Chapter 8 Summary and Outlook

8.1 Summary

We are currently in the stage where we are able to unveil the nature of the extreme astrophysical phenomena with the synergies between electromagnetic photons, neutrinos, gravitational waves, and cosmic rays. In this thesis, we studied the neutrino and electromagnetic signals from various promising sources, such as galaxy mergers, SMBH mergers, short GRBs in AGN disks, and blazars. We attempted to answer these two essential questions in theoretical aspects: what physical mechanisms and processes produce the high-energy astrophysical electromagnetic and neutrino signals, and how we can reconstruct the physical conditions of the source and the environment from the observations using different messengers. All works included in this dissertation are summarized below.

In chapter 2, we calculated the cumulative diffuse neutrino and γ-ray fluxes contributed by galaxy/cluster mergers. We found that high-redshift mergers contribute a significant amount of the cosmic-ray luminosity density, and the resulting neutrino spectra could explain a large part of the observed diffuse neutrino flux above 0.1 PeV up to $\sim$ PeV. We also showed that our model can somewhat alleviate tensions with the extragalactic γ-ray background. First, since a larger fraction of the CR luminosity density comes from high redshifts, the accompanying γ-rays are more strongly suppressed through $\gamma\gamma$ annihilations with CMB and EBL. Second, mildly radiative-cooled shocks may lead to a harder CR spectrum with spectral indices of $1.5 \lesssim s \lesssim 2.0$. Our study suggests that halo mergers, a fraction of which may also induce starbursts in the merged galaxies, can be promising neutrino emitters without violating the existing *Fermi* γ-ray constraints on the non-blazar component of the extragalactic γ-ray background.

In chapter 3, we demonstrated that the synchrotron and inverse Compton emissions produced by secondary electrons/positrons can explain the radio and X-ray fluxes of merging galaxies such as NGC 660 and NGC 3256. Using our model in combination with the observations, we can constrain the gas mass, shock velocity, magnetic field and the CR spectral index s of these systems. For NGC 660 a single-zone model with a spectral index $2.1 \lesssim s \lesssim 2.2$ is able to reproduce simultaneously the radio and X-ray observations, while a simple one-zone scenario with $s \sim 2$ can describe the radio and a large fraction of X-ray observations of NGC 3256. Our work provided a useful approach for studying the dynamics and physical parameters of galaxy mergers, which can play an important part in future multi-messenger studies of similar and related extragalactic sources.

In chapter 4, we considered neutrino counterpart emission originating from the jets launched after the SMBH merger. We modeled the jet structures and relevant interactions therein, and then evaluated neutrino emission from jet-induced shocks. We found that month-to-year high-energy neutrino emission from the post-merger jet after the gravitational wave event is detectable by IceCube-Gen2 within approximately five to ten years of operation in optimistic cases where the cosmic-ray loading is sufficiently high and a mildly super-Eddington accretion is achieved. We also estimated the contribution of SMBH mergers to the diffuse neutrino intensity, and found that a significant fraction of the observed very high-energy ($E_\nu \gtrsim 1$ PeV) IceCube neutrinos could originate from them in the optimistic cases. In the future, such neutrino counterparts together with gravitational wave observations can be used in a multi-messenger approach to elucidate in greater detail the evolution and the physical mechanism of SMBH mergers. In chapter 5, we showed that the non-thermal EM signals from SMBH mergers would be detectable up to the detection horizon of future GW facilities such as the LISA. Calculations based on our model predict slowly fading transients with time delays from days to months after the coalescence, leading to implications for EM follow-up observations after the GW detection.

In chapter 6, we focused on a special scenario where short gamma-ray bursts produced by CBO mergers are embedded in disks of AGN, and we investigate the γ-ray emission produced in the internal dissipation region via synchrotron, synchrotron self-Compton and EIC processes. In this scenario, isotropic thermal photons from the AGN disks contribute to the EIC component. We showed that a low-density cavity can be formed in the migration traps, leading to the embedded mergers producing successful GRB jets. We found that the EIC component would dominate the GeV emission for typical CBO mergers with an isotropic-equivalent luminosity of $L_{j,\rm iso} = 10^{48.5}$ erg s^{-1} which are located close to the central supermassive black hole. Considering a long-lasting jet of duration $T_{\rm dur} \sim 10^2 - 10^3$ s, we find that the future CTA will be able to detect its $25 - 100$ GeV emission out to a redshift $z = 1.0$. In the optimistic case, it is possible to detect the on-axis extended emission simultaneously with GWs within one decade using MAGIC, H.E.S.S., VERITAS, CTA, and LHAASO-WCDA. Early diagnosis of prompt emissions with *Fermi*-GBM and HAWC can provide valuable directional information for the follow-up observations.

