UNIVERSITY OF NOTRE DAME

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Feeding the First Black Holes:

Dark Matter and the Loss-Cone Bottleneck



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From the first stars to the first black holes

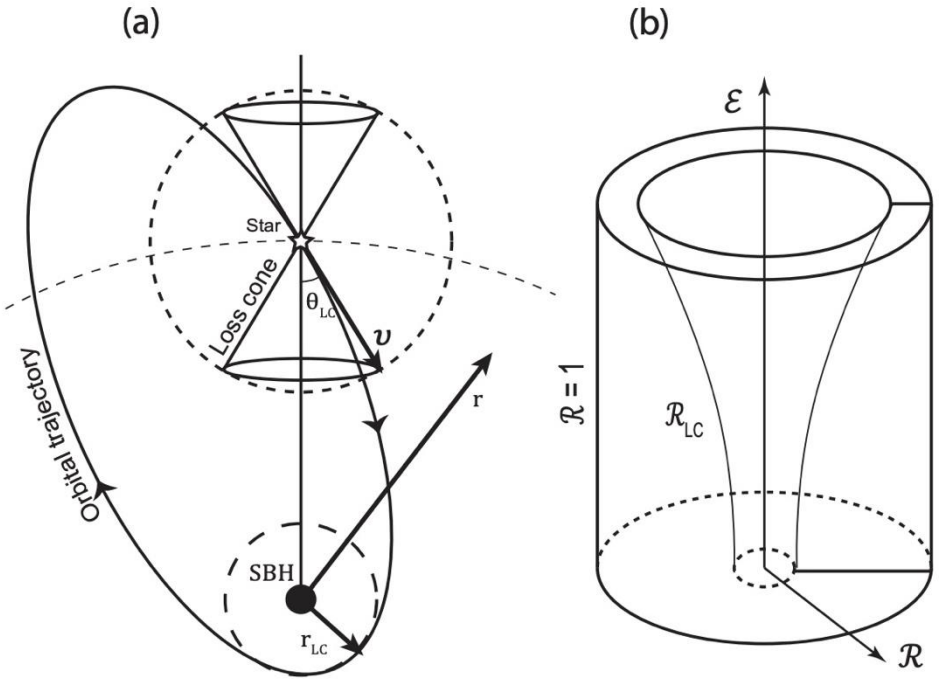
Based on Zhang & Mathews, JCAP (2026), accepted for publication.

Being Nearby Is Not Enough: The Loss Cone

- Objects must have sufficiently low angular momentum to be captured.
- Most orbits, even at small radii, are not lost to the black hole.
- The loss cone is a small region in angular-momentum space.

$$J < J_{lc} = 4GM_{BH}/c$$

Orbits within the loss cone are captured.



(Merritt D. 2013)

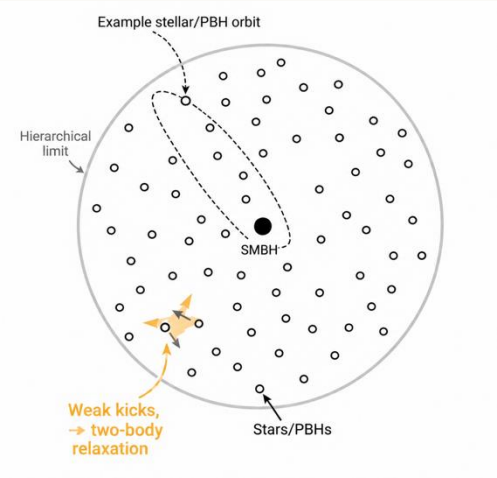
$$R \equiv J^2/J_c^2$$
$$R_{lc} = J_{lc}^2/J_c^2$$

Who Refills the Loss Cone?

1. Gravitational scattering

Stars and primordial black holes (PBHs)

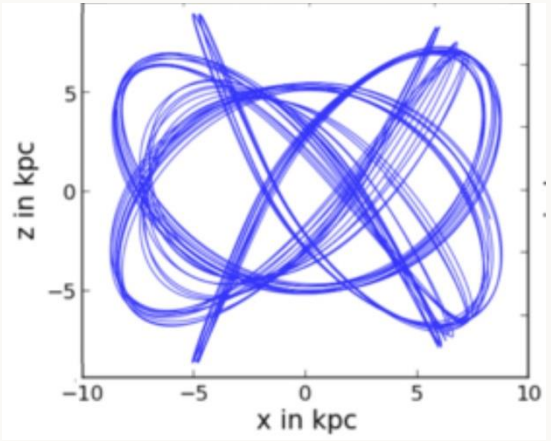
- Two-body encounters scatter angular momentum.
- Massive and dense perturbers enhance angular-momentum diffusion.



