

The background of the slide is a composite image. On the left, a satellite, the Galaxy Evolution Explorer (GALEX), is shown in space. It has a central cylindrical telescope with a gold-colored exterior and several solar panels extending outwards. The satellite is positioned in the foreground, looking towards the right. On the right side, there is a view of Earth from space, showing the blue and white clouds of the planet's surface. A bright, multi-colored rainbow-like arc of light stretches across the top right, suggesting a sunrise or sunset over the horizon. The overall scene is set against the dark, star-filled background of space.

# Ongoing Formation of Bulges and Black Holes in the Local Universe: New Insights from GALEX

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# Background

- Filters used from GALEX
  - NUV = 1750-2750 Å  $\lambda_{\text{eff}} = 2271$  Å
  - FUV = 1350-1750 Å  $\lambda_{\text{eff}} = 1528$  Å
- Filters used from SDSS
  - G = 3359 - 5919 Å  $\lambda_{\text{eff}} = 4639$  Å
  - R = 4972 - 7272 Å  $\lambda_{\text{eff}} = 6122$  Å
  - I = 6209 - 8669 Å  $\lambda_{\text{eff}} = 7439$  Å

# History of the bulge-dominated galaxies

- History 1:
  - Predominantly old and metal-rich
  - Stars were formed at roughly the same epoch
- History 2:
  - Galaxies form through hierarchical mergers
  - Expected to have high gas densities and cool through radiative processes

# Cooling Crisis??

- Cooling = new stars.
- Young blue stars should be created
- AGN solution
  - AGN feedback adds energy to the disk.
- Merging galaxies
  - Outflows from merging galaxies add energy to disk
- Need to use observation to study these processes.

# UV Galaxies

- Star formation rates of massive galaxies is known and is on average low
- Observational evidence of stars still being formed in a subset of these galaxies
  - Optical spectra exhibit line emission and blue continua
  - Excess UV light from central cluster galaxies
- Advantages in studying UV
  - UV luminosities are very sensitive to residual star formation
  - But, can only get data from space for galaxies at low redshifts

# Data Selection

- Matched a parent sample from GALEX to the SDSS Data release
- Created sample of bulge-dominated galaxies
- Limited by redshift ( $z < 0.07$ ) and velocity dispersion
- GALEX data taken from MIS
  - Spatial resolution  $\sim 5''$

# Optical Data

- A sample of 51,246 galaxies were matched between SDSS and GALEX
  - Any galaxy farther than 30' from the center of the field were excluded
- Also obtained from SDSS spectra
  - $D_n(4000)$ ,  $H\delta_A$
  - Equivalent width of  $H\alpha$
  - AGN classifiers
- Cosmology:  $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$ ,  $\Omega_\Lambda=0.7$

# Bias against non-star forming galaxies

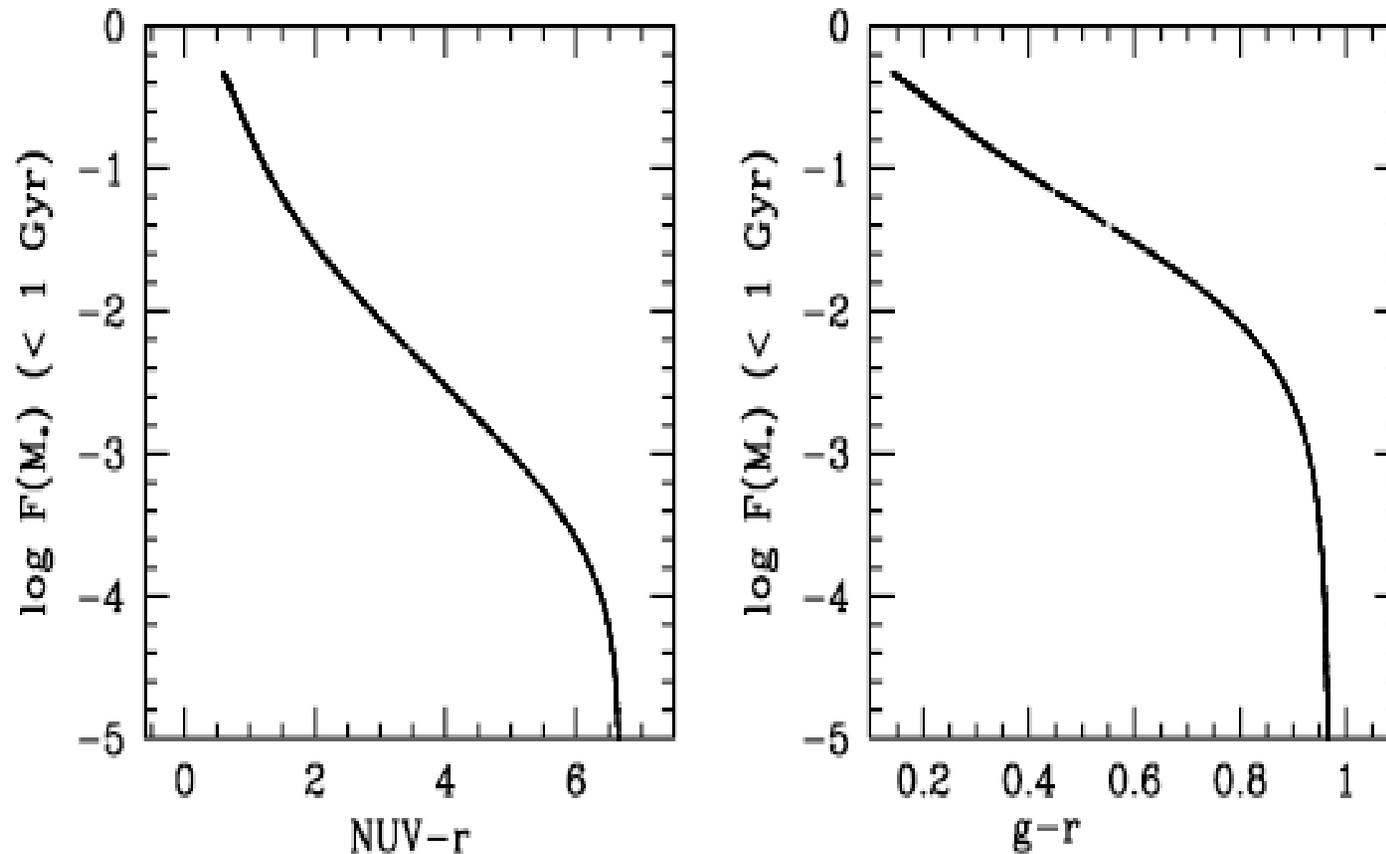


FIG. 1.—Fraction of mass in stars in the galaxy formed in the last gigayear is plotted as a function of  $\text{NUV} - r$  (left) and  $g - r$  color (right) for model galaxies that gave smooth, exponentially declining star formation histories.

