# Association of IceCube neutrinos with major blazar flares in radio and optical bands

**Elina Lindfors**, T. Hovatta, I. Liodakis, P.M. Kouch, K. Koljonen, K. Nilsson, S. Kiehlmann, W. Max-Moerbeck, M. J. Graham, M. Hodges, T. J. Pearson, A. C. S. Readhead, R.A. Reeves, J. Jormanainen, V. Fallah Ramazani, A. Lähteenmäki, M. Tornikoski, S. Suutarinen

Hovatta, Lindfors et al. 2021
Liodakis, Hovatta et al. (including EL) 2022
Kouch, Lindfors et al. 2023, submitted to A&A

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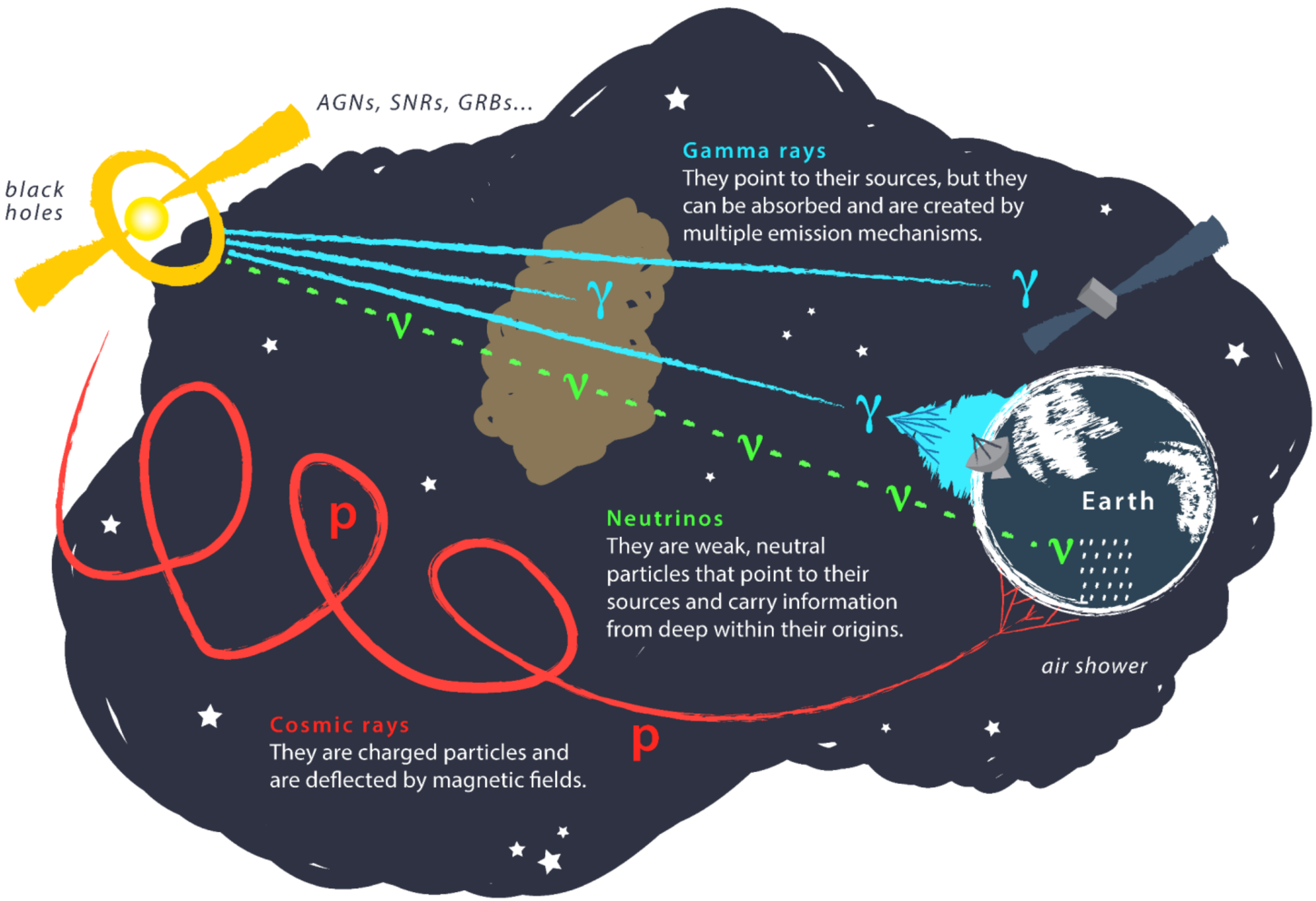
# Motivation




Credit: Juan Antonio Aguilar and Jamie Yang IceCube/WIPAC.

- Origin of cosmic rays and neutrinos is still unknown
- Neutrinos are produced when protons interact with photons
- Unlike cosmic rays that are deflected by magnetic fields, neutrinos arrive at Earth unabsorbed

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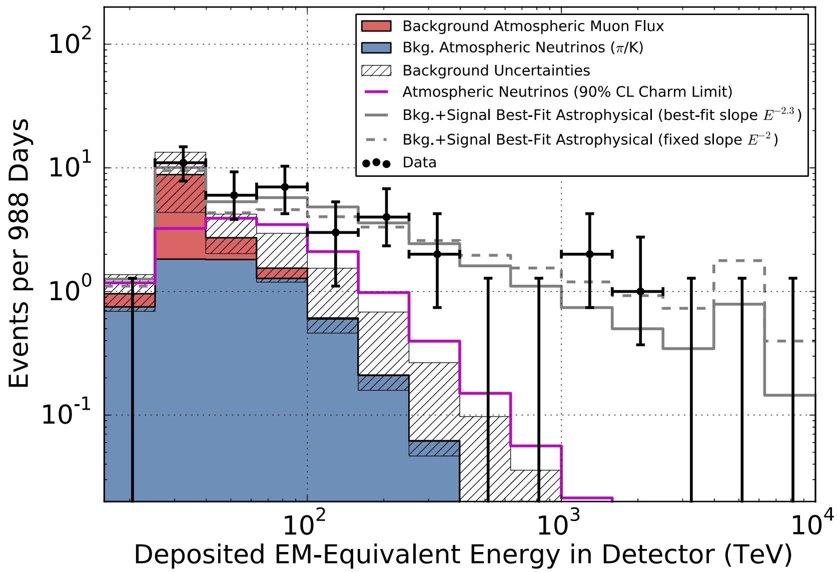
# Era of neutrino astronomy started 10 years ago

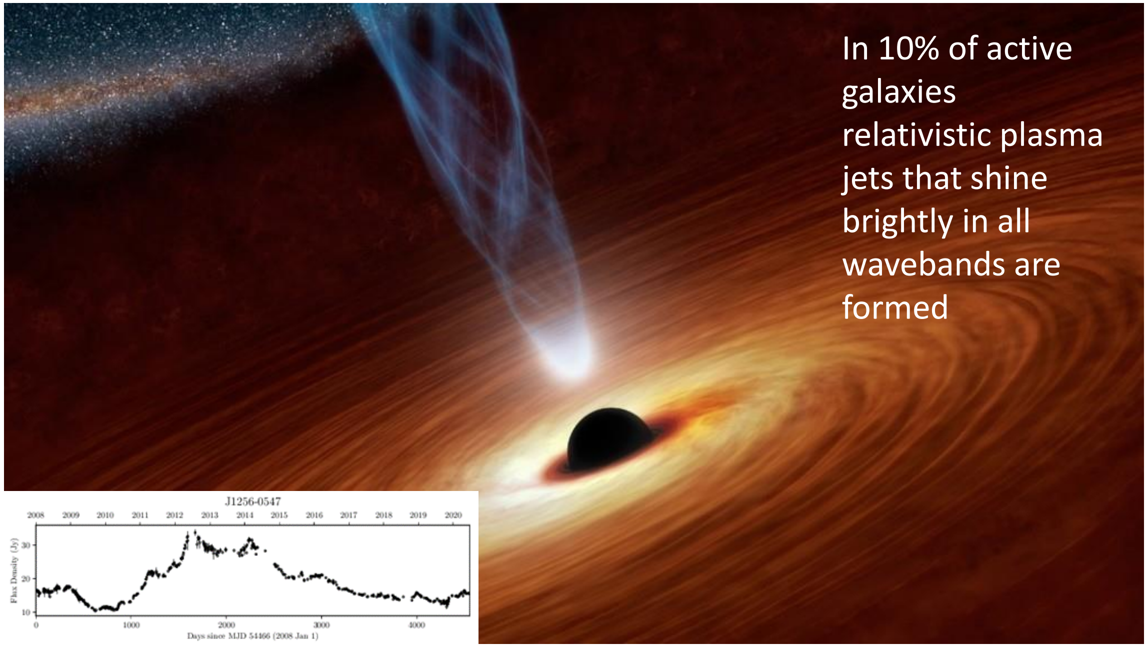
- IceCube detected an excess of *astrophysical* high-energy neutrinos
- There's no clear one-to-one correspondence between neutrino arrival directions and any given type of astronomical objects
- Three sources that IceCube has established: blazar TXS0506+056, Seyfert Galaxy NGC1068 and Galactic Plane



Aartsen et al. 2014 (IceCube collaboration)

# Blazars as candidate neutrino emitters

- Blazars are active galactic nuclei with relativistic plasma jets pointing towards us
- Electrons are accelerated to high energies in the jets, so also good candidates for proton acceleration
- TXS0506+056 has been followed with many more candidate associations
- Variability studies of candidate sources, but in association studies variability is usually not included
- Radio band: synchrotron emission from shock  is a good tracer of the jet activity




