Trinity's sensitivity to UHE Tau Neutrinos from X-ray bright, obscured Blazars

SAMEEKSHA SAINI for the *Trinity* Collaboration

SAMEEKSHA.SAINI@DURHAM.AC.UK

DURHAM UNIVERSITY | THE *TRINITY* PeV NEUTRINO OBSERVATORY

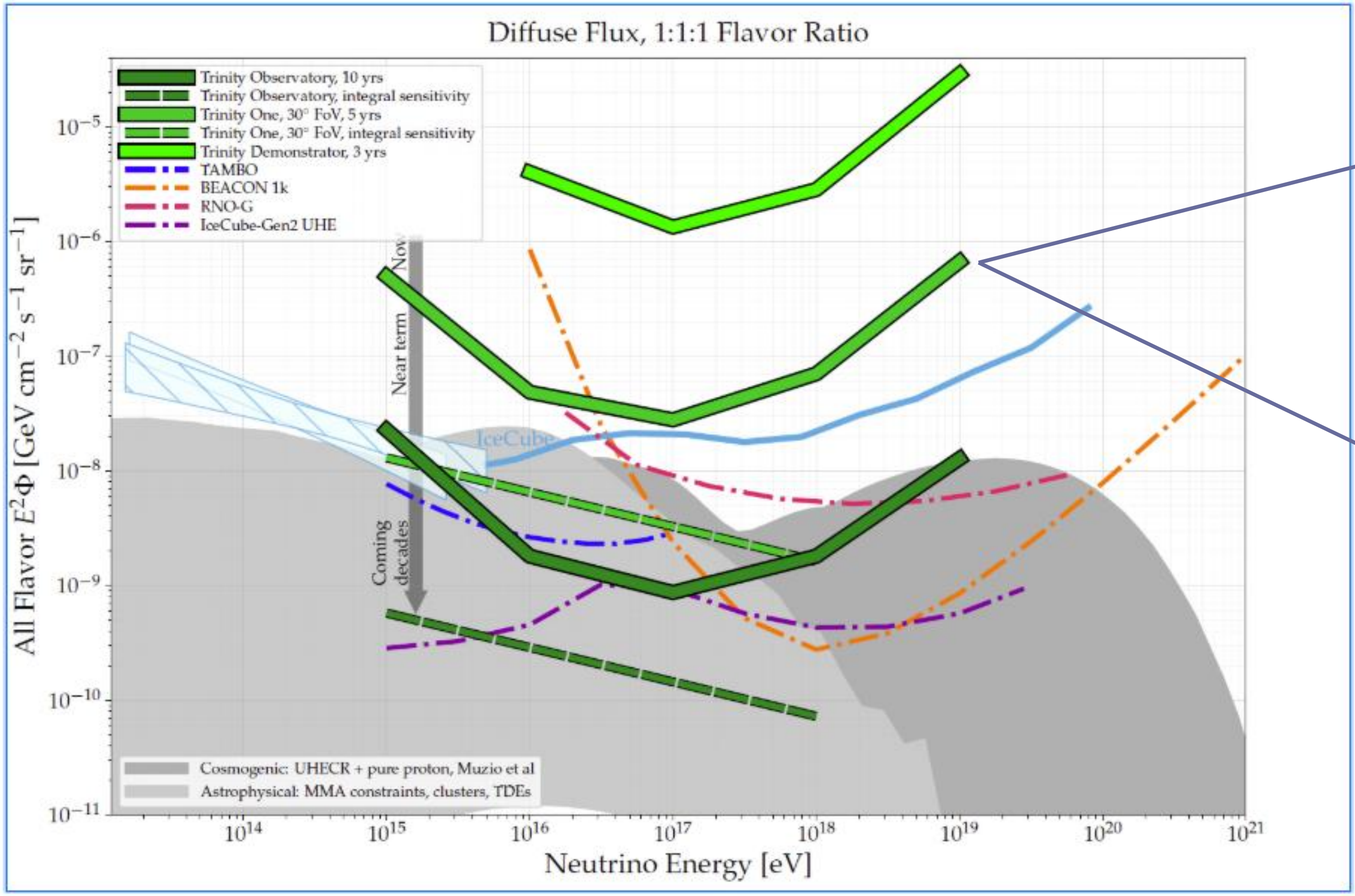
Supported by:

The Butler Engage Fund, Josephine Butler College, Durham University

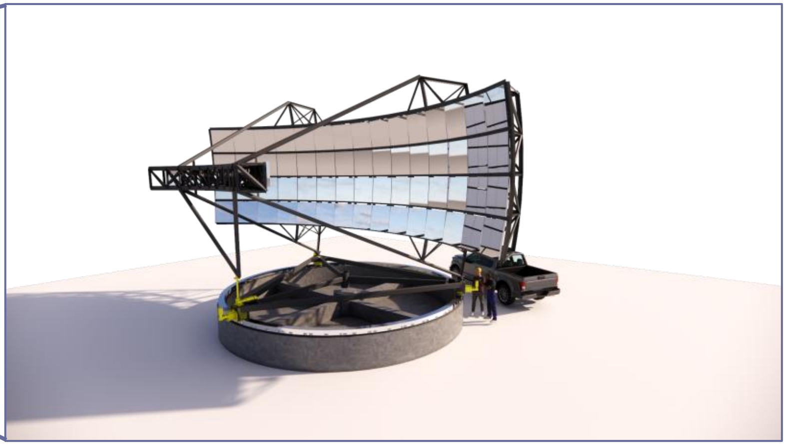
The Ellis Student Travel Fund, Durham University Physics Department

Sameeksha Saini
sameeksha.saini@durham.ac.uk

The *Trinity* Observatory



Air shower imaging of Earth-skimming PeV-EeV tau neutrinos



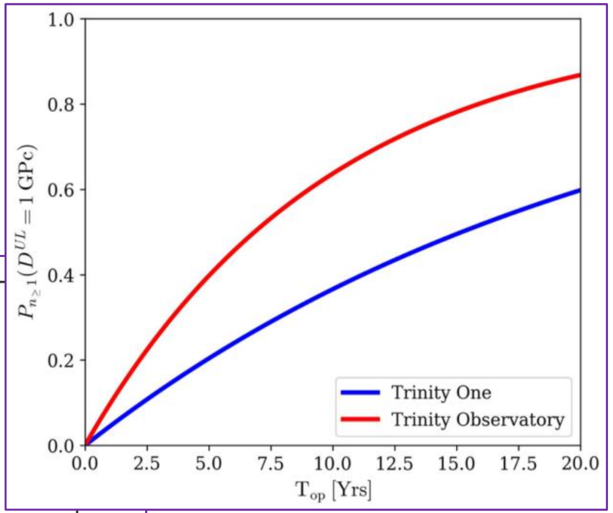
Trinity **One:**

- First pointing telescope of the observatory
- Azimuthal slew for point-source targeting
- FoV 5° × 60°
- Angular resolution 0.3°

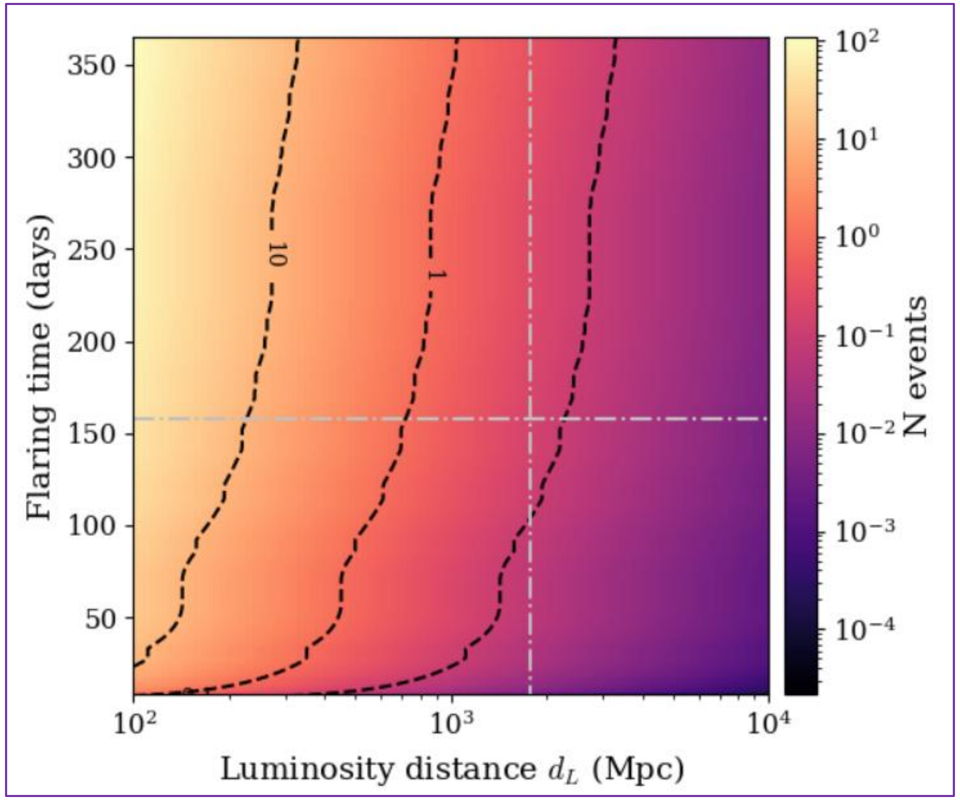
Sameeksha Saini
sameeksha.saini@durham.ac.uk

Trinity One science reach

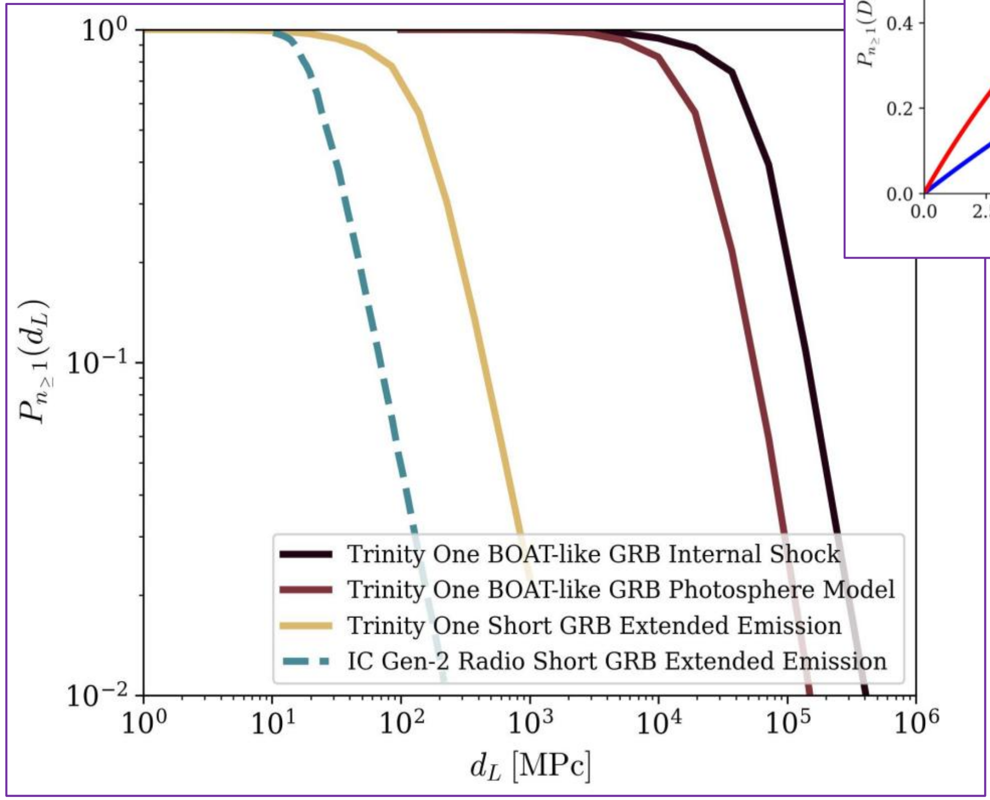
Trinity One paper: [arXiv:2509.18237]



