中質量黑洞的質量分布函數及其起源

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摘要

我們結合XMM-Newton（Winter et al. 2006）和Chandra（Berghea et al. 2008）太空望遠鏡的觀測數據，針對極亮X射線源（ultra-luminous X-ray sources, ULXs）區分出66個中質量黑洞候選天體（大於20倍太陽質量）做爲主要討論的目標。首先，我們發現這些極亮X射線源的X射線光度和其本質柱密度有正向的關聯性，意味著X射線光度可能會受到其周遭環境的影響，更進一步暗示著可能有些中質量黑洞處在氣體較稀少的區域而不能發出足夠強的X射線光度讓我們觀測到。另外，我們建立了在本地宇宙的中質量黑洞光度分布函數以及質量分布函數，雖然其分布函數較暗或較低質量端的樣本並不完整。最後，以X射線數據爲基礎並整合針對這些X射線源和其宿主星系的多波段觀測，我們進一步檢驗4個中質量黑洞可能的形成模型，並且嘗試討論中質量黑洞和星系中心超大質量黑洞之間可能的關聯。

The mass function and origins of intermediate-mass black holes in the local universe

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Abstract

We have merged ULXs (ultra-luminous X-ray sources, $Lx>10^{39}$ ergs/s) data obtained from XMM-Newton (Winter et al. 2006) and Chandra (Berghea et al. 2008) and identified 66 intermediate-mass black holes (IMBH, $M > 20M_{\odot}$) from the compilation. We find that the ULXs X-ray luminosity correlates relatively well with their intrinsic column density, suggesting a possible physical relationship between X-ray luminosity and local environment, and a clue to the hidden IMBH population located in a gas-poor environment. With our IMBH sample, we have constructed the luminosity function and mass function of the IMBH in the local universe, although the faint part is likely incomplete. Based on the X-ray data combined with follow-up observations in other wavelengths and the properties of the host galaxies, we have examined four scenarios for IMBH formation, and discuss the possible fate of IMBH as the supermassive black hole in the galactic center.

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1. Introduction

The ultra-luminous X-ray sources (ULXs) were first imaged by the Einstein Observatory (Fabbiano 1989) and the term ULX started to appear in works on ASCA spectral analysis of these extremely luminous X-ray sources (Mizuno et al.1999, Makishima et al. 2000). The name "ultra-luminous" is in comparison with "normal" X-ray binaries, an alternative term is "Intermediate-luminosity X-ray Objects," (IXOs) (Cobert et al. 2002). This simply indicates that their X-ray luminosities are intermediate between those of AGNs and "normal" stellar-mass black holes in X-ray binaries. Given the maximum mass of a stellar-mass black hole ~20 $M_\odot$ (Fryer et al. 2001), the Eddington luminosity (the bolometric luminosity limit; see Eqs. 1 and 2) of an theoretically inferred "intermediate-mass" black hole (IMBH) is greater than about 3×10^{39} ergs/s. But at the time of Einstein Observatory, whose resolution is relatively poor (~1'), it is not clear whether these ULXs were single or multiple objects, or really coincident with galactic nuclei (see Fabbiano 1989 for a review). After ROSAT satellite launched, it began producing X-ray images of ~10"-20" resolution (Voges et al. 1999, Snowden et al. 1995). The sensitivity and spatial resolution were improved over the Einstein Observatory, many ULXs were discovered. It was soon found that ULXs were not coincident with galactic nuclei (e.g. Colbert et al.1995), and thus IMBH could be a solution for ULXs judged from their spectral type (e.g. Shrader et al. 2003), variability (Strohmayer et al. 2003) and Eddington luminosity (Colbert et al. 2002).

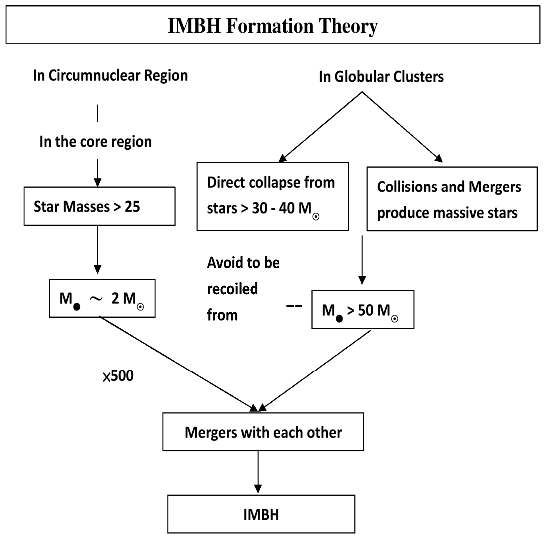

Fig. 1-a: Flowchart to connect the 4 IMBH formation scenarios.