Credit: NASA JPL/Caltech

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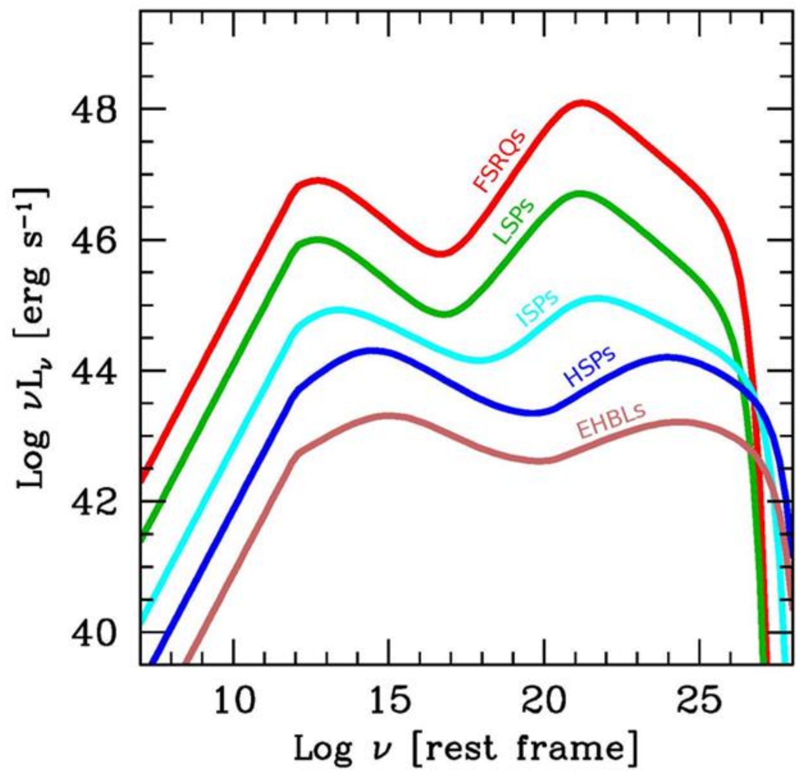
# All blazar classes or just some of them?

- Highly debated question and also conflicting tentative results, also from theory point of view not obvious
- FSRQs: most luminous ones, strong external photon fields (=target photons for photopion production, but also strong internal absorption and efficient cooling)
- HSPs, EHSPs: most numerous VHE gamma-ray sources (particles accelerated to high energies), no strong target photon fields?
- LSPs/ISPs something in middle, some arguments that they have external photon fields, but emission from the jet outshines them
- Variability strong at radio/optical for FSRQs/LSPs, less so for HSPs/EHSPs




Credit: G.Ghisellini

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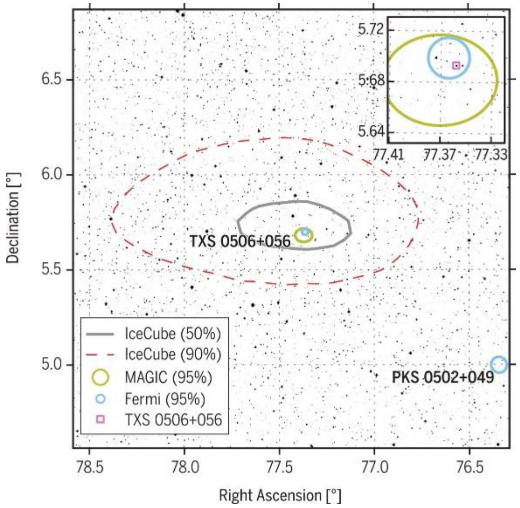
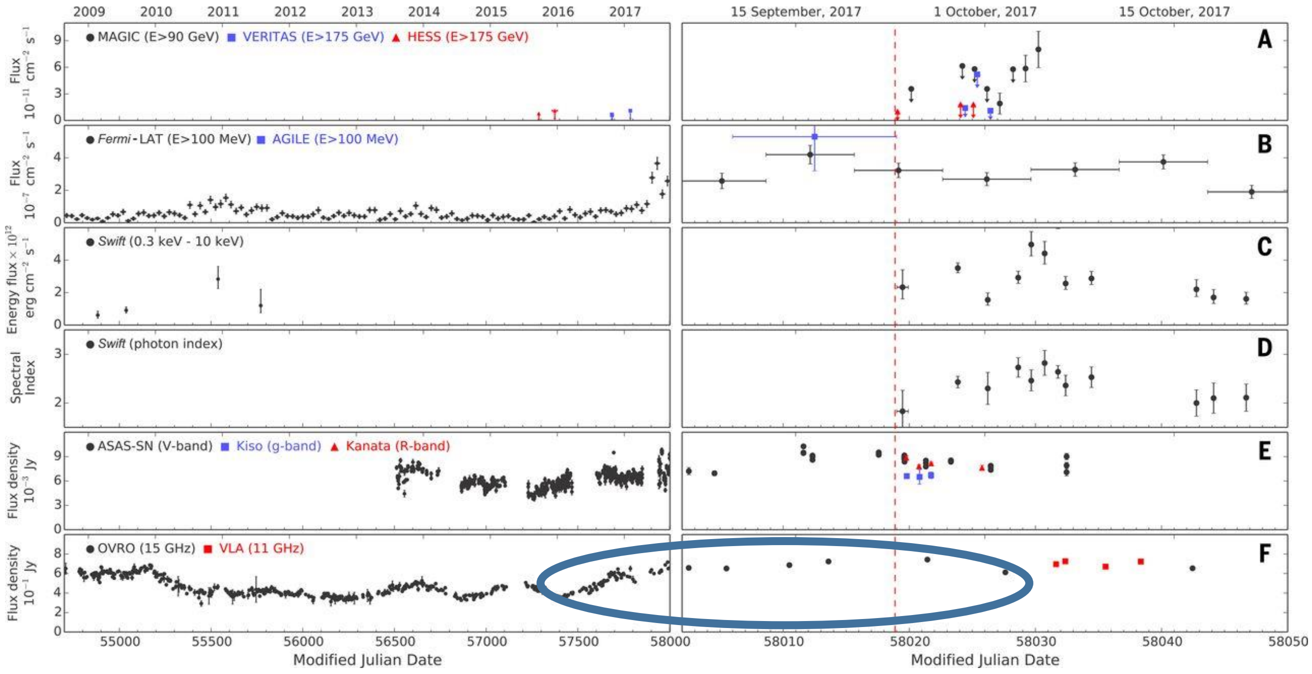
# TXS 0506+056 radio association

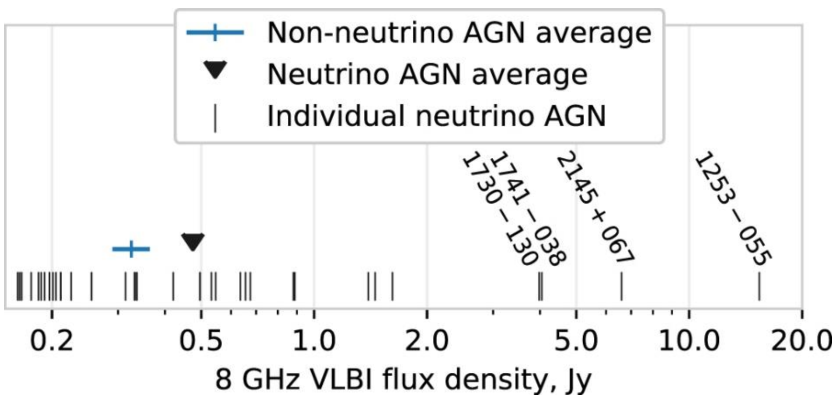


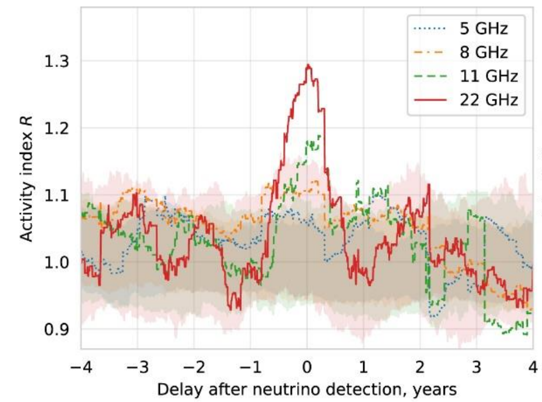

IceCube collaboration et al. 2018, Science

# Association of neutrinos with compact radio sources and their variability?

Crossmatching radio fundamental catalogue (RFC) and neutrinos with >200TeV
Variability data from RATAN-600




- 36 AGN associated with 26 neutrino events
- Mean flux density of neutrino-associated sources is higher than in a random AGN population
- Chance-coincidence probability 0.2%




(a) All sources: 18 AGN close to neutrino events.

