**Course:** The Physics and Evolution of Active Galactic Nuclei

**Reading report #1**

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**Paper name:** AGN EVOLUTION FROM GALAXY EVOLUTION VIEWPOINT - II

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**Paper abstract:**

In order to relate the observed evolution of the galaxy stellar mass function and the luminosity function of active galactic nuclei (AGN), we explore a co-evolution scenario in which AGN are associated only with the very last phases of the star-forming life of a galaxy. We derive analytically the connections between the parameters of the observed quasar luminosity functions and galaxy mass functions. The $(m_{bh}/m_*)_{\rm Qing}$ associated with quenching is given by the ratio of the global black hole accretion rate density (BHARD) and star-formation rate density (SFRD) at the epoch in question. Observational data on the SFRD and BHARD suggests $(m_{bh}/m_*)_{\rm Qing} \propto (1+z)^{1.5}$ below redshift 2. This evolution reproduces the observed mass-luminosity plane of SDSS quasars, and also reproduces the local $m_{bh}/m_*$ relation in passive galaxies. The characteristic Eddington ratio, $\lambda_*$, is derived from both the BHARD/SFRD ratio and the evolving $L_*$ of the AGN population. This increases up to $z \sim 2$ as $\lambda_* \propto (1+z)^{2.5}$ but at higher redshifts, $\lambda_*$ stabilizes at the physically interesting Eddington limit, $\lambda_* \sim 1$. The new model may be thought of as an opposite extreme to our earlier co-evolution scenario in Caplar et al. 2015. The main observable difference between the two co-evolution scenarios, presented here and in Caplar et al. 2015, is in the active fraction of low mass star-forming galaxies. We compare the predictions with the data from deep multi-wavelength surveys and find that the "quenching" scenario developed in the current paper is much to be preferred.

**Q1. What is this work all about? What is your overall impression on the quality of this work (poor, average, good, or great)? Explain briefly your assessment. [$\gtrsim$100 words required]**

This work develops the model which includes both the evolving galaxy and AGN population based on their previous paper and investigates the evolution of star formation rate density (SFRD), black hole accretion rate density (BHARD), the characteristic Eddington ratio, $\lambda_*$ and the black hole - galaxy mass ratio, $m_{hb}/m_*$, to present a quenching co-evolution scenario. My overall impression on the quality of this work is good. On one hand, authors are well aware of the key to improve their previous model and provide straightforward ways without adding unrelated factors. On the other hand, they present a better physical scenario by comparing of their current results with both observation and their previous results.

**Q2. Why do the authors carry out this work (including, e.g., current research status, issues, scientific motivations)? [$\gtrsim$150 words required]**

As we all know, a normal galaxy, especially a massive galaxy, hosts a SMBH (supermassive black hole) in it galactic center and their connections, e.g. co-evolution, plays an important role in galaxy evolution, which has been drawing many researchers' attention for many years. Moreover, recent studies show that there exists many similarities between the galaxy property, SFRD, and the BH property, BHARD, both of which evolves with $z$. In addition to the related observations, simulation studies of co-evolution also help us to understand the evolution of galaxies. In 2015, according to the evolving mass function of star-forming (SF) galaxies and evolving X-ray luminosity of AGN, the authors constructed a "convolution model" and presented a co-evolution scenario. However, observed BH mass and quasar luminosity based on SDSS shows that $m_{hb}/m_*$ at redshift $z \sim 2$ is 10 times larger than that at $z \sim 0$, which are not consistent in their previous model. Without using the star formation history of galaxies, it is difficult for their previous model to reproduce the observation facts. Therefore, they want to carry out this work by improving their model and propose new explanations.

**Q3. How do the authors manage to finish this work (including, e.g., using new data, new techniques, new models)? [$\gtrsim$250 words required]**