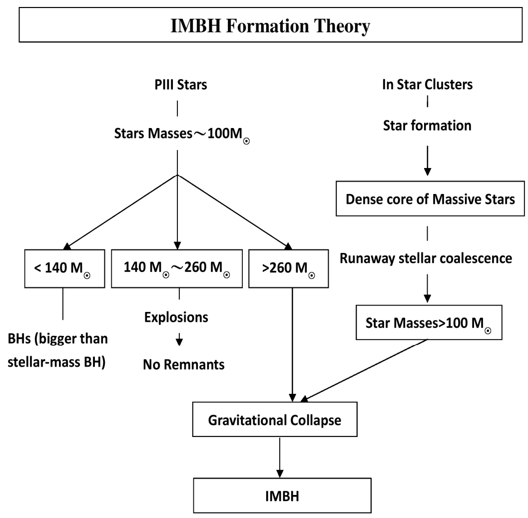

Fig. 1-b: Flowchart to connect the 4 IMBH formation scenarios (continued).

There are 4 scenarios of IMBH formation proposed by previous studies, including (see the Fig.1) IMBH formed: (1) in the circumnuclear region through mergers of several compact remnants (Taniguchi et al. 2000), (2) in globular clusters (Miller et al. 2002), (3) via direct collapse of population III (PIII) stars (Bond et al. 1984 & Heger et al. 2001) or (4) from massive stars during runaway merging in a star cluster (Quinlan et al. 1990 & Ebisuzaki et al. 2001).

In this paper, we focus on exploring the origins and discussing the mass function of IMBH. We have compiled ULXs data from XMM-Newton and Chandra with identification of IMBH in § 2. In § 3 we present the distribution functions of physical properties of individual IMBH. The implication of mass function and examination of IMBH formation scenarios are discussed in § 4.

2. IMBH Identification & Data Compilation

The ULX data sets used in this study are from XMM-Newton (Winter et al. 2006, hereafter Win06) and Chandra (Berghea et al. 2008) observations (cf. Liu et al. 2005 for a similar compilation). The classification of ULX in different states (i.e. LS ULX and HS ULX) and theoretically inferred IMBH is based on the scheme in Win06; and the BH mass of individual source can be derived accordingly. The resulting mass boundary of BH is consistent with that in Fryer & Kalogera 2001.

The same host galaxy distance data in Win06 and Berghea et al. (2008) are used in this paper. While the data in Berghea et al. (2008) are all from Tully (1998), the distance data in Win06 are compiled from various literatures (see Win06 and references therein). All the measurements are based on redshift-independent methods, which can also be found in NED archive (see
ned.ipac.caltech.edu/Library/Distances/
for an more updated database). The resulting luminosity uncertainty as propagated from the distance error distribution is about 40 percent on average.

We noted that the released X-ray luminosities of the Chandra data are not in the same energy band given by XMM (Win06), so we recalculate the luminosity of each source with the spectral fitting result from Berghea et al. (2008) adopted.

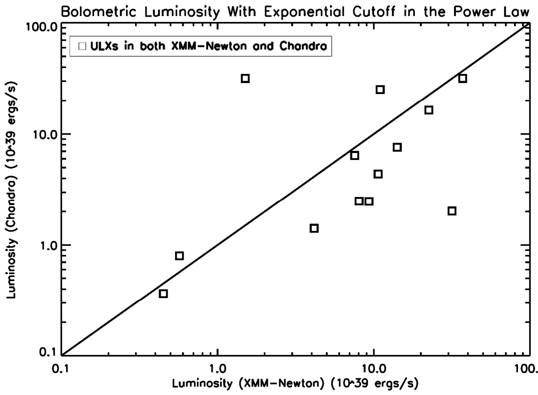

Fig. 2: Comparison of XMM-Newton and Chandra bolometric luminosities of sources detected by both telescopes

To check the agreement between the bolometric luminosities derived respectively from Chandra and XMM-Newton observations, we compare the luminosities of sources available in both data archives. The comparison (Fig. 2) shows that the bolometric luminosity is approximately correlated.

