Spectral Energy Distributions, Dust, and Black Hole Properties: A Statistical, Multi-Wavelength Quasar Analysis

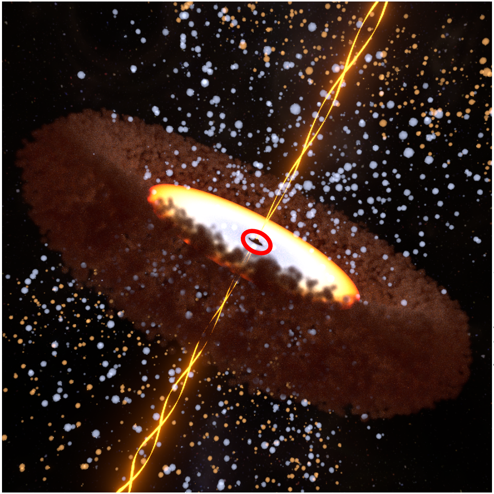
Coleman Krawczyk

Drexel University

9/4/2014

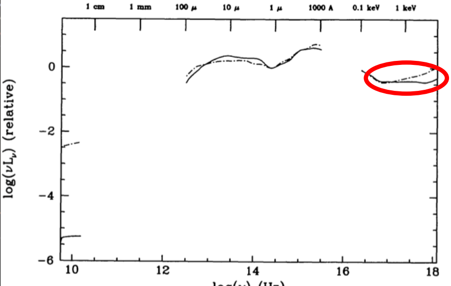
What is a quasar?

- A super massive black hole at the center of a distant galaxy that is actively accreting material
- This accretion process is so luminous that it can outshine all the stars in the host galaxy
- Quasar appear as point sources
- Some quasars have powerful radio jets

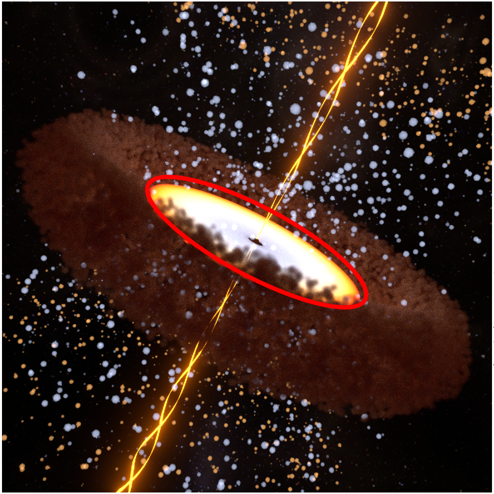


What makes up a quasar?

- The corona near the black hole produces emission in the X-ray ($\sim$AU)

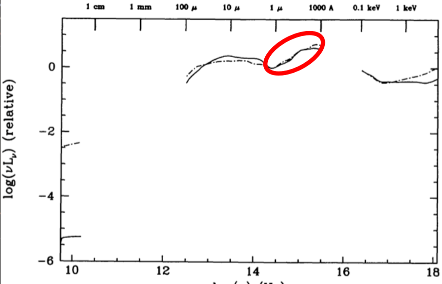


Elvis et al. (1994)



What makes up a quasar?

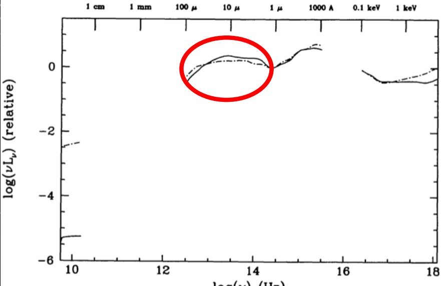
- The accretion disk produces thermal emission in the optical–UV ($\sim$1000 AU)



Elvis et al. (1994)

What makes up a quasar?

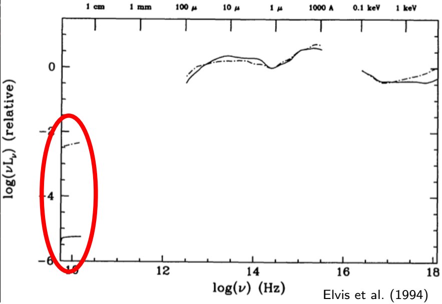
- The dusty torus absorbs the UV light and reemits it in the IR ($\sim$pc)



Elvis et al. (1994)

What makes up a quasar?

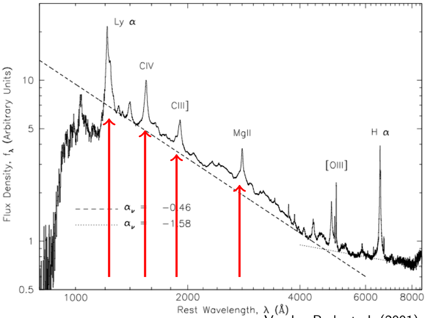
- In radio loud quasars the jets produce synchrotron radiation ($\sim$100 kpc)



Elvis et al. (1994)

What makes up a quasar?

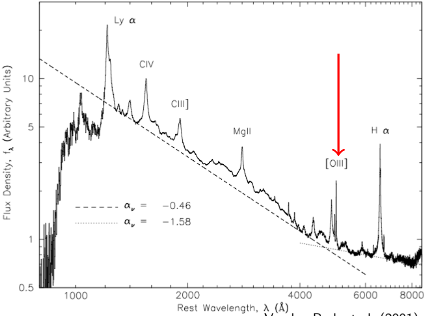
- Ionized gas within the potential well of the black hole create broad emission lines (~pc)



Vanden Berk et al. (2001)

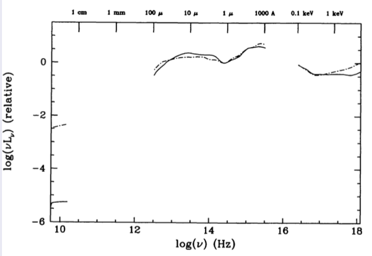
What makes up a quasar?

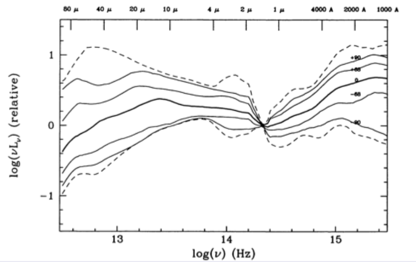
- Ionized gas outside the potential well of the black hole create narrow emission lines (∼kpc)



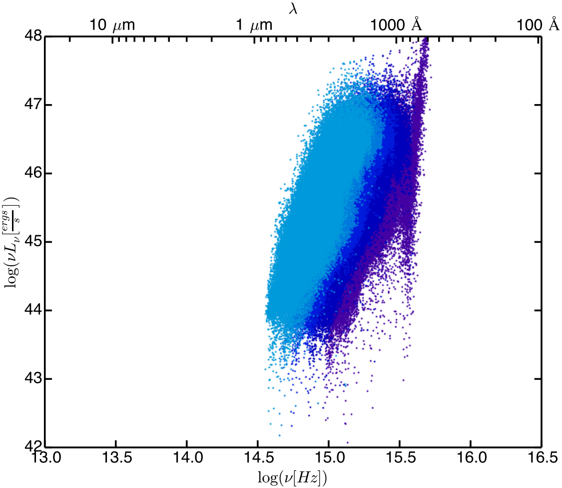
Vanden Berk et al. (2001)

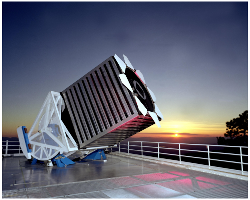
Elvis et al. (1994) mean SEDs and uncertainties





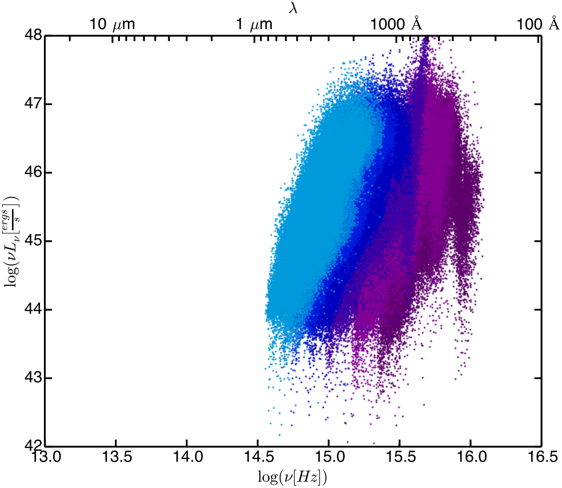
"...the large dispersion of shapes in individual objects means that the mean SED should be used only with caution, and that the variety of shapes should contain information about the physics of quasars."

