LeHaMoC : A Versatile and Efficient Time-Dependent Lepto-Hadronic Code for Astrophysical Sources

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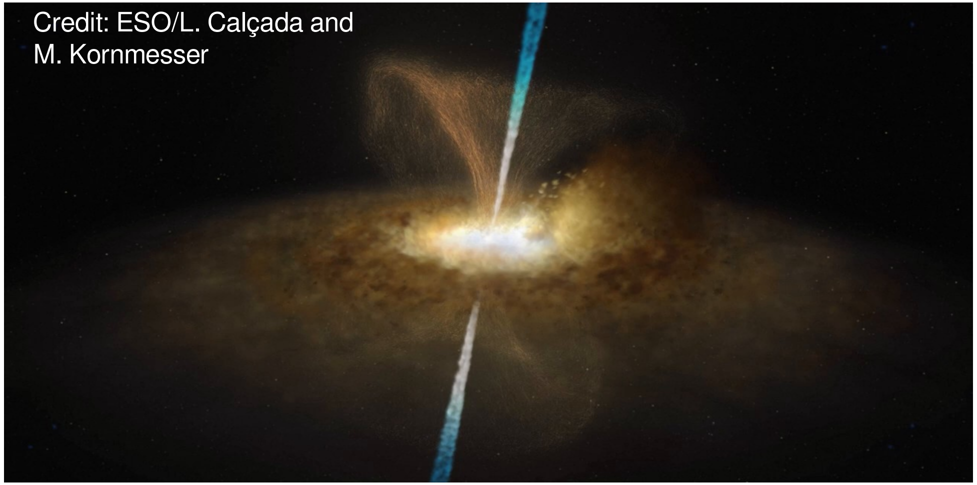
UNTRAPHOB

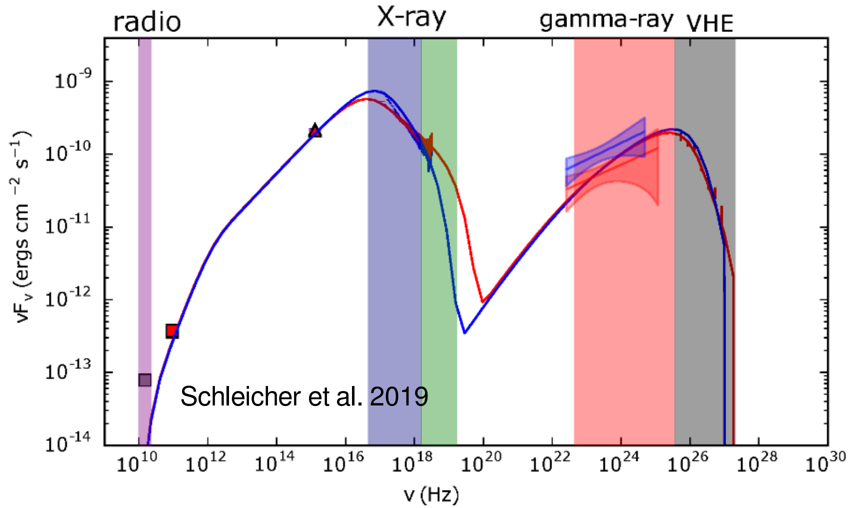
H.F.R.I. Hellenic Foundation for Research & Innovation

Introduction: AGN and Blazars

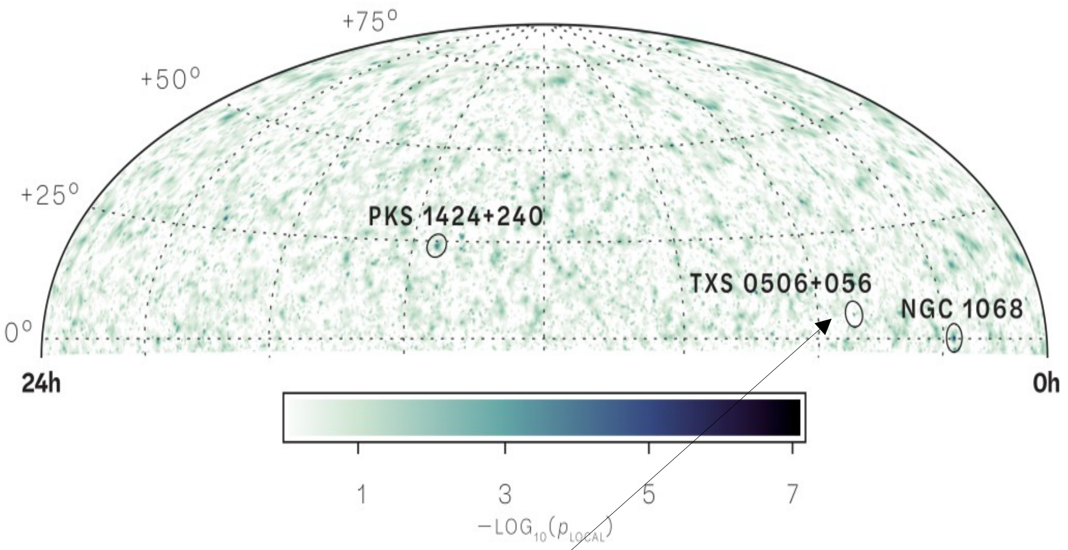
AGN: Supermassive black holes at the center of the galaxies which produce non-stellar high luminosity
- Characteristics: High energy emission, accretion disks and jets

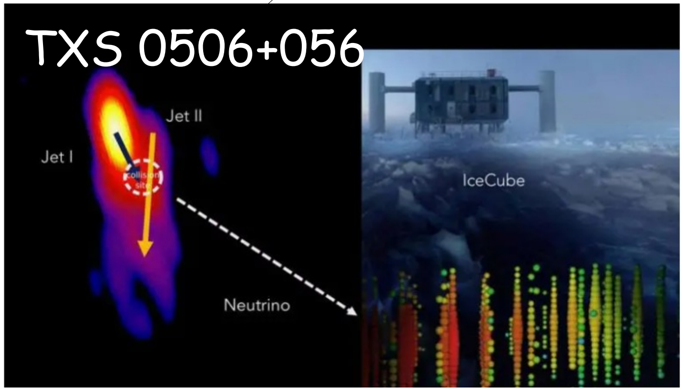
Blazar: Subset of AGN whose relativistic jet points towards the observer
- Characteristics: Extreme variability, non-thermal radiation, polarized emission, high energy flares, doppler boosting effect





