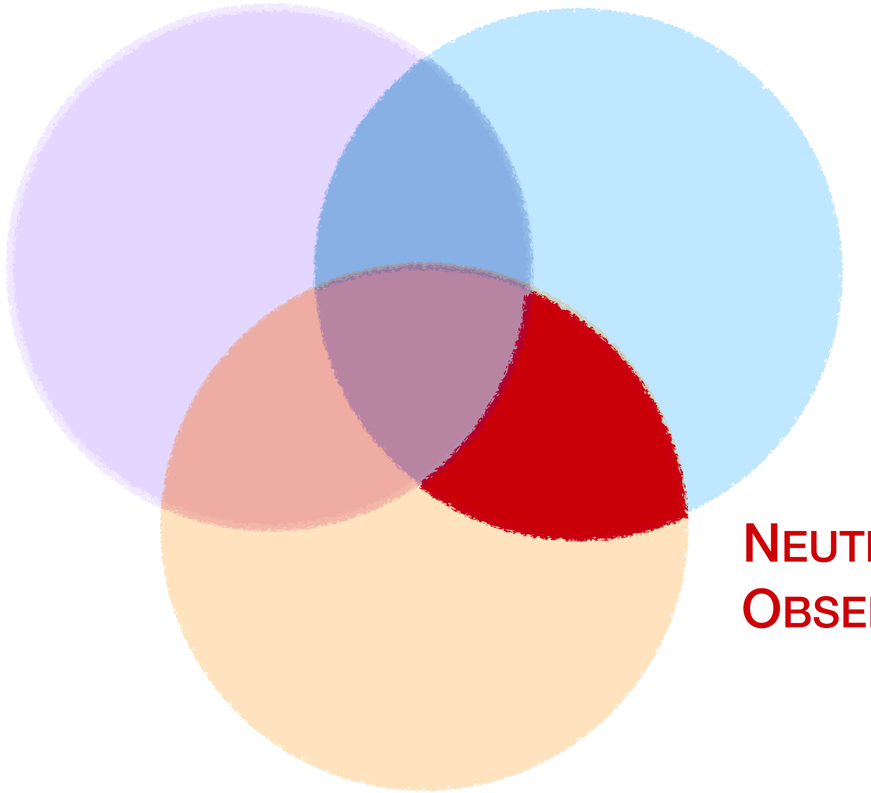
The dawn of multi-messenger astrophysics

[H.E.S.S. collaboration (2017) ApJL, 850, L22]



Multi-wavelength and multi-messenger follow-ups helped putting first constrains on VHE emission from BNS mergers

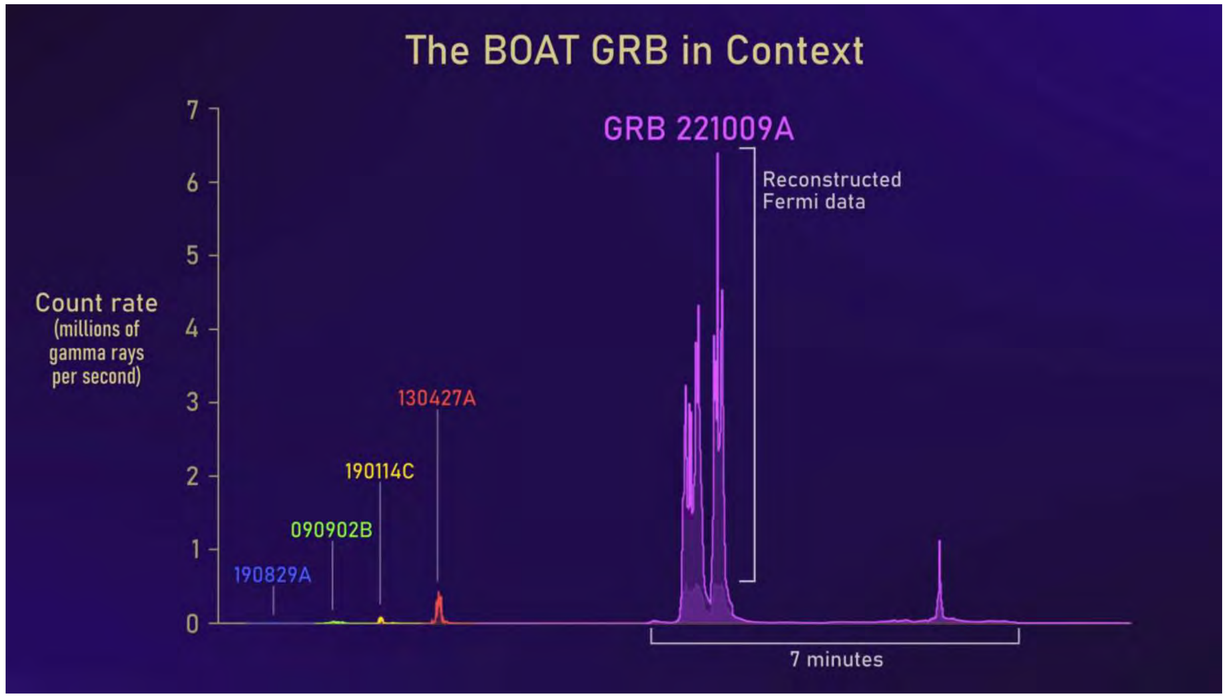
Multi-messenger observations



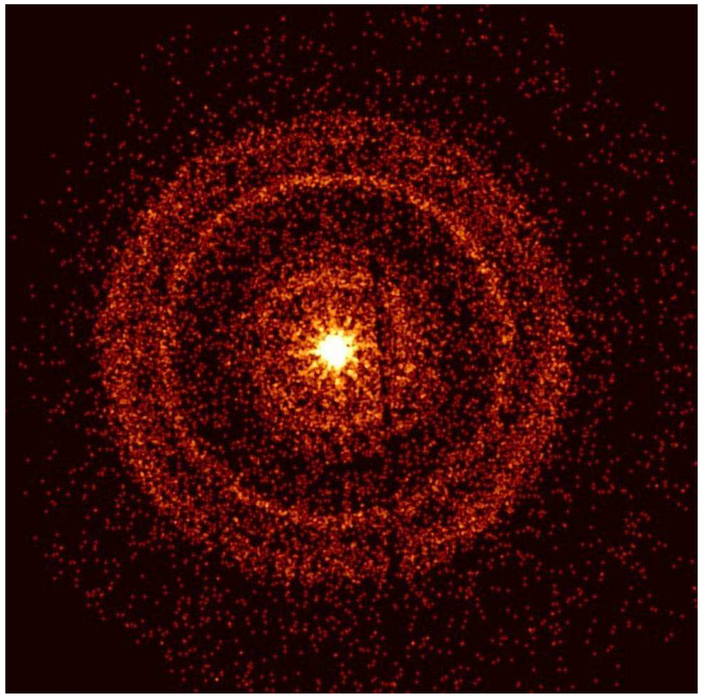
NEUTRINO-EM OBSERVATIONS

GRB 221009A

The Brightest Of All Time (B.O.A.T.)



Credit: NASA's Goddard Space Flight Center and Adam Goldstein (USRA)



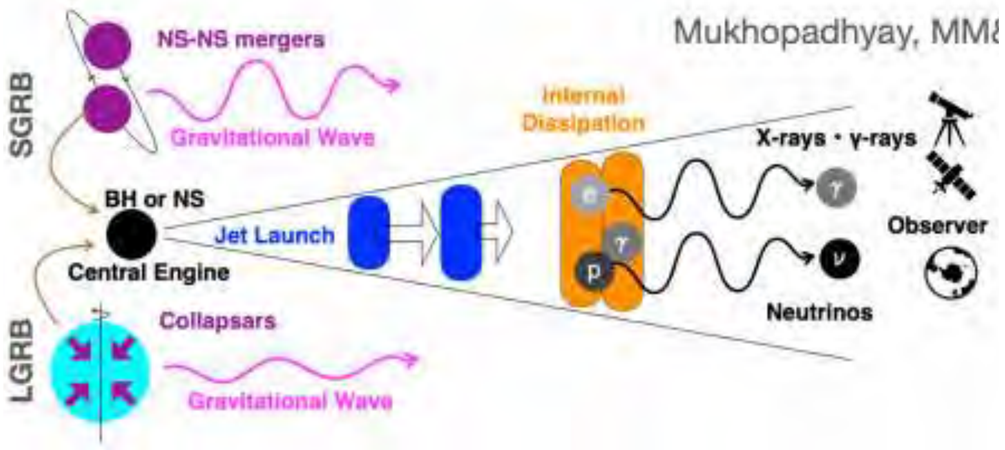
[A. Tiengo et al, (2023) ApJL **946** L30]

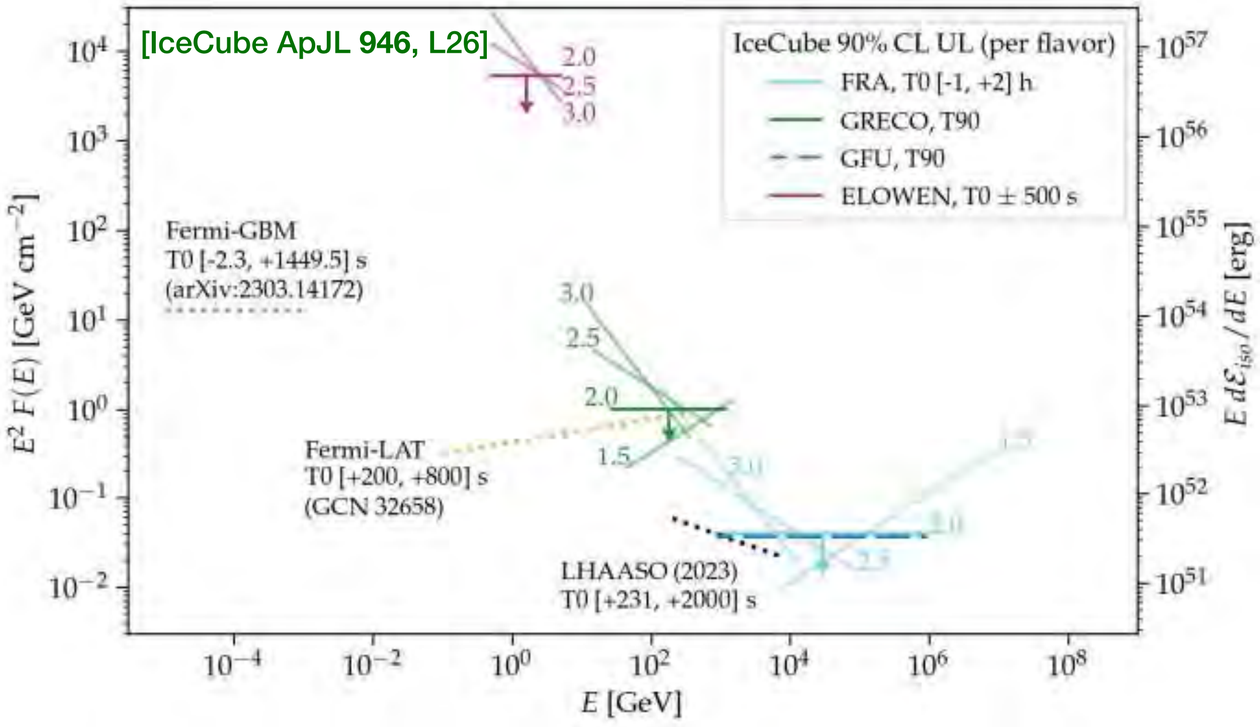
Brightest GRB first observed
by Fermi-GBM and Fermi-LAT up to ~400 GeV:
isotropic equivalent gamma-ray energy ~$1.2 \cdot 10^{55}$ erg

Afterglow reported by Swift as a bright
X-ray and optical transient near the
plane of the Milky Way

