

Fermi-LAT realtime follow-ups of high-energy neutrino alerts

S. Garrappa (DESY), S. Buson (Uni-Würzburg), A. Franckowiak (RU-Bochum, DESY), M. Giroletti (IRA-INAF) and I. Liodakis on behalf of the *Fermi*-LAT Collaboration, C. Nanci (UniBO,IRA-INAF)

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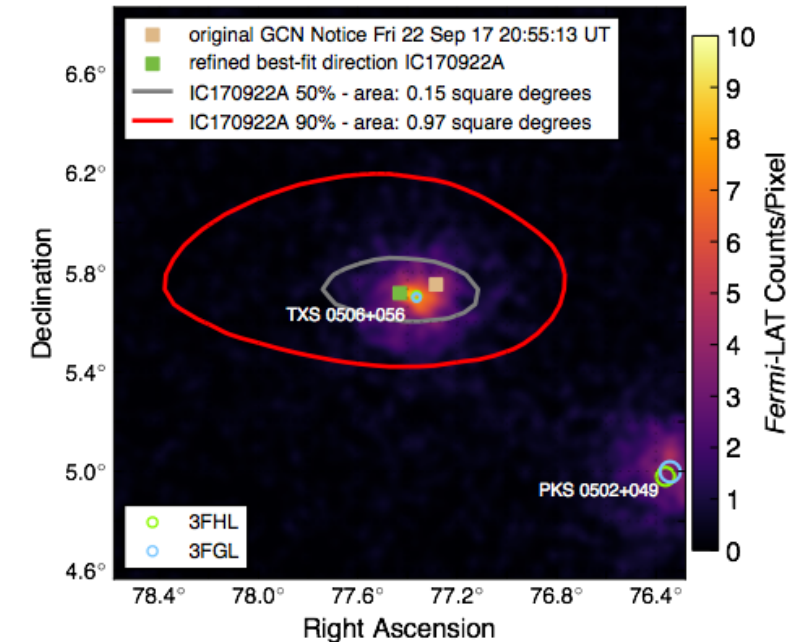
Online - Berlin, Germany

Gamma-ray and neutrinos

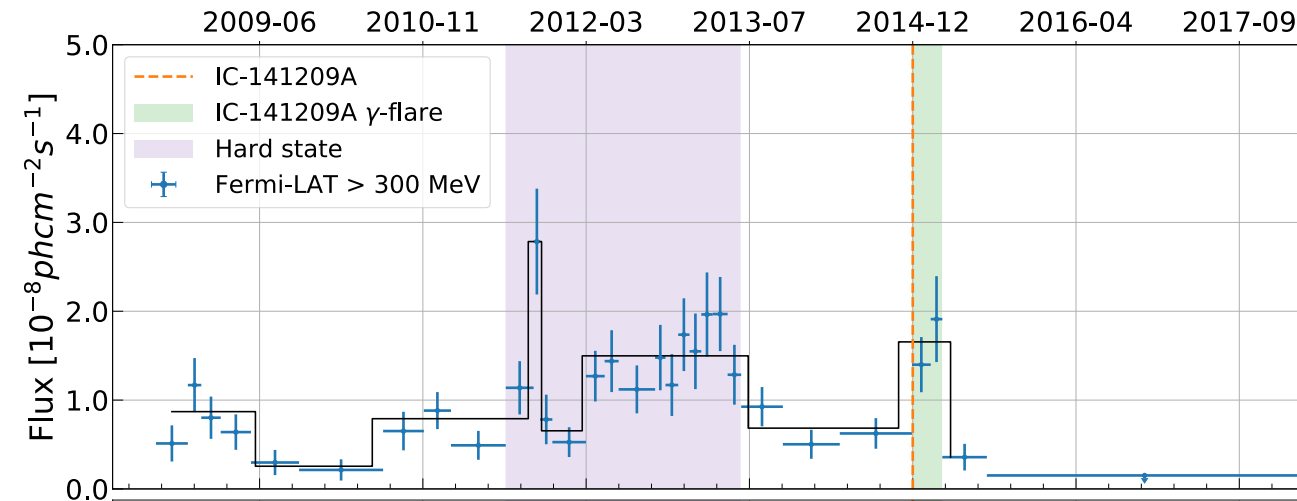
Fermi-LAT role in the multi-messenger astronomy

