X-ray Detectability of Accreting Isolated Black Holes in Our Galaxy

Daichi Tsuna,1,2⋆ Norita Kawanaka,3,4 and Tomonori Totani5,1

1Research Center for the Early Universe (RESCEU), the University of Tokyo, Hongo, Tokyo 113-0033, Japan
2Department of Physics, School of Science, the University of Tokyo, Hongo, Tokyo 113-0033, Japan
3Department of Astronomy, Graduate School of Science, the University of Tokyo, Hongo, Tokyo 113-0033, Japan
4Hakubi Center, Yoshida Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
5Department of Astronomy, School of Science, the University of Tokyo, Hongo, Tokyo 113-0033, Japan

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ABSTRACT
Detectability of isolated black holes (IBHs) without a companion star but emitting X-rays by accretion from dense interstellar medium (ISM) or molecular cloud gas is investigated. We calculate orbits of IBHs in the Galaxy to derive a realistic spatial distribution of IBHs, for various mean values of kick velocity at their birth $v_{\text{avg}}$. X-ray luminosities of these IBHs are then calculated considering various phases of ISM and molecular clouds, for a wide range of the accretion efficiency $\lambda$ (a ratio of the actual accretion rate to the Bondi rate) that is rather uncertain. It is found that detectable IBHs mostly reside near the Galactic Centre (GC), and hence taking the Galactic structure into account is essential. In the hard X-ray band, where identification of IBHs from other contaminating X-ray sources may be easier, the expected number of IBHs detectable by the past survey by NuSTAR towards GC is at most order unity. However, 30–100 IBHs may be detected by the future survey by FORCE with an optimistic parameter set of $v_{\text{avg}} = 50$ km s$^{-1}$ and $\lambda = 0.1$, implying that it may be possible to detect IBHs or constrain the model parameters.

Key words: accretion, accretion discs – black hole physics – Galaxy: general – X-rays: ISM – X-rays: stars

1 INTRODUCTION
A black hole is thought to form in the last stage of stellar evolution, when a massive star gravitationally collapses at the end of its life. Owing to the development of X-ray observation technology, more than 20 strong black hole candidates have been detected in our Galaxy as X-ray binaries (see, e.g., Remillard & McClintock 2006 for a review). An even stronger proof of the existence of stellar mass black holes has been obtained by the recent detections of gravitational waves from binary mergers of two black holes (Abbott et al. 2016a,b, 2017a,b,c). However it is expected that there are many more black holes without a companion star, which are often called isolated black holes (IBHs). The number of black holes that formed in the Milky Way in the past is estimated to be $\sim 10^8$, based on stellar evolution theory, total stellar mass of the Galaxy, observed metallicity and chemical evolution modeling (e.g., Shapiro & Teukolsky 1983; van den Heuvel 1992; Samland 1998; Caputo et al. 2017).

IBHs, which are probably occupying more than half of the total black hole population (Fender et al. 2013), are expected to shine by accreting surrounding gas. If mass accretion onto IBHs can be described by the Bondi spherical accretion formula (Hoyle & Lyttleton 1939; Bondi & Hoyle 1944; Bondi 1952), the accretion rate is proportional to $\rho v^3$, where $\rho$ and $v$ are density of surrounding gas and IBH velocity, respectively. Therefore IBHs that plunge into a dense gas cloud (which mainly exists in the Galactic disc) with a sufficiently low velocity can obtain a large mass accretion. Such IBHs may be brighter than isolated neutron stars (INSs), because of heavier masses and slower velocities, though INSs are expected to be more abundant than IBHs by an order of magnitude (Arnett et al. 1989; Sartore et al. 2010).

There have been many studies on the detectability of such accreting INSs (Ostriker et al. 1970; Treves & Colpi 1991; Blaes & Madau 1993; Treves et al. 2000; Perna et al. 2003; Ikhsanov & Biermann 2007) and IBHs (Shvartsman 1971; Grindlay 1978; Carr 1979; McDowell 1985; Campana & Pardi 1993; Popov & Prokhorov 1998; Fujita et al. 1998; Armitage & Natarajan 1999; Grindlay et al. 2001; Agol & Kamionkowski 2002; Maccarone 2005; Mii & Totani 2005; Sartore & Treves 2010;
Motch & Pakull 2012; Barkov et al. 2012; Fender et al. 2013; Ioka et al. 2017; Matsumoto et al. 2018). A number of observational searches have also been performed in the past for such accreting INSs and IBHs (Stocke et al. 1995; Walter et al. 1996; Wang 1997; Schwope et al. 1999; Chisholm et al. 2003; Muno et al. 2006). Although several INSs candidates have been identified by their thermal emission (e.g. “The Magnificent Seven” identified by the ROSAT satellite; see e.g. Haberl 2007; Kaplan 2008 for reviews), no accretion-powered INSs or IBHs have been detected so far.

In estimates of accretion-powered IBH detectability, there are some sources of uncertainty. One is the natal kick velocity $v_{\text{kick}}$ of black holes. In spite of intense theoretical and observational studies (White & van Paradijs 1996; Jonker & Nelemans 2004; Gualandris et al. 2005; Miller-Jones et al. 2009; Fryer et al. 2012; Repetto et al. 2012; Reid et al. 2014; Wong et al. 2014; Repetto & Nelemans 2015; Mandel 2016; Wysocki et al. 2017; for a recent extensive review see Belczynski et al. 2016), the distribution and mean value of $v_{\text{kick}}$ (hereafter denoted as $v_{\text{avg}}$) are still highly uncertain. BH kick velocities may be smaller or comparable to that of neutron star kicks (typically a few hundred km s$^{-1}$; Hobbs et al. 2005) that can be inferred from proper motion of pulsars. Another source of uncertainty is the efficiency of accretion, $\lambda$, which is the ratio of actual accretion rate onto IBHs to the Bondi rate. The spherical Bondi accretion formula can be applied only when angular momentum of accretion flow is negligible. Once angular momentum becomes important, the accretion flow should be described by other modes, such as radiatively inefficient accretion flow (RIAF) (Ichimaru 1977; Narayan & Yi 1995; Kato et al. 2008). It is generally expected that accreting matter is lost by outflow on various scales, and hence the actual accretion reaching to BH horizons can be significantly reduced. In other words, observational searches for IBHs will give constraints on these parameters of $v_{\text{avg}}$ and $\lambda$.

