Constraining the neutrino emission from BL-Lacs & FSRQs using a multi-messenger approach

– Ankur Sharma

II Year PhD student

Supervisor: Dr. Antonio Marinelli

Istituto Nazionale di Fisica Nucleare
Sezione di Pisa

Università di Pisa

KM3NeT

Motivations

- Evidence of astrophysical neutrino signal – Icecube
- Galactic contribution ~ 10 %
- 90% -> extragalactic sources

Source population ?

- GRBs, Starbursts disfavoured. Blazars ??

IceCube recently announced the identification of an astrophysical neutrino source (a BL-Lac)

Blazars

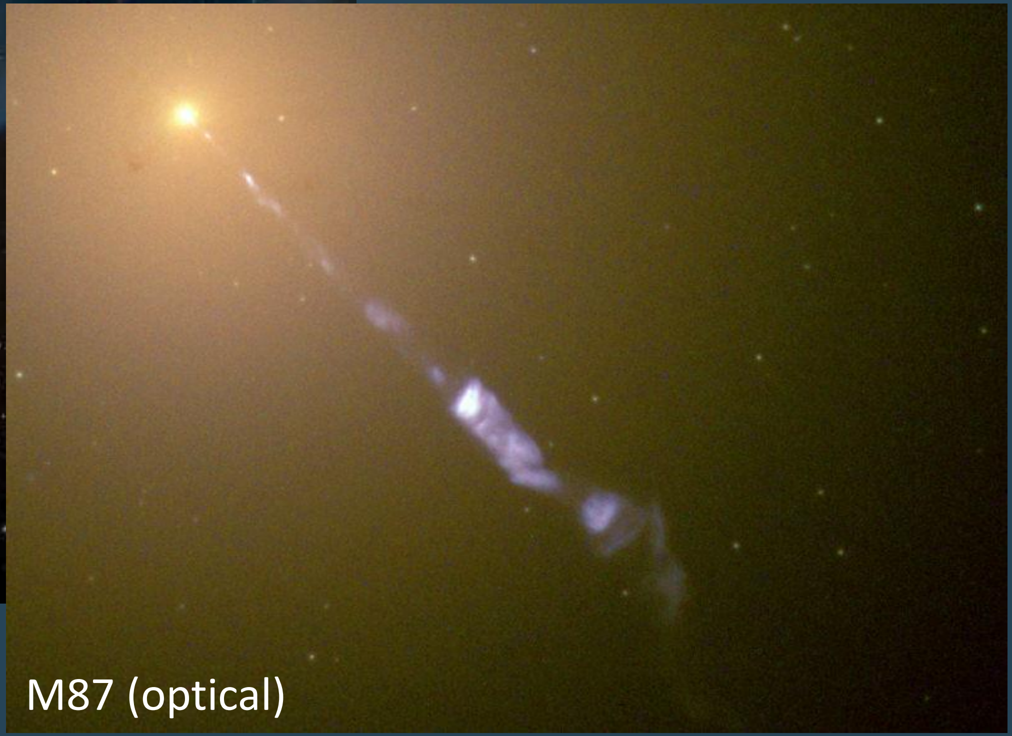
Blazars : AGNs with jets pointed at small angles from Earth


Artist's Rendition

Bulk Lorentz Factor:
$\Gamma \sim 10\text{-}40$

Blazars

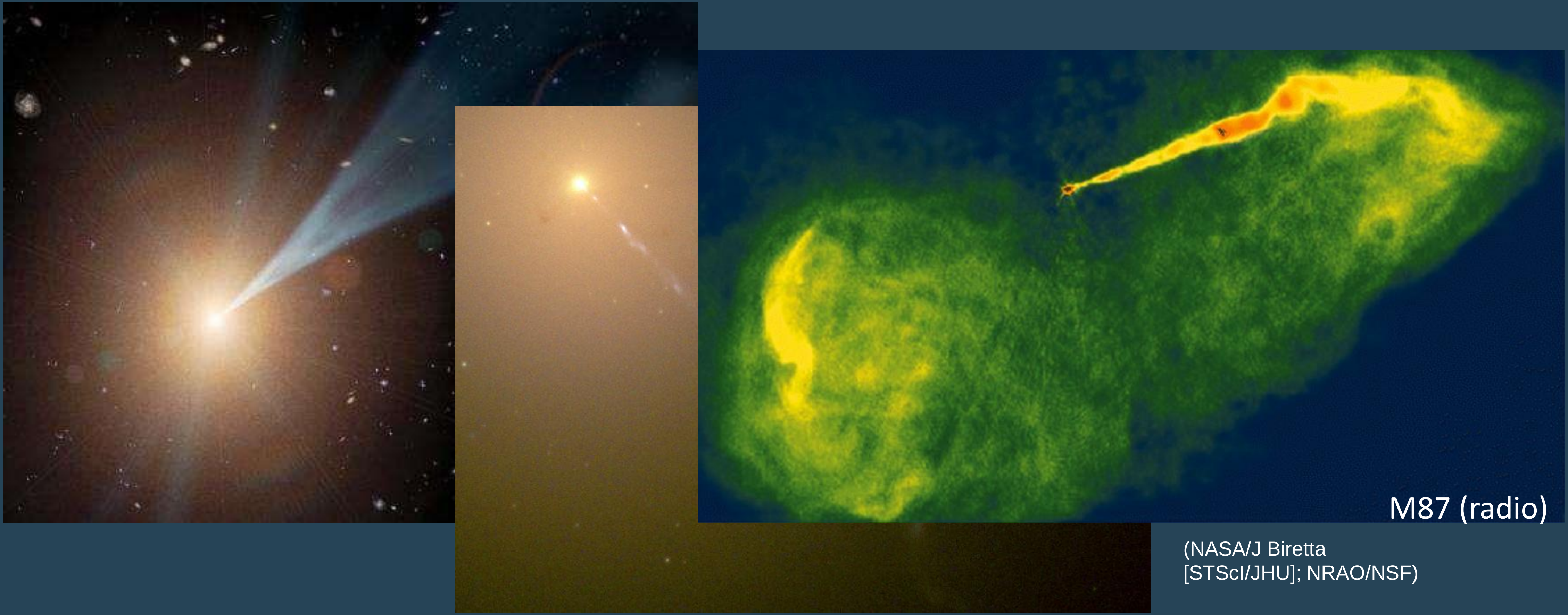
Blazars : AGNs with jets pointed at small angles from Earth



M87 (optical)

Blazars

Blazars : AGNs with jets pointed at small angles from Earth



(NASA/J Biretta
[STScI/JHU]; NRAO/NSF)

Blazars: BL-Lacs and FSRQs

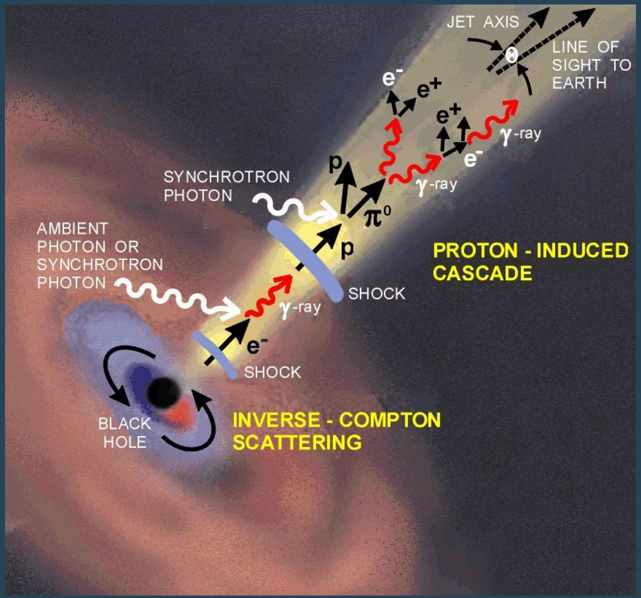
- Two categories:

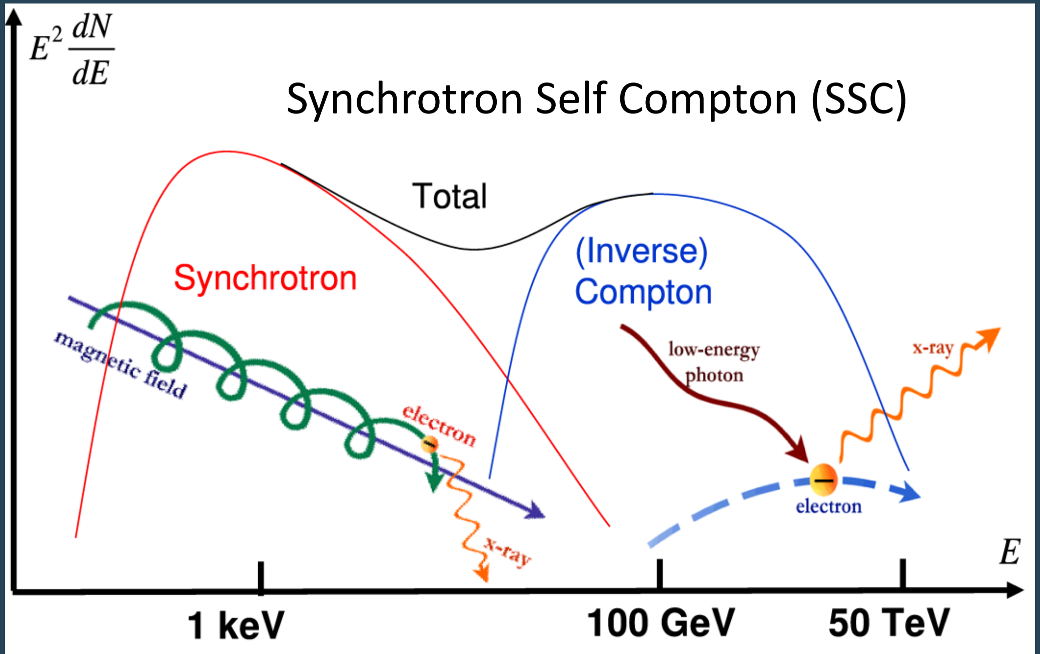
1. **BL-Lacertae objects (BL-Lacs)**: Show high optical polarization and rapid variability

2. **Flat Spectrum Radio Quasars (FSRQs)**: High and rapid variability and more luminosity

Emission from Blazar Jets: The Synchrotron Self-Compton (SSC) Model

- Non-thermal emission over a broad band of the EM spectrum
- Spectrum defined by the SSC model. Two major humps
  1. Electron Synchrotron: Emission from relativistic e- gyrating under the high magnetic fields
  2. Inverse Compton: Compton up-scattering of the synchrotron photons





arXiv:0712.0315v6

Emission from Blazar Jets: Hadronic emission

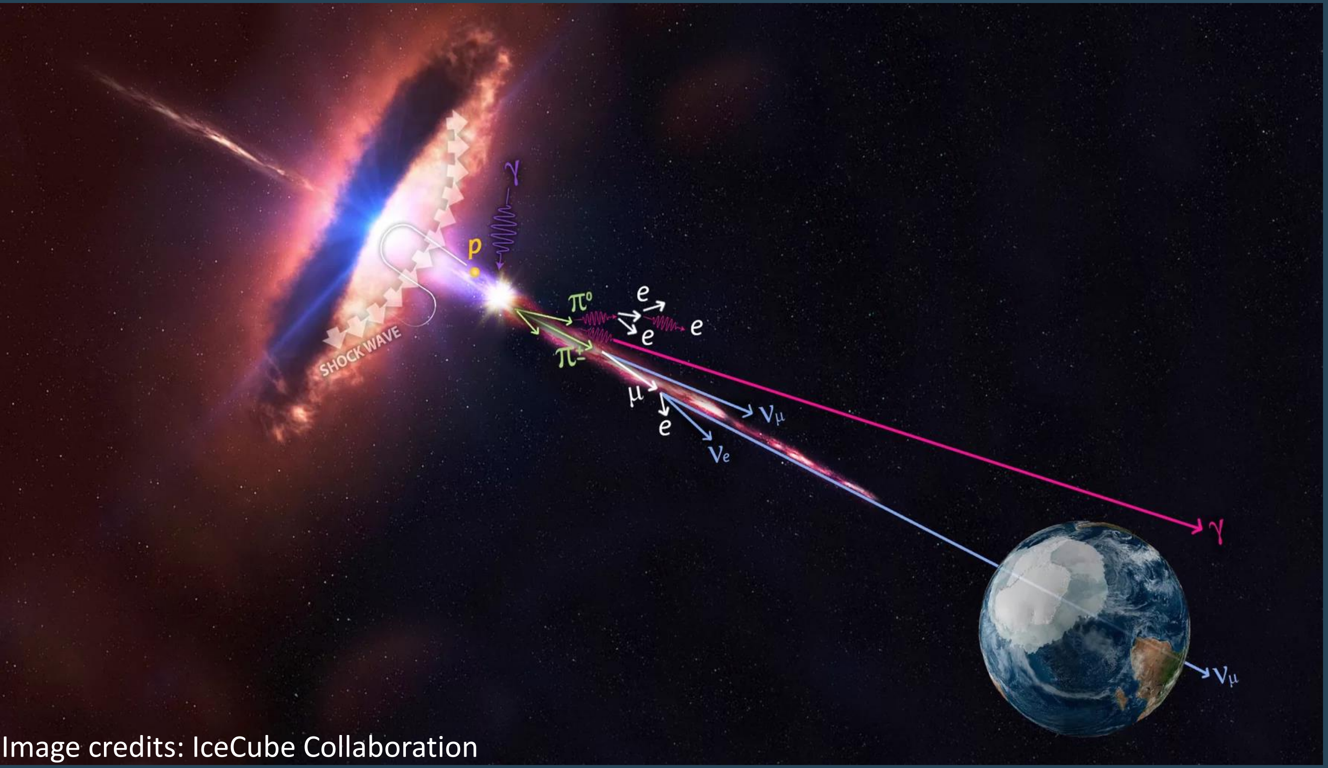


Image credits: IceCube Collaboration

Neutrinos can be traced back to reveal their source

- Photo-mesonic interactions of protons produce pions

$$p\gamma \rightarrow N + k\pi$$

($E_p > m_\pi c^2 (1+ m_\pi/2\, m_\pi p) \sim 145$ MeV)

- These pions decay to produce neutrinos
- Neutrino takes away 5-10% of parent proton's energy (100 TeV ν => 1 PeV proton)
- If a source can accelerate protons to sufficiently high energies, it can emit very high energy (VHE) neutrinos

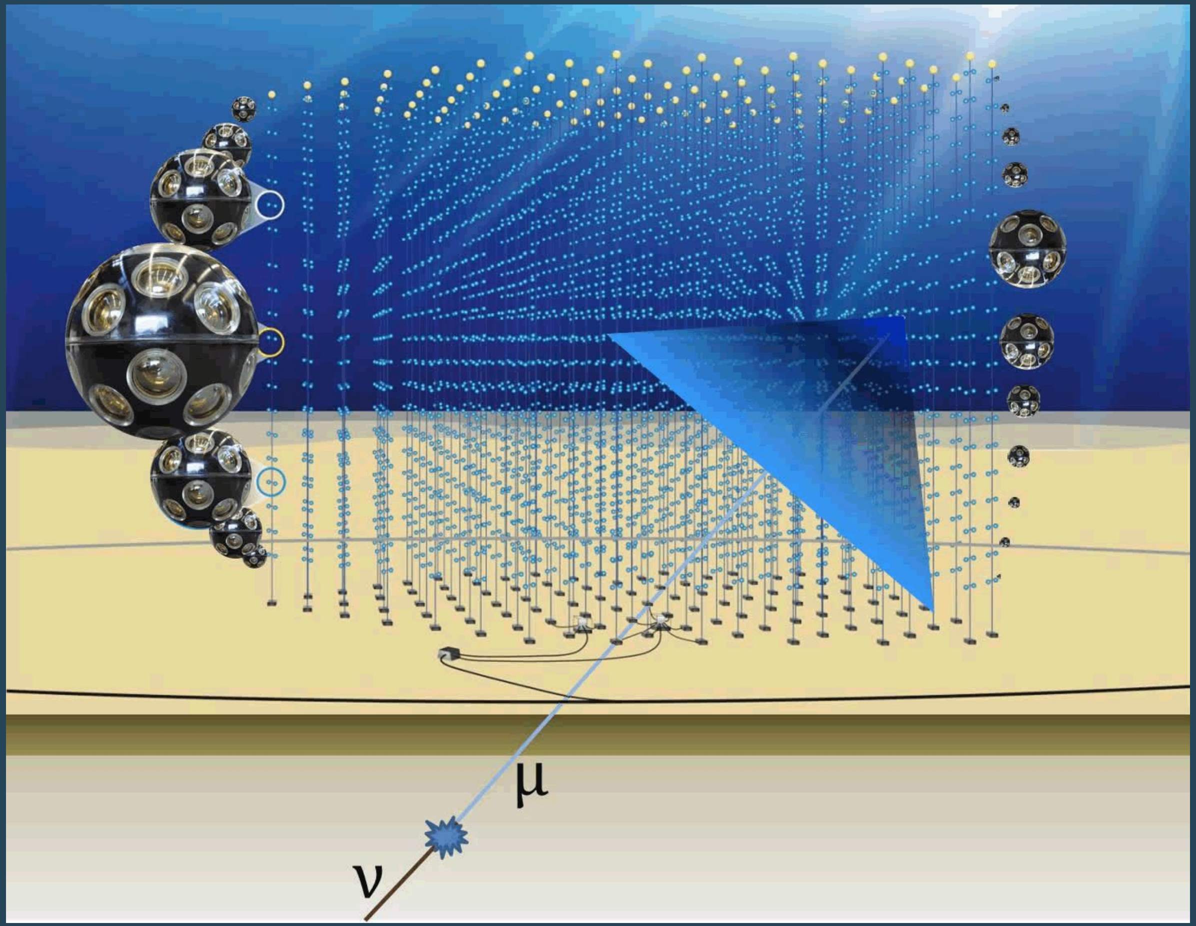
Neutrino Astronomy

- Two VHE neutrinos observatories currently active
  1. **ANTARES** in the Mediterranean Sea (Northern Hemisphere)
  2. **IceCube** at the South Pole (Southern Hemisphere)

     ($A_{eff} \sim 100\ m^2$ at 100 TeV)

- Upcoming: **KM3NeT** – also in the Mediterranean Sea

Neutrino Detection



- Look for ν arriving at the detector through the Earth – background suppression
- Absorption in Earth important at E > 50 TeV; declination dependent
- Two major topographies:
  1. *Shower*: ν_e produces an EM cascade in the detector, excellent energy resolution
  2. *Track*: ν_μ produces a track geometry in the detector, excellent angular resolution (< 1^o)

ν_μ can be used to identify point sources

Analysis of two Blazars

TXS 0506+056 and OP 313

AMON: IceCube real-time alert system

- IceCube has a real-time alert system in place (since 2016)

- Alerts for candidate astrophysical ν_μ events (EHE & HESE)

  1. *EHE*: Extreme High-Energy Events (E > 200 TeV)
  2. *HESE*: High Energy Starting Events (event vertex contained in the detector)

IC-170922A

- EHE event alert on 22nd Sept. 2017 (E_ν = 290 TeV)
- BL-Lac TXS 0506+056 (within 1° of the alert coord… …orted to be in a flaring state by Fermi
- Increased γ-ray activity from the dire… …ed by MAGIC telescope (28th Sept – 4th…
- Unblinded analysis of… …s in the sample of total reconstructed ν_μ even… …tion over a 110 day period (Dec. 2014 – Feb. 2015)…

Is TXS 0506+056 an astrophysical neutrino emitter??

