



Title	Proton acceleration by collisionless shocks in black-hole coronae : first-principles constraints for high-energy neutrino sources
Author(s)	Sano, Takayoshi; Minh Nhat, Ly
Citation	サイバーメディアHPCジャーナル. 2026, 16, p. 25-28
Version Type	VoR
URL	https://doi.org/10.18910/106227
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

<https://ir.library.osaka-u.ac.jp/>

The University of Osaka

Proton acceleration by collisionless shocks in black-hole coronae: first-principles constraints for high-energy neutrino sources

Takayoshi Sano¹ and Minh Nhat Ly^{1,2}

¹Institute of Laser Engineering, The University of Osaka

²Department of Physics, Graduate School of Science, The University of Osaka

Abstract. This research aim to study collisionless shocks in active-galactic-nucleus (AGN) coronae utilizing high-performance-computing particle-in-cell (PIC) simulations. The question is whether a hot plasma corona around a supermassive black hole can accelerate protons fast enough to explain the TeV neutrino signal from the Seyfert galaxy NGC 1068, while remaining faint in TeV gamma rays. The simulations, originally reported in Ly et al. [1], follow shock formation, magnetic-field amplification, particle injection, and diffusive shock acceleration (DSA) from first principles. Across the surveyed coronal parameter space, quasi-parallel trans-relativistic shocks generate their own magnetic turbulence and accelerate protons robustly. The measured dimensionless acceleration rate is $\mathcal{R}_{\text{acc}} = d(\gamma\beta_{\text{sh}}^{-2})/d(t\Omega_{\text{ci}}) \simeq 0.1$, and the non-thermal proton energy fraction is approximately 10%. These values are high enough, within the representative NGC 1068 coronal model considered here, for protons to reach ~ 100 TeV before cooling or escaping. The report also identifies the main limitation of the present survey: the calculations are 1D3V and therefore prioritize long ion-time evolution and parameter coverage over fully multidimensional turbulence.

1. Introduction

High-energy neutrinos are useful probes of cosmic-ray acceleration because they are produced when energetic hadrons interact with gas or radiation fields. The nearby Seyfert galaxy NGC 1068 is a particularly important example: IceCube has reported TeV neutrino emission from this source, whereas the corresponding TeV gamma-ray flux is strongly suppressed [2–4]. This combination points to a compact, radiation-rich accelerator near the central supermassive black hole. In such an environment, neutrinos escape, but high-energy gamma rays are absorbed by photon-photon pair production [5–7]. A hot AGN corona is therefore a natural candidate site.

The remaining problem is microphysical. Neutrinos with energies $E_\nu \sim 1.5\text{--}15$ TeV require parent protons with energies of order $E_p \sim 30\text{--}300$ TeV. Phenomenological models can assume an acceleration time or a diffusion coefficient, but those quantities depend on plasma processes at scales far below the size of the corona. In particular, the coronal shocks of interest are expected to be hot, weakly magnetized, trans-relativistic, and in many cases only mildly supersonic. These conditions are outside the simple strong-shock picture usually adopted in analytic models.

Diffusive shock acceleration (DSA) is a leading mechanism for converting bulk flow energy into non-thermal particles [8, 9]. In DSA, charged particles gain energy by crossing a collisionless shock many times while scattering off magnetic fluctuations on both sides of the shock. The key question for an HPC calculation is therefore clear: can the shock generate the turbulence and injection conditions needed for DSA, without imposing them by hand? The PIC method addresses this question by evolving particles and electromagnetic fields self-consistently.

2. Physical model and Numerical method

We consider a hot corona of radius $R_c = r_c R_g$ around a black hole of mass M_{BH} , where $R_g = GM_{\text{BH}}/c^2$ is the gravitational radius. If the shock is driven by infalling gas, its speed is of the order of the free-fall speed,

$$\frac{v_{\text{sh}}}{c} \simeq 0.14 \left(\frac{r_c}{100} \right)^{-1/2}, \quad (1)$$

where v_{sh} is measured in the upstream rest frame and $\beta_{\text{sh}} \equiv v_{\text{sh}}/c$. The sonic Mach number $M_s = v_{\text{sh}}/c_s$ de-