The aim of this paper is to make the best estimate currently possible for the number and luminosities of IBHs that are formed by normal stellar evolution and shining by accretion from ISM. We then evaluate detectability by the past and present X-ray observations such as ROSAT and NuSTAR, and especially we focus on the prospect of a future project FORCE (Mori et al. 2016) in hard X-ray band. Since luminous IBHs are expected to be found in dense gas regions, hard X-ray observation would be particularly powerful because of less absorption. Discrimination of IBHs from other populations of X-ray sources is also important, and the hard X-ray band is useful to examine the spectral difference between IBHs and cataclysmic variables (Remillard & McClintock 2006; Nobukawa et al. 2016). In order to obtain a more reliable estimate than previous studies, we calculate the spatial distribution of IBHs by solving their orbits in the gravitational potential of the Galaxy with various values of kick velocities. Then accretion rate is estimated by using a realistic gas distribution in the Galaxy based on latest observations.

The paper is organized as follows. In Section 2 we give formulations of our calculations, with discussions about the plausible ranges of $v_{\text{avg}}$ and $\lambda$. Then main results, including the expected number of detectable IBHs for the wide ranges of $v_{\text{avg}}$ and $\lambda$, are presented in Section 3 with prospects of future observations. After some discussion on the caveats in our work in Section 4 we conclude in Section 5.

2 FORMULATIONS

2.1 The Galactic Structure

In a realistic picture within the framework of cosmological galaxy and structure formation driven by cold dark matter, the dynamical structure of our Galaxy should have evolved in time (e.g. Amôres et al. 2017). However, it is difficult to construct a reliable model of accurate time evolution for our Galaxy, and here we use a simplified model in which the Galactic structure does not evolve, and is composed of three components: the central bulge, the Galactic disc, and a spherical dark halo surrounding them. First we introduce the model of the Galactic gravitational potential that we use, and then we present our model of IBH birth location and history. Here we use a cylindrical coordinate system of radius, azimuth, and height ($r, \phi, z$), with the $z$-direction perpendicular to the Galactic plane.

We follow the gravitational potential model of Irrgang et al. (2013) (the Model II). For the gravitational potential of the spherical bulge and disc, the model proposed by Miyamoto & Nagai (1975) is assumed, which is described as

\[ \phi_i(r, z) = -\frac{G M_i}{\sqrt{r^2 + a_i^2 + z^2}} \]

where $i = 1, 2$ represent the bulge and disc respectively. The spherical model of Wilkinson & Evans (1999) is assumed for the dark halo potential:

\[ \phi_{\text{halo}} = -\frac{G M_h}{R_h} \ln \left( \frac{R^2 + R_h^2}{R} \right) \]

where $R = \sqrt{r^2 + z^2}$. Irrgang et al. (2013) obtained the values of the constants $M_i, a_i, b_i, M_h$, and $R_h$ by comparison with observational data, e.g. the Galactic rotation curve and the mass densities in the solar vicinity. These are:

\[ M_1 = 4.07 \times 10^9 \, M_\odot, \quad a_1 = 0, \quad b_1 = 0.184 \, \text{kpc} \]

\[ M_2 = 6.58 \times 10^{10} \, M_\odot, \quad a_2 = 4.85 \, \text{kpc}, \quad b_2 = 0.305 \, \text{kpc} \]

\[ M_h = 1.62 \times 10^{12} \, M_\odot, \quad R_h = 200 \, \text{kpc} \]

We assume that the IBH birth rate per unit volume has an exponential radial profile, $\rho_{\text{IBH}} \propto \exp(-r/r_d)$ with the scale length $r_d = 2.15$ kpc of the stellar disc (Licquia & Newman 2015). Along the disc height $\rho_{\text{IBH}}$ is assumed to be uniform in the region of $|z| < h$, where we adopt $h = 75$ pc which is the scale height of molecular clouds in the Galaxy (see Table 1 in Section 2.4). A spherical exponential profile is assumed for $\rho_{\text{IBH}}$ in the bulge, as $\rho_{\text{IBH}} \propto \exp(-R/R_h)$ and $R_h = 120$ pc, following (Sofue 2013), who found that the spherical exponential profile fits better to the observed data than the de Vaucouleurs law that is conventional as the profile of spheroidal galaxies.

The total number of IBHs born in the past in the Galaxy is set to $N_{\text{IBH}} = 1 \times 10^8$, and of course the final
number of the observed IBHs found in this work scales with this parameter. Recent observations show that the Galactic bulge contains \( \sim 15 \) per cent of the total stellar mass in the Galaxy, while the remaining \( \sim 85 \) per cent are in the disc (Licquia & Newman 2015). Hence we determine the IBH birth rate in the disc and bulge so that the disc-to-bulge number ratio of the total IBH numbers is the same as that of stellar mass. This is a reasonable assumption provided that the initial mass function (IMF) does not depend on time or location throughout the Milky Way (for a discussion on IMF variability over cosmic history and within the Milky Way, see Bastian et al. 2010 and Wegg et al. 2017 respectively). The IBH birth rate in the disc is assumed to be constant with time from 10 Gyrs ago to now. On the other hand, the bulge is composed mostly by old stellar populations, which were presumably formed in the early stage of the history of the Galaxy. Quantitative star formation history of the bulge is still under debate (see Nataf 2016 for a review), and here we assumed a simple history that bulge stars formed uniformly in a time period of 2 Gyrs spanning from 10 to 8 Gyrs ago, which is within the range of uncertainty about the bulge star formation history.

