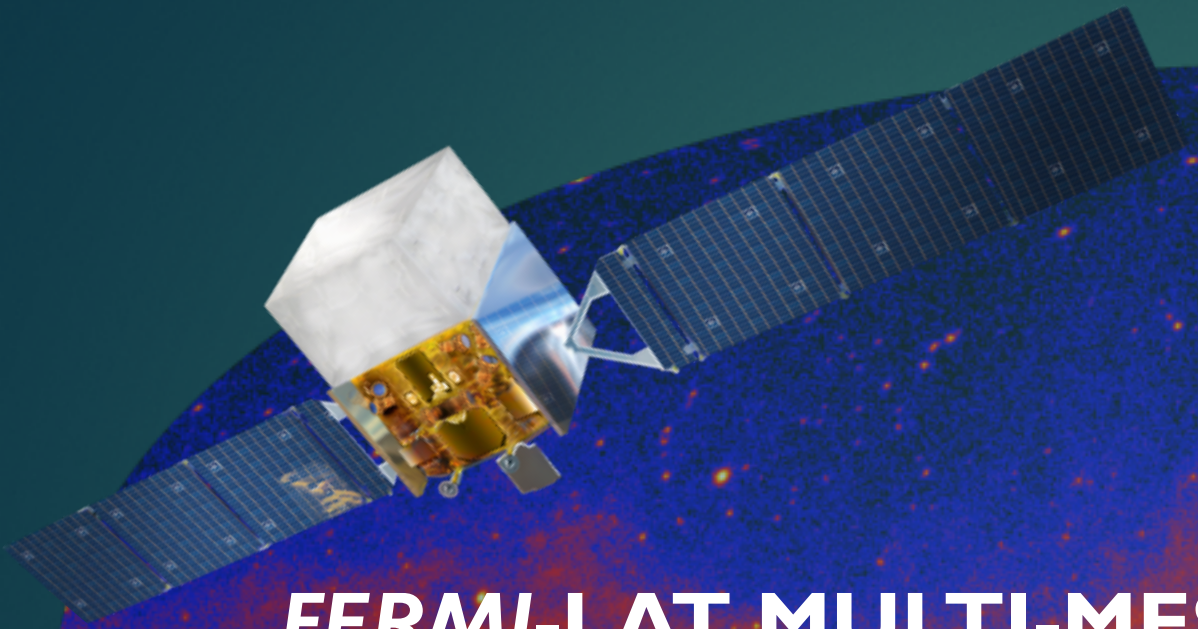


FERMI-LAT MULTI-MESSENGERS FOLLOW UP
FOCUS ON HIGH-ENERGY NEUTRINOS / AGN

SARA BUSON*

S. GARRAPPA,

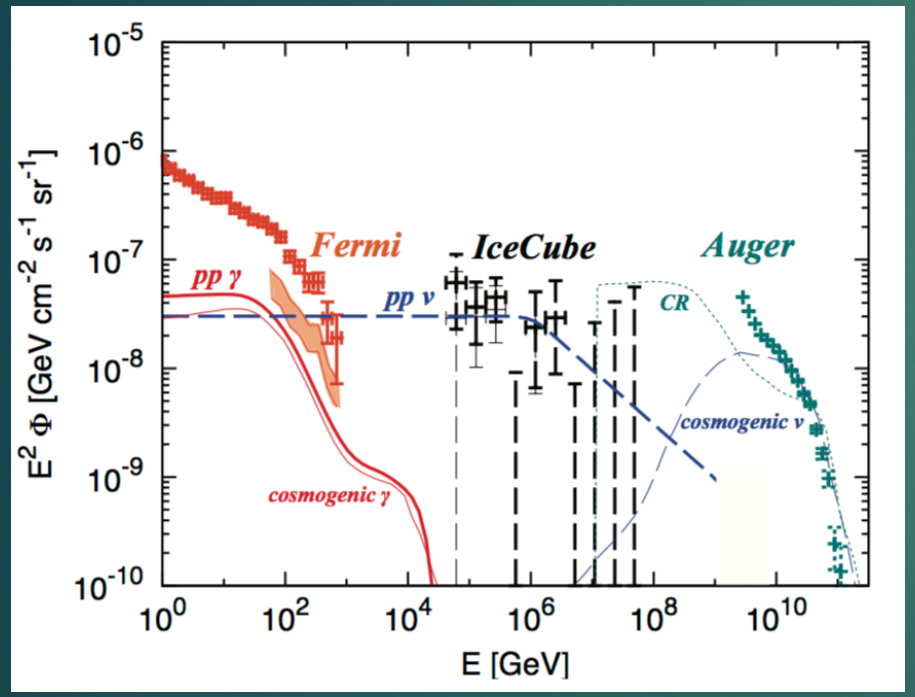
ON BEHALF OF THE FERMI-LAT COLLABORATION

***UNIVERSITY OF WÜRZBURG**

Low-latency alerts & Data analysis for MMA Workshop @Paris

