Multi-messenger emission from magnetically dominated baryon-loaded blazar jets

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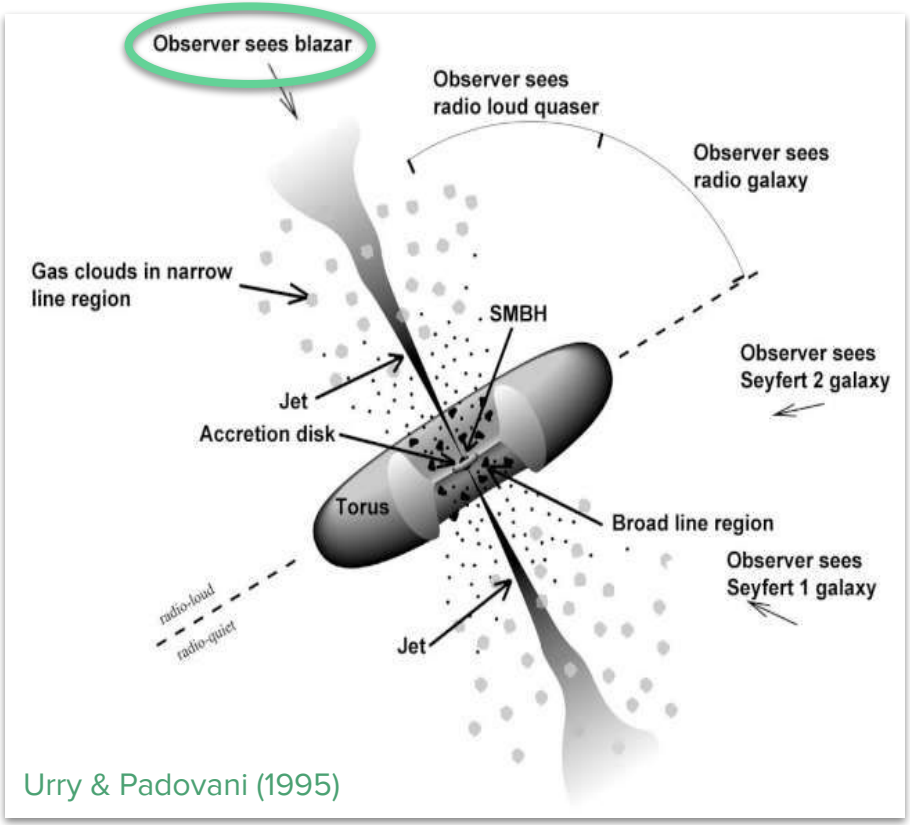
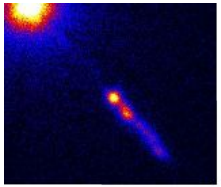
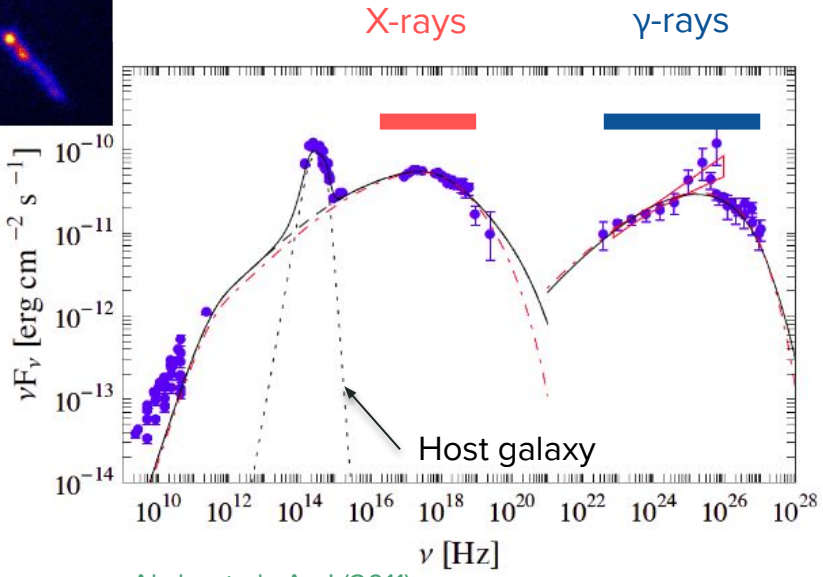
AGN jets as high-energy* non-thermal emitters



Urry & Padovani (1995)

