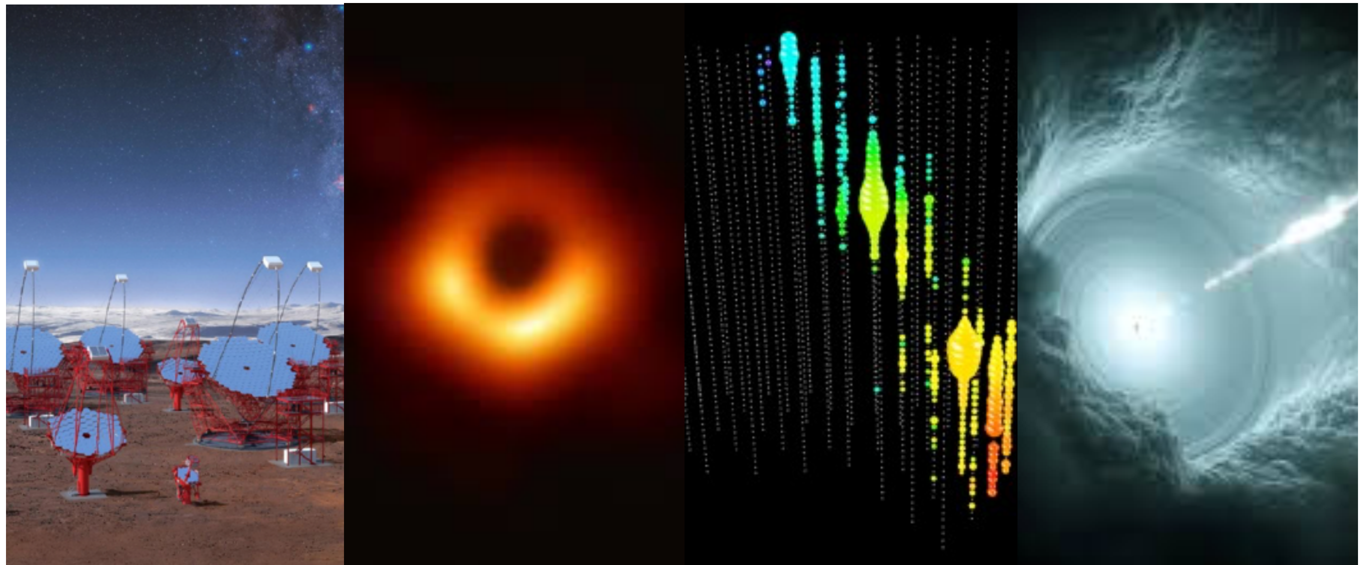


Hadronic Code Comparison

Final Results and Data Release

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

Université Paris Cité

Astroparticule et Cosmologie (APC)

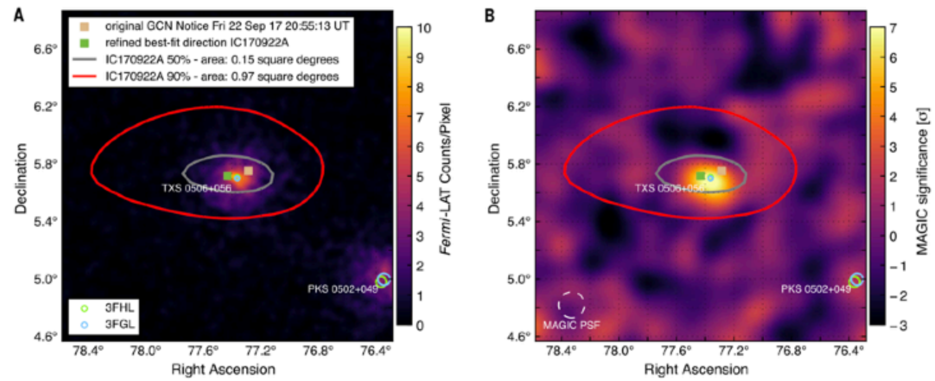
Workshop on Numerical Multimessenger Modeling

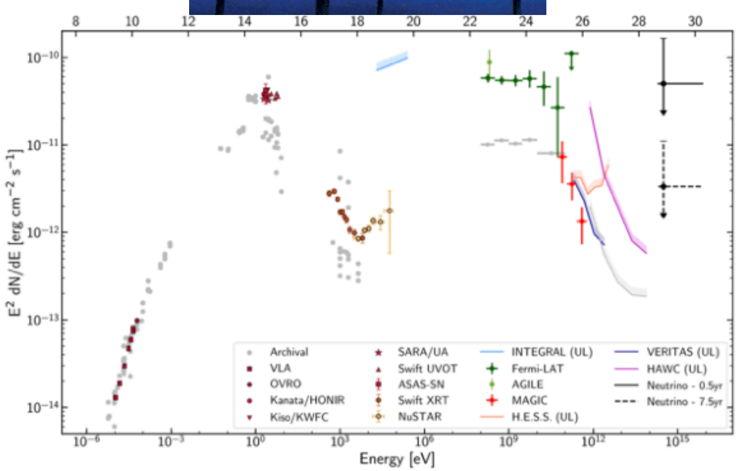
Paris

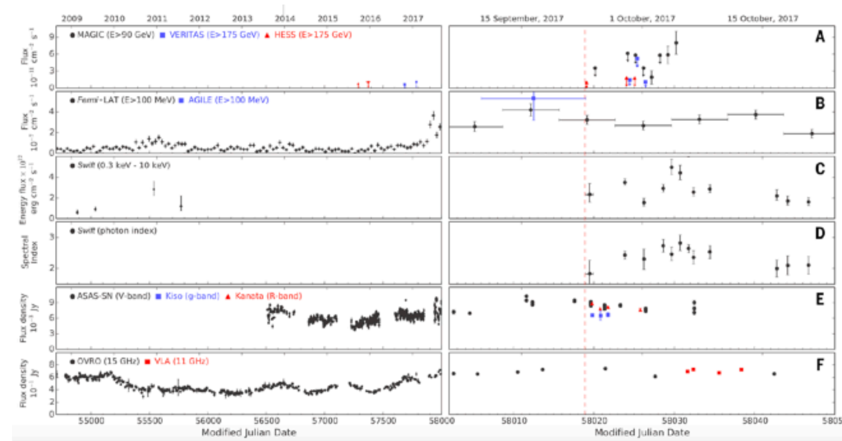
February 21, 2024

IceCube-170922A / TXS 0506+056

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



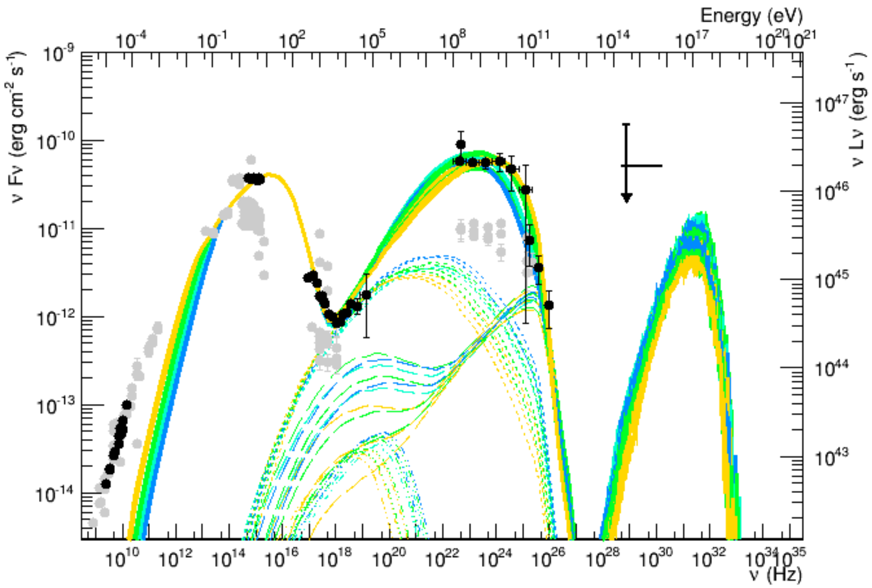




[IceCube, Fermi, MAGIC et al. 2018](#)

