



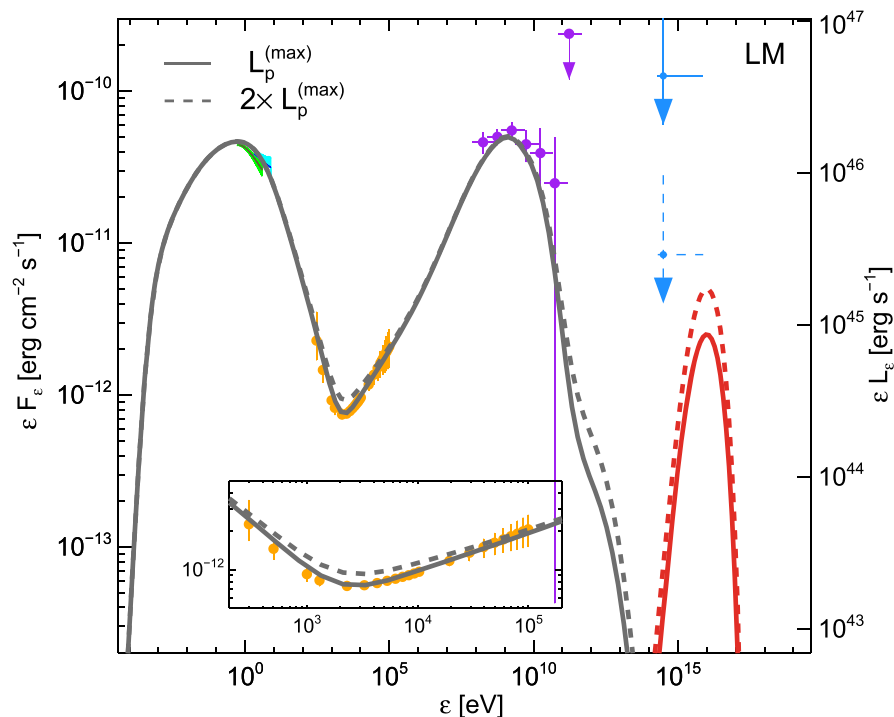
A Leptonic Model for Neutrino Emission from Blazars

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Hadronic Models



TXS 0506+056 $z=0.3365$. EM emission from synch/SSC model (Keivani et al. 2018)

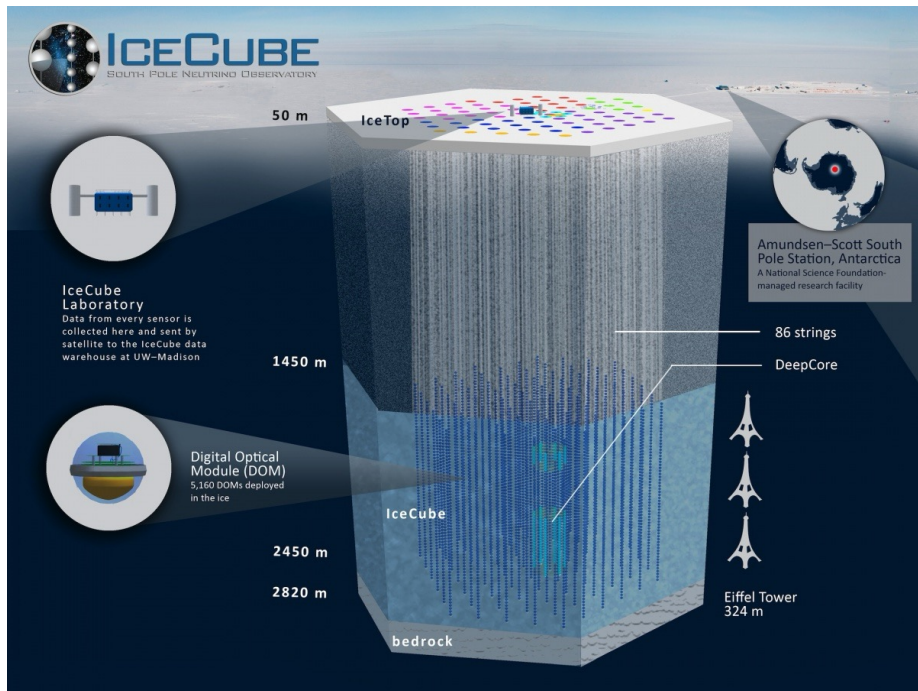
First source with significant neutrino association (3σ)

Accelerated protons cannot explain X/ γ -rays and neutrinos with same component

Hadronic models require jet powers greater than the Eddington luminosity for $10^9 M_{\text{Sun}}$ black hole.

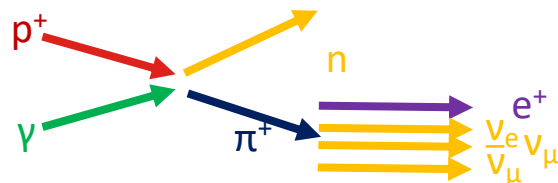


Neutrinos

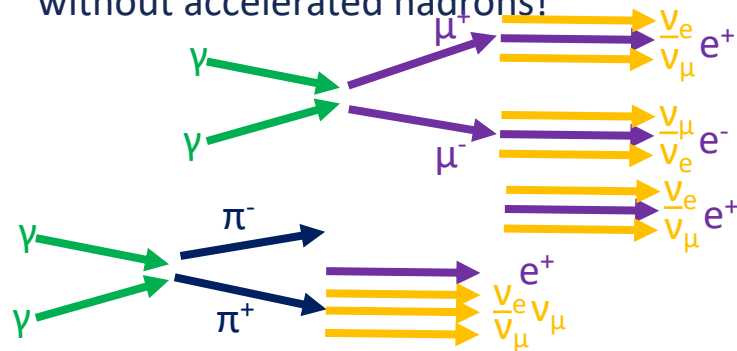


IceCube neutrino detector at south pole.