- 18 AGN associated with 14 neutrino events
- Mean activity index calculated from radio monitoring observations by the RATAN-600 telescope is higher in the neutrino associated sample
- Chance-coincidence probability 5%

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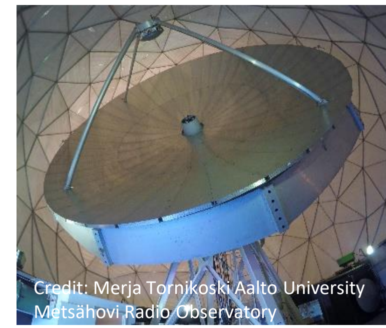
Plavin et al. 2020, ApJ, 894, 101

# Systematic study using Owens Valley and Metsähovi blazar monitoring data

http://www.astro.caltech.edu/ovroblazars/

- OVRO 40-m monitoring program
  - 1795 AGN monitored twice / week
  - 1157 of them (CGRaBS sample) since 2008, others since 2009-2011
  - 15 GHz

- Metsähovi blazar monitoring program
  - 1000 AGN monitored
  - Some > 40 years
  - ~ 400 observed regularly
  - 183 had enough data between 2008-2020 to be included in this study
  - 37 GHz

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- Same set of neutrinos as in Plavin et al. 2020, except using energy limit E >= 200 TeV
- In total 56 neutrino events

Hovatta, Lindfors et al. 2021, A&A, 650, 83

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# Statistical analysis

- Associate neutrino events and radio source positions
  - 8-20 associated AGN with 7-16 neutrino events (depending on the radio sample used)
- Calculate the mean radio flux density of the associated sources
- Calculate the activity index around the neutrino event
  - See definition of activity index on the next slide
  - window size 2.3 yrs at 15 GHz, 1.4 yrs at 37 GHz (= typical flaring time scale)
- Compare these to random samples generated by shifting the IceCube neutrino positions randomly in right ascension

→ Obtain a random chance probability

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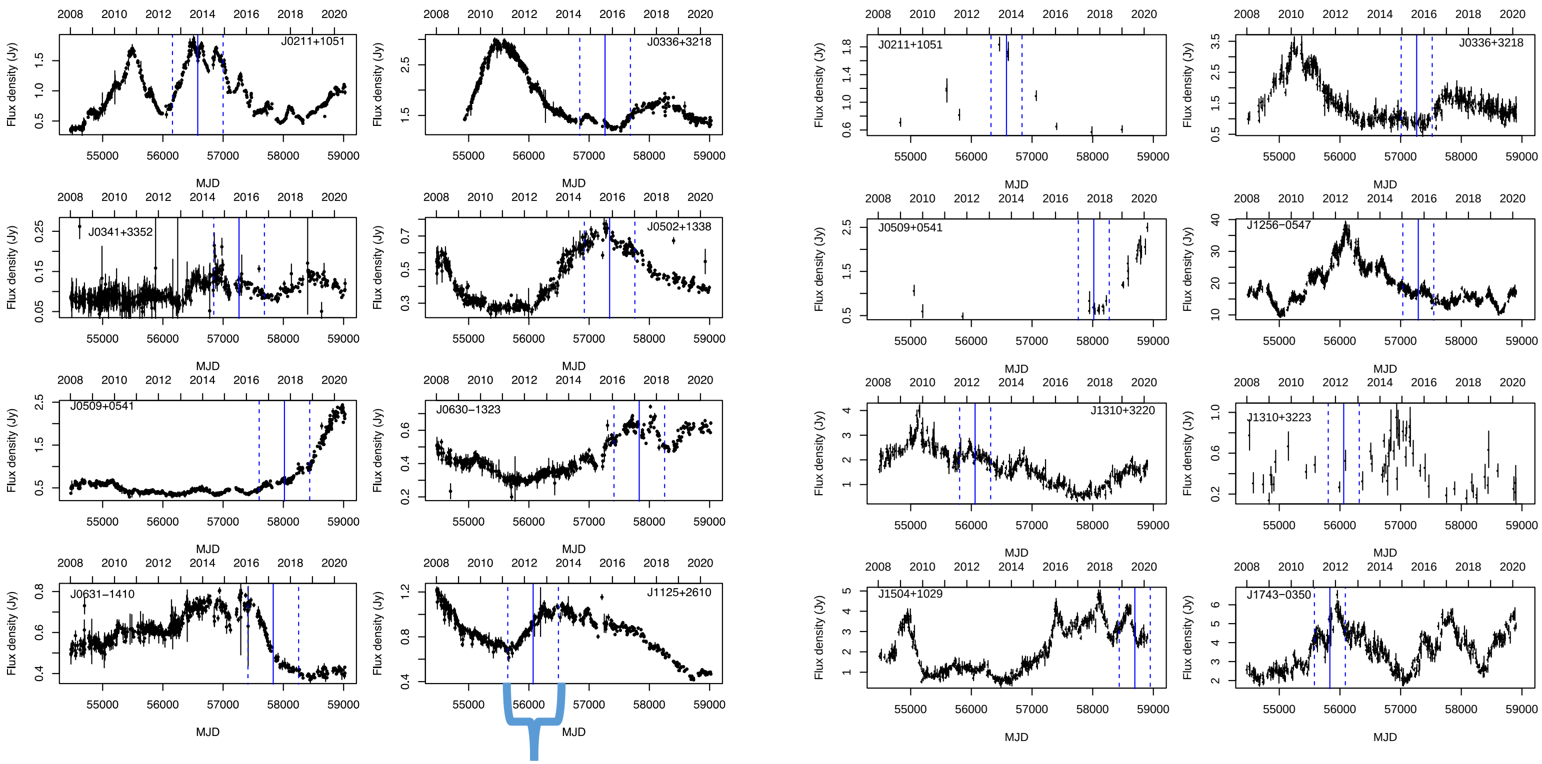
# Radio light curves of some of the associations

OVRO 15 GHz

Metsähovi 37 GHz




Activity index = mean around the neutrino event / mean of the remaining LC

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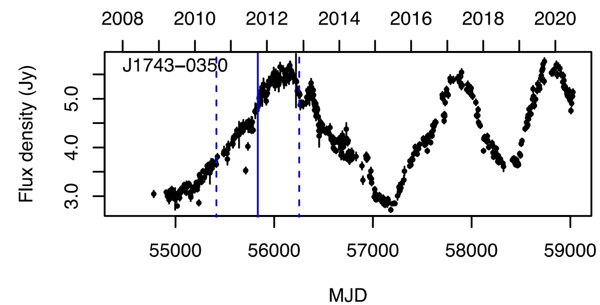
# Caveats

- Activity index is not necessarily the best tool for identifying temporal association in well-sampled light curves
    - Need a more localized approach
    - But, defining a flare (objectively) is always challenging!
- Our samples (esp. CGRaBS is very FSRQ and LSP dominated) do not include all potential neutrino emitters
    - E.g., high-synchrotron peaked sources are missing due to their radio faintness but were found in Giommi et al. 2020 to be the best candidates
        - Activity index analysis would not work anyway because they are less variable in radio frequencies

OVRO 15 GHz light curve




When defining ”flaring” sources based on the activity index, this source was not among them because the activity index is only 1.20 due to high flux density outside the neutrino arrival time

# Results: activity index

**Table 6.** Chance coincidence for the activity index analysis.

| Sample (1) | $N_S$ (2) | $\Delta\psi$ (deg) (3) | $N_A$ (4) | ⟨A.I.⟩ (5) | $p$ pre (6) | $p$ post (7) | $N_f$ (1%) (8) | $p$ pre (9) | $p$ post (10) | $N_f$ (0.01%) (11) | $p$ pre (12) | $p$ post (13) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OVRO all-AGN | 1795 | 0.9 | 18 | 1.15 | 0.003 | 0.007(×5) | 8 | 0.280 | 0.376(×5) | 6 | 0.019 | 0.027(×5) |
| CGRaBS | 1157 | 0.9 | 17 | 1.20 | 0.010 | 0.023(×5) | 8 | 0.072 | 0.108(×5) | 6 | 0.005 | **0.006**(×5) |
| OVRO-350 mJy | 589 | 0.9 | 12 | 1.29 | 0.011 | 0.024(×5) | 7 | 0.013 | 0.018(×5) | 5 | 0.002 | **0.003**(×5) |
| RFC-150 mJy | 1156 | 0.9 | 16 | 1.21 | 0.005 | 0.014(×5) | 7 | 0.132 | 0.193(×5) | 5 | 0.017 | 0.025(×5) |
| Metsähovi | 183 | 0.5 | 7 | 1.26 | 0.096 | 0.158(×5) | 4 | 0.0012 | 0.0015(×5) | 1 | 0.057 | 0.058(×5) |

**Notes.** Column (1) indicates the sample studied and Col. (2) gives the number of sources in that sample. Column (3) gives the optimal systematic uncertainty parameter $\Delta\psi$, which for each sample was found to be the same for all the A.I. analyses. Column (4) gives the number of associations found using this systematic uncertainty. The pre-trial and post-trial $p$-values are given in Cols. (6) and (7), respectively. Column (8) gives the number of flaring sources in the sample when 1% false-detection rate is used. The threshold is A.I. > 1.1 for the OVRO samples and A.I. > 1.16 for the Metsähovi sample. Column (11) is the same for 0.01% false-detection rate, which is A.I. > 1.29 for the OVRO samples and A.I. > 1.71 for the Metsähovi sample. The additional trial factor due to multiple samples is shown as a multiplicative factor in Cols. (7), (10), and (13) (see Sect. 3.1). Values significant at the $2\sigma$ level when also this trial factor is accounted for are shown in bold for the samples considered to be statistically complete.

