UJ CAPP

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Ultrahigh-energy cosmic-ray induced gamma-ray and neutrino fluxes from blazars

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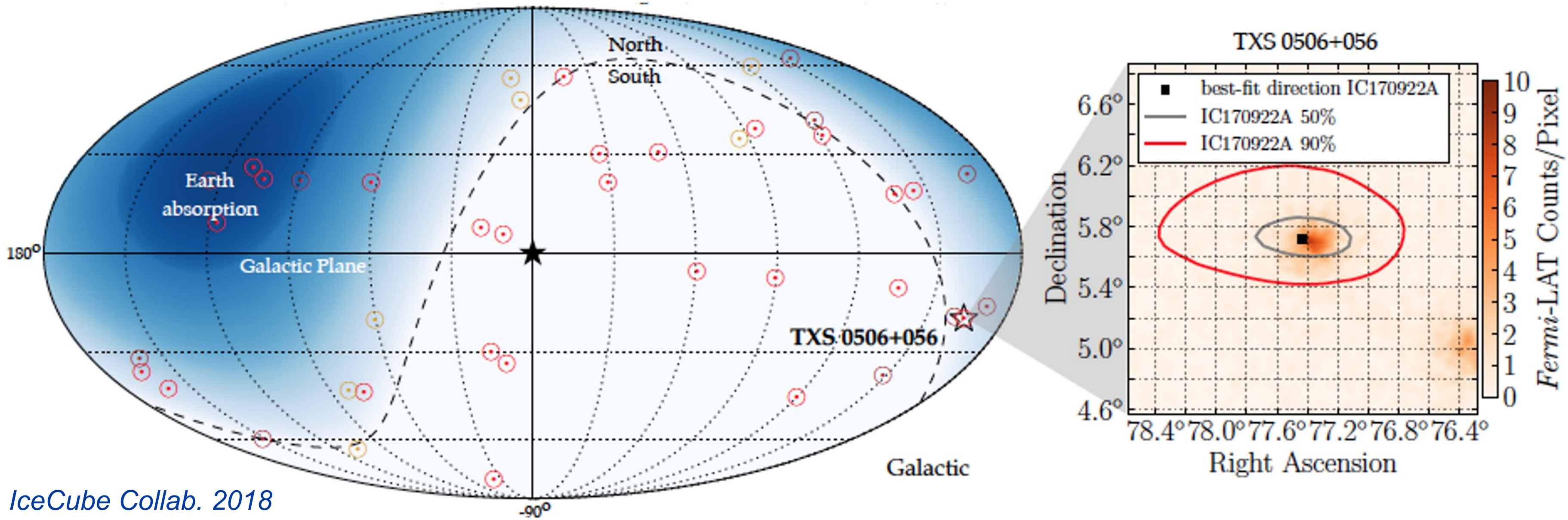
With Saikat Das and Nayantara Gupta

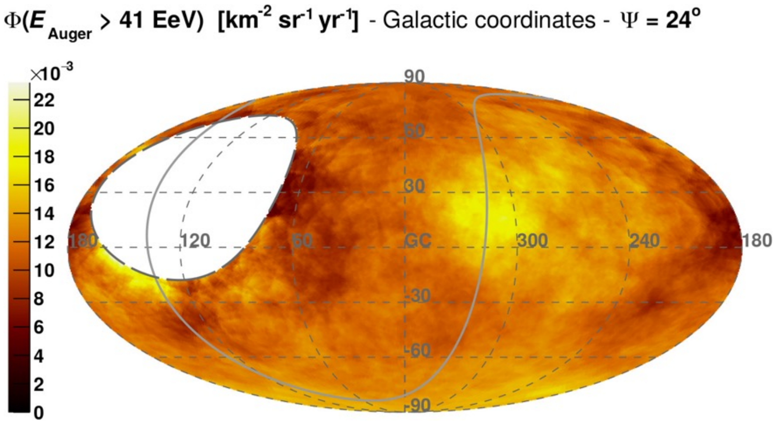
Plausible association of blazars and ν

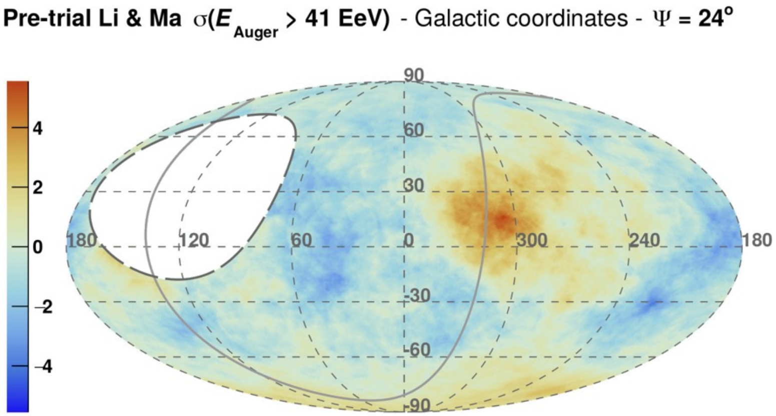
- IC -170922A event detected from the direction of BL Lac TXS 0506+056 during flare in 2017
- Chance coincidence can be rejected at 3 sigma level