3C 273



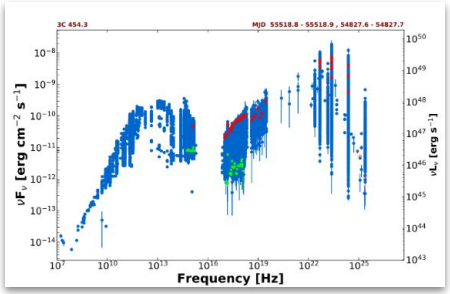


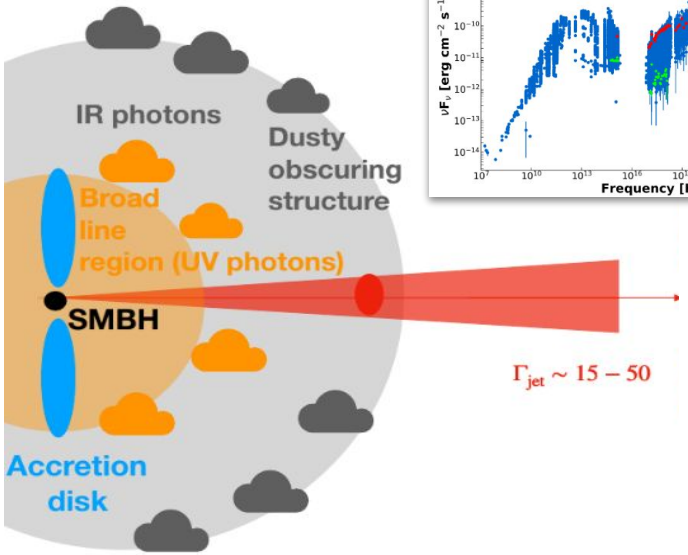
Abdo et al., ApJ (2011)

** E > 0.1 keV*

Blazar classes

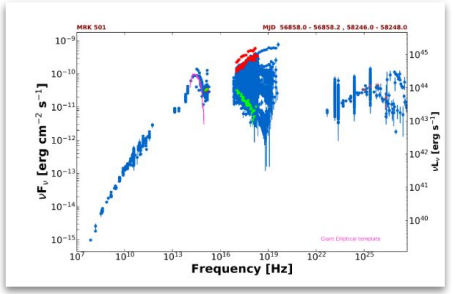
FSRQs

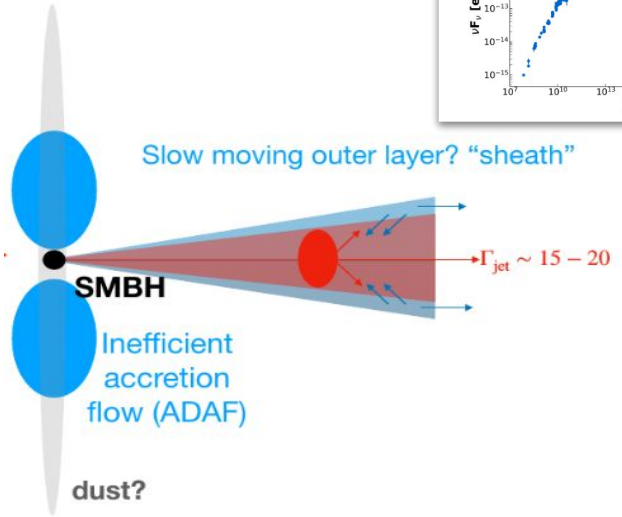




- Broad emission lines in optical spectra
- Radiatively efficient disks
- Strong external fields
- High jet power & γ-ray luminosity

BL Lacs



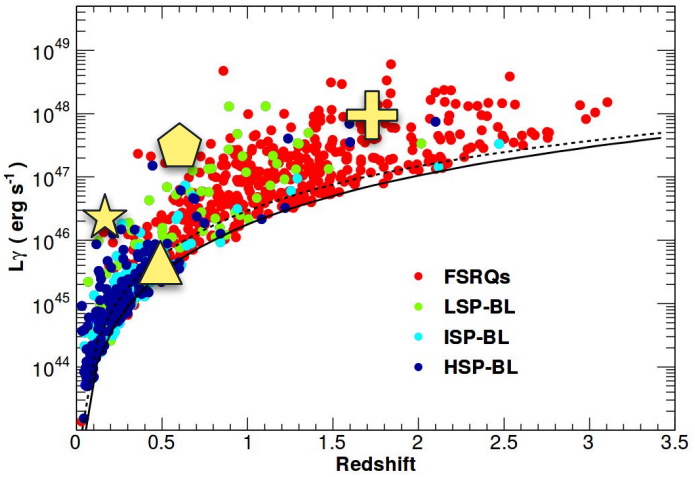


- Weak/absent broad emission lines in optical spectra
- Radiatively inefficient disks
- Weak/absent external fields
- Low jet power & γ-ray luminosity

