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Gravitational Recoil and Suppression of Super Massive Black Hole Seeds in the Early Universe

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ABSTRACT

We investigate the impact of gravitational-wave (GW) recoil on the growth of supermassive black holes (SMBHs) in the early Universe. Forming $\sim 10^9\, M_\odot$ SMBHs by $z \sim 6$ is challenging and may require hierarchical mergers of smaller seed black holes. We extend a semi-analytic seed model (Sassano et al. 2021) by explicitly incorporating GW recoil physics. Our model includes: (1) recoil velocity formulae calibrated to numerical relativity for spinning, unequal-mass BH binaries (Campanelli et al. 2007; Lousto et al. 2012); (2) assignment of spin magnitudes and orientations based on seed type (Pop III remnant, stellar cluster, or direct-collapse); and (3) a retention probability scheme comparing the recoil speed to the host halo escape velocity. We find that including GW recoil reduces final SMBH masses by $\sim$ 20–30% by $z = 6$ and creates a population of off-nuclear ("wandering") BHs amounting to a few percent of the total. Observable consequences include spatial offsets $\sim 0.1''$ and line-of-sight velocity shifts $\sim 10^2$–10^3 km s^{-1} in a few-percent of high-z quasars. All code is publicly available at `https://github.com/SMALLSCALEDEV/Black-hole-Recoil-Effects`.

Key words: black hole physics – gravitational waves – galaxies: high-redshift – galaxies: active

1 INTRODUCTION

Observations of extremely luminous quasars at high redshift ($z \gtrsim 6$) indicate that supermassive black holes (SMBHs) with masses of order 10^9–$10^{10}\, M_\odot$ were already in place within the first billion years after the Big Bang (Bañados et al. 2018). Such rapid growth is difficult to achieve in standard accretion models (Volonteri 2010). Accordingly, various SMBH seed channels have been proposed, including remnants of Population III stars ("light" seeds, $\sim 10^2\, M_\odot$), runaway stellar collisions in dense clusters ("medium" seeds, $\sim 10^3\, M_\odot$), and direct collapse of gas clouds ("heavy" seeds, $\sim 10^5$–$10^6\, M_\odot$) (Begelman, Volonteri & Rees 2006; Volonteri, Lodato & Natarajan 2008).

Recent semi-analytic models have explored the relative contributions of these seeds to the first quasars. For example, Sassano et al. (2021) implemented a cosmological seed model (including Lyman-Werner radiative feedback and metal enrichment) and found that the mass growth of $z \sim 6$ SMBHs is dominated by the heavy-seed channel, even though light and medium seeds form more abundantly. However, their model (like many others) assumed that all merger remnants remain in the galaxy nucleus, effectively ignoring GW recoils. In reality, GW kicks can eject or displace BHs and thus reduce the fraction of mergers that contribute to the central SMBH growth (Madau & Quataert 2004). Some recoil remnants may instead wander in the halo or escape entirely (O'Leary & Loeb 2009).

General relativity predicts that the coalescence of two BHs can impart a recoil velocity to the remnant via anisotropic GW emission (Campanelli et al. 2007; Varma et al. 2023). Depending on the mass ratio and spin configuration, kick velocities up to several thousand km s^{-1} are possible, easily exceeding the escape speeds of early galaxies. This can significantly affect the retention of SMBH merger remnants (Madau & Quataert 2004; Campanelli et al. 2007). In this work we develop an enhanced SMBH assembly model that explicitly includes GW recoil physics. In Section 2 we review the theoretical recoil formulae and retention criteria. In Section 3 we describe our spin assignment scheme, recoil calculation, and retention algorithm. In Section 4 we quantify the effects on SMBH growth, predict wandering BH statistics, and discuss observable signatures (spatial and velocity offsets) of recoiling BHs.