No increased gamma-ray activity, but spectral hardening was observed

Source Selection

- *Selection criteria*: Spatial coincidence with an astrophysical VHE neutrino candidate event
- Candidate ν_μ events (E > 100 TeV):
  1. IC AMON alert program (2016 - present) – 10 EHE & HESE events
  2. Before the AMON alert program (29 events) – IceCube Collaboration, Observation and Characterization of a Cosmic Muon Neutrino Flux From the Northern Hemisphere Using Six Years of IceCube Data. *The Astrophysical Journal, 833:3 (18pp),* December 2016
  3. Another 7 events – The IceCube Collaboration, A Measurement of the Diffuse Astrophysical Muon Neutrino Flux Using Eight Years of IceCube Data. *PoS (ICRC2017) 1005*, 2017

(36 + 10 in total)

Source Selection: Source Catalogs

- Source classes: BL-Lacs & FSRQs

- Source catalogs: Fermi *3FGL* & *3FHL*

Sample Selection: sources

- A sample of 12 sources found in coincidence
- Criteria further strengthened
  - ✓ Within 2^o of the alert coordinates
  - ✓ Long duration flare in γ
- Two sources shortlisted for analysis
  - ✓ TXS 0506+056
  - ✓ OP 313

S.no.	Source Name	RA (deg)	Dec.(deg)	Source Class	z
1	MG3 J225517+2409	343.805	24.1807	bll	NULL
2	RX J2030.8+1935	307.751	19.6032	bll	NULL
3	RX J1533.1+1854	233.312	18.8712	bll	NULL
4	PKS 2047+039	312.508	4.1466	bll	NULL
5	1RXS J211242.5+081831	318.18	8.3179	bll	NULL
6	PMN J2110+0810	317.518	8.2021	fsrq	1.58
7	OX 036	320.921	5.5629	fsrq	1.941
8	1ES 0229+200	38.2236	20.2984	bll	0.1390
9	OP 313	197.649	32.351	fsrq	0.998
10	NVSS J232538+164641	351.423	16.8334	bll	NULL
11	SDSS J085410.16+275421.7	133.532	27.8826	bll	0.494
12	TXS 0506+056	77.3636	5.7066	bll	0.3365

- ➢ 3 FSRQs and 9 BL-Lacs
- ➢ To be studied for the thesis

TXS 0506+056 and OP 313

- TXS 0506+056:

  RA: 77.35°

  Dec: 5.69°

  z: 0.3365
- Most likely counterpart of IC-170922A (E_ν = 290 TeV)
- Major gamma flare started in June 2017

- OP 313:

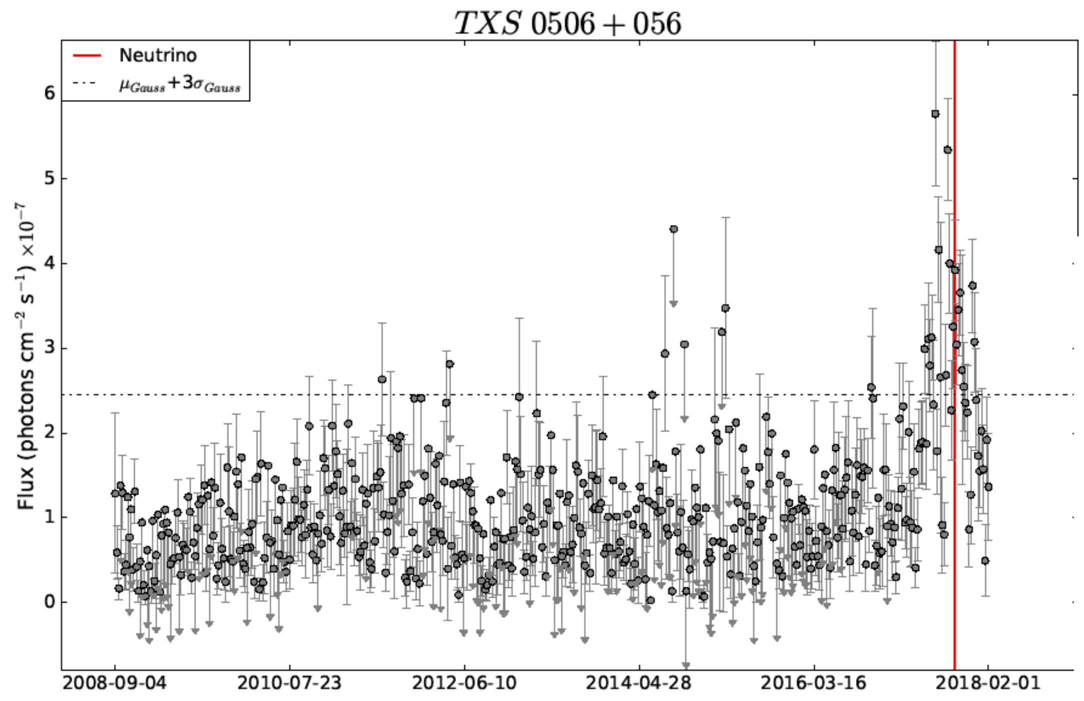
  RA: 197.619°

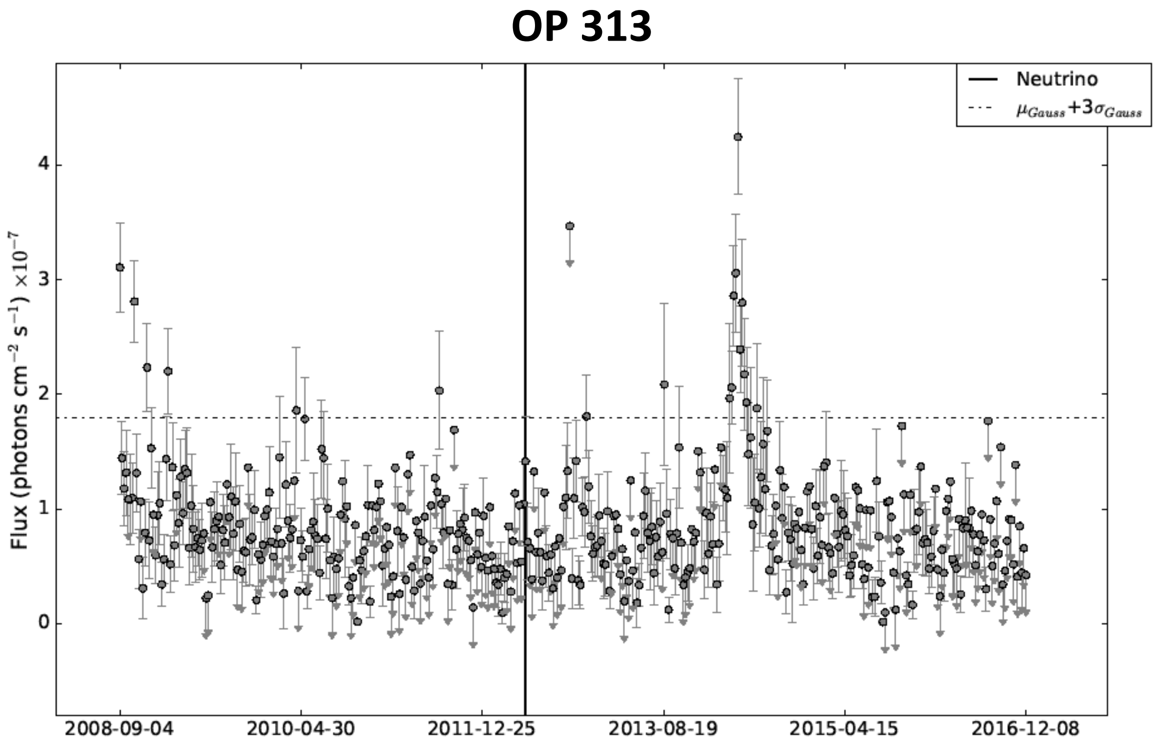
  Dec: 32.345°

  z: 0.998
- Coincident with an EHE ν_μ from 15th May 2012 (E_ν > 200 TeV)
- Major gamma-ray flare in April 2014

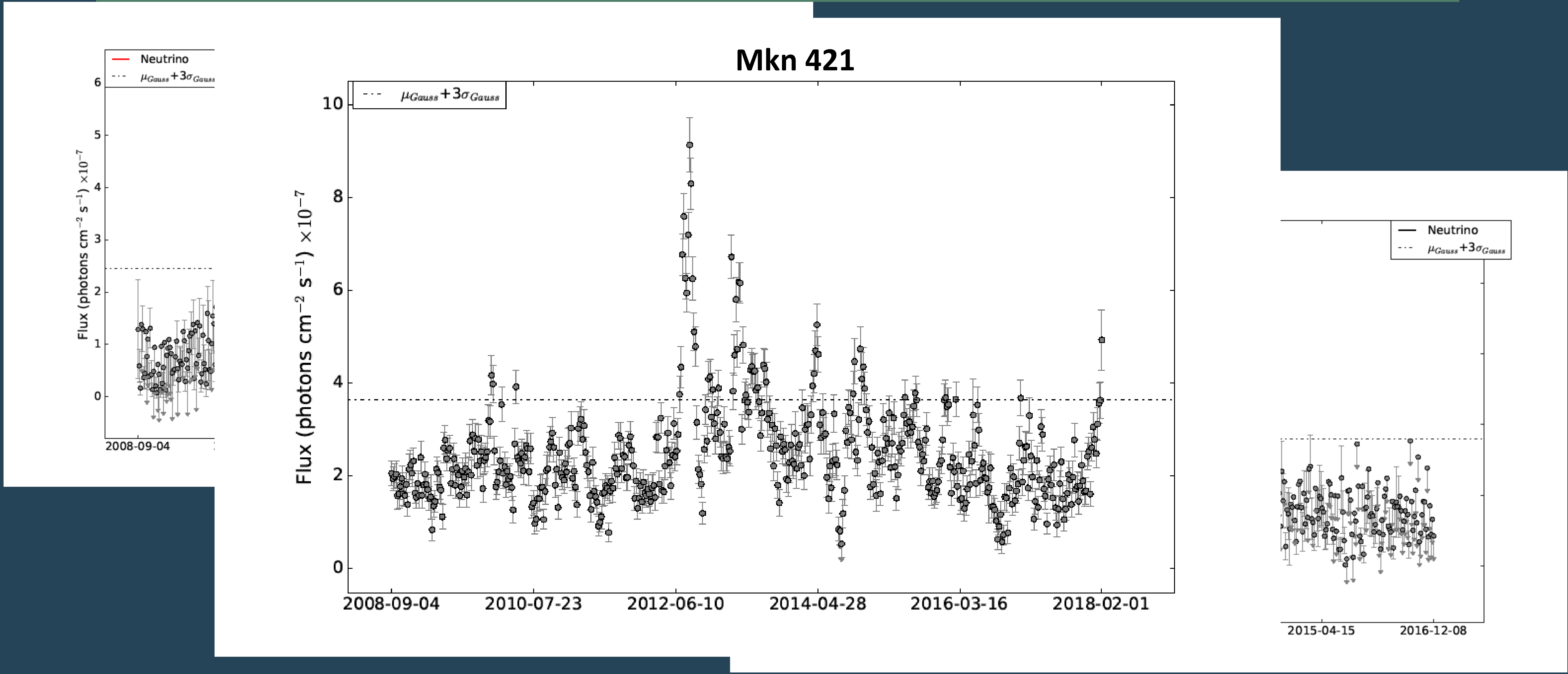
Gamma-ray Light curves

E = 0.1 – 300 GeV





Gamma-ray Light curves



Duty Cycles

- Duty Cycle of a source is the fraction of time it spends in an active state

$$DC = \frac{T_{HE}}{T_{HE}+T_{bl}}$$

where T_{HE} is the time spent in high-energy flux state and T_{bl} is the time spent in the baseline flux state

- Provides an estimate of how frequently active a source is (more active the source, more likely to emit neutrinos)
- Can be used to determine the duration of a flare

Duty Cycle – Calculation

- Plot flux distribution to define active states
- Fit function: Gaussian + LogNormal
- Gaussian defines the quiescent states, LogN defines the active states
- Removing time dependence

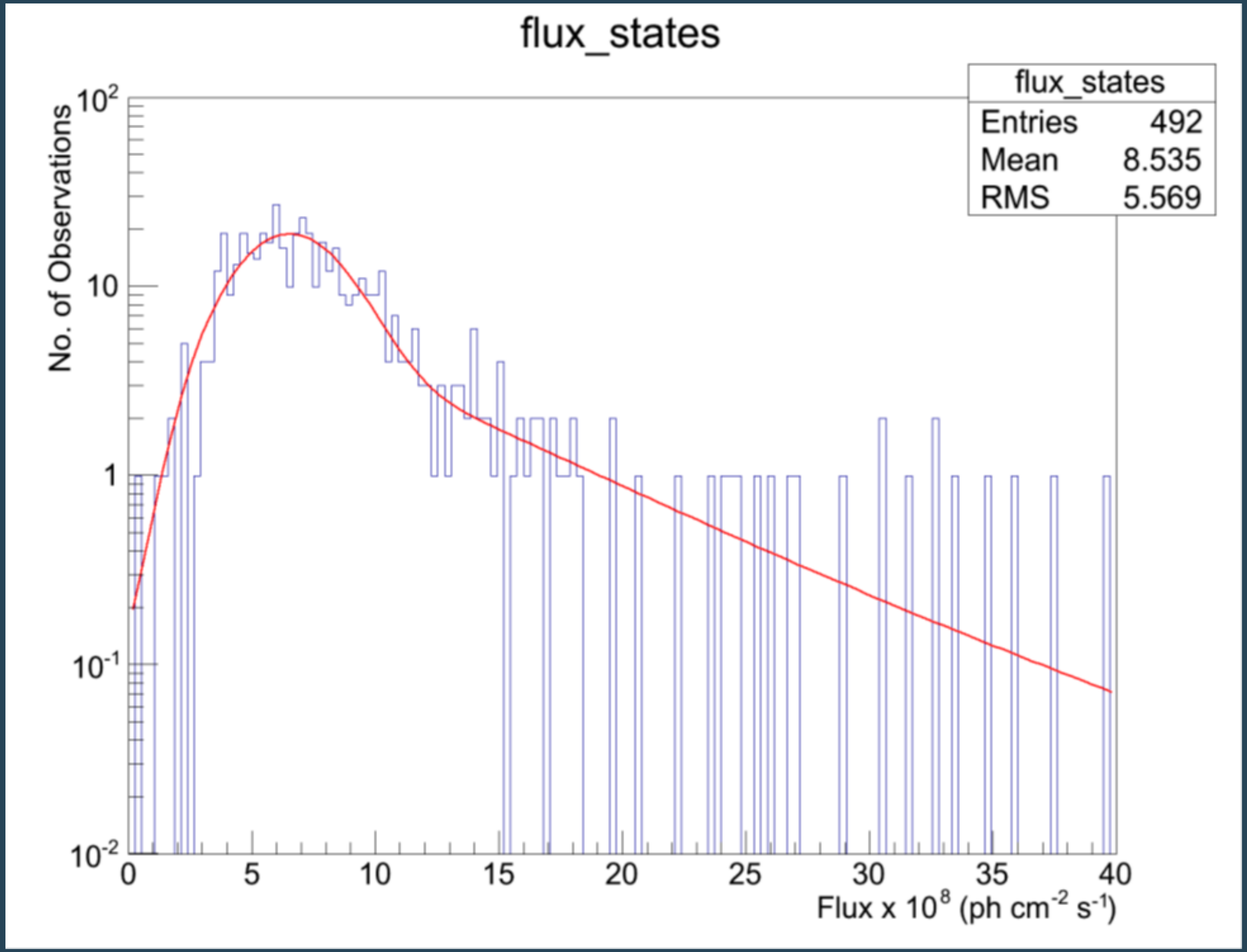
$$DC = \frac{F_{avg} - F_{bl}}{\langle F_{fl} \rangle - F_{bl}}$$

F_{bl} = μ_{gaus} + 3 σ_{gaus} (baseline flux)

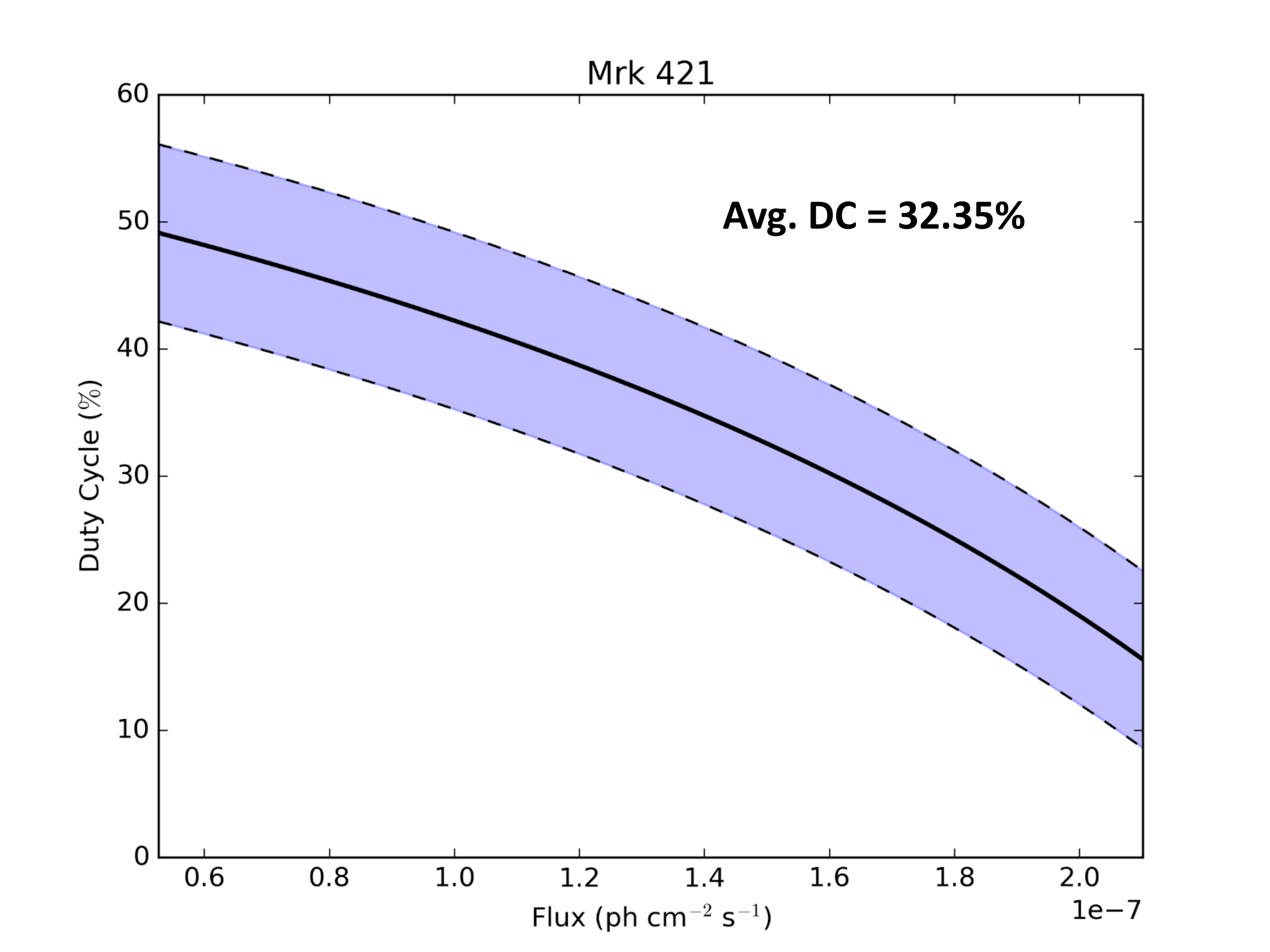
where F_{avg} -> avg. flux over 9 all observations

