Cold Dark Matter and Strong Gravitational Lensing: Concord or Conflict?

Model Components

- NFW

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

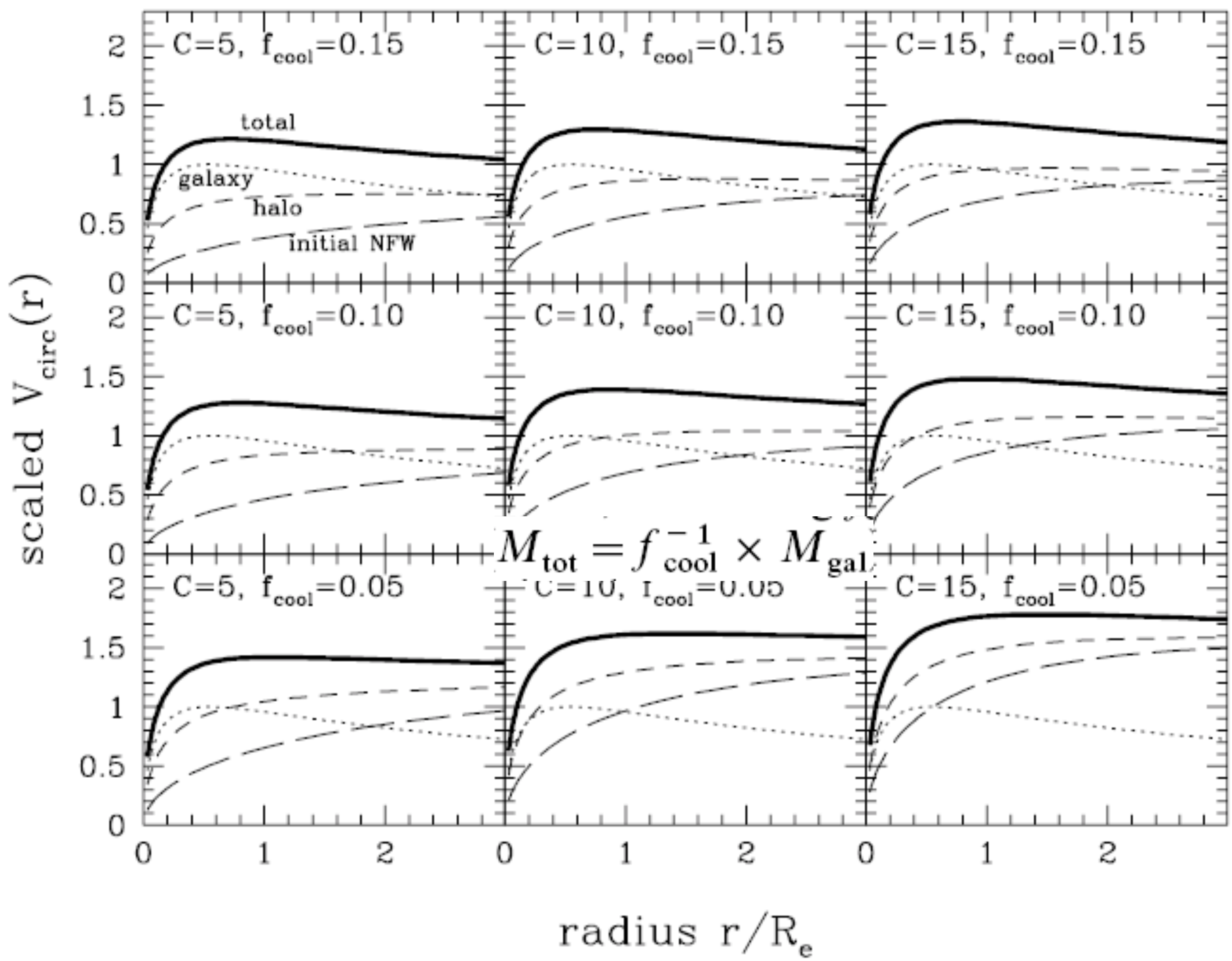
- Moore

$$\rho(r) = \frac{\rho_s}{(r/r_s)^{1.5}[1 + (r/r_s)^{1.5}]}$$

Parameters:

$$C = r_{200}/r_s$$

$$f_{\rm cool} = M_{\rm gal}/M_{\rm tot}$$



$$M_{\rm tot} = f_{\rm cool}^{-1} \times M_{\rm gal}$$

FIG. 1.—Rotation curves for sample star + halo models with NFW halos. Each panel has the specified values of the concentration C of the initial halo and the cooled mass fraction $f_{\rm cool}$; all models have $R_d/r_{200} = 0.03$. The solid curves show the total rotation curves, while the dotted and dashed curves show the contributions from the galaxy and halo, respectively. For comparison, the long-dashed curves show the rotation curves of the initial NFW halos before adiabatic contraction. The velocities are scaled by the peak velocity of the *galaxy* component.

