Neutrino and gamma-ray astronomy in the era of multi-messenger astrophysics

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LPNHE Seminar

March 20th, 2023

cnrs
SORBONNE UNIVERSITÉ
LPNHE PARIS
l'Observatoire de Paris

Cosmic Messenger Connection

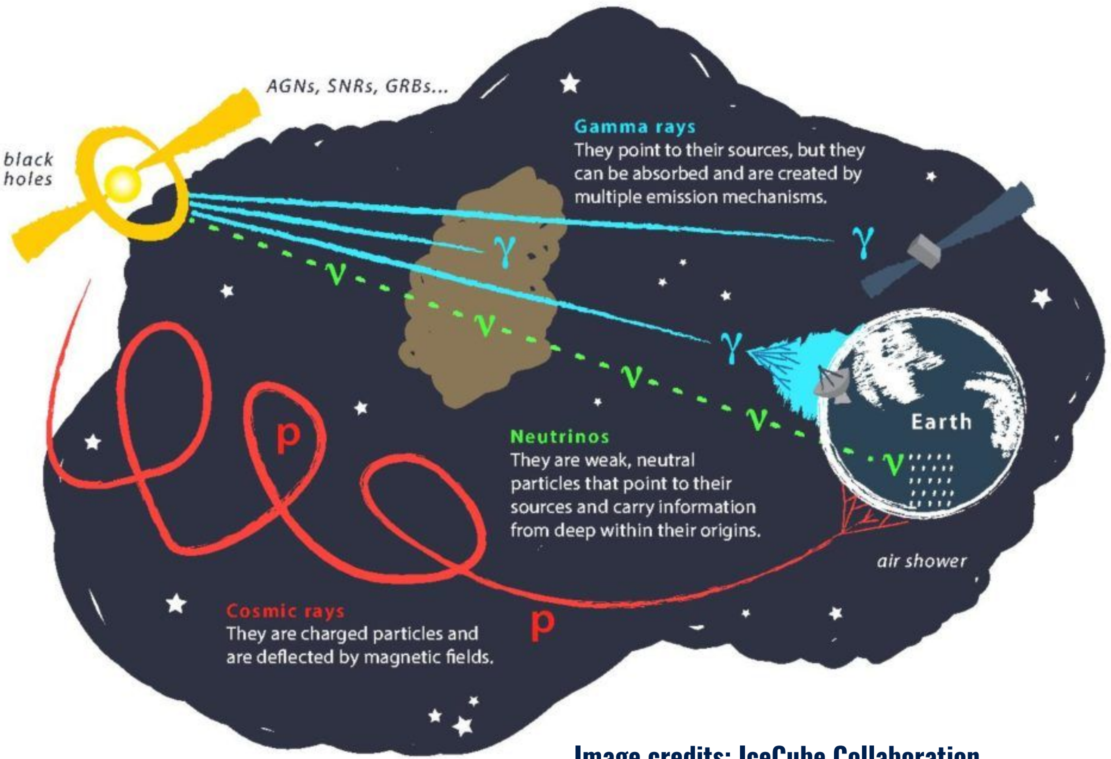
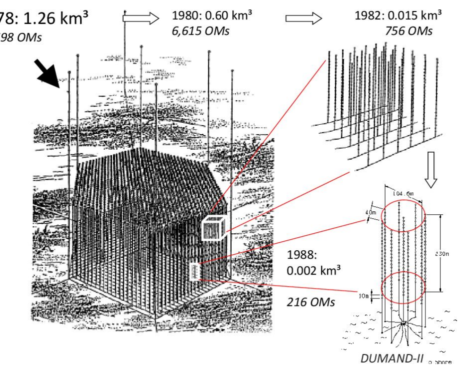


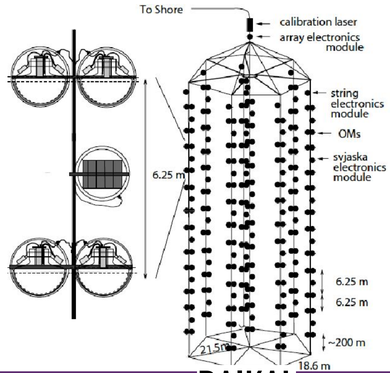
Image credits: IceCube Collaboration

A neutrino/gamma-ray connection is expected if hadronic processes occurs in astrophysical sources (such as AGN)

Neutrinos are considered ideal cosmic messengers and 'smoking gun' for hadronic interactions

Neutrino Telescopes Timeline





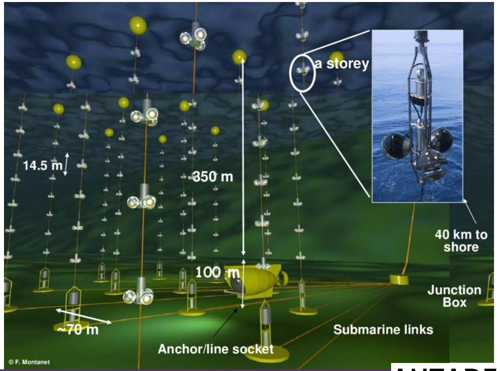


Image credits:
A. Rosales de León

DUMAND
(1973-1995)

BAIKAL
1980s

ANTARES
(2002-2008)

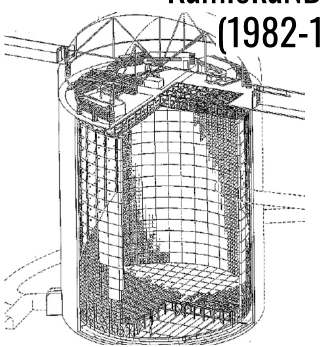
1970 1980 1990 2000 2010 ....

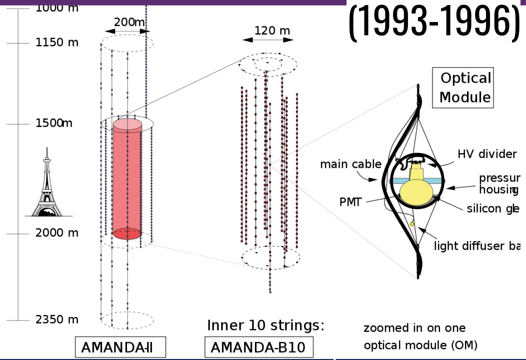
KamiokaNDE I and II
(1982-1988)

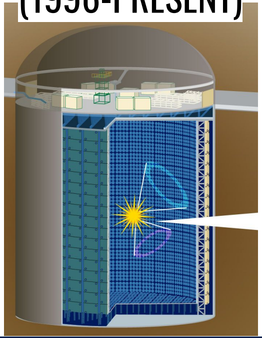
AMANDA
(1993-1996)

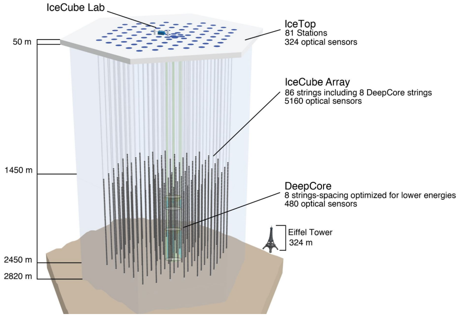
SUPER-K
(1996-PRESENT)

ICECUBE
(2005-PRESENT; COMPLETED 2011









Gamma-ray Timeline

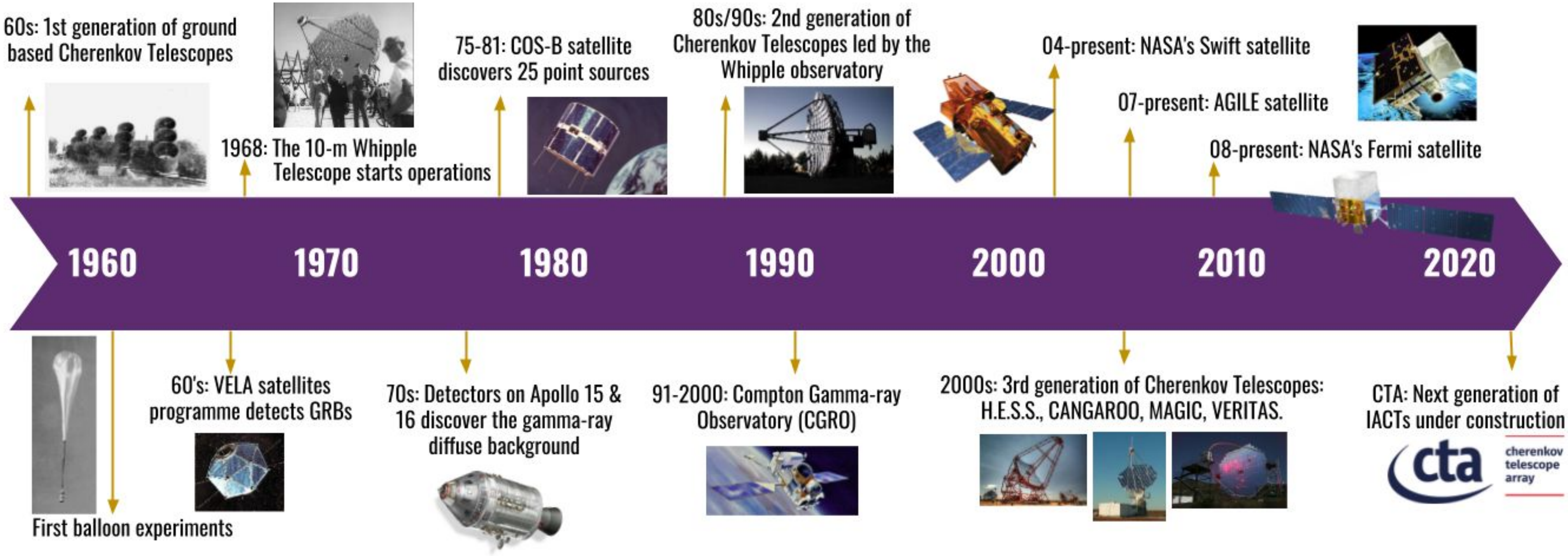
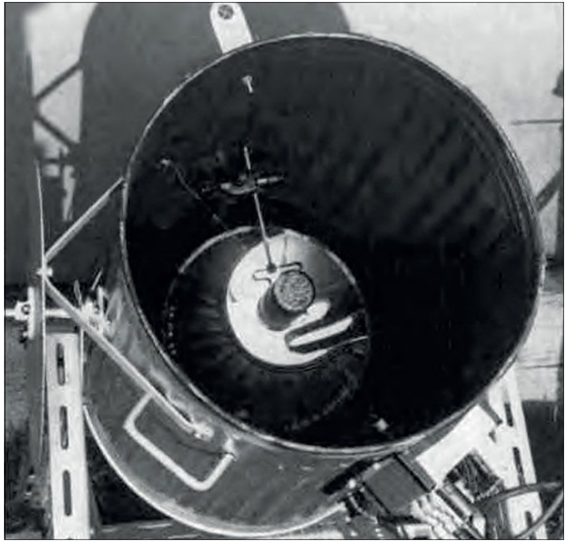


