HE Neutrinos vs Blazar flares in Radio & Optical

* Kouch et al. 2023, submitted to A&A

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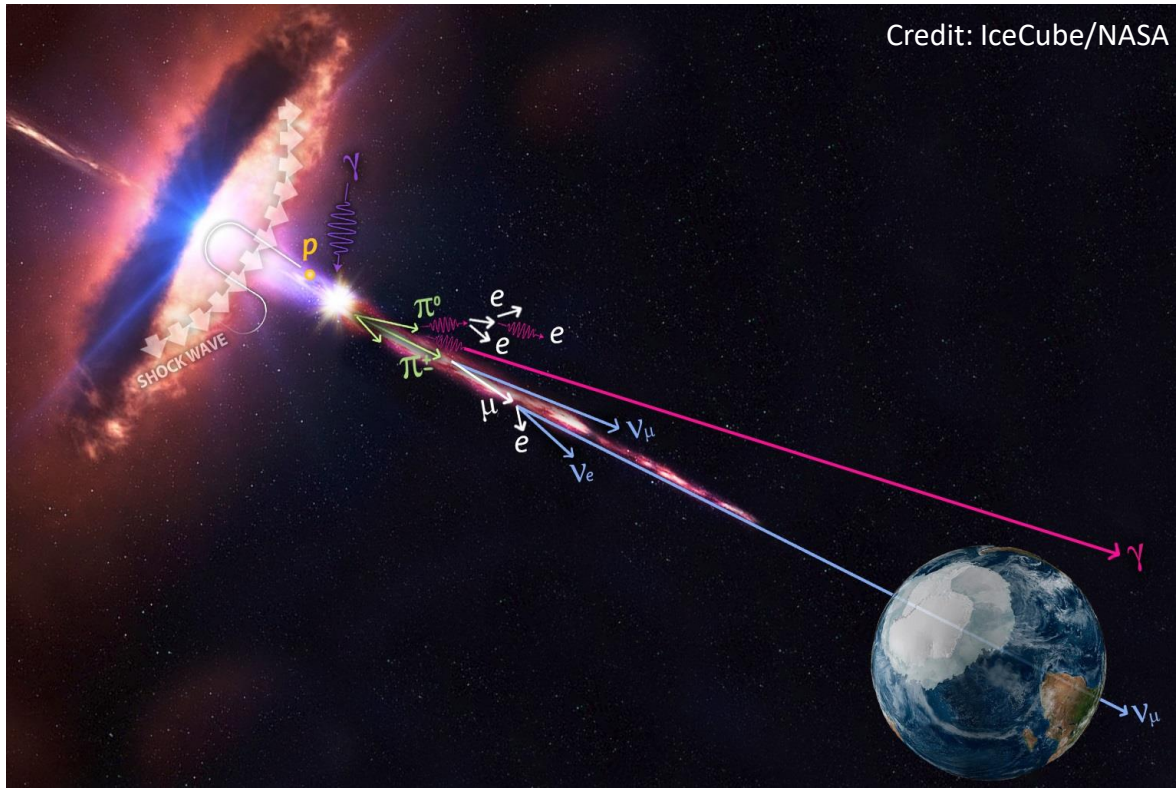
Image credit:
Quanta Magazine

September 2023 - TeVPA, Naples

Blazars as candidate neutrino emitters

- Blazars: AGN with relativistic plasma jets pointed at us
- Two main emission components:
  - LE (Radio – UV) ⟶ synchrotron emission by leptons
  - HE (X – VHE-γ) ⟶ debated: leptonic vs hadronic
- Hadronic models typically involve pγ interactions:
  ⟶ HE neutrinos released as byproduct
- TXS0506+056 remains the most convincing individual blazar-neutrino association with several other associations following it
- A high σ population-based correlation is yet to come…



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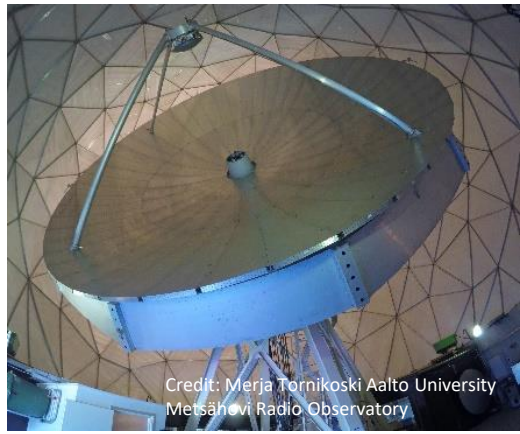
Radio as tracer of jet activity

Hovatta et al. 2021

- Following Plavin et al. 2020 (which showed $\sim 3\sigma$ correlations in radio)
- Using high-cadence radio light curves via long term monitoring
  - E.g. OVRO blazar monitoring program
    ⟶ 1795 AGN monitored @15 GHz
    ⟶ 1157 CGRaBS blazars since 2008
  - E.g. Metsähovi blazar monitoring program
    ⟶ 1000 AGN monitored (~400 regularly) @37 GHz
    ⟶ some light curves 40+ years long
    ⟶ 183 with enough data be included
- 56 HE ($\geq$200TeV) IceCube neutrino track events

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

CalTech's
40-m OVRO
(Owen's Valley
Radio Observatory)