Low number of associations, not all neutrinos associated with blazar flares (at least not of the blazars that are monitored by OVRO)

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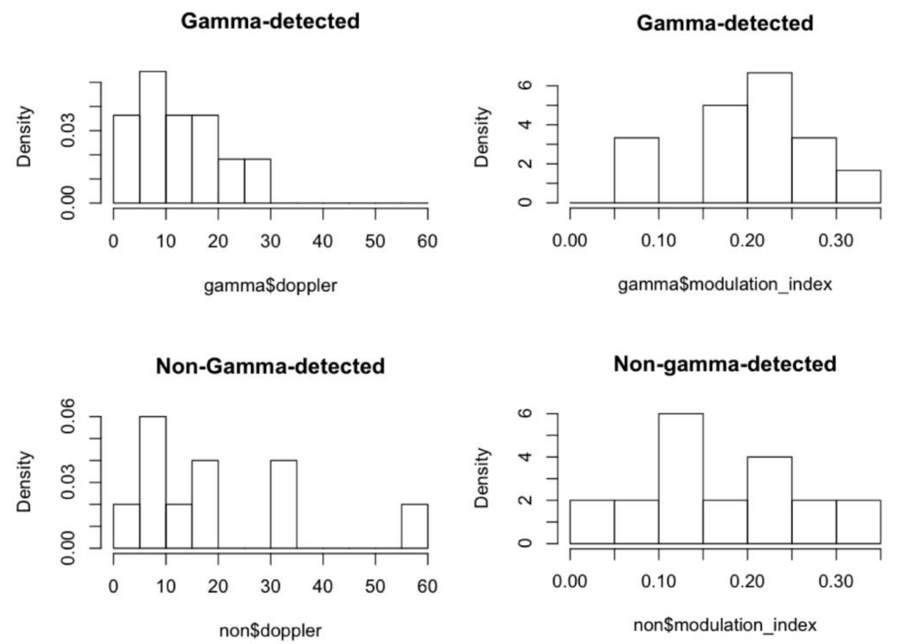
# Note on associated sources: half of them are **not** gamma-ray sources

- 10 / 22 of the OVRO associations are not detected by Fermi-LAT in GeV gamma-ray energies
- They have as high Doppler beaming factors and radio modulation indices as the gamma-ray detected sources
- Have fairly low synchrotron peak frequencies, which may explain their gamma-ray non-detection (see Lister et al. 2015, ApJ, 810, L9)
    - Dense photon fields required for neutrino emission may also absorb gamma-ray emission
- These sources are missing from most neutrino-blazar studies which concentrate on Fermi-detected sources only!

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The main finding: If there is a large radio flare at the same time as a neutrino event, it is unlikely to happen by random coincidence (but this is 2σ result)

Hovatta, Lindfors et al. 2021, A&A, 650, 83

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# What would we see in ideal case?

- We simulated neutrino counterpart populations under the null hypothesis that those neutrinos are emitted during radio flares.
- Simple question: can we detect a correlation if all neutrinos are astrophysical and if all were produced during the peaks of radio flares?
- The radio light curves and the neutrino sample from Hovatta et al. 2021. Assigned new arrival times so that neutrinos coincide with peaks of radio flares. Flares identified with Bayesian blocks.
- Remember:

1. Only half of the neutrinos are real astrophysical neutrinos and we do not know which ones
2. Only 18/56 neutrinos were associated to blazars, some of them had multiple blazars in the field of view and we do not know which one of them is the right one!

- Repeat the analysis we did in Hovatta et al. 2021

Liodakis, Hovatta et al. (including EL), 2022, A&A, 666, A36

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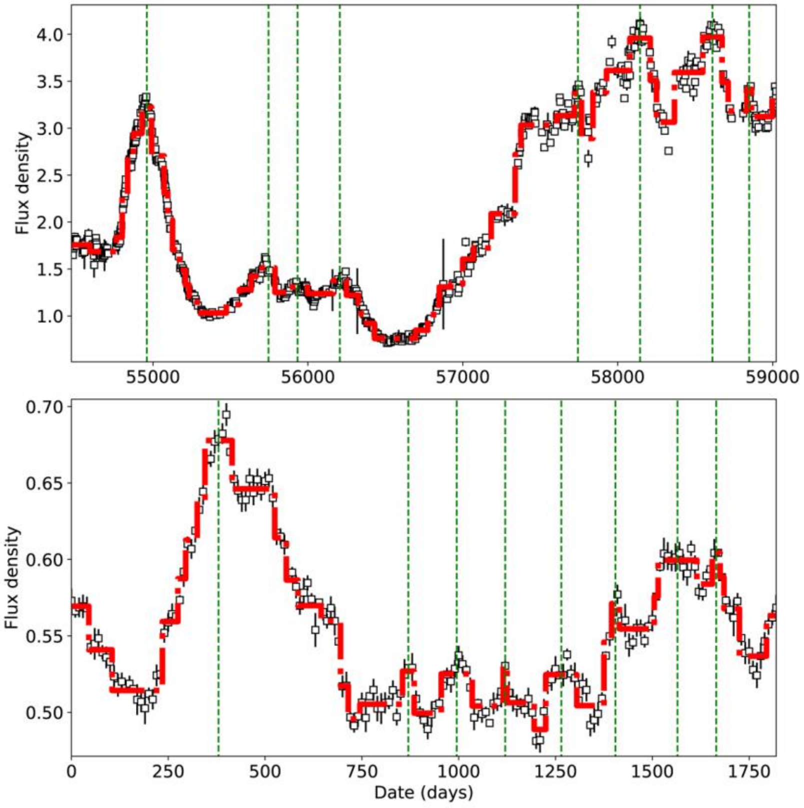
# What would we see in ideal case?

- Simulation where neutrinos are placed to arrive on during radio flares (vertical lines are the peaks of the flares)
- Repeat the analysis we did in Hovatta et al. 2021
- Consider three cases:

1. we randomly select identified flares in the light curve
2. we randomly select flares whose peak blocks have a flux density higher than the median of the flares in that light curve
3. we select only the highest flux-density flare.

- Repeat 1000 times, check in how many cases we would get at least 2-3σ result
- We also tested what will happen if we could monitor larger sample

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Liodakis, Hovatta et al. (including EL), 2022, A&A, 666, A36

# What would we see in ideal case?

**Table 1.**

And would have arrived on highest flare of the light curve, we should have seen it, so median case is more likely

Percentage of 1000 simulations meeting the specific significance level in a given test.

All neutrinos astrophysical

| Selected flares | Signalness | $N_{src}$ | Mean A.I. | | Flaring sources | | Mean flux density | |
|---|---|---|---|---|---|---|---|---|
| | (Y/N) | | $p \leq 3\sigma$ | $p \leq 2\sigma$ | $p \leq 3\sigma$ | $p \leq 2\sigma$ | $p \leq 3\sigma$ | $p \leq 2\sigma$ |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| Any | N | 1158 | 6.3 | 33.1 | 0.3 | 16.3 | 0 | 0.2 |
| ≥ Median | N | 1158 | 46.8 | 88.1 | 9.2 | 57.1 | 0 | 0.8 |
| Maximum | N | 1158 | 100 | 100 | 70.9 | 100 | 0 | 0.9 |
| Median | Y | 1158 | 15 | 50.7 | 1.7 | 31.1 | 0 | 1.6 |
| Maximum | Y | 1158 | 41.5 | 82.3 | 10.8 | 67.9 | 0 | 1.4 |
| Median, no flux cut | Y | 5000 | 0.1 | 40.2 | 0.1 | 13.5 | 0 | 0 |
| Maximum, no flux cut | Y | 5000 | 0.5 | 97.8 | 0.9 | 60.7 | 0 | 0 |
| Median, ≥0.5 Jy | Y | 5000 | 4.6 | 56 | 7.1 | 37.1 | 100 | 100 |
| Maximum, ≥0.5 Jy | Y | 5000 | 60.4 | 98.9 | 43.0 | 82.9 | 100 | 100 |
| Median, ≥1.0 Jy | Y | 5000 | 4.0 | 84.1 | 40.1 | 78.7 | 100 | 100 |
| Maximum, ≥1.0 Jy | Y | 5000 | 42.8 | 100 | 94.9 | 100 | 100 | 100 |

Liodakis, Hovatta et al. (including EL), 2022, A&A, 666, A36

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# What would we see in ideal case?

**Table 1.**

Percentage of 1000 simulations meeting the specific significance level in a given test.

Now taking into account that we dont know which are the astrophysical ones

| Selected flares | Signalness | $N_{src}$ | Mean A.I. | | Flaring sources | | Mean flux density | |
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# What would we see in ideal case?

**Table 1.**

Percentage of 1000 simulations meeting the specific significance level in a given test.

Increasing sample size will only help, if it is just the strongest sources that contribute

| Selected flares | Signalness | $N_{src}$ | Mean A.I. | | Flaring sources | | Mean flux density | |
|---|---|---|---|---|---|---|---|---|
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Liodakis, Hovatta et al. (including EL), 2022, A&A, 666, A36