$$M_{\rm tot} = f_{\rm cool}^{-1} \times M_{\rm gal}$$

Adiabatic contraction

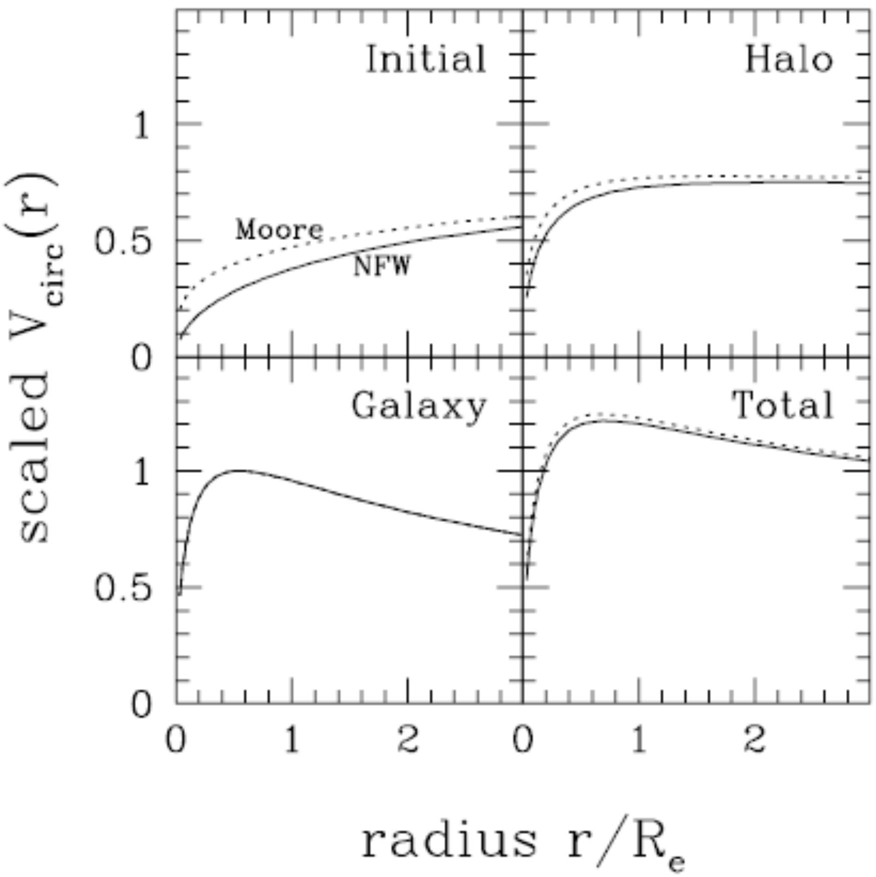


FIG. 2.—Comparison of rotation curves for NFW and Moore models. The four panels show the various components of the rotation curve. The solid curves indicate NFW models, and the dotted curves show Moore models. Results are shown for $C = 5, f_{cool} = 0.15$, and $R_e/r_{200} = 0.03$.