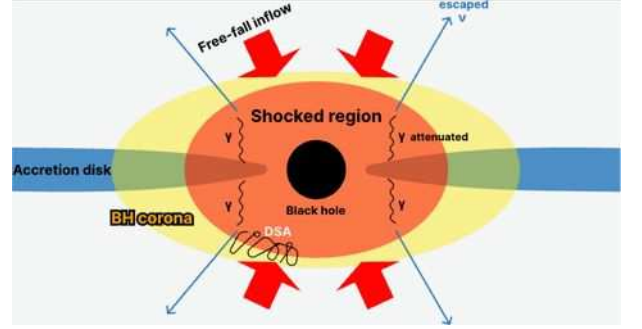


Figure 1. Physical picture of the neutrino-production scenario in a black-hole corona [1]. Infalling plasma can form a collisionless shock inside the hot corona. Protons accelerated near the shock interact with gas and photons, producing neutrinos (ν) that escape. The accompanying gamma rays (γ) are attenuated by the dense X-ray/UV radiation field, so the source can be neutrino bright while remaining faint at TeV gamma-ray energies.

pends on the sound speed $c_s = [\gamma_{\text{ad}}(T_i + T_e)/m_i]^{1/2}$, with ion temperature T_i , electron temperature T_e , ion mass m_i , and adiabatic index $\gamma_{\text{ad}} = 5/3$. For MeV-scale ion temperatures, shocks with M_s of a few are expected. The Alfvénic Mach number $M_A = v_{\text{sh}}/v_A$ depends on $v_A = B_0/(4\pi n_0 m_i)^{1/2}$, where B_0 and n_0 are the upstream magnetic field and density. Millimeter measurements of radio-quiet Seyferts indicate coronal fields of roughly 10–100 G, motivating moderate M_A values [10–12]. The likely two-temperature nature of collisionless coronal plasmas motivates the survey over T_i/T_e [13, 14].

The simulations follow Ly et al. [1] and use the open-source PIC code SMILEI [15]. A drifting electron-ion plasma reflects from a conducting wall, launching a shock into the incoming flow in the downstream rest frame. The model is one-dimensional in space and three-dimensional in velocity and field components (1D3V). This design is a practical HPC compromise: it keeps the kinetic physics of ion and electron motion while making it possible to follow hundreds of ion gyroperiods over a large parameter survey. The upstream magnetic field is quasi-parallel, with an initial obliquity $\theta_{Bn} = 30^\circ$ relative to the shock normal. Times are reported in units of the ion gyrofrequency