GRB 221009A

MM observations during prompt phase: neutrinos



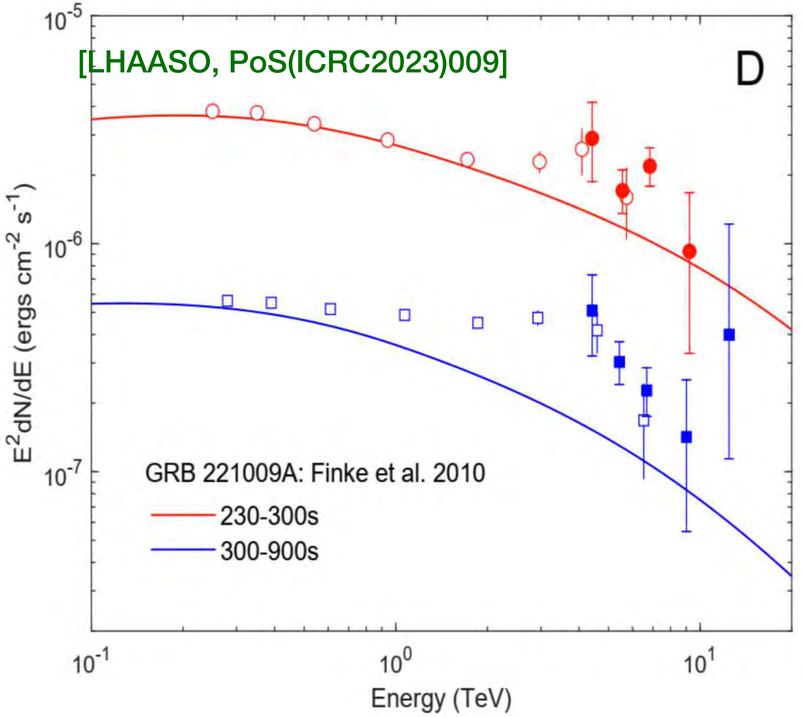


v emission is expected in the prompt phase: initial jet launch can accelerate protons and interaction with matter can create HE neutrinos

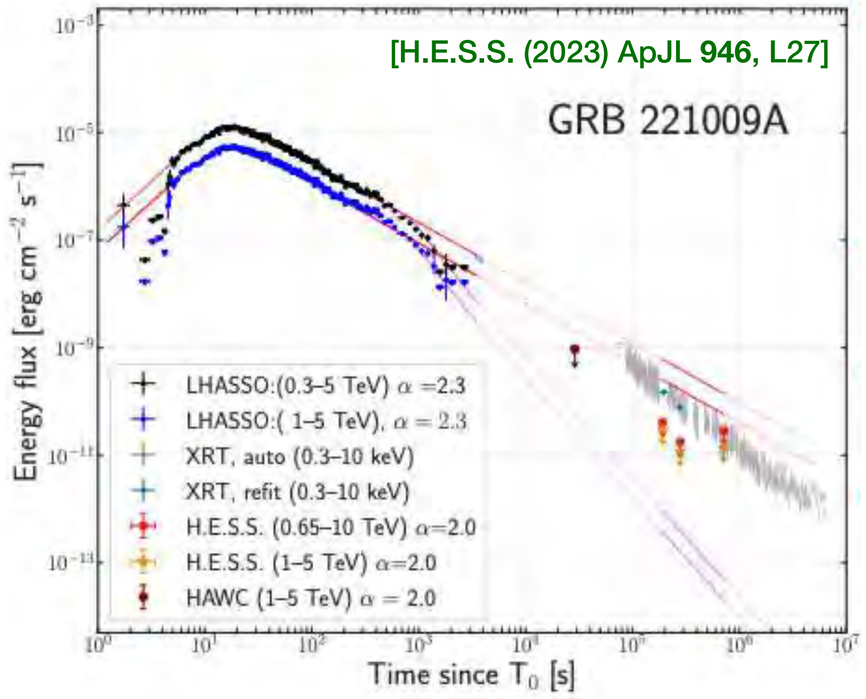
No neutrino detection in MeV-PeV but for the first time theoretical prediction are below IceCube sensitivity → constraints on hadronic emission

GRB 221009A

MM observations during afterglow: high-energy gamma-rays



Detected by LHAASO within 3000s:
over 64,000 γ with energies up to 13 TeV

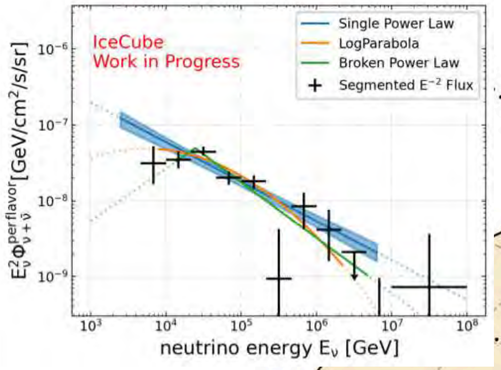


No IACTs detection: H.E.S.S. ULs can constrain
the slow decay of the LHAASO observation

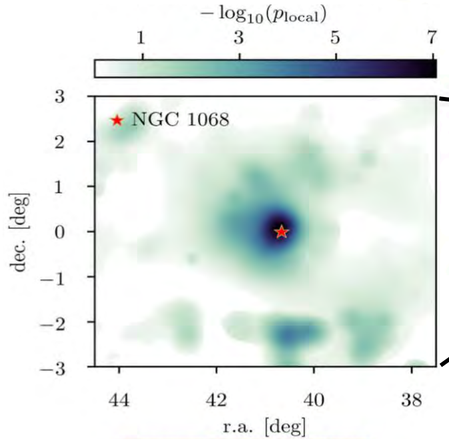
Spectrum consistent with a power law and a SSC model in GeV-TeV range, but spectral steepening in SSC emission > 3 TeV → a new component may be needed

The IceCube high energy neutrino sky

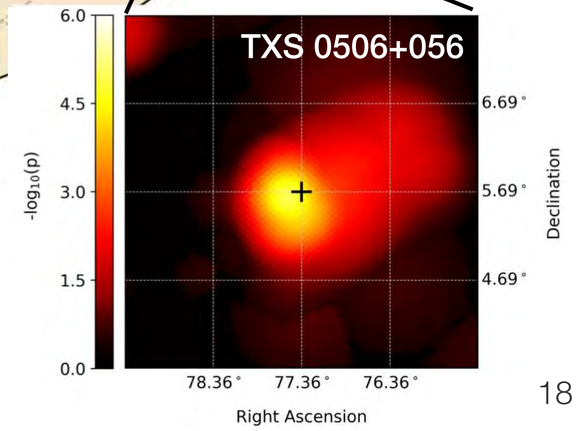
[IceCube, PoS-ICRC2023-1064]



[IceCube (2022) Science **378**, 6619, 538-543]



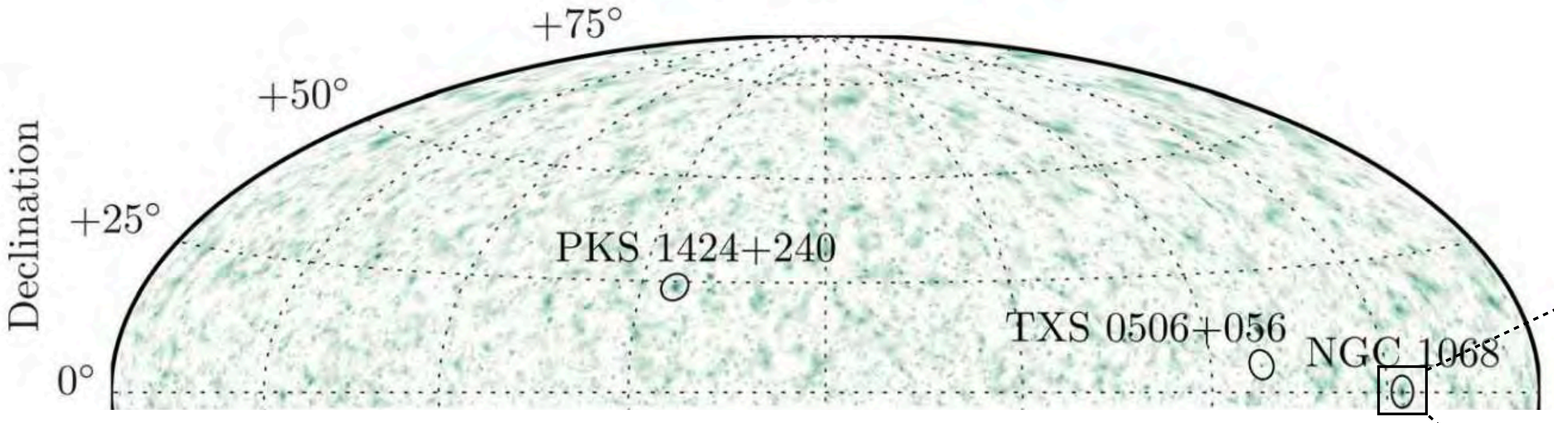
[IceCube (2023) Science **380**, 6652, 1338-1343]

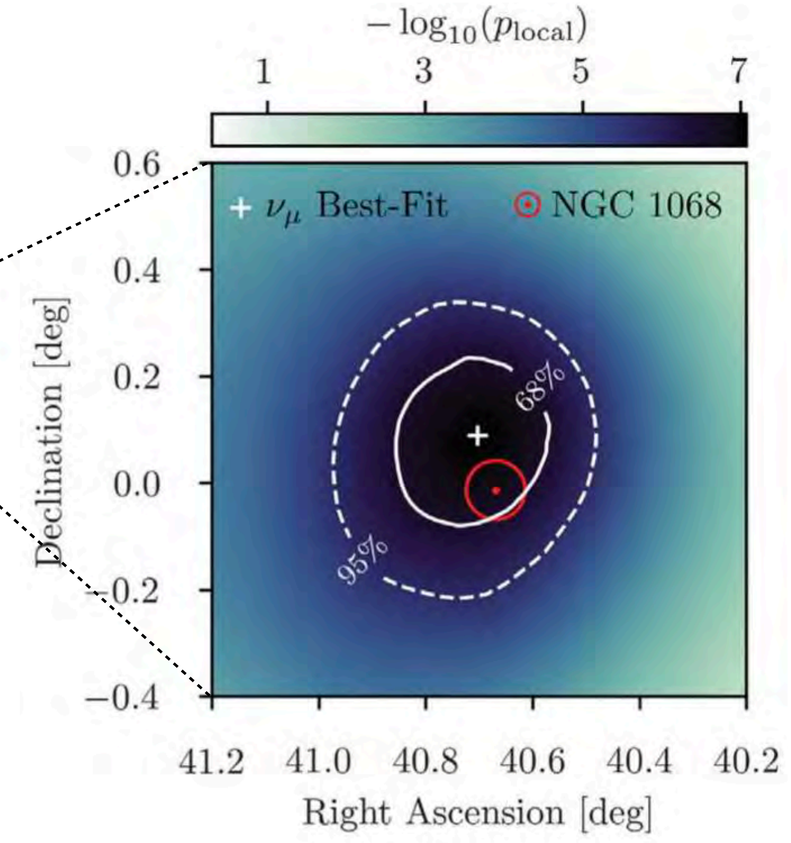


[IceCube (2018) Science **361**, 6398]

NGC 1068

Neutrino excess in 8 years of IceCube data by performing a Northern-sky search for point sources