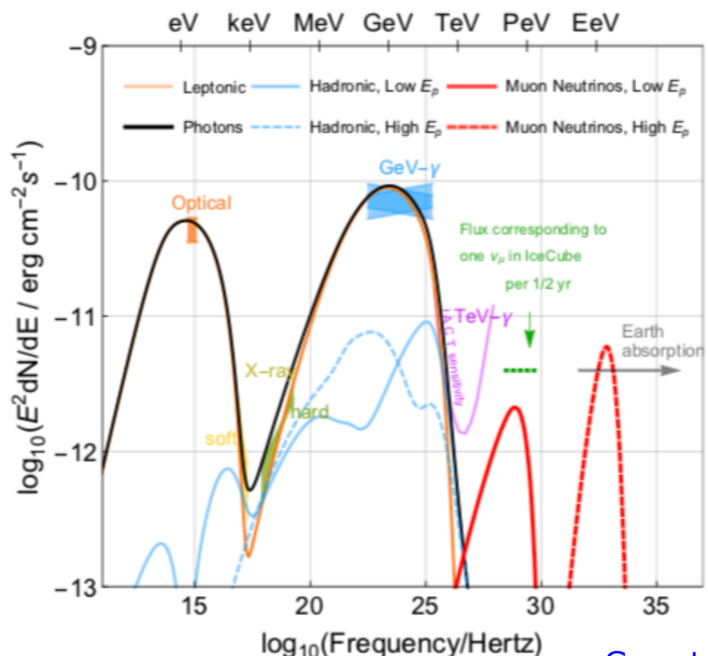
TXS0506+056: the 2017 flare

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]

$L_{jet} \simeq \times 10^{50} erg/s$
$\nu = 0.3\ yr^{-1}$

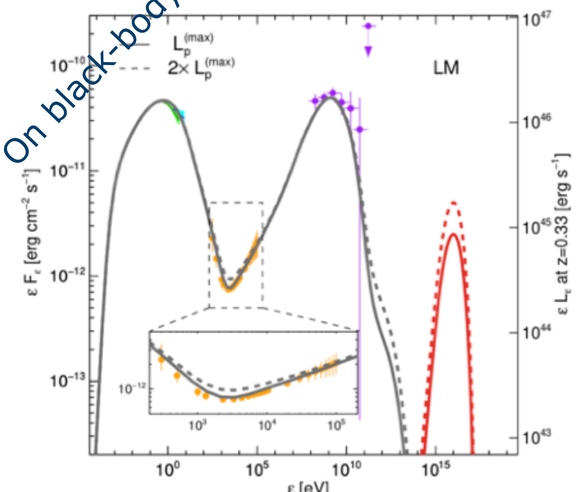
They can work: neutrino rates of the order of 0.1 / yr

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

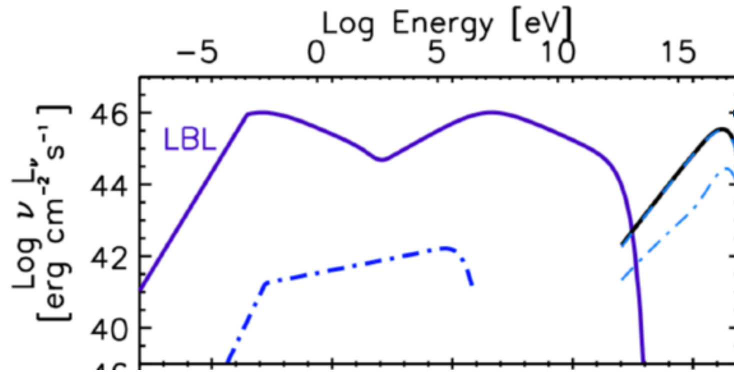
On black-body



Keivani et al. 2018

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

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



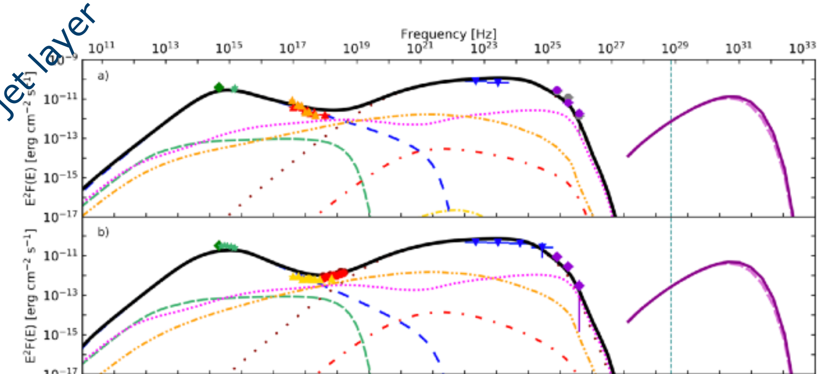
On RIAF

Righi et al. 2019

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

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

On jet layer



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

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

Ansoldi et al. 2018

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)
  - 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 a[…]012)
  - Time-dependent
  - Photo-meson from tabulated SOPHIA (Mücke et al. 2000); Be[…]om Protheroe and Johnson 1996
- **Böttcher13** (Böttcher et al. 2013)
  - Steady-state solver
  - Photo-hadronic interactions following Kelne[…]
- **LeHa-PARIS** (Cerruti et al. 2015)
  - Steady-state solver
  - Photo-meson running SOPHIA; Bethe-Heitler f[…]haronian 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

Table 1. Physical processes included in the numerical codes.

Physical Processes	Codes			
	AM^3	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	✓	✓	✗	✗
neutron decay	✗	✓	✗	✗
kaon synchrotron radiation	✗	✓	✗	✗
pion synchrotron radiation	✓	✓	✗	✗
muon synchrotron radiation	✓	✓	✗	✓

THE FOUR CODES

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

	Codes			
Features	AM^3	ATHEνA	B13	LeHa-Paris
steady state	✓	✓	✓	✓
time dependent	✓	✓	✗	✗
linear EM cascades	✓	✓	✓	✓
non-linear EM cascades	✓	✓	✗	✗
Implementation				
Photo-pion process	following Ref.[a]	tabulated SOPHIA[b]	following Ref.[c]	running SOPHIA[b]
Photo-pair process	following Ref.[c]	tabulated from Ref.[d]	n/a	following Ref.[c]

References— [a]Hummer et al. (2010), [b]Mücke et al. (2000), [c]Kelner & Aharonian (2008), [d]Protheroe & Johnson (1996)

THE TESTS

- Leptonic:
  - Electron break comparison
  - SSC with low gamma_max
  - SSC with high gamma_max (deep into Klein Nishina)
  - KN cooled electrons
- Hadronic (test cases)
  - Mono-energetic protons on black-body photons (varying gamma_p)
  - Power-law protons on power-law photons
  - Power-law protons on black-body photons
- Hadronic (realistic tests)
  - Proton synchrotron solution
  - Lepto-hadronic solution
- Other tests
  - Non-linear electron cooling
  - Non-linear proton cooling

THE TESTS

9

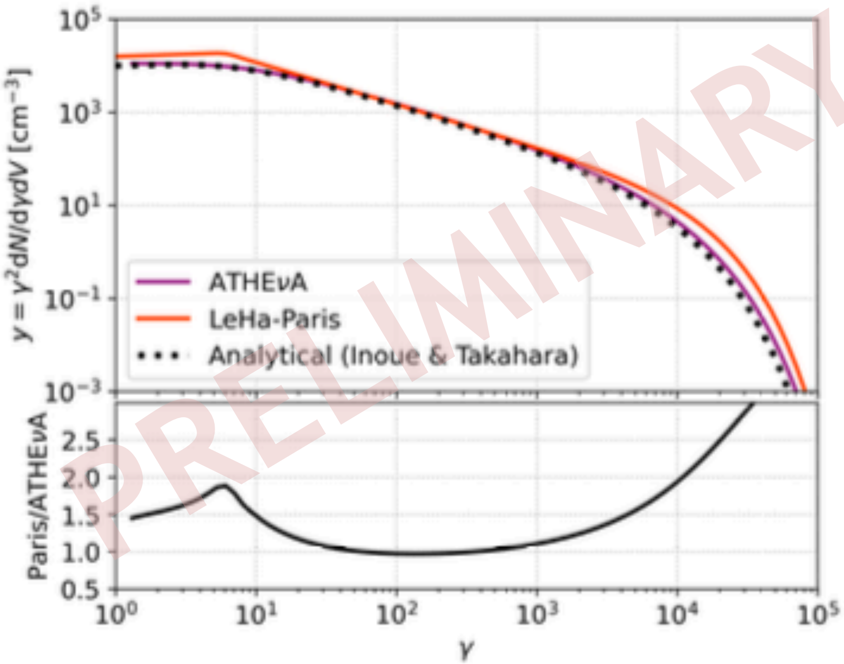
Table 3. Input parameter values used for each scenario for the code comparison.