Zoom, 13.01.2022

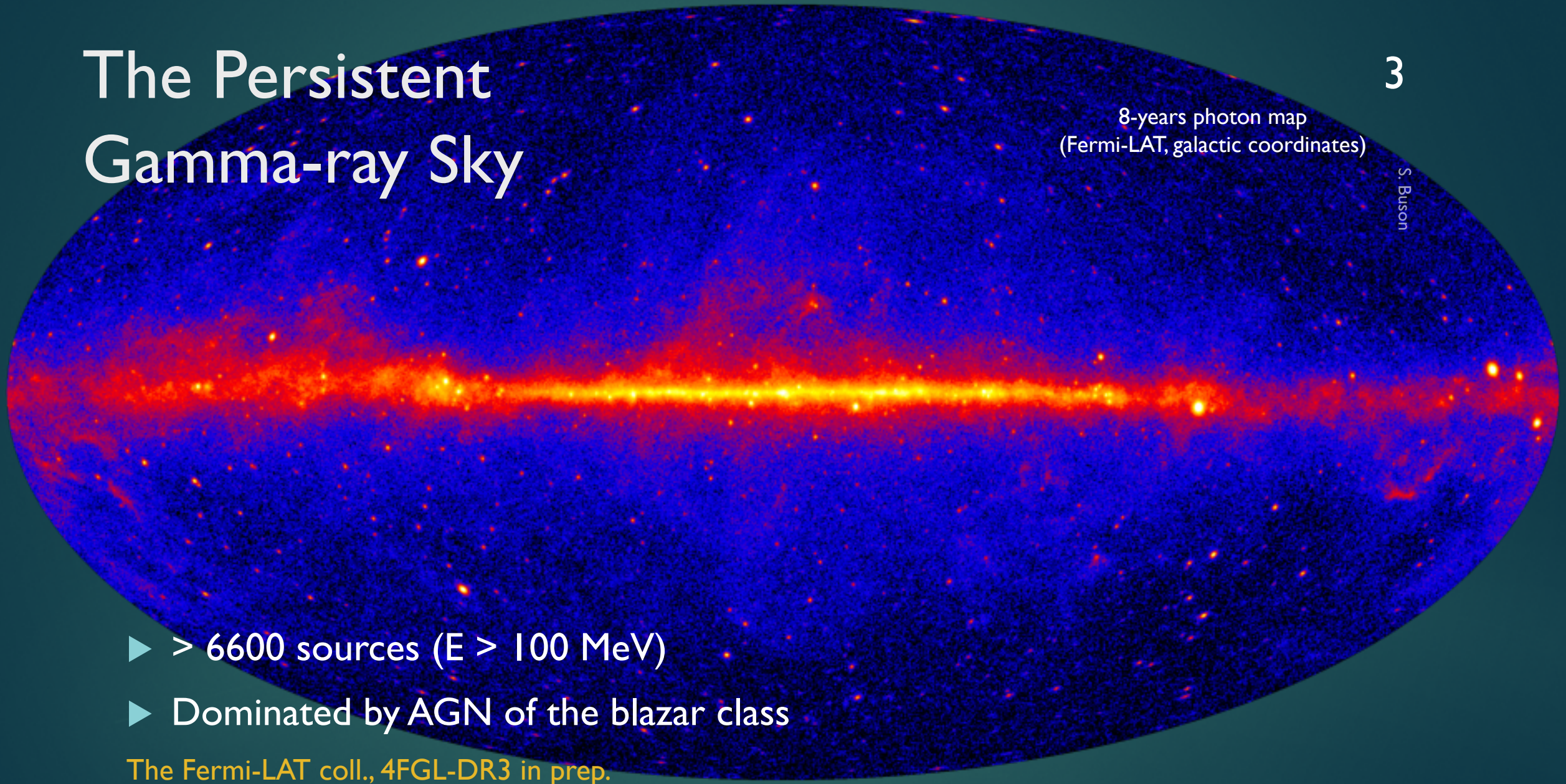
Energy Density in the Universe in γ rays, neutrinos and cosmic rays is similar



Murase & Waxam 2016

Diffuse energy fluxes of sub-TeV γ rays, PeV neutrinos, and UHECRs are all comparable, while particle energy spans over ten orders of magnitude.