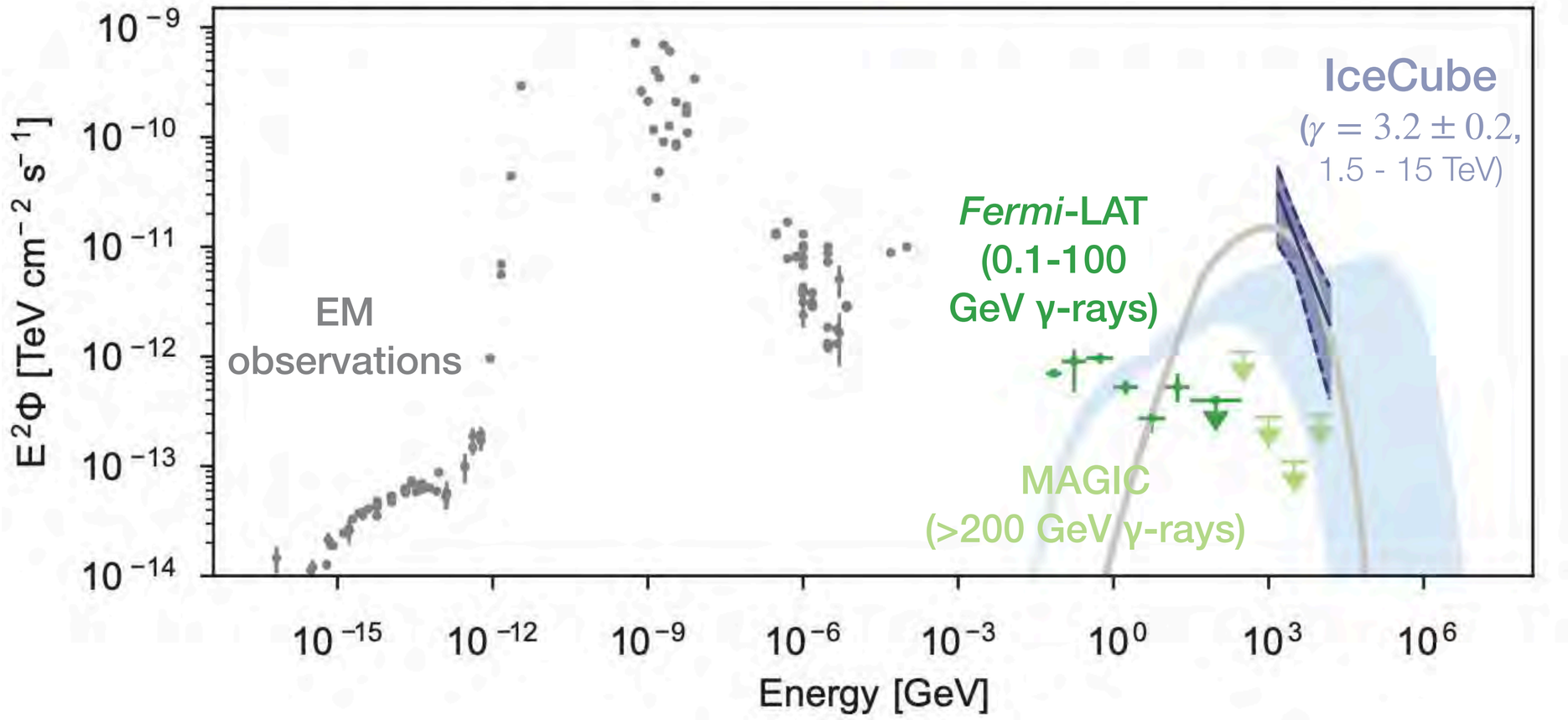


Northern hot spot in the vicinity of Seyfert II galaxy **NGC 1068** with significance of **4.2σ** (trial-corrected for 110 sources)

[IceCube, Science 378, 538-543 (2022)]

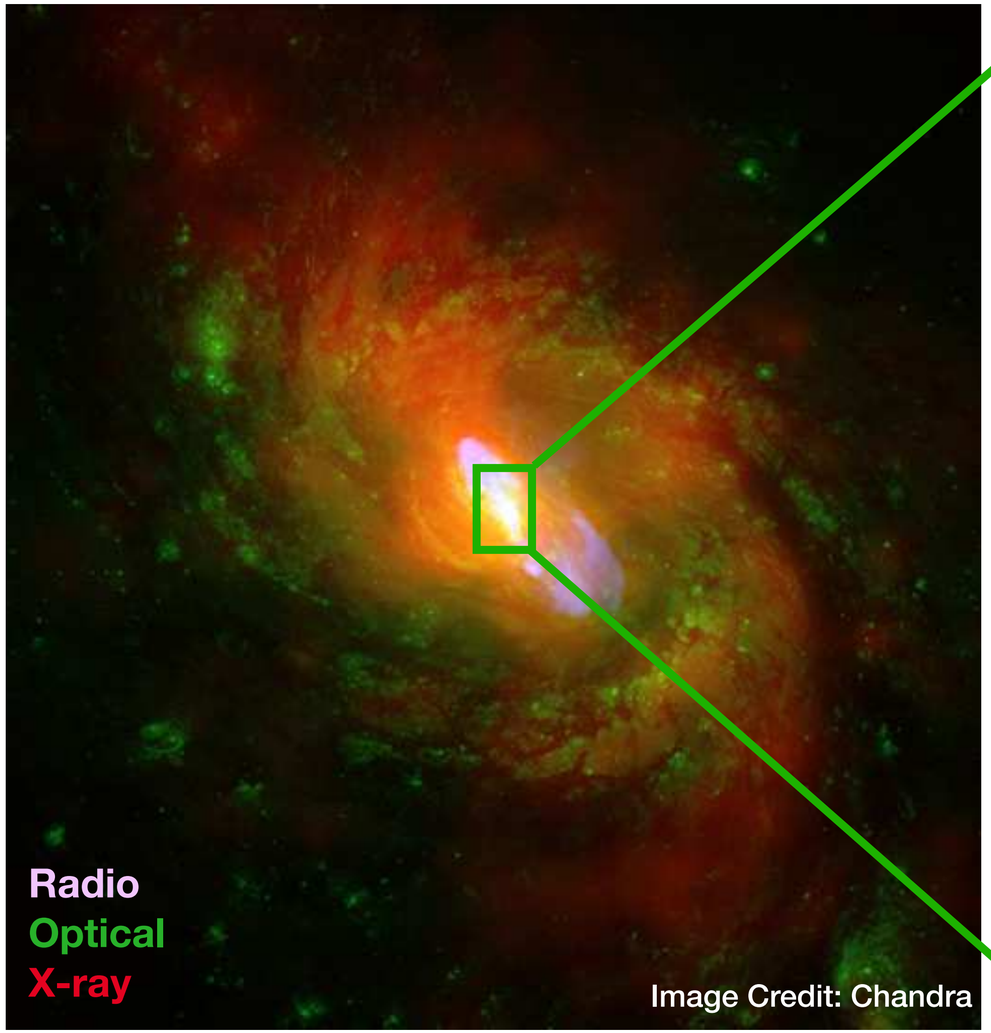
NGC 1068's obscured core

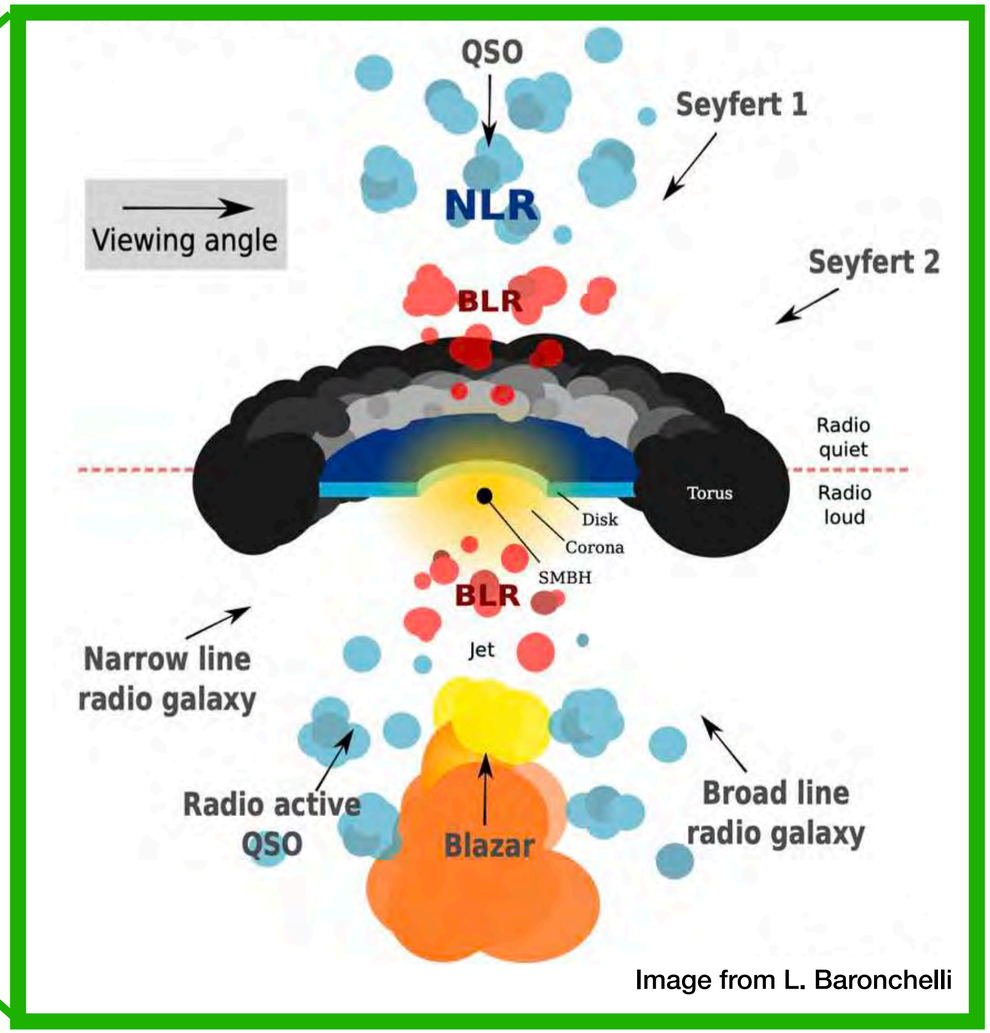
Measured neutrino flux exceeds TeV gamma-ray upper limits



[IceCube, Science **378**, 538-543 (2022)]

AGN cores as neutrino sources

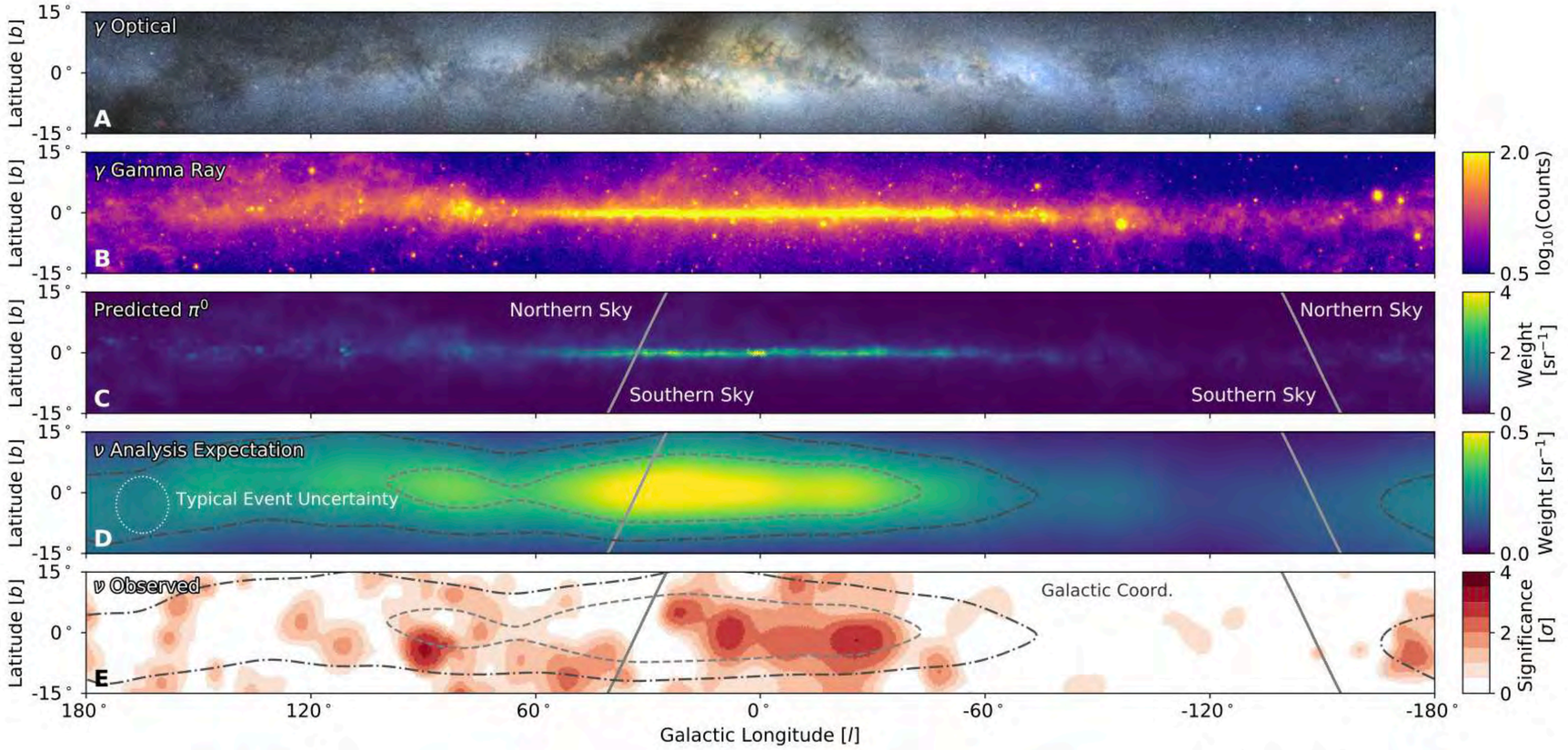




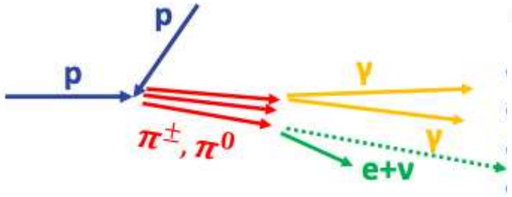
ν produced in γ-ray obscured environment (AGN corona model)