2. Non-spherical torques

A non-spherical gravitational potential

- Collisionless torques/triaxiality change J even without gravitational scattering.
- Can keep the loss cone populated.



Hesp, C., & Helmi, A. (2018)

Key parameter:

$$\Xi = f_{\mathrm{PBH}} m_{\mathrm{PBH}}$$

PBH mass fraction × PBH mass

$$f_{ch}$$

Phenomenological centrophilic fraction

From Diffusion to Gravitational Capture

Orbit-averaged Fokker–Planck equation

$$\frac{\partial f(\epsilon, R, t)}{\partial t} \simeq \mu(\epsilon) \frac{\partial}{\partial R}\left(R \frac{\partial f}{\partial R} \right)$$

$R \equiv J^2 / J_c^2$

at fixed energy

Characteristic-radius closure

$$\mu(\epsilon) \sim t_{\rm rel}^{-1}[r_{\rm char}(\epsilon)]$$

Approximate numerical evaluation of μ

Quasi-steady loss-cone capture spectrum

$$q \equiv \frac{P\,\mu}{R_{\rm lc}}$$

$$\frac{d\dot{M}_{\rm BH}(\epsilon, t)}{d\epsilon} \simeq \underbrace{\frac{dM(\epsilon, t)}{d\epsilon}}_{\text{Available mass}} \times \underbrace{\frac{R_{\rm lc}(\epsilon, t)}{P(\epsilon, t)}}_{\text{Orbital draining rate}} \times \underbrace{\frac{q(\epsilon, t)}{\ln[1/R_{\rm lc}(\epsilon, t)] + q(\epsilon, t)}}_{\text{Refilling factor}}$$

Full loss cone: the refilling factor tends to 1

$$\dot{M}_{\rm BH}\Big|_{\rm full} = 16\pi (G M_{\rm BH})^2 \rho c^{-2} \left\langle v^{-1} \right\rangle$$

$$\dot{M}_{\rm BH}\Big|_{\rm full} = \rho \left\langle \sigma_{\rm capt}(v)\, v \right\rangle$$

$\Leftrightarrow$

$$q \gg \ln(1/R_{\rm lc})$$

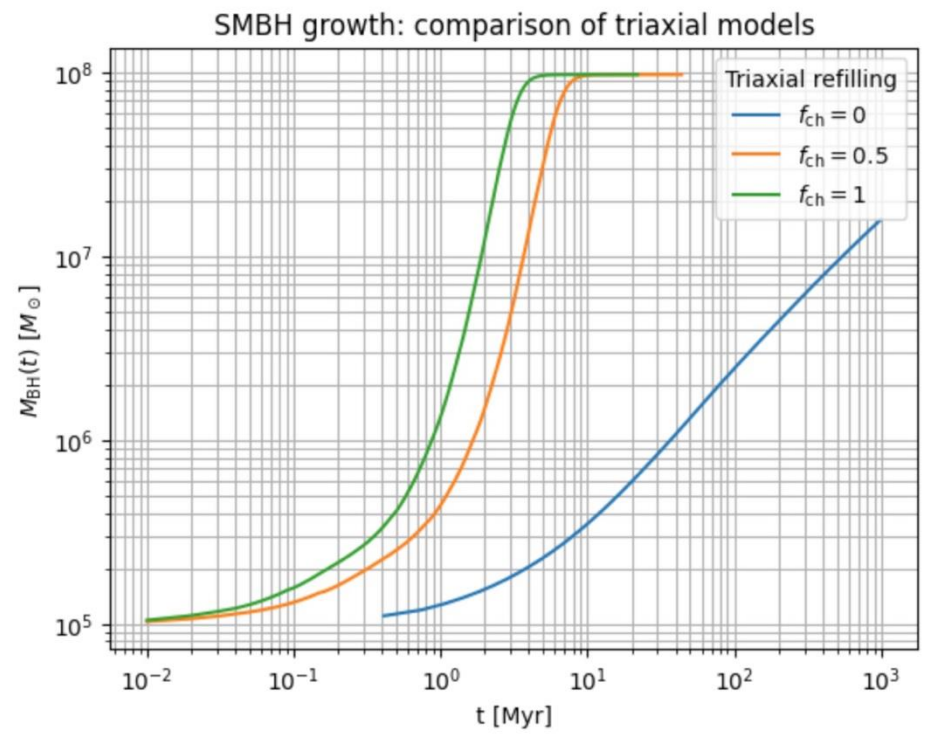
$$\sigma_{\rm capt}(v) = 4\pi R_s^2 \left(\frac{c}{v_\infty} \right)^2$$