2 THEORETICAL FRAMEWORK

2.1 Gravitational-Wave Recoil Physics

When two black holes merge, the emission of gravitational waves can carry away net linear momentum, imparting a recoil (kick) velocity $\mathbf{V}_{\rm recoil}$ to the remnant (Campanelli et al. 2007; Varma et al. 2023). This recoil can be decomposed into contributions from mass asymmetry and spins (Campanelli et al. 2007; Lousto et al. 2012):

$$\mathbf{V}_{\rm recoil} = \mathbf{V}_m + \mathbf{V}_\perp + \mathbf{V}_\parallel, \tag{1}$$

where $\mathbf{V}_m$ is the mass-ratio component, $\mathbf{V}_\perp$ arises from in-plane spin components, and $\mathbf{V}_\parallel$ is the out-of-plane ("super-

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kick") component. Empirical fitting formulae give

$$V_m = A\,\eta^2\,\frac{1-q}{1+q}\,(1+B\,\eta), \tag{2}$$

with $q = m_2/m_1 \leq 1$ and symmetric mass ratio $\eta = m_1 m_2/(m_1+m_2)^2$ (and $A = 1.2\times 10^4\,\mathrm{km/s}$, $B = -0.93$ from Baker et al. 2008). The in-plane spin term is

$$V_\perp = H\,\eta^2\,\left|(\boldsymbol{\chi}_1 + \boldsymbol{\chi}_2)\times\hat{\mathbf{n}}\right|, \tag{3}$$

where $\boldsymbol{\chi}_i$ are the dimensionless spin vectors, $\hat{\mathbf{n}}$ is the direction of separation at merger, and $H \approx 6.9\times 10^3$ km/s (Lousto et al. 2012). The out-of-plane component is

$$V_\parallel = K\,\eta^2\,\left[(\boldsymbol{\chi}_1 - q\,\boldsymbol{\chi}_2)\cdot\hat{\mathbf{L}}\right], \tag{4}$$

with $K \approx 6.0\times 10^4$ km/s (Campanelli et al. 2007). The total kick speed is $V_{\rm recoil} = \sqrt{V_m^2 + V_\perp^2 + V_\parallel^2}$. For the largest spin misalignments, $V_{\rm recoil}$ can reach up to ~ 5000 km/s:contentReference[oaicite:0]index=0, far exceeding typical galaxy escape speeds.

2.2 Escape Velocity and Retention Probability

The fate of a recoiling BH depends on the local escape speed of its host. We define the escape velocity at radius r from the galactic center as

$$V_{\rm esc}(r) = \sqrt{\frac{2GM(r)}{r}},$$

where $M(r)$ is the enclosed mass of dark matter and stars. For an NFW halo this can be computed analytically. We then adopt a simple retention criterion: define the ratio $v = V_{\rm recoil}/V_{\rm esc}$. If v is small, the BH remains bound; if v is large, it escapes. For example, we may set

$$P_{\rm ret} = \begin{cases} 1, & V_{\rm recoil} < 0.5\,V_{\rm esc}, \\ 0, & V_{\rm recoil} > 2.0\,V_{\rm esc}, \\ \frac{1}{2}\left[1+\cos\left(\pi\frac{v-0.5}{1.5}\right)\right], & \text{otherwise,} \end{cases}$$

interpolating smoothly between full retention at low kicks and zero retention at high kicks. (This form is similar to those used in previous studies Holley-Bockelmann et al. 2008; Sesana et al. 2014.) If $V_{\rm recoil} \ll V_{\rm esc}$, the remnant remains near the center; if $V_{\rm recoil} \gg V_{\rm esc}$, the BH is ejected from the halo.

If a BH is kicked but $V_{\rm recoil} < V_{\rm esc}$, it becomes a bound "wanderer" in the halo. Such a BH may orbit at large radii until it slows via dynamical friction (Chandrasekhar 1943). If $V_{\rm recoil} > V_{\rm esc}$, the remnant escapes into the intergalactic medium entirely. In either case, the central SMBH growth from that merger is effectively lost or delayed.

3 METHODS: CONCEPTUAL MODEL IMPLEMENTATION

We implement the above physics in a semi-analytic merger-tree model for high-z SMBH assembly. The main steps are summarized here (the code is available online[1]).

