THE COSMIC EVOLUTION OF NUCLEAR BLACK HOLES

Laura Ferrarese (NRC/HIA), Patrick Côté (NRC/HIA), Michael M. De Robertis (York U.), Luigi C. Gallo (Saint Mary's U.), Patrick Hall (York U.), John Hutchings (NRC/HIA), Brian McNamara (U. of Waterloo), Chien Y. Peng (NRC/HIA), & Chris Willott (NRC/HIA)

This White Paper addresses four open questions that are of fundamental importance in understanding the origin of supermassive black holes and the evolutionary connection they share with their host galaxies: 1) What is the characterization of the local black hole mass function at the low- and high-mass ends; How do black hole scaling relations depend on environment; Are they the same for galaxies across the entire Hubble sequence or with differing levels of nuclear activity? 2) How do black hole scaling relations evolve with time? 3) What are the modalities of growth of supermassive black holes in the first few hundred million years after the Big Bang? and 4) How do supermassive black holes form? Two new facilities are necessary to answer these questions: 1) A 30m diffraction-limited optical/NIR ground-based facility, such as TMT, equipped with an $R \sim 10,000$ optical spectrograph, preferably in the form of an Integral Field Unit; and 2) a 1.5m-class NIR wide-field imaging space telescope. Two companion papers, by B. McNamara and P. Côté, address issues that are strongly complementary to the ones discussed in the paper, namely the nature of the AGN accretion and feedback processes, and the dynamical and structural properties of galaxies in the local universe — properties that are known to be affected by the central supermassive black holes.

1. HISTORICAL PROSPECTIVE

The years straddling the new millenium have been a "golden era" for the study of supermassive black holes (SBHs). Their existence (long regarded as unavoidable amongst AGN researchers) was demonstrated conclusively in NGC4258 (Miyoshi et al. 1995) and the Milky Way (Ghez et al. 2003) based on dynamical studies of the motion of gas and stars located deep within the galactic cores. For an additional, three dozen nearby galaxies, dynamical models applied to high spatial resolution kinematical data have unveiled dark objects with 10^6 to 10^9 $M_\odot$ confined within the innermost few cubic parsecs (see Ferrarese & Ford 2005 for a review). As a result, SBHs, once regarded with polite skepticism, have come to be accepted as an integral component of real galaxies.

Somewhat unexpectedly, they also emerged as key players in the assembly and evolution of galaxies. Following the discovery of numerous scaling relations linking SBHs to global galactic properties (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Graham et al. 2001; Ferrarese 2002; Haring & Rix 2004), nuclear activity in the form of AGN feedback has been invoked as an explanation for several long-standing observational challenges, such as the bimodal separation of galaxies into "red" and "blue" sequences, the observed high star formation rate at large redshifts, the existence of a population of massive galaxies at $z \sim 5$, and the thermal and chemical properties of the intracluster medium (e.g., Cattaneo et al. 2006; Bower et al. 2006; Romeo et al. 2006; Kang et al. 2006; Best et al. 2006; Sijacki & Springel 2006). Further strengthening the symbiotic nature of the relationship between SBHs and host galaxies, most low-luminosity galaxies have been discovered to host nuclear star clusters whose masses correlate with the large-scale stellar velocity dispersion in a relation analogous to the "$M-\sigma$" relation for SBHs (Ferrarese et al. 2006; Côté et al. 2006; Wehner & Harris 2006; Rossa et al. 2006, Figure 1). At the dawn of a new decade, the message is clear: the interconnections between AGNs, the global properties of galaxies, and the evolution of structure over cosmic time cannot be ignored.

But many challenges remain. A secure characterization of SBH scaling relations in local galaxies is sorely needed. The redshift evolution of these scaling relations is poorly constrained. Nothing is known of the critical few hundred million years that separate the formation of seed black holes from the 10^9 $M_\odot$ heavy-weights observed at $z = 6$. With the imminent launch of JWST and the commissioning of ALMA, Canadian astronomers are poised to lead research in this field. However, a pair of new facilities — an $R \sim 10,000$ spectrograph (ideally an Integral Field Unit) on a diffraction-limited 30m ground based optical telescope (e.g., TMT), and a 1.5m-class wide-field NIR imaging space telescope — are needed to usher in the next golden era in the study of SBHs.

2. DEFINING LOCAL SCALING RELATIONS.

With a few notable exceptions, dynamical measurements of SBH masses, M_{BH}, have been the exclusive territory of HST. A requirement for detections relying on the dynamical modeling of spatially resolved (stellar or gaseous) kinematics is to map the SBH *sphere of influence*: i.e., the region of space within which the SBH dominates the gravitational potential and therefore the kinematics of the surrounding material. The sphere of influence has radius $r_h = GM_{BH}/\sigma^2 \sim 11.2(M_{BH}/10^8$ $M_\odot)$ / $(\sigma/200$ km/s$)^2$ pc, with σ being the stellar velocity dispersion. Under the very best seeing conditions, non-AO instruments on ground-based telescopes can target 10^8 $M_\odot$ SBHs ($r_h \sim$14 pc) out to a distance of 5 Mpc. By reaching ~ 25 Mpc, HST/STIS allowed access to the brightest galaxies in the Virgo and Fornax clusters.

Indeed, ten years of research with HST have produced almost three dozen SBHs detections. However, after some frenetic activity in the early 2000s, HST's resolution and light gathering abilities have now been exploited to their fullest. Progress has slowed significantly, and entire classes of galaxies have remained unexplored.

Two issues deserve particular attention. As an essential diagnostic tool for theoretical models for the formation and evolution of SBHs, the current sample — mostly early-type galaxies in low-density regions — must be expanded to cover galaxies across the entire Hubble sequence and in a variety of environments. Likewise, the high- ($> 10^9$ $M_\odot$) and low-mass ($< 10^6$ $M_\odot$) end of the SBH mass function — largely unexplored at the present time — must be characterized, as these SBHs represent the end-products and building blocks, respectively, of the structural assembly of black holes and galaxies.