$$\Omega_{\text{ci}} = \frac{eB_0}{m_i c}, \quad (2)$$

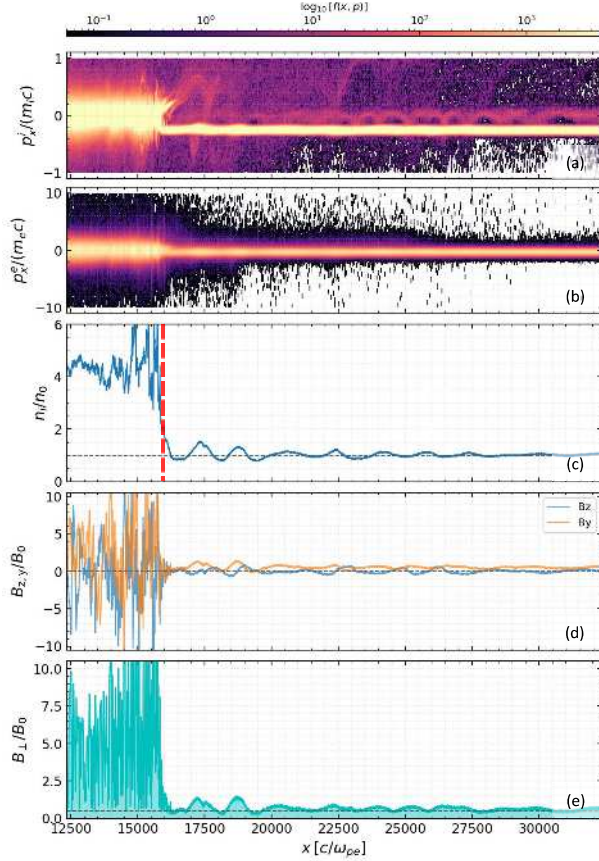


Figure 2. Reference quasi-parallel shock structure from the PIC simulation [1]. Panels (a) and (b) show ion and electron phase space. Panel (c) shows the ion-density jump that identifies the shock front. Panels (d) and (e) show transverse magnetic-field fluctuations and their amplified amplitude. The figure illustrates the complete kinetic sequence: ion reflection, upstream streaming, magnetic-field amplification, and particle scattering.

with proton charge e and speed of light c .

The HPC cost is set by the separation between electron and ion kinetic scales. The grid spacing and time step must resolve the electron plasma scale, whereas shock formation, upstream magnetic-field growth, and DSA appear only after many ion gyroperiods. The largest runs therefore require very long domains, millions of time steps, and large particle numbers to control noise in the non-thermal tail. This scale hierarchy is precisely why a reduced fluid or test-particle calculation is insufficient: such methods would have to assume the turbulence level, injection threshold, and diffusion coefficient that the PIC simulations measure self-consistently.

3. Shock structure and acceleration mechanism

Figure 2 shows the reference run with $M_s = 8$, $M_A = 26$, $T_i/T_e = 10$, and $v_{pt}/c = 0.25$. A sharp ion-density ramp marks the shock front. A population of reflected and accelerated ions streams into the upstream region, carrying an electric current. This current amplifies transverse magnetic fluctuations ahead of the shock. In most of the survey, the dominant fluctuations are consistent with the non-resonant streaming instability, often called Bell’s instability [16]; at lower M_A , resonant modes can also contribute. In either case, the important physical outcome is the same: the shock generates the scattering centers required for DSA [1, 17].

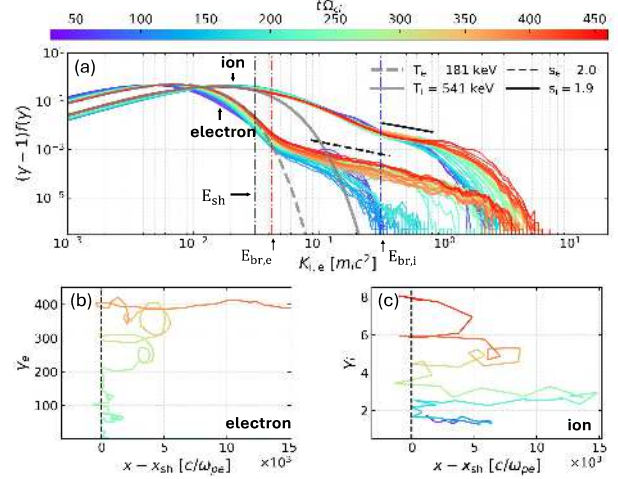


Figure 3. Downstream spectra and tracked particle trajectories [1]. Panel (a) shows the time evolution of the ion and electron energy spectra; the thermal peak is followed by a non-thermal tail. Panels (b) and (c) track representative electron and ion trajectories relative to the moving shock front. Repeated returns to the shock, together with secular growth of γ , are the kinetic signatures of DSA.

The downstream spectra and representative particle tracks are summarized in Figure 3. Both ions and electrons develop non-thermal tails above their thermal populations, but their energetics differ. Protons are injected efficiently and can repeatedly return to the shock. Electrons require pre-acceleration because their smaller gyroradii make it harder for them to sample the ion-scale turbulence. This scale separation explains why electron acceleration is more sensitive to upstream temperature and local magnetic-field amplification than proton acceleration.

For source modeling, the main value of the PIC calculation is that it replaces an uncertain microphysical assumption with a measured number. AGN-neutrino models often write the acceleration time in terms of a prescribed diffusion coefficient or gyrofactor. Here, the turbulence, scattering, and energy growth emerge from the same kinetic calculation. The measured acceleration rate can therefore be inserted into radiation and neutrino models without separately choosing an arbitrary scattering strength.

