Line of sight neutrinos and gamma-rays from blazars associated with IceCube neutrinos

Soeb Razzaque | Centre for Astro-Particle Physics and

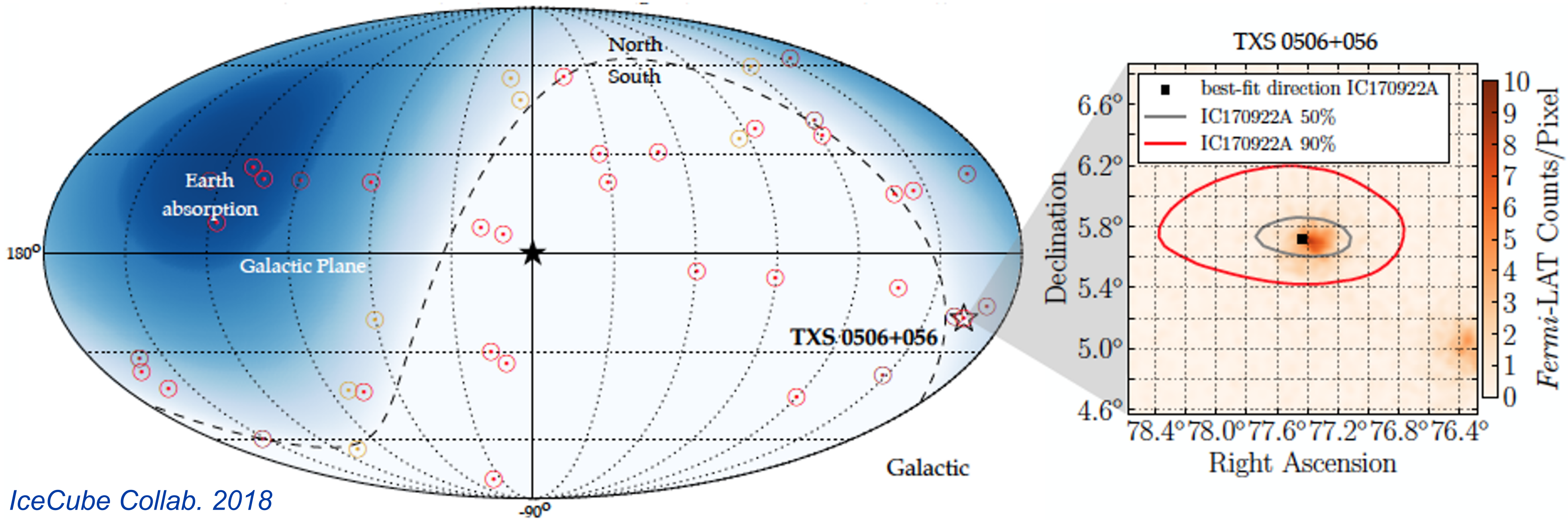
Department of Physics, University of Johannesburg

srazzaque@uj.ac.za | https://www.uj.ac.za/faculties/science/capp

With Saikat Das (Kyoto University) and Nayantara Gupta (Raman Research Institute)

Discovery of a Neutrino Source

- IC -170922A event detected from the direction of BL Lac TXS 0506+056 during flare in 2017
- Chance coincidence can be rejected at 3 sigma level