Skymap of high energy neutrino point sources in the Northern Hemisphere

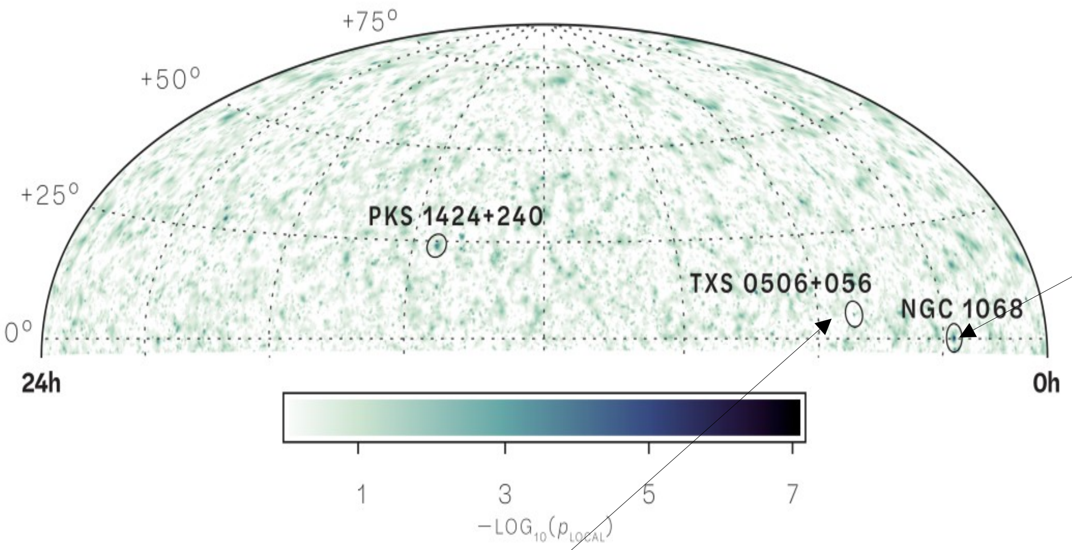


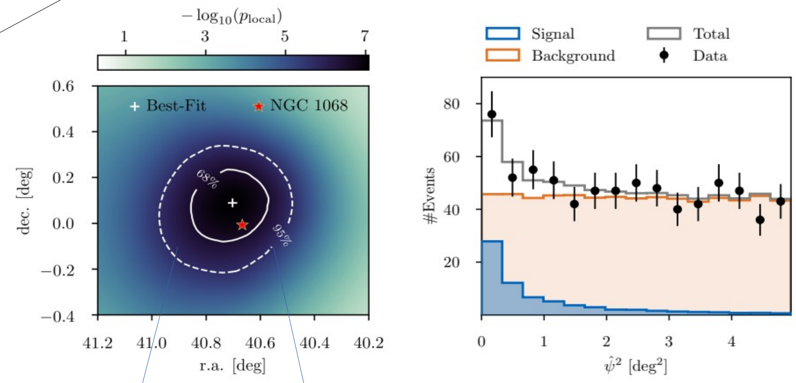


Credit: IceCube Collaboration, MOJAVE, S. Britzen, & M. Zajaček

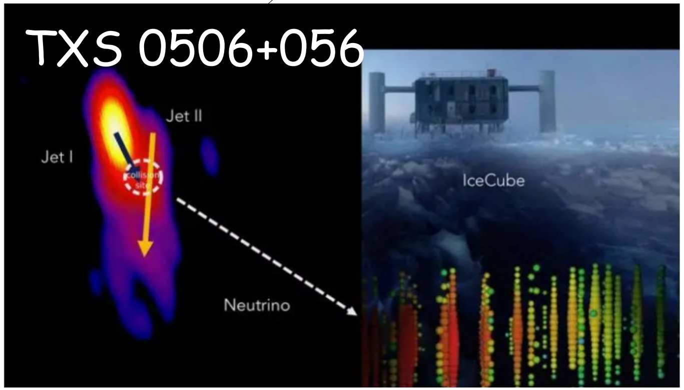
Skymap of high energy neutrino point sources in the Northern Hemisphere

- IceCube Collaboration reported an excess 79 neutrino events
- Hottest spot 4.2σ





IceCube Collaboration, Science, 2022



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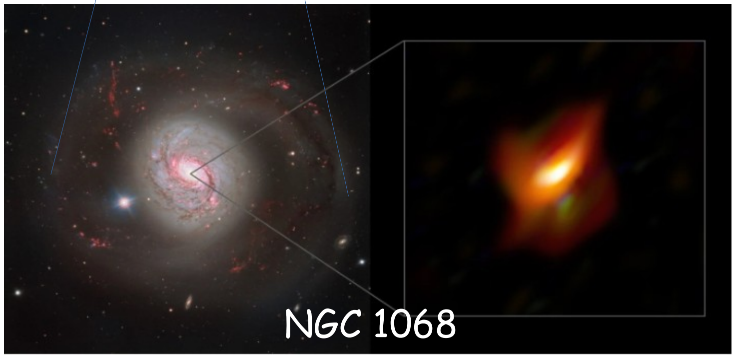
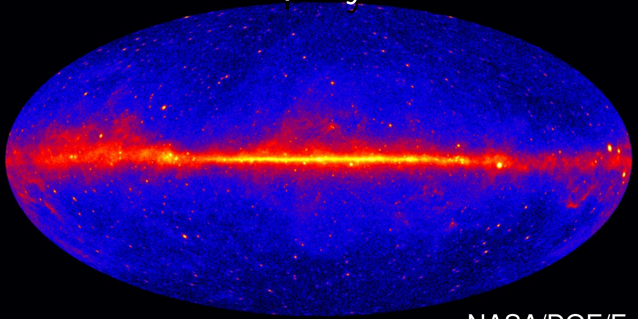


ESO/Jaffe, Gámez-Rosas et al.

