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

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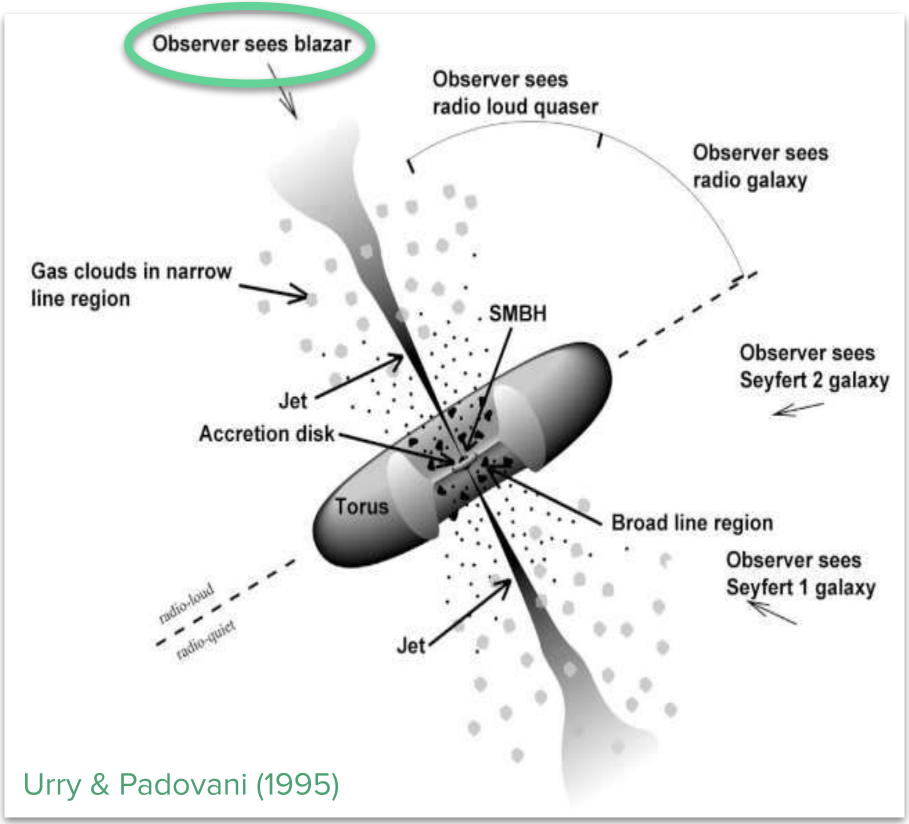
H.F.R.I. Hellenic Foundation for Research & Innovation

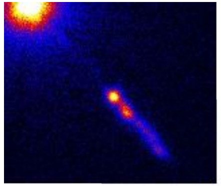
MERAC

AGN jets as high-energy* non-thermal emitters



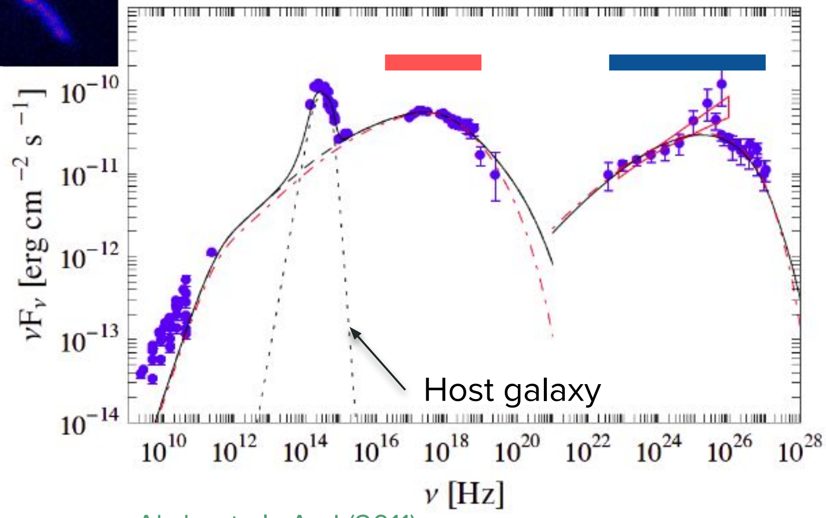
Urry & Padovani (1995)

3C 273



X-rays

γ-rays

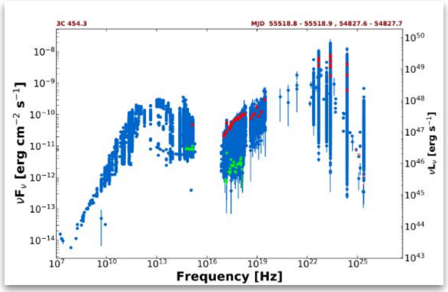


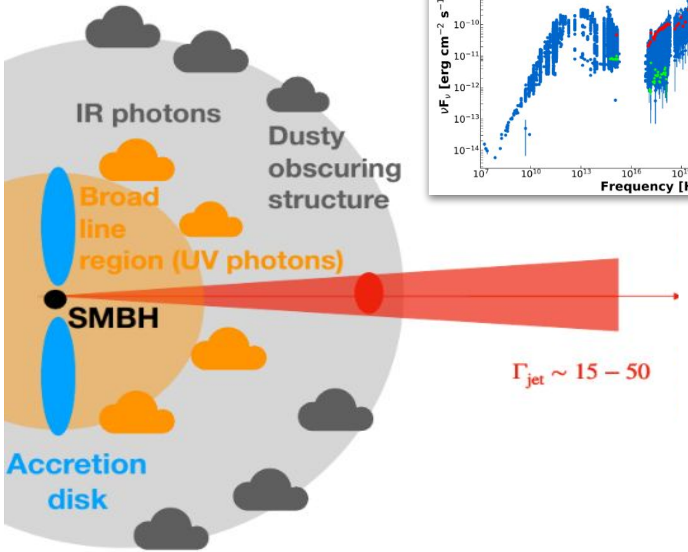
Abdo et al., ApJ (2011)