The Persistent Gamma-ray Sky



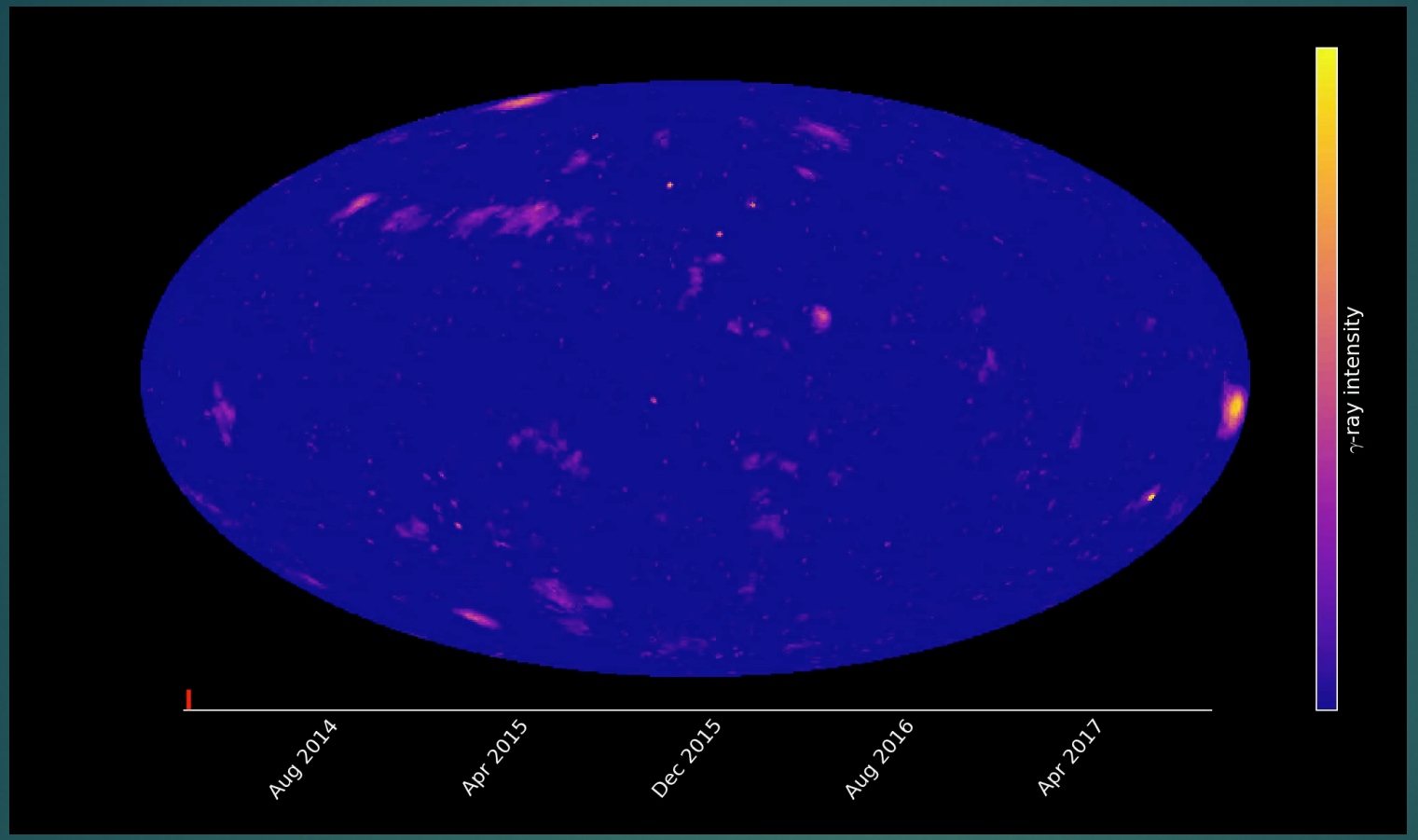
8-years photon map
(Fermi-LAT, galactic coordinates)

S. Buson

- > 6600 sources (E > 100 MeV)
- Dominated by AGN of the blazar class

The Fermi-LAT coll., 4FGL-DR3 in prep.

The Variable Gamma-ray Sky



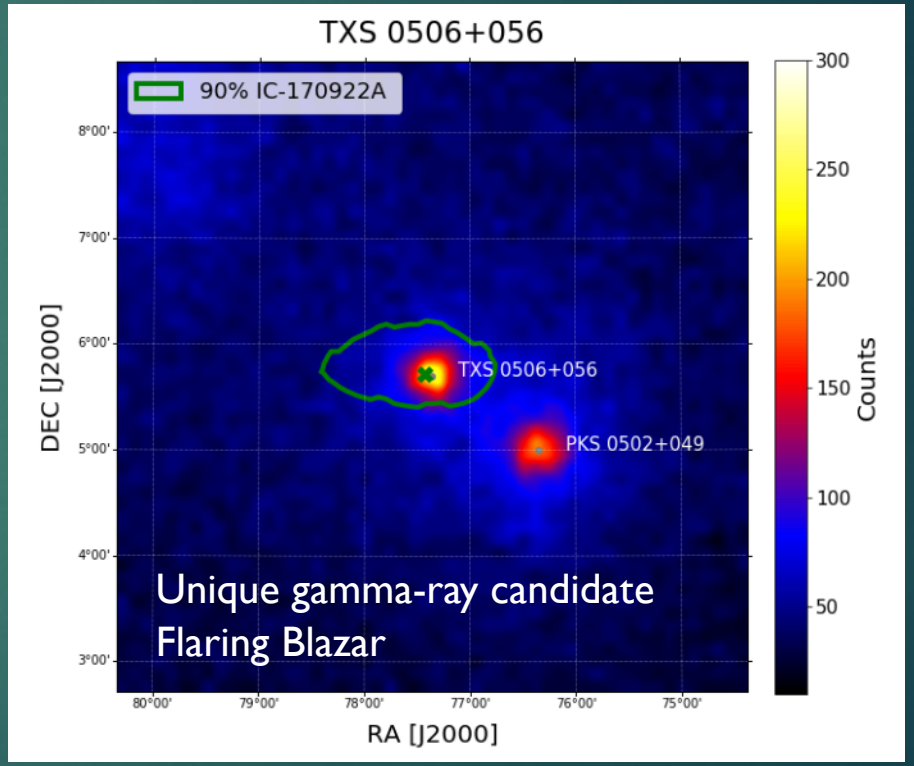
- Flare Advocates daily monitoring; FAVA weekly monitoring
- Lightcurve repository enables to track variability of some 4FGL-DR2 blazars: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

Cosmic neutrinos may originate in blazars - a first compelling neutrino candidate

