An abstract visualization of neutrino sources. It features a dark background with numerous vertical white lines. A red arrow points from the left towards the center. Several vertical columns of green spheres are arranged, with some columns being taller and more densely packed than others. A few red spheres are scattered among the green ones.

RUHR-UNIVERSITÄT BOCHUM

OBSERVING PLAN FOR NEUTRINO SOURCES

Anna Franckowiak for Cole Miller and the SOC, TDAMM Workshop, Oct. 28, 2025

Source class overview: Low vs. High-energies

MeV neutrinos from nuclear processes and thermal neutrinos

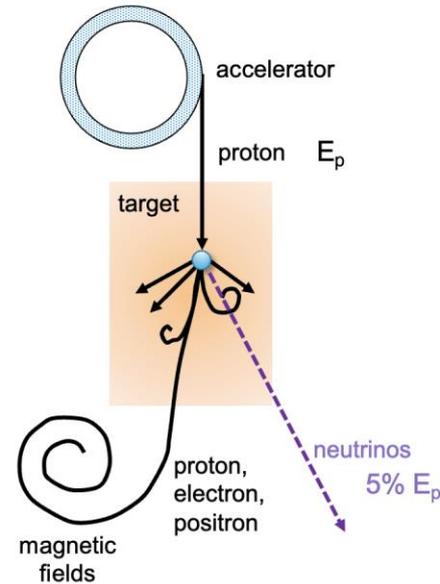


Source class overview: Low vs. High-energies

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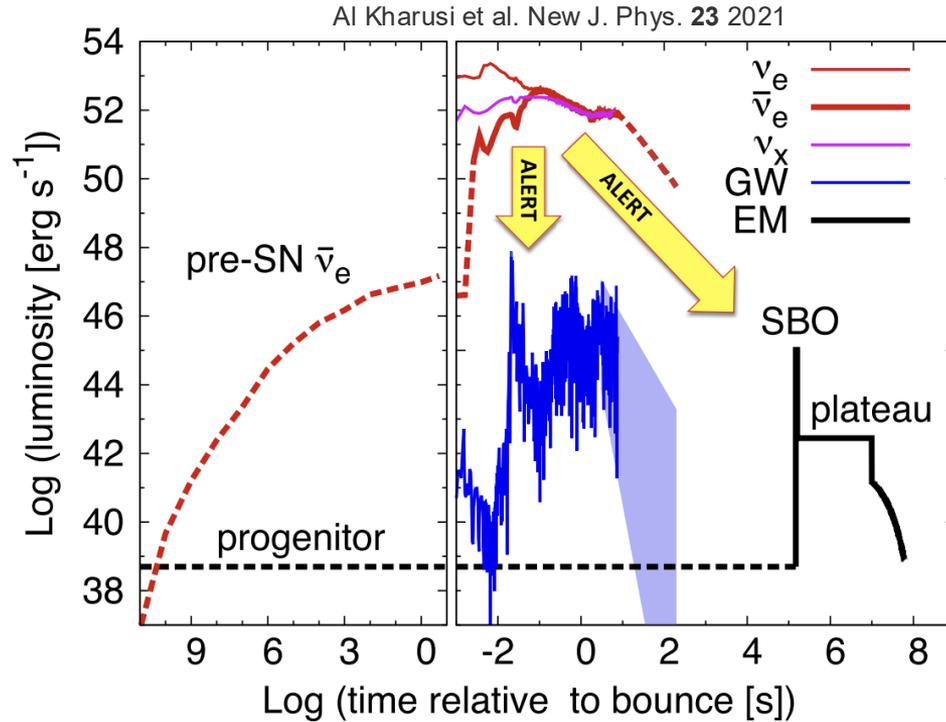
TeV-PeV neutrinos from cosmic-ray “beam dumps”



Ingredients:

- Hadronic acceleration
- Target for interaction

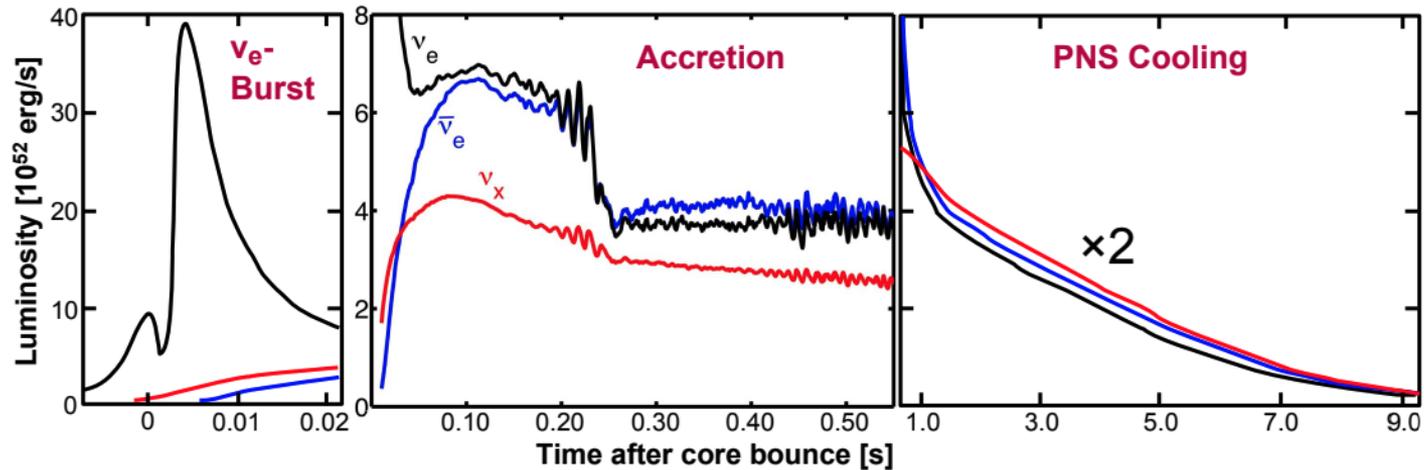
Source class overview: MeV Neutrinos from Galactic Supernova



Source class overview: MeV Neutrinos from Galactic Supernova

Scientific Importance:

- get information from neutron star formation

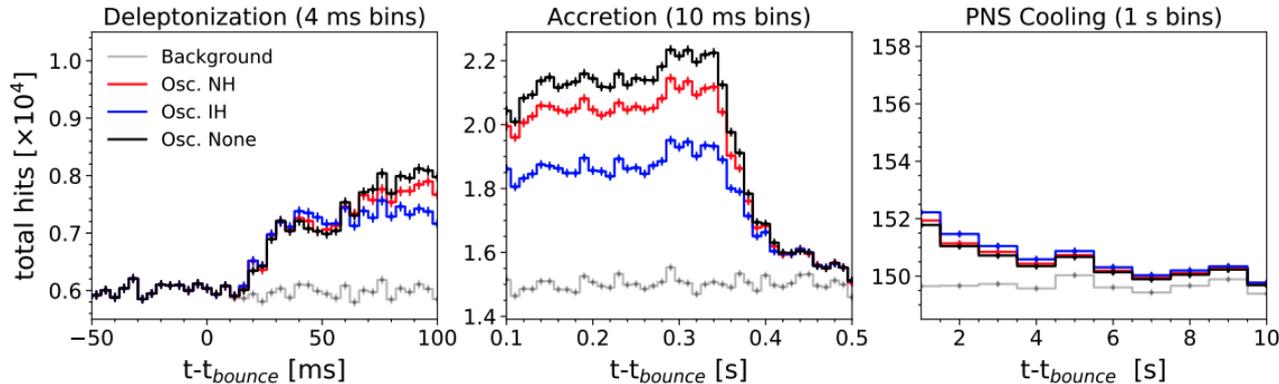
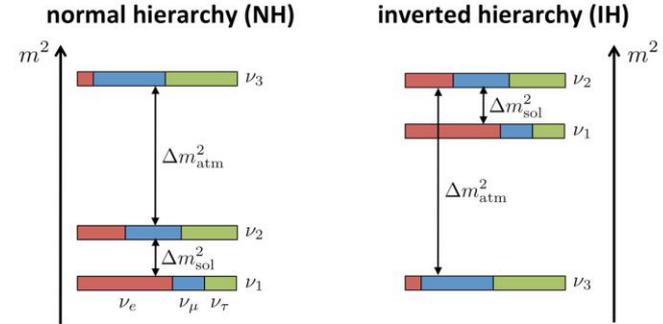


Janka 2017

Source class overview: MeV Neutrinos from Galactic Supernova

Scientific Importance:

- get information from neutron star formation
- learn about particle physics properties of neutrinos



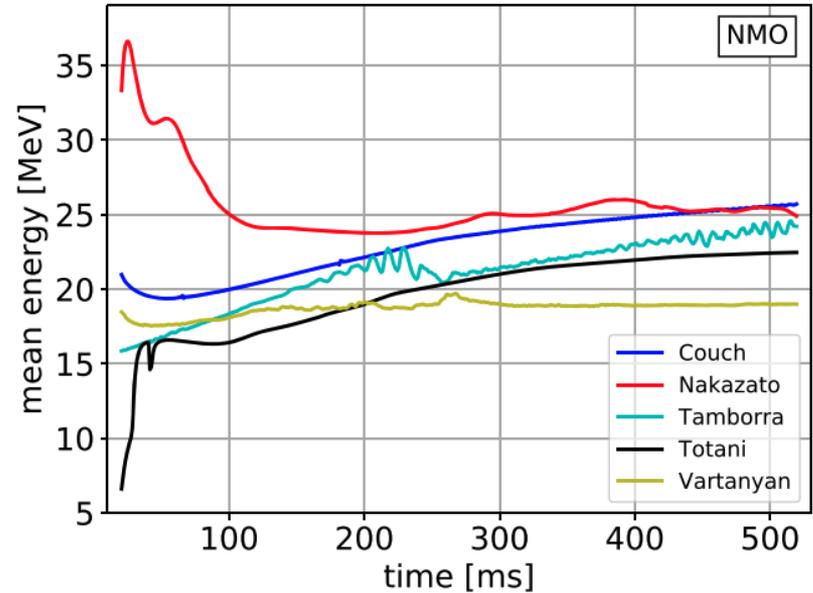
Simulated signal
observable by IceCube for
a $13 M_{\text{sun}}$ star at $d=10$ kpc

IceCube Coll. PoS-ICRC2019-889

Source class overview: MeV Neutrinos from Galactic Supernova

Scientific Importance:

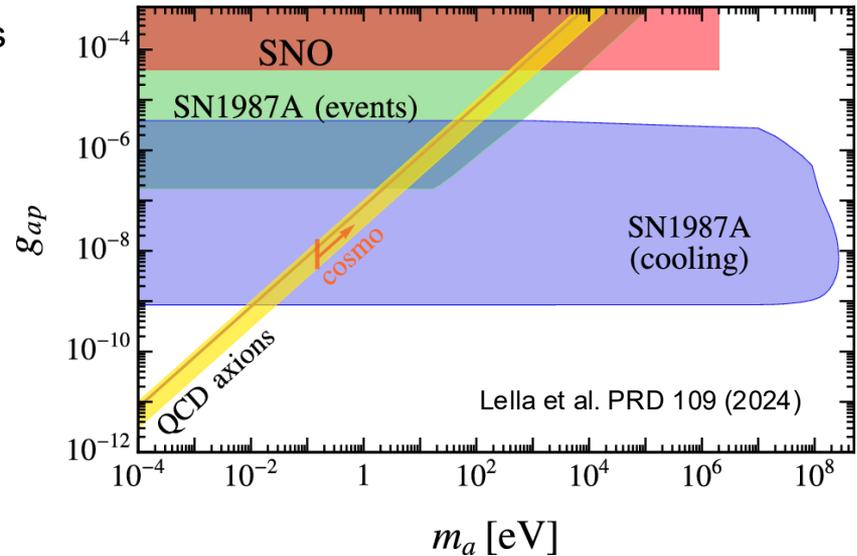
- get information from neutron star formation
- learn about particle physics properties of neutrinos
- learn about supernova models



Source class overview: MeV Neutrinos from Galactic Supernova

Scientific Importance:

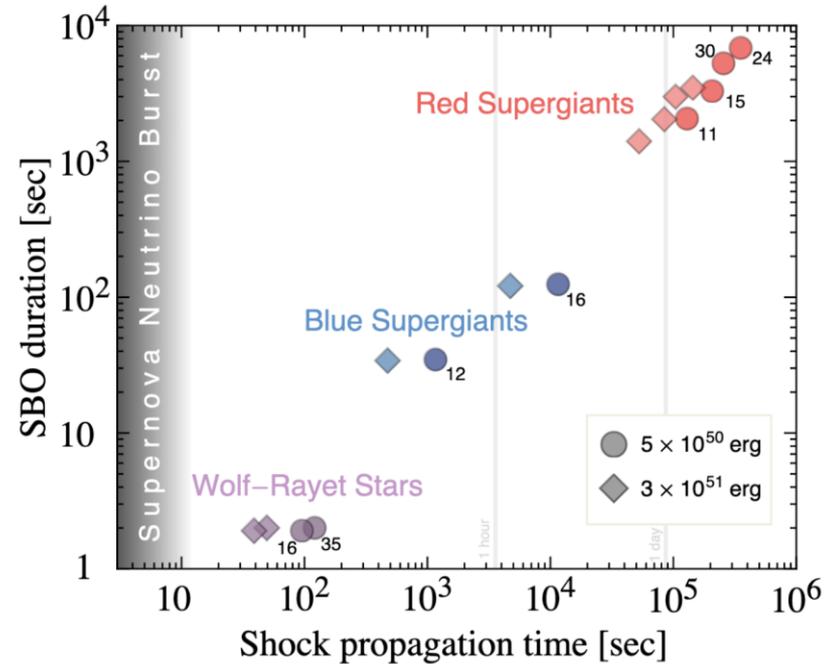
- get information from neutron star formation
- learn about particle physics properties of neutrinos
- learn about supernova models
- probe exotic physics (e.g. axions)



Source class overview: MeV Neutrinos from Galactic Supernova

Scientific Importance:

- get information from neutron star formation
- learn about particle physics properties of neutrinos
- learn about supernova models
- probe exotic physics (e.g. axions)
- trigger early EM observations