** E > 0.1 keV*

Blazar classes

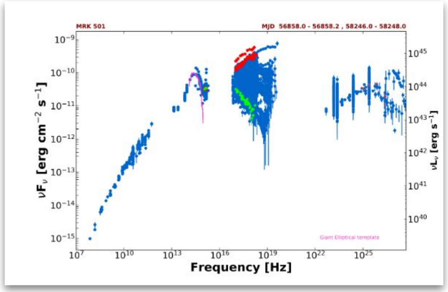
FSRQs

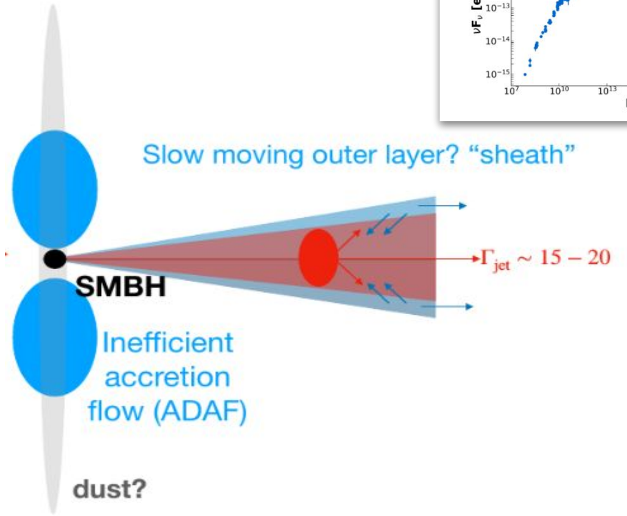




- Broad emission lines in optical spectra
- Radiatively efficient disks
- Strong external fields
- High jet power & γ-ray luminosity

BL Lacs



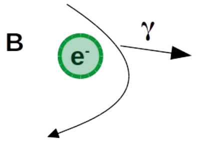


- Weak/absent broad emission lines in optical spectra
- Radiatively inefficient disks
- Weak/absent external fields
- Low jet power & γ-ray luminosity

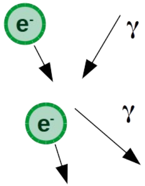
Most common non-thermal radiative processes