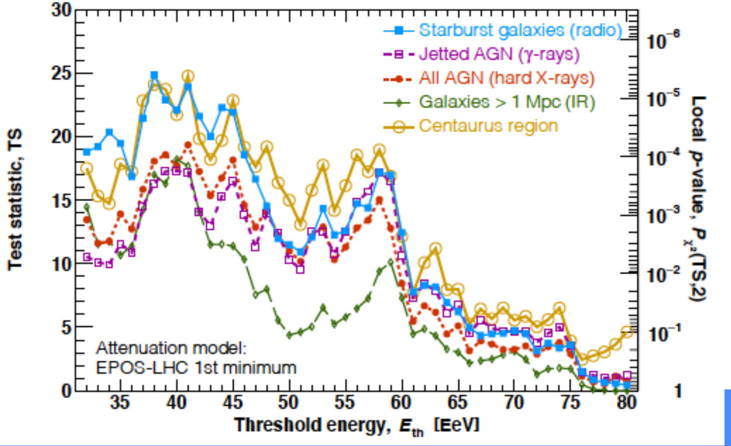
IceCube Collab. 2018

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



Motivation …

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

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

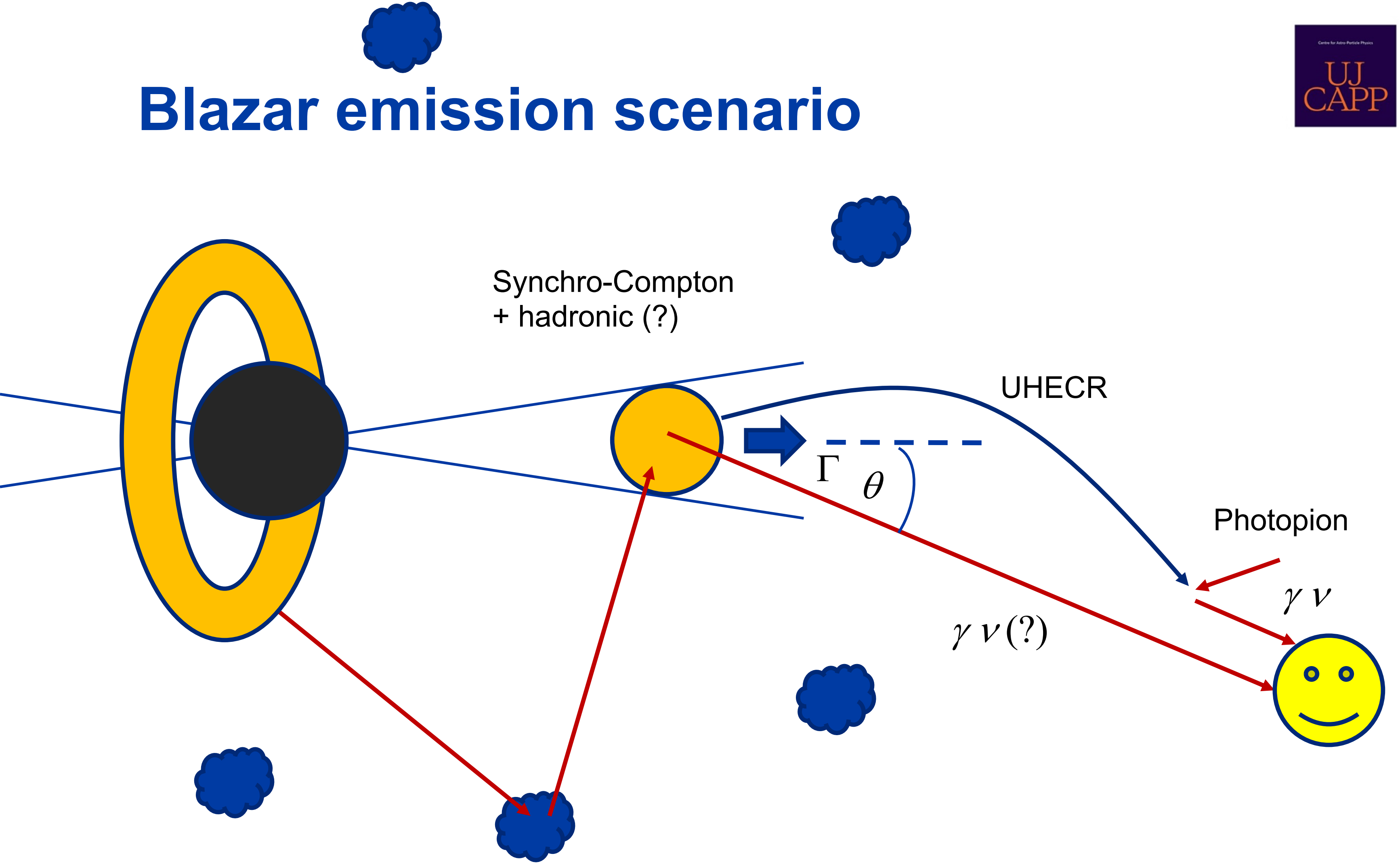
→ Escaping UHECRs from IceCube blazars can interact in the microwave, infrared, optical background field

→ Produce line of sight neutrinos and gamma rays, if the intervening magnetic field is low, $< 10^{-14}$ G

Detection can establish blazars as UHECR sources

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

Blazar emission scenario



Strategy …

- Select blazars with non-variable VHE emission

  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 SEDs with single-zone leptonic SSC model + LoS gamma rays from UHECRs