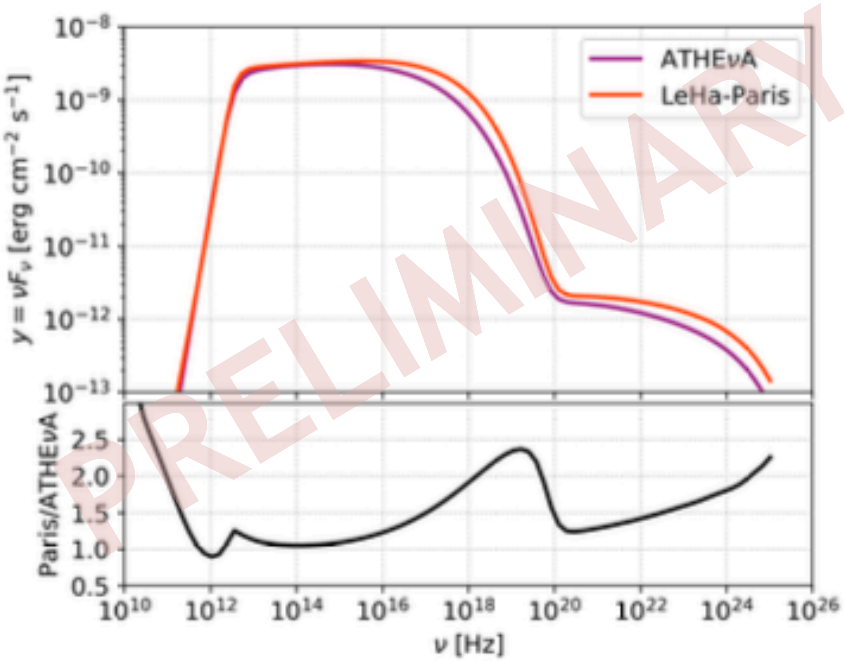
		SYN-cool	SSC-TH	SSC-KN	pγ-MONOGB	pγ-PLPL	PS	LeHa
Input parameters	Symbol [Units]				Values			
Emission Region Radius	R [cm]	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{15}	10^{16}
Magnetic field strength	B [G]	50	0.1	0.1	10		10	0.1
Min. e$^-$ Lorentz factor	$\gamma_{e,\min}$	1	1	1	–	–	1	1
Max. e$^-$ Lorentz factor	$\gamma_{e,\max}$	10^4	10^4	10^6	–	–	10^3	3×10^5
e$^-$ power-law index	s_e	1.9	1.9	1.9	–	–	1.9	2.0
e$^-$ injection luminosity[a]	$L_e^{\rm inj}$ [erg s^{-1}]	–			–	–	1.6×10^{38}	3.7×10^{40}
e$^-$ injection compactness[b]	$\log(\ell_e^{\rm inj})$	-4.5	-4.47	-4.18	–	–	7.47	-5.1
Steady-state e density[c]	$n_e^{\rm ss}\|_{\gamma=1}$ [cm^{-3}]	1.65×10^4	10^4	10^4	–	–	10	
e$^-$ escape timescale	$t_{e,\rm esc}$ [R/c]	1	1	1	–	–	1	1
Min. p Lorentz factor	$\gamma_{p,\min}$	–	–	–	$10^{6(7)}$	1	1	1
Max. p Lorentz factor	$\gamma_{p,\max}$	–	–	–	$10^{6.2(7.2)}$	10^8	10^8	10^7
p power-law index	s_p	–	–	–	1.9	1.9	1.9	2.0
p injection luminosity[a]	$L_p^{\rm inj}$ [erg s^{-1}]	–	–	–	8.5×10^{43}	8.5×10^{43}	10^{44}	2.8×10^{46}
p injection compactness[b]	$\log(\ell_p^{\rm inj})$	–	–	–	-4.0	-4.0	-4.93	-2.5
Steady-state p density[c]	$n_p^{\rm ss}$ [cm^{-3}]	–	–	–	$2.4(1.9)\times10^5$	8490	1000	
p escape timescale	$t_{p,\rm esc}$ [R/c]	–	–	–	1	1	1	1

NOTE—[a]AM^3, [b]ATHEνA , [c]LeHa-Paris and B13. Particle cooling neglected in SSC-TH, SSC-KN, pγ-MONOGB, pγ-PLPL, and $\gamma-\gamma$-annihilation was omitted in PS. pγ-MONOGB: grey-body external photon field of compactness $\ell_\gamma = 8.1\times10^{-6}$ and temperature $T_\gamma = 10^6$ K. pγ-PLPL: Power-law external field of compactness $\ell_\gamma = 10^{-5}$ between $E_{\gamma,\min} = 10^{-6} m_e c^2$ and $E_{\gamma,\max} = 10^{-1} m_e c^2$, with power-law index $p_\gamma = 2.0$.

LEPTONIC TESTS

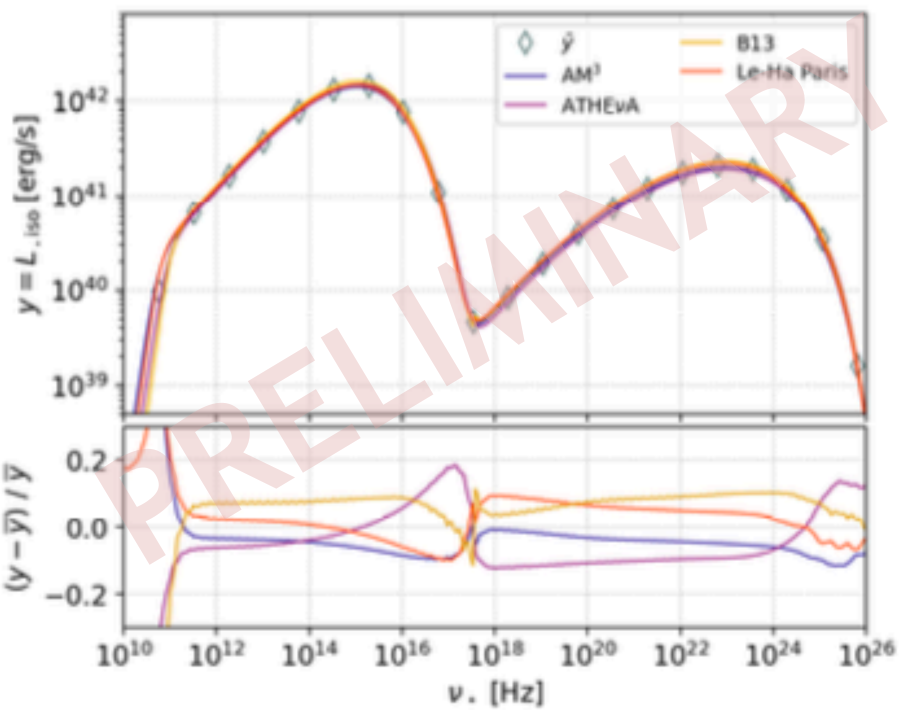
Difference between sharp break and self-consistent cooling break