$\langle F_{fl} \rangle$ -> avg. flux during all flares

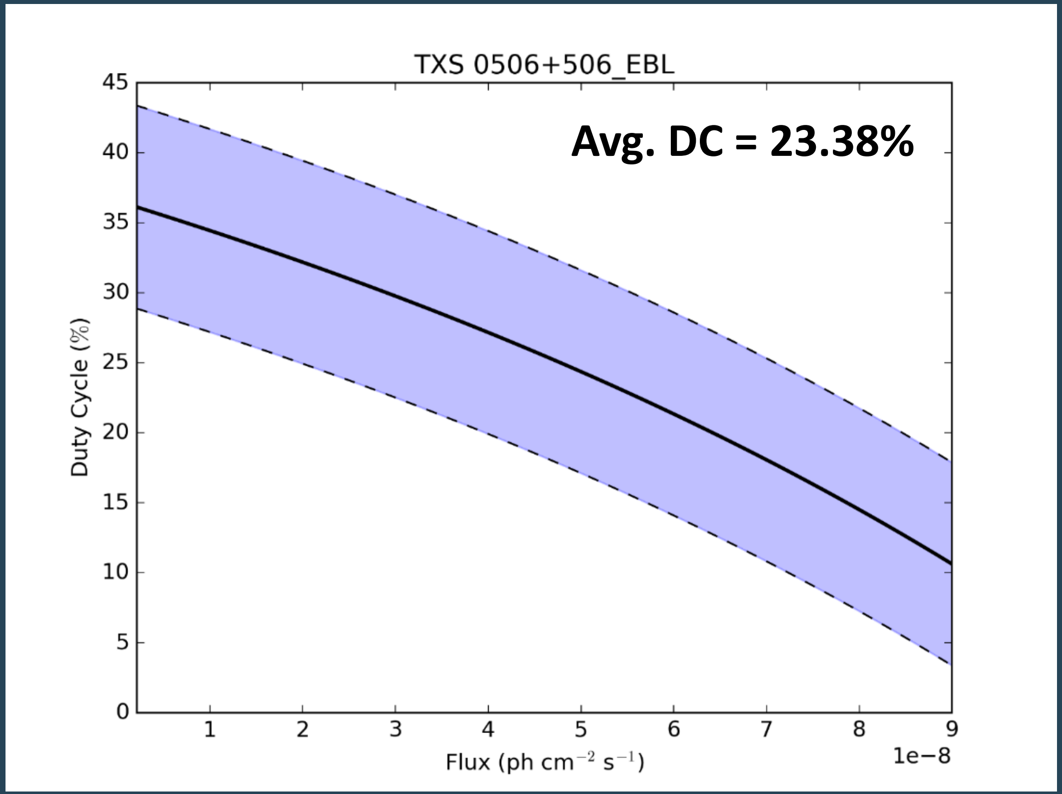
- Vary the baseline to calculate the DC distribution

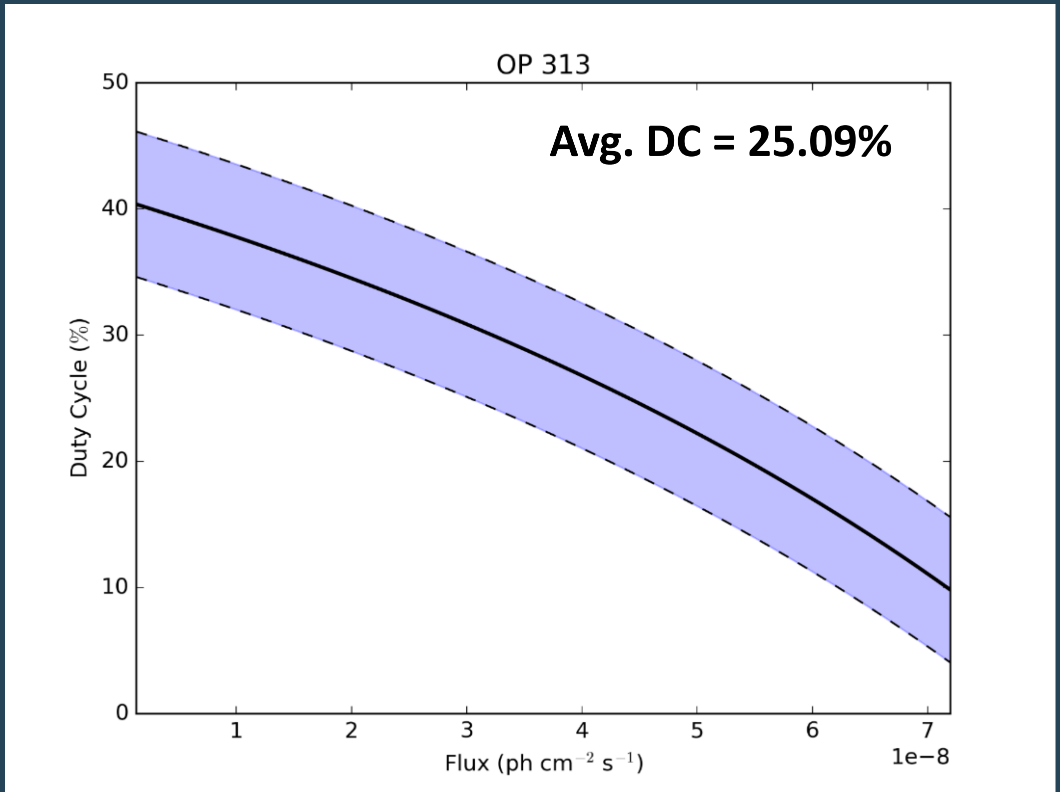


Duty Cycles – Mkn 421



Duty Cycles – TXS 0506+056 and OP 313





DC of the two sources is comparable

The γ-ray Luminosities

- Isotropic γ-ray luminosities calculated for major flare
- Flare duration from duty cycle calculation ($> 3\ \sigma_{gaus}$)
- Standard cosmology from:

M. G. Aartsen and et al. Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science*, 361(6398), 2018

- OP 313 ~5 times as bright as TXS 0506+056

Source	Luminosity
Mkn 421	**1.15066e+44**
TXS 0506+056	**1.41188e+46**
OP 313	**7.42466e+46**

The Neutrino Light Curves

- Conversion of γ-ray flux in the range 1-316 GeV to neutrino flux
- Based on Villante, Vissani (2008)

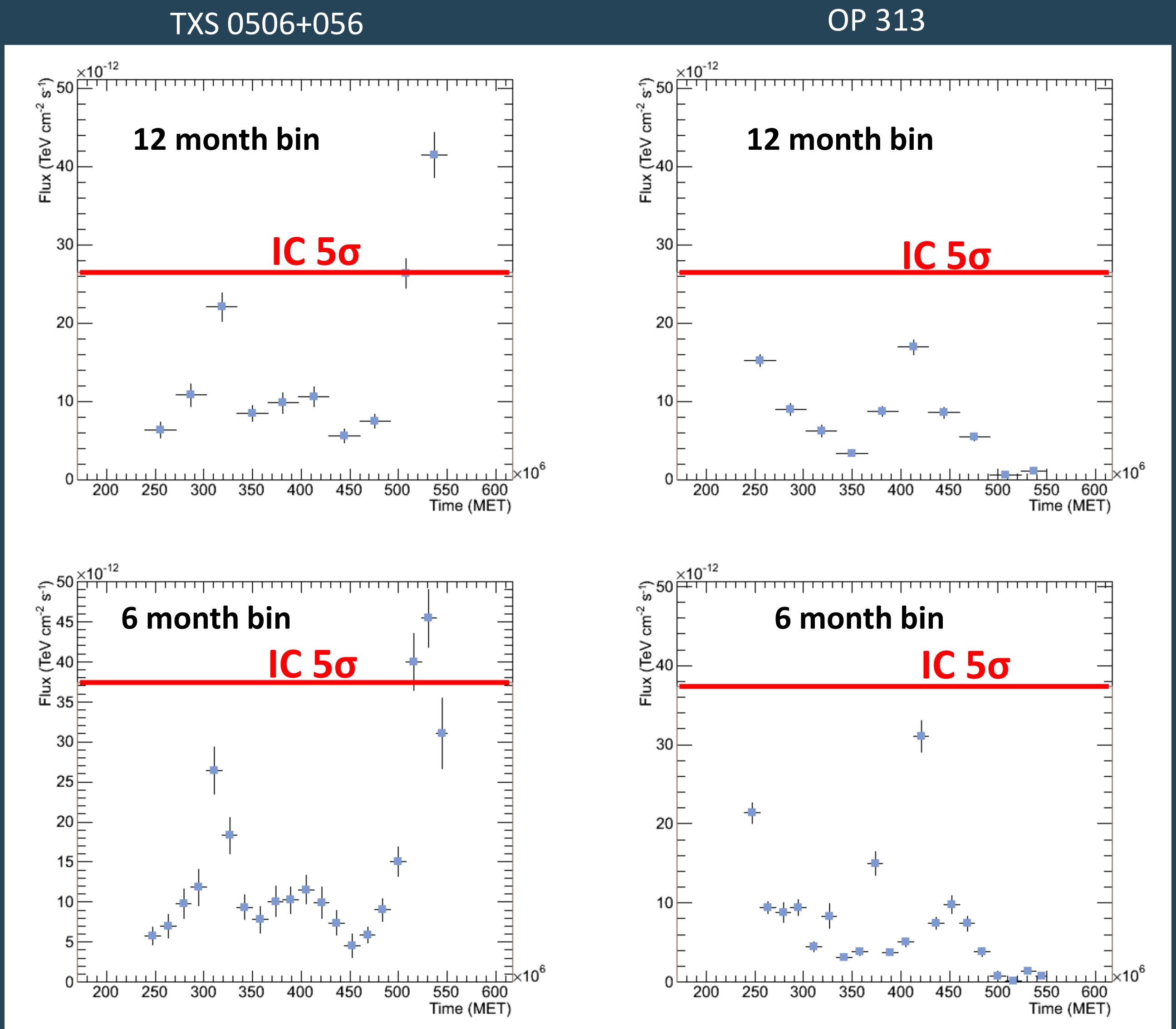
$$\phi_{\nu_\mu}[E] = 0.38\phi_\gamma[2.34E] + 0.013\phi_\gamma[1.05E] + \int_0^1 \frac{dx}{x} k_{\nu_\mu}[x]\phi_\gamma[E/x]$$

- Accounting for pion, kaon decay channels and oscillations
- Assumed ν spectrum of E^{-2}
- A fully hadronic origin of γ-ray flux assumed
- EBL (extra-galactic background light) absorption considered

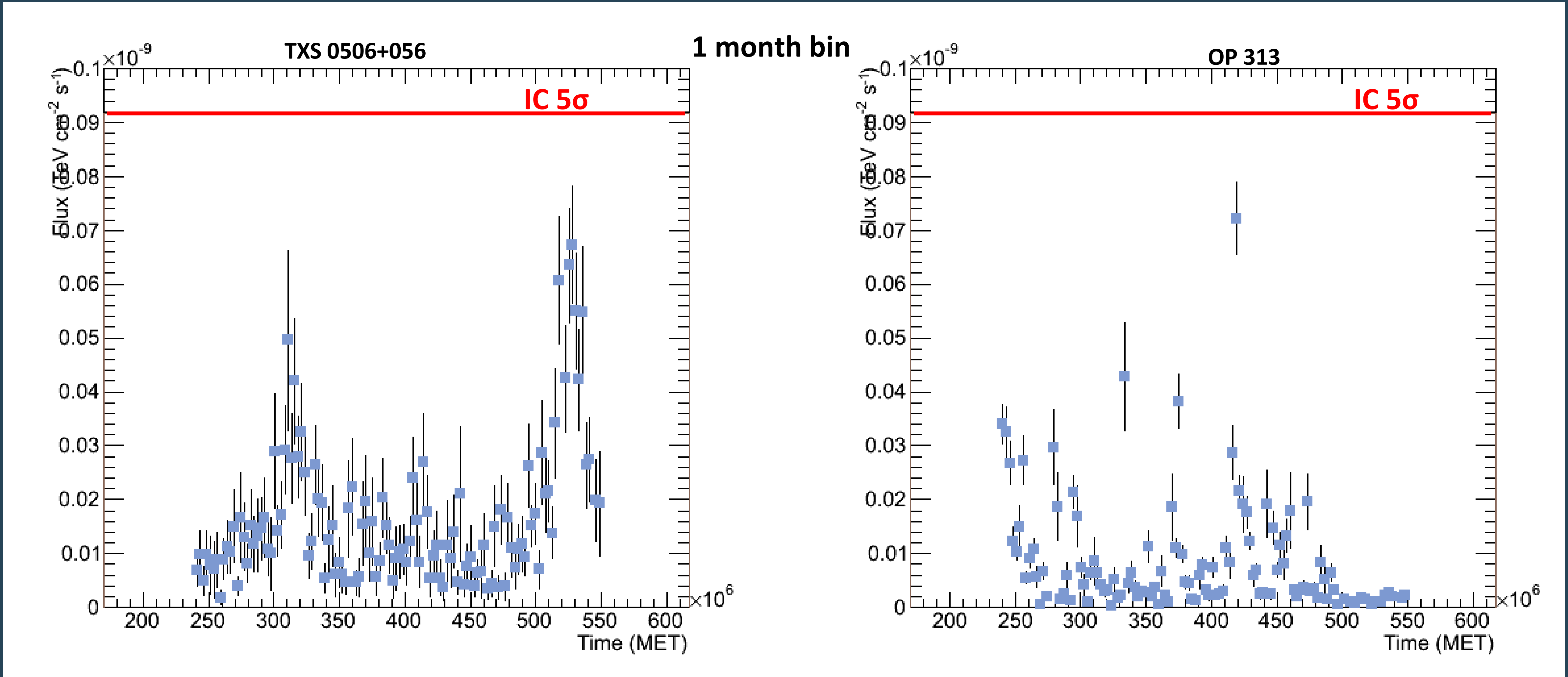
The Neutrino Light Curves

- Light curves computed for yearly, half-yearly and monthly bins with 9.5 yrs of Fermi data
- The 5σ discovery potential of IceCube for the corresponding bin period was over-plotted

> ➢ A flare of atleast 6 months is required for a source to be observable in neutrinos



The Neutrino Light Curves



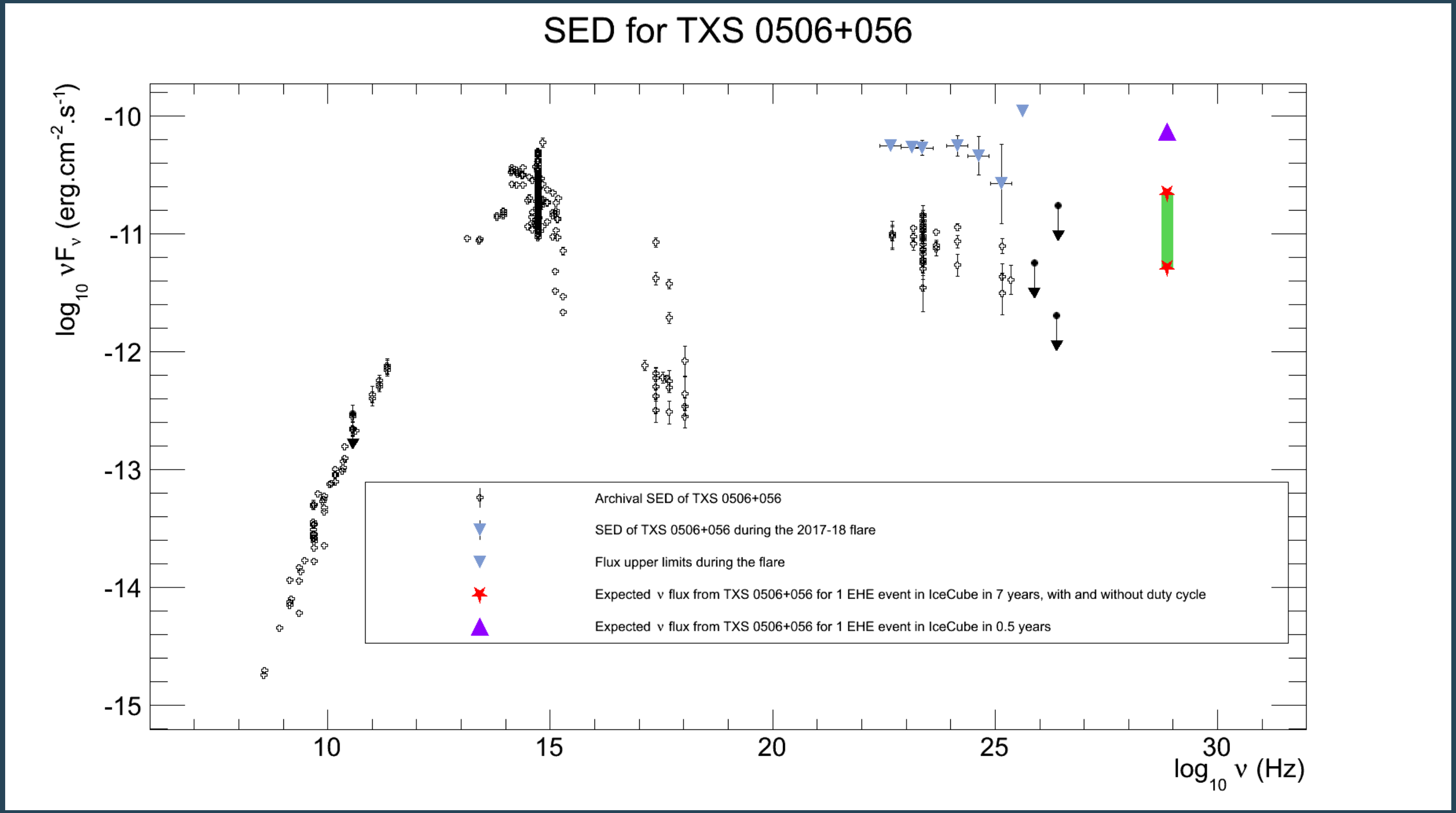
A one-month flare not enough to reach discovery potential of km^3 detector

Spectral Energy Distribution (SED)

- SED data:
  - Archival SED of OP 313 and TXS 0506+056
  - SED during their major flares
  - Expected neutrino flux for 1 EHE event in 0.5 yrs in IceCube
  - Expected neutrino flux for 1 EHE event in 7 yrs in IceCube
  - Expected neutrino flux for 1 EHE event in 7 yrs in IceCube, accounting for duty cycle
- For OP 313, E_ν = 250 TeV (assumed)
- Effective area taken from:

M.G. Aartsen et al. All-sky Search for Time-integrated Neutrino Emission From Astrophysical Sources With 7 Yr of IceCube Data. *The Astrophysical Journal, 835:151 (15pp),* February 2017