Most blazar models produce neutrinos with accelerated protons (hadrons):

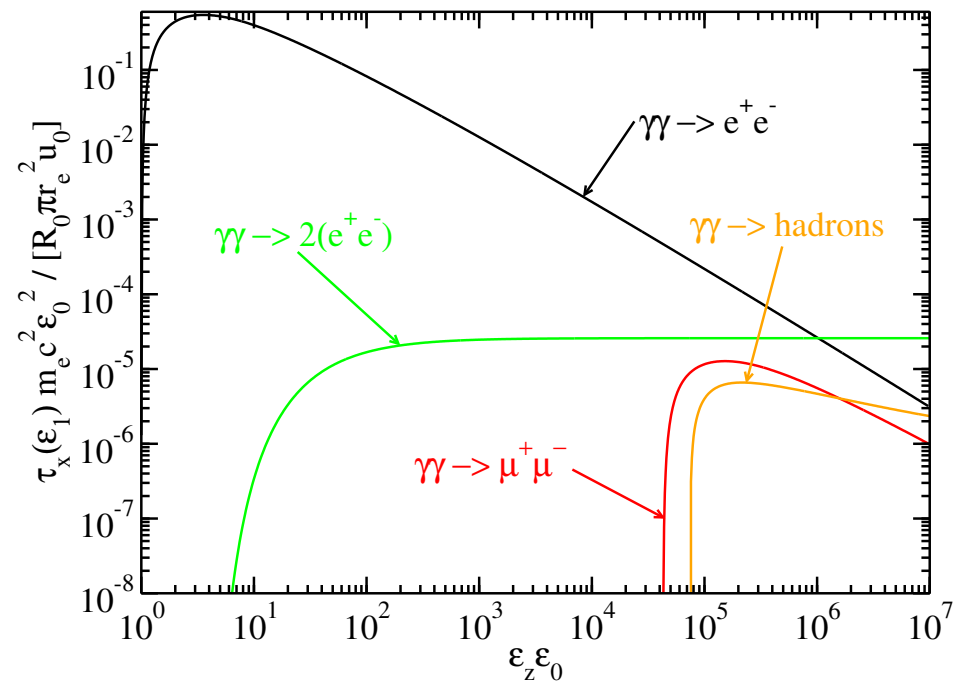


But it is possible to produce neutrinos without accelerated hadrons!





Neutrino production



The electron pair production process is common in astrophysics and in blazars (including interactions with the EBL).

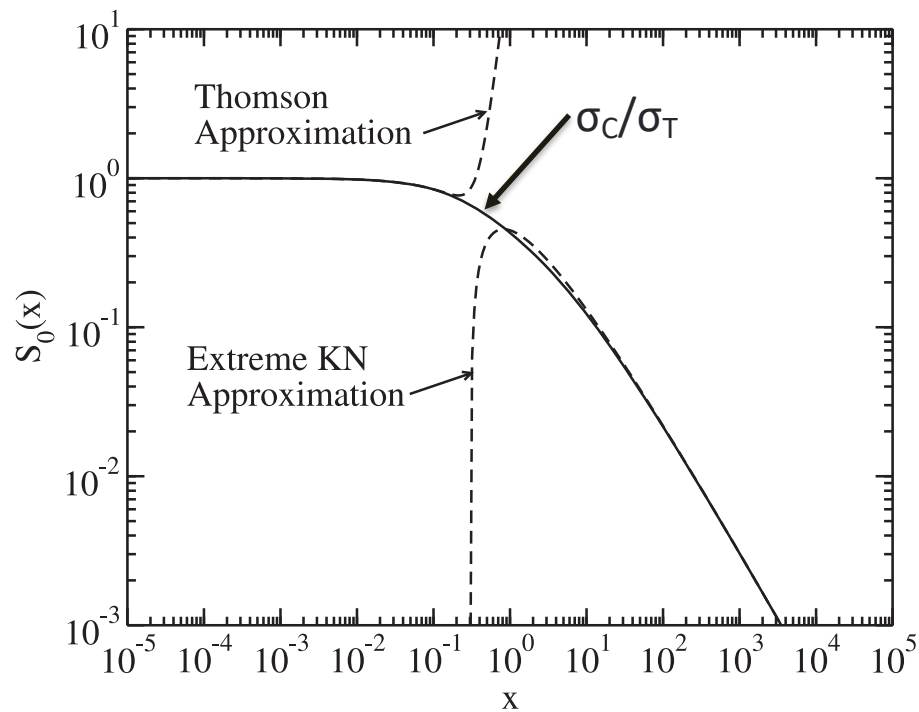
The muon production process has a threshold $(m_\mu/m_e)^2$ higher, and a cross section $(m_\mu/m_e)^2$ lower

Hadron production cross section similar to muons

Need γ -rays extending to PeV energies produced through purely leptonic processes



Leptonic Model for neutrinos

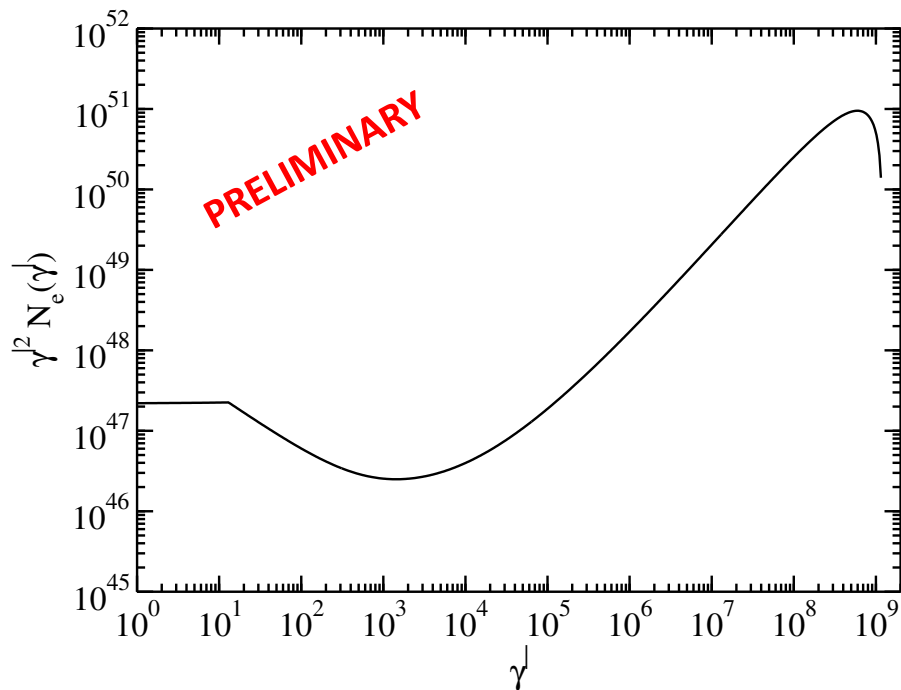


Problem: at high energies, the Compton cross section turns over, making it hard to produce PeV γ -rays.