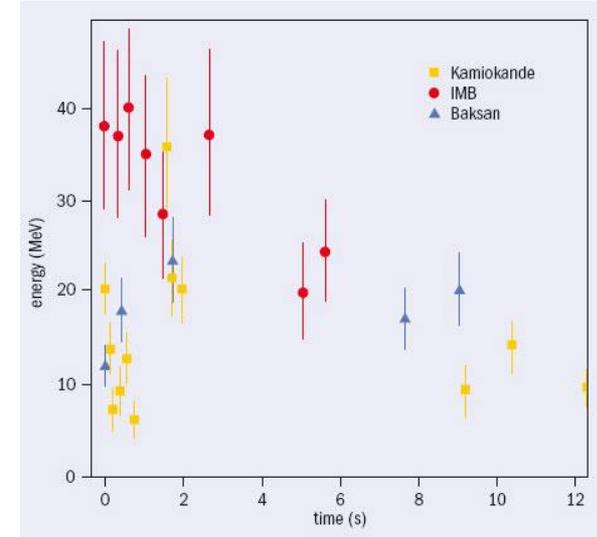
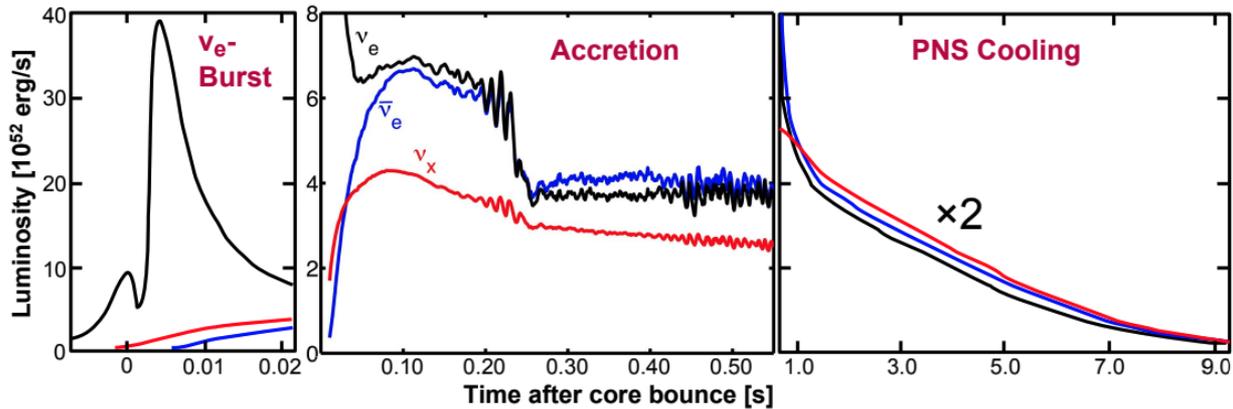


Kistler et al., ApJ 778 (2013)

Source class overview: MeV Neutrinos from Galactic Supernova

Typical Timescales:

- ~10sec neutrino burst (~10MeV) when neutron star forms
- hours to days before shock breakout depending on progenitor star

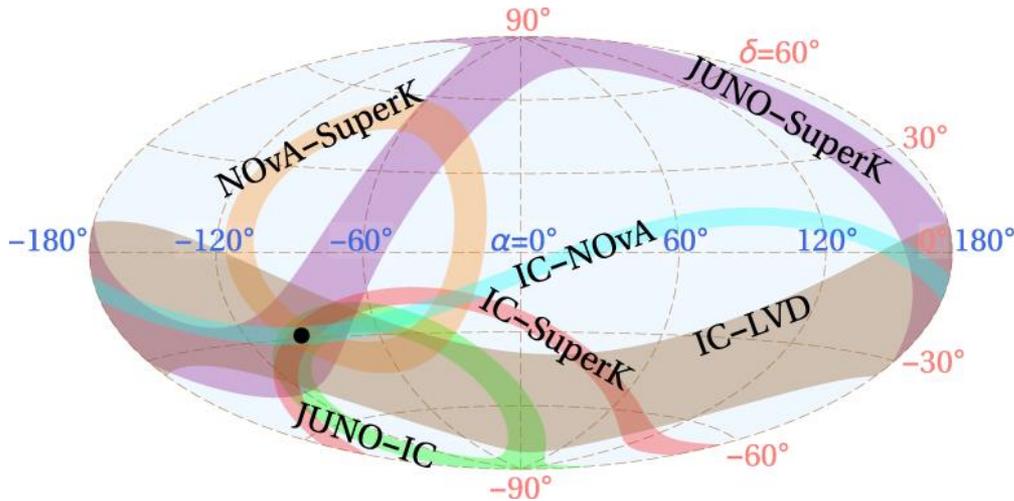


Janka 2017

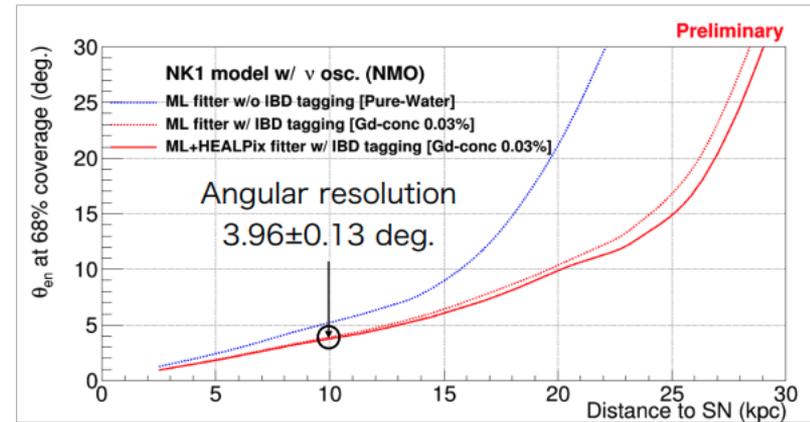
Source class overview: MeV Neutrinos from Galactic Supernova

Localization from neutrino signal:

- no / poor localization from single experiment
- few square degrees using triangulation of several detectors



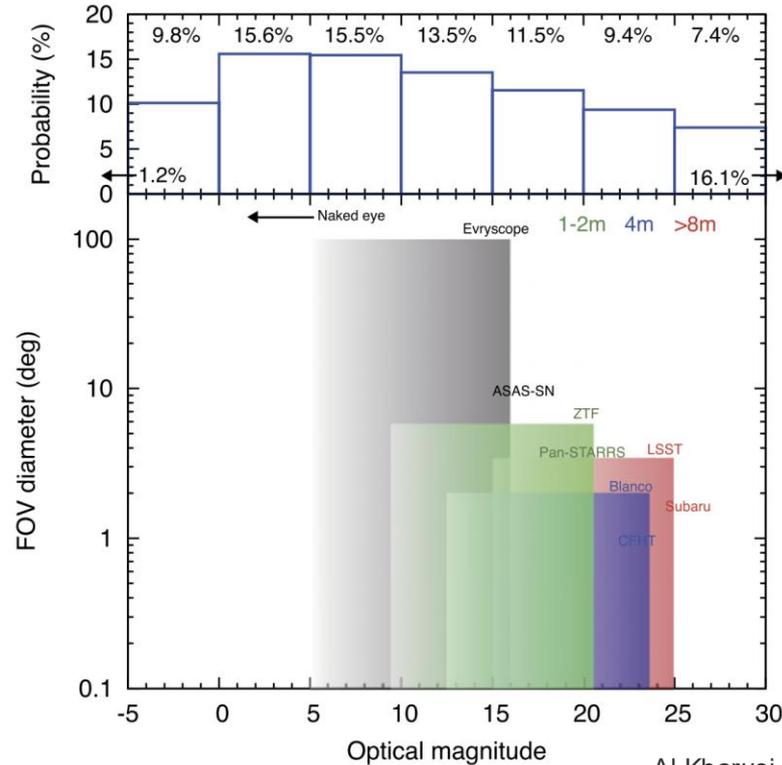
SuperK with Gd can do pointing
with few degree resolution