# Color Distributions

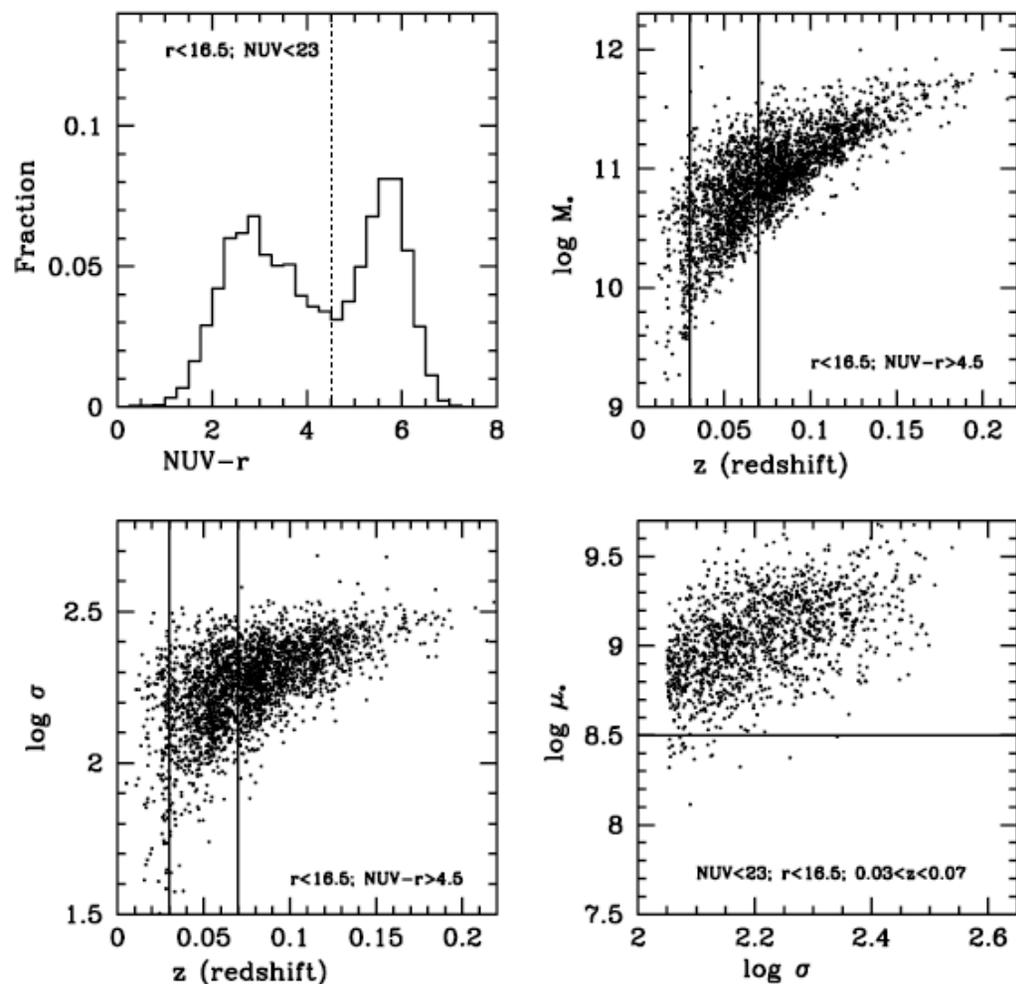


FIG. 2.—*Top left:*  $NUV-r$  color distribution of galaxies with  $r < 16.5$  and  $NUV < 23$  in our sample. *Top right, bottom left:* Stellar mass and stellar velocity dispersion plotted as a function of redshift for galaxies with  $NUV-r > 4.5$ ,  $r < 16.5$ , and  $NUV < 23$ . *Bottom right:* Stellar surface mass density is plotted as a function of stellar velocity dispersion for galaxies with  $\log M_* > 10.4$ ,  $\log \sigma > 2.05$ ,  $r < 16.5$ ,  $NUV < 23$ , and  $0.03 < z < 0.07$ . The horizontal line indicates the “transition” value of  $\mu_*$  between galaxies with ongoing star formation and galaxies where star formation has largely shut down.

# Useful knowledge

- Spectra Quantities:
  - Measure of the age of the stellar population in the bulge
    - $D_n(4000)$  = 4000 Å break.
    - $H\delta_A$  - Hydrogen Delta transition
    - EQW( $H\alpha$ ) - equivalent width of H-alpha
  - Colors = measure of the age of the stellar population as a whole
    - NUV-r
    - G-r

# Color Relations

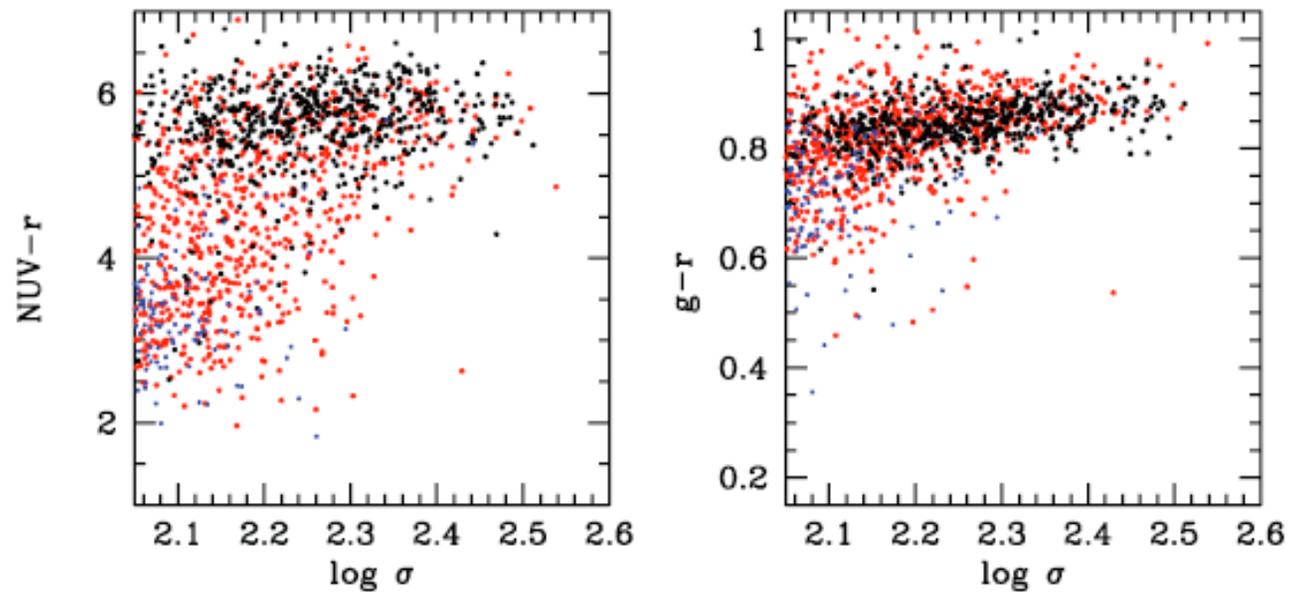


FIG. 3.— Relations between  $\text{NUV} - r$  and  $g - r$  colors and central stellar velocity dispersion for the galaxies in our sample. Black dots indicate galaxies with emission lines that are too weak to classify, red dots show AGNs, and blue dots show star-forming galaxies.