Solution: Same turnover means electrons at high energies lose energy very rarely. This can lead to an “upturn” in electron distribution at high energies (e.g. Moderski et al. 2005)! Requires very small synchrotron energy losses.



Electron distribution



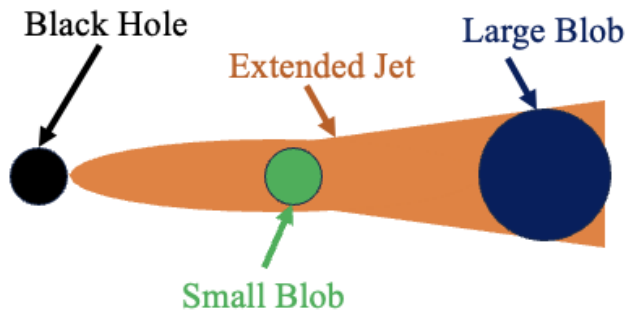
Electron distribution after energy losses.
Electrons injected as $\sim \gamma^{-1.9}$ between 13 and 3×10^9

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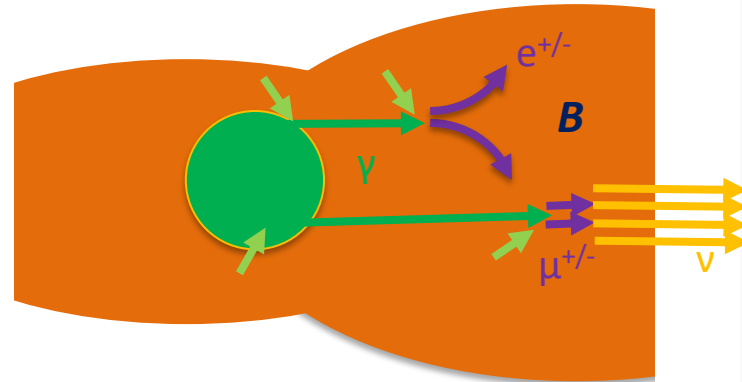
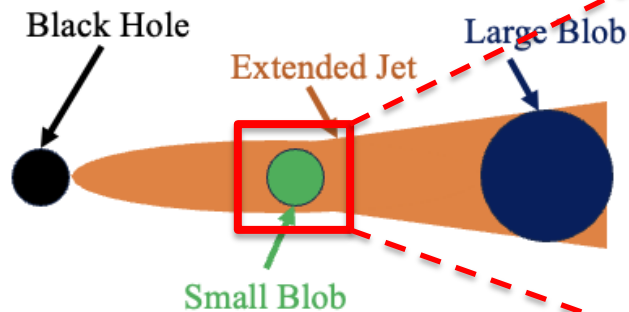
Leptonic model for neutrinos



Large blob: Electrons produce synchrotron and synchrotron self-Compton. Does not interact with **extended jet photons**.



Leptonic model for neutrinos

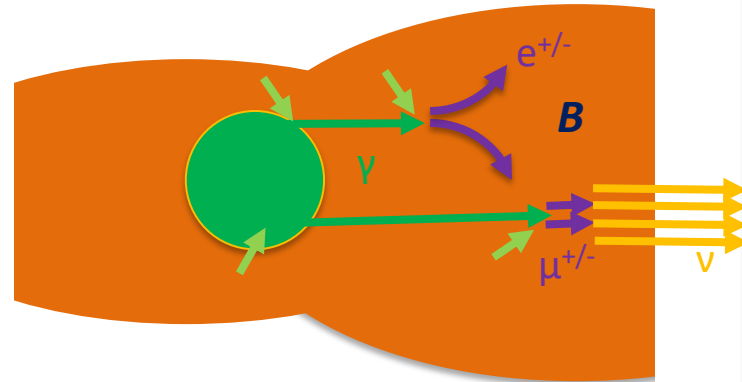
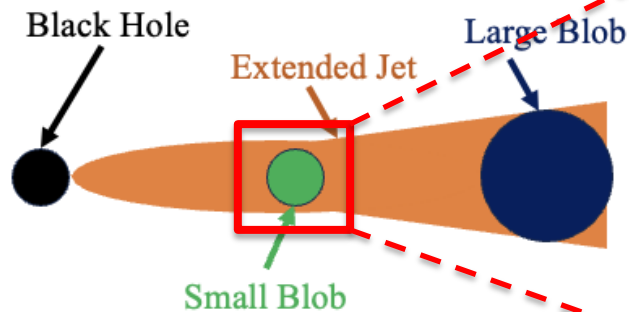


Small Blob: electrons in blob produce γ -rays through Compton scattering of extended jet photons.

Extended jet: produces radio-optical emission that is scattered by small blob and absorbs γ -rays. Only portion around small blob matters for our purposes.