Image credits: A. Rosales de León

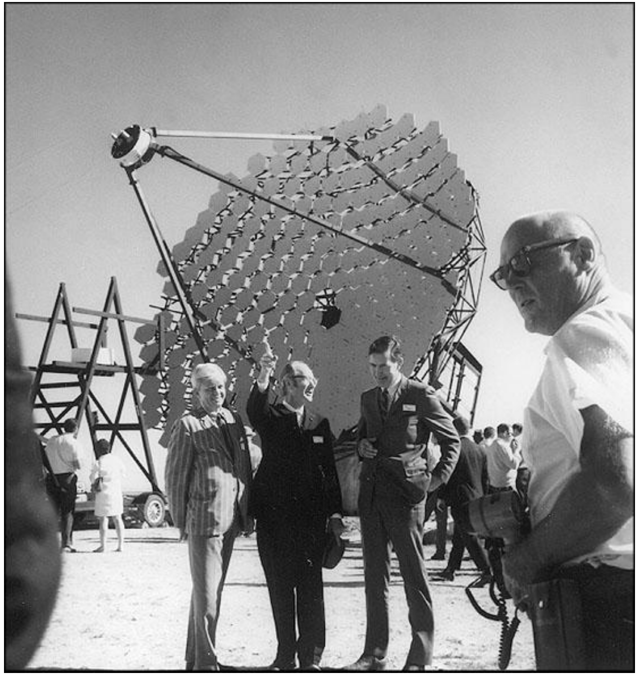
Gamma-ray observatories/detectors around the world

Locations of the current operating (blue spots) and future (green spots) gamma-ray observatories around the world, including SGSO (yellow ellipse). While VERITAS, H.E.S.S., MAGIC and CTA are IACTs; HAWC, TIBET, TAIGA, LHAASO and the proposed SGSO are based on particle detector arrays. Image credit: W. Hofmann (Talk at TeVPA2018).



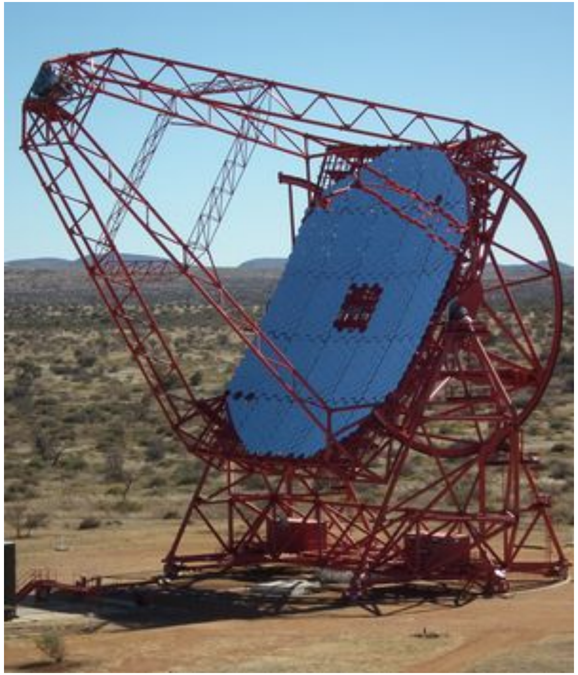
The first Cherenkov detector used by B. Galbraith and J. V. Jelley in 1953. A 25-cm parabolic mirror with a PMT attached at the focus inside a garbage can.

Image credit: Jelley (1987).



Fred Whipple at Mount Hopkins Observatory's opening day in 1968.

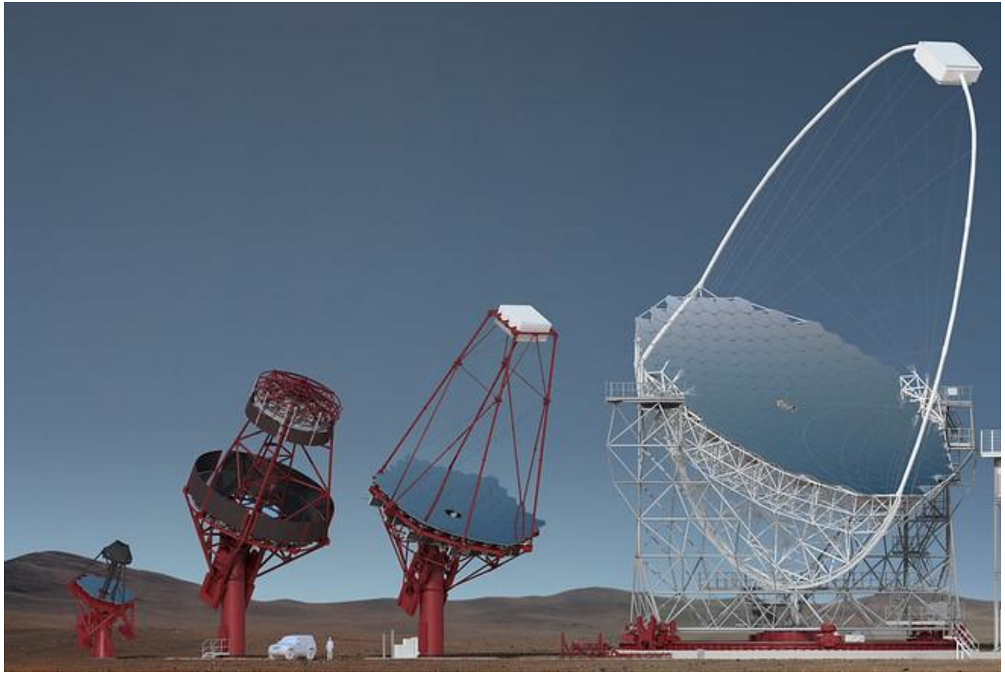
Image credit: Whipple Observatory.



H.E.S.S-II is the largest Cherenkov telescope ever built (up to date), with a 28-metre-sized mirror.

Image credit: H.E.S.S. collaboration.

CTA is coming....



Schematics of the 3 different telescope sizes developed for CTA. From left to right: Small-Sized Telescopes (SSTs), Medium-Sized Telescopes (MSTs), and Large-Sized Telescopes (LSTs). For the MSTs, 2 designs are being built and tested. Image credit: CTA consortium

	LSTs	MSTs/SCTs	SSTs
Energy range	20 GeV - 3 TeV	80 GeV - 50 TeV	1 TeV - 300 TeV
Reflector diameter	23.0 m	11.5/9.7 m	4.3 m
Effective area	370 m^2	88/41 m^2	8 m^2
Focal length	28 m	16/5.6 m	2.15 m
Field of view (FoV)	4.3°	7.5/7.7/7.6°	10.5°
Photodetector type	PMT	PMT/SiPM	SiPM
Pixels per camera	1855	1754/1855/11328	2368
Pixel size (imaging)	0.1°	0.17/0.17/0.07°	0.19°
Repositioning time (any point in the sky)	50 s	90 s	90 s
# of telescopes for CTA-N	4	15	-
# of telescopes for CTA-S	4	25	70

Technical specifications for the 3 different CTA telescope sizes. For the midle-sized telescopes, two designs are being built and tested: MST and SCT.

For further details, see: www.cta-observatory.org/project/technology/

Neutrino + Gamma-ray correlation ?

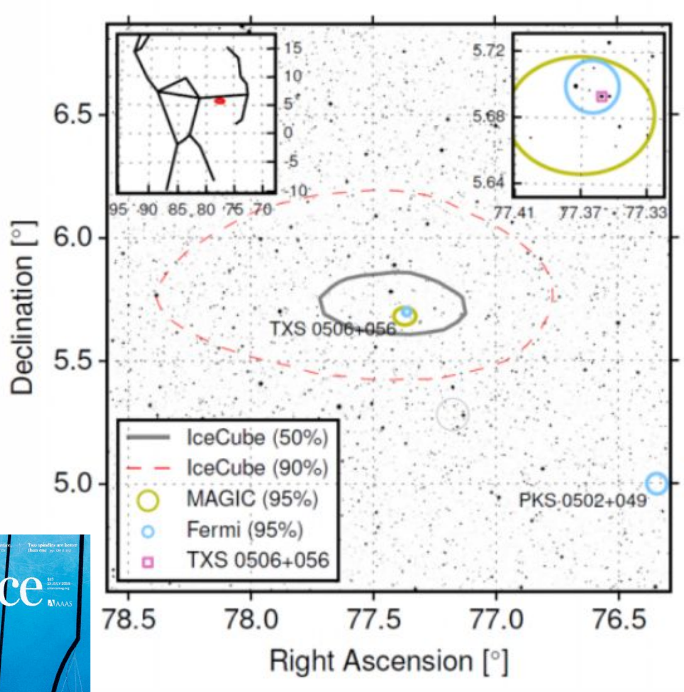
Neutrino alerts
+
Follow-up MWL Observations

- **Radio**
- **Optical and UV**
- **X-ray**
- **Gamma–ray**

Steady Neutrino sources (bright enough to be detected)

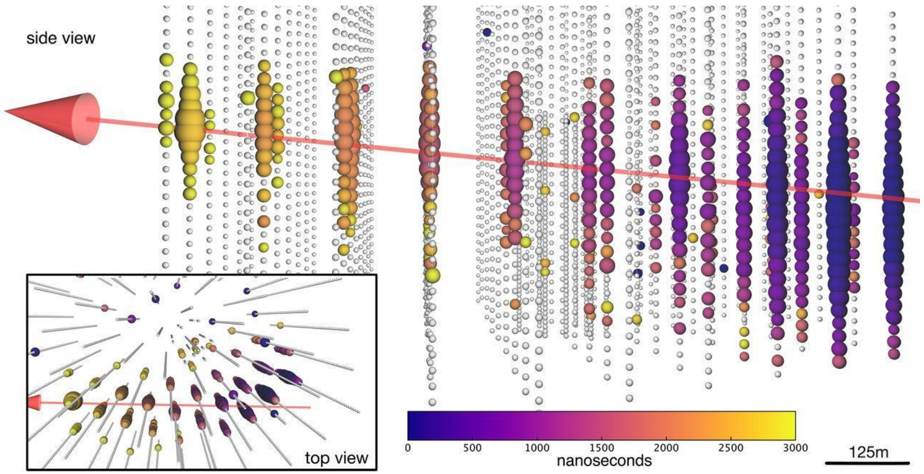
- **Population studies to search for correlation with IceCube HESE**
- **Depends on the sensitivity and exposure time**

Multi-messenger astronomy: IceCube-170922A & TXS 0506+056



Science 361, 147 (2018)

Science 361, 361 (2018)