- Since 2016, *Fermi*-LAT follows up realtime detection of high-energy neutrinos
- IC170922A in spatial and temporal coincidence with the flaring blazar TXS 0506+056
 - *Fermi*-LAT observations triggered an extensive multi-wavelength campaign
- So far the the most significant neutrino source candidate association (3σ)
- More associations identified from archival LAT observations
 - IceCube events detected before 2016
- Examples are GB6 J1040+0617 (SG et al. 2019) and PKS 1424-41 (Kadler et al. 2016)
- Realtime programs are crucial to obtain multi-wavelength observations of interesting candidates

Aartsen et al. 2018, Science 361



GB6 J1040+0617

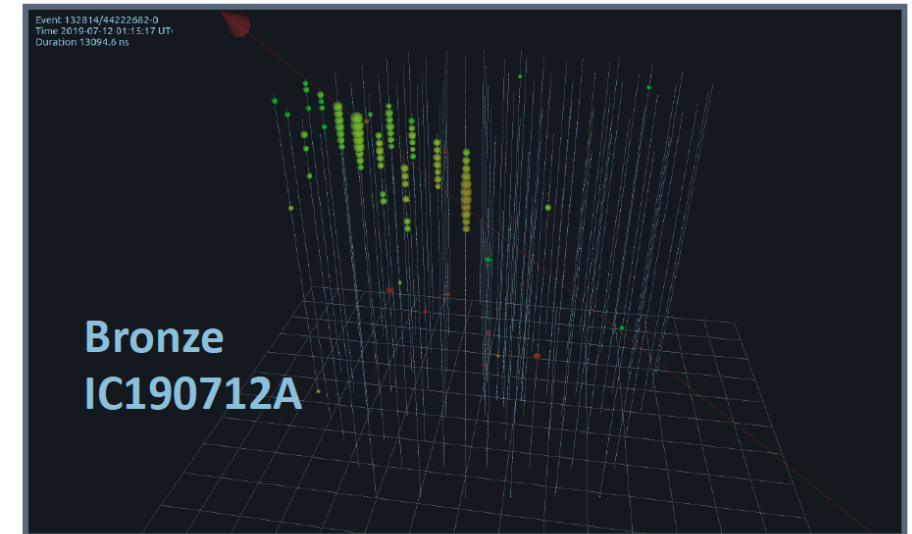
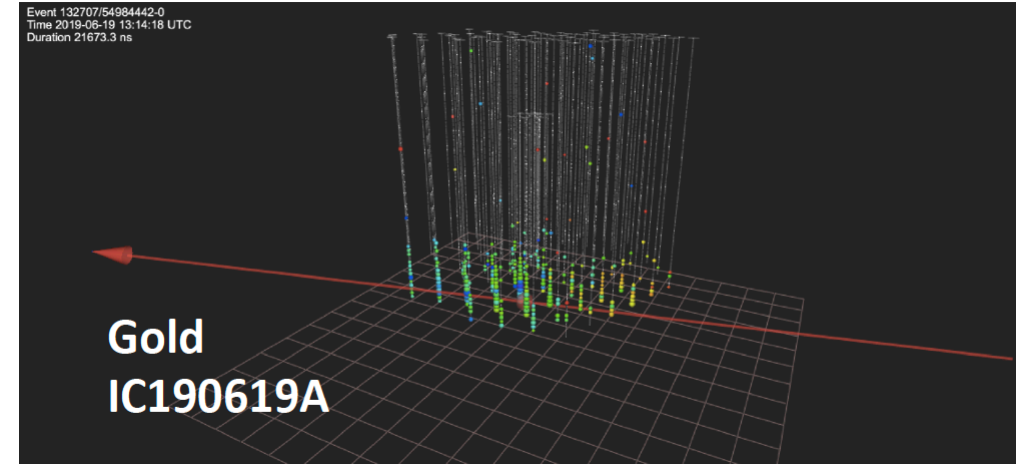