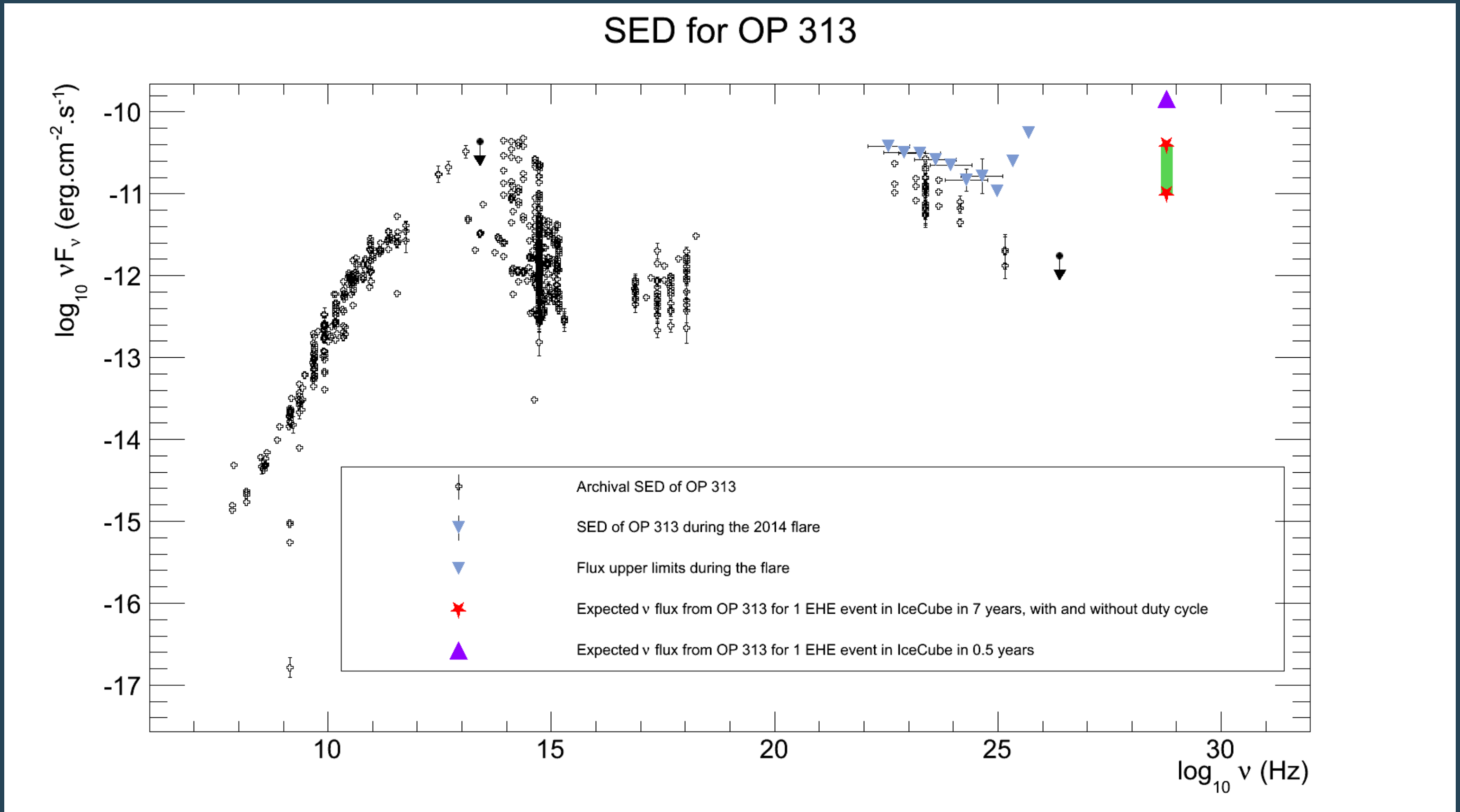
SED – TXS 0506+056



- Flaring state SED at similar level of the six-month ν flux
- Proton synchrotron peak also at the same level as the 7 yr expected flux
- One EHE event during the flare can be justified from this SED

Petropoulou M. et al. Photo-hadronic origin of gamma-ray BL Lac emission: implications for IceCube neutrinos. *MNRAS 448, 2412–2429*, January 2015

SED – OP313



- Proton synchrotron peak at similar level of the 7 yr expected flux
- SED during the flare does not show any significant rise
- 1 EHE event in IceCube will probably require 7 yrs for this source

Analysis Summary

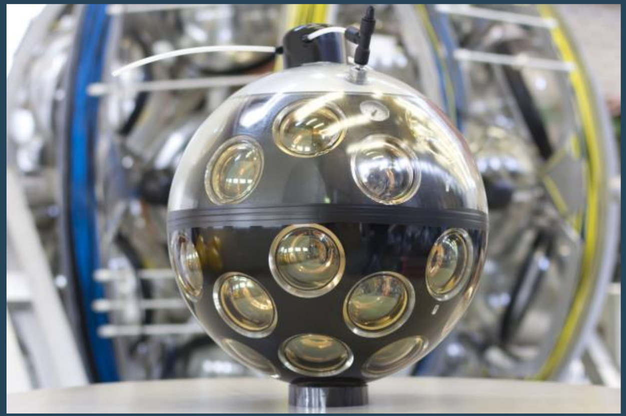
- Both sources have a high duty cycle (20-25% on average).
- To be observable in a *km*3 detector like IceCube, flare period of 6 months or more required from these sources, something not observed in Mkn 421.
- SEDs of the two blazars justify 1 EHE event in IceCube in 7 yrs for OP 313 and in 6 months for TXS 0506+056.
- No significant spectral hardening observed for OP 313 for a period of six months around the neutrino event.
- OP 313, at z =1, is effected significantly by EBL absorption above 100 GeV
- The overall significance of a multi-wavelength observation for a single flare will only increase significantly if we have a global network of neutrino observatories that can simultaneously detect neutrino events from the same source at different locations

The KM3NeT Experiment

Detector Calibration and PMT signal characterization

KM3NeT

- Deep-Sea Cherenkov Neutrino telescope, to be built in Mediterranean Sea
- Multiple detector blocks: ARCA & ORCA
- Main detection unit: Digital Optical Module (DOM)



- Objectives:
  - Astroparticle Research with ARCA
  - ν-oscillations and particle physics with ORCA
  - Marine Biology research, Oceanography and Geophysics
- Together with IceCube, will form a global neutrino observatory

Time Calibration with Atmospheric Muons

The Concept

- Off-shore calibration strategy to correct DOM reference times (T0s)
    - Applicable to inter-DOM and inter-DU calibration (DU -> Detection Unit)
- Based on the knowledge of expected arrival time of light on a DOM from a reconstructed muon track
    - Assumption: relative DOM positions known
- Calibration data stored in a detector file, under separate columns for the PMTs, DOMs and DUs
    - Total calibration to be applied is the sum of all three
- Hit time residual (HTR) -> difference between measured and expected hit time from muon track
    - HTR distribution expected to peak at 0 for a correctly calibrated DOM

Methodology

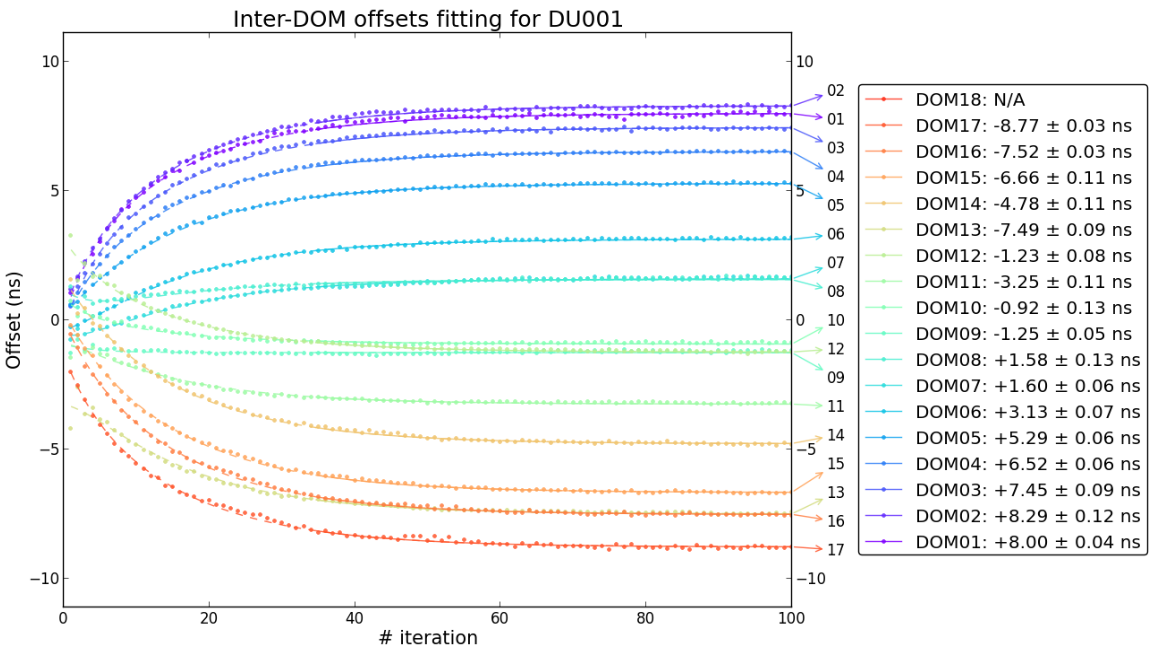
1) Reconstruct tracks excluding the component to calibrate (DOM, DU)

2) Collect median of the HTR distribution of the tracks with the component to calibrate
    - This median is the first estimation of the quantity called ‘offset’, which is the cumulative average of these medians added iteratively, until they no longer vary

3) Include found corrections on the calibration (update detector file)

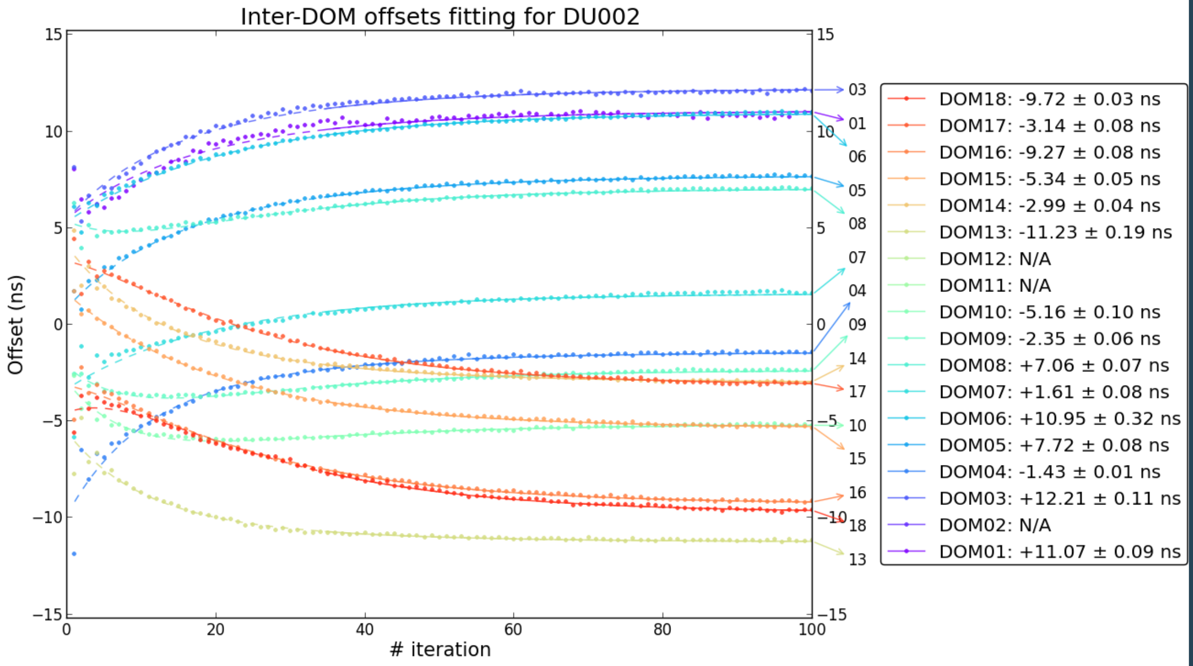
4) Repeat until stability reached

Results – ARCA data

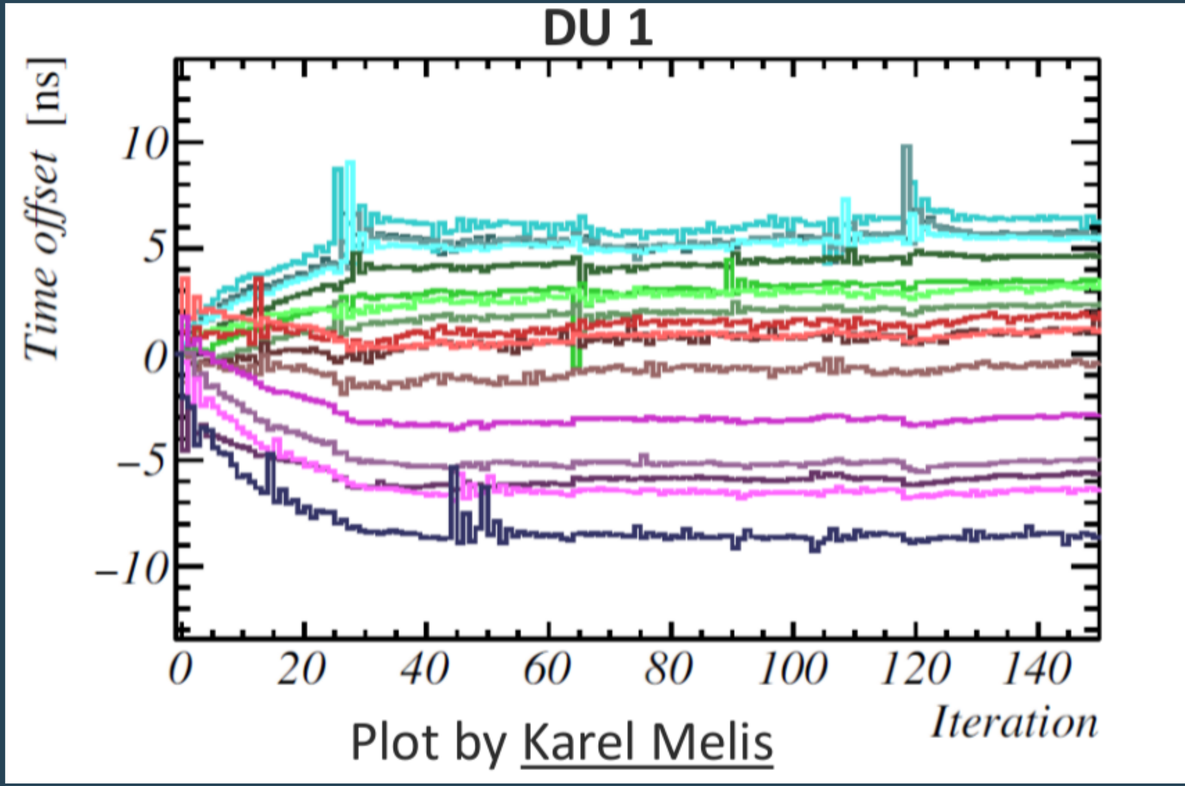


ARCA DU1

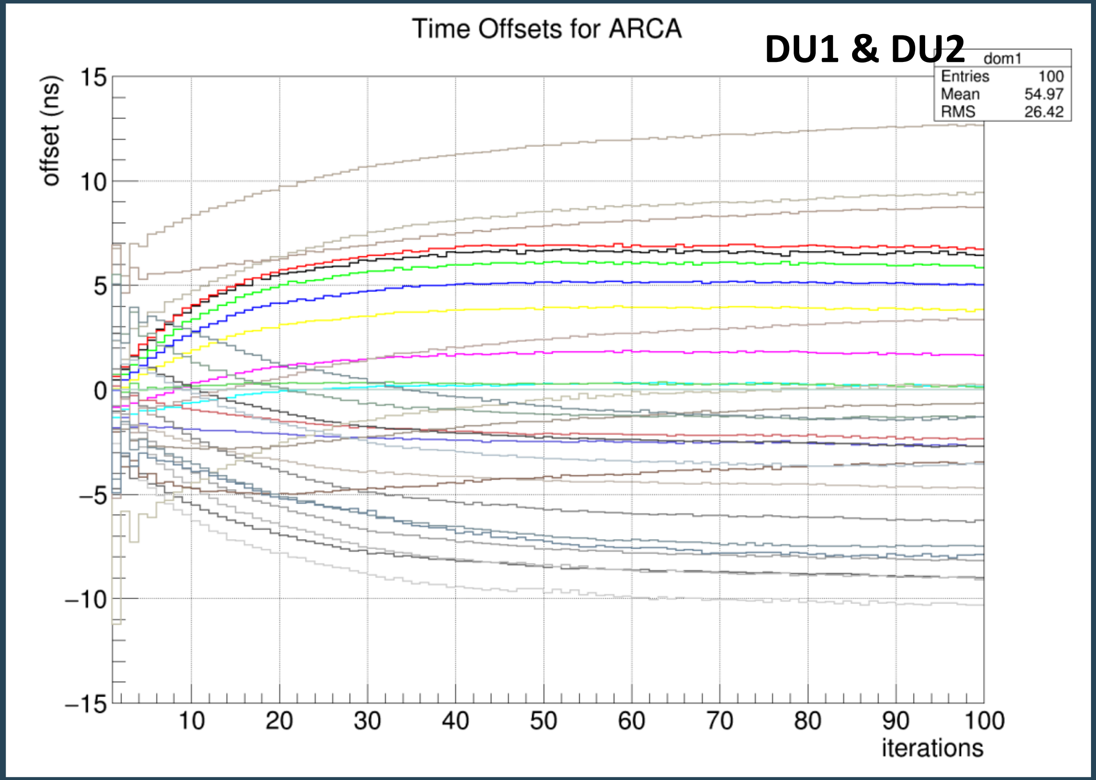
ARCA DU2



Results – Validation



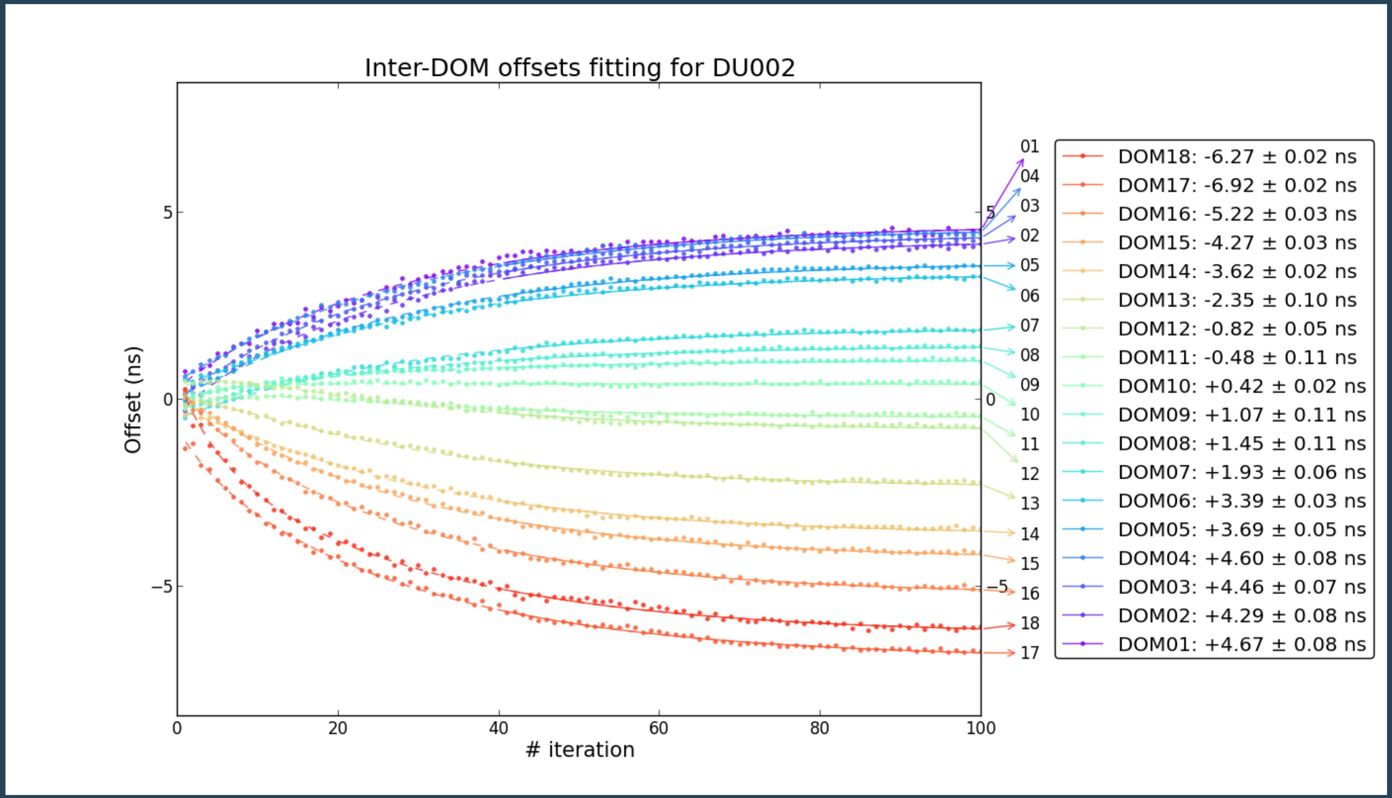
Offsets with MC - based strategy



Offsets with current strategy

Bumps seen with the MC – based strategy vanish

Results – ORCA data



ORCA DU2

#DOM	DU002
1	+4.5
2	+4.1
3	+4.3
4	+4.4
5	+3.5
6	+3.3
7	+1.9
8	+1.4
9	+1.1
10	+0.5
11	-0.4
12	-0.7
13	-2.2
14	-3.5
15	-4.1
16	-5.0
17	-6.7
18	-6.1
OFFSETS (ns)	