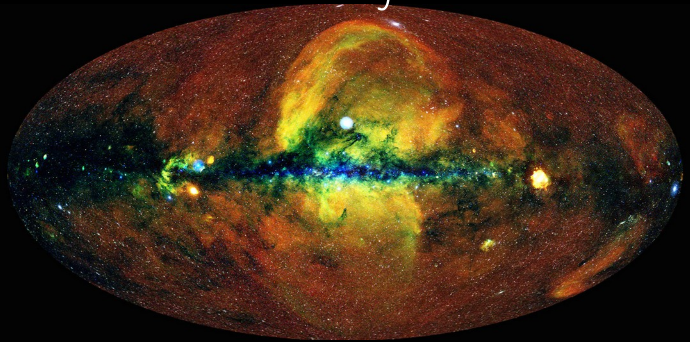
Motivation and aims

γ-rays



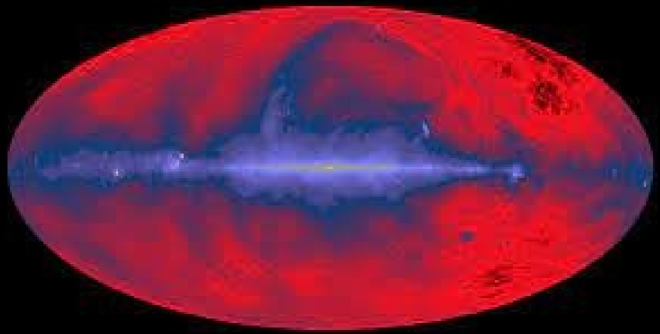
NASA/DOE/Fermi LAT Collaboration

X-rays

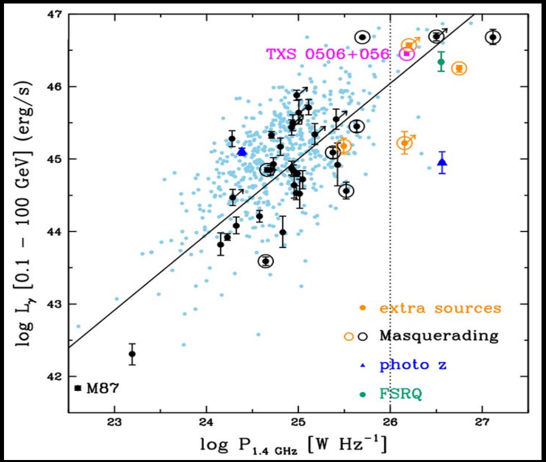


eROSITA

Radio



Max Planck Institute for Radio Astronomy



P.Padovani et.al. 2021

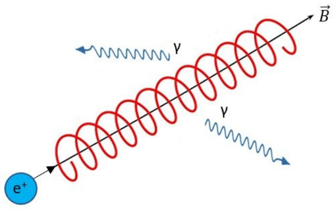
- Association between AGN, bright blazars and HE neutrinos

- Rapid increase in the amount of multi-wavelength data of these sources

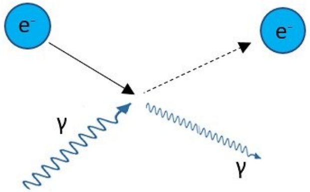
  Underscores the need for efficient computational tools to analyze and interpret this information

LeHaMoC-Non thermal processes

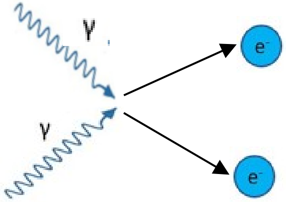
e-syn

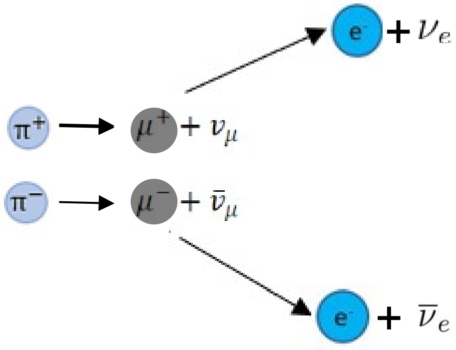


e-ICS

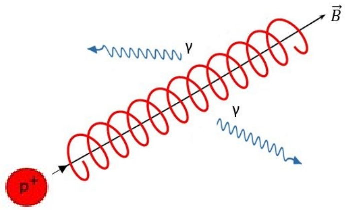


γγ-> pair production





p-syn



Bethe-Heitler
Pair production

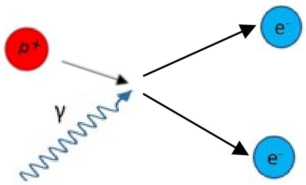
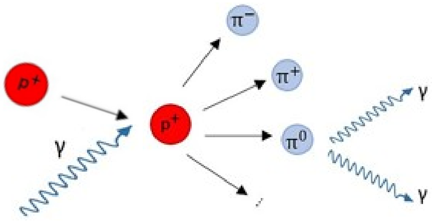
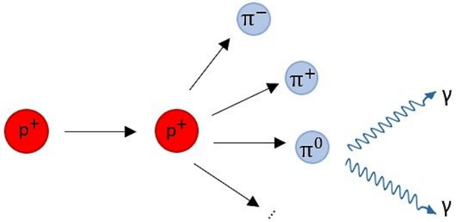


Photo-pion
production



Proton-proton
collision



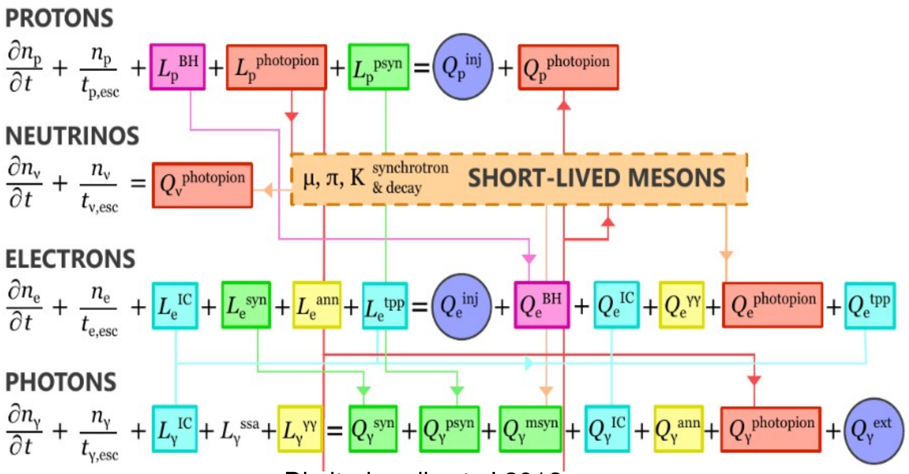
The kinetic equation and challenges

- Particles occupy a region (spherical)
- Description of the numerical density of particles in time and energy through partial differential equations

$$\frac{\partial N_i(E,t)}{\partial t} + \frac{\partial}{\partial E}\left(b(E)N_i(E,t)\right) + \frac{N_i(E,t)}{t_{esc}(E,t)} = Q_{inj}(E,t) + Q_{ext}(E,t)$$