These goals, which require a significant boost in both angular resolution and light gathering power compared to HST, can only be achieved by the next generation of large, diffraction-limited, ground-based telescopes. Figure 2, which addresses resolution constraints, shows that late-type galaxies host SBHs that are too "small" to be detected by HST, and while an 8m diffraction-limited telescope can target galaxies spanning the entire Hubble sequence, it will not break the 10^6 $M_\odot$ barrier. A 30m aperture, however, would allow this limit to be lowered by an order of magnitude. Moreover, once sensitivity requirements are folded in, a 30m aperture is required to reach SBHs in galaxies as far as 100 Mpc (Figure 3). The advantage of two-dimensional spectroscopy is harder to quantify, although existing studies have shown the central kinematics of galaxies to be very complex (e.g., Emsellem et al. 2007). Neglecting this complexity will lead to incorrect or incomplete dynamical models, and biased estimates of the central potential and mass distribution.

In conclusion, a TMT-like diffraction-limited (at 8000 Å) facility with medium resolution ($R \sim 10,000$) spectroscopic capabilities (preferably an IFU, even if over a limited field of view) would open a new frontier in the study of local SBHs, akin to what HST has done in the past decade: i.e., investigate the existence of SBHs below 10^6 $M_\odot$, explore the demography of SBHs in the richest Abell clusters within 100 Mpc, and address the connection between SBHs, galaxy structure, and environment.

3. THE COSMIC EVOLUTION OF GALAXIES AND SBHS.

The cosmic evolution of scaling relations linking SBH masses to the global properties (luminosity, velocity dispersion) of the host galaxy is a direct probe of the mechanisms that regulate the joint evolution of galaxies and SBHs (e.g., Croton 2006; Robertson et al. 2006). The flurry of observational activity in this area is therefore not surprising, but has failed to produce a consensus view. The challenge is that a succession of different techniques/galaxies must be adopted/targeted as the redshift increases, as no consistent method or sample is applicable throughout. Dynamical studies of resolved kinematics — which define the local relations in quiescent galaxies — cannot, at present, be applied to galaxies beyond the local volume. At distances larger than $\sim$ 100 Mpc, SBH mass measurements are restricted exclusively to Type 1 AGNs. In these galaxies, reverberation mapping (e.g., Peterson 2002) can provide precise estimates of SBH masses under the assumption of a virialized Broad Line Region (BLR). However, since the method is observationally very intensive, SBH masses are generally measured using secondary empirical mass estimators — again applicable only to Type 1 AGNs — that rely on single-epoch spectroscopic observations (e.g., Wandel et al. 1999; Vestergaard & Peterson 2006). In addition to measuring M_{BH}, characterizing the large-scale properties of the host galaxy becomes increasingly difficult (both because of the large angular distance and because the galaxies are nearly always outshined by the central AGN). High-resolution HST imaging is a must in the most nearby ($z \lesssim 0.6$) Seyfert galaxies, for which the central AGN is relatively faint (e.g., Treu et al. 2007; Woo et al. 2008; Bennert et al. 2010). At greater distances, gravitational lensing has been used successfully to magnify and resolve the host galaxies (e.g., Peng et al. 2006a, 2006b; but see also Decarli et al. 2010).

A TMT facility presents a unique opportunity to homogenize these different techniques and build a coherent picture from the local volume to cosmologically significant redshifts. With TMT, dynamical studies of resolved kinematics in *quiescent* galaxies can be pushed to $z \sim 0.4$, 0.1 and 0.025 as the SBH mass is decreased from 10^9 to 10^8 and 10^7 $M_\odot$.[1] A dynamical detection of SBHs in reverberation mapped AGNs (of which many examples are available within $z < 0.4$) will not only offer a direct insight onto the morphology and kinematics of the BLR (Onken et al. 2004), but also provide a direct calibration for the method and all empirical scaling relations used to push SBH detections to higher redshifts.

TMT will also be instrumental in the study of the dynamics and structural properties of the AGN hosts. In a 3-hr exposure, TMT can measure stellar velocity dispersions in galaxies with effective radii as low as 1.5 kpc (expected to host SBHs of 10^8 $M_\odot$) out to $z \sim 2.5$. For comparison, a 10m-class telescope could only reach out to $z \sim 1.0$, and likely significantly less in galaxies with strong AGN components. At higher redshifts, TMT will be able to produce direct imaging of quasar hosts.

4. THE EARLY GROWTH OF SBHS.

From local galaxies to high-redshift quasars, SMBs have been traced from the present day all the way back to when the universe was less than 1 Gyr old ($z = 6.44$). More distant quasars not only probe the growth of SBHs during the earliest phases of galaxy formation, but also act as beacons with which to trace the reionization history of the universe, as their bright continuum at rest-frame UV wavelengths provides an opportunity for Lyα absorption by neutral hydrogen in the intervening IGM.

The SDSS and Canada-France High-z Quasar Survey (CFHQS, Willott et al. 2009), have discovered close to 50 bright ($M_{1450} \lesssim -24.2$, roughly $m(J) \sim 22$ AB mag) quasars at $z \sim 6$. This is an impressive achievement, but not sufficient to probe a deep enough path-length of the IGM to witness how reionization unfolds. SDSS J114816.64+525150.3 at $z = 6.42$, is powered by a several 10^9 $M_\odot$ black hole (Willott et al. 2003), comparable to the most massive SBHs known in the local universe. The challenge for the next decade will be to bridge the gap — in time and mass — that separates SDSS J114816.64+525150.3 from the birth of the first seed black holes.

The detection of high-redshift quasars is based on the unique color produced as Lyα transitions across the filter bandpasses as the redshift increases. At $z \gtrsim 6.6$ quasars become z-band dropouts, requiring observations at longer wavelengths. Figure 4 (from Willott et al. 2010) shows that ground-based NIR surveys are too shallow and/or do not have wide enough areal coverage to detect a significant number of quasars beyond $z = 7$. The true advance in this field will only come with the next generation of space-based telecopes designed to perform wide, medium-deep and deep surveys, such as Euclid (ESA) and JDEM (NASA/DOE). Both missions are in the planning stages and full operational details are

[1] Sensitivity requirements reduce these limits to $z \lesssim 0.1$ for the most massive SBHs if stellar kinematics are used, but not if gas kinematics are available.

not known. However, their main science objective — the evolution of dark energy through a combination of supernovae, baryonic acoustics oscillations and weak lensing — require deep NIR surveys over wide areas. Assuming a 20,000 square degree imaging survey to a depth of H = 23.3 mag, Figure 4 shows that Euclid/JDEM would be able to detect ~ 1000 quasars at $z \sim 7$, ~ 400 at $z \sim 8$, and ~ 100 at $z \sim 9$. At even higher redshifts, predictions become increasingly more uncertain. As one moves further towards the epoch of SBH formation, quasars not only dim because of the increased luminosity distance, but also because their SBHs are growing with time: a bright quasar at $z = 6$ is expected to be at least 800 times fainter at $z = 17$, and possibly significantly fainter, depending on the radiative efficiency of accretion (Figure 5). It follows that deeper surveys are required the higher the redshift of the objects targeted.