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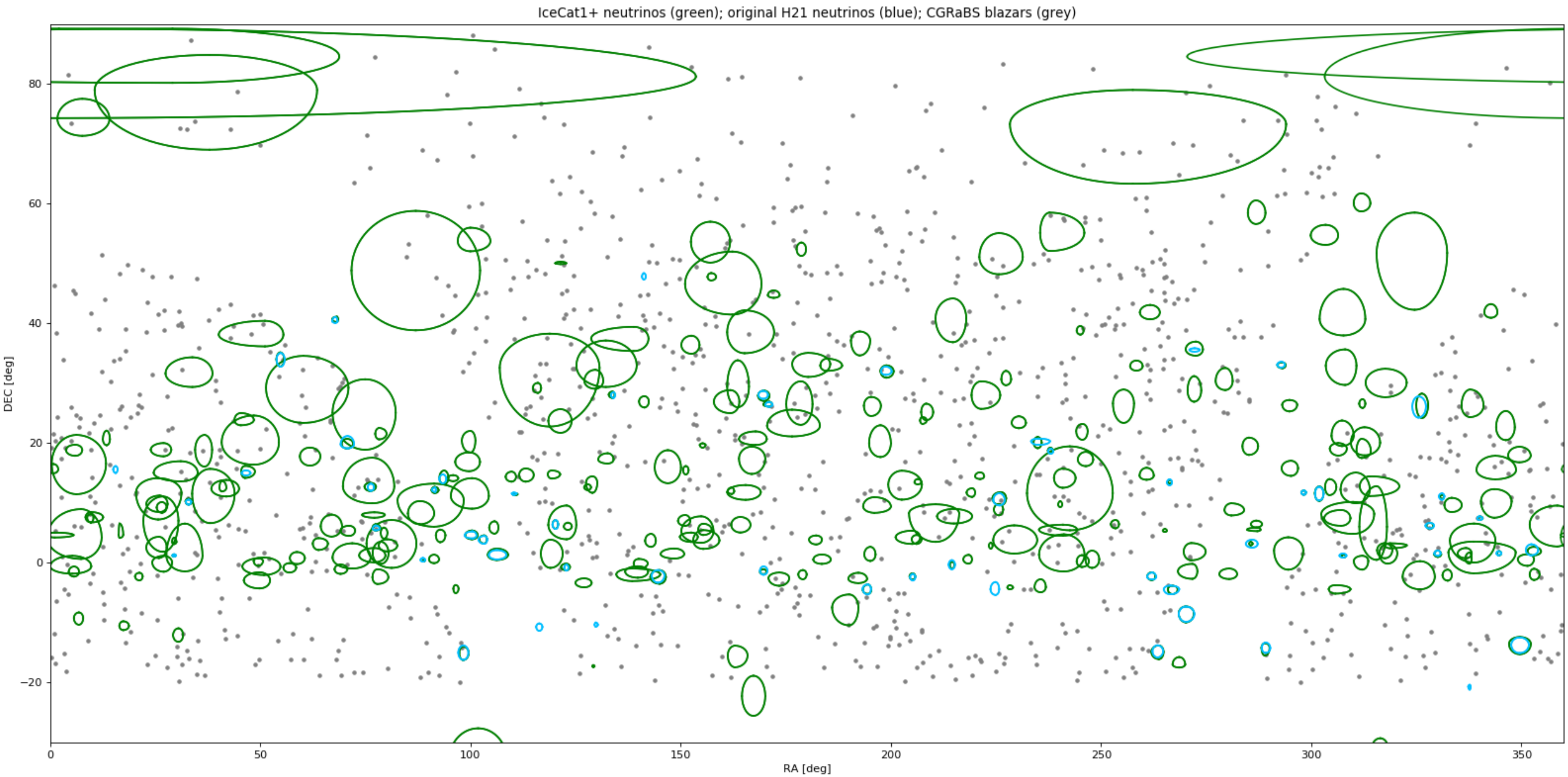
# Updated analysis

- Hovatta et al. 2021 included ~11 years of data (2008-2019), additional 3 years collected since then
- More uniform neutrino sample from ICECAT-1 (but keeping the good events also from 2008-2009 not included in ICECAT-1) which contains also the signalness: 283 neutrinos
- Allows also more sophisticated analysis

Kouch, Lindfors, Hovatta et al. 2023, submitted to A&A

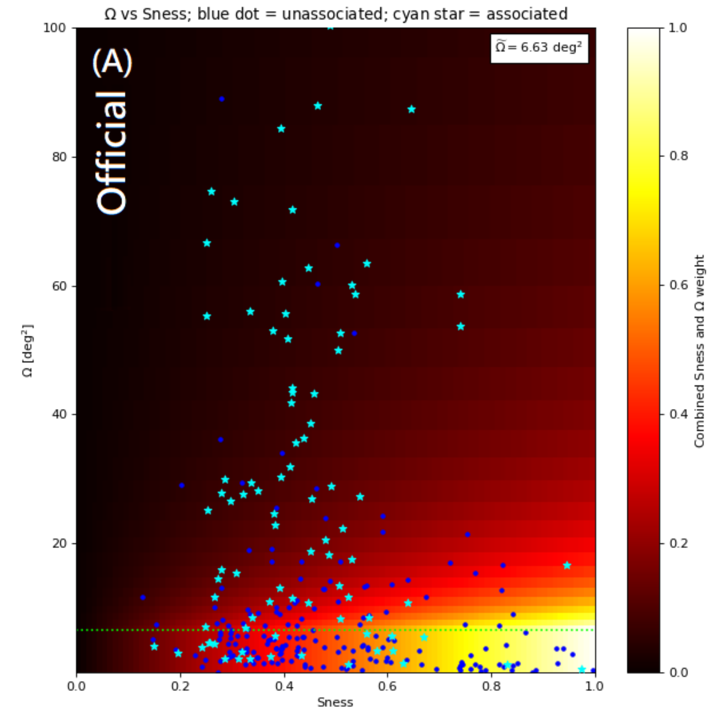
# Updated analysis

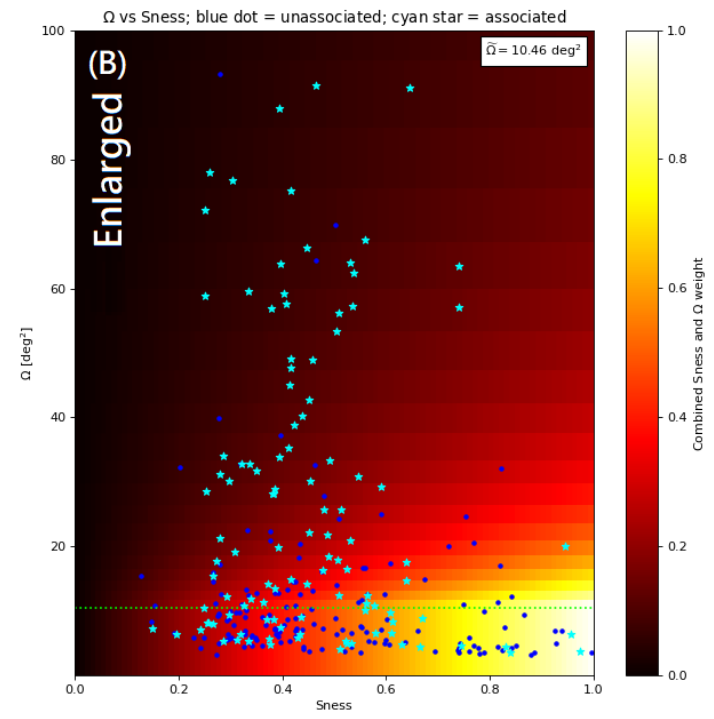



IceCat1+neutrinos (green); original H21 neutrinos (light blue); CGRaBS blazars (grey)

# Updated analysis

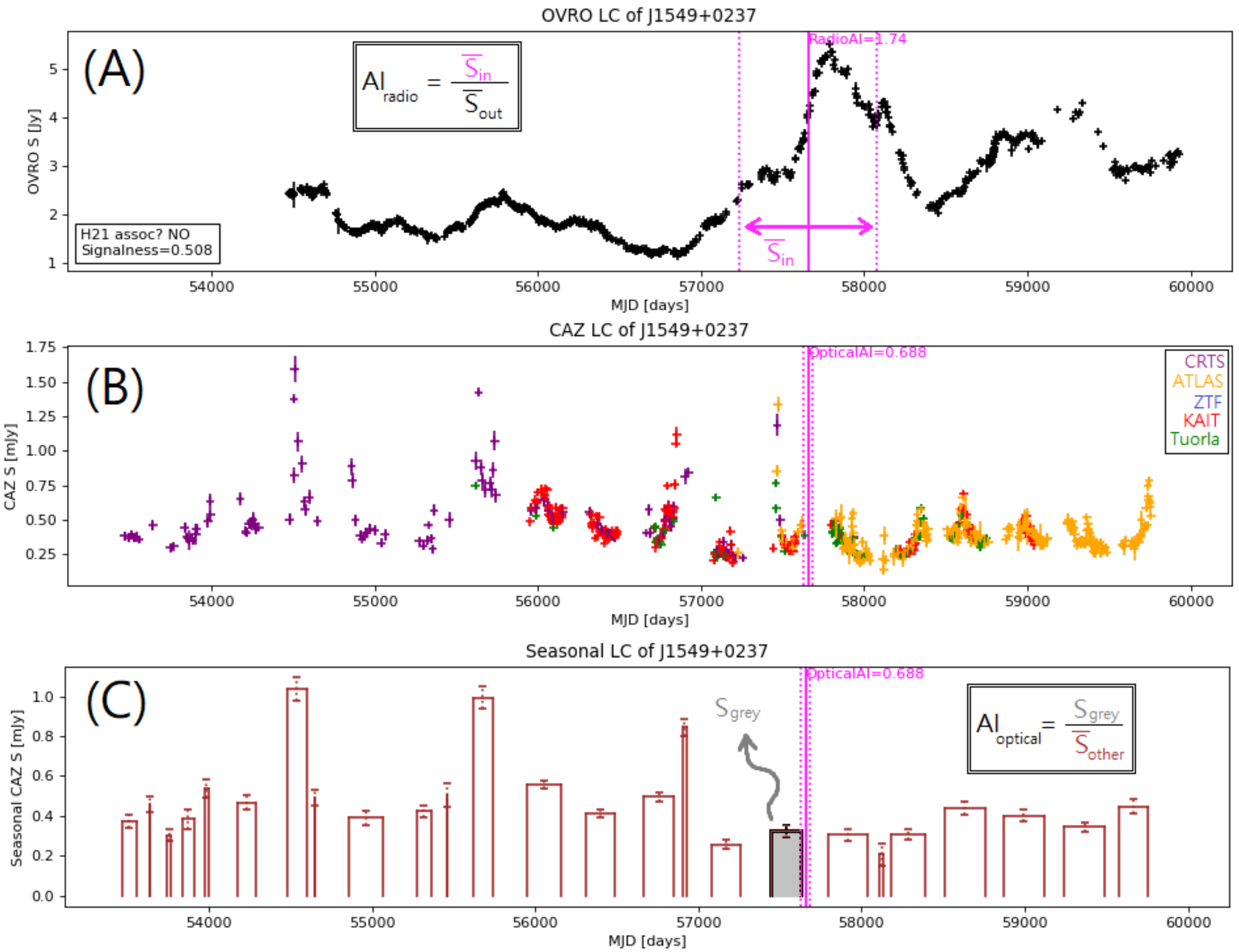
- To use the full neutrino information instead of simple cuts, we use weighting based on signalness and positional accuracy
- We consider two different scenarios for systematic errors. IceCube official (A)=0.0 and Enlarged (B)=1.0
- We now only consider one blazar sample: CGRaBS (1157) as it is most uniformly selected and statistically most complete and in H21 we got similar results to all samples (expected as there is large overlap in samples)
- In addition to radio flaring, we are also looking at the optical flaring as for some weak radio sources it could be better tracer of jet activity