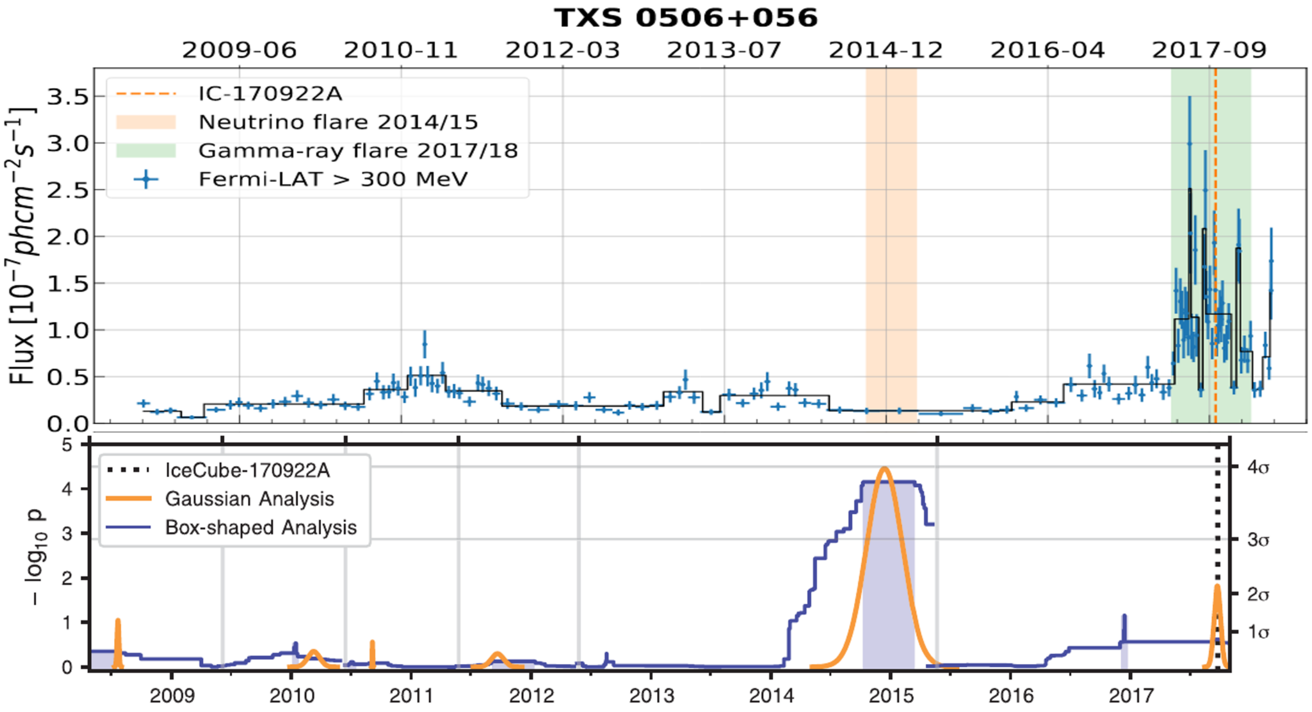


IceCube Collab. 2018

Neutrino Flare from TXS 0506+056

- IceCube detected a "neutrino flare" of 13+/-5 events in archival data from 2014/15
- 3.5 sigma significance of the flare, independent of the 2017 IC event

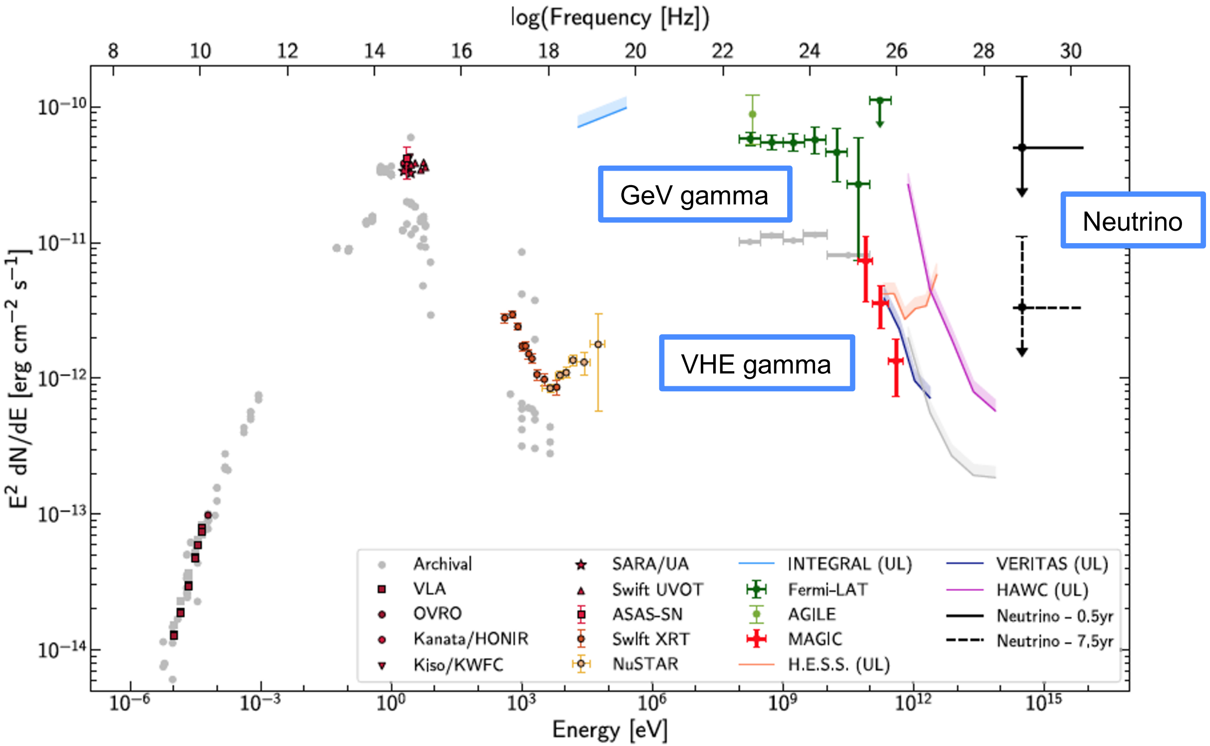
IceCube Collab. 2018



Detection of neutrinos from TXS 0506+056 does not meet the golden criteria of 5 sigma but it is very interesting

Gamma and Neutrino from TXS 0506

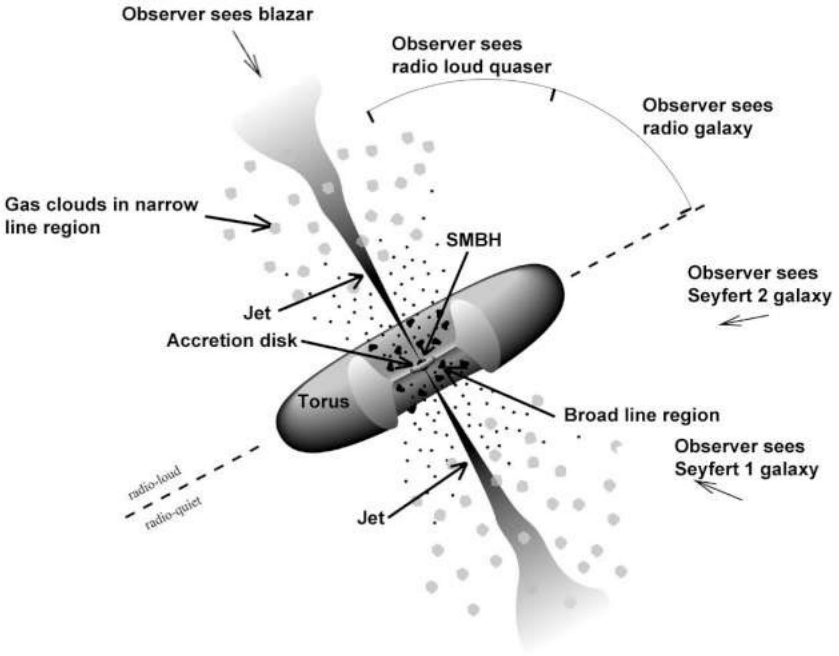
Multiwavelength SED and estimated neutrino flux



Can a blazar SED model explain observed neutrino?