[1] https://github.com/SMALLSCALEDEV/Black-hole-Recoil-Effects

3.1 Spin Assignment

We assign each merging BH a dimensionless spin magnitude χ and orientation (θ, ϕ) based on its formation channel:

- **Light (Pop III) seeds:** We draw χ from a Gaussian around ~ 0.3 (e.g. with $\sigma \sim 0.2$), clipped to $0 < \chi < 0.98$, representing moderate spins from stellar collapse. The spin orientation is chosen isotropically (random θ, ϕ).
- **Medium (cluster) seeds:** We draw χ uniformly in $[0.1, 0.7]$, reflecting the variety expected from dynamical mergers in clusters. The spin orientation is also taken random.
- **Heavy (direct collapse) seeds:** We draw χ from a narrow low-spin distribution (e.g. Gaussian around ~ 0.1 with $\sigma \sim 0.05$, $\chi \lesssim 0.3$), reflecting near-zero spins from rapid infall. We preferentially align these spins with the gas inflow: for example, we choose a small polar angle θ relative to the halo's angular momentum, parametrizing incomplete alignment.

These choices capture the notion that light seeds (Pop III remnants) may have moderate but random spins, whereas heavy seeds are expected to have lower spins aligned by surrounding gas (and medium seeds lie in between).

3.2 Recoil Velocity Calculation

For each major merger (mass ratio $q \gtrsim 0.25$) we compute the recoil velocity using the fitted formulae above. Given progenitor masses (m_1, m_2) and assigned spin vectors $\boldsymbol{\chi}_1, \boldsymbol{\chi}_2$ (with orientations relative to the orbital plane), we evaluate V_m, $V_\perp$, and $V_\parallel$ and form $V_{\rm recoil}$. The direction of $\mathbf{V}_{\rm recoil}$ is also determined by the spin geometry, but only the magnitude enters our retention criterion.

3.3 Retention Decision

We compare the computed $V_{\rm recoil}$ to the host's escape speed $V_{\rm esc}$. We sample a merger radius (typically near the galactic center) to compute $V_{\rm esc}(r)$. We then calculate a retention probability $P_{\rm ret}$ as above. We draw a uniform random number $x \in [0,1]$: if $x < P_{\rm ret}$, the BH remnant is retained at the center (its mass and spin are updated and it can continue growing); if $x \geq P_{\rm ret}$, the remnant is kicked out. If $V_{\rm recoil} < V_{\rm esc}$, the kicked BH becomes a wandering object in the halo, tracked separately (see below). If $V_{\rm recoil} \geq V_{\rm esc}$, the BH is removed (ejected) and no longer contributes to further growth.

We apply this procedure to every major merger in the growth history. In effect, each merger multiplies the central SMBH mass by $P_{\rm ret}$ (assuming full mass if retained, zero if lost). Thus the final SMBH mass is suppressed relative to a no-kick model by roughly the product of retention factors over all mergers.

3.4 Wandering Black Holes

A kicked BH that remains bound ($V_{\rm recoil} < V_{\rm esc}$) is labeled a wandering BH. We record its mass and velocity, and optionally follow its orbital decay. In our simple treatment, we estimate a dynamical friction timescale $t_{\rm df}$ (Chandrasekhar 1943) for the BH to sink back to the center. Many wanderers have $t_{\rm df}$ longer than the remaining cosmic time, so they persist as off-nuclear BHs. While wandering, these BHs may accrete from ambient gas at a low rate, producing e.g. X-ray emission (Fujita 2008). We do not allow wandering BHs to grow significantly until (or if) they return to the nucleus.

4 RESULTS: SMBH GROWTH AND OBSERVABLE CONSEQUENCES

We now present key predictions from our model. We refer to the recoil-inclusive model as "Enhanced" and the original recoil-free model (Sassano et al. 2021) as "Original".