Convergence reached after 60 iterations

Summary & Scope

- An in-situ calibration strategy, derived from ANTARES
- No MC input required
- Stable inter-DOM offsets computed for ARCA & ORCA with faster convergence
- Good agreement in general with the MC-fit based strategy and nano-beacon calibration

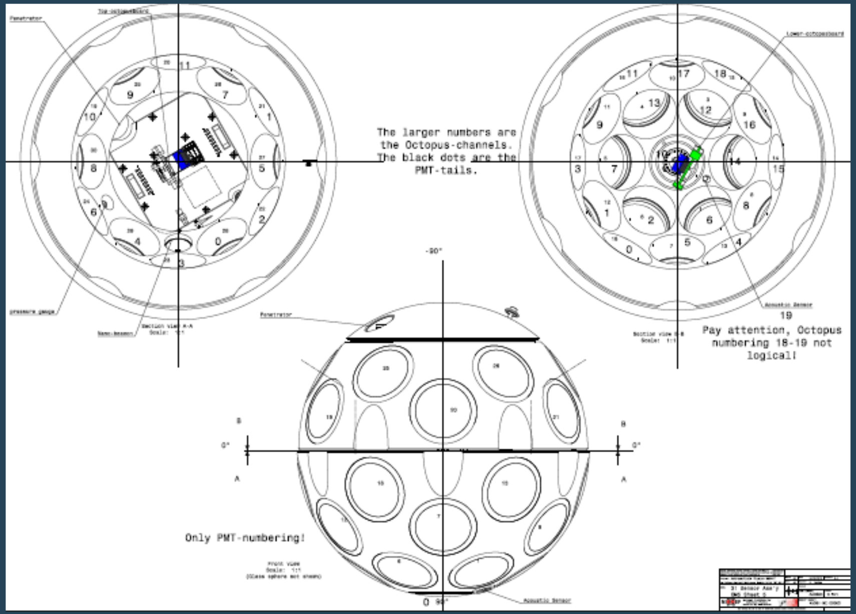
Summary & Scope

- Study evolution of offsets with iterations – understand limitations
- Incorporate official KM3NeT reconstruction chain
- Validate the results on MC

PMT Signal Characterization (ToTs)

ToT in KM3NeT

- *Time over Threshold (ToT):* Time spent by a PMT pulse above the pre-set threshold
- Measure of the charge deposited in a PMT
- Can be used to estimate the energy of the particle
- KM3NeT uses 3 inch PMTs – 31 in 1 DOM, arranged in rings

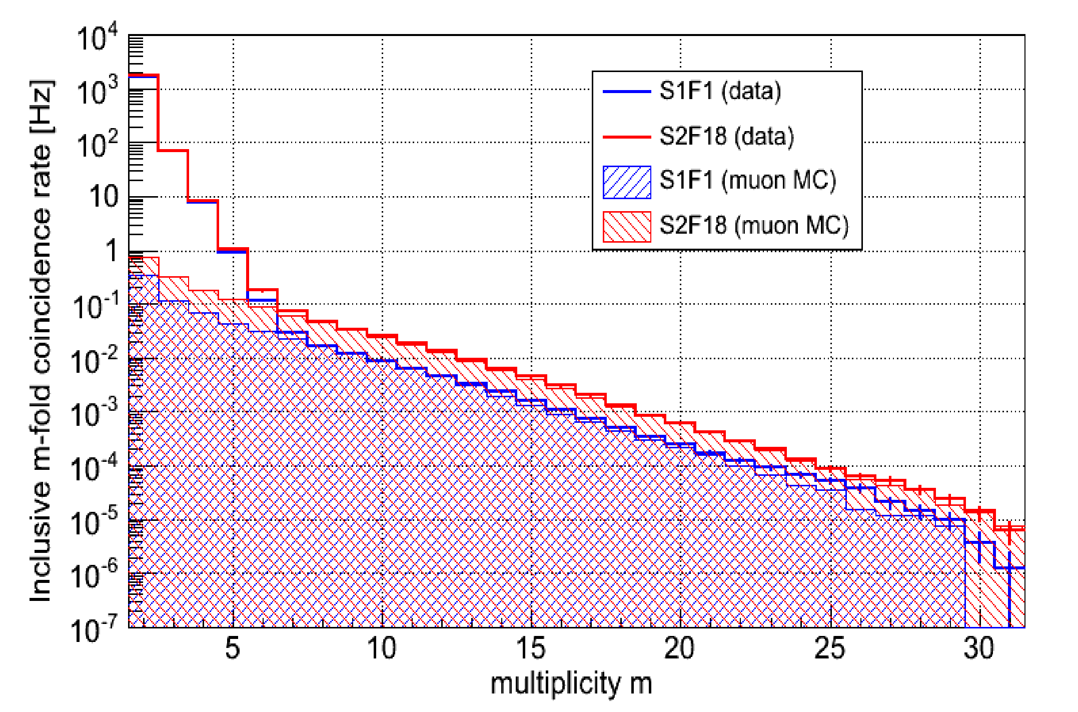


Description

- ToT signal shapes and PMT rates analysed for DOMs of ARCA DU1 and DU2, with muonic data
- Filter applied to identify atmospheric muons
- Filter based on *multiplicity* of L1 hits
  - L1 hit -> Two or more hits on DOM within a 25 ns window
- Strategies for defining *multiplicity*:
  1. Multiple hits allowed per PMT
  2. Only one hit per PMT
  3. Only one hit per PMT and HRV frame rejection
- Statistics: ~ 9.5 days of data

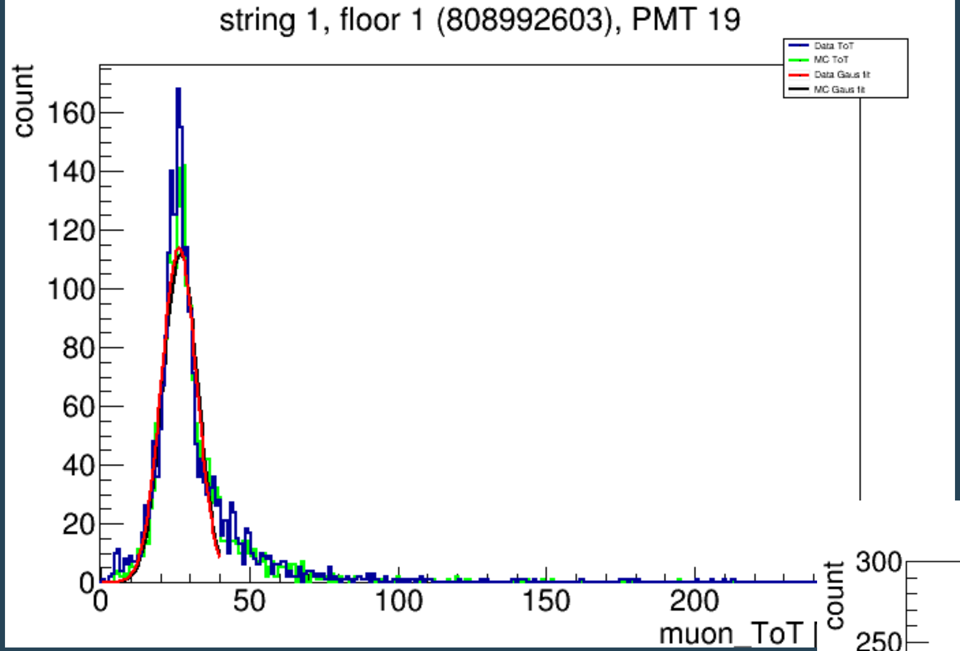
Muon filter

- 8-fold inclusive multiplicity or higher sufficient to filter background



Plot Credits: Maarten Jongen

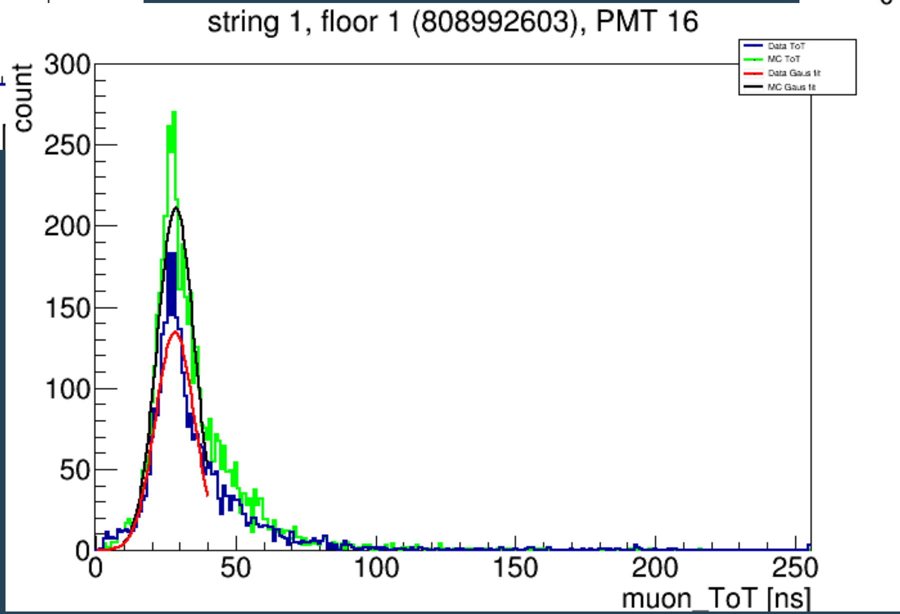
ToT Shapes

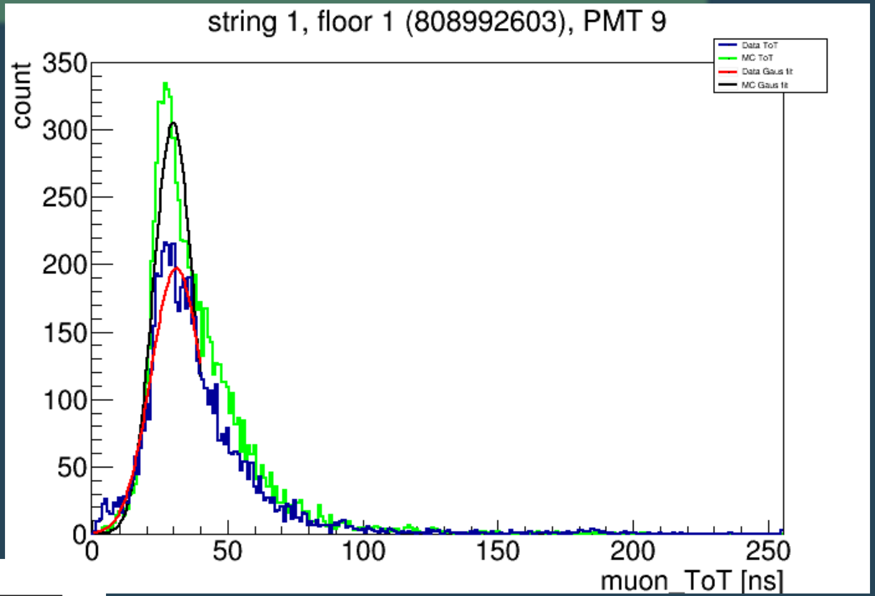


(Lower hemisphere PMT)

S1F1

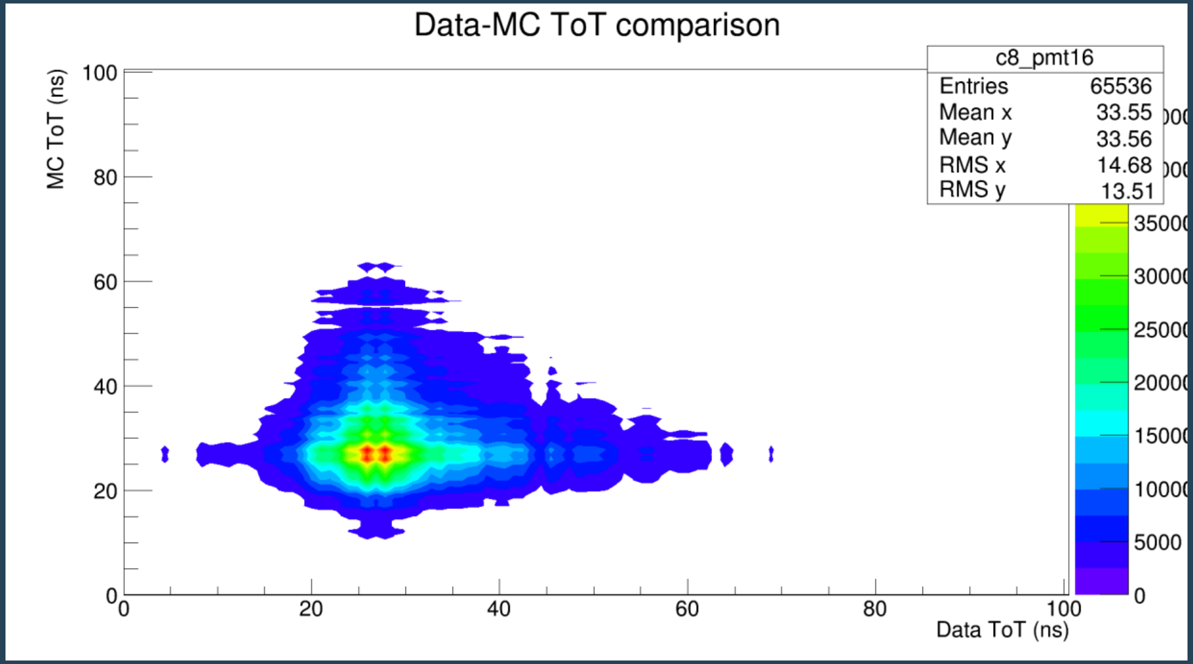
(Equatorial PMT)



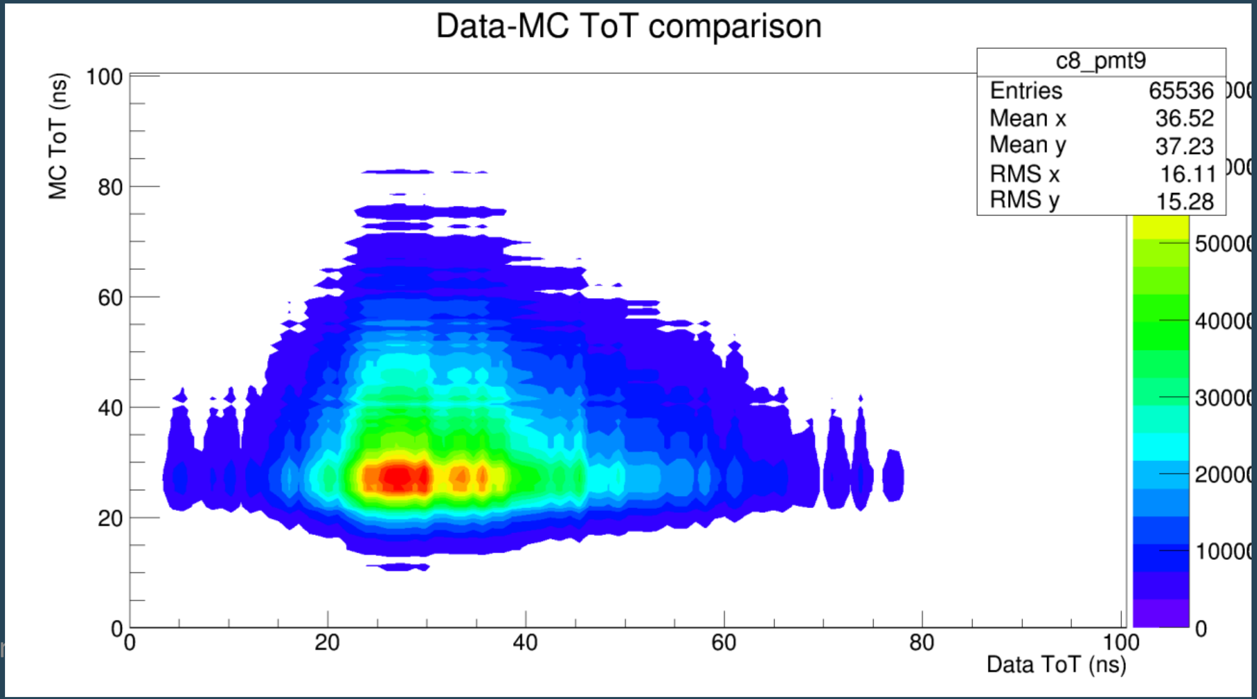


(Upper hemisphere PMT)

