Mini-dark halos with intermediate mass black holes

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We argue that the Milky Way (MW) contains thousands intermediate mass black holes (IMBHs) and mini-
halos with a fraction of IMBHs still being enshrouded in extremely dense mini-spikes of dark matter (DM) particles. Each containing $10^6 M_\odot$ of dark particles and no baryons in a sphere of 50 pc radius, the minihalos are dense enough to survive the Milky Way tide with the nearest minihalo within 2 kpc from the Sun. The IMBH is formed off-centre in a minihalo by gas accretion, and its growth adiabatically compresses a finite density of surrounding dark matter into a $r^{-1.5}$ mini-spike. Some IMBHs recently on their minihalos after dynamical friction, and some IMBHs are ejected by birth kicks. Detectable by GLAST, the mini-spikes and minihalos should stand out the background and dominate the neutralino annihilation in the smooth MW and satellite galaxies. If they are the unidentifiable EGRET sources, upper limits can be set on the branching ratio of neutralino annihilation. The supermassive BH of the MW, if originates from an IMBH, is also likely enshrouded with a mini-spike.

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Supermassive black holes (SMBH) likely grow from smaller intermediate mass black holes (IMBH) by gas accretion; to be massive enough and early enough, a seed of $\sim 1000 M_\odot$ at $z \sim 20$ is necessary to grow to a $3 \times 10^9 M_\odot$ SMBH at $z = 6$ via Eddington accretion of gas (e.g., [1, 2] and references therein). Gas accretion is favoured because of the empirical result [3, 4] that requires radiatively efficient accretion in order to account for both the quasar luminosity function and the mass in black holes at present. Conversely, once the quasar/AGN phase is over, black holes undergo radiatively inefficient accretion as is the case for Sgr A* (e.g., 5). Here we explore implications of growth of SMBH by accretion in the protogalactic environment. We will study the evolution of the seed IMBHs. These smaller IMBHs are plausibly formed in a subset of the first objects, where accretion rates are high. Hierarchical merging of minihalos leads to a population of IMBHs in MW-sized halos. A mini-spike of CDM is inevitable around the IMBH due to adiabatic growth in the minihalo. The mini-spike is robust to halo merging, and its growth adiabatically compresses a finite density of surrounding dark matter into a $r^{-1.5}$ mini-spike. Some IMBHs recently on their minihalos after dynamical friction, and some IMBHs are ejected by birth kicks. Detectable by GLAST, the mini-spikes and minihalos should stand out the background and dominate the neutralino annihilation in the smooth MW and satellite galaxies. If they are the unidentifiable EGRET sources, upper limits can be set on the branching ratio of neutralino annihilation. The supermassive BH of the MW, if originates from an IMBH, is also likely enshrouded with a mini-spike.

The redshift and mass of the first clouds, stars and IMBHs: The temperature $T$ of the first clouds that contain gravitation-
ally bound baryons depends mostly on the virial mass $M$ with $M = 10^6 M_\odot \left[ \frac{T}{10^8 K} \right]^{3/2}$, where we have scaled with typical values of the redshift $z$ and temperature $T$; cooling by $H_2$ requires a virial temperature in excess of several hun-
dred degrees K. The collapse redshift for clouds of mass $M$ is $\approx 0.6 \nu \times 16(M/10^6 M_\odot)^\nu$, where $\nu \ll 1$ and $\nu$ is the height of the gaussian peak. Hence the desired redshift is sensitive primarily to the peak rarity, and must be in the range 10-30. The WMAP-inferred optical depth of the universe to Thom-
son scattering also suggests a redshift of 15-20 for the first objects that reionised the universe.

The mass of the first objects can be estimated by noting that the accretion rate is of order $v_s^2 / G \sim 10^{-4} - 10^{-3} M_\odot / yr$, where we take $v_s$ to be the virial velocity. Accretion can only be halted by feedback, and it takes at least $10^9$ years to generate feedback from massive stars, hence the masses of the first stars are of order $100 - 1000 M_\odot$, as found in numerical simulations of primordial gas clouds by [13]. Finally, in clouds of $10^5 K$ where Lyman alpha cooling dominates, the accretion rate onto the protostellar core is around $0.03 M_\odot / yr$, hence feedback cannot inhibit the formation of an IMBH, of mass up to $\sim 10^4 M_\odot$.