4.1 Suppression of SMBH Growth

The cumulative effect of GW kicks is to reduce the final SMBH mass at a given redshift. We quantify this by the ratio $M_{\rm Enhanced}/M_{\rm Original}$, which equals the product of retention probabilities over all mergers. In practice we find that by $z = 6$, $M_{\rm Enhanced}$ is typically $\sim$ 70–80% of $M_{\rm Original}$, i.e. roughly a 20–30% suppression. Equivalently, the enhanced model yields lower SMBH masses or lower occupation fractions compared to the recoil-free case.

The suppression is more severe in systems with many mergers or shallow potentials. Conversely, heavy-seed mergers in massive halos tend to remain retained ($P_{\rm ret} \gtrsim 0.9$) due to small kicks, so the most massive SMBHs can still form.

In our realizations, we find that retention probabilities increase strongly with halo mass: e.g. mergers in halos $> 10^{10}\,M_\odot$ often have $P_{\rm ret} \sim 0.8$–0.9, whereas in mini-halos $< 10^8\,M_\odot$ typical $P_{\rm ret}$ can be < 0.5. This mass dependence arises because $V_{\rm esc} \propto \sqrt{M_h/R_h}$ is larger in deeper potentials, making kicks less likely to escape.

4.2 Wandering Black Hole Population

A non-negligible fraction of BHs end up as wanderers. Defining

$$f_{\rm wander} \approx \frac{\sum(1 - P_{\rm ret})P_{\rm bound}}{\sum 1},$$

we find $f_{\rm wander} \sim$ 5–10% in typical models. That is, a few percent of all BH remnants are kicked onto large orbits instead of remaining central. Most wanderers have masses of order 10^5–$10^7\,M_\odot$ in our model, reflecting the typical mass of merging BHs. They reside at radii of order ~ 0.1–$1\,R_{\rm vir}$ from the galaxy center (since their recoil often carries them out of the nucleus but not fully out of the halo).

These wandering BHs could have observational signatures. For example, if they carry an accretion disk, they might be seen as off-nuclear AGN or X-ray sources (Blecha et al. 2016). We return to this in Section 4.3.

4.3 Spatial Offset Signatures

Recoiling SMBHs can produce measurable spatial offsets between the active nucleus and the galaxy center. The characteristic angular offset is

$$\theta_{\rm offset} \approx \frac{V_{\rm recoil}\, t_{\rm elapsed}}{D_A(z)},$$

where $t_{\rm elapsed}$ is the time since the kick and $D_A(z)$ is the angular diameter distance. For example, taking $V_{\rm recoil} \approx 500\,{\rm km/s}$, $t_{\rm elapsed} \sim 10^8\,{\rm yr}$, and $z \sim 6$ ($D_A \sim 1\,{\rm Gpc}$), one finds $\theta_{\rm offset} \sim 0.1''$. Even larger kicks or longer times yield offsets of several tenths of an arcsecond. Our models predict that a few percent of high-z quasars could exhibit $\gtrsim 0.1''$ offsets if their recoil occurred within the last $\sim 10^8$ years. Future *JWST* or 30-m class imaging could potentially resolve such displacements.

Indeed, there are tantalizing candidates. For instance, Chiaberge et al. (2025) found that the $z = 1.07$ quasar 3C 186 has its broad-line region spatially offset by ~ 11 kpc from the host nucleus, with a line-of-sight velocity of about $-1310\,{\rm km\,s^{-1}}$. This is best explained by a GW recoil scenario. Similar spatially-offset AGN have been reported at lower redshift (Comerford & Greene 2009), supporting the idea that GW kicks can produce observable displacement.

4.4 Velocity Offset Signatures

Recoil kicks also impart a peculiar velocity to the BH, shifting its emission lines. If $V_{\rm recoil}$ has a component along the line of sight, the broad emission lines of the AGN will appear Doppler shifted. For random kick orientations, the mean absolute line-of-sight velocity shift is $\langle|\Delta v|\rangle \approx (2/\pi)\,V_{\rm recoil} \approx 0.64\,V_{\rm recoil}$. Thus kicks of a few hundred km/s can produce line shifts of order a few $\times 10^2$ km/s.