### 2.2 IBH Initial Conditions

Here we describe the initial conditions of IBHs, namely the BH mass distribution and initial velocities. We adopt the IBH mass distribution of Özel et al. (2010) obtained from observation of X-ray binaries: a normal distribution of average \( 7.8 \, M_\odot \) and standard deviation \( 1.2 \, M_\odot \). This distribution is consistent with a parallel Bayesian estimation by Farr et al. (2011). It is assumed that the mass change due to accretion is negligible.

The initial velocity of an IBH is calculated as the sum of the velocity of the progenitor star and the kick velocity given at the time of the IBH formation. Velocities of IBH progenitors formed in the disc are assumed to follow the rotation velocity of the Milky Way consistent with the potential model of Irrgang et al. (2013), which is approximated as

\[
\nu_\phi = \begin{cases} 
265 - 1875(r - 0.2)^2 & \text{km s}^{-1} \quad (r < 0.2) \\
225 + 15.625(r - 1.8)^2 & \text{km s}^{-1} \quad (0.2 < r < 1.8) \\
225 + 3.75(r - 1.8) & \text{km s}^{-1} \quad (1.8 < r < 5.8) \\
240 & \text{km s}^{-1} \quad (r > 5.8)
\end{cases}
\]

where \( r \) is measured in kpc. The motion of stars in the bulge is instead dominated by random motion rather than rotation. Thus we assume that the progenitors of IBHs in the bulge have a Maxwell-Boltzmann velocity distribution with the mean of 130 km s\(^{-1}\), which is consistent with velocity measurements of stars located near the Galactic Centre (hereafter GC) (Kunder et al. 2012).

The kick velocity distribution of BHs is hardly known. It is often supposed that a natal kick speed decreases with BH mass, as expected in the case of a fixed momentum. This implies a reduced BH kick speed compared to neutron stars (e.g., Fryer et al. 2012). A study of 233 pulsars by Hobbs et al. (2005) concluded that neutron star kicks obey a Maxwell-Boltzmann distribution with 1D standard deviation \( \sigma = 265 \) km s\(^{-1}\), which corresponds to an average 3D kick velocity of about 420 km s\(^{-1}\). If we simply extrapolate this result to black holes with conserved momentum, we obtain an average kick speed as low as 50 km s\(^{-1}\). However some studies (Repetto et al. 2012; Repetto & Nelemans 2015) claim that this may not be the case, and the present locations of some X-ray binary systems require a natal kick broadly in the range of 100–500 km s\(^{-1}\), which is comparable to neutron star kicks. Janka (2013) proposed a possible theoretical explanation about this result. This is still a matter of debate, and here we assume a Maxwell-Boltzmann kick velocity distribution with a 3D average velocity \( \nu_{avg} \) in the range of 50–400 km/s, and we assume that the kick speed is not correlated with BH mass for simplicity.

If the initial kick velocity is generated by the Monte-Carlo method obeying the Maxwell-Boltzmann distribution, the probability of getting a velocity much lower than the average is small, but such IBHs have a high chance of detection by higher Bondi accretion rate. Because of the limitation of computing time, the number of orbital calculations \( (N_{MC} \sim 10^6) \) is much smaller than the actual IBH number \( N_{IBH} \sim 10^8 \), and the small velocity IBHs are not well sampled by the Monte-Carlo generation. Therefore we set the grids of kick velocity for the orbital calculation that is more uniform than the Maxwell-Boltzmann distribution, and multiply the probability distribution of the kick velocity in the final output of the detectable number of IBHs (e.g., X-ray source counts).

### 2.3 Equation of Motion

IBHs formed and kicked in our Galaxy will move following the Galactic gravitational potential. By simple calculation using eq. 1 and eq. 2 we obtain the equations of motion as follows:

\[
\frac{dr}{dt} = \nu_r \\
\frac{dz}{dt} = \nu_z \\
\frac{d\nu_r}{dt} = \frac{\partial \Phi}{\partial r} + \frac{j_z^2}{r^3} \\
= \frac{j_z^2}{r^3} - \sum_{i=1,2} \frac{GM_i r}{\{r^2 + [a_i + (z^2 + b_{i}^2)^{1/2}]^{1/2}\}^{3/2}} \\
= \frac{GM_h}{\sqrt{r^2 + z^2}} \frac{r}{\sqrt{r^2 + z^2} \sqrt{r^2 + z^2 + R_h^2}} \\
\frac{d\nu_z}{dt} = \frac{\partial \Phi}{\partial z} \\
= -\sum_{i=1,2} \frac{GM_i [a_i + (z^2 + b_{i}^2)^{1/2}]}{\{r^2 + [a_i + (z^2 + b_{i}^2)^{1/2}]^{1/2}\}^{3/2} \sqrt{z^2 + b_{i}^2}} \\
= \frac{GM_h}{\sqrt{r^2 + z^2}} \frac{z}{\sqrt{r^2 + z^2} \sqrt{r^2 + z^2 + R_h^2}} \right}
\]

We have used \( \Phi \equiv \phi_r + \phi_z + \phi_{halo} \) to denote the total Milky Way potential. Here \( j_{z} \equiv r \nu_{\phi} \) is the \( z \)-axis specific angular momentum, and since the potential \( \Phi \) is independent of \( \theta \), \( j_{\theta} \) will be conserved. Thus the rotational velocity \( \nu_{\phi} \) can be obtained from the conservation of \( j_{\phi} \), which greatly simplifies...
our calculation. The four equations are integrated using the 4th-order Runge-Kutta method, and as a result the present location and velocity of each IBH are obtained.

Dynamical friction by stars or gas in molecular clouds (Ostriker 1999; Mii & Totani 2005; Inoue & Kusenko 2017) is not considered in our calculation of IBH orbits. These effects are larger for more massive black holes, but negligible for stellar mass black holes.

### 2.4 Interstellar Gas

Once the present location and velocity of the IBHs are calculated, the next information needed for estimating the accretion rate is the profile of interstellar gas clouds in the Milky Way. We consider five ISM phases that differ by temperature and density (Bland-Hawthorn & Reynolds 2000). The densest are the molecular clouds composed mostly of H$_2$, followed by the cold neutral medium (warm H I), warm ionized medium (warm W II), and hot ionized medium (hot H II) which occupy the majority of the volume.

