ONLINE ICRC 2021
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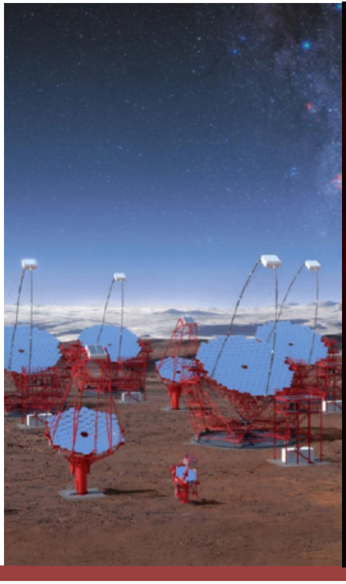
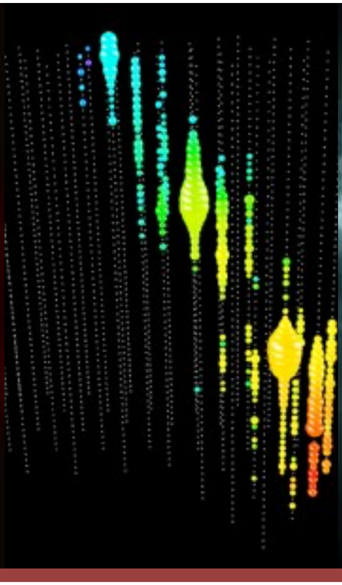
Berlin | Germany
37th International
Cosmic Ray Conference
12–23 July 2021

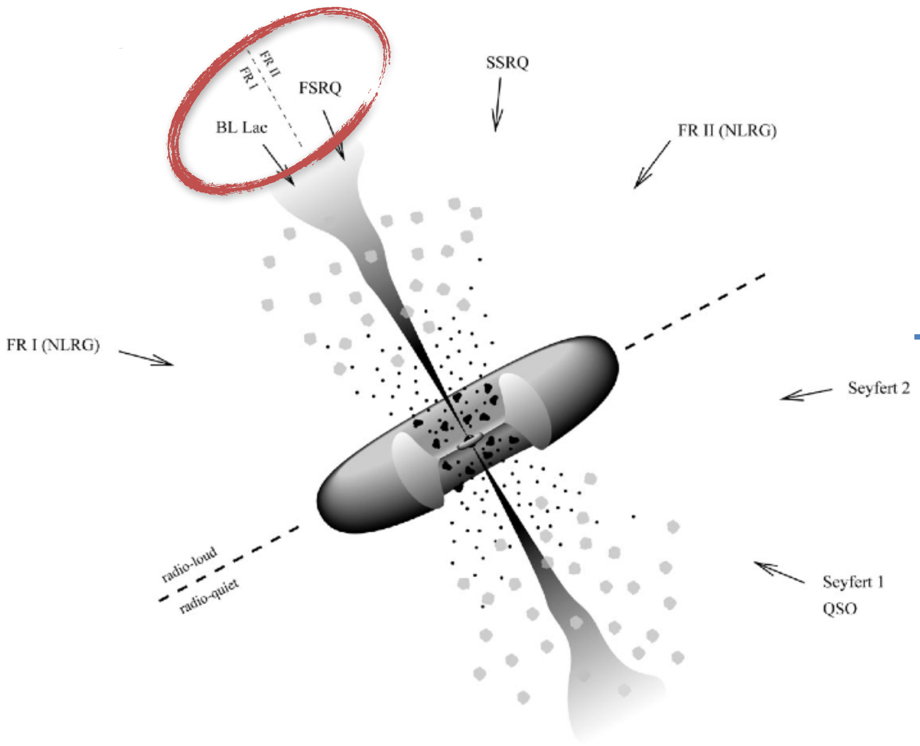




The Blazar Hadronic Code Comparison Project

Matteo Cerruti, Michael Kreter, Maria Petropoulou, Annika Rudolph, Foteini Oikonomou, Markus Böttcher, Stavros Dimitrakoudis, Anton Dmytriiev, Shan Gao, Apostolos Mastichiadis, Susumu Inoue, Kohta Murase, Anita Reimer, Joshua Robinson, Xavier Rodrigues, Walter Winter, Andreas Zech, Natalia Żywucka

BLAZARS



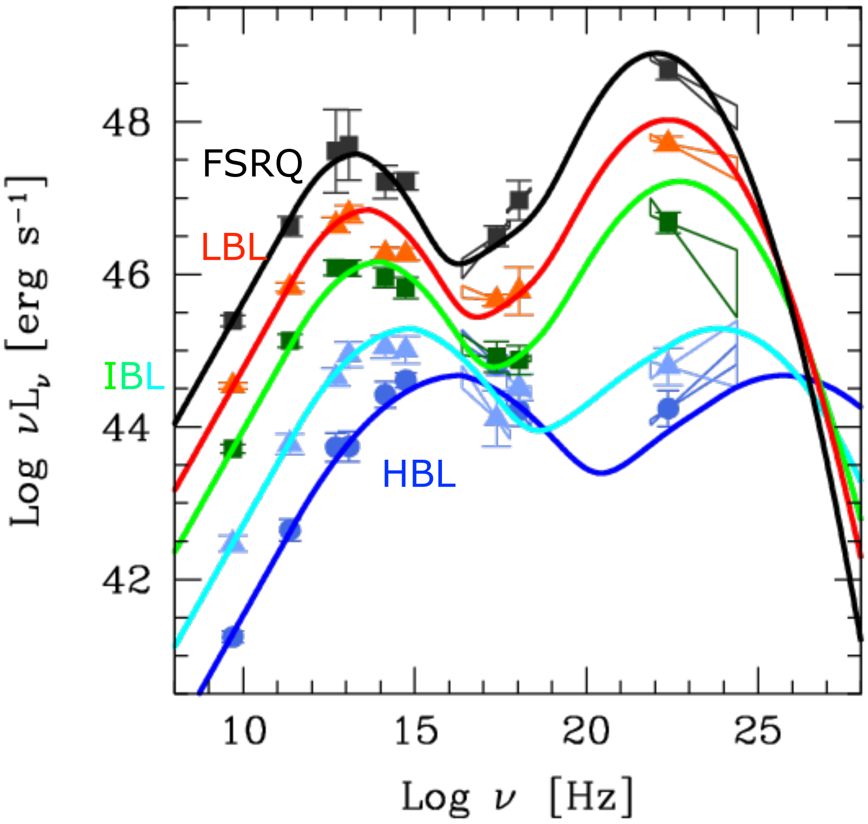
Blazar: radio-loud AGN whose relativistic jet points towards the observer