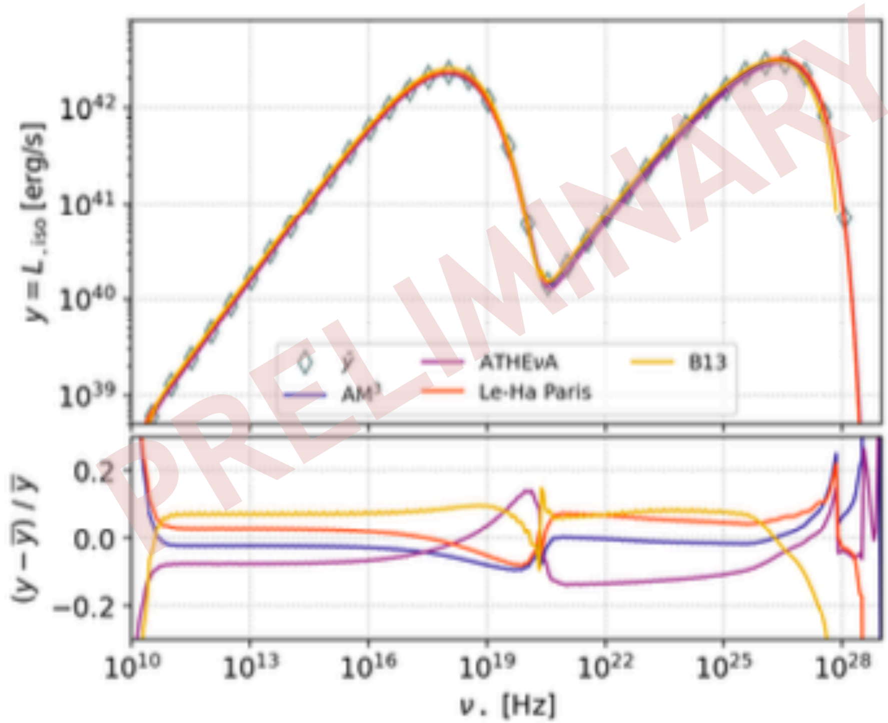




LEPTONIC TESTS

Agreement for SSC tests

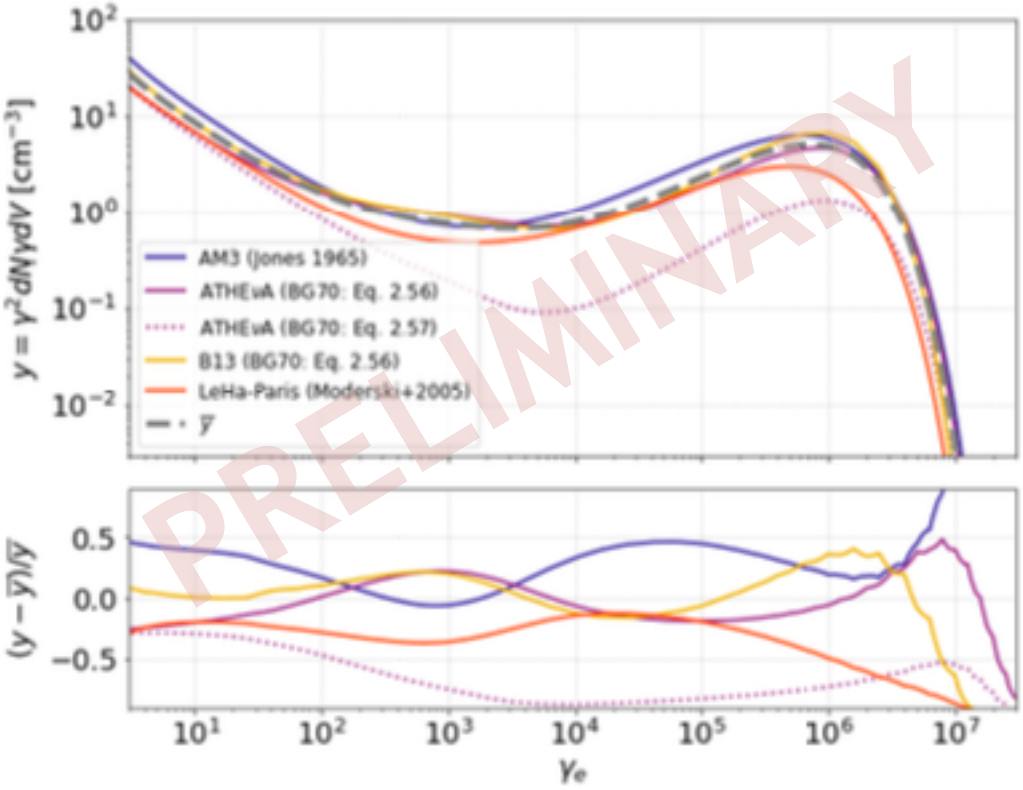




Low E_max ***Low E_max (Klein-Nishina)***

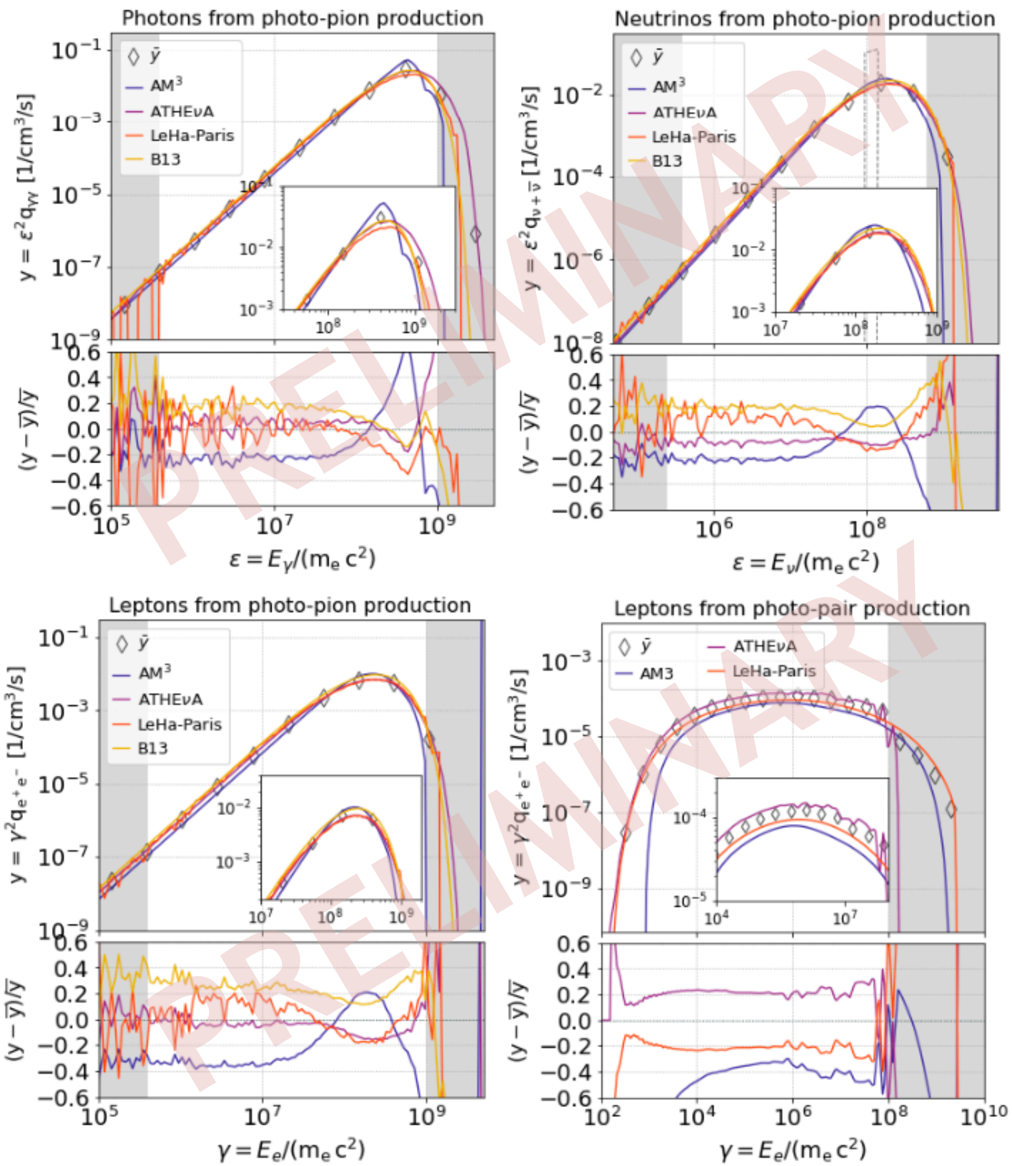
LEPTONIC TESTS

Klein-Nishina cooled distribution



(Understood as continuous vs discrete losses approximation)