Among the data, 76 out of the ULXs are identified based on power-law (low-state) or two-component (high-state) model from the table 3 in

Win06 (eg, XMM-Newton data archives) as well as table 3 & table 5 in Chandra data archives (Berghea et al. 2008). The classification of low-state ULX sources (LS ULXs) is based on (1) the shape of the spectrum-well fitted by an absorbed power-law, (2) $Lx>10^{38}$ergs/s and (3) the X-ray location of the object is within its host galaxy in optical; On the other hand, high-state ULX sources (HS ULXs) are based on the following criteria: (1) spectra characterized by an absorbed power-law and blackbody model, (2) unabsorbed luminosities $Lx \gtrsim 2.7\times10^{39}$ergs/s, and (3) X-ray source within the optical extent of its host galaxy.

If ULXs are isotropic emitters with luminosity and spectral form similar to Galactic stellar mass X-ray binaries (Makishima et al. 2000), we can use black hole model hypothesis. To estimate black hole mass by Eddington limit, we need to know X-ray bolometric luminosity by using the exponential model *cutoffpl* in XSPEC, with a cutoff energy of 10 keV (see Win06). It is assumed that black holes are radiating at 10% Eddington luminosity in LS ULXs ($0.1L_{\rm Edd}$; Done et al. 2003, see Eq. 1) and can be up to 100% Eddington limit (Eq. 2) in HS ULXs (Win06). The black hole mass M for LS ULXs or HS ULXs based on Win06 classification scheme can therefore be obtained from the relations as described by the two equations below:

$$\frac{M}{M_\odot} = \frac{L_{bol}}{0.1L_{Edd}} \quad \text{10\% Eddington limit} \qquad (1)$$

$$\frac{M}{M_\odot} = \frac{L_{bol}}{L_{Edd}} \quad \text{100\% Eddington limit} \qquad (2)$$

Our identified IMBHs are in general with a mass approximately of M > 20 $M_\odot$ while others of M < 20 $M_\odot$ are classified as stellar-mass BHs (Win06, Fryer et al. 2001). An overview map of the classification and sample numbers are summarized in Fig. 3.

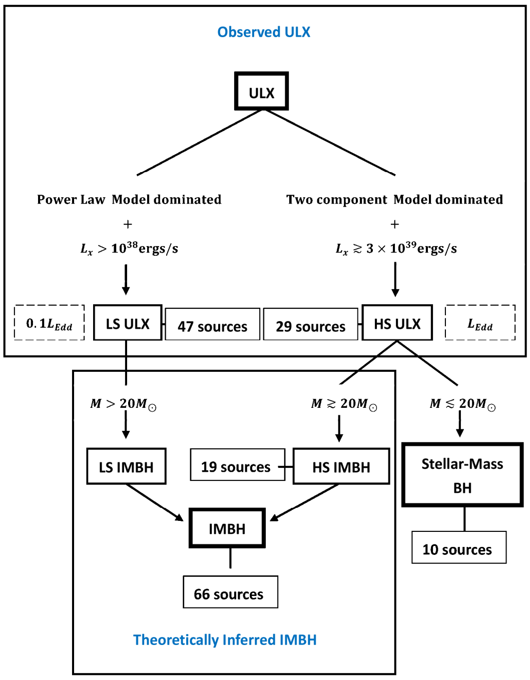

Fig. 3: Flowchart for classification and sample numbers.

3. Results

Combining the theoretically inferred IMBH X-ray data and optical images of their host galaxies, we have obtained a general picture of their locations in the host galaxies, environmental gas richness, and finally their luminosity and mass functions. The environment of ULXs, the origins of IMBH and the specific mass function of IMBH are the main issues of discussion below.

a. Distribution of Distances Ratio:

In order to understand where the theoretically inferred IMBH are located, we calculated the distance from the center of galaxies to each ULX. As these ULXs are in the local Universe, we can directly determine the distance between the centers of host galaxy to ULXs without assumed cosmology. Because not all the galaxies are faced-on to Earth, the projection factor must be estimated and corrected. We assume that these galaxies incline only away from Earth (the inclination θ) in the line of sight, and there is a factor $cos\theta$ between the projected and 'true' distance. The inclination angle is estimated by the ratio of minor diameter and major diameter of the host galaxy which are also compiled from SIMBAD. We found that some of IMBH and stellar-mass BH are located at the distance beyond the disk radius defined by *B* band image and most of them are beyond 10% of their host galaxy's radius (see Fig. 4 for the distribution of black hole distance from the host galaxy's center, the distance is in units of the host galaxy's radius). But there are no ULXs within the circumnuclear region.