Table 1 lists the ISM parameters around the solar neighbourhood adopted in this work. For the densest two phases (molecular clouds and cold H I) we assume that the probability distribution of gas particle density at a given point is described by a power law with an index β = 0.28. In all other cases, the probability distribution of gas particle density at a given point is described by a power law distribution, $\frac{d\xi}{dn} = \frac{\beta - 1}{n_1^\beta - n_2^\beta} \xi(r,z)n^{-\beta}$, including outflow, respectively, where the subscript 0 in this formulation, but we assume that the relative proportion of these two phases is 3.1:3.5 and constant throughout the Galaxy. $\xi_0$ is defined as the ratio of $\xi_{H_2}$ to $\xi_{HI}$ at the solar neighbourhood with the parameters given in Table 1. Then the filling fraction of the three phases of H$_2$ and H I has been determined throughout the Galaxy. It is shown in Table 1 that the filling fraction of H$_2$ is less than one everywhere in the Galaxy with the observed values of Σ(r).

The filling fractions thus determined in this work are different from $\xi_{BR}$ even at a mid-plane point of the Sun’s Galactocentric distance ($r = R_0 = 8.3$ kpc, Gillessen et al. 2009; Russeil et al. 2017; this is consistent with Irrgang et al. 2013 model II as well), which are also shown in Table 1.

### 2.5 Mass Accretion from ISM

There are studies that claim the accretion onto compact objects could be much less than the Bondi accretion rate, due to material outflow in the process of accretion. These claims are supported by theoretical modelings of accretion flows including outflow (Blandford & Begelman 1999) and hydrodynamical and MHD simulations (see Perna et al. 2003).

These studies suggest that the ratio of the actual accretion to the Bondi accretion, $\dot{M}_r$, scales as $(R_{in}/R_{out})^p$, where $R_{in}$ and $R_{out}$ are the inner and outer radius of the accretion flow respectively, and index $p$ being an uncertain number around 0.5–1 (Yuan & Narayan 2014). The inner radius $R_{in}$ is generally expected to be about a few to few tens times the Schwarzschild radius, but $R_{out}$ should be dependent on the angular momentum at the Bondi radius.
If angular momentum is sufficiently large to make the accretion flow rotationally supported at the Bondi radius, $R_{\text{out}}$ will be comparable to the Bondi radius. This is for the case of Sgr A*, as assumed by several authors (Yuan et al. 2003; Totani 2006), and in this case $R_{\text{in}}/R_{\text{out}}$ will be extremely small, down to $10^{-8} - 10^{-9}$. If we simply adopt this and use $p = 0.5 - 1$, we get $\lambda$ no higher than $10^{-3}$. However for Sgr A* a smaller index $p = 0.27$ is preferred from fit to observations (Yuan et al. 2003), which gives $\lambda \sim 0.01$. This agrees with the observation of nearby active galaxies by Pellegrini (2005), who estimated $\lambda$ to be around 0.01. We do not know, however, whether this can be applicable to stellar-mass black holes, since their Bondi radii are very different in scale from supermassive black holes.

The study by Perna et al. (2003) discusses the case for accretion onto INSs, which concluded that $\lambda \lesssim 10^{-3}$ is consistent with the null detection of accreting INSs by ROSAT. However, neutron stars have magnetic fields and hard surfaces which significantly affect the accretion rate (e.g., Toropina et al. 2012). Thus we cannot simply assume that IBHs would follow this constraint.

Some studies (e.g., Fujita et al. 1998; Agol & Kaminowiski 2002; Ioka et al. 2017; Matsumoto et al. 2018; Inoue & Kusenko 2017) used observations of the density (Armstrong et al. 1995) or velocity fluctuations (Larson 1981) of the interstellar medium, deriving that $R_{\text{out}}$ is much smaller than the Bondi radius. They obtain $R_{\text{out}} \sim 10^2 R_s$, which gives a range $\lambda = 10^{-4} - 10^{-2}$ for $p = 0.5 - 1$. However the observational results for ISM density fluctuations include significant uncertainties, and, more importantly, the observation by Armstrong et al. (1995) targets ionized hot gas. Thus we cannot apply this relation in the case when IBHs accrete neutral molecular gas, which is the most observable case.

Estimates based only on ISM velocity fluctuations would be a lower limit of the initial angular momentum, because it would increase by density fluctuations and the velocity of the black hole. The IBH velocity is typically much larger than the turbulent velocity of the interstellar medium.

To summarize, there is a large uncertainty about the accretion efficiency $\lambda$ both theoretically and observationally. Therefore here we simply test $\lambda$ in the range of $10^{-3} - 10^{-1}$. Although this may be rather optimistic, we adopt this because later we will find in our calculations that IBHs may be detectable by future surveys only when $\lambda \gtrsim 0.01$.

### 2.6 IBH Luminosity and Flux

We estimate the bolometric luminosity $L$ from the Bondi-Hoyle accretion rate with the $\lambda$-factor, as

$$ M = \lambda \cdot 4\pi (GM)^2 \rho \left( \frac{c^2 + v^2}{c^2} \right)^3/2 \approx 3.7 \times 10^{15} \left( \frac{\lambda}{0.1} \right) \left( \frac{M}{10 M_\odot} \right)^2 \left( \frac{\rho}{10^4 \text{ cm}^{-3} \text{ m}_p} \right) \left[ \frac{v^2 + c_s^2}{10 \text{ km s}^{-1}} \right]^{-3/2} \frac{\text{s}^{-1}}{\text{erg}}, $$

where $G$ is the gravitational constant, $M$ the BH mass, $\rho$ the gas mass density, $m_p$ the proton mass, $v$ the speed of the BH relative to the interstellar gas, and $c_s$ the effective sound speed taken from Table 1.