HADRONIC TESTS



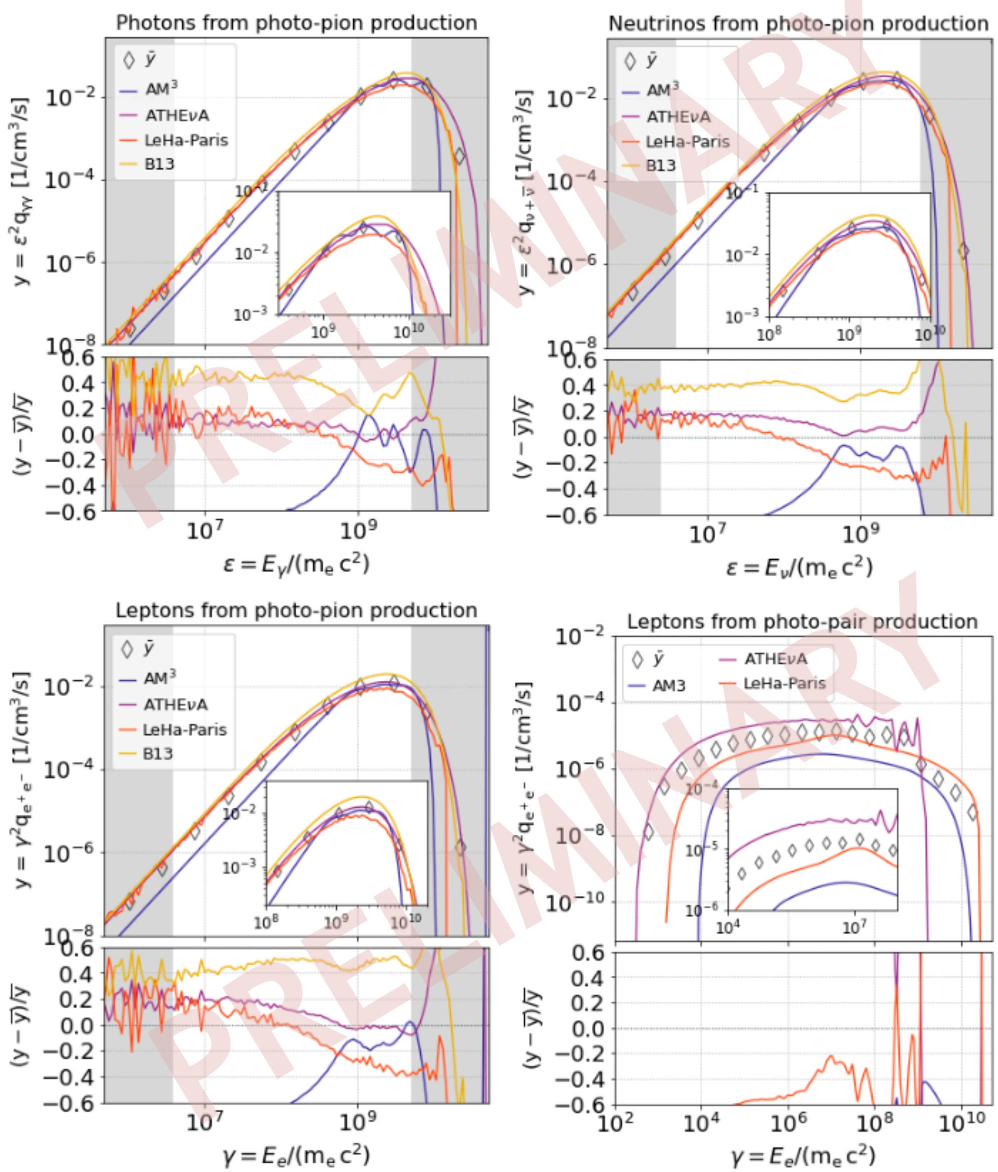
Test cases

1) (quasi) Monoenergetic Protons (log10(E) in 6-6.2)

Photo-meson in very good agreement

Bethe-Heitler not so well?

HADRONIC TESTS



Test cases

2) (quasi) Monoenergetic Protons

(log10(E) in 7-7.2)

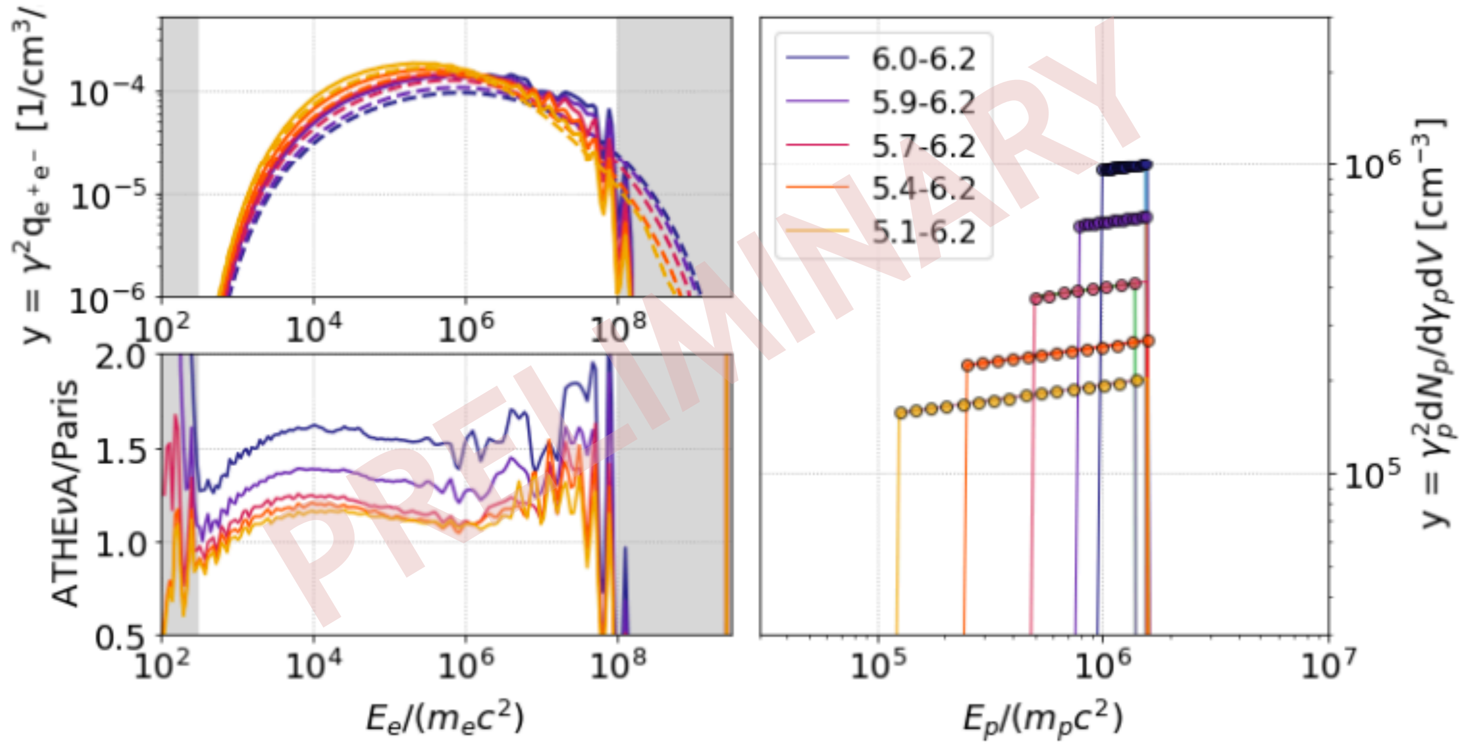
Photo-meson in very good agreement

Bethe-Heitler even worse!