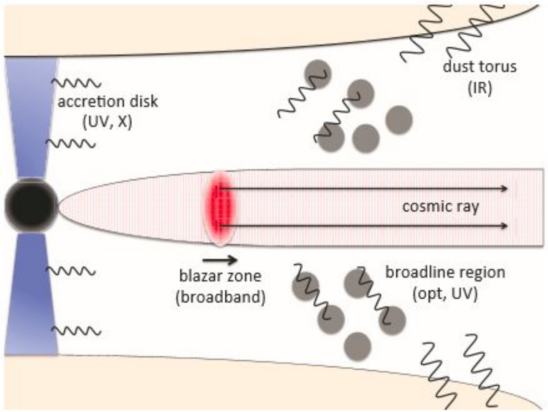
Leptonic processes

Synchrotron

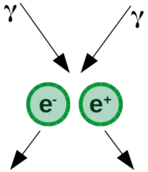


Inverse Compton scattering



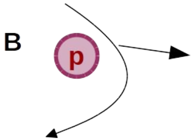


Photon-photon pair production

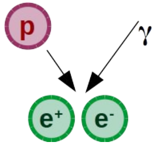


Hadronic processes

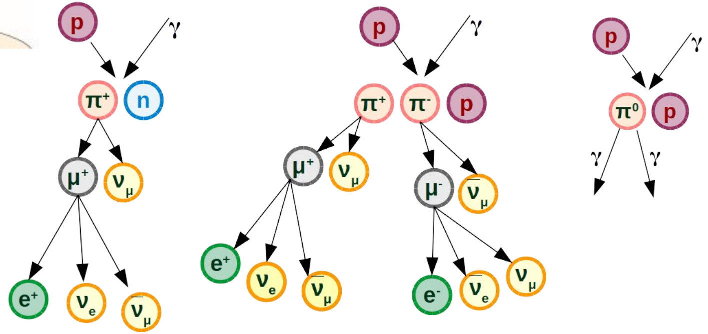
Synchrotron



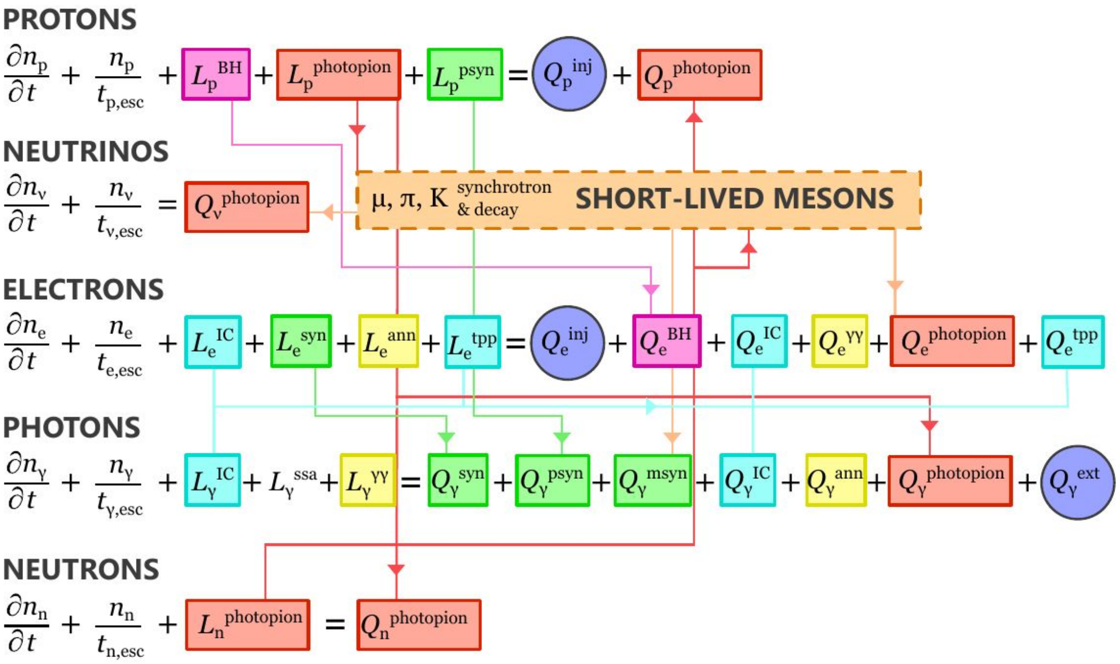
Proton-photon pair production



Proton-photon pion production



Numerical approach (1)



ATHEvA

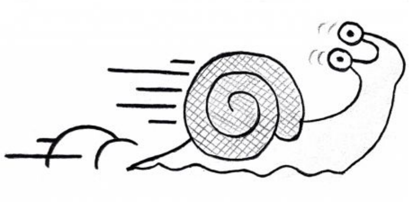
Free parameters for 1 radiation zone:

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

A. Mastichiadis, S. Dimitrakoudis, M. Petropoulou

Numerical approach (2)

A faster and user-friendly time-dependent code in Python with extra features is being developed by PhD candidate S. Stathopoulos



A Practical Difference Scheme for Fokker–Planck Equations*

J. S. CHANG AND G. COOPER

Lawrence Radiation Laboratory, University of California, Livermore, California 94550

Received July 28, 1969

Features

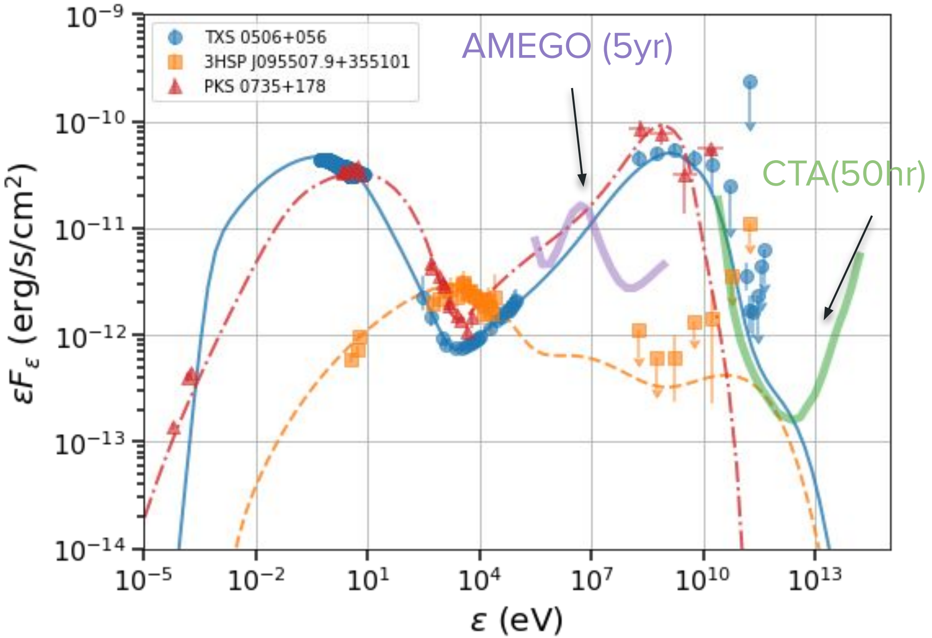
- **Time-dependent**
- **Expanding sources**
- **Pγ + PP interactions**
- Diffusive acceleration
- Electron bremsstrahlung

Implicit PDE solver

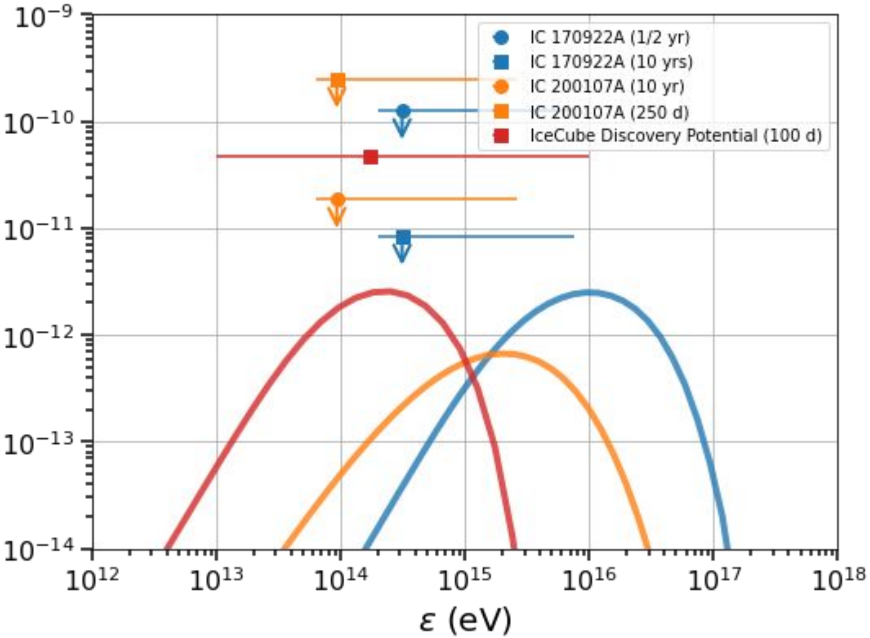
- Slower computation of solution at each time step (compared to explicit solvers)
- Larger time steps
- Shorter total computational time