Interesting neutrino alerts & blazars

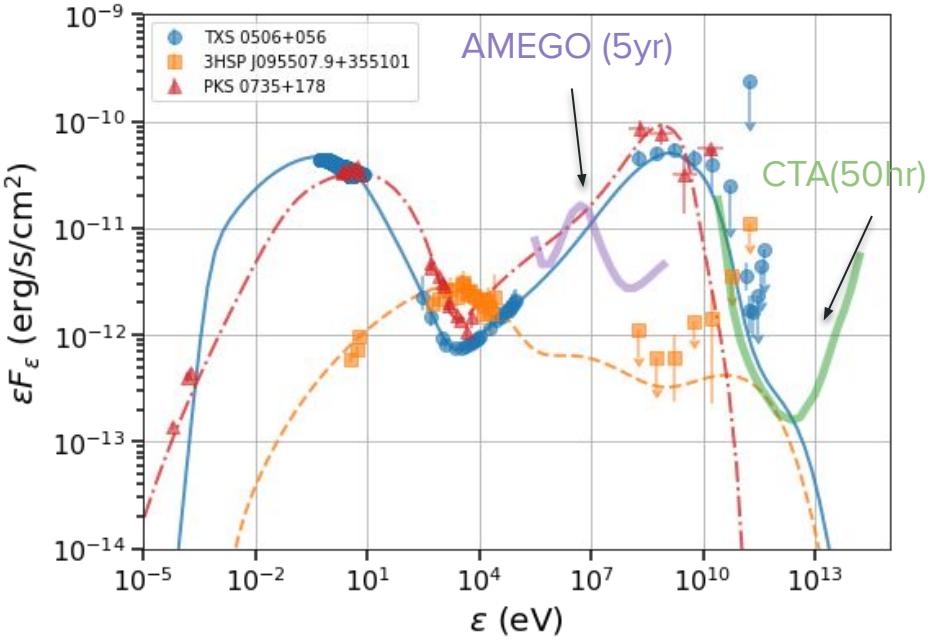
- TXS 0506+056 / IC - 170922A (IceCube collaboration 2018, Science)
  - *Masquerading BL Lac* with Esyn,pk < 4 eV [ISP] (Padovani et al. 2019, MNRAS)
  - Neutrino (~ 290 TeV) detected during a MW 6 month-long flare
- 3HSP J095507.9+35510 / IC-200107 (Giommi et al. 2020, MNRAS; Paliya et al. 2020, ApJ)
  - *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)