4. Results

4.1. Proton acceleration rate

After the shock and upstream turbulence reach a quasi-steady state, the maximum proton Lorentz factor grows approximately linearly with time, as expected for DSA. The simulations measure the dimensionless rate

$$\mathcal{R}_{\text{acc}} \equiv \frac{d(\gamma\beta_{\text{sh}}^{-2})}{d(t\Omega_{\text{ci}})} \simeq 0.1, \quad (3)$$

where γ is the proton Lorentz factor [1]. Across the survey, this value varies only by a factor of about two. Equivalently, the time needed to reach a given Lorentz factor is

$$t_{\text{acc}}(\gamma) \simeq \mathcal{R}_{\text{acc}}^{-1} \gamma \beta_{\text{sh}}^{-2} \Omega_{\text{ci}}^{-1} \simeq 10 \gamma \beta_{\text{sh}}^{-2} \Omega_{\text{ci}}^{-1}. \quad (4)$$

The scaling has the expected DSA form for Bohm-like diffusion: a stronger magnetic field increases Ω_{ci} , and faster shocks accelerate particles more rapidly as β_{sh}^2 [8, 9]. The weak

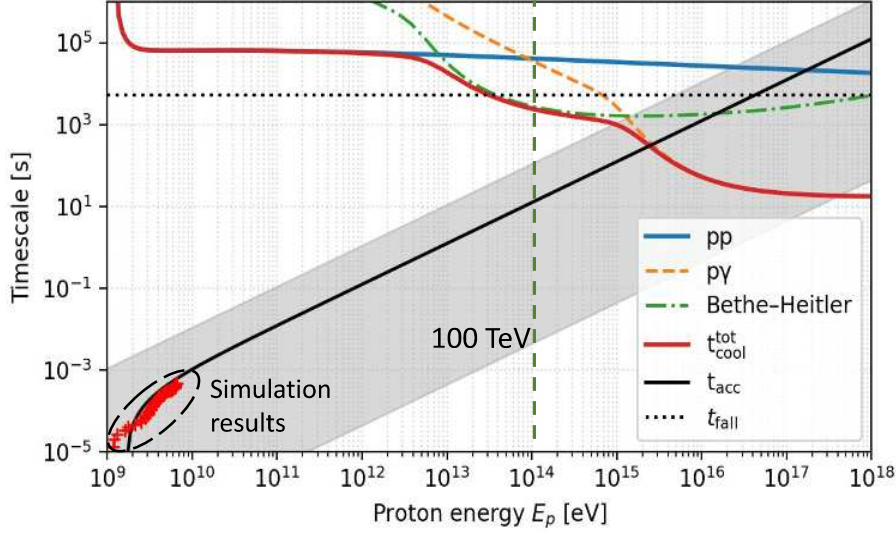


Figure 4. Application to NGC 1068 using the simulation-calibrated acceleration rate [1]. The black line is the proton acceleration time t_{acc} , while the colored curves show cooling times from pp , $p\gamma$, and Bethe-Heitler interactions in the coronal plasma. The vertical dashed line marks $E_p \approx 100$ TeV, a representative parent-proton energy for TeV neutrinos. Efficient shock acceleration is viable where t_{acc} is shorter than both cooling and dynamical times.

dependence on M_s is especially important for AGN corone, because coronal shocks may be only mildly supersonic.

The main departures from the typical value occur when the character of the self-generated turbulence changes. At very low M_A , magnetic fluctuations are weaker and acceleration slows. At very high M_A , intermittent magnetic structures can partly disrupt the regular shock-crossing cycle. Over the coronal range favored by current observations, however, the acceleration rate remains close to Equation (3). This robustness is the central computational result of the parameter survey.