Source class overview: MeV Neutrinos from Galactic Supernova

**Expected event rates:
Galactic SN rate 1-3 /
century**

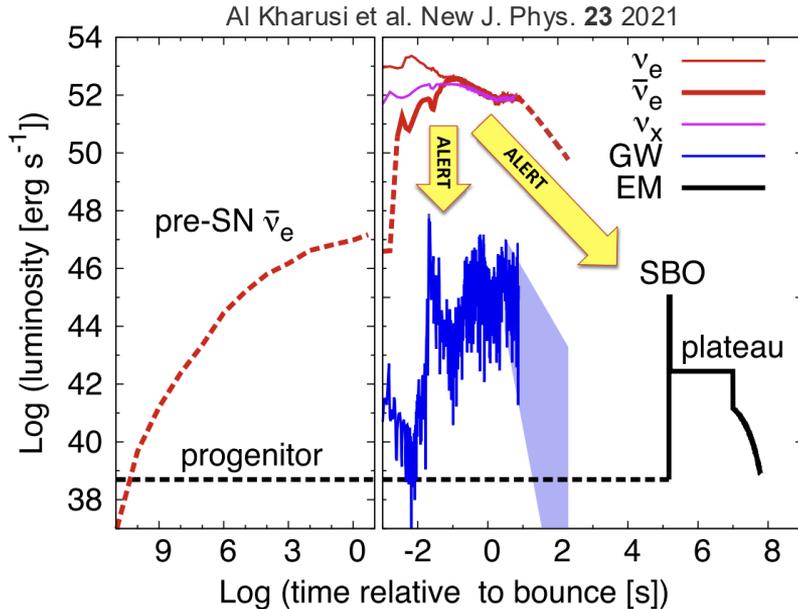
Once in a lifetime event!



Al Kharusi et al. New J. Phys. **23** 2021

Source class overview: MeV Neutrinos from Galactic Supernova

Triggering criteria: SNEWS alert



MeV neutrino burst as trigger for electromagnetic supernovae observations

SNEWS 2.0:

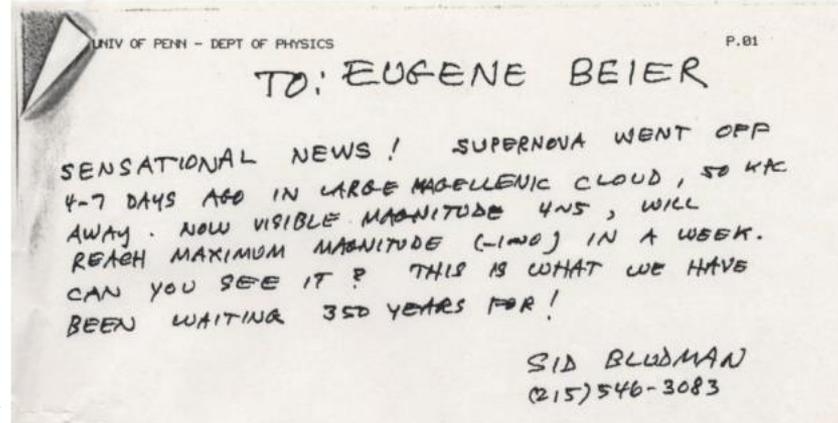
- new infrastructure
- public sub-threshold alerts
- pointing using inter-experiment triangulation
- searches for pre-supernova neutrinos

See presentation by Alec Habig

Source class overview: MeV Neutrinos from Galactic Supernova

Lesson learned: SN1987A

- Neutrinos arrived 2h before light
- IAU circulars reported optical supernova, FAX sent to University of Tokyo, data had to be extracted from tape
- Science conclusion: neutrinos are main driver of explosion, estimation of total energy release



Source class overview: MeV Neutrinos from Galactic Supernova

What could be improved

- No realtime neutrino detection in place, no neutrino network, no neutrino trigger (neutrinos found in archival data after discovery of SN1987A)
- Shock breakout not observed
- Now we have SNEWS and data sharing among neutrino observatories

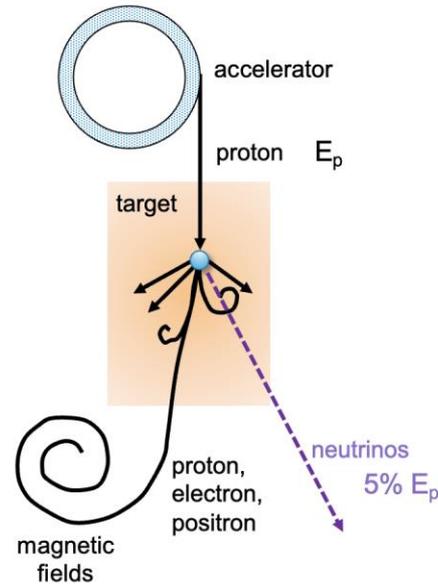
Role of specific facilities: Discovery of SN in LMC by Siding Spring Observatory and Las Campanas Observatory in Chile, Spectroscopic classification with 1.5m telescope in South Africa, study of CSM with late time multi-wavelength observations

Source class overview: Low vs. High-energies

MeV neutrinos from nuclear processes and thermal neutrinos



TeV-PeV neutrinos from cosmic-ray “beam dumps”



Ingredients:

- Hadronic acceleration
- Target for interaction

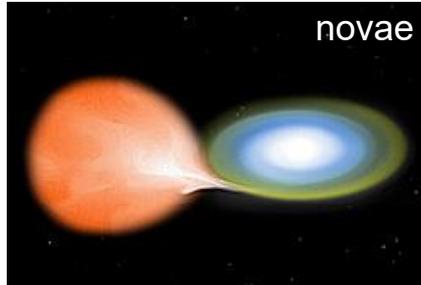
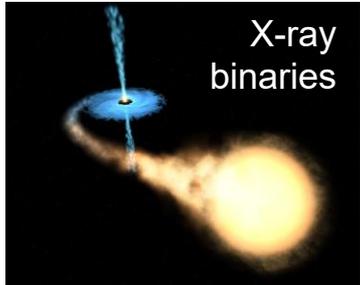
Source class overview: TeV-PeV neutrino sources

Source classes: everything that can accelerate protons and heavier nuclei and has a target