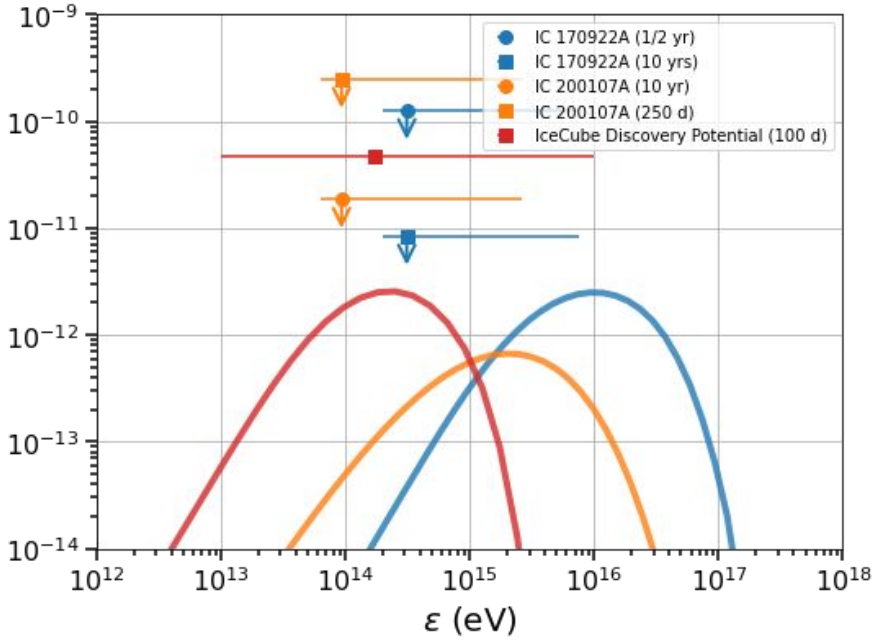


Models of multi-messenger blazar emission

Photon spectra

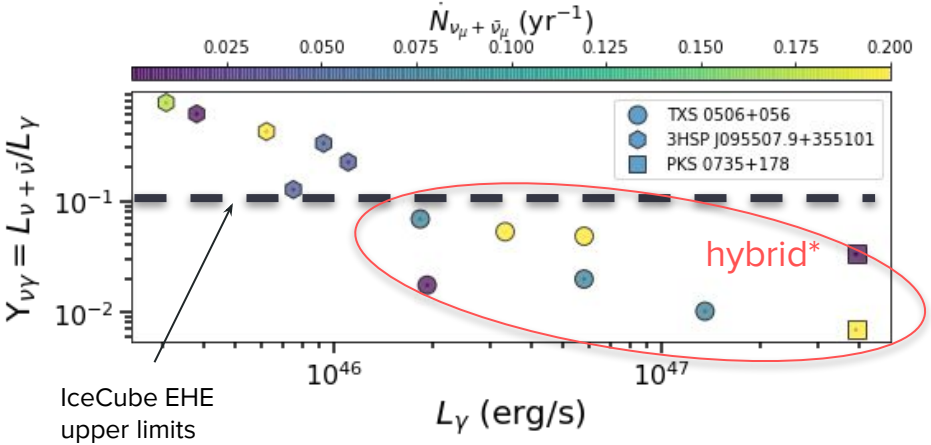


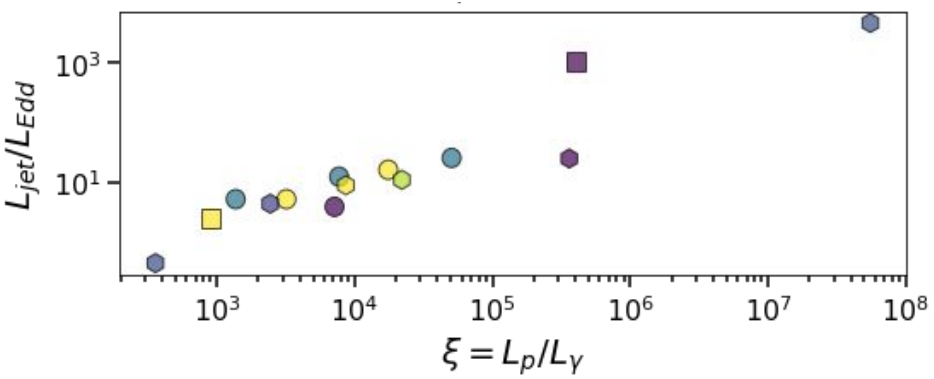
Neutrino spectra



Adopted from Keivani et al., ApJ (2018), Petropoulou et al., ApJ (2020), Sahakyan et al., MNRAS submitted

Comparison of modeling results





*hadronic EM emission not directly observed

- 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 ➔ what's the physical reason ?
- Very high baryon loading factors needed (not constrained by UHECR obs)
- L_jet > L_Edd even for hybrid models

A simple, but physically motivated jet emission model

Petropoulou, Psarras, Giannios, in prep.

Main model ingredients

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

Total jet energy flux per unit rest-mass energy flux