→ Radiative emission from the jet dominates over all other components (non-thermal emission from radio to gamma-rays and fast variability)

Flat-spectrum-radio-quasars : optical/UV spectrum with broad emission lines

BL Lacertae objects : featureless optical/UV spectrum

BLAZAR SPECTRAL ENERGY DISTRIBUTIONS



Spectral energy distributions (SED): two distinct radiative components

FSRQs show a peak in the IR

BL Lacs are classified into:

-IR peak: low-frequency peaked (LBLs)

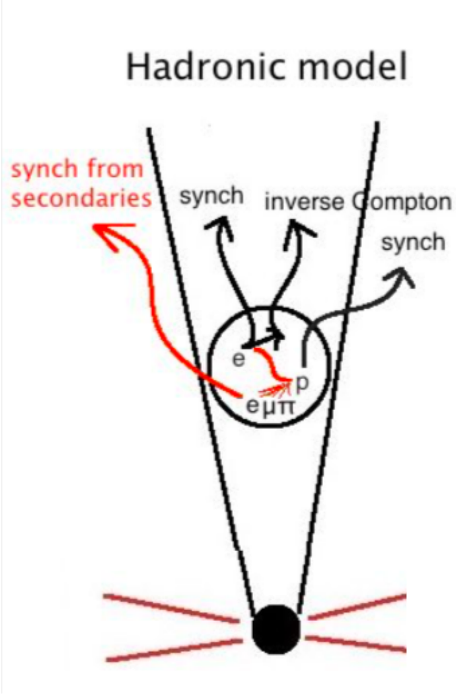
- optical peak: intermediate (IBLs)

- UV/X peak: high (HBLs)

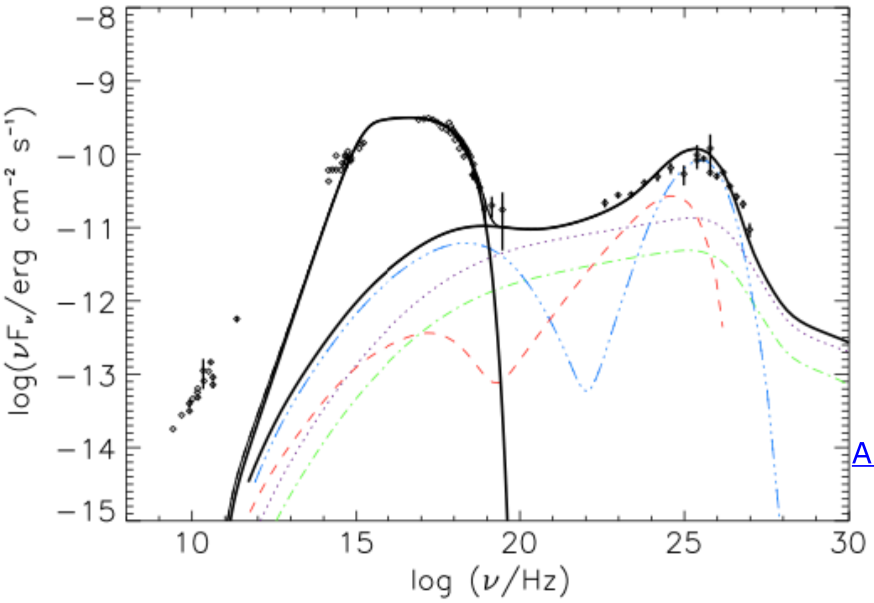
BLAZARS EMISSION MODELS

Hadronic models

- Natural link with cosmic rays and neutrinos



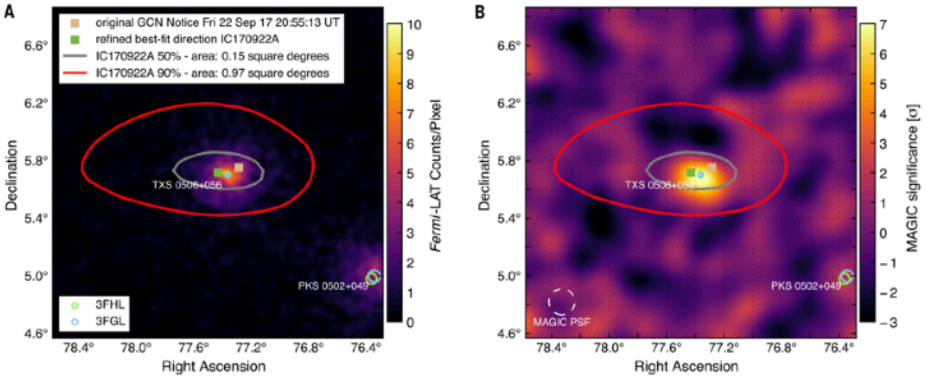
- High energy SED component associated with
  - Proton synchrotron radiation
  - Secondary particles coming from p-gamma interactions (neutral and charged pions)
  - Neutrino produced in the pion decay