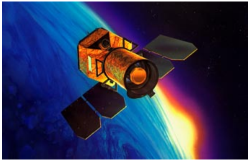




Optical

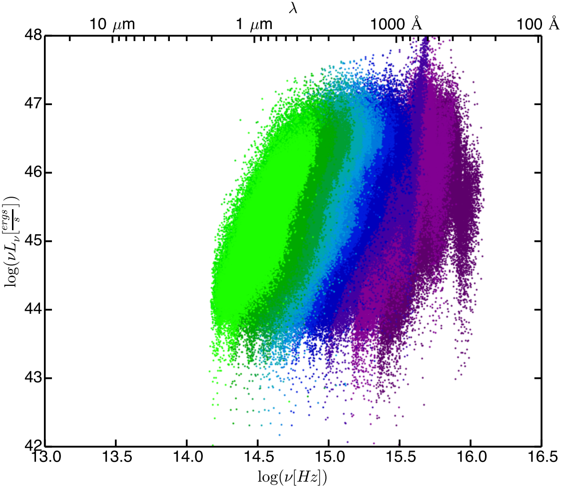
- Our sample is taken from the SDSS DR7 quasar catalog containing 105,783 broad-lined quasars
- We supplement this sample with 15,757 lower luminosity quasars from various other studies

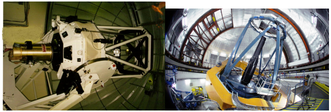




Ultra Violet

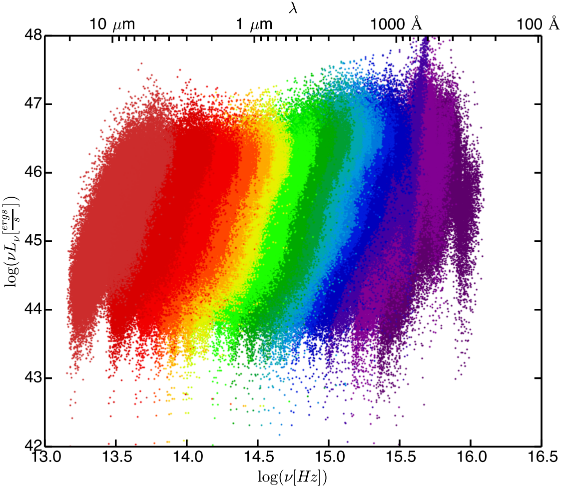
- In the UV our sample was matched to *GALEX* data (Budavári et al. 2009)

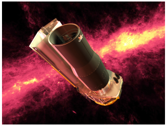


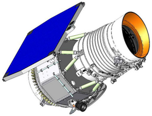


Near-Infrared

- In the near-IR our sample was matched to both 2MASS (23,088) and UKIDSS (35,749)

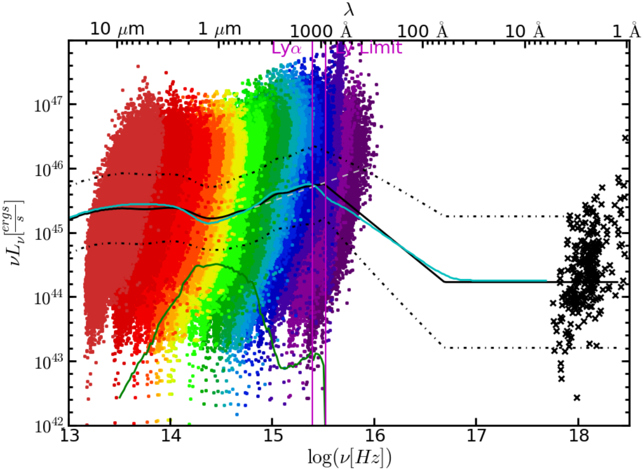






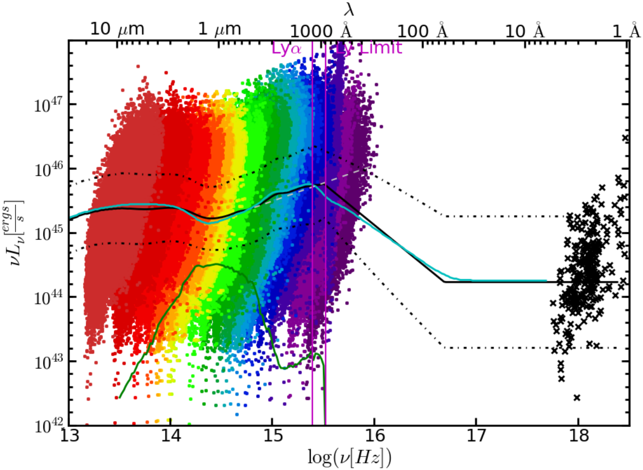
Mid-Infrared

- In the mid-IR our sample was matched to both *WISE* (85,358) and *Spitzer* (1,196)



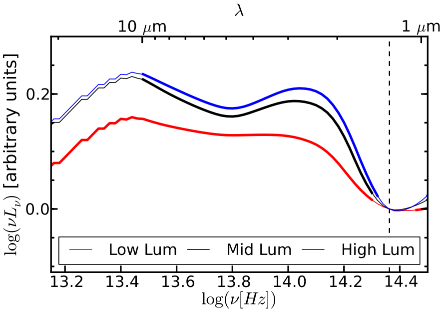
Mean SED

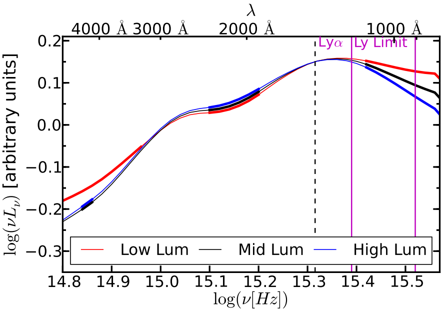
- Black line: New mean SED
- Cyan line: Richards et al. (2006) mean SED
- Green line: Typical host galaxy contribution
- Black X's: X-ray data



Mean SED

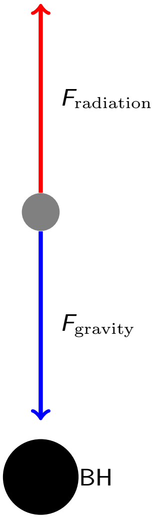
"...the large dispersion of shapes in individual objects means that the mean SED should be used only with caution, and that the variety of shapes should contain information about the physics of quasars."





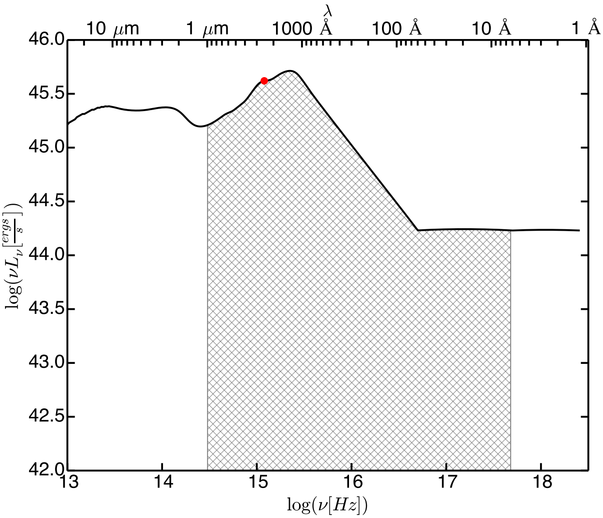
Luminosity Dependence of SEDs

- High-luminosity quasars show more hot dust emission in the mid-IR
- High-luminosity quasars have a softer (redder) UV continuum