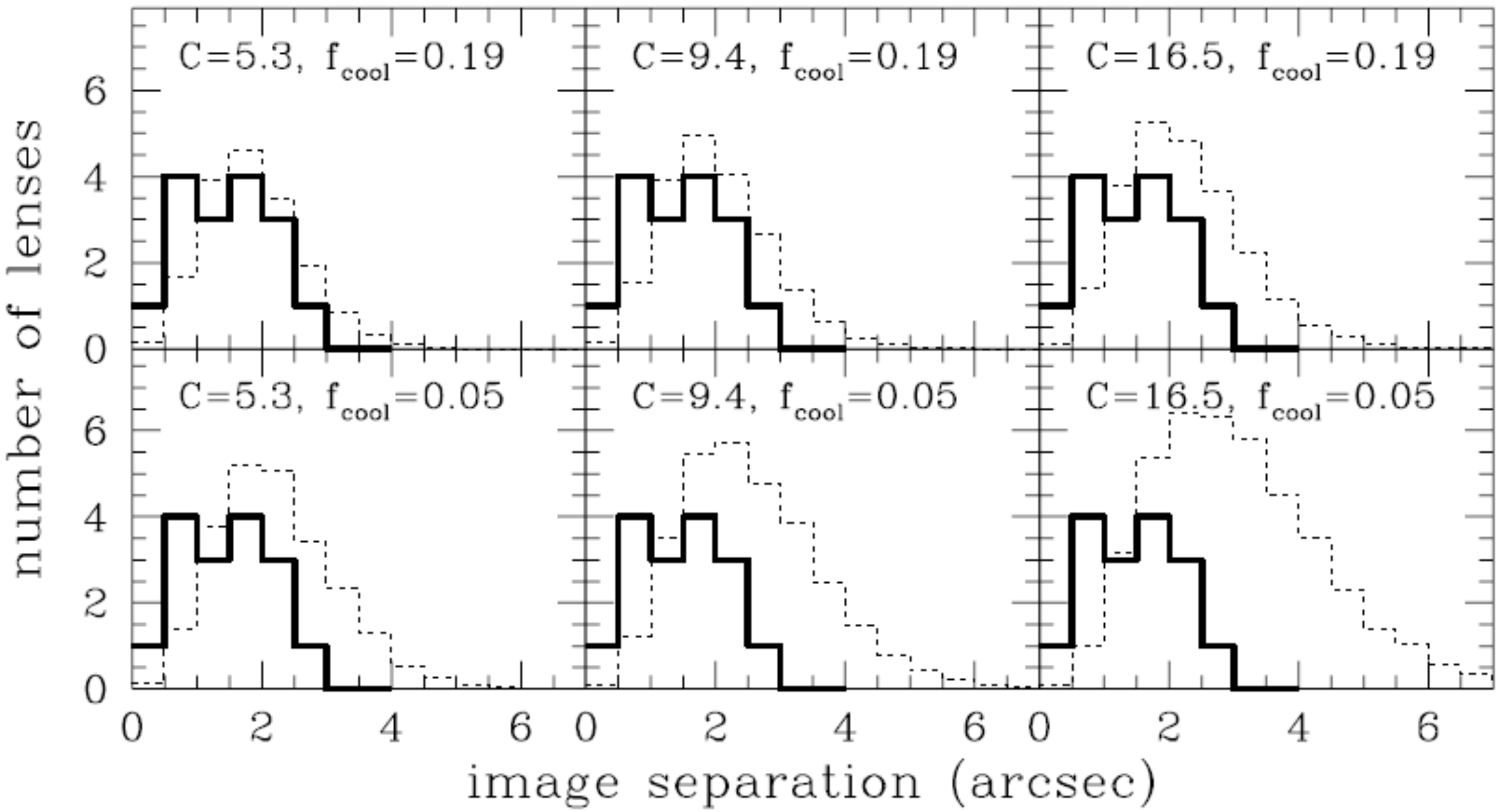


FIG. 3.—Image separation histograms for the CLASS data (*solid lines*) and for sample models (*dotted lines*). Model results are shown for the fiducial models in an $\Omega_M = 0.2$ flat cosmology. The model parameters are indicated in each panel.