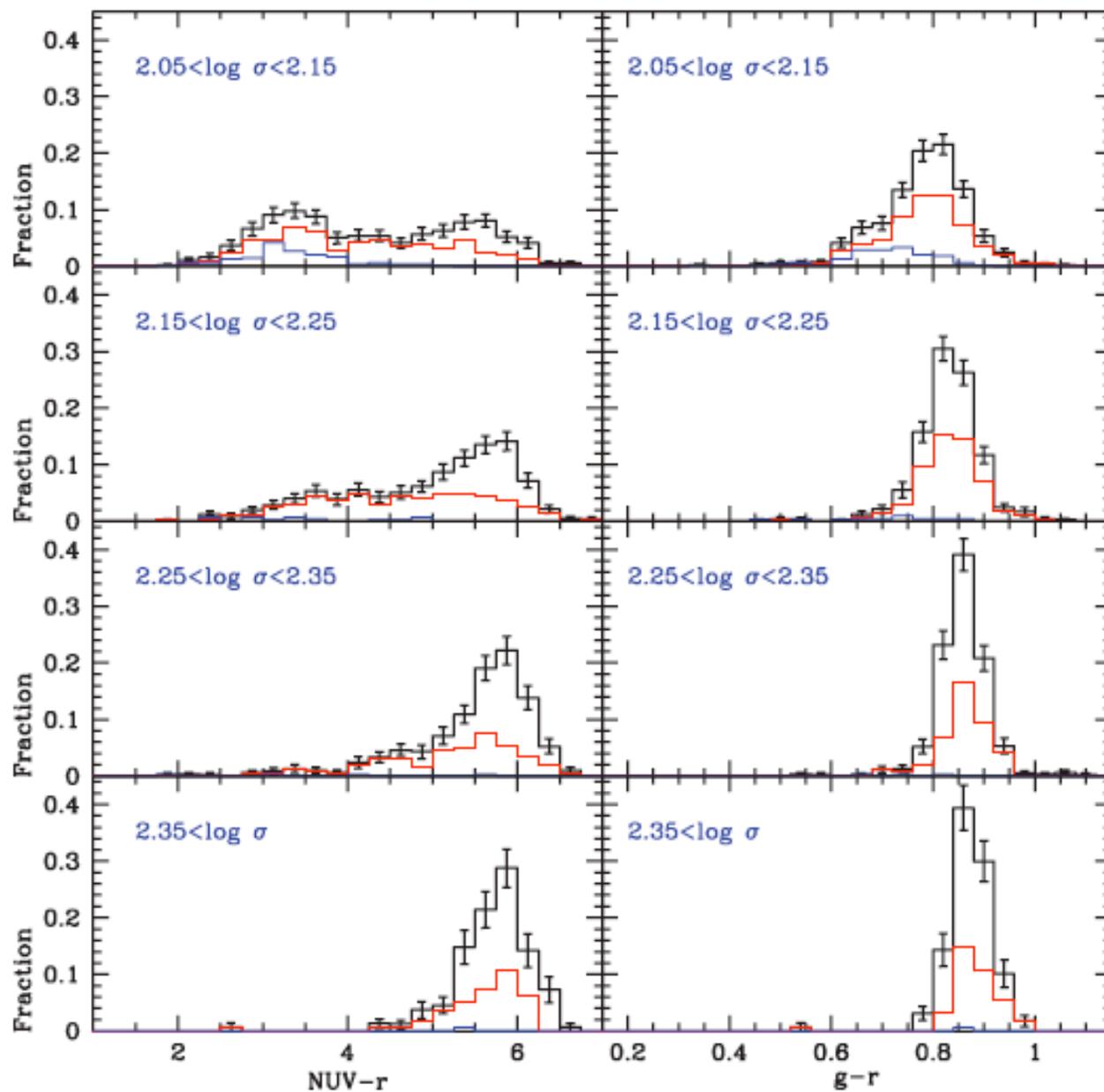


FIG. 4.—Distribution of  $\text{NUV} - r$  and  $g - r$  colors in different ranges of central velocity dispersion. Black histograms are for the whole sample, red shows the contribution from AGNs, and blue shows that from star-forming galaxies.