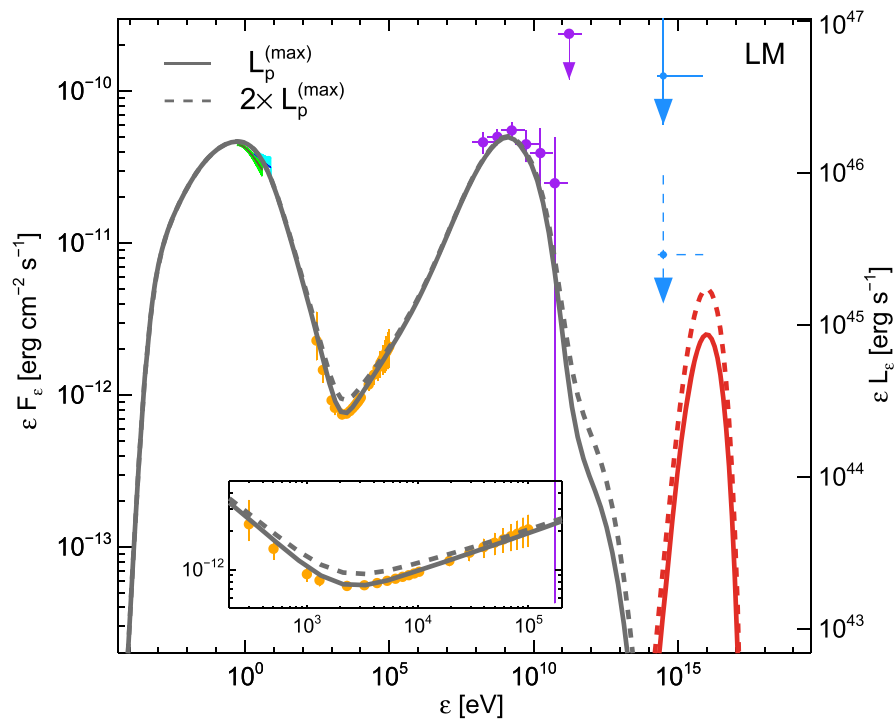
Leptonic model for neutrinos



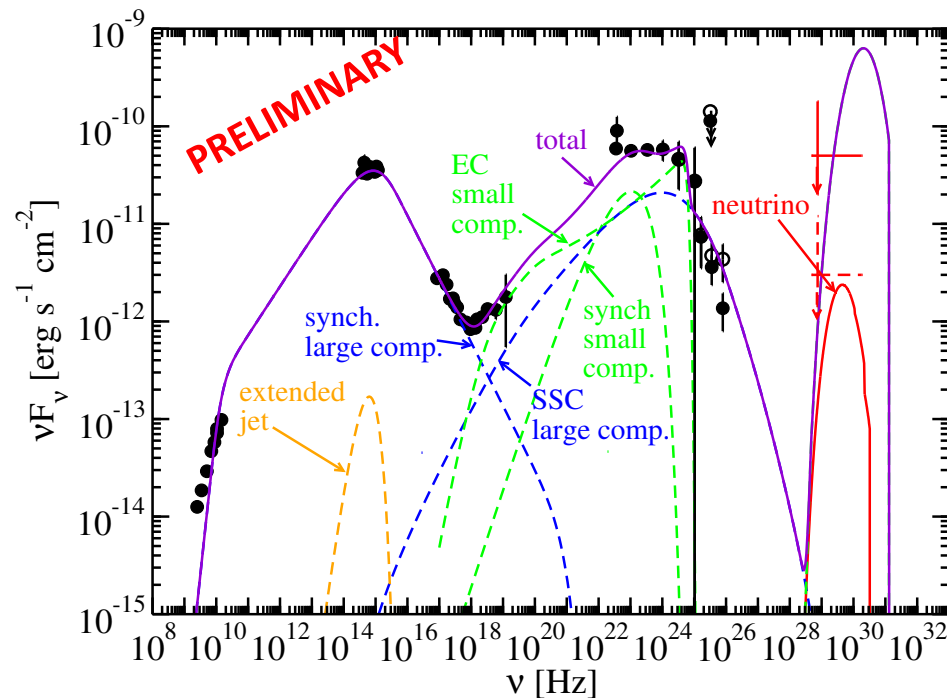
Extended jet photons absorb γ -rays to produce $e^{+/-}$ pairs. Pairs deflected by magnetic field.

Extended jet photons absorb γ -rays to produce $\mu^{+/-}$ pairs. Pair immediately (for our purposes) decay to produce neutrinos.

TXS 0506+056



TXS 0506+056 $z=0.3365$. EM emission from synch/SSC model (Keivani et al. 2018)



TXS 0506+056 (data from Aartsen et al. 2018)

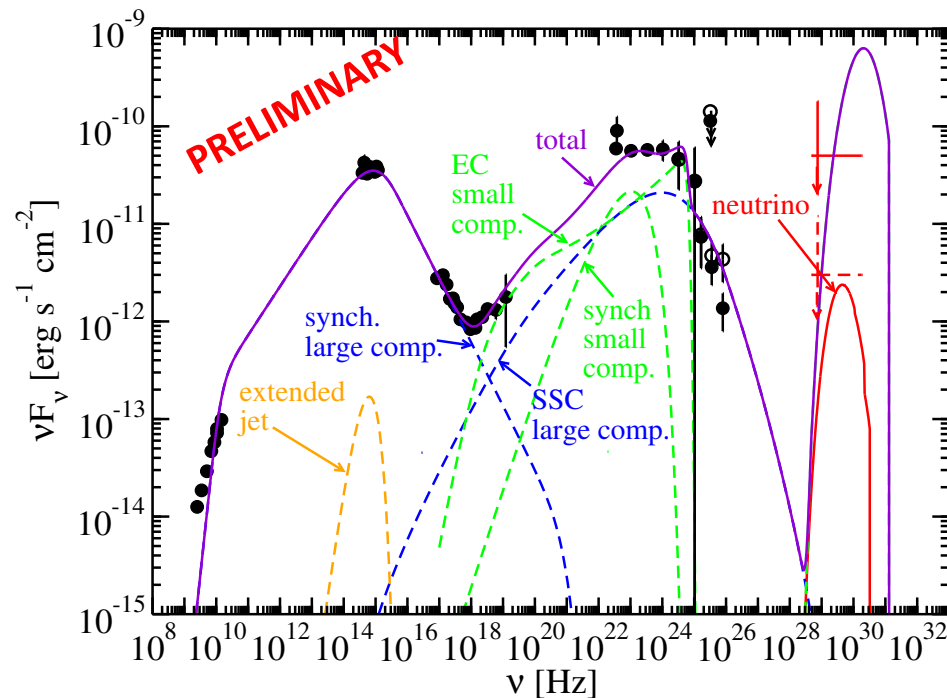
Leptonic model can completely explain SED, including neutrinos.