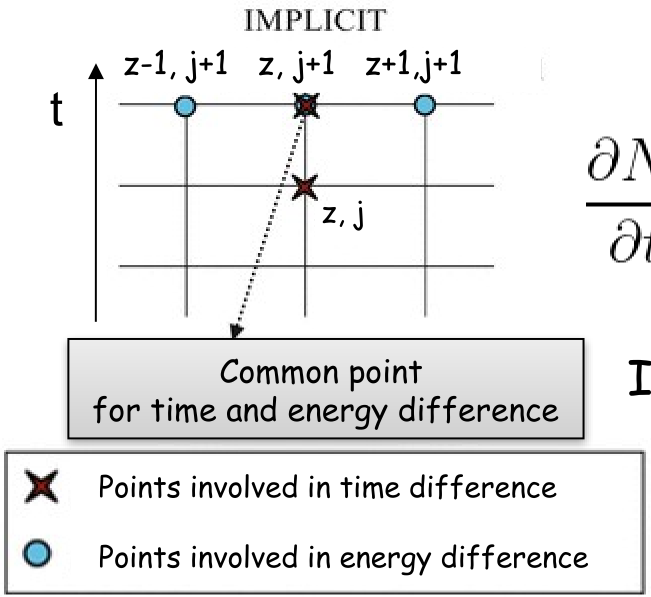
Evolution in time | Energy gain-losses | Escape term | Injection terms

System of coupled kinetic equations for protons, electrons , photons and neutrinos



Dimitrakoudis et.al 2012

The kinetic equation and LeHaMoC



$$\frac{\partial N_i}{\partial t} + \frac{\partial}{\partial x}(\mathcal{P}_i(x,t)N_i) + \frac{N_i}{t^i_{esc}(t)} = Q_i$$

+

Implicit Method (Chang and Cooper)

Faster computational time
(No constraint on dt)
+
Stability of the solution

Discretization

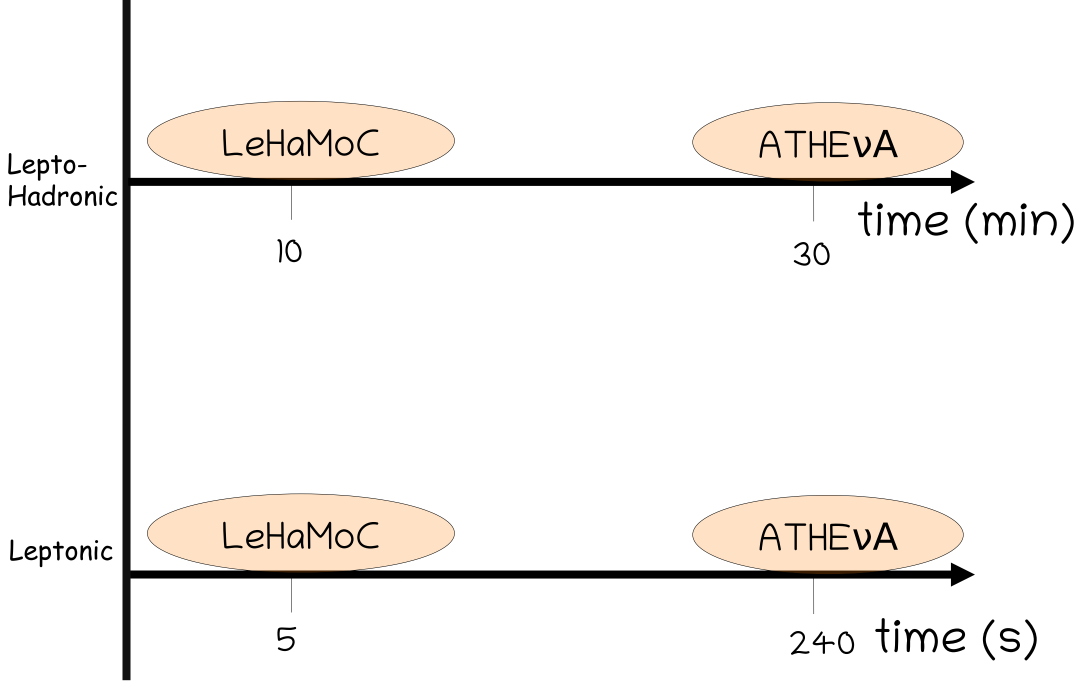
$$\frac{\partial N_i}{\partial t} = \frac{N_{i,z}^{j+1} - N_{i,z}^{j}}{\Delta t}$$ (Euler's Method)

$t = (t_1, t_2, .., t_n)$, $j \in (1,n)$
$x = (x_1, x_2, .., x_m)$, $z \in (1,m)$

$$\frac{\partial}{\partial x}(\mathcal{P}_i(x,t)N_i) = \frac{F_{i,z+\frac{1}{2}}^{j+1} - F_{i,z-\frac{1}{2}}^{j+1}}{\Delta x}, \quad F_{i,z\pm\frac{1}{2}}^{j+1} \equiv \mathcal{P}_i(x_{z\pm\frac{1}{2}}, t^j)N_{i,z\pm\frac{1}{2}}^{j+1}$$