Models of multi-messenger blazar emission

Photon spectra

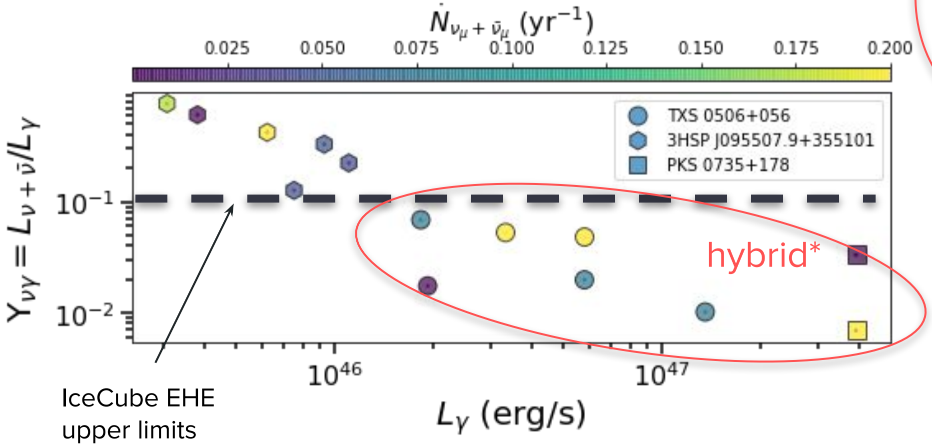


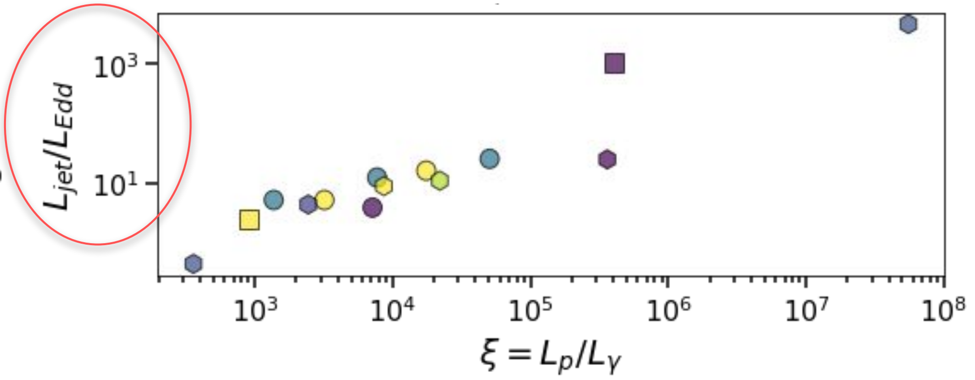
Neutrino spectra



Adopted from Keivani et al., ApJ (2018), Petropoulou et al., ApJ (2020), Sahakyan et al., MNRAS (2023)

Comparison of modeling results





*hadronic EM emission not directly observed

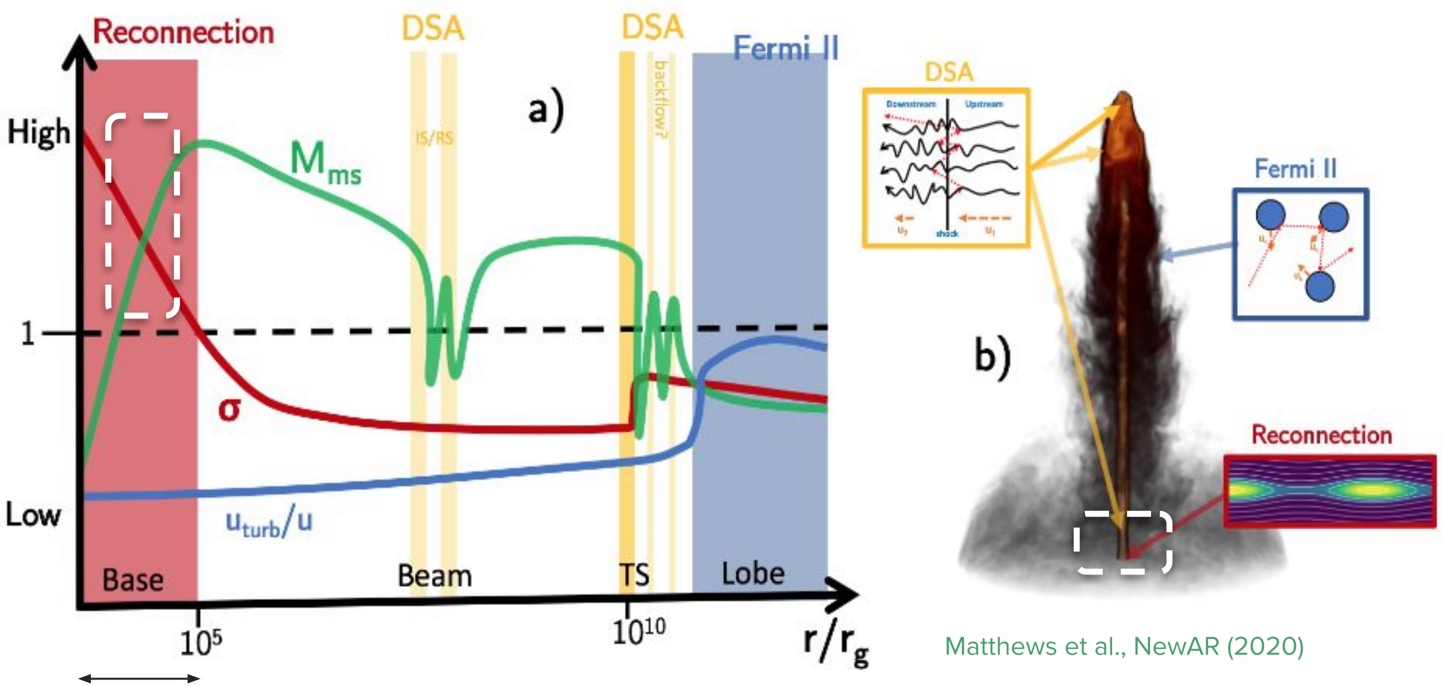
- Rate of muon neutrinos 0.02-0.2/yr ➔ consistent with non detection of multiple ν
- $Y_{\nu\gamma}$ values of hybrid models consistent with EHE upper limits
- Hint for a trend between $Y_{\nu\gamma}$ and L_γ ➔ what's the physical reason ?
- Very high baryon loading factors needed (not constrained by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