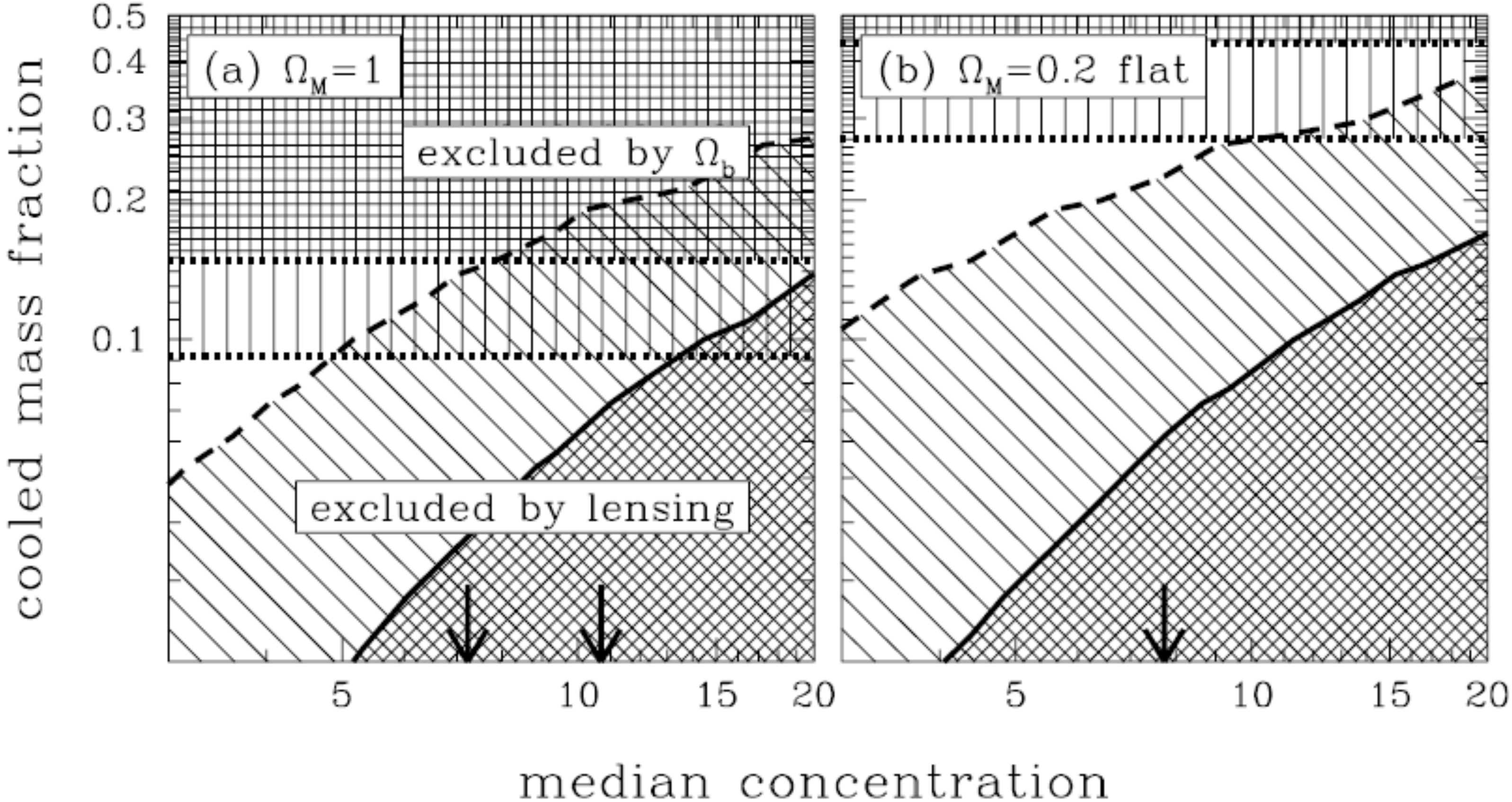


FIG. 4.—Confidence regions in the ($\hat{C}$, f_{cool})-plane for the fiducial models. The shaded regions below the diagonal curves are excluded at 95% confidence by the lens data; the lower and upper curves correspond to the N and θ tests, respectively. The shaded regions above the horizontal lines are excluded by measurements of the cosmic baryon density Ω_b. The lower curve corresponds to $\Omega_b h^2 = 0.019 \pm 0.0024$ from measurements of deuterium (Tytler et al. 2000), and the upper curve corresponds to $\Omega_b h^2 < 0.037$ (95% confidence) from the cosmic microwave background (Tegmark et al. 2001). The arrows on the x-axes indicate concentrations predicted by CDM simulations (see text). Results are shown for two cosmologies.

$$\mathcal{M}(r) \equiv \left\langle \frac{M_{\rm halo}(r)}{M_{\rm gal}(r)} \right\rangle$$

TABLE 1

HALO/GALAXY MASS RATIO

Case	Radius	$\Omega_M = 1$	$\Omega_M = 0.2$ Flat
1……	R_e	$\mathcal{M} < 0.50$	$\mathcal{M} < 0.41$
	$2R_e$	$\mathcal{M} < 0.66$	$\mathcal{M} < 0.55$
2……	R_e	$\mathcal{M} < 0.43$	$\mathcal{M} < 0.27$
	$2R_e$	$\mathcal{M} < 0.57$	$\mathcal{M} < 0.35$
3……	R_e	$\mathcal{M} < 0.50$	$\mathcal{M} < 0.44$
	$2R_e$	$\mathcal{M} < 0.68$	$\mathcal{M} < 0.60$
4……	R_e	$\mathcal{M} < 0.50$	$\mathcal{M} < 0.41$
	$2R_e$	$\mathcal{M} < .065$	$\mathcal{M} < 0.52$

NOTES.—The 95% confidence upper limits on the halo/galaxy mass ratio, defined in eq. (20), computed at two radii for two cosmologies. The four different cases are defined in the text.