LeHaMoC

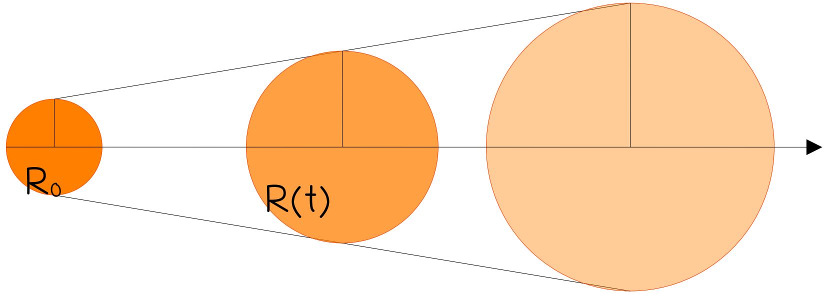
- Versatility and speed advantage

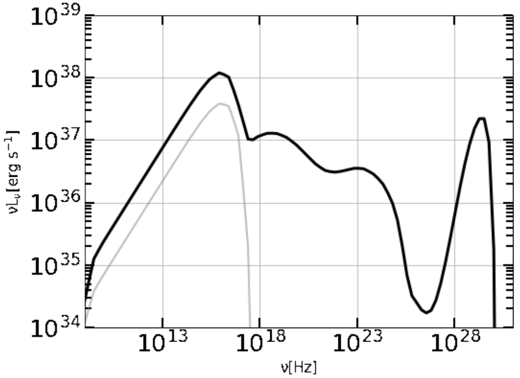


Comparison with the ATHEνA code (a time-dependent one-zone lepto-hadronic code)
Mastichiadis & Kirk 1995; Dimitrakoudis et. al. 2012