A simple, but physically motivated jet emission model

Petropoulou, Psarras, Giannios, MNRAS (2023)

AGN jets: a multi-scale physical system

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



Matthews et al., NewAR (2020)

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

Main model ingredients

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

Total jet energy flux per unit rest-mass energy flux

Jet Lorentz factor

Jet plasma magnetization

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

Disk 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

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

BLR luminosity

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

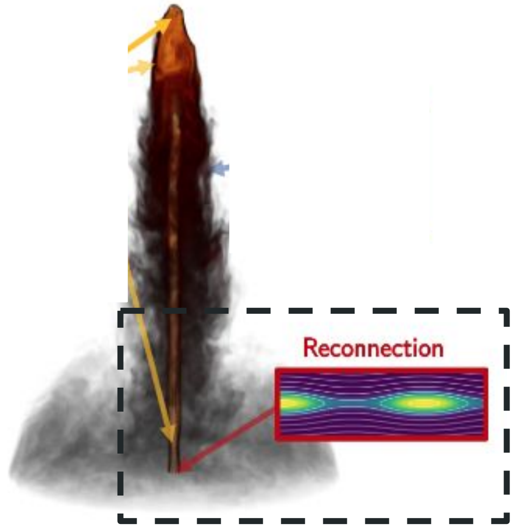
Poynting jet luminosity

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

Accretion rate -
jet Lorentz factor scaling

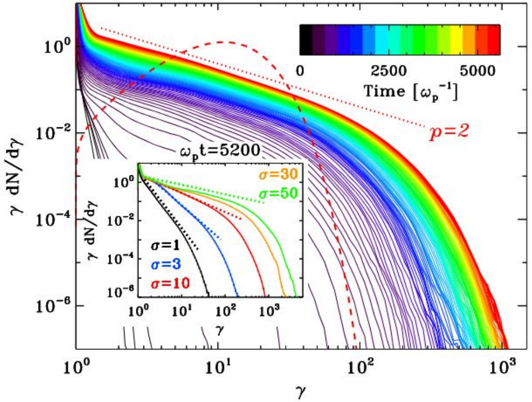
Properties of relativistic particles

<u>Assumption:</u> jet energy dissipated via magnetic reconnection



Matthews et al., NewAR (2020)

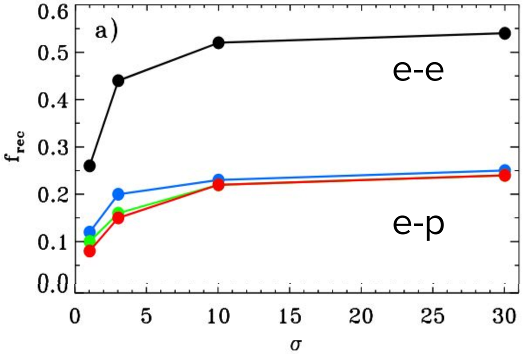
Particle distribution



Sironi & Spitkovsky 2014 (ApJL)

$$p = f(\sigma)$$

Dissipation efficiency



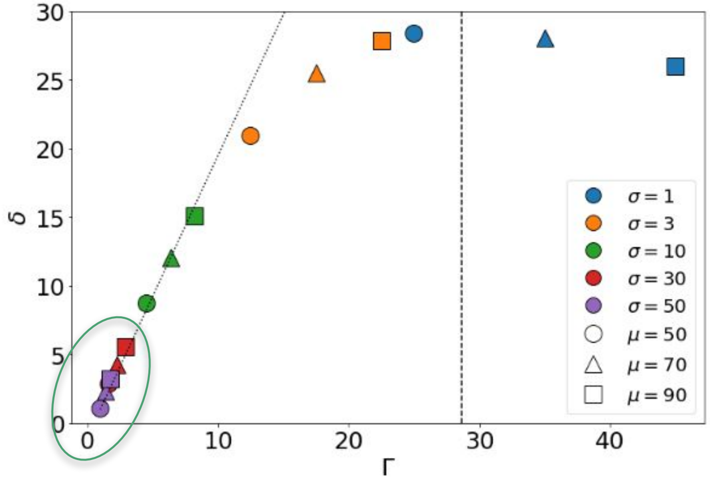
Sironi, MP, Giannios 2015 (MNRAS)