Figure 6 attempts to predict the quasar number density expected in ultra deep ($K \sim 28$ mag) surveys. The solid curves show the cumulative space density per square degree extrapolated from the $z = 6$ quasar luminosity function of Willott et al. (2010) under the assumption of no black hole growth; while the dashed curves fold in the luminosity evolution expected for $\epsilon = 0.4$. Under the (unrealistic) assumption of no black hole growth, a survey reaching $K = 28$ mag and covering ~ 10 square degrees could detect $\sim 10-20$ quasars for every 100 million year interval in lookback time between redshift 6 and 15; the number would be reduced by as much as an order of magnitude (depending on the redshift) in the case of active SBH growth with $\epsilon = 0.4$.[2] Surveys of this magnitude can *only* be carried out by a space-based mission as ambitious (or more) as Euclid or JDEM.

5. POPULATION III STARS AND SEED BLACK HOLES.

While the formation of stellar-mass black holes is grounded in the solid framework of stellar evolutionary theory, models for the formation of SBHs are entirely unconstrained at the present time.

Seed black holes, in the range of hundreds of solar masses, are predicted to be left behind by the collapse of the first generation of stars which form from primordial, metal-free gas as early as $z = 30$–50 and possibly as late as $z = 5$. Below 140 $M_\odot$ and above 260 $M_\odot$, Pop III stars are predicted to collapse directly into a black hole, but for intermediate masses, they are believed to undergo a pair-instability supernova (SN) explosion (Heger et al. 2002; Langer et al. 2007) that makes them ≈ 100 times brighter than a typical Type Ia SN.

Pop III stars play a central role in establishing the physical conditions under which the first galaxies form, figuring prominently in models for the initial stages of reionization, the chemical enrichment of the IGM, and the formation of seed black holes. An understanding of their redshift distribution, formation mechanisms, and mass function would therefore have a profound impact on our understanding of structure formation in the universe.

Unfortunately, no Pop III star has ever been observed. Gamma ray bursts (GRBs) that *might* be generated as Pop III stars collapse (Bromm & Loeb 2006) are within the reach of the Swift satellite, but have not yet been detected (e.g. Salvaterra et al. 2009; Tanvir et al. 2009). An alternative approach is through the direct detection, in the near-infrared, of Pop III pair instability SN explosions. Figure 7 shows the theoretical light curve expected at different wavelengths (in the observer's rest frame) for a SNa originating from a 250 $M_\odot$ Pop III stars at $z = 20$ (from Heger et al. 2002). As the figure shows, the time spent near peak brightness, and therefore the likelihood of discovery, is higher at longer wavelengths. The time Δt spent by the SN within 1 mag of peak brightness varies as $\lambda/(1+z)$, where λ is measured in the observer's frame. In the $K-$band, at $z = 10$ and $z = 17$ (beyond which Lyα is redshifted out of the band) $\Delta t \sim 1$ month and 3 weeks, respectively, while peak brightness is $K \sim 25$-26 mag. Folding in the (conservative) assumption that the surface density of Pop III SNe is a few per square degree per year, a search for $z = 10 - 17$ Pop III SNe must therefore observe $\gtrsim 10$ square degrees at a depth of $K \leq 27$ during a minimum of two successive visits separated by at least a month.

Is this feasible with JWST? The NIRCAM instrument can reach $K = 27.0$ mag (10σ detection) in 250 seconds, but given the 4.75 arcmin^2 field of view, it would take ~ 50 hours to cover 1 deg^2. However, a revisit of the same area two more times at intervals of $\sim$ several months (needed to confirm transients) would effectively produce a 3 deg^2 survey, and possibly detect a few to a few tens of Pop III SNe. While this would be a very significant discovery, it would not have the statistics sufficient for a proper characterization of Pop III stars. The latter goal would require a wide-field NIR space telescope. A facility like JDEM (i.e. a 0.4–2.0 μm imager with a 0.312 deg^2 FOV, on a 1.2–1.7m platform) would be an order of magnitude less sensitive than JWST/NIRCAM, but ~ 250 times more efficient in areal coverage, presenting a $20\times$ improvement in efficiency for a SN search. Follow-up spectroscopy, on the the hand, is a task that is uniquely suited to JWST/NIRSpec. Of course, this suggests that the discovery observations must be carried out during the time frame when JWST is operational.

6. CONCLUSIONS AND RECOMMENDATIONS.

In this White Paper, we have focused on four science questions and the two specific technological advances required to answer them: a 30m diffraction-limited optical/NIR ground-based facility, and a 1.5m NIR wide-field imaging space telescope. Canada is well poised to make timely and significant contribution to both endevours.

We will conclude by mentioning the existing or planned facilities that will also play a part in this game. Among the current facilities, if equipped with a wide-field, high angular resolution (~ 0.3 arcsec) optical imager, CFHT stands out as being the most beneficial. It would act as a complement for deep wide-field NIR surveys, and would allow a detailed study of the nuclear-to-global structural parameters for SBH host galaxies in the nearby universe. JWST and ALMA will begin full operation in 2014 and 2013, respectively. Both will allow the measurement of SBH masses in nearby universe; ALMA in particular will provide up to an order of magnitude improvement in spatial resolution over HST, and – in the presence of circumnuclear molecular gas – will target galaxies 10 times as far, or hosting SBHs ~ 6 times less massive than

[2] Note that the survey would have to be carried out over multiple filters to detect dropout and confirm the redshifts, and would require TMT/JWST follow-up.

currently known. JWST is capable of detecting a few quasars and/or Pop III SN at $z > 7$, but not of building statistically significant samples of either. However, both JWST and ALMA will be indispensable for the follow-up of high redshift sources, and for the study of the dust-enshrouded SBH host galaxies over cosmic time. On a more distant horizon, the (yet to be funded) International X-ray Observatory (IXO) will provide a complete census of accreting SBHs (as small as a few 10^6 $M_\odot$) out to $z \sim 7-8$ (see also White Paper by L. Gallo). By being sensitive to optically obscured AGNs, IXO will complement the optically bright quasar surveys discussed in this White Paper.