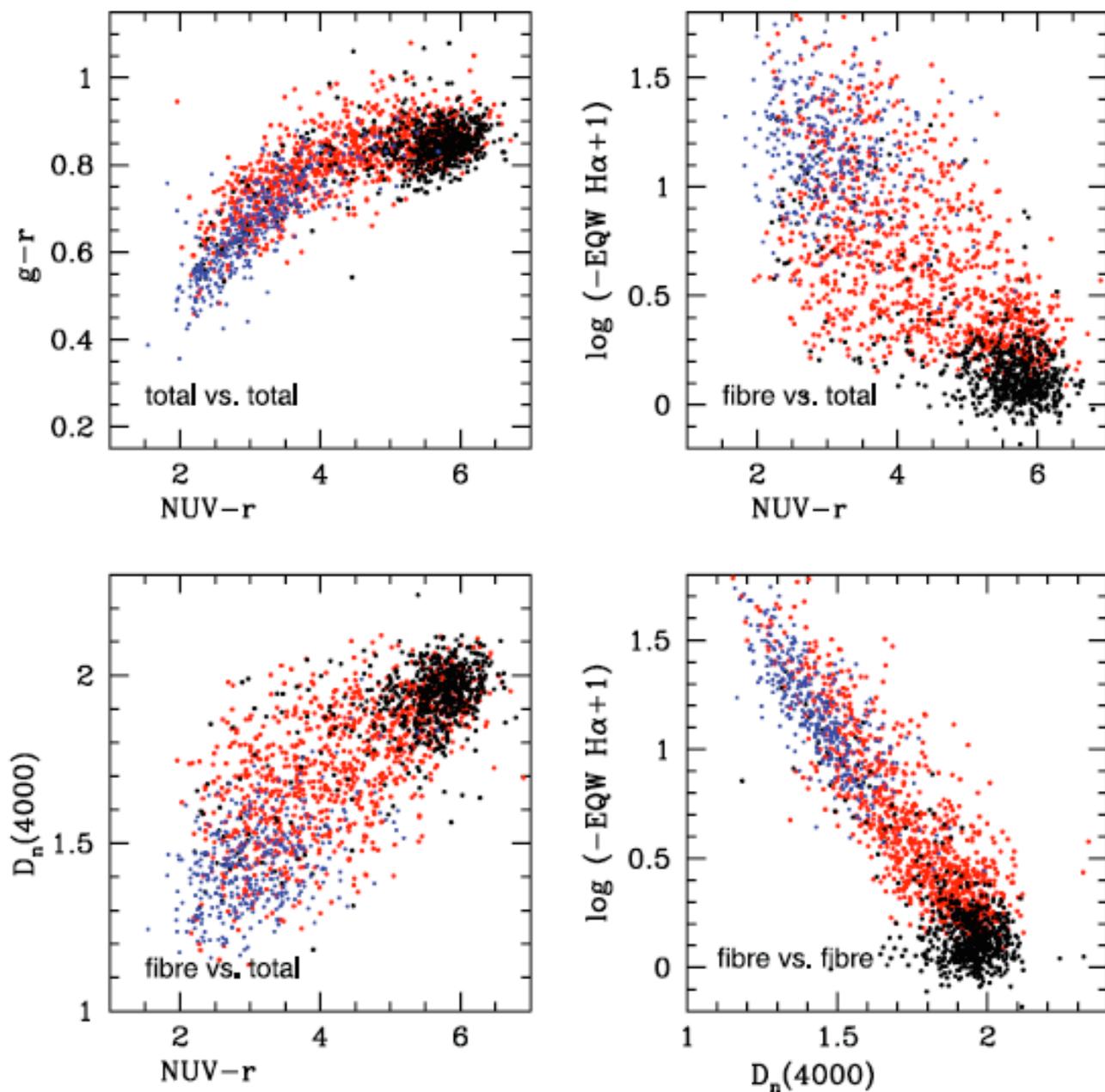
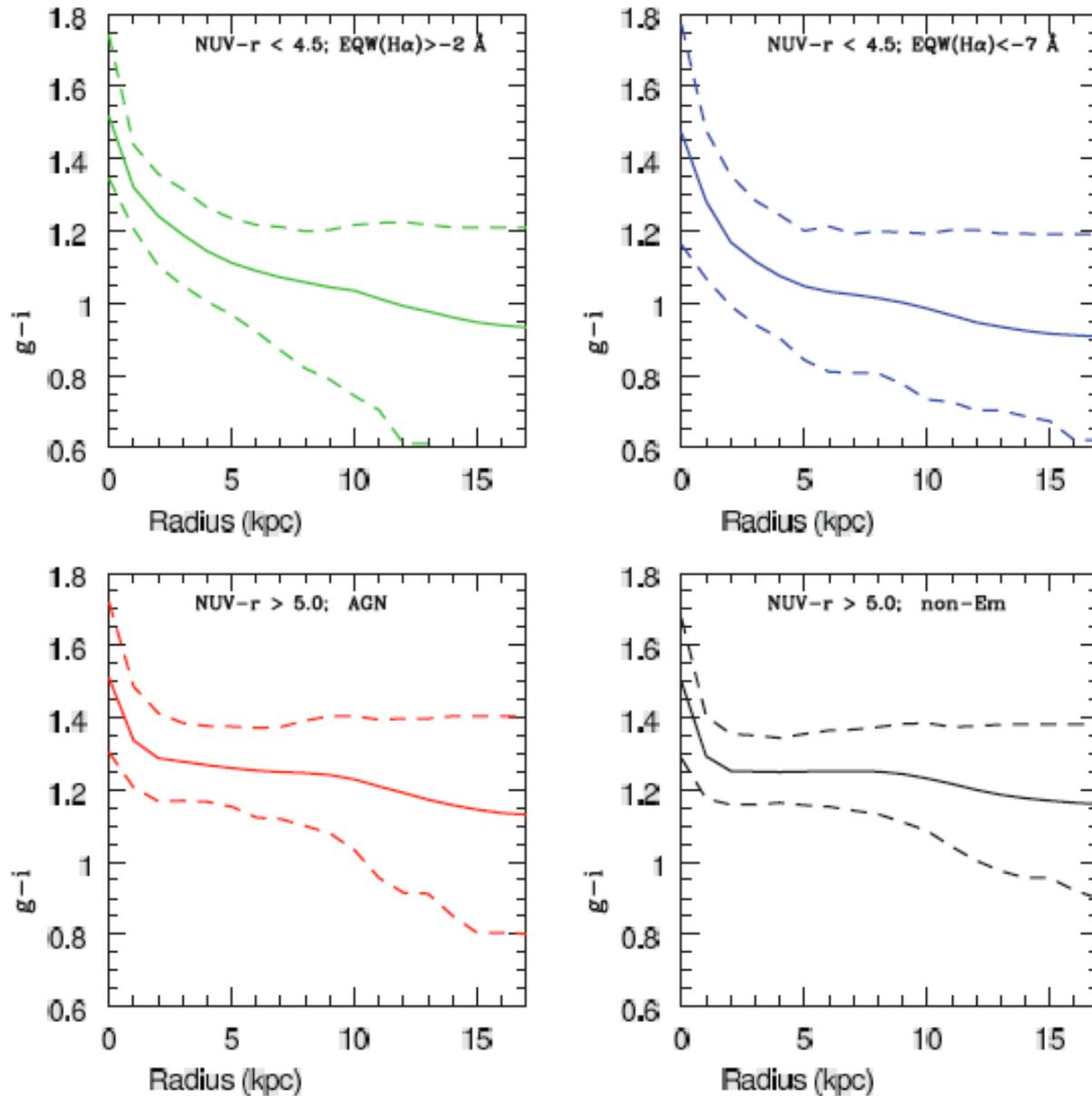


FIG. 5.—Relations between four different stellar population indicators: the  $NUV-r$  color, the  $g-r$  color, the 4000 Å break index  $D_n(4000)$ , and the equivalent width of the  $H\alpha$  emission line. Galaxies with emission lines that are too weak to classify are shown as black dots, AGNs are shown in red, and star-forming galaxies are plotted in blue.

# Color Profiles



# Link between the UV emission and the AGN activity

- Shown UV-Emission bulge-dominated galaxies is a tracer of young stars in the OUTER region of the galaxy.
- What is the link between extended UV emission and the activity of the nucleus?

## Link #2

- O[III] emission line is indicator of the rate at which matter is accreted on to the SMBH.
  - [O III] emission is relatively weak in metal rich H II regions
  - In type 1 Seyfert galaxies and quasars, line luminosity is correlated with continuum luminosity and therefore BH accretion rate.

