Multi-messenger programs searching for VHE gamma-ray emission associated with high-energy neutrinos

F. Schüssler, H. Ashkar, E. Bernardini, A. Berti, F. Bradascio, S. Buson, D. Dorner, W. Jin, G. Kukec Mezek, M. Santander, K. Satalecka, B. Schleicher, M. Senniappan, I. Viale, et al.

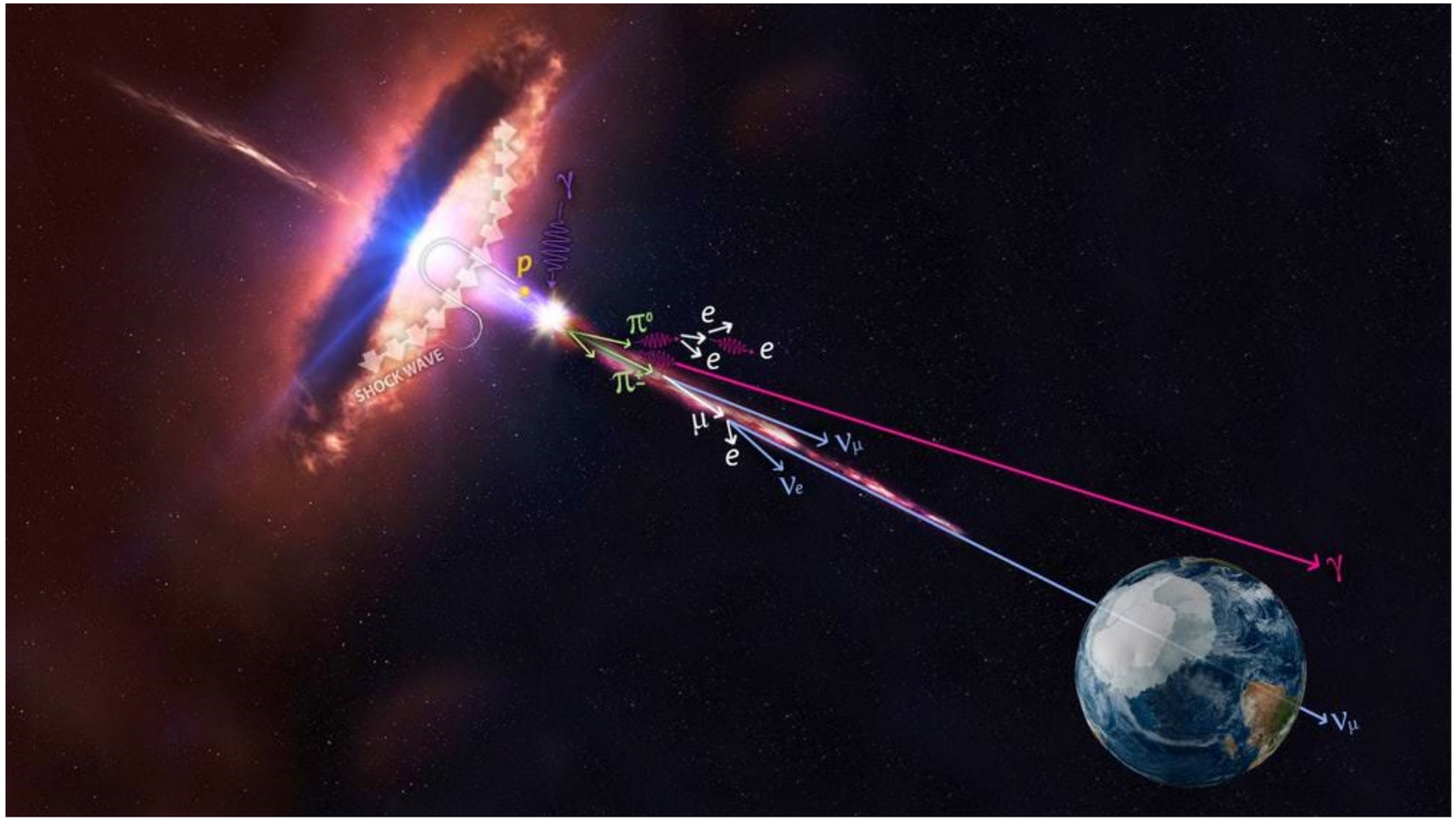
Contributions from the FACT, Fermi-LAT, H.E.S.S., IceCube, MAGIC and VERITAS collaborations

cea irfu

Multi-messenger astrophysics in a nutshell

- **Space (and time !!) correlations** would provide ”smoking gun” signal for joint emission processes

=> CR interaction/acceleration

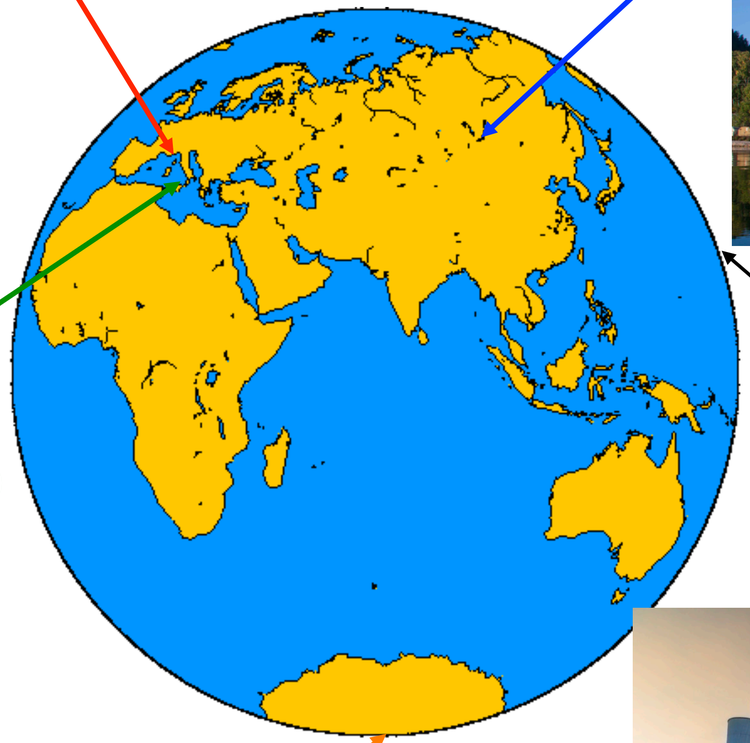


cf. introduction by Volodymyr Savchenkov

Neutrino telescopes: monitoring the neutrino sky

ANTARES: La-Seyne-sur-Mer, France

BAIKAL: Lake Baikal, Siberia

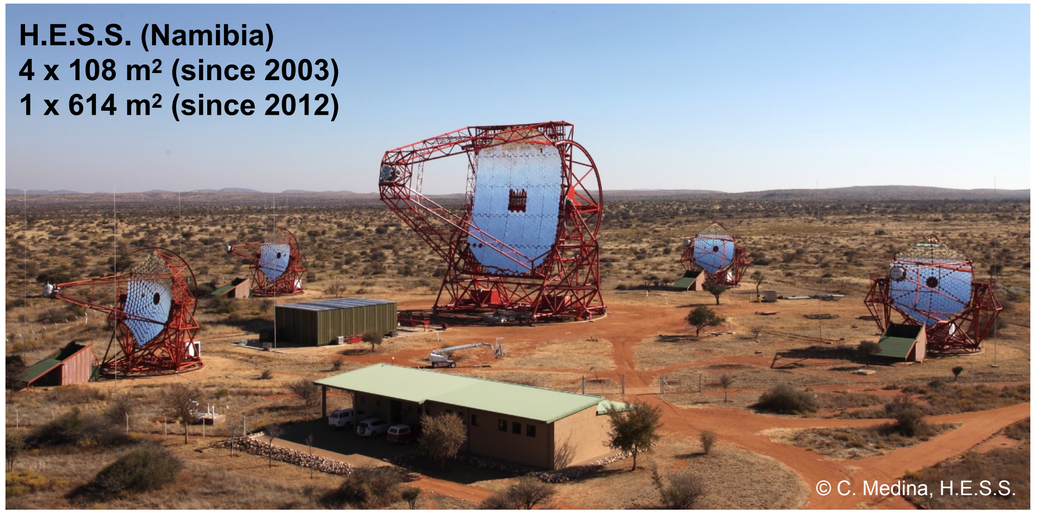


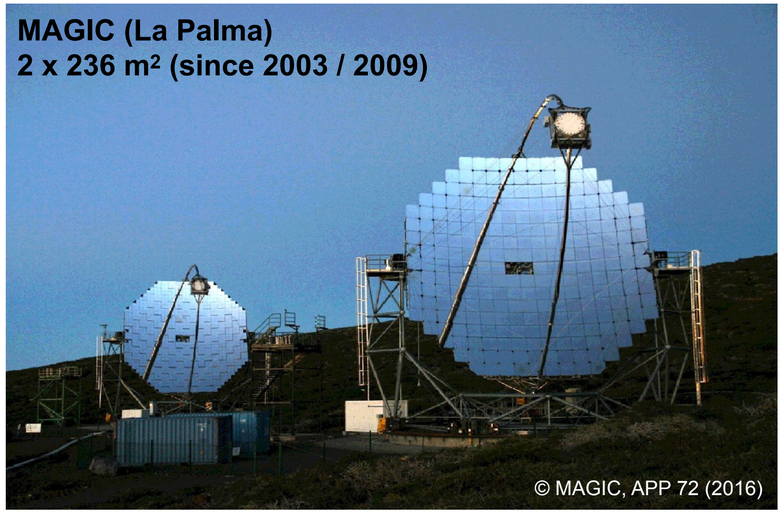
KM3NeT (Catania, Italy)

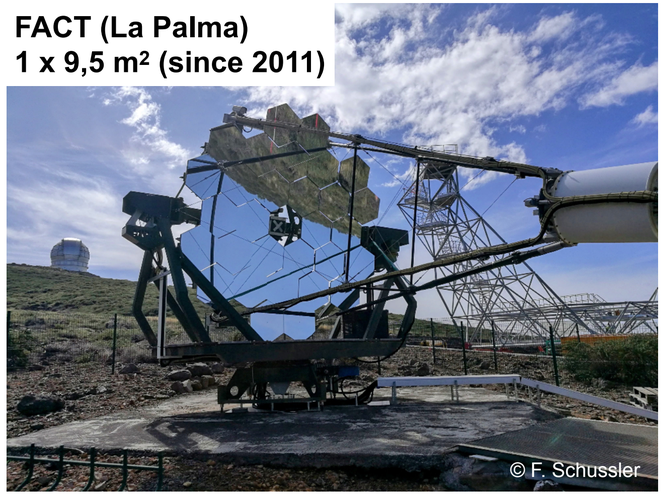
DUMAND, Hawaii
(cancelled 1995)