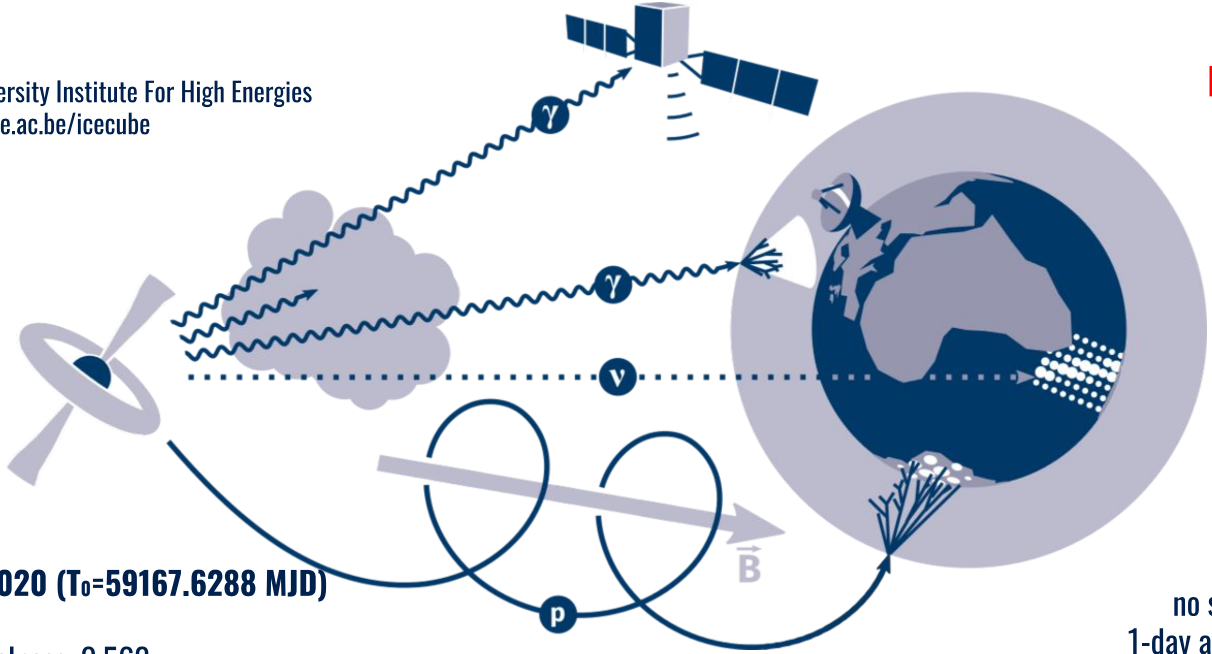


2017: ~3σ correlation between a muon neutrino event with a reconstructed energy of 290 TeV and the flaring source TXS-0506+056.

2014-2015: Excess of HE neutrino events coming from the direction of the source at significance level of ~3.5σ

Multi-messenger astronomy:
IceCube-201114A & TXS 0506+056

Image Credit: Inter-University Institute For High Energies
www.iihe.ac.be/icecube



Improved IC alert system:

Gold alerts: 50%
Bronze alerts: 30%
astrophysical origin

Blaufuss et al. (2019)

November 14th, 2020 (T_0=59167.6288 MJD)

signalness=0.562
false alarm rate=0.92 events/year
R.A.=105.25° +1.28°/-1.12°; Dec=6.05°±0.95°
E~ 214.29 TeV

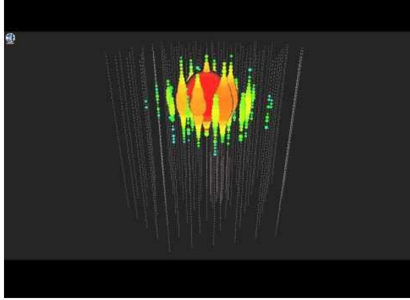
Alert distributed worldwide

4FGL J0658.6+0636 (NVSS J065844+063711)

Blazar, HSP, z >0.5
0.8° away from the best-fit event position
Identified as a VHE (E>20 GeV) source

Fermi-LAT reported:
no significant detection of the source
1-day and 1-month prior to the neutrino alert

Follow Up Observations:
X-RAY: Swift, NICER, eROSITA
Radio: MPIfR



Video Credits: IceCube Collab

Motivations: Neutrinos

Other possible neutrino candidates from flaring blazars:

3HSP J095507.9+355101 (BL Lac) → IC200107A
muon track event 0.62° away from the best-fit position

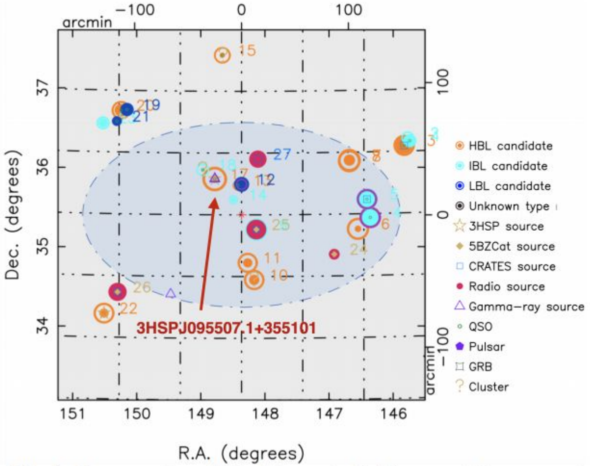
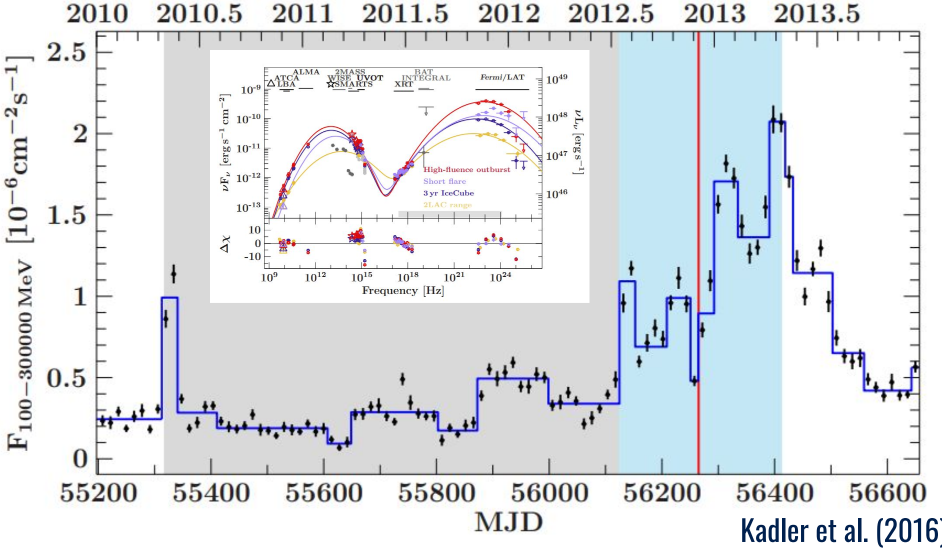


Fig. 1. Known and candidate blazars (radio/X-ray matching sources) around the 90% containment region of IceCube200107A, approximated by the darker elliptical area.

Giommi et al. (2020)

HESE Astrophysical neutrinos

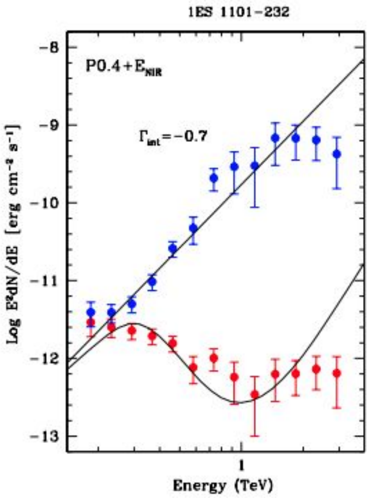
PKS B1424-418 (FSRQ) → IC HESE-35 'Big Bird' (2012)
Cascade event, 2PeV, RA=208.4°, Dec = −55.8°, R=15.9°



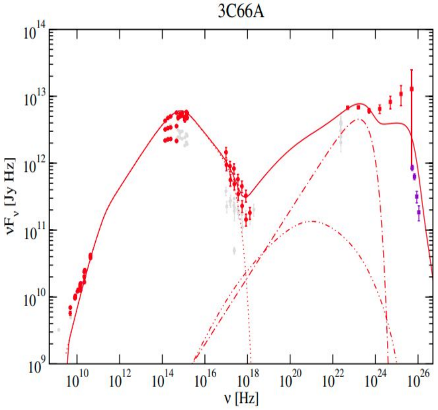
Kadler et al. (2016)

Motivations: gamma rays

Hadronic emission has been proposed as a possible explanation of observed gamma-ray spectral hardening at TeV energies:



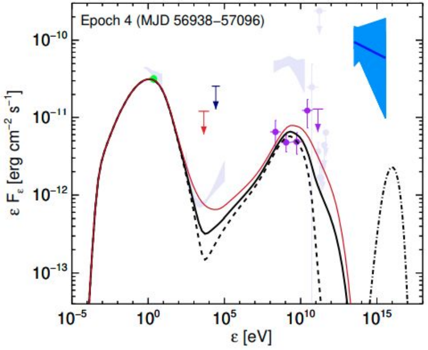
1ES 1101-232 and
H 2356-309
Aharonian et al. (2006)



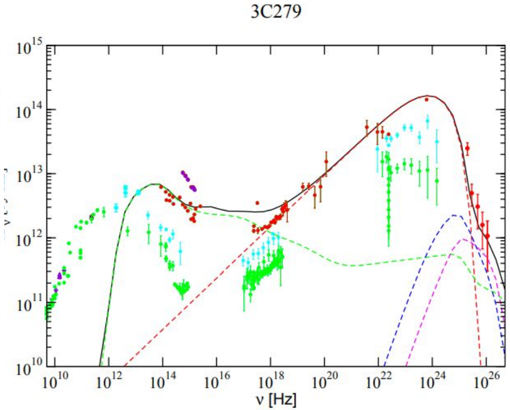
3C 66A
Böttcher et al. (2013)

‘Successful’ SED modelling for flaring blazars:

Markarian 501 - Mücke &Protheroe (2001)
3C 279 - Diltz & Böttcher (2016)
TXS 0506+056 - Petropoulou et al. (2020)
etc....