Jet plasma magnetization

Jet Lorentz factor

$$L_{\rm d} = \eta_{\rm d}\dot{M}c^2 = \dot{m}L_{\rm Edd}$$

Disk luminosity

$$L_{\rm BLR} = 0.1L_{\rm d}$$

BLR luminosity

$$L_{\rm j} = \eta_{\rm j}\dot{M}c^2 = \frac{\eta_{\rm j}}{\eta_{\rm d}}\dot{m}L_{\rm Edd}$$

Jet luminosity

$$L_B = \frac{\sigma}{\sigma+1}L_j$$

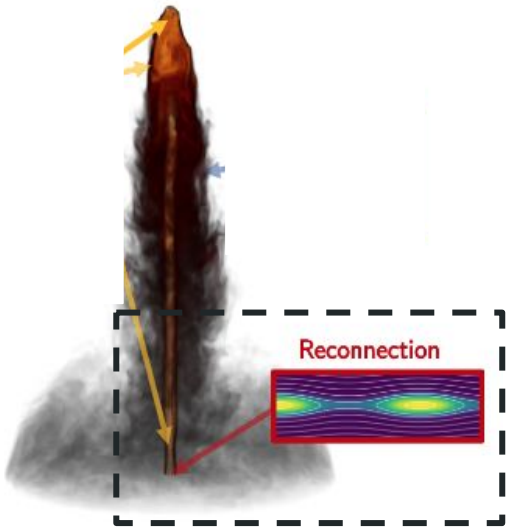
Poynting jet luminosity

$$\dot{m} \simeq 1.6\times10^{-5}\,\Gamma^3$$

Accretion rate -
jet Lorentz factor scaling

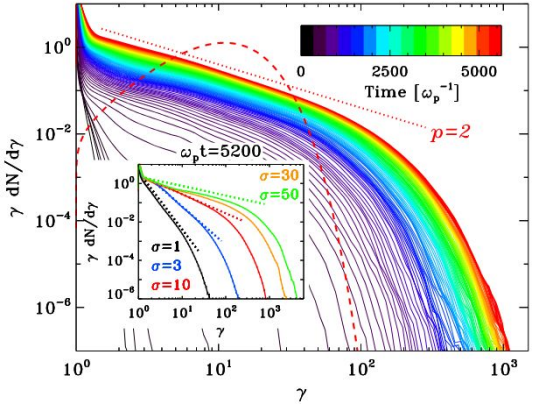
Properties of relativistic particles

Assumption: jet energy dissipated via magnetic reconnection



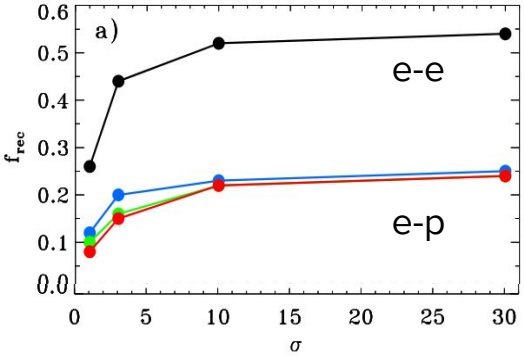
Matthews et al., NewAR (2020)

Particle distribution



Sironi & Spitkovsky 2014 (ApJL)

Dissipation efficiency



Sironi, MP, Giannios 2015 (MNRAS)