Examples: limited to transient / variable objects

See presentation by Ali Kheirandish

Galactic sources



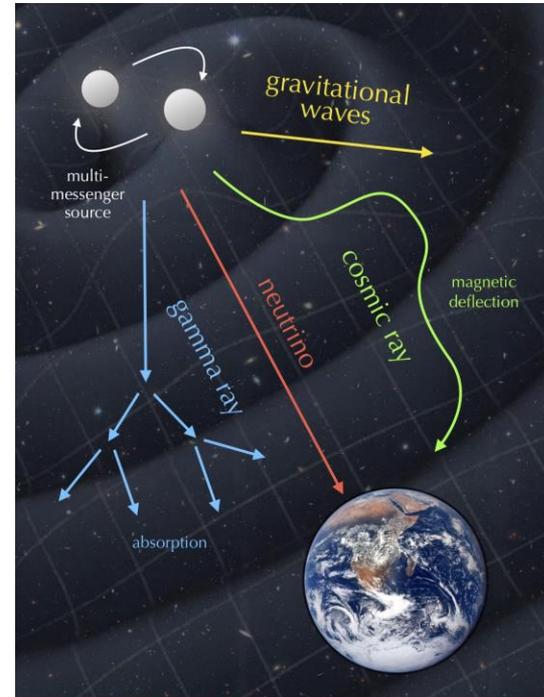
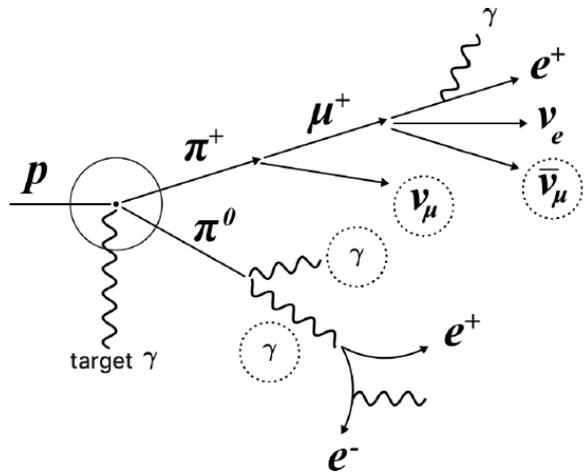
Extragalactic sources



Source class overview: TeV-PeV neutrino sources

Scientific importance:

- trace sites of hadronic acceleration
- study high-energy (but gamma-dark?) sources



Source class overview: TeV-PeV neutrino sources

Typical Timescales: depends on source class

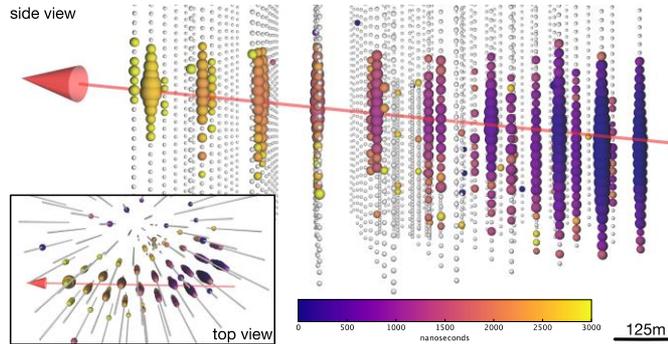
- **Novae:** expect neutrino signal correlated with gamma-ray signal, which is correlated with optical light curve
- **X-ray binaries:** minutes to months, neutrinos expected to correlate with EM signatures
- **GRBs:** prompt neutrinos seem most promising, but models predict precursor and afterglow neutrinos)
- **Choked-jet supernovae:** short prompt-GRB-like neutrino signal, followed by shock breakout in the EM
- **Interacting supernovae:** long-lasting neutrino signal, days to months, probably correlated with light curve, if also powered by the interaction
- **TDEs:** long-lasting neutrino signal, weeks to months, maybe delayed compared to optical peak
- **AGN flares:** days to months, neutrino signal expected to correlate with electromagnetic tracers, X-rays seem promising

Source class overview: TeV-PeV neutrino sources

Expected event rate

Rate of single high-energy muon neutrino track events released by IceCube:

- ~30/year with $p_{\text{astro}} > 30\%$
- ~10/year with $p_{\text{astro}} > 50\%$



See presentation
by Justin
Vandenbroucke

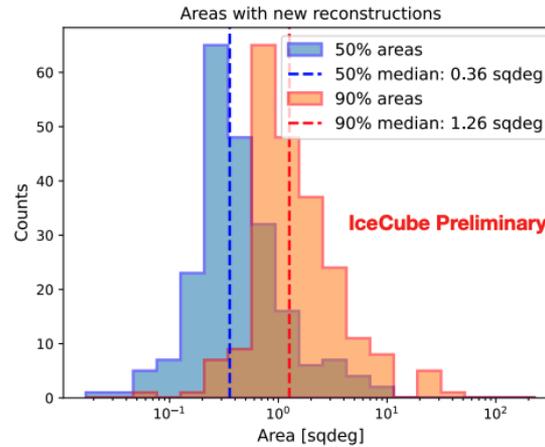
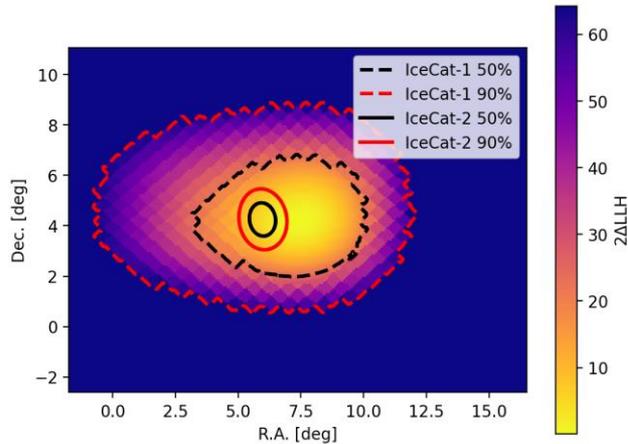
Future:

- all-sky clusters with duration up to 180 days, 30 days, 1000 sec
- New instruments will join (e.g. KM3NeT)

Source class overview: TeV-PeV neutrino sources

Triggering Criteria:

- Signalness /p_astro
- Angular uncertainty (typically ~1 square degree)
- Counterpart found by wide-field survey (e.g. ZTF/VRO, Swift-XRT, Fermi-LAT)