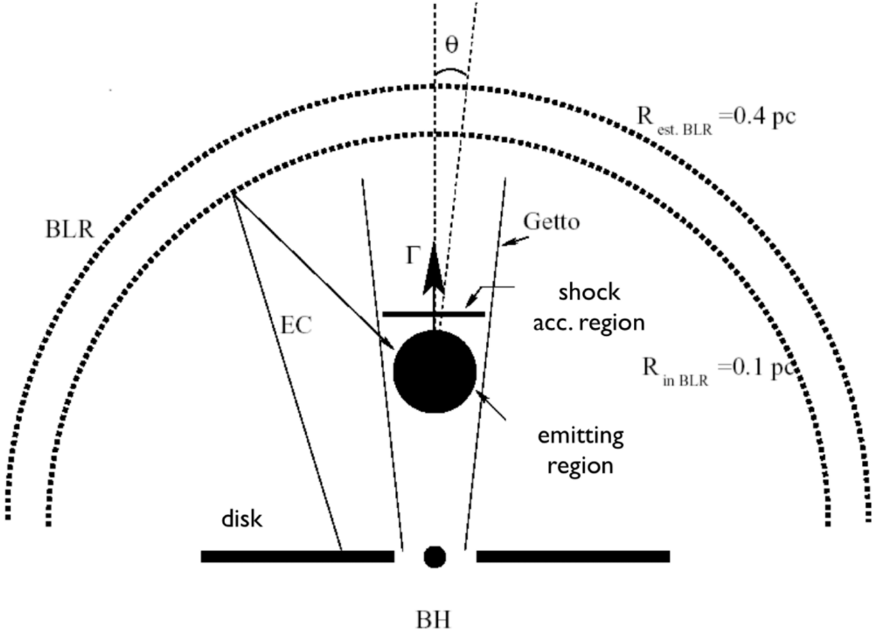
IceCube Collaboration, Fermi - LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift/NuSTAR, VERITAS and VLA/17B-403 teams 2018