14-m Metsähovi
Radio Observatory

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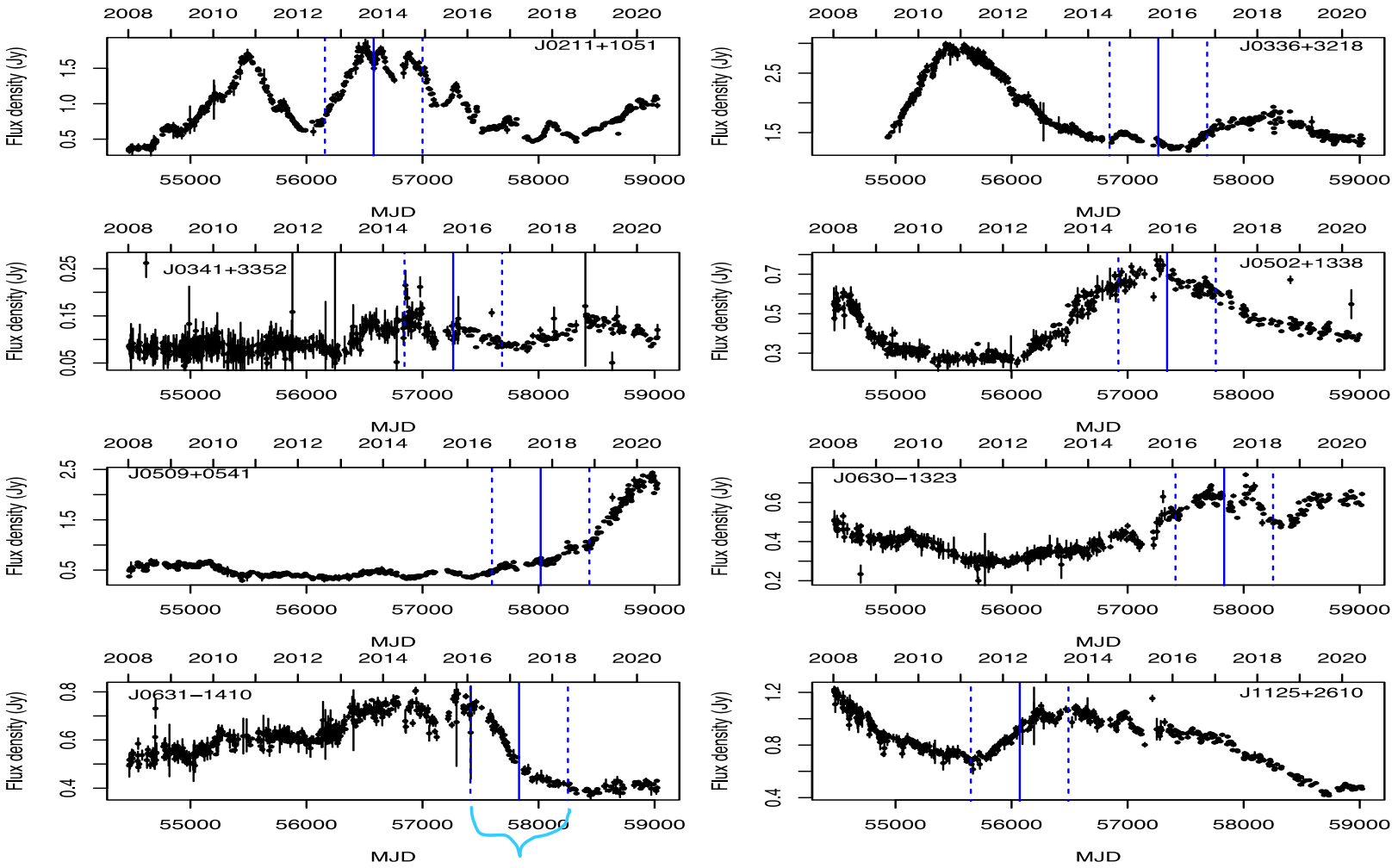
A few associated light curves

Hovatta et al. 2021

OVRO 15 GHz light curves



[2.3 years window]

$\bar{S}_{\mathrm{in}}$

AI = $\bar{S}_{\mathrm{in}}$ / $\bar{S}_{\mathrm{out}}$ (AI: activity index)

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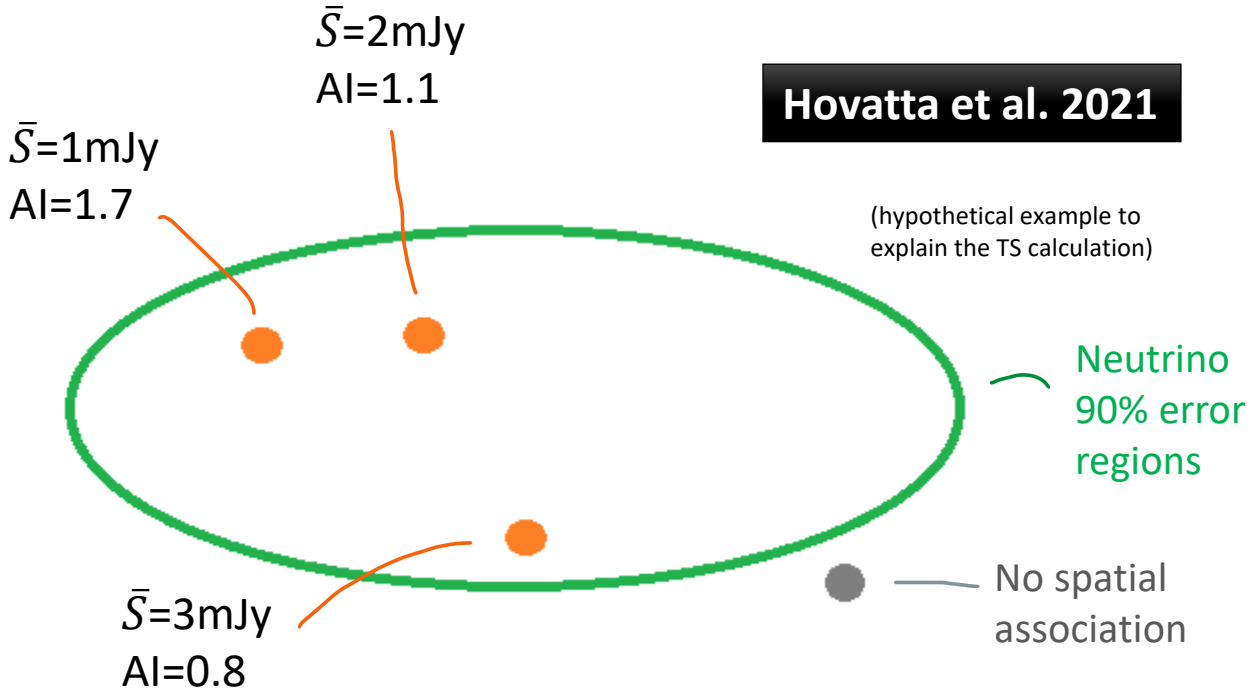
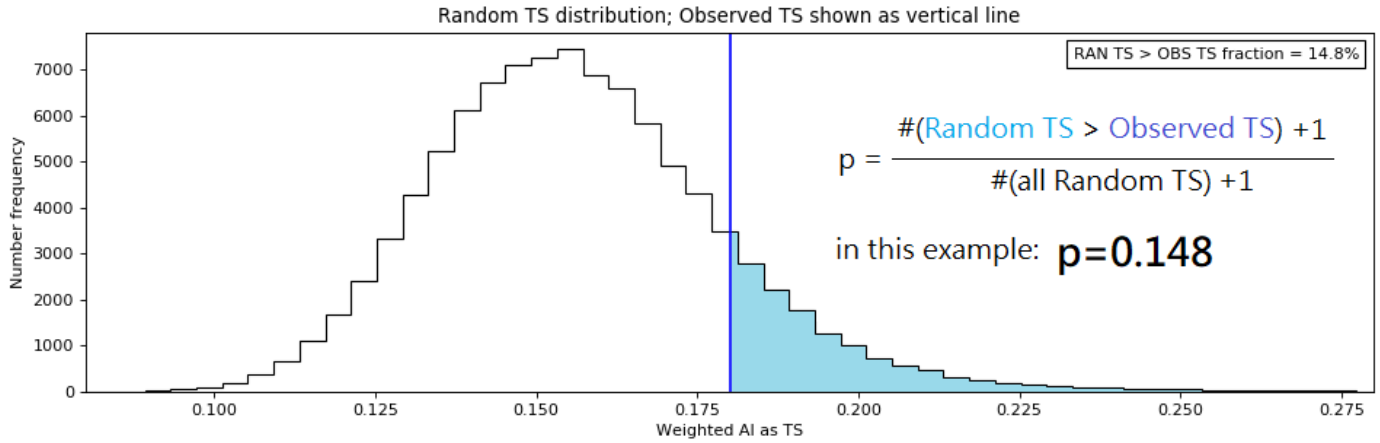
The statistics