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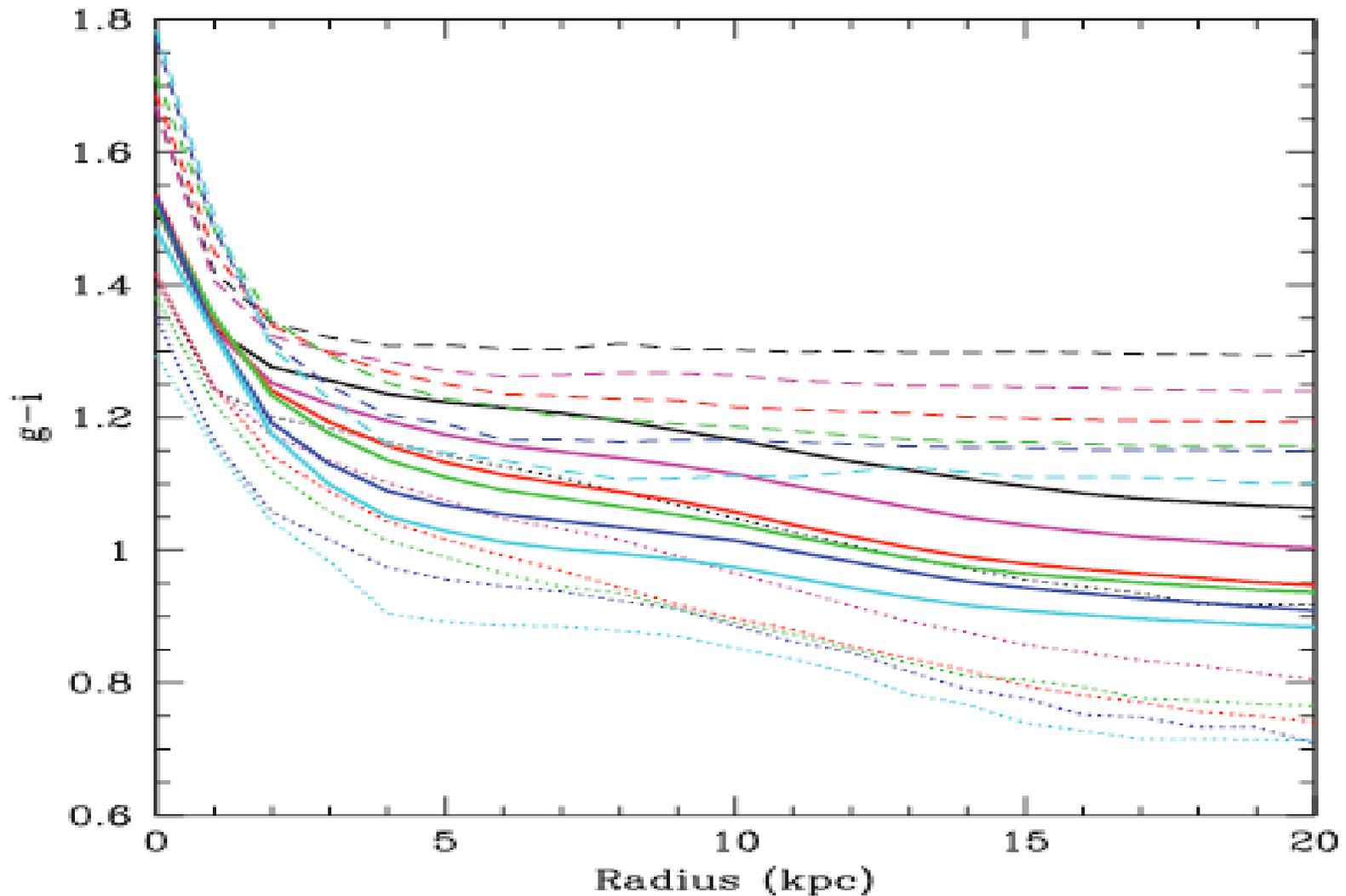


FIG. 10.—Color  $g - i$  plotted as a function of physical radius for galaxies in six different ranges of black hole accretion rate, which is parameterized by the quantity  $\log L[\text{O III}]/M_{\text{BH}}$ . The black, magenta, red, green, blue, and cyan lines are for AGNs with  $\log L[\text{O III}]/M_{\text{BH}}$  in the ranges  $[< -2.0]$ ,  $[-2, -1.3]$ ,  $[-1.3, -0.6]$ ,  $[-0.6, 0.1]$ ,  $[0.1, 0.7]$ , and  $[>0.7]$ , respectively. The solid lines show the average profile, while the dashed and dotted lines indicate the 90th and 10th percentiles of the color distribution at a given radius, respectively.

# Another Paradox!!

- Why would accretion onto a central black hole be more strongly modulated by conditions in the outer regions of the galaxy??
- Remember: Colors are sensitive to ages and metallicities of the stellar population but also to DUST!