AMANDA/IceCube: Antarctica
Until 2009

IACTs: gamma-ray follow-up observatories

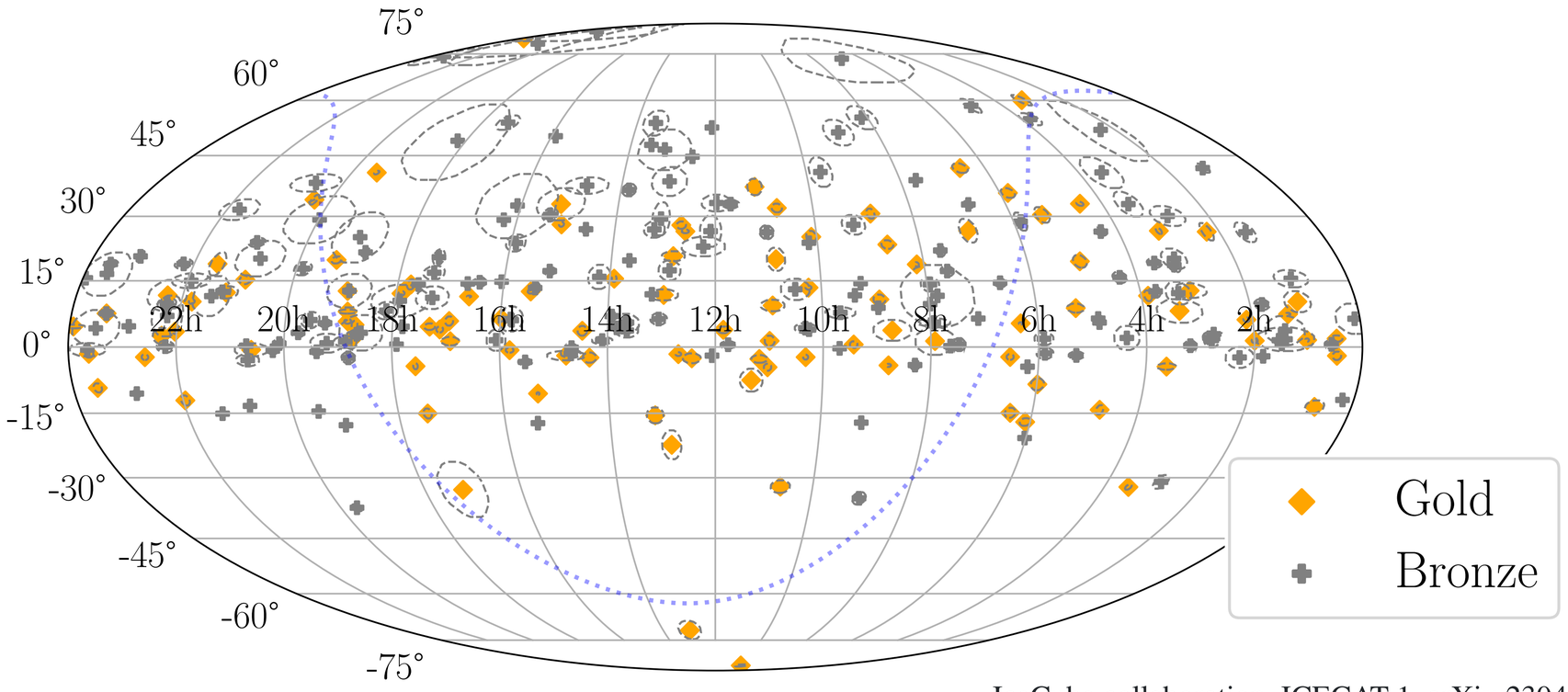






IceCube alert streams (I): single neutrino events

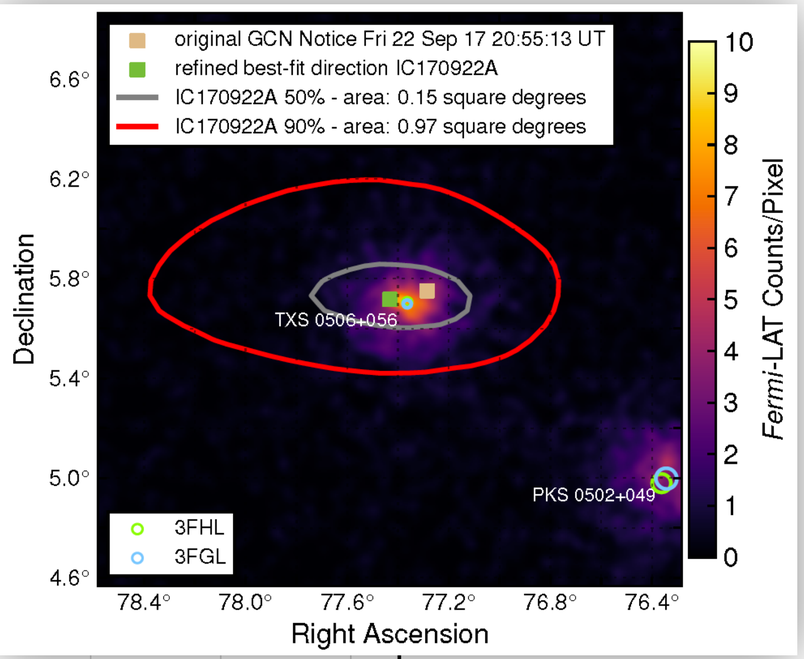
- Since April 2016: EHE + HESE event selections
- Upgrade in 2019: Bronze/Gold alert streams (30%/50% astrophysical probability)
- Publicly distributed via AMON/GCN => follow-up observations by all IACTs
- Aim: identify a plausible EM counterpart to the neutrino event



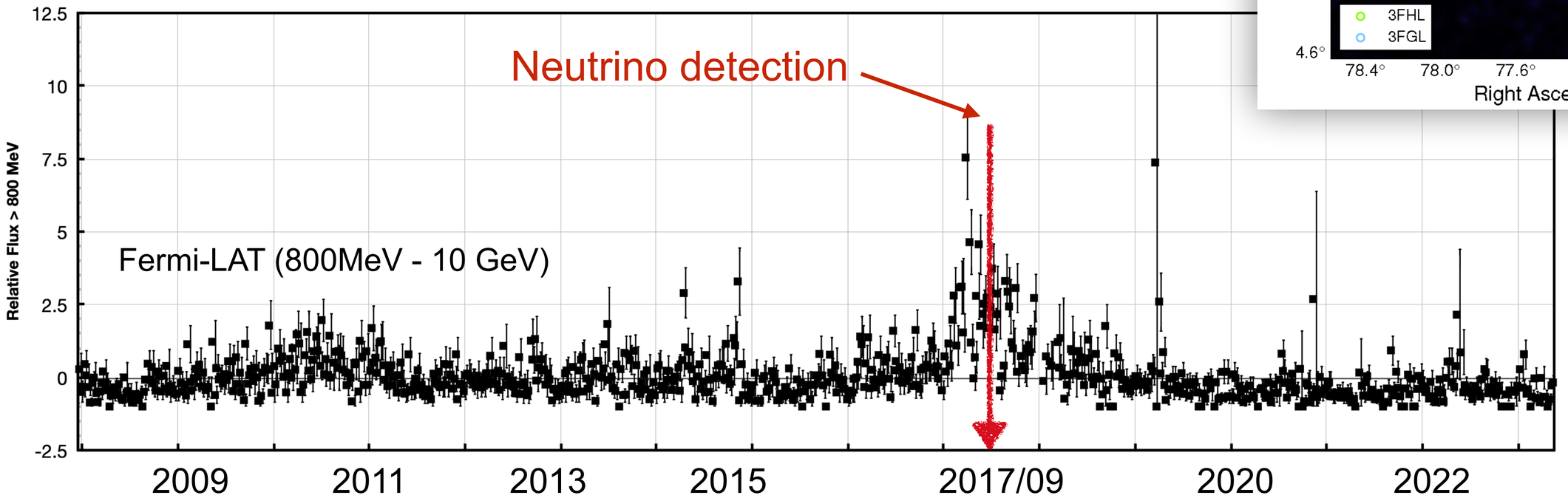
IceCube collaboration, ICECAT-1, arXiv:2304.01174

IceCube-170922A and TXS 0506+056

- 28/09/2017 *Fermi*-LAT: Detection of an active blazar within the neutrino uncertainty region + MAGIC/VERITAS TeV detection + MWL campaign …

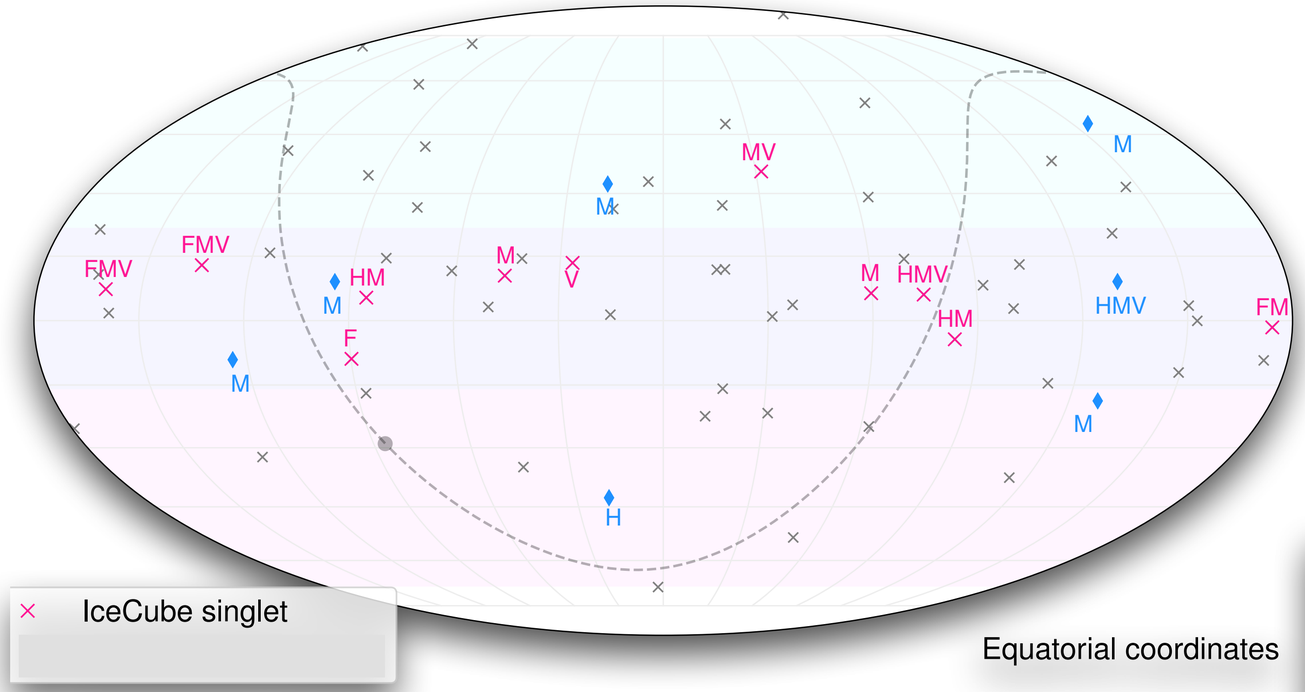


Science, 2018



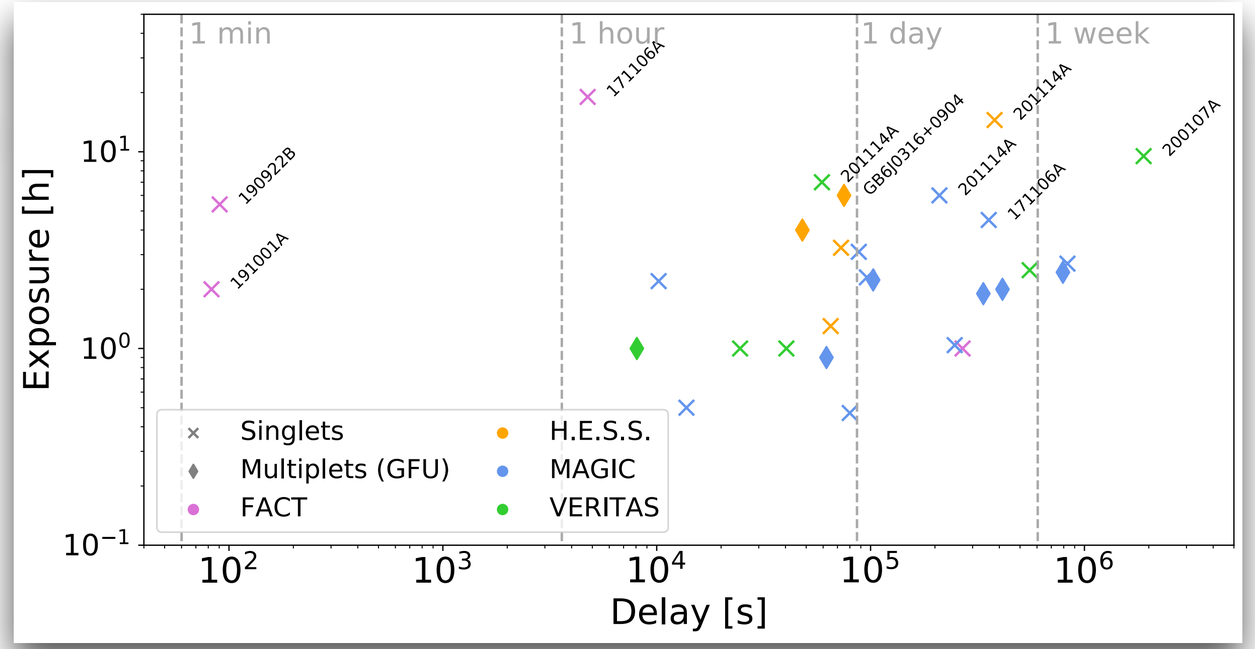
Fermi All-sky Variability Analysis (FAVA); Abdollahi et al., ApJ 846 (2017)