Galactic Plane

The multi-messenger view of our own Galaxy



[IceCube (2023) Science **380**, 6652, 1338-1343]

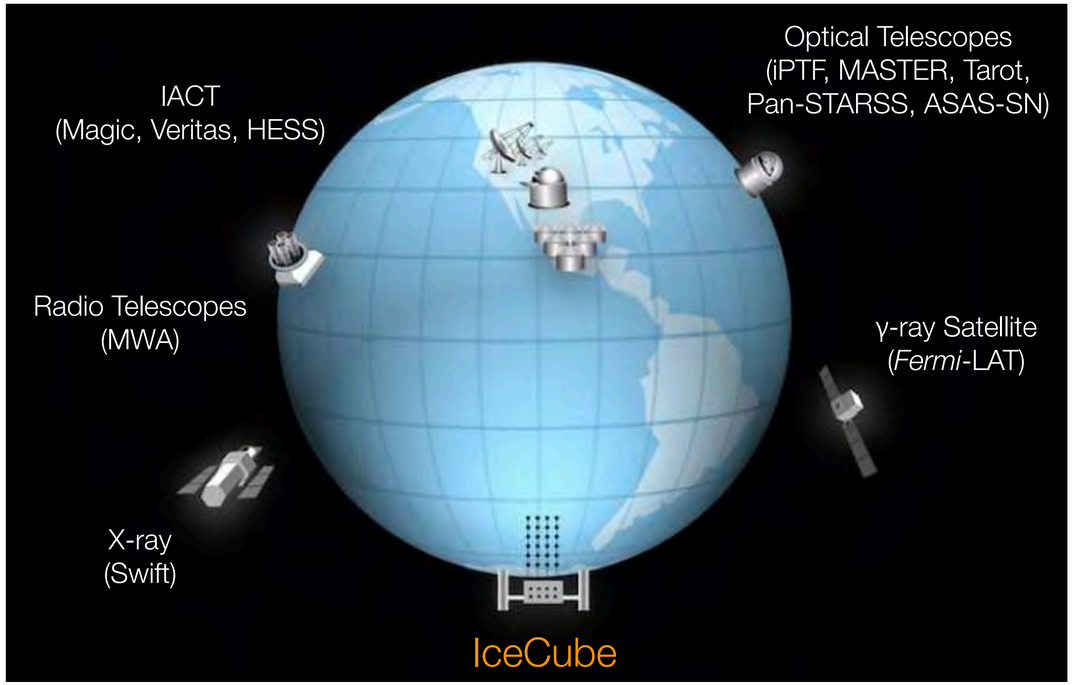


First observation of the GP by IceCube

IceCube realtime alert system

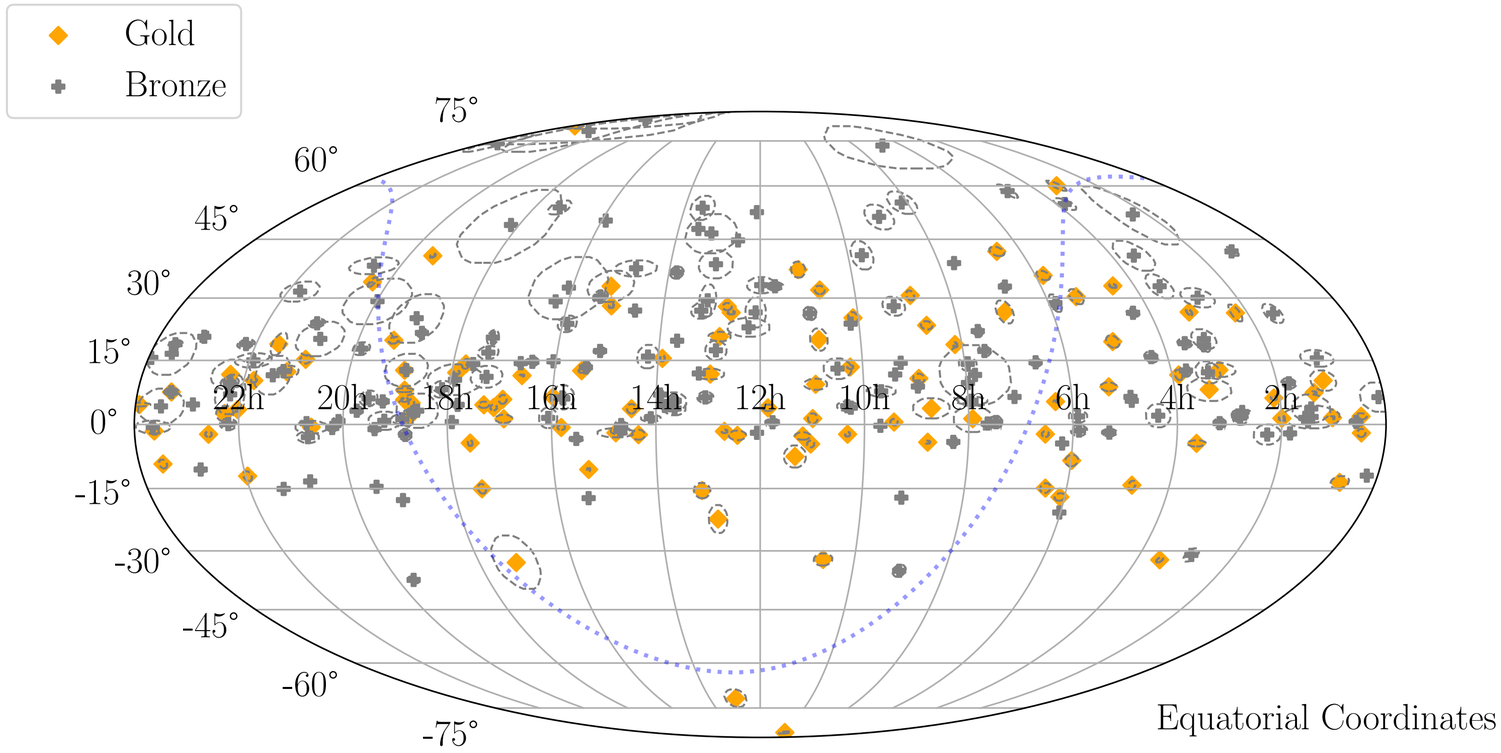
Follow-up of astrophysical neutrino events

- Single high-energy muon track events with high probability of being astrophysical ($E \gtrsim 100$ TeV)
- Since 2016, alerts are distributed through GCN network to ground and space-based observatories for rapid follow-ups
- Average alerts rate of ~2/month
- Median latency ~30 sec



Single neutrino public alert stream

Neutrino alerts with **50%** and **30%** probability of being astrophysical

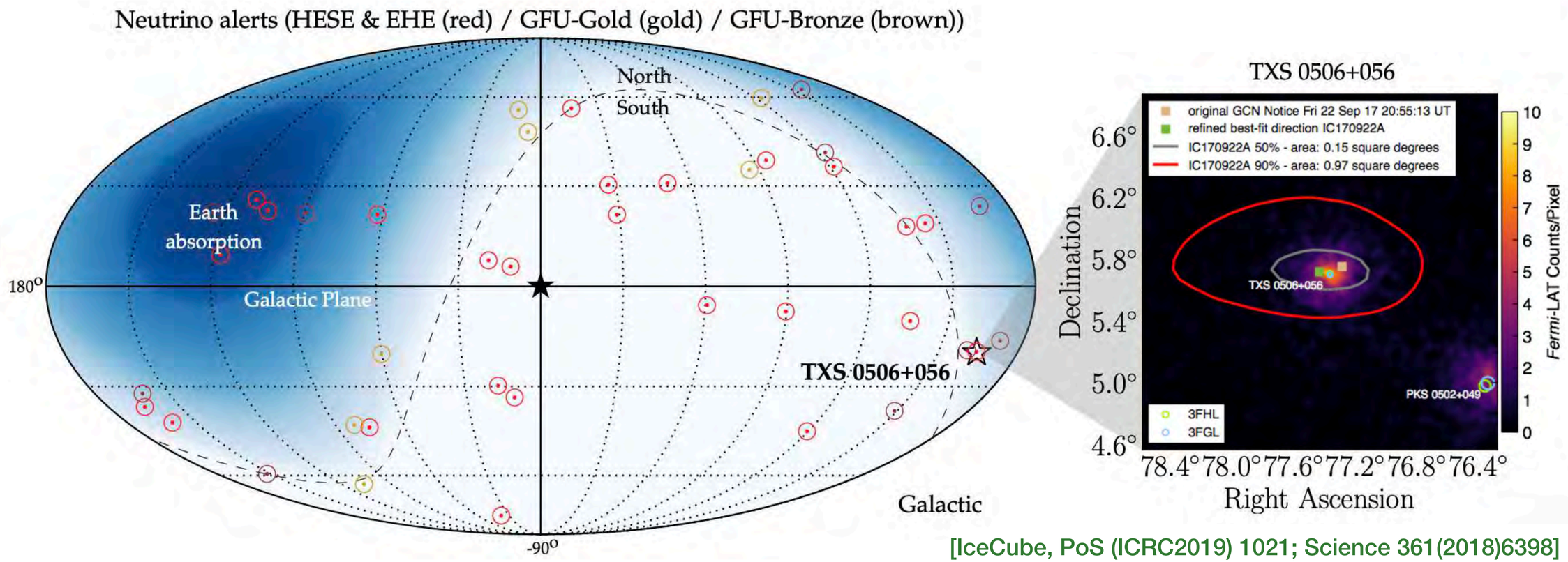


[IceCube 2023 arXiv:2304.01174]

Goal: find electromagnetic counterpart to the neutrino event

TXS 0506+056

IceCube ν event IC-170922A (290 TeV) observed in coincidence with flaring **gamma-ray blazar**

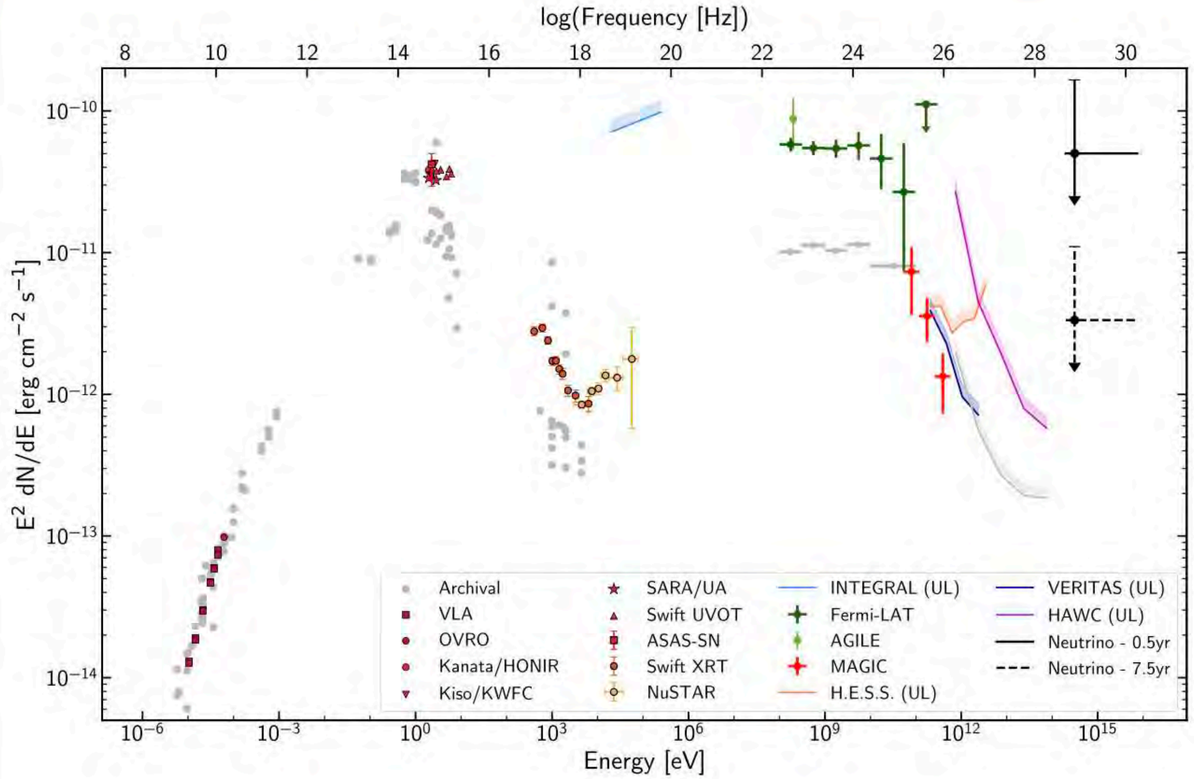


[IceCube, PoS (ICRC2019) 1021; Science 361(2018)6398]

