Hadronic models of high-energy radiation from AGN jets

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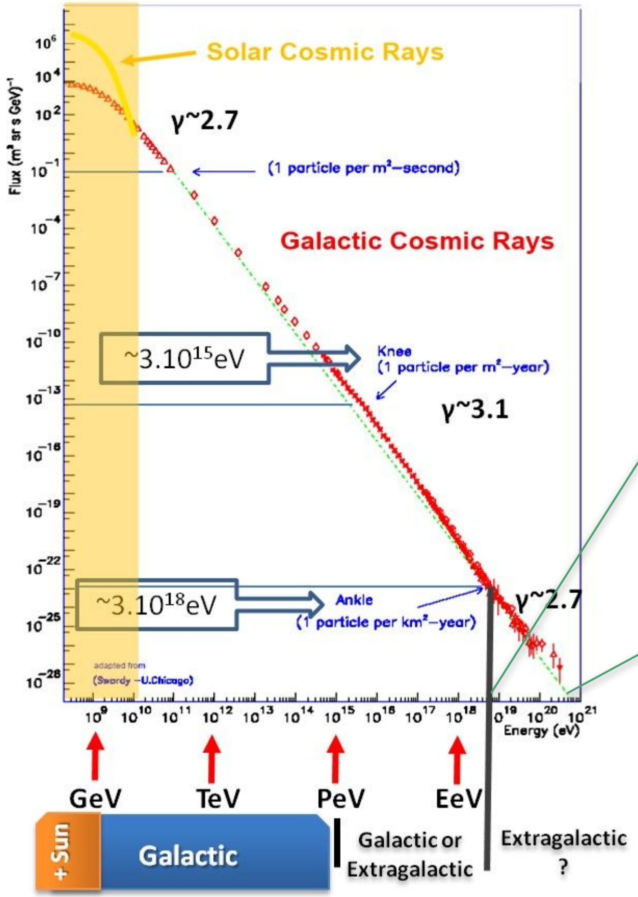
MSc & PhD students: S. I. Stathopoulos (NKUA), F. Psarras (NKUA)

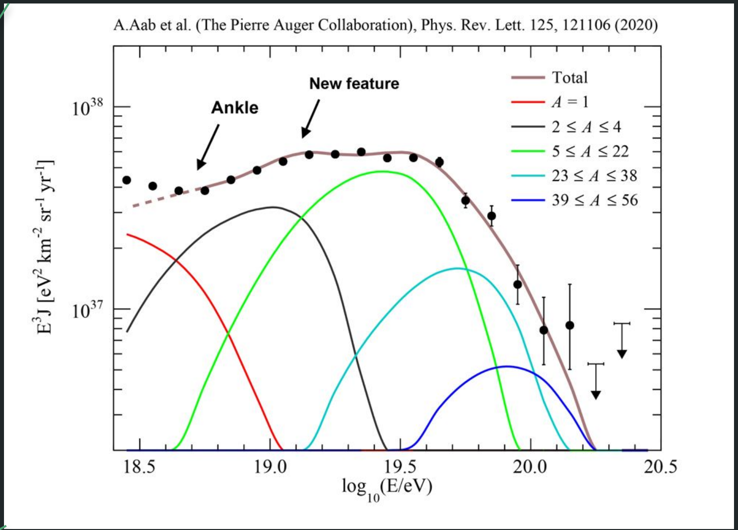
MERAC

Introduction

The Cosmic-ray (CR) flux spectrum

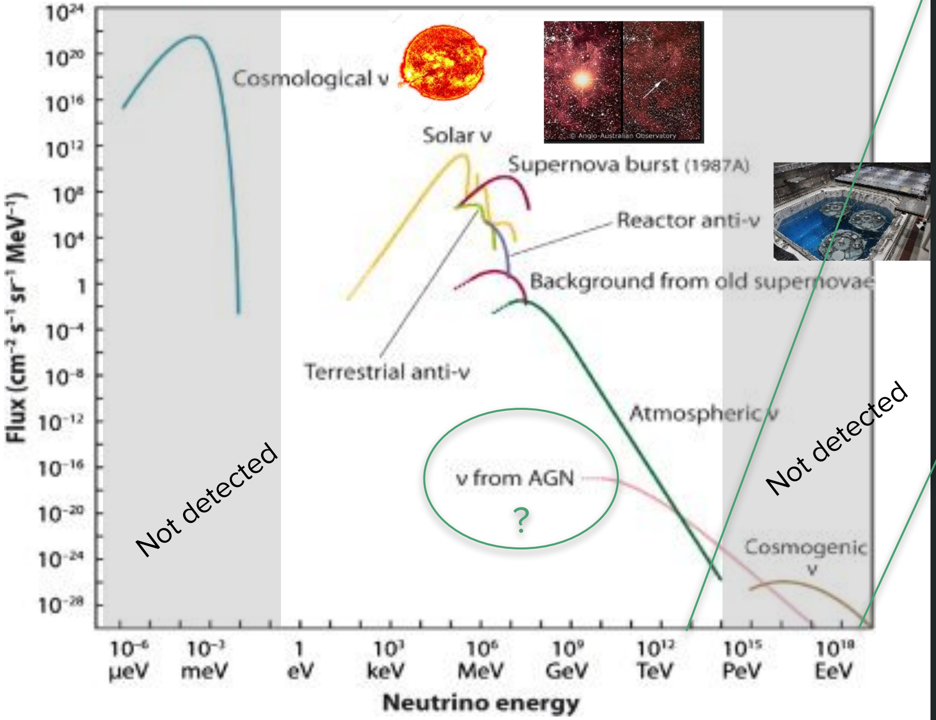


Credit: A. Papaioannou, adopted from the CR spectrum by S. Swordy



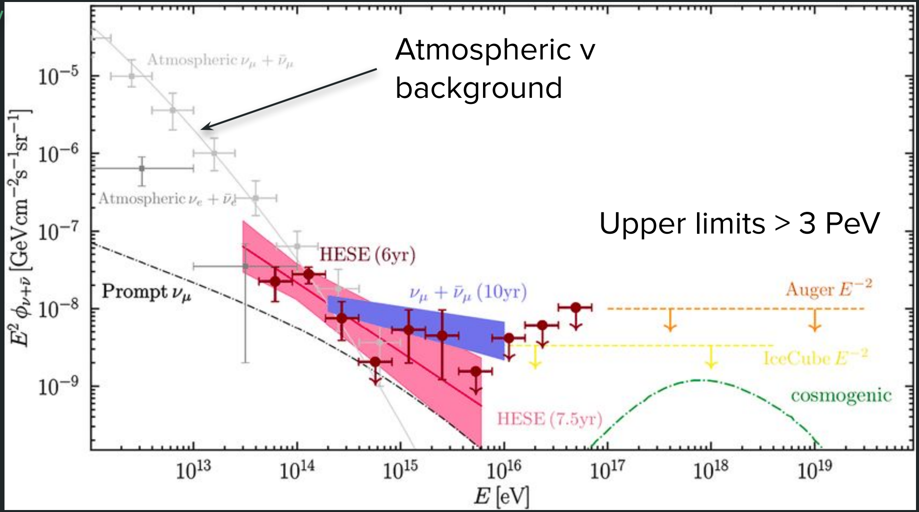
- Detection of UHECRs (E > EeV) ➔ direct evidence for presence of extragalactic hadronic accelerators
- Sources of UHECRs are still not known

The Neutrino (ν) flux spectrum



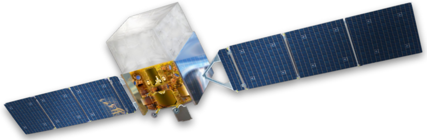
Katz & Spiering 2012, PPNP

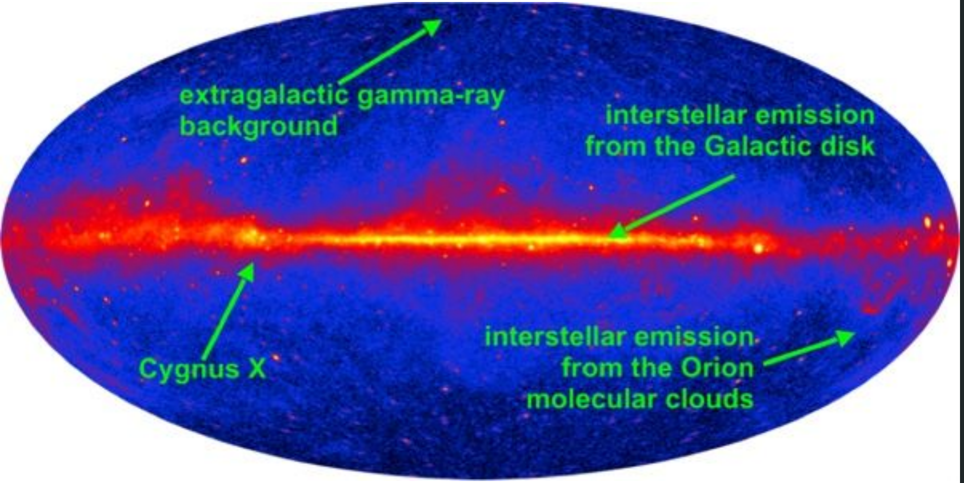
Kheirandish, A. 2020, A&SS



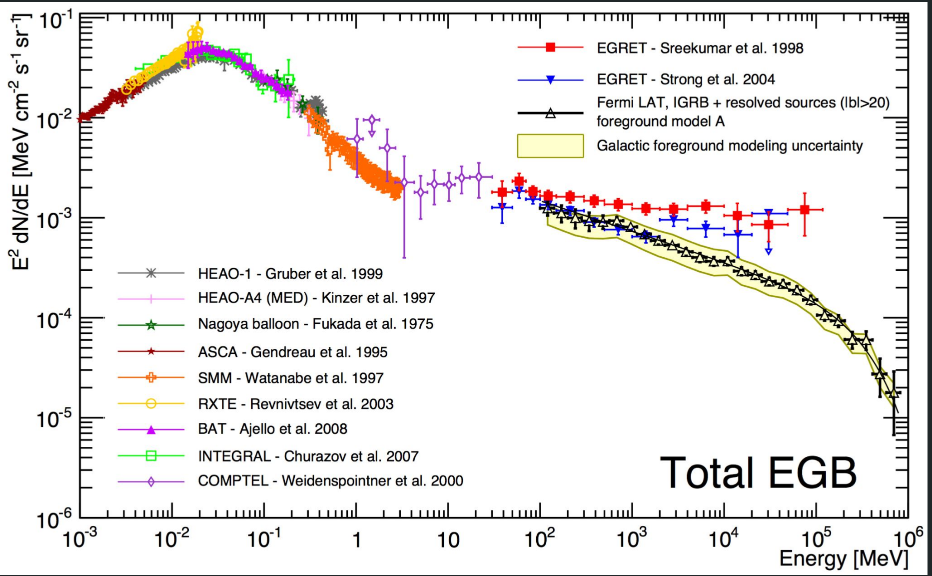
- Detection of HE ν (E > 10 TeV) ➔ evidence for presence of hadronic accelerators
- Sources of HE ν are still not known

The extragalactic Gamma-ray (γ) background





5yr Fermi sky map of γ-rays above 100 MeV



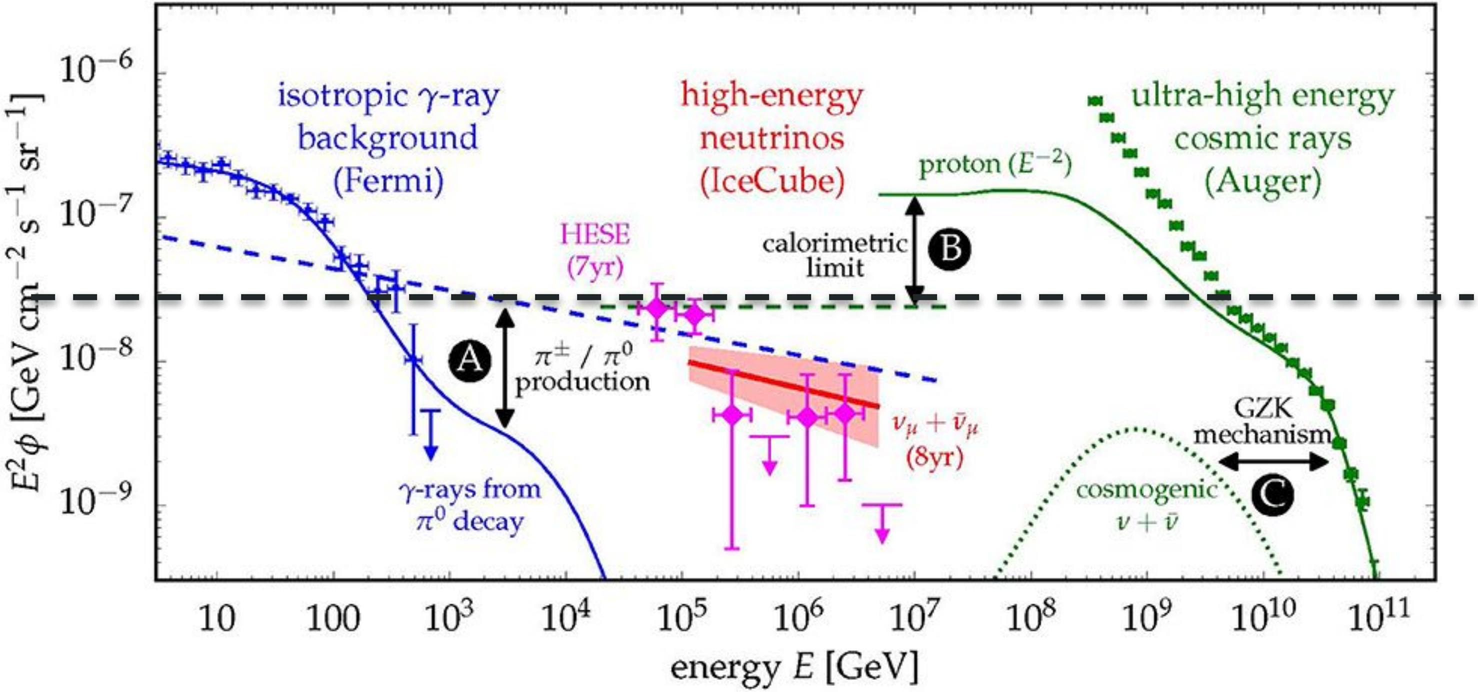
Extragalactic Gamma-ray Background (EGB) is the sum of:

1. truly diffuse extragalactic γ-ray emission
2. emission from unresolved sources

Ackermann et al. 2015, ApJ

The multi-messenger picture

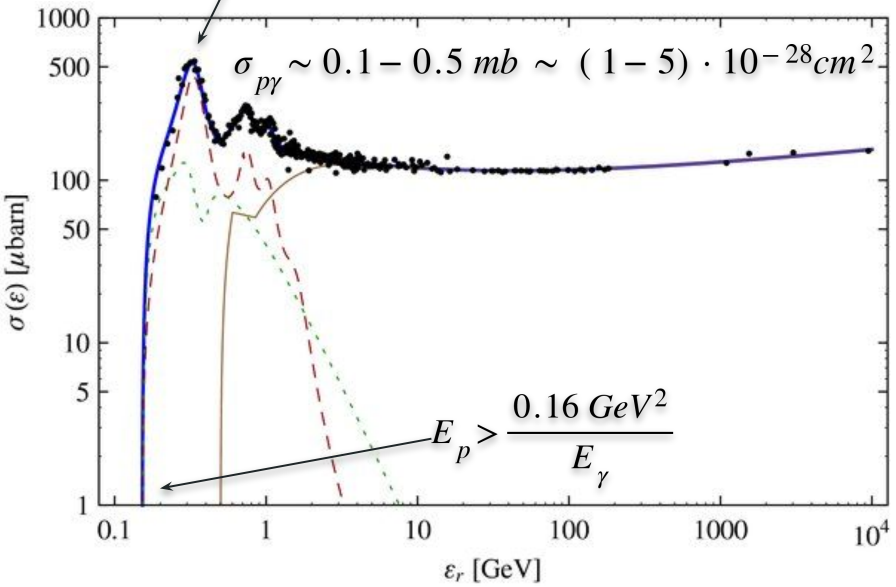
Energy production rates are comparable to a few ~10^{43} erg Mpc^{-3} yr^{-1} → Common sources?