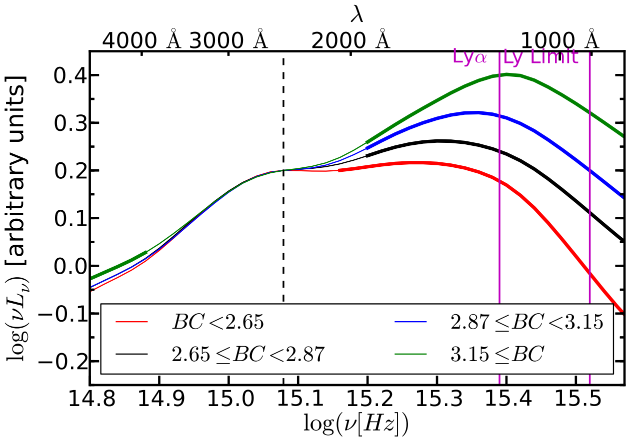
Eddington Luminosity

- The luminosity when the outward radiation pressure balances the inward gravitational force
  - $L_{\mathrm{Edd}} \simeq 1.23 \times 10^{38} \frac{\mathrm{erg}}{\mathrm{s}} \left(\frac{M_{\mathrm{BH}}}{M_{\odot}}\right)$
- Assuming a constant accretion rate, the bolometric luminosity can also be written:
  - $L_{\mathrm{Bol}} = \eta \dot{M} c^2$
- Defining $\dot{M}_{\mathrm{Edd}}$ as the accretion rate associated with L_{Edd}
  - $\frac{L_{\mathrm{Bol}}}{L_{\mathrm{Edd}}} = \frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}$



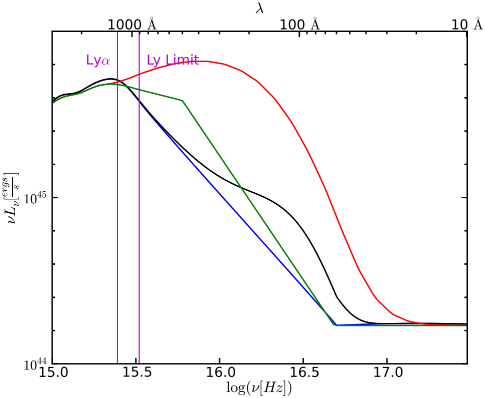
BCs

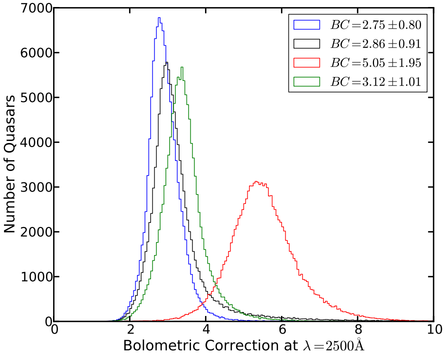
- The bolometric luminosity can only be measured if you have a full multi-wavelength SED
- When this is not the case a bolometric correction (BC) is used to convert a mono-chromatic luminosity into a bolometric one



Bolometric Correction Dependence of SEDs

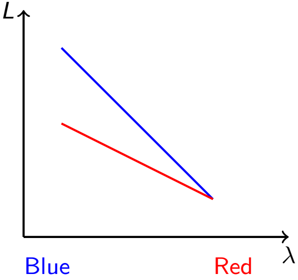
- BC is the multiplication factor needed to turn $L_{2500\text{Å}}$ into L_{bol}
- The range of BCs come from differences in the UV continua





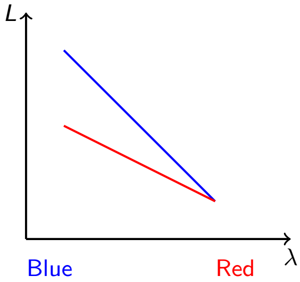
Various models for the extreme-UV and the resulting BCs

- Blue: Powerlaw
- Black: Fixed luminosity blackbody
- Red: Theory based (from CLOUDY; Casebeer et al. 2006)
- Green: Data based (Scott et al. 2004)



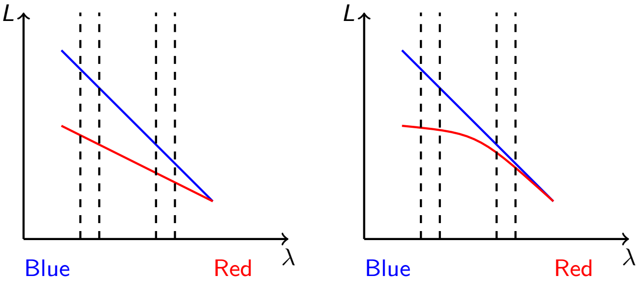
Red vs. Reddened

- Quasars that are intrinsically red follow a powerlaw in the optical–UV
- Quasars that are dust reddened have shorter wavelength absorbed by dust adding curvature to the optical–UV
- Color is the slope between each set of dashed lines



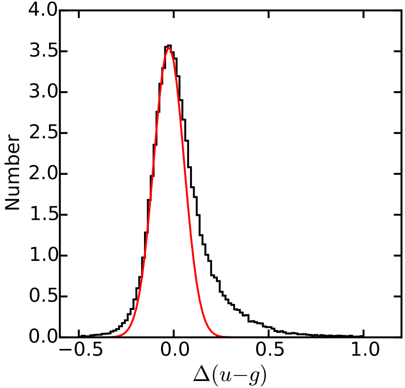
Red vs. Reddened

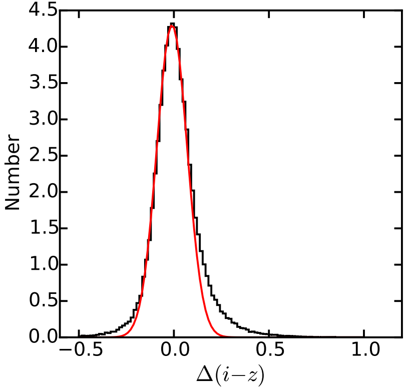
- Quasars that are intrinsically red follow a powerlaw in the optical–UV
- Quasars that are dust reddened have shorter wavelength absorbed by dust adding curvature to the optical–UV
- Color is the slope between each set of dashed lines



Red vs. Reddened

- Quasars that are intrinsically red follow a powerlaw in the optical–UV
- Quasars that are dust reddened have shorter wavelength absorbed by dust adding curvature to the optical–UV
- Color is the slope between each set of dashed lines



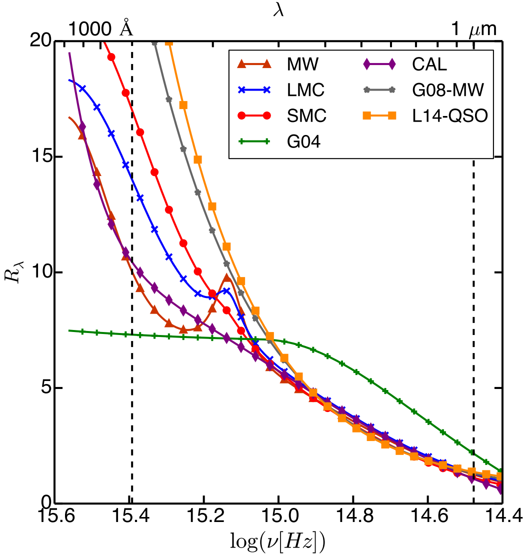


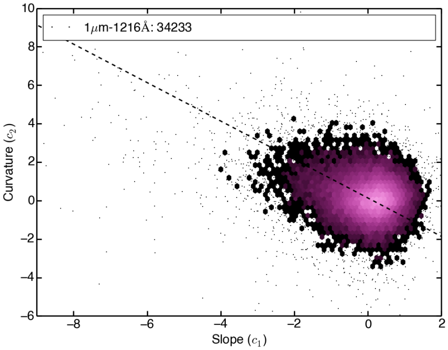
Red vs. Reddened

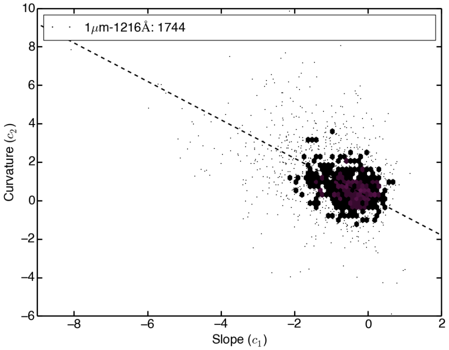
- Dust reddening causes the colors at shorter wavelengths (left) to have a heavier red tail than the colors at longer wavelengths (right)

Extinction Laws

- In order to study properties that are associated with the physics of a quasar we need to find the *intrinsic* SED
- Extinction laws characterize how much light various types of dust absorb at a given wavelength
- The strength of dust extinction is measured using the color excess E(B-V)