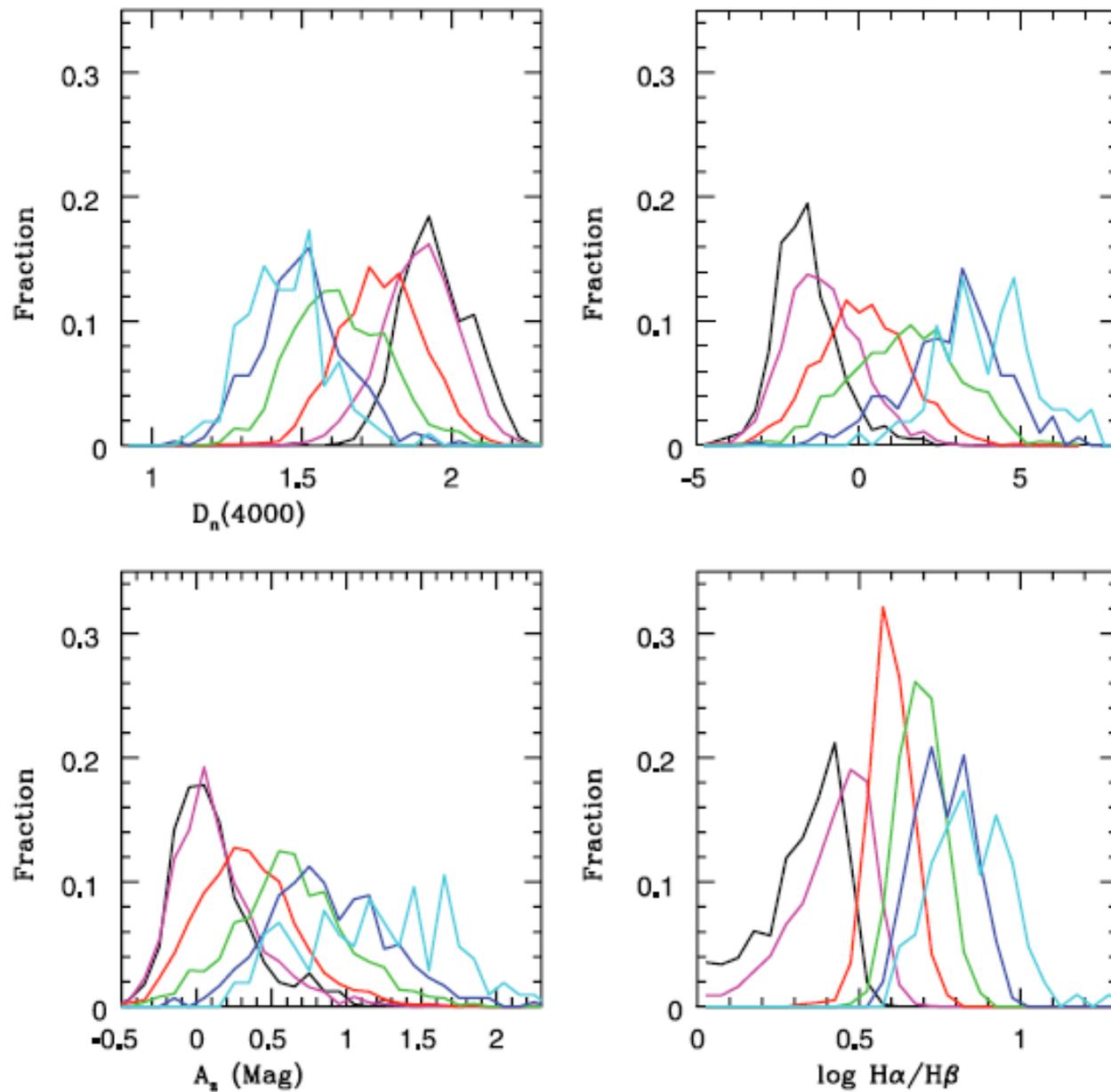
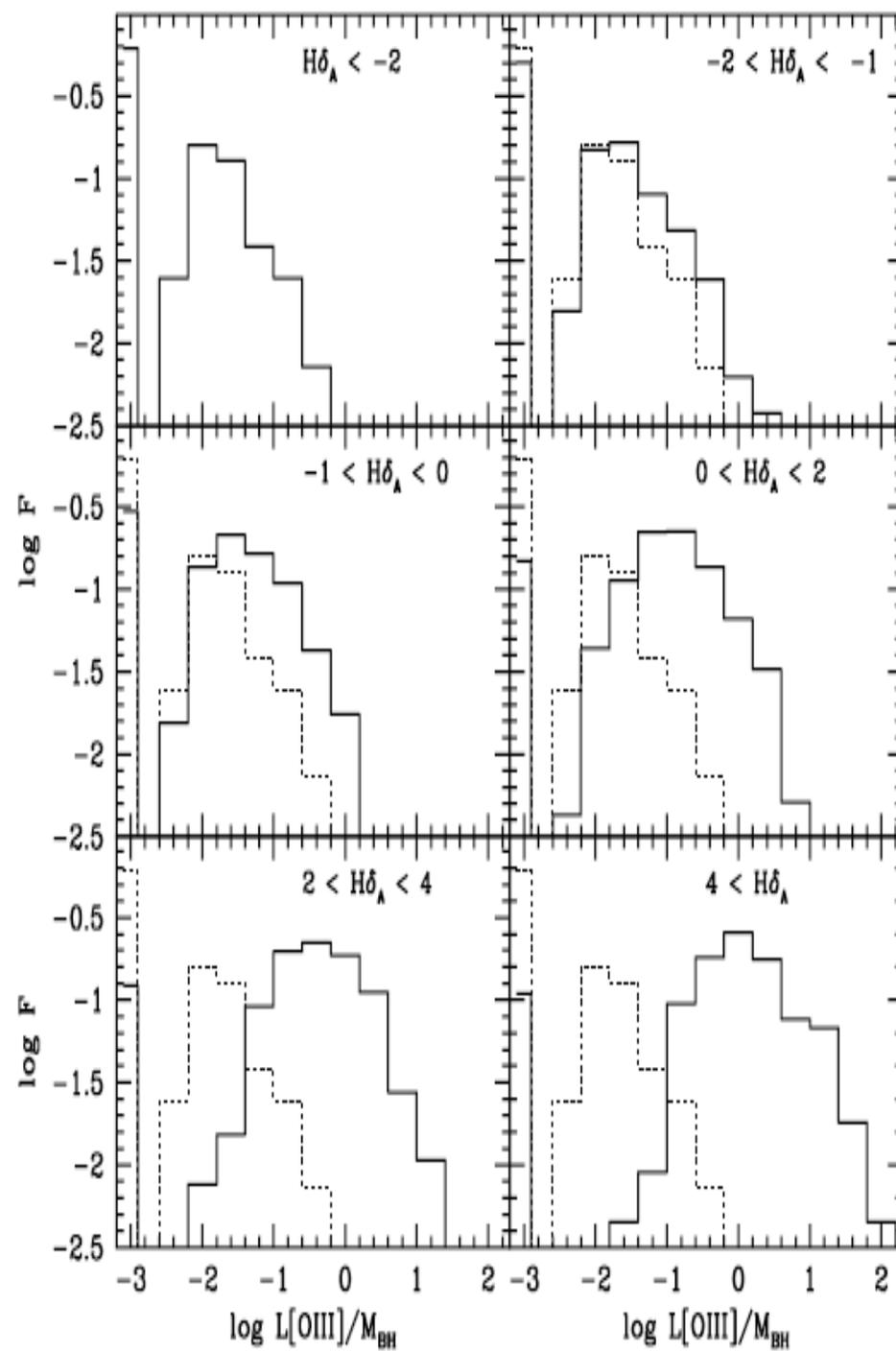
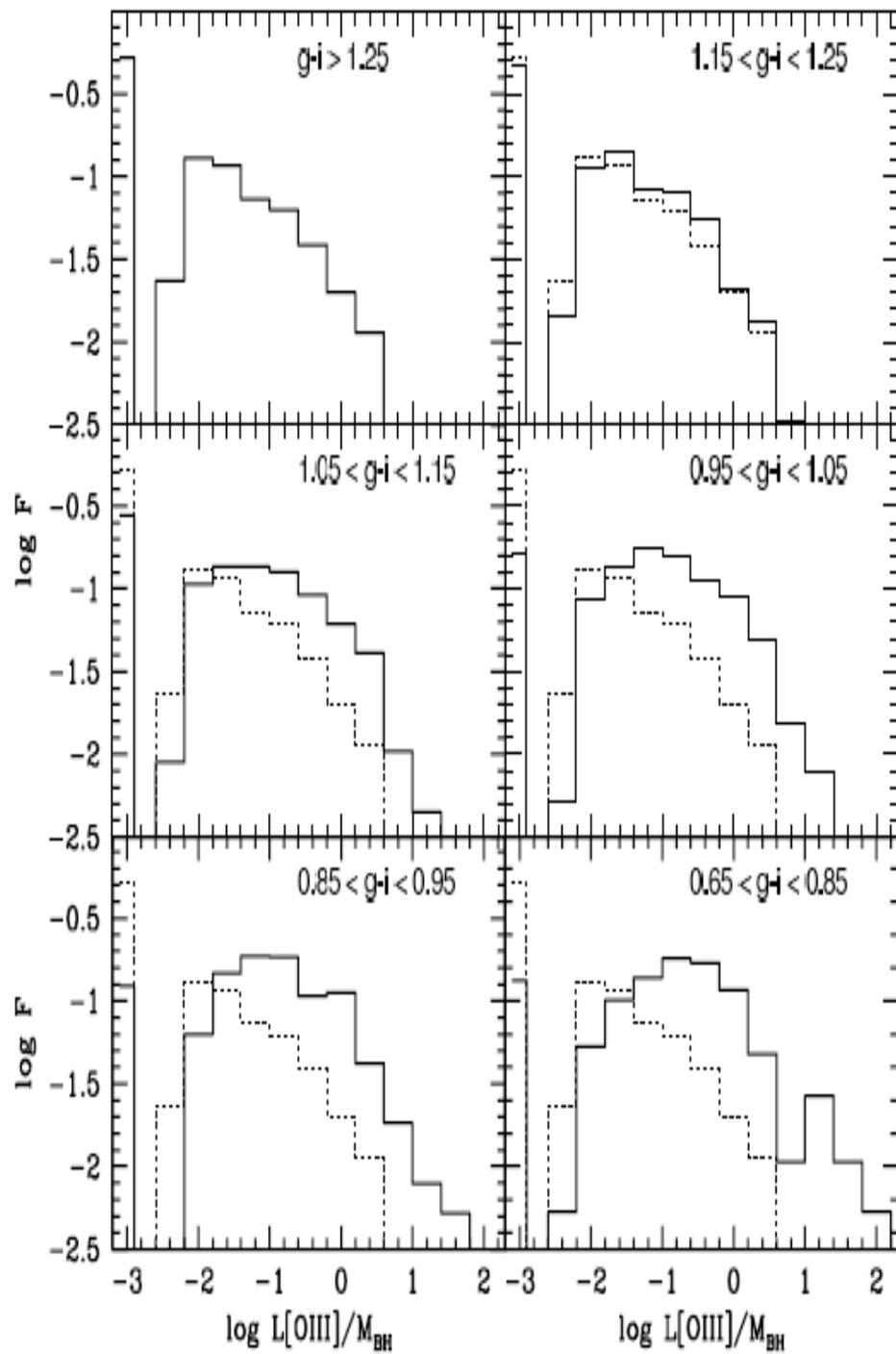


FIG. 11.—Distributions of the age-sensitive spectral indices  $D_n(4000)$  and  $H\delta_\delta$ , as well as two dust-sensitive measures, in bins of black hole accretion rate parameterized by the quantity  $\log L[\text{O III}]/M_{\text{BH}}$ . The color coding on the curves is the same as in the previous figure.