TXS 0506+056-like source

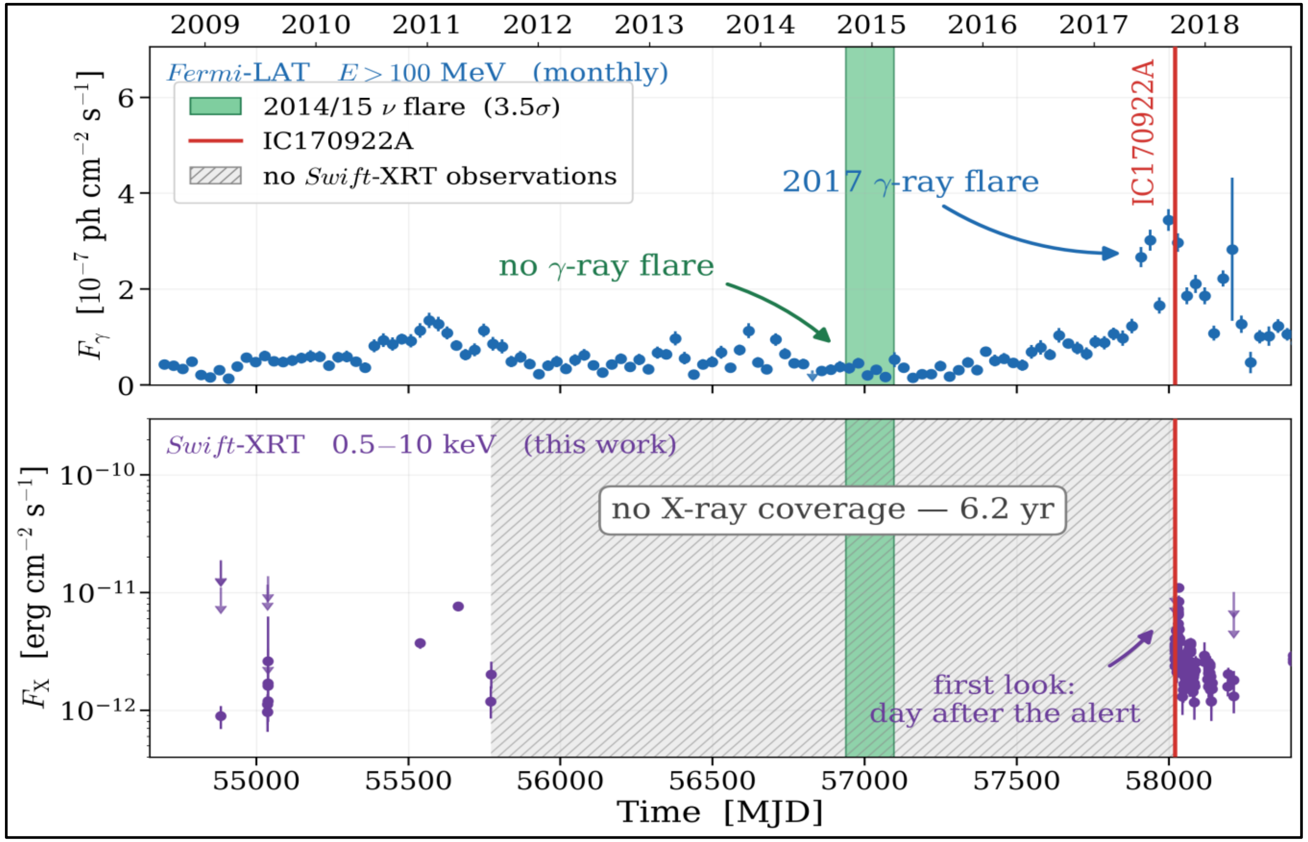


HL/s - Gamma Ray Bursts



Sameeksha Saini
sameeksha.saini@durham.ac.uk

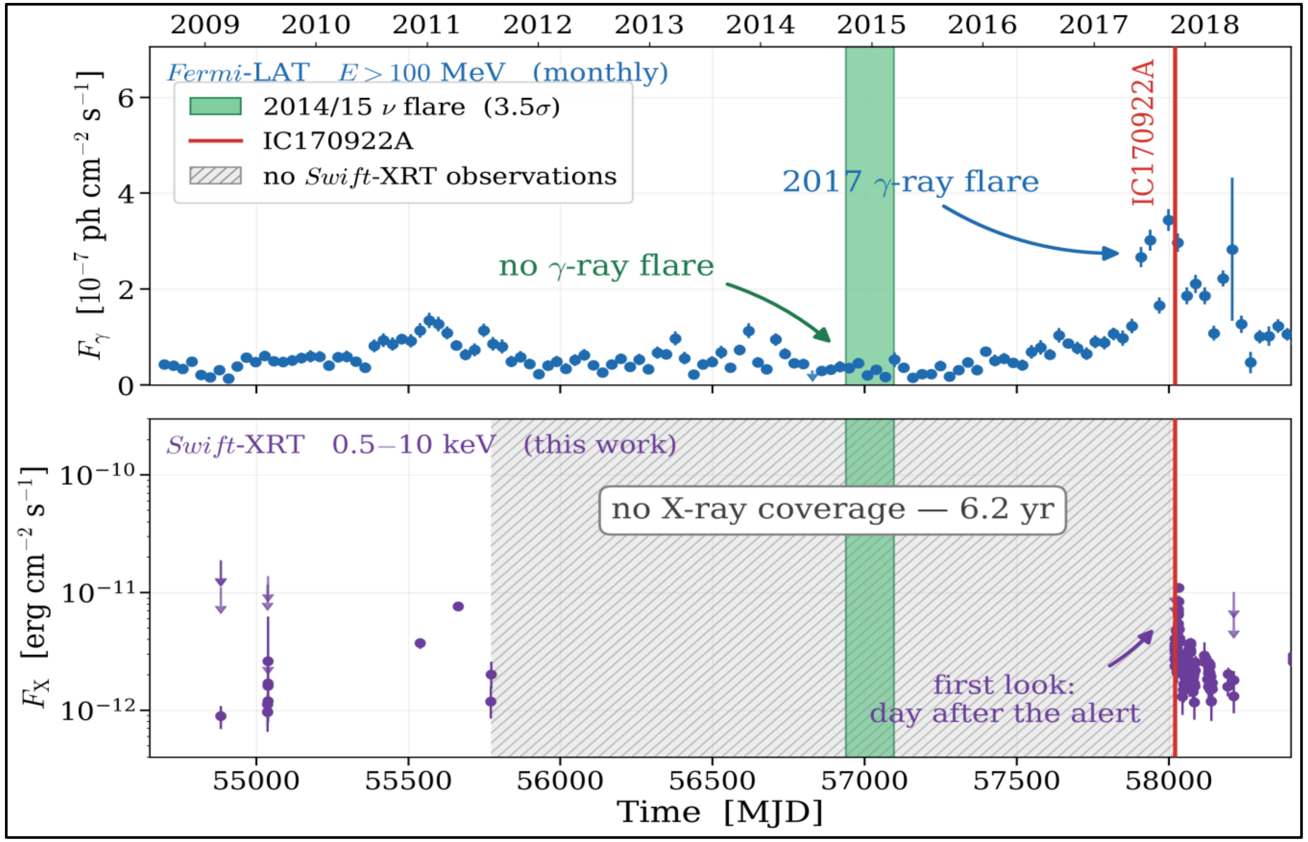
Neutrinos without γ-rays



- **2017:** IC170922A + γ-ray flare of TXS 0506+056.

Sameeksha Saini
sameeksha.saini@durham.ac.uk

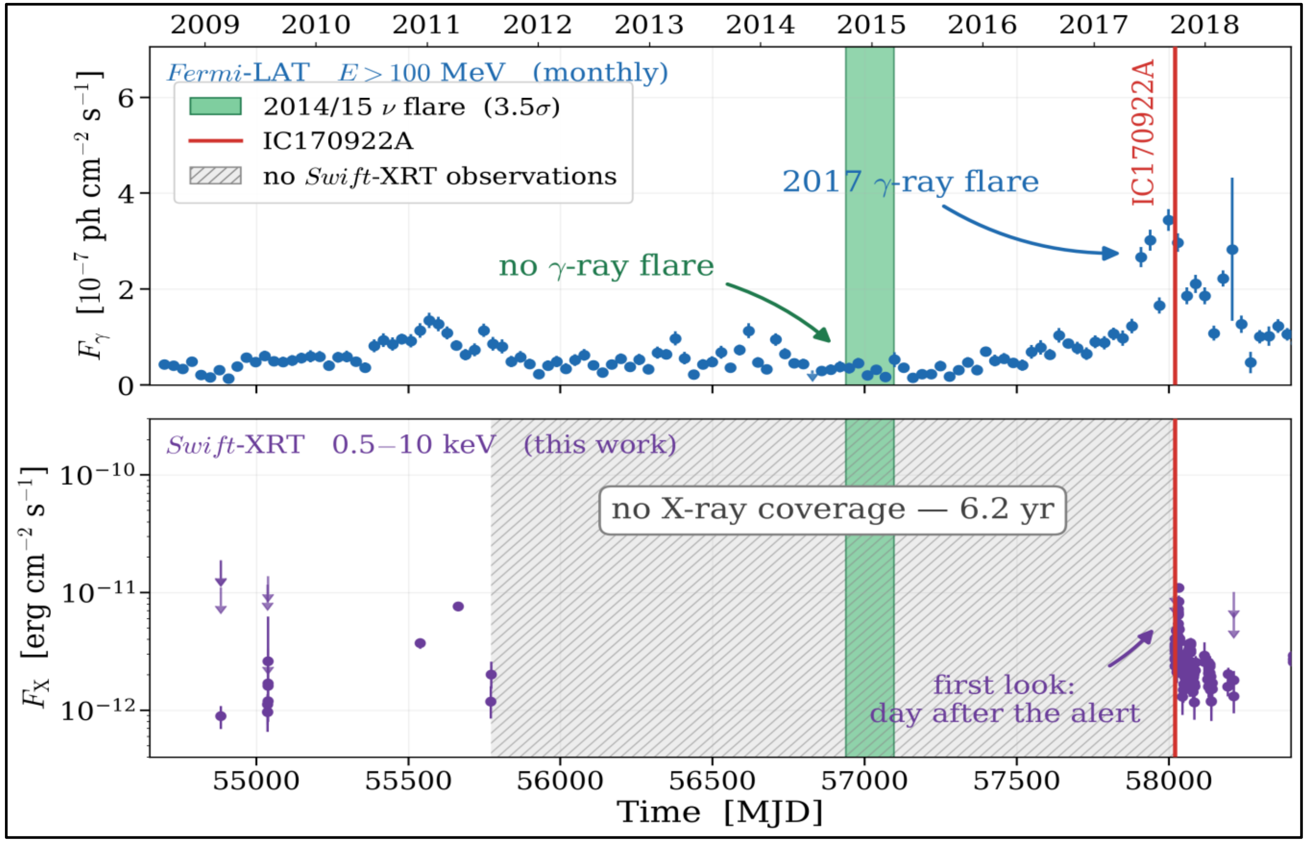
Neutrinos without γ-rays



- **2017:** IC170922A + γ-ray flare of TXS 0506+056.
- **2014/15:**
  - archival search finds excess
  - no γ-ray flare
  - no X-ray data at all till day after alert

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Neutrinos without γ-rays



- **2017:** IC170922A + γ-ray flare of TXS 0506+056.
- **2014/15:**
  - archival search finds excess
  - no γ-ray flare
  - no X-ray data at all till day after alert

X-ray + neutrino association in 2020: IC-200107A event follow-up found 3HSP J095507.9+355101 in an X-ray flare.