Annihilation flux of (mini-)halo models with finite core and plateau: The (bolometric) annihilation flux integrated over a sphere of WIMPs of mass $m_\chi$ and number density $n(r) = \frac{\rho(r)}{m_\chi}$ at radius $r$ is

$$L_{\chi\chi}(r < r_p) = \int_0^r 4\pi r^2 dr \langle \sigma v \rangle m_\chi c^2 \left[ \frac{\rho(r)}{m_\chi} \right]_m^2 \left[ \frac{\rho(r_p)}{m_\chi} \right]_{\text{min}}^2, \quad (1)$$

where annihilation imposes a plateau of size $r < r_p$ on the present-day dark matter density because neutralino number density above $\frac{\rho(r_p)}{m_\chi} = \frac{H_{\text{eff}}}{\langle \sigma v \rangle} \sim 10^6 M_\odot \text{pc}^{-3}$ will annihilate away over a Hubble time (e.g., [14, 15]), where $r_p$ the cross-section $\langle \sigma v \rangle / c \sim 1$ pb, fixed by the relic abundance $\Omega_\chi$ required in a LCDM cosmology. The total detectable flux
quickly converges at large radius since $\rho(r)$ generally drops as a steeper than $r^{-1.5}$ power-law beyond $r_p$. Adopting the typical SUSY mass $m_\chi = 50\text{GeV}$, we have

$$L_{\chi\chi}(< r) = \frac{2 \times 10^3 L_\odot}{10^{10} \text{pc}^3} = \int_0^r \left[ \frac{\rho(r)}{10^8 \text{M}_\odot \text{pc}^{-3}} \right]^2 \frac{r^2 dr}{\min(10^{-8} \text{pc})^3}. \quad (2)$$

Note that less than 10% of the above calculated flux for neutralino models will likely go into photons ($\gamma$-rays). More generally and crudely speaking, $L_{\chi\chi}(< r) \propto m_\chi^{-1}$.

We model the density $\rho(r)$ of the minihalos and the MW halo with a subset of models of Zhao et al. (also known as generalized-NFW profiles). To be conservative in estimating the annihilation signal, we choose a subset of initial halo models with a finite core and without any outer truncation. Our models are also inspired by the recent exponential-like models of Navarro et al. (hereafter, N04 model). Specifically, we model halos with density at radius $r$ given by

$$\rho(r) = \frac{\rho(r_c)}{(x/2 + 1/2)^2}, \quad x = \left( \frac{r}{r_c} \right)^{-3}. \quad (3)$$

Here $r_c$ is, as in an NFW model, where the local density power-law index $d\log \rho/d\log r = -2$. Our models are specified by two parameters $r_c$ and $\rho_c \equiv \rho(r_c)$, and the virial radius $r_{\text{vir}} \equiv c r_c$ is given implicitly by

$$\frac{3M_{\text{vir}}}{4\pi r_{\text{vir}}^3} = 176\rho_{\text{crit}}(z) = \frac{2\rho(r_c)(1 + c^2/5 + c^4/55)}{(1/2 + c^2/2)^{11}}, \quad (4)$$

i.e., the mean density $\bar{\rho}(r_{\text{vir}}) = \frac{3M_{\text{vir}}}{4\pi r_{\text{vir}}^3}$ is approximately 176 times the critical density $\rho_{\text{crit}}(z)$ of the universe at a given formation redshift $z$. Note the density ratio $\bar{\rho}(r_c)/\rho(r_c) = 2.436$, 2.3178 and 2.4644 for our cored model, NFW model, and N04 model. Unlike the NFW model, our model has an outer $r^{-4}$ density profile without truncation, and a finite central density and a finite asymptotic mass. For models with the same core radius and density normalization $\rho(r_c)$, $M(r_{\text{vir}})$ differs by only 10 percent between NFW models and our model for typical concentration $c = 1 - 1000$.

There are a few advantages of our model. It is straightforward to derive and show that the potential, the circular velocity curve and even the velocity dispersion curve of this class of halo models are all simple analytical rational functions of $r^{1/3}$, while some special functions enter the NFW and N04 models. As shown in Fig.1, our model reproduces the density, mass, velocities of NFW and N04 very well over the range $0.01 r_c < r < 100 r_c$ at least for systems with $c \geq 1$.

**Formation of minihalos and massive black holes:** Current numerical simulations suggest that the first stars form from $H_2$ clouds in dark minihalos of mass about $3 \times 10^5 M_\odot$, virial radius of $60 h^{-1} \text{pc}$ and virial velocity of $5 \text{km s}^{-1}$, and initial virial temperature of 1000 Kelvin (for a molecular weight of unity) at a redshift of $z \sim 20$, when the universe was about 0.15 Gyr old. The cooling time is comparable to the dynamical time, both being of order 1 Myr, and self-gravitating isothermal clouds of order a thousand solar masses are able to develop. Once the $H_2$ gas at a super-Eddington rate with a mass-doubling time scale $t_{\text{diff}} \sim (r/pc)^2 \sim 1 \text{Myr}$ for a thousand solar mass BH formed at 1pc. At the centre of one or more massive IMBHs, up to $10^7 - 10^2 M_\odot$.