See presentation
by Justin
Vandenbroucke

Source class overview: TeV-PeV neutrino sources

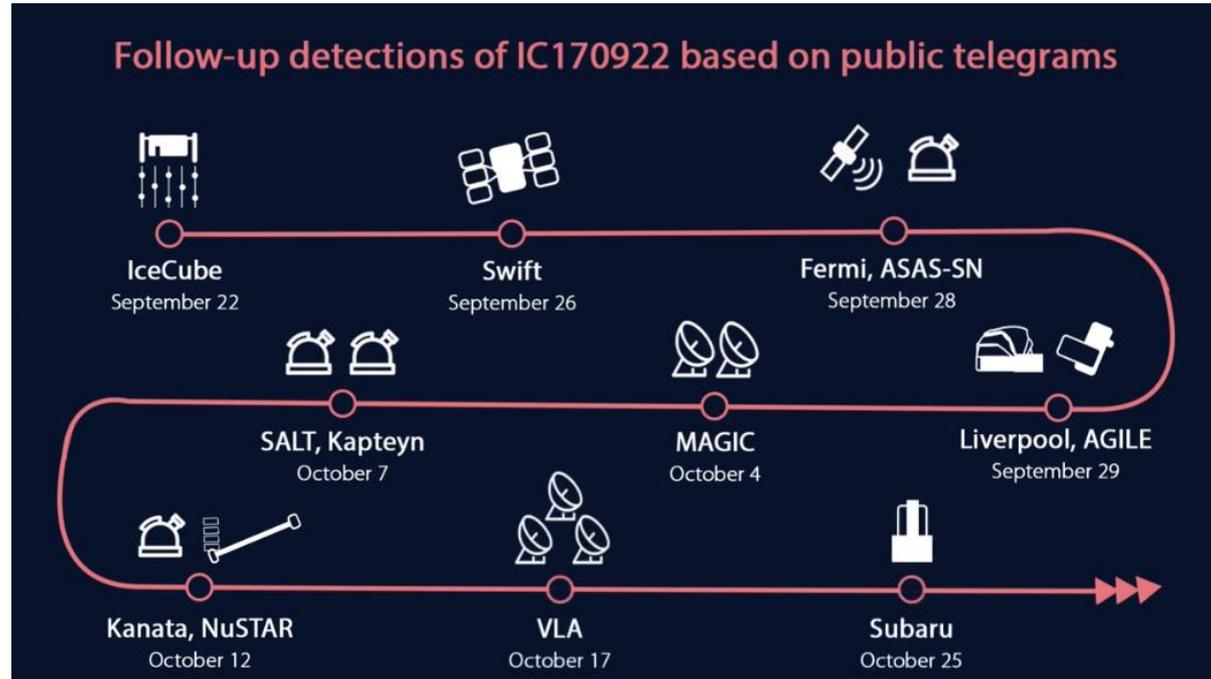
**Lesson learned: TXS 0506+056
and IceCube-170922A**

What worked well:

- Fermi-LAT detection led to large observing campaign
- Including X-ray crucial for modelling

What could be improved

- ATel from Fermi took several days to be sent → known Fermi sources now included in IceCube GCN

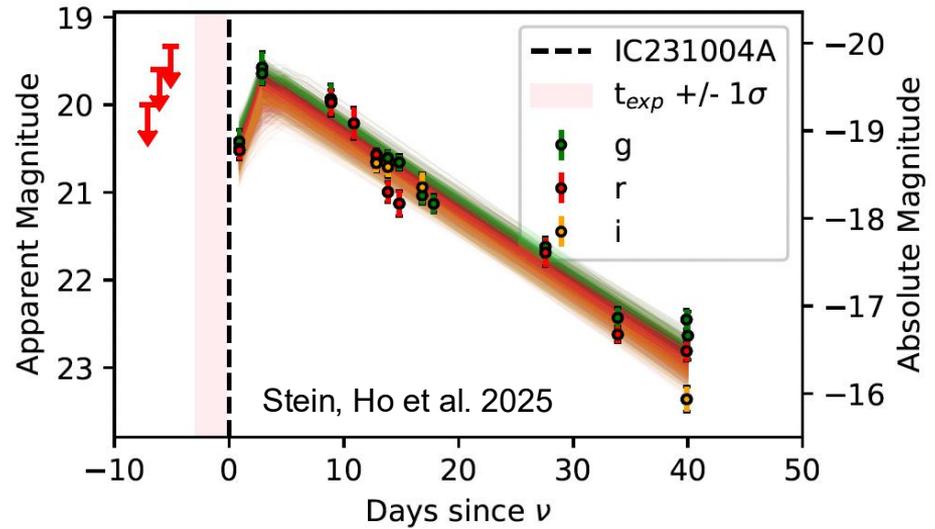


Source class overview: TeV-PeV neutrino sources

Lesson learned: SN 2023uqf and IceCube-231004A

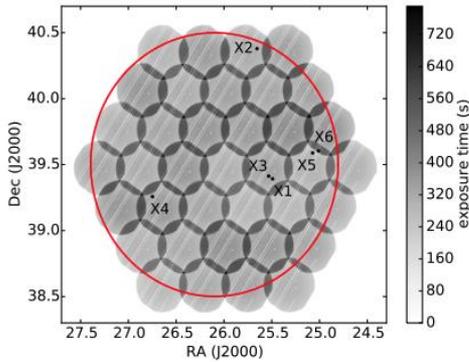
What worked well:

- Detection of counterpart candidate by ZTF in 4.3 square degree neutrino footprint
- Spectral classification by ALFOSS at NOT and LRIS at Keck-I

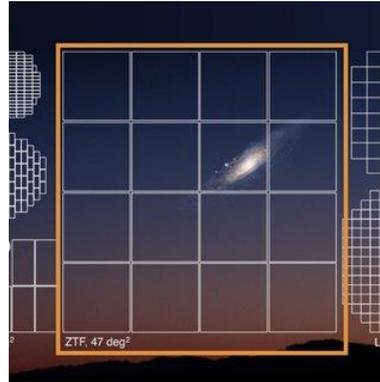


Recommended observing timeline (TeV-PeV neutrino sources)

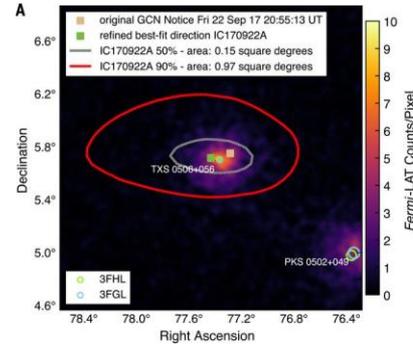
- T0 + 0–24 hr: Rapid-response triggers with wide-field-of view instruments (ideally all wavelength: IR, optical, UV, gamma-ray, X-ray), photometric classification of candidates



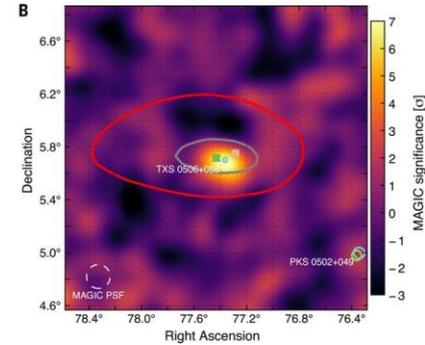
Swift-XRT tiling of neutrino footprint



ZTF 47 deg² field of view



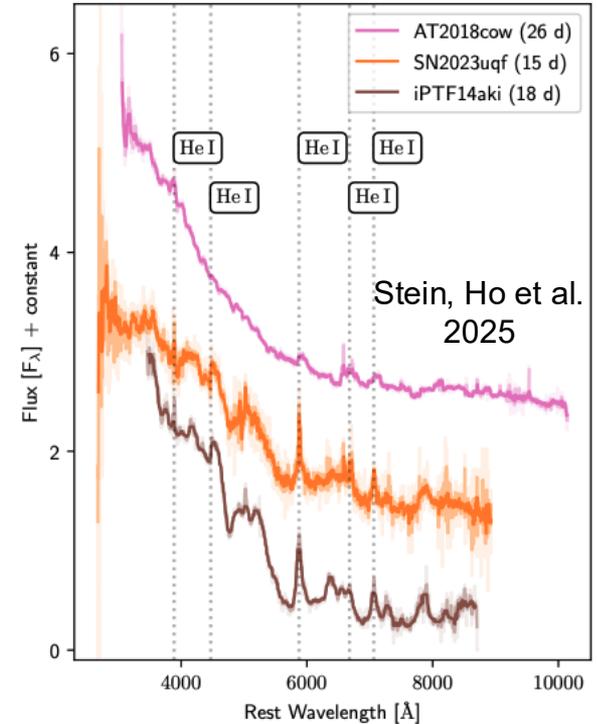
Fermi-LAT counts map of neutrino footprint