The lensed image separations imply that dark matter can contribute no more than about 33% of total mass inside R_e or about 40% of the mass inside 2R_e (95% confidence)

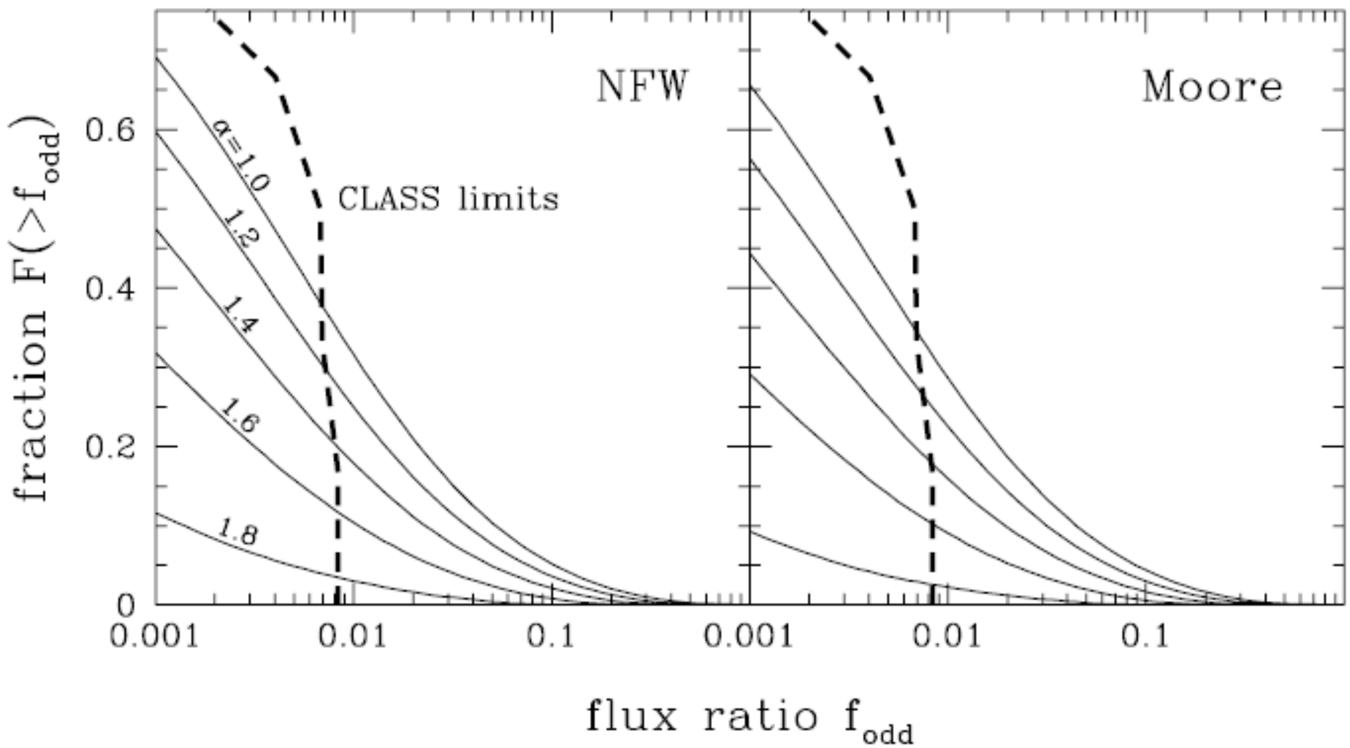


FIG. 7.—Cumulative fraction of (two-image) lenses where the ratio of the odd image to the brightest image is greater than f_{odd}. Results are shown for models with $\hat{C} = 7.7$ and $f_{cool} = 0.19$, in an $\Omega_M = 0.2$ flat cosmology. The galaxy components are modeled as $\rho \propto r^{-\alpha}(r_s + r)^{\alpha-4}$, and each curve shows results for a particular value of α; the fiducial Hernquist model corresponds to $\alpha = 1.0$. The initial mass distribution is modeled with an NFW (*left panel*) or Moore (*right panel*) profile. The heavy dashed curves show the *upper* limits derived from six two-image CLASS lenses (Rusin & Ma 2001).