Continued searches for additional correlations



Alerts (Oct. 2017 - Dec. 2020):
62 singlets

Observed by IACTs:
11 singlets



Joint effort by all IACTs

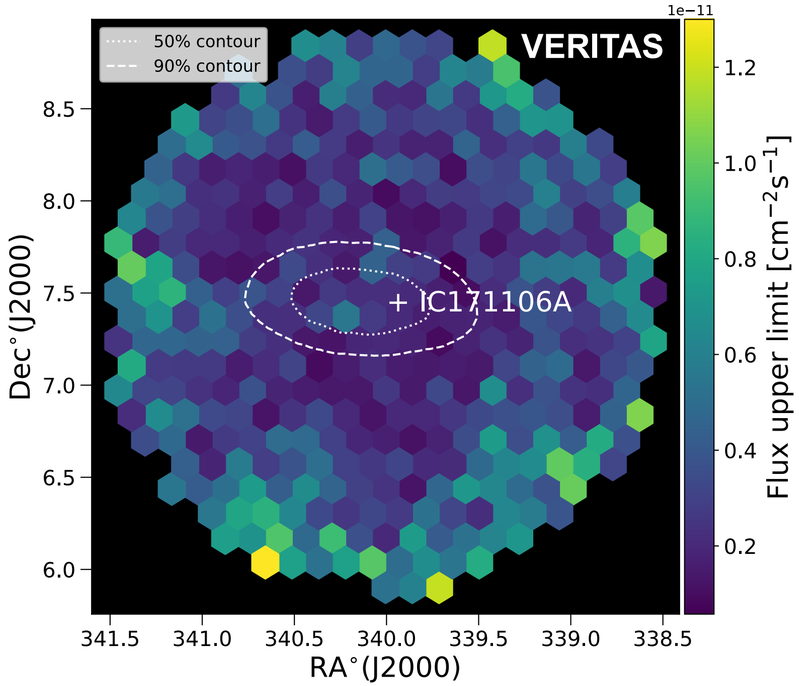
Santander et al. ICRC 2017
Satalecka et al., ICRC 2021
Schüssler et al., ICRC 2023

paper in preparation

Examples: follow-ups of single neutrino events

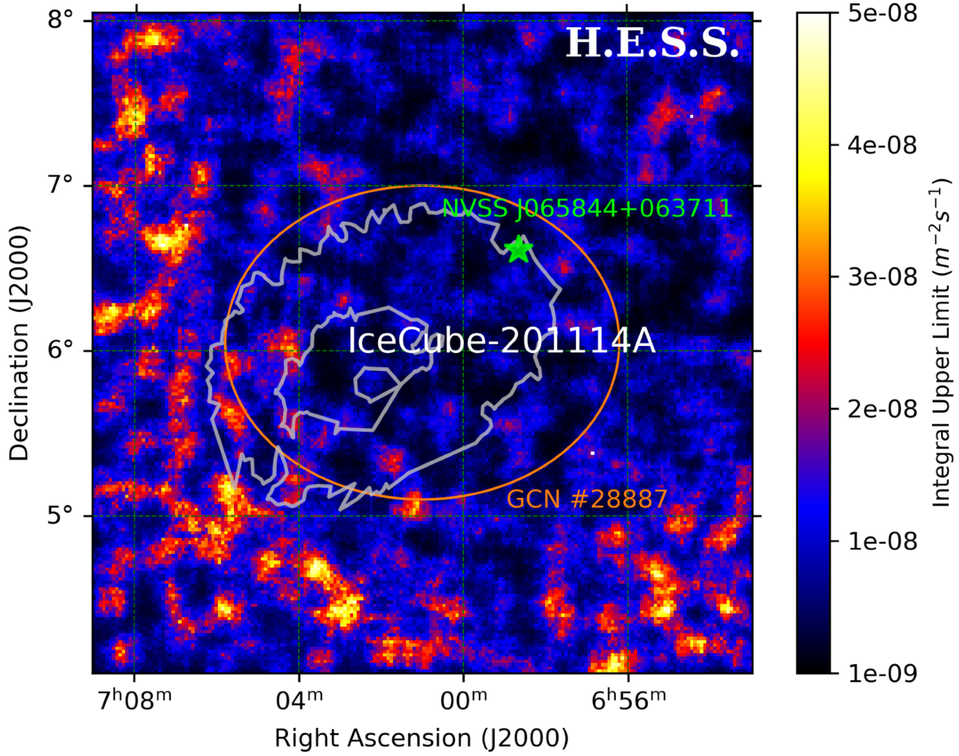
IceCube-171106A

- E ~ 230 TeV; P_{astro} ~75%
- No obvious source within the localisation uncertainty
- Maps of upper limits on the gamma-ray flux



IceCube-201114A

- E ~214 TeV; P_{astro} ~56%
- GeV emitting blazar NVSS J065844+063711 marginally within the localisation uncertainty
- Maps of upper limits on the gamma-ray flux



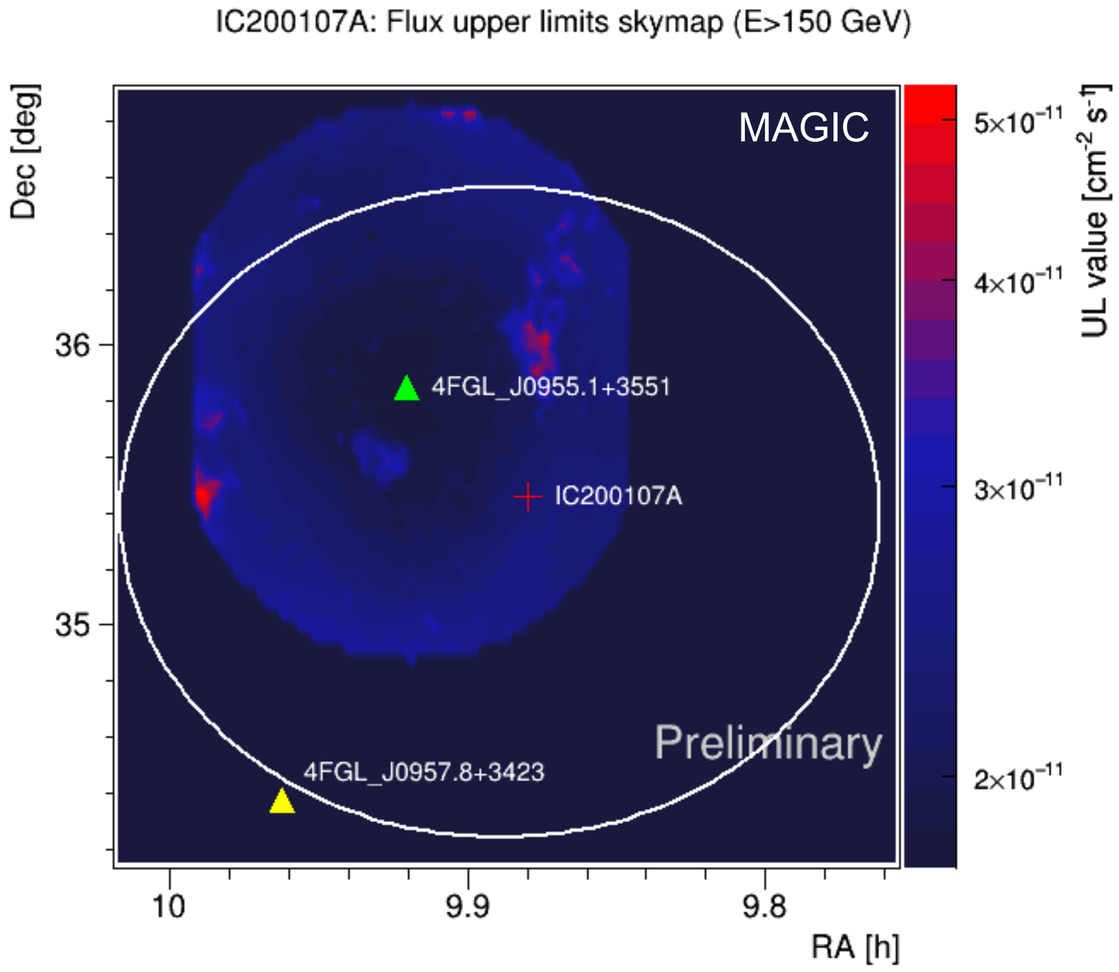
Examples: follow-ups of single neutrino events

IceCube-200107A

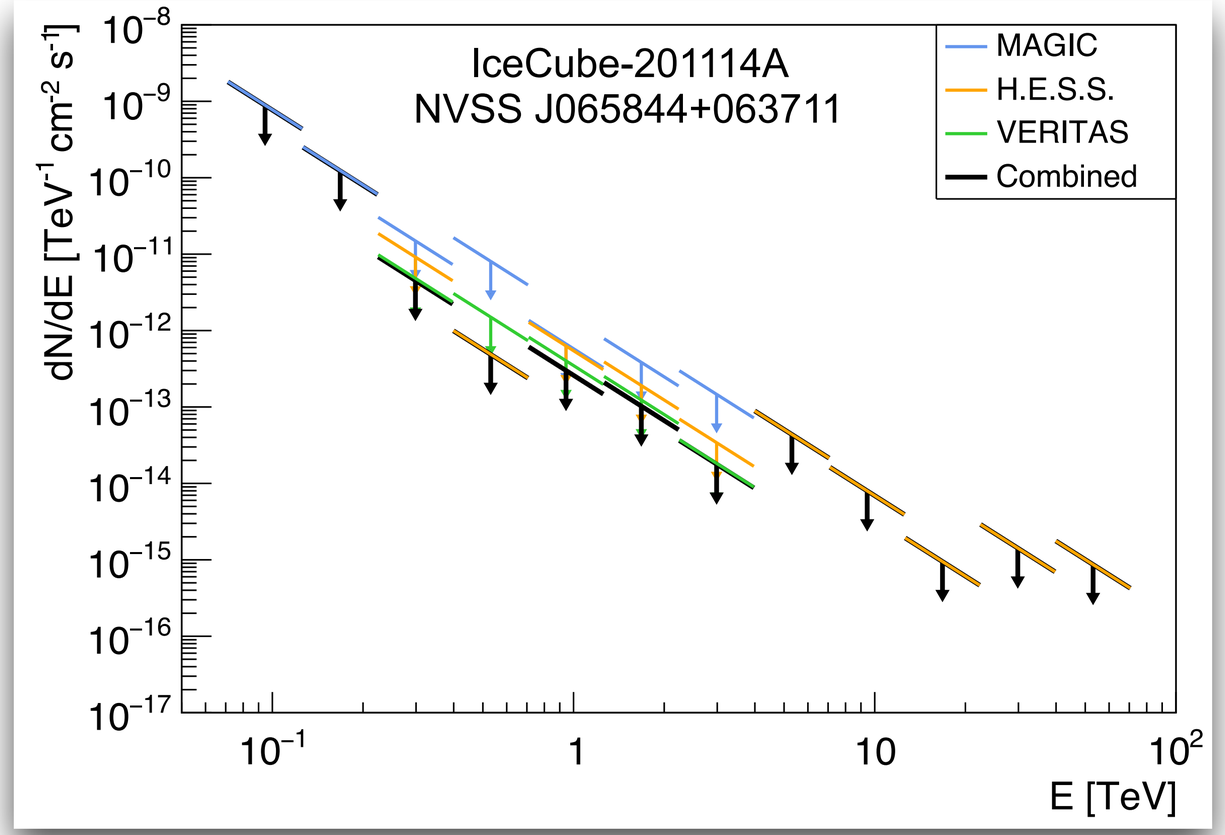
- GCN #26655
- Interesting event but not fulfilling the Gold/Bronze criteria
  => no FAR, no P_{astro}