Halzen & Kheirandish, 2019, Frontiers

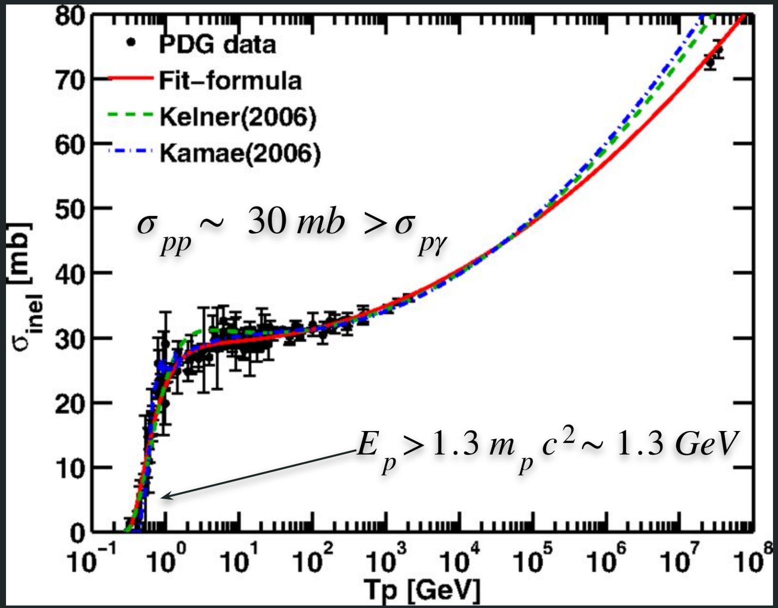
Photohadronic (pγ) interactions

$$p + \gamma_{target} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0} \left(Br = 2/3 \right) \\ n + \pi^{+} \left(Br = 1/3 \right) \end{cases}$$



P-P inelastic collisions

$$p + p_{gas} \rightarrow \begin{cases} p + \pi^{0} \\ n + \pi^{+} \end{cases}$$



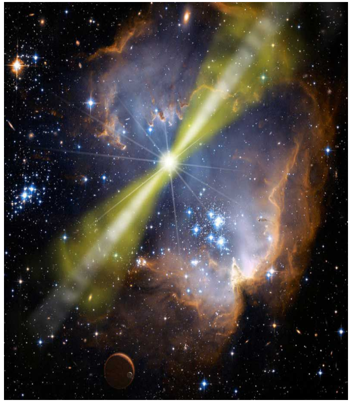
Photohadronic (pγ) interactions

$$\tau_{p\gamma} \sim \sigma_{p\gamma} \cdot n_{\gamma, target} \cdot R$$

Photon number density   Typical source size

Abundant radiation fields

Active Galaxies



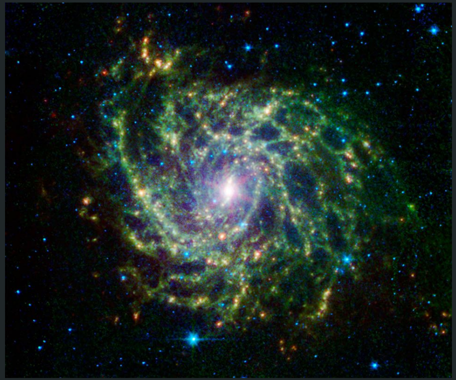
Gamma-Ray Bursts

P-P inelastic collisions

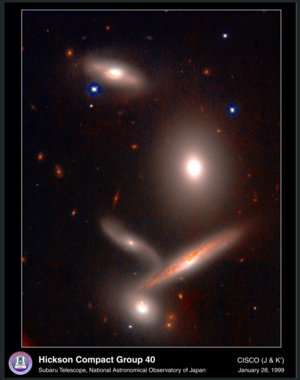
$$\tau_{pp} \sim \sigma_{pp} \cdot n_{gas} \cdot R$$

Cold proton number density   Typical source size

Abundant gas



Star-forming galaxies



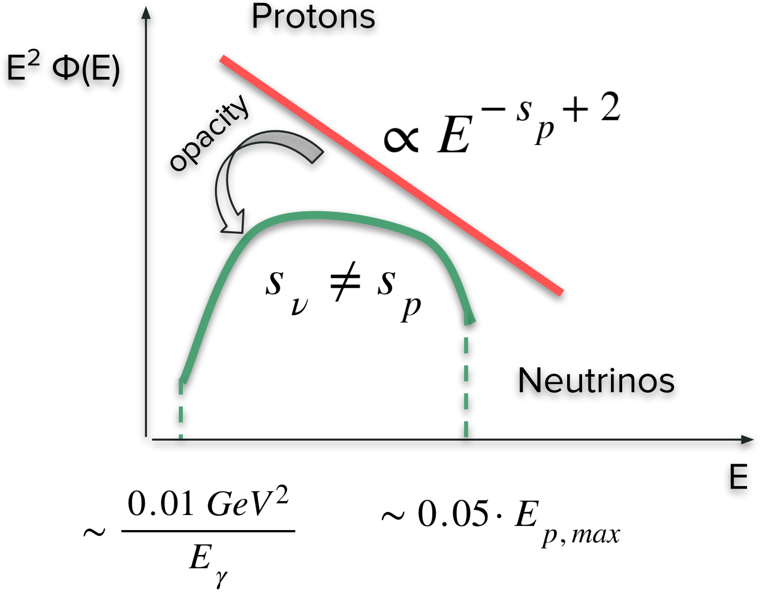
Galaxy groups/clusters

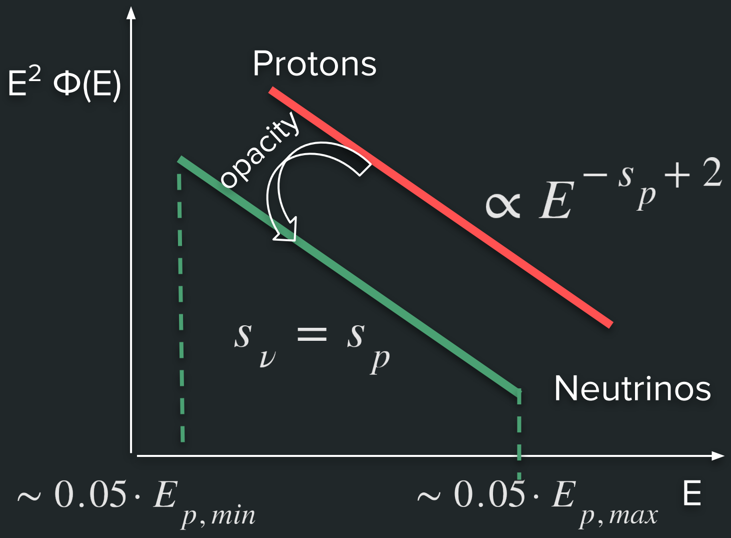
By-products of pγ interactions

By-products of P-P interactions

$$\pi^0 \rightarrow \gamma + \gamma$$

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



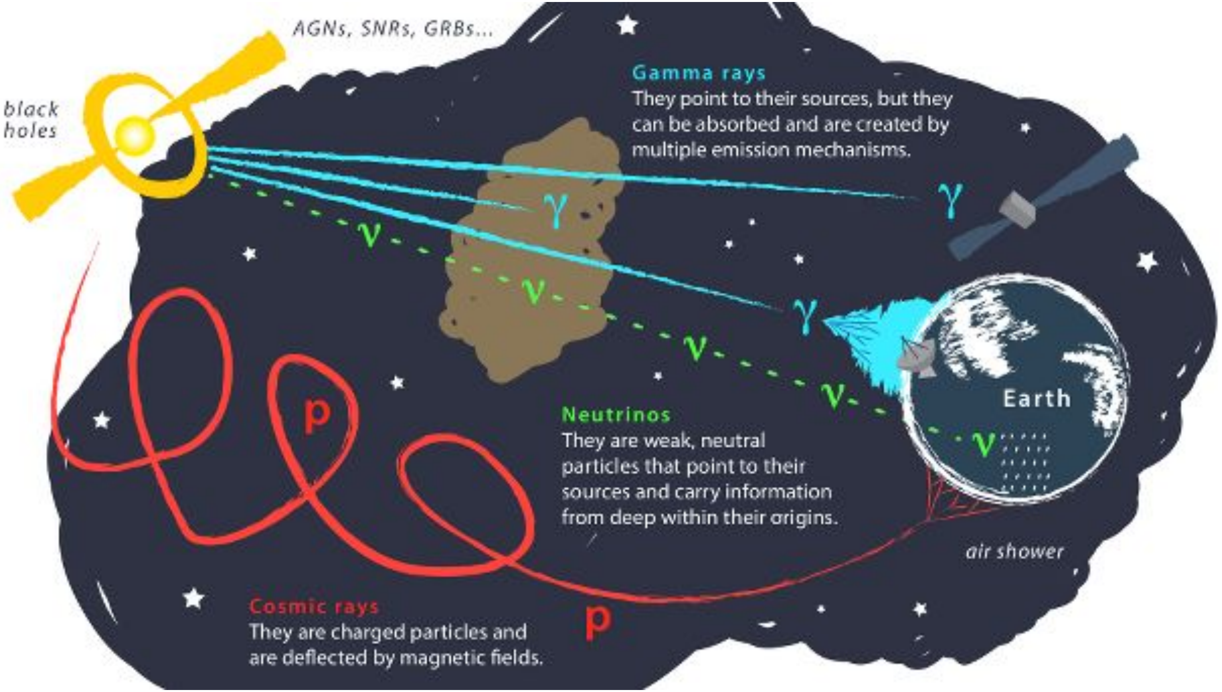


$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$n \rightarrow p + e^- + \bar{\nu}_e$$

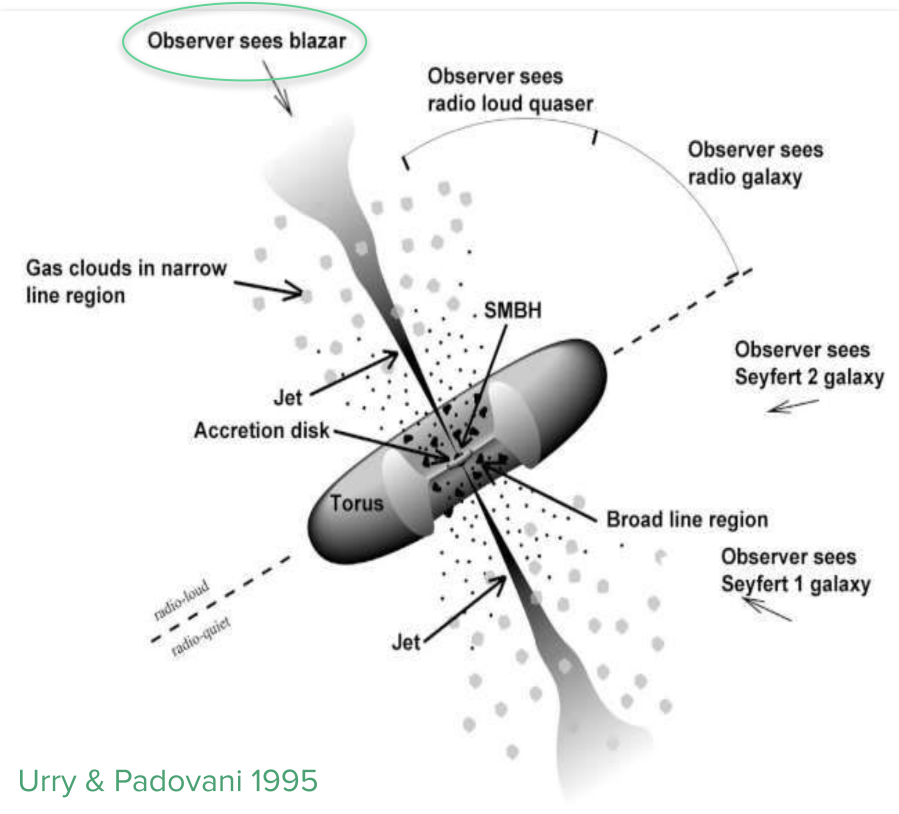
- γ-rays may escape the source without attenuation
- ν always escape the source without attenuation
- n usually escape the source and decay outside



Credit: Juan Antonio Aguilar & Jamie Yang, IceCube/WIPAC

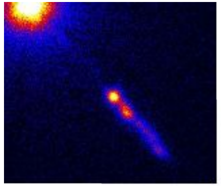
AGN jets in a multi-messenger context

AGN jets are high-energy* non-thermal emitters



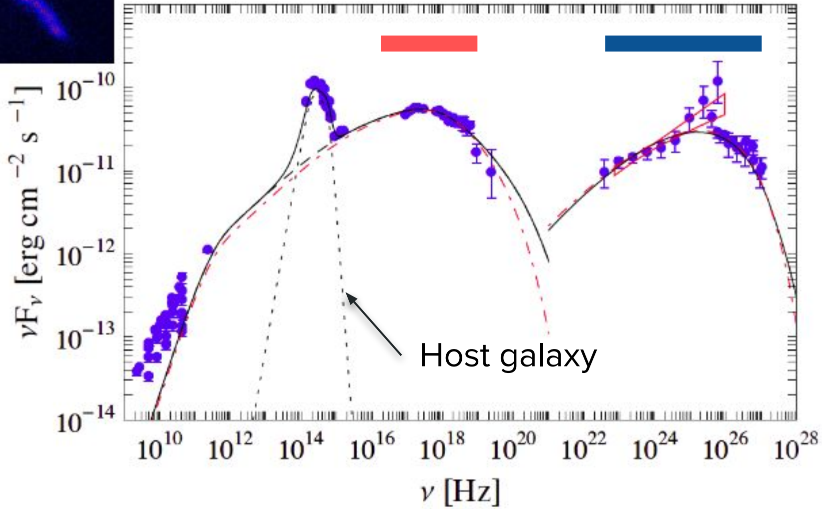
Urry & Padovani 1995

3C 273



X-rays

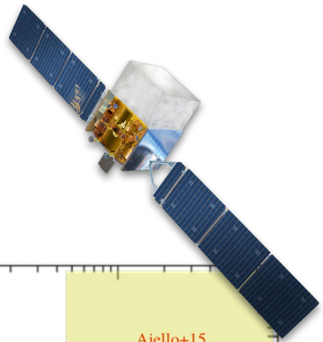
γ-rays



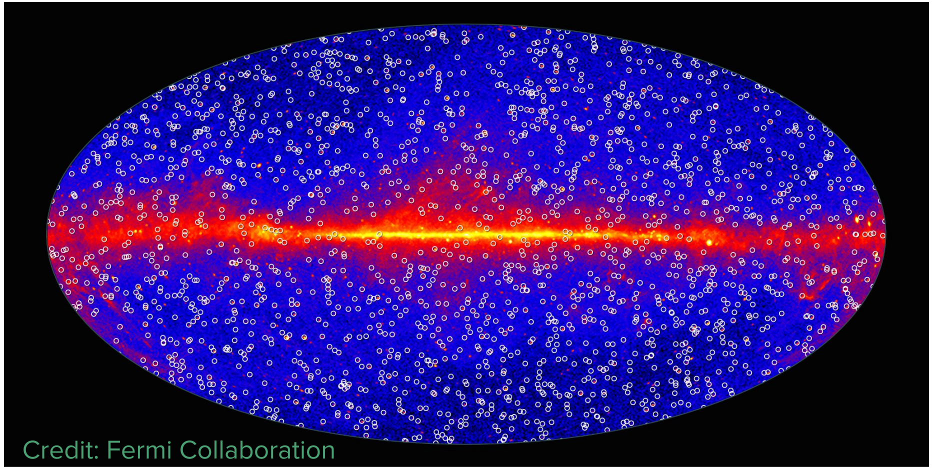
Abdo et al. 2011, ApJ

** beyond soft X-rays*

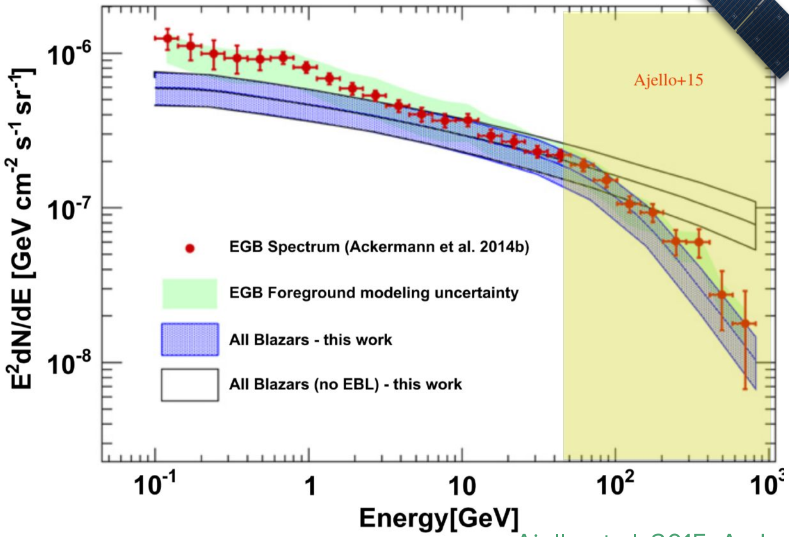
AGN jets dominate the extragalactic γ-ray sky