  Fit quiescent/steady-state spectrum

- Check if gamma-rays from UHECRs improve fit to VHE data

1ES 1011+496, 1ES 0229+200, 1ES 1101-232, 1ES 0414+009

UHECR accel. and escape from jet

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

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

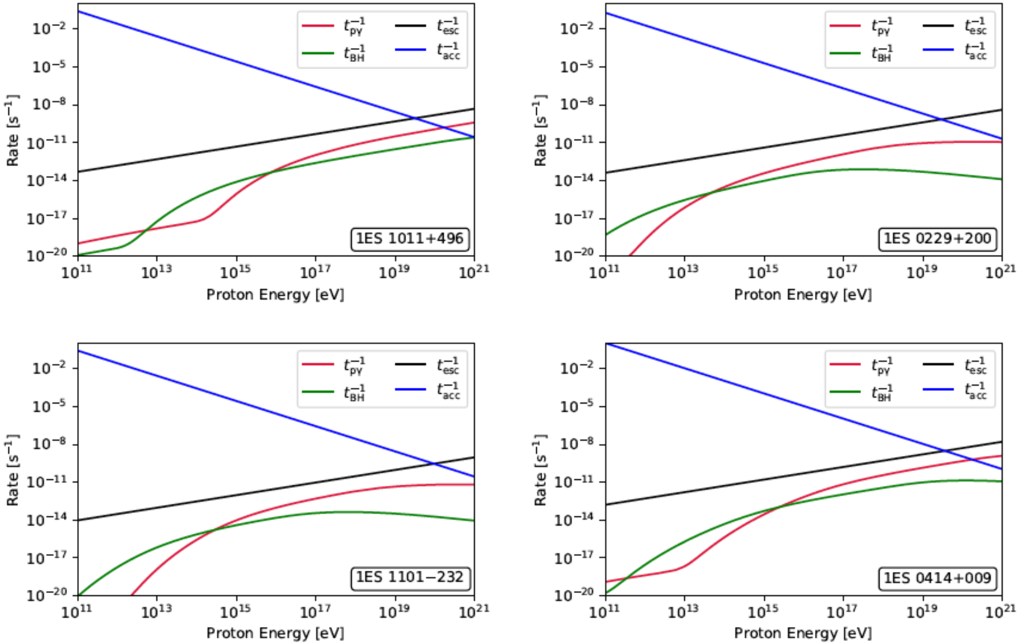
Diffusion coefficient $D_0(E/E_0)^{2-q}$

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 2020, ApJ

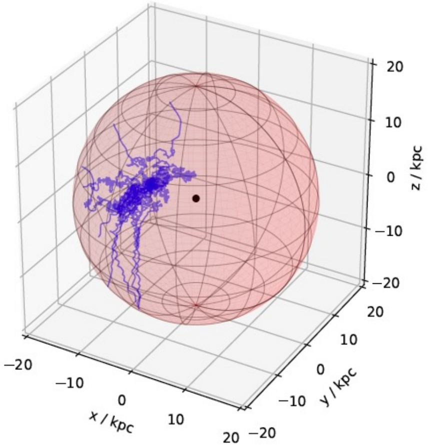


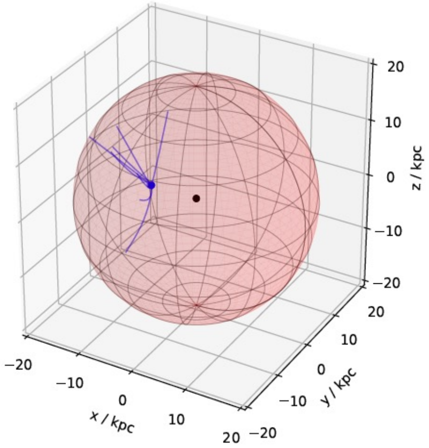
- Escape dominates over energy loss rate for protons
- Acceleration is limited by escape time
- Maximum proton energy escaping as UHECRs ~ 10^{20} eV