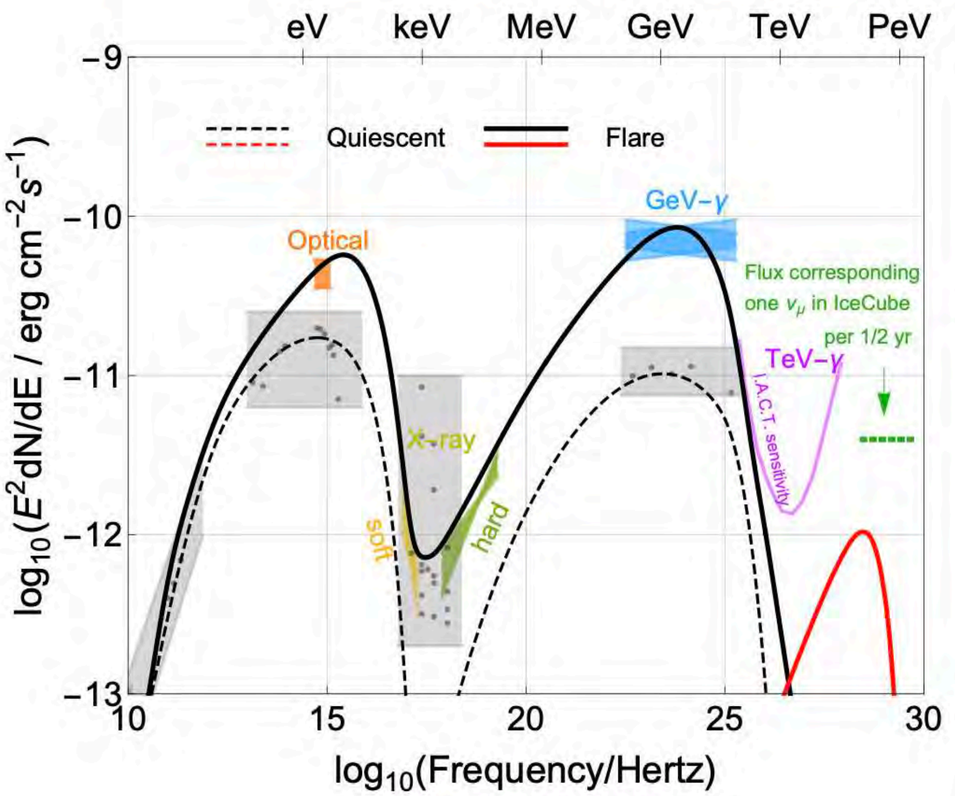
Chance correlation can be rejected at the 3σ-level

TXS 0506+056

Multi-wavelength observations



[IceCube++, Science 361 (2018) 6398]

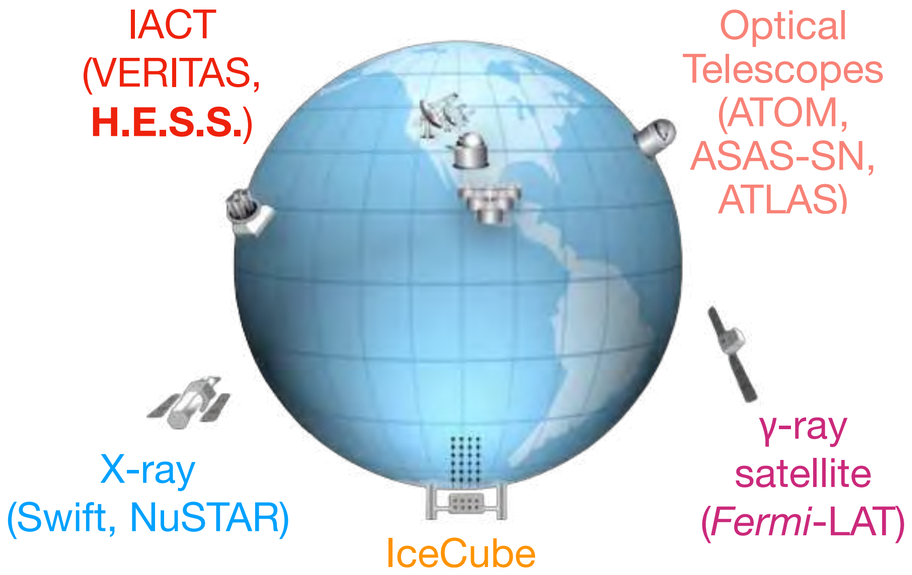


[Gao *et al.*'18]

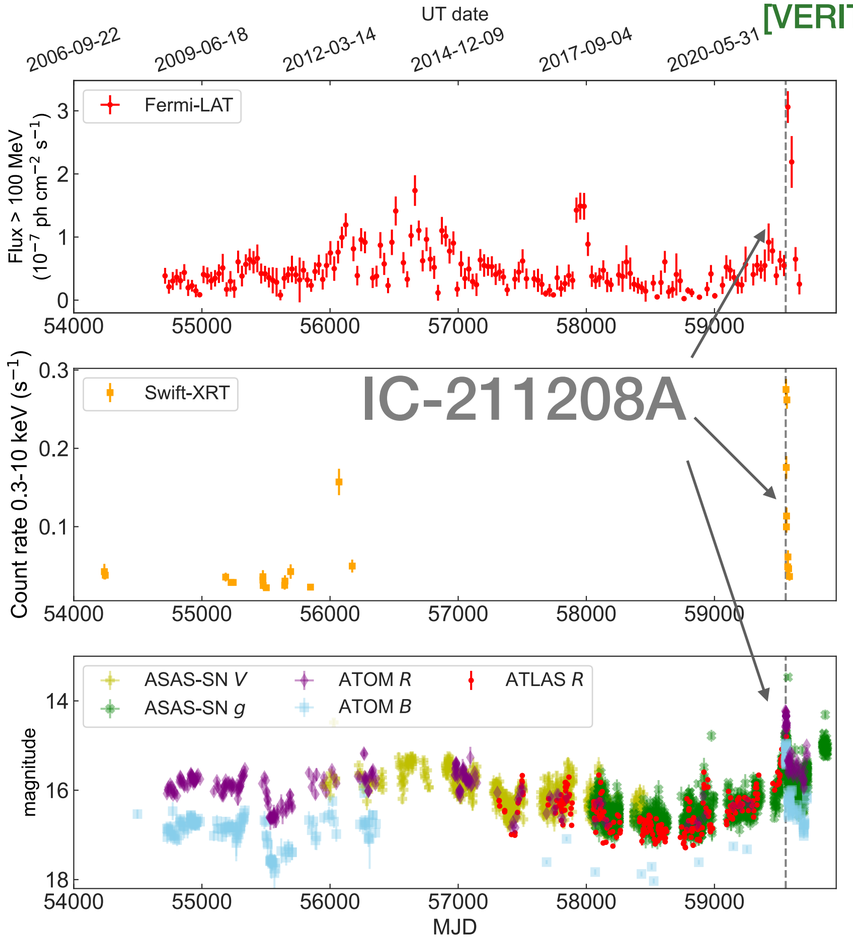
Photon SED can be modeled by lepton-hadronic or proton-synchrotron models

PKS 0735+178

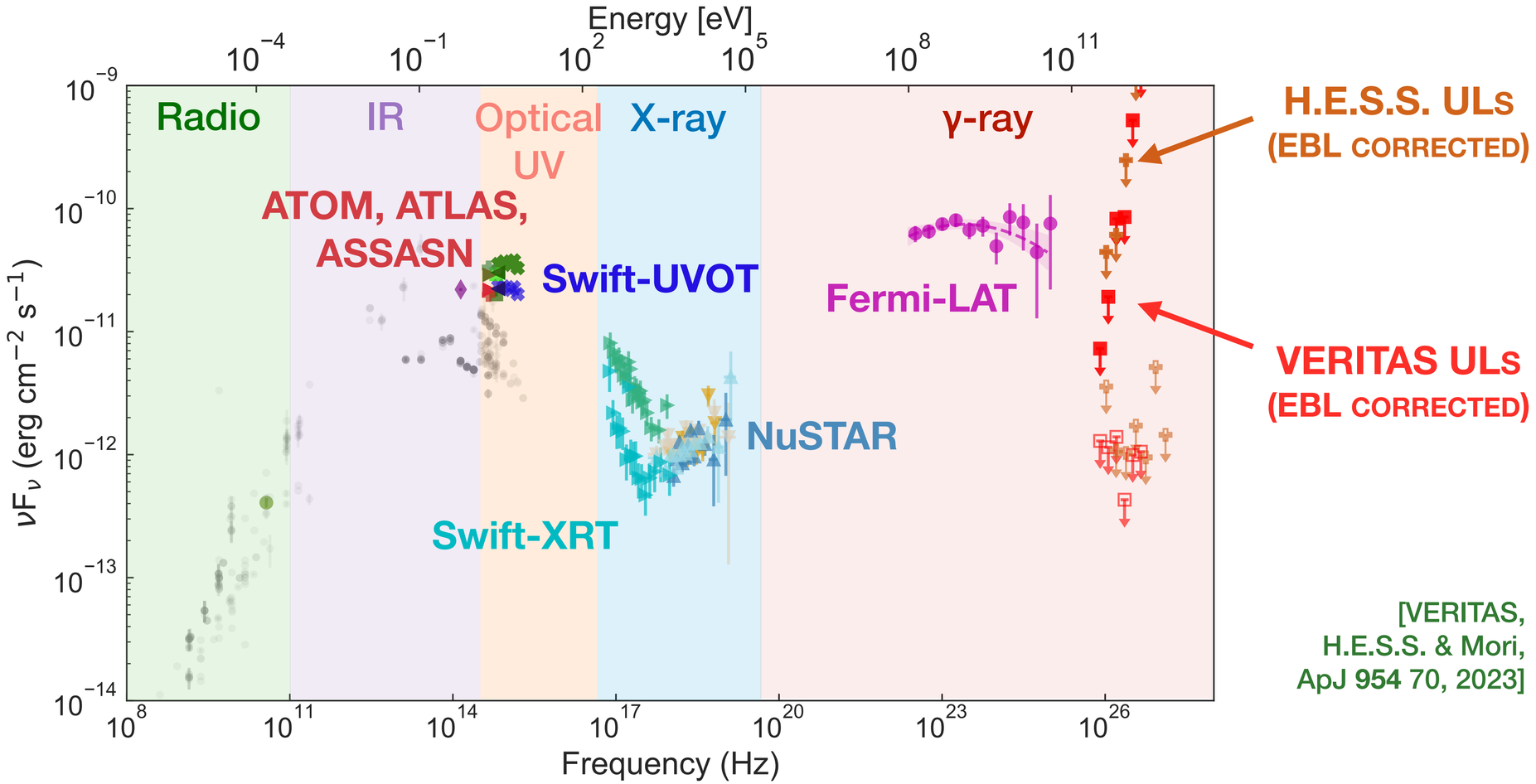
IceCube ν event IC-211208A (171 TeV) observed in coincidence with flaring **gamma-ray blazar**



[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]