Active Galactic Nuclei - Blazars

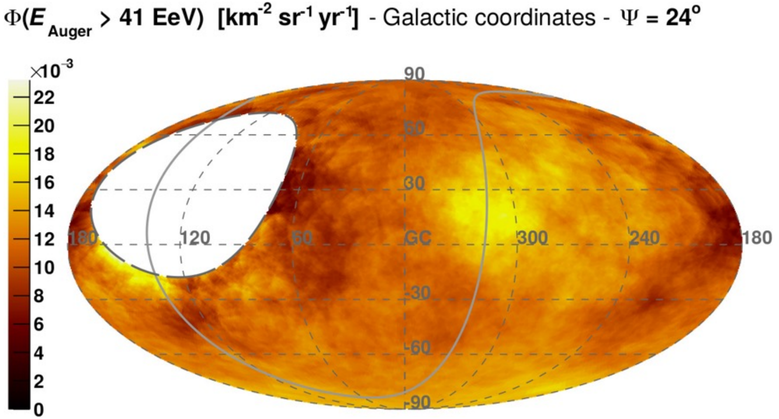


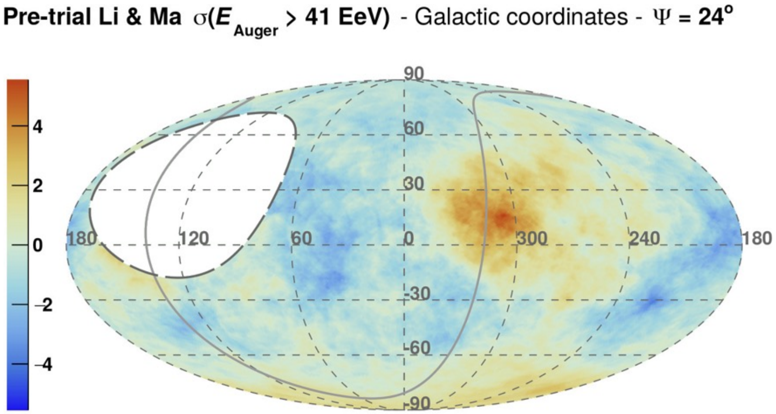
Urry & Padovani 1995

Blazar emission scenario

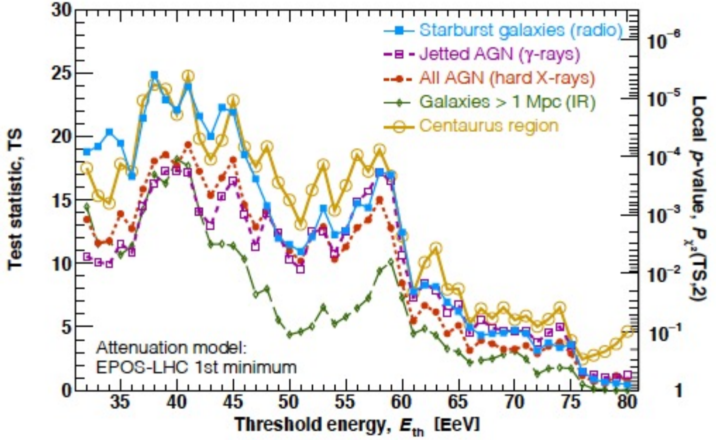


UHECR Sky



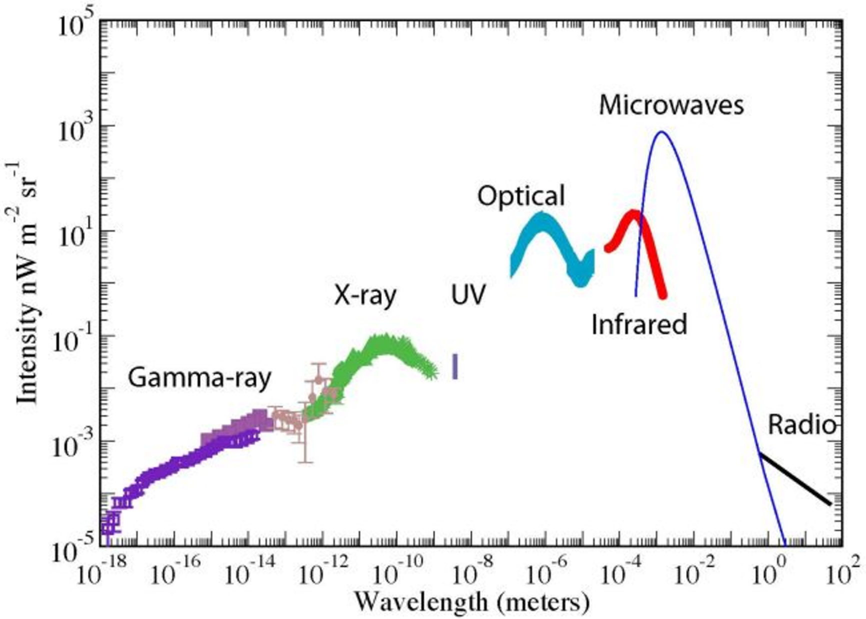


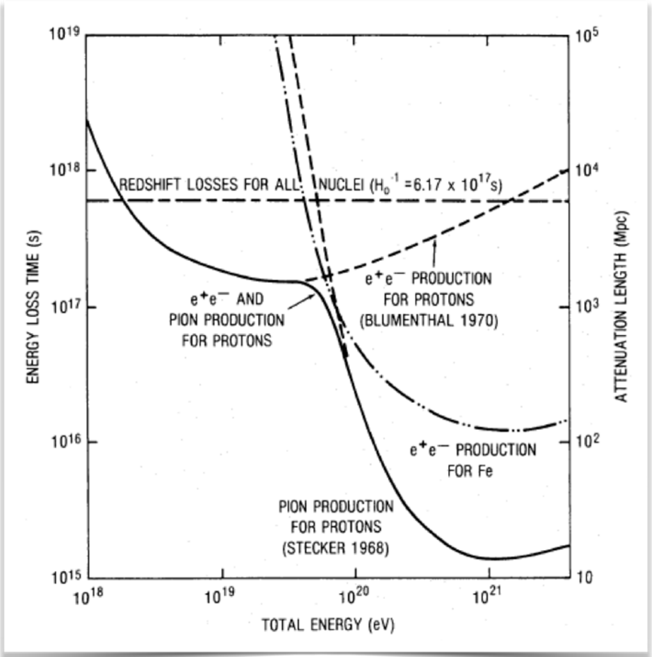
- Auger flux map with a top-hat smoothing function
- Auger pre-trial TS map of over-dense regions
- TS profile of association with source catalogs



Cosmogenic Neutrinos from UHECRs

- Universe is filled with background radiation from radio to gamma –rays
- Interactions of UHECRs with background photons reduce their propagation (**GZK effect**)
- Produce secondary neutrinos and gamma ray





Puget, Stecker & Bredekamp 1976

Motivation …

→ Detection of PeV neutrinos from blazars implies acceleration of cosmic rays to ≥ 10 PeV

→ Blazars are hot candidates for UHECRs, capable of accelerating particles to 10^{20} eV

→ Escaping UHECRs from IceCube blazars can interact in the microwave, infrared, optical background field

→ Produce line of sight neutrinos and gamma rays, if the intervening magnetic field is low, $\lesssim 10^{-15}$ G

Essey & Kusenko 2010
Essey, Kalashev, Kusenko & Beacom 2010
Razzaque, Dermer & Finke 2012
Kalashev, Kusenko & Essey 2013

Motivation …

→ Detection of PeV neutrinos from blazars implies acceleration of cosmic rays to ≥ 10 PeV

→ Blazars are hot candidates for UHECRs, capable of accelerating particles to 10^{20} eV

→ Escaping UHECRs from IceCube blazars can interact in the microwave, infrared, optical background field

→ Produce line of sight neutrinos and gamma rays, if the intervening magnetic field is low, $\lesssim 10^{-15}$ G

Detection can establish blazars as UHECR sources

Essey & Kusenko 2010
Essey, Kalashev, Kusenko & Beacom 2010
Razzaque, Dermer & Finke 2012
Kalashev, Kusenko & Essey 2013

UHECR Accel and Escape from Blazars

Proton shock-acceleration time $t^p_{acc} \simeq \frac{20\eta}{3}\frac{r_L}{c} \simeq \frac{20\eta}{3}\frac{\gamma_p m_p c}{eB}$