UHECR propagation in intergal. media

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

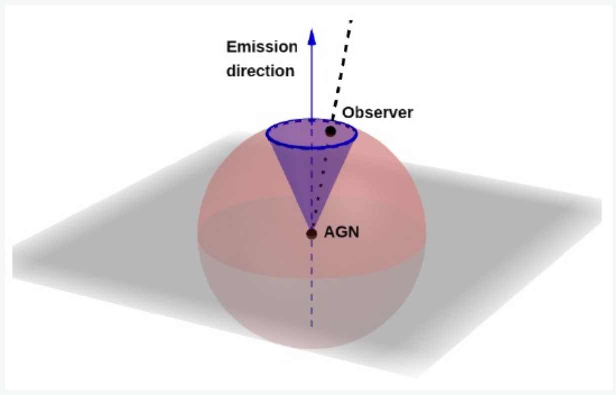
10^{17} eV

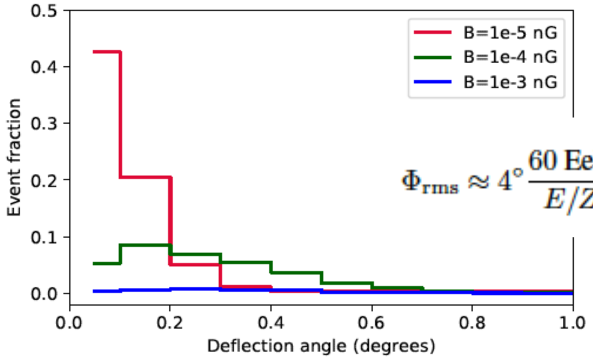




10^{19} eV

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 2020, ApJ

Interactions and secondaries

Injection of UHECRs
Injected as a power law

Interactions
Pair production
Photopion
Photodisintegration
With EBL models

Magnetic deflections

Propagation of secondaries
Nucleon, gamma, neutrino

Earth

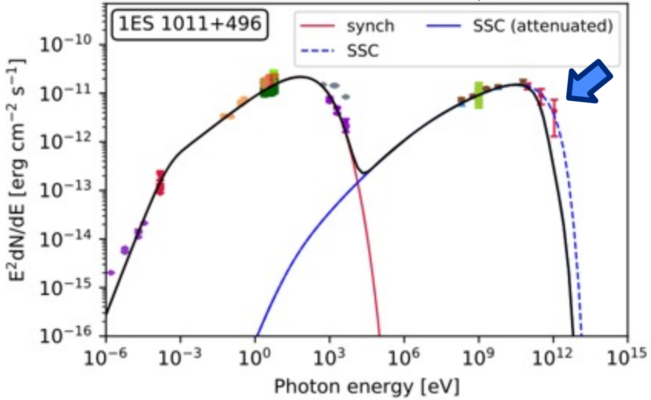
CRPropa 3 — *Batista et al. 2016*

DINT — *Heiter et al. 2018*

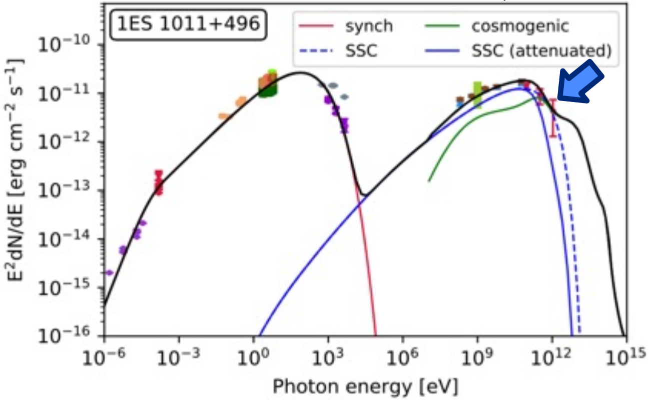
One-zone SSC emission from the jet is calculated with GAMERA - http://libgamera.github.io/GAMERA/docs/main_page.html