Lastly, it must be stressed that involvement in even the most exciting missions will not come to full fruition unless a proportional investment is made in hiring qualified personnel. Canada has a distinguished history in training excellent students in Astronomy, but a poor record in supporting postdoctoral research. If Canada is to remain competitive, astronomers at Universities and Reseach Institutes across the country must have access to grants to fund project-specific postdoctoral positions.

REFERENCES

Bennert, V., et al. 2010, ApJ, 708, 1507
Best, P.N., et al. 2006, MNRAS, 368, 67
Bower, R.G., et al. 2006, MNRAS, 370, 645
Broom, V., & Loeb, A. 2006, AIPC, 836, 503
Cattaneo, A., et al. 2006, MNRAS, 370, 1651
Côté, P., et al. 2006, ApJS, 165, 57
Croton, D. 2006 MNRAS, 369, 1808
Decarli, R., et al. 2010, MNRAS, in press
Emsellem, E., et al. 2007, MNRAS, 379, 401
Ferrarese, L. 2002, ApJ, 578, 90
Ferrarese, L., & Ford, H. 2005; Space Science Reviews, 116, 523
Ferrarese, L. & Merritt, D. 2000, ApJL, 539, 9
Ferrarese, L., et al. 2006, ApJ, 644, L21
Gebhardt, K., et al. 2000, ApJ, 539, L13
Ghez, A., et al. 003, ApJ, 586, L127
Graham, A., et al. 2001, ApJ, 563, L11
Haring, N., & Rix, H.-W. 2004, ApJ, 604, 89
Heger, A. et al. 2002, in Lighthouses of the Universe, ed. Gilfanov, Sunyaev, & Churazov, Springer-Verlag, p. 369
Kang, X., et al. 2006, ApJ, 648, 820
Langer, N. et al. 2007, A&A, 475, 19
Miyoshi, M. et al. 1995, Nature, 373, 127
Onken, C. A., et al. 2004, ApJ, 615, 645
Peng, C. Y., et al. 2006a, ApJ, 640, 114
Peng, C. Y., et al. 2006b, ApJ, 649, 616
Peterson, B., 2002, in "Advanced Lectures on the Starburst-AGN Connection". Singapore: World Scientific, p.3
Robertson, B, et al. 2006, ApJ, 641, 90
Romeo, A.D., et al. 2006, MNRAS, 371, 548
Rossa, J., et al. 2006, AJ, 132, 1074
Salvaterra, R., et al. 2009, Nature, 461, 1258
Sijacki, D., & Springel, V. 2006, MNRAS, 366, 397
Tanvir, N.R., 2009, Nature, 461, 1254
Treu, T., et al. 2007, ApJ, 667, 117
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Wandel, A., Peterson, B. M., & Malkan, M. A. 1999, ApJ, 526, 579
Wehner, E., & Harris, W.E. 2006, ApJL, 644, L17
Willott, C., et al. 2003,ApJ, 587, L15
Willott, C., et al. 2009, AJ, 137, 3541
Willott, C., et al. 2010, AJ, 139, 906
Woo, J.-H., et al. 2008, ApJ, 681, 925