Sameeksha Saini
sameeksha.saini@durham.ac.uk

X-ray flares as neutrino tracers

$$p \longrightarrow p + \gamma_{\rm syn}$$

X-ray flare

$$p + \gamma_{\rm syn} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \mathrm{Br} = 2/3 \\ n + \pi^+, & \mathrm{Br} = 1/3 \end{cases}$$

target = its *own* photons

$$\pi^0 \longrightarrow \gamma + \gamma \longrightarrow e^\pm \xrightarrow{\text{synchrotron}} e^\pm + \gamma_{\rm MeV-GeV}$$

cascade, **not** X-rays

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

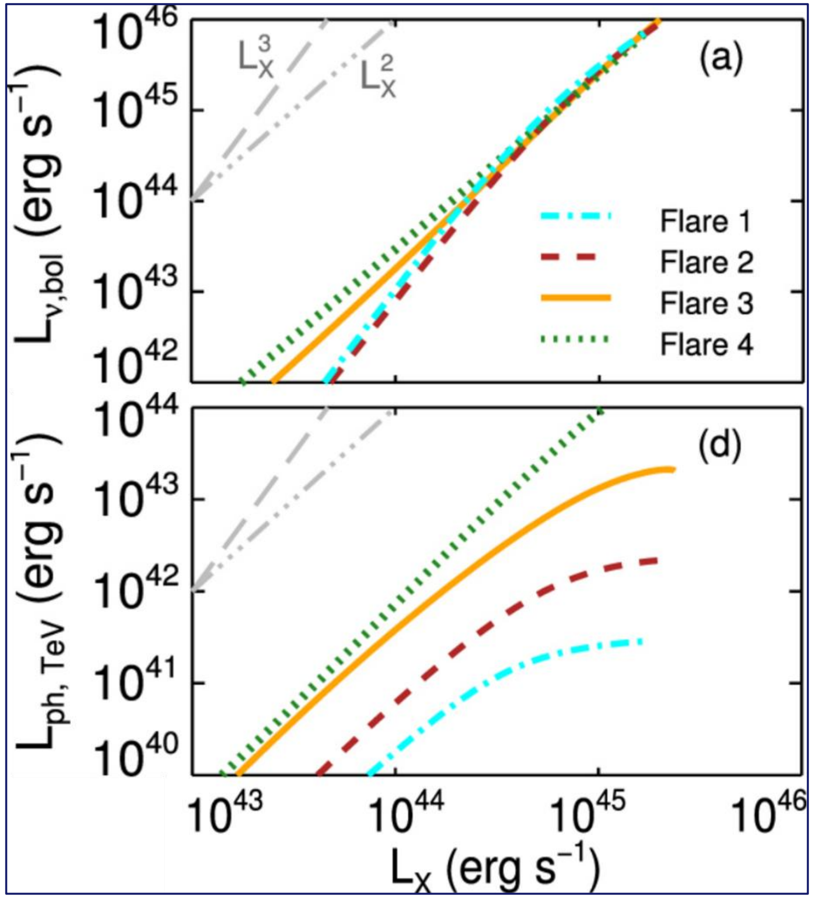
$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$

Sameeksha Saini
sameeksha.saini@durham.ac.uk

X-ray flares as neutrino tracers

$p \longrightarrow p + \gamma_{\rm syn}$	**X-ray flare**
$p + \gamma_{\rm syn} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \mathrm{Br} = 2/3 \\ n + \pi^+, & \mathrm{Br} = 1/3 \end{cases}$	target = its *own* photons
$\pi^0 \longrightarrow \gamma + \gamma \longrightarrow e^\pm \xrightarrow{\text{synchrotron}} e^\pm + \gamma_{\rm MeV-GeV}$	cascade, **not** X-rays
$\pi^+ \longrightarrow \mu^+ + \nu_\mu \longrightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$	
n (escapes) $\longrightarrow p + e^- + \bar{\nu}_e$	

ν tracks the X-rays; TeV saturates – γγ absorption



Mastichiadis, A. & Petropoulou, M., 2021, ApJ, 906, 131

Sameeksha Saini
sameeksha.saini@durham.ac.uk

X-ray flares as neutrino tracers

$p \longrightarrow p + \gamma_{\rm syn}$	**X-ray flare**
$p + \gamma_{\rm syn} \longrightarrow \Delta^{+} \longrightarrow \begin{cases} p + \pi^{0}, & {\rm Br} = 2/3 \\ n + \pi^{+}, & {\rm Br} = 1/3 \end{cases}$	target = its *own* photons
$\pi^{0} \longrightarrow \gamma + \gamma \longrightarrow e^{\pm} \xrightarrow{\text{synchrotron}} e^{\pm} + \gamma_{\rm MeV-GeV}$	cascade, **not** X-rays
$\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu} \longrightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e} + \nu_{\mu}$	
$n\ (\text{escapes}) \longrightarrow p + e^{-} + \bar{\nu}_{e}$	

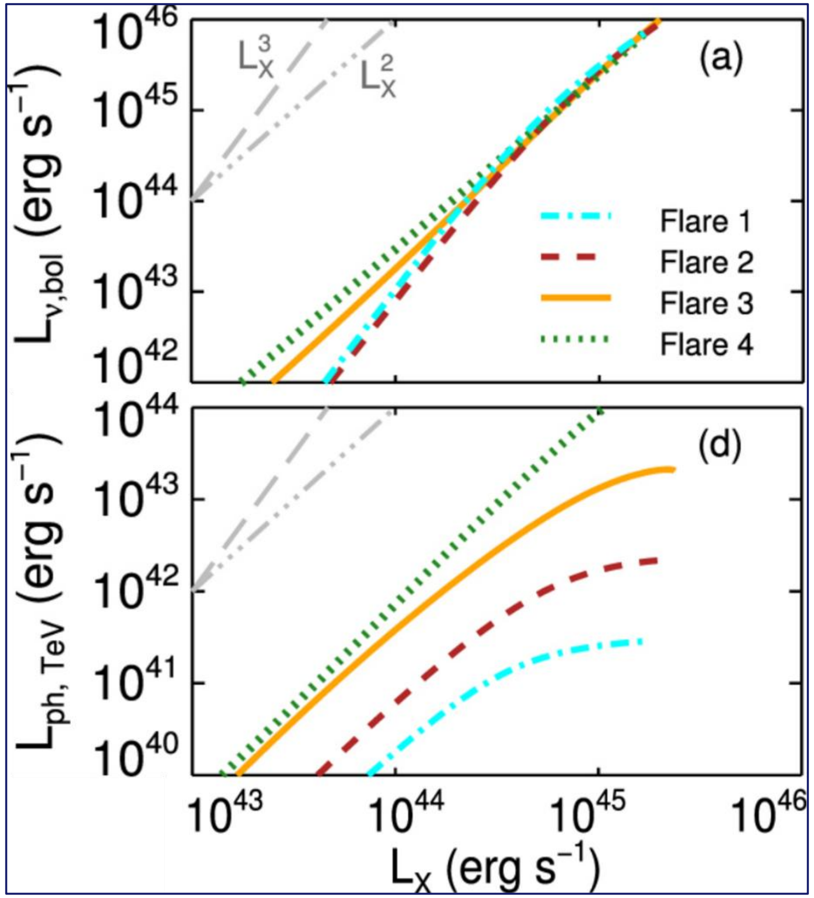
proton-synchrotron flares, ν -rich limit:

$$L_{\nu} = \xi_{x} \cdot L_{X}\ ,$$

$$\xi_{x} = 1$$

co-temporal: ν flare occurs during X-ray flare

ν tracks the X-rays; TeV saturates – $\gamma\gamma$ absorption

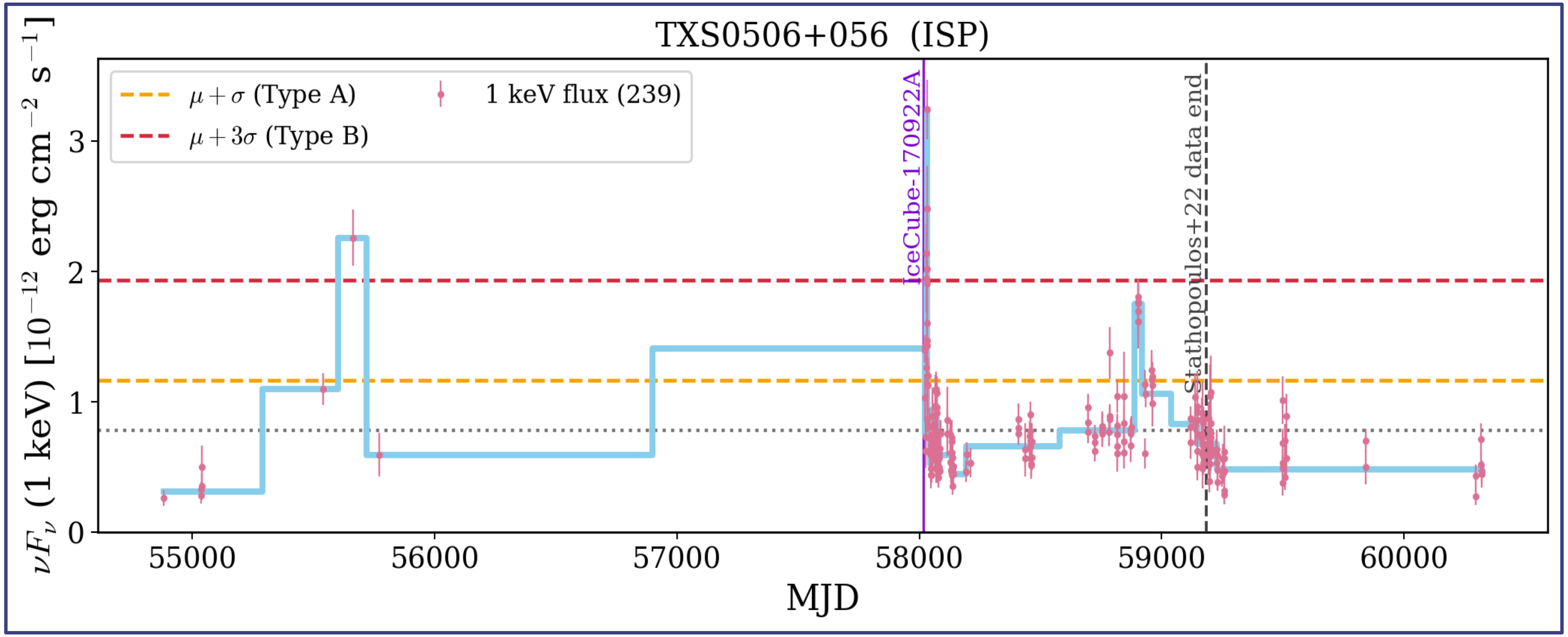


Mastichiadis, A. & Petropoulou, M., 2021, ApJ, 906, 131

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Blazar X-ray data

- *Swift*/XRT archival 1keV light curves : 66 ‘frequently observed’ sources

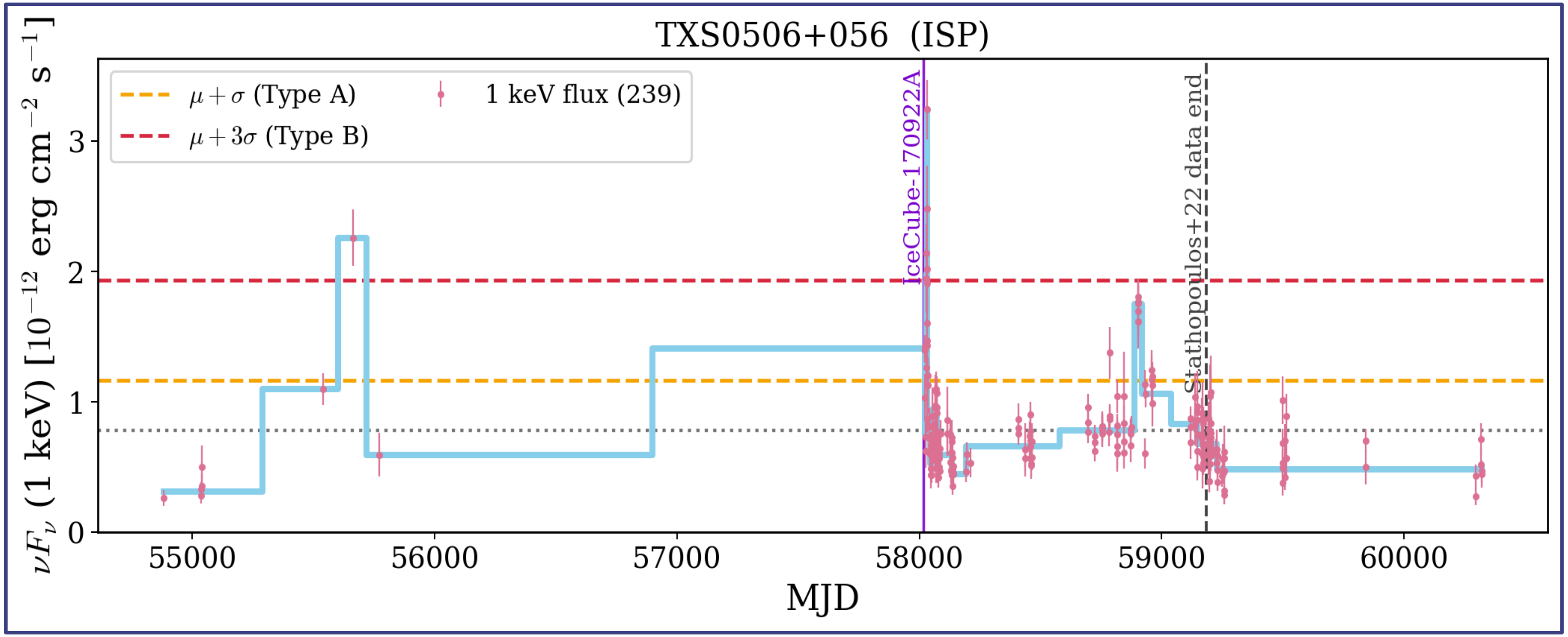


*Light curve construction and treatment from
Giommi. P. et al, 2021, MNRAS, 507, 4
Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Blazar X-ray data

- *Swift*/XRT archival 1keV light curves : 66 ‘frequently observed’ sources
- Bayesian blocks to handle irregular sampling (p_0 = 0.1)

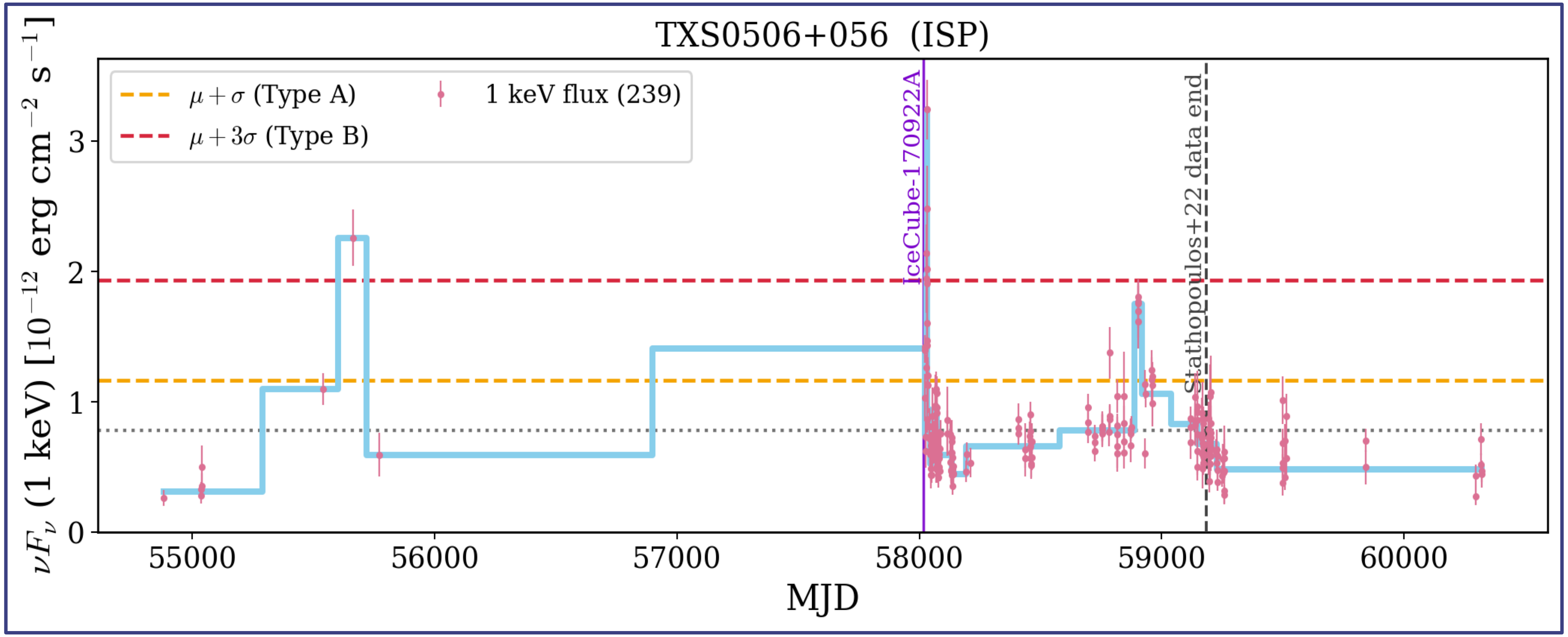


*Light curve construction and treatment from
Giommi. P. et al, 2021, MNRAS, 507, 4
Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Blazar X-ray data

- *Swift*/XRT archival 1keV light curves : 66 'frequently observed' sources
- Bayesian blocks to handle irregular sampling (p_0 = 0.1)



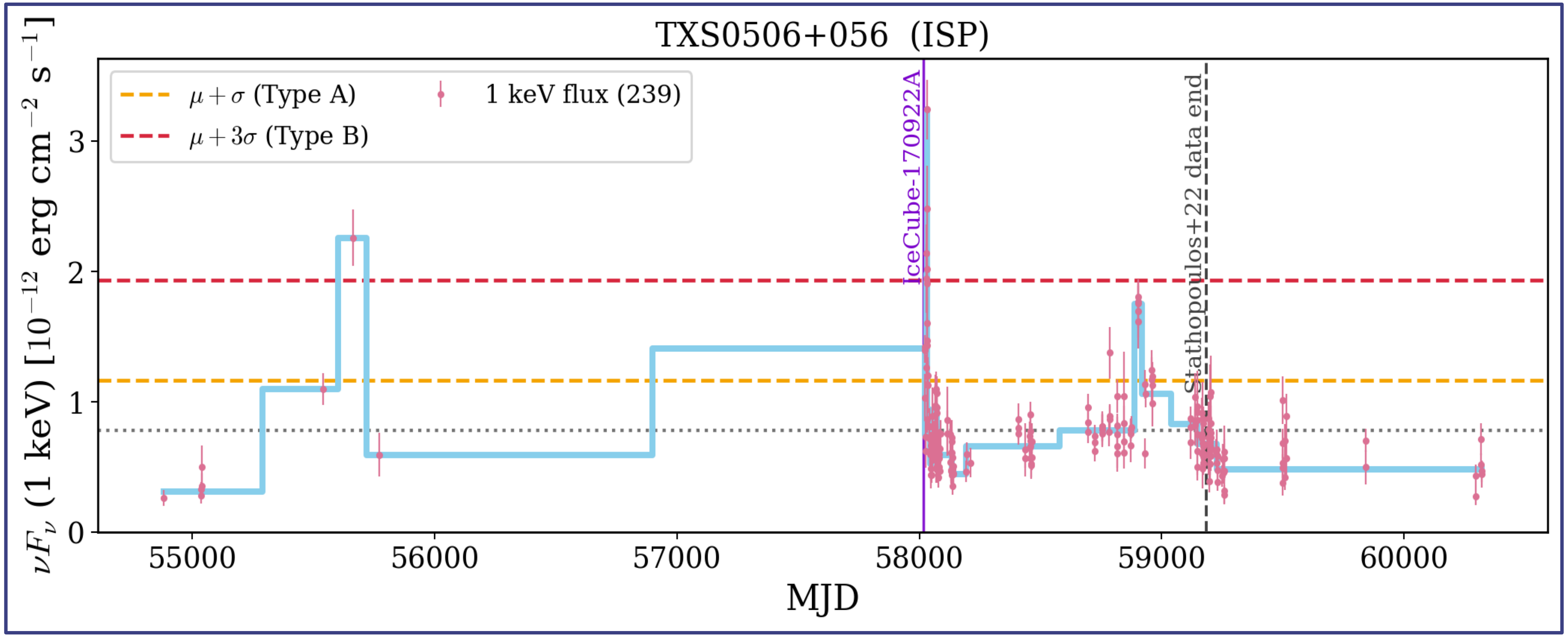
leptonic baseline
μ

*Light curve construction and treatment from
Giommi. P. et al, 2021, MNRAS, 507, 4
Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Blazar X-ray data

- *Swift*/XRT archival 1keV light curves : 66 'frequently observed' sources
- Bayesian blocks to handle irregular sampling (p_0 = 0.1)
- 928 flares across 62 flaring sources



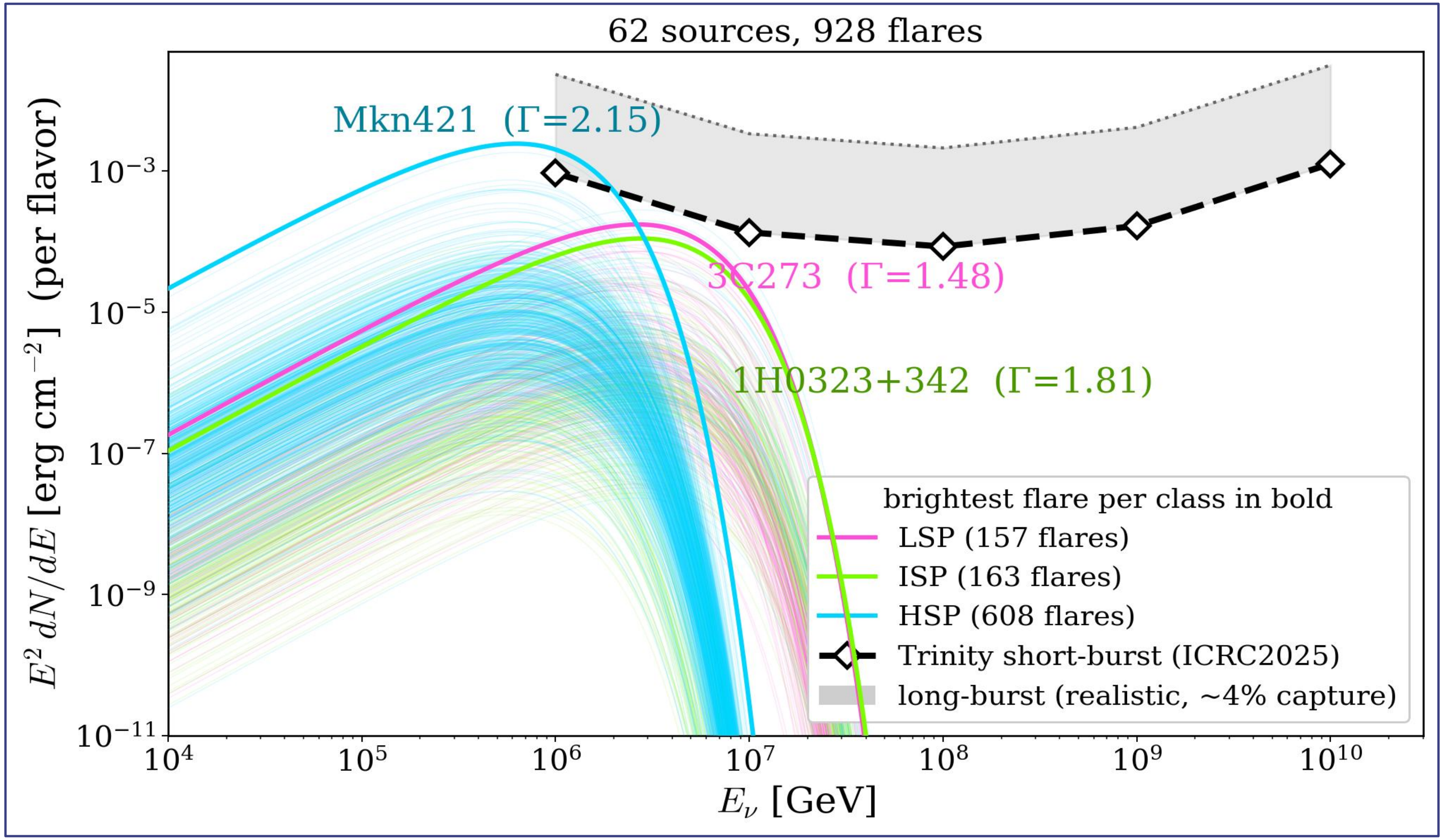
TYPE B FLARE
$\mu + 3\sigma < f_B$

TYPE A FLARE
$\mu + \sigma < f_B < \mu + 3\sigma$

leptonic baseline
μ

*Light curve construction and treatment from
Giommi. P. et al, 2021, MNRAS, 507, 4
Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Neutrino spectra from flares