Can produce comparable neutrino flux than some lepto-hadronic models

Total jet power (4.0×10^{46} erg/s) less than Eddington luminosity for $10^9 M_{\text{Sun}}$ black hole

Disadvantages: More free parameters than lepto-hadronic models (22 versus 16)

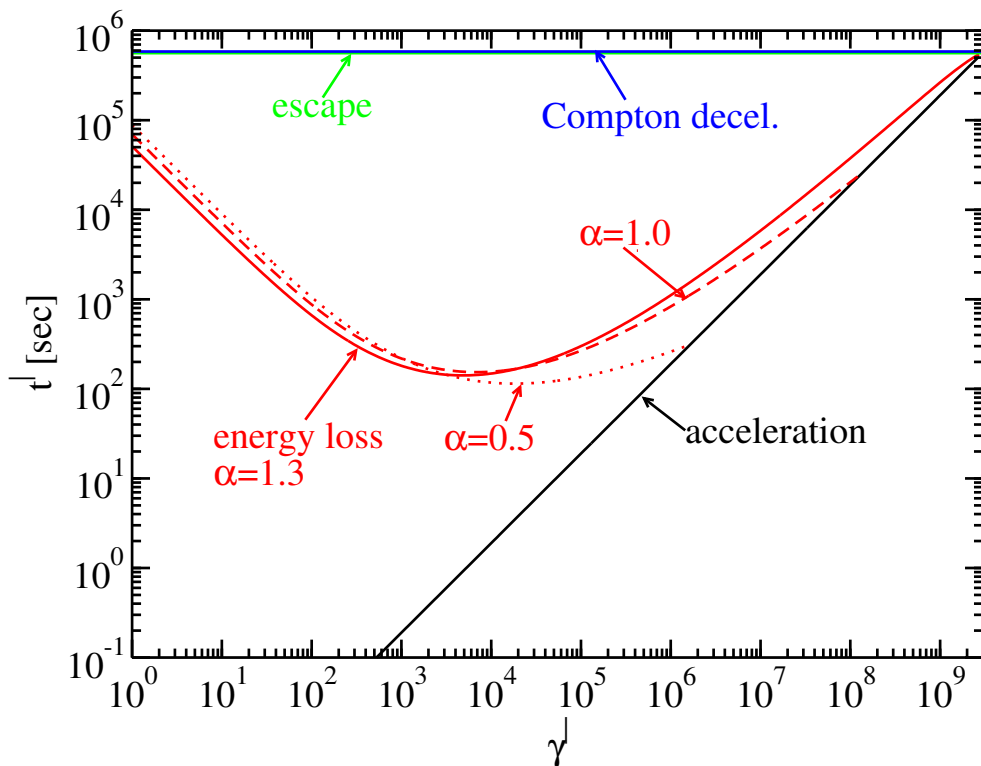
Requires hard radiation field for acceleration of electrons to very high energies ($\gamma=10^9$)



TXS 0506+056 (data from Aartsen et al. 2018)



Timescales

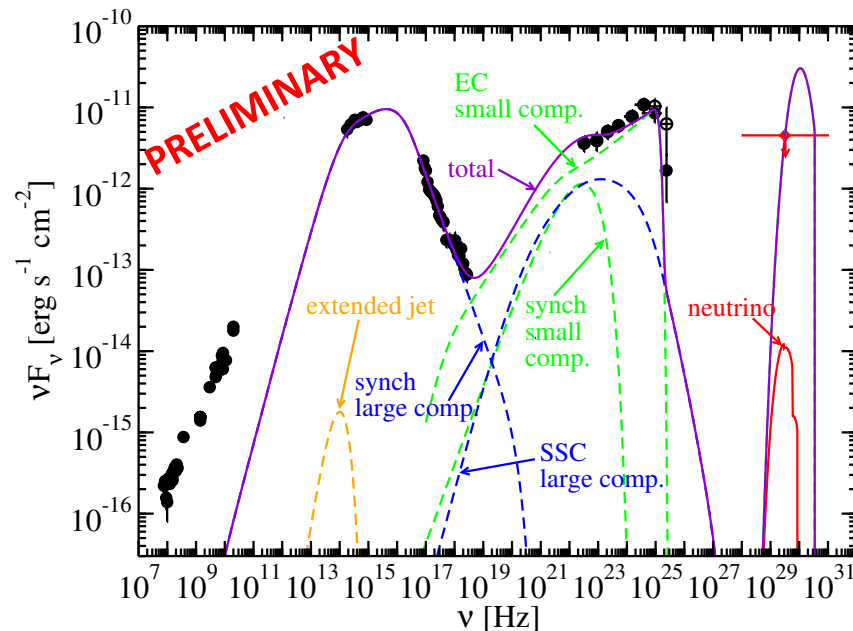
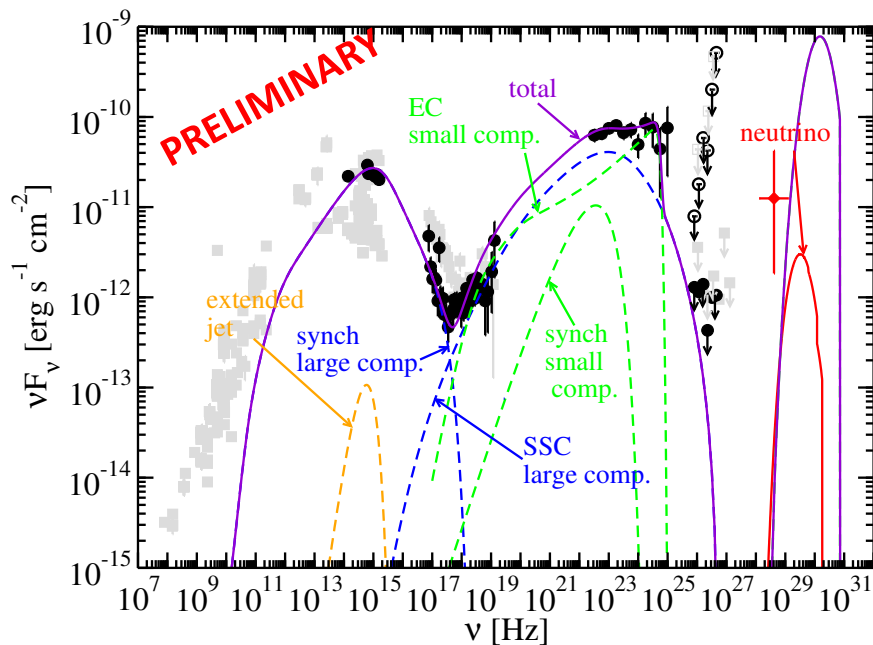