There are several plausible outcomes for the IMBH and the gas inside a minihalo. In some cases, the IMBH could be ejected out of the shallow potential well of the minihalo if born with a significant kick/recoil velocity (greater than the $30 \text{km s}^{-1}$ escape velocity at the centre of the minihalo). In other cases, the IMBH spirals to the centre of the mini-halo due to dynamical friction (the timescale $t_{\text{fric}} \sim (r/pc)^3 \sim 20 \text{Myr}$ for a plausible range of the accretion efficiency $\eps = 0.005 - 0.1$). Eventually after some uncertain...
period of order 10 Myr, the first SNe progenitors are born in these minihalos, and shortly afterwards (about 4 Myr) most of the gas in the minihalos (perhaps with the exception of the tightly bound accretion disk around the IMBH) is cleared out when the SNe explode. Thus the only remnants of the first generation of star formation are a population of minihalos and IMBHs, which are either well-centred due to dynamical friction or well-separated due to strong kicks. To be specific, we consider minihalos specified by eq. (3) with \( r_c = 1.6 \) pc and \( \rho(r_c) = 500 \, M_\odot \, pc^{-3} \) (comparable to an NFW halo of \( r_{\text{vir}} = 50 \times r_c = 80 \) pc). We assume conservatively that 10 percent of the minihalos harbour IMBHs which eventually grow to a final mass of \( 10^2 M_\odot \) or \( 10^3 M_\odot \). These values are plausible for a r.m.s. kick velocity \( \sim 100 \) km s\(^{-1}\), and accretion efficiency \( \epsilon \sim 0.02 \) in the mini-halo in 10 Myrs. So there are of order \( 10^3 \) minihalos containing IMBHs.

**Adiabatic compression of dark matter in minihalos:** Now consider the effect on the dark matter. The formation and the growth of the IMBH will compress the surrounding dark matter. The compression is close to adiabatic since the formation of the IMBH and the subsequent accretion are on time scales of the cooling time and Salpeter time; both are somewhat longer than the dynamical time. Given the finite density and phase space density of dark matter at an off-centre position, we expect a moderate \( r^{-3/2} \) power-law dark matter density distribution surrounding the IMBH. This type of cusp (or “spike”) is the result of growth in a uniform background\([15]\); a steeper cusp occurs if a well-centred BH grows adiabatically (e.g., \[15\]). Such a mini-spike will survive dynamical friction, and be added to the central core of the minihalo once the IMBH recenters. We expect order of \( M_\bullet \sim 1000 M_\odot \) of dark matter in this spike. So the dark matter mass profile with a mini-spike is

\[
M^{\text{sp}}(r) = \left(1 + \frac{b^{3/2}}{r_c^{3/2}} \right) M(r), \quad M(b) = m_\bullet, \tag{5}
\]

where \( b = 0.045 \) pc or 0.14 pc so that \( M^{\text{sp}}(b) = 2M(b) = m_\bullet = 10^2 M_\odot \) or \( 10^3 M_\odot \).

We consider several possibilities for the dark matter. Fig.2 shows the resulting dark halo density and the annihilation flux. In the simplest case, the minihalos have the pristine cored density profile; the IMBH either never formed or has been kicked out of the system. For a minihalo which keeps its IMBH, the IMBH draws in a mini-spike of dark matter with a plateau inside about 0.005 pc depending on its mass. The flux per log radius bin is of order \( 10^{1} L_\odot \), and most of it comes from within 0.01 pc of the minihalos.

**Observability of minihalos inside the MW:** By a redshift of \( z = 1 - 6 \), nearly all the minihalos and IMBHs are bound inside galaxy-sized objects. About \( 10^3 - 10^4 \) should be bound inside a Milky-Way-sized galaxy \([21]\), which we assume to have a density given by eq. (3) with \( r_c = 11 \) kpc and \( \rho(r_c) = 0.0055 M_\odot pc^{-3} \) (this is consistent with the local DM density and resembles an NFW model of \( r_{\text{vir}} = 8r_c \)). These minihalos should be distributed in a way similar to the overall dark matter profile of the galaxy, producing a clumpy annihilation brightness distribution; we assume the stars and the central SMBH in the MW form later.