TXS 0506+056
Petropoulou et al. (2020)



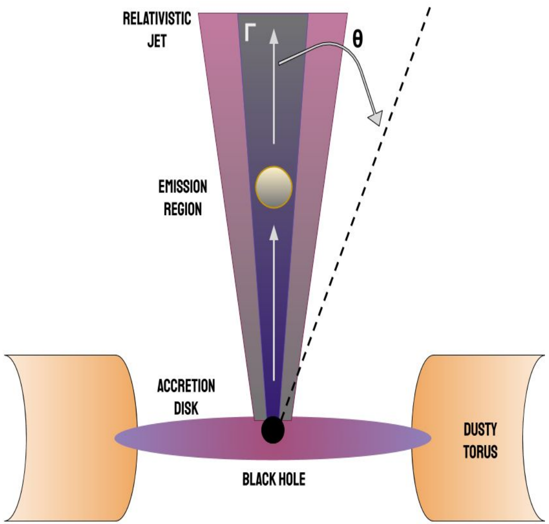
3C 279
Diltz & Böttcher (2016)

Photo-hadronic contributions

Let's assume the standard interpretation of the leptonic model:

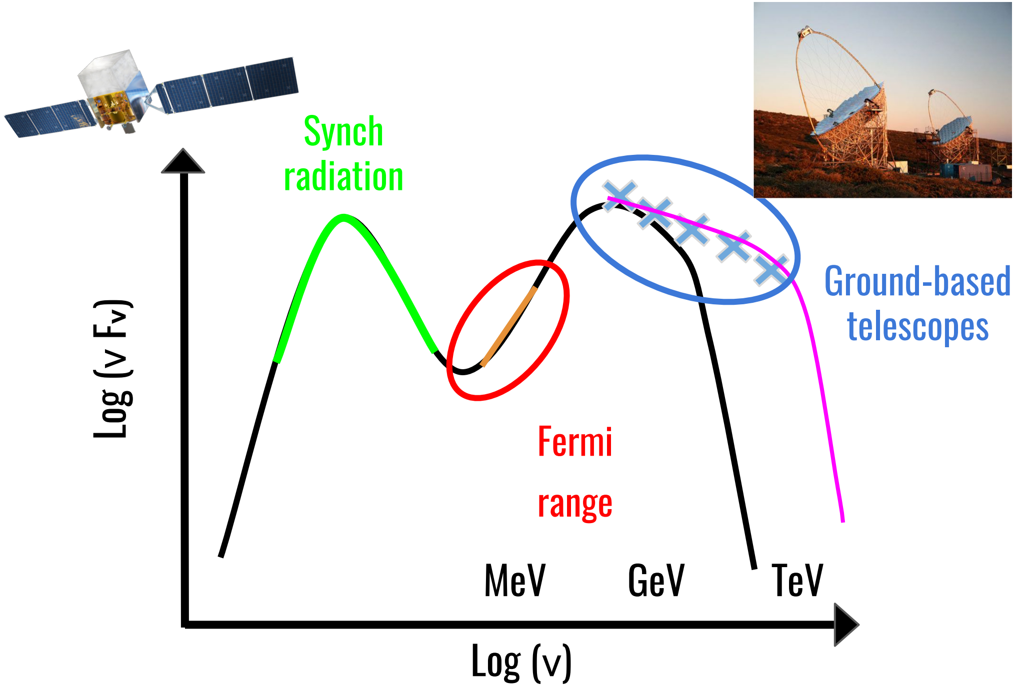
Standard Leptonic = electron-synchrotron + SSC

Physical Parameters: {R, δ, Γ, B}



Hadronic (pγ) contributions at VHE:

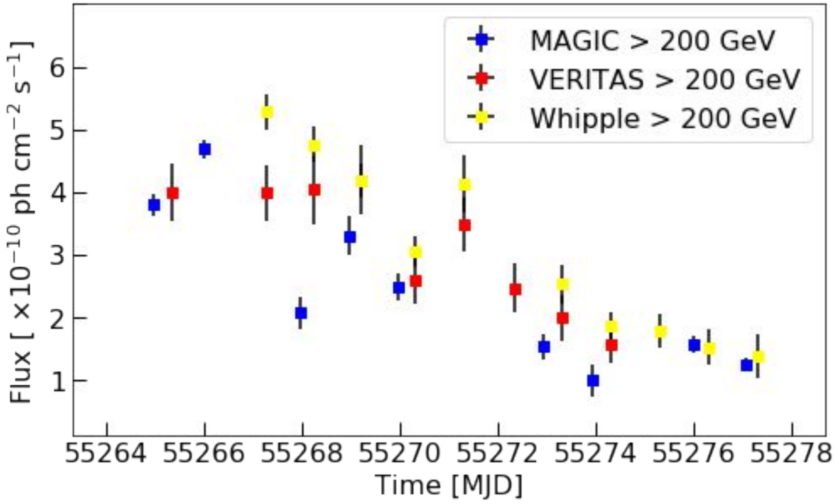
$$p + \gamma \rightarrow \Delta^{+} \rightarrow \begin{cases} p\pi^{0},\ \pi^{0} \rightarrow \gamma\gamma \\ n\pi^{+},\ \pi^{+} \rightarrow \mu^{+}\nu_{\mu},\ \mu^{+} \rightarrow e^{+} + \nu_{e} + \bar{\nu_{\mu}} \end{cases}$$

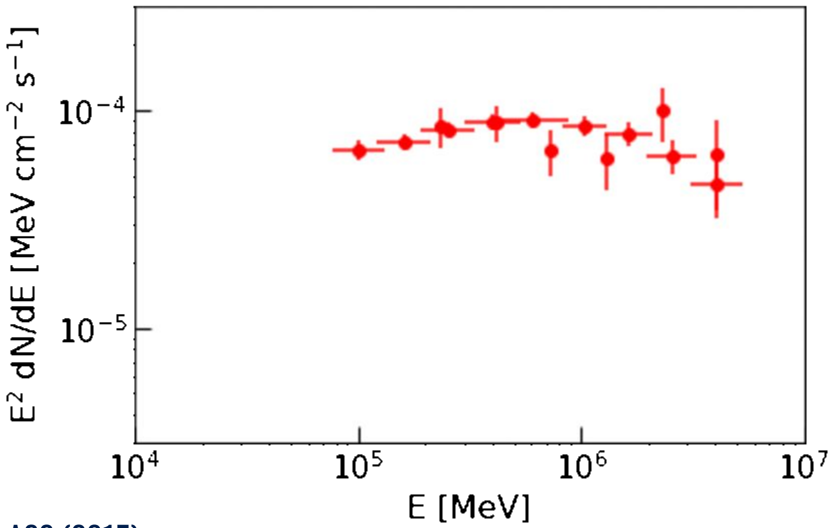


A case study: Markarian 421, 2010 flaring activity

Mrk 421: prominent blazar (BL Lac)
RA=66.114°, Dec = 38.209°, z=0.031
near bright gamma-ray source (TeV),
highly active, constant monitoring (MWL campaign 2010)

2010 Flaring activity:
14-days in March 2010 (MJD 55264–55277)
remarkable flux variability at the VHE band (E > 100 GeV)





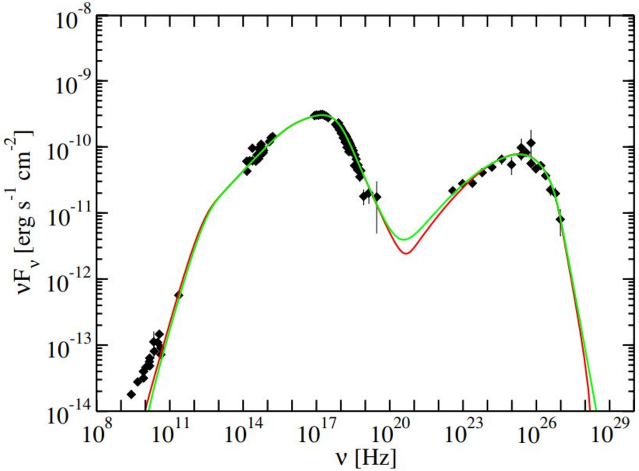
Aleksić et al., A&A 578, A22 (2015)

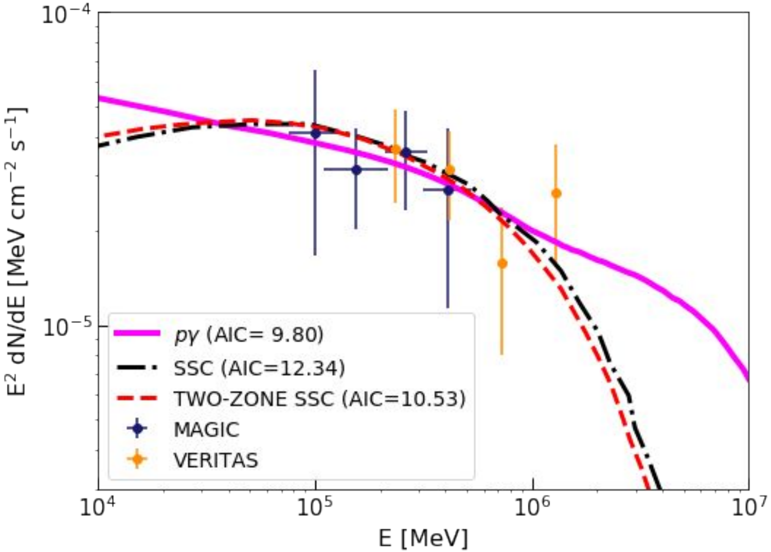
Modelling
Markarian 421 (2010 Flare)

Output

One-Zone Leptonic Model as a base
+ Hadronic ($p\gamma \rightarrow \Delta$-resonance approx)

Model output: pγ contribution
EBL Model of Dominguez et al. (2011)





Fixed parameters: δ=21, B=3.8x10^{-2} G, R=5.2x10^{16} cm
Abdo et al. 2011

Leptonic models from Aleksic et al. 2015)

Akaike Information Criterion (AIC)

Akaike (1974)

Is a method to compare and select "the best" model from a set of models.
Seeks the preferred model based on:

$$AIC_s = -2ln(L_s) + 2k_{f\,s}$$

1) goodness of the fit:

How close it is to the true values
L_s = Likelihood of a model s

2) simplicity of the model:

k_{fs} = Number of free parameters

AIC Difference

$$\Delta AIC_{p,q} = AIC_p - AIC_q$$

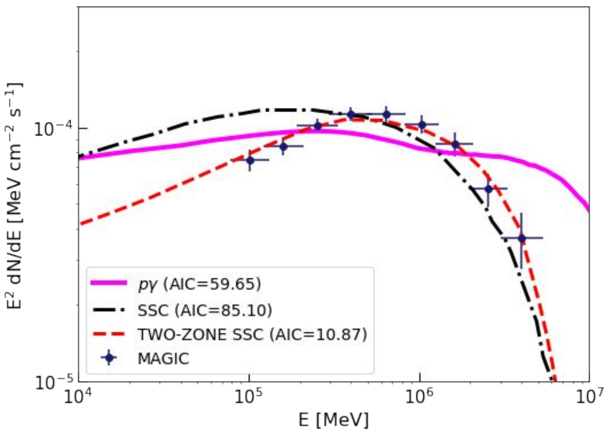
pγ vs one-zone SSC
pγ vs two-zone SSC

The larger the difference, the less plausible it is that the fitted model is the best model, given the data. As a rule of thumb:

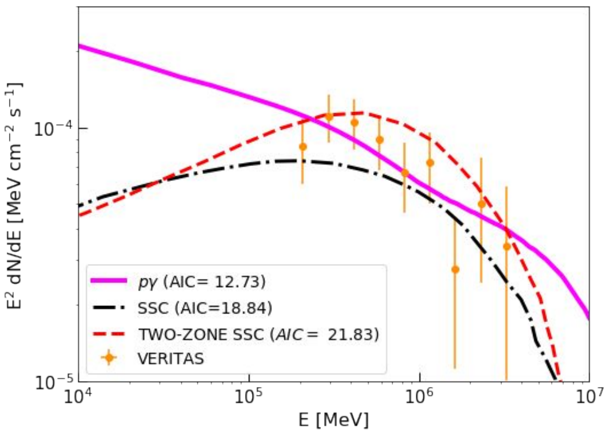
Δ_i	Level of Empirical Support of Model i
0-2	Substantial
4-7	Considerably less
> 10	Essentially none.