9yr γ-ray sky map with AGN highlighted



Credit: Fermi Collaboration



Ajello et al. 2015, ApJ

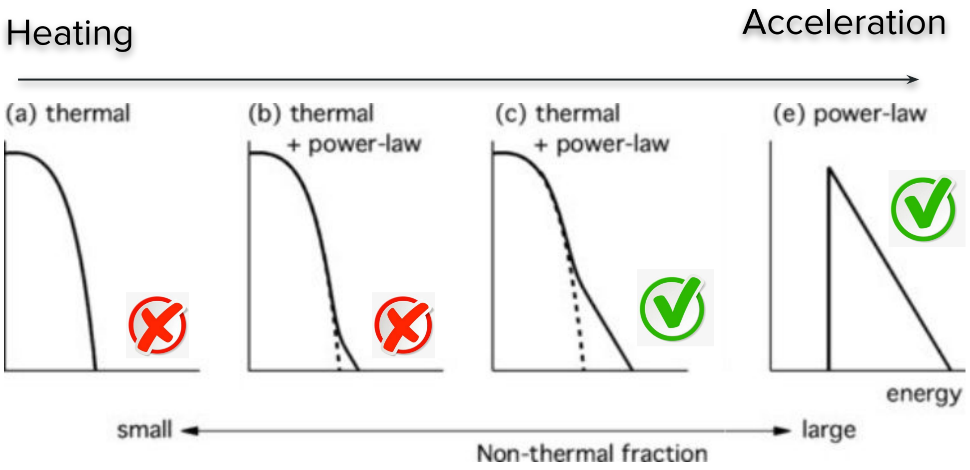
4th Fermi-LAT point-source catalog (4FGL):

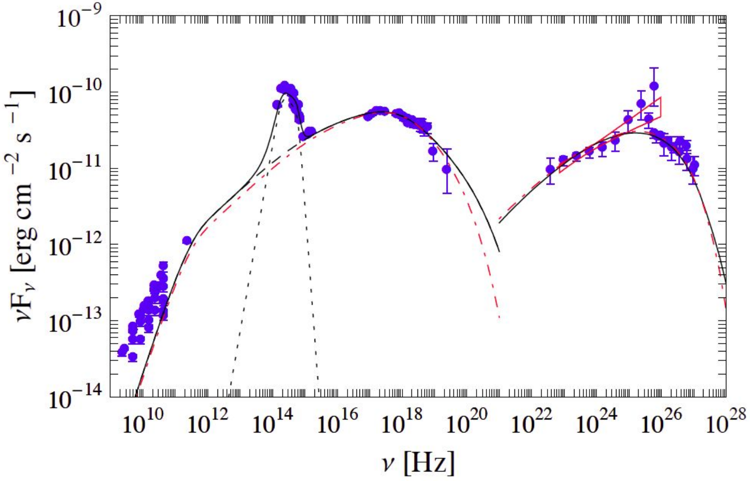
- 8 yr science data
- 5,064 sources
- ~60% AGN (out of which ~56% blazars)

Blazars produce:

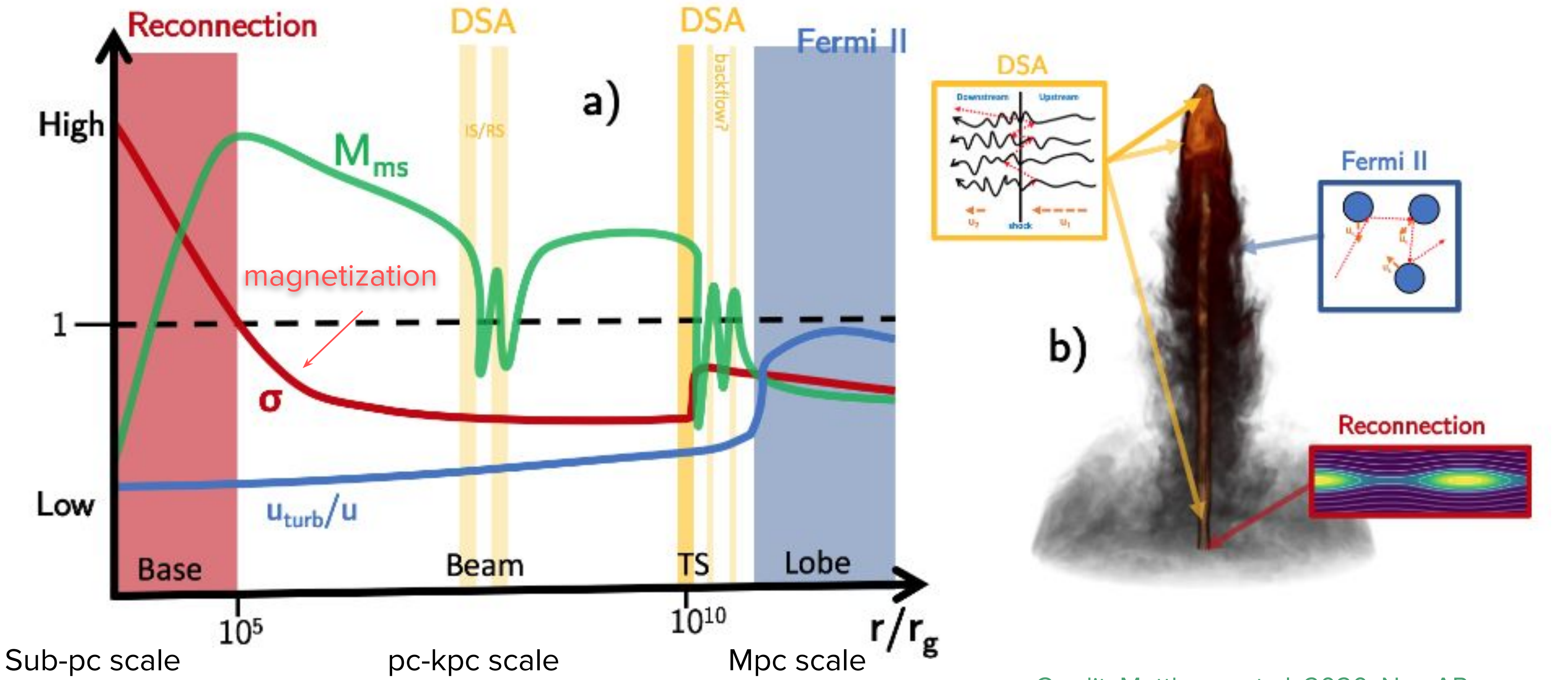
- ~50% of the total EGB
- ~100 % of EGB >60 GeV

AGN jets contain relativistic particles



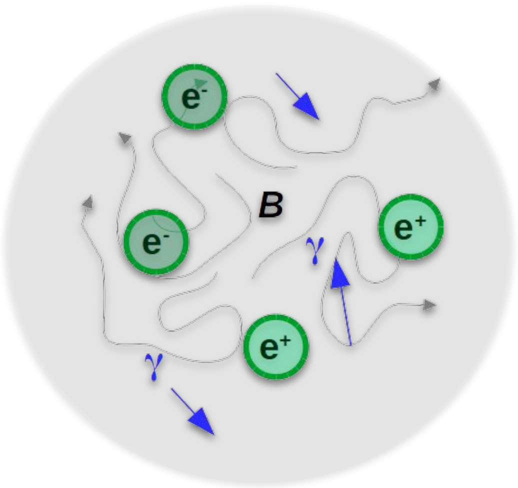


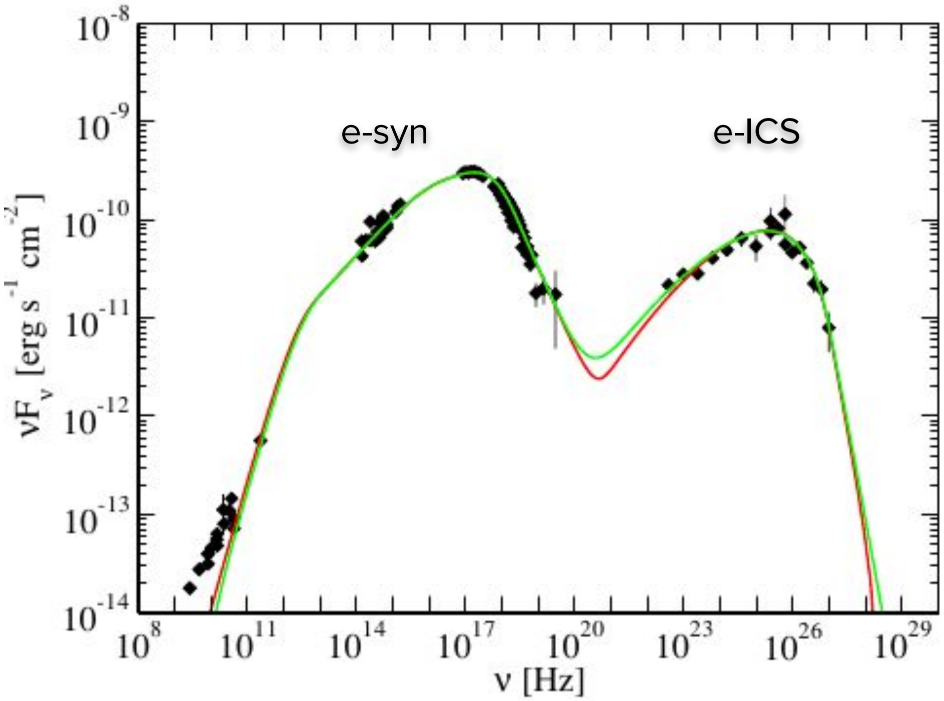
A variety of particle acceleration mechanisms in jets



Credit: Matthews et al. 2020, NewAR

Leptonic radiation models



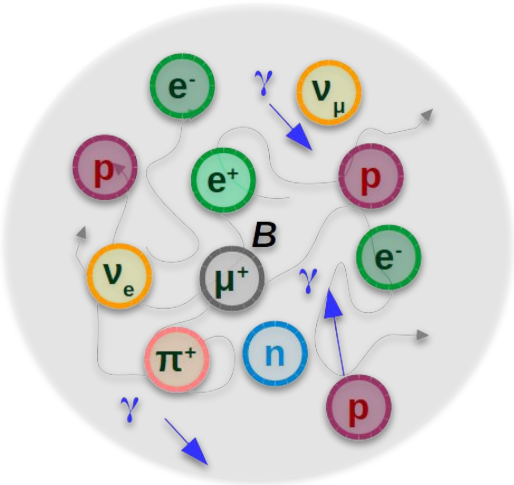


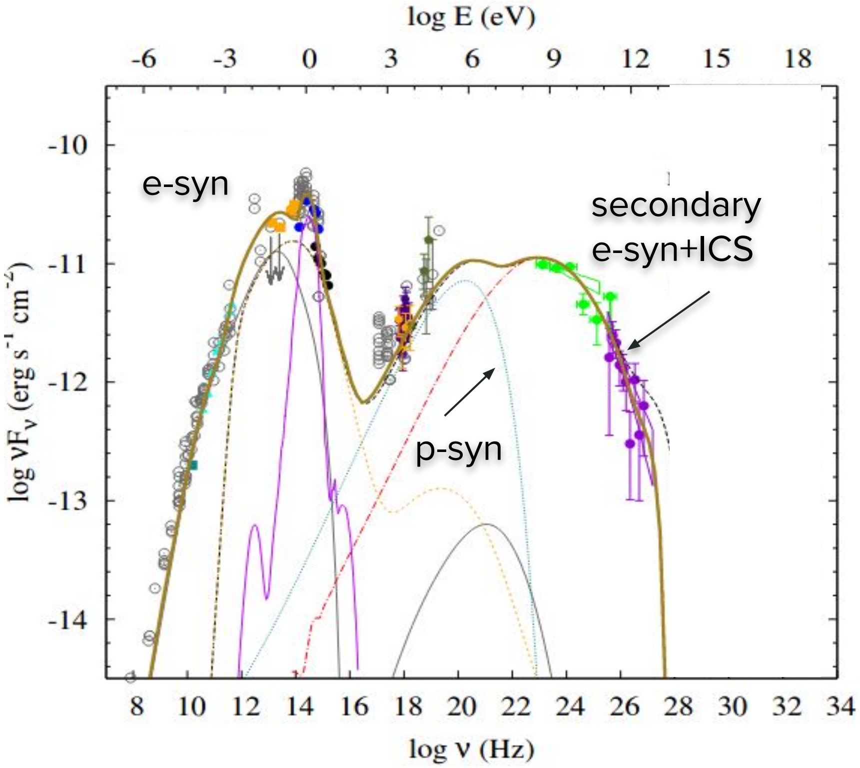
Abdo et al. 2011, ApJ

Physical processes:

- Electron synchrotron radiation (e-syn)
- Inverse Compton scattering (e-ICS)
- Photon-photon pair production (γγ)

Hadronic radiation models





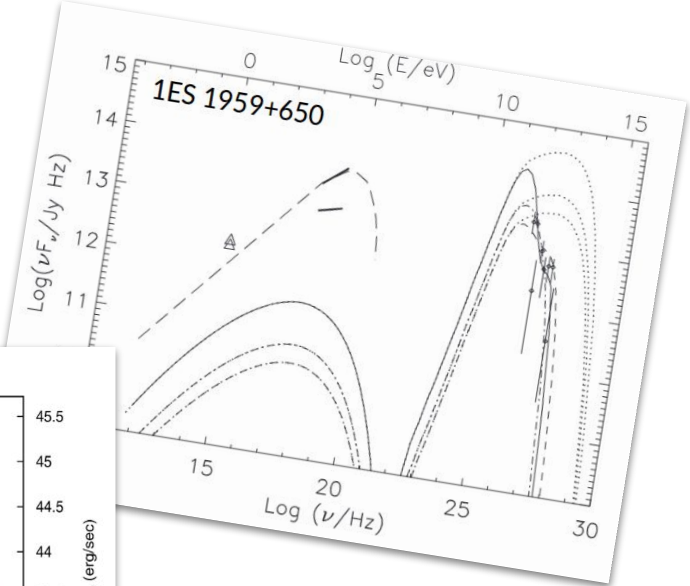
MP, Vasilopoulos, Giannios, 2016, MNRAS

Physical processes:

- Electron synchrotron radiation (e-syn)
- Inverse Compton scattering (e-ICS)
- Photon-photon pair production (γγ)
- Proton synchrotron radiation (p-syn)
- Photohadronic (pγ) interactions
- Photopair (pe) interaction