Particle injection luminosity

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

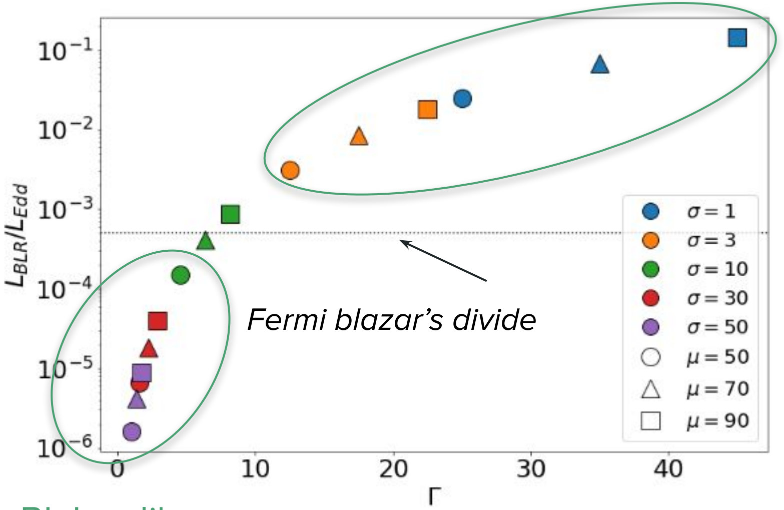
Results

Doppler beaming



BLR luminosity

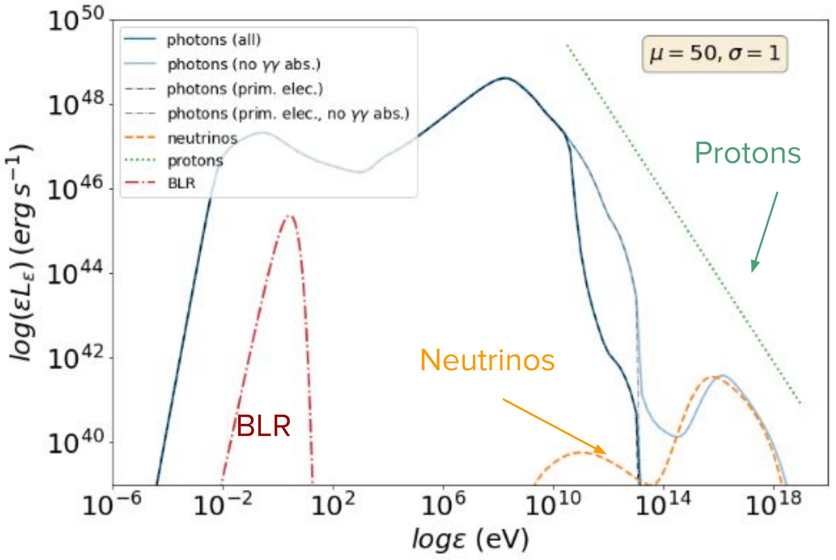
FSRQ-like

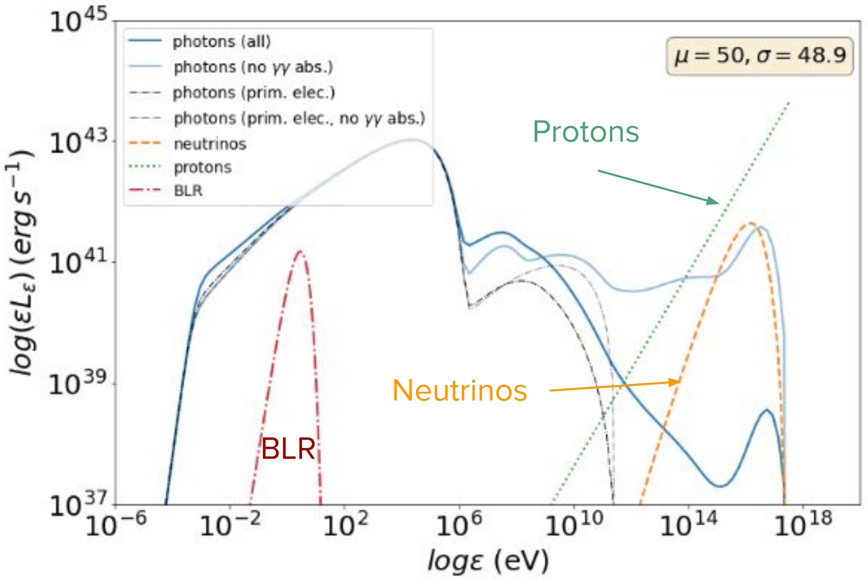


BL Lac-like

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

Photon & neutrino spectra

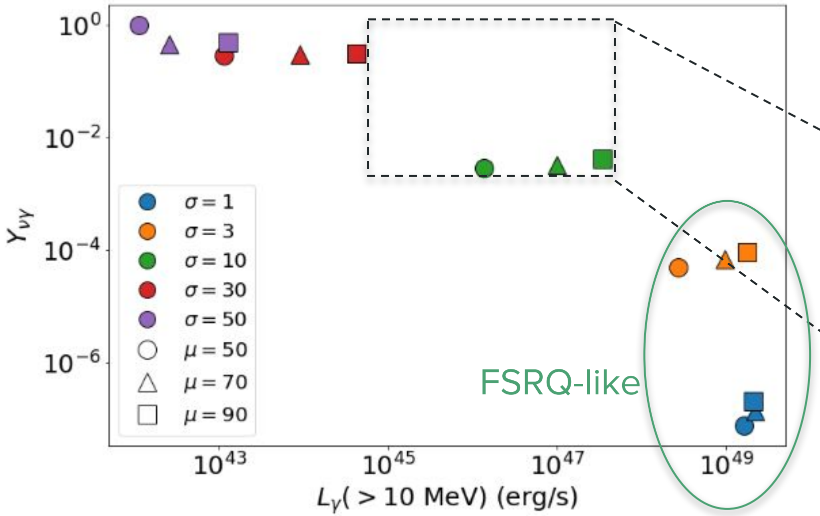




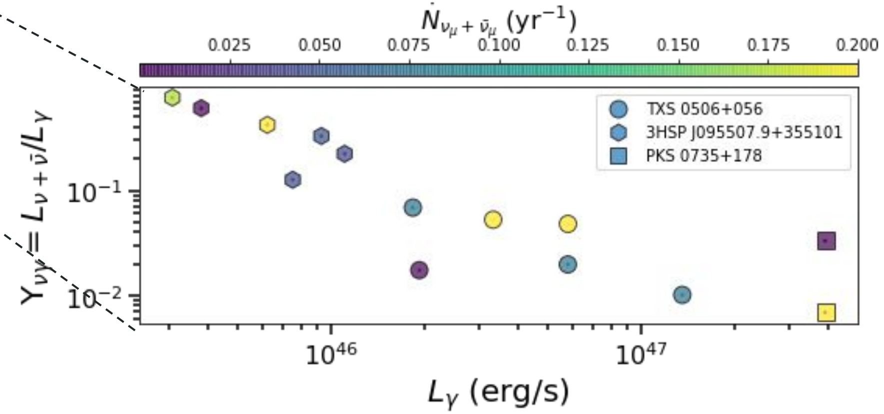
- Steep proton spectra (p=3)
- High Lγ ➔ external Compton
- Yνγ << 1