Proton escape time $t^p_{esc} = \frac{R^2}{4D}$

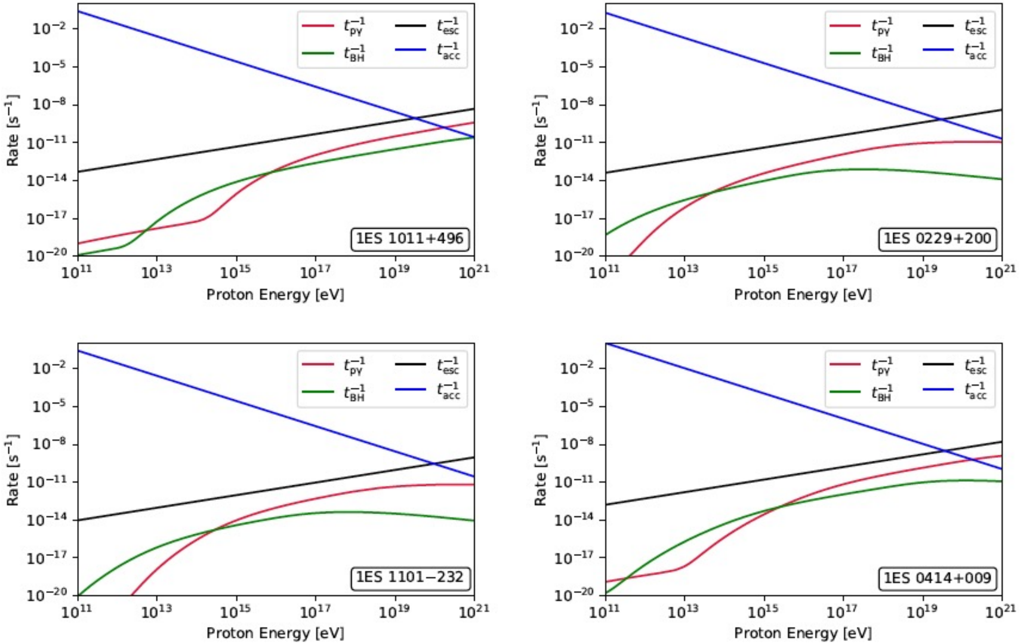
Diffusion coefficient $D_0(E/E_0)^{2-q}$

q = 3/2 Kraichnan turbulence
D_0 ~ 10^{27} - 10^{30} cm^2 /s

Pion and e+e- pair energy loss time

$$\frac{1}{t_{p\gamma}} = \frac{c}{2\gamma_p^2}\int_{\epsilon_{th}/2\gamma_p}^{\infty} d\epsilon'_\gamma \frac{n(\epsilon'_\gamma)}{\epsilon'^2_\gamma}\int_{\epsilon_{th}}^{2\epsilon\gamma_p} d\epsilon_r \sigma(\epsilon_r)K(\epsilon_r)$$

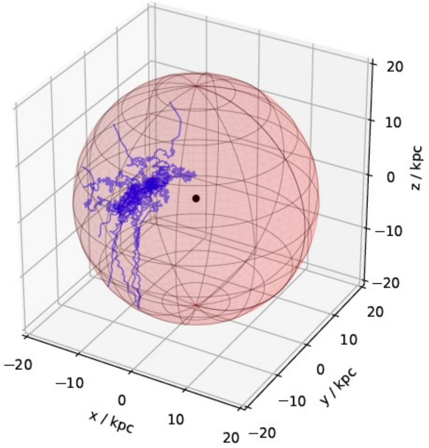
Das, Gupta & Razzaque 2019



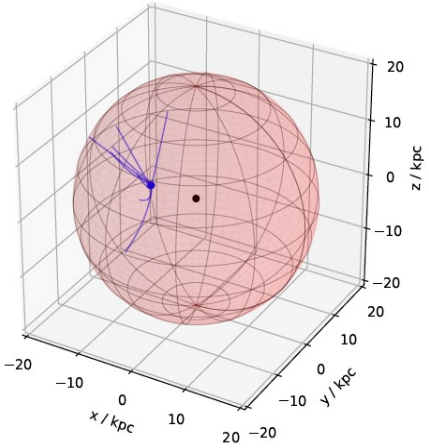
- Escape dominates over energy loss rate for protons
- Acceleration is limited by escape time
- Maximum proton energy escaping as UHECRs ~ 10^{19} eV

UHECR Propagation from Blazars

- Magnetic fields scramble directionality at low energies
- Deflection becomes smaller at higher energies

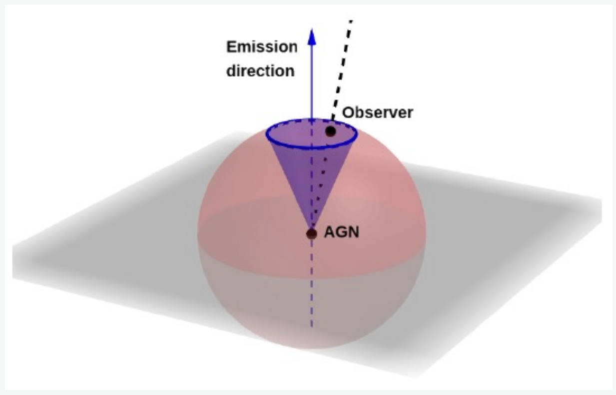


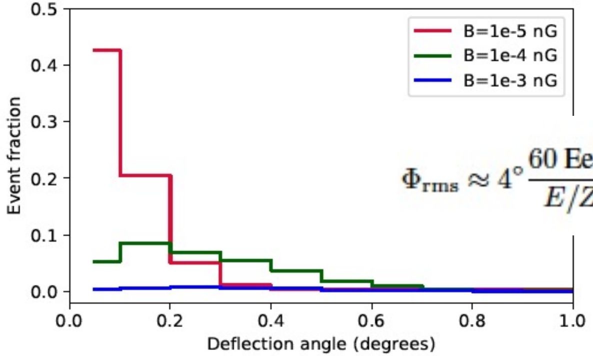
10^{17} eV



10^{19} eV

LoS propagation





$$\Phi_{\rm rms} \approx 4^\circ \frac{60\ {\rm EeV}}{E/Z} \frac{B_{\rm rms}}{10^{-9}\ {\rm G}} \sqrt{\frac{D}{100\ {\rm Mpc}}} \sqrt{\frac{l_c}{1\ {\rm Mpc}}}$$