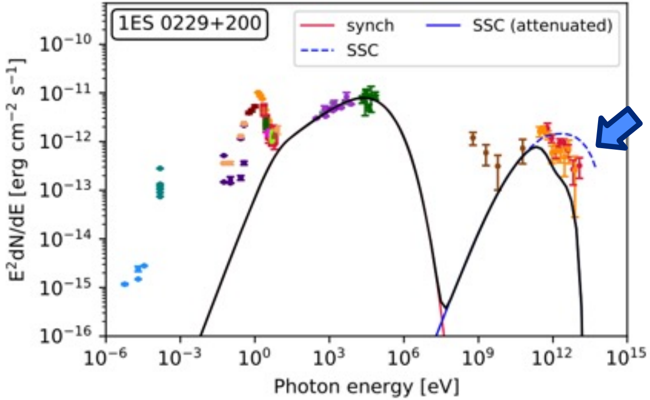
Fits to blazar SEDs with LoS γ rays

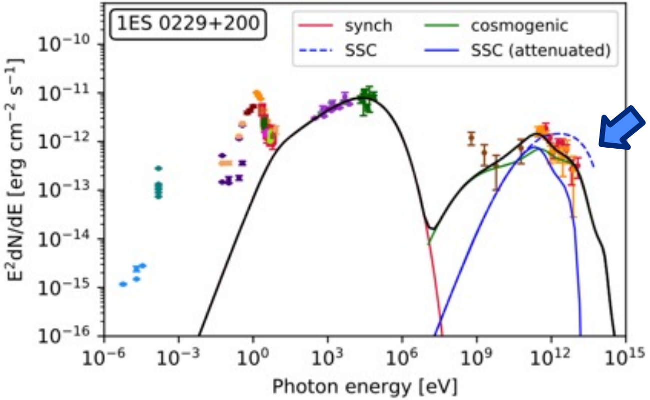
Without UHECR LoS γ



With UHECR LoS γ



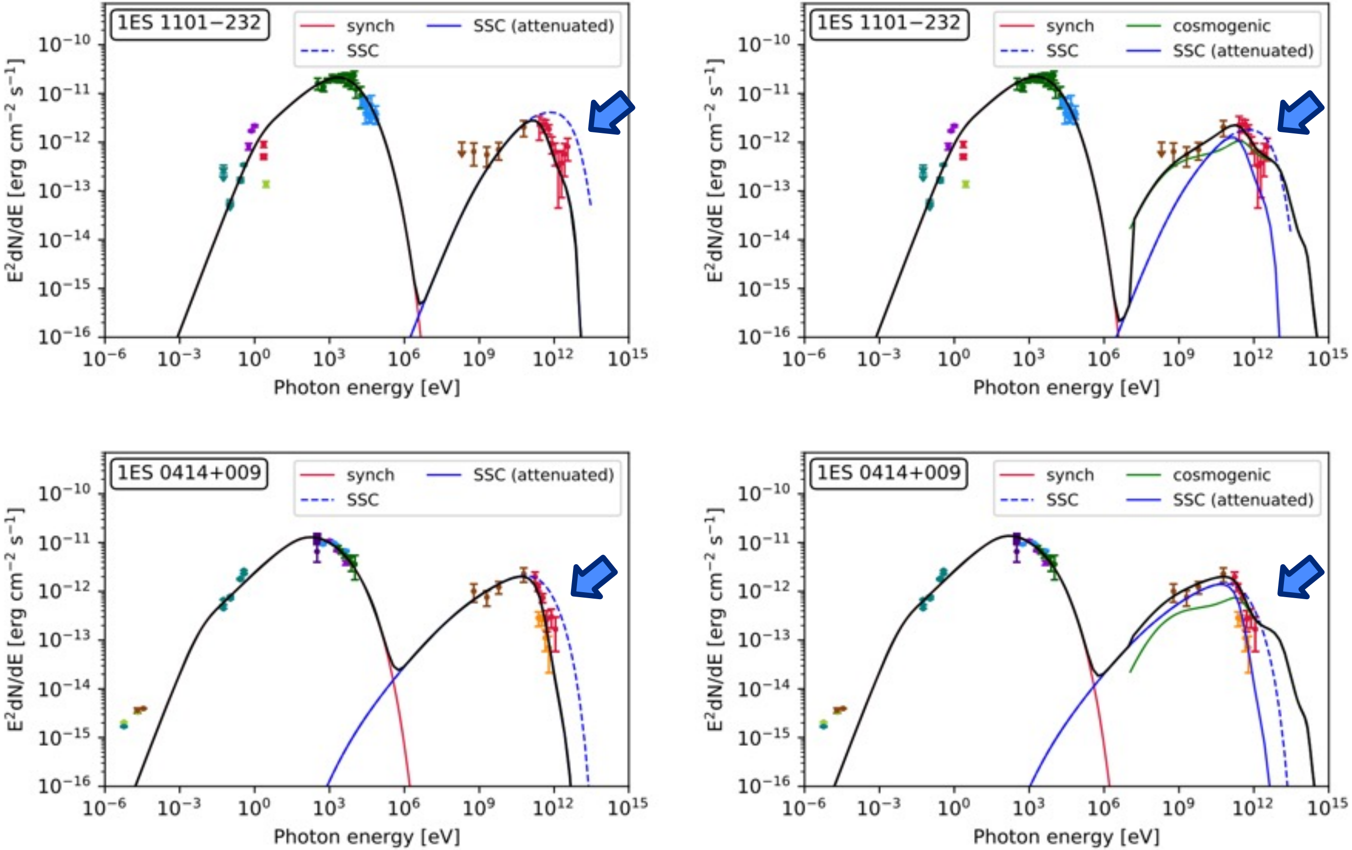




Das, Gupta & Razzaque 2020, ApJ

Fits to blazar SEDs with LoS γ rays

Without UHECR LoS γ | With UHECR LoS γ



Das, Gupta & Razzaque 2020, ApJ

SED model parameters

Table 2
Fit Parameters for the Multiwavelength SED Modeling in Figure 4

HBL	$E_{e,\min}$ (GeV)	$E_{e,\mathrm{cut}}$ (GeV)	α	R (cm)	B (Gauss)	δ_D	L_e (erg s^{-1})	L_B (erg s^{-1})	L_{UHECR} (erg s^{-1})	L_{Edd} (erg s^{-1})
Pure-leptonic model										
1ES 1011+496	0.08	75.0	2.2	1.5×10^{17}	0.024	20	5.8×10^{38}	1.9×10^{43}	...	...
1ES 0229+200	10.00	1500.0	2.2	1.0×10^{16}	0.015	40	1.3×10^{38}	1.3×10^{41}	...	...
1ES 1101–232	5.70	550.0	2.0	8.4×10^{16}	0.020	22	6.0×10^{37}	5.1×10^{42}	...	...
1ES 0414+009	0.20	200.0	2.0	7.0×10^{16}	0.080	22	7.6×10^{37}	5.7×10^{43}	...	...
Leptonic + hadronic (UHECR) model										
1ES 1011+496	0.04	65.0	2.0	2.2×10^{17}	0.020	20	3.8×10^{38}	2.9×10^{43}	4.8×10^{44}	5.1×10^{46}
1ES 0229+200	10.00	1500.0	2.2	1.0×10^{16}	0.015	40	1.3×10^{38}	1.3×10^{41}	2.6×10^{43}	1.7×10^{47}
1ES 1101–232	5.70	500.0	2.0	1.4×10^{17}	0.020	22	3.5×10^{37}	1.4×10^{43}	3.0×10^{43}	1.0×10^{47}
1ES 0414+009	0.20	200.0	2.0	9.0×10^{16}	0.080	22	5.9×10^{37}	9.4×10^{43}	1.0×10^{44}	2.0×10^{47}