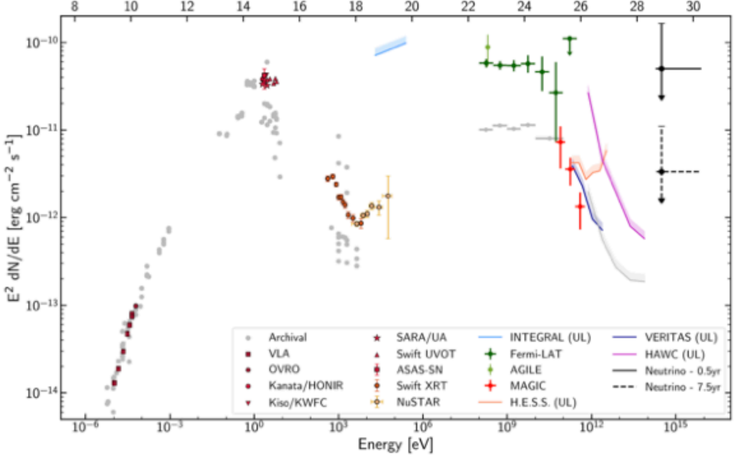


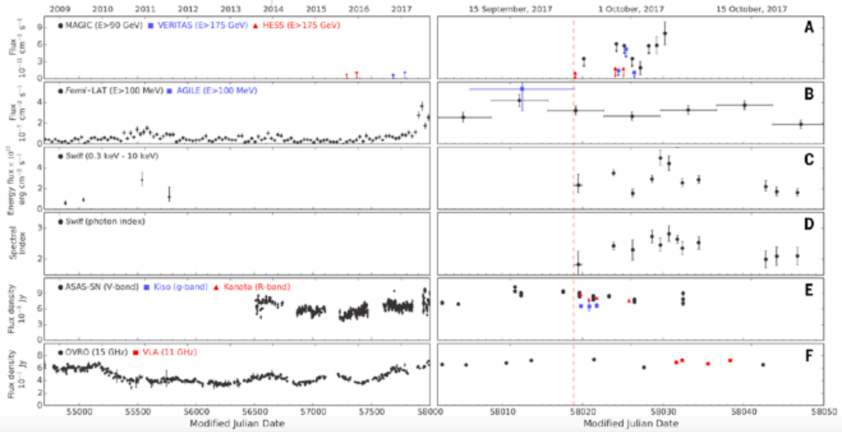
Abdo et al. 2011

IceCube-170922A / TXS 0506+056

Most significant association (3σ)
of a high-energy (290 TeV) neutrino with an astrophysical source



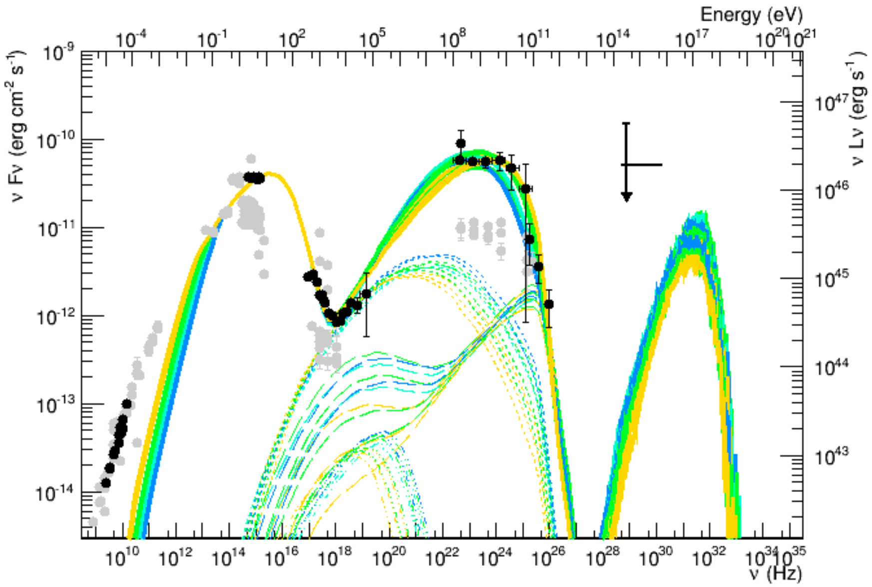




IceCube, Fermi, MAGIC et al. 2018

TXS0506+056: the 2017 flare

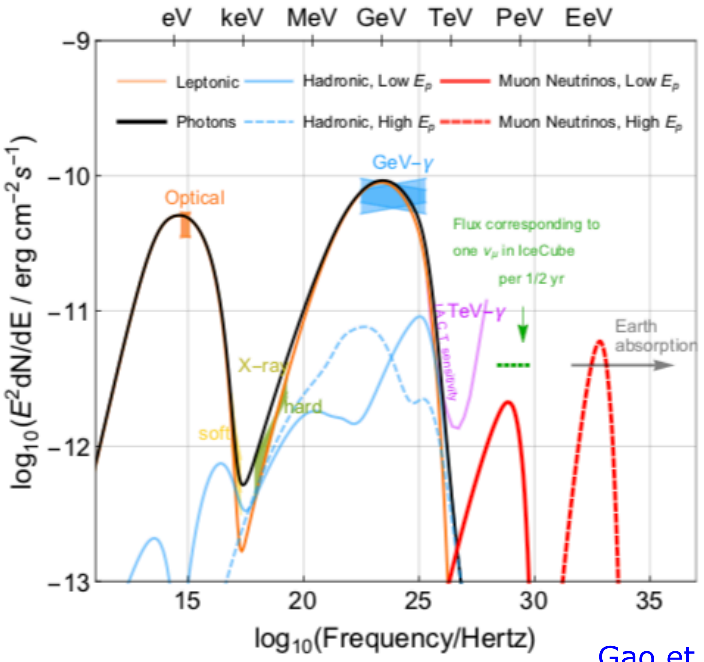
Lepto-hadronic solutions



[Cerruti et al. 2019](#)

$L_{jet} = (9 - 60) \times 10^{47} erg/s$

$\nu = 0.01 - 0.06\ yr^{-1}$



[Gao et al. 2018](#)

$L_{jet} \simeq \times 10^{50} erg/s$

$\nu = 0.3\ yr^{-1}$

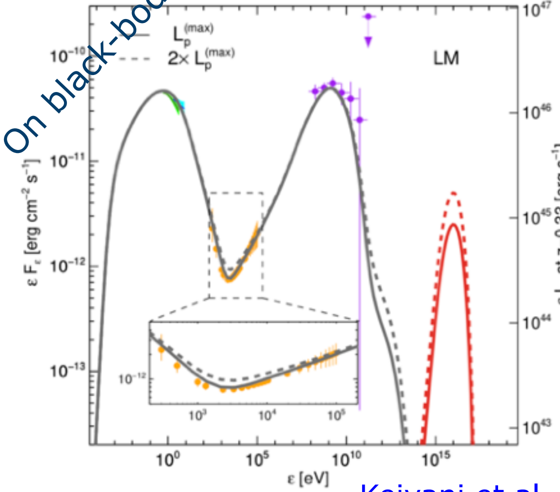
They can work: neutrino rates of the order of 0.1 / yr