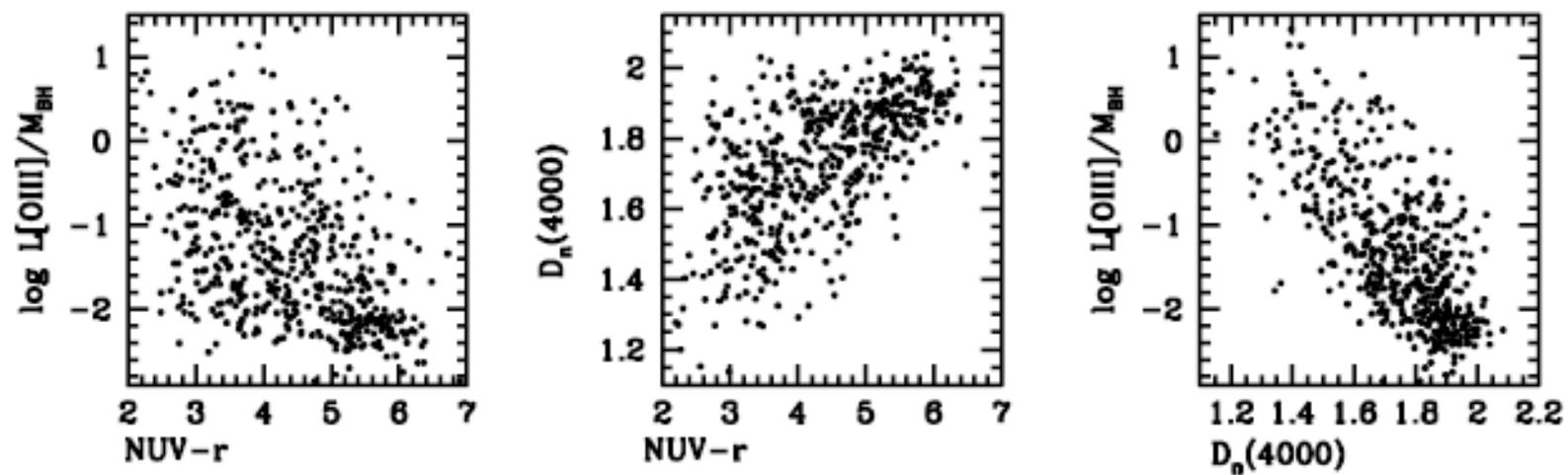


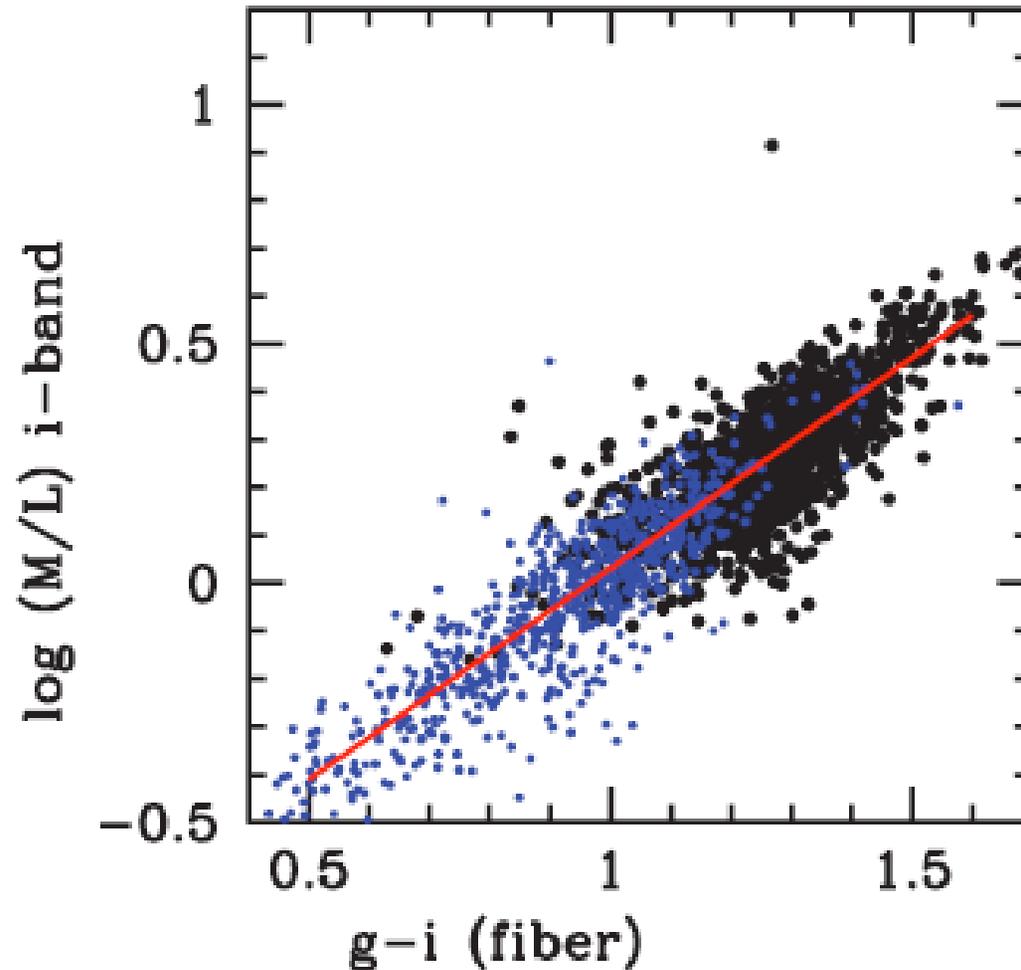
FIG. 14.—Correlations between  $\text{NUV} - r$  (an indicator of the age of stars in the outer galaxy),  $D_n(4000)$  (an indicator of stellar age in the inner galaxy), and  $L[\text{O III}]/M_{\text{BH}}$  (an indicator of accretion rate onto the black hole). *Left:* Black hole vs. disk. *Middle:* Bulge vs. disk. *Right:* Black hole vs. bulge.