4.2. Energy partition

The energy fraction carried by each component is computed from the downstream particle spectrum,

$$\frac{E_j^k}{E_{\text{tot}}} = \frac{\int d\gamma (\gamma - 1) m_j c^2 f_j^k(\gamma)}{\sum_{j,k} \int d\gamma (\gamma - 1) m_j c^2 f_j^k(\gamma)}, \quad (5)$$

where $j \in \{i, e\}$ denotes ions or electrons, $k \in \{\text{th}, \text{nt}\}$ denotes thermal or non-thermal particles, m_j is the particle mass, and f_j^k is the corresponding distribution function. Across the survey, non-thermal ions receive roughly 10% of the downstream particle energy. This efficiency persists even for $M_s \approx 2$, a regime that is often assumed to be unfavorable for strong acceleration. Non-thermal electrons remain below 1%, and for coronal-like $T_i/T_e \gtrsim 10$ are typically closer to 10^{-3} . This low electron fraction is consistent with the sensitivity of electron injection to pre-heating, thermal speed, and magnetic obliquity in quasi-parallel shocks [18, 19].

5. Implications for NGC 1068

Figure 4 applies the simulation-calibrated acceleration rate to NGC 1068. For representative coronal parameters $M_{\text{BH}} = 10^{7.2} M_\odot$, $R_c = 20 R_g$, $B_0 = 100$ G, and $\beta_{\text{sh}} = 0.32$, Equation (4) gives an acceleration time of order seconds at $E_p \sim 100$ TeV. This is shorter than the relevant cooling times from proton-proton, photomeson, and Bethe-Heitler

interactions, and also shorter than the coronal dynamical time. The finite-size Hillas condition is satisfied for magnetic fields above roughly 10 G and shock speeds above a few percent of the speed of light [1, 7, 20].

The 10% non-thermal proton energy fraction is also sufficient at the energy budget level. If the shock radius is comparable to the coronal radius, the available shock power is large enough that the proton luminosity required for the IceCube spectrum is only a few percent of the estimated shock power. Thus the HPC simulations provide a quantitative bridge between the microscopic plasma physics of collisionless shocks and the macroscopic neutrino luminosity of AGN cores [1, 4, 7].

The conclusion is not that every AGN corona must be a neutrino source. Rather, the calculation removes a major obstacle for shock-based models: under coronal-like conditions, quasi-parallel collisionless shocks can accelerate protons rapidly and efficiently enough to supply the required parent cosmic rays. The same dense radiation field that enables efficient neutrino production also hides the accompanying gamma rays, making the scenario consistent with the multi-messenger appearance of NGC 1068.

6. Discussion and Conclusion

The important outcome from this research is that the result is not based on a single demonstration run. The survey campaign spans cold and two-temperature plasmas, low and moderate sonic Mach numbers, different Alfvénic Mach numbers, and different shock velocities. Across these cases, the proton acceleration rate and non-thermal energy fraction remain clustered around $\mathcal{R}_{\text{acc}} \approx 0.1$ and $E_i^{\text{nt}}/E_{\text{tot}} \sim 10\%$. These simulation-calibrated values can be reused by source modelers as sub-grid inputs for radiation and neutrino-production calculations in AGN corone.

The main caveat is dimensionality. The present survey uses 1D3V simulations, which are ideal for reaching long ion times and broad parameter coverage but cannot capture all trans-

verse filamentation, shock rippling, and multi-dimensional turbulence. Future two- and three-dimensional simulations will be needed to test how these effects modify the numerical coefficient in Equation (3). Even so, the present survey establishes a physically grounded baseline: if shocks form in radio-quiet AGN coronae with magnetic fields of order 10–100 G and speeds of order $0.1c$ – $0.5c$, they can provide both the acceleration timescale and the proton power required by the observed neutrino emission.