SG, S. Buson, A. Franckowiak et al. 2019, ApJ 880 103

The IceCube Realtime alerts system v2.0

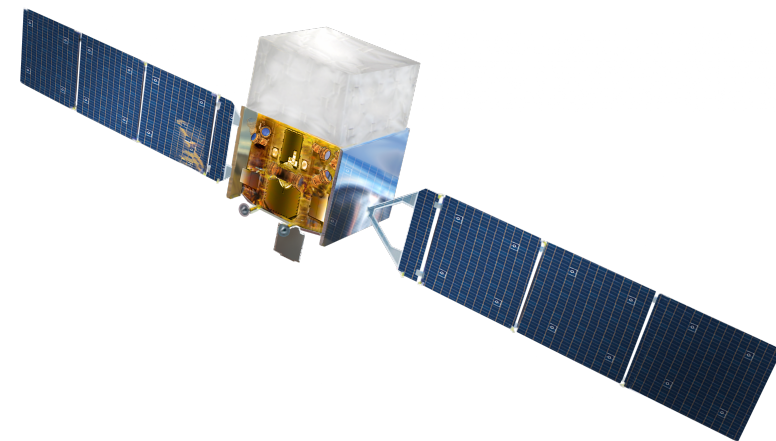
- New realtime stream started in June 2019
- Classification based on event signalness (probability of being of astrophysical origin)
- Increased event rate compared to the old EHE/HESE streams

Updated alerts	Gold	Bronze
Signalness	> 50%	>30%
Expected signal/yr	6.6	2.8
Expected bkgd/yr	6.1	14.7

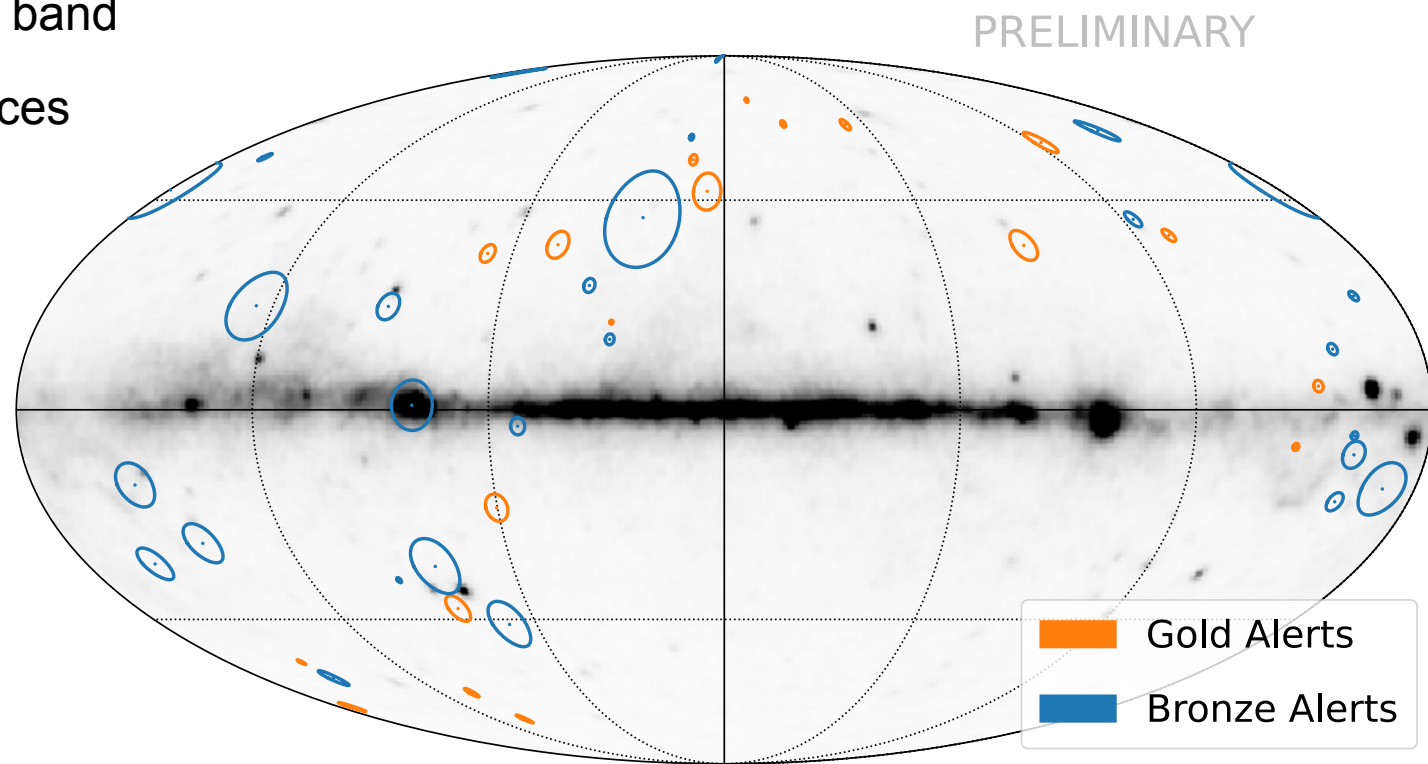


D. Williams (ICRC 2019)

Follow-up observations with *Fermi*-LAT



- *Fermi*-LAT all-sky survey:
 - Full sky coverage every ~3hrs
 - Point source analysis in 100 MeV - 1TeV band
 - 4FGL-DR2 catalog containing 5064 sources (10 years of observations)
- Follow-up of all alerts in the IceCube realtime stream 2.0 (as of June 18, 2021):
 - Total of 46 realtime alerts
 - 19 **Gold**
 - 27 **Bronze**