  - FoV smaller than ROI
    => need to focus on potential sources or tiling of the whole region

  - Two known GeV sources within the ROI
    => need to decide which is more promising

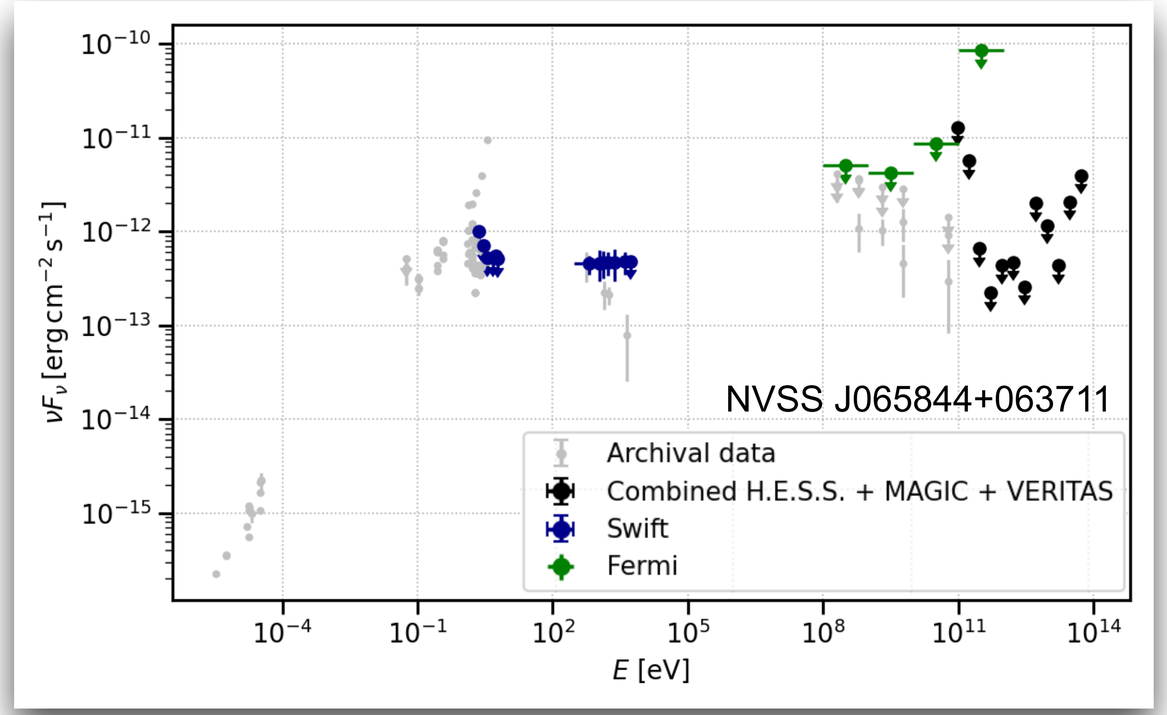


Combined analyses across several IACTs



IceCube-201114A

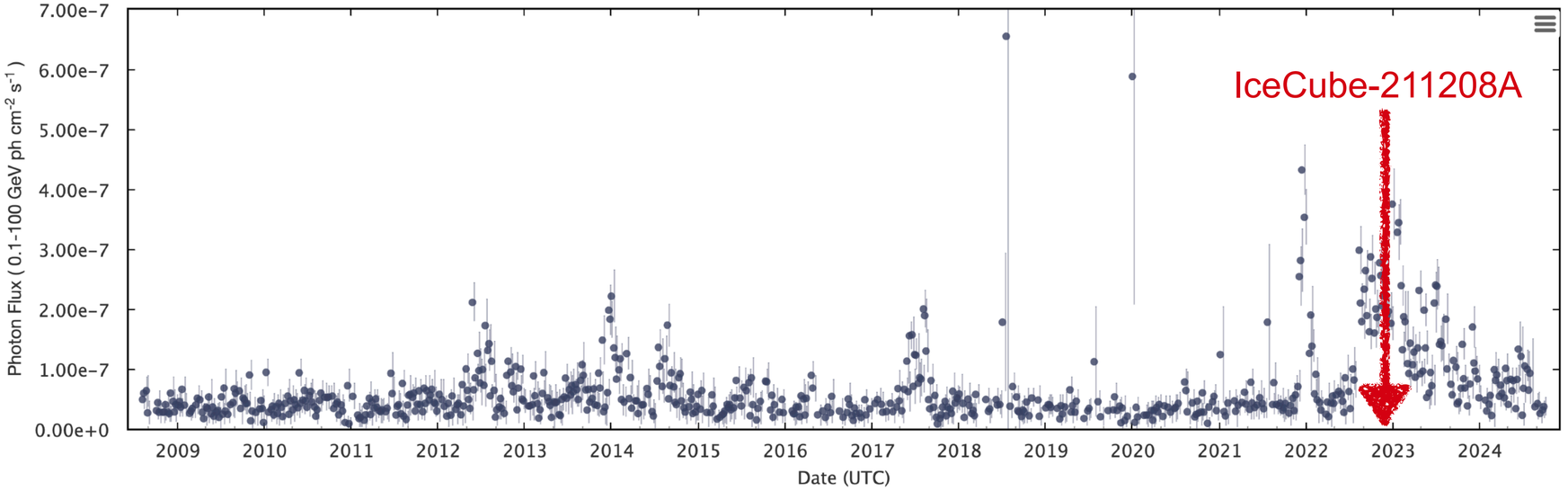
- E ~214 TeV; P_{astro} ~56%
- GeV emitting blazar NVSS J065844+063711 marginally within the localisation uncertainty
- Combined upper limits across all IACTs
- MWL SED comparing ToO and archival data



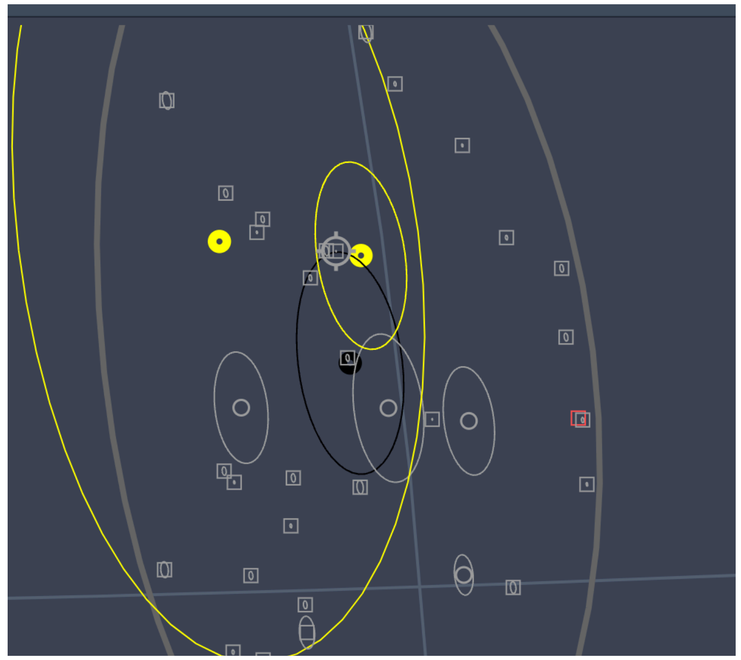
Example: IceCube-211208A and PKS 0735+17

IceCube-211208A

- E ~ 171 TeV; P_{astro} ~50%
- Several GeV sources within the localisation uncertainty
- PKS 0735+17 (z~0.45) in a flaring GeV state
- ‘Additional’ neutrinos reported by Baikal-GDV + KM3NeT + Baksan
- ToOs triggered in H.E.S.S., VERITAS, NuSTAR, Swift



Femi-LAT Light Curve Repository, Abdollahi et al. 2023



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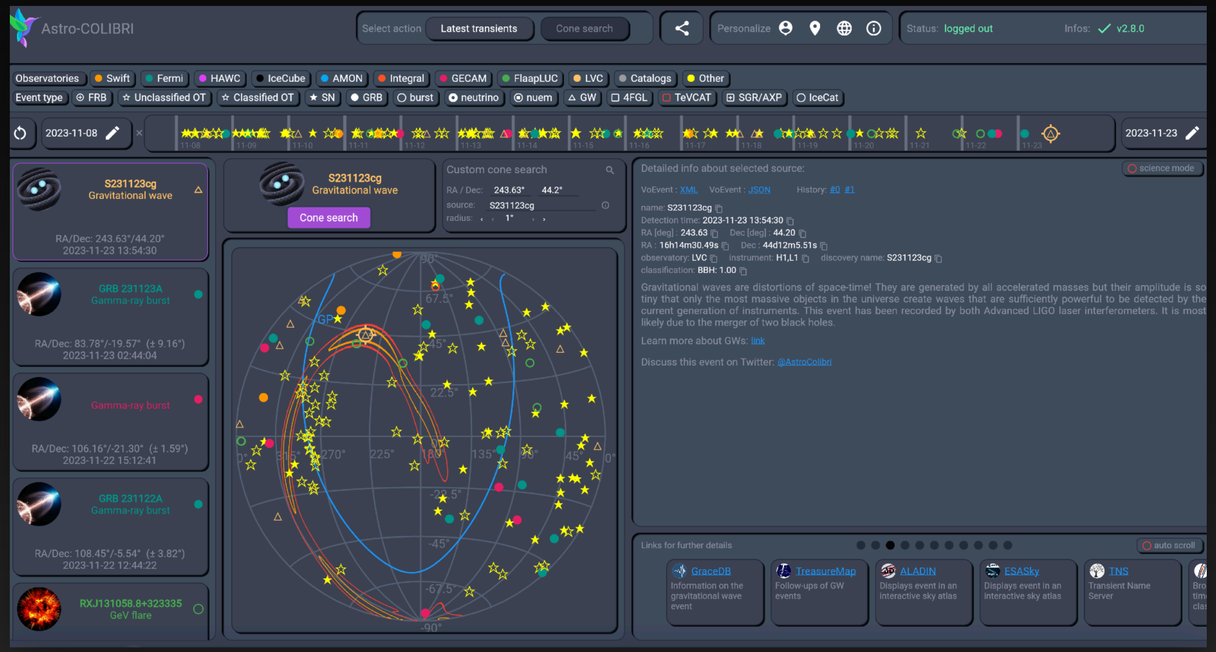
https://astro-colibri.com