IC 170922A & TXS 0506+056

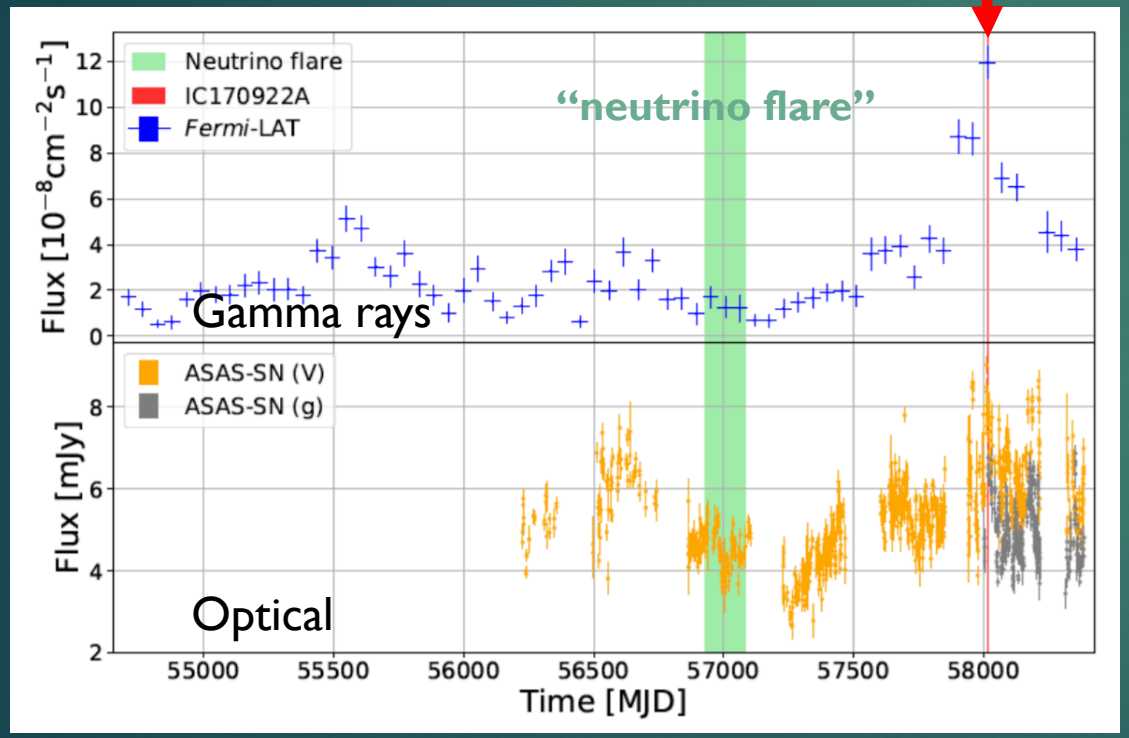
- Intriguing high-energy *Neutrino/Blazar* Association
  - High-energy neutrino event with >183TeV
  - Flaring γ–ray blazar (Tanaka, SB+ Atel#10791)
  - ~3σ post-trial chance coincidence correlation
- Lepto-hadronic models can adequately explain the observations (IC170922A)

IceCube, Fermi, MAGIC+ Science 361, 146 2018



Garrappa, SB+ 2019 ApJ

Observations challenge theoretical interpretation



Reimer, Böttcher and SB 2019

- Substantially different electromagnetic behavior during time periods of putative neutrino emissions
- Models producing neutrinos and γ rays require leptonic-dominated γ-ray production!
- Multiple neutrino emission regions in blazar jets ?
- *Multiple neutrino physical processes in blazar jets ?*

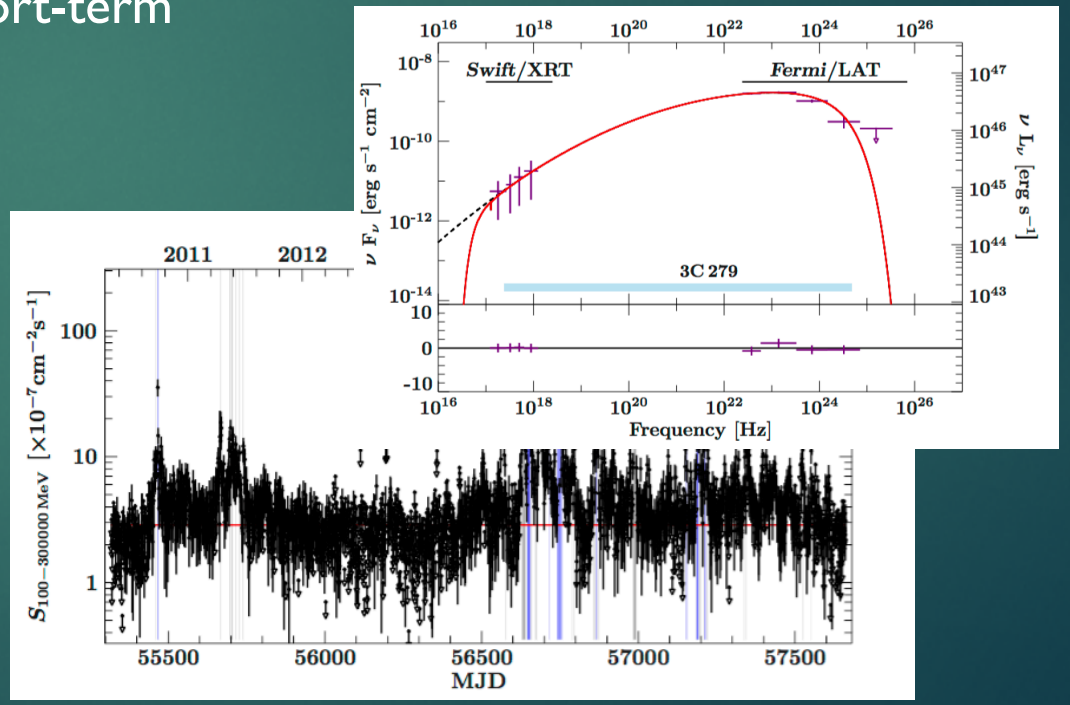
(e.g. Garrappa, SB et al. 2019, Rodrigues+ 2019, Halzen+ 2019, Petropoulou+ 2020, Kun+ 2020)