MAGIC significance map of neutrino footprint

Recommended observing timeline (TeV-PeV neutrino sources)

- T0 + 24h - 7 days: Spectroscopic classification of candidates

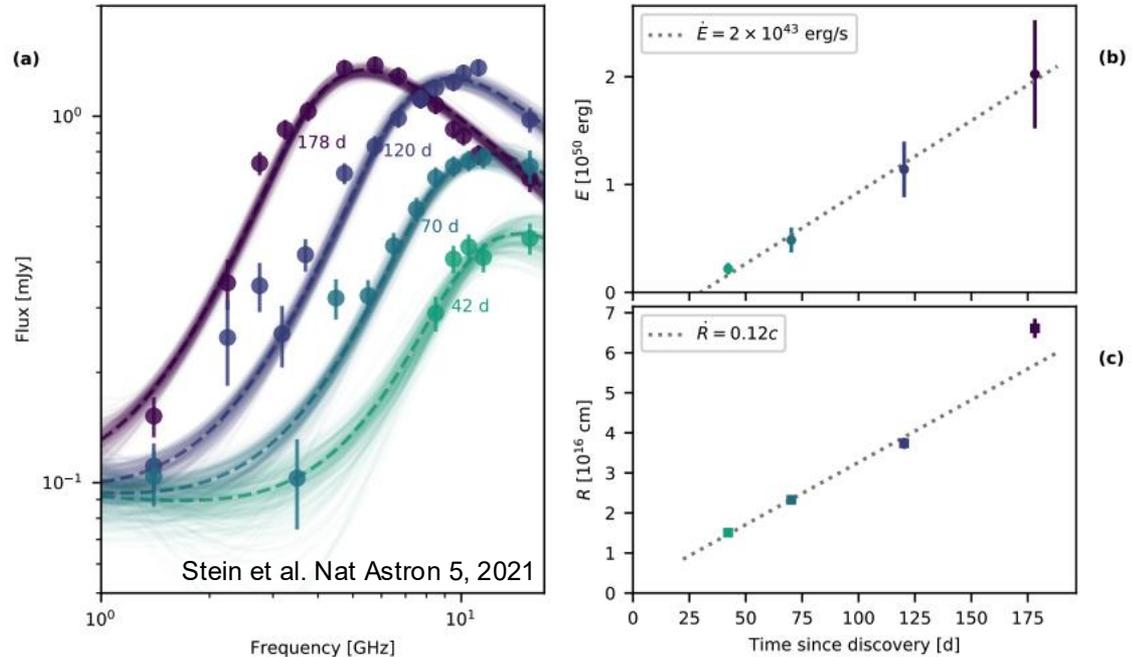


Spectroscopic classification
of neutrino counterpart
candidate SN2023uqf

Recommended observing timeline (TeV-PeV neutrino sources)

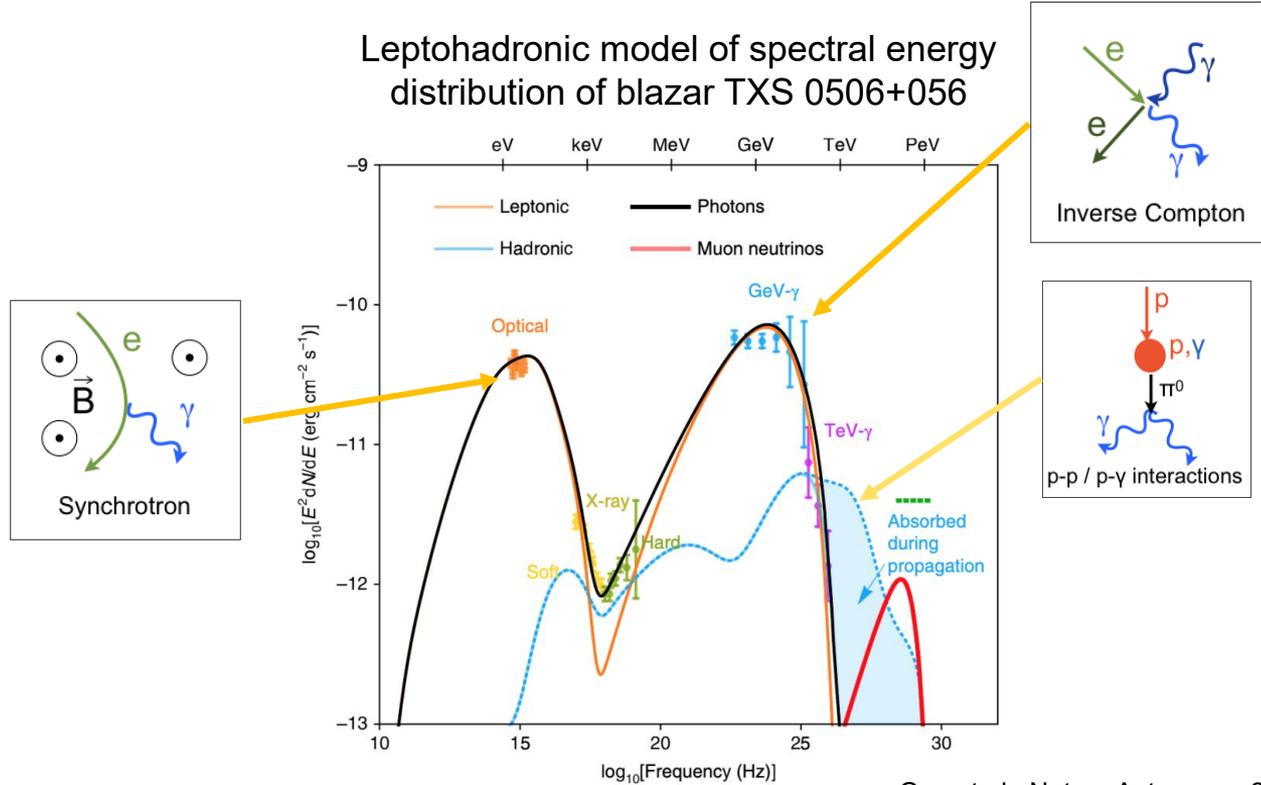
- T0 + 1–14 days: Monitoring of candidates multi-epoch coverage across all wavelength
- T0 + weeks–months: For confirmed interesting candidates: Monitor ejecta and environment evolution