But rather high energetic requirement : $L_{jet} \gg L_{Edd} \simeq \times 10^{46-47}\ erg/s$

TXS0506+056: the 2017 flare

Proton-photon interaction on external photon fields

On black-body

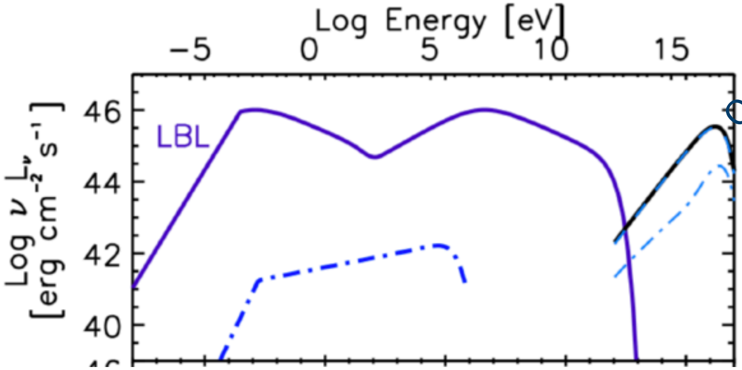


Keivani et al. 2018

$$L_{jet} = (4-150)\times 10^{45} erg/s$$

$$\nu_{max} = 0.02\ yr^{-1}$$

On RIAF

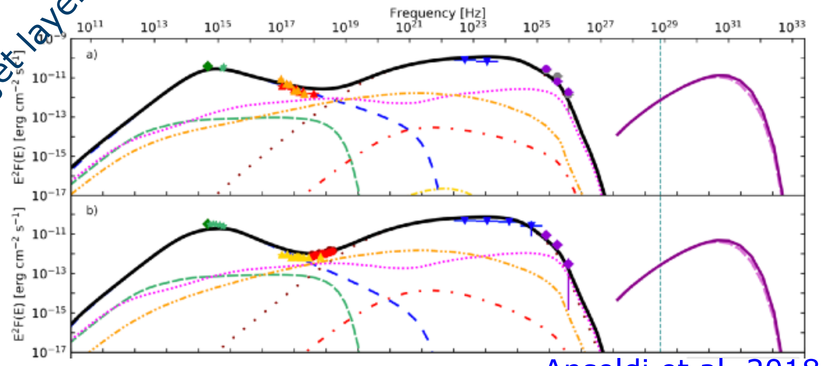


Righi et al. 2019

$$L_{jet} = 6.3\times 10^{45} erg/s$$

$$\nu = 0.14\ yr^{-1}$$

On jet layer



Ansoldi et al. 2018

$$L_{jet} = (3-8)\times 10^{45} erg/s$$

$$\nu = 0.12-0.34\ yr^{-1}$$

HADRONIC CODE COMPARISON

What is the level of agreement reached by state-of-the-art numerical simulations?

- Compare outputs from 4 Numerical codes:
  AM3, ATHEνA, B13, LeHa-PARIS

- Check also widely used analytical approximation for neutrino emission

- Estimate spread among outputs from numerical codes for a wide part of the parameter space
  → *systematic uncertainty* (on i.e. neutrino rates) coming from numerical simulations

- Release all results in tabulated form as benchmark tests to help future numerical developments

THE FOUR CODES

- AM3 (Gao et al. 2018)

  Time-dependent

  Photo-meson interactions following Hümmer et al. 2010; Bethe-Heitler following Kelner and Aharonian 2008

- ATHEνA (Mastichiadis & Kirk 1995, Mastichiadis et al 2005, Dimitrakoudis et al 2012)

  Time-dependent

  Photo-meson from tabulated SOPHIA (Mücke et al. 2000); Bethe-Heitler from Protheroe and Johnson 1996

- Böttcher13 (Böttcher et al. 2013)

  Steady-state solver

  Photo-hadronic interactions following Kelner and Aharonian 2008

- LeHa-PARIS (Cerruti et al. 2015)

  Steady-state solver

  Photo-meson running SOPHIA; Bethe-Heitler following Kelner and Aharonian 2008

THE FOUR CODES

- **AM3** (Gao et al. 2018)

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- **LeHa-PARIS** (Cerruti et al. 2015)

  Steady-state solver

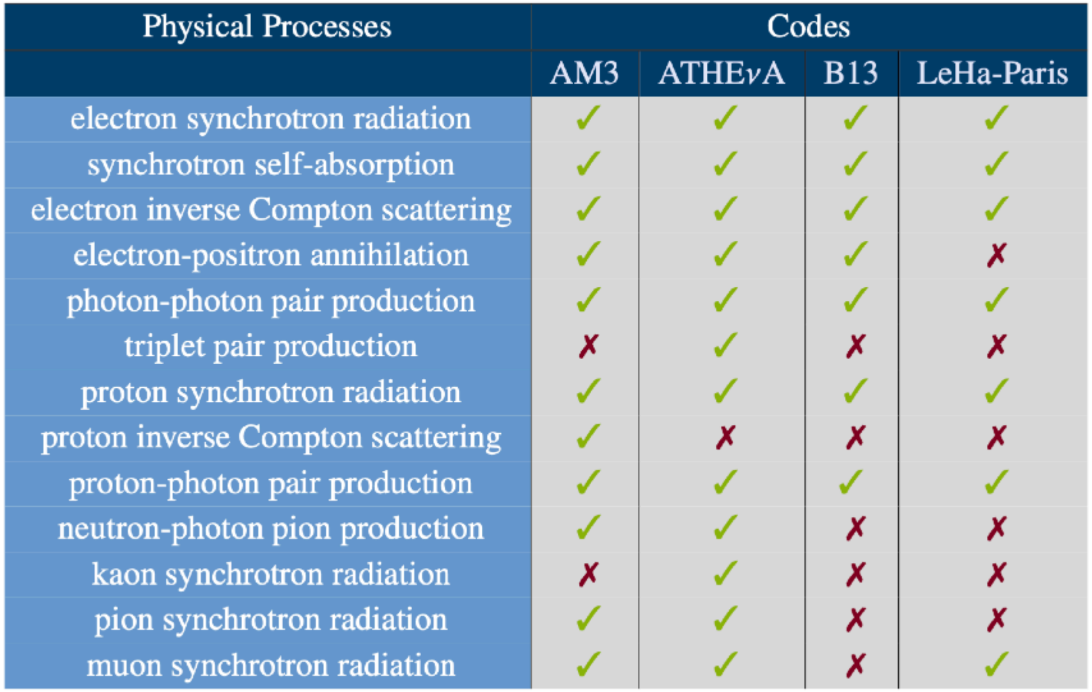
  Photo-meson running SOPHIA; Bethe-Heitle d Aharonian 2008