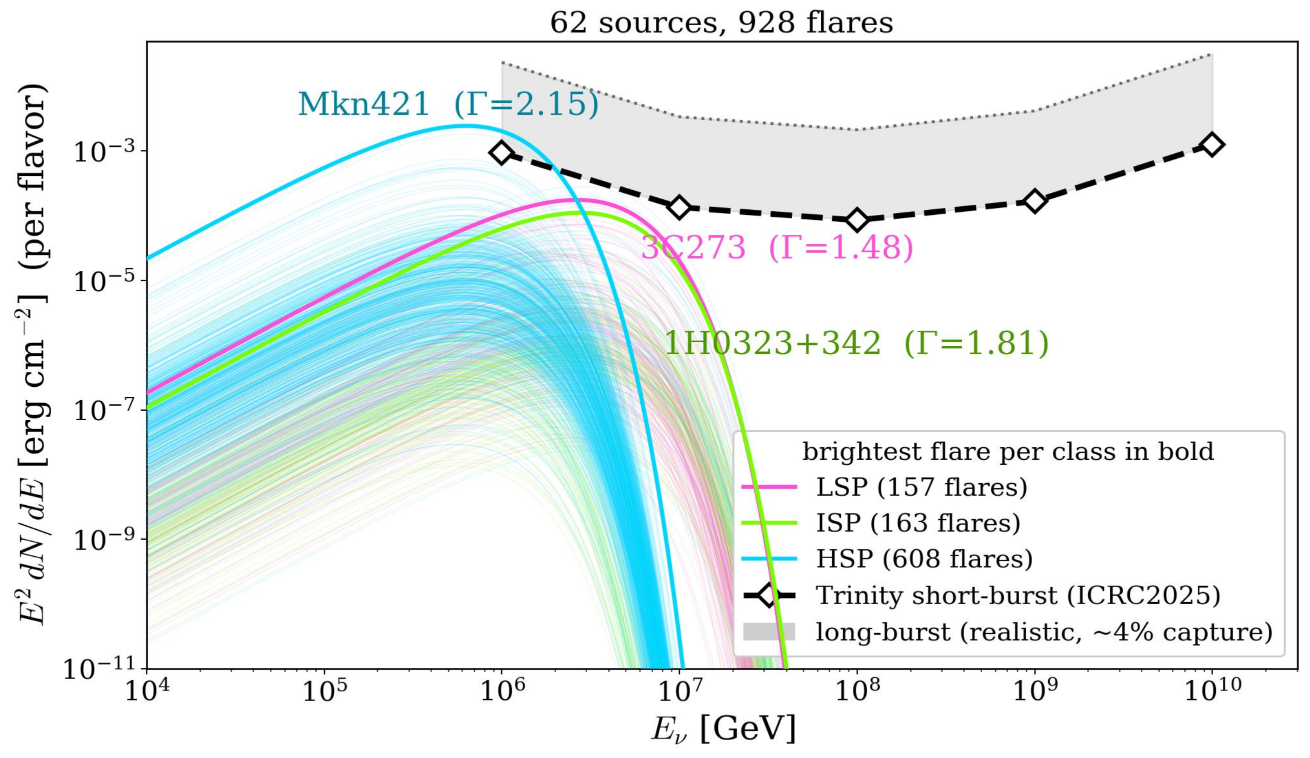
Model from *Mastichiadis, A. & Petropoulou, M., 2021, ApJ, 906, 131*
+ Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Neutrino spectra from flares

Model ingredients:

Inputs (per flare)	$F_X \to$ normalisation, $\Gamma \to \varepsilon_{\rm pk}$, $z \to$ redshift $\mathcal{D} = 10$, $B' = 10\,\mathrm{G}$
Peak rule	$\Gamma < 2 \Rightarrow \varepsilon_{\rm pk} = 10\,\mathrm{keV}$, $\Gamma > 2 \Rightarrow \varepsilon_{\rm pk} = 0.5\,\mathrm{keV}$
Cut-off	$\varepsilon_c = 0.6\sqrt{\frac{\mathcal{D}_1\,\varepsilon_{\rm pk}^{[\rm keV]}}{B_1'\,(1+z)}}\ \mathrm{PeV} = 0.6\sqrt{\frac{\varepsilon_{\rm pk}^{[\rm keV]}}{1+z}}\ \mathrm{PeV}$
Spectrum	$E^2\frac{dN}{dE} \propto E^{1.5}\exp\left(-\frac{E}{\varepsilon_c}\right)$
Normalisation	$L_\nu = \xi_X\,L_X$, $\xi_X = 1$



Γ sets the cut-off

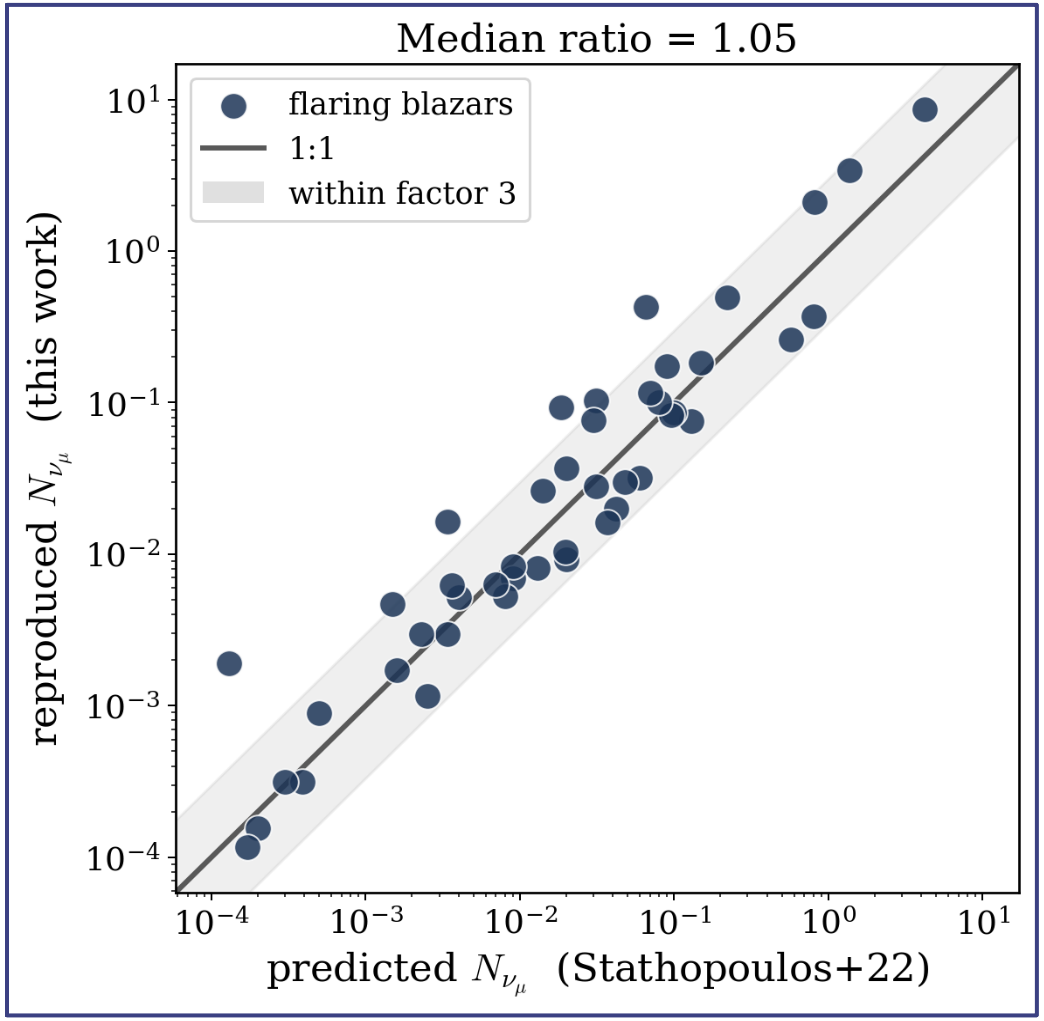
Mkn 421 (Γ = 2.15 → 0.5 keV) peaks at **0.6 PeV**;

3C 273 (Γ = 1.48 → 10 keV) at **2.6 PeV**

Model from *Mastichiadis, A. & Petropoulou, M., 2021, ApJ, 906, 131*
+ Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Sameeksha Saini
sameeksha.saini@durham.ac.uk