To obtain the luminosity we apply the treatment of Mii & Totani (2005), which takes into account the transition from the standard disc to the RIAF (radiatively-inefficient accretion flow) mode in low accretion rate regime. At high accretion rates the BH accretion is described with the standard disc model, where the radiation efficiency $\eta \equiv L/(\dot{M}c^2)$ is constant and the luminosity is proportional to the accretion rate. However when the accretion rate drops below a threshold, the disc will switch to the RIAF phase and $\eta$ becomes proportional to the accretion rate, making the luminosity proportional to the square of the accretion rate (Narayan & Yi 1995; Kato et al. 2008). The threshold is expected to be around 1/10 of the Eddington accretion rate, and hence

$$ M_{\text{th}} = \dot{m}_\text{th} \dot{M}_{\text{Edd}} = 1.4 \times 10^{18} \left( \frac{M}{10 M_\odot} \right) \left( \frac{\dot{m}_\text{th}}{0.1} \right) \left( \frac{\dot{M}_{\text{Edd}}}{0.1} \right)^{-1} \frac{\text{s}^{-1}}{\text{erg}}. $$

where $\dot{M}_{\text{Edd}} \equiv L_{\text{Edd}}/(\eta_{\text{ad}} c^2)$ is the Eddington accretion rate corresponding to the Eddington luminosity, and $\eta_{\text{ad}}$ is the radiation efficiency in the standard disc regime. Then requiring that $\eta$ changes continuously around the threshold, we model

$$ \eta = \begin{cases} \eta_{\text{ad}} (M/M_{\text{th}}) & \text{ (when } M < M_{\text{th}}) \\ \eta_{\text{ad}} (M_{\text{th}}/M) & \text{ (when } M_{\text{th}} < M < 2M_{\text{Edd}}). \end{cases} $$

We adopt the standard values of $\dot{m}_\text{th} = 0.1$ and $\eta_{\text{ad}} = 0.1$ in all of our calculations in this work, and uncertainties about these parameters are discussed in in Section 4.
bolometric luminosity is then calculated as
\[ L = n M c^2 \]
\[ = 3.4 \times 10^{37} \text{erg s}^{-1} \]
\[ = \eta d \left( \frac{M}{10 M_\odot} \right)^2 \left( \frac{\rho}{10^3 \text{ cm}^{-3}} \right) \left( \frac{\nu^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right)^{3/2} \]
which becomes
\[ L = 9.0 \times 10^{32} \text{erg s}^{-1} \]
\[ \left( \frac{M}{10 M_\odot} \right)^2 \left( \frac{\rho}{10^3 \text{ cm}^{-3}} \right) \left( \frac{\nu^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right)^{3/2} \]
in the RIAF regime and
\[ L = 3.4 \times 10^{35} \text{erg s}^{-1} \]
\[ \left( \frac{M}{10 M_\odot} \right)^2 \left( \frac{\rho}{10^3 \text{ cm}^{-3}} \right) \left( \frac{\nu^2 + c_s^2}{(10 \text{ km s}^{-1})^2} \right)^{3/2} \]
in the standard disc regime.

When the accretion rate largely exceeds the Eddington limit, the accretion flow would be described by the slim disc rather than the standard disc. In this regime we adopt the formula by Watarai et al. (2000):
\[ L = 2L_{\text{Edd}} \left[ 1 + \ln \left( \frac{M}{M_{\text{Edd}}} \right) \right] \]
for \( M > M_{\text{Edd}} \), which is smoothly connected to the standard disc regime when \( \eta_{\text{Edd}} = 0.1 \) is assumed.

### 2.7 IBH Spectrum

Although the spectrum of IBHs is essentially unknown, past studies (e.g., Agol & Kamilenkov 2002; Fender et al. 2013) assumed that their characteristics are similar to those observed from BH binaries. The spectrum of BH binaries is divided into two categories depending on the accretion rate: the soft state and the hard state (Kato et al. 2008). BH binaries are considered to show the soft state spectrum in the standard disk regime (i.e. when the accretion rate is high), and the radiation spectrum is dominated in X-rays by a multi-temperature black body radiation from an optically-thin accretion disk. The hard state is typical for low-accreting IBHs in the RIAF regime, and the radiation is described as a power law with a photon index of \( \zeta = 1.4-2.1 \) (Remillard & McClintock 2006), where the differential photon spectrum is \( dF_{\text{ph}}/dE_{\text{ph}} \propto E^{-\zeta} \).

Due to the low density of the interstellar matter, we expect that a majority of IBHs are in the RIAF regime. Therefore, following Fender et al. (2013), we assume that the IBH spectrum is a power-law with \( \zeta = 1.6 \). We will see in Section 3.2 that most of the detectable IBHs are indeed in the RIAF regime. We assess quantitatively in Section 4 how our results would change by varying the photon index. We also assume that the bolometric luminosity \( L \) is dominantly radiated in the X-ray band of 0.1–100 keV, and then the fraction \( f_{\text{band}} \) of the luminosity in the observed band is \( f_{\text{band}} = 0.31 \) for the NuSTAR and FORCE bands (10 – 40 keV), and \( f_{\text{band}} = 0.17 \) for the ROSAT band (0.1 – 2.4 keV).

### 2.8 Absorptions

Furthermore we introduce two parameters, \( f_{\text{MC}} \) and \( f_{\text{MW}} \), to take into account the photoelectric absorption of X-rays. When an IBH is accreting in a molecular cloud, the flux is reduced by a factor of \( f_{\text{MC}} \) by absorption within the cloud. We calculate \( f_{\text{MC}} \) assuming a hydrogen column density of \( N_H = 5 \times 10^{21} \text{ cm}^{-2} \), which is calculated from the density-size relation of molecular clouds (Larson 1981). According to this relation, \( N_H \) is not sensitive to the size of molecular clouds, though there exists a scatter from the mean relation by up to an order of magnitude. We calculate using the model of Wilms et al. (2000) that there is a significant photoelectric absorption of \( f_{\text{MC}} \sim 0.3 \) in the ROSAT band, but \( f_{\text{MC}} \sim 1 \) for other satellites. X-rays are absorbed also by ISM in the Galaxy along the line of sight to the observer by a factor of \( f_{\text{MW}} \). The value of \( f_{\text{MW}} \) depends on the location of an IBH, and if it is located in GC, X-rays in the ROSAT band are seriously absorbed by \( f_{\text{MW}} \sim 0.01 \) with a large column density of \( N_H \sim 6 \times 10^{24} \text{ cm}^{-2} \) (Baganoff et al. 2003; Muno et al. 2009). On the other hand, the absorption is negligible in the hard X-ray NuSTAR and FORCE band. These are taken into account when our results are compared with observational constraints.