We also study simple semi analytical approximations for neutrino emission :

$$\varepsilon_\nu L_{\varepsilon_\nu} \approx \frac{3}{8} f_{p\gamma}(\varepsilon_p)\varepsilon_p L_{\varepsilon_p}$$

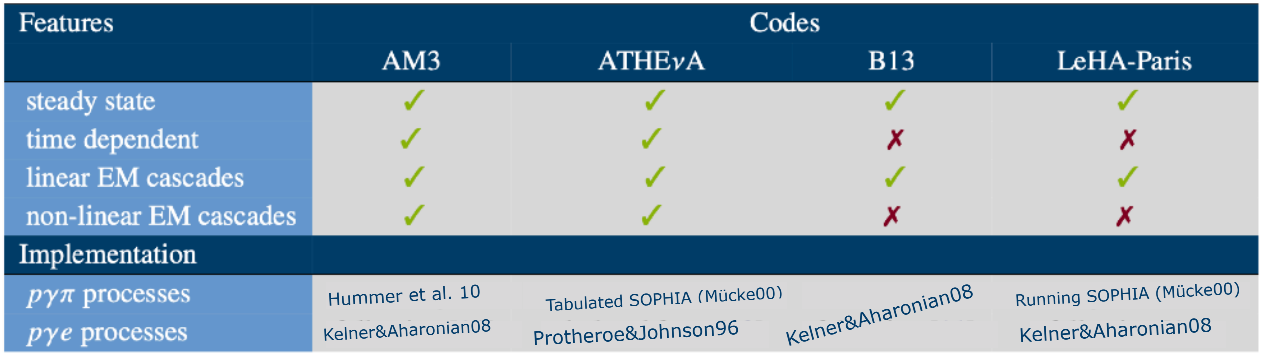
With $f_{p\gamma} \equiv t_{\rm cool}/t_{p\gamma}$,

THE FOUR CODES



Physical Processes	Codes			
	AM3	ATHEνA	B13	LeHa-Paris
electron synchrotron radiation	✓	✓	✓	✓
synchrotron self-absorption	✓	✓	✓	✓
electron inverse Compton scattering	✓	✓	✓	✓
electron-positron annihilation	✓	✓	✓	✗
photon-photon pair production	✓	✓	✓	✓
triplet pair production	✗	✓	✗	✗
proton synchrotron radiation	✓	✓	✓	✓
proton inverse Compton scattering	✓	✗	✗	✗
proton-photon pair production	✓	✓	✓	✓
neutron-photon pion production	✓	✓	✗	✗
kaon synchrotron radiation	✗	✓	✗	✗
pion synchrotron radiation	✓	✓	✗	✗
muon synchrotron radiation	✓	✓	✗	✓

Table 1: Physical processes included in the numerical codes.

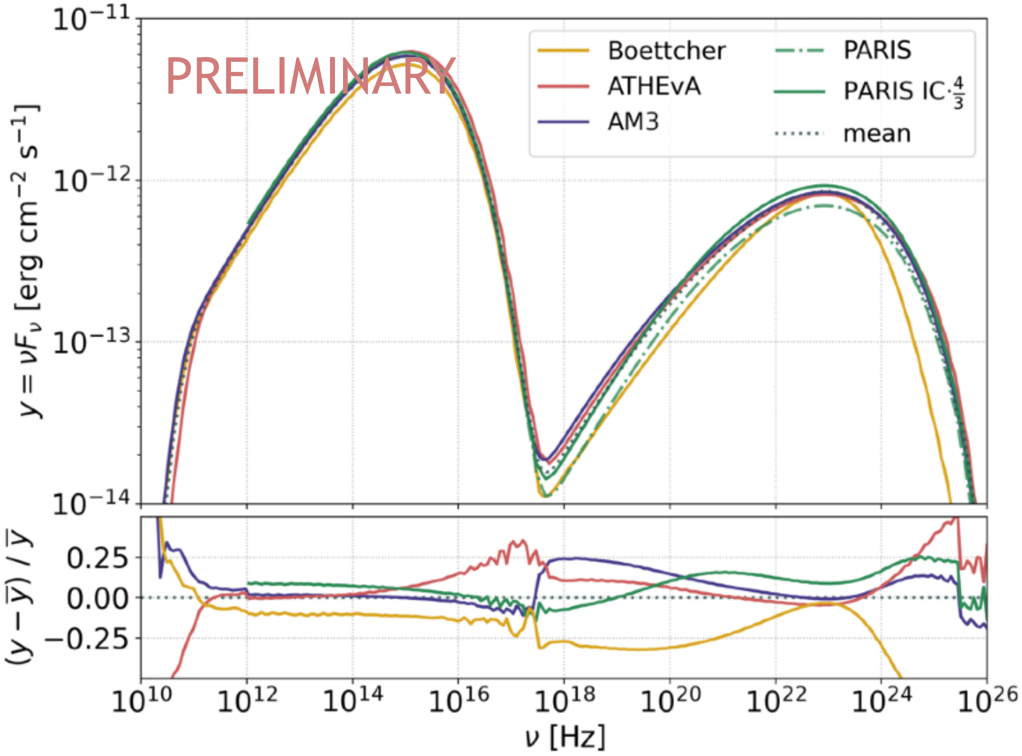


Features	Codes			
	AM3	ATHEνA	B13	LeHA-Paris
steady state	✓	✓	✓	✓
time dependent	✓	✓	✗	✗
linear EM cascades	✓	✓	✓	✓
non-linear EM cascades	✓	✓	✗	✗
Implementation				
$p\gamma\pi$ processes	Hummer et al. 10	Tabulated SOPHIA (Mücke00)	Kelner&Aharonian08	Running SOPHIA (Mücke00)
$p\gamma e$ processes	Kelner&Aharonian08	Protheroe&Johnson96		Kelner&Aharonian08

Table 2: Main features of numerical codes and implementation of hadronic processes.