First – reproduce published result

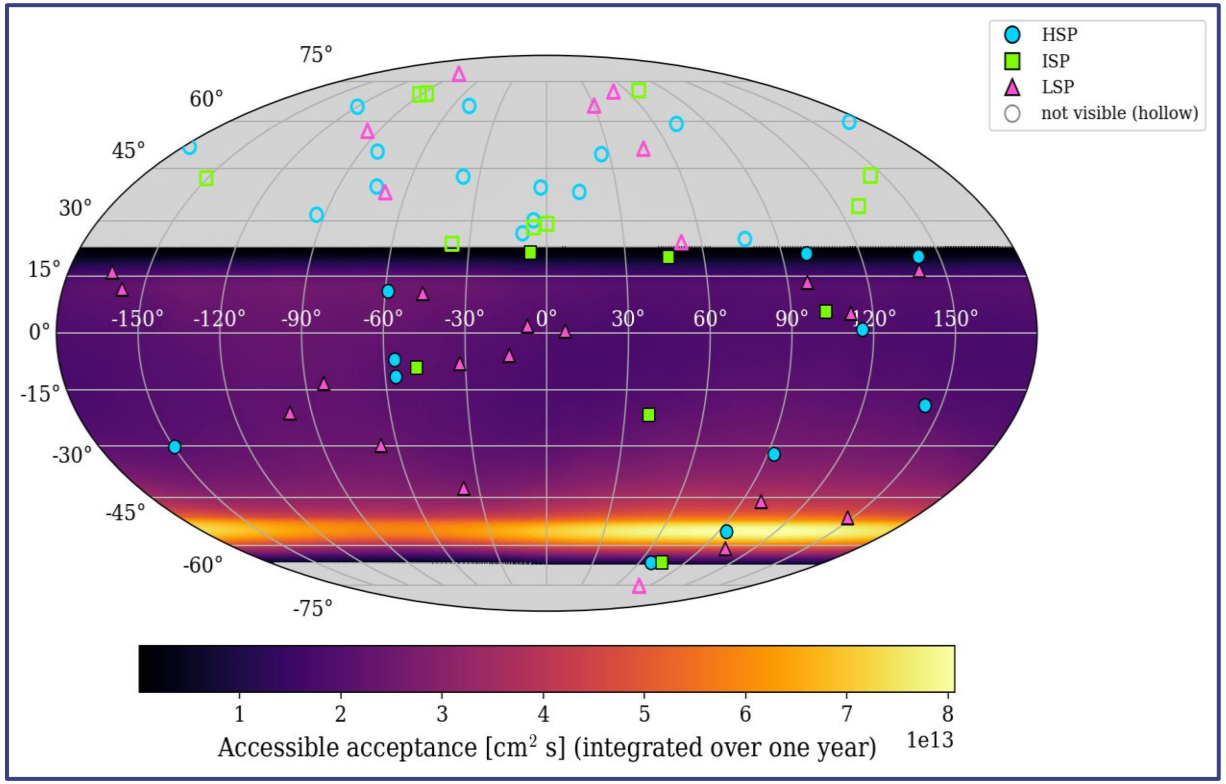


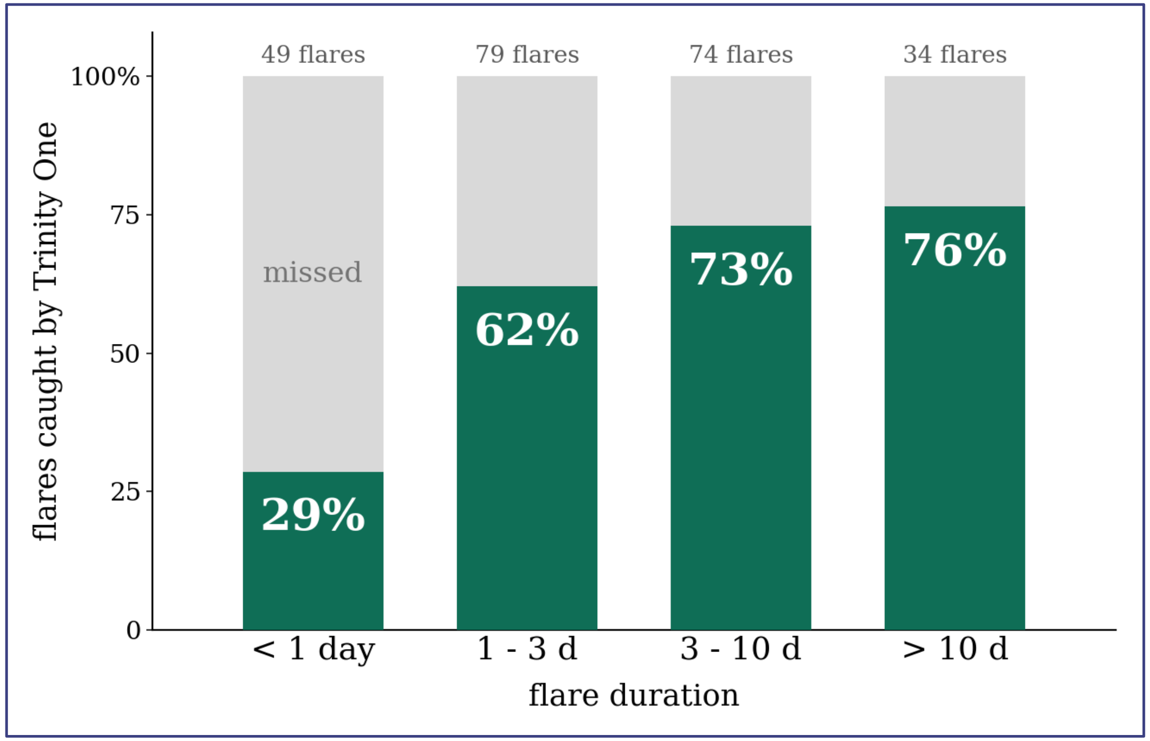
- Same pipeline, run through *IceCube's* exposure: calculated N_ν per source vs Stathopoulos+22
- median ratio = 1.05
- Spearman = +0.94
- 87% within ×3
- top-10 sources: 10/10 within ×3, rank order preserved
- → only *then* do we swap in *Trinity* One's effective area

Published results from Stathopoulos, S.I. et al, 2022, MNRAS, 510, 4063

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Trinity One's accessibility





$A_{eff} \times visibility \times dark\ time$

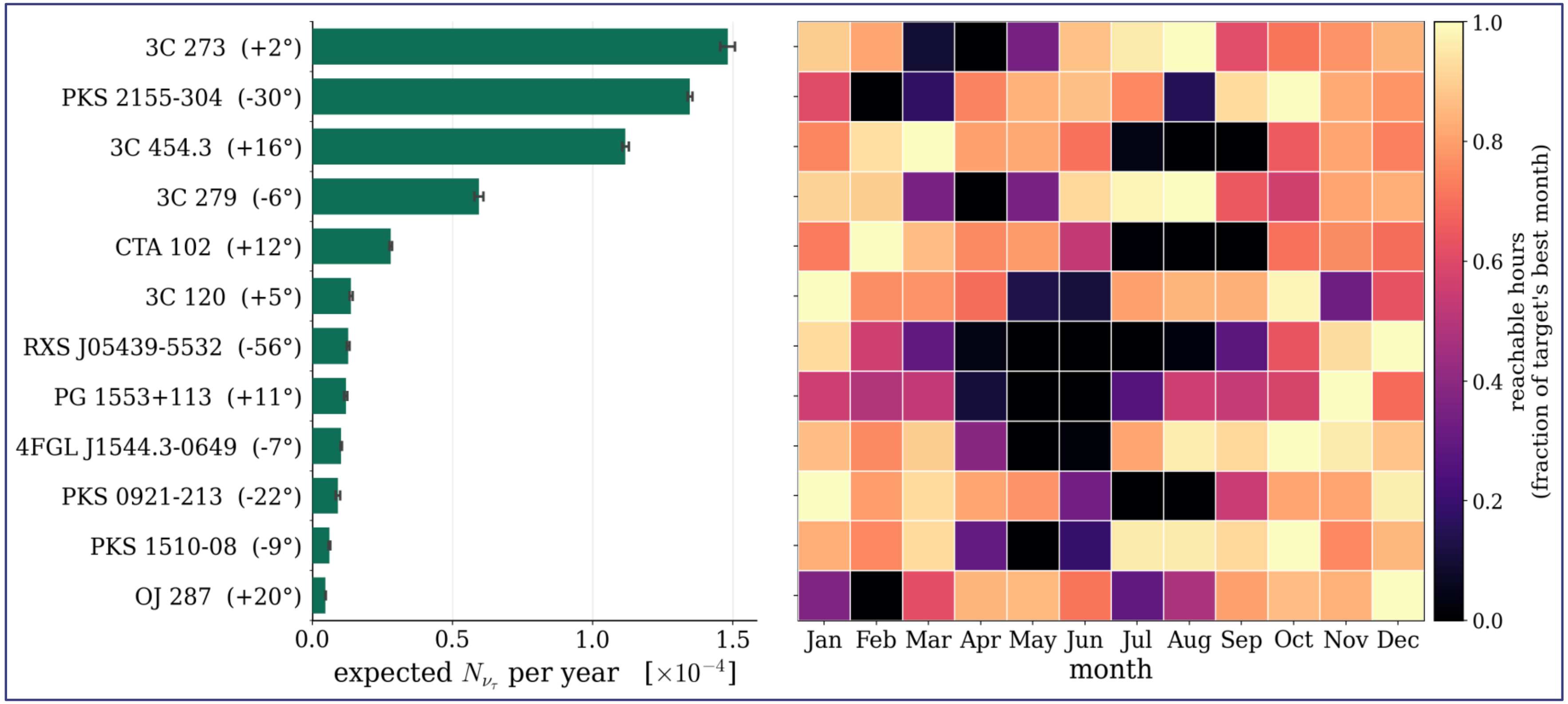
Accessibility ~260 hr/year for typical target

Limited sky but well matched to how long flares last.

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Preliminary pointing strategy

- Ranked by expected events per year
- Leading sources are equatorial/southern:
  - 3C 273
  - PKS 2155-304
  - 3C 454.3
- Top targets reachable most of the year



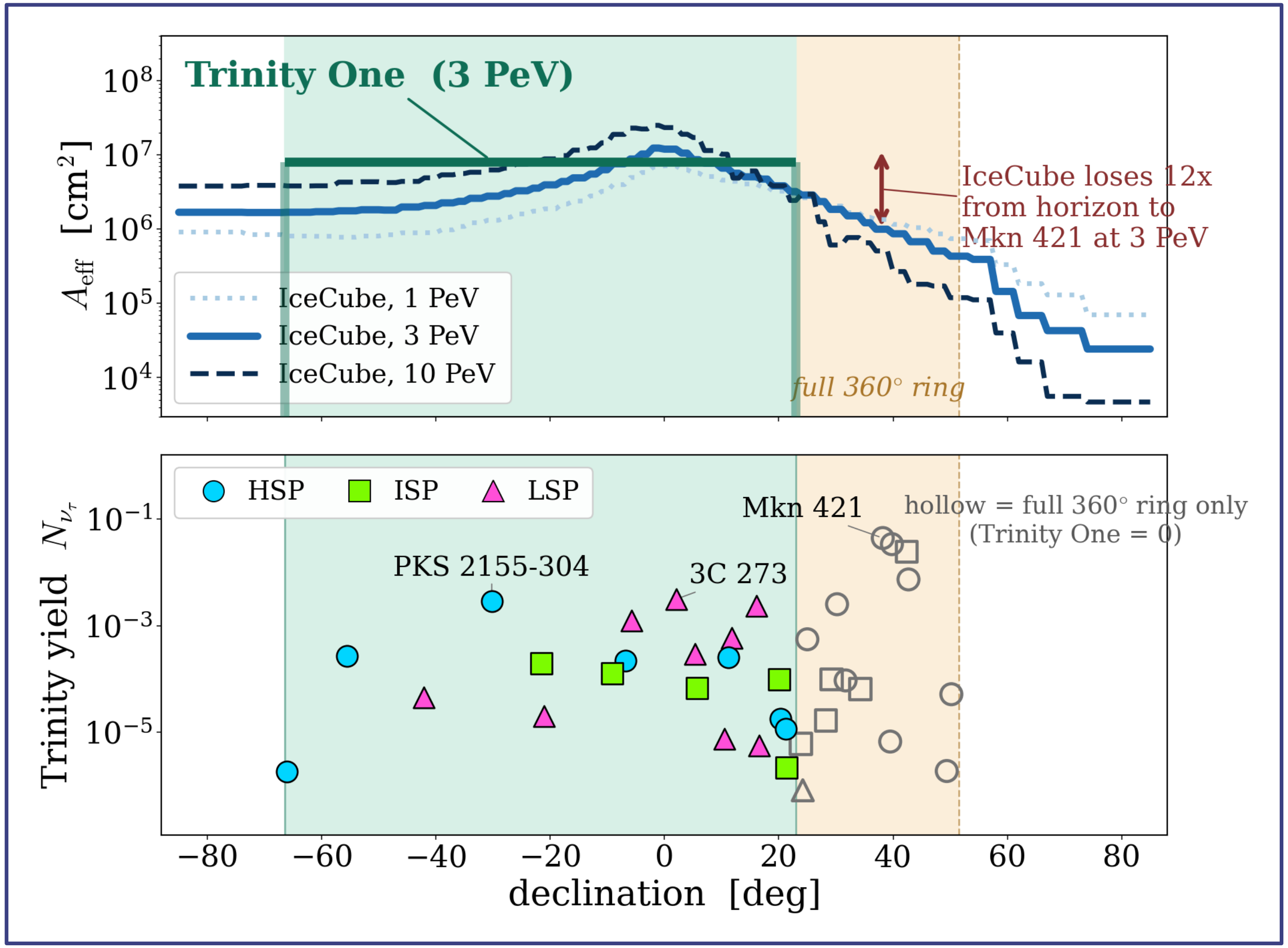
- Far-south is exception: RXS J05439-5532 gives 184hrs in December, 0 in May-July

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Sky complementarity

- *Trinity*-One covers southern/equatorial sky:
  $$-67° < dec < +23°$$
- Shared targets: 5 of IceCube's top 10 are also in *Trinity* One's top 10

Gold band: An unobstructed northern horizon extends the band to +51° - 'full ring'



Durham University

Outlook

X-ray observed blazars → Identify flares → ν spectrum → *Trinity* response → Target ranking

Broaden band
Other x-ray missions (e.g. NuSTAR, 3-79 keV); re-test the proxy and ε_{pk} rule

Definitions
Alternatives to flare: shape, duration, thresholds, etc.