Finally, we assume that the emission is isotropic, and flux measured on the Earth is calculated assuming that the Sun is located in the mid-plane (i.e., \( z = 0 \)) at the Galactocentric distance of \( R_0 = 8.3 \text{ kpc} \).

### 3 RESULTS

#### 3.1 Distribution of IBHs in the Milky Way

For a given set of model parameters, we generate typically \( N_{\text{MC}} = 10^{5} \text{ IBHs} \) in our Galaxy with physical quantities obeying the distributions described in previous sections by the Monte Carlo method. The number of generated IBHs is larger for larger \( \nu_{\text{avg}} \) because of its higher probability of escaping from the Galaxy potential. Then the final estimate of detectable IBHs will be scaled to match the real number of IBHs in the Galaxy, \( \eta_{\text{MW}} \).

The present spatial distribution of IBHs in the Galaxy, after orbital calculations described in Section 2.3, is shown in Fig. 1 for two values of average kick velocity, \( \nu_{\text{avg}} = 50 \) and 400 km s\(^{-1}\). We find an obvious trend that IBH distribution becomes more extended from the GC with increasing \( \nu_{\text{avg}} \). Note that a portion of IBHs have positive total (kinetic plus potential) energy and eventually escape the Galaxy. The fraction is negligibly small for \( \nu_{\text{avg}} = 50 \text{ km s}^{-1} \), whereas it increases to 0.01, 3, 17, and 37 per cent for \( \nu_{\text{avg}} = 100, 200, 300 \) and 400 km s\(^{-1}\), respectively.

Fig. 2 shows the surface number density of IBHs on the Galactic plane, in comparison with the uniform (i.e. constant surface density) distribution and an exponential distribution with the scale length of 2.15 kpc, which was adopted for the initial IBH distribution at their birth. It can be seen that the distribution after orbital evolution becomes more extended than the initial exponential shape, and this effect becomes stronger with larger kick velocity. It should also be noted that there is an excess of IBHs near the GC within 1 kpc, which is due to the contribution from the Galactic bulge component.
3.2 X-ray Source Counts

Here we present X-ray source counts, i.e., number of IBHs as a function of X-ray flux. According to the modelling presented in the previous section, we can assign an X-ray flux for each of the IBHs whose location and velocity have been calculated by time integration of their orbits. Figure 3 shows the cumulative X-ray source counts into the direction of the GC, for a few different values of the average kick velocity \( v_{avg} \) and accretion efficiency \( \lambda \). Here calculation is for the hard X-ray band where absorptions are negligible, i.e., \( f_{MC} = f_{MW} = 1 \). Figure 4 is the same but shows the contribution from each ISM phase in the case of the GC direction. Figures 5 and 6 are the same as Figure 3 but for all sky. To compare with the ROSAT result, we assumed \( f_{MC} = 0.3 \) for the absorption in molecular clouds in the ROSAT band. The absorption in ISM depends on IBH locations, and here we show two extreme cases: no absorption \( (f_{MW} = 1) \) and absorption towards GC \( (f_{MW} = 10^{-2}) \) in Figures 5 and 6, respectively.

It should be noted that the number of IBHs generated by Monte Carlo \( N_{MC} \) is 1–2 orders of magnitude smaller than the actual number of IBHs in the Galaxy, \( N_{IBH} \), because of the limited computing time. The results shown in these figures are scaled up to match the actual number of \( N_{IBH} \). One may consider that in this case our calculation cannot resolve a population of IBHs whose number is smaller than \( N_{IBH}/N_{MC} \) in the Galaxy. However the results shown in Figures 5 and 6 well extend to the region of small number \( (\ll 1) \) in all sky. This is because we consider the weight of probability distribution about kick velocity and gas density in molecular clouds and cold H I ISM. The difference of \( N_{MC} \) and \( N_{IBH} \) may also change the distance to the nearest IBH from the Sun, but it is not important because the nearest IBHs are not the major component in the detectable IBHs (see Section 3.3, Fig. 7).
As a comparison with observations, we first consider the ROSAT all-sky survey (Voges et al. 1999). Fig. 5 implies that many IBHs may be detected by the ROSAT sensitivity of $\sim 1 \times 10^{-12} \text{erg/s/cm}^2$ in all sky with optimistic model parameters, but it should be noted that the flux plotted in this figure is not corrected for absorption by intervening ISM, and evidently it is more difficult to detect if maximal absorption is assumed (see Fig. 6).

Fig. 7 shows the distribution of distance from the Sun to IBHs detectable by the ROSAT all sky survey. It can be seen that IBHs towards GC are dominated by those located around GC. This is not only because IBHs are concentrated around GC, but also because the abundance of molecular clouds around GC is high.

This result tells us that considering only the Solar vicinity is not sufficient for estimating the detectability of IBHs, but it is necessary to take the entire Galaxy, especially the GC region, into consideration. Soft X-ray flux in the ROSAT band is seriously reduced by a factor of $f_{\text{MW}} \sim 0.01$ due to absorption by ISM along the sightline to GC, and hence it is difficult to derive a strong constraint on IBH parameters even if no IBH is included in the ROSAT catalog.