Data-MC Correlation: ToT distributions

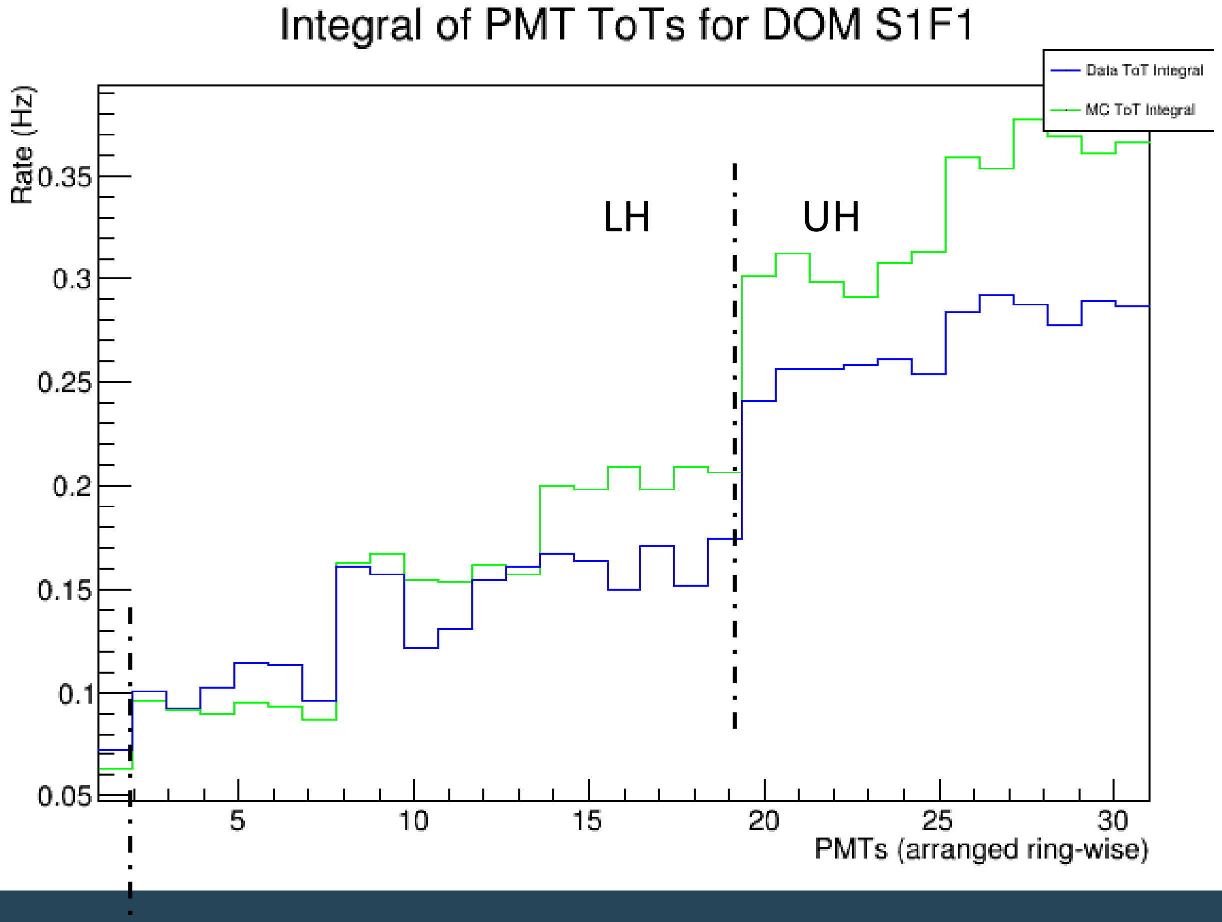


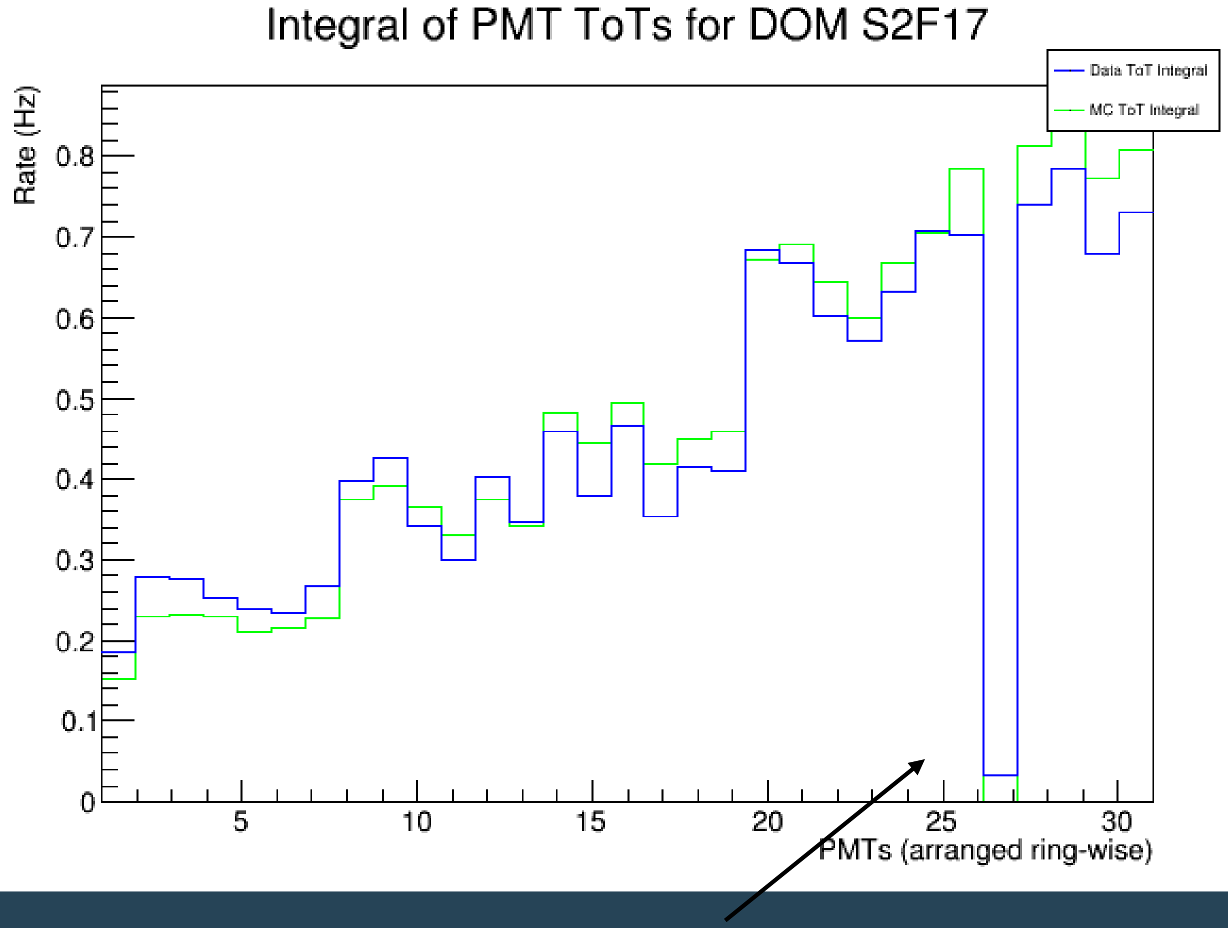
S1F1



No sign of a 2nd p.e. peak in distributions

PMT Rates





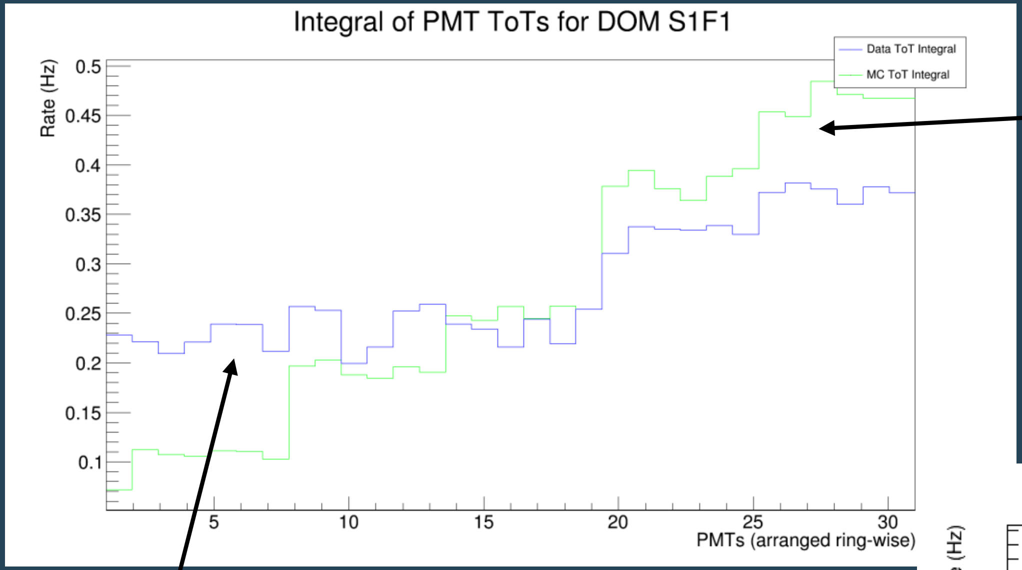
Downward facing

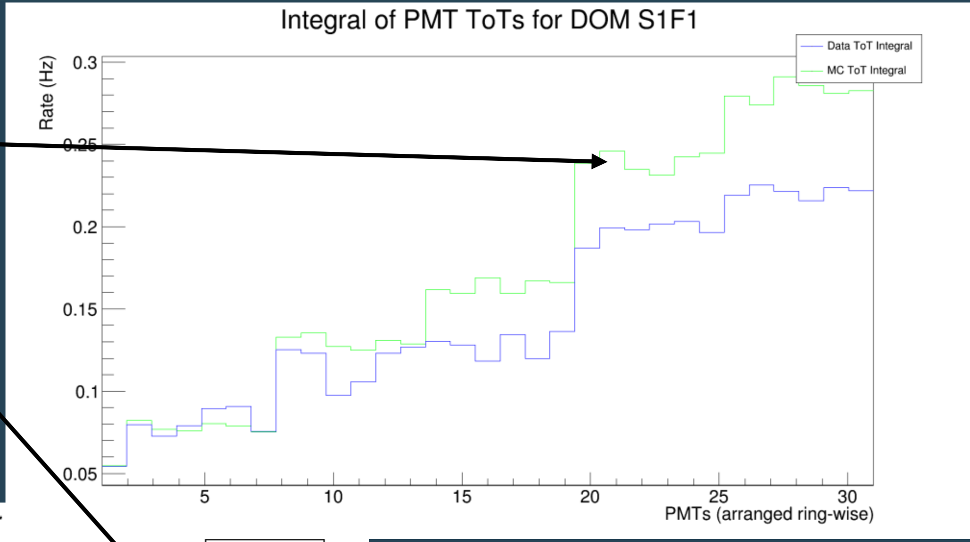
Bad PMT no. 4

Changing *multiplicity*

7, 8 and 9 fold inclusive

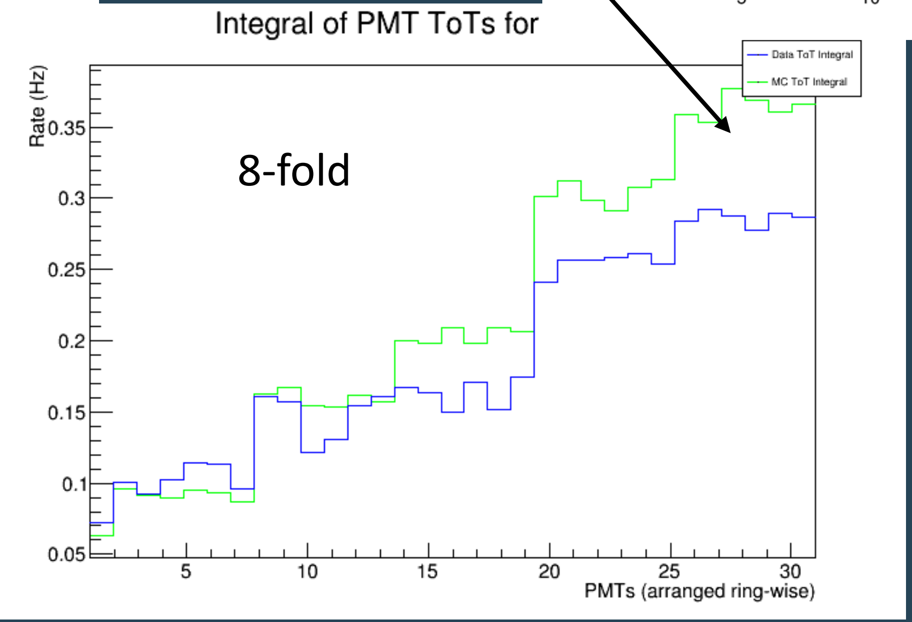
Rates





More MC

S1F1



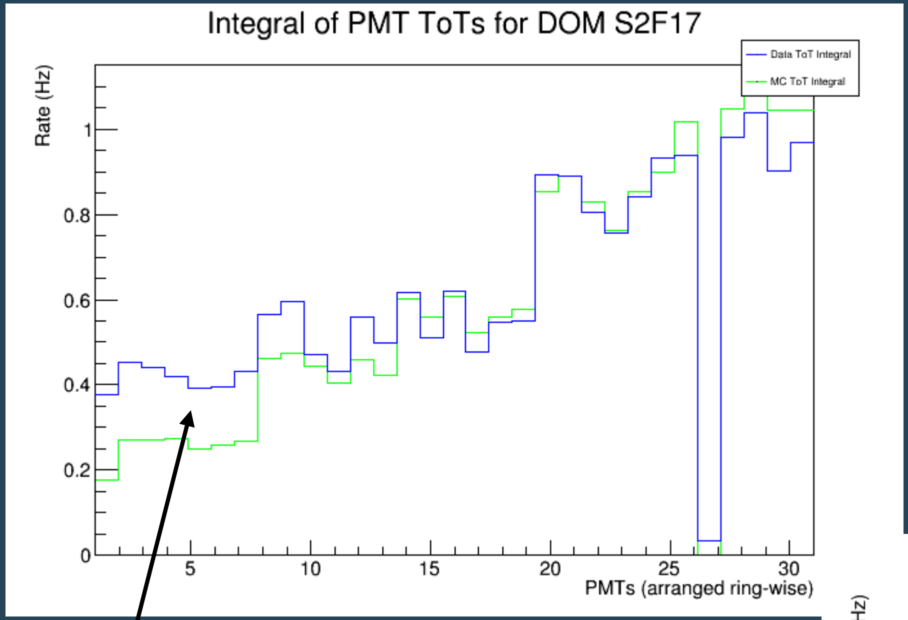
7-fold

9-fold

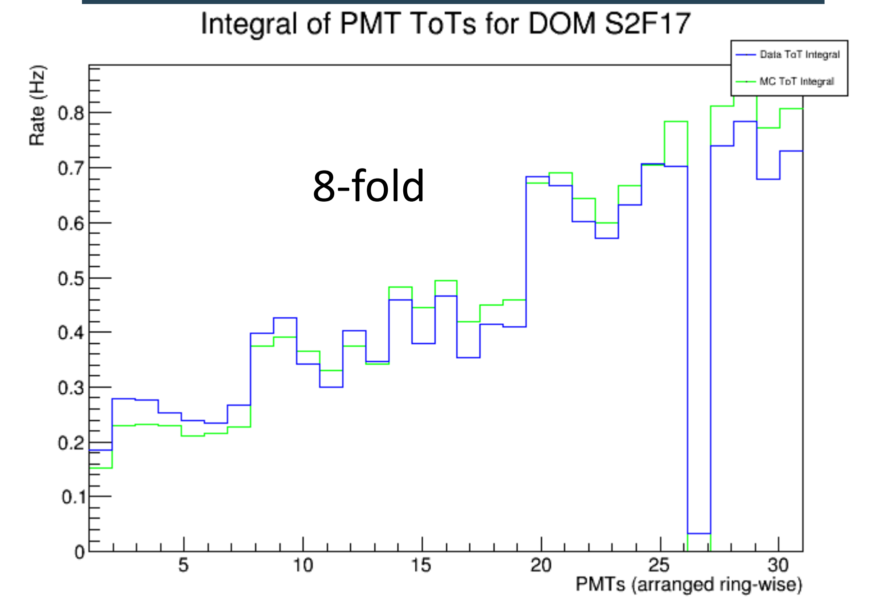
More data in the lower half of DOM

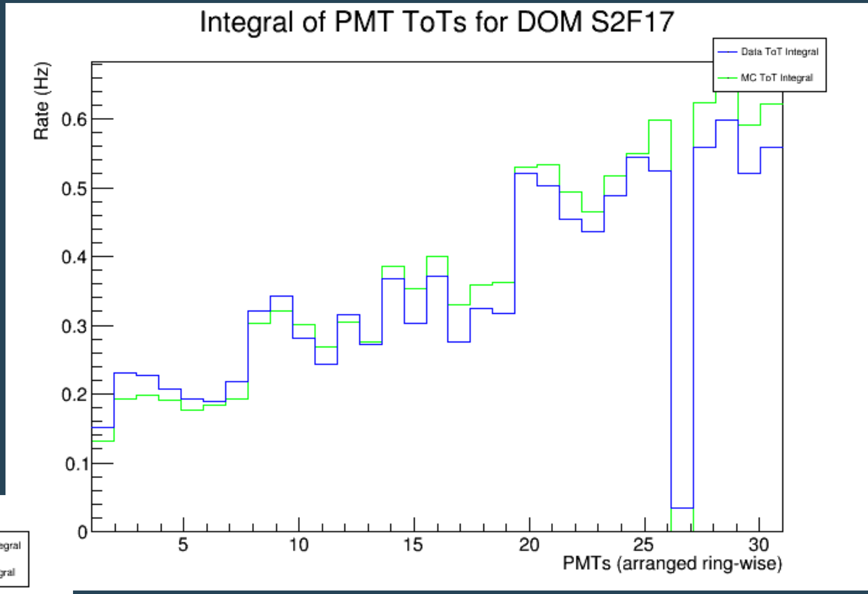
For 8 and 9 fold, data rate no more higher in the lower half but MC rate still higher in the upper half

Rates



S2F17





7-fold

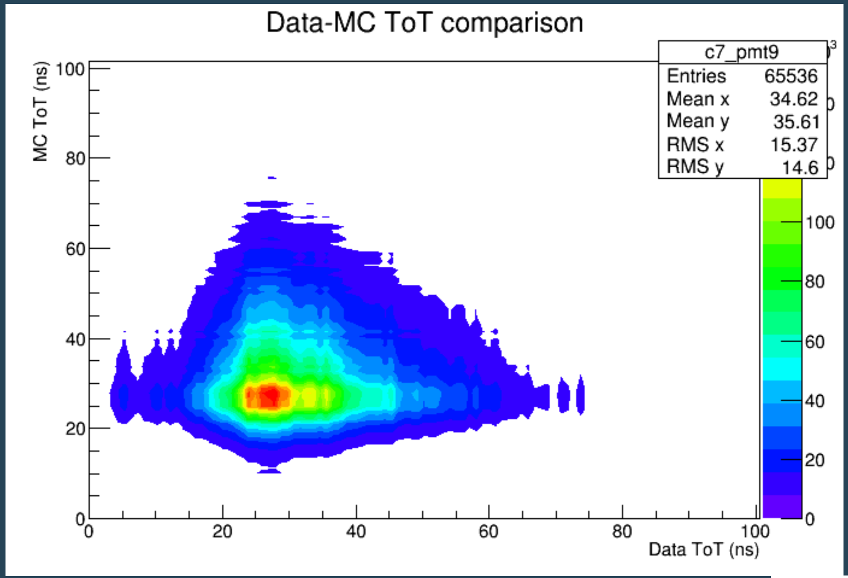
8-fold

9-fold

More data in the lower half of DOM

For 8 and 9 fold, data and MC rates in the upper half in agreement

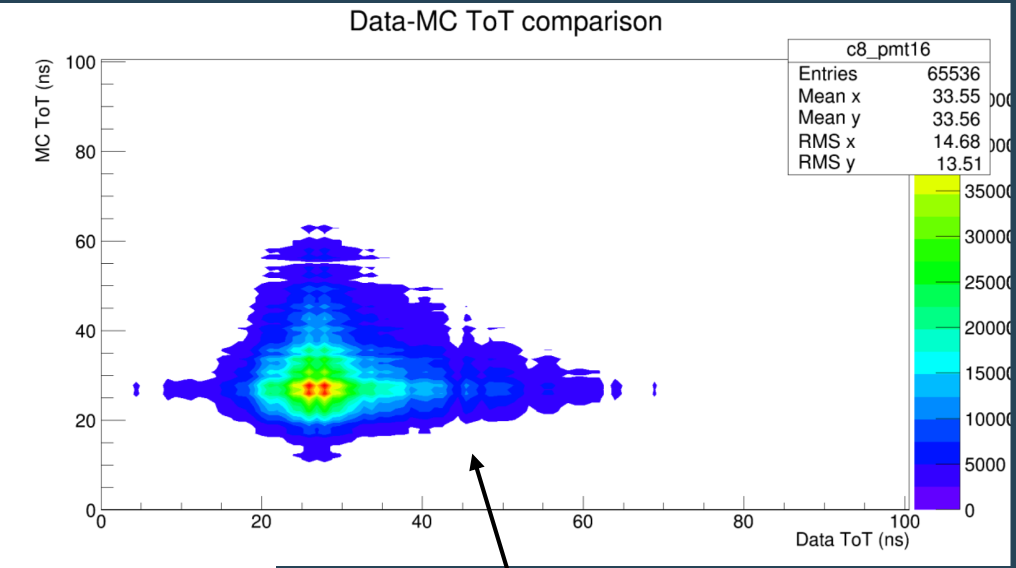
Data-MC Correlation

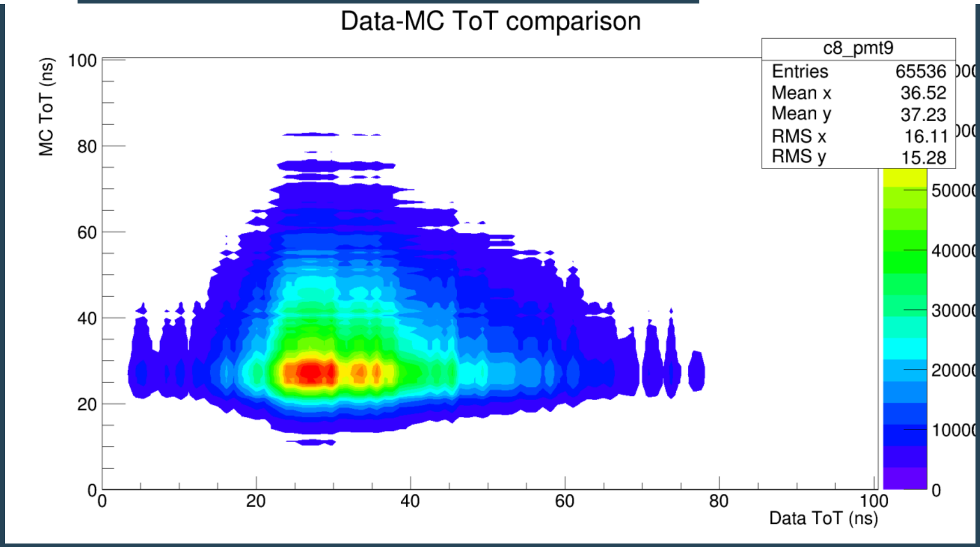


7-fold

S1F1

8-fold





9-fold

Data and MC distributions more pronounced at high multiplicity

Summary

1. ToT shapes of data and MC are compatible at high multiplicities
2. No sign of a 2^{nd} photo-electron peak evident, even at higher multiplicities
3. The first p.e. peaks stable to within 4 ns for both data and MC, across DOMs, when a filter for atmospheric muons is applied
4. For lower multiplicities, PMTs in the lower rings of the lower hemisphere of DOMs show signs of background contamination
5. For higher multiplicities, the upper hemisphere PMTs of the DOMs have an excess of MC over data. Trend vanishes upon moving from the bottom to the top of the DU
6. Data-MC discrepancy can be explained if MC does not take into account the depth dependence of muon events in the detector, due to which DOMs lower down the detector see less muon events