$$R_s = 2GM_{\rm BH}/c^2$$

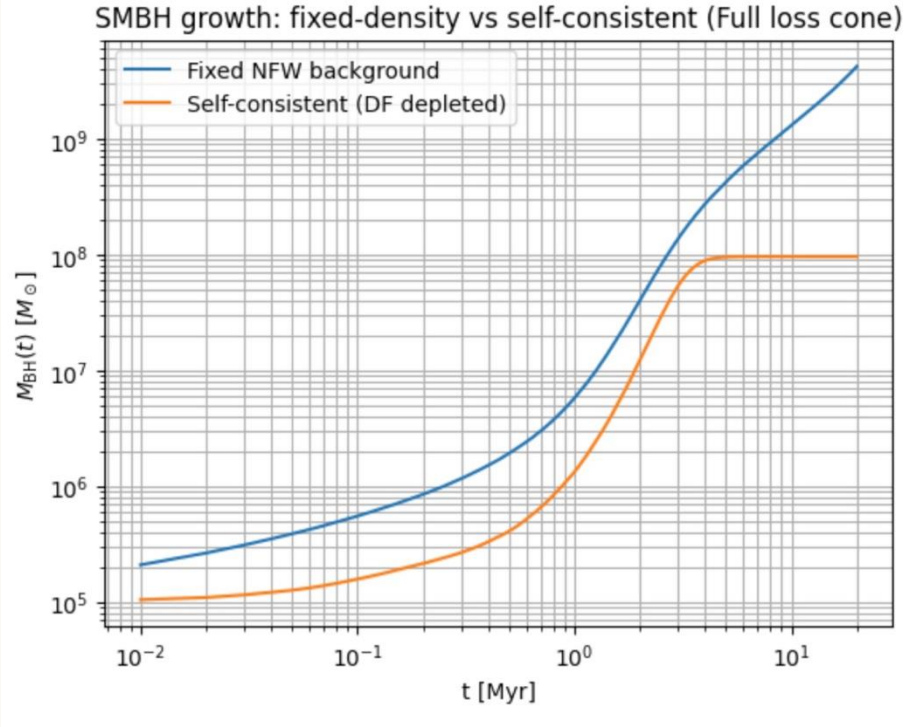
Cross-section limit: stationary isotropic bath at infinity; $v \equiv v_\infty \ll c$ (Schwarzschild capture).