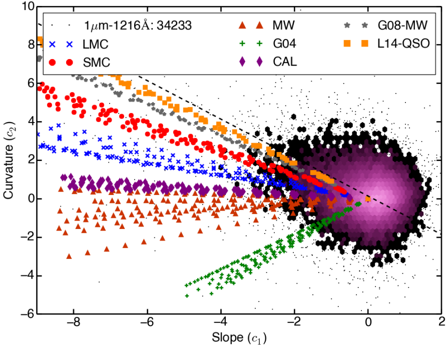


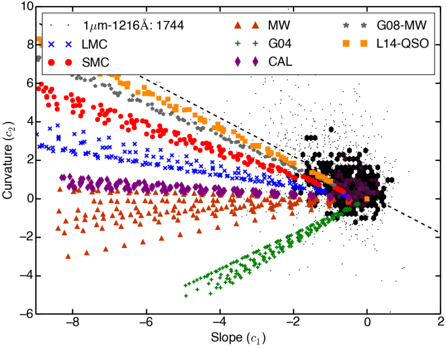




C_1 vs. C_2

- We can determine the extinction law to use by looking at the slopes and curvatures of the SEDs
- The quasars seem to follow the steeper reddening laws: Small Magellanic Cloud (SMC) and/or multiple scattering (Goobar 2008) laws





c_1 vs. c_2

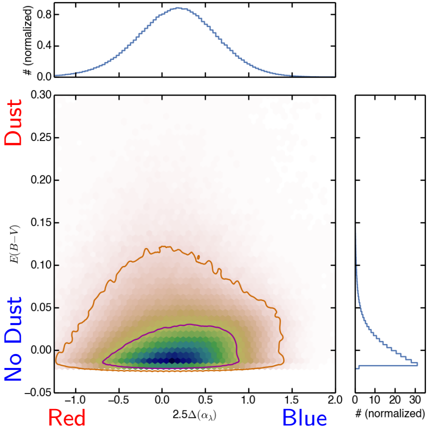
- We can determine the extinction law to use by looking at the slopes and curvatures of the SEDs
- The quasars seem to follow the steeper reddening laws: Small Magellanic Cloud (SMC) and/or multiple scattering (Goobar 2008) laws

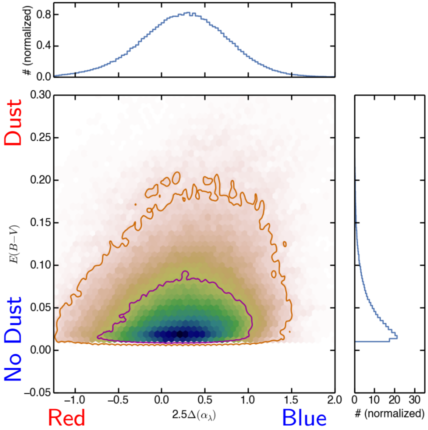
Goal

- Fit for *individual* values for both the powerlaw index w.r.t. the mode, $\Delta(\alpha_\lambda)$, and the reddening amount, E(B-V)
- Break the degeneracy between these values
- Fit for the *ensemble* distributions for $\Delta(\alpha_\lambda)$ and E(B-V)

Method

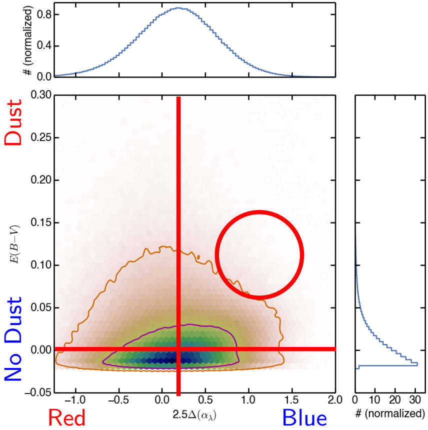
- Hierarchical Bayesian model
  - Assume functional form for the ensemble distributions
  - Fits for both the individual values *and* the shapes of the ensemble distributions at the same time
  - This allows errors to be propagated across all levels of the model

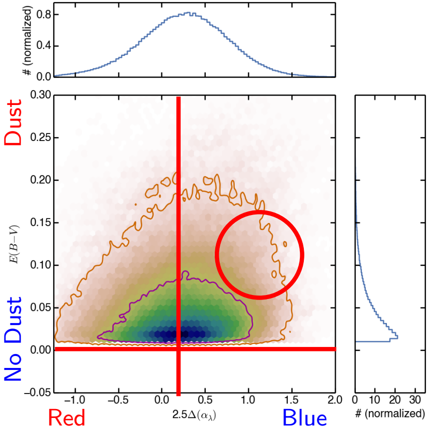




SMC fit

- The BAL sample has more dust reddening
- The heavily reddened BAL quasars are bluer than heavily reddened non-BAL quasars



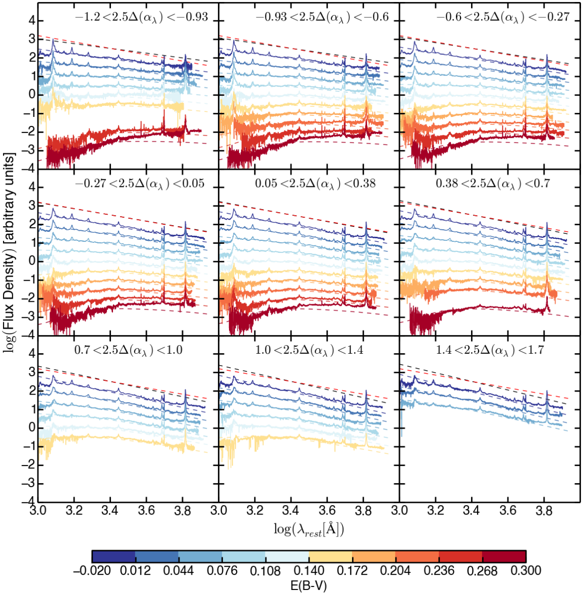


SMC fit

- The BAL sample has more dust reddening
- The heavily reddened BAL quasars are bluer than heavily reddened non-BAL quasars

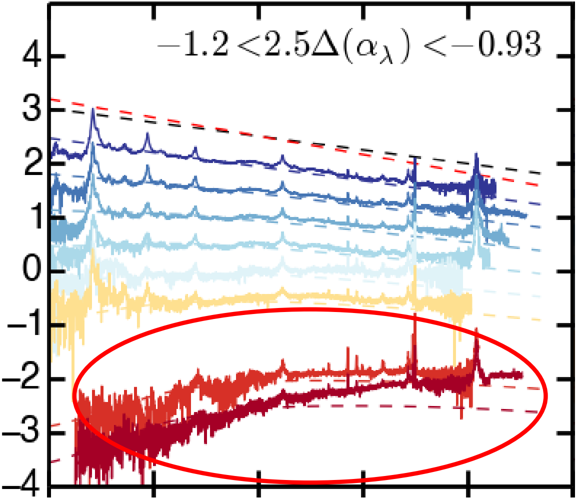
SMC non-BAL

- Black: typical powerlaw in bin
- Red: modal powerlaw
- Colors: amount of reddening
- Dashed: fit based on photometry
- The fits based on the photometry track the spectra well



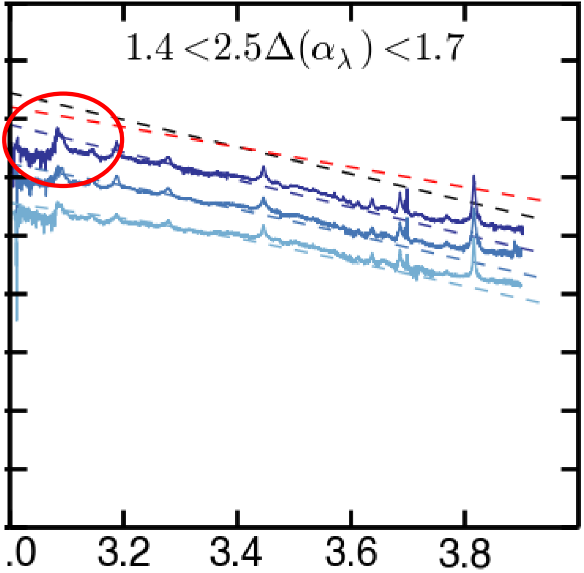
SMC non-BAL

- The most reddened spectra in each bin require a steeper reddening law
- The least reddened blue spectra starts to turn over faster (i.e. has a softer SED in the EUV)