For the GC direction, past surveys by Chandra (flux limit $5 \times 10^{-14} \text{erg/s/cm}^2$ in 0.5–8 keV, survey area 1.6 deg$^2$), XMM-Newton (2.5 $\times 10^{-14} \text{erg/s/cm}^2$ in 2–10 keV, 22.5 deg$^2$), and Nustar (6 $\times 10^{-13} \text{erg/s/cm}^2$ in 10–40 keV, 0.6 deg$^2$) have detected 9017, 2204, and 70 sources, respectively (Muno et al. 2009; Warwick et al. 2011; Hong et al. 2016). Here, the flux limits for Chandra and XMM-Newton are those corrected for absorption by ISM, as given in the references. The correction factor is $\sim 3$ for Chandra, but it is negligible in the NuSTAR band. The expected number of IBHs with a parameter set of $\lambda = 0.1$ and $v_{\text{avg}} = 50 \text{ km/s}$ are 36, 2.4 $\times 10^6$, and 4, respectively (when $f_{\text{band}} = 0.3$ for Chandra and XMM-Newton bands are assumed). Though the number expected for XMM-Newton largely exceeds unity, it is difficult to discriminate IBHs for other populations of X-ray sources. Therefore we conservatively set upper limits that the number of IBHs cannot exceed those of all detected sources in these surveys. These upper limits are shown in Fig. 3, which do not give a strong constraint on IBH parameters.

As mentioned in the Introduction, hard X-ray band may be useful to discriminate IBHs from other X-ray populations. However, the expected number of IBHs detectable by the past NuSTAR survey is at most of order unity. Therefore we consider a survey towards GC by the proposed mission FORCE. A sensitivity limit of about $1 \times 10^{-14} \text{erg/s/cm}^2$ in the 10–40 keV can be achieved by 100 ksec observation for each field-of-view, by the improved angular resolution compared with NuSTAR. The sensitivity flux limit is indicated in Fig. 3. A total survey area of about 1 deg$^2$ is possible with a realistic telescope time. We show in Fig. 8 the expected number of IBH detections by a survey by FORCE as a function of $v_{\text{avg}}$ with two values of $\lambda$, assuming a total survey area of 0.5 and 1.5 deg$^2$. The expected number becomes much larger than unity at an optimistic parameter region of $\lambda = 0.1$ and $v_{\text{avg}} \lesssim 100 \text{ km/s}$, and hence no detection of an IBH by this survey can exclude this parameter region, provided that discrimination of IBHs from other X-ray source populations is successful.

Figure 4. Same as Fig. 3, but broken into contributions from each ISM phase. An average kick velocity of $v_{\text{avg}} = 50 \text{ km/s}$ and $\lambda = 0.1$ are assumed for this figure. It should be noted that the contribution from IBHs in the hot HII ISM phase is too faint to appear in this plot.

Figure 5. Same as Fig. 3, but for IBHs in all sky observed in the ROSAT 0.1 – 2.4 keV band. Here we assume the absorption correction as $f_{\text{MC}} = 0.3$ and $f_{\text{MW}} = 1$.

Figure 6. Same as Fig. 5, but $f_{\text{MW}} = 0.01$ is assumed.

### 3.3 Comparison with Observations and Future Detectability

As a comparison with observations, we first consider the ROSAT all-sky survey (Voges et al. 1999). Fig. 5 implies that many IBHs may be detected by the ROSAT sensitivity of $\sim 1 \times 10^{-12} \text{erg/s/cm}^2$ in all sky with optimistic model parameters.
Detectability of Galactic Isolated Black Holes

Hong et al. 2016 shows the distribution of IBH velocities. In this regime the IBH luminosity is approximately proportional to $n^2 c_s^6 \propto n^{4.1}$ by eq. (18), and we obtain $\alpha \sim 1.8 \times 1.05/4.1 \sim 0.7$, which is consistent with the slope observed at fluxes above the break.

The break flux should correspond to that for the minimum density of molecular clouds, $n_1 = 10^2$ cm$^{-3}$, with $\nu \sim c_s = 3.7$ km s$^{-1}$. Using these parameters, we find $\sim 3 \times 10^{-13} (A/0.1)^2$ erg s$^{-1}$ cm$^{-2}$ at GC for the mean BH mass of $M = 7.8$ M$_\odot$, which is consistent with the break flux found in the figure. On the other hand, the sharp drops of the counts at the bright end of $F_X \sim 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ common for all curves corresponds to the transition luminosity, where the RIAF regime switches into the standard disc regime. The luminosity here is equivalent to 0.1 times the Eddington luminosity, which gives $F_X \sim 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ when an IBH at GC is assumed.

The source counts below the break flux is dominated by IBHs having velocities larger than $c_s$ and hence fainter flux. When $\nu > c_s$ but still $\nu < v_{\text{avg}}$, the number of IBHs with a velocity lower than $\nu$ roughly scales as $N(< \nu) \propto \nu^3$. Therefore $\alpha \sim 0.5$ should be found in this range, which is also consistent with the curves in the figure.

The source counts in all sky (Figures 5 and 6) show similar breaks and drops to those found in the counts towards GC. However they appear more smoothed out because distances of IBHs from the Sun are more widely distributed with less concentration to GC, as seen in Fig. 7.

3.5 Properties of Detectable IBHs

Fig. 9 shows the distribution of IBH velocities $\nu$ (with respect to the frame of the Galactic rotation) and IBH masses, for IBHs detectable by the future FORCE survey towards GC. As expected from eq. 18, detectable IBHs are dominated by those with low velocities. The velocity distribution becomes flatter when $\nu$ becomes close to the effective sound speed of the molecular gas ($c_s \lesssim 10$ km s$^{-1}$). On the other hand, the observable IBH mass distribution is almost the same as that of the entire IBH population, though the peak of the former is slightly shifted to larger mass. This is because IBH masses are narrowly distributed, although X-ray luminosity is proportional to the cube of BH mass in the RIAF regime (eq. 18).