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Download on the App Store

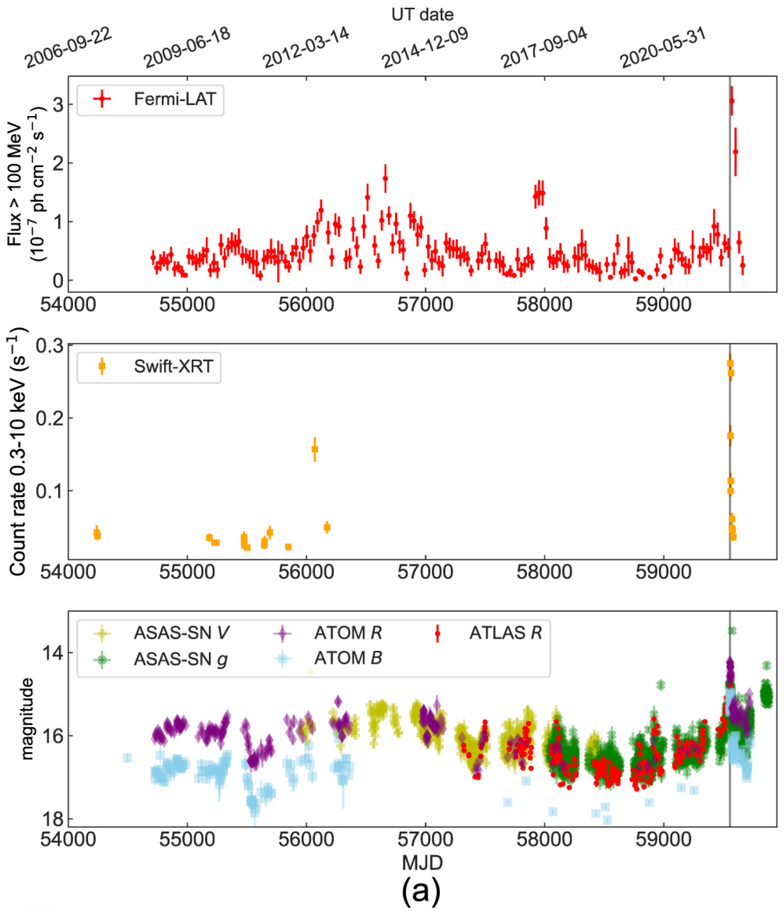
https://astro-colibri.science

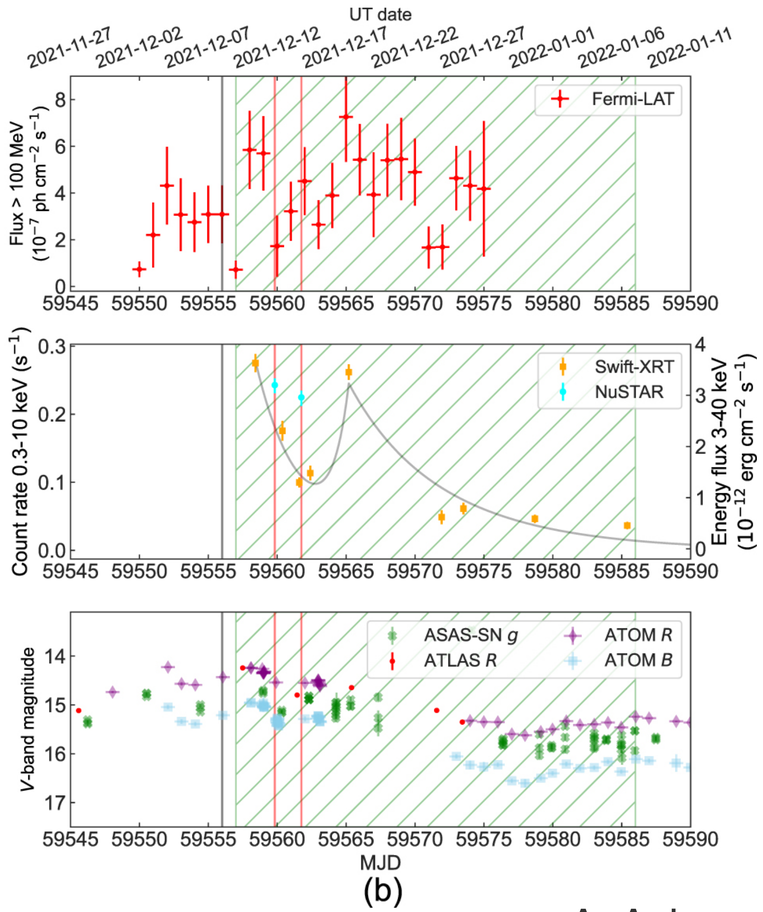
Example: IceCube-211208A and PKS 0735+17

Joint analysis of data from H.E.S.S., VERITAS, NuSTAR, Swift, ATOM, ATLAS,…

- Highest flux during IC neutrino event at all frequencies

Variability at different timescales





Variability at daily timescales

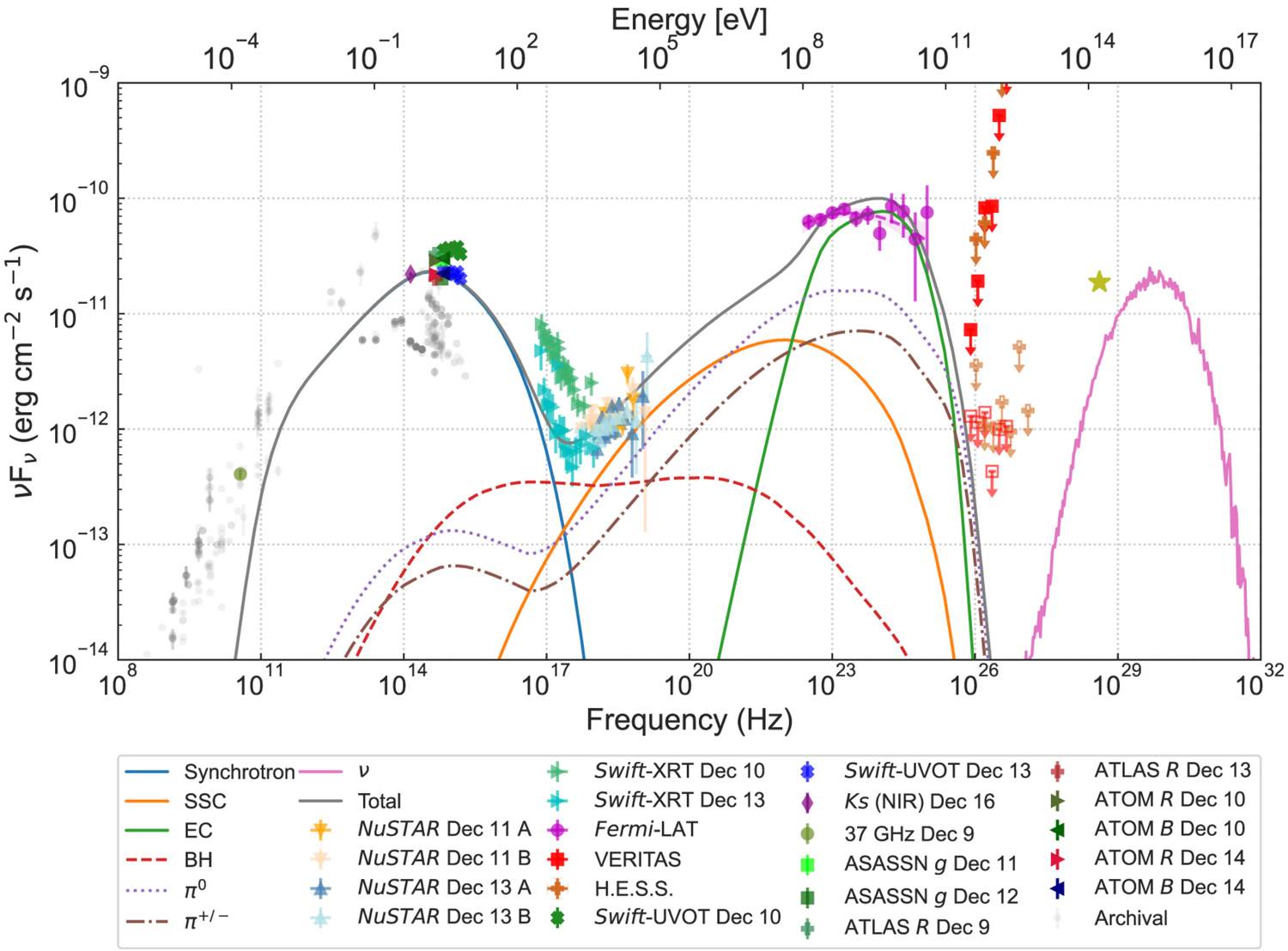
A. Acharyya *et al* 2023 *ApJ* **954** 70

Example: IceCube-211208A and PKS 0735+17

Joint analysis of data from H.E.S.S., VERITAS, NuStar, Swift, ATOM, ATLAS,…

- Highest flux during IC neutrino event at all frequencies
- H.E.S.S. + VERITAS: cutoff in the gamma-ray emission around 100GeV
- Difficult to model without an external photon field (EC)

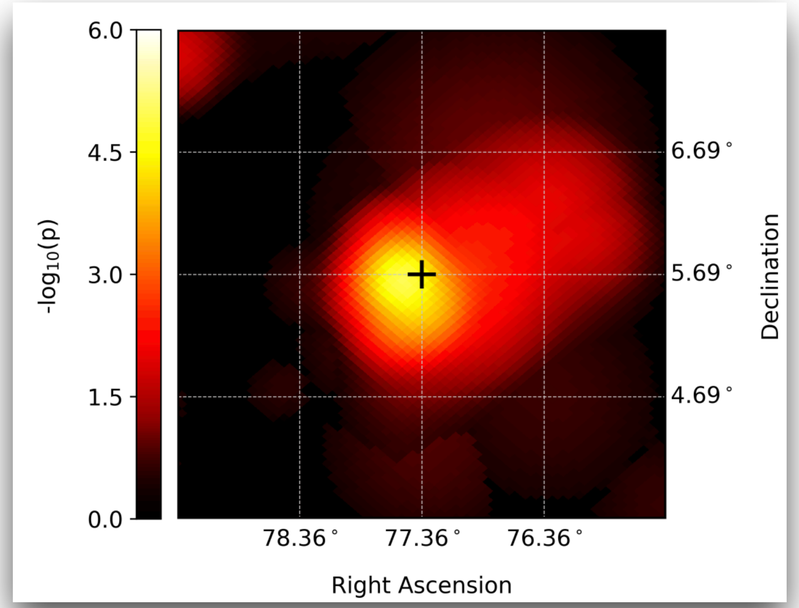
- Independent modelling attempts
  - A. Omeliukh et al., submitted to A&A (arXiv:2409.04165)
  - A.M. Bharathan et al., MNRAS 529, 4, (arXiv:2401.12680)