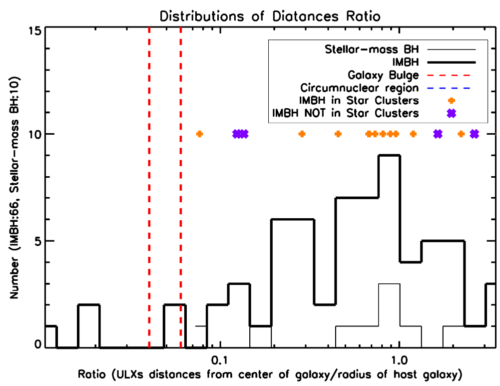

Fig. 4: Distribution of ULX galactocentric distance to galaxy radius ratio. The ratio for the case of the circumnuclear region is smaller than 0.01 which is not shown in this figure.

b. N_*H* – L_x Diagram:

The column density (N_*H*) from X-ray spectra reflects the X-ray opacity along the light of sight. Physically, it is reasonable to assume the intrinsic column density (after the contribution from the Milky Way removed) could show how the interstellar medium (ISM) around the ULXs. We found that the intrinsic column densities towards ULXs and the ULX X-ray luminosities have approximately a power-law relation. Based on the assumption of intrinsic N_*H*, it also seems that not only accretion rate but environment can affect the luminosity of black holes, especially, in comparison with HS IMBH, the X-ray luminosity of LS IMBH is more sensitive to nH (Fig. 5).

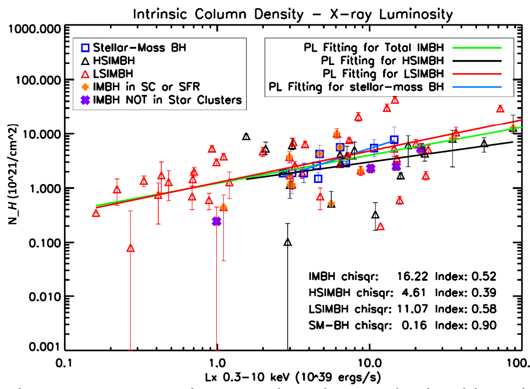

Fig. 5: N_H - Lx Diagram. There is no selection bias with distance. We use different colors and symbols to denote different types of black holes and to indicate whether the IMBH is associated with star cluster or not.

c. IMBH Luminosity Function (LF) and Mass Function (MF):

We have calculated the X-ray luminosity (in 0.3-10 keV based on XMM-Newton) of each ULX and derived the BH mass based on the models above. The cumulative LF/MF is to count ULXs are per galaxy as a function of luminosity/mass. For galaxy types, most of our IMBH host galaxies are spiral (30/39), but still contain few elliptical (2/39) and irregular (7/39) galaxies; all of stellar-mass BHs are in spiral galaxies. Each of the constructed cumulative LF and MF with IMBH is fitted by a broken power-law model. The luminosities of our ULXs samples for IMBH and all stellar-mass BH are in the range of 10^{38} ~ 10^{41}

ergs/s, and IMBH mass ranges from ~20 $M_\odot$ to ~20000 $M_\odot$ (Figs. 6 and 7).

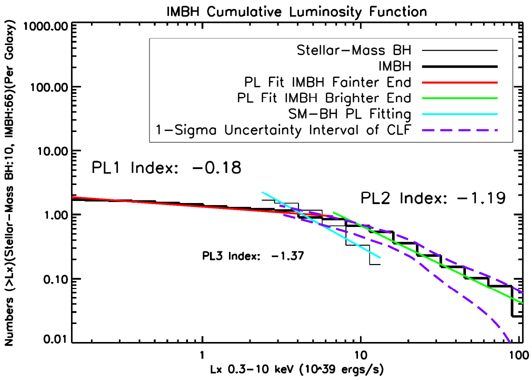

Fig. 6: IMBH cumulative Luminosity Function. The dashed lines are 1 sigma upper/lower bounds of brighter part of the cumulative LF with effect of luminosity uncertainly (error propagated from distance measurements) taken into account.