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

Neutrino-to-γ-ray luminosity ratio

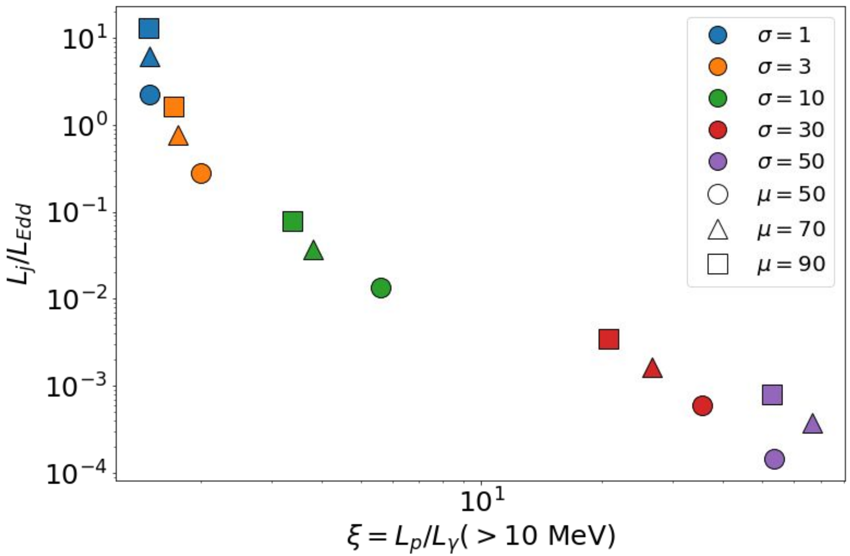


Comparison to phenomenological emission models

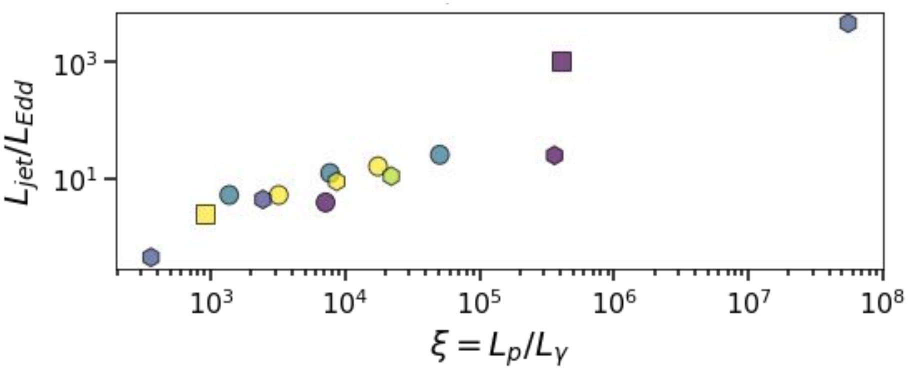


- Strong evolution of Yνγ with Lγ
- Low-σ jets (FSRQs) are dim ν sources

Baryonic loading



Comparison to phenomenological emission models

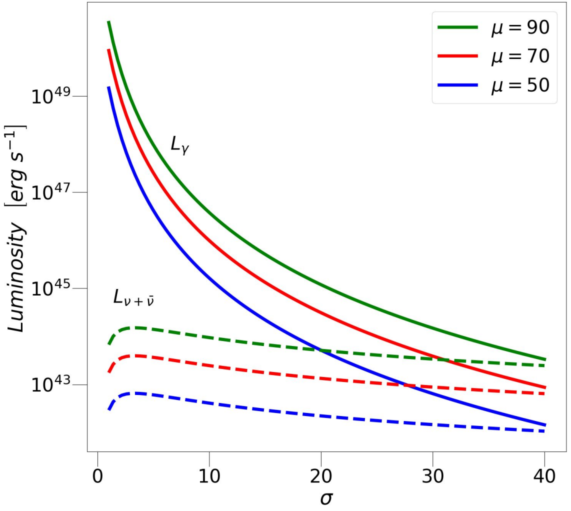


- High-σ jets have Lj << LEdd
- Low-σ jets have Lj ~(0.3-10) LEdd
- Baryonic loading factor is 1-30