KN energy losses allow acceleration of electrons to $\gamma > 10^9$. Very hard external radiation field needed.

$$u(\epsilon) \sim \epsilon^\alpha e^{-\epsilon/\epsilon_0}$$

Large numbers of cold protons needed so that jet decelerate via bulk Comptonization

Other Blazars





Leptonic Model Signatures

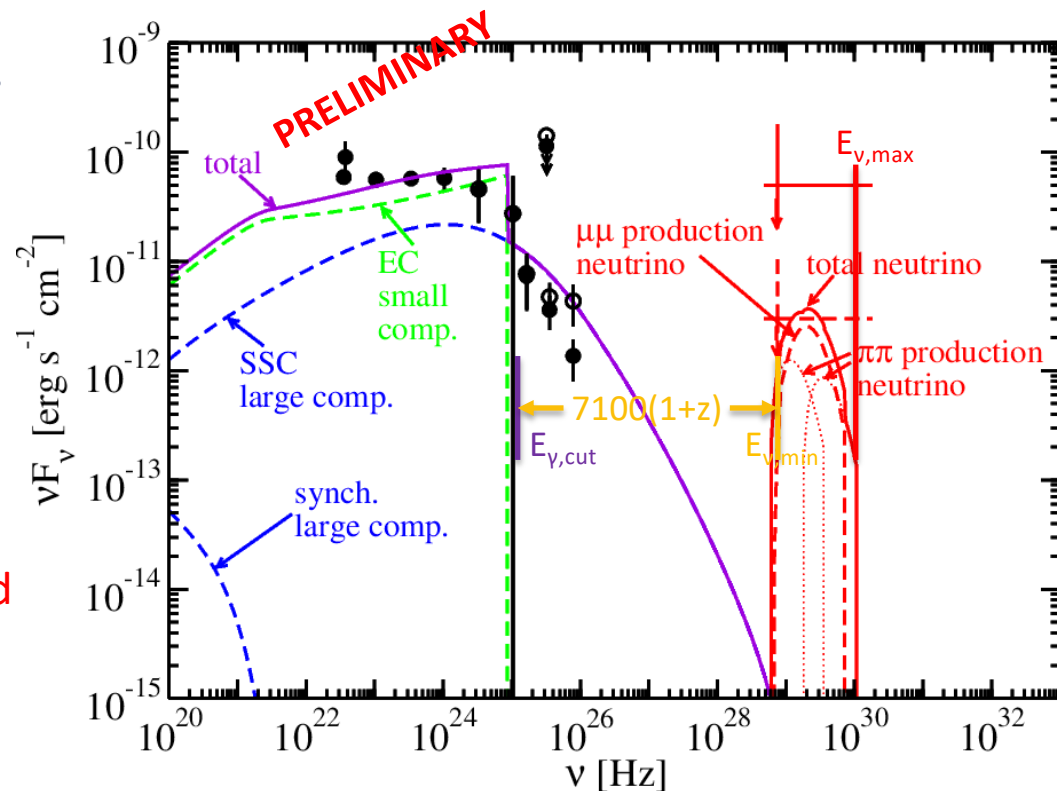
Sharp cutoff in γ -ray spectrum required.

$$E_{\nu,\min}/E_{\gamma,\max} = 7100(1+z)$$

$$E_{\nu,\max} = 4 (\delta/50)(\gamma_2/10^9)/(1+z) \text{ PeV}$$

$$E_{\gamma,\text{cut}} < 560 (\delta/50)(\gamma_2/10^9) \text{ GeV}$$

Can't explain 220 PeV neutrino detected by KM3NeT





Summary

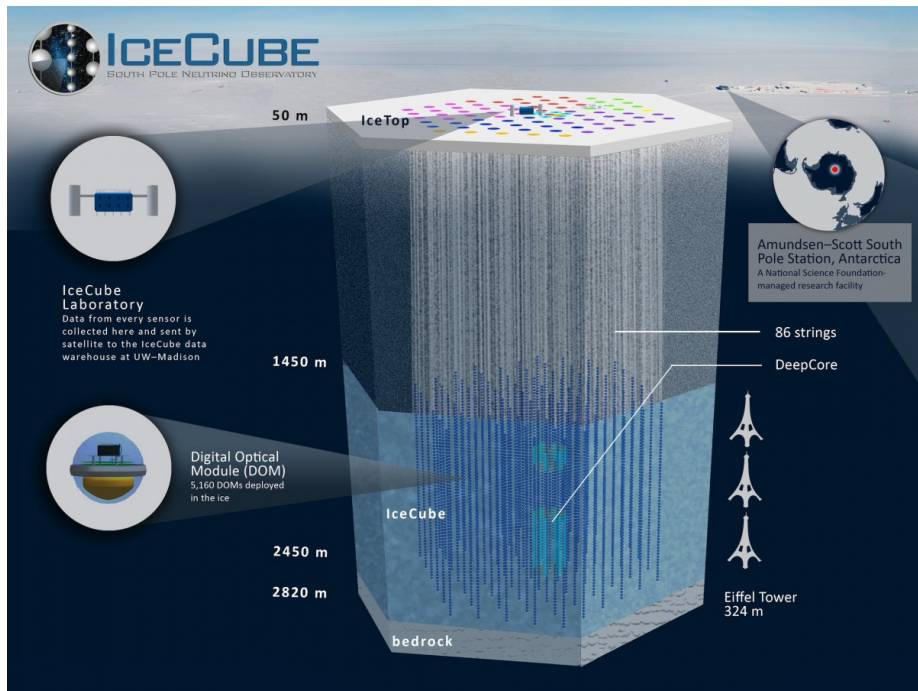
- We have created a leptonic model that can reproduce electromagnetic and neutrino emission from blazars. It can produce neutrino flux comparable to leptohadronic models with sub-Eddington jet powers.
- A very hard external radiation field needed to allow electrons to be accelerated to PeV energies; and large number of cold protons needed to prevent deceleration from bulk Comptonization
- Neutrino detection from blazars alone may not be a signature for accelerated hadrons.
- The leptonic model has a number of signatures that are potentially observable
 - Break in γ -ray spectrum
 - Ratio of neutrino energy to γ -ray break energy
 - Neutrino flavor ratio