HADRONIC CODE COMPARISON

Leptonic (SSC) model to compare synchrotron/SSC processes (low magnetic field B = 0.01 G, no pair-production,

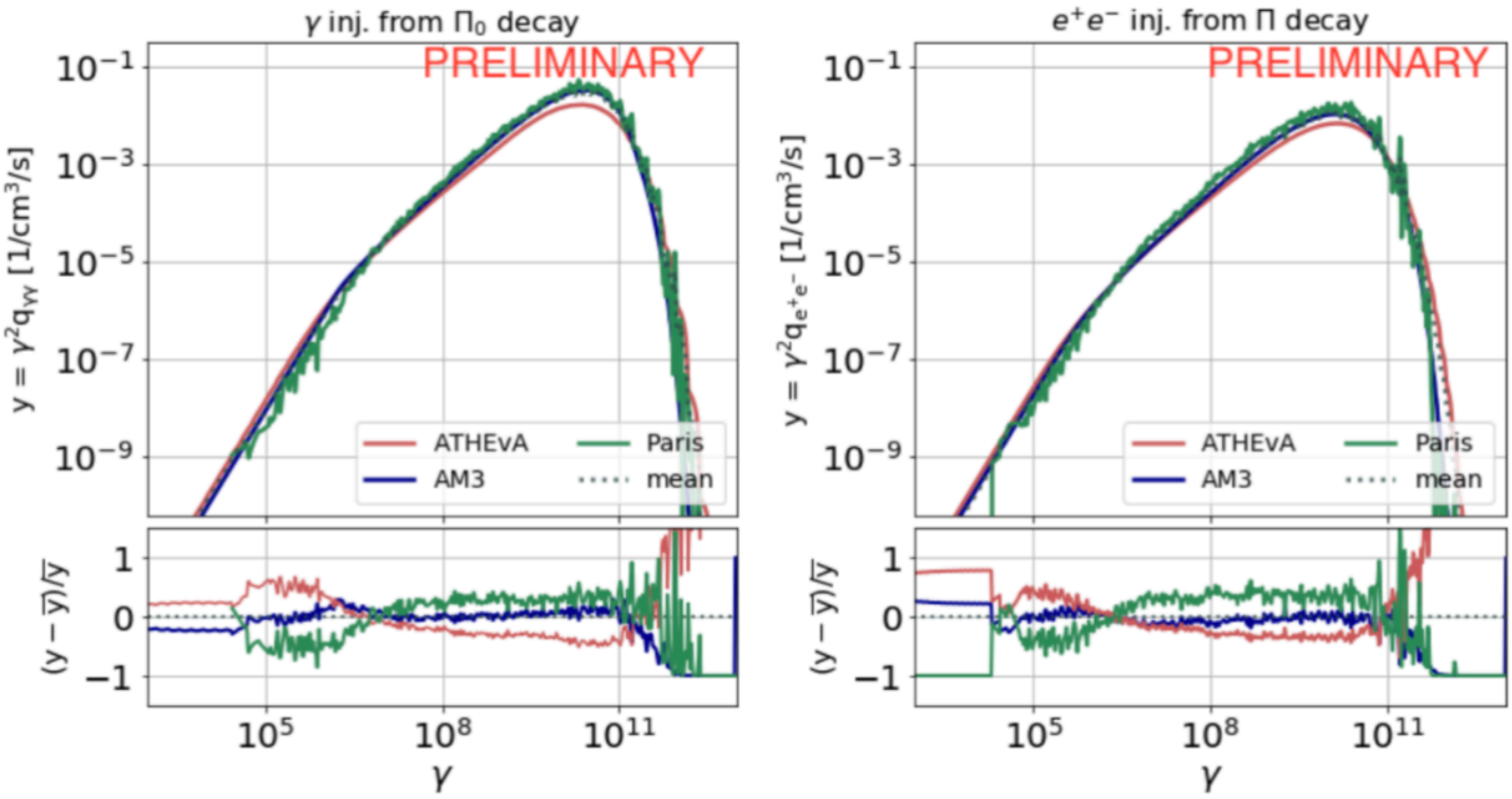


HADRONIC CODE COMPARISON

Proton-photon interactions on a power-law photon field:

$\alpha_p = 1.9;\ \gamma_{min,p} = 1;\ \gamma_{Max,p} = 10^8$ $\alpha_{ph} = 2.0;\ \epsilon_{min,ph} = 10^{-6};\ \epsilon_{Max,ph} = 0.1$

$\delta = 30;\ B = 10\ \mathrm{G};\ \mathrm{R} = 10^{15}\ \mathrm{cm};\ \mathrm{z} = 0.01$