The authors manage to finish this work by developing their previously model and comparing with observation data from SDSS, C-COSMOS field and CDF-S field. First of all, based on the old formalism, Schechter galaxy mass function ($M_*, \phi^*_{SF}$ and $\alpha$) and double power-law of the quasar luminosity function ($L_*, \phi^*_{QLF}$ and $\gamma_1, \gamma_2$) are still used to describe the galaxy and quasar respectively. Then, both the expected AGN and host galaxy mass function can be calculated. Extensively, rather than assuming BH mass grow on similar time scales as the build up of the stellar mass, they add "mass-quenching"(quenching mass function) into the co-evolution scenario to let the growth of the BH connected at the end of star formation. The big difference is that AGN fraction of SF galaxies increases with mass while the previous one was mass independent. According to the connection between mass accretion and the mass function of galaxies and AGN and making the ratio ($m_{bh}/m_*$) as output prediction instead of input parameter, they are able to calculate SFRD, BHLD, $(m_{bh}/m_*)_{\rm Qing}$, characteristic Eddington ratio, $\lambda_*$ and BHARD to get the mass build up over time. With the observational constraints, they can obtain the evolution of the SFRD, BHARD, $(m_{bh}/m_*)_{\rm Qing}$ and $\lambda_*$ for the black hole - galaxy mass scaling relation. Therefore, they successfully overcome the previous difficulty that the degeneracy between BH mass and Eddington ratios by connecting both BH growth and stellar mass growth to Main Sequence sSFR. At last, they compare the results with previous results and observation data from 0.9 deg$^2$ C-COSMOS field and 0.11 deg$^2$ CDF-S field on the ratio of the mean X-ray luminosity and mean SFR, $< L_x >/< SFR >$ plane to show the quenching co-evolution scenario.

**Q4. What are the main results and conclusions of this work? What are the differences/improvements of this work compared to previous relevant works? [$\gtrsim$250 words required]**

Based on the development of this model, authors presents a quenching co-evolution scenarios and reproduces the decline of the $m_{bh}/m_*$ ratio between $z$ at 0 and 2, which is a great improvement of this work compared with its previous model. And the main difference between them, co-existence and quenching co-evolution scenarios, comes from the mass function of galaxies with AGN. The quenching scenario shows a linear mass dependence (Fig.4) and provides a better explanation based on the comparisons of two scenarios with observation data, C-COSMOS and CDF-S field (Fig.11). With the analysis of the connection between two mass functions, the normalization of the AGN mass function, $\phi^*_{AGN}$, owns positive correlation with the normalization of the star-forming galaxy mass function, $\phi^*_{SF}$, and the ratio between the characteristic specific star formation rate of the Main Sequence, and the black hole growth rate $< \lambda_* >$: $\phi^*_{AGN} \sim \phi^*_{SF} \cdot \frac{rsSFR}{<\lambda_*>}$ (Eq. 20). According to the global BHARD/SFRD ratio and its evolution (Fig.6), this work gets the black hole - galaxy mass scaling relation for the galaxies that are closed to quench. Besides, from the redshift evolution of the characteristic Eddington ratio, $\lambda_*$ (Fig.7), the formalism of $\lambda_*$ should be $\lambda_* \sim (1+z)^{2.5}$ up to $z \sim 2$ and $\lambda_* \sim 1$ at higher $z$.

**Q5. What are the main contributions (i.e., scientific significances) of this work? [$\gtrsim$100 words required]**

As far as I'm concerned, on one hand, it presents a quenching co-evolution scenario based on its self-consistent model to reproduce and describe the observation facts. On the other hand, for observations, this model enables to give some predictions, e.g. the evolution of the mean AGN luminosity/SFR ratio. And for other similar evolution models of galaxy hosting AGN, results in this work provide their physical constraints, e.g. the evolution of $\lambda_*$ and the distribution in the $< L_x >/< SFR >$ plane.

**Q6. Why can the authors make such contributions (e.g., using new idea, new data, new techniques, new theories)? [$\gtrsim$100 words required]**

In my opinion, firstly, the previous model, which can fully explain the observed quasar luminosity function, is a relatively stable and reliable model even though some phenomena cannot be reproduced or explained. Secondly, authors can clearly recognize why their origin model cannot reproduce the decline of $m_{bh}/m_*$, the growth of BH to the end of the SF life of galaxy and successfully present a quenching co-evolution scenario. Although the process of derivations in this work is complicated, yet the assumptions and developments based on the previous model are clear. Last but not the least, compared with the observation data can convince readers of their model.

## Q7. Can you think of some way to improve this work or to verify it? [$\gtrsim$100 words required]

From my point of view, although the quenching co-evolution scenario is presented, as a reader, yet I still want more descriptions and explanations. Therefore, adding more descriptions and explanations about this scenario, e.g. what exactly effects it may produce in galaxy evolution, might help readers, like me, to understand the model more easily. Moreover, I think more evidences are needed except for the evolution of the mass ratio because only one reproduced result is hard to convince me. However, the length of the article is long enough. So if I were one of the authors, I would do attempts in next work, e.g. compare this model with more observation results and improve the model based on it, and give more predictions for the galaxy evolution.