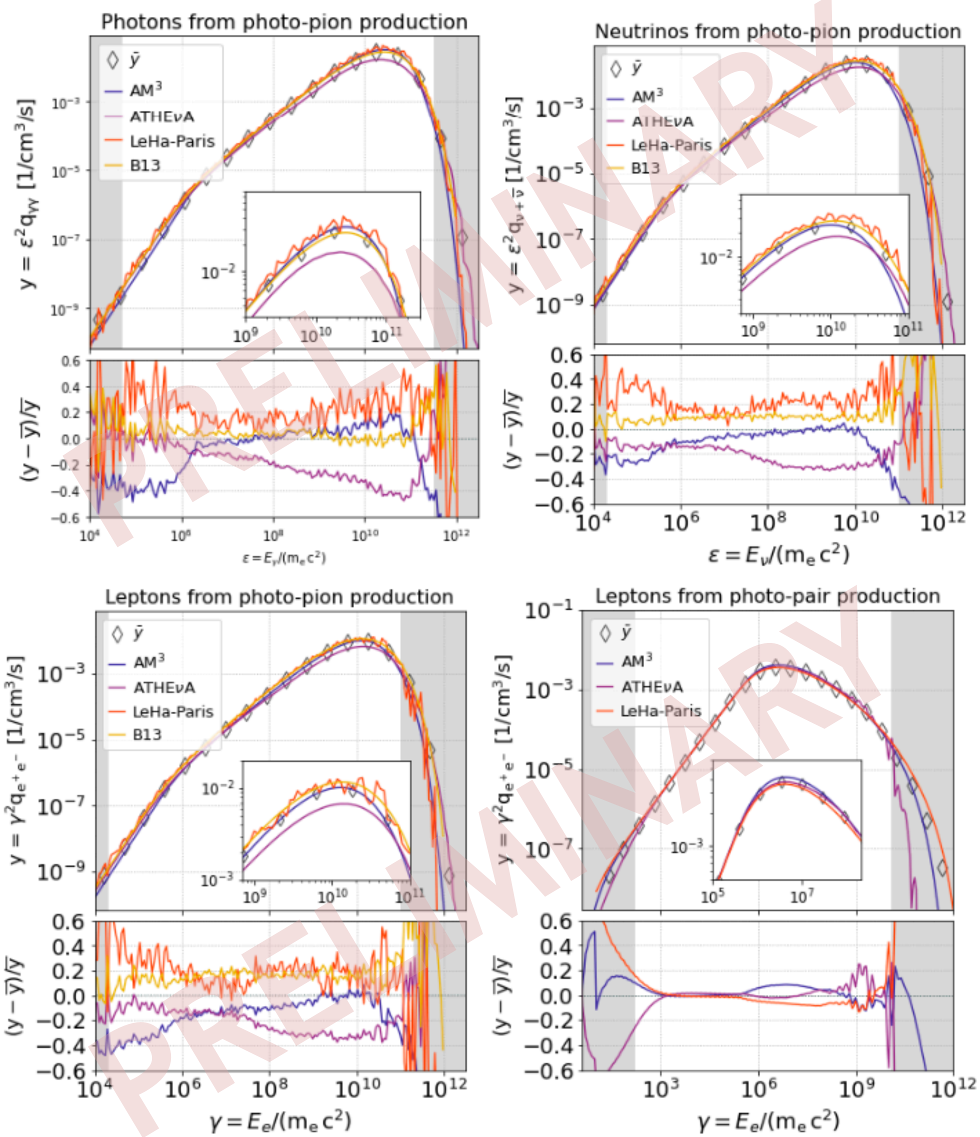
HADRONIC TESTS

Understood! Issue with very narrow distributions (and low number of bins)

(Extending the proton distribution improves the agreement)