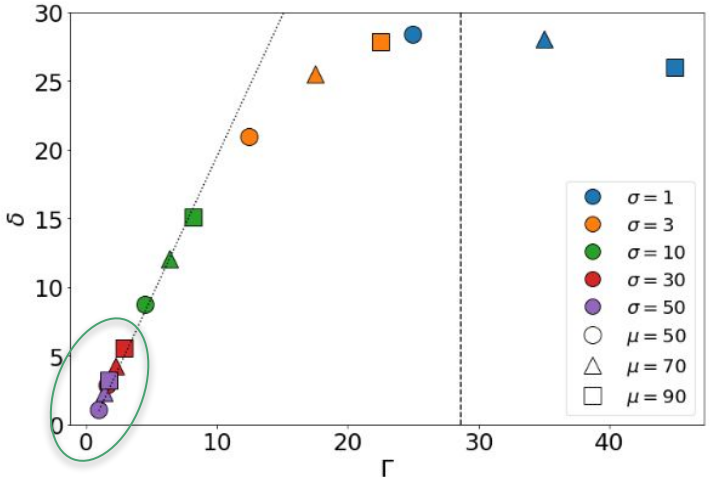
$$p = f(\sigma)$$

Particle injection luminosity

$$L'_e = L'_p = f_{rec}\frac{2L_B}{3\beta\Gamma^2}$$

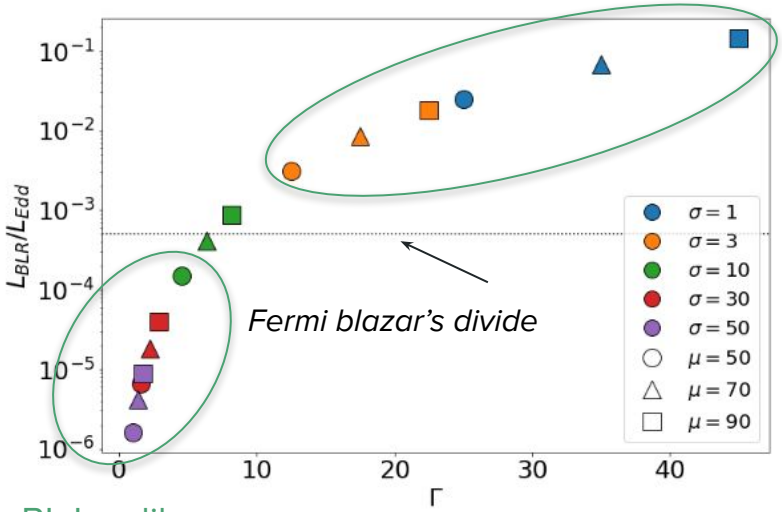
Results

Doppler beaming



BLR luminosity

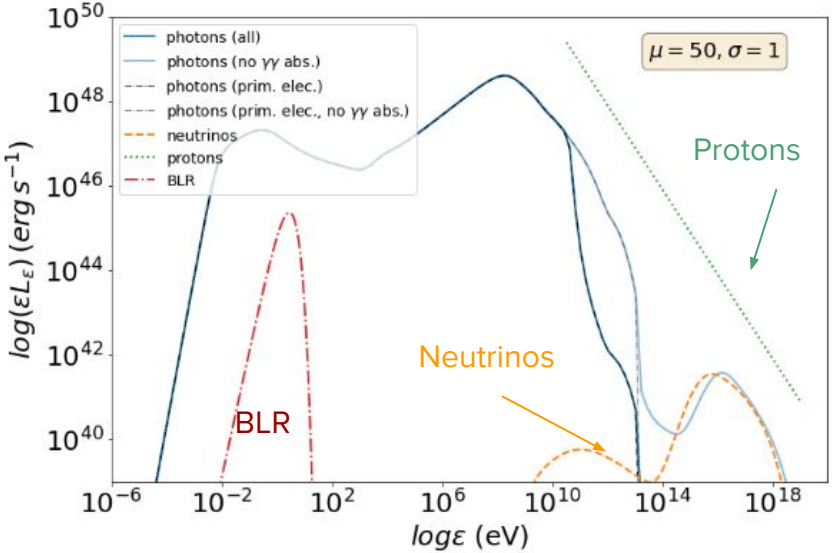
FSRQ-like



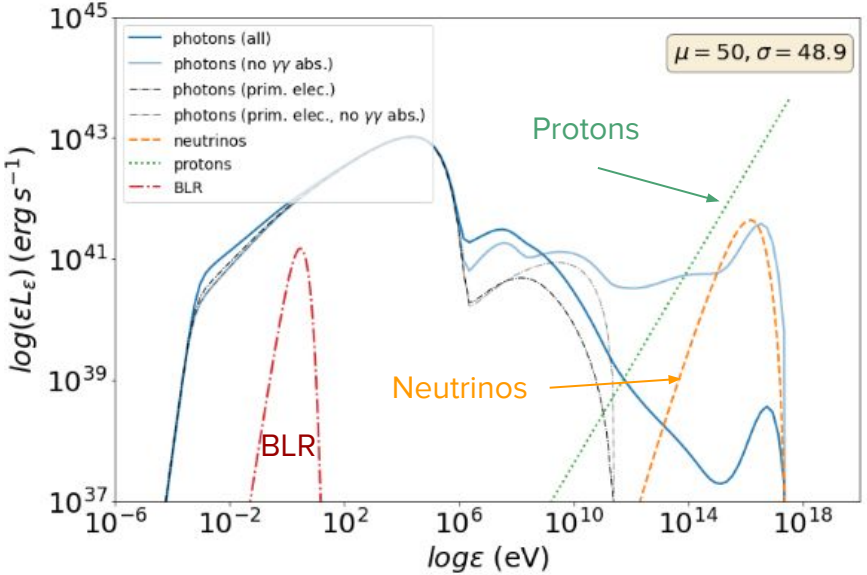
BL Lac-like

- High-σ jets ➜ low Doppler factors
- Low-σ jet ➜ high Doppler factors

Photon & neutrino spectra

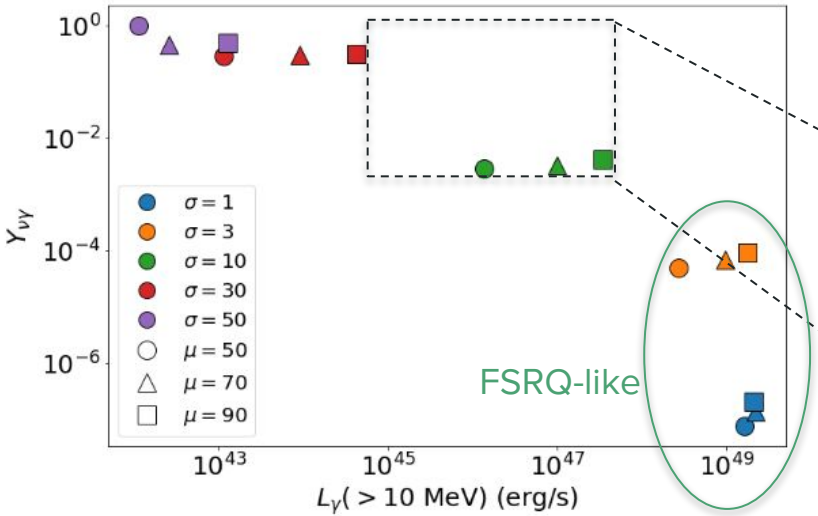


- Steep proton spectra (p=3)
- High Lγ ➔ external Compton
- Yνγ << 1

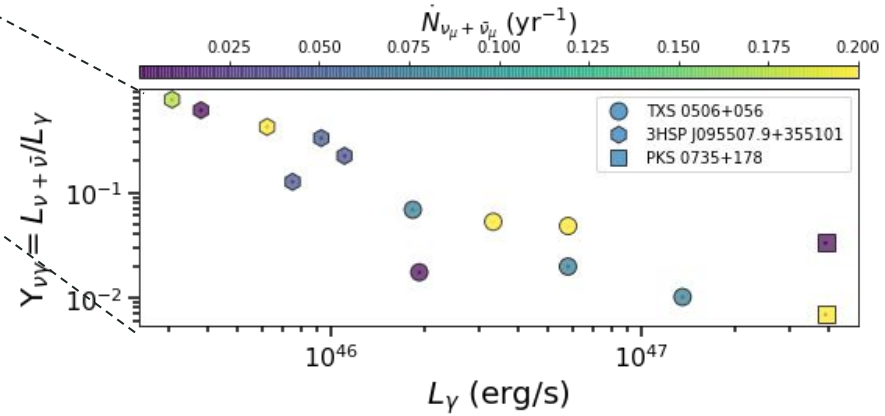


- Hard proton spectra (p=1.2)
- Low Lγ ➔ SSC + hadronic proc.
- Yνγ ~ 1

Neutrino-to-γ-ray luminosity ratio

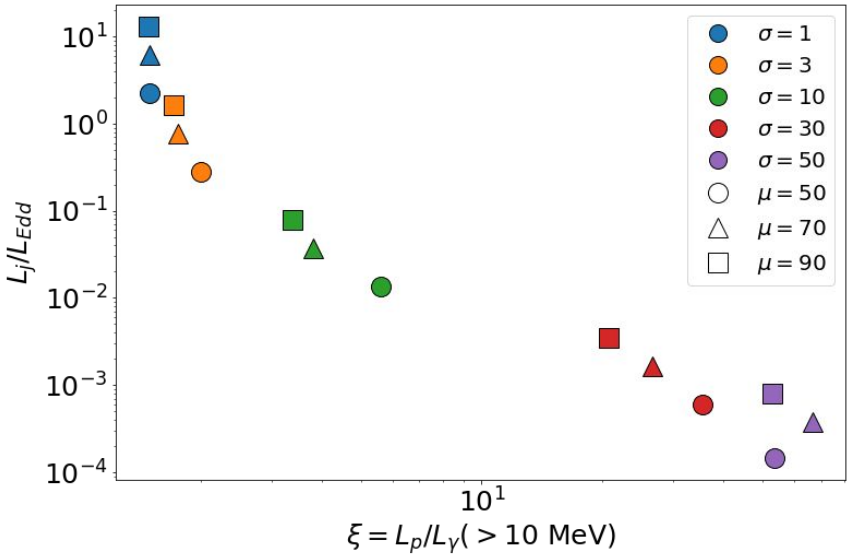


Comparison to phenomenological emission models