Das, Gupta & Razzaque 2019

Propagation Details

Injection of UHECRs
Injected as a power law

Interactions
Pair production
Photopion
Photodisintegration
With EBL models

Propagation of secondaries
Nucleon, gamma, neutrino

Magnetic deflections

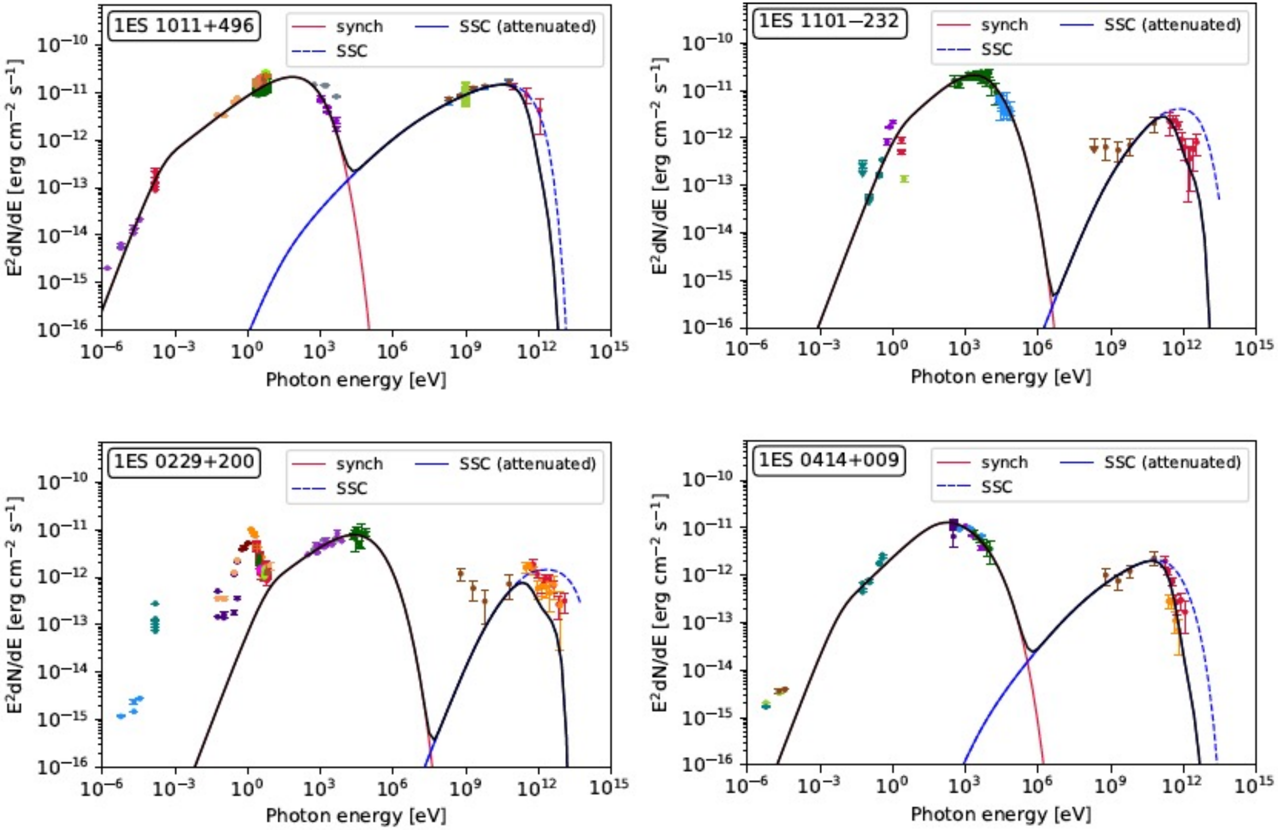
Earth

CRPropa 3 *Batista et al. 2016*

DINT *Heiter et al. 2018*

Leptonic Model Fits to Selected Blazars

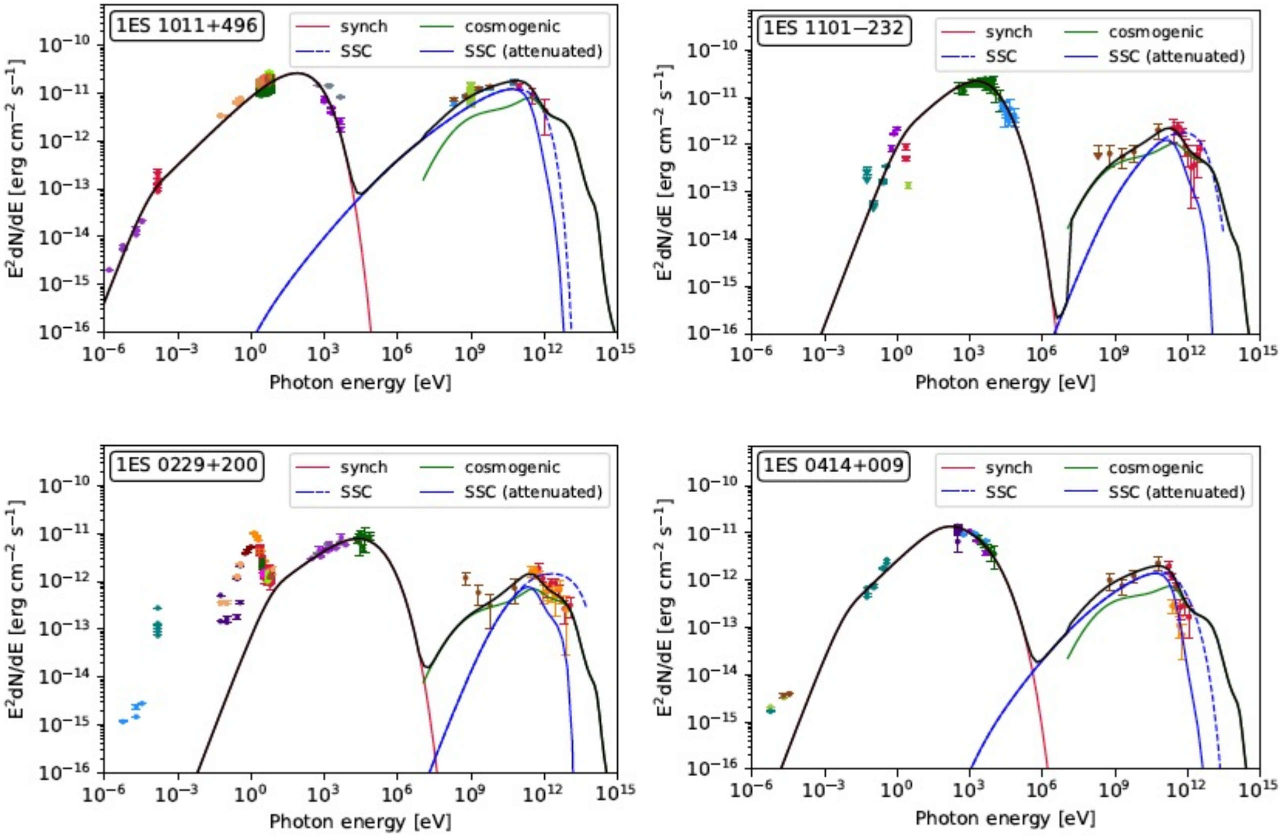
- UHECR contribution is relevant only for non-variable gamma-ray emission from blazars
- Any variability in gamma rays from UHECRs will wash-out while propagation
- Fit quiescent/steady-state spectrum
- Single-zone leptonic (synchrotron + Compton) model is inadequate



Das, Gupta & Razzaque 2019

Fits to Blazar SEDs with LoS Photons

- Leptonic SSC model with LoS gamma rays from UHECR
- UHECR contribution is relevant only for non-variable gamma-ray emission from blazars
- Any variability in gamma rays from UHECRs will wash-out while propagation
- Fit quiescent/steady-state spectrum