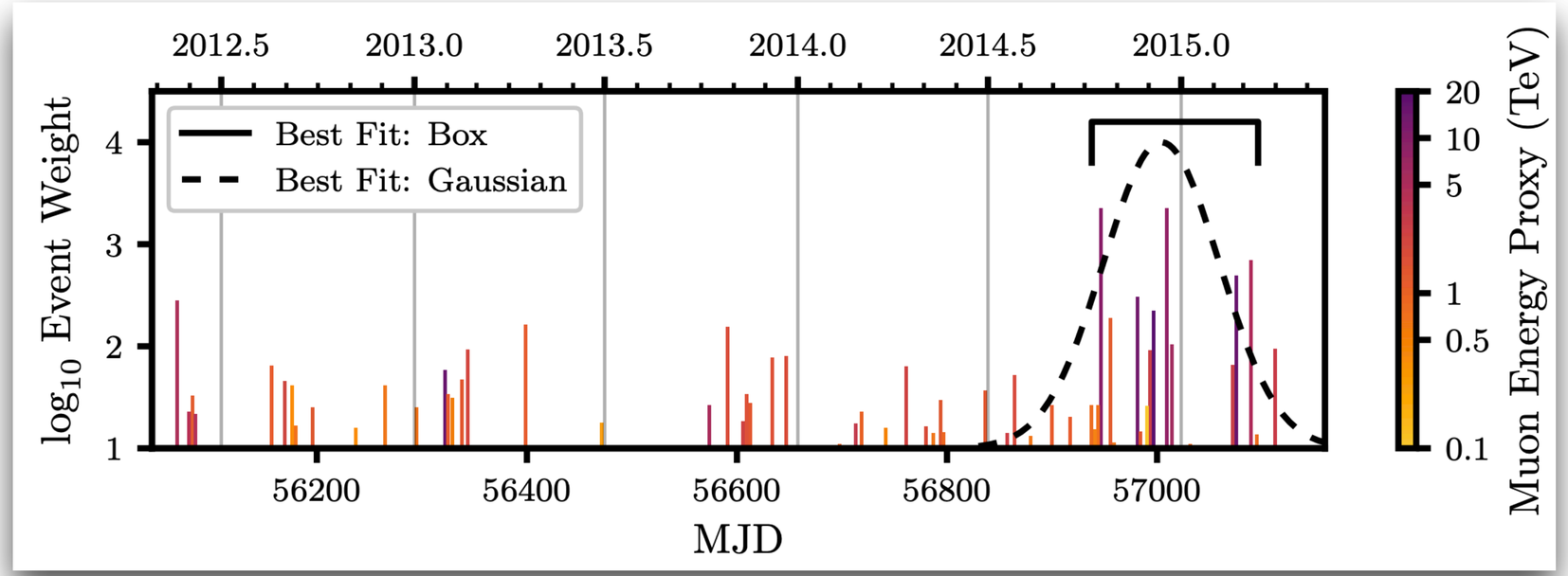


A. Acharyya *et al* 2023 *ApJ* **954** 70

IceCube alert streams (II): Gamma-ray follow-up (“GFU”)

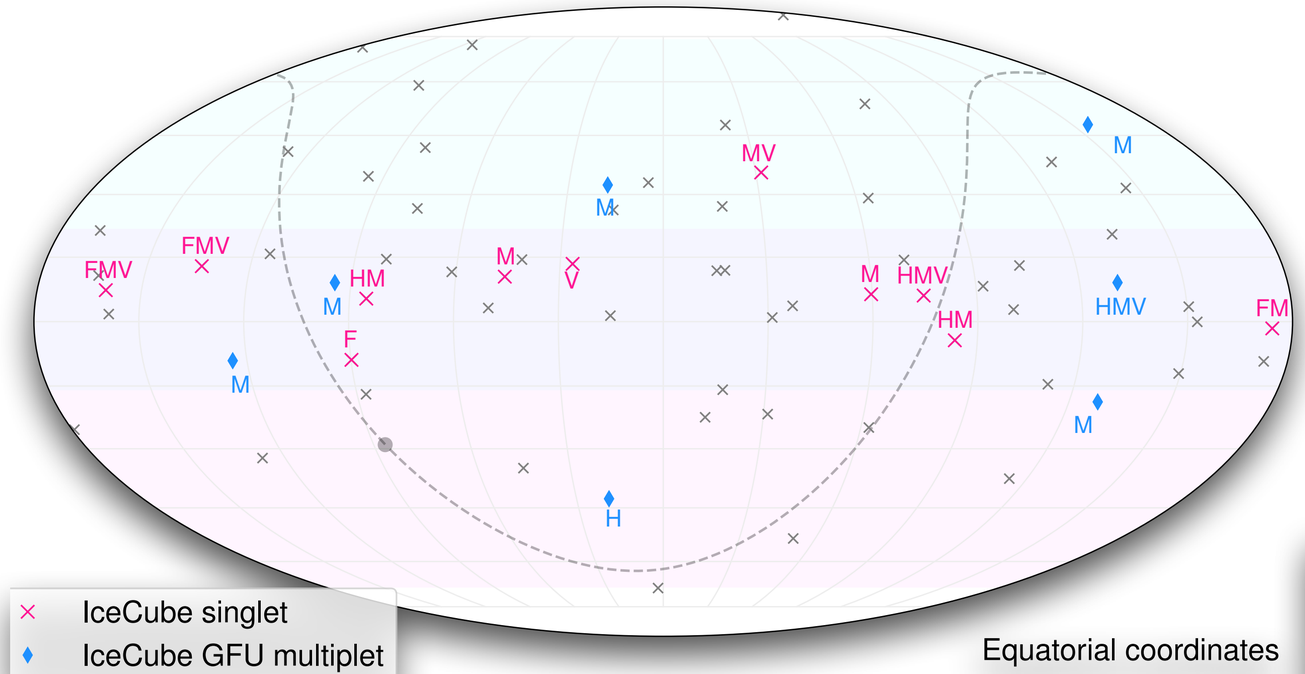
- Searches for neutrino multiplets (“flares”) in the IC online data stream
  - Time periods ranging from seconds to 180days





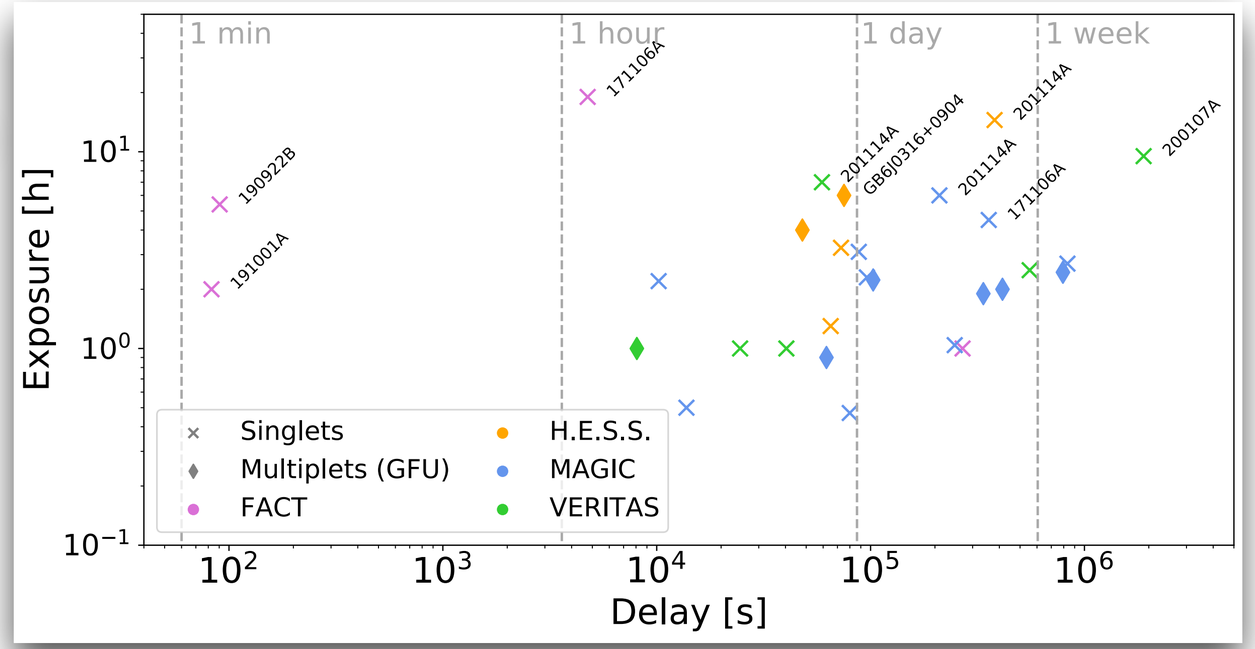
IceCube collaboration, Science 361 (2018) 147-151

Continued searches for additional correlations



Alerts (Oct. 2017 - Dec. 2020):
62 singlets
27 GFUs from 17 sources

Observed by IACTs:
11 singlets
GFUs from 7 sources



Joint effort by all IACTs

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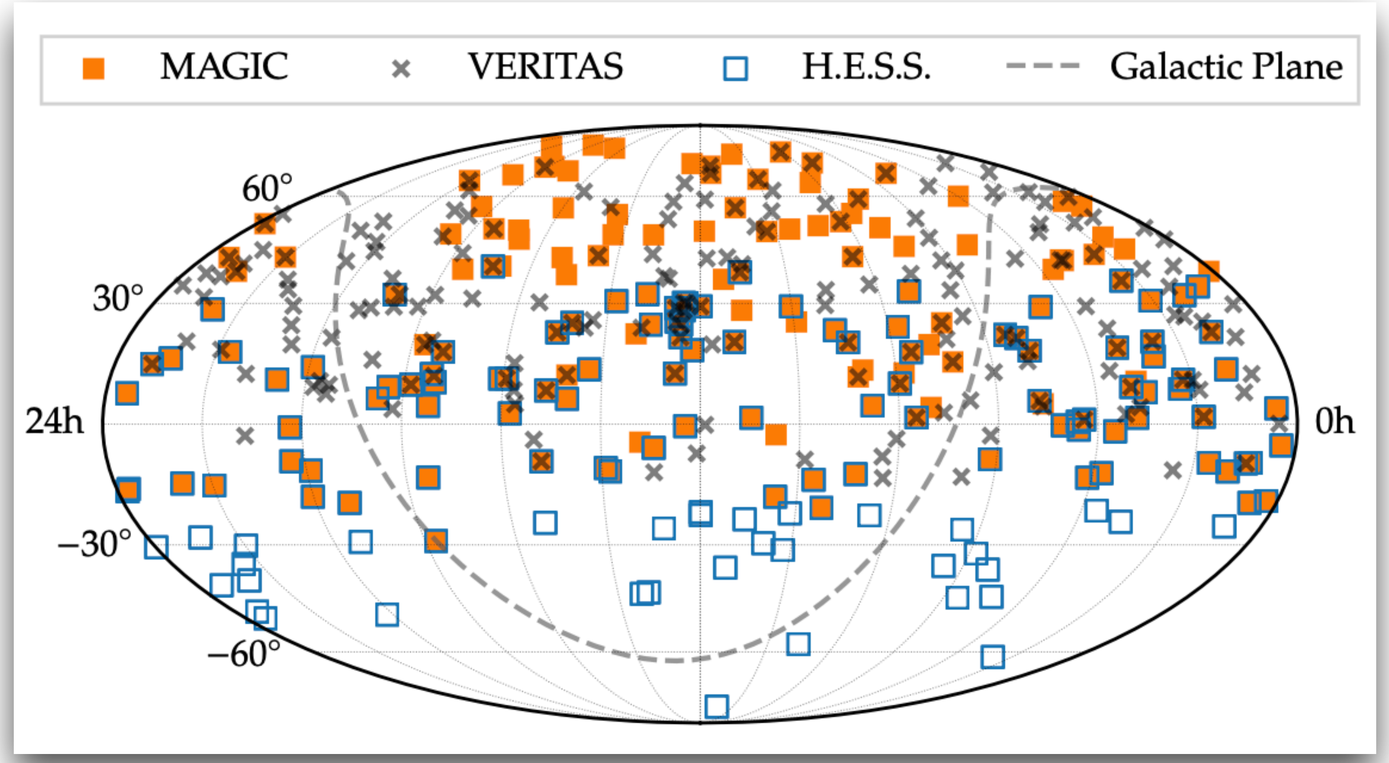
Satalecka et al., ICRC 2021
Schüssler et al., ICRC 2023

paper in preparation

IceCube alert streams (II): Gamma-ray follow-up (“GFU”)