Burnham and Anderson (2002).

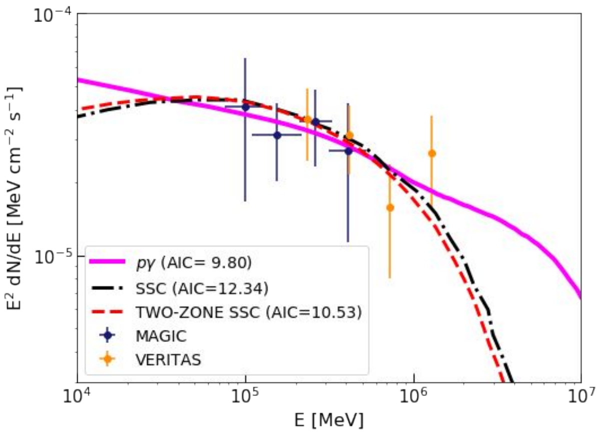
MJD 55266



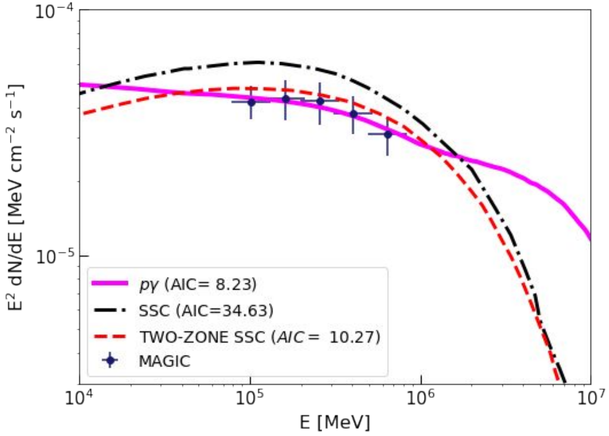
MJD 55267



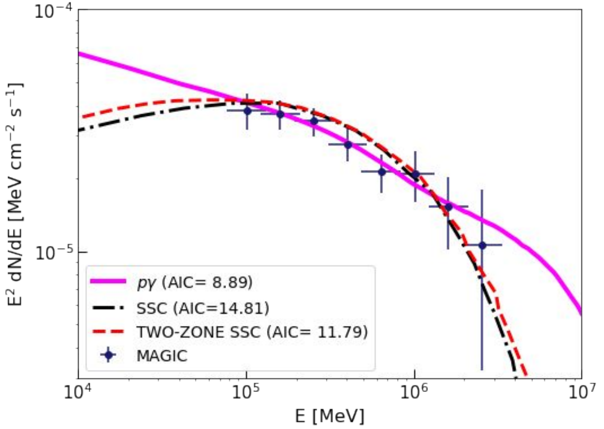
MJD 55274



MJD 55276



MJD 55277



Likelihood is assessed using a $\chi 2$ statistic.

Advantages:
Balance: goodness of the fit & simplicity

Caveats:
Extension to lower energies?
Other hadronic components?

Rosales de León et al., MNRAS, Volume 501, 2198 (2021)

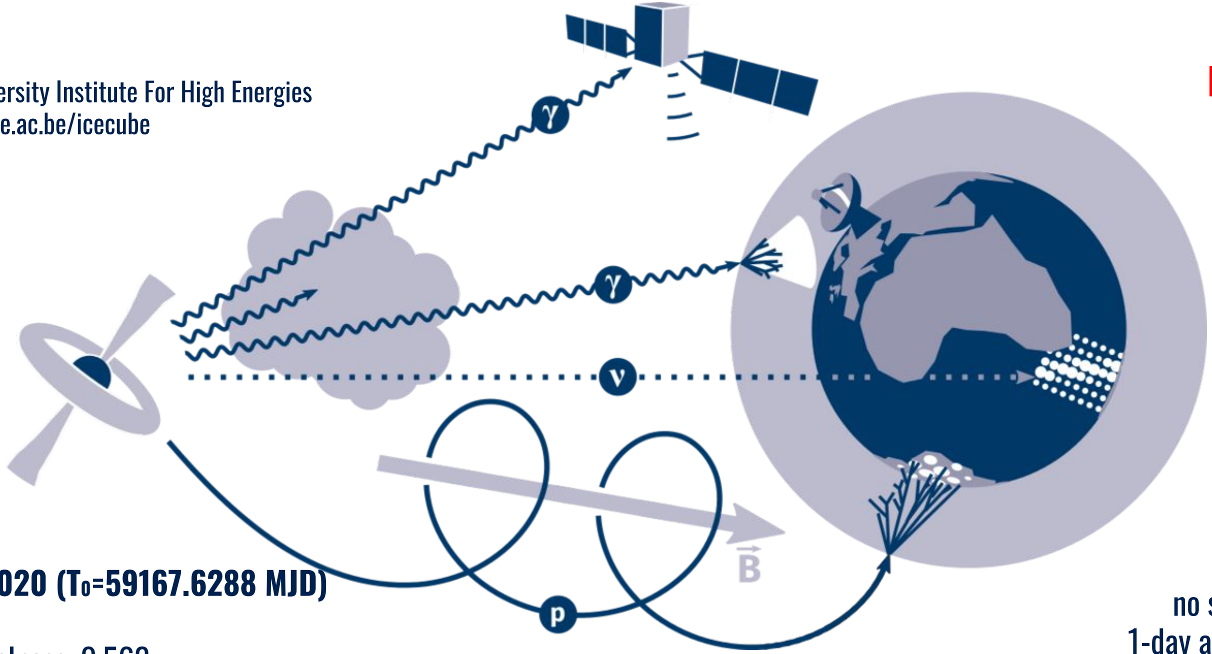
Results

Time MJD	A_γ	α	Preferred Model	$\Delta AIC_{SSC,p\gamma}$	$\Delta AIC_{two-zone\,SSC,p\gamma}$
55266	5.02 ± 2.74	3.12 ± 0.07	two-zone SSC	25.45	-48.78
55267	27.24± 12.79	3.41 ± 0.09	$p\gamma$	6.11	9.10
55274	0.19 ± 0.01	2.31 ± 0.03	inconclusive	2.54	0.73
55276	0.10 ± 0.02	2.17 ± 0.03	$p\gamma$	26.40	2.04
55277	0.18 ± 0.02	2.32 ± 0.03	$p\gamma$	5.92	2.90

- In all cases the pγ model was favoured as a better fit description than the one-zone leptonic model and in the majority of cases with respect to the two-zone model from Aleksić et al. 2015.
- The high frequency of the seed photons considered lowers the energy threshold for the protons: 800 GeV < E_p < 50 TeV (observer's reference frame)
- Neutrinos Expected? For IC-59, during the 14 days the expected value is $N_{events} \ll 1$

Multi-messenger astronomy: IceCube Neutrino Alerts
IC-201114A alert

Image Credit: Inter-University Institute For High Energies
www.iihe.ac.be/icecube



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Bronze alerts: 30%
astrophysical origin

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false alarm rate=0.92 events/year
R.A.=105.25° +1.28°/-1.12°; Dec=6.05°±0.95°
E~ 214.29 TeV

Alert distributed worldwide

4FGL J0658.6+0636 (NVSS J065844+063711)

Blazar, HSP, z >0.5
0.8° away from the best-fit event position
Identified as a VHE (E>20 GeV) source

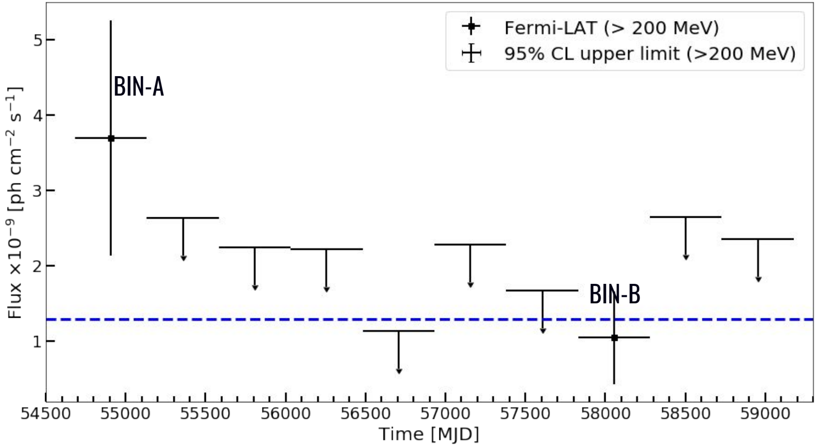
Fermi-LAT reported:
no significant detection of the source
1-day and 1-month prior to the neutrino alert

Follow Up Observations:
X-RAY: Swift, NICER, eROSITA
Radio: MPIfR

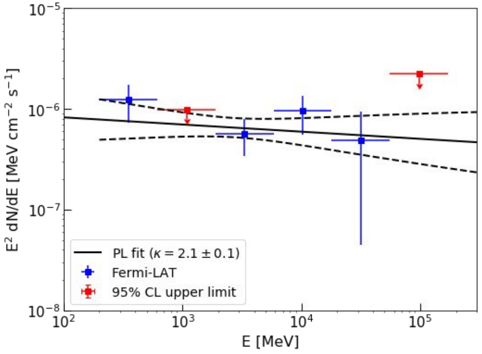
IC-201114A alert
Fermi-LAT analysis

12.3-year data set: 54683-59178 MJD
IRFs: Pass8v6 & 4FGL-DR2 catalog
Energy range: 200 MeV - 300 GeV
RoI: 15°; bin size=0.1°/pixel
'SOURCE' class events (evclass=128 & evtype=3)

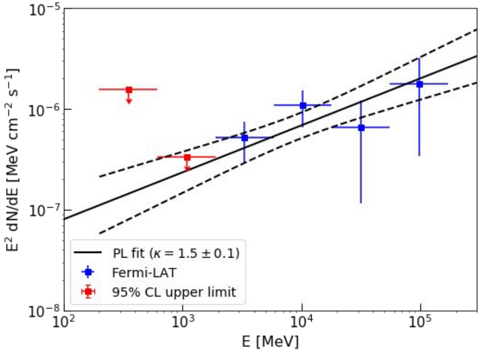
12.3 year data set light curve



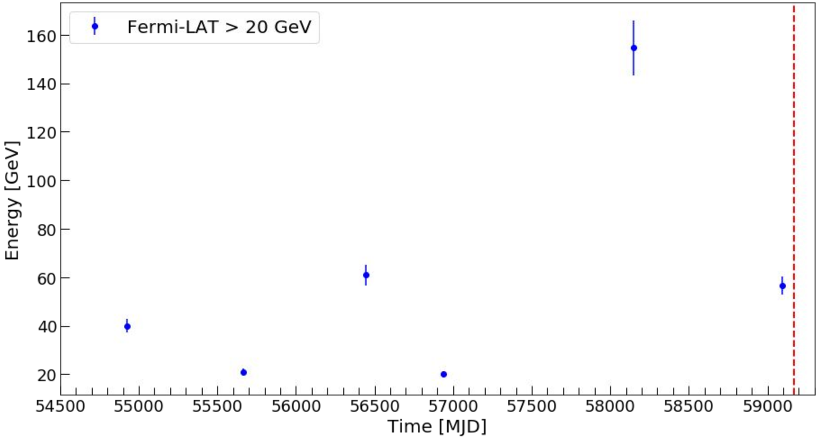
BIN-A: (2008/08/04 - 2009/10/28)