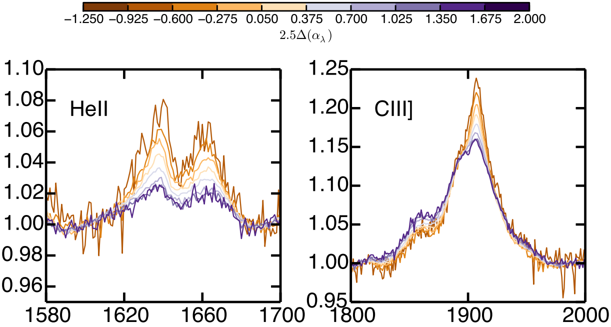
SMC non-BAL

- The most reddened spectra in each bin require a steeper reddening law
- The least reddened blue spectra starts to turn over faster (i.e. has a softer SED in the EUV)



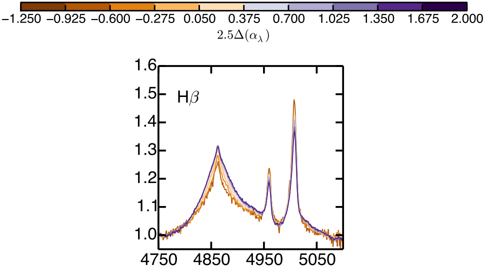
non-BAL Spectral Lines

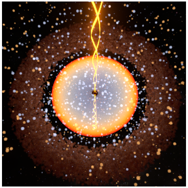
- The trends seen in He II, C III], and Al III indicate the bluer quasars have softer (redder) EUV spectra
- The Hβ line indicates that the bluer quasars could be seen closer to edge-on and/or have larger central black hole masses

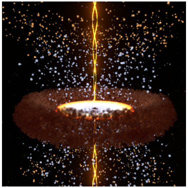


non-BAL Spectral Lines

- The trends seen in He II, C III], and Al III indicate the bluer quasars have softer (redder) EUV spectra
- The Hβ line indicates that the bluer quasars could be seen closer to edge-on and/or have larger central black hole masses

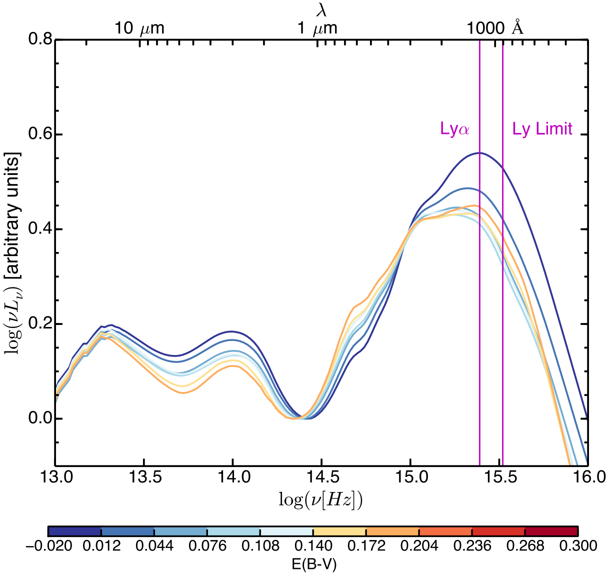






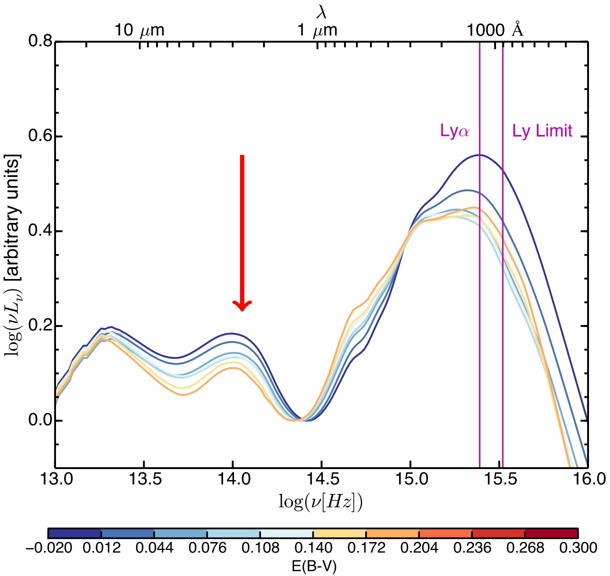
E(B-V) dependent SEDs

- With more physical variables defined we look for trends in the mean SEDs
- Some sample selection and/or intrinsic effect is a function of E(B-V)
- More reddened quasars have less hot dust emission
- More reddened quasars have a redder spectral index from 5–11μm



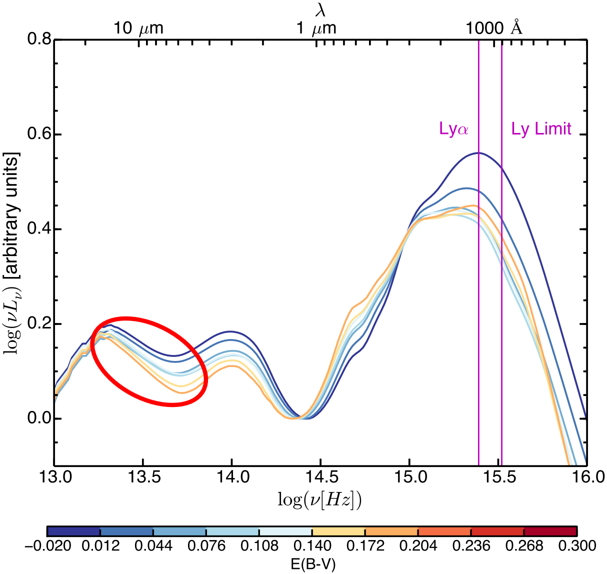
E(B-V) dependent SEDs

- With more physical variables defined we look for trends in the mean SEDs
- Some sample selection and/or intrinsic effect is a function of E(B-V)
- More reddened quasars have less hot dust emission
- More reddened quasars have a redder spectral index from 5–11μm



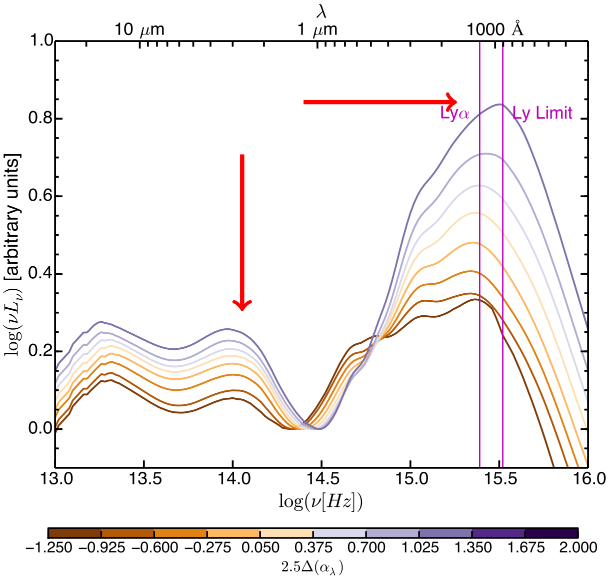
E(B-V) dependent SEDs

- With more physical variables defined we look for trends in the mean SEDs
- Some sample selection and/or intrinsic effect is a function of E(B-V)
- More reddened quasars have less hot dust emission
- More reddened quasars have a redder spectral index from 5–11μm