Extras



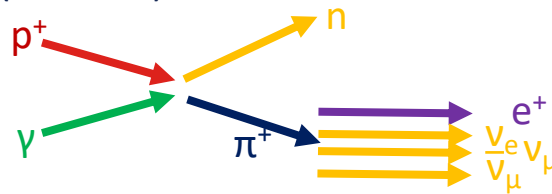
Neutrinos



IceCube neutrino detector at south pole.

Three flavors: e , μ , τ

Most blazar models produce neutrinos with accelerated protons (hadrons):





Model Parameters

PRELIMINARY

Parameter	Symbol	TXS 0506+056	PKS 0735+178	5BZB J0630-2406
1. Bulk Lorentz Factor	Γ	50	50	50
2. Doppler factor	δ_D	50	50	50
Extended Jet Parameters				
3. Extended Jet Luminosity [erg s ⁻¹]	L_{ext}	8.0×10^{43}	1.0×10^{44}	2.0×10^{43}
4. Extended Jet Size Scale [cm]	R_{ext}	4.0×10^{16}	4.0×10^{16}	4.0×10^{16}
5. Extended Jet Turnover Energy	ϵ_0	3.0×10^{-6}	3.0×10^{-6}	8.0×10^{-7}
6. Extended Jet Magnetic Field Strength [G]	B_{ext}	7×10^{-4}	7×10^{-4}	7×10^{-4}
7. Extended Jet opening angle [rad]	θ_j	0.020	0.020	0.020
Large Blob Parameters				
8. Large Blob Radius [cm]	R'_l	2.6×10^{17}	1.3×10^{16}	8.7×10^{15}
9. Large Blob Magnetic Field [G]	B'_l	6.0×10^{-3}	9.0×10^{-2}	1.0
10. Electron Distribution Normalization	$N'_{e,0}$	4.6×10^{45}	1.3×10^{45}	3.6×10^{43}
11. Electron Index 1	p_1	2.0	2.0	2.5
12. Electron Index 2	p_2	4.3	4.4	5.0
13. Minimum Electron Lorentz Factor	γ'_1	1×10^2	2×10^2	1×10^3
14. Maximum Electron Lorentz Factor	γ'_2	3.0×10^7	1.3×10^5	1×10^6
15. Break Electron Lorentz Factor	γ'_b	3.3×10^4	9.6×10^3	1.0×10^4
Jet Power in Electrons [erg s ⁻¹]	$P_{j,e}$	1.1×10^{46}	3.5×10^{45}	1.8×10^{44}
Jet Power in Magnetic Field [erg s ⁻¹]	$P_{j,B}$	4.5×10^{43}	2.7×10^{43}	1.4×10^{45}
Small Blob Parameters				
16. Small Blob Radius [cm]	R'_s	1.1×10^{15}	1.0×10^{15}	6.7×10^{14}
17. Small Blob Magnetic Field [G]	B'_s	3.0×10^{-4}	3.0×10^{-4}	7.0×10^{-4}
18. Electron Escape Time Constant	ξ_{esc}	15	12	20
19. Electron Injection Index	q	1.7	1.7	1.7
20. Minimum Electron Injection Lorentz Factor	γ'_1	6.0	13	1.0×10^2
21. Electron Injection Power [erg s ⁻¹]	$L'_{e,\text{inj}}$	5.7×10^{41}	1.6×10^{42}	1.5×10^{42}
22. Cold Electron to Proton ratio	$N_{e,c}/N_p$	0.966	0.964	0.916
Maximum Electron Injection Lorentz Factor	γ'_2	3.0×10^9	1.8×10^9	1.3×10^9
Co-moving Frame Deceleration Timescale [s]	t'_{decel}	5.8×10^5	4.7×10^5	1.3×10^5
Jet Power in Cold Electrons [erg s ⁻¹]	$P_{j,e,c}$	1.3×10^{43}	3.6×10^{43}	1.4×10^{43}
Jet Power in Nonthermal Electrons [erg s ⁻¹]	$P_{j,e}$	3.6×10^{45}	6.4×10^{45}	3.5×10^{45}
Jet Power in Magnetic Field [erg s ⁻¹]	$P_{j,B}$	2.1×10^{36}	1.8×10^{36}	4.1×10^{36}
Jet Power in Cold Protons [erg s ⁻¹]	$P_{j,p}$	2.5×10^{46}	6.8×10^{46}	2.8×10^{46}
Total Jet Power (Small+Large Blobs) [erg s ⁻¹]	$P_{j,\text{tot}}$	4.0×10^{46}	7.8×10^{46}	3.3×10^{46}