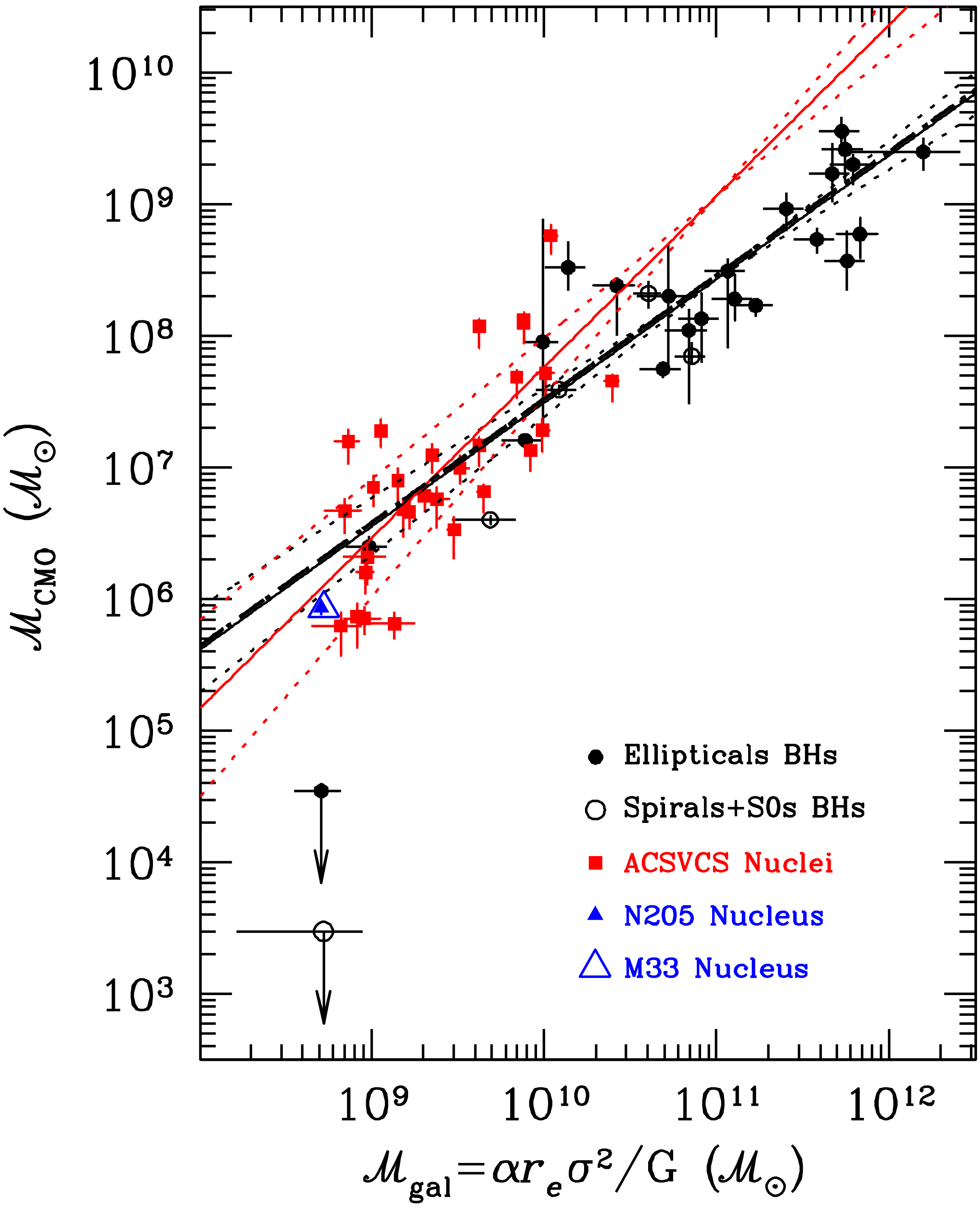

FIG. 1.— The correlation between the mass of central massive objects (M_{CMO}) and galaxy mass for SBHs (in black) and stellar nuclei (in red). All galaxies with secure SBH masses based on resolved kinematics are shown; these are mostly early-type galaxies and all are within 100 Mpc. The nuclei are those detected in early-type galaxies in the Virgo cluster by Côté et al. (2006). In galaxies spanning four orders of magnitudes in mass, a constant 0.2% of the mass is confined in a nuclear structure, regardless of whether this is a nuclear star cluster or a SBH, possibly suggesting an evolutionary path that is regulated by similar mechanisms. The solid lines are fits to the data; the dashed lines represent 1σ uncertainties on the fit. From Ferrarese et al. (2006)

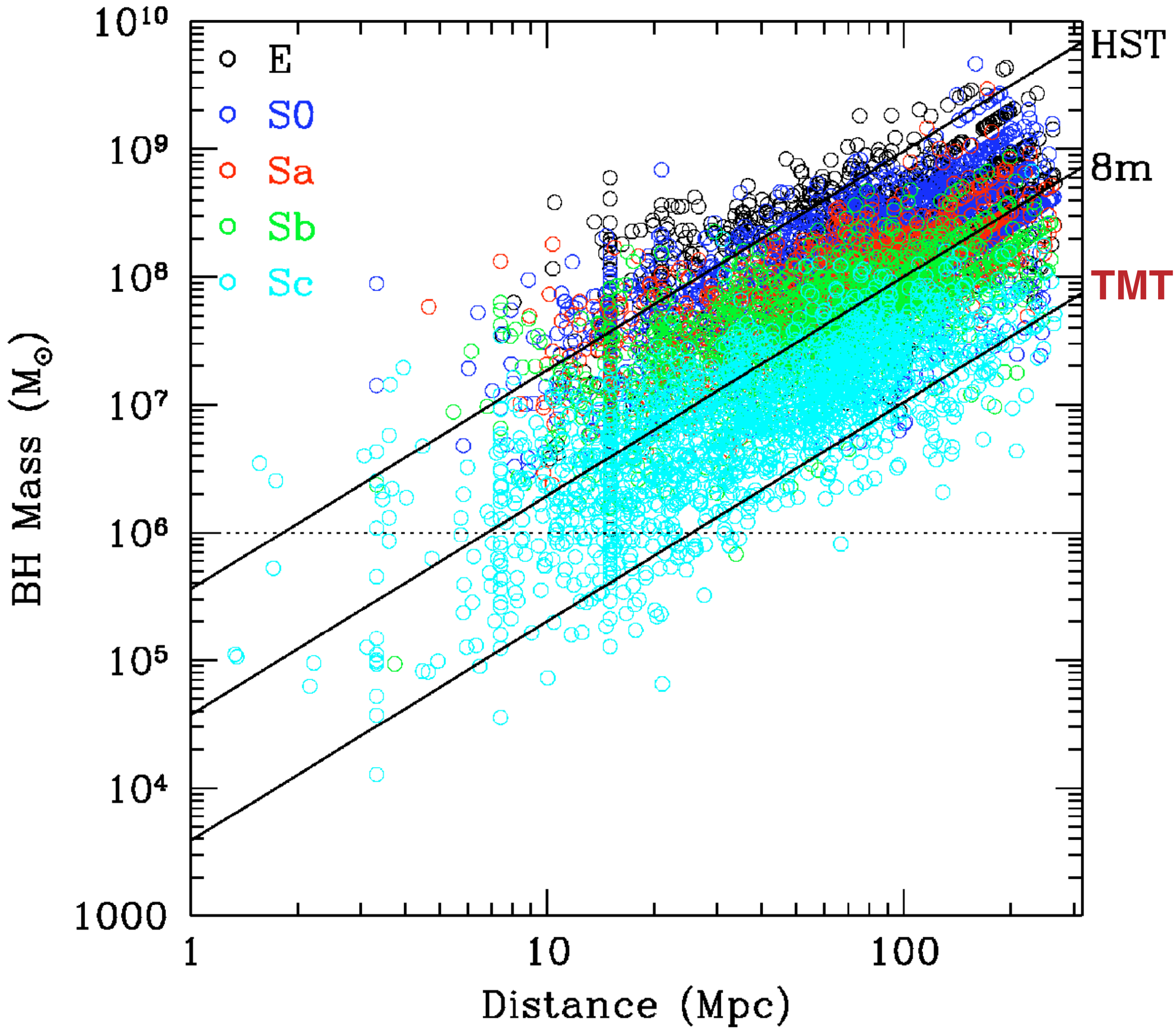

FIG. 2.— Resolution requirements for the detection of SBHs in local galaxies. For each galaxy in the CfA redshift sample (Huchra et al. 1990), the SBH mass has been estimated using the known relation with bulge luminosity (as in Ferrarese & Ford 2004). The solid lines identify SBHs for which r_h is equal to the diffraction-limited resolution of a 2.4m (HST), 8m and 30m (TMT) aperture at 8550 Å (i.e., at the Ca triplet). For each facility, spatial resolution requirements necessary for resolved dynamical studies are met only by galaxies which lie above the corresponding solid line. The galaxies are color coded according to their Hubble type, as shown in the legend.