Fast Feeding — but a Finite Supply

Black hole growth history



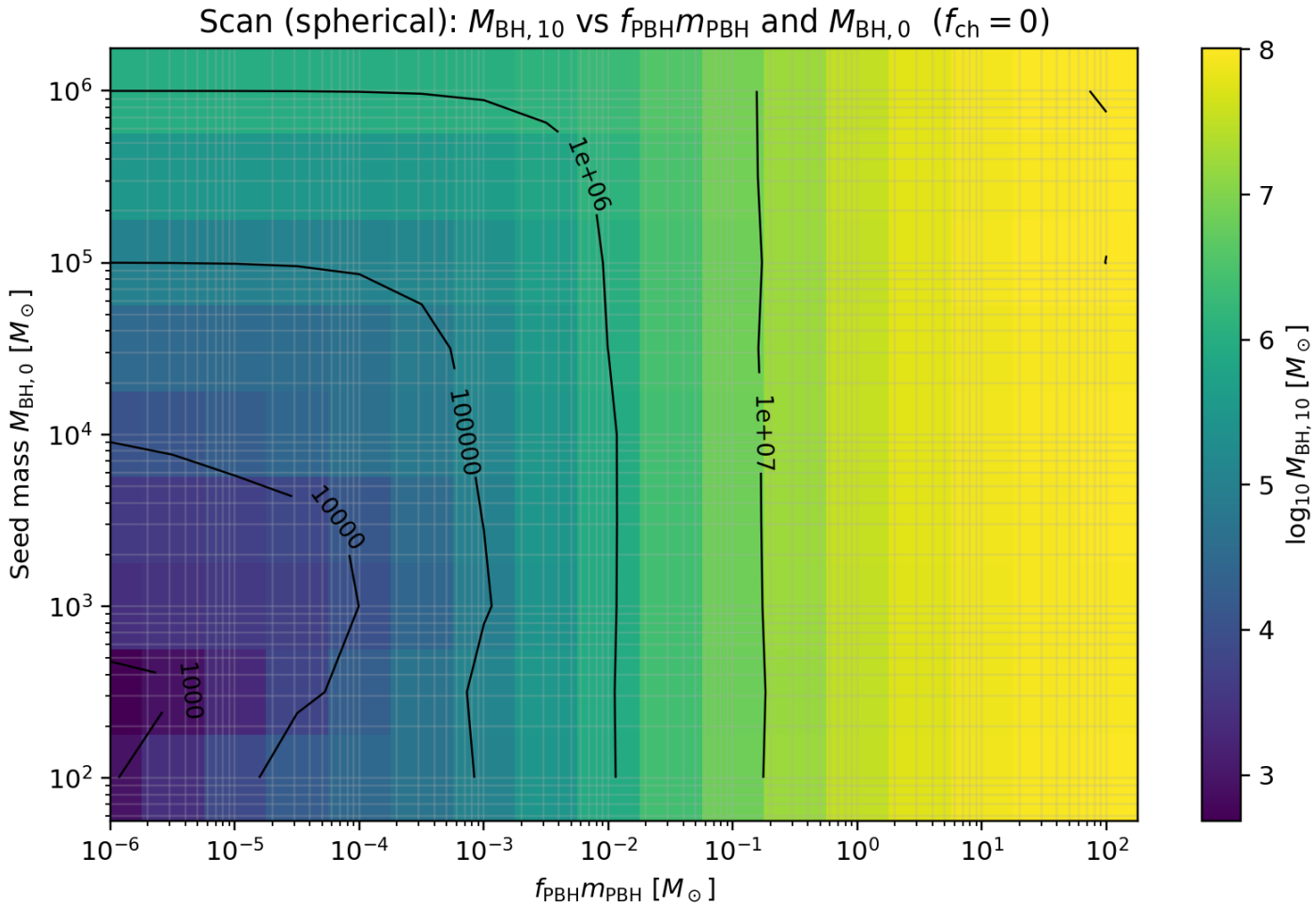
Fixed background vs. self-consistent



$$M_{BH,0} = 10^5 M_\odot, \quad M_{vir} = 10^8 M_\odot, \quad r_{1/2} = 0.1 \text{ pc}$$

Accreted mass can outweigh the initial seed

Compact spherical halo, evolved from z = 30 to z = 10



Nearly vertical contours

Final mass becomes less sensitive to the initial seed.

$$M_{\rm acc} \gg M_{\rm BH,0}$$

Weak seed dependence can occur before the loss cone is full.

The Reality Check: A TNG50-Calibrated Halo

Two benchmarks

1. Compact (theoretical)

- $\dot{M}_{BH} \propto \rho_{DM} M_{BH}^2 / \tilde{v}$
- Optimistic early growth requires

$$\rho_{\rm DM} \sim 10^8\, M_\odot\, {\rm pc}^{-3}$$

to achieve $\sim 10^7\, M_\odot$ at $z \sim 7$.

2. TNG50-like (NFW)

- Calibrated to TNG50 z ≥ 6 halos

$$\rho_s \simeq 2.49 \pm 1.05\, M_\odot\, {\rm pc}^{-3},$$
$$r_s \simeq 210.63 \pm 38.62\, {\rm pc}.$$

$$\rho(r) \sim \rho_s \frac{r_s}{r} \sim (530 \pm 360) \left(\frac{1\,{\rm pc}}{r}\right) M_\odot\, {\rm pc}^{-3}$$

- Negligible growth by $z \sim 7$ even with a full loss cone.

2. TNG50-like (Pseudo-Jaffe)

$$\rho(r) \sim (2.6 \pm 1.4) \times 10^4 \left(\frac{1\,{\rm pc}}{r}\right)^2 M_\odot\, {\rm pc}^{-3}$$

- Not excluded.

What Should We Take Away?

1

The loss-cone bottleneck is real.

- Being nearby is not enough — only low-J orbits are captured.
- The loss cone is typically underpopulated.

2

Refilling the loss cone makes a big difference.

- Stellar relaxation, PBHs, and non-spherical torques can enhance angular-momentum transport.
- Two key parameters are

$$\Xi \equiv f_{\mathrm{PBH}} m_{\mathrm{PBH}}, \quad f_{\mathrm{ch}}$$

3

Growth is fast — but self-limiting.

- Compact environments can support a rapid boost, followed by saturation as the reservoir drains.
- The adopted cosmological NFW benchmark gives negligible growth, but the TNG50 benchmark does not rule out growth by DM capture.