- **Key features of LeHaMoC**

- Expansion of the source





- Proton-proton interactions

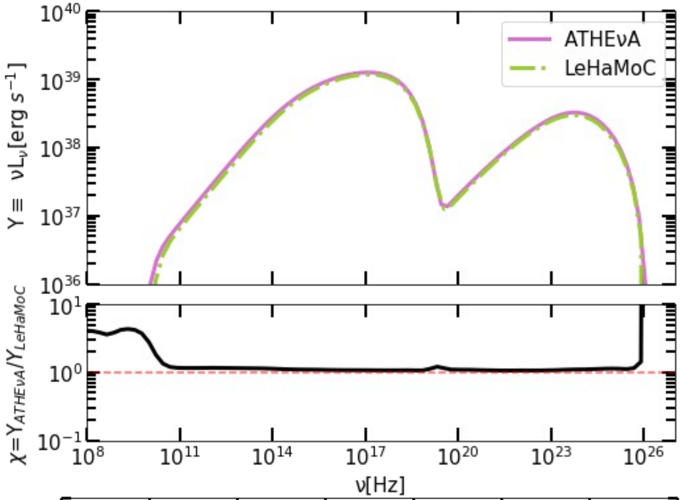
$$p + p \to p + p + \pi^0$$

$$p + p \to p + n + \pi^+$$

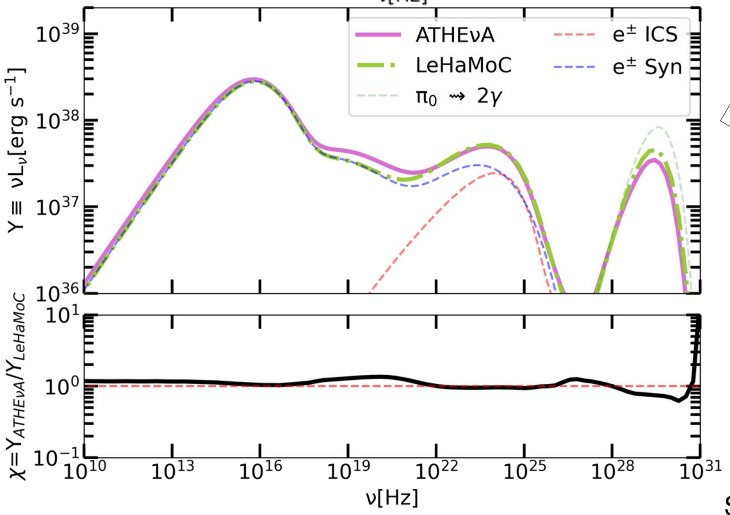
$$p + p \to n + n + 2\pi^+$$

LeHaMoC results-Validation and Comparison

Comparison with the ATHEνA code

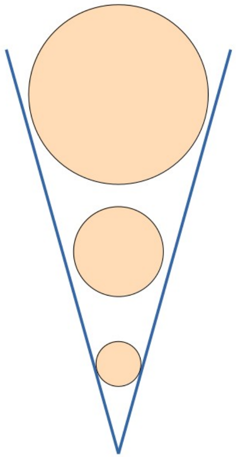


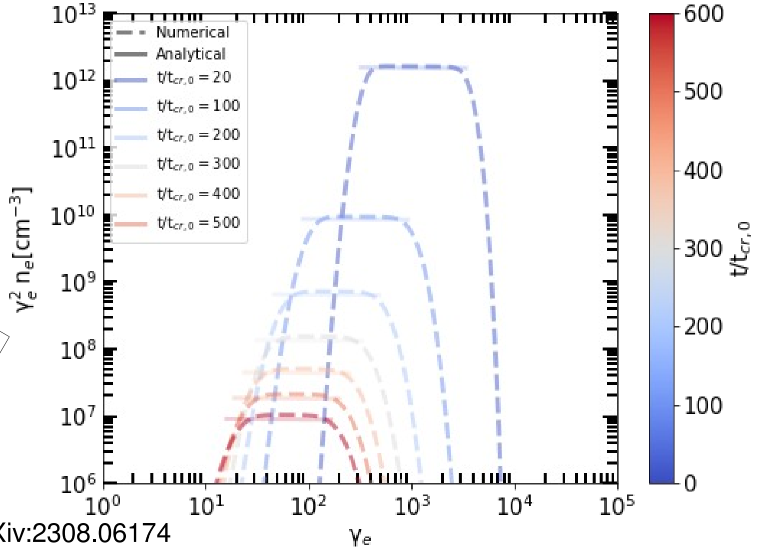
Leptonic model



Lepto-hadronic model

Analytical model



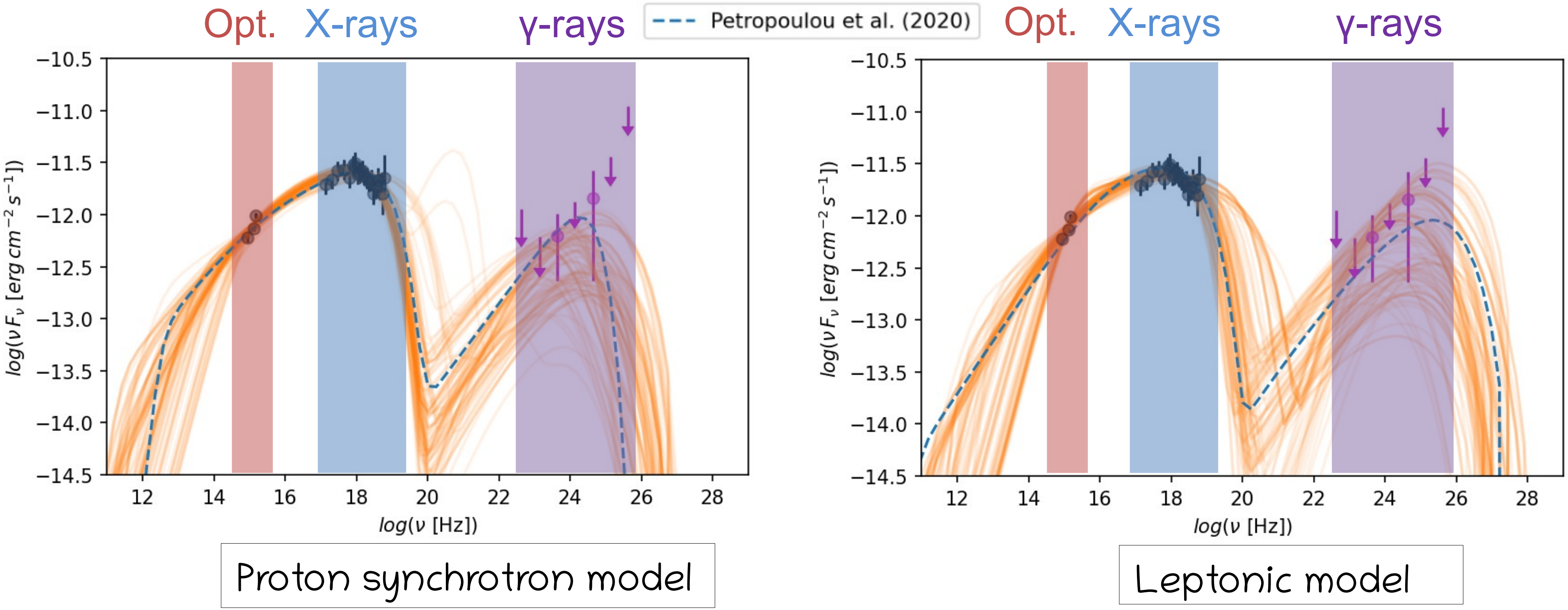


Stathopoulos et al. , A&A submitted, arXiv:2308.06174

LeHaMoC results-Illustrative Example 1: Blazar SED Fitting

LeHaMoC + emcee → Better understanding of the physics inside the emitting region

3HSP J095507.9+355101



Orange lines: Random sample of 100 points from the posterior distribution.

https://github.com/mariapetro/LeHaMoC

Stathopoulos et al. , A&A submitted, arXiv:2308.06174

LeHaMoC results-Illustrative Example 2: NGC 1068 SED Fitting

Source characteristics

$M_{SMBH} \sim 10^{7.3} M_{SUN}$

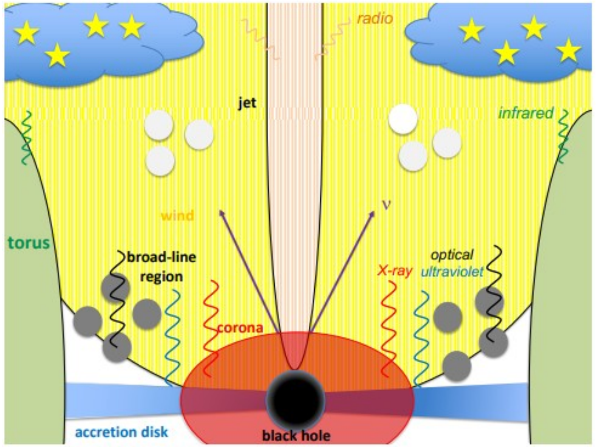
$R_s \sim 6\ 10^{12}$ [cm]

Intrinsic X-ray luminosity ~ 10^{44} [erg s^{-1}]

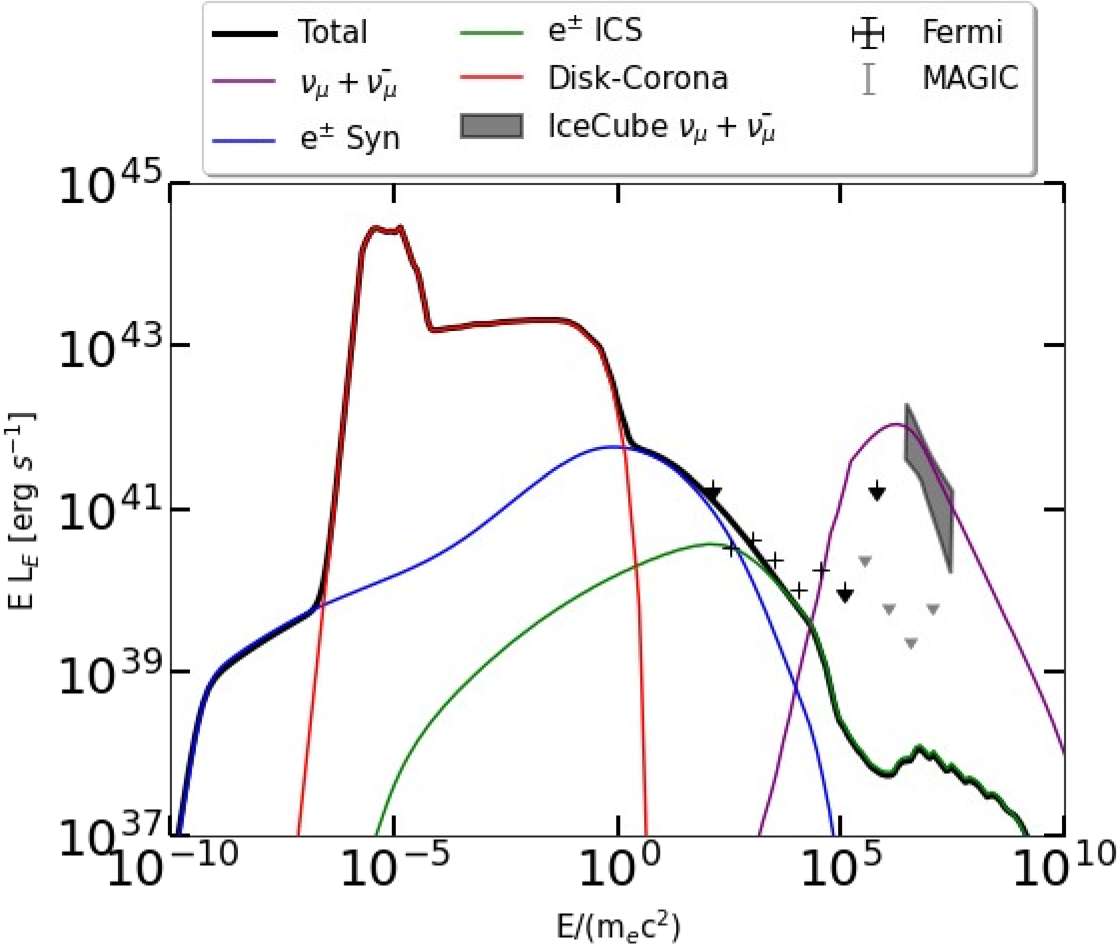
Opaque in 0.1-10GeV ($\tau_{\gamma\gamma}$>1) → R<100R_s