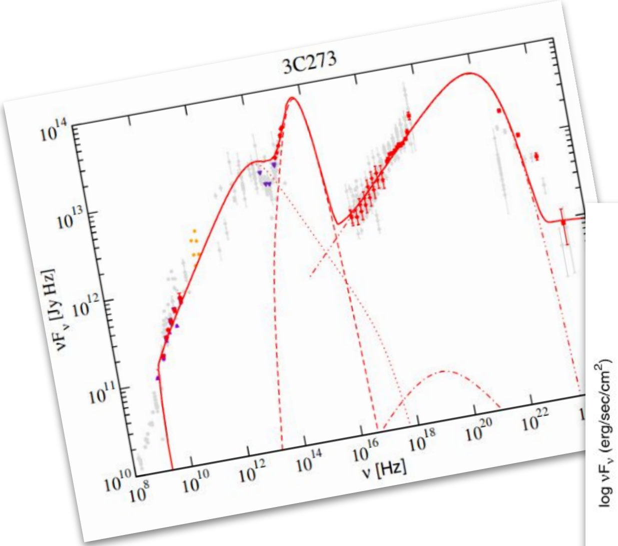
Variants of hadronic radiation models

π^0 -decay model



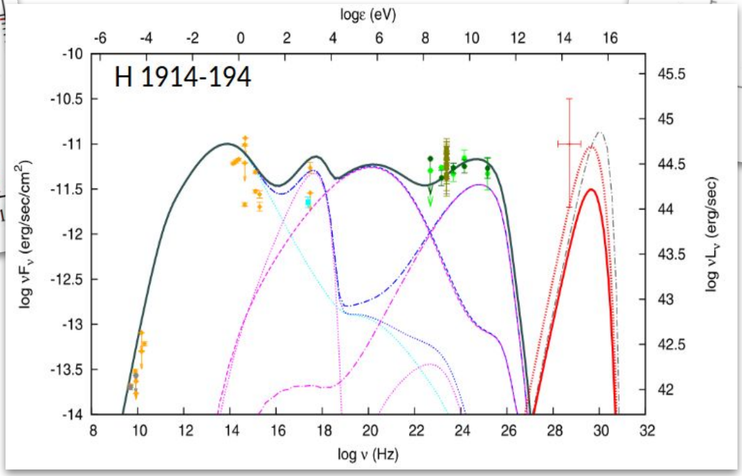
Reimer et al. 2005, ApJ

Proton-synchrotron (PS) model



Boettcher et al. 2013, ApJ

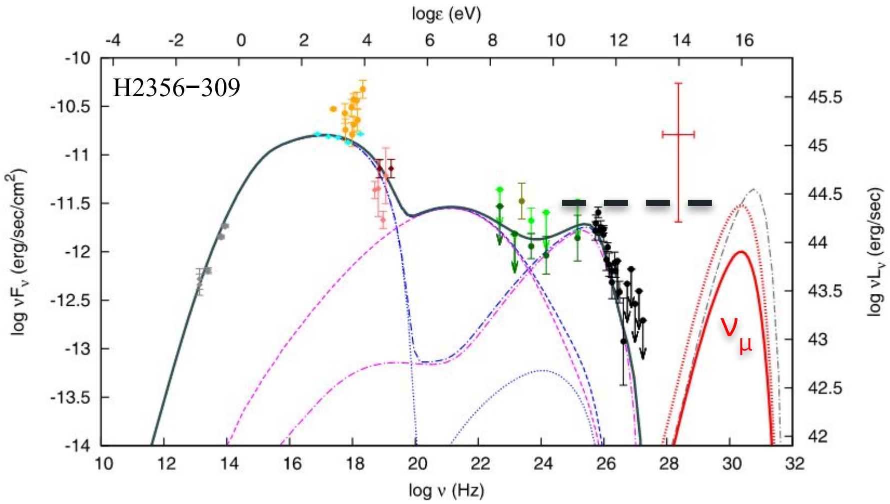
Proton-cascade (PC) model

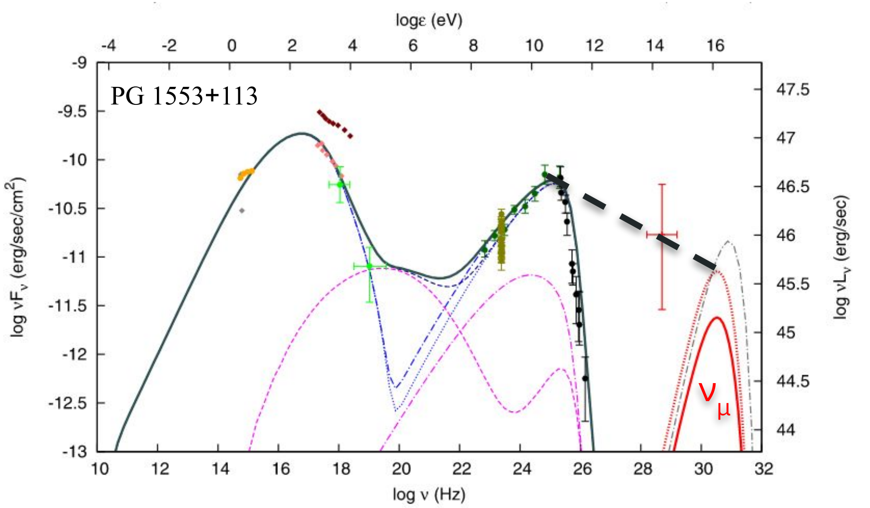


MP, Dimitrakoudis, Padovani et al. 2015, MNRAS

MP, Dimitrakoudis, Padovani et al. 2015, MNRAS

Proton-initiated Cascade (PC) model



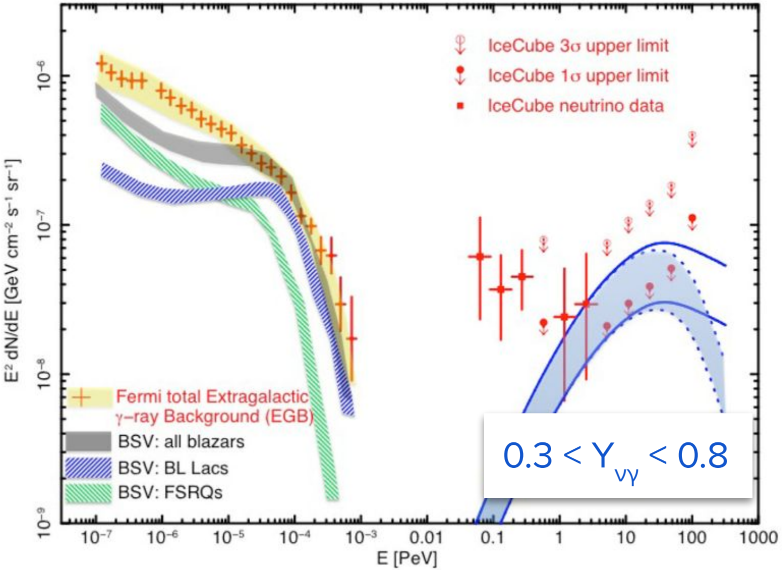


- PeV neutrinos, no UHECR protons
- High $Y_{\nu\gamma}=L_\nu/L_\gamma \sim 1$ → Hadronic γ-rays
- Syn-cascades dominate GeV γ-rays
- Jet power >> Eddington luminosity

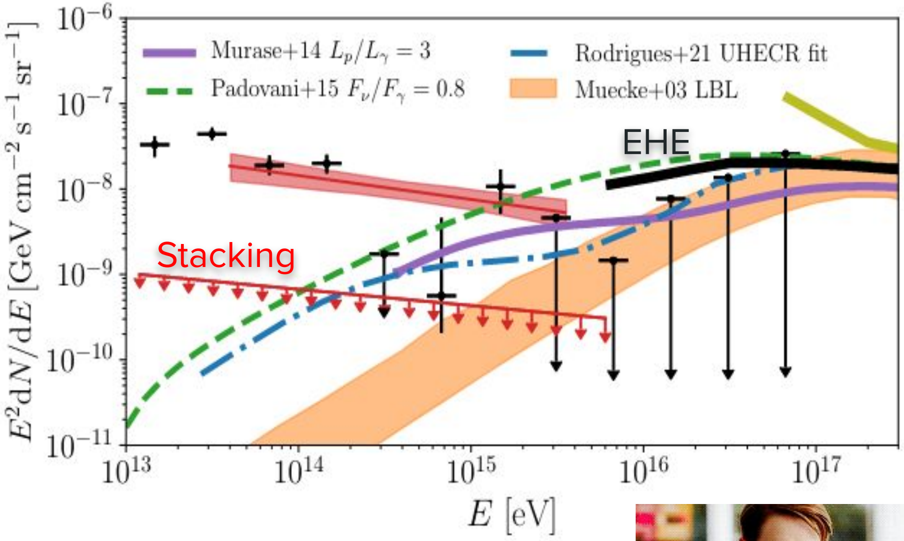
- PeV neutrinos, no UHECR protons
- Low $Y_{\nu\gamma}=L_\nu/L_\gamma << 1$ → Leptonic γ-rays
- ICS of accelerated electrons dominates GeV γ-rays
- Jet power >> Eddington luminosity

Diffuse ν fluxes in the PC model

Oikonomou 2022 (arXiv:2201.05623)

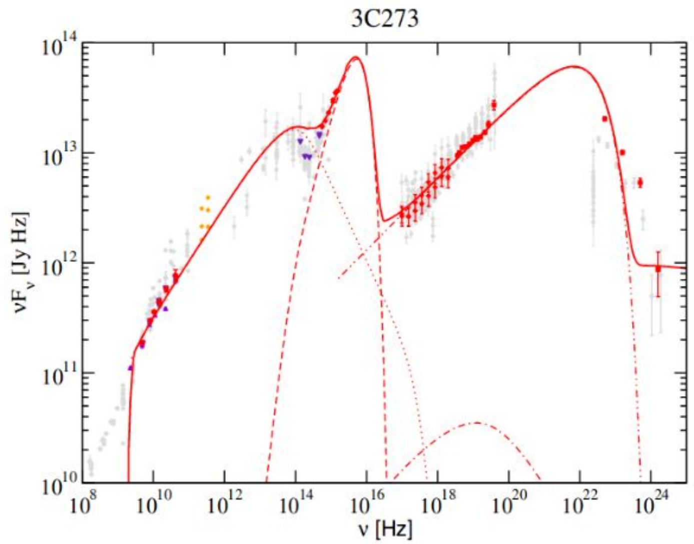


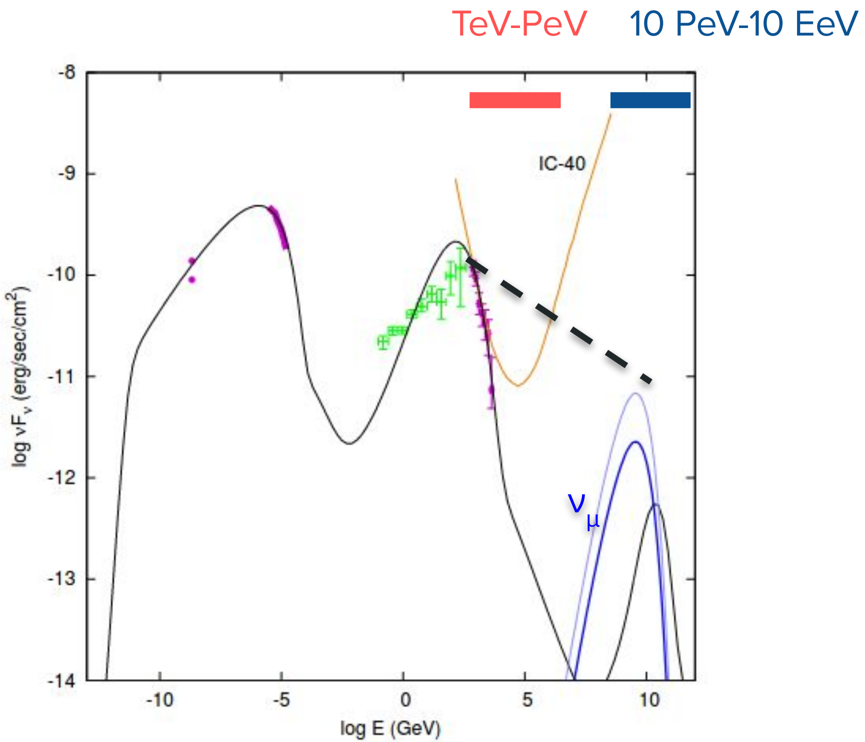
Padovani, MP, Giommi et al. 2015, MNRAS



- BL Lacs can explain ~100% of the EGB > 100 GeV and ~10% of the total diffuse ν flux
- Absence of event clustering ➜ blazar contribution <10-20% to diffuse ν flux
- Stacking limits (Fermi 3LAC) ➜ blazar contribution <5-15% to diffuse ν flux
- IceCube 9yr extreme high-energy (EHE, > 5 PeV) limits ➜ <10^{-8} GeV cm^{-2} s^{-1} sr^{-1} ➜ $Y_{\nu\gamma} < 0.1$

Proton-synchrotron (PS) model



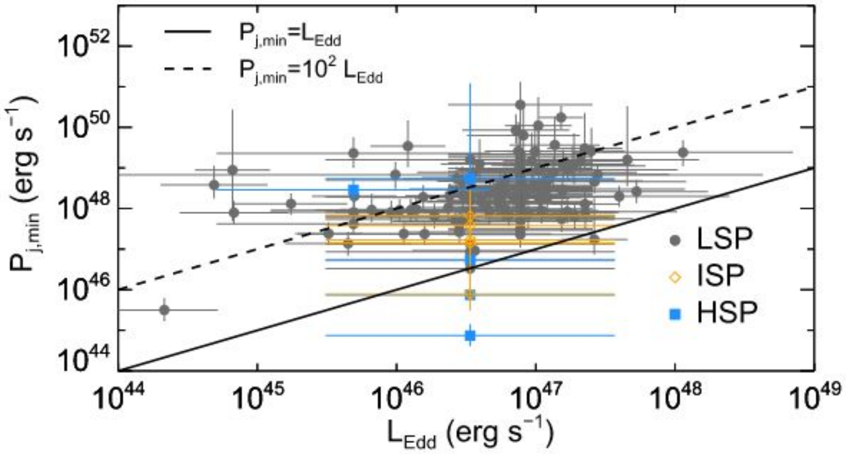


- EeV neutrinos, UHECR protons
- Low $Y_{\nu\gamma}=L_\nu/L_\gamma \ll 1$
- Proton-synchrotron dominates GeV γ-rays
- Jet power > Eddington luminosity

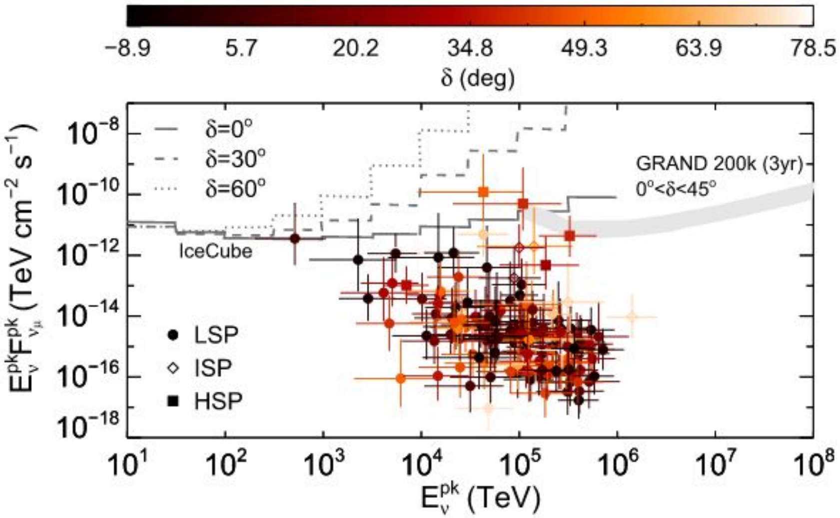
Dimitrakoudis, MP, Mastichiadis 2014, APh

Proton-synchrotron (PS) model

Minimum jet power vs Eddington luminosity



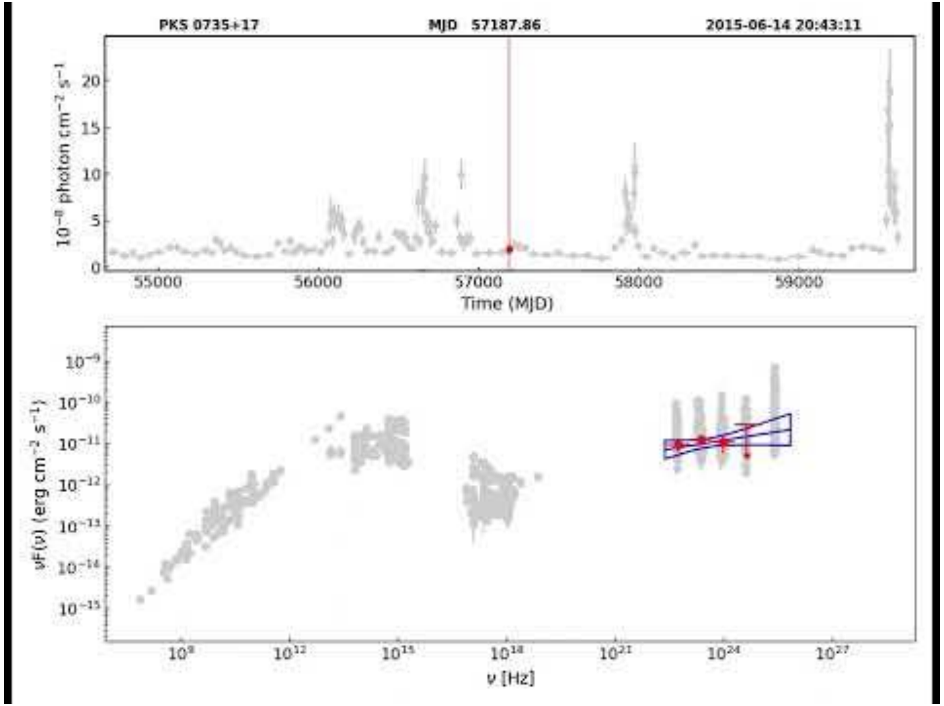
Predictions of neutrino peak fluxes & energies



Liodakis & Petropoulou 2020, ApJL

- Results from modeling of individual sources are consistent with findings of a statistical analysis of 145 blazars from 4LAC
- Future directions: Contribution to UHECR flux and cosmogenic ν flux

Jet emission is variable!