Test physics
$\xi_X < 1,\ D, B', \varepsilon_{pk}$; alternate leptohadronic models.

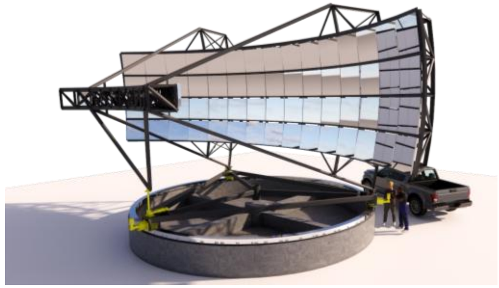
Configure + ToO
Other sites, scale up to full observatory, trigger on flares (ToO)

More sky
New source classes, full Open Universe

Sameeksha Saini
sameeksha.saini@durham.ac.uk

Summary

Trinity



- Earth-skimming method to probe tau neutrinos
- Rich point-source sensitivity
- Opens the PeV-EeV window
- Scales up in sky access and exposure with each telescope – **deeper sensitivity**
- **A natural complement to current detectors and methods!**
- ***Trinity* One:** first of 18 telescopes, slew-targeted

- Proton-synchrotron model for hadronic X-ray flares, neutrino-rich →*Trinity*-One sensitivity and predicted yields
- Top targets: 3C 273, PKS 2155-304, 3C 454.3: 34 of 66 reachable, each with its own season
- Preparation for first light:
  'When and where should *Trinity* One look?'

Supported by:
The Butler Engage Fund, Josephine Butler College, Durham University
The Ellis Student Travel Fund, Durham University Physics Department

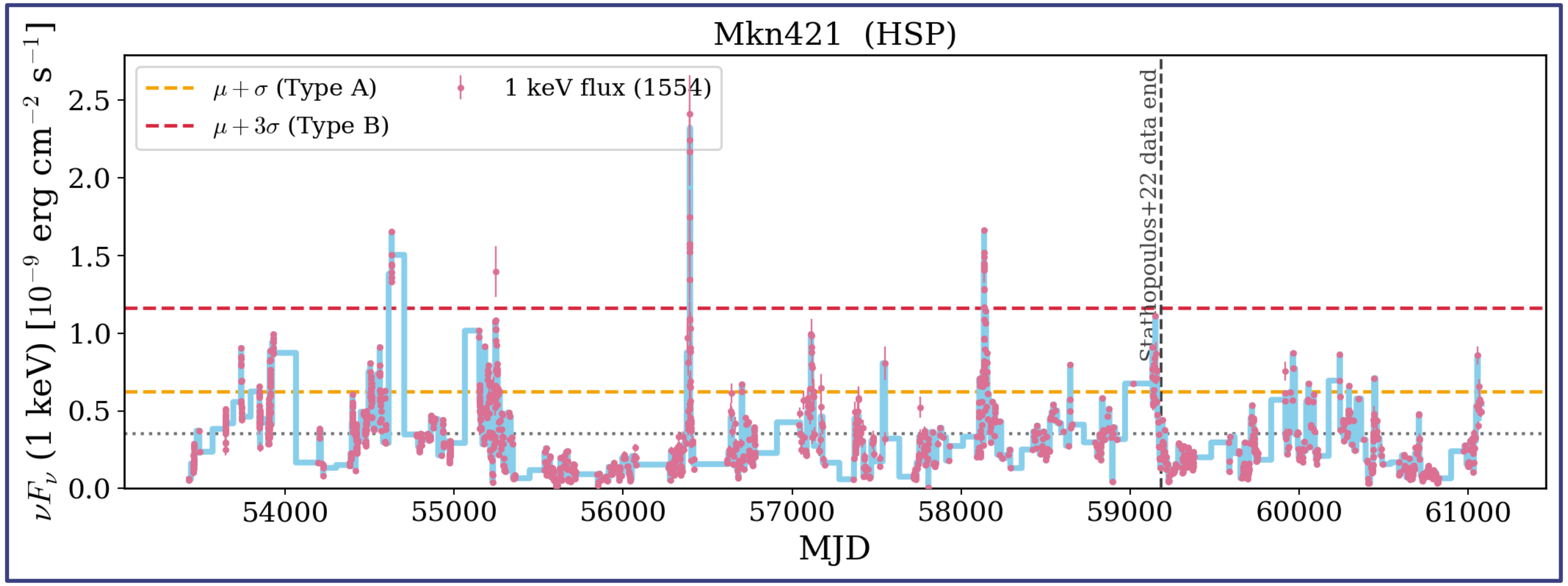
trinity.physics.gatech.edu

Sameeksha Saini
sameeksha.saini@durham.ac.uk

BACKUP SLIDES

Sameeksha Saini
sameeksha.saini@durham.ac.uk
Durham University

B1: From counts to fluence



- XRT count rate $\rightarrow$ per-source power-law fit (Γ, N_{H}, ECF)
- $\rightarrow$ **1 keV flux** $\rightarrow$ light curve $\rightarrow$ Bayesian blocks ($p_0 = 0.1$) $\rightarrow$ Type A / B
- $\rightarrow$ **0.5–10 keV** band flux $\times$ duration $=$ fluence S_X $\rightarrow$ ν normalisation
- Γ also sets $\varepsilon_{\mathrm{pk}}$, and therefore the cut-off energy

Sameeksha Saini
sameeksha.saini@durham.ac.uk

B2: Neutrino spectrum per flare

All-flavour fluence spectrum, normalised to the flare's X-ray output:

$$\frac{dN}{dE} = N_0\, E^{-0.5} \exp\left(-\frac{E}{\varepsilon_c}\right), \qquad \int_{10^2\ \mathrm{GeV}}^{10^{10}\ \mathrm{GeV}} E\,\frac{dN}{dE}\,dE = \xi_X\, S_X,$$

with S_X the unabsorbed 0.5–10 keV flare fluence (block flux minus the quiescent mean, times duration). In SED form

$$E^2\frac{dN}{dE} \propto E^{1.5} \exp\left(-\frac{E}{\varepsilon_c}\right), \qquad \text{peaking at } E = 1.5\,\varepsilon_c.$$

Per flavour: $\times\, 1/3$ (vacuum mixing, assumed equipartition at Earth).

Sameeksha Saini
sameeksha.saini@durham.ac.uk

B3: Exposure → events

Exposure is replayed minute-by-minute over each flare's real dates, so a flare only counts when the source is actually reachable:

$$N_{\nu_\tau} = \int E\,\frac{d\Phi_{\nu_\tau}}{dE}\,\mathcal{E}(E)\,d\ln E, \qquad \frac{d\Phi_{\nu_\tau}}{dE} = \frac{1}{3}\,\frac{1}{\Delta t}\,\frac{dN}{dE},$$

where $\mathcal{E}(E)$ $[\mathrm{cm}^2\,\mathrm{s}]$ is the accessible acceptance accumulated over the flare window and Δt is the flare duration. Integration uses the five tabulated decade nodes ($\log_{10} E/\mathrm{GeV} = 6, 7, 8, 9, 10$), ln-space Simpson.

Inverting B3 for the fluence that yields $N_{\rm thr}$ events:

$$S_{\rm sens}(E) = \frac{N_{\rm thr}\,E}{A_{\rm eff}(E)\,\ln 10} \times \left(\mathrm{erg\ GeV}^{-1}\right) \qquad [\mathrm{erg\,cm}^{-2}].$$

Short-burst (best case) assumes the whole flare is observed. The realistic long-burst floor is $S_{\rm long} = S_{\rm short}/f_{\rm cap}$ with median capture $f_{\rm cap} \simeq 0.04$ (16–84%: 1.3–6%), measured from the per-flare replay.

Sameeksha Saini
sameeksha.saini@durham.ac.uk

B4: Assumptions and uncertainties

Three model choices:

- ξ_x = 1 hadronic-flare value, conservative end of MP21's range
- D = 10, B' = 10 G fixed, not fitted
- ε_{pk} from Γ step rule at Γ = 2; Mkn 421 sits near the edge (×2 effect)

Also assumed:

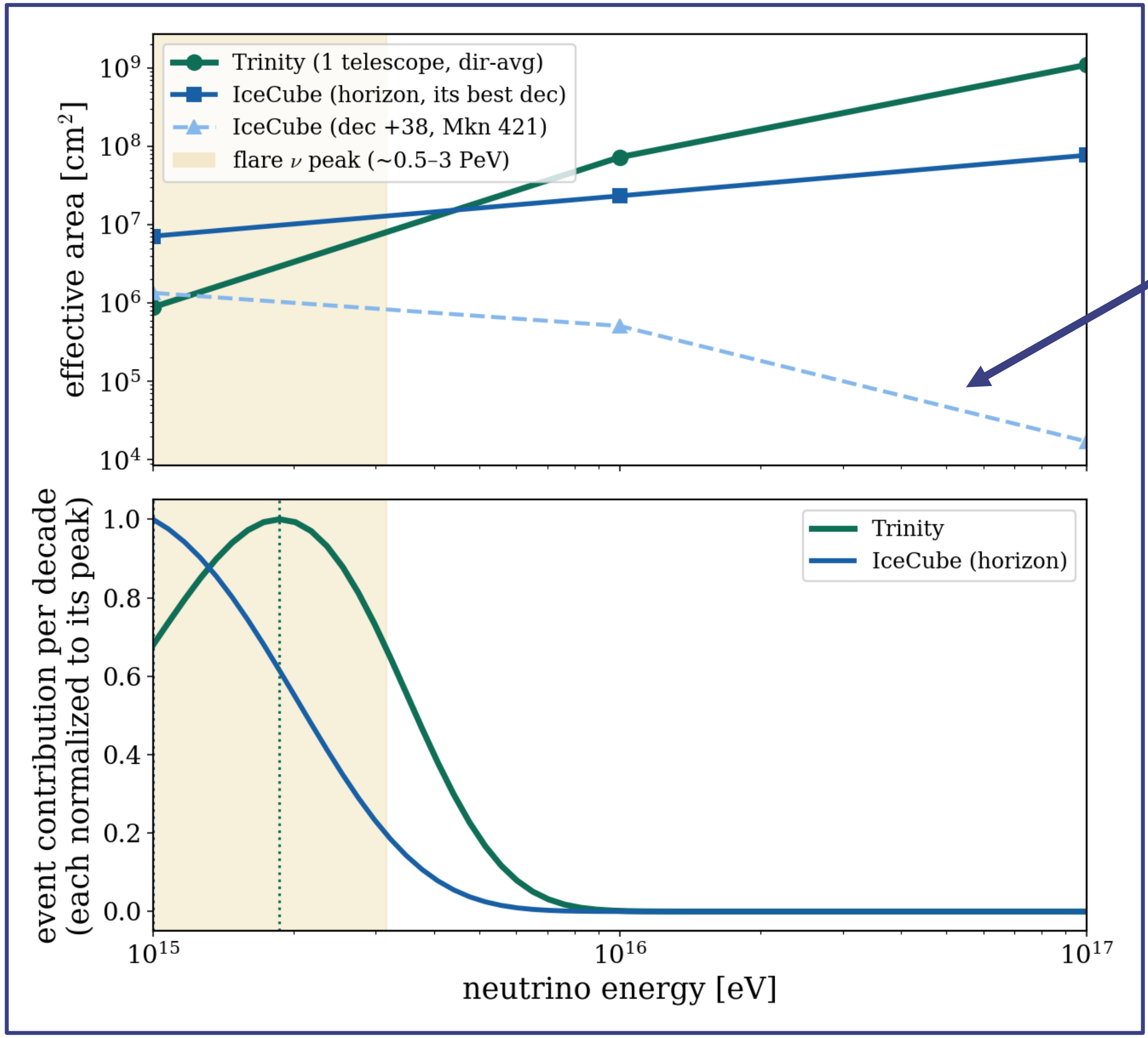
- MP21 single-zone
- flavour 1/3 at Earth
- mean spectrum across the flare
- background-free - validated: 550 h, zero τ candidates

Error bars:

- Poisson + X-ray flux-error Monte Carlo
- Dominant uncertainty is model systematics, not statistics

B5: *Trinity* and IceCube A_{eff}

- $A_{eff,\ Trin} > A_{eff,IC}$ northern reach at 1.2 PeV – flares peak here
- $A_{eff,\ Trin} > A_{eff,\ IC}$ best declination at 4.4 PeV.