BIN-B: (2017/03/17 - 2018/06/10)



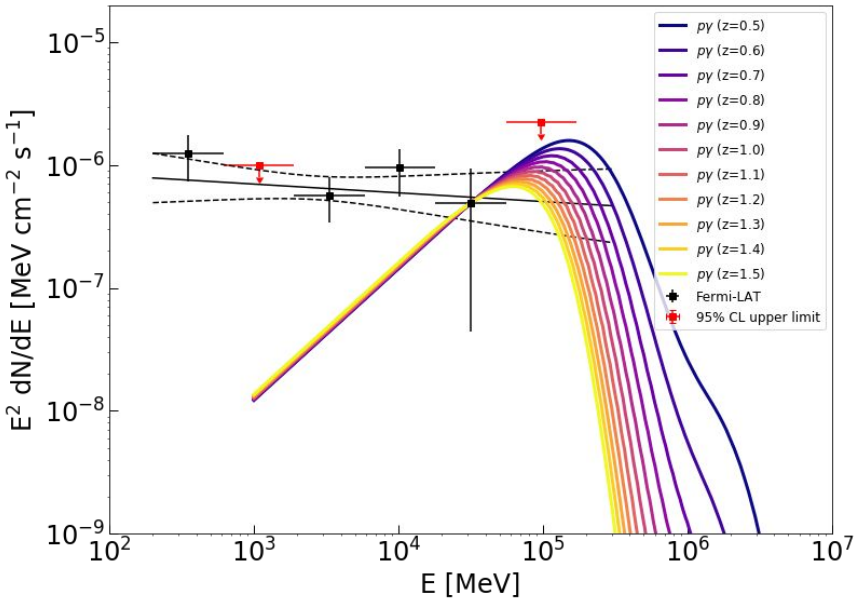
VHE photons associated with 4FGL J0658.6+0636 (≥ 90%)



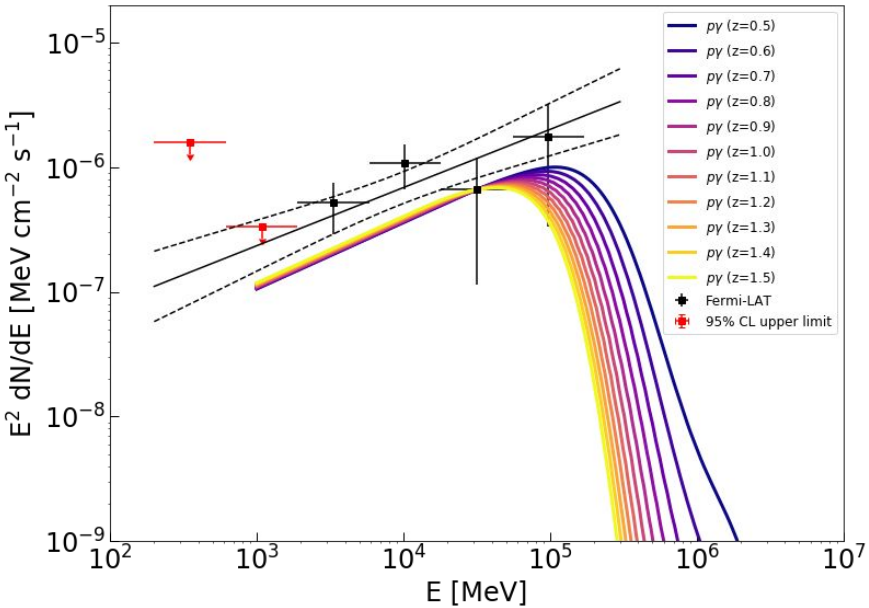
Power-Law (PL): $$\frac{dN}{d\epsilon_\gamma} = N_{\rm PL}\left(\frac{\epsilon_\gamma}{\epsilon_0}\right)^{-\kappa}$$

Photo-hadronic contribution:

BIN-A



BIN-B



BIN	TS	Flux 10^{-9} [ph cm^{-2} s^{-1}]	N_{PL} 10^{-14} [MeV cm^{-2} s^{-1}]	κ	A_γ 10^{-2}	A_ν 10^{-12} [TeV cm^{-2} s^{-1}]	**MDT** Time [days]	$F_{\nu,\mathrm{int}}$ 10^{-5} [TeV cm^{-2}]
BIN-A	38	3.69 ± 1.56	8.9 ± 2.2	2.1 ± 0.2	1.85 - 1.92	6.35 - 6.93	160 (IC40)	8.66 - 9.46
							100 (IC59)	5.54 - 6.05
BIN-B	34	1.04 ± 0.61	4.6 ± 2.1	1.5 ± 0.2	29.9 - 53.9	186.15 - 352.21	2.5 (IC86)	4.02 - 7.61

Minimum Detection Time (**MDT**): the estimated time elapsed for IceCube to detect a couple of neutrino events during an active state of the source.

Results

- For BIN-B: a dominant photo-hadronic contribution is compatible with the SED behaviour of the source
  MDT~2.5-days is expected and coincides with the most energetic VHE photon registered (E = 155~GeV)
  About 16-days to emulate the 13 excess events from 2014-15 neutrino flare of TXS 0506+056

- For BIN-A: the predicted spectrum does not match the Fermi-LAT data
  Low-level gamma-ray emission over an extended period
  Expected MDT between 100-160-days

Fermi Gamma-ray Space Telescope

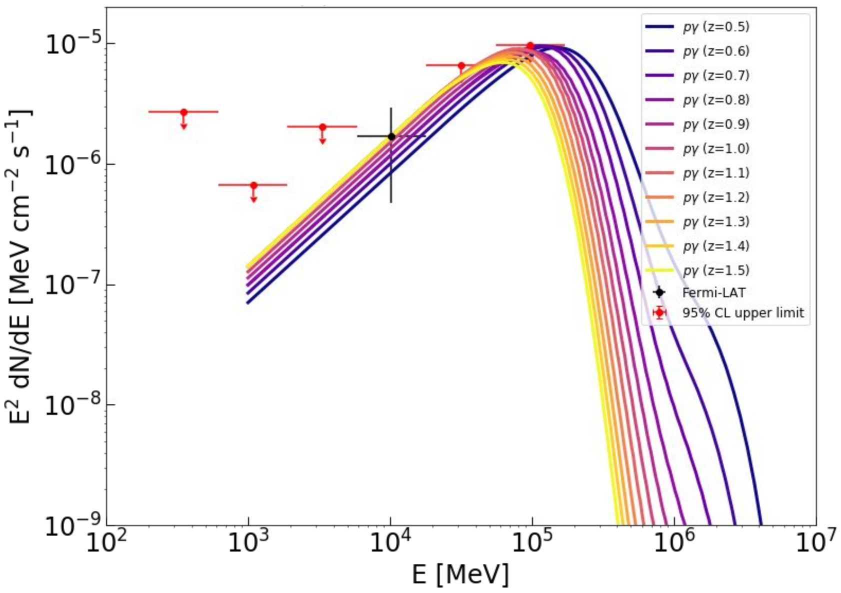
4-month data set: 59108-59228 MJD
centered at the time of the neutrino alert
IRFs: Pass8v6 & 4FGL-DR2 catalog
Energy range: 200 MeV - 300 GeV
RoI: 15° ; bin size=0.1°/pixel
'SOURCE' class events (evclass=128 & evtype=3)

No significant gamma-ray activity during this time window.
Assuming a photon target spectrum similar to
BIN-A or BIN-B

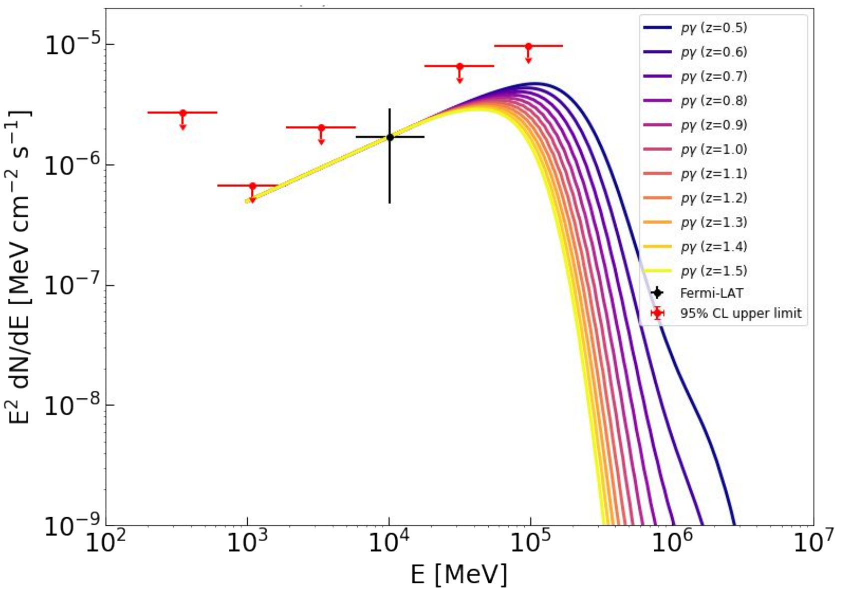
Photo-hadronic contribution for IC-20114A

Photo-hadronic contributions around IC-201114A

BIN-A like spectrum



BIN-B like spectrum



Parameter	Typical Value / Range
z	0.5 - 1.5
R'_f	(1.35-2.25) $\times 10^{16}$ cm^2
B	1 G
$\mathcal{D}$	13
α	2.2

Assumed Behaviour	A_γ	A_ν [TeV cm^{-2} s^{-1}]	MDT	$F_{\nu,\text{int}}$ $\times 10^{-5}$ [TeV cm^{-2}]
BIN-A like	0.11 - 0.20	(3.66 - 7.15)$\times 10^{-11}$	12-days	3.80- 7.42
BIN-B like	1.39 - 2.24	(1.05 - 1.78)$\times 10^{-8}$	~ 1-hour	3.79 - 6.41

Rosales de León et al., PoS (ICRC 2021), 1001
DOI: https://doi.org/10.22323/1.395.1001

In Summary...

There are some interesting results and motivations to hadronic component in the blazars:

- Mrk 421 flaring activity in 2010
  A hadronic component could be dominant at VHE in specific days, followed by a dominant SSC leptonic component. If the proton injection occurs randomly, there is no preferred time for hadronic dominance during the flare.

- IC-201114A alert & 4FGL J0658.6+0636
  Under the assumptions made a photo-hadronic scenario, we found some compatible results with the behaviour of the source, although more evidence is needed to claim that 4FGL J0658.6+0636 is a neutrino emitter.

- We are living the dawn of multi-messenger Astronomy.
  To explore the neutrino/gamma-ray connection in the upcoming years, the next generation of gamma-ray and neutrino observatories, such as CTA, SWGO, AMEGO, IceCube-Gen2, Trinity, will play a crucial role...