Conclusions

Neutrinos are produced in the vicinity of the SMBH → Corona-disk region



Murase, 2022

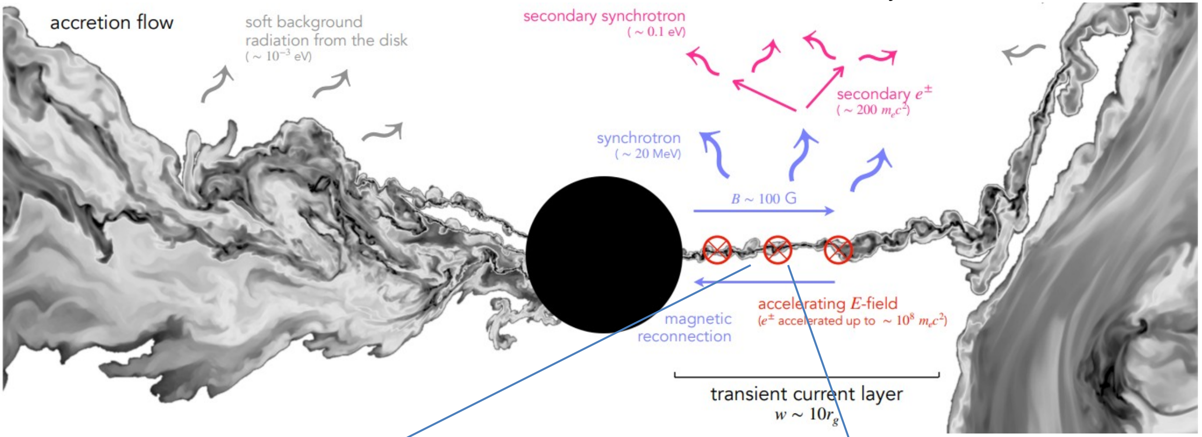


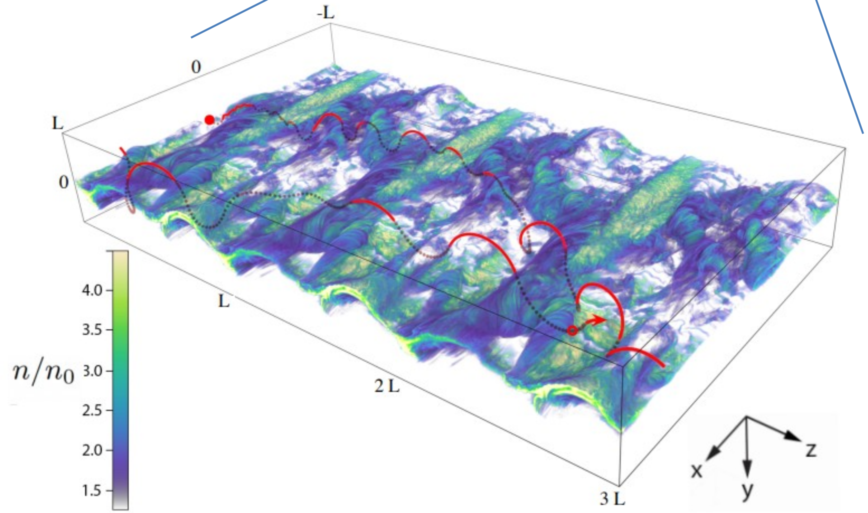
Stathopoulos et al. , A&A submitted,arXiv:2308.06174

LeHaMoC: Cosmic-ray acceleration in M87 current sheets (work in progress)

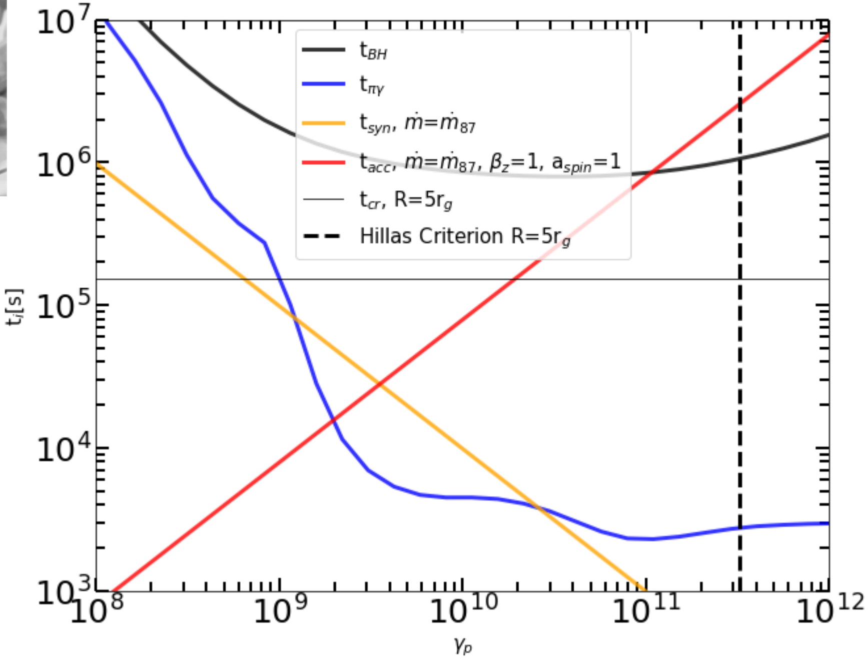
in collaboration with M.Petropoulou, D.Giannios and L.Sironi