- Look for spatial association between neutrinos (56) and blazars (of different samples)

- **TS — SPATIAL only**:
  Calculate $\bar{S}$ of the spatially associated blazars and average globally
- **TS — SPATIO-TEMPORAL 1**:
  Calculate AI of spatially associated blazars around the neutrino arrival time and average globally
- **TS — SPATIO-TEMPORAL 2**:
  Globally count spatially associated blazars significantly flaring (AI > threshold) at neutrino arrival time

- Randomized by shifting neutrino RA positions
- Compare observed test statistic to random ones to obtain p-value





(example from Kouch et al. 2023)

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The spatio-temporal results

Hovatta et al. 2021

(**TS**: # of spatio-temporally associated blazars)

Sample	N_S	$\Delta\psi$ (deg)	N_A	⟨A.I.⟩	p pre	p post	N_f (1%)	p pre	p post	N_f (0.01%)	p pre	p post
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(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)

$> 2\sigma$ (post-trial)

If there is a large radio flare at the same time as a neutrino event, it is unlikely to happen by random coincidence

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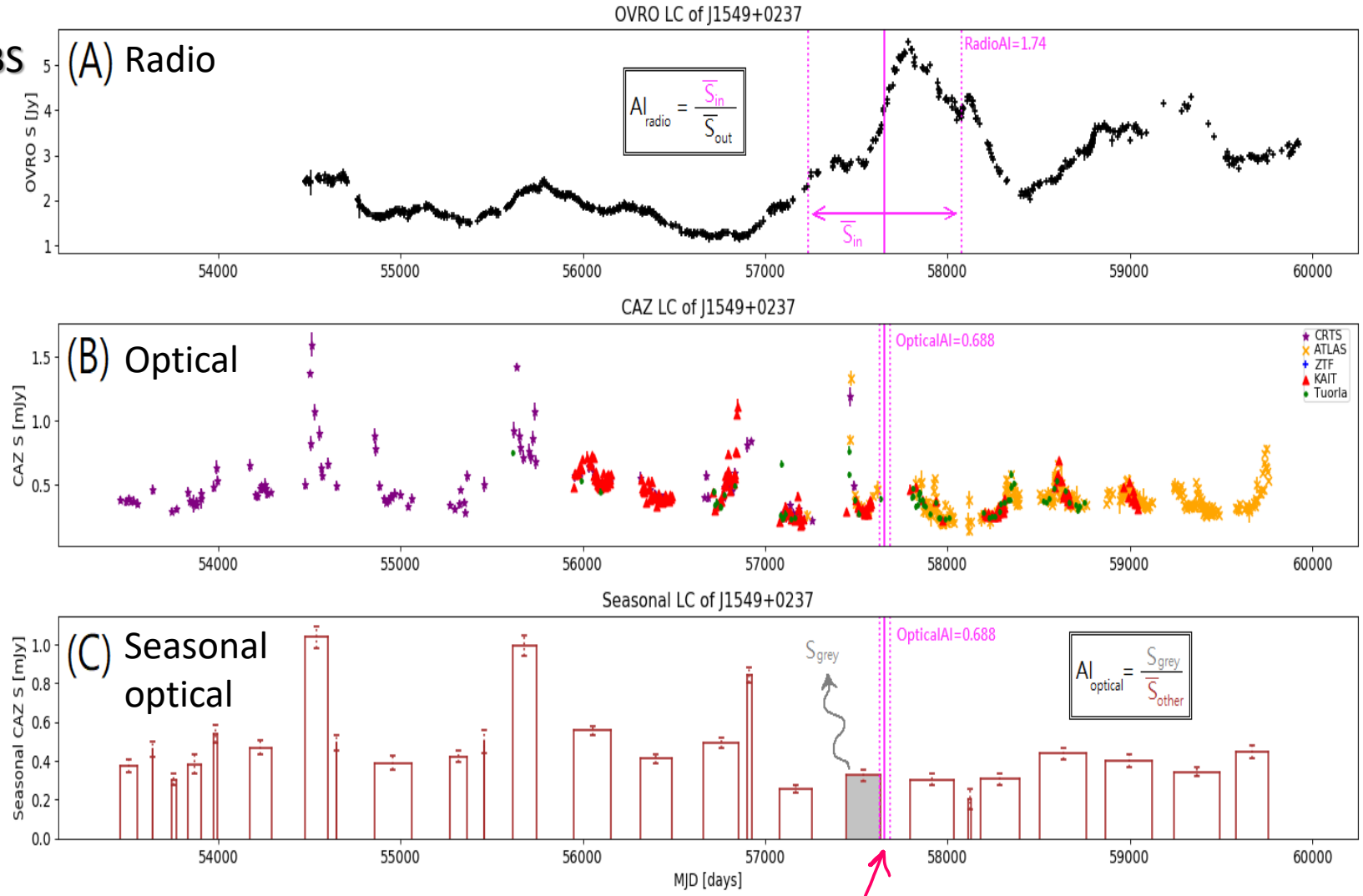
The update study

Kouch et al. 2023

- Most statistically complete sample: CGRaBS
  - ⟶ **1157** blazars
  - ⟶ OVRO light curves since 2008 (extended by 3 years)
  - ⟶ complete to 65 mJy @4.8 GHz
  - ⟶ caveat: dominated by FSRQs
- Optical band analysis
  - ⟶ using all-sky survey light curves
  - ⟶ via long-term trends (seasonal)
- Most up-to-date IceCube data
  - ⟶ **283** HE neutrino events (IceCat-1 & Abbasi et al. 2022)
- More sophisticated analysis