High-energy neutrinos from individual blazar flares

- Fluence of most individual blazar flares is too small to yield a substantial probability for the detection of one or more neutrinos with IceCube
- Absolute neutrino expectation for short-term blazar flares is negligible

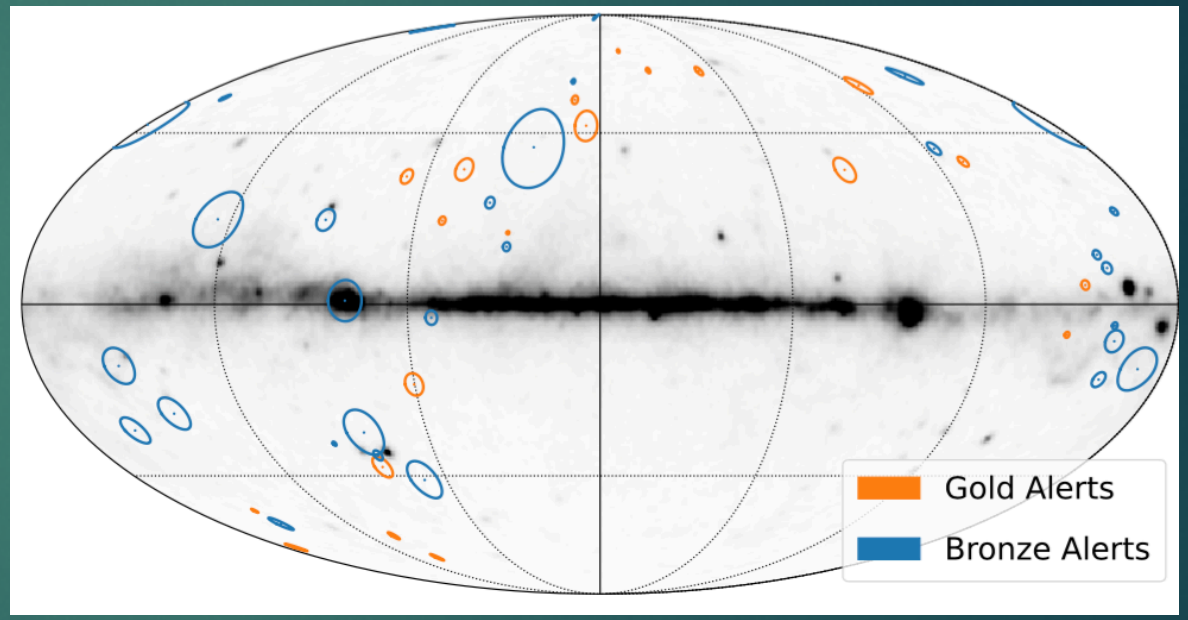
Possible contribution from individual flaring sources to the IceCube neutrino diffuse flux is modest, still possible for long-term flares

E.g. Kreter, … SB+ 2020, Oikonomou+ 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 Jan 12, 2022):
  - Total of 56 realtime alerts
    - 22 **Gold**
    - 34 **Bronze**



Garrappa, SB et al. ICRC 2021 (arXiv:2112.11586)

*** Newer observation strategy in place due to solar panel issue leads to exposure gaps up to a ~week**

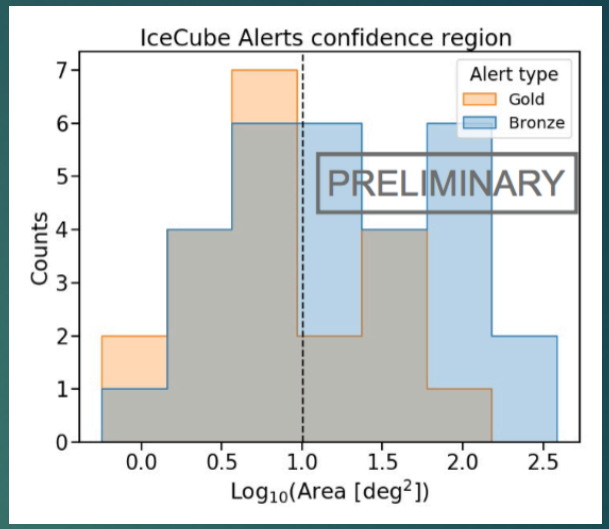
Follow-up observations with *Fermi*-LAT -- Analysis strategy