Das, Gupta & Razzaque 2020, ApJ

Blazars associated with IceCube ν

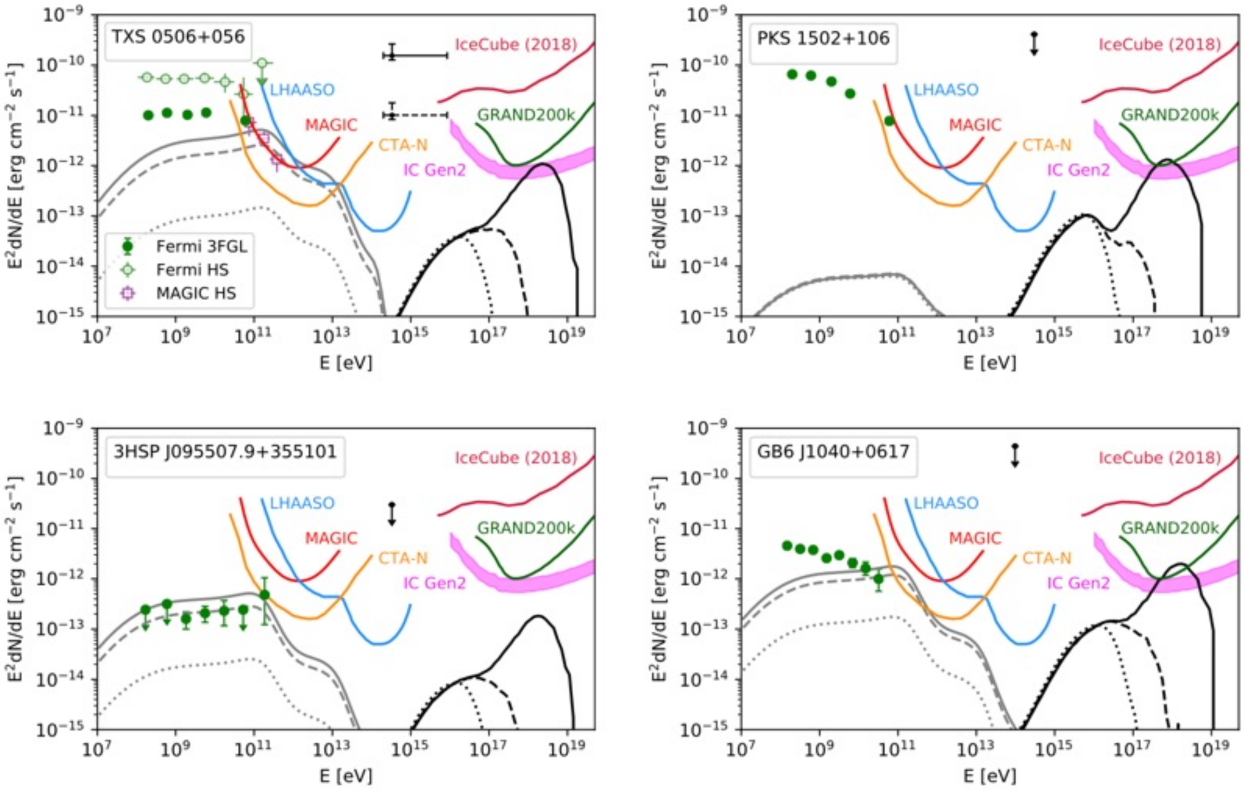
Four source candidates

- **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: $L_{\mathrm{UHCR}} = \alpha\, L_{\mathrm{IC}\nu}$
- Inject UHECR protons with spectrum $E^{-2.2}$, $B_{\mathrm{IGMF}} = 10^{-16}$ 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 2022, A&A Lett.

Prospects for Detection

✅ • **TXS 0506+056** can be detected with LoS neutrinos by IC Gen-2 and with LoS photons by CTA, if $L_{UHCR} \geq 5L_{IC\nu}$ (7.5 yr) ~ $2\text{x}10^{46}$ erg/s

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

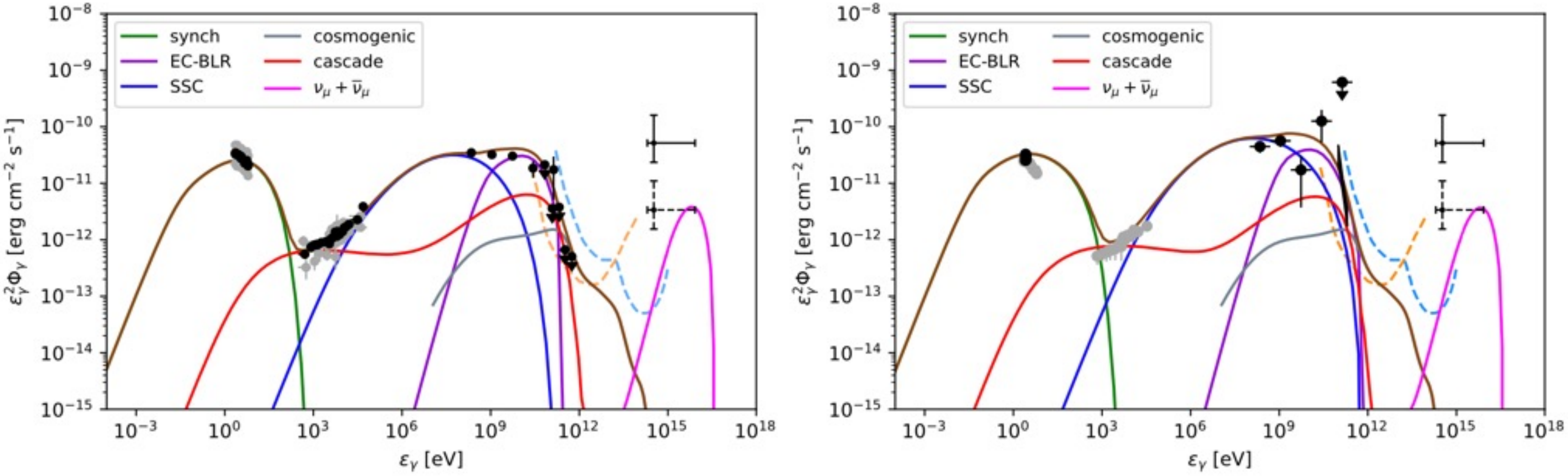
✅ • **3HSP J095507.9+355101** can be detected with LoS neutrinos by IC Gen-2, if $L_{UHCR} \geq 10L_{IC\nu}$ (10 yr) ~ $4\text{x}10^{47}$ erg/s and with LoS photons by CTA, if $L_{UHCR} \geq 5L_{IC\nu}$ ~ $2\text{x}10^{47}$ erg/s