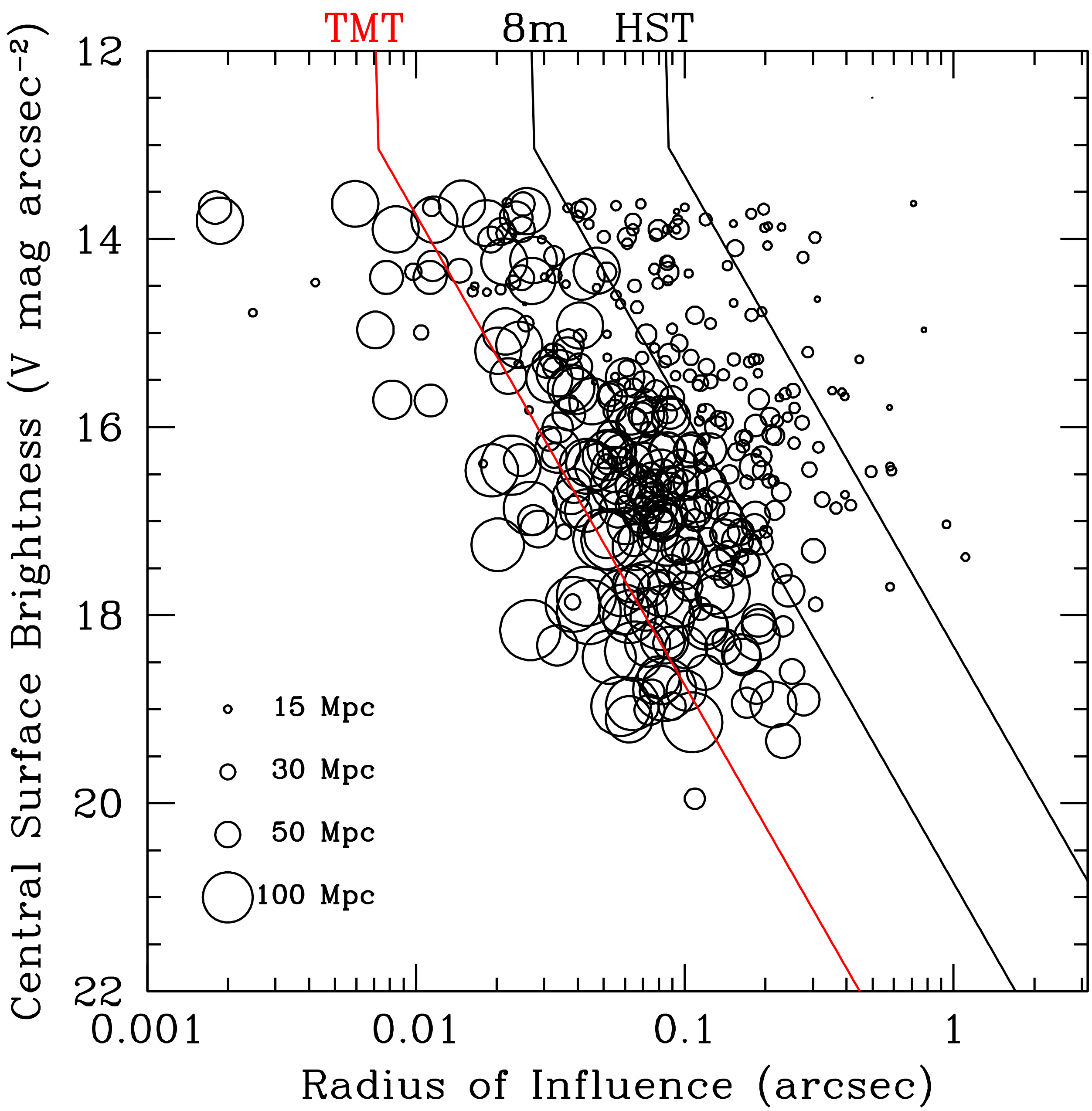

FIG. 3.— SBH radius of influence vs. central surface brightness for the early-type galaxy sample of Faber et al. (1989). The size of the symbol is proportional to the galaxy distance, as shown in the legend. The solid lines show the constraints dictated by the requirements on resolution (the vertical segment) and sensitivity (slanted lines) for 2.4m (HST), 8m and 30m (TMT) diffraction-limited apertures. The photometric zero points for the 8m and 30m apertures are assumed equal to the HST/STIS photometric zero points (in other words, it is assumed that the increase in aperture size is exactly balanced by the decrease in the size of the resolution element), which gives a S/N=50 in a 9000s exposure for $\mu_V = 13$ mag arcsec^{-2}.The spectra are spatially binned to match the SBH radius of influence.

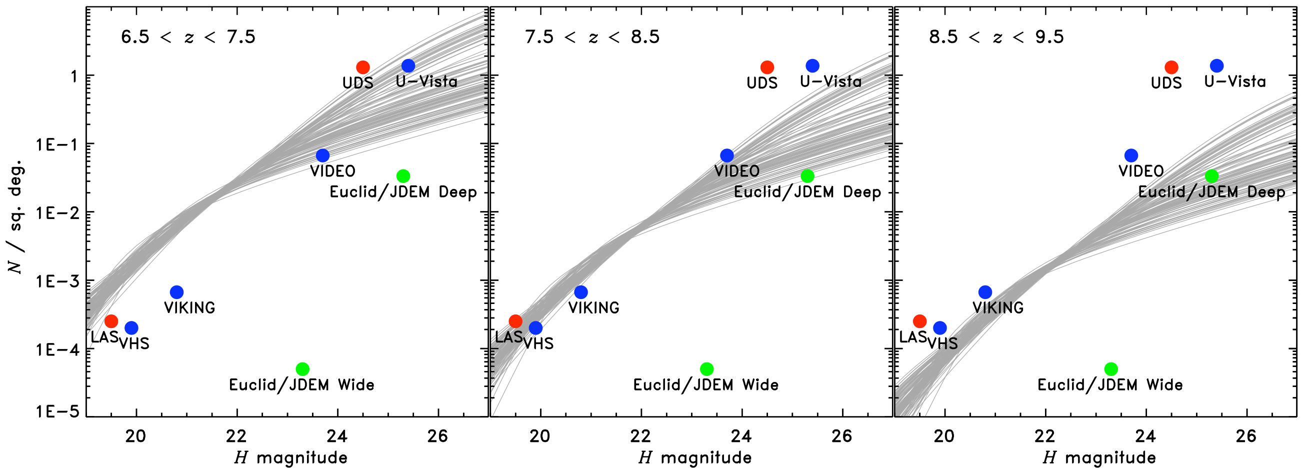

Fig. 4.— The gray lines show different bootstrap realizations of the predicted cumulative sky surface density (in number per square degree) for quasars in three redshifts slices (as shown in the upper left corner of each panel) based on the luminosity function from Willott et al. (2010), which includes a redshift density evolution as given by Fan et al. (2001). The depths reached by several on-going or planned NIR surveys are shown by the symbols, which are placed at the surface density necessary to produce the detection of one quasar in any given redshift slice. Only surveys that are found one or more orders of magnitude below the gray curves are expected to produce a significant advance in this field. From Willott et al. (2010).