Credit: N. Sahakyan

https://youtu.be/ipGJhhDkMMs

- Flux variability on multiple timescales (min to months)
- Flares across the EM spectrum (not always correlated)

Blazar flares:

1. Shorter time window for ν search ➔ fewer background events
2. Target photon luminosity increases ➔ opacity for pγ interaction increases

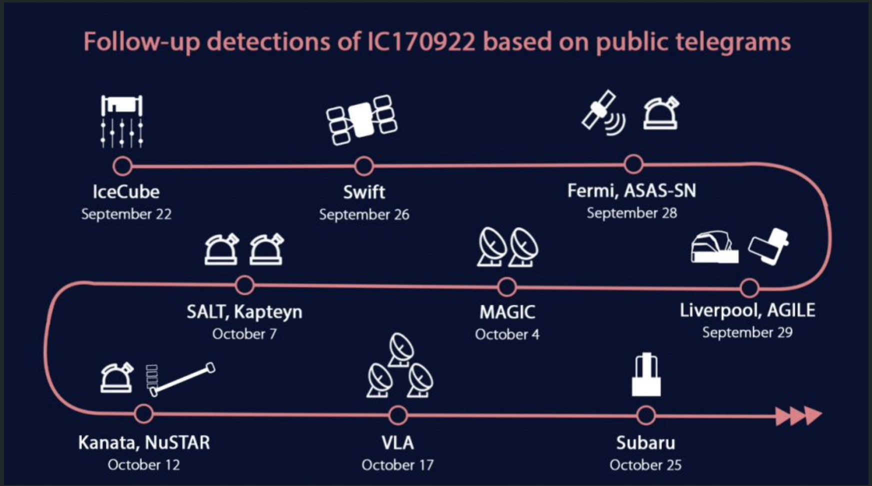
$$L_\nu \propto \tau_{p\gamma} L_p \propto n'_{\gamma, target} \cdot R' \cdot L_p \Rightarrow$$

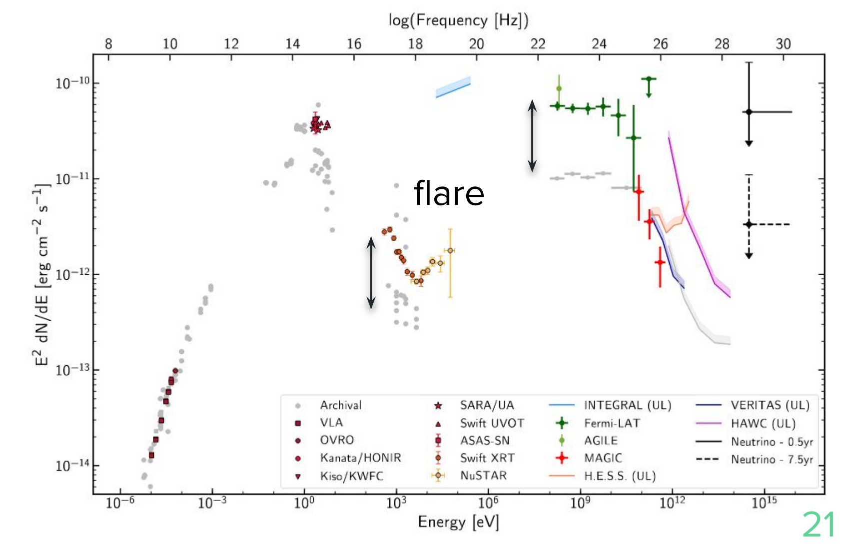
$$L_\nu \propto \frac{L_{\gamma, target}}{E_{\gamma, target}} \cdot \frac{1}{\delta^2\, t_v} \cdot L_p$$

Neutrino alerts & blazars

TXS 0506+056 / IC-170922A

Credit: Axel Mellinger (Central Michigan University) and NASA/DOE/Fermi LAT Collaboration

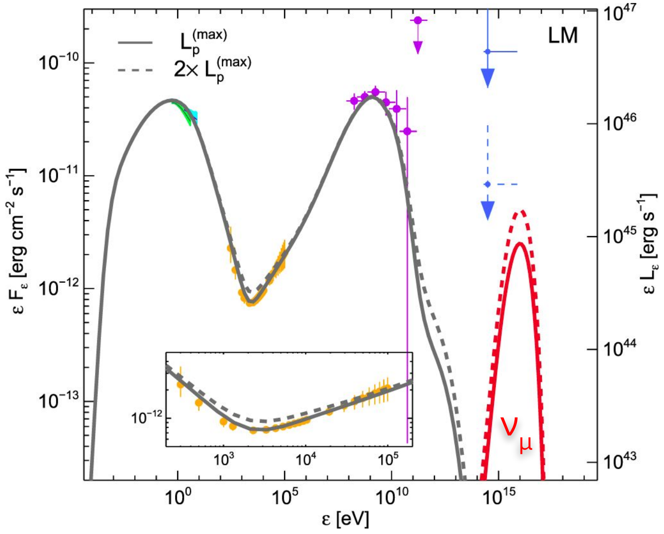




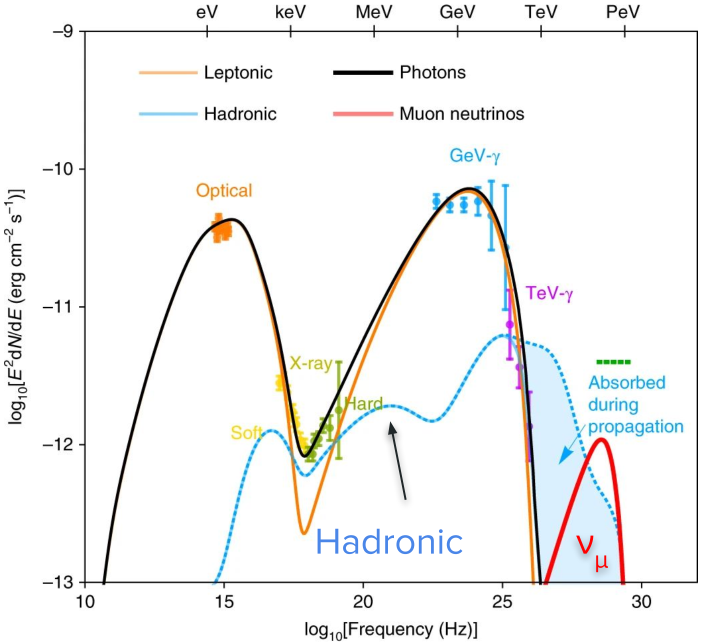
IceCube Collaboration 2018, Science

Modeling of the 2017 flare of TXS 0506+056

Keivani, Murase, MP et al. 2018, ApJ



Gao et al. 2019, Nat. Ast.

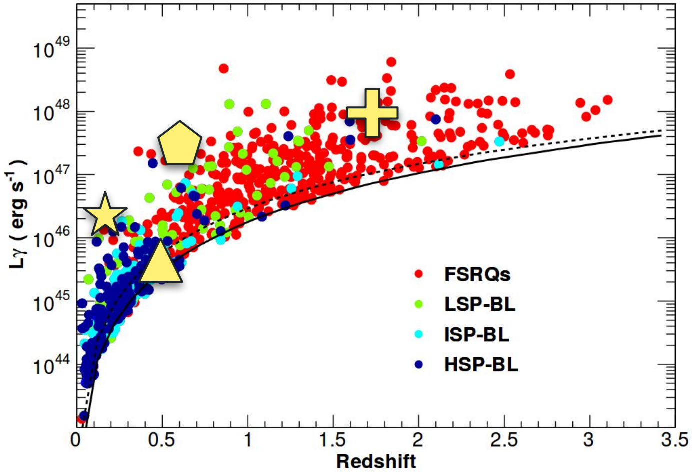


- Leptonic γ-rays ➔ ICS of accelerated electrons
- "Hidden" hadronic emission below the leptonic component ➔ Hybrid model
- A PeV neutrino source, but not a UHECR source
- ~ 0.1 of muon neutrinos in 1 yr ➔ maximum ν luminosity set by X-ray luminosity

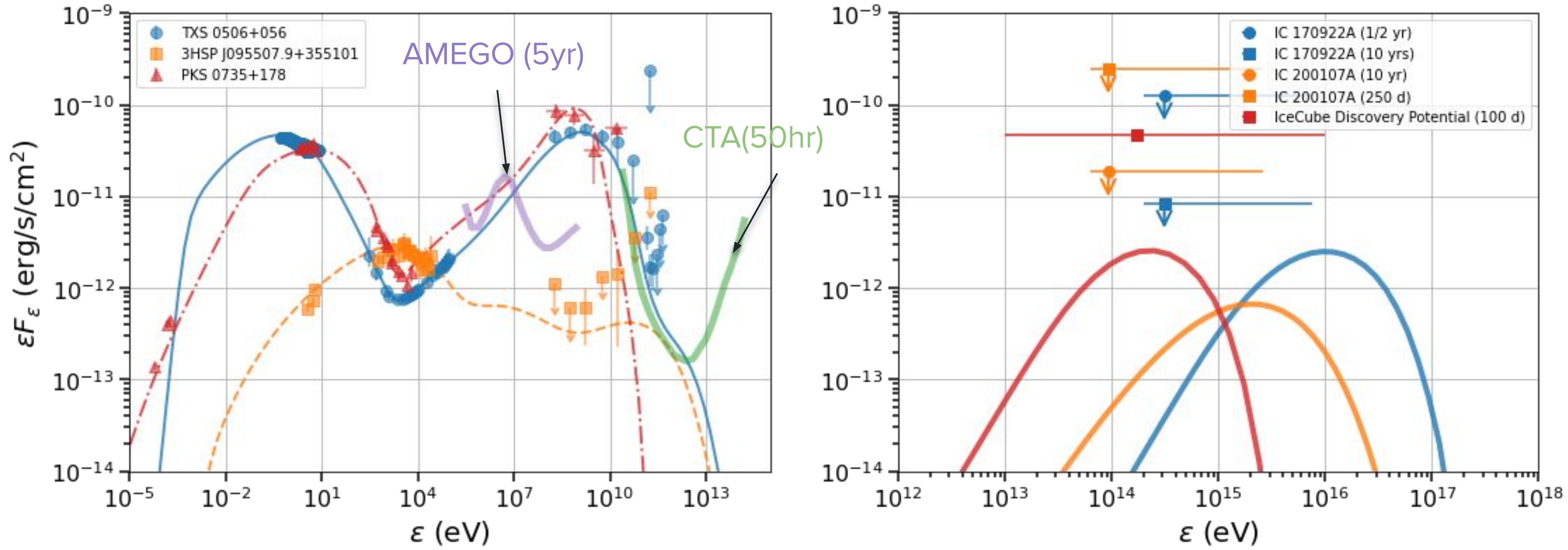
A summary of interesting neutrino alerts & blazars

- TXS 0506+056 / IC - 170922A (IceCube collaboration 2018, Science)
  - Masquerading BL Lac with Esyn,pk < 4 eV [ISP] (Padovani et al. 2019, MNRAS)
  - Neutrino (~ 290 TeV) detected during a MW 6 month-long flare
- 3HSP J095507.9+35510 / IC-200107 (Giommi et al. 2020, MNRAS; Paliya et al. 2020, ApJ)
  - BL Lac with Esyn,pk > 1 keV ["extreme" HSP]
  - Neutrino (??) detected 1 day before a hard X-ray flare in 2020 - no γ-ray flare
- PKS 0735+178 / IC-211208A (Sahakyan,... MP ... 2022, arXiv:2204.05060)
  - Masquerading BL Lac with Esyn,pk < 4 eV [ISP]
  - IC neutrino (~ 172 TeV)detected at peak of a 3-week γ-ray flare
  - Lower energy neutrinos detected by Baikal, KM3Net (low significance)
- PKS 1502+106 / IC-190730A (Franckowiak et al. 2020, ApJ)
  - FSRQ with Esyn,pk < 0.4 eV [LSP]
  - Neutrino (~ 300 TeV) detected during period of low MW activity (no flare)

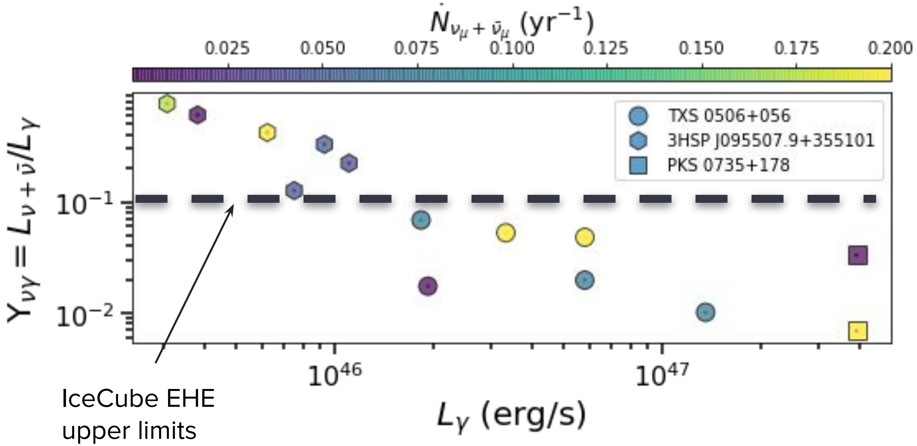
Fermi 3LAC (2015)

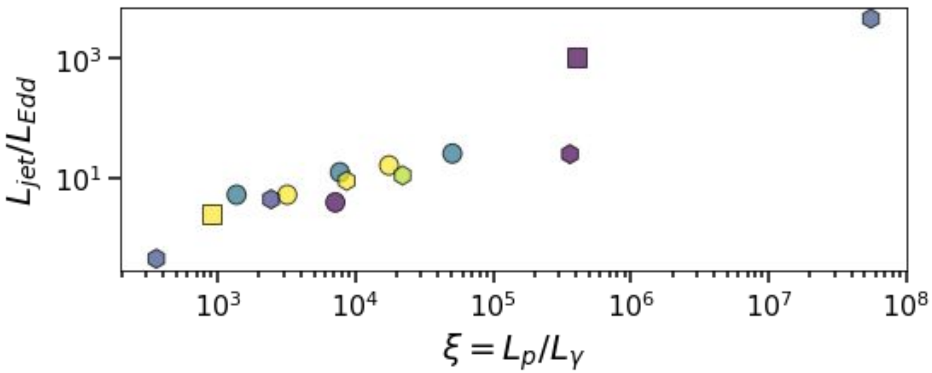


A comparison of multi-messenger results



A comparison of multi-messenger results





- Rate of muon neutrinos 0.02-0.2/yr ➔ consistent with non detection of multiple ν
- $Y_{\nu\gamma}$ values of hybrid models consistent with EHE upper limits
- Hint for a trend between $Y_{\nu\gamma}$ and L_γ
- Very high baryon loading factors needed , but not constrained by UHECR obs.
- L_jet > L_Edd even for hybrid models

1. Neutrinos are not always associated with γ-ray flares ➔ Models connecting flares in other energy bands with neutrinos ?