Follow-up observations with *Fermi*-LAT

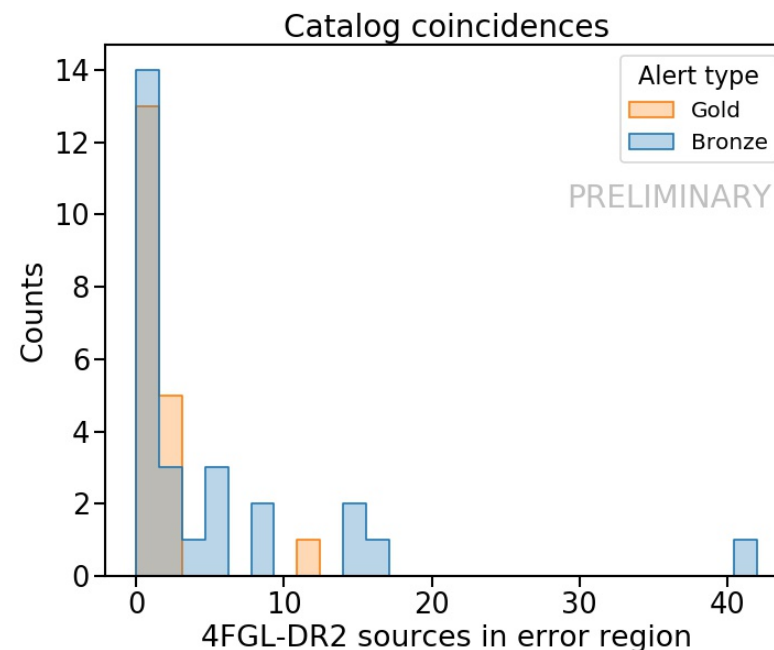
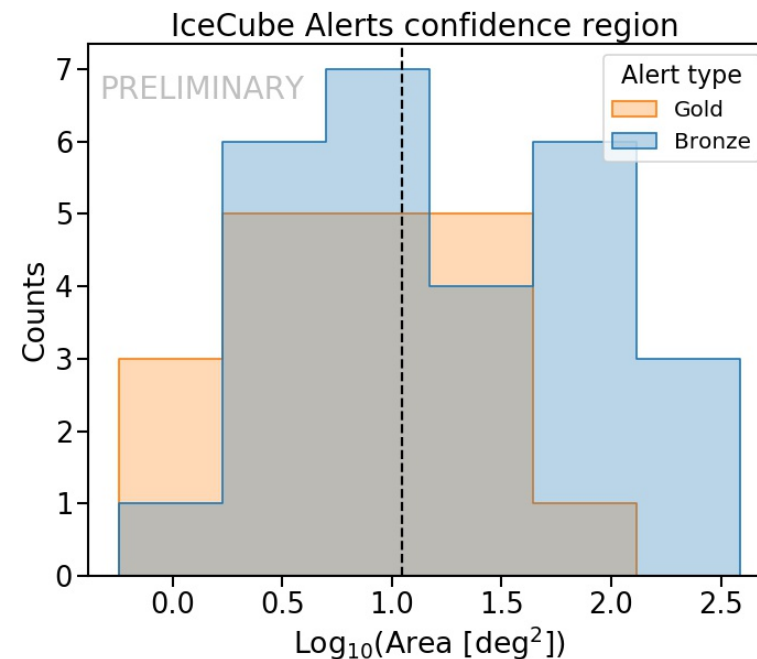
Analysis strategy