- Systematic analysis of LAT sky regions around the neutrino direction
- Investigate 3 timescales during a pre-defined follow-up (T_0 = neutrino detection time):
  - One-day before T_0: Detect fast, bright transients coincident with the neutrino
  - One-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 not (yet) included in LAT catalogs and positionally consistent with neutrino localization
- When a transient is detected in the one-day or one-month timescales, dedicated lightcurve analyses are performed up to one-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, corresponding to the detection of a power-law source (index 2.0).
- Findings released via GCN Circulars/ATels

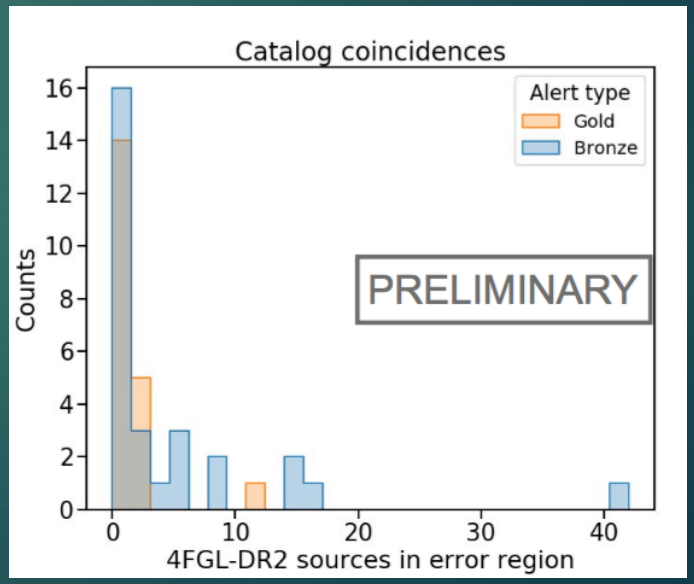
Follow-up observations with *Fermi*-LAT -- Results

- Neutrino 90% containment regions from 0.57 deg^2 up to 385 deg^2
- Median extension from full sample: 10.2 deg^2
  - 5.5 deg^2 for Gold alerts
  - 12.2 deg^2 for Bronze alerts
- 22 events (45%) have no coincident sources in 4FGL-DR2
- 8 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

(Based on follow up alerts up to Sep 13, 2021)



Garrappa, SB et al. ICRC 2021 (arXiv:2112.11586)



Follow-up observations with *Fermi*-LAT -- Results

- Selection of well-reconstructed alerts:
  - 90% containment smaller than observed median (10.2 deg^2)
  - 23 alerts left in the sample (12 Gold, 11 Bronze) Only 7 with at least one 4FGL source coincident

4FGL Name	Class[1]	E.Flux [erg cm^{-2} s^{-1}]	Redshift	Event	Type	Sig.
J1504.4+1029	FSRQ	$(1.9 \pm 0.02)\times10^{-10}$	1.84	IC190730A	Gold	0.67
J0946.2+0104	BL Lac	$(2.55 \pm 0.55)\times10^{-12}$	0.577	IC190819A	Bronze	0.29
J1003.4+0205	BCU	$(1.64 \pm 0.39)\times10^{-12}$	2.075	IC190819A	Bronze	0.29
J0658.6+0636	BCU	$(3.7 \pm 0.73)\times10^{-12}$	-	IC201114A	Gold	0.56
J0206.4-1151	FSRQ	$(1.22 \pm 0.06)\times10^{-11}$	1.663	IC201130A	Gold	0.15
J1342.7+0505	BL Lac	$(2.98 \pm 0.49)\times10^{-12}$	0.13663	IC210210A	Gold	0.65
J1747.6+0324	unid.	$(7.03 \pm 0.92)\times10^{-12}$	-	IC210510A	Bronze	0.28

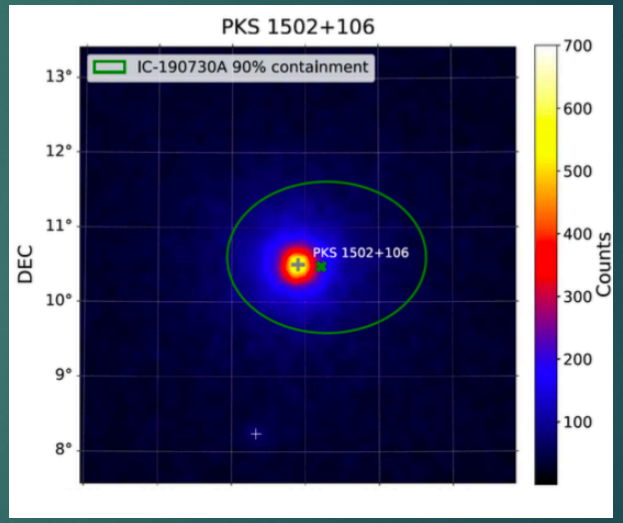
[1]Classification in 4FGL-DR2

Garrappa, SB et al. ICRC 2021 (arXiv:2112.11586)

Follow-up observations with *Fermi*-LAT -- Remarkable coincidences with a single candidate counterpart

IceCube-190730A and PKS 1502+106

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



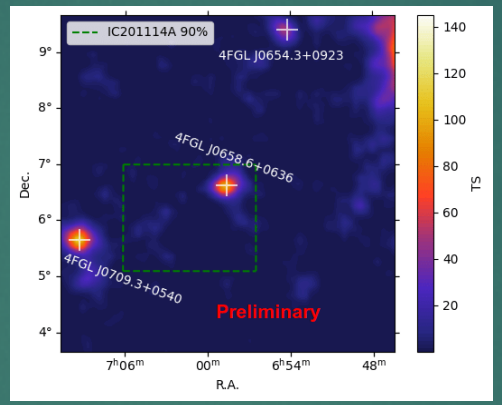
Franckowiak et al. 2020, ApJ 893, 2, 162