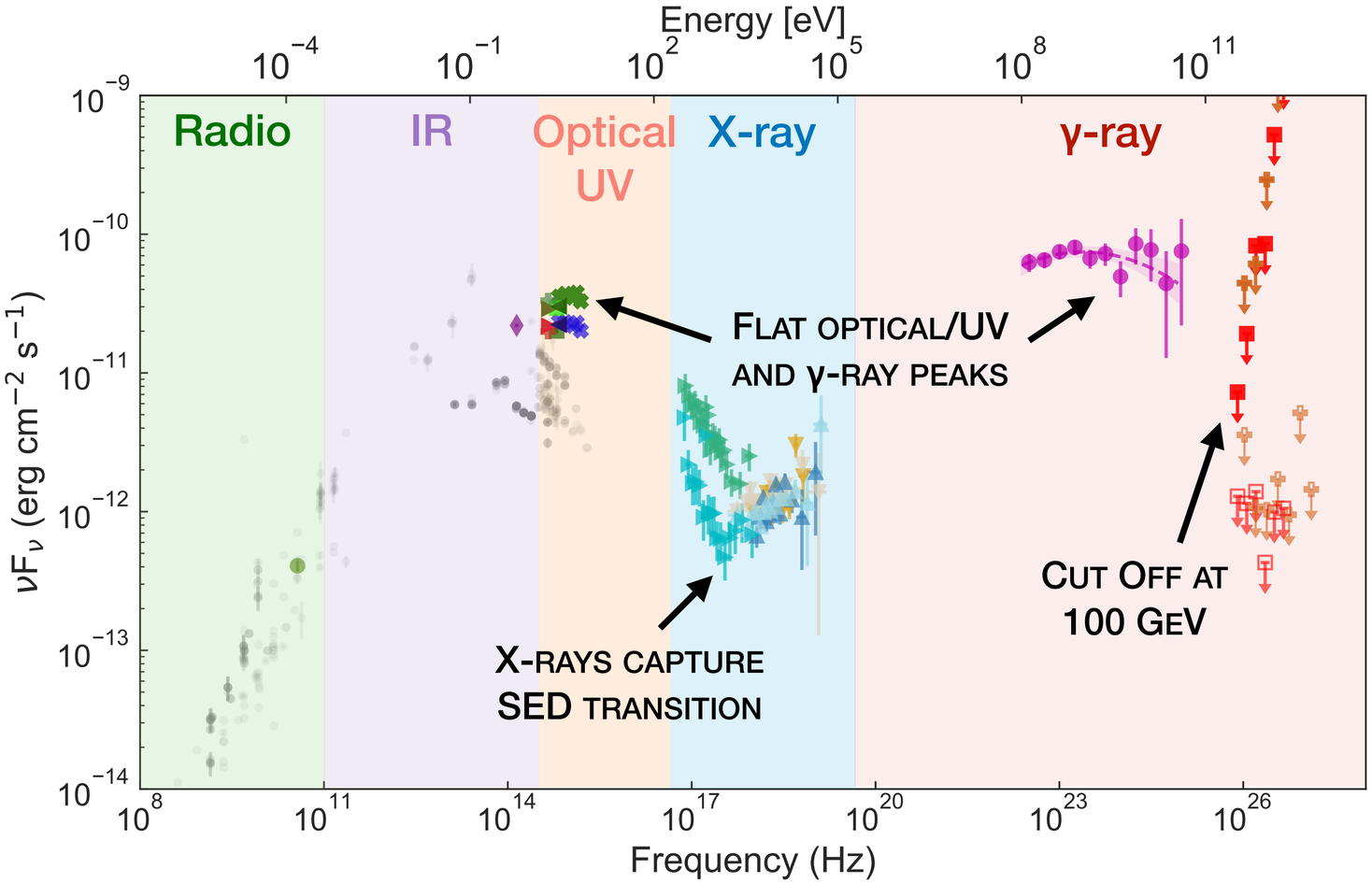
PKS 0735+178 MW observations



[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]

Multiwavelength observations in optical, UV, X-ray and γ-rays

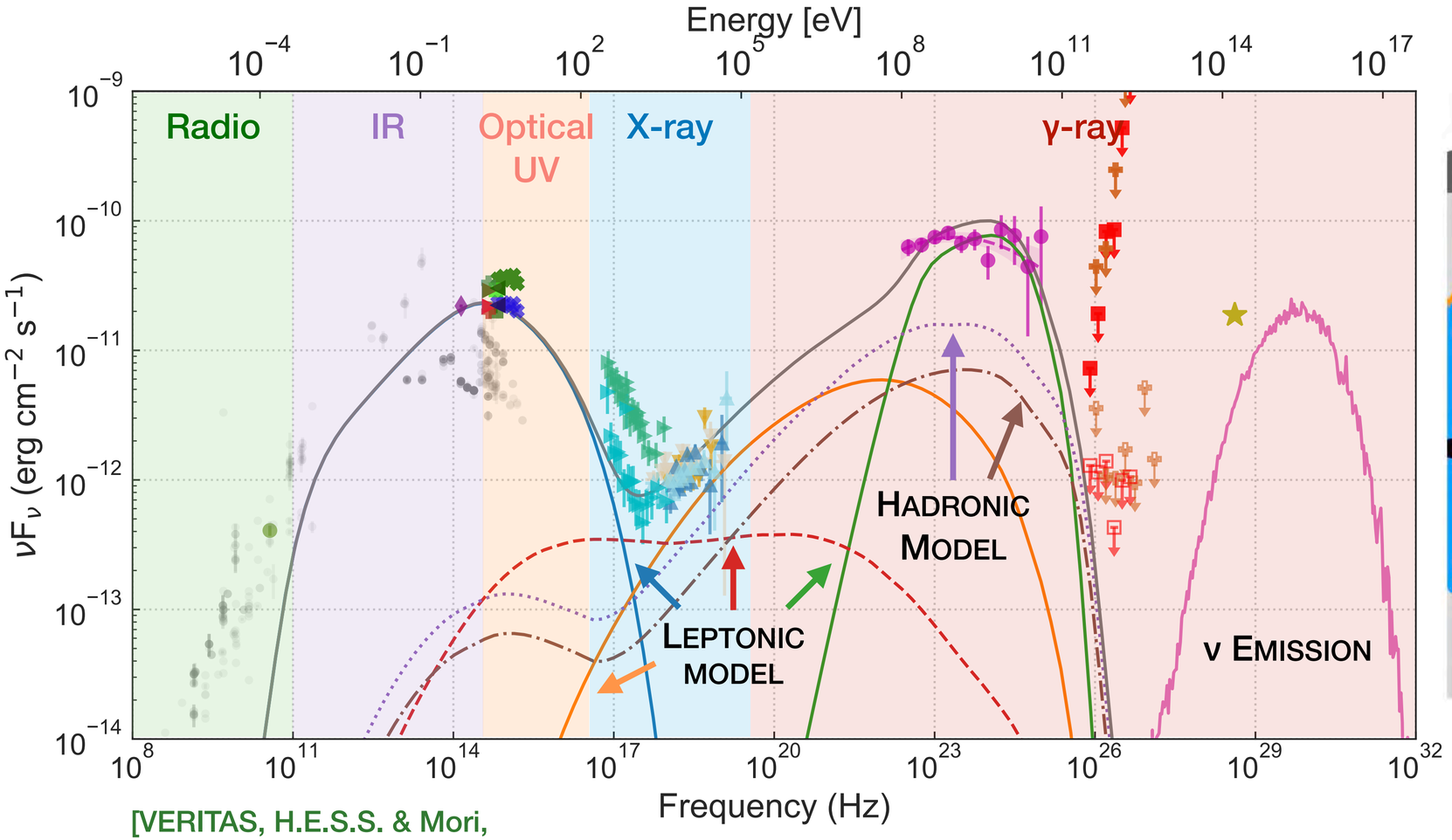
PKS 0735+178 MW observations



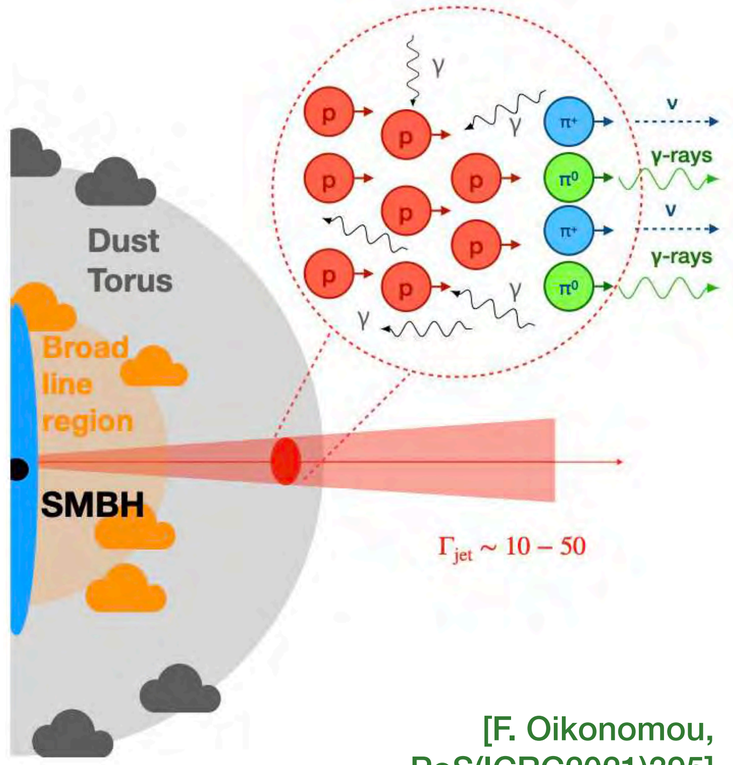
[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]

Modelling of the SED to reproduce the neutrino detection

PKS 0735+178 MW observations



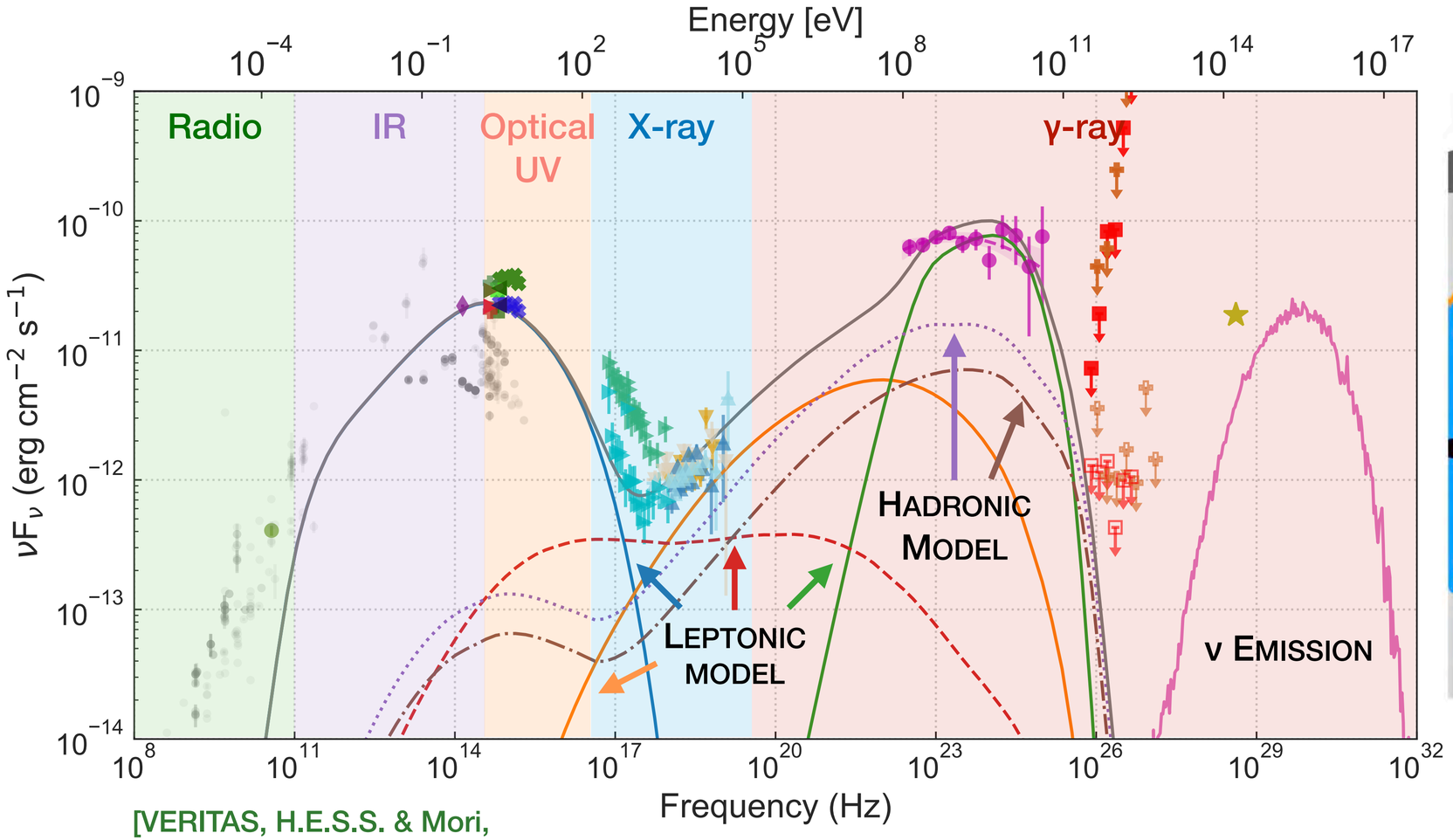
[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]