- Systematic analysis of sky regions around the neutrino direction
- We investigate 3 timescales during a standard follow-up (T_0 = neutrino detection time):
 - 1-day before T_0 : Detect fast, bright transients coincident with the neutrino
 - 1-month before T_0 : Detect recent transients, sources in bright state (with time lags consistent with the most credited models)
 - Full-mission data: Detect weak gamma-ray sources out of LAT catalogs and coincident with neutrino position
- In the case of significant detection of a transient at 1-day or 1-month timescales, dedicated lightcurve analyses are performed up to 1-year timescale before T_0 .
- In the case of a non-detection at the best-fit position of the neutrino, 95% CL upper limits are reported, correspondent to the detection of a power-law source (index 2.0).
- Reports are sent via GCN Circulars/ATels

Follow-up observations with *Fermi*-LAT

Results

- Neutrino 90% containment regions from 0.57 deg² up to 385 deg².
- Median extension from full sample: 11.4 deg²
 - 5.6 deg² for Gold alerts
 - 13.4 deg² for Bronze alerts
- 20 events (43%) have no coincident sources in 4FGL-DR2
- 7 events have a single 4FGL-DR2 candidate
- With a 4FGL-DR2 source density of ~ 0.12 deg⁻² (~ 0.07 deg⁻² for 4LAC sources) we still expect a non-negligible rate of random chance coincidences



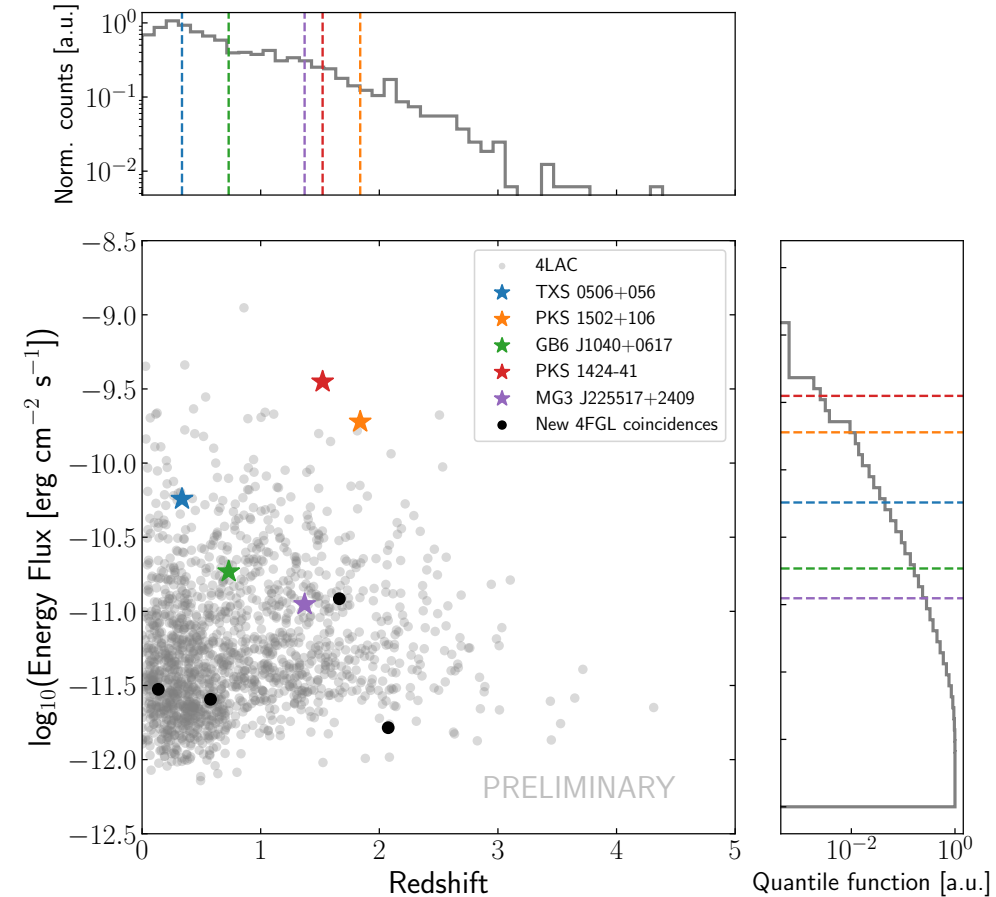
Follow-up observations with *Fermi*-LAT

Results

- Selection of well-reconstructed alerts:
 - 90% containment smaller than observed median (11.4 deg²)
- 23 alerts left in the sample (12 Gold, 11 Bronze)
 - Only 7 with at least one 4FGL source coincident
- Gamma-ray brightness might be correlated with single high-energy neutrino emission (Franckowiak, SG et al. 2020)