IceCube's reach to northern sources absorbed

Higher area ≠ more events

***Trinity* complements with higher energy (PeV-EeV) and tau flavour**

IceCube public release; Raudales, D. & Otte, A.N, ICRC 2025

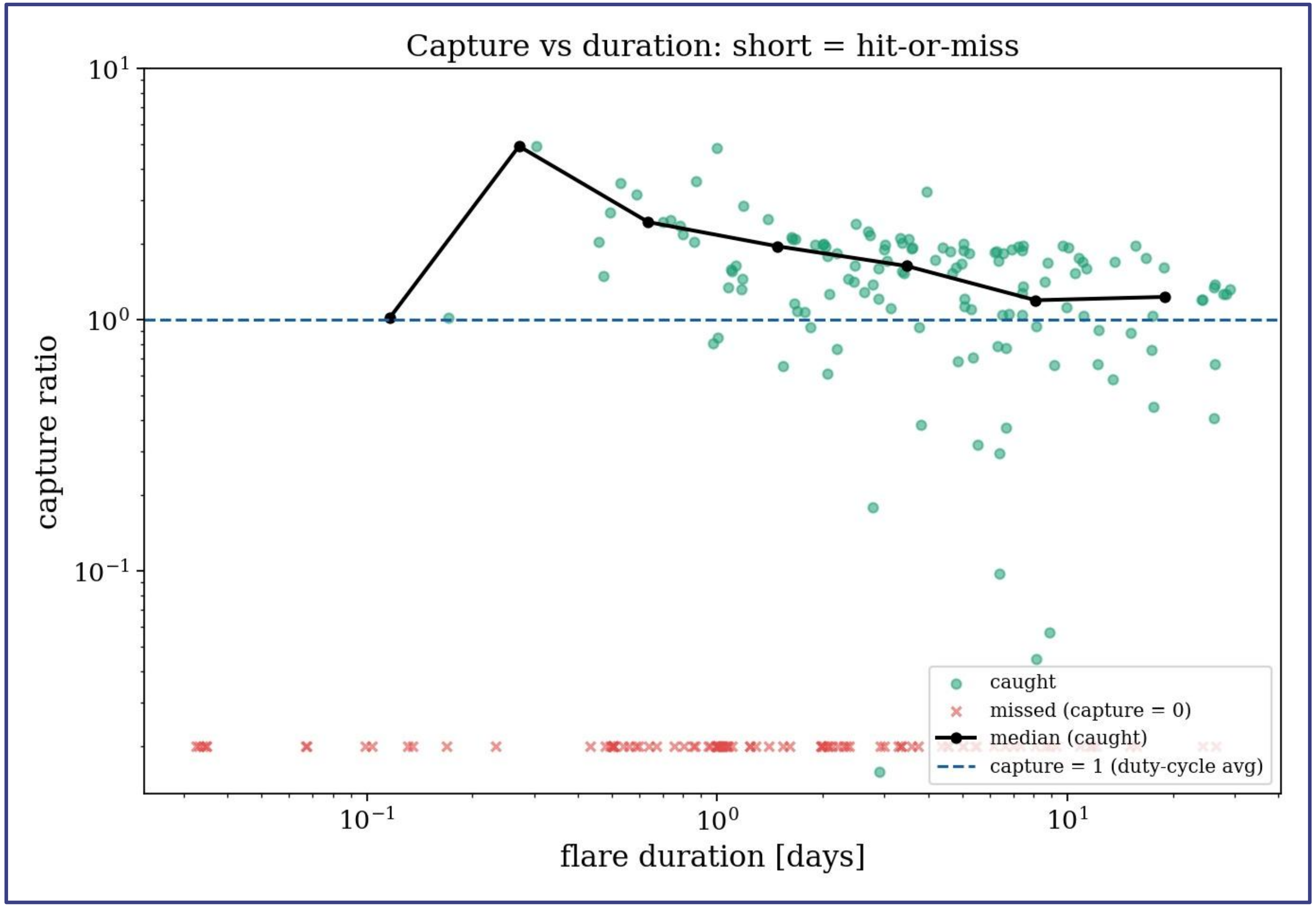
B5: *Trinity* and IceCube A_{eff}

	Trinity One	IceCube		
E_ν	1 telescope, dir.-avg.	horizon (best dec)	dec +38° (Mkn 421)	Trinity / IC_{hor}
100 TeV	—	1.29×10^6 †	7.91×10^5 †	—
1 PeV	8.84×10^5 †	7.13×10^6 †	1.35×10^6 †	0.12
2 PeV	3.32×10^6 *	1.02×10^7 *	1.01×10^6 *	0.33
3 PeV	7.34×10^6 *	1.26×10^7 *	8.45×10^5 *	0.58
5 PeV	1.94×10^7 *	1.63×10^7 *	6.82×10^5 *	1.18
10 PeV	7.26×10^7 †	2.33×10^7 †	5.09×10^5 †	3.1
100 PeV	1.10×10^9 †	7.69×10^7 †	1.71×10^4 †	14
1 EeV	4.06×10^9 †	—	—	—
10 EeV	4.31×10^9 †	—	—	—

All values in cm^2. † tabulated * log–log interpolated

Sameeksha Saini
sameeksha.saini@durham.ac.uk

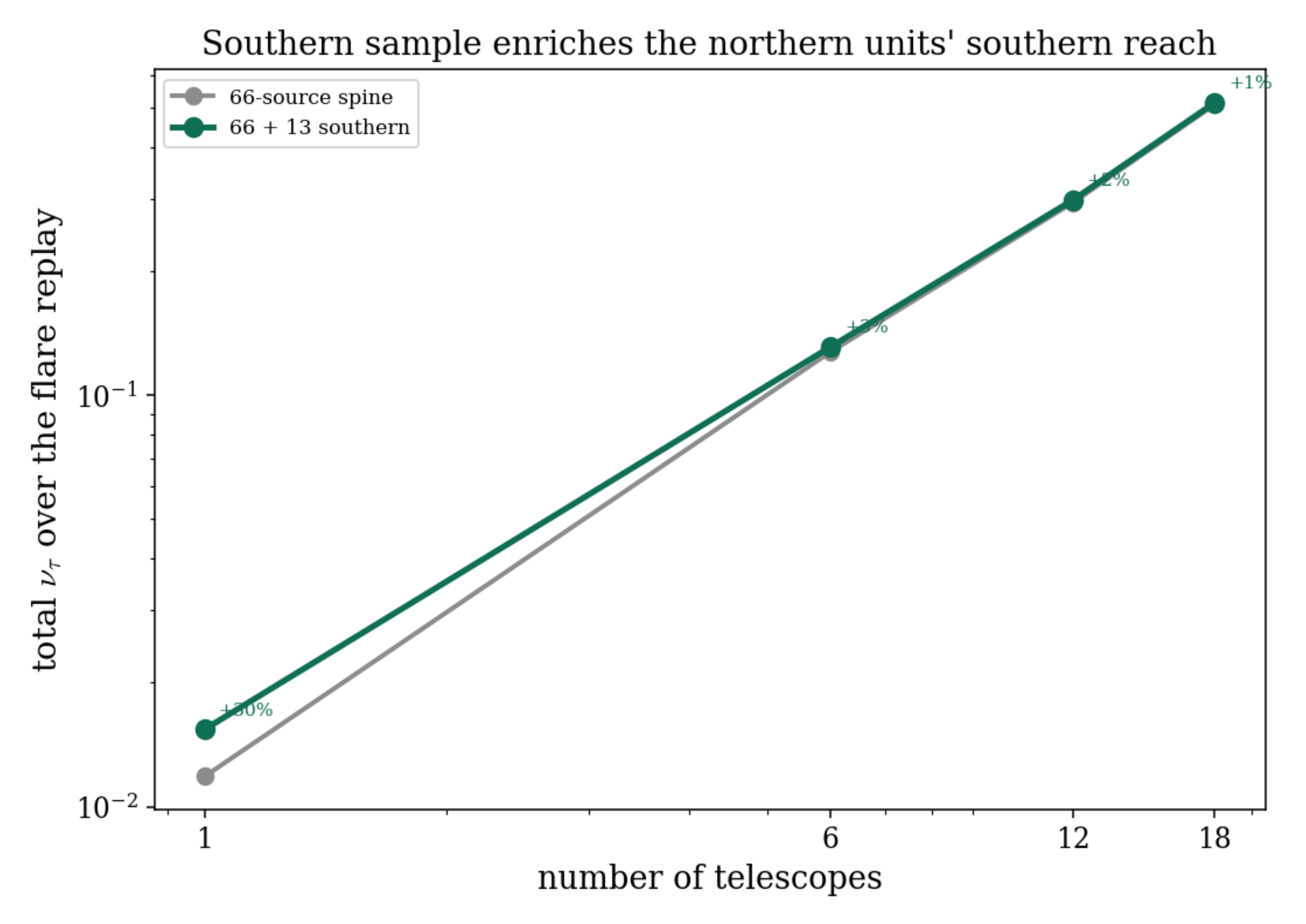
B6: Why short flares are hit-or-miss



- Every flare replayed minute-by-minute through *Trinity's* schedule
- Long flares → coverage averages out
- Short flares → hit-or-miss (29% caught) → Target of Opportunity (ToO) triggering

Sameeksha Saini
sameeksha.saini@durham.ac.uk

B7: Scaling up in telescopes



- 1 → 6 → 12 → 18 telescopes: reachable sources 21 → 36 → 47
- Total events over the replay: ×43 (0.012 → 0.51)
- The 13 southern sources add 30% for *Trinity* One
- One telescope views a given source at a time
- A full ring does **not** lower the per-flare fluence floor : buys access and capture, not area

Exploratory: assumes azimuth-symmetric acceptance

B8: What *Trinity* One needs to see a source

Condition	Requirement	Set by
Sun altitude	$< -15°$	dark time
Moon phase	$\leq 90\%$	sky brightness
Moon altitude	$< -2° \Rightarrow$ no constraint	—
Moon azimuth	else exclude $\pm 30°$	half the 60° FoV
Source altitude	$-15° < \text{alt} < 0°$	Earth-skimming shell
Source azimuth	60°–300°	**Frisco terrain**, not the mount

B8: What *Trinity* One needs to see a source

Consequence	median	best
Declination band	$-66.5°$ to $+23.0°$	
Sources reachable	34 of 66	
Hours per year	260	861
Nights per year	220	245
Hours per *reachable* night	1.1	4.5

Reference year 2025; 1-minute sampling. Hours per year 16–84%: 159–335. Best target throughout: RXS J05439−5532 (dec −55.5 ∘).