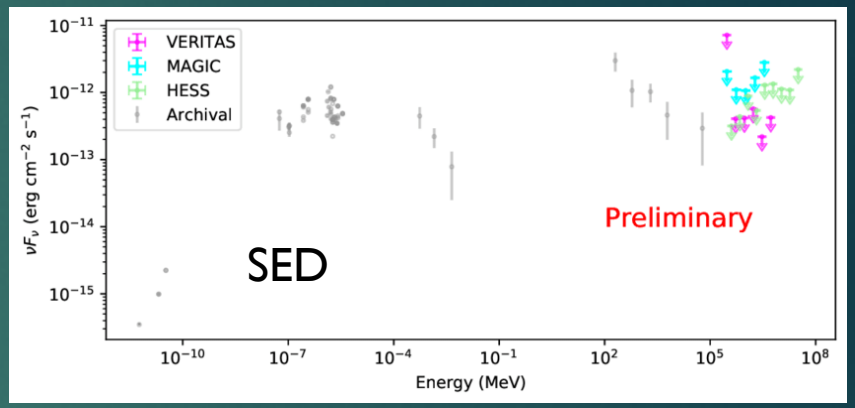
Follow-up observations with *Fermi*-LAT -- Remarkable coincidences with a single candidate counterpart

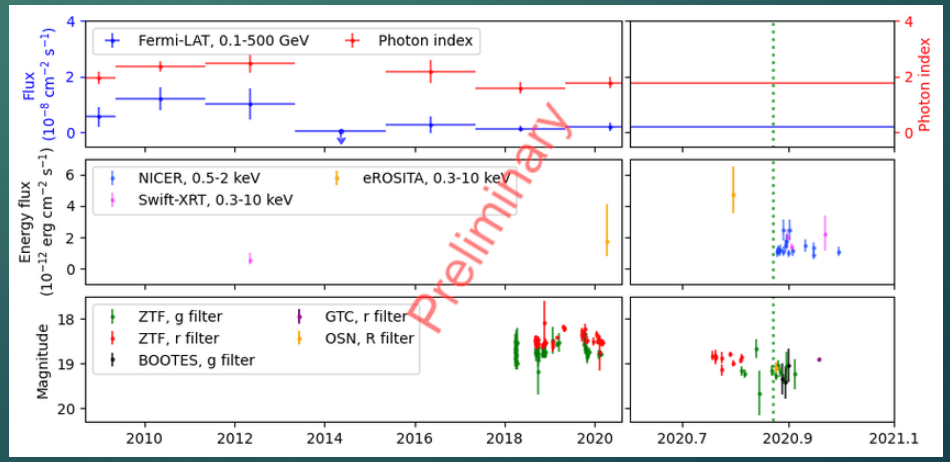
S. Buson

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 de Menezes, SB et al. (ICRC 2021), de Menezes et al in prep.



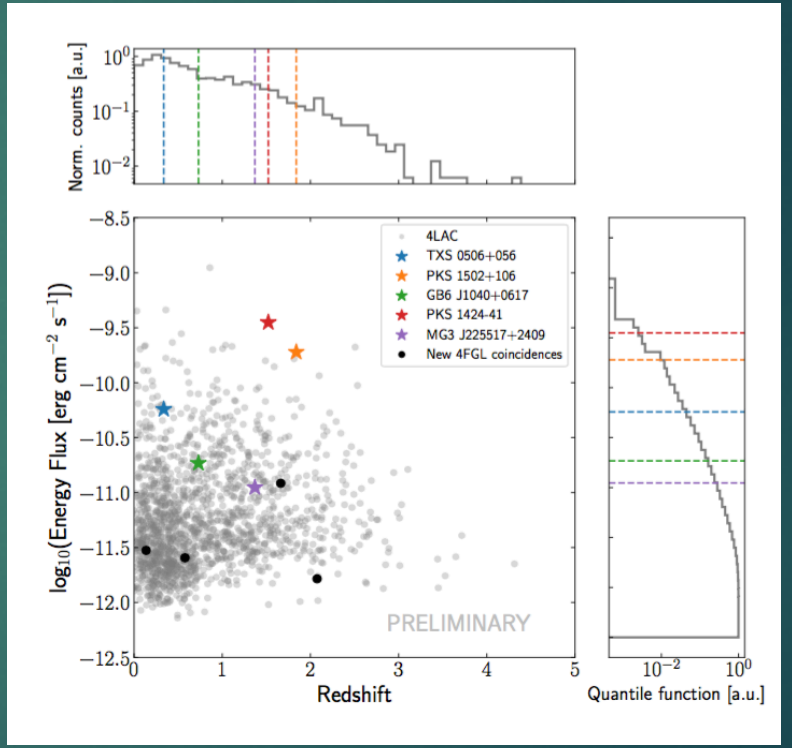




Follow-up observations with *Fermi*-LAT -- Results

Patterns in the Behavior of γ-ray-Candidate Neutrino Blazars

- Neutrino-emitting blazar candidates are statistically compatible with hypotheses of both a linear correlation and no correlation between neutrino and gamma-ray energy flux.