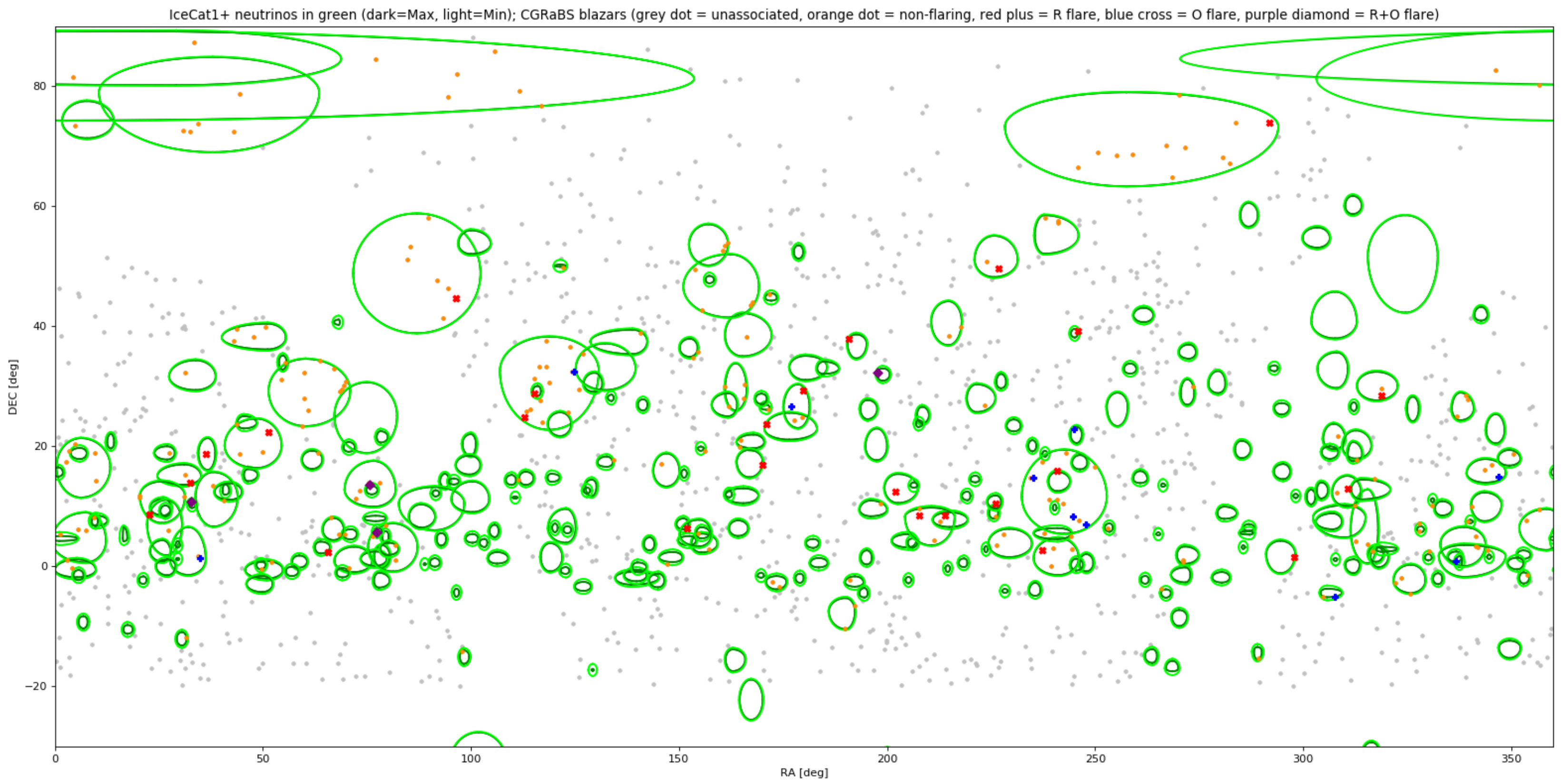



# Updated analysis

- In optical: seasonal gaps, no typical flaring timescales: the flux of the closest seasonal block



# Results




Associated blazars: not flaring (orange), radio flare (red), optical flare (blue), optical+radio (purple)

# Results

| Error (1) | Band (2) | $\overline{S}$ (3) | AI (4) | $AI_{1\%}$ (5) | $AI_{0.01\%}$ (6) |
|---|---|---|---|---|---|
| MIN | R | $0.58 \rightarrow 0.05$ (p=0.5719) | $0.99 \rightarrow 0.10$ (p=0.2252) | $54 \rightarrow 4.91$ (p=0.7739) | $22 \rightarrow 2.53$ (p=0.2963) |
| | O | $0.63 \rightarrow 0.05$ (p=0.3462) | $0.96 \rightarrow 0.10$ (p=0.4368) | $22 \rightarrow 2.47$ (p=0.4687) | $11 \rightarrow 1.38$ (p=0.4446) |
| | R+O | $1.07 \rightarrow 0.09$ (p=0.4491) | $1.00 \rightarrow 0.11$ (p=0.3372) | $7 \rightarrow 0.419$ (p=0.7580) | $1 \rightarrow 0.023$ (p=0.7588) |
| MAX | R | $0.58 \rightarrow 0.09$ (p=0.5445) | $0.99 \rightarrow 0.16$ (p=0.1652) | $66 \rightarrow 11.7$ (p=0.3149) | $29 \rightarrow 7.10$ (**p=0.0107**) |
| | O | $0.59 \rightarrow 0.08$ (p=0.3595) | $0.99 \rightarrow 0.18$ (p=0.1477) | $31 \rightarrow 7.01$ (**p=0.0352**) | $15 \rightarrow 4.34$ (**p=0.0377**) |
| | R+O | $1.03 \rightarrow 0.14$ (p=0.4326) | $1.01 \rightarrow 0.18$ (p=0.1186) | $11 \rightarrow 3.14$ (**p=0.0256**) | $4 \rightarrow 2.270$ (**p=0.0014**) |

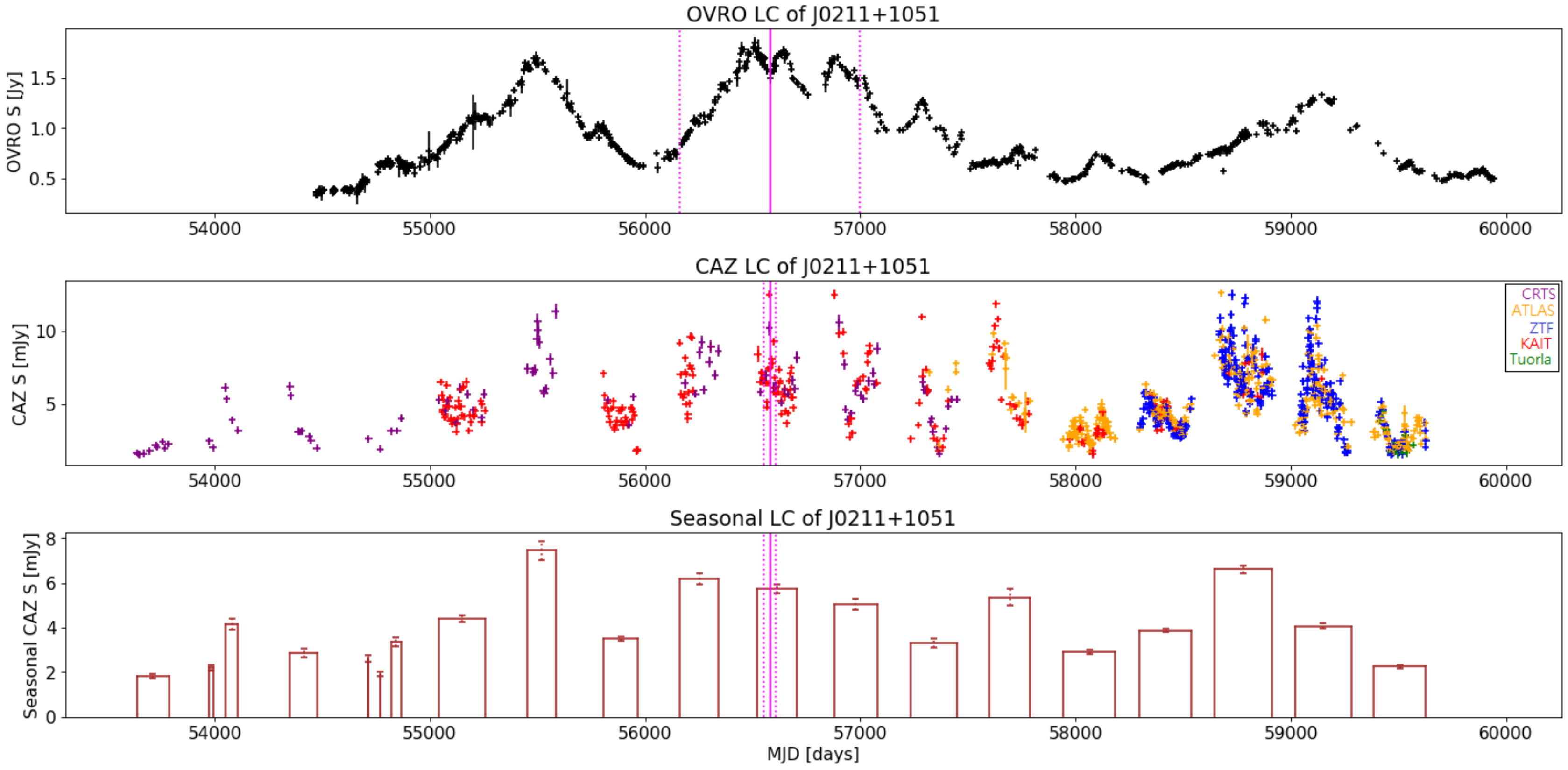
- With official error regions: nothing in none of TS parameters we study. In agreement with Abbasi et al. 2023 (they did not study variability though).
- Allowing for larger error regions:

✓ The main result of Hovatta, Lindfors et al. 2021 persisted: If there is a large radio flare at the same time as a neutrino event, it is unlikely to happen by random coincidence

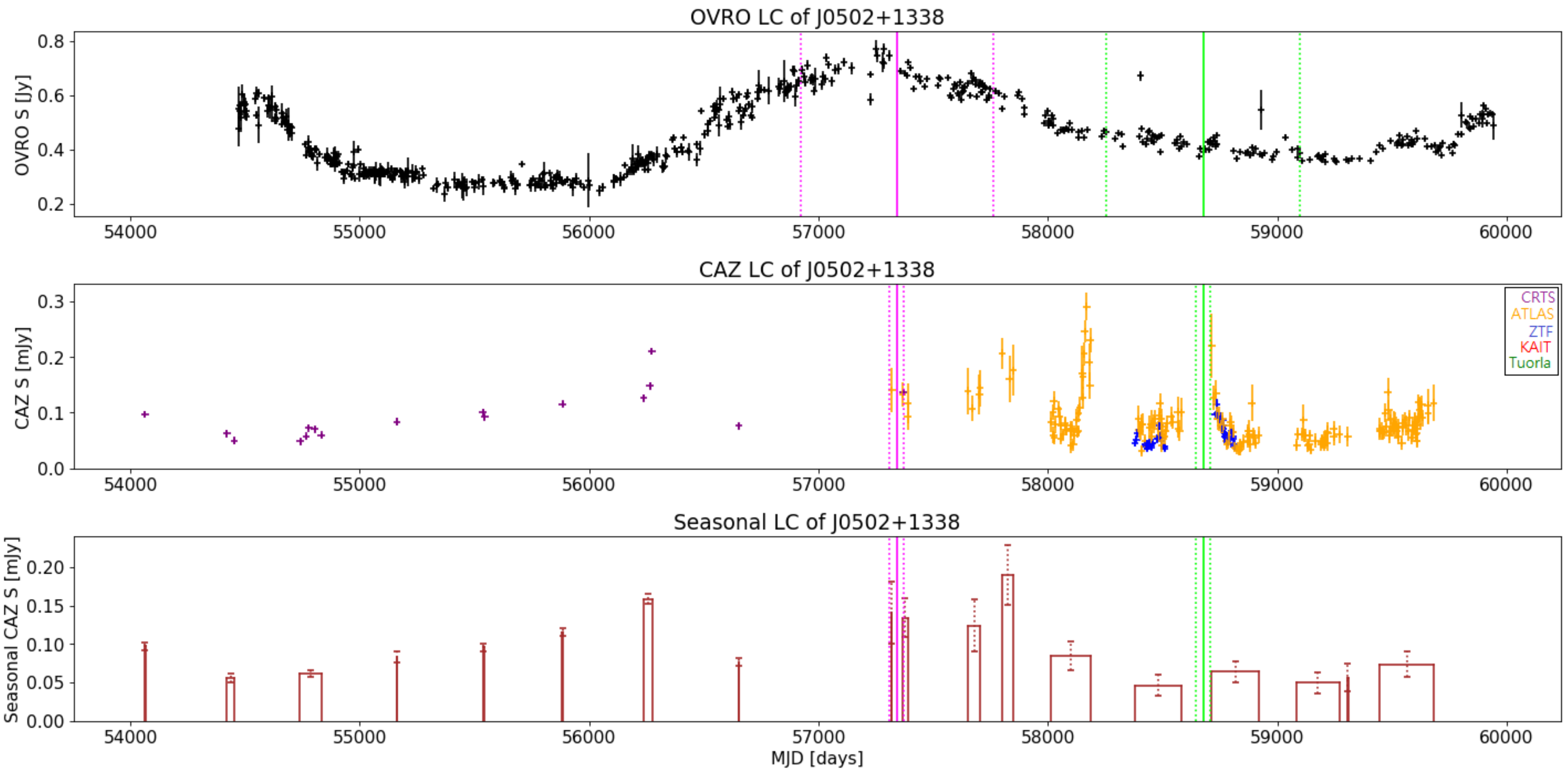
✓ Same is true for large optical flares

✓ Smallest p-value derived for R+O large flares, but that consists only of four sources