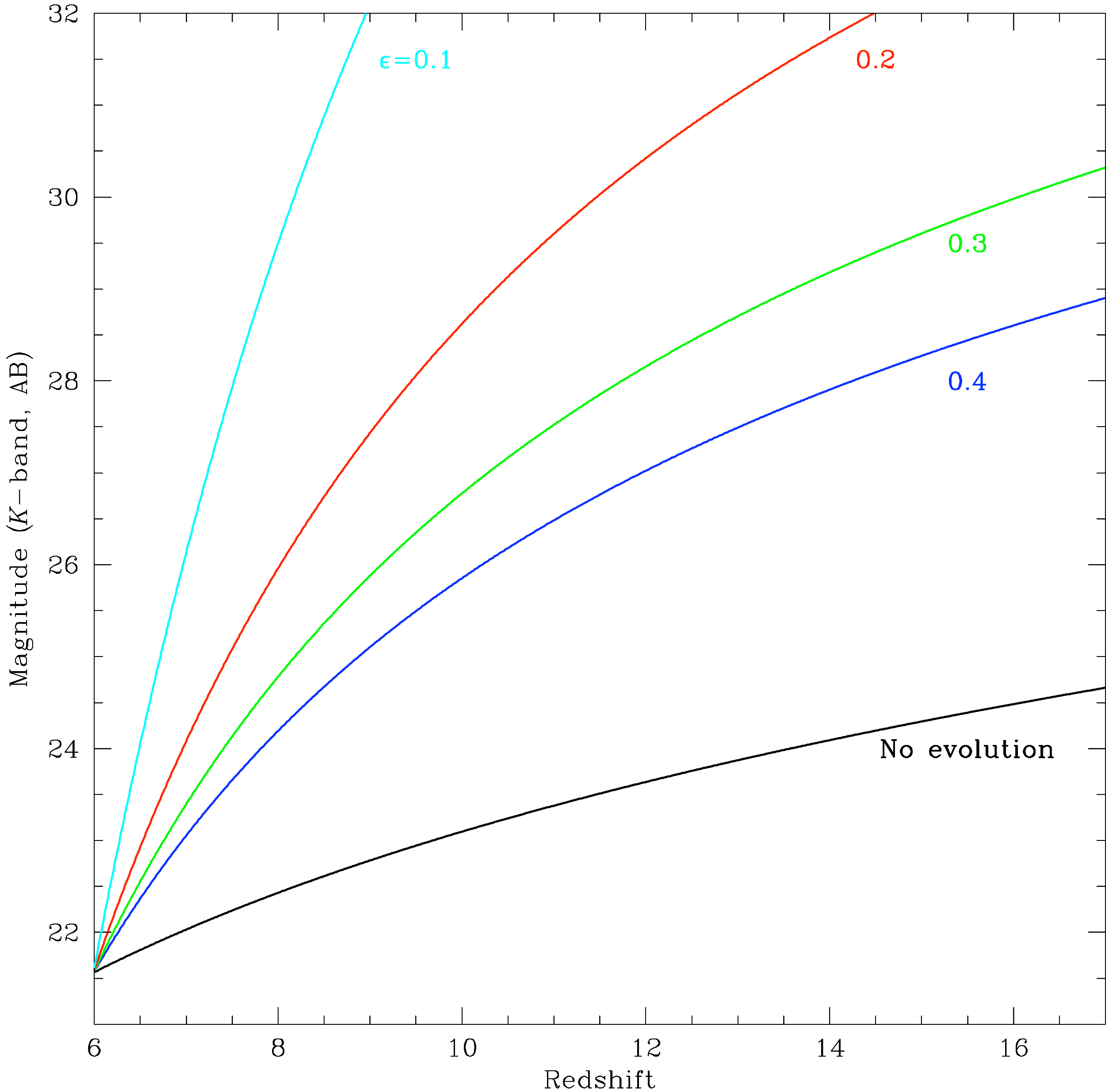

FIG. 5.— The redshift evolution of a quasar whose 1450 Å monochromatic magnitude at $z = 6$ is −25 ($K \sim 21$ mag); this corresponds to the faintest quasars detected at this redshift (see Willott et al. 2010). The curves show cases for a constant ratio of bolometric to Eddington luminosity $\eta = 1$ (which is imposed by the need to assemble massive, 10^9 $M_\odot$ quasars by a redshift $z = 6$) and different values of the radiative efficiency, $\epsilon = L/c^2/\dot{M}$, where L is the quasar luminosity and $\dot{M}$ is the mass accretion rate.