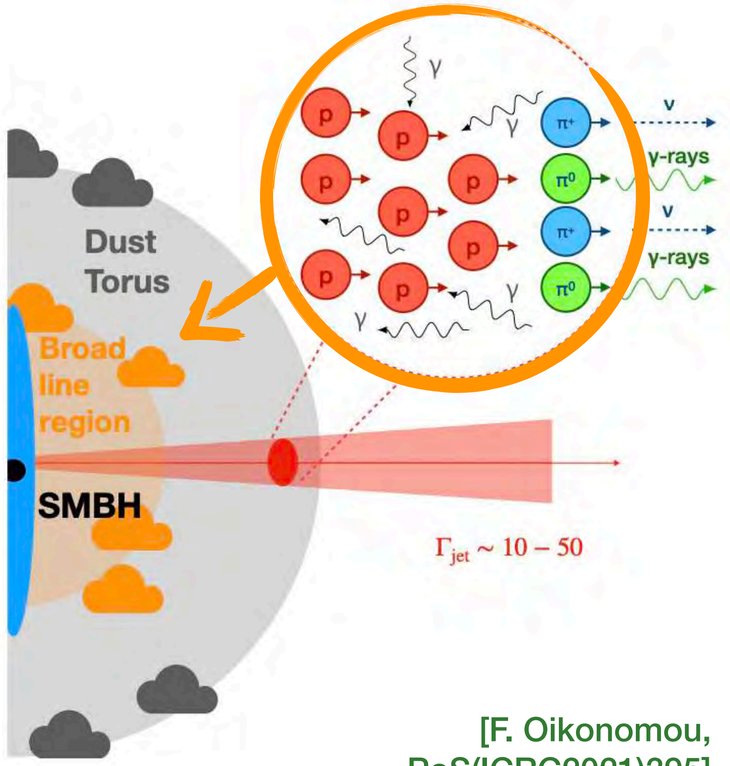
[F. Oikonomou, PoS(ICRC2021)395]

Lepto-hadronic model with external photon field target (BLR)

PKS 0735+178 MW observations



[VERITAS, H.E.S.S. & Mori, ApJ 954 70, 2023]

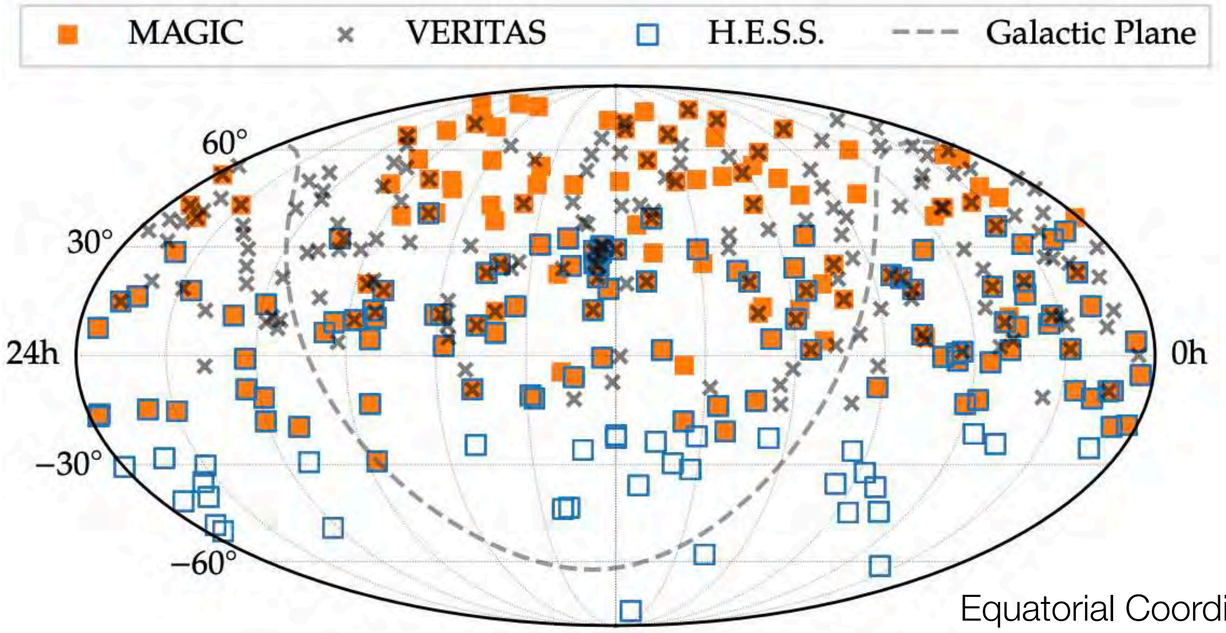


[F. Oikonomou, PoS(ICRC2021)395]

Lepto-hadronic model with external photon field target (BLR)

Gamma-ray **F**ollow-**U**p (GFU) private stream

Neutrino multiplets (*flares*) from pre-defined source list:
339 sources from 3LAC/3FHL and TeVCAT

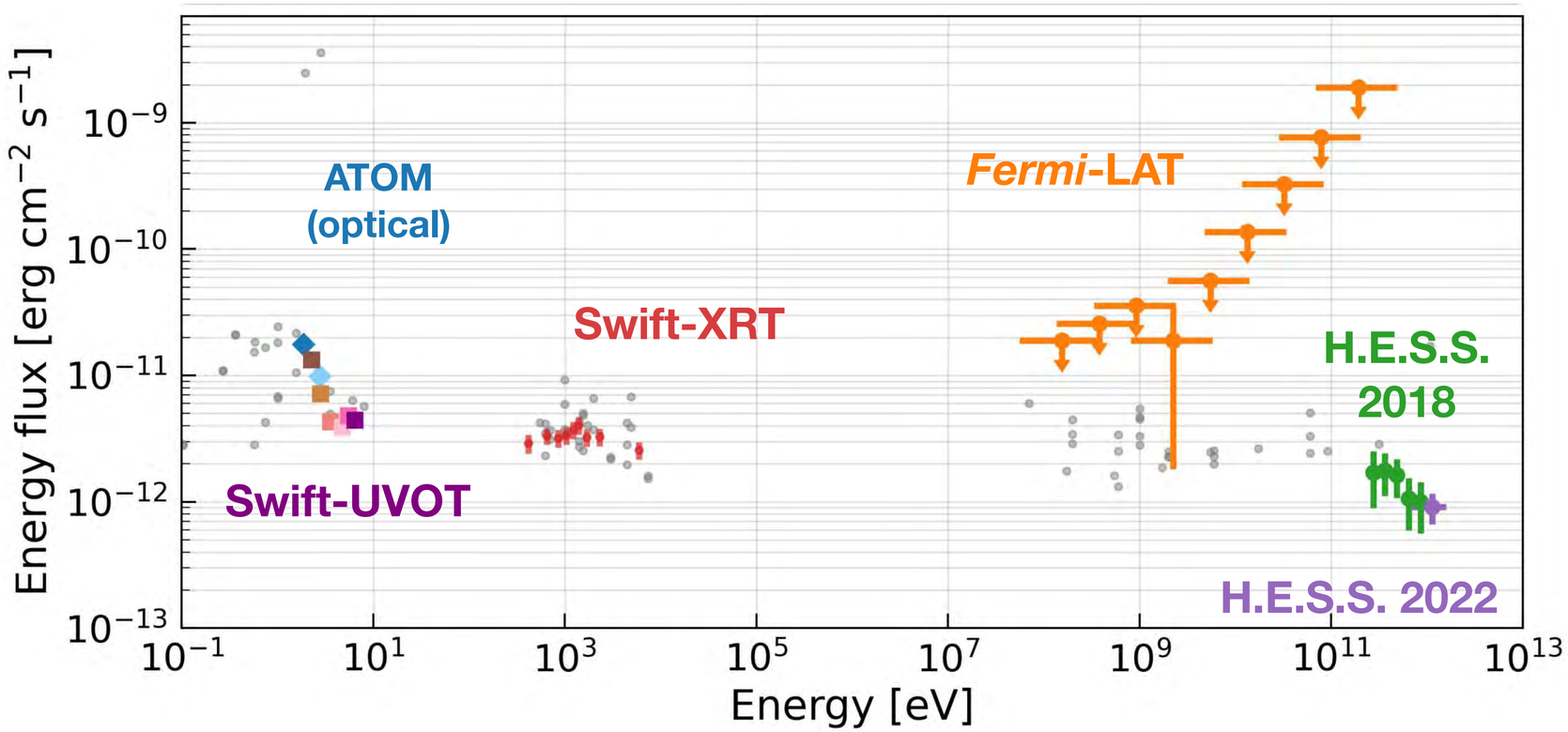


[T. Kintscher, PhD thesis, 2020, doi:10.18452/21948]

Goal: determine changes in the source state

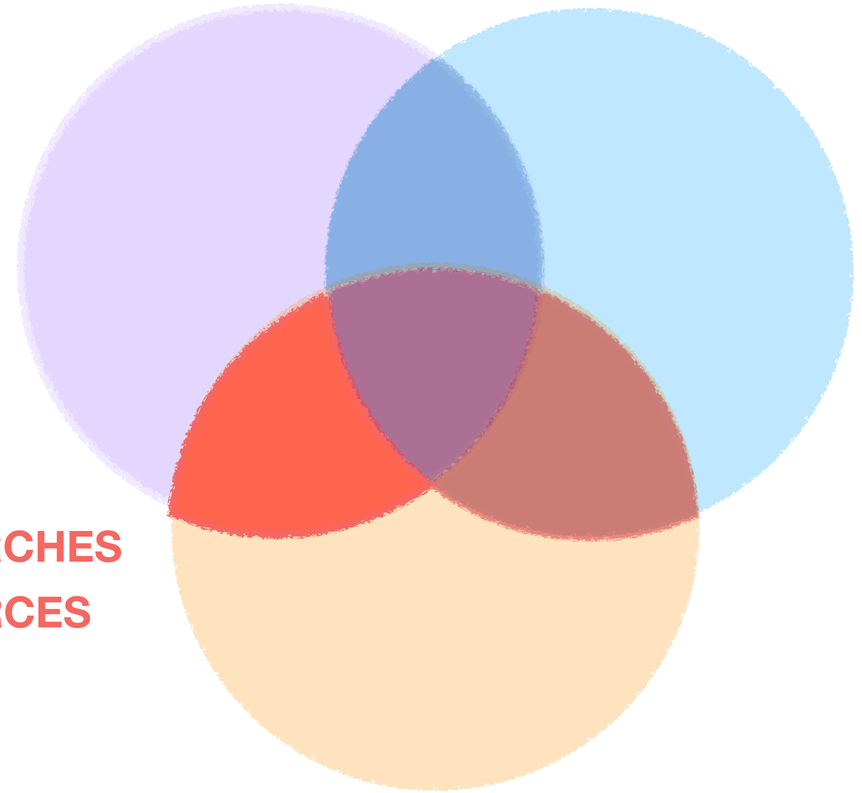
PKS 0625-35

H.E.S.S. detection of blazar PKS 0625-35 (3.5σ) during IceCube neutrino flare but no flux variation observed