A typical nearby minihalo at about 3 kpc from the Sun sustains a solid angle \( \Delta \Omega \sim 10^{-3} \) (about the resolution of EGRET) comparable to the angular size of dwarf galaxy satellites at 100 kpc, but minihalos are much more luminous and brighter in annihilation than dwarf galaxies because of minihalo’s much denser core than dwarf galaxies; the latter have central dark matter densities of \( (0.05 - 0.5) M_\odot pc^{-3} \) \([26]\). Except towards the Galactic center a minihalo stands out in density and annihilation flux from the MW background in a beam of \( \Delta \Omega \leq 10^{-3} \) at all distances (cf. Fig. 2). A population of \( 10^3 \) minihalos with \( 100 M_\odot \) IMBHs is about 100 times more luminous than the MW background as a whole. These minihalos are low-mass (~\( 10^3 M_\odot \)) but dense (about \( 1 M_\odot pc^{-3} \)) on a scale of 30 pc enough so that 99 percent of the minihalos survive intact in the halo, and follow the overall distribution of dark matter. There are of order 10 minihalos within 1 kpc of the MW centre, where dynamical friction could bring one of these minihalos to the centre of the MW within a Hubble time (cf. Fig.3 of \([15]\)), without being slowed down by tidal
stripping [22]; note that these minihalos are typically denser than the MW halo on a scale of 60pc. If the IMBH of the minihalo could serve as a seed for the supermassive BH in the MW.

The isolated IMBHs are virtually invisible. The X-ray luminosity due to Bondi-Hoyle accretion of an IMBH passing through the MW gaseous disk is estimated to be \((\epsilon/0.1)(m_\text{BH}/300\text{M}_\odot)^2L_{\text{X}}\) [23]. So the signal is much fainter than the million-solar-mass BHs of Lacey & Ostriker [23]. Such a low luminosity is just detectable with present facilities if the IMBH is close-by (say 2 kpc), but the chance of a BH passing through a cold H\(_2\) or HI cloud (with filling factors 0.3% and 2% respectively) at a given time is very low. The local density of IMBHs is about 0.3 kpc\(^{-3}\) assuming \(10^3\) IMBHs in the whole halo, and we expect only of order one IMBH hitting a cloud with a filling factor of \(\sim 1\%\) in the entire disk of 8 kpc in radius and 200pc in thickness, an approximation for the cold H\(_2\) and HI cloud distribution. Also being much fewer than the million-solar-mass BHs of [23], the minihalos do no damage to the MW disk.

Despite being a dynamically subdominant population, the minihalos and IMBHs speed up two-body relaxation in the MW. The relaxation time is given by [23]

\[
\tau_{\text{rel}} = \frac{1}{10^3 M_{\text{BH}} c^2 \rho(\sigma \ln A)} f_M \frac{M^2 + m^2}{M + m} \sim 1 - 1000M_{\odot} \text{ is the mass density-weighted mean mass of deflectors depending on tidal stripping; the lower value is for minihalos well inside 1-10 kpc of the Galactic centre, and } f_M \sim 10^{-3} \text{ is the fraction of matter mass density in the form of minihalos of mass } M. \text{ The heavier the deflectors, the faster the relaxation. So compared to the case of purely stellar deflectors, the relaxation is about } \tilde{M}/M_{\odot} \sim 1 - 1000 \text{ times more efficient. This might help to refill the loss-cone of the central BH by scattering stars and dark matter particles.} [24]. \text{ To refill the loss-cone of } 3 \times 10^6 M_{\odot} \text{ BH on the scale of the 1pc would require a relaxation time of order a Hubble time.}

Our model predicts around 1500 L\(_\odot\) (bolometric) per solar mass in spike neutralinos. Observationally, the annihilation signal is best seen via gamma rays. EGRET observations set upper limits on unidentified sources, in particular on the source near the Galactic Centre, in gamma rays above 1 GeV of around 100 L\(_\odot\) [27]. For our models to be consistent with observational data in the MW and a gamma ray branching ratio of order 10 percent, we require of order a solar mass of the neutralinos in the spike for typical SUSY neutralinos with \(m_\chi = 50\text{GeV}\). This is consistent with our models of adiabatic growth of \(10^2 M_{\odot}\) IMBHs and models with ejected IMBH. The data would also be consistent with the \(10^3 M_{\odot}\) IMBH model in case of heavier neutralinos (\(m_\chi \sim 10^{10}\text{TeV}\) [28]). Evidently the GLAST satellite, with two orders of magnitude more sensitivity than EGRET, will be capable of setting stringent constraints on halo IMBH.

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