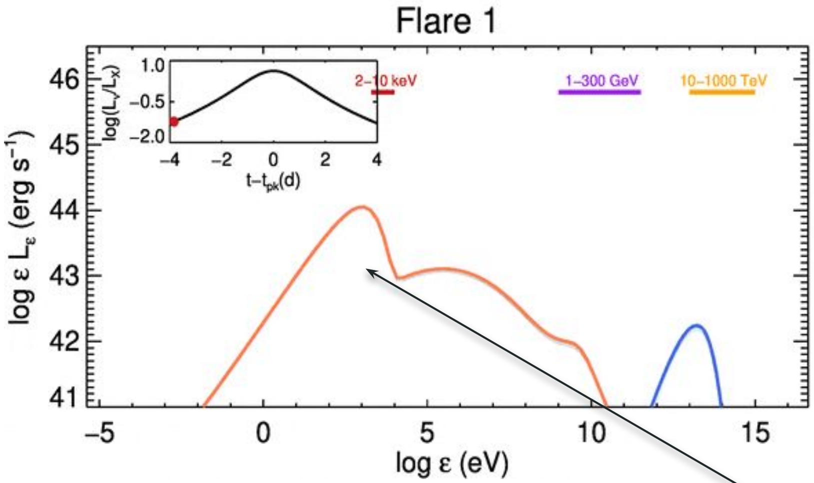
2. Even hybrid models require L_jet > L_Edd ➔ More physically constrained models ?

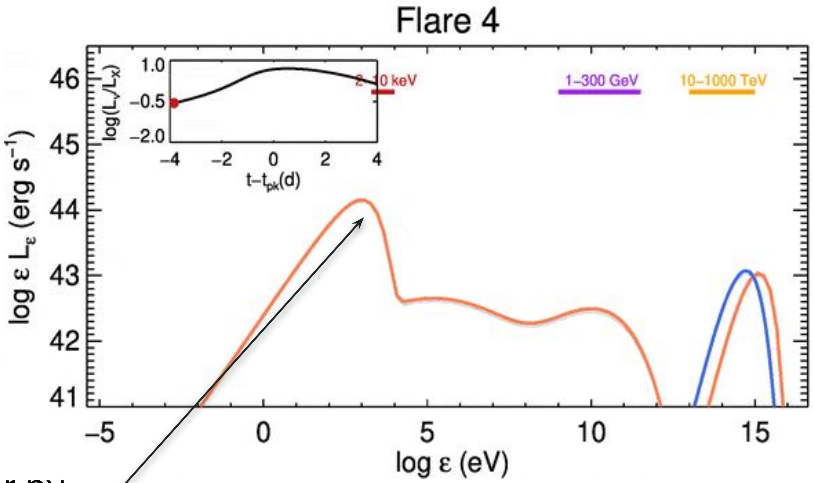
1. A pure hadronic model for X-ray flares + PeV neutrinos

2. An MHD-inspired model for baryon loaded jets

Hadronic X-ray flares

Mastichiadis & Petropoulou 2021, ApJ

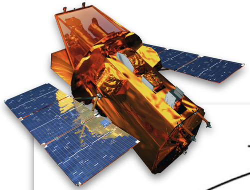


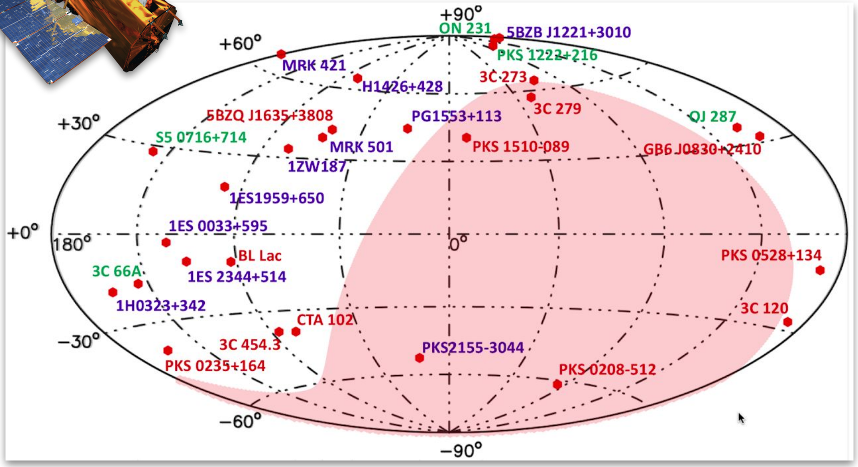


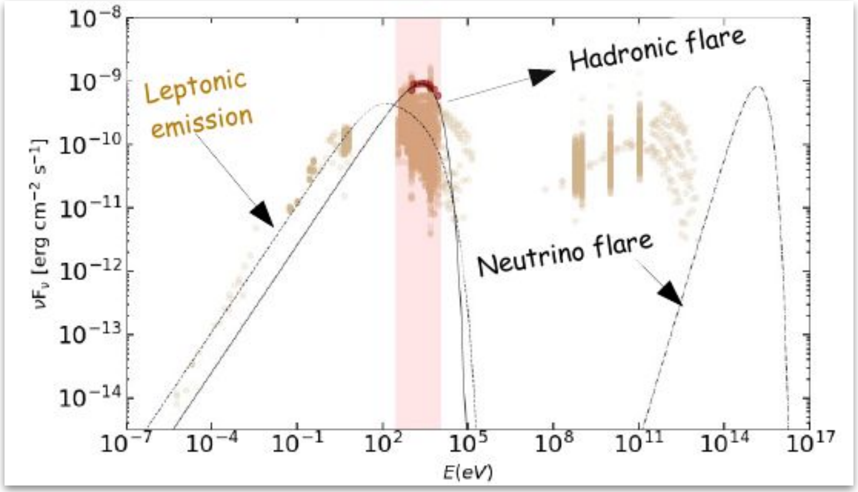
Targets for pγ interactions

- X-ray flares powered by PS radiation ➔ photons for pγ interactions ➔ non-linear problem
- Neutrino flare with similar duration & flux as X-ray flare
- “GeV γ-ray dark” neutrino flares are possible for strong magnetic fields and small regions

Application to Swift/XRT blazar flares



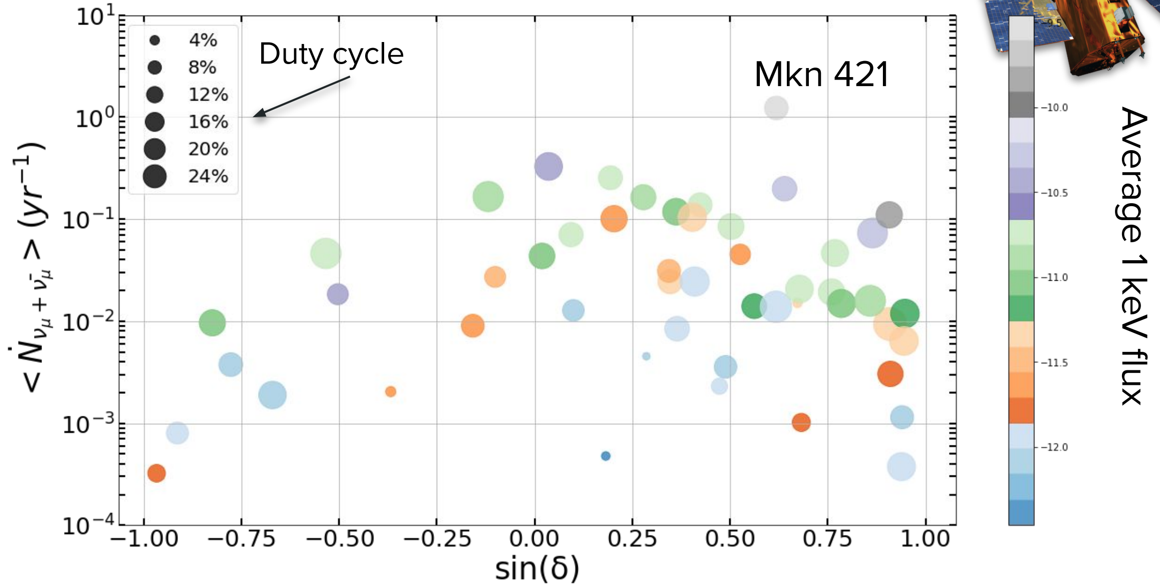


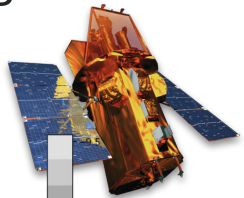


- 66 blazars observed >50 times with XRT
- 1 keV light curve → identification of flares
- 0.5 – 10 keV fluence → neutrino fluence
- Blazar type → neutrino peak energy

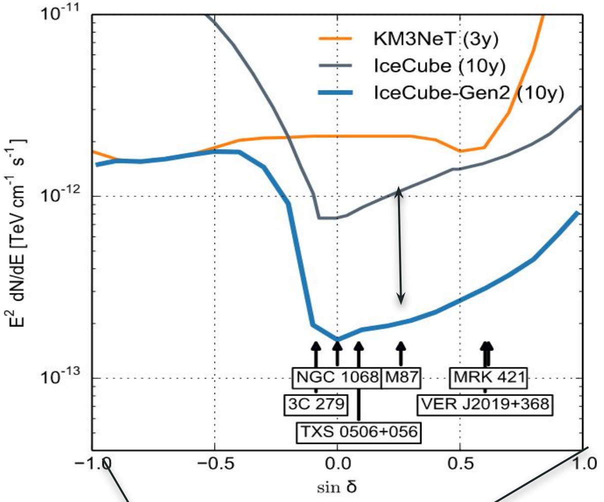
Stathopoulos, MP, Giommi et al. 2022, MNRAS
Stathopoulos et al. 2021, *PoS(ICRC2021)1008*

Application to Swift/XRT blazar flares





Credit: A Karle

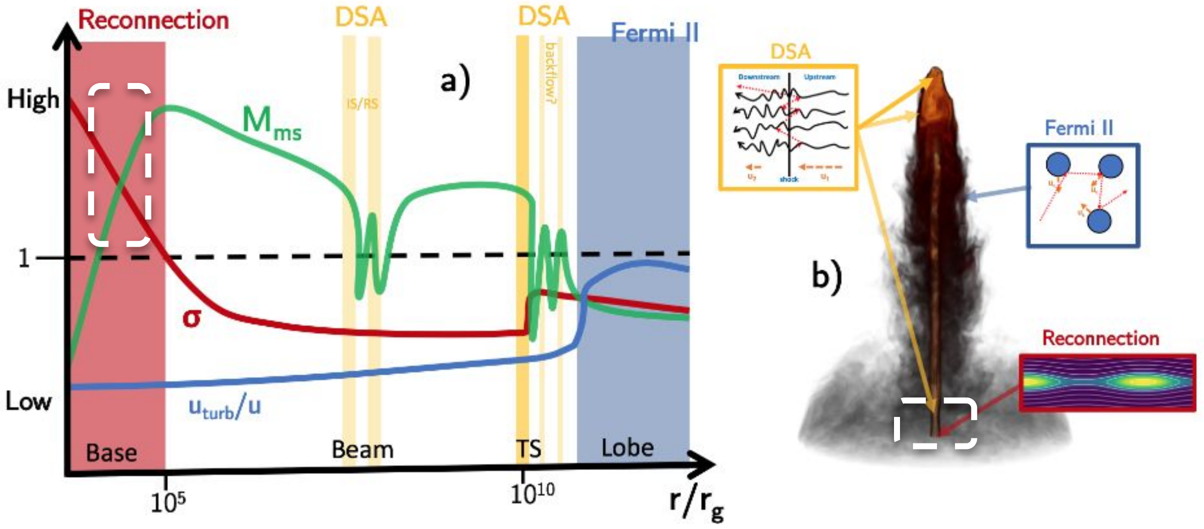


- No correlation between average X-ray flux and ν rate
- Median rate ~0.03 ν_μ / yr
- Constraints on Mkn 421 can be placed now!

Future directions

- IceCube Gen-2
- Stacking searches for signal from X-ray flares

An MHD-inspired model for baryon loaded jets



Total energy flux per unit rest-mass energy flux (baryon loading)

$$\mu = (\sigma + 1)\,\Gamma$$

$$L_{jet} = \xi L_{Edd}\dot{m} \propto \Gamma^{s}$$

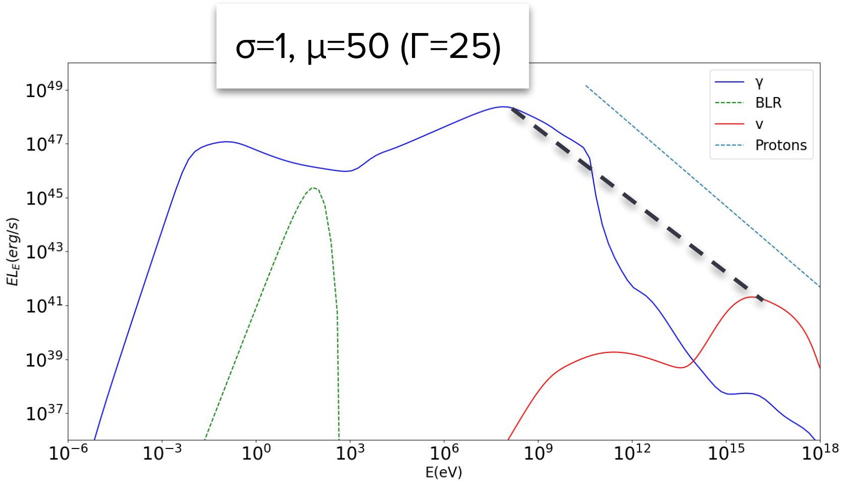
$$L_B = \frac{\sigma}{\sigma + 1} L_{jet}$$

$$L_p = L_e \propto f_{rec}\frac{L_B}{\Gamma^2},\ p = f(\sigma)$$

$$L_d \propto L_{Edd}\dot{m}$$

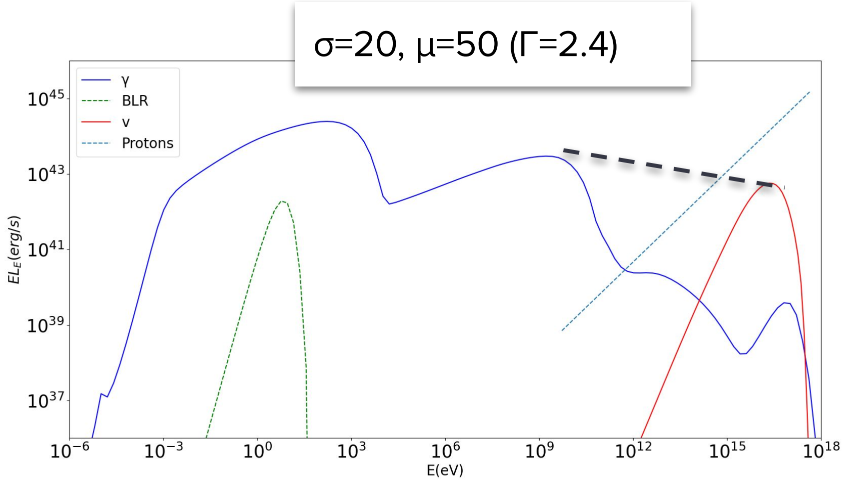
An MHD-inspired model for baryon loaded jets

preliminary



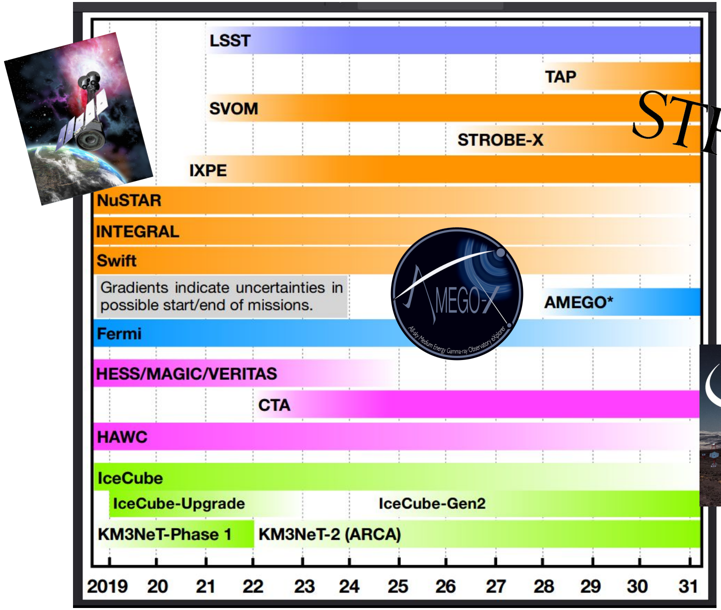
- Steep proton spectra
- Yνγ << 1 for high Lγ
- L_jet is a fraction of L_Edd

- Hard proton spectra
- Yνγ ~ 1 values for low Lγ
- L_jet is a fraction of L_Edd



Outlook

The future is bright in multi-messenger astronomy!