Neutrino Target of Opportunity (NToO) for CTA

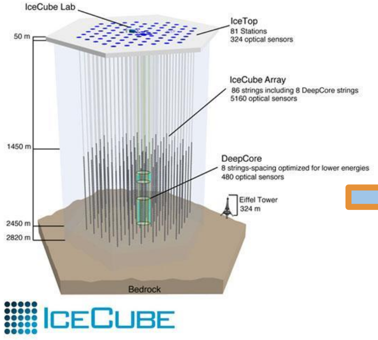
CTA will be able to look for a gamma-ray counterpart from a neutrino source alert and also monitorate "hot-spots" that exceeds IceCube (IC) sensitivity

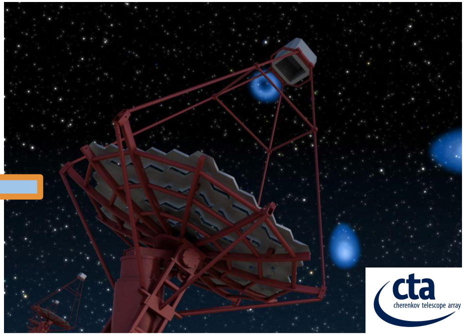
SIMULATIONS:

Hadronic contributions: $p\gamma$ process

Steady Sources - Looking for an excess point ("hot-spot") above IC limit

Transient Sources - Alerts coming from flaring blazar sources





Different CTA configurations are being tested:

Alpha configuration

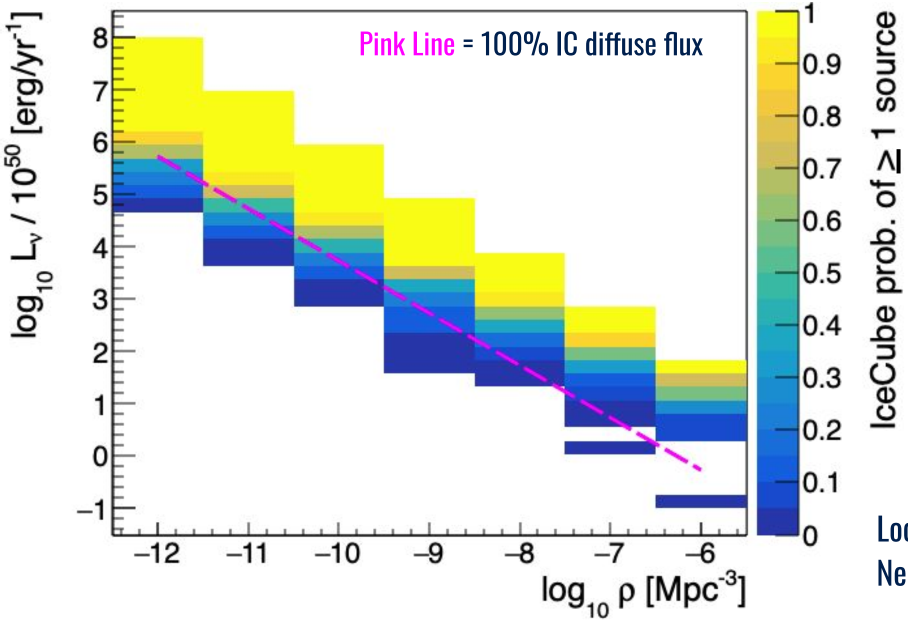
Omega configuration

High NSB (x5 NSB; moon observations)

FIRESONG

First Extragalactic Simulation of Neutrinos and Gamma-rays

Steady Sources



Tung et al., JOSS, 6(61), 3194 (2021)

https://github.com/ChrisCFTung/FIRESONG

Simulates a neutrino population, given:

Source evolution (e.g. star formation rate)

Luminosity function (e.g. standard candle)

Density vs Luminosity

Steady Sources

Local source density (sources/Mpc^3)

Neutrino luminosity

Transient Sources

Local burst density rate (% flaring blazars)

Neutrino flare luminosity

Output: z (redshift), A_ν (neutrino flux @100 TeV) & θ (declination)

FIRESONG Simulations

Steady Sources

Standard candles, follow the SFR evolution model of Madau & Dickinson (2014).

Local density ρ = 10^{-12} to 10^{-5} Mpc^{-3}.
Luminosities: L_ν = $5x10^{47}$ to 10^{57} erg/year

Gamma-ray flux parametrised assuming $p\gamma$ interactions
Ahlers & Halzen (2018)

Sources exceeding IceCube's sensitivity (Aartsen et al., IceCube Collaboration, (2019)) are used as seeds of the NToO for CTA

Assuming all the sources are always observable by CTA

Transient Sources

Standard candles and flat cosmological evolution

Based on neutrino flare model of TXS 0506+056 in 2014-2015
Halzen et al., ApJ 874 (2019).

Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

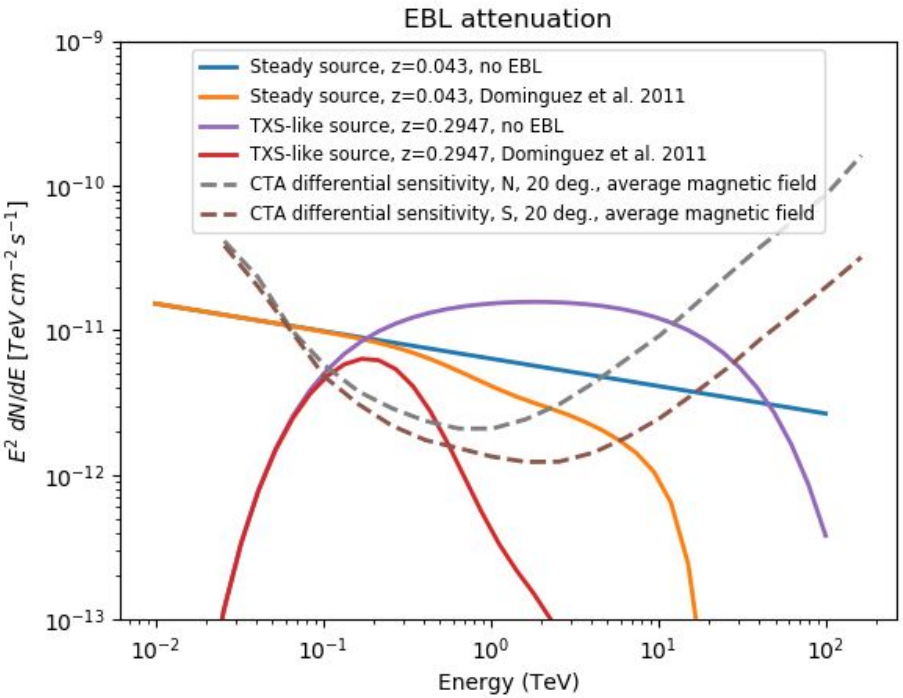
All the sources are assumed to have the same flare duration in their reference frame (110 days @z TXS)

Assuming IC Gold alerts and events always observable by CTA.

CTA follow up observations

cherenkov telescope array

Energy spectra vs CTA differential sensitivity for detected sources



SIMULATIONS: ctools-1.6.2 with prod3b-v2 IRFs
Zenith angles: 20º/40º/60º and Average/N/S B-field
Right ascension (RA) assigned randomly
Energy range: 0.03 - 200 TeV
Observation duration: 30 min
EBL absorption by Dominguez et al. 2011

Source is detected, if the test statistics TS ≥ 25 (~5σ)

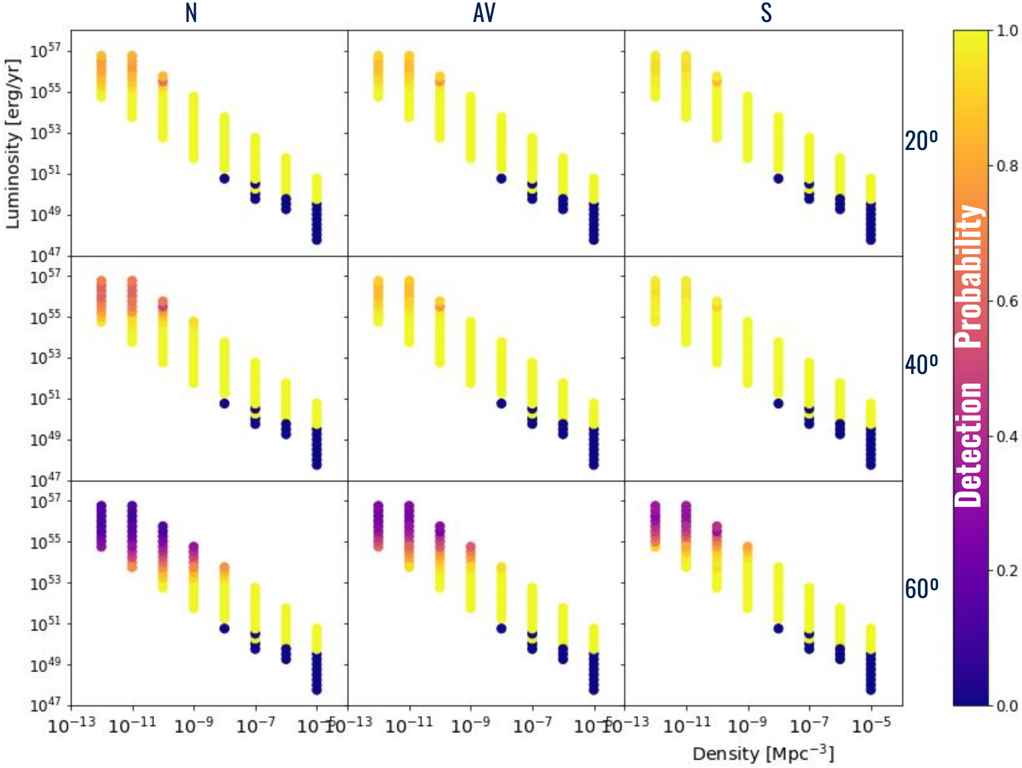
$$TS = 2\left(\ln L(M_s + M_b) - \ln L(M_b)\right)$$

$\ln L(M_s + M_b)$ log-likelihood of: Source + Background

$\ln L(M_b)$ log-likelihood of: Background only

Results: Steady Sources

CTA-N; 30 min obs; SFR evolution



Assuming these sources will be always observable by CTA:

At low-mid zeniths (20º-40º) CTA-N detects all sources up to ρ= 10^{-9} Mpc^{-3}

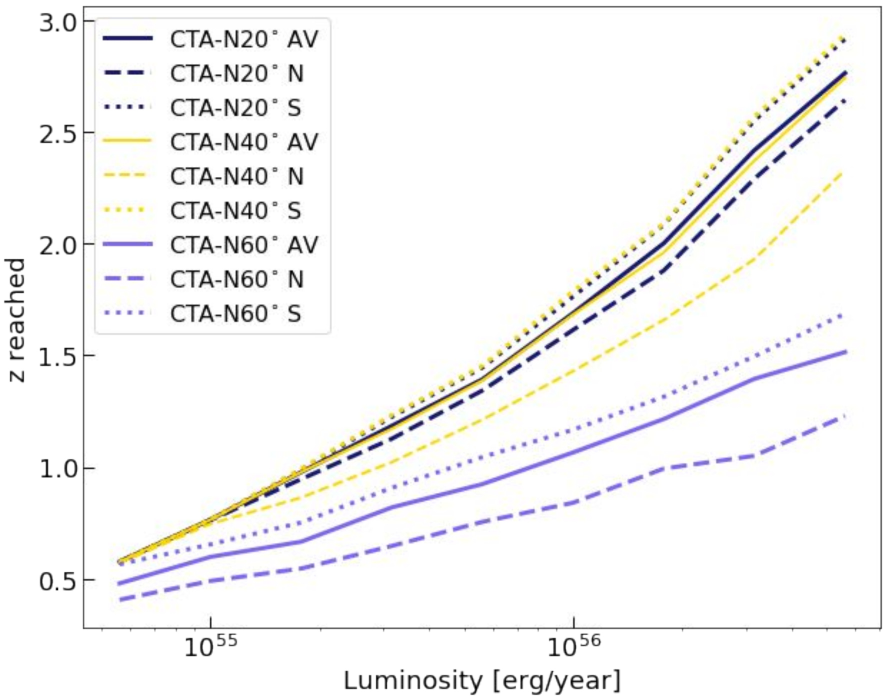
Drastic performance loss, up to 65%, at high zeniths (60º)

Magnetic field effect: 10-30% difference for low to high zeniths

For sources with flat redshift evolution the trends are similar, but less pronounced

Results: Redshift reach

CTA-N; 30 min obs; SFR evolution; ρ= 10^{-12} Mpc-3



The redshift reach is defined as the maximum redshift up to which 90% of sources are detected (cut the last decile)

Highest redshift reach is obtained at low densities and high luminosities (For ρ= 10^{-12} Mpc^{-3} up to z~2.8)

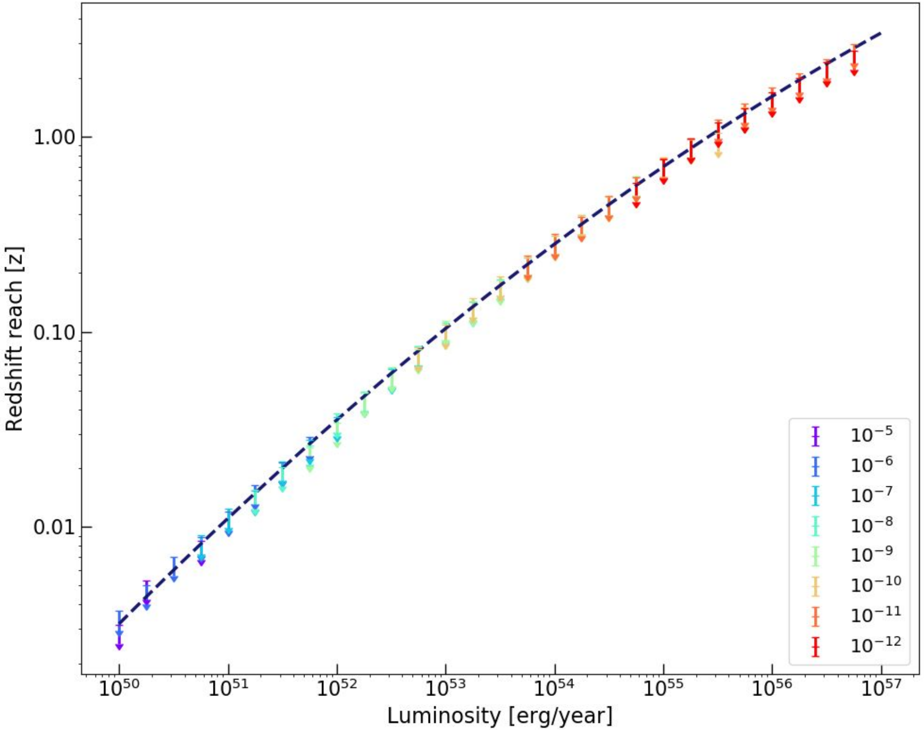
Redshift reach goes down at higher zeniths: For 20° and 40° the redshift reach is similar, but there is a huge drop at 60°

There is a cut in redshift coming from an IceCube preselection effect

Sources with a flat cosmological evolution follow the same trend, but the redshift reach is lower than for SFR evolution cherenkov telescope array

Results: Redshift reach

CTA-N; 30 min obs; SFR evolution



Redshift reach for (a) CTA-N and (b) CTA-S in the steady source scenario following the SFH evolution model of Madau and Dickinson (2014).

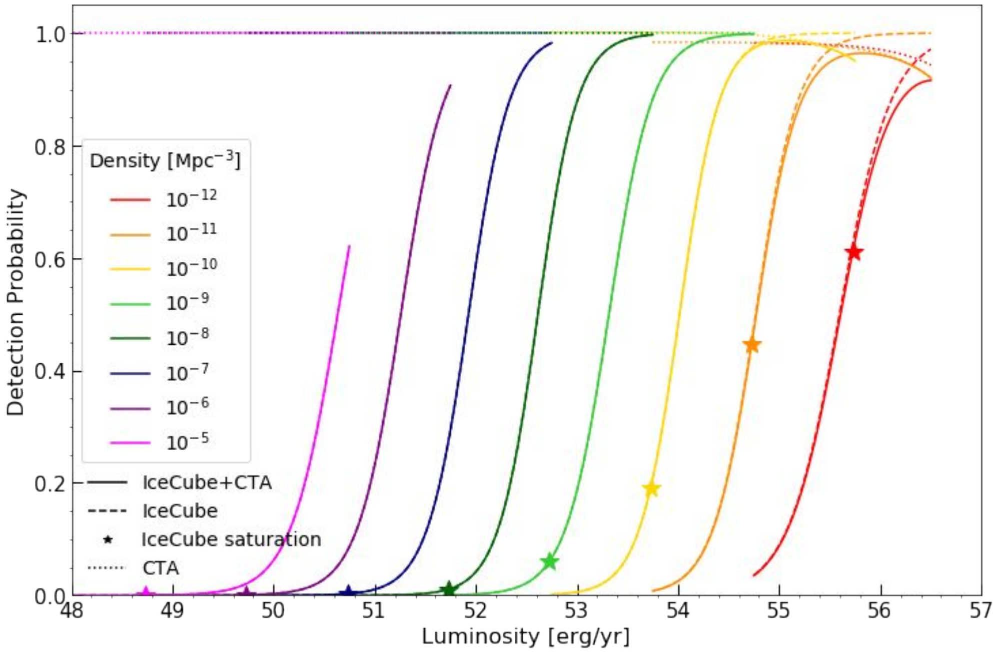
Each coloured arrow represents the redshift reach of a different simulated population in the parameter space. The dotted line is the best fit curve to the redshift reach points in log-log space.

As expected, the redshift reach increases with higher luminosities.

SFH evolution Source density Mpc^{-3}	Max Luminosity $5.62\times$ erg/year	Redshift reach CTA-N	 CTA-S
10^{-5}	10^{50}	0.01	0.01
10^{-6}	10^{51}	0.03	0.03
10^{-7}	10^{52}	0.08	0.09
10^{-8}	10^{53}	0.2	0.2
10^{-9}	10^{54}	0.6	0.6
10^{-10}	10^{55}	1.4	1.4
10^{-11}	10^{56}	3.0	3.0
10^{-12}	10^{56}	2.8	2.9

Results: Transient Sources (Flaring blazars)

CTA-N 30 mins obs; Flaring blazars



Selecting IC Gold alerts (>50 %) and assuming observable conditions by CTA:

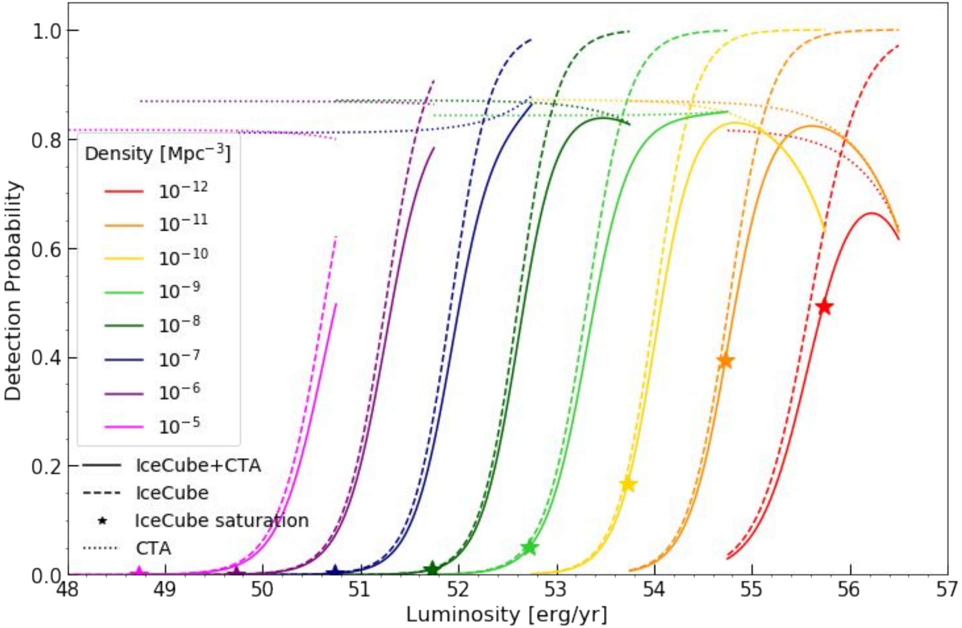
Plot shows the detection probability for the simulated neutrino hot-spots detected by IceCube and observed with CTA-N in 30-min observations.

The coloured dashed curves show the IceCube detection probability, the coloured dotted curves the CTA detection probability and the solid curves the combined detection probability.

The coloured stars mark the points at which the simulated populations saturate the IceCube neutrino diffuse flux.

Results: Transient Sources (Flaring blazars)

CTA-S 30 mins obs; Flaring blazars



For CTA-S, the combined detection probability is lower in comparison to CTA-N. This is expected as IceCube is more sensitive to the neutrino sources in the northern hemisphere.

A drop in CTA-S detected sources plays a bigger role in the final shape of the combined detection probability curves, especially at low densities ($\rho_0 < 10^{-9}$ Mpc−3).

Conclusions and Outlook for CTA

CTA will enhance our understanding of the high energy universe and play a key role in multi-messenger astronomy.

CTA prospects are particularly promising for the flaring blazars case, up to 37% chances of detection with 30 mins observations.

Results also show a high CTA detection probability for steady sources in certain parameter space regions.

In future, we plan to investigate:

- Longer observation times, especially for steady sources (5 hrs, 50 hrs)
- Different durations for transient sources: 100s to few hours
- Include CTA visibility constraints for steady and transient sources
- Include effect of delays introduced by the alert system and the telescope re-pointing.
- More configurations: Results for the sub-arrays and high night sky background (NSB) are being analysed

Thanks for your attention

For more gamma-ray and neutrinos discussions:

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