We investigated also the blazar contribution to the cumulative neutrino intensity in chapter 7, assuming a generic relationship between neutrino and gamma-ray luminosities, $L_\nu \propto (L_{\rm ph})^{\gamma_{\rm lw}}$. Using the gamma-ray luminosity functions for blazars including flat spectrum radio quasars (FSRQs) and BL Lac objects, as well as the *Fermi*-LAT detection efficiency, we estimated contributions from blazars resolved by *Fermi*-LAT as well as the unresolved counterpart. Combining the existing upper limits from stacking analyses, the cumulative neutrino flux from all blazars (including *Fermi*-LAT resolved and unresolved ones) are constrained in the range $0 \lesssim \gamma_{\rm lw} \lesssim 2.5$. We also evaluated the effects of the redshift evolution and the effective local number densities for each class of FSRQs, BL Lacs, and all blazars, by which we place another type of constraint on the blazar contribution using the non-detection of high-energy neutrino multiplets. We demonstrated that these two upper limits are complementary, and that the joint consideration of the stacking and multiplet analyses not only supports the argument that blazars are disfavored as the dominant sources of the 100-TeV neutrino background, but it extends this argument by including also *Fermi*-LAT-unresolved blazars as well, for a more generic luminosity correlation $L_\nu \propto (L_{\rm ph})^{\gamma_{\rm lw}}$.

8.2 Outlook

More joint multi-messenger detections are expected in the next few decades with upgraded instruments and newly built next-generation facilities. For high-energy neutrinos in the energy range $E_\nu \gtrsim 10^{17}$ eV (100 PeV), POEMMA, ARA/ARIANNA, CHANT, and GRAND would shed more light on the cosmogenic neutrinos produced by UHECRs and test our SMBH merger models. Here I list some possible projects for the future research program on multi-messenger astrophysics.

- *HE neutrinos from short GRBs in AGN disks*
  In addition to the γ-ray emitters, CB mergers are also promising origins of high-energy neutrinos. The cosmic rays accelerated in the jet will interact with the dense non-thermal photons and produce neutrinos via the photohadronic process, which is

also crucial for neutrinos originating in AGNs. The CRs accelerated in the successful jet can efficiently interact with disk photons and produce high-energy neutrinos via the photomeson production process. High-energy neutrinos are expected in the PeV range, and they will make an additional contribution to those predicted by isolated short GRBs, e.g., [446]. Future multi-messenger analyses of the embedded short GRBs can provide unprecedented insights into understanding the formation and evolution of CBs inside the AGN disks and the origin of high-energy emissions. Next, I propose to study the high-energy neutrino emission associated with GRBs in AGN disks and discuss the implications for future astrophysical surveys and how the AGN-assisted short GRBs contribute to the diffuse neutrino background.

- *Asrophysical neutrinos from AGNs*
  Despite the fact that the current constraints disfavor the blazars as the primary source of diffuse neutrino background, it would be intriguing to study the contribution from γ-ray faint blazars, low-luminosity AGNs, and AGN cores. The motivation is that the IceCube collaboration searched the archival data and found that the neutrino flux from the blazar TXS 0506+056 is dominated by a previous neutrino flare in 2014 [473]. One prominent task is to unveil the physical mechanism of neutrino flares in the γ-ray quiet epoch. The multizone scenarios that systematically model the particle interactions in the AGN disk, jet, and core regions to interpret the neutrino flares should be implemented to explain the efficient neutrino production and strong γ-ray suppression.

- *Proton synchrotron model for the VHE γ-ray emissions from GRBs*
  The recent detection of TeV photons from GRB 190114C [10, 11] and GRB 180720B [12] has opened a new window for multi-messenger and multi-wavelength astrophysics of high-energy transients. The detection of VHE γ-rays from GRBs can exert stringent constraints on the physics of relativistic shocks involving particle acceleration, as well as the radiation mechanisms of GRBs. [391, 404] suggest that the VHE γ-rays reported by MAGIC Collaboration at a $\sim 3\sigma$ statistical significance could be attributed to the EIC emission associated with the extended and plateau emission. Such EIC VHE γ-rays are promising targets for future Imaging Atmospheric Cherenkov Telescopes. In the following work, we propose to calculate the VHE γ-ray emission from protons and nuclei synchrotron process in the ultra-relativistic jets with the presence of very strong magnetic fields. We plan to implement the hadronic model to explain the origins of the TeV γ-ray

photons detected by MAGIC and HESS and discuss the implications for CTA and LHAASO.

In addition to the breakthroughs with more specialized theoretical models and advanced next-generation detectors, the multi-messenger collaboration programs will also play an integral role in exploiting the synergies between the four messengers. Among the existing programs, the Astrophysical Multimessenger Observatory Network (AMON) will enhance the coincident discovery abilities of astrophysical transients by combining the sub-threshold signals received by collaborating observatories [474, 475]. Another purpose of AMON is to send following-up alerts to guide the other observatories rapidly. The Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics (SCiMMA) program enables the multi-messenger astrophysics organizations, including AMON, IceCube, and LIGO, to rapidly handle, combine, and analyze the very large-scale distributed data from all types of astronomical measurements [476], which makes the multi-messenger analyses faster and more reliable in the data transfer, storage, and processing levels. Our understanding of the most energetic and extreme processes in the universe will keep refreshing by combining detailed analytical and semi-analytical models, numerical simulations, powerful detectors, and well-designed data analysis networks. We may also observe the unknowns in the uncharted universe.