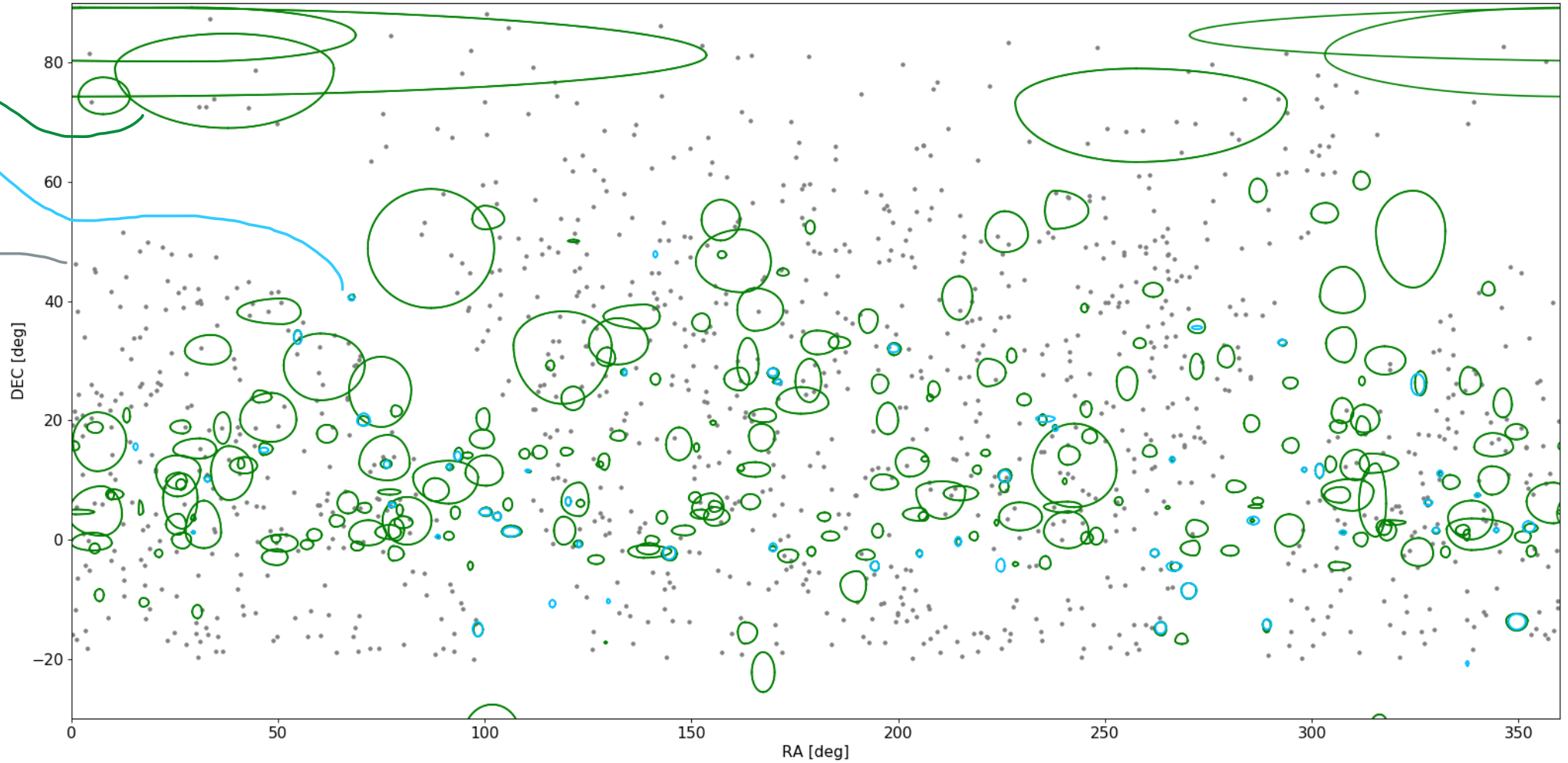
Old vs updated neutrinos

Kouch et al. 2023

Updated neutrinos (283)

Old neutrinos (56)

CGRaBS blazars (1157)



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The updated analysis

- No E, $\mathcal{S}$, or Ω cuts → many poorly reconstructed events
- Handled by adding weights

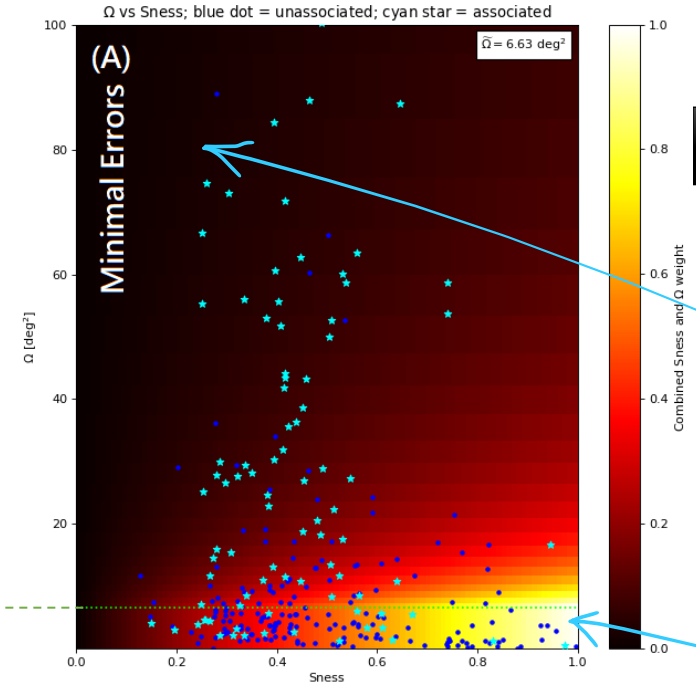
$$W = \begin{cases} \mathcal{S} & \text{if } \Omega \leq \widetilde{\Omega} \\ \mathcal{S} \cdot \widetilde{\Omega} \,/\, \Omega & \text{if } \Omega > \widetilde{\Omega} \end{cases}$$

signalness — Med(Ω) — 90%-likelihood error region

$\propto \frac{\mathcal{S}}{\Omega}$

Med(Ω)