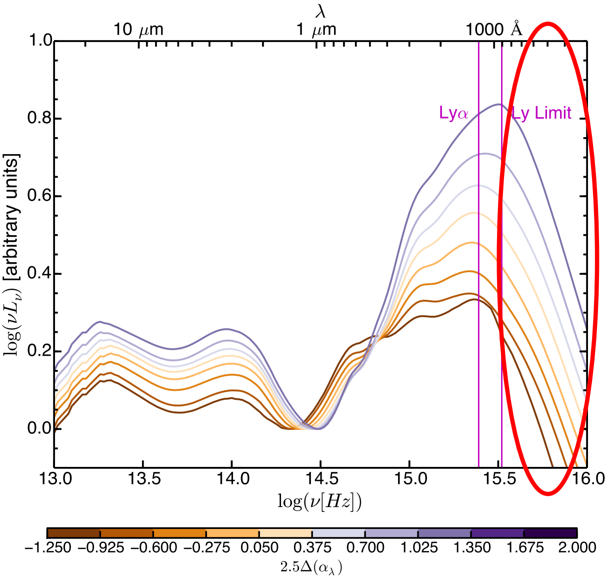
Intrinsic color dependent SEDs

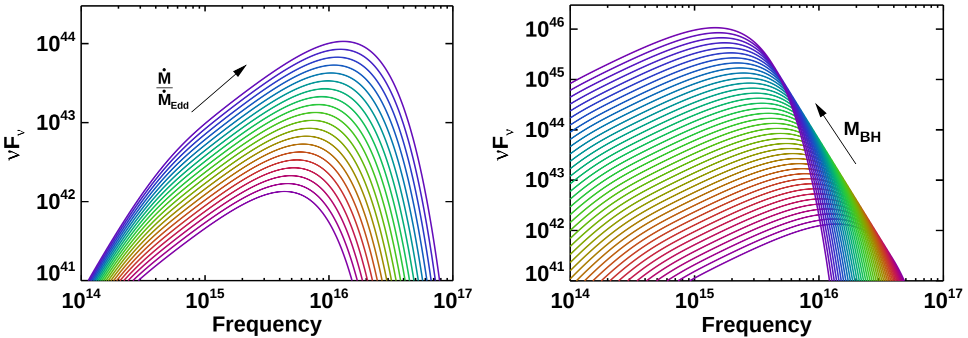
- Bluer quasars have more hot dust and a BBB that peaks at shorter wavelengths
- These are both consistent with a hotter accretion disk
- The blue quasars have *harder* EUV SEDs, contrary to what the spectra indicated



Intrinsic color dependent SEDs

- Bluer quasars have more hot dust and a BBB that peaks at shorter wavelengths
- These are both consistent with a hotter accretion disk
- The blue quasars have *harder* EUV SEDs, contrary to what the spectra indicated





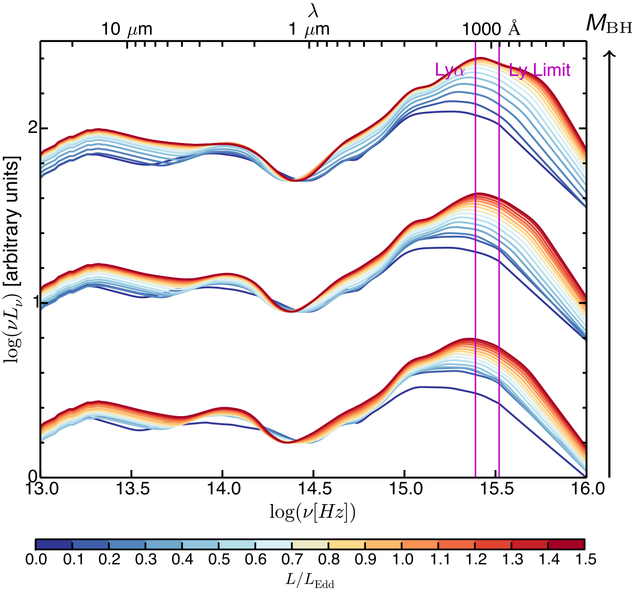
Plots courtesy of Karen Leighly

α-disk (Shakura & Sunyaev 1973)

- Observed SED only dependent on efficiency (η), BH mass (M_{BH}), BH accretion rate ($\dot{M}_{BH}$)
- $kT_{eff} \propto \eta^{-1/4} \left(\frac{M_{\rm bh}}{M_\odot}\right)^{-1/4} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4}$

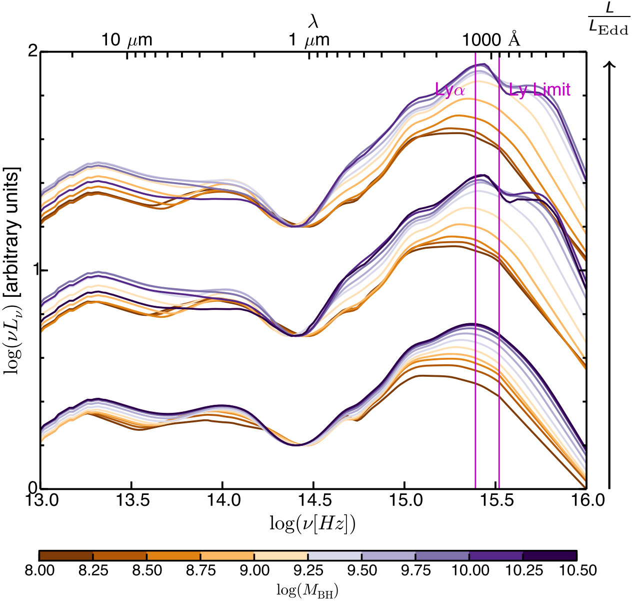
SEDs grouped by M_{BH}

- The SEDs become bluer as L/L_{Edd} increases
- The BBB peaks at shorter wavelengths as L/L_{Edd} increases
- Larger L/L_{Edd} is consistent with a hotter accretion disk
- This is the same trend predicted by the α-disk model



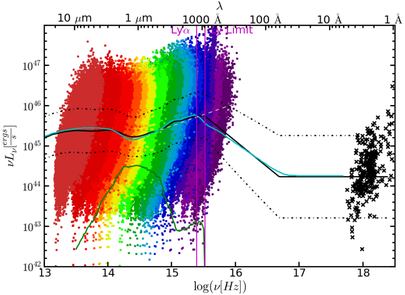
SEDs grouped by L/L_{Edd}

- The SEDs become bluer as M_{BH} increases
- The BBB peaks at shorter wavelengths as M_{BH} increases
- Larger M_{BH} is also consistent with a hotter accretion disk
- This is the opposite trend predicted by the α-disk model



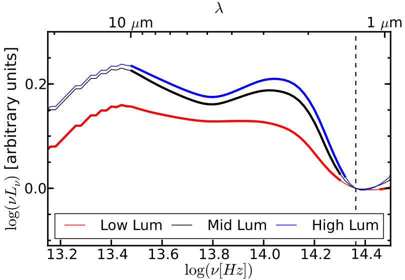
Mean SEDs

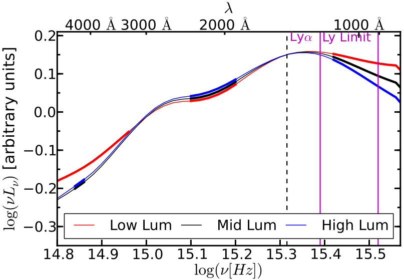
- We constructed a new mean quasar SED using over 100,000 SDSS selected quasars
- We found luminosity trends in the SED shape
  - High-luminosity quasars have more hot dust emission
  - High-luminosity quasars have a softer UV continuum
- The range of BCs come from differences in the UV continuum



Mean SEDs

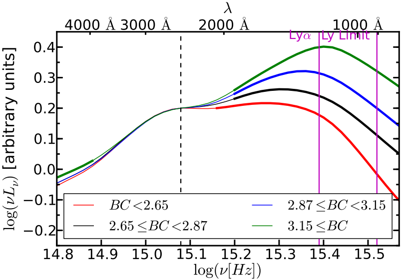
- We constructed a new mean quasar SED using over 100,000 SDSS selected quasars
- We found luminosity trends in the SED shape
  - High-luminosity quasars have more hot dust emission
  - High-luminosity quasars have a softer UV continuum
- The range of BCs come from differences in the UV continuum





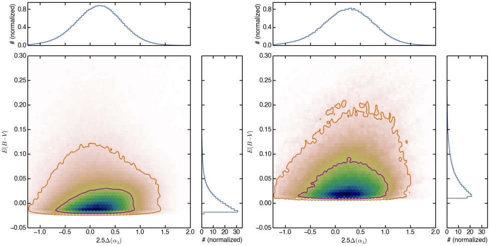
Mean SEDs

- We constructed a new mean quasar SED using over 100,000 SDSS selected quasars
- We found luminosity trends in the SED shape
  - High-luminosity quasars have more hot dust emission
  - High-luminosity quasars have a softer UV continuum
- The range of BCs come from differences in the UV continuum