- NFW

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

r << r_s , we have density ~ r^(-1)

- Moore

$$\rho(r) = \frac{\rho_s}{(r/r_s)^{1.5}[1 + (r/r_s)^{1.5}]}$$

r << r_s , we have density ~ r^(-1.5)

- The lack of odd images requires steep density profiles:

  $\rho \propto r^{-\alpha}$ with $\alpha > 1.8$ at 90% confidence

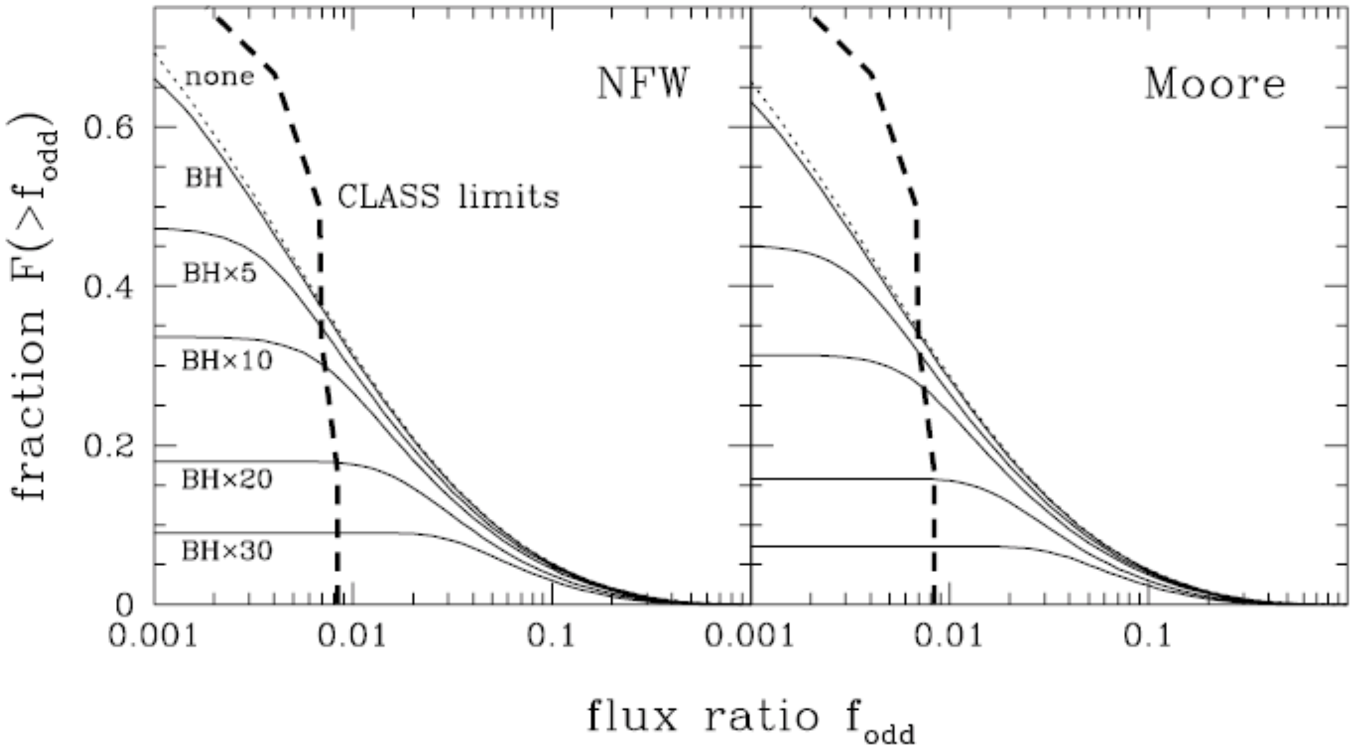


FIG. 8.—Similar to Fig. 7, but showing the effects of supermassive black holes. The dotted curves show results for star+halo models without black holes, for NFW (*left panel*) and Moore (*right panel*) models. The solid curves show results when central black holes are added. For the curves labeled "BH," the black hole masses are normalized by the empirical correlation between black hole mass and galaxy velocity dispersion (Ferrarese & Merritt 2000; Merritt & Ferrarese 2001). In the curves labeled "BH × *N*," the black holes are made systematically more massive by the factor *N*. (All galaxies have $\alpha = 1.0$.) The heavy dashed curves again show the upper limits from six CLASS lenses.