HADRONIC TESTS



Test cases

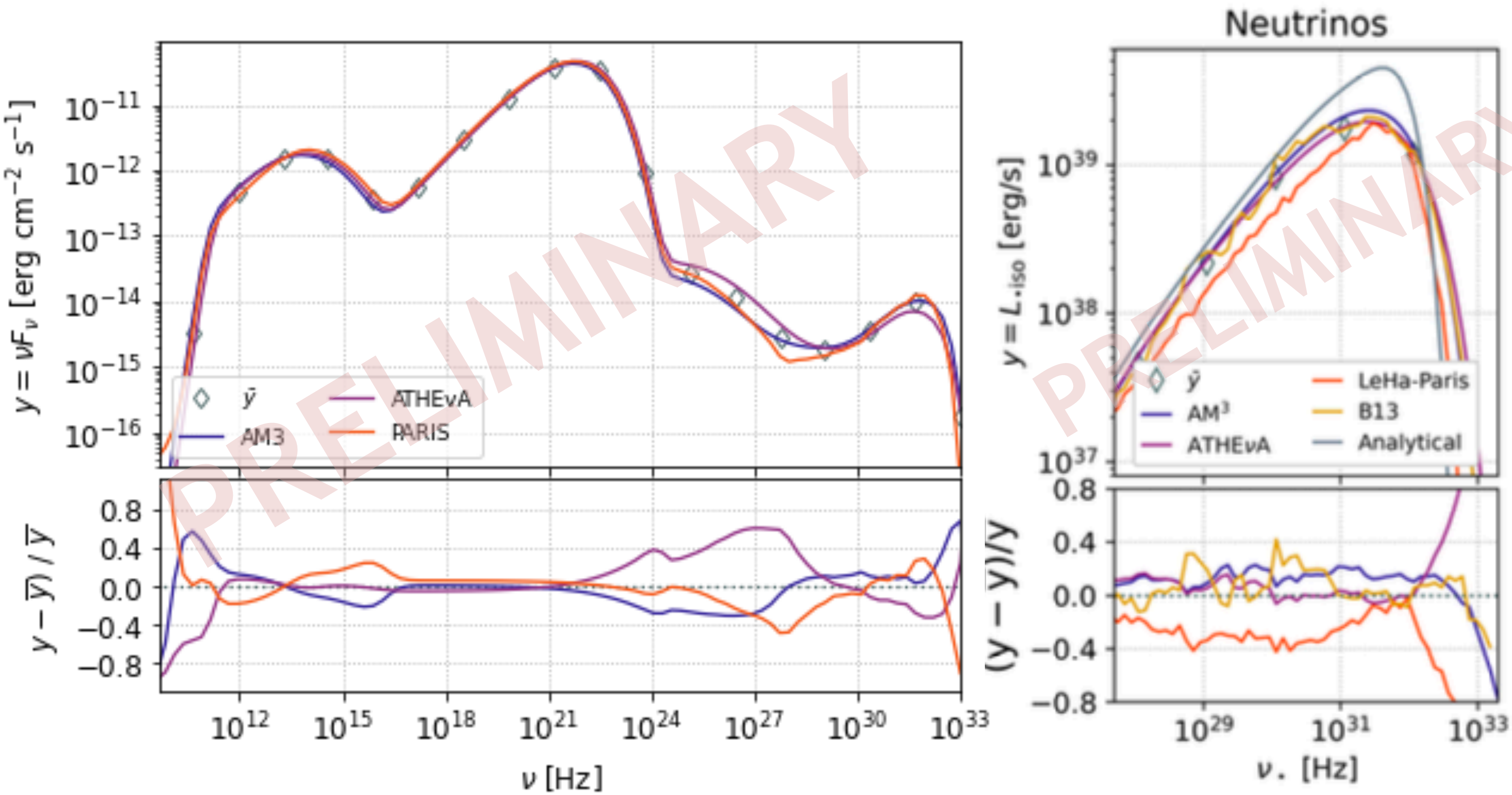
3) power-law on power-law

Photo-meson in very good agreement

Bethe-Heitler in extremely good agreement

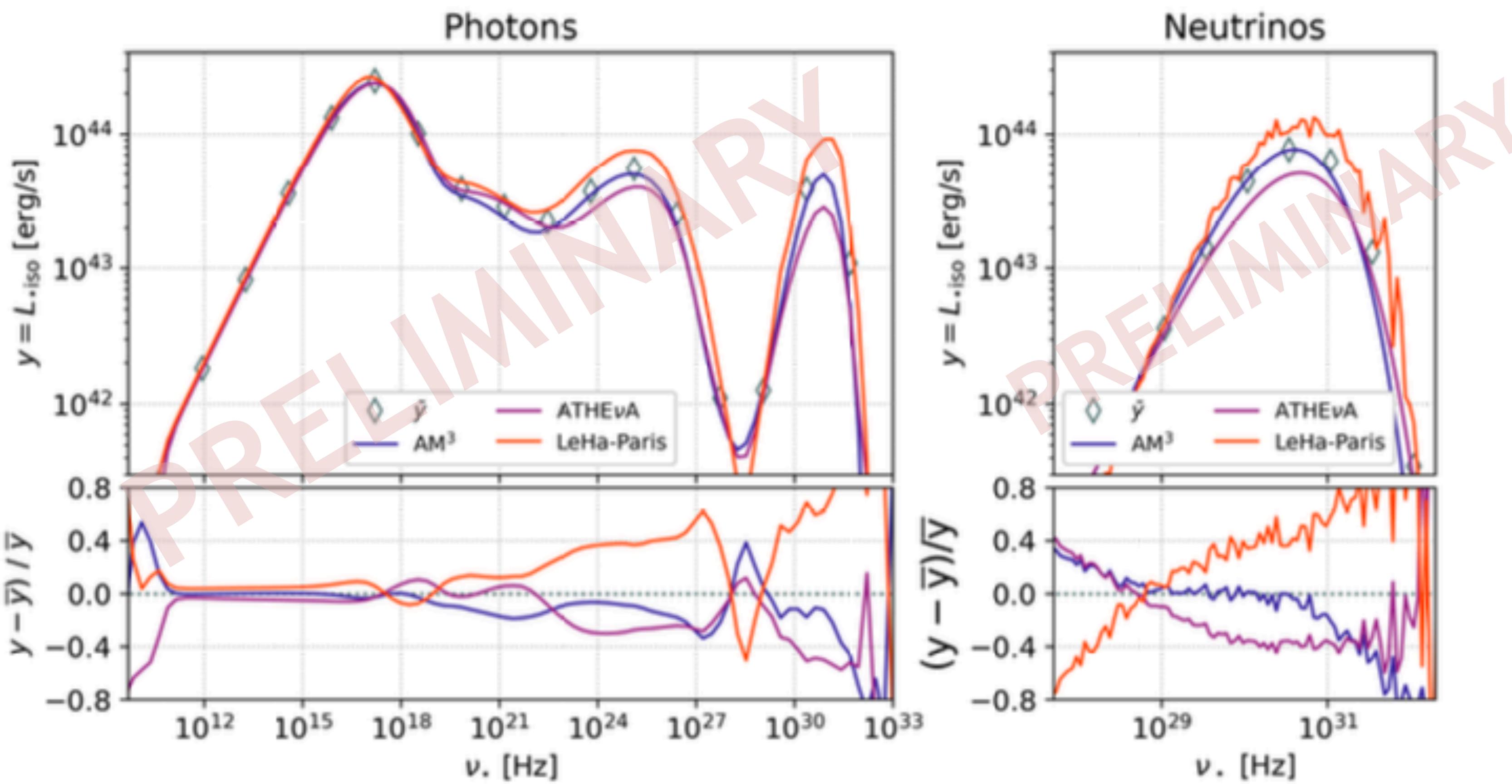
HADRONIC TESTS

SED comparison for typical proton synchrotron scenario



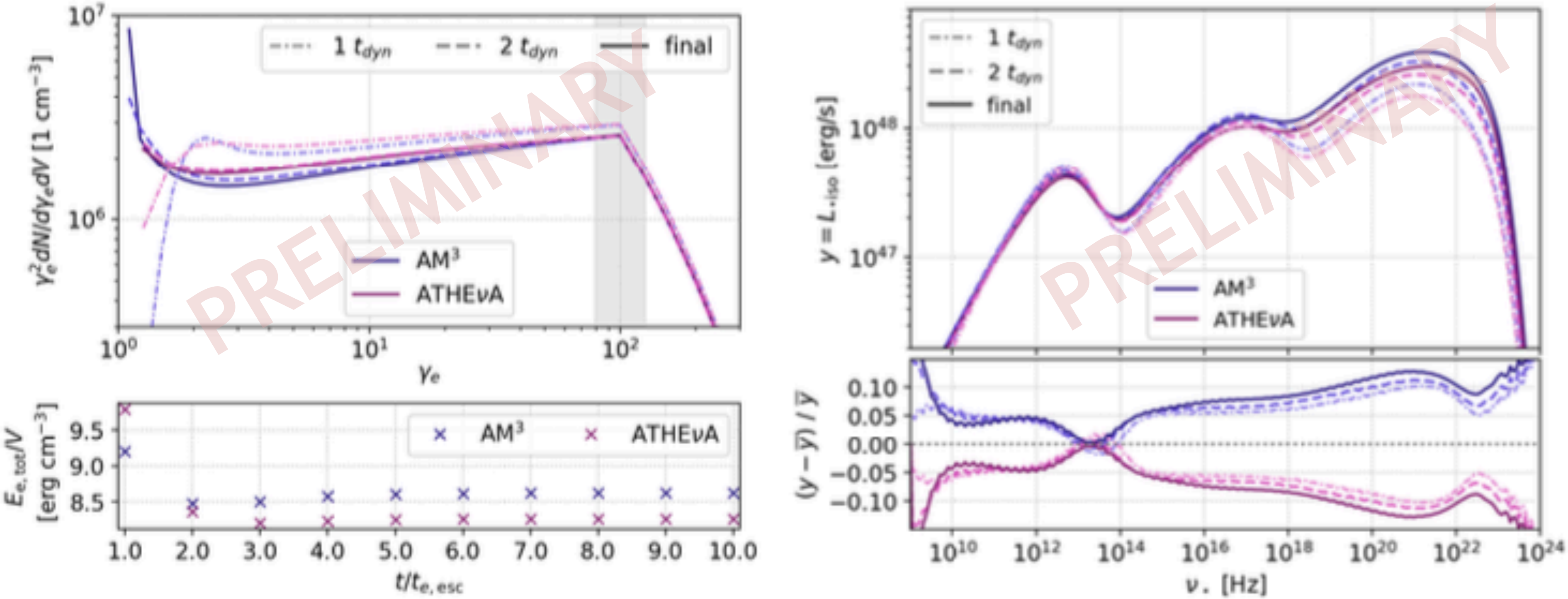
HADRONIC TESTS

SED comparison for typical lepto-hadronic scenario



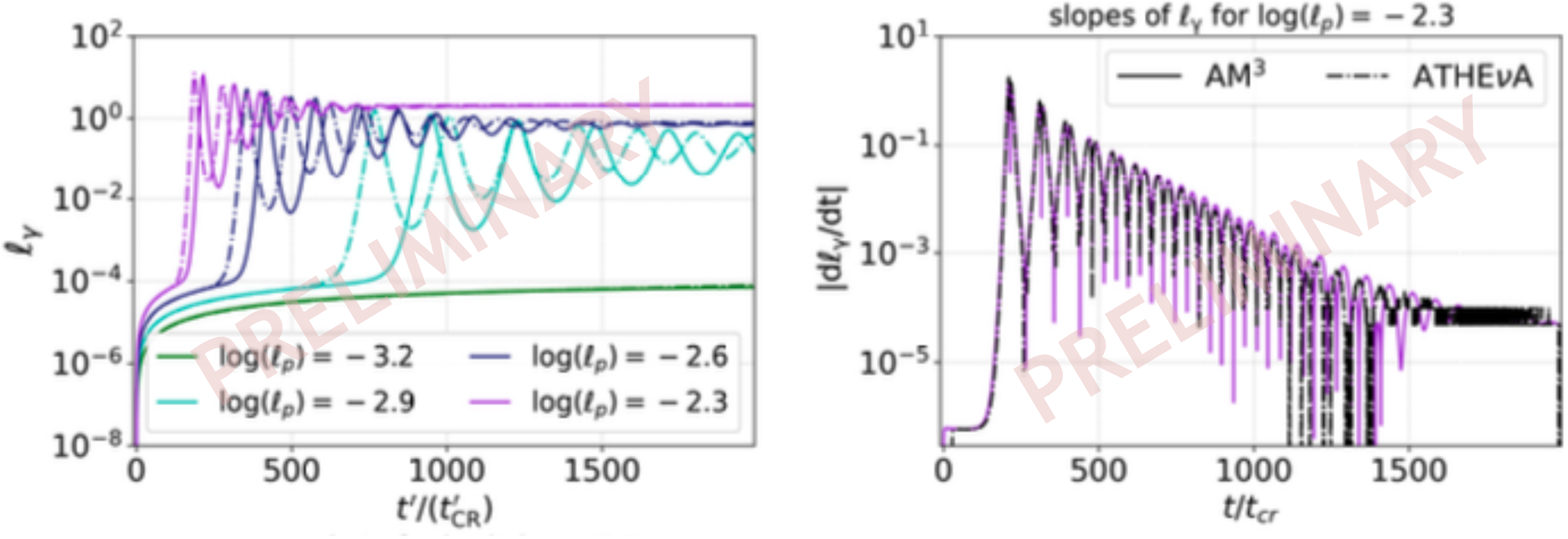
OTHER TESTS

Non-linear electron cooling: Compton catastrophe