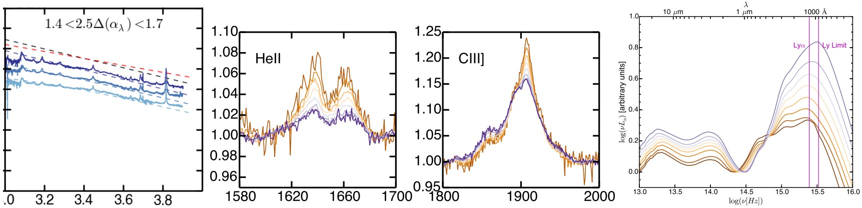
Dusty Quasars

- Using a hierarchical Bayesian model we fit SMC reddening laws to a subset of our data
- BAL quasars showed stronger dust extinction than non-BAL quasars
- The heavily reddened BAL quasars are bluer than heavily reddened non-BAL quasars
- The spectra for the intrinsically blue quasars imply they have a softer EUV continuum than the mean SEDs suggest
    - This could happen if the broad line region sees a very different SED than we do



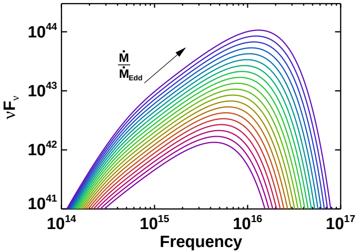
Dusty Quasars

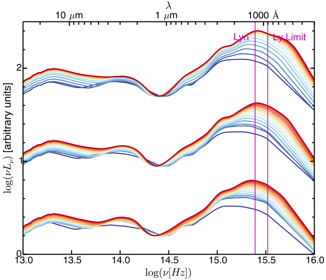
- Using a hierarchical Bayesian model we fit SMC reddening laws to a subset of our data
- BAL quasars showed stronger dust extinction than non-BAL quasars
- The heavily reddened BAL quasars are bluer than heavily reddened non-BAL quasars
- The spectra for the intrinsically blue quasars imply they have a softer EUV continuum than the mean SEDs suggest
  - This could happen if the broad line region sees a very different SED than we do



Black Hole Properties

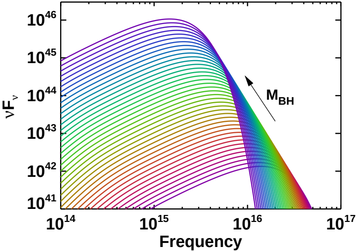
- Larger accretion rates lead to hotter accretion disks
  - This is consistent with the Shakura & Sunyaev (1973) accretion disk model
- Larger black hole masses also lead to hotter accretion disks
  - This is *not* consistent with the Shakura & Sunyaev (1973) accretion disk model
  - Deviations from this model could be caused by various effects such as accretion disk winds

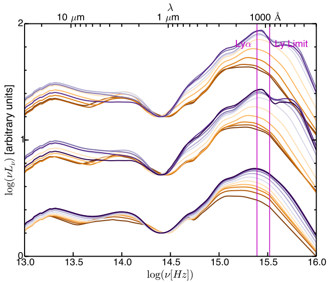




Black Hole Properties

- Larger accretion rates lead to hotter accretion disks
  - This is consistent with the Shakura & Sunyaev (1973) accretion disk model
- Larger black hole masses also lead to hotter accretion disks
  - This is *not* consistent with the Shakura & Sunyaev (1973) accretion disk model
  - Deviations from this model could be caused by various effects such as accretion disk winds





Budavári, T., Heinis, S., Szalay, A. S., et al. 2009, ApJ, 694, 1281

Casebeer, D. A., Leighly, K. M., & Baron, E. 2006, ApJ, 637, 157

Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 95, 1

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306

Goobar, A. 2008, ApJ, 686, L103

Park, D., Woo, J.-H., Denney, K. D., & Shin, J. 2013, ApJ, 770, 87

Rafiee, A., & Hall, P. B. 2011, MNRAS, 415, 2932

Richards, G. T., Lacy, M., Storrie-Lombardi, L. J., et al. 2006, ApJS, 166, 470

Schneider, D. P., Richards, G. T., Hall, P. B., et al. 2010, AJ, 139, 2360

Scott, J. E., Kriss, G. A., Brotherton, M., et al. 2004, ApJ, 615, 135

Shakura, N. I., & Sunyaev, R. A. 1973, in IAU Symposium, Vol. 55, X- and Gamma-Ray Astronomy, ed. H. Bradt & R. Giacconi, 155

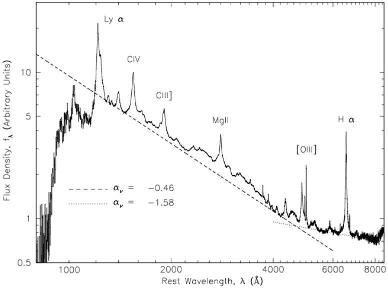
Shen, Y., Richards, G. T., Strauss, M. A., et al. 2011, ApJS, 194, 45

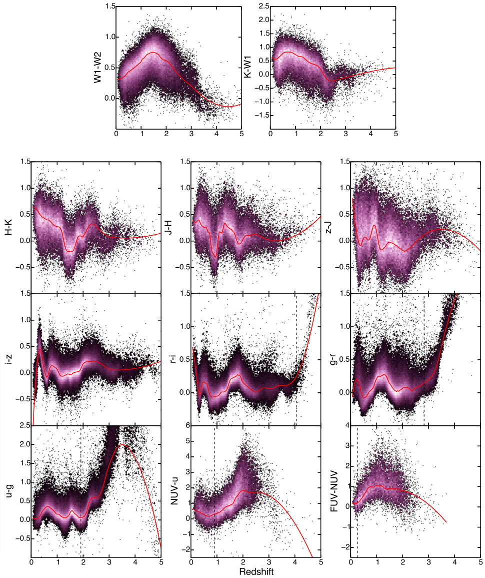
Stalin, C. S., Srianand, R., & Petitjean, P. 2011, MNRAS, 413, 1013

Vanden Berk, D. E., Richards, G. T., Bauer, A., et al. 2001, AJ, 122, 549

SED Corrections

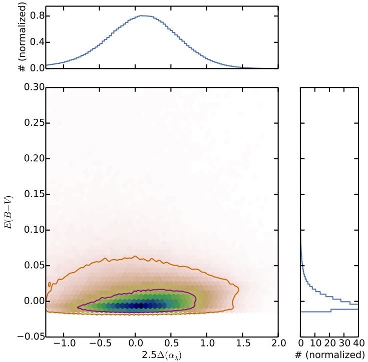
- Lyman–α forest
  - The neutral hydrogen between us and the quasar absorbs wavelengths shorter than 912Å
  - We use a model for the distribution of these hydrogen clouds to statistically correct for this effect
- Strong emission lines
  - Strong emission lines can change the shape of the observed SEDs
  - We remove the effects of these lines by modeling how the filters change in response to the mean quasars spectrum placed at different redshifts
- Host galaxy
  - Low luminosity quasars are contaminated by host galaxy light in the mid-IR
  - Using scaling relations from Shen et al. (2011) and Richards et al. (2006) we estimate the host galaxy contribution
- Gap filling
  - Not every filter has data for every quasar
  - We estimate “missing” data in an iteratively based on the mean SED within subsamples of quasars

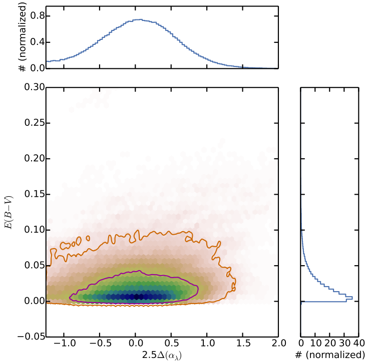




Modal Colors

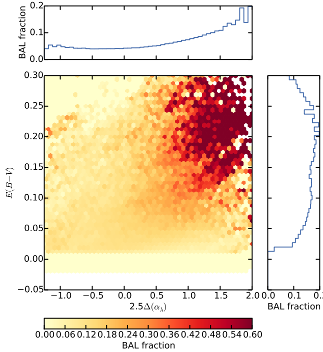
- Strong spectral lines cause trends in the colors of quasars as a function of redshift
- Using these trends we can find the "modal" quasar color for any given redshift

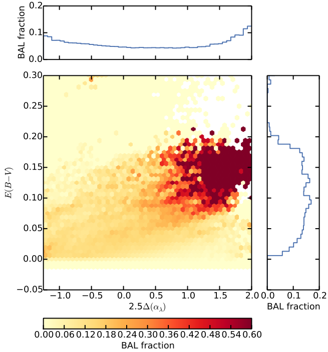




L14-QSO fit

- Both samples have lower E(B-V) values than before
- The BAL sample is slightly redder than the the non-BAL sample