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

Detailed SED modeling to further constrain UHECR components

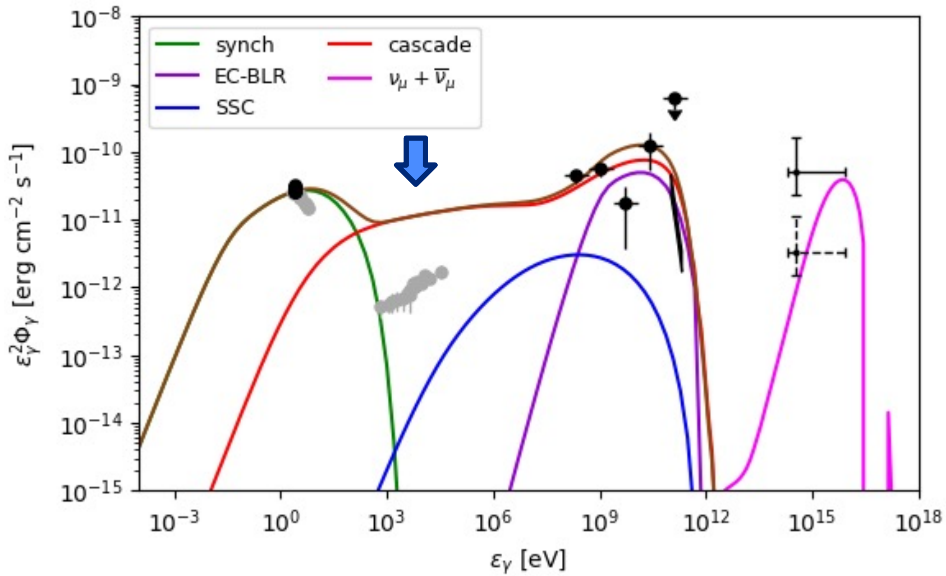
MM SED Model of TXS 0506+056

- MAGIC campaign: Nov 2017 – Feb 2019 → Flaring in VHE in Dec 2018 (No neutrinos)
- Modeling with leptonic (Synchro+SSC+EC) and hadronic (pγ+cascade) and UHECR emissions
- No variation in neutrino flux from modeling → fitting 7.5 yr IceCube flux



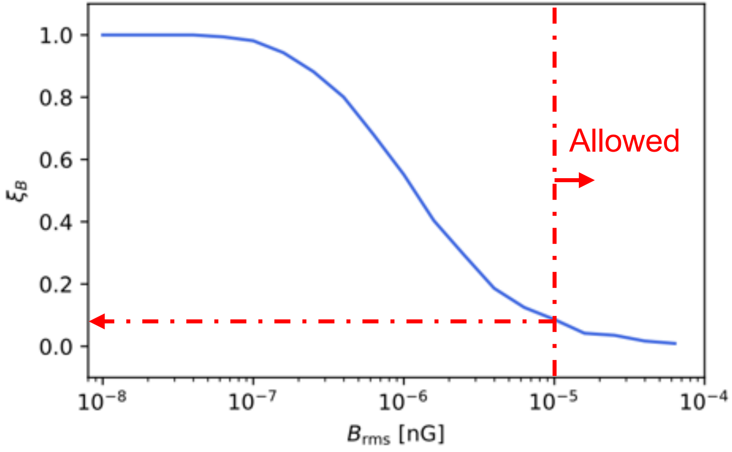
MM SED Model of TXS 0506+056

- Constraint from X-ray data disfavors 0.5 yr IceCube neutrino flux
- Gamma-ray and neutrino flares are uncorrelated



Constraints on model parameters

Lower limit on extragalactic magnetic field from fraction UHECR-induced radiation along line-of-sight



CTA observations can further constrain $B_{\rm rms}$

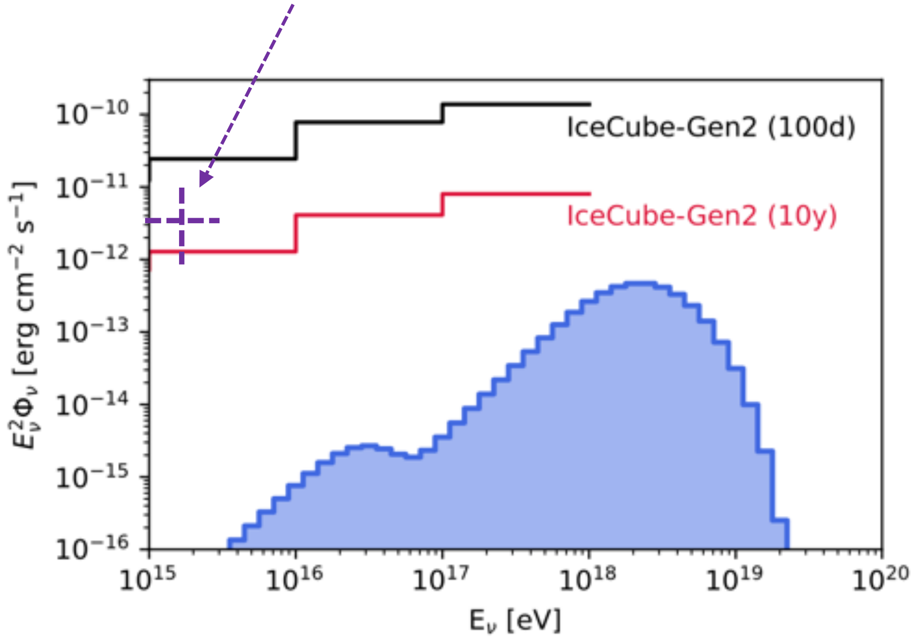
No significant variation in parameters

Parameters	Low State	High State
δ_D	28	"
B' [G]	0.28	"
R' [cm]	10^{16}	"
$u'_{\rm BLR}$ [erg/cm^3]	0.01	"
$T'_{\rm BLR}$ [K]	2×10^5	"
α (e/p spectral index)	2.0	"
β (log parabola index)	0.3	"
E_0 [MeV]	500	"
$E'_{\rm e,min}$ [GeV]	0.20	0.25
$E'_{\rm e,max}$ [GeV]	10	25
$L_e^{\rm obs}$ [erg/s]	5.8×10^{44}	7.6×10^{44}
$E'_{\rm p,min}$ [GeV]	10	"
$E'_{\rm p,max}$ [PeV]	6.3	"
$L_p^{\rm obs}$ [erg/s]	1.6×10^{48}	"