KM3NeT

ICECUBE GEN2

Unraveling the **N**on-**T**hermal **R**adiation **PH**ysics **O**f **B**lazars

UNTRAPHOB

Existing theoretical models will be scrutinized in search of spectral & temporal signatures that will indicate neutrino emission

Application of existing models to large samples of blazars with good MW coverage

New physically motivated models are needed that will account for different dissipation sites in AGN jets!

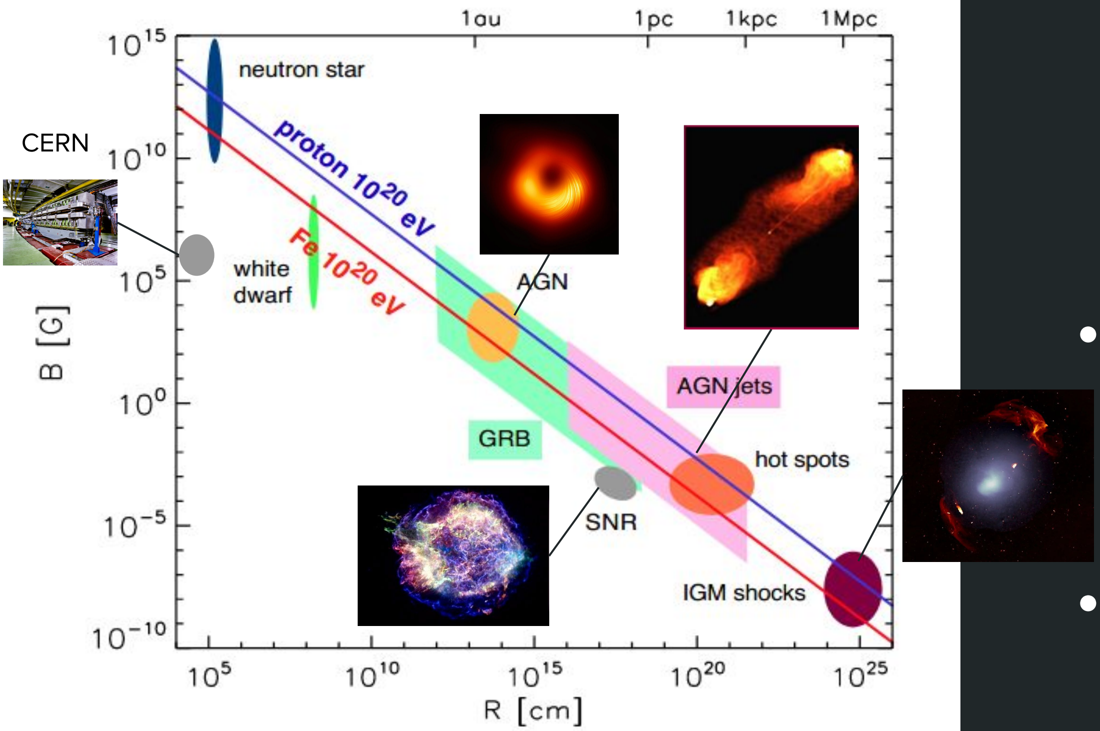
H.F.R.I. Hellenic Foundation for Research & Innovation

Conclusions

- The diffuse fluxes of the 3 messengers are likely explained by different source populations
- AGN jets contribute ~10% to the total diffuse neutrino flux, but some may be detected as neutrino point sources
- PC models disfavored for ISP/LSP blazars, but still acceptable for HSP blazars ➜ no UHECRs, PeV neutrinos, $L_\nu/L_\gamma \sim 1$, $L_{jet} \gg L_{Edd}$
- PS models disfavored for ISP/LSP blazars, but still acceptable for HSP blazars ➜ UHECRs, EeV neutrinos, $L_\nu/L_\gamma \ll 1$, $L_{jet} \gtrsim L_{Edd}$
- Hybrid models favored for ISP/LSP blazars like TXS 0506+056 ➜ no UHECRs, PeV neutrinos, $L_\nu/L_\gamma < 1$, $L_{jet} > L_{Edd}$
- Some neutrino events may be associated with "γ-ray dark" EM flares
- Hadronic X-ray flares from compact magnetized regions can lead to TeV -PeV neutrino flares that are γ-ray dark.
- Reconnection in high-σ jets with constant baryon loading μ can naturally produce the decreasing trend of $Y_{\nu\gamma}$ with L_γ , no excessive power requirements

Back-up slides

The Hillas plot



Kotera & Olinto 2011, ARA&A

- Confinement criterion for charged particles

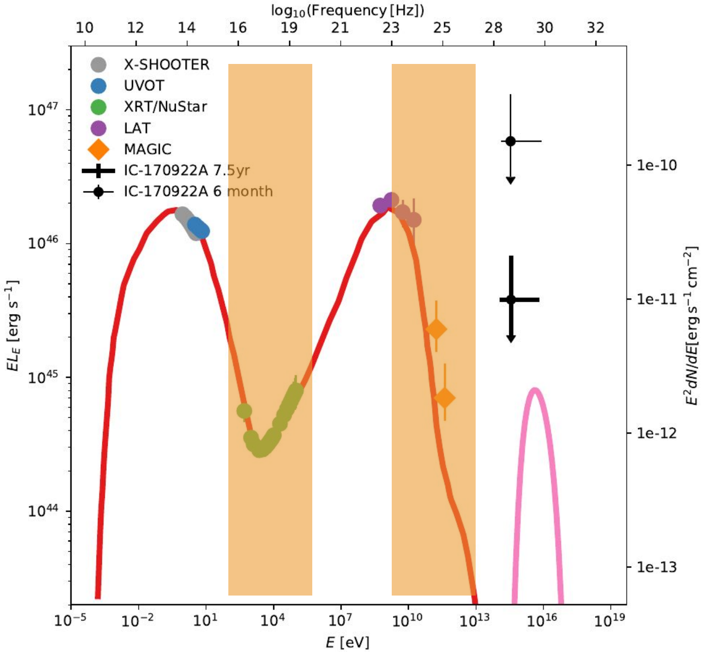
$$r_g \leq R \Rightarrow B = \frac{E}{Ze} \cdot \frac{1}{R}$$

- Necessary but not sufficient condition for hadronic accelerators

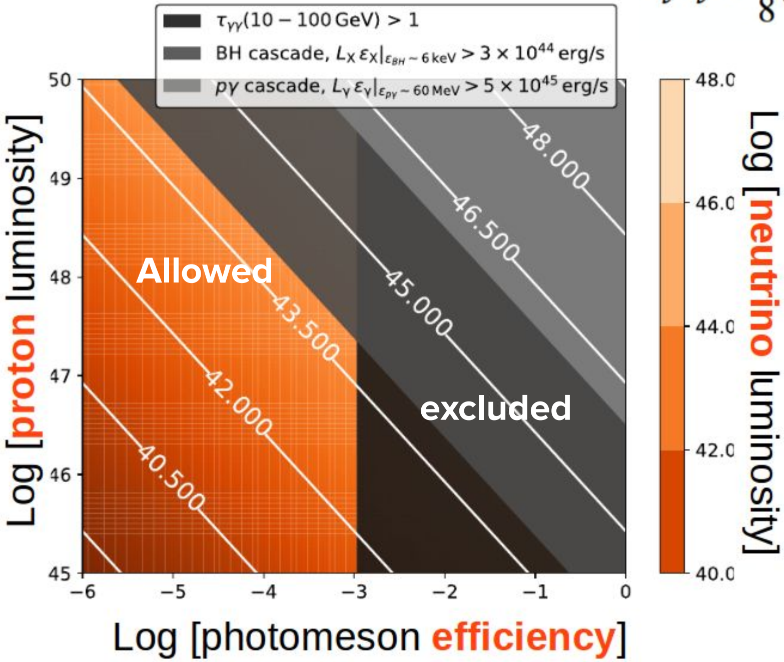
- Source physics important for understanding the multi-messenger connection!

Maximum neutrino luminosity

$$\varepsilon_\nu L_\nu \approx \frac{3}{8} f_{p\gamma}\, \varepsilon_p L_p$$

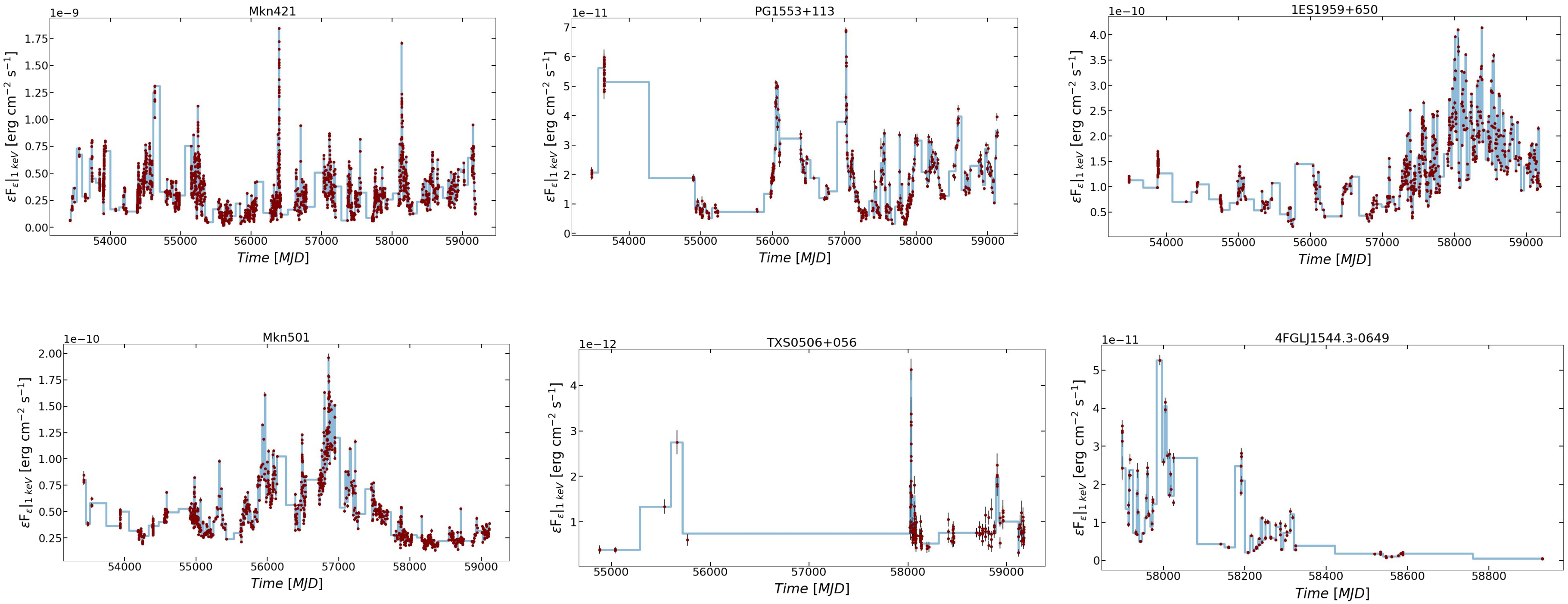


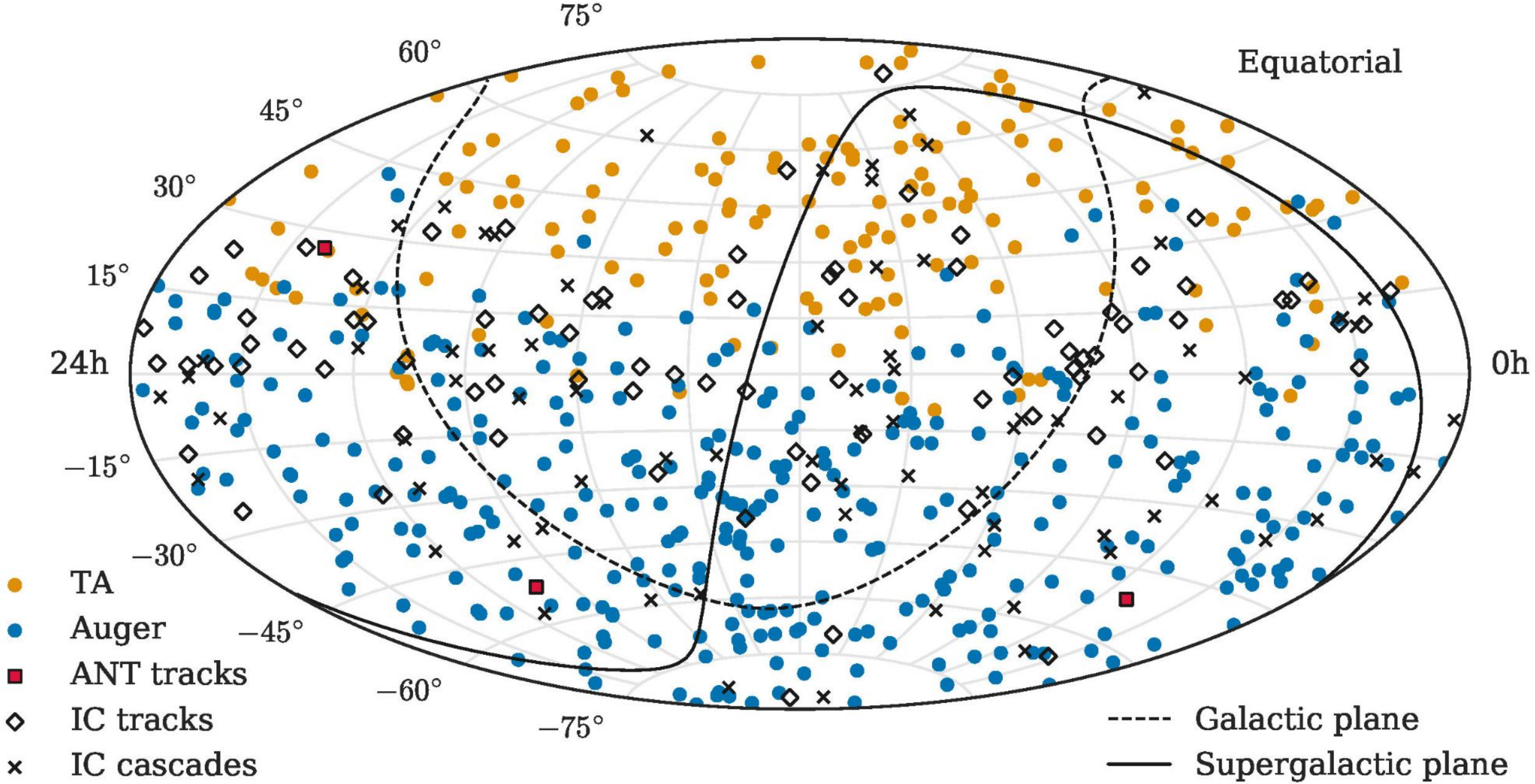
Murase, Oikonomou, MP 2018, ApJ



$$E_\nu L_{E_\nu} \lesssim 10^{45}\ \mathrm{erg\ s^{-1}}\ \frac{L_{X,\mathrm{lim}}}{3\times10^{44}\ \mathrm{erg\ s^{-1}}}\ \frac{0.1}{f_x}$$