- Searches for neutrino multiplets (“flares”) in the IC online data stream
  - Time periods ranging from seconds to 180days
- Predefined targets + all-sky search (in preparation)
- Alerts distributed privately under MoU
  - Northern Sky: MAGIC & VERITAS since 2012
    - CTA/LST-1 since 2023
  - Southern Sky: H.E.S.S. since 2019
  - INTEGRAL: since 2016/2017
  - **Will become publicly available soon**
- Current source selection based on
  - GeV+TeV catalogs; variability; distance; visibility, …
- Aim: determine the state of the source
  - quiescence vs flaring state
  - spectral changes



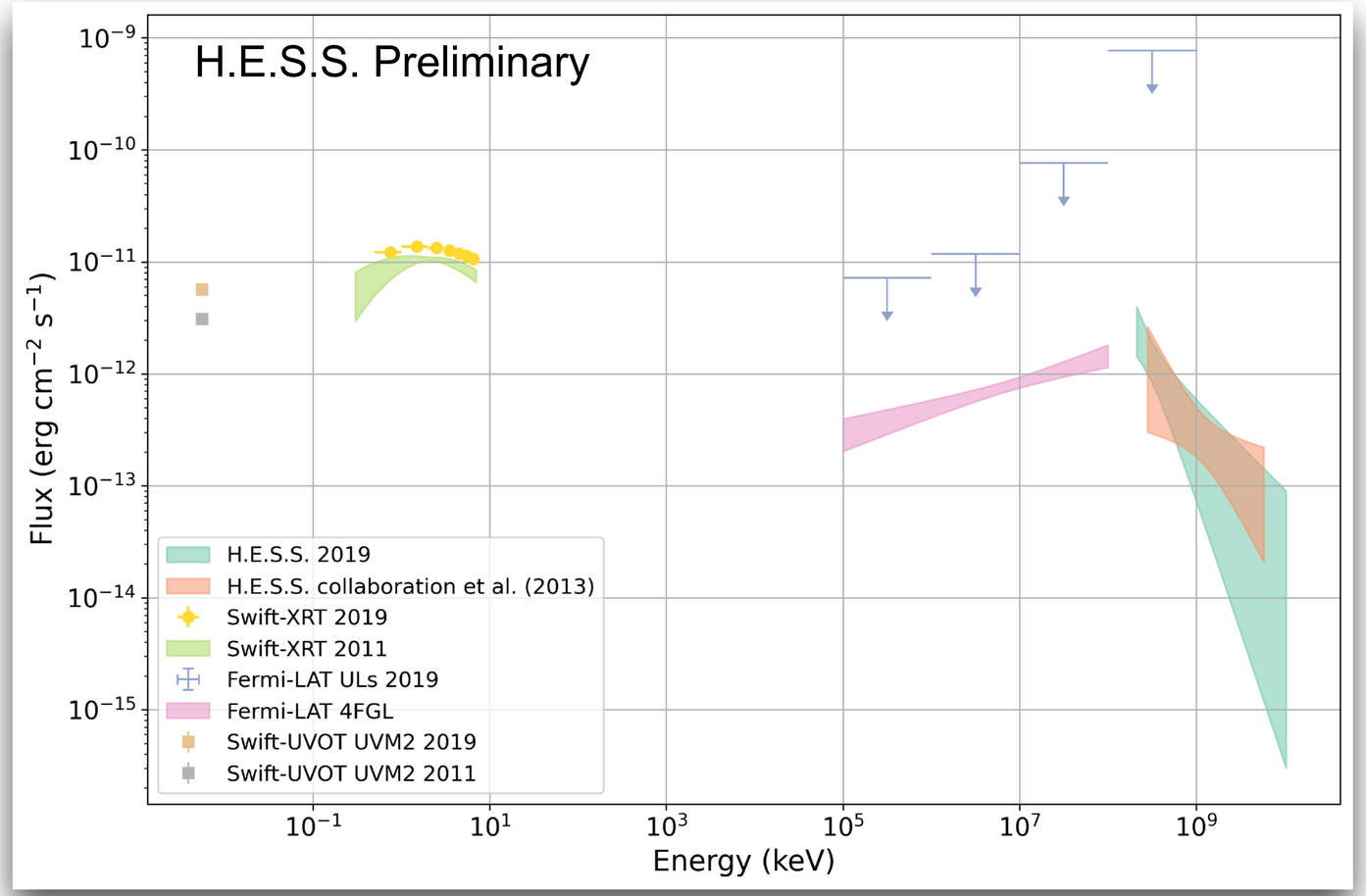
T. Kintscher, PhD thesis, Humboldt-University Berlin, 2020

Example: Neutrino multiplet and VHE gamma-rays from 1ES 1312-423

- Neutrino ‘flare’ detected by IceCube (duration 6.5 hours)
- H.E.S.S. ToO observations => re-detection of the source (~4sigma)

- Contemporaneous MWL observations ATOM + Swift (UVOT + XRT)

- No significant change in the non-thermal emission during the ToO



Caveats to VHE neutrino - gamma-ray correlations

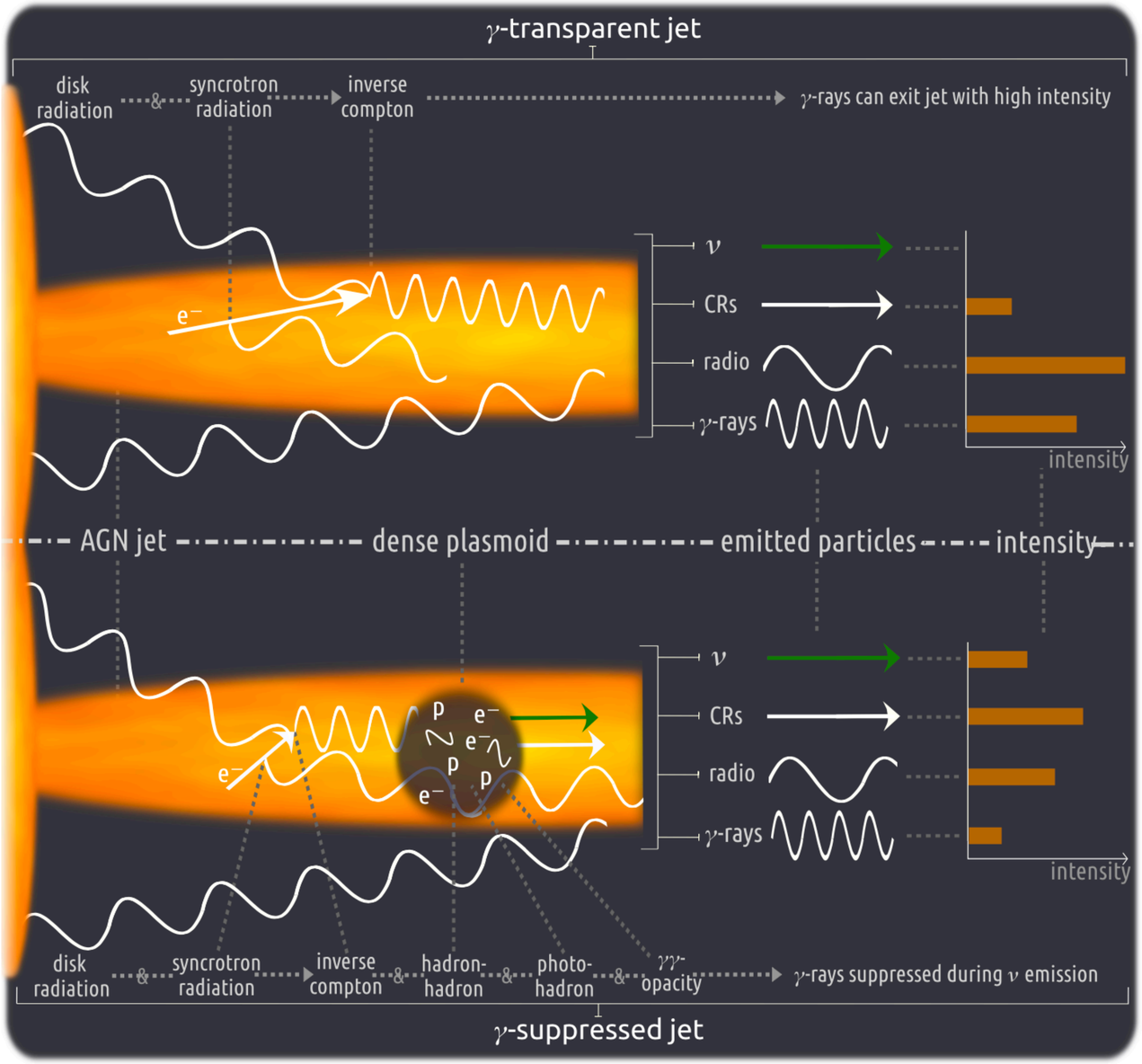
P. Reichherzer

- Neutrino backgrounds are important
  - Atmospheric neutrinos
  - No cosmic horizon

- Neutrino emission requires hadrons + sizable target densities
  - High densities cause gamma-ray absorption