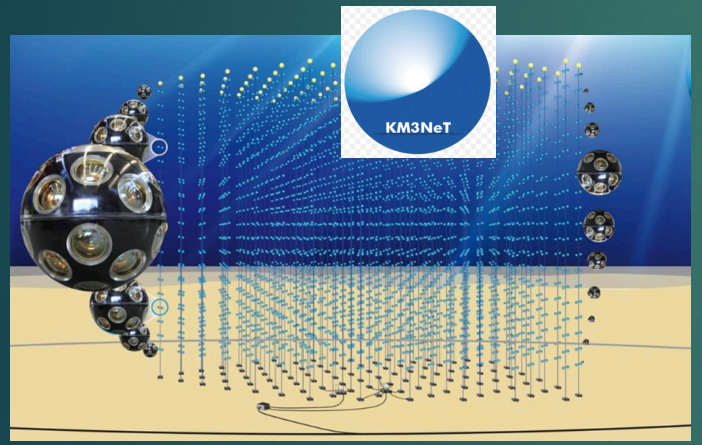
Garrappa, SB et al. ICRC 2021 (arXiv:2112.11586)
Adapted from Franckowiak, .. SB et al 2020

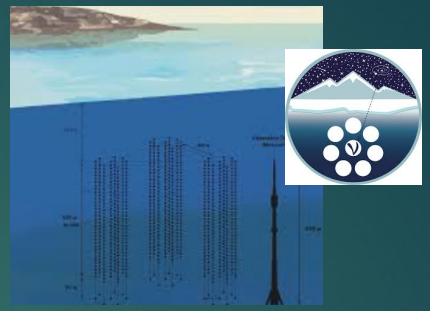
Bright g-ray blazars are only the "tip of the iceberg"

- It has to be kept in mind that a small fraction of the total observed γ-ray emission of all blazars is associated with the brightest individual objects.
- Only ~ 70% of the blazar γ-ray emission has been resolved into point sources so far by *Fermi*-LAT.
- For any high-energy neutrino event, there will always remain a large probability of being associated with the population of faint and/or remote sources, which are not individually resolved.

Forthcoming Decade

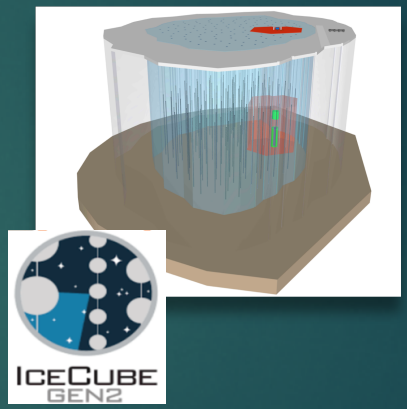
KM3Ne T-ARC A
1 km^3 volume
< 0.1° angular resolution for **tracks**
< 2° angular resolution for **showers**

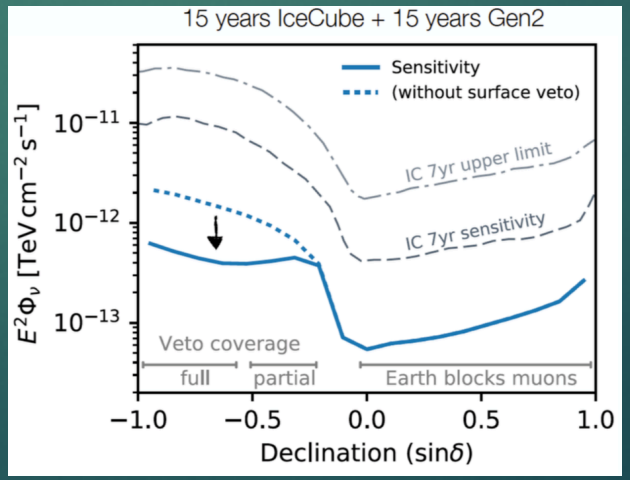




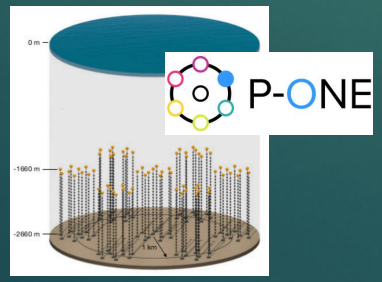
Baikal-GVD
1 km^3 volume
0.25°-0.5° angular resolution for **tracks**
3.5°-5.5° angular resolution for **cascades**

IceCube-Gen2
10x larger than IceCube
< 0.3° angular resolution for **tracks**
< 5° angular resolution for **cascades**





P-ONE
New R&D
Agostini+ 2020



More in the afternoon session

Summary

- *Fermi*-LAT keeps playing 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
- LAT team is also involved in active proposals for multi-wavelength follow-up observations

Future "wish-list":

- Common standards for cross-detectors analysis
- Long-term strategy for the release of these data to the broader community (similarly to e.g. g-ray, gravitational waves ..)
- Independent confirmation of constraints / detections
- Extension of the sensitivity to higher-neutrino energies also employing new promising detection techniques, e.g. radio-neutrino detectors such as ARIANNA, GRAND, RNO, ..
- Enhanced cooperation e.g. GNN: https://www.globalneutrinonetwork.org

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