4FGL Name	Class ¹	E.Flux [erg cm ⁻² s ⁻¹]	Redshift	Event	Type	Sig.
J1504.4+1029	FSRQ	$(1.9 \pm 0.02) \times 10^{-10}$	1.84	IC190730A	Gold	0.67
J0946.2+0104	BL Lac	$(2.55 \pm 0.55) \times 10^{-12}$	0.577	IC190819A	Bronze	0.29
J1003.4+0205	BCU	$(1.64 \pm 0.39) \times 10^{-12}$	2.075	IC190819A	Bronze	0.29
J0658.6+0636	BCU	$(3.7 \pm 0.73) \times 10^{-12}$	-	IC201114A	Gold	0.56
J0206.4-1151	FSRQ	$(1.22 \pm 0.06) \times 10^{-11}$	1.663	IC201130A	Gold	0.15
J1342.7+0505	BL Lac	$(2.98 \pm 0.49) \times 10^{-12}$	0.13663	IC210210A	Gold	0.65
J1747.6+0324	unid.	$(7.03 \pm 0.92) \times 10^{-12}$	-	IC210510A	Bronze	0.28

¹Classification in 4FGL-DR2



Adapted from: A. Franckowiak, SG et al. 2020, ApJ 893, 2, 162

Follow-up observations with *Fermi*-LAT

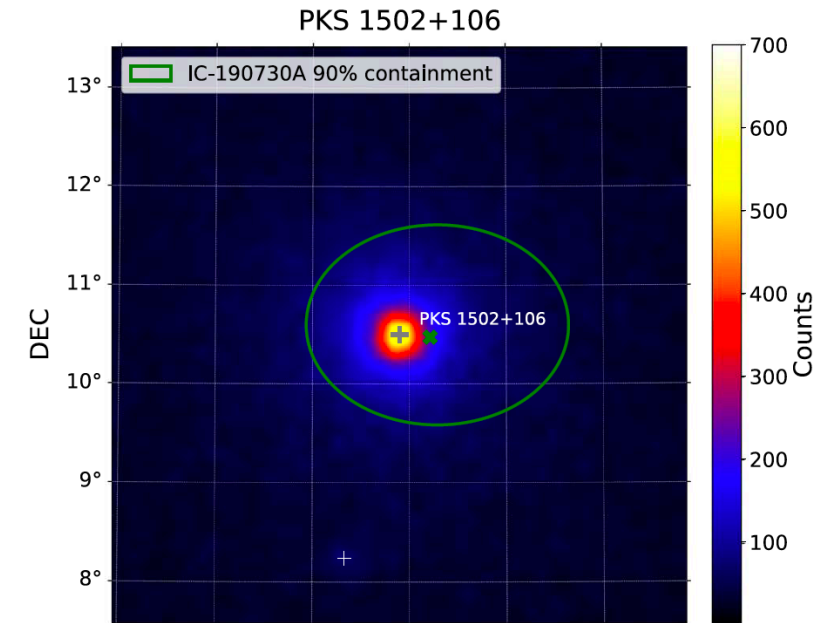
Outstanding coincidences with a single candidate counterpart

IceCube-190730A and PKS 1502+106

- Gold alert with 67% signalness, well-reconstructed
- PKS 1502+106 is a FSRQ with a large redshift of $z = 1.84$
 - It is the 15th brightest blazar in the 4LAC catalog
- Detected in low gamma-ray state at neutrino arrival
- Neutrino production supported by several works (Rodrigues+2021, Britzen+ 2021, Plavin+ 2021)

IceCube-201114A and NVSS J065844+063711

- Gold alert with 56% signalness, well-reconstructed
- Known high-energy emitter (3FHL catalog), detection up to 155 GeV
- Not significantly detected in LAT data at short timescales
- Rich multi-wavelength campaign right after neutrino detection
- Preliminary results in R. de Menezes talk (ICRC 2021)



A. Franckowiak, SG et al. 2020, ApJ 893, 2, 162

Summary

- *Fermi*-LAT has a key role in the identification of neutrino counterparts
- *Fermi*-LAT is continuously improving its follow-up strategies towards a faster and more detailed reporting of observations
 - Prompt triggers to multi-wavelength facilities on interesting target candidates
- The LAT team is also involved in active proposals for multi-wavelength follow-up observations:
 - European VLBI Network (EVN), Nordic Optical Telescope (NOT), Skinakas Observatory, *Swift*-XRT and more.

We are ready for the next outstanding neutrino candidate source!