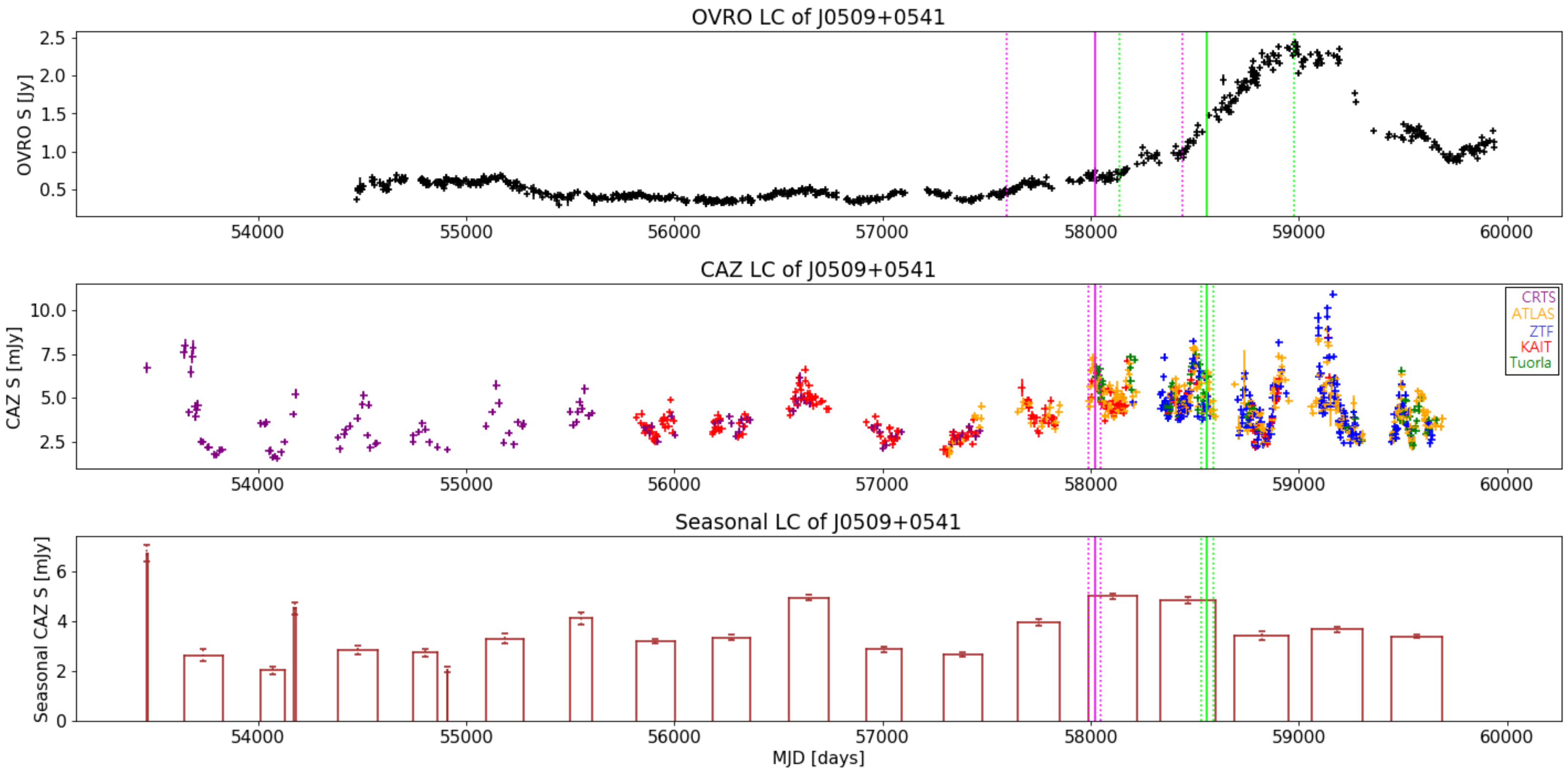
# Radio-optical flaring ones



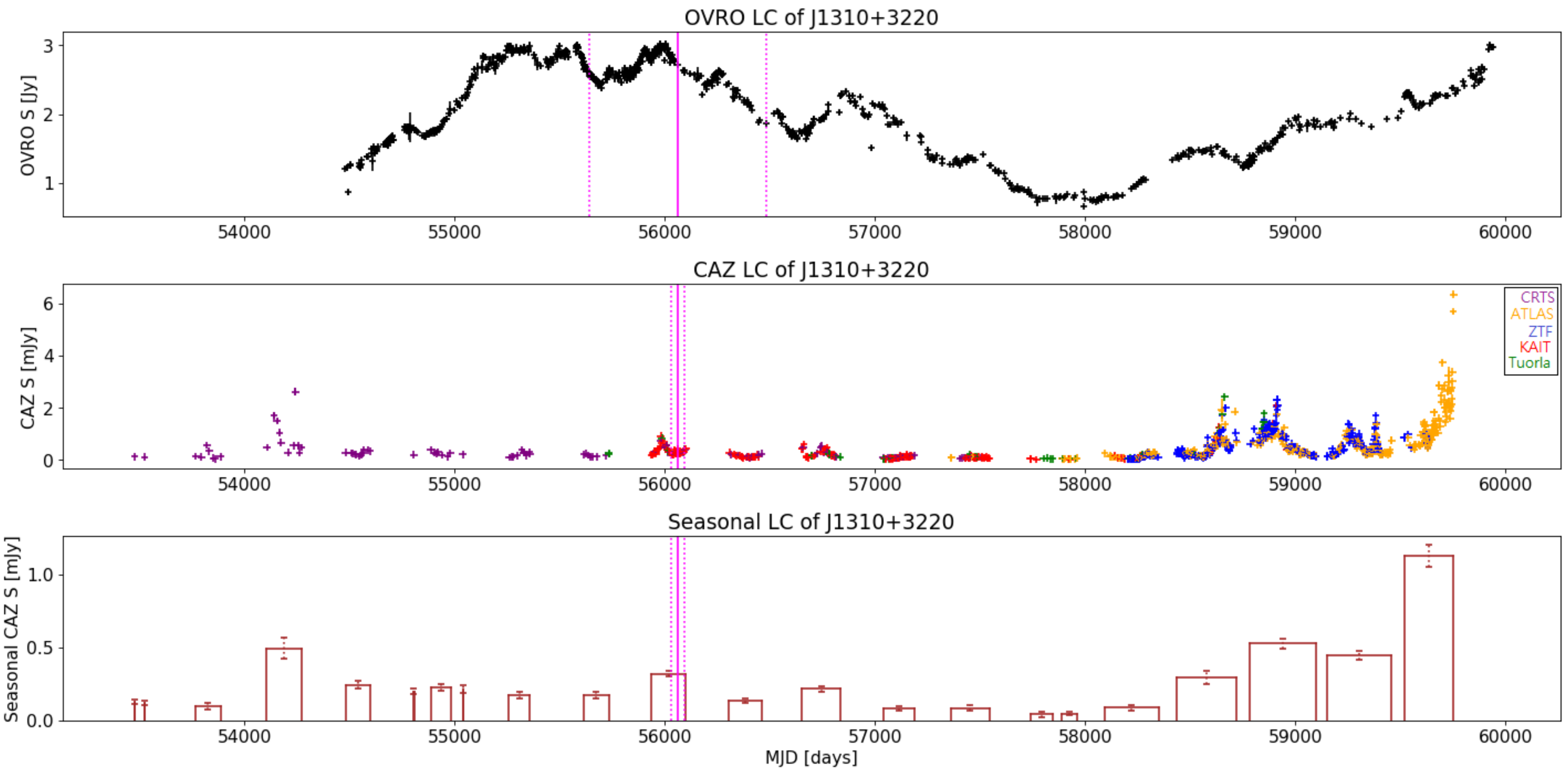
# Radio-optical flaring ones



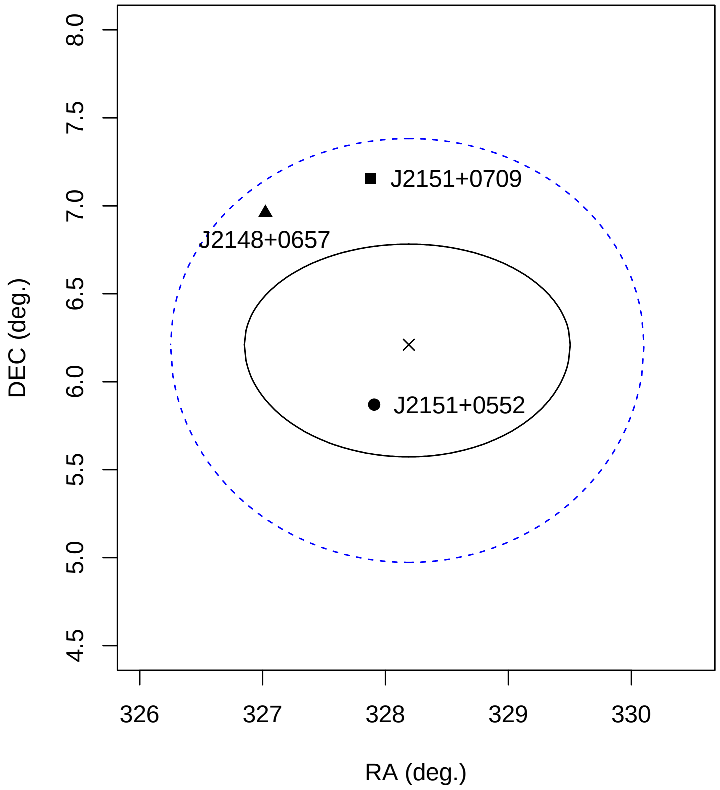
# Radio-optical flaring ones



# Radio-optical flaring ones



# Comment on IceCube error regions and systematic uncertainty




- In earlier works IceCube stated that systematic uncertainty was not included, which they say is ~ 0.5-1 deg
- This has a significant effect when associating the samples and in many works errorbars were enlarged
- Plavin et al. 2020 used an iterative approach to estimate the sys uncertainty
    - They found it to be 0.5-0.7 degrees in their samples
    - They account for multiple trials in their MC simulations
    - Using same method in Hovatta et al. 2021, we also got similar result.

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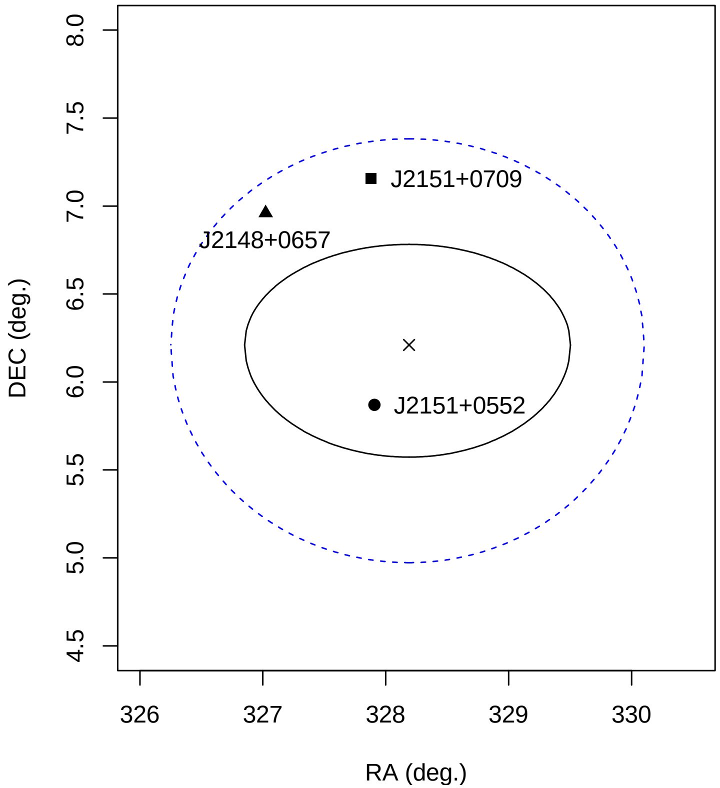
# Comment on IceCube error regions and systematic uncertainty




- Most recent IceCube paper: Systematic uncertainties are added to the contours before publishing them, although one could argue that there are unknown systematics. This is currently being studied (see, e.g., Abbasi et al. 2021b), but the method to calibrate the errors is conservative, and the real uncertainties could be smaller. However, it is worth investigating this scaling up of the contours since other analyses have also found interesting hints of signals following a similar procedure (although in some cases with a very different neutrino data sample focused on lower energies; e.g., Giommi et al. 2020; Buson et al. 2022).

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# Summary and Conclusions

- We find that some IceCube neutrinos are likely to be associated with strongly flaring blazars
- We only got 2-3$\sigma$ results, but we also showed with simulations that with the observational data in hand it is actually unlikely to be able to do better
- We eagerly wait for IceCube to publish their systematic uncertainties, it would also allow us to implement it into our weighting scenario in more sophisticated manner
- We continue to investigate if optical data, which would allow us to address full population of blazars can be further used for such studies
- In the following years we look forward to extend our efforts to higher radio frequencies: new Metsähovi Radio Observatory receiver and African millimetre telescope are coming!