Late time radio follow-up of candidate-neutrino TDE AT2019dsg



Recommended observing timeline (TeV-PeV neutrino sources)

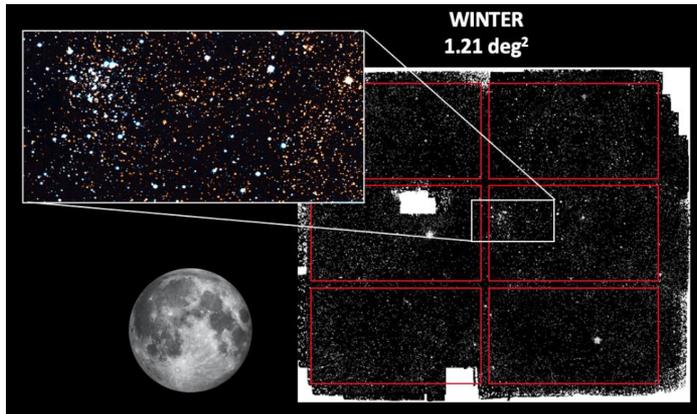
- Simultaneous multi-wavelength coverage important for modeling



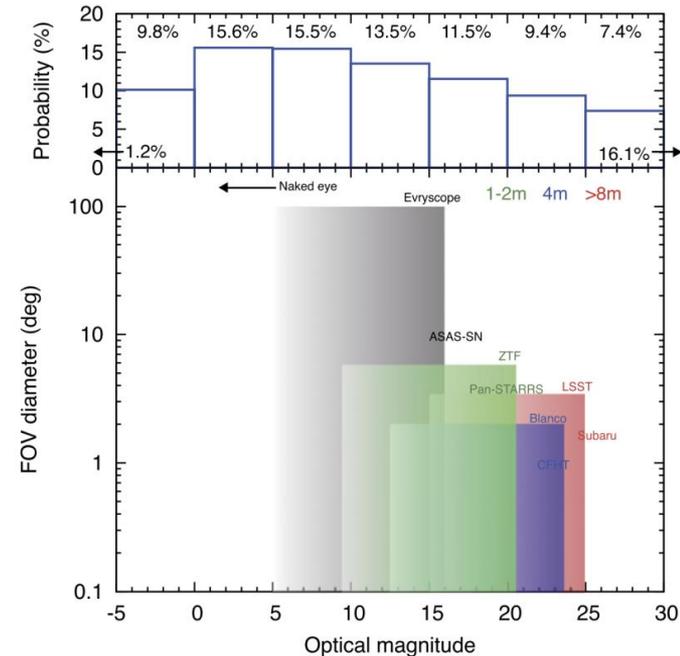
Gao et al., Nature Astronomy 2018

Recommended observing timeline (MeV Neutrinos from Galactic Supernova)

- T0 + 0–24 hr: Rapid-response triggers with wide-field-of view instruments (IR, optical, UV, X-ray) to catch shock breakout and localize source



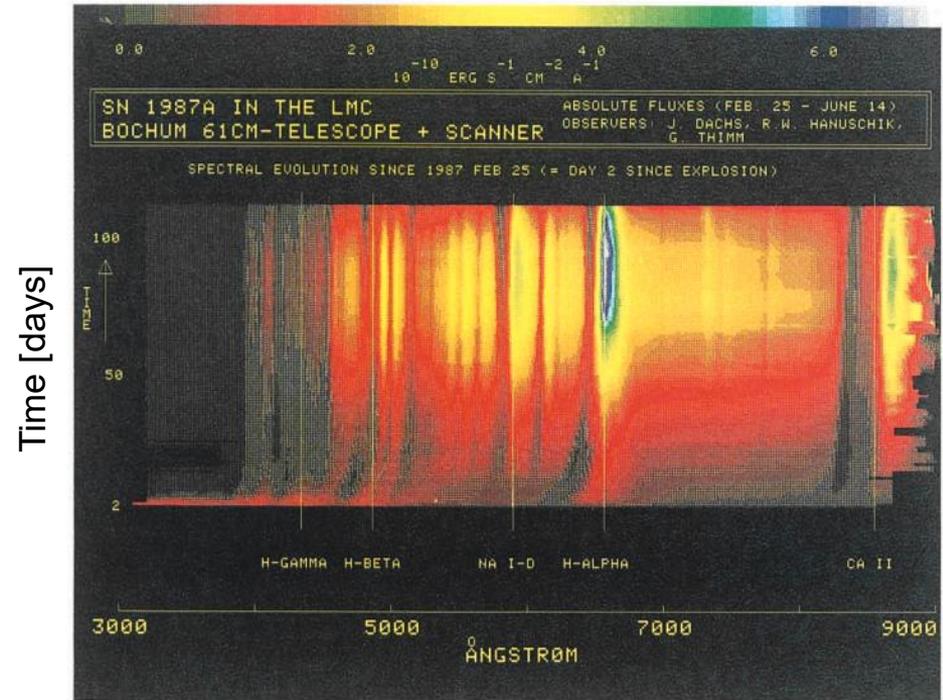
IR crucial for dust obscured sources (WINTER and PRIME)



Al Kharusi et al. New J. Phys. **23** 2021

Recommended observing timeline (MeV Neutrinos from Galactic Supernova)

- $T_0 + 24\text{h}$ – weeks-months: Monitor spectral evolution, ejecta and environment evolution in all wavelength



Open questions

What parameter space remains underexplored for this source?

- TeV-PeV: majority neutrino sources unknown (What are EM tracers? Where are neutrinos produced? What is production mechanism (pp or pgamma)? What is the particle acceleration mechanism?)
- MeV: Details of SN explosion models, neutron star equation of state

Open questions

What parameter space remains underexplored for this source?

- TeV-PeV: majority neutrino sources unknown (What are EM tracers? Where are neutrinos produced? What is production mechanism (pp or pgamma)? What is the particle acceleration mechanism?)
- MeV: Details of SN explosion models, neutron star equation of state

Are there new facilities coming online that will improve follow-up?

- Infrastructure: SNEWS 2.0, GCN over Kafka
- Neutrino detectors: KM3NeT, P-ONE, IceCube-Upgrade/Gen2, TRIDENT, HUNT, new technologies going to higher neutrino energies (RNO-G, Earth-skimming tau detection), Hyper-Kamiokande
- New realtime streams for IceCube: improvements in GeV range (important for novae) and in Southern hemisphere (important for Galactic sources)
- ULTRASAT, VRO, CTAO
- Important to have continuous support by Swift and Fermi-LAT

Open questions

What are the biggest limitations in current strategies?

- TeV-PeV: Not knowing source class
- Neutrino angular resolution
- Small number of high-energy neutrinos from individual extragalactic sources
- TeV-PeV: Poor sensitivity for Galactic events with IceCube → improved neutrino stream under development, KM3NeT in better location

Community coordination needs

Who Needs to Be Alerted: Neutrino telescopes, EM community (through SNEWS, GCN)

Preferred Alert Channels: SNEWS, GCN

Data Products and Timescales:

- MeV neutrinos: lightcurves
- TeV – PeV neutrinos: energy, time, p-Astro (community needs to agree on a common definition), angular uncertainty, false alarm rate (usually not trial corrected)
- EM: spectra, lightcurves