Hakobyan et al. 2023





Zhang H. et al. 2023



Summary

- LeHaMoC: Versatile and efficient numerical tool for calculating spectra for high energy astrophysical sources
- The code's versatility and speed make it well suited for analyzing GRB, Blazars and other high-energy sources

Thank you!

https://github.com/mariapetro/LeHaMoC

Stathopoulos et al. , A&A submitted, arXiv:2308.06174

[1] Kelner & Aharonian 2009

[2] Kelner & Aharonian 2008

[3] Kirk & Mastichiadis 1995

[4] Rybicki & Lightman 1985

Leptons

ENERGY LOSSES

- [4] Synchrotron
- [3] Inverse Compton
- Adiabatic

INJECTION

- [1] BH pair production
- [1] Photopion production
- [2] p-p collisions
- [3] Pair creation

Protons

ENERGY LOSSES

- [4] Synchrotron
- [4] Inverse Compton
- [1] BH pair production
- [1] Photopion production
- [2] p-p collisions
- Adiabatic

Photons

INJECTION-LOSSES

- [4] Synchrotron
- [3] Inverse Compton
- [1] Photopion production
- [2] p-p collisions
- [3] γ-γ absorption
- [4] SSA

Parameters	Test 1	Test 2	Test 3	Test 4
R_0 [cm]	10^{15}	10^{15}	10^{13}	10^{16}
B_0 [G]	1	10	10	0.1
V_{exp}/c	0	0	0.1	0
$\gamma_{e,\min}$	1	-	10^3	$10^{0.1}$
$\gamma_{e,\mathrm{coff}}$ *	-	-	-	$10^{5.5}$
$\gamma_{e,\max}$	10^6	10^4	10^4	10^{11}
$\gamma_{p,\min}$	-	1	-	$10^{0.1}$
$\gamma_{p,\mathrm{coff}}$ *	-	10^8	-	$10^{6.2}$
$\gamma_{p,\max}$	-	10^9	-	10^7
s_e	1.9	-	2.01	2.01
s_p	-	1.9	-	2.01
L_e^{inj} [erg s^{-1}]	$3.1 \cdot 10^{40}$	-	10^{48}	$3.7 \cdot 10^{40}$
L_p^{inj} [erg s^{-1}]	-	$1.1 \cdot 10^{45}$	-	$2.8 \cdot 10^{46}$
U_{ext} [erg s^{-1}]	-	$3.6 \cdot 10^{-2}$	-	-
$\epsilon_{ext}^{\min}$ [erg]	-	$8.2 \cdot 10^{-13}$	-	-
$\epsilon_{ext}^{\max}$ [erg]	-	$8.2 \cdot 10^{-8}$	-	-
Photon Index	-	2	-	-

* Particle distribution is modeled as $N_i(\gamma) = K\gamma^{-s_i}e^{-\gamma/\gamma_{i,\mathrm{coff}}}$, for $\gamma \geq \gamma_{i,\min}$.

Introduction to the "emcee" Sampler: Exploring Posterior Distributions with MCMC

- The "emcee" sampler is a Python package for MCMC sampling.
- It uses ensemble sampling with multiple walkers to explore the parameter space.
- Walkers propose new parameter sets based on current positions, accepting or rejecting based on data likelihood.
- Through iterations, walkers converge towards regions of higher posterior probability.
- Samples generated by "emcee" provide estimates of statistical properties (mean, median, etc.) for inference and uncertainty quantification.

In the application we used 48 walkers that are propagated 50,000 steps each and discard the first 5,000 steps of each chain as burn-in.

LeHaMoC: Cosmic-ray acceleration in M87 current sheets (work in progress)

Reconnection rate from 3D PIC: $\eta_{rec} = \frac{v_{rec}}{c} \sim 0.06$

Typical size of current sheets: $l \sim (5 - 10) \cdot r_g$

Acceleration timescale from 3D PIC:

$$\frac{d\gamma_{acc}}{dt} \approx \frac{eE_{rec} v_z}{mc^2} = \frac{e\eta_{rec} B_0 \beta_z}{mc} = \eta_{rec} \beta_z \omega_0$$

In the MAD regime the dimensionless magnetic flux, threading the black hole horizon takes the maximum value 50:

$$\varphi_{BH} = \frac{\Phi_{BH}}{\sqrt{c r_g^2 \dot{M}}} \xrightarrow{MAD} \Phi_{BH} \sim 50 \sqrt{c r_g^2 \dot{M}}$$

$$\Phi_{BH} \simeq 4\pi r_H^2 B_0$$

$$\dot{M} = \dot{m}\, \dot{M}_{EDD} = \dot{m} \frac{L_{EDD}}{\eta_c c^2} \overset{\eta_c=0.1}{\simeq} 10^{27} \dot{m} M_9 \, [g/s]$$

$$B_0 = 10^{5.24} \frac{\dot{m}^{1/2} (M_9 \eta_{c,-1})^{-1/2}}{(1 + \sqrt{(1-\alpha_s)})^2} [G]$$

The electron distribution:

$$\frac{\partial N_{free}}{\partial t} + \frac{\partial}{\partial \gamma}\Big(f(\gamma) N_{free} \Big) + \frac{N_{free}}{t_{esc}(\gamma)} = Q_{e,inj} \delta(\gamma - \gamma_{inj})$$

Identical power law indexes for electrons and protons in the free phase: 1.

Hillas criterion:

$$\gamma_{i,max}^{HC} = \frac{q B_0 R}{m_i c^2} = 10^{17.1} \frac{(\dot{m} M_9)^{1/2} \mathcal{R}_1 \eta_{c,-1}^{-1/2}}{(1 + \sqrt{1-\alpha_s})^2} \frac{m_e}{m_i}$$