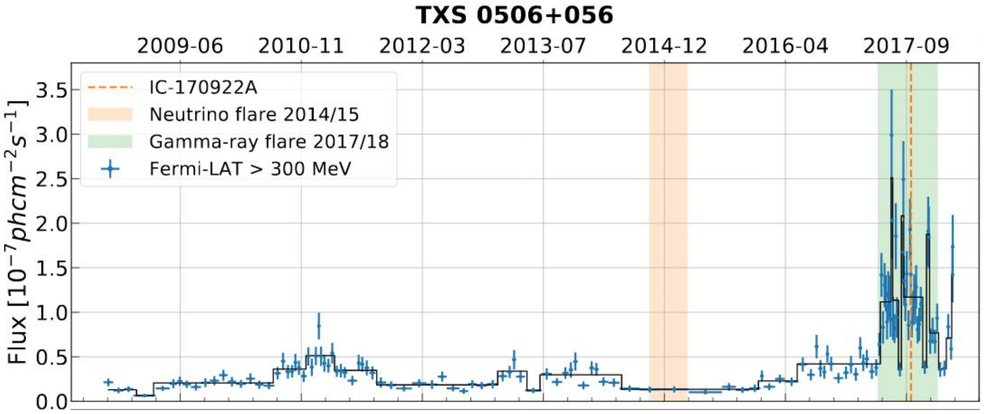
Swift/XRT light curves



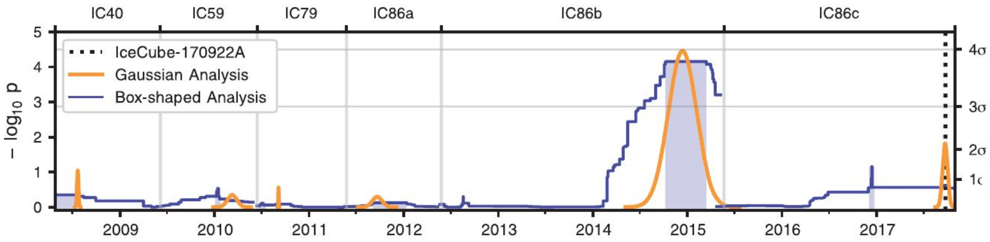


75°
60°
45°
30°
15°
24h
0h
−15°
−30°
−45°
−60°
−75°
Equatorial
TA
Auger
ANT tracks
IC tracks
IC cascades
Galactic plane
Supergalactic plane

The 2014/15 “neutrino flare” of TXS 0506+056



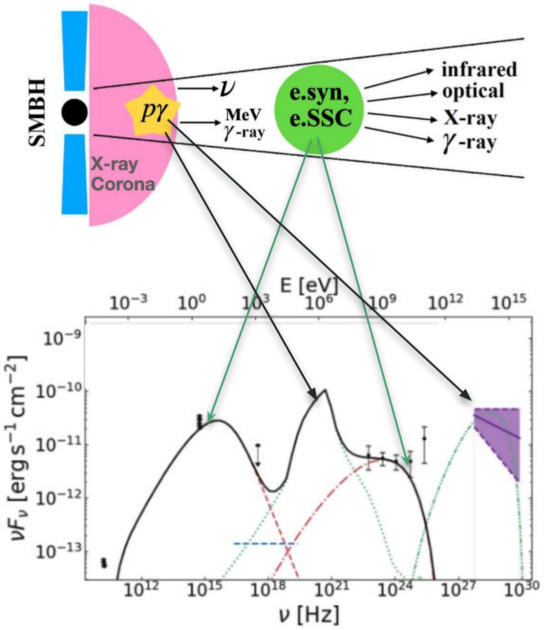
Fermi-LAT Collaboration 2019
(see also Padovani et al. 2018)

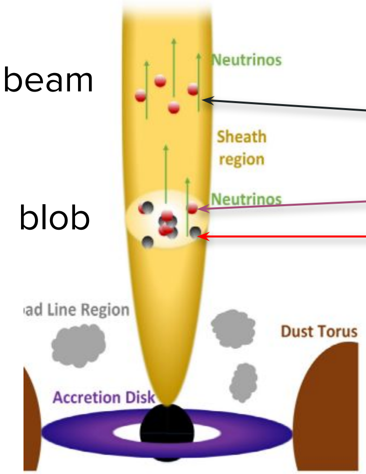


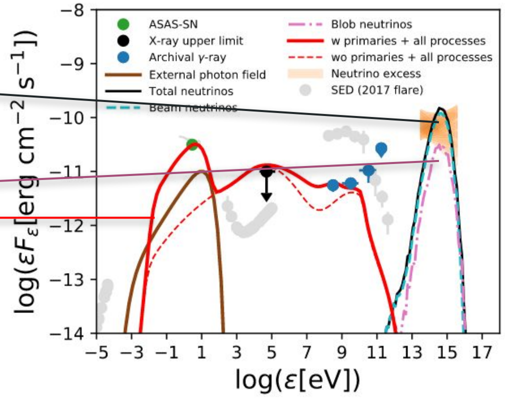
- 13 +/- 5 neutrinos above atmospheric background over ~6 months (~3.5 σ)
- Neutrino luminosity (averaged in ~6 months) 4 times larger than average γ-ray luminosity!
- No γ-ray flaring activity in 2014-15. No evidence for flares at other energies either

IceCube Colloboration 2018b

Decoupled ν/γ-ray production sites ?



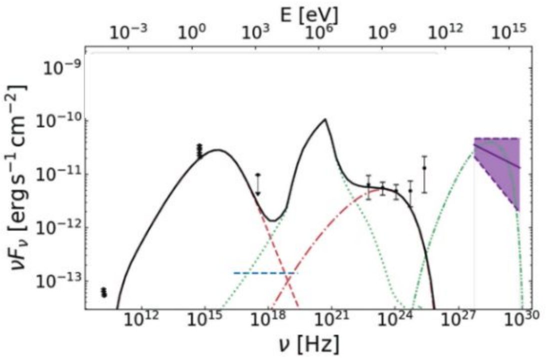


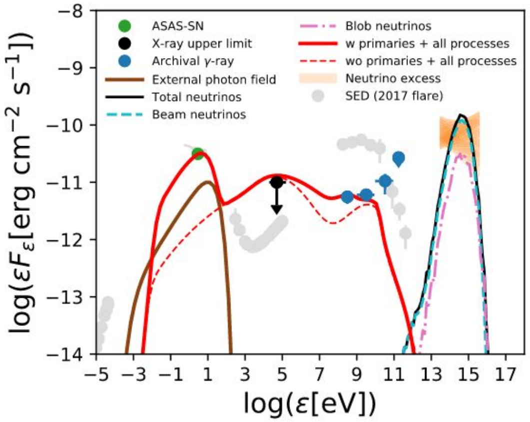


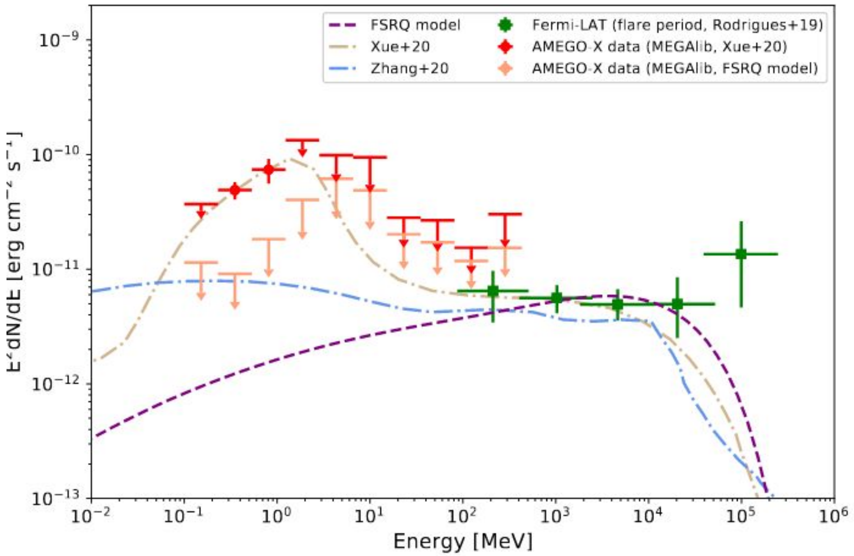
Zhang, MP, Murase, Oikonomou, 2020, ApJ

- GeV attenuation in neutrino production site due to high-opacity in pγ interactions (Rodrigues et al. 2019, Reimer et al. 2019, Zhang, MP et al. 2020, Xue et al. 2021)
- No strong constraints on models due to lack of deep X-ray limits + MeV observations.

Decoupled ν/γ-ray production sites ?

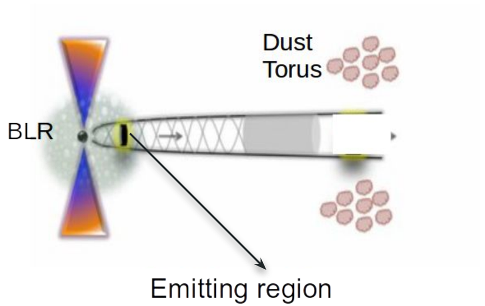


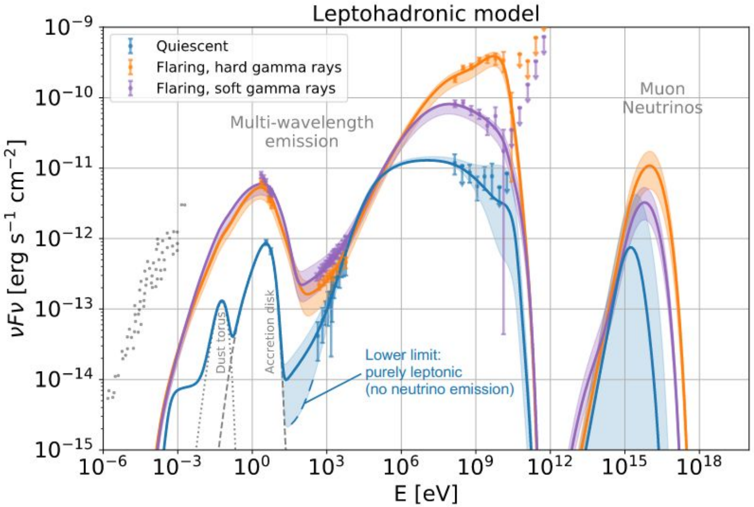


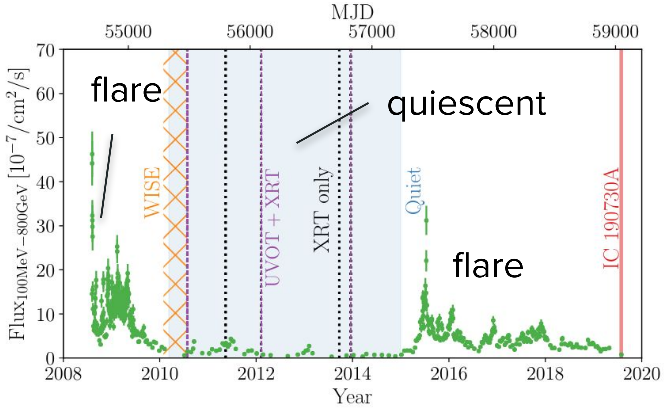


- First simulations for the proposed MeV all-sky monitor AMEGO-X are available (Lewis et al. 2021, arXiv:2111.10600)

A leptohadronic model for PKS 1502+106/IC-190730A



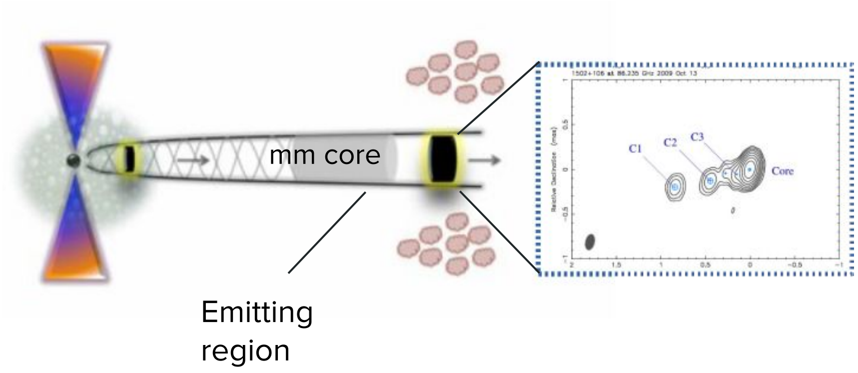


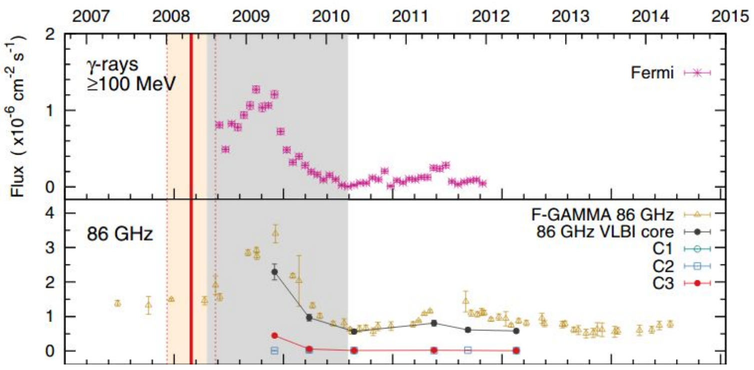


- Flares and “quiescent” emission originate within the BLR
- Leptohadronic model predicts ~ 5-16 muon neutrinos from hard flares and ~1-10 muon neutrinos from quiescent periods in 10 yr (Point Source analysis)
- The 8-yr IceCube Point Source analysis finds zero events (Aartsen et al. 2019)

Rodrigues et al. 2021, ApJ

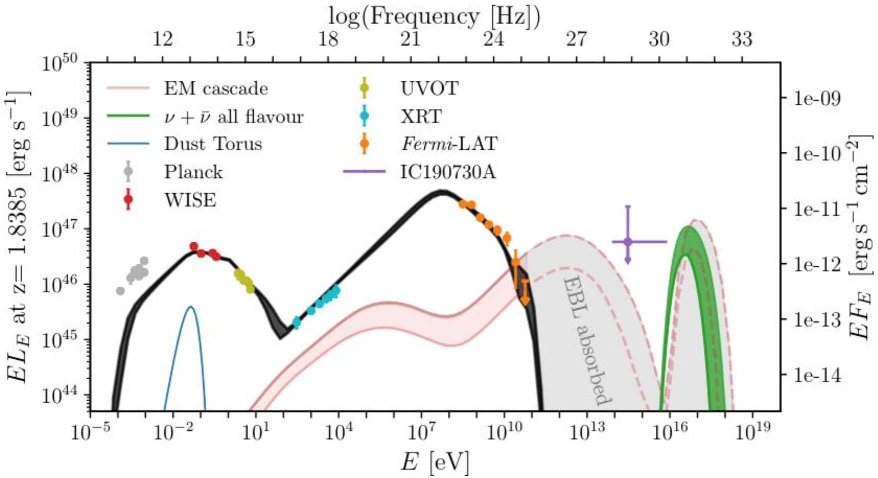
γ-ray flares from the pc-scale jet in PKS 1502+106

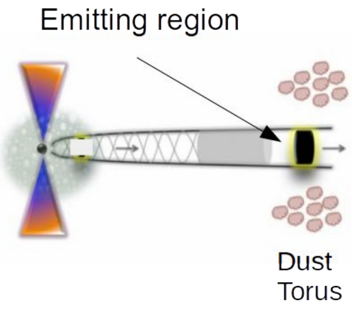


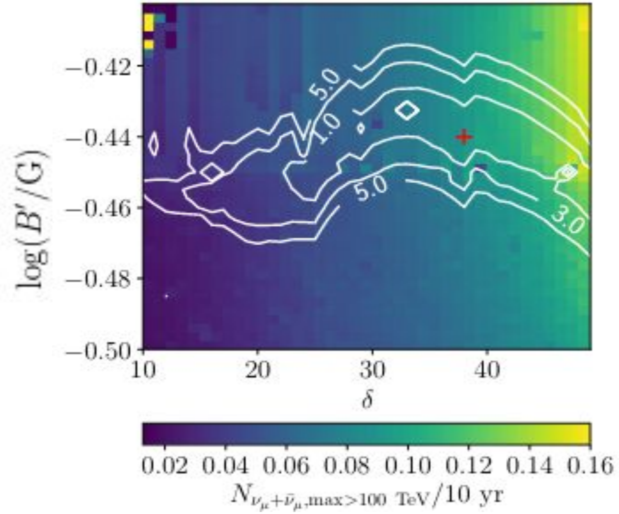


- Evidence for γ-ray flares outside the BLR (Karamanavis+2016a,b)
- Time of ejection of knot C3 from core coincides with onset of 2008 γ-ray flare
- Location of γ-ray flaring region outside BLR (~1 – 5 pc)
- Lower neutrino expectation from γ-ray flares than the one found by Rodrigues+2021 due to de-boosting of BLR photon density

ν production at pc scales?







- ~0.1 EeV neutrino energies
- ~0.1 muon neutrinos in 10 yr of IceCube obs→ consistent with 1 neutrino detection
- Similar neutrino predictions as the PS model of Rodrigues+2021 but with lower proton power needed!