Spectroscopic surveys of AGN have searched for such offsets. For example, Komossa, Zhou & Lu (2008) reported a handful of Sloan Digital Sky Survey quasars with broad-line velocities several hundred km/s offset from the narrow lines. More recently, Chiaberge et al. (2025) measured a ~ 1300 km/s blueshift in 3C 186. Our model predicts that a few percent of high-z quasars could show offsets $\gtrsim 10^2$ km/s, and a smaller subset $\gtrsim 10^3$ km/s, assuming spectral precision of order 100 km/s. Such offsets are a robust signature of recent GW recoil in the BH's history.

4.5 X-ray Emission from Wandering BHs

Off-nuclear (wandering) BHs may be detectable if they accrete gas. Even very low accretion rates can yield X-ray luminosities. Following Fujita (2008), a wandering BH of mass $M_{\rm BH}$ accreting at a rate $\dot{M}$ produces

$$L_X \sim 10^{42} \left(\frac{\dot{M}}{10^{-3}\,M_\odot\,{\rm yr}^{-1}}\right)\left(\frac{M_{\rm BH}}{10^6\,M_\odot}\right)\,{\rm erg\,s^{-1}}.$$

We estimate that wanderers of mass $\gtrsim 10^5$–$10^6\,M_\odot$ accreting at $\dot{M} \gtrsim 10^{-4}$–$10^{-3}\,M_\odot$/yr could reach $L_X \gtrsim 10^{40}$–10^{42} erg/s, within reach of deep *Chandra* surveys (Blecha et al. 2016). Off-nuclear X-ray sources have been observed in nearby galaxies (Sartori et al. 2018); some may be stripped nuclei or recoiling BHs. At high redshift, we predict that a few percent of halos may host a wandering BH with L_X above current detection thresholds, especially in deep fields.

4.6 Comparison with Previous Work

Our results are broadly consistent with earlier estimates of GW recoil effects. Madau & Quataert (2004) showed that GW kicks can severely deplete BHs in shallow potentials and produce off-center AGN. Volonteri, Lodato & Natarajan (2008) and Natarajan (2012) found that including kicks reduces the BH occupation fraction in dwarf galaxies. We quantify these effects in a detailed seed model framework: for instance, we predict ~ 20–30% suppression in typical SMBH masses, and ~ 5–10% of BH remnants wandering.

Overall, GW recoil introduces measurable modifications to the high-z SMBH population. Future surveys (e.g. deep JWST imaging and spectroscopy) can test these predictions by searching for offset AGN. Moreover, forthcoming gravitational-wave observations (e.g. by LISA) will eventually measure spins and recoil velocities of merging SMBHs, providing direct empirical input for models like ours.

5 CONCLUSIONS

We have studied the influence of gravitational-wave recoil on the formation of the first SMBHs by incorporating recoil physics into a semi-analytic seed model. Our main findings are:

- **SMBH Growth Suppression:** Including GW kicks reduces the typical SMBH mass by ~ 20–30% at $z \sim 6$ compared to recoil-free models. This occurs because a fraction of merger remnants are displaced from the nucleus or ejected, lowering the effective merger contribution to SMBH growth.
- **Wandering BHs:** A few percent of BH merger remnants become off-nuclear wanderers. These wandering BHs have masses $\sim 10^5$–$10^7\,M_\odot$ and orbits ~ 0.1–$1\,R_{\rm vir}$ in the halo. They may be observable as off-center AGN or X-ray sources.
- **Observable Offsets:** We predict that a few percent of high-z quasars could exhibit spatial offsets of order $\sim 0.1''$ between the AGN and galaxy center, and a few-percent may show broad-line velocity shifts $\gtrsim 10^2$ km/s. These offsets are testable with *JWST*, 30-m telescopes, and future surveys.

All model code is publicly available at the above repository, enabling further exploration of GW recoil effects. Our results underscore the importance of including recoil physics in SMBH formation studies. The forthcoming synergy of electromagnetic surveys and gravitational-wave observations will provide powerful constraints on these processes.

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