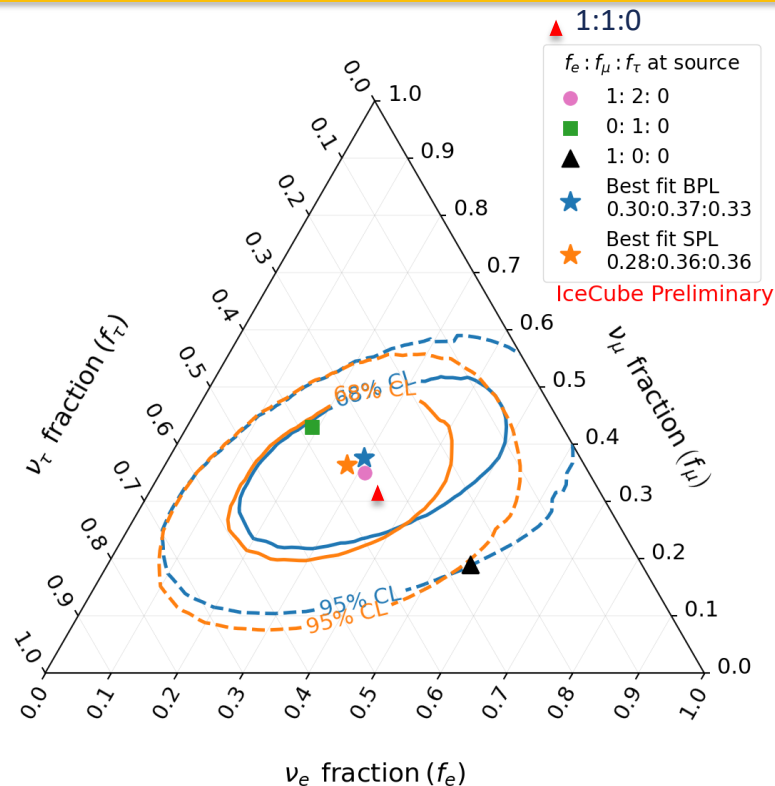


Leptonic Model Signatures: Flavor ratio

Muon decay produces neutrinos with ratio 0.5 : 0.5 : 0. After neutrino oscillations gives **0.36 : 0.31 : 0.33**.

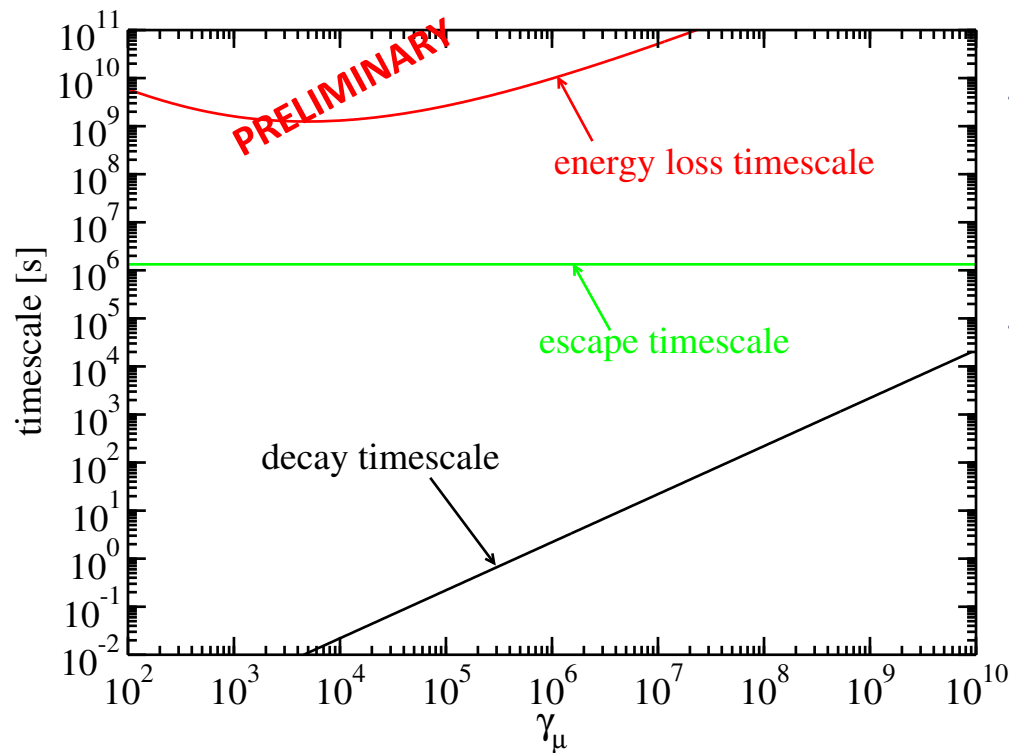
Pion decay produces neutrinos with ratio 0.33 : 0.67 : 0 After neutrino oscillations gives **0.30 : 0.36 : 0.33**.

In principle observations could distinguish models. Thus far, measurement of all astrophysical neutrinos by IceCube cannot distinguish them.





Muon Energy loss timescale

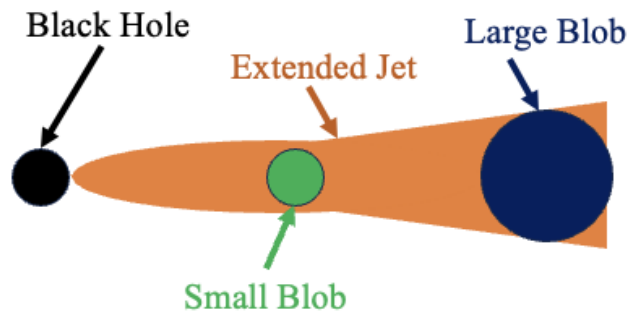


Muons decay on timescale $2.2 \mu\text{s}$ in their rest frame.

Must make sure muons decay and produce neutrinos before they lose all their energy to Compton scattering.

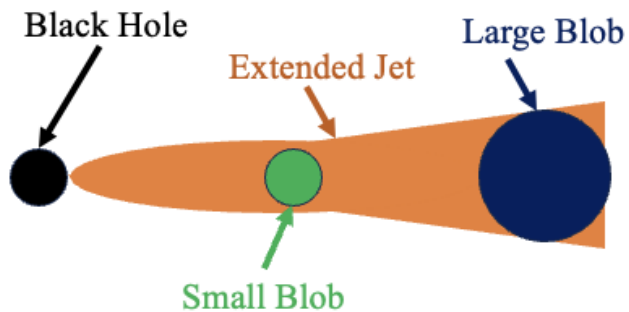


Leptonic model for neutrinos





Leptonic model for neutrinos



Large blob: Electrons produce synchrotron and synchrotron self-Compton. Does not interact with **extended jet photons**.

Small Blob: electrons in blob produce γ -rays through Compton scattering of **extended jet photons**

Extended jet: produces radio-optical emission that is scattered by **small blob** and absorbs γ -rays. Only portion around small blob matters for our purposes.

broad line region and dust torus doesn't produce enough photons to absorb γ -rays and produce sufficient muons and neutrinos.

Cascade