Detection of cosmogenic ν unlikely

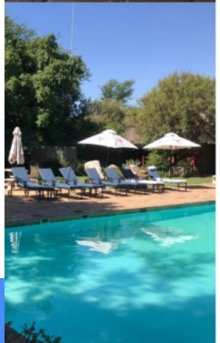
TXS 0506+056

7.5 yr IceCube neutrino flux



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 gamma-ray 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
- TXS 0506+056 is the prime targets for upcoming CTA to probe UHECR acceleration in blazar jets



Important Deadlines

1 May 2022

Abstract submission opens

1 June 2022

Registration opens

8 August 2022

~~31 July 2022~~

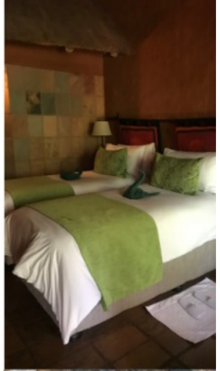
Abstract submission closes

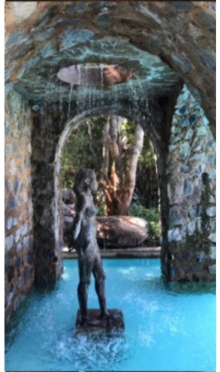
15 August 2022

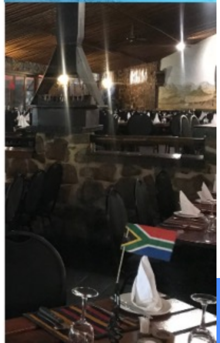
Notification of talks/posters

2 September 2022

Registration closes







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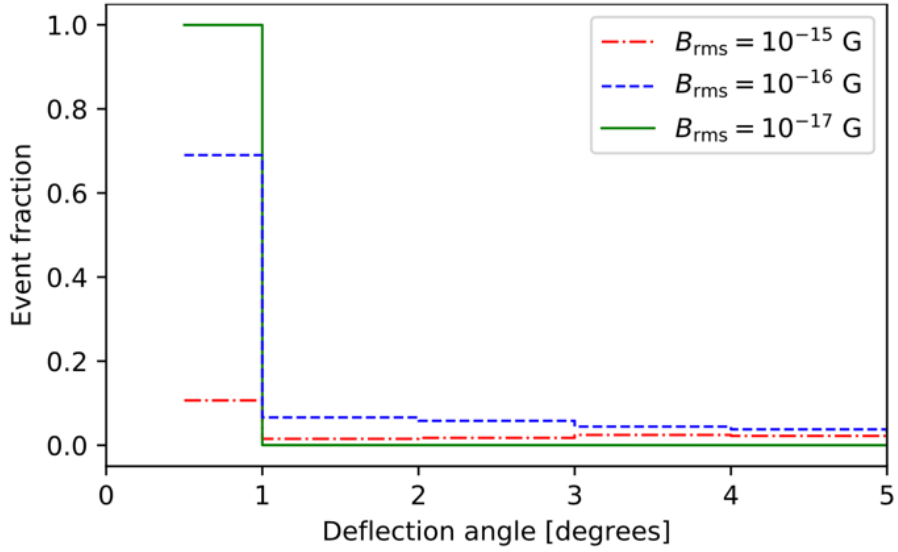
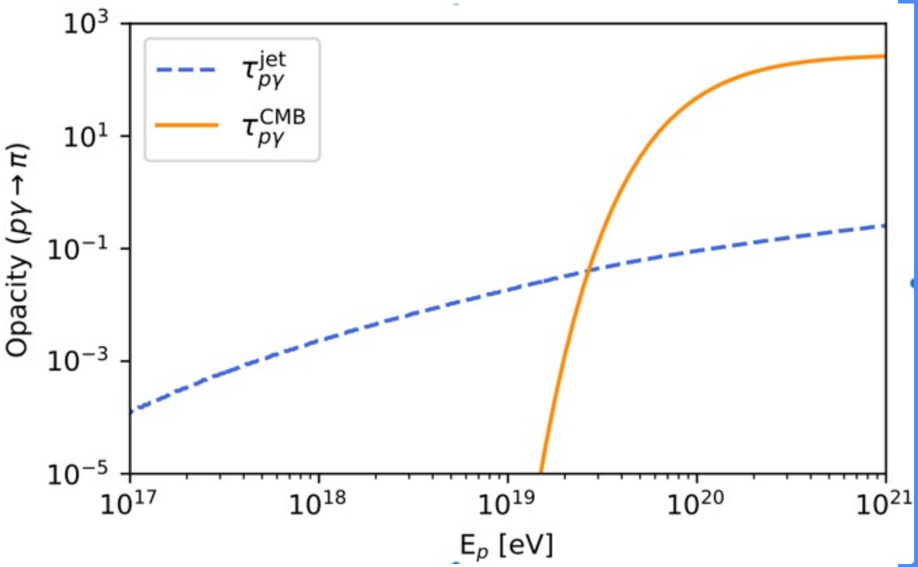
Thank you!

Backup slide – TXS 0506+056





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