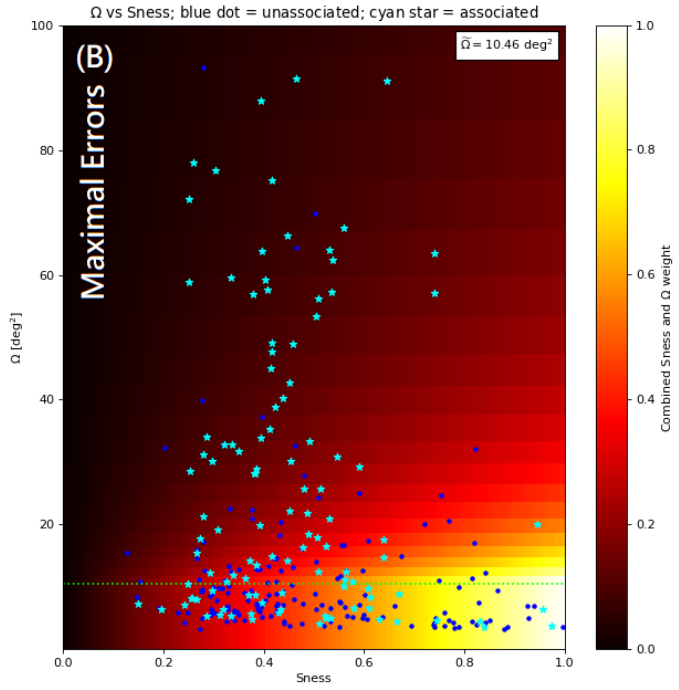
$\propto \mathcal{S}$



Kouch et al. 2023

Low weight (~0)

High weight (~1)



- Handling of the unknown IceCube systematic errors
  - ⟶ estimated upper limit is 1° (Aartsen et al. 2013)
  - ⟶ we consider two scenarios
    - (A) **MINIMAL**: systematic errors added = 0.0°
    - (B) **MAXIMAL**: systematic errors added = 1.0°

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The updated results

(**TS**: # of spatio-temporally associated blazars)

Kouch et al. 2023

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

Minimal scenario = no correlation

Maximal scenario = suggestive correlation

(at best: post-trial $\sim 3\sigma$)

- Most of the highest weighted spatio-temporal associations are only in MAX (not in MIN)

- In MAX:
  - The previous conclusion is reaffirmed and extended to the optical regime
  - The strongest correlation occurs with simultaneous Radio+Optical flaring activity
    ⟶ N.B. this arises from four associations only

It is unlikely to have such significant radio and/or optical flaring activity at the same time as a neutrino event by random chance alone

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The sky-map of the associations

Kouch et al. 2023

In maximal scenario of 1157 blazars:

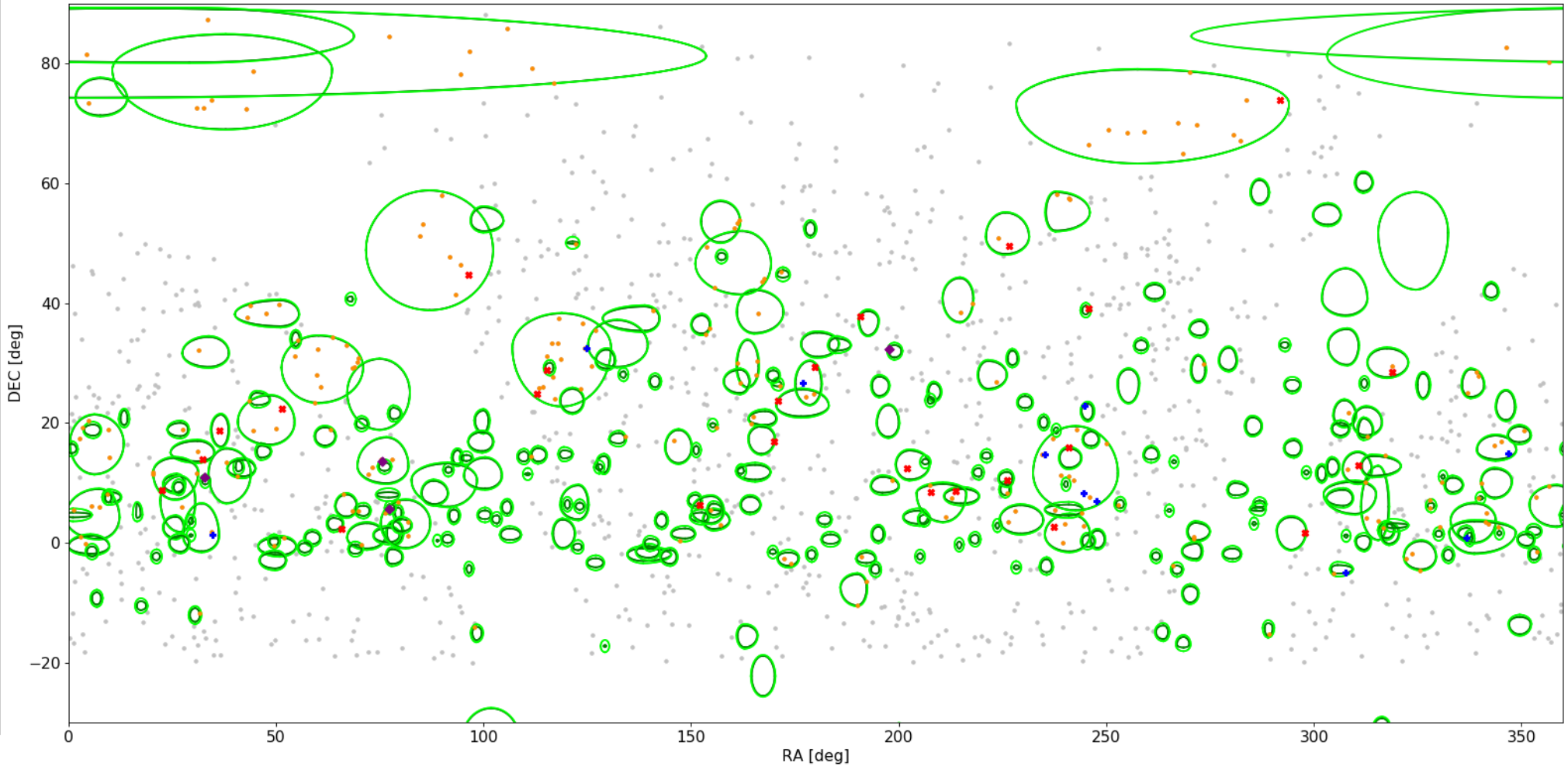
[915] no spatial assoc

[203] spatial but no temporal assoc

[25] spatio-temporal assoc in RADIO only

[10] spatio-temporal assoc in OPTICAL only

[4] spatio-temporal in RADIO + OPTICAL



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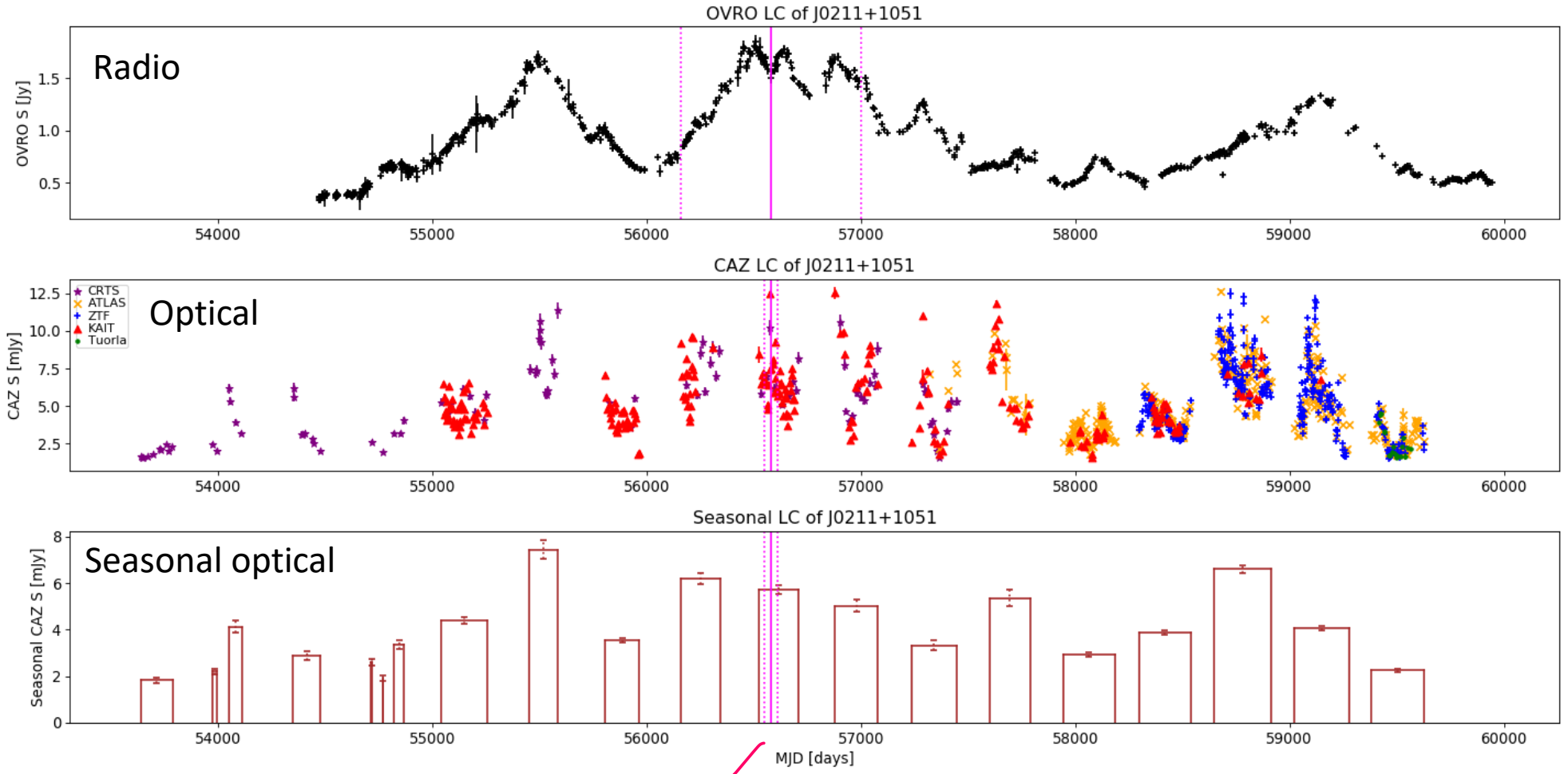
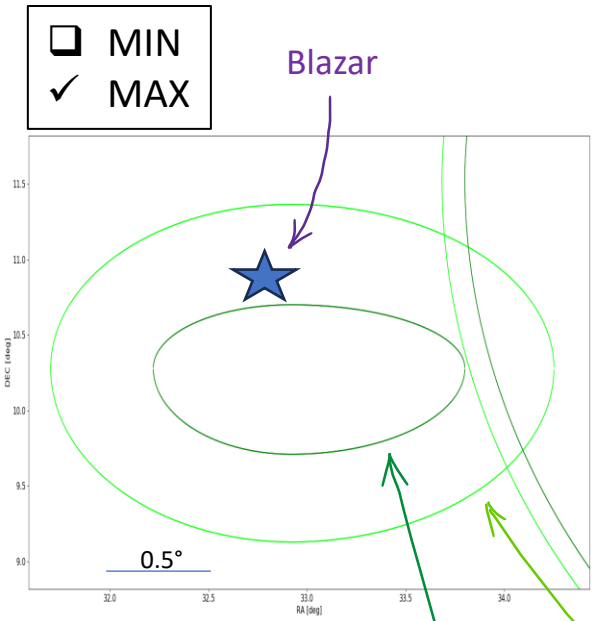
J0211+1051