References

- [1] Minh Nhat Ly, Yoshiyuki Inoue, Yasuhiko Sentoku, and Takayoshi Sano. Proton acceleration by collisionless shocks in supermassive black hole coronae: Implications for high-energy neutrinos. *The Astrophysical Journal*, 2026. doi: 10.3847/1538-4357/ae61ab.
- [2] S. R. Kelner, F. A. Aharonian, and V. V. Bugayov. Energy spectra of gamma rays, electrons, and neutrinos produced at proton-proton interactions in the very high energy regime. *Physical Review D*, 74: 034018, 2006. doi: 10.1103/PhysRevD.74.034018.
- [3] S. R. Kelner and F. A. Aharonian. Energy spectra of gamma rays, electrons, and neutrinos produced at interactions of relativistic protons with low energy radiation. *Physical Review D*, 78:034013, 2008. doi: 10.1103/PhysRevD.78.034013.
- [4] IceCube Collaboration. Evidence for neutrino emission from the nearby active galaxy ngc 1068. *Science*, 378:538–543, 2022. doi: 10.1126/science.abg3395.
- [5] Yoshiyuki Inoue, Dmitry Khangulyan, Susumu Inoue, and Akihiro Doi. On high-energy particles in accretion disk coronae of supermassive black holes. *The Astrophysical Journal*, 880:40, 2019. doi: 10.3847/1538-4357/ab2715.
- [6] Kohta Murase, Shigeo S. Kimura, and Peter Meszaros. Hidden cores of active galactic nuclei as the origin of medium-energy neutrinos. *Physical Review Letters*, 125:011101, 2020. doi: 10.1103/PhysRevLett.125.011101.
- [7] P. Padovani, E. Resconi, M. Ajello, et al. High-energy neutrinos from the vicinity of the supermassive black hole in ngc 1068, 2024.
- [8] L. O’C. Drury. An introduction to the theory of diffusive shock acceleration of energetic particles in tenuous plasmas. *Reports on Progress in Physics*, 46:973–1027, 1983. doi: 10.1088/0034-4885/46/8/002.
- [9] Roger Blandford and David Eichler. Particle acceleration at astrophysical shocks: A theory of cosmic ray origin. *Physics Reports*, 154:1–75, 1987. doi: 10.1016/0370-1573(87)90134-7.
- [10] Tomonari Michiyama, Yoshiyuki Inoue, and Akihiro Doi. The centimeter-to-submillimeter broad-band radio spectrum of the central compact component in ngc 1068. *Publications of the Astronomical Society of Japan*, 75:874–882, 2023. doi: 10.1093/pasj/psad044.
- [11] S. del Palacio, C. Yang, S. Aalto, et al. Millimeter emission from supermassive black hole coronae. *Astronomy & Astrophysics*, 701: A41, 2025. doi: 10.1051/0004-6361/202554936.
- [12] Isaac M. Mutie, Santiago Del Palacio, Robert J. Beswick, et al. A consistent radio to sub-mm pc-scale study of the nucleus of ngc 1068. *Monthly Notices of the Royal Astronomical Society*, 539:808–819, 2025. doi: 10.1093/mnras/staf524.
- [13] Ryoji Kawabata and Shin Mineshige. Radiative spectra from disk corona and inner hot flow in black-hole x-ray binaries. *Publications of the Astronomical Society of Japan*, 62:621, 2010. doi: 10.1093/pasj/62.3.621.
- [14] Feng Yuan and Ramesh Narayan. Hot accretion flows around black holes. *Annual Review of Astronomy and Astrophysics*, 52:529–588, 2014. doi: 10.1146/annurev-astro-082812-141003.
- [15] J. Derouillat, A. Beck, F. Perez, et al. Smilei: A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation. *Computer Physics Communications*, 222:351–373, 2018. doi: 10.1016/j.cpc.2017.09.024.
- [16] A. R. Bell. Turbulent amplification of magnetic field and diffusive shock acceleration of cosmic rays. *Monthly Notices of the Royal Astronomical Society*, 353:550–558, 2004. doi: 10.1111/j.1365-2966.2004.08097.x.
- [17] Damiano Caprioli and Anatoly Spitkovsky. Simulations of ion acceleration at non-relativistic shocks. i. acceleration efficiency. *The Astrophysical Journal*, 783:91, 2014. doi: 10.1088/0004-637X/783/2/91.
- [18] Siddhartha Gupta, Damiano Caprioli, and Anatoly Spitkovsky. Return currents in collisionless shocks. *The Astrophysical Journal*, 968:17, 2024. doi: 10.3847/1538-4357/ad3e75.
- [19] Siddhartha Gupta, Damiano Caprioli, and Anatoly Spitkovsky. Speed-dependent threshold for electron injection into diffusive shock acceleration, 2025.
- [20] A. M. Hillas. The origin of ultra-high-energy cosmic rays. *Annual Review of Astronomy and Astrophysics*, 22:425–444, 1984. doi: 10.1146/annurev.aa.22.090184.002233.