It is interesting to see the relative contributions to detectable IBHs from those formed in the Galactic disc or bulge. This is shown as the expected number of IBHs detectable by the future FORCE survey for several values of $v_{\text{avg}}$ and assuming $\lambda = 0.1$, in Table 2. We see that the disc fraction becomes smaller as $v_{\text{avg}}$ increases, because IBHs in the disc region are more efficiently expelled by a large kick velocity from dense gas regions than those in the bulge. Since the expected number of bulge IBHs is always much much less than unity, IBHs detectable by FORCE would be mostly of the disc origin, though they are located around GC.

4 DISCUSSION

In this section we mention some caveats and important notes of our work.
The purpose of this work was to estimate the number and X-ray luminosity of IBHs accreting from ISM or molecular cloud gas, and investigate detectability by past and future surveys, by taking into account the realistic structure of our Galaxy. The orbit of each IBH is calculated by integrating the equation of motion in the Galactic potential, and luminosity is calculated considering various phases of ISM and molecular clouds. An important result is that most of the detectable IBHs are near the GC, not only for surveys targeted to GC but also for the ROSAT survey in all sky. This demonstrates the importance of considering the entire Galactic profile in a search for IBHs.

The detectable number of IBHs was calculated with two different methods: the average kick velocity $v_{\text{avg}}$ and the ratio of actual accretion to the Bondi accretion rate $\lambda$. The results show that the number of detectable IBHs is at most a factor of two higher than estimated by $v_{\text{avg}}$. We also investigated the detectability of IBHs in future surveys, such as the FORCE survey, showing separately those born in the Galactic disc and bulge. For all calculations $\lambda = 0.1$ is assumed.

### 4.1 Parameters for Radiative Efficiency of Accretion Flow

The parameter $\epsilon_h$ in Section 2.6 is sensitive to the viscosity parameter $\alpha$. Narayan & Yi (1995) have shown that $\epsilon_h$ can become approximately $10^{-3} - 10^{-1}$ with $\alpha = 0.03 - 0.3$. When $\epsilon_h$ smaller than our value $10^{-1}$ is assumed, the radiation efficiencies of IBHs whose accretion rates are smaller than the threshold would be larger. This increases the luminosities of IBHs in the RIAF regime, thus significantly increasing the number of detections. For example, by changing $\epsilon_h$ to $10^{-3}$ we find that the number of IBHs detectable by FORCES is increased to $2.8 \times 10^2$ by a factor of about ten, assuming $v_{\text{avg}} = 50$ km s$^{-1}$, $\lambda = 0.1$, and the survey area 0.5 deg$^2$. The parameter $\eta_{\text{ad}}$ is likely less uncertain, which is known to be 0.06 for a Schwarzschild black hole and 0.4 for a maximally rotating Kerr black holes (e.g., Thorne 1974).

### 4.2 IBH Spectrum

Considering a different X-ray spectrum of IBHs will change $f_{\text{band}}$ of each telescope and consequently the flux observed in each band. We have assumed a power-law spectrum because detectable IBHs are almost always in the RIAF regime, and if we consider the photon index to be $\xi = 1.4$ (2.1) and maintain all the other assumptions, $f_{\text{band}}$ of ROSAT and FORCES changes to 0.092 (0.55) and 0.33 (0.16), respectively, from the values of $f_{\text{band}} = 0.17$ and 0.31 for $\xi = 1.6$. From the discussions in Section 3.4, the number of detections by ROSAT and FORCES changes by the flux limit to the power of at most 0.7. Then the change of detectable IBH number is at most a factor of two.

### 4.3 Identification of IBHs

If an IBH candidate is found in hard X-ray surveys like FORCES, it is then necessary to distinguish from other sources emitting X-rays, such as cataclysmic variables (CVs) or X-ray binaries. Soft and/or thermal sources, such as CVs, may be discriminated by selecting hard power-law spectrum sources as expected for RIAF. Discrimination from X-ray binaries may be possible by looking for a binary companion using infrared telescopes (e.g., Matsumoto et al. 2018). Our calculation predicts that IBHs will be found preferentially in dense molecular clouds, and IBH candidates would be particularly strong if they are embedded in molecular clouds around GC found by radio observations. Background AGNs may be removed by checking variability time scales and long-term proper motions (Fender et al. 2013). The purpose of this work is to predict the number of IBHs that are bright enough to be detected, and detailed observational strategies to identify them are beyond the scope of this paper.

### 5 CONCLUSIONS

In this work we estimated the number and X-ray luminosity of IBHs accreting from ISM or molecular cloud gas, and investigate detectability by past and future surveys, by taking into account the realistic structure of our Galaxy. The orbit of each IBH is calculated by integrating the equation of motion in the Galactic potential, and luminosity is calculated considering various phases of ISM and molecular clouds. An important result is that most of the detectable IBHs reside near the GC, not only for surveys targeted to GC but also for the ROSAT survey in all sky. This demonstrates the importance of considering the entire Galactic profile in a search for IBHs.

The detectable number of IBHs was calculated with two main model parameters: the average kick velocity $v_{\text{avg}}$ and the ratio of actual accretion to the Bondi accretion rate $\lambda$. The results show that the number of detectable IBHs is at most a factor of two.
We found that a few tens of IBHs would be detected by ROSAT with an optimistic parameter set of $t_{\text{avg}} = 50$ km s$^{-1}$ and $d = 0.1$, if we ignore absorption. However, most of such IBHs are in GC and soft X-rays should be severely absorbed in ISM, and hence non-detection of IBHs by ROSAT does not give a strong constraint. The expected number for the survey by XMM-Newton towards GC is a few hundred for the same parameter set, and IBHs may have been detected in the XMM-Newton sources, though discrimination from other X-ray source populations may be difficult. The hard X-ray band may have an advantage about discrimination, but the expected number for the survey performed by NuSTAR is at most order unity ($\sim 4$). The future FORCE survey towards GC in hard X-ray may detect 30–100 with the same parameter set, although this depends on the actual survey parameters. It should be noted that $d$ can be smaller than 0.1 depending on the physics of accretion, and in such a case IBH detection may be difficult even in the foreseeable future.

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