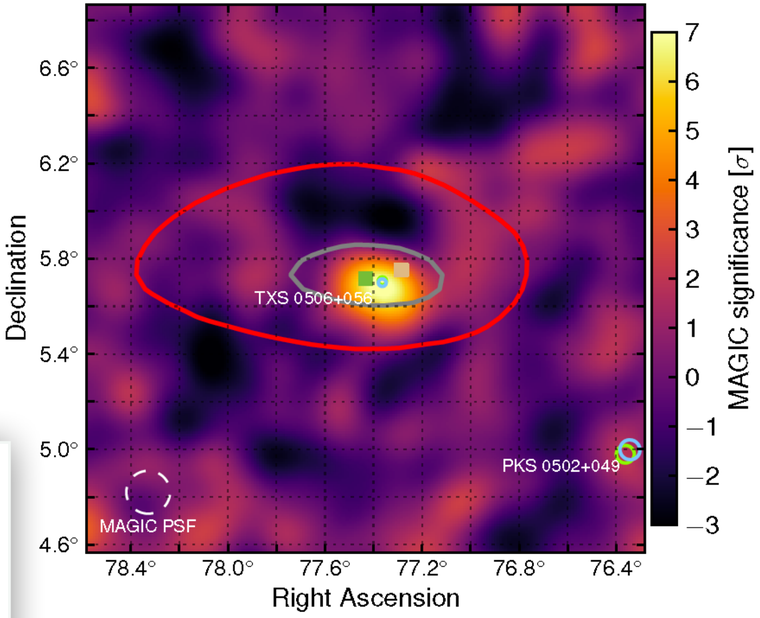
e.g. NGC 1068

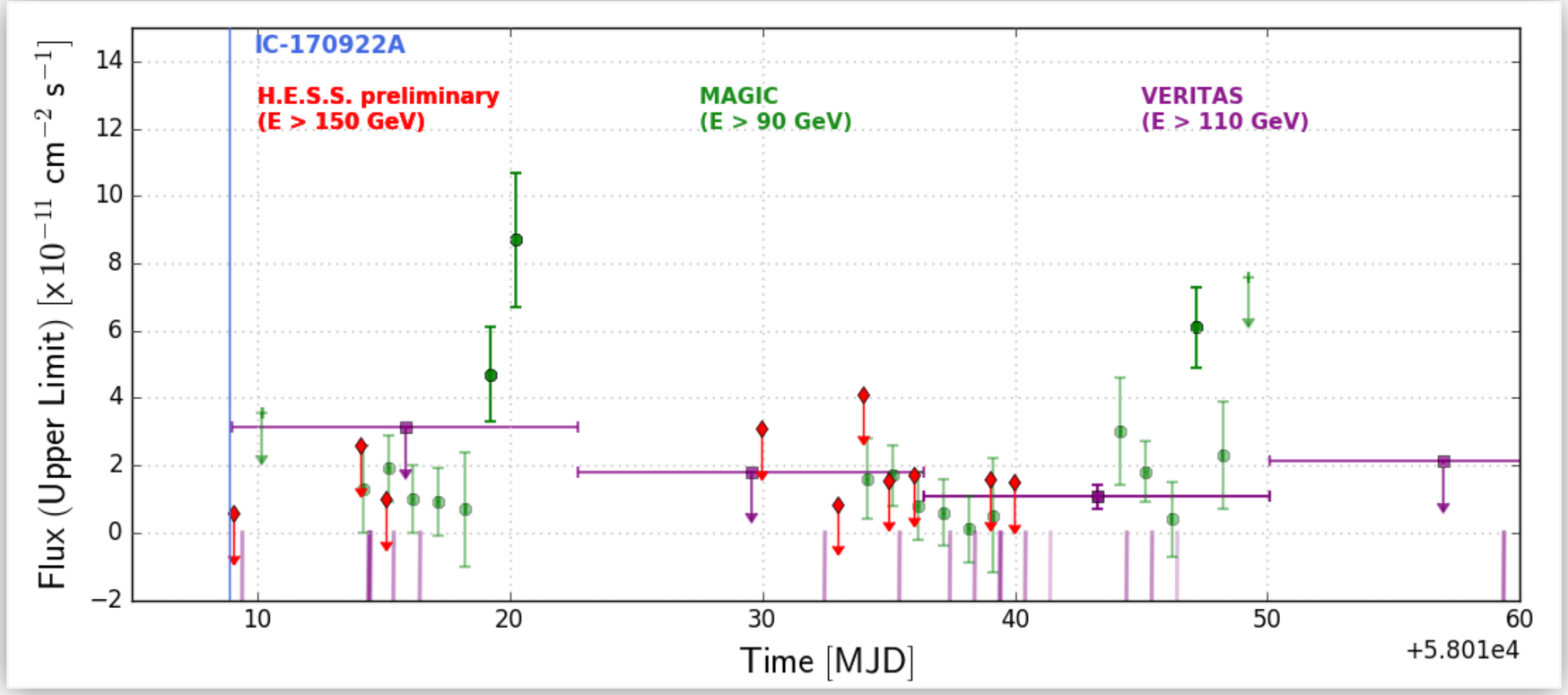
Importance of large MWL coverage
cf. talk by Antoine Foisseau



Observational challenges

- Time scales unclear
  - ΔT between neutrino(s) and gamma rays (TXS 0506+056: >10days)
  - Variability time scale (TXS 0506+056: ≲1day)
- => Long and deep follow-up campaigns

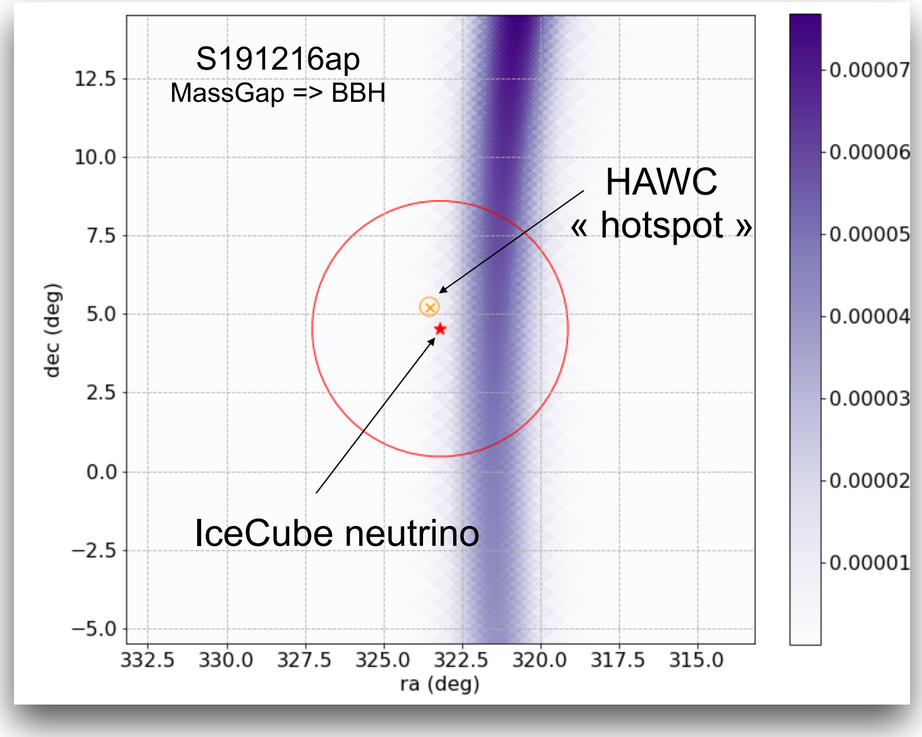




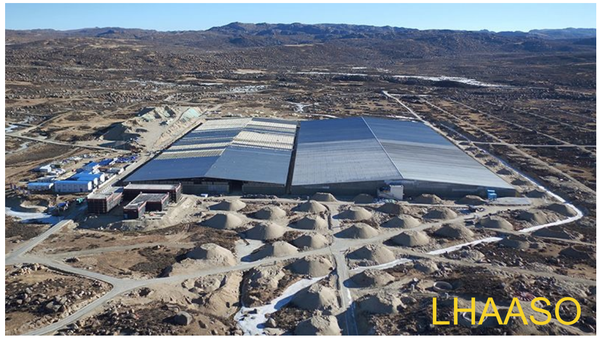
FS et al, TeVPA 2018

Searches with air shower arrays

- HAWC + LHAASO (+ SWGO, ALPACA, etc.)
- Large FoV + high duty-cycle
  - **Smaller instantaneous sensitivity + higher $E_{threshold}$**
- HAWC: automatized searches for excess at several timescales (0.3s - 100s)



I. Martinez + H. Schoorlemmer et al. (HAWC)



GCN #26455
GCN #26463
GCN #26472
…

Joint searches by FACT, H.E.S.S., MAGIC, and VERITAS for VHE gamma-ray emission associated with neutrinos detected by IceCube

- **Several years of preparation coming to fruition**
  - automatic alert systems + dedicated data analysis tools + MoUs + …

- **Sources of high-energy neutrinos**
  - diffuse astrophysical flux detected
  - transient sources promising (reduced background)
  - IceCube-170922A and TXS 0506+056: a first hint
  - IceCube-211208A and PKS 0735+17: a new puzzle piece

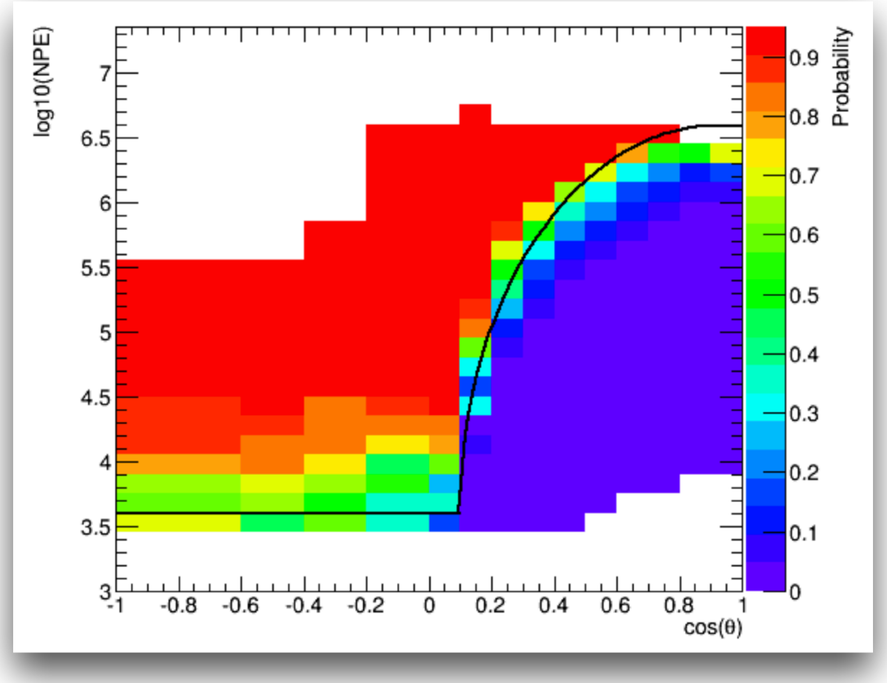
- **VHE gamma-ray follow-ups with all IACTs**
  - important part of the multi-messenger and transients programs
  - different + complementary approaches
  - joint analyses allow to obtain deeper limits and broader (MWL) coverage

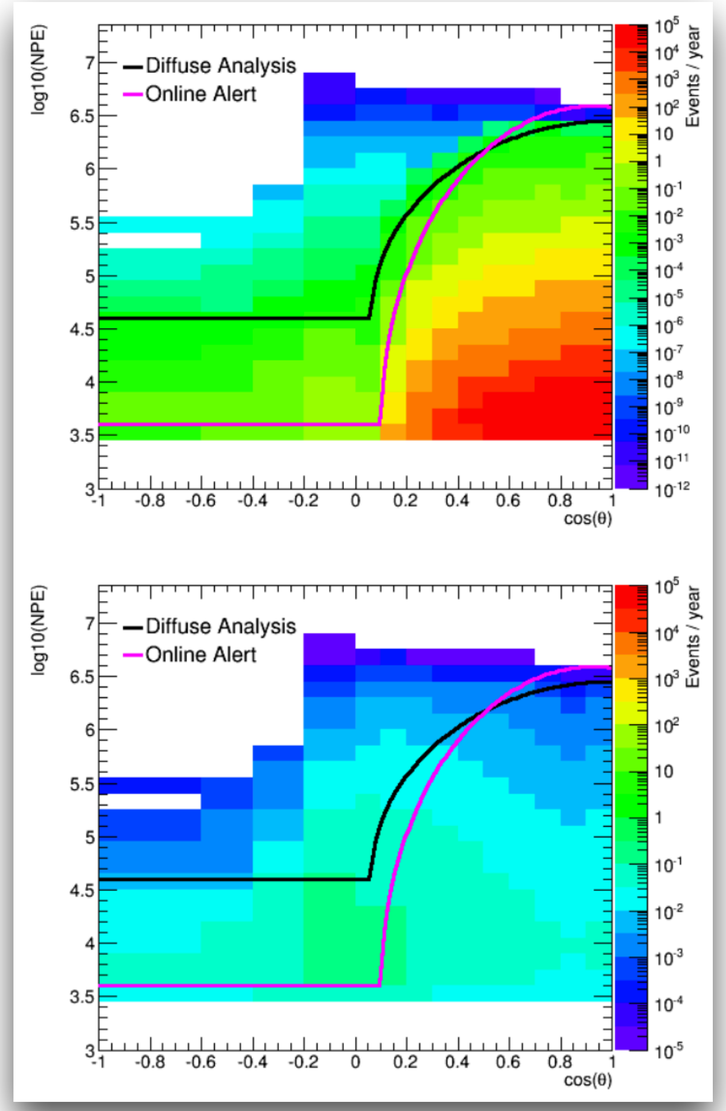
Interpretation of ToOs requires extensive archives (e.g. INTEGRAL archive)

Backup

Neutrino alert emission

- Data recorded by neutrino telescopes is dominated by atmospheric background
- Multi-dimensional cuts to increase the SNR
- Event-by-event estimation of “signalness”, P_{astro}
- Reconstruction + filtering + alert emission fully automatic => delays < 10s





IceCube collaboration, Astroparticle Physics 92 (2017) 30-41