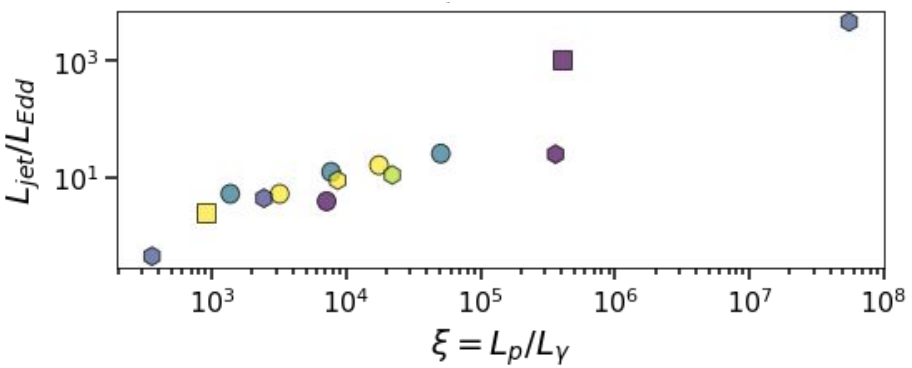


- Strong evolution of Yνγ with Lγ
- Low-σ jets (FSRQs) are dim ν sources

Baryonic loading



Comparison to phenomenological emission models



- High-σ jets have Lj << LEdd
- Low-σ jets have Lj ~(0.3-10) LEdd
- Baryonic loading factor is 3-30

Conclusions

- Multi-messenger jet emission model with 3 main parameters: μ, σ, mdot
- Low-luminosity blazars ➜ less powerful slow, high-σ jets with Lν ~(0.3-1)Lγ
- High-luminosity blazars ➜ more powerful fast, low-σ jets with Lν << Lγ
- Weak dependence of baryonic loading on μ,σ (ξ~3-30)

Outlook

What is the contribution of blazar jets to the diffuse IceCube neutrino flux ?

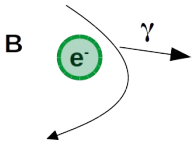
Thank you!

Backup slides

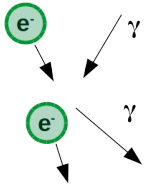
Most common non-thermal radiative processes