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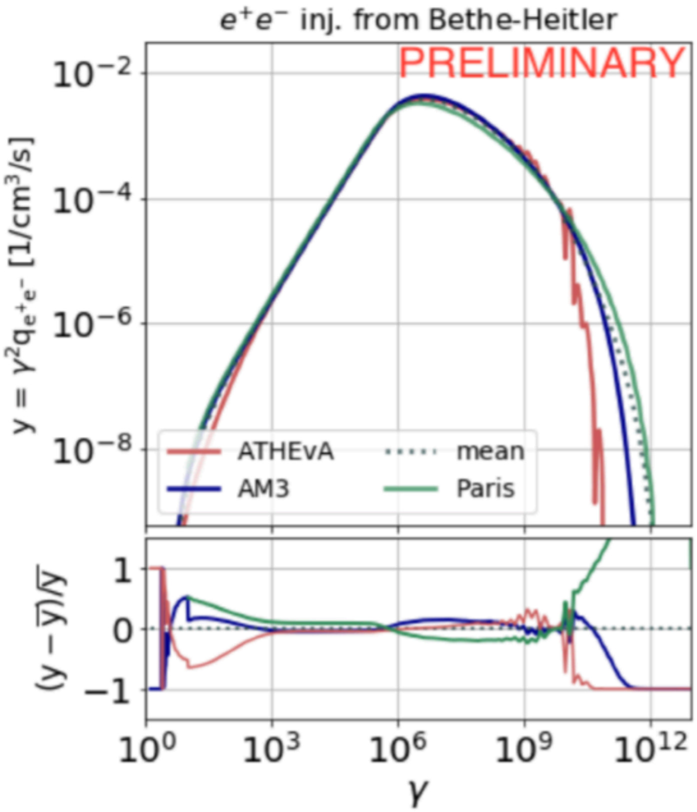
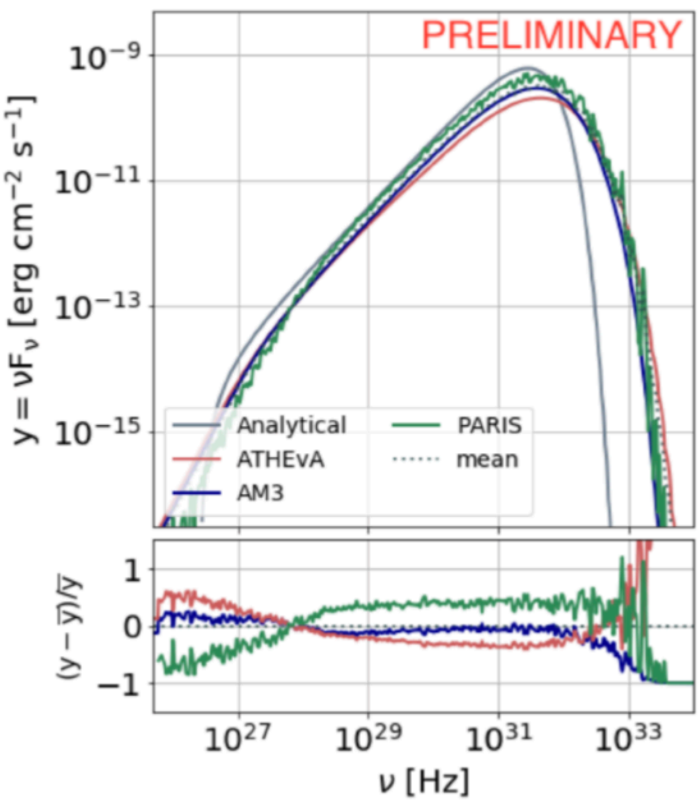


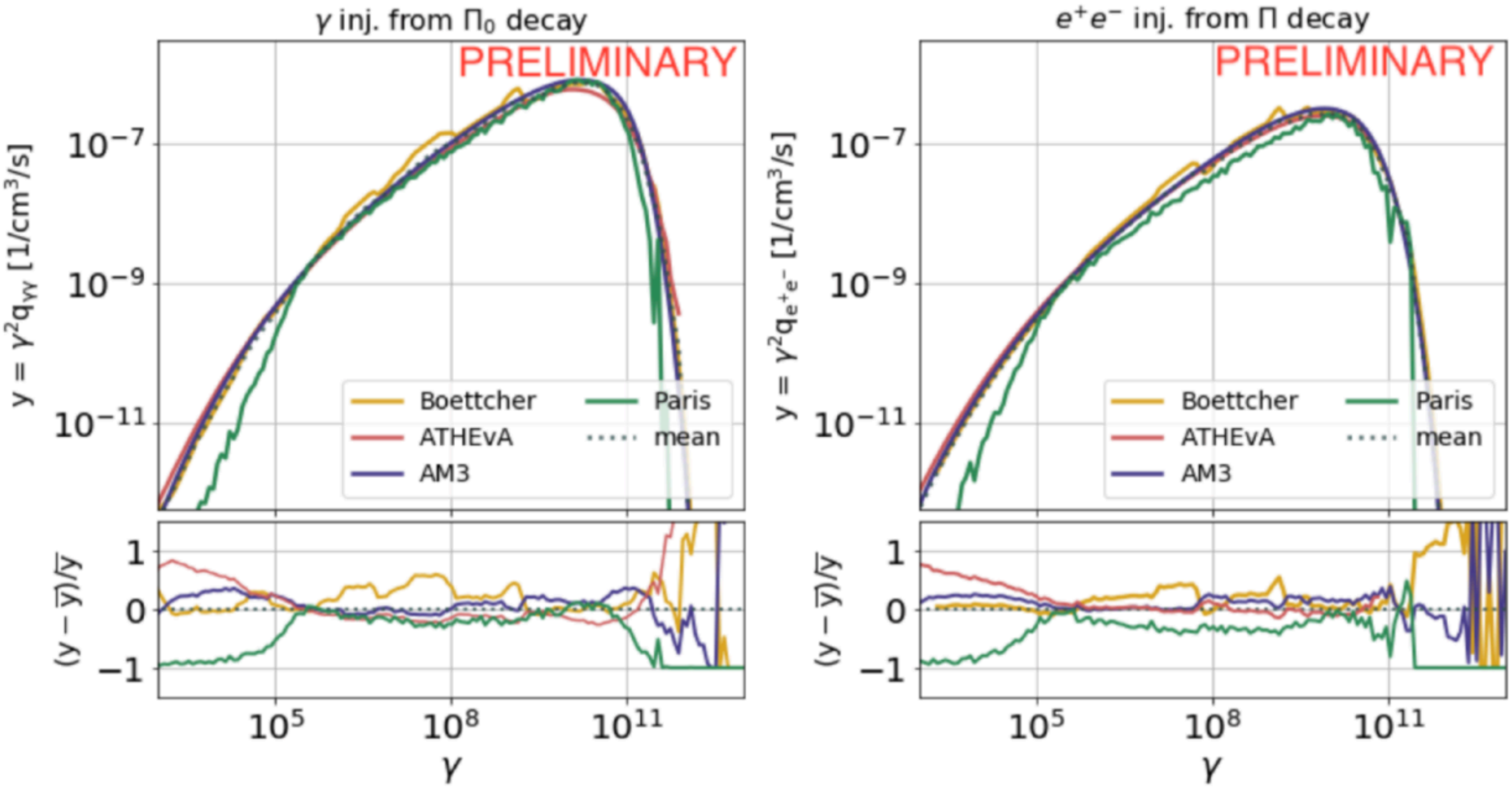


HADRONIC CODE COMPARISON

Proton-synchrotron solution:

$\alpha_p = 1.9;\ \gamma_{min,p} = 1;\ \gamma_{Max,p} = 10^8$ $\alpha_e = 1.9;\ \gamma_{min,e} = 1;\ \gamma_{Max,e} = 10^3$

$\delta = 30;\ B = 10\ \mathrm{G};\ \mathrm{R} = 10^{15}\ \mathrm{cm}; \mathrm{z} = 0.01$



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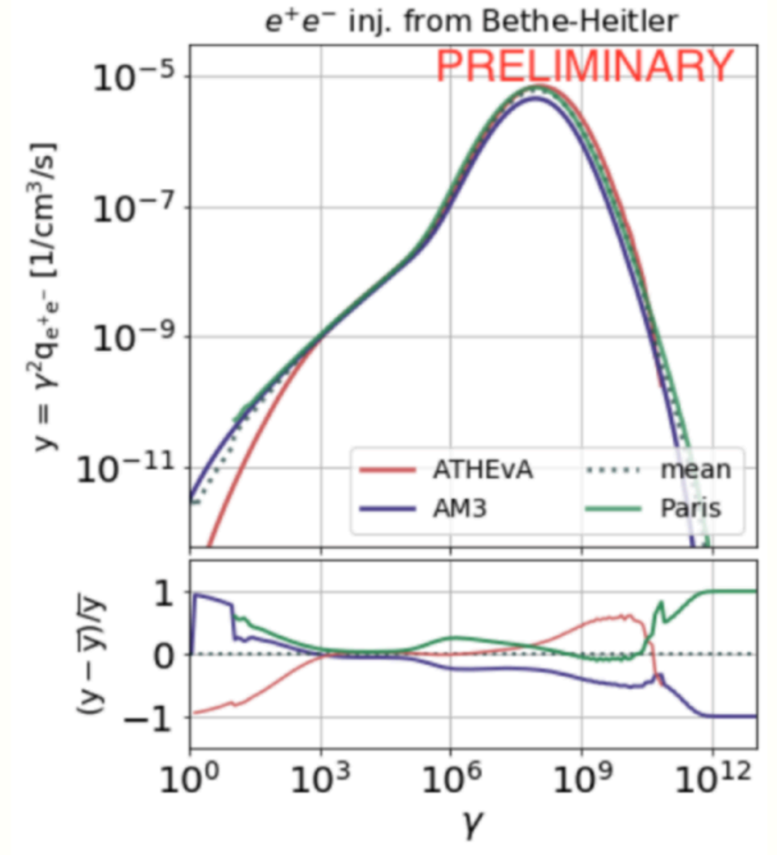

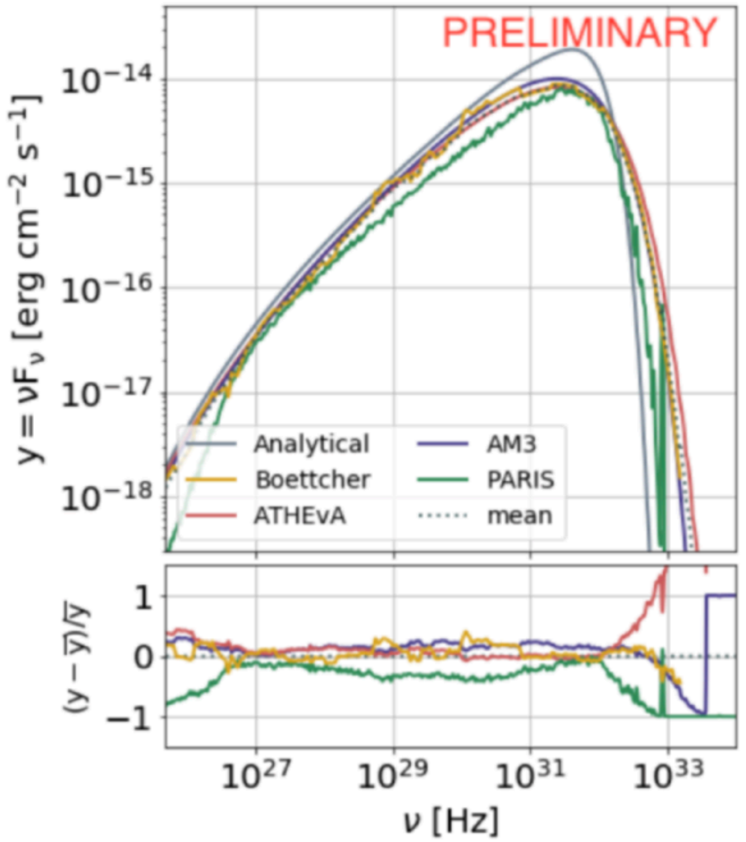

CONCLUSIONS

- General agreement in spectral shapes. Distortions at cut-offs but with minor impact on the final result
- *At relevant energies* there is still about 30/40% systematic spread in normalizations among numerical models
- Scattering in modeling attributed to the different numerical implementations and/or assumptions done when computing radiative emission
- Analytical approximation for neutrino emission work well to estimate peak energy and flux. Treatment of cascade emission from pions and Bethe-Heitler should be done numerically
- Additional tests in progress: external-inverse-Compton; tests on mono-energetic protons; high-opacity regimes with proton cooling; time-dependent evolutions
- All curves from all codes will be released together with the paper. Contact us if interested in early access