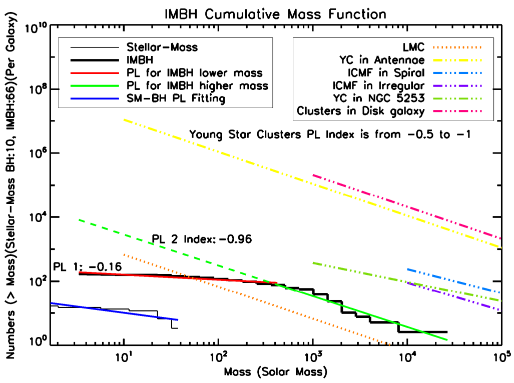

Fig. 7: IMBH Mass Function. Note that the normalization for IMBH and stellar-mass BH are not scaled.

4. Discussion

4.1. IMBH Formation Scenarios:

How do our results, combined with follow-up observations of ULXs in optical, constrain the four IMBH formation scenarios (see Introduction), namely, IMBH formed in circumnuclear region by merger of several compact remnants, in the globular cluster, by massive stars during runaway merging in a star cluster or by directly collapse of population III (PIII) stars?

If we assume the size fractions of bulge and circumnuclear region of IMBH host galaxies are similar to those of our Milky Way, then most of our data are not located within the bulge region (Fig. 4), except three IMBH which are still not in the circumnuclear region. Thus, the circumnuclear region scenario is not supported by our result.

Furthermore, we found that the X-ray luminosity of IMBH becomes fainter with decreasing intrinsic column density (Fig. 5). If our N_*H* – L_x relation indicates that the local environment of ULX is correlated with its X-ray luminosity, then current IMBH sources detected in X-ray are less likely formed in gas-poor globular clusters.

For the PIII formation model (Bond et al. 1984 & Heger et al. 2001), it has been pointed out in Win06 that there is a gap in the distributions of disk temperature (ULXs) in their results, which is a clue to the origin and evolutions from PIII to IMBH; however, our IMBH sample based on a 10% and 100% Eddington limit assumption cannot produce such a mass gap in our IMBH samples (MF, Fig. 7).

The star cluster scenario is thus the remaining model for IMBH formation; indeed optical follow up observations of ULXs provide strong evidence to support this scenario (see Table 1 and references therein). There are at least thirteen ULXs associated with star clusters, star forming region or OB associations, and only four ULXs (also see Table 2) are certainly far from or do not have clear connection with star clusters.

4.2. IMBH LF & MF:

The cumulative IMBH LF and ML in this work are made by 66 IMBH in our samples. Because of the incompleteness of the faint part, the models are only fit to the bright parts of the 2 distribution functions. The best fitting power-law indexes of cumulative LF and MF are -1.19 and -0.96 (the differential LF and MF are therefore -2.19 and -1.96 as derived directly from the cumulative functions), respectively.

We have also taken into account of the luminosity errors propagated from galaxy distance measurement uncertainty, the effect on our single power-law model fitting of the cumulative LF is marginal, the best-fitting power-law index is -0.90+/-0.30.

Recently, Swartz et al. (2011) have reported their analysis of ULX LF based on 107 sources, and the best-fitting slope of a single power-law mode for differential LF is ~ -1.6, consistent with previous works (e.g. Grimm et al. 2003; Mineo et al. 2011). In comparison with our differential IMBH LF result (-2.19), their deviation is seemingly obvious, however, the data quality of current analysis cannot tell us much about whether it is real or not.

If we further modify the star cluster model by assuming one star cluster can only produce one IMBH, and the IMBH mass ($M_{\rm IMBH}$) is proportional to its parent star clusters mass ($M_{\rm SC}$), then we can formulate their mass relation by a simple power-law $M_{IMBH} = xM_{SC}^{y}$. The y index in the mass transfer function can be derived by comparing the observed MF of star clusters $N(M_{SC}) = aM_{SC}^{b}$ (which is galaxy-type dependent) and that of IMBH $N(M_{IMBH}) = cM_{IMBH}^{z}$ (z = -1.96, from our fitting result). After a simple calculation, one can obtain $y=b/z$, where the b parameter of star cluster MF can be obtained from previous studies (see Table 3), the y parameter is therefore expected to be 0.89 for spiral galaxies, 0.79 to 1.02 for irregular galaxies, and 1.02 for both interacting spirals and disk populations in spiral galaxies.