Kouch et al. 2023





Simultaneous R+O spatio-temporal association

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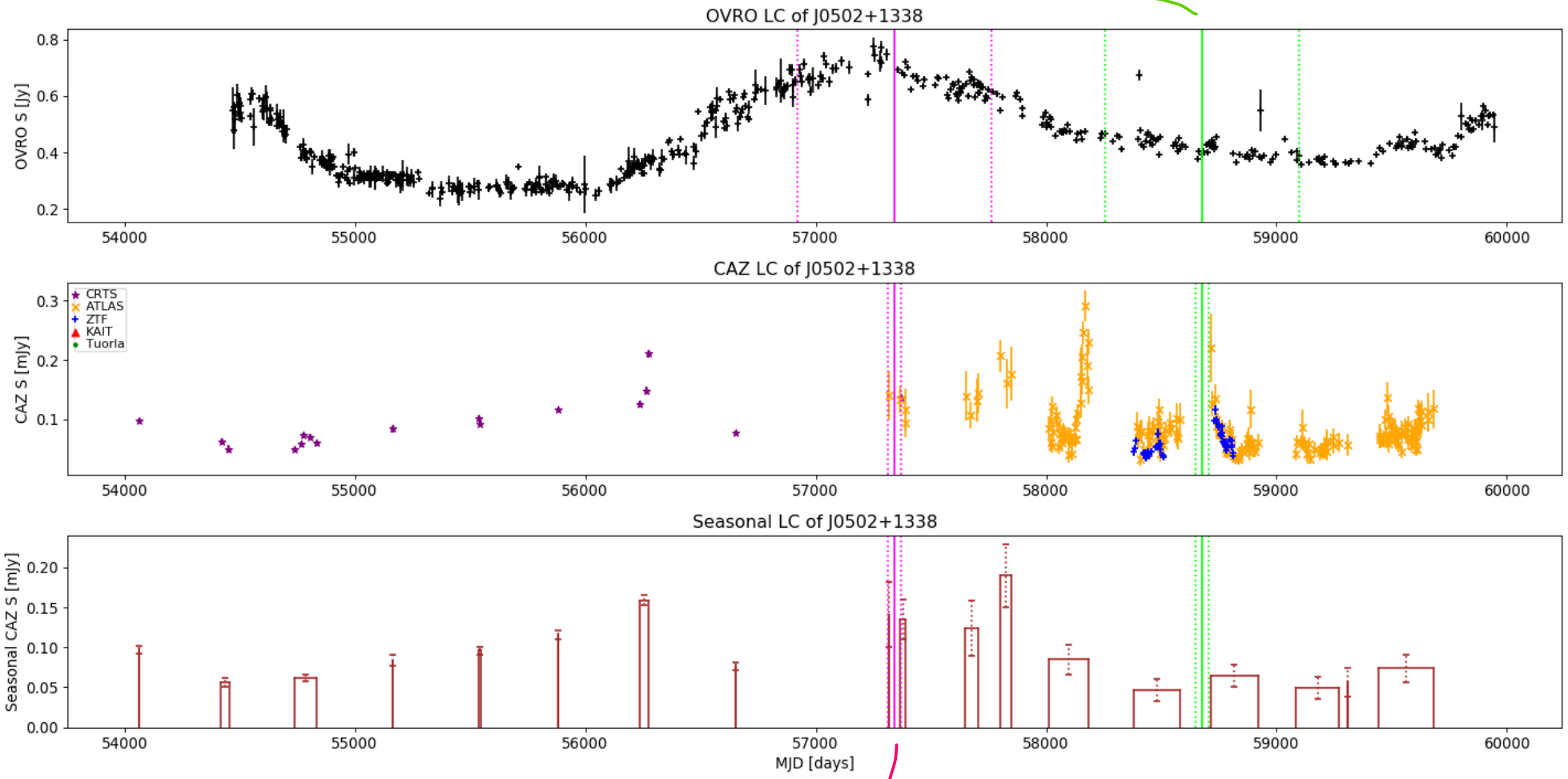
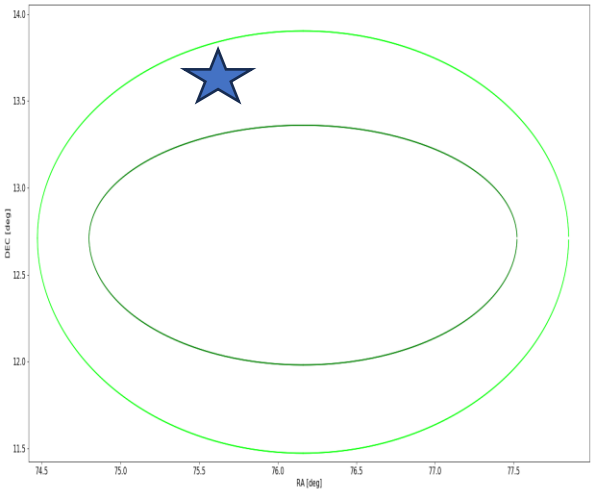
J0502+1338

No significant flares in R or O (large Ω)

Kouch et al. 2023



- ❑ MIN
- ✓ MAX



Simultaneous R+O spatio-temporal association

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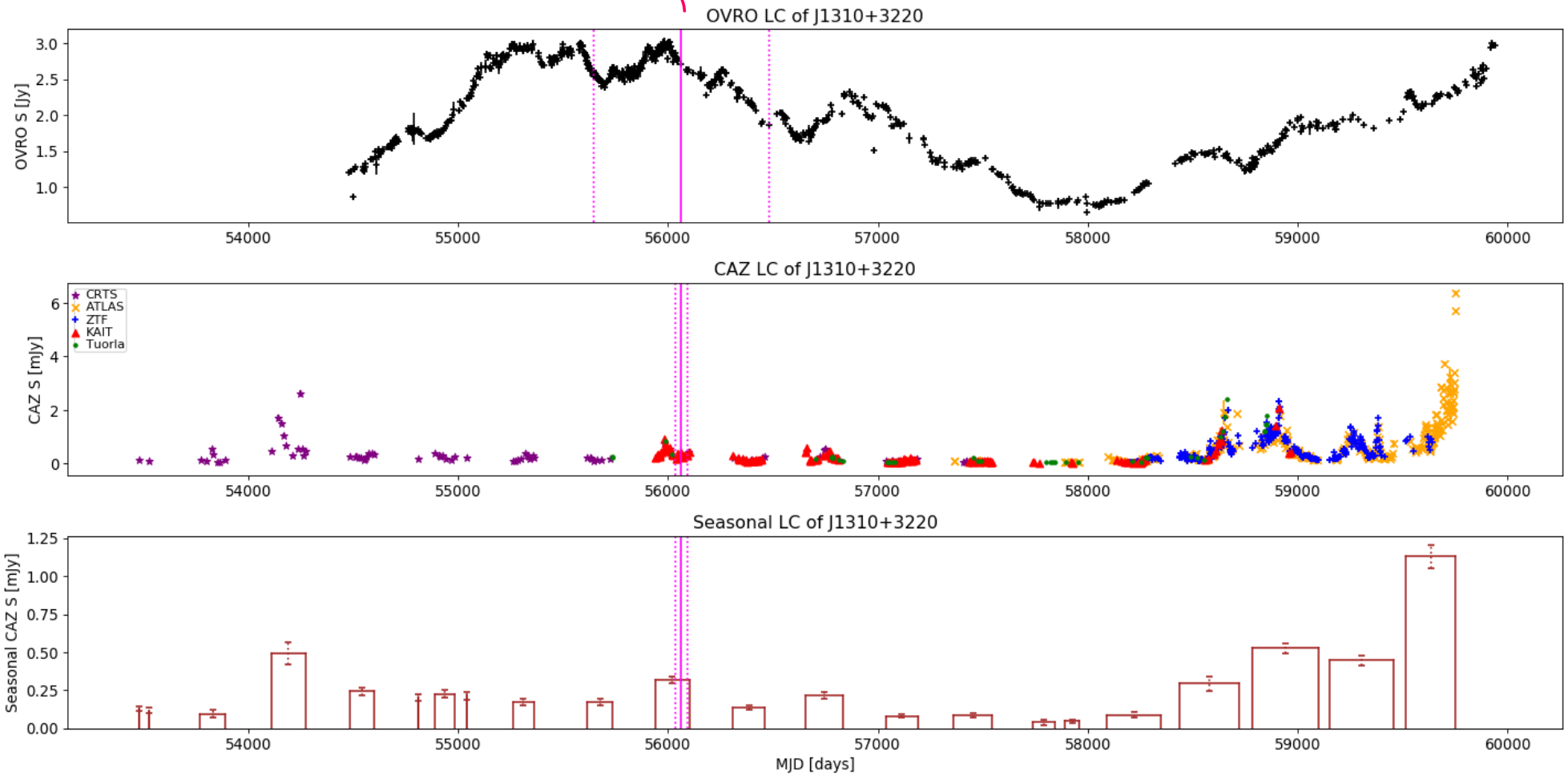
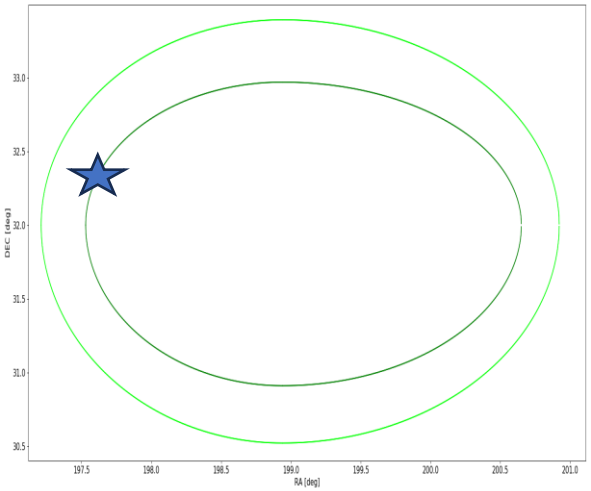
J1310+3220