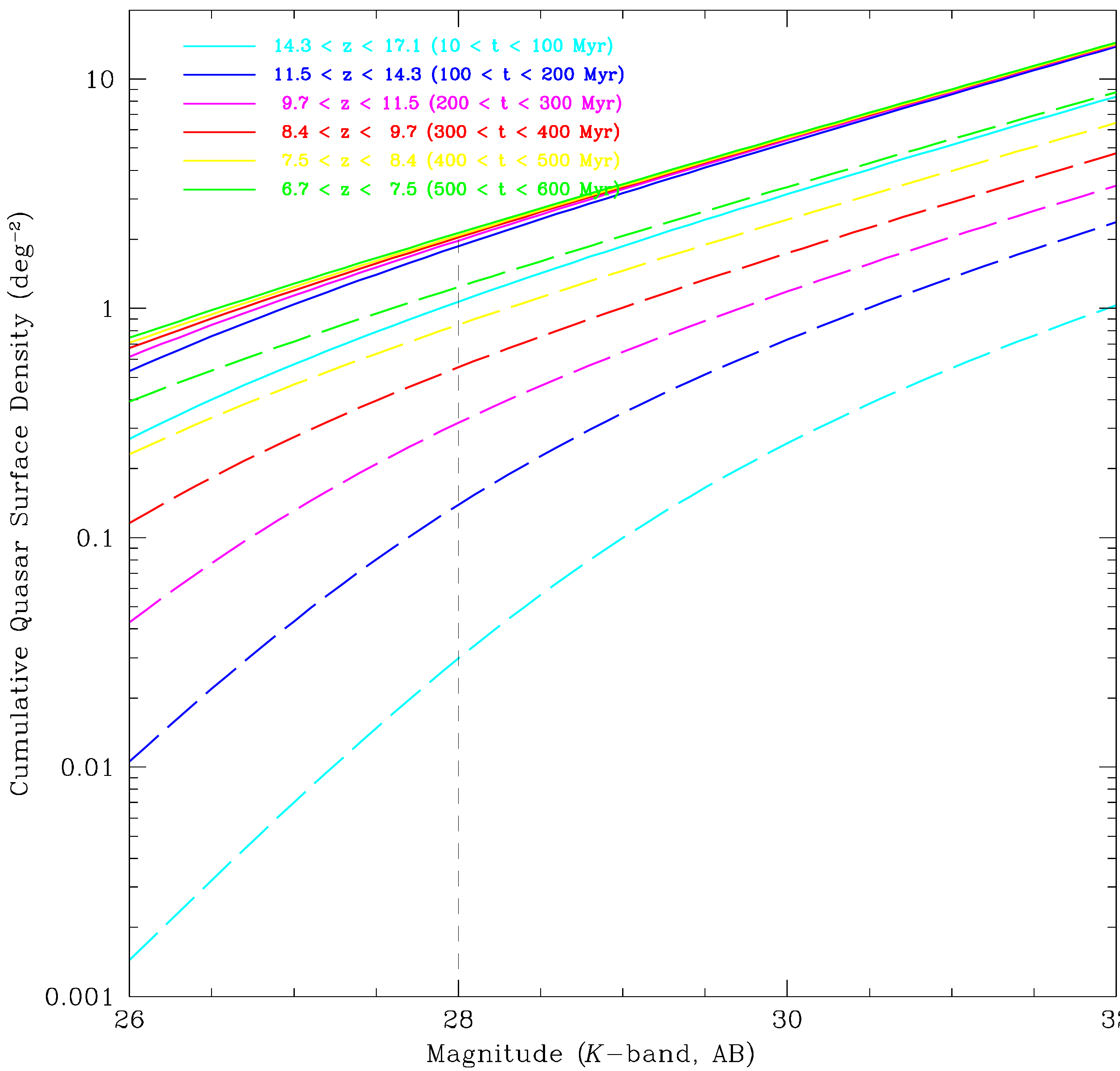

Fig. 6.— Cumulative surface density of quasars as a function of limiting magnitude, calculated for various redshift ranges (corresponding to 100 Myr intervals in lookback time) as shown in the legend, and based on the extrapolation of the $z = 6$ luminosity function of Willott et al. (2010). The solid curve represents the idealized case in which the number density of quasar does not vary with redshift, and the quasar dimming is due simply to the increased luminosity distance. The dashed curves show the case in which the quasars are accreting at the Eddington rate (and therefore their mass decreases exponentially with increasing redshift) and are radiating with radiative efficiency $\epsilon = 0.4$.

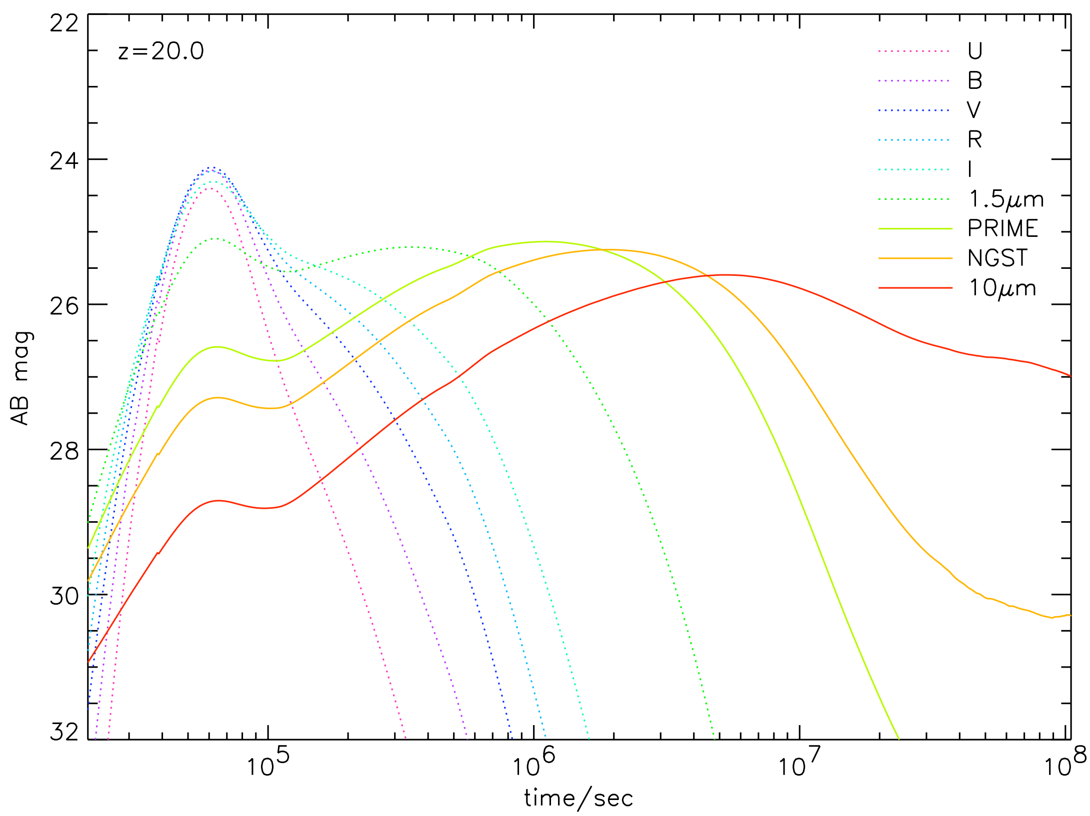

FIG. 7.— Predicted light curves, at different wavelengths, for a supernova explosion generated by a 250 $M_\odot$ Pop III star progenitor at $z = 20$. All quantities are given in the observer's rest frame; light curves shown as dotted lines (i.e., bluewards of 2.55 μm at $z = 20$) cannot be observed because of intervening IGM Lyα absorption. The curves labeled as "PRIME" and "NGST" are calculated at 3.5 and 5 μm, respectively. From Heger et al. (2002).