Leptonic processes

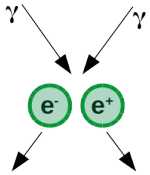
Synchrotron

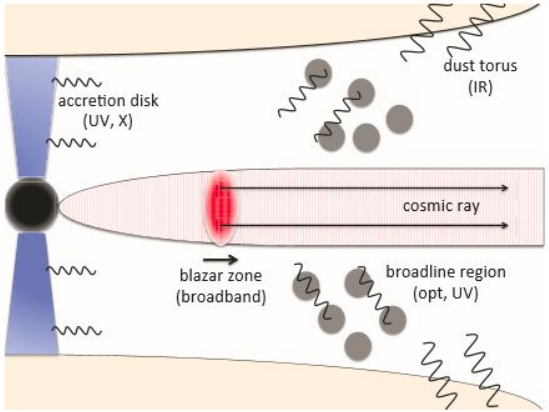


Inverse Compton scattering



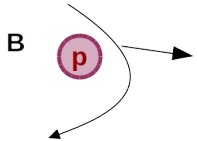
Photon-photon pair production



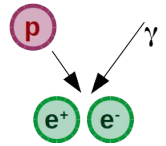


Hadronic processes

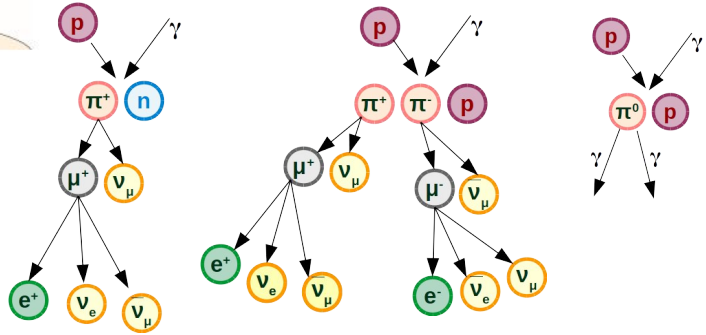
Synchrotron



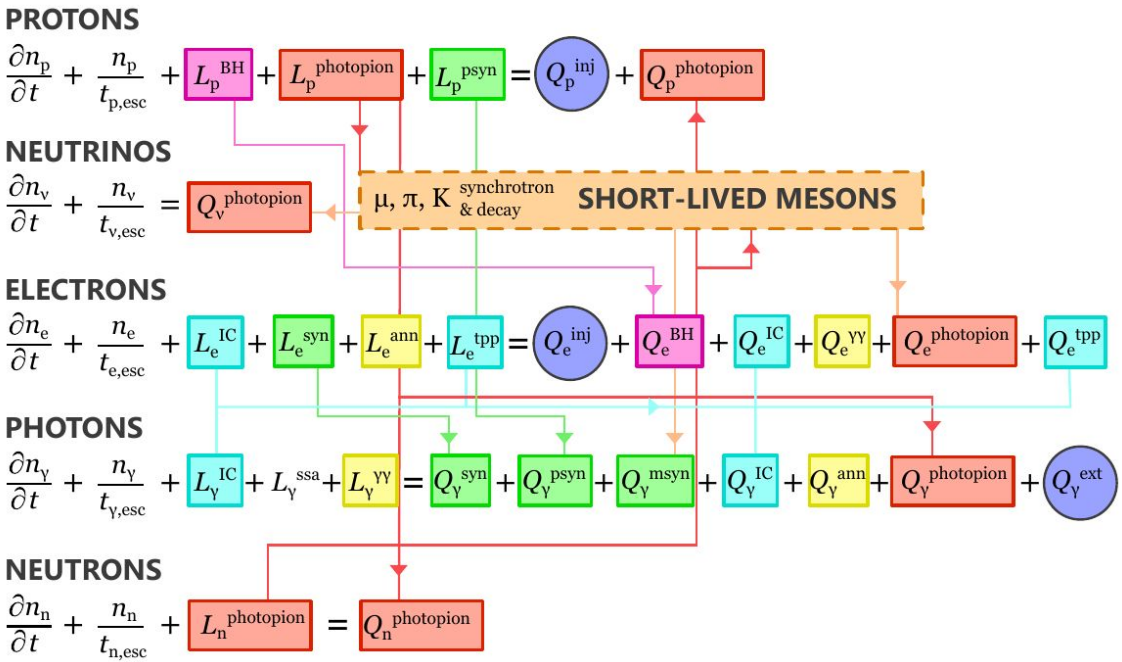
Proton-photon pair production



Proton-photon pion production



Numerical approach

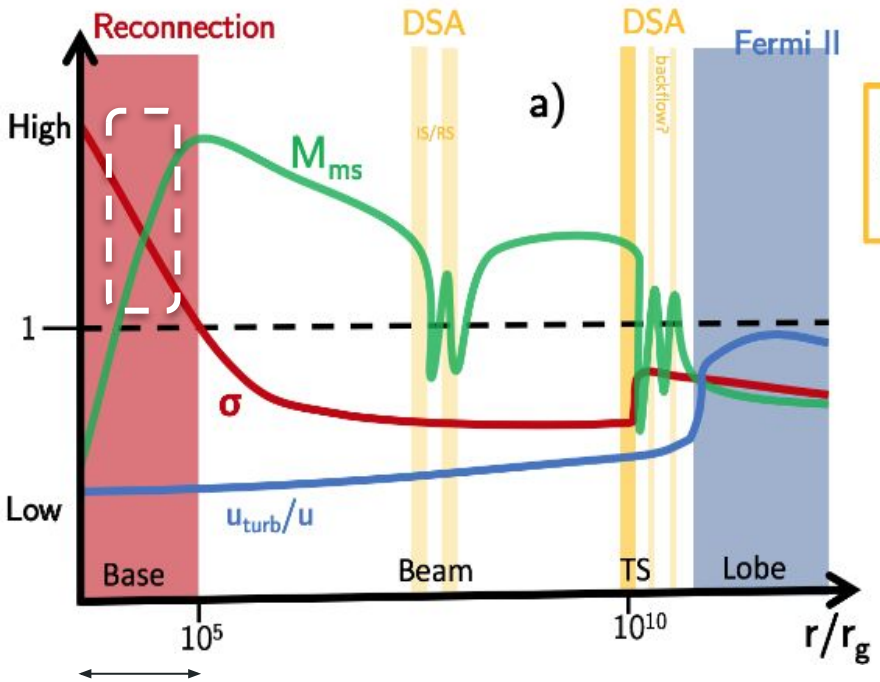


Free parameters for 1 radiation zone:

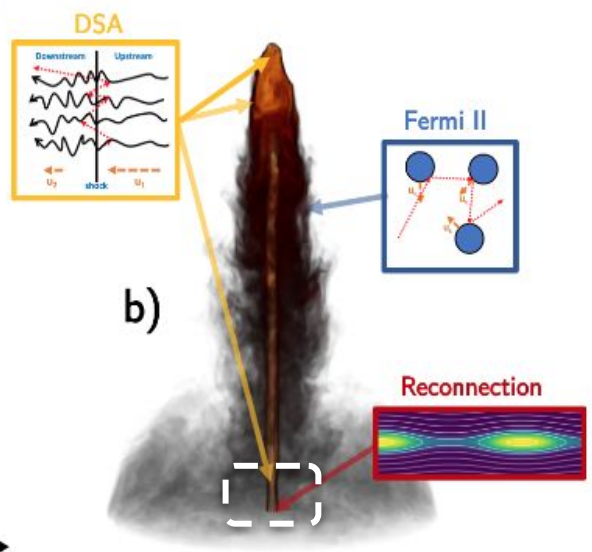
1. Emitting region (3)
2. Relativistic electron distribution (4)
3. Relativistic proton distribution (4)

An MHD-inspired model for baryon loaded jets

$$\sigma = \frac{B'^2}{4\pi\rho' c^2}$$



~5 pc (for 10^9 M_{sun})



Matthews et al., NewAR (2020)

Photon & neutrino spectra