Future Perspectives

- Objectives achieved:
  - ✓ Select a sample of sources of candidate sources for VHE neutrinos
  - ✓ Study their long-term behaviour and identify major flares in gamma
  - ✓ Calculate gamma-ray duty cycles to quantify the flares
  - ✓ Estimate neutrino emission from these sources

Future Prospectives

- Coming up……..
  - Study the selected flares in X and radio
  - Calculate time-dependent sensitivities of KM3NeT ARCA for the specific source positions
  - Source modelling – Best fit models to obtain source parameters
  - Obtain an estimate of the cumulative neutrino emission from the two classes of blazars – BL-Lacs & FSRQs

- All relevant neutrino alerts during the thesis period will be followed up

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- N.K. Chowdhury – Collaborator (KM3NeT)
- Dr. Agustin Sanchez Losa – Collaborator (KM3NeT)

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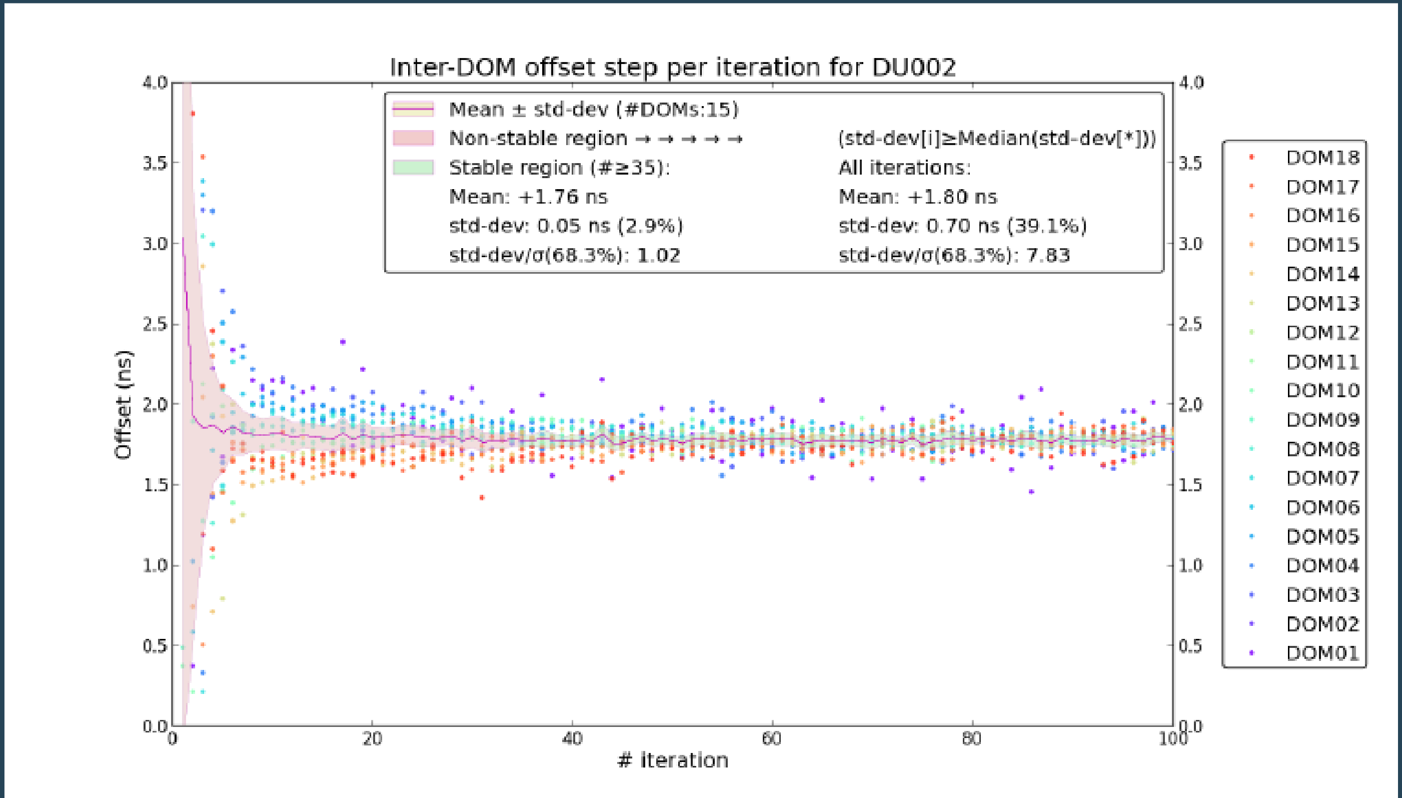
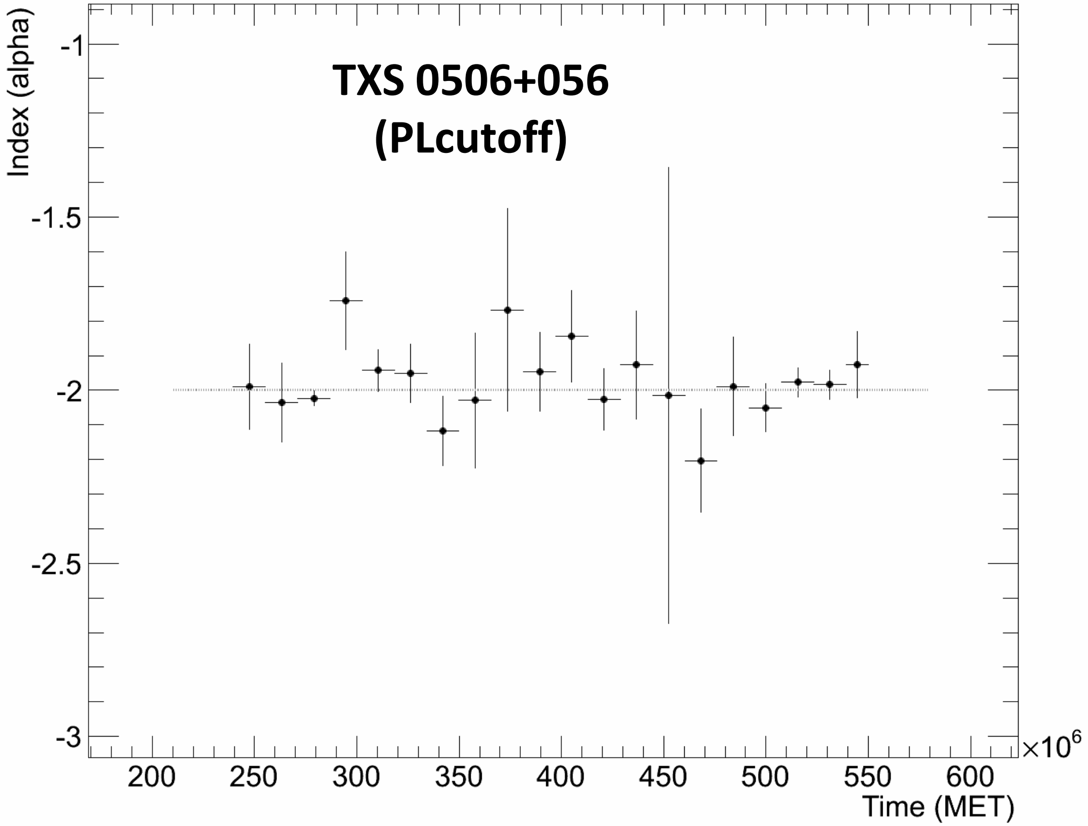
BACKUP SLIDES