Simultaneous R+O spatio-temporal association

Kouch et al. 2023



- ❑ MIN
- ✓ MAX



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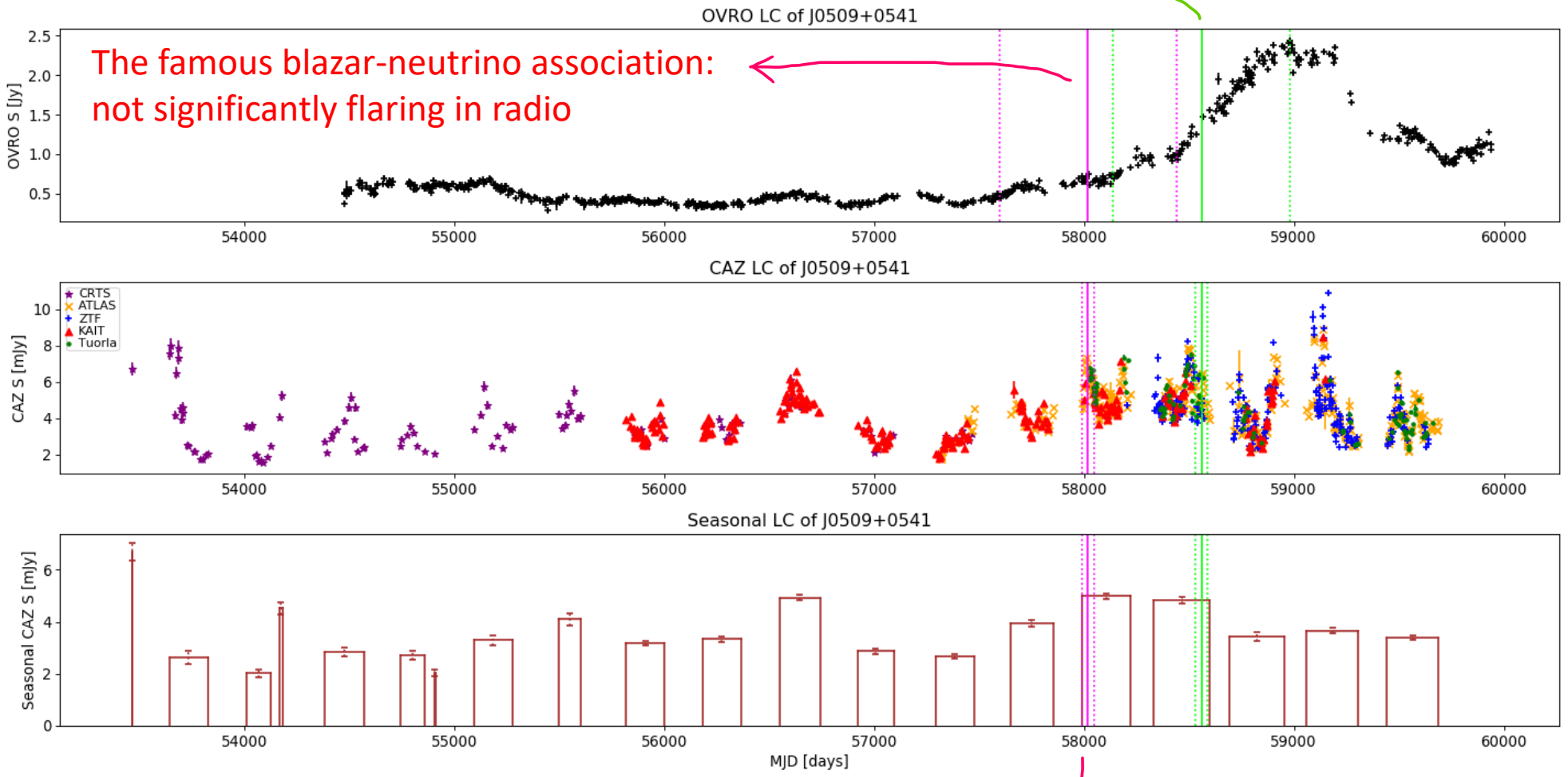
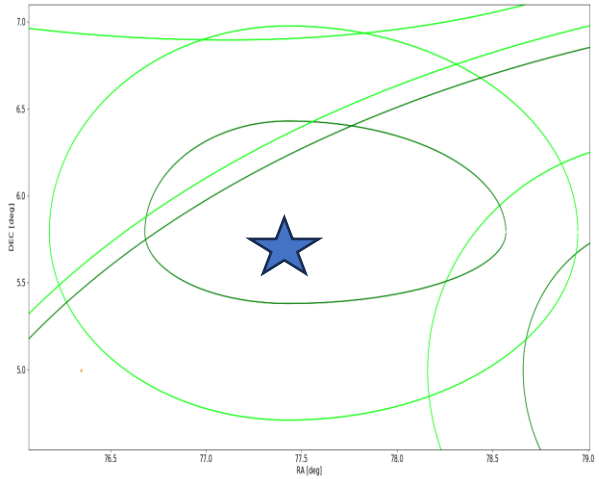
J0509+0541 (TXS 0506+056)

Simultaneous R+O spatio-temporal association (large Ω)

Kouch et al. 2023



- ✓ MIN
- ✓ MAX



Optical-only spatio-temporal association

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Conclusions

- Our population analysis results in a spatio-temporal blazar-neutrino correlation in both the radio and optical bands
- The results critically depend on the unknown nature of the IceCube systematic errors