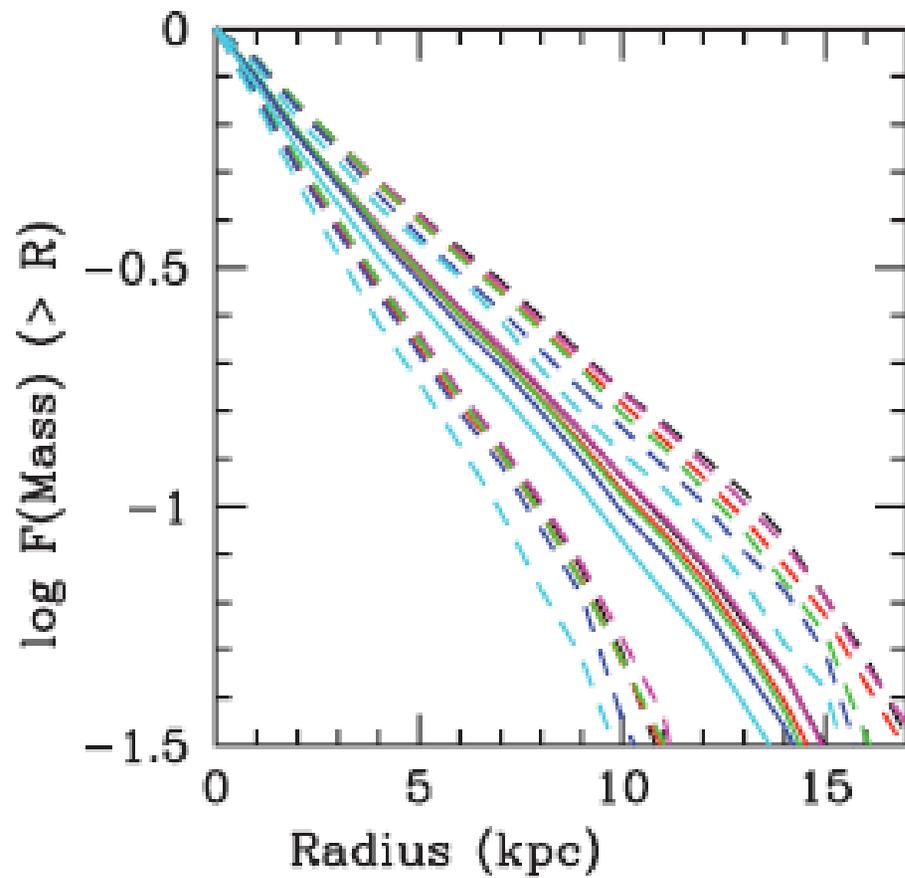
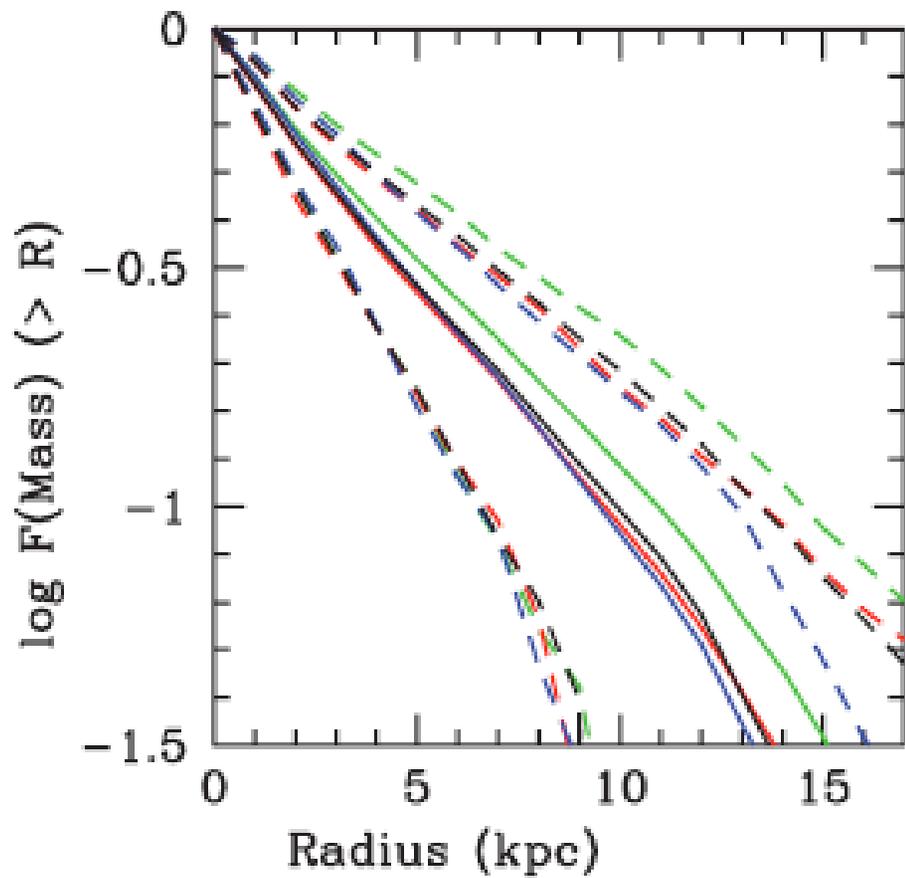
# Stellar Mass Profiles

- UV light traces an extended reservoir of H I gas that surrounds a subset of the bulge-dominated galaxies in our sample
  - Presumably in the form of a rotationally supported disk
- Evidence that black hole fuelling is strongly linked to the amount of cold gas in the inner region of the galaxy

# UV-Bright components = outer disk?

- Need to analyze the radial distribution of the stars.
  - Transform the radial surface brightness profile into a stellar mass profile





# Evolution

- Bulges and central SMBH form from gas located in an outer disk
  - Disk accreted from gas in the surrounding dark matter halo
- Undisturbed
  - Very little gas will manage to get to the BH and create an AGN
- But eventually
  - Gas will flow from the disk to the bulge
    - Trigger star formation
    - Growth of black hole
    - Increase of stellar mass in the bulge is larger than the increase in the disk, develops a more centrally concentrated stellar mass profile
    - Once gas is exhausted, mass profile becomes more like a classical elliptical

# Summary 1

- Bulge dominated galaxies exhibit a much larger spread in NUV-r color than in optical g-r color.
- Nearly all of the galaxies with blue NUV-r colors are classified as AGN
- GALEX images and SDSS color profiles demonstrate that the UV excess is associated primarily with an extended outer component of the galaxy
- Galaxies with red outer regions almost never have a strong AGN or a young bulge. Galaxies with blue outer regions have a wide range in bulge/black hole properties. Galaxies with strongly accreting black holes and young bulges almost always have blue outer regions
- Black hole growth rate correlates much more strongly with the age of the stellar population in the bulge than in the outer region of the galaxy
- The amount of extinction in the bulge is also strongly linked to black hole growth and the age of the bulge stars
- At fixed central stellar velocity dispersion, the radial distribution of the stellar mass in the host galaxy shows only a small variations as a function of black hole growth rate and the color of the disk

# The End

- Questions?
- Comments?
- Rude Remarks?

Thanks.