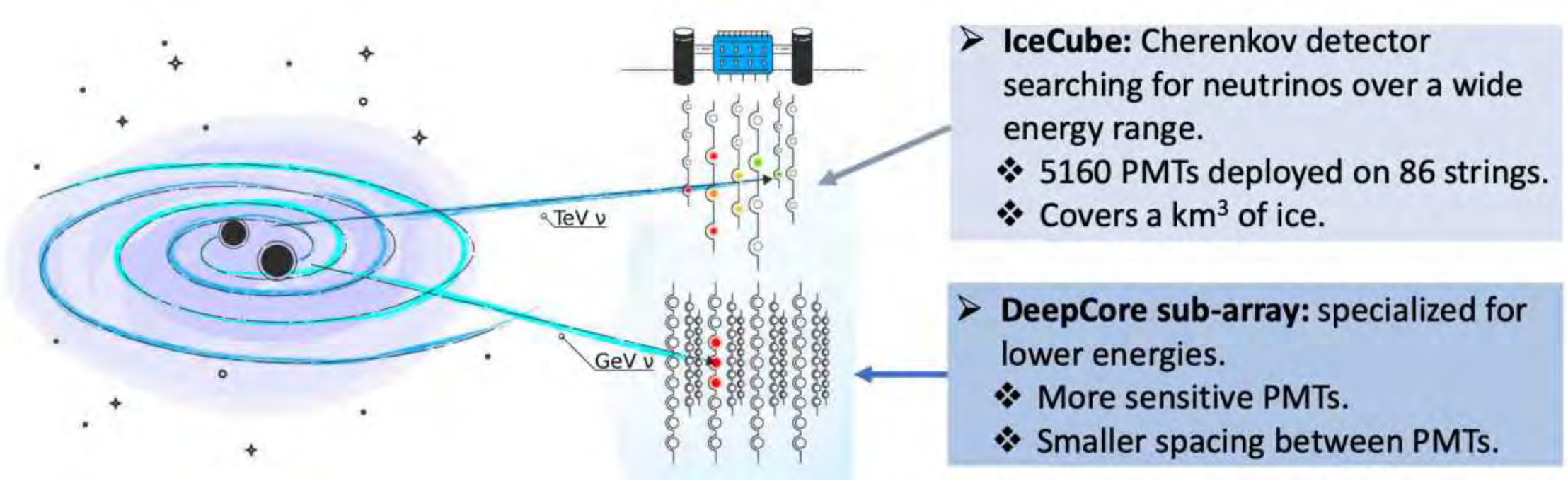
[FB for H.E.S.S. & IceCube, PoS(ICRC2023)1546]

Multi-messenger observations



NEUTRINO SEARCHES FOR GW SOURCES

Neutrino follow-up of GW events



- **IceCube:** Cherenkov detector searching for neutrinos over a wide energy range.
  - 5160 PMTs deployed on 86 strings.
  - Covers a km^3 of ice.
- **DeepCore sub-array:** specialized for lower energies.
  - More sensitive PMTs.
  - Smaller spacing between PMTs.

[IceCube, PoS(ICRC2023)1571]

Search for GeV neutrinos detected by IceCube in coincidence with 9 GW alerts (O3): no detection, only ULs

Summary

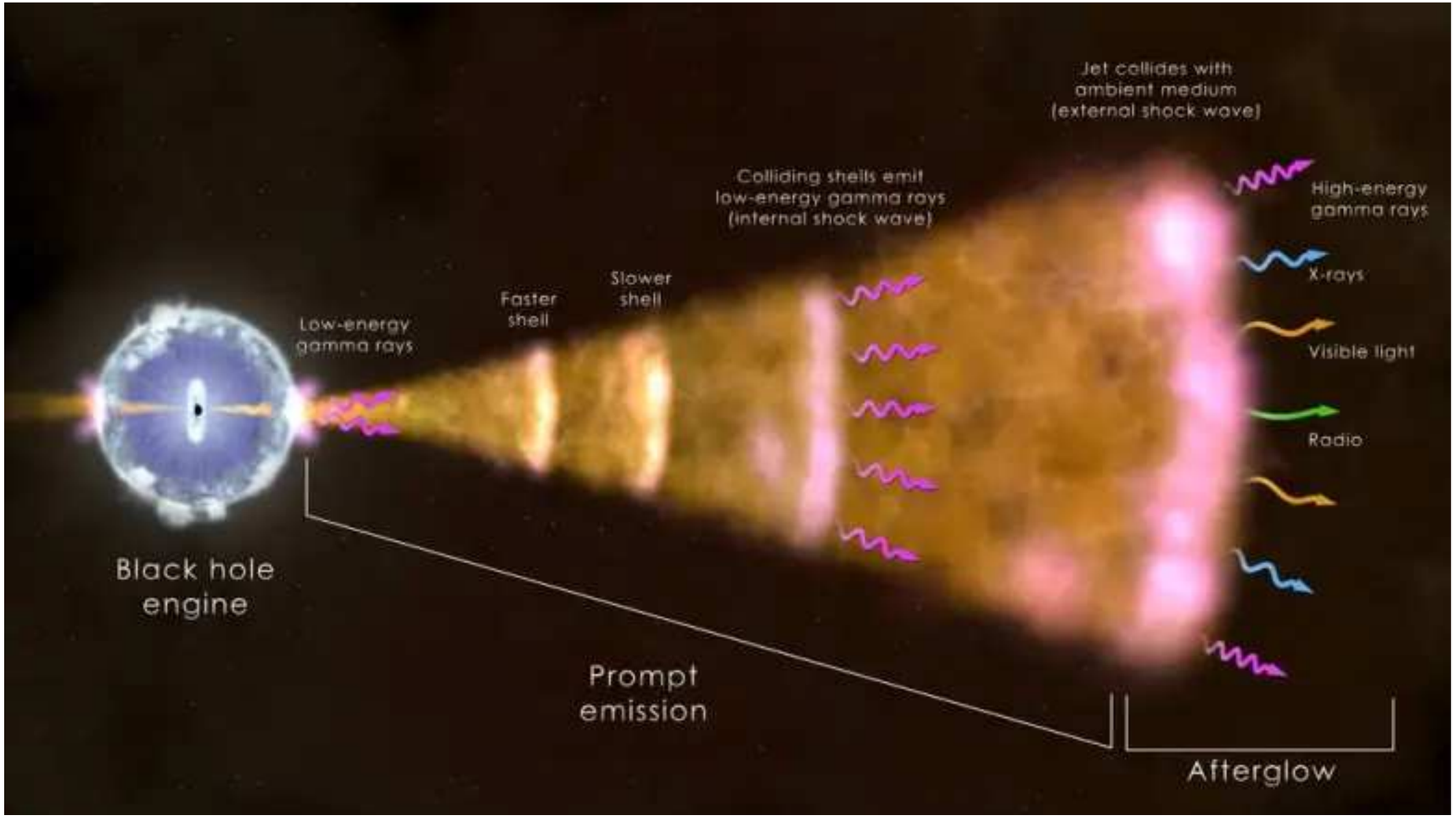
GW 170817

**TXS 0506+056,
NGC 1068, Galactic Plane**

GRB 221009A

Backup

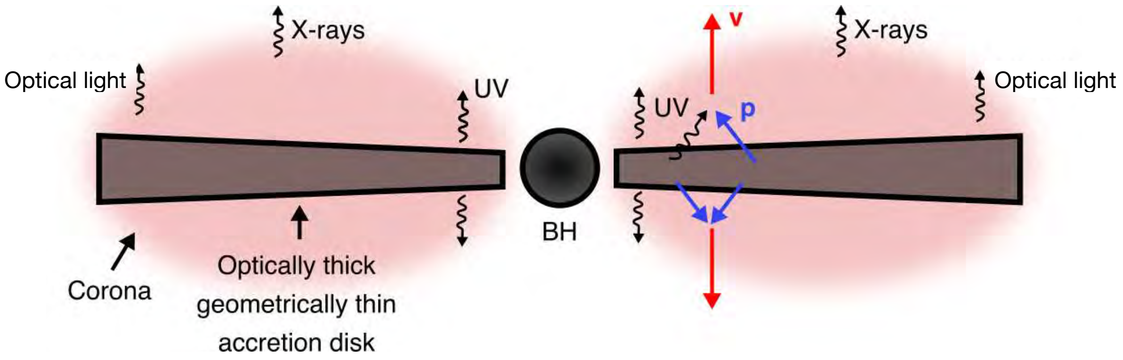
MM sources: Gamma-Ray Bursts

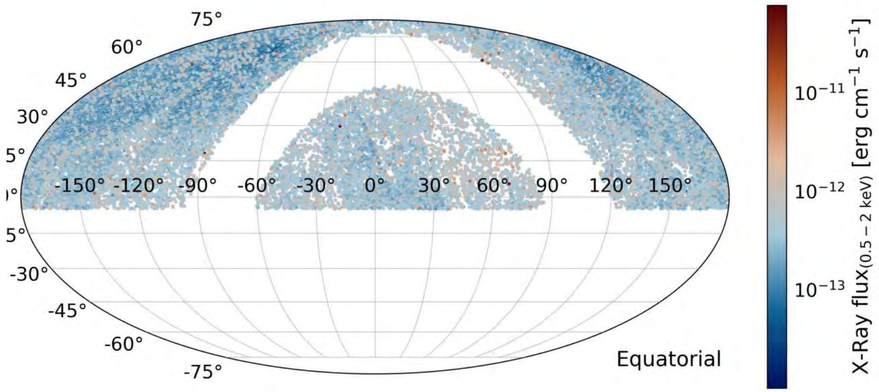


[credit: NASA's Goddard Space Flight Center]

AGN as neutrino sources

Neutrinos produced by CRs accelerated in AGN accretion disk





Neutrino luminosity approximated by X-ray luminosity

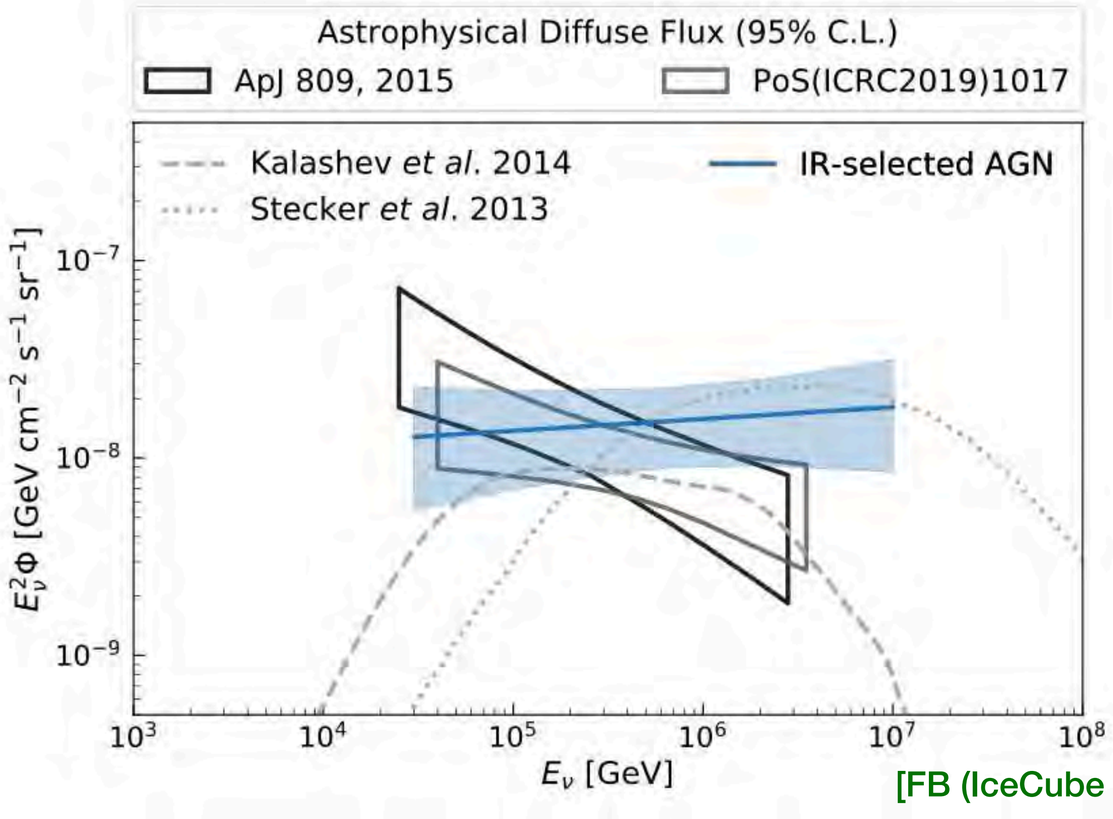
[Stecker et al. (2013), Kalashev et al. (2014)]

32k AGN sources selected by combing Radio, X-ray and IR emission

Stacking Analysis: search for combined signal from all AGNs in the catalogue

AGN as neutrino sources

Neutrinos produced by CRs accelerated in AGN accretion disk



[FB (IceCube Collaboration), PRD **106** (2022) 2]

Cores of AGN can explain 27%—100% of diffuse neutrino flux @100 TeV