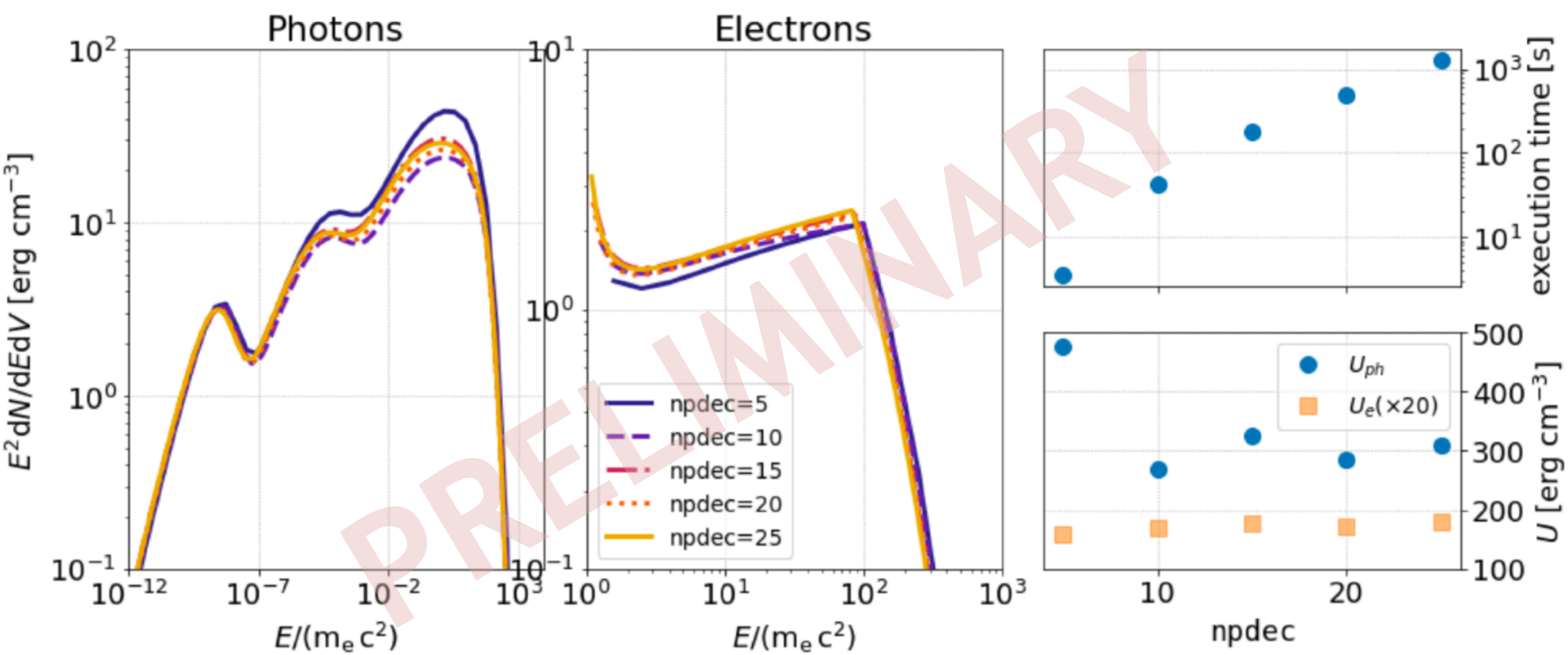
HADRONIC TESTS

Non-linear proton cooling: pair loops



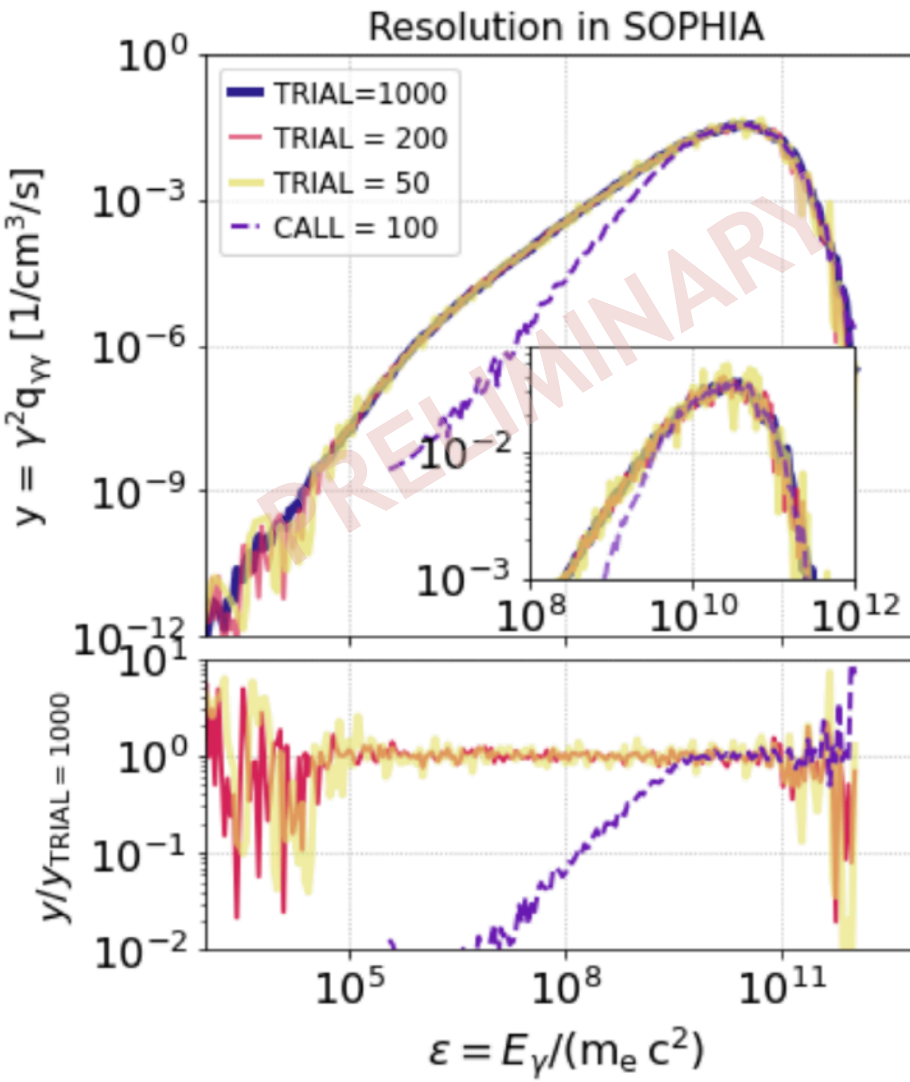
BONUSES

Resolution in codes



BONUSES

Resolution in codes



PAPER AND DATA RELEASES

Paper exists!

PAPER AND DATA RELEASES

Data release:

* *ALL code outputs for all tests performed*
* *ALL python scripts to produce the plots shown in the paper*

Expected in the upcoming months (really)

If you want early data access, just ask us