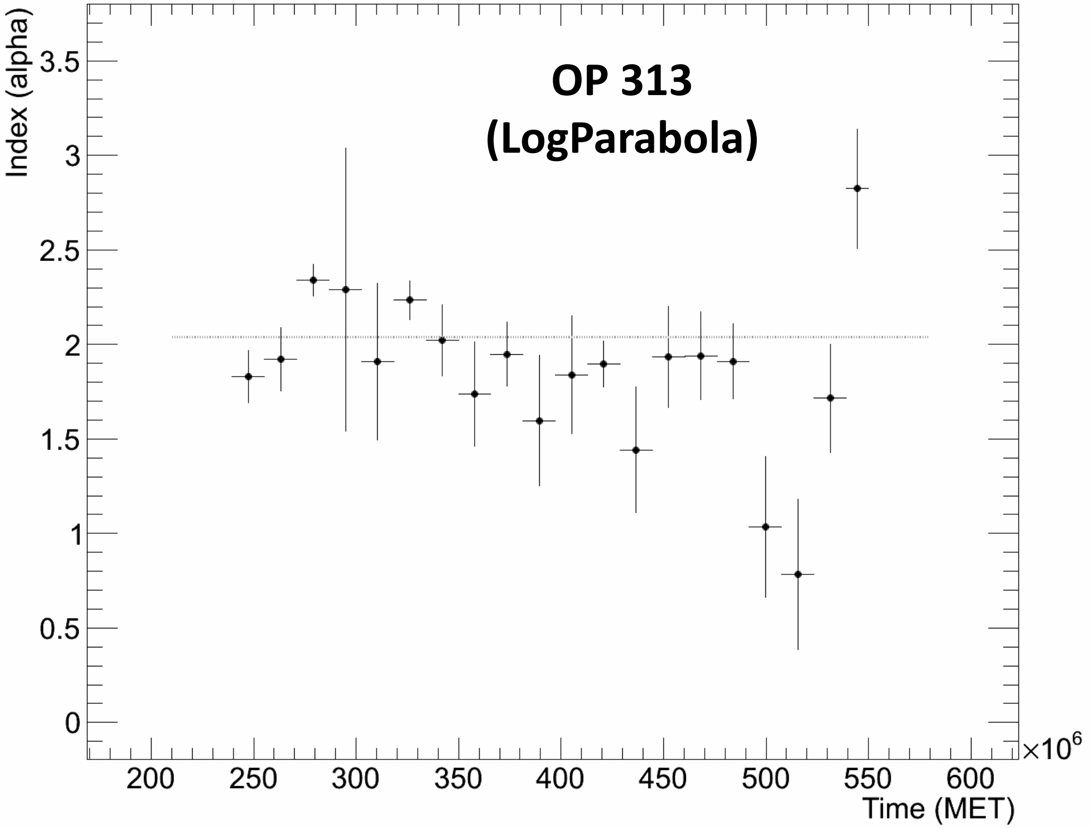
Results – Evolution of Offsets



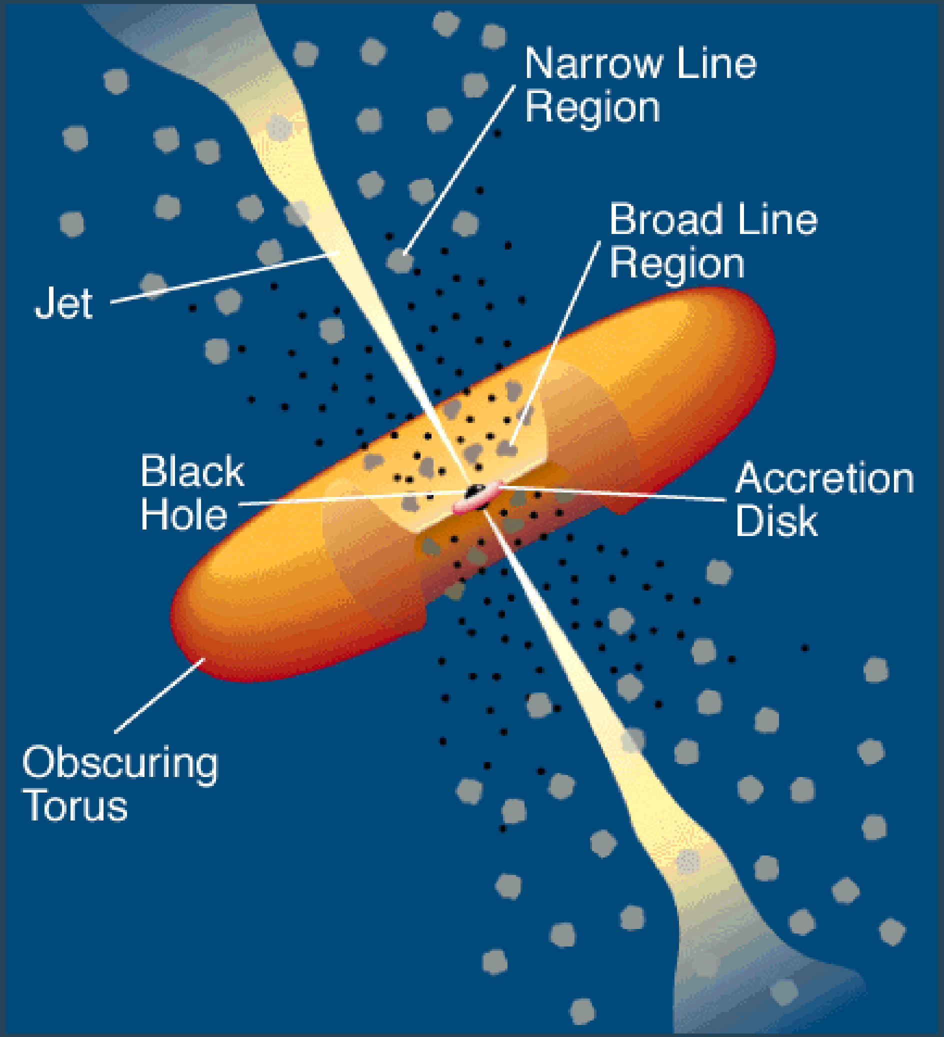
ORCA DU2

Index Variation

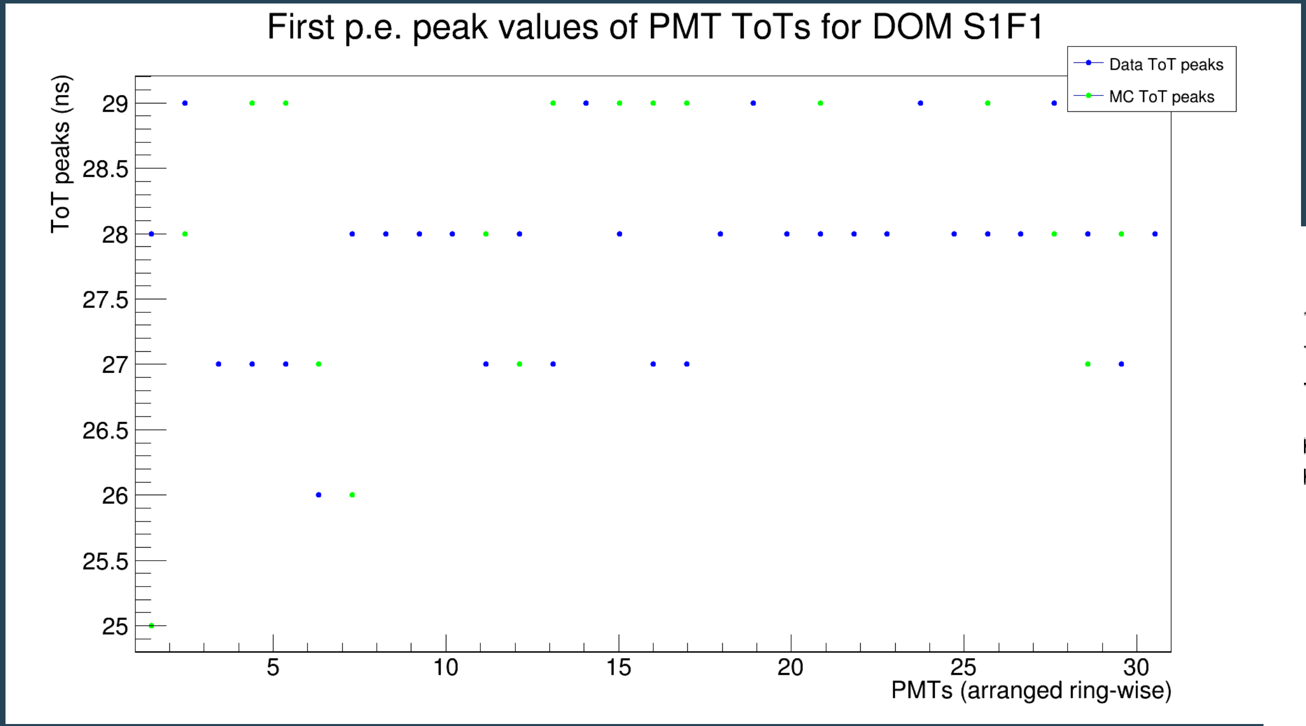


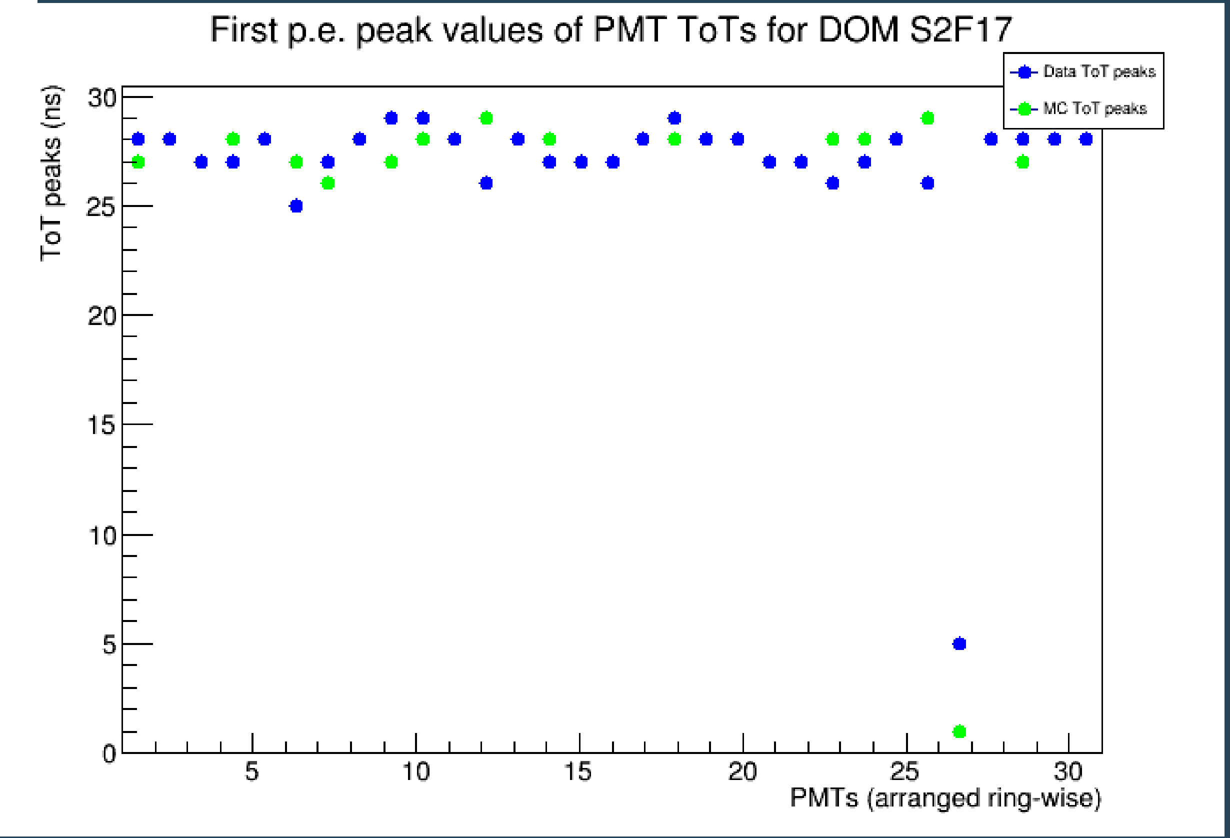


Emission from Blazar



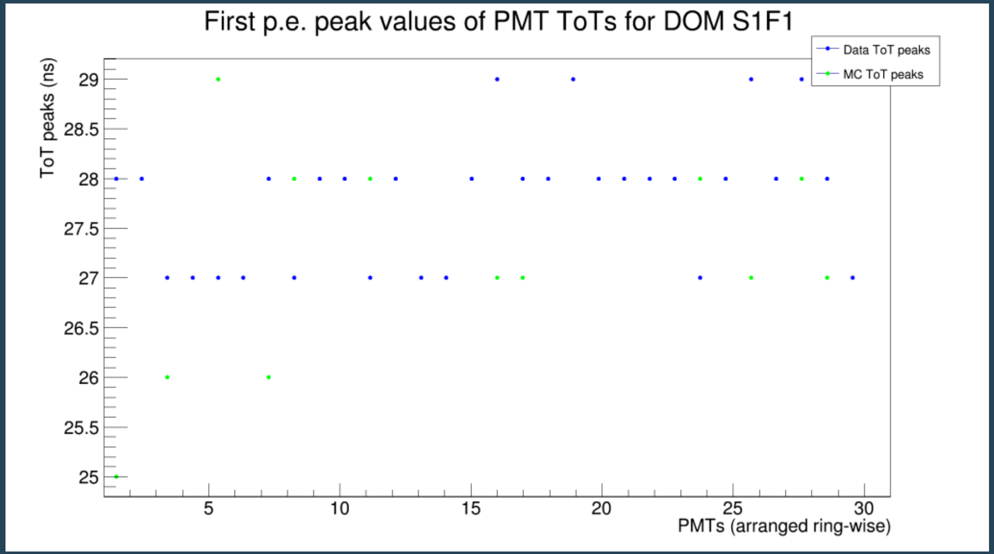
1st p.e. peaks across DOMs





Variation of 1st peak position in the range of ~4 ns for both data and MC

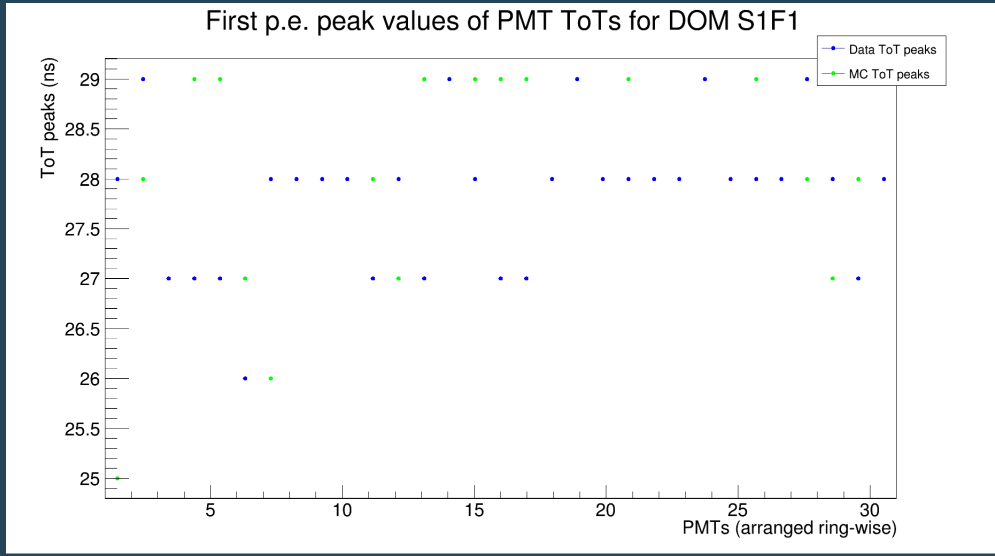
1st p.e. Peak Values



7-fold

S1F1

8-fold



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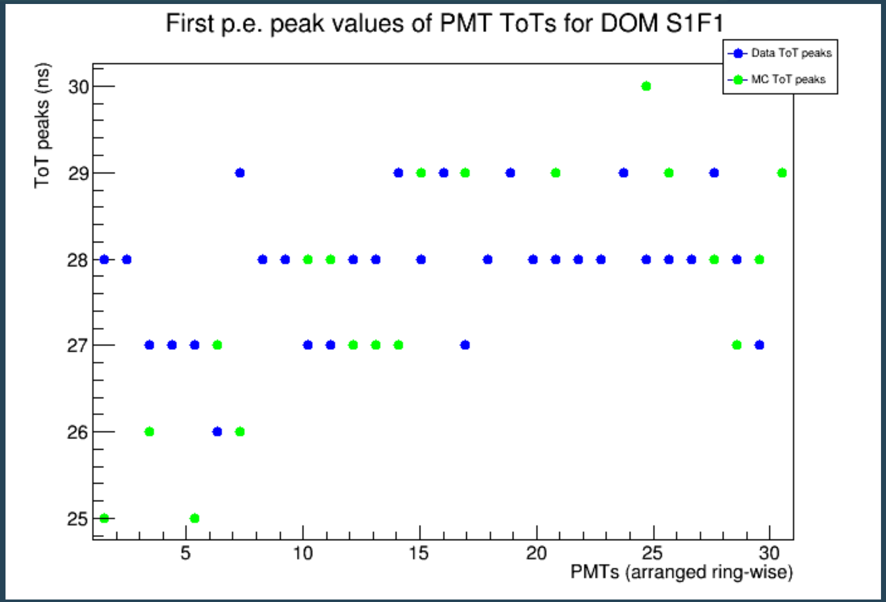
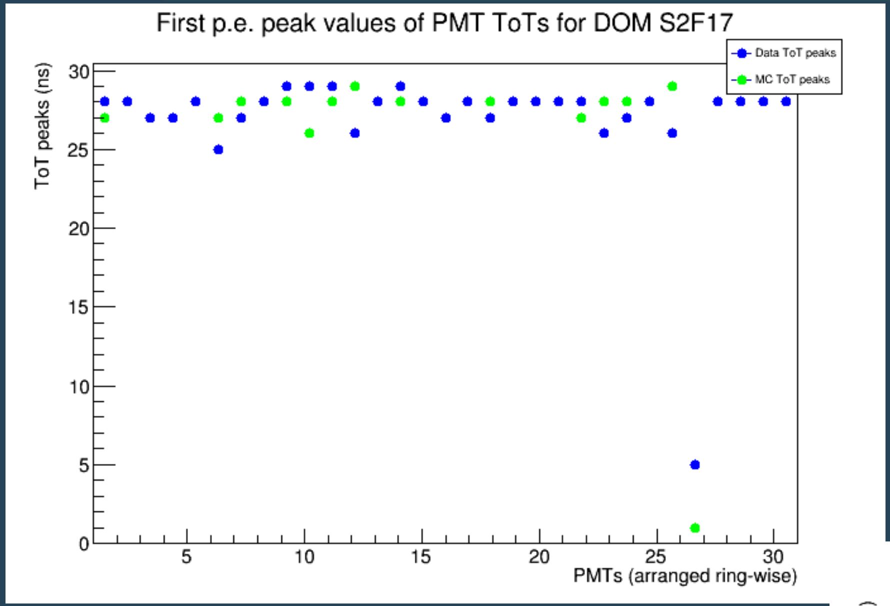


The peak values move slightly with change in multiplicity

1st p.e. Peak Values



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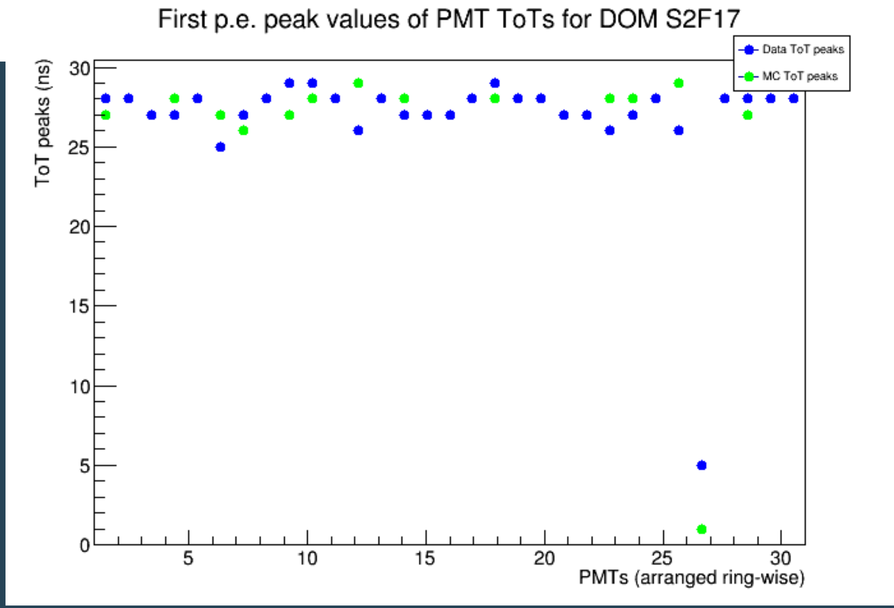

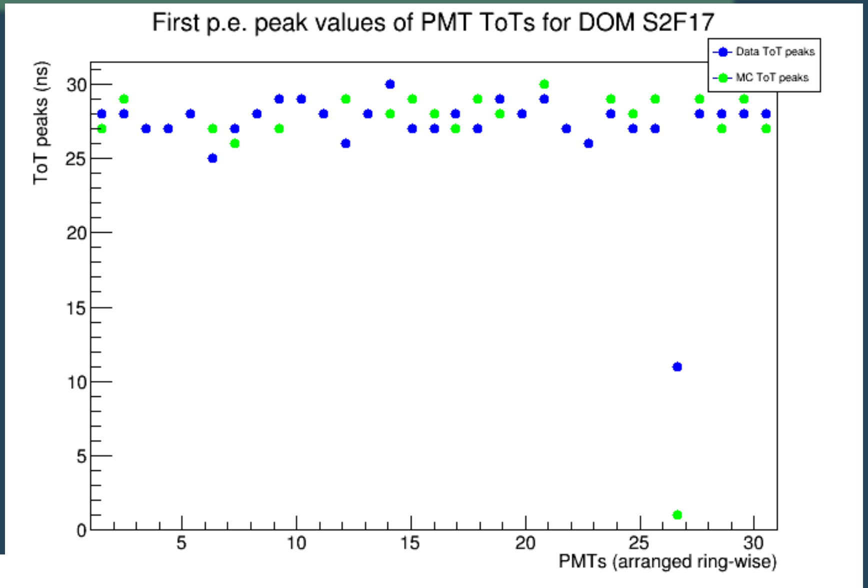

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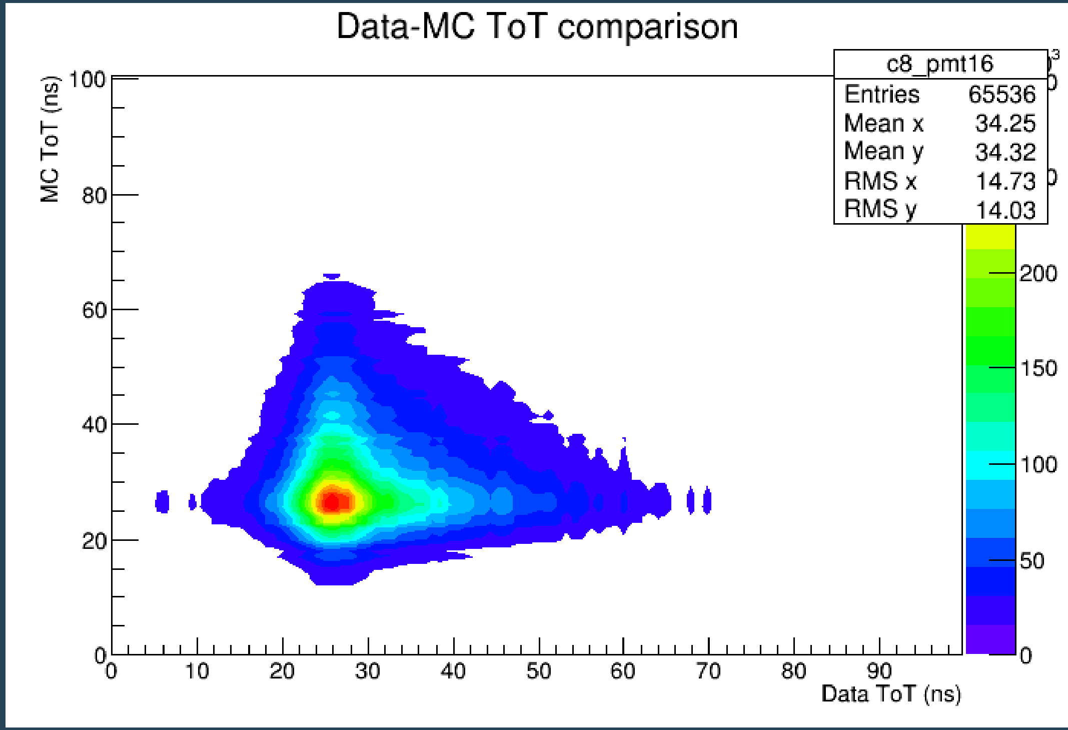
Data-MC Correlation



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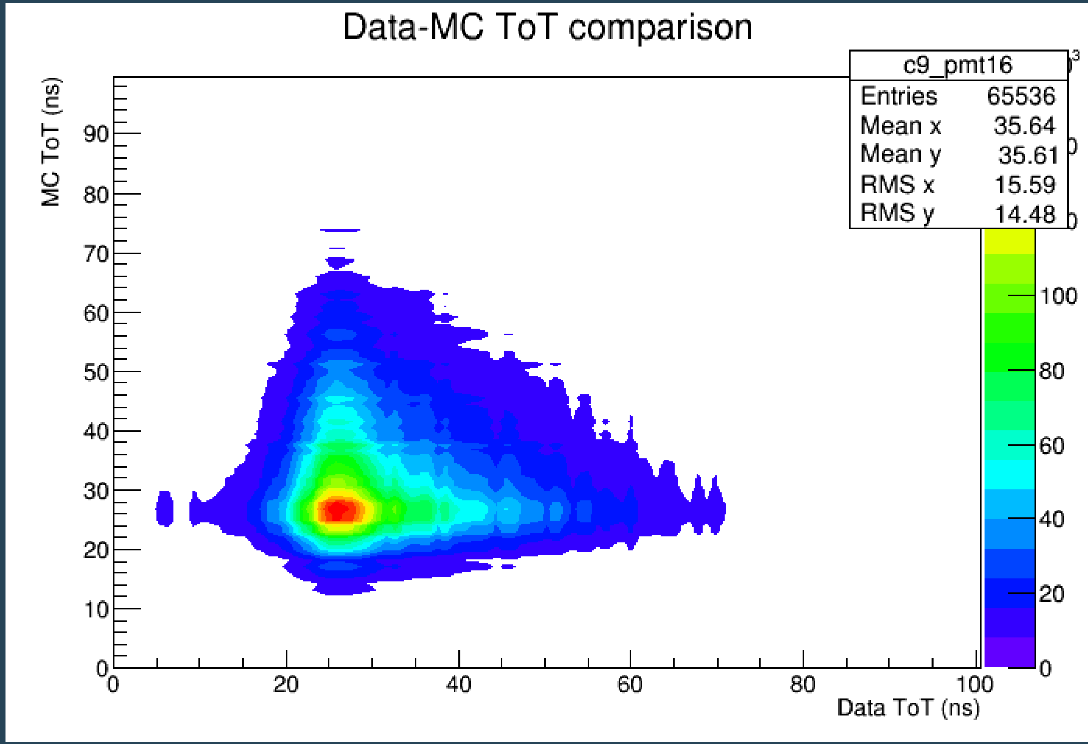

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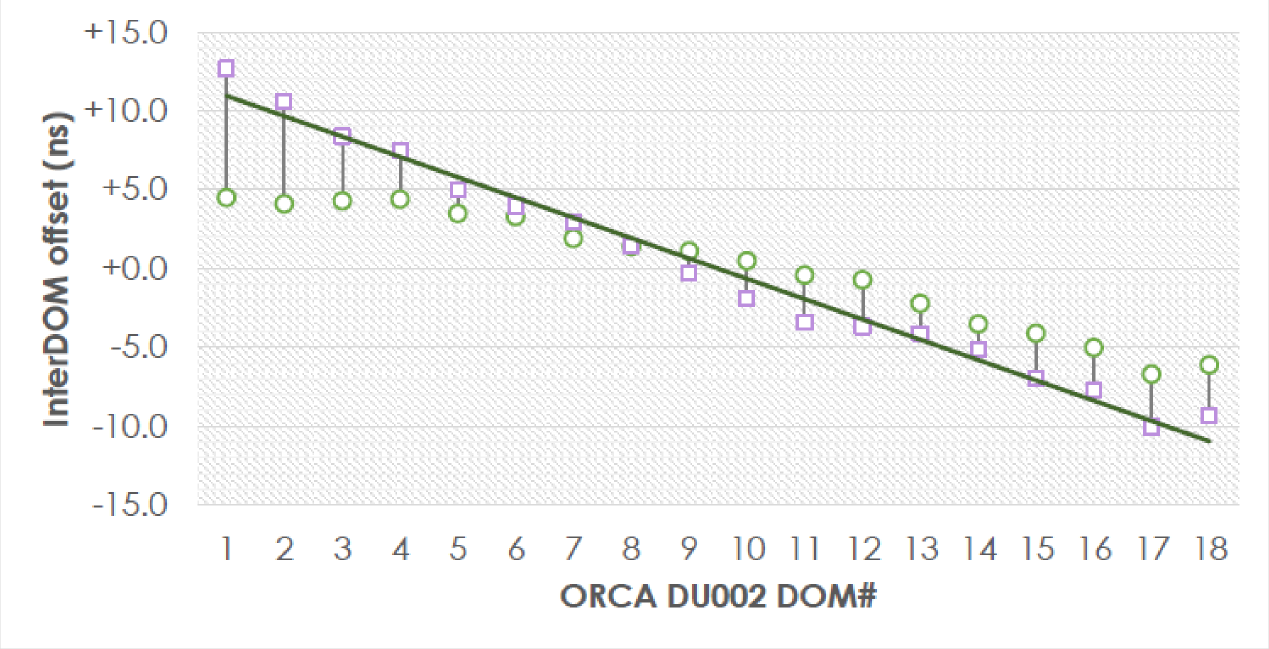
S1F1

Results – Comparison with Nanobeacons

#	Offset (ns)		
	w/o MC	NB	DIFF
1	+4.5	+12.7	**-8.2**
2	+4.1	+10.6	**-6.5**
3	+4.3	+8.4	**-4.1**
4	+4.4	+7.5	**-3.1**
5	+3.5	+5.0	**-1.5**
6	+3.3	+4.0	**-0.7**
7	+1.9	+3.0	**-1.1**
8	+1.4	+1.4	**+0.0**
9	+1.1	-0.3	**+1.4**
10	+0.5	-1.9	**+2.4**
11	-0.4	-3.4	**+3.0**
12	-0.7	-3.7	**+3.0**
13	-2.2	-4.1	**+1.9**
14	-3.5	-5.2	**+1.7**
15	-4.1	-6.9	**+2.8**
16	-5.0	-7.7	**+2.7**
17	-6.7	-10.0	**+3.3**
18	-6.1	-9.3	**+3.2**
ORCA-DU2			



Muon method may suffer from some bias on lower DOMs

The EBL: Extragalactic Background Light

- Diffuse extra-galactic background of light
- IR, optical, UV
- Creates opacity for high-energy CR and photons
- Redshift dependent