Das, Gupta & Razzaque 2019

Blazars associated with IceCube ν

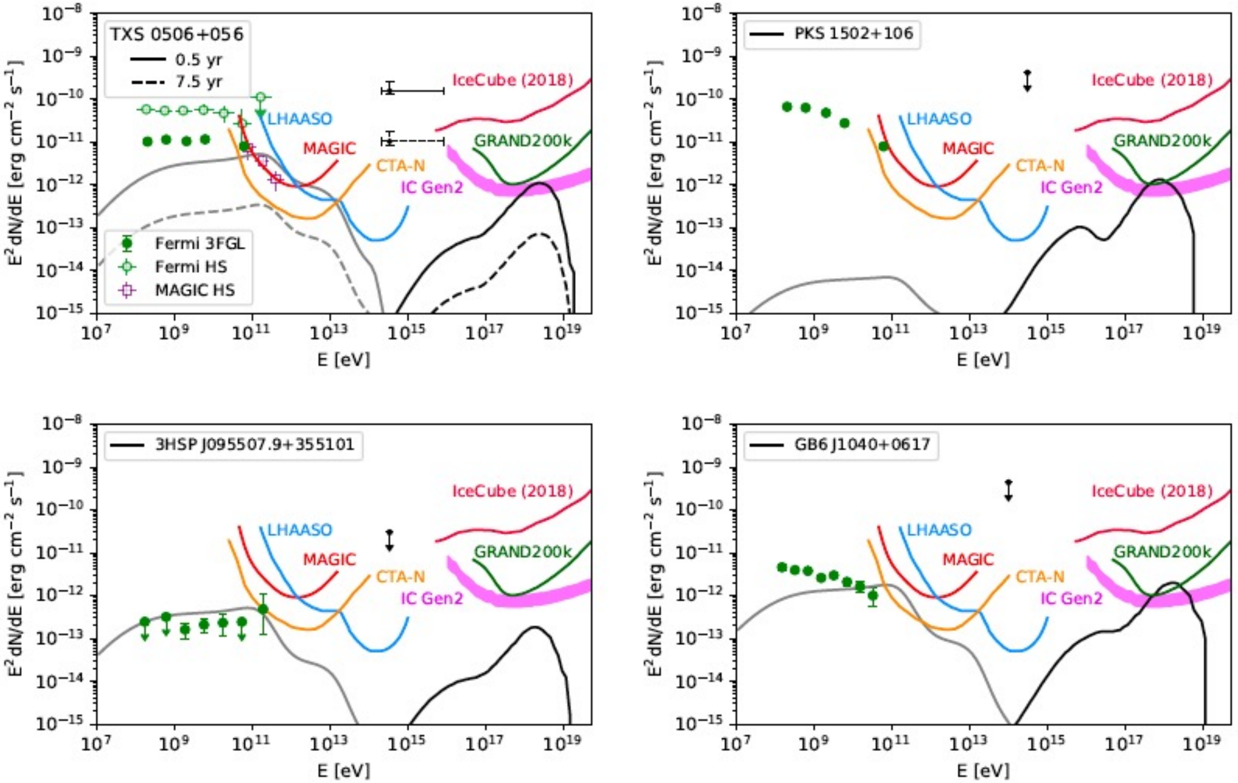
Four source candidates

- **IC-170922A:** TXS 0506+056 (z = 0.3365) — *IceCube Collab. 2018*
- **IC-190730A:** PKS 1502+106 (z = 1.84) — *IceCube Collab. 2019*
- **IC-200107A:** 3HSP J095507.9+355101 (z = 0.557) — *IceCube Collab. 2020*
- **IC-141209A:** GB6 J1040+0617 (z = 0.7351) — *Garappa et al. 2019*

- Calculate neutrino luminosity from IceCube event in the relevant energy range
- UHECR proton (> 10^{17} eV) luminosity: $L_{\rm UHCR} = \alpha\, L_{\rm IC\nu}$
- Inject UHECR protons with spectrum $E^{-2.2}$, $B_{\rm IGMF} = 10^{-16}$ G
- LoS ν and γ fluxes have hard spectra compared to source fluxes
- Detection of LoS ν and/or γ fluxes can confirm IC blazars as UHECR sources

LoS ν and γ from IceCube Blazars

- IceCube (2018) flux upper limit from 9 years of (*Aartsen et al. 2018*)
- IceCube Gen2 with radio upgrade 5 yr sensitivity (*Aartsen et al. 2019*)
- GRAND 200k is sensitivity is for 3-yr observation (*Alvarez-Muniz et al. 2020*)
- LHAASO 1-yr sensitivity (*Vernetto 2016*)
- MAGIC 50-hr sensitivity (*Aleksic et al. 2016*)
- CTA-N 50-hr sensitivity (*Gueta, ICRC 2021*)
- See also future neutrino follow-up by CTA (Sergijenko, *ICRC 2021*)



Das, Razzaque & Gupta 2021

Prospects for Detection

- **TXS 0506+056** can be detected with LoS neutrinos by IC Gen-2 and with LoS photons by CTA, if $L_{UHCR} \geq 5L_{IC\nu} \sim 2\text{x}10^{46}$ erg/s
- **PKS 1502+106** can be detected with LoS neutrinos by IC Gen-2, but $L_{IC\nu} \sim 10^{49}$ erg/s is already above the Eddington luminosity because of its high redshift
- **3HSP J095507.9+355101** can be detected with LoS neutrinos by IC Gen-2, if $L_{UHCR} \geq 10L_{IC\nu} \sim 4\text{x}10^{47}$ erg/s and with LoS photons by CTA, if $L_{UHCR} \geq 5L_{IC\nu} \sim 2\text{x}10^{47}$ erg/s
- **GB6 J1040+0617** can be detected with LoS neutrinos by IC Gen-2 and with LoS photons by CTA, but $L_{IC\nu} \sim 10^{48}$ erg/s is already above the Eddington luminosity because of its high redshift

Prospects for Detection

✅ • **TXS 0506+056** can be detected with LoS neutrinos by IC Gen-2 and with LoS photons by CTA, if $L_{UHCR} \geq 5L_{IC\nu} \sim 2\text{x}10^{46}$ erg/s

❌ • **PKS 1502+106** can be detected with LoS neutrinos by IC Gen-2, but $L_{IC\nu} \sim 10^{49}$ erg/s is already above the Eddington luminosity because of its high redshift

✅ • **3HSP J095507.9+355101** can be detected with LoS neutrinos by IC Gen-2, if $L_{UHCR} \geq 10L_{IC\nu} \sim 4\text{x}10^{47}$ erg/s and with LoS photons by CTA, if $L_{UHCR} \geq 5L_{IC\nu} \sim 2\text{x}10^{47}$ erg/s

❌ • **GB6 J1040+0617** can be detected with LoS neutrinos by IC Gen-2 and with LoS photons by CTA, but $L_{IC\nu} \sim 10^{48}$ erg/s is already above the Eddington luminosity because of its high redshift

Conclusions

- Line-of-sight neutrino and gamma-ray fluxes can probe UHECR acceleration in sources, if the intergalactic magnetic field is relatively low
- Line-of-sight fluxes are expected to appear as hard components compared to source fluxes, within sensitivity reaches of upcoming telescopes
- Fits to SEDs of a few gamma-ray balazars can be improved with LoS gamma ray fluxes together with conventional source SED models
- Detection of LoS neutrino and gamma-ray fluxes from blazars associated with IceCube neutrino detection can establish those as UHECR sources
- Blazars TXS 0506+056 and 3HSP J095507.9+355101 should be prime targets for upcoming telescopes such as IceCube Gen-2 and CTA

Conclusions

- Line-of-sight neutrino and gamma-ray fluxes can probe UHECR acceleration in sources, if the intergalactic magnetic field is relatively low
- Line-of-sight fluxes are expected to appear as hard components compared to source fluxes, within sensitivity reaches of upcoming telescopes
- Fits to SEDs of a few gamma-ray balazars can be improved with LoS gamma ray fluxes together with conventional source SED models
- Detection of LoS neutrino and gamma-ray fluxes from blazars associated with IceCube neutrino detection can establish those as UHECR sources
- Blazars TXS 0506+056 and 3HSP J095507.9+355101 should be prime targets for upcoming telescopes such as IceCube Gen-2 and CTA

Thank you!