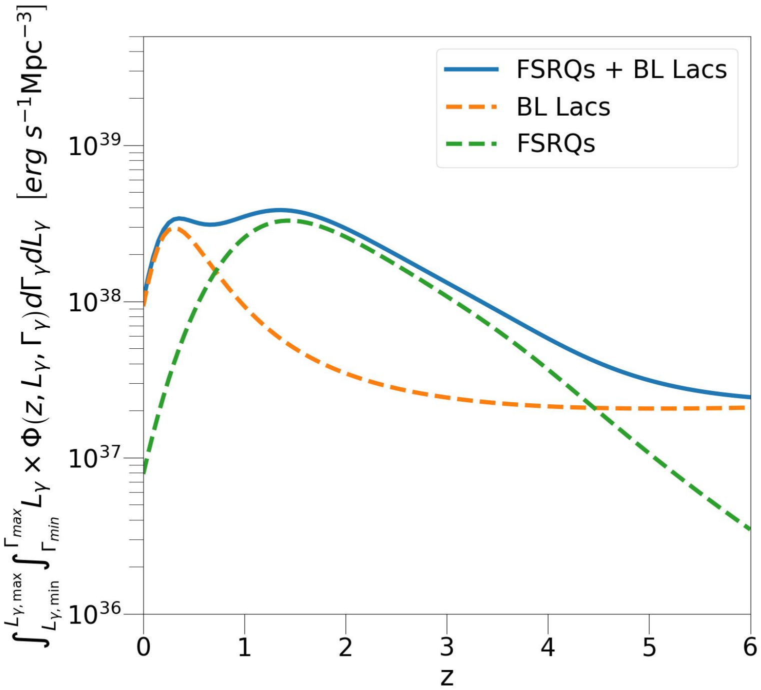
Neutrino emission from the blazar population

- This model can be combined with the distributions function ($\Phi(L_\gamma, \Gamma_\gamma, z)$) for blazars to analyze the contribution to the neutrino background
- To do this, we map the luminosity function parameters to the emission Model parameters

$$L_\gamma \rightarrow L_\gamma(\mu, \sigma) \qquad \Gamma_\gamma \rightarrow \Gamma_\gamma(\mu, \sigma)$$



- With the parameterized distribution function, we are able to study the blazar neutrino background contribution and characteristics of the largest contributors.



Conclusions

- Multi-messenger jet emission model with 3 main parameters: μ, σ, mdot
- Low-luminosity blazars ➔ less powerful slow, high-σ jets with L_ν ~(0.3-1)L_γ
- High-luminosity blazars ➔ more powerful fast, low-σ jets with $L_\nu \ll L_\gamma$
- Weak dependence of baryonic loading on μ,σ (ξ~1-30)

Outlook & Challenges

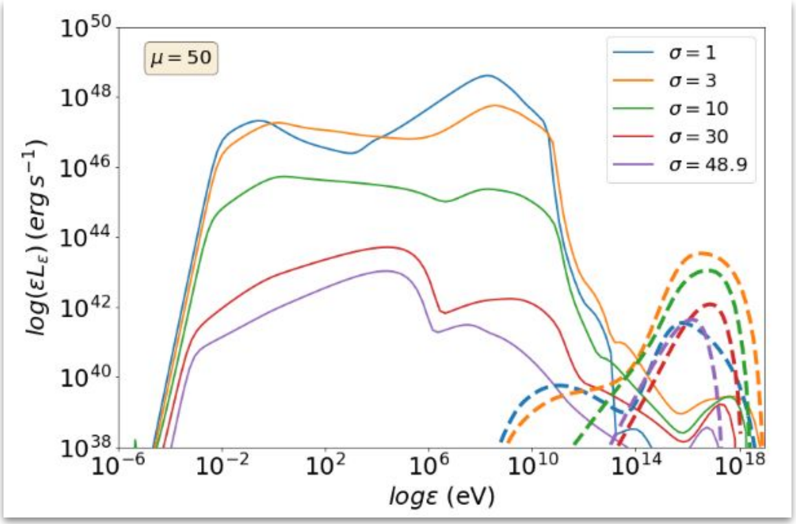
What is the contribution of blazar jets to the diffuse IceCube neutrino flux ?

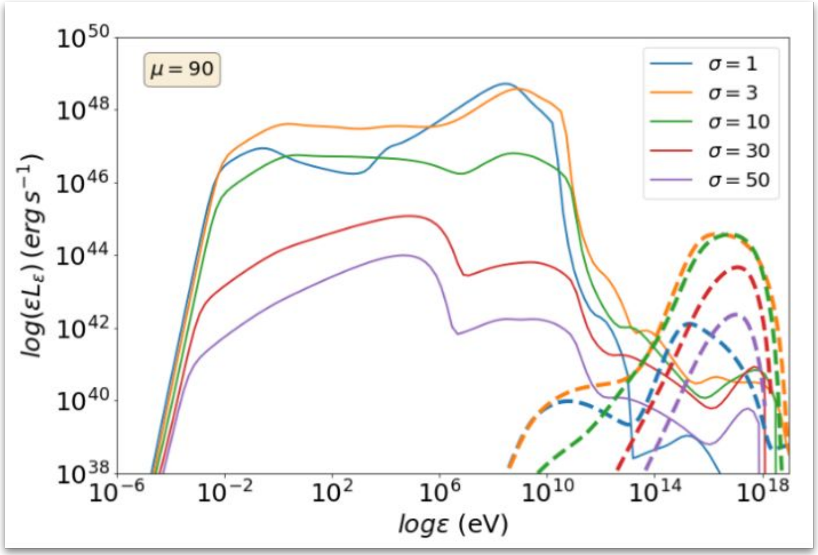
How can we connect the microphysics of particle acceleration to the macrophysics of jet dynamics to radiation models?

Thank you!

Backup slides

Photon & neutrino spectra





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)