BAL fraction

- The BAL fraction ranges from $\sim$0.05–0.2 as the $\Delta(\alpha_\lambda)$ value changes for both dust laws
- BAL quasars dominate the intrinsically blue and highly reddened part of the parameter space

Deviance Information Criterion (DIC)

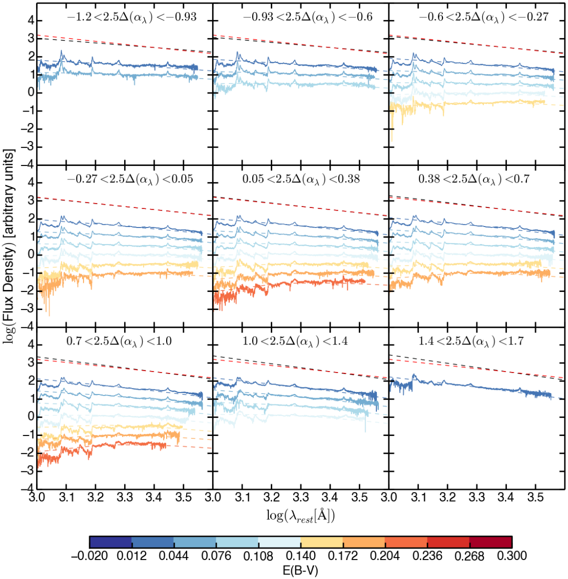
- Bayesian analysis allows for the direct comparison of multiple models
- Looking at the difference between the DIC values between the two models tells us what one fits better

What model fits better

- non-BAL quasars
  - SMC: 95.6%
  - either model: 4.3%
  - L14-QSO: 0.06%
- BAL quasars
  - SMC: 88.6%
  - either model: 11%
  - L14-QSO: 0.4%

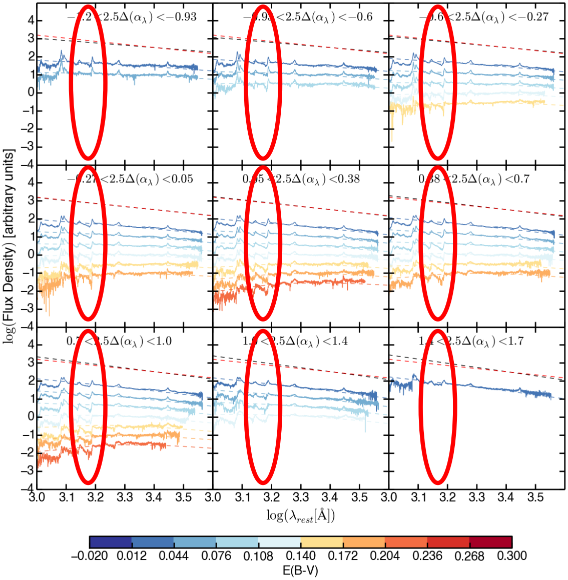
SMC BAL

- As before, the fits based on the photometry track the spectra well
- The depth of the C IV absorption trough increases with E(B-V)
- The width of the C IV absorption trough increases with intrinsic color



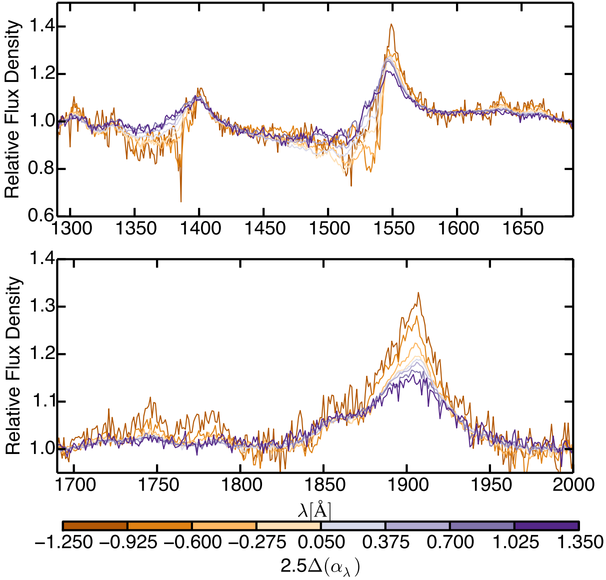
SMC BAL

- As before, the fits based on the photometry track the spectra well
- The depth of the C IV absorption trough increases with E(B-V)
- The width of the C IV absorption trough increases with intrinsic color



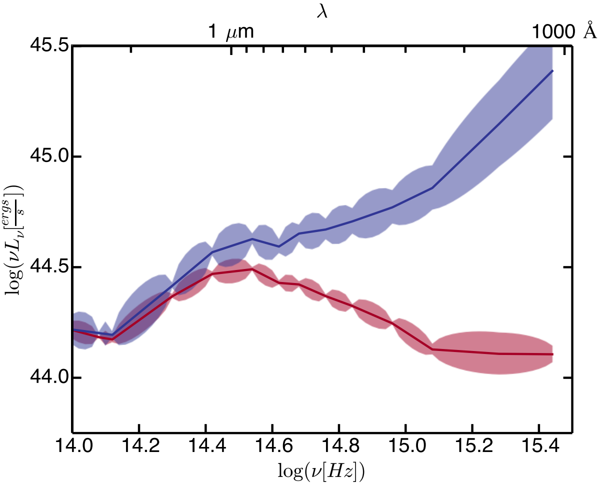
BAL Spectral Lines

- The shape/size of the absorption troughs is correlated with SED shape
- The narrow, low velocity absorption in the redder BALs could be an indication of a weaker wind or a higher RL fraction
- C IV and C III] shows similar emission line trends as the non-BAL spectra



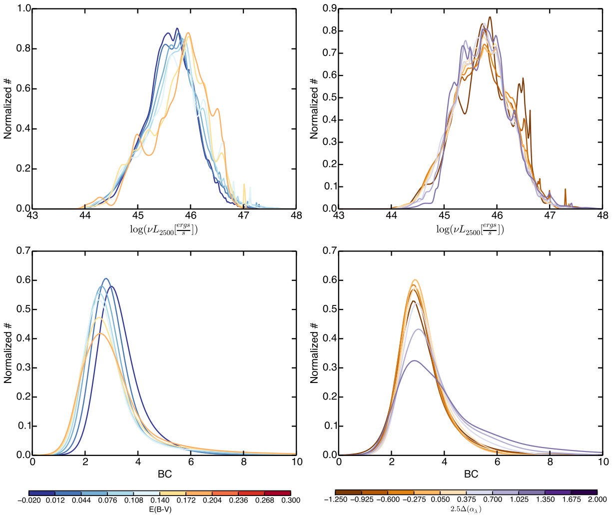
Dust Correction

- Dust extinction correction for a quasar with E(B-V)=0.2
- Red: Observed SED
- Blue: Corrected SED
- Less then 0.1% of our sample needs a correction this extreme



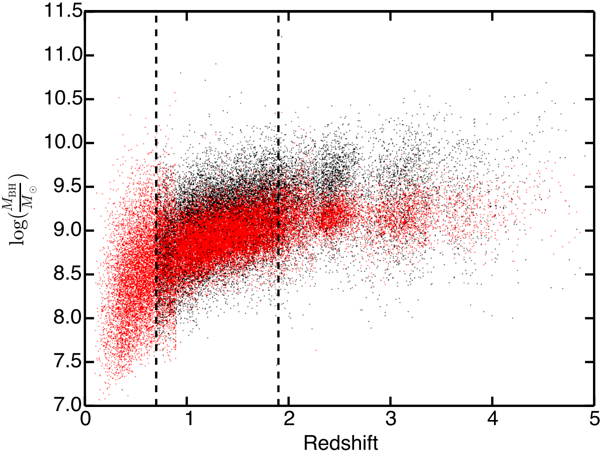
Luminosity and BC distributions

- More reddened quasars have higher luminosities, and as a result, lower BCs
- There are no luminosity trends with intrinsic color, but the bluer quasars have larger BCs



Central black hole masses

- Estimated from emission line widths
- Started with a catalog of masses estimated using the FWHM of various broad lines
- Applied re-calibrations to account for the FWHM over estimating the masses



Luminosity and BC distributions

- Quasars with hither accretion rates have higher luminosities and higher BCs
- More massive quasars have slightly higher luminosities and no trends with BC