Table 1. Compiled list of ULXs associated with star clusters, star forming regions or OB associations.

ULXs Name	Classes	Reference
Holmberg II XMM1	IMBH	Lehmann et al. 2005
NGC4490 XMM1-XMM2	Stellar-mass BH	Roberts et al. 2002
NGC4490 XMM3-XMM5	IMBH	Roberts et al. 2002
NGC1313 XMM3	IMBH	Liu et al. 2007
NGC5204 XMM1	IMBH	Goad et al. 2002
M51 XMM2, XMM3, XMM6	IMBH	Terashima et al. 2006
U8 in NGC2681	IMBH	Swartz et al. 2009
U46 in NGC7424	IMBH	Soria et al. 2006

Table 2. Known ULXs not associated with star clusters

ULXs Name	Classes	Reference
M51 XMM4	IMBH	Terashima et al. 2006
U4 in M77, U26	IMBH	Swartz et al. 2009
U26 in NGC 4559	IMBH	Swartz et al. 2009
U47 in NGC 7424	IMBH	Soria et al. 2006

Table 3. Star Cluster MF in Different Types of Galaxies

Galaxy Type	Galaxy count	index for MF (b)	Reference
Spirals galaxies	spiral galaxies (358)	-1.75	Dowell et al. (2008)
	disk galaxies(6)	-2.0	Laren (2002)
Irregular Galaxies	irregular galaxies (321)	-1.88	Dowell et al. (2008)
	LMC	-2.0	Hunter et al. (2003)
	NGC 5253	-1.56	Cresci et al. (2004)
Interacting spiral galaxy	Antennae	-2.0	Zhang & Fall (1999)
Our ULXs host galaxies type:		Spiral/irregular/elliptical: 31/7/2	

4.3. Mass Comparison of the Most Massive IMBH and SMBH:

It is natural to expect the mass of the central SMBH is related to the total IMBH mass in the same galaxy, if the SMBH is formed through IMBH merging. We therefore estimate the total

IMBH mass in each of the IMBH host galaxies of our data based on the best-fitting IMBH MF obtained in this work. We note that for galaxies with total IMBH more massive than 10,000 solar mass, their SMBH are all more massive than 10 million solar mass, but no obvious correlation is found (Fig. 8).

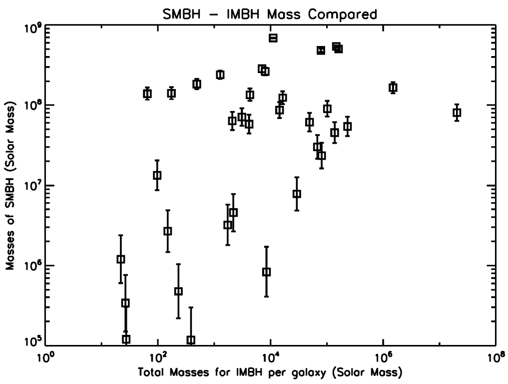

Fig. 8: Mass_SMBH – Mass_IMBH relation (total IMBH mass).

5. Summary

1. We have compiled a large fraction of currently known ULXs from XMM-Newton and Chandra, based on the same criteria of Win06 to identify IMBH candidates.
2. We find that ULXs intrinsic column density and X-ray luminosity are well correlated; it may suggest the X-ray luminosity of black holes is fueled by the gas in environment rather than stellar companions. This relation could further imply that there may have more hidden sources being obscured or in dry-fuel regions.
3. Examining the IMBH formation scenarios by our samples with other multi-wavelength follow up results, we find that star clusters become an interesting candidate of IMBH birthplace; there are at least thirteen ULXs (12 IMBH and 1 stellar-mass BH) are related with star clusters.
4. The most intriguing result is that using our best-fitting IMBH MF and observed star cluster MF from literature, we have constrained the cluster-IMBH mass transfer function,

$$M_{IMBH} = xM_{SC}^{y}.$$

where the power-law index y is galaxy type dependent. Our result suggests the mass of IMBH produced by a star cluster is roughly proportional to the cluster mass linearly. A more detailed analysis and further investigation of this linear relation will be carried out in our future work.

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