Extinction Curves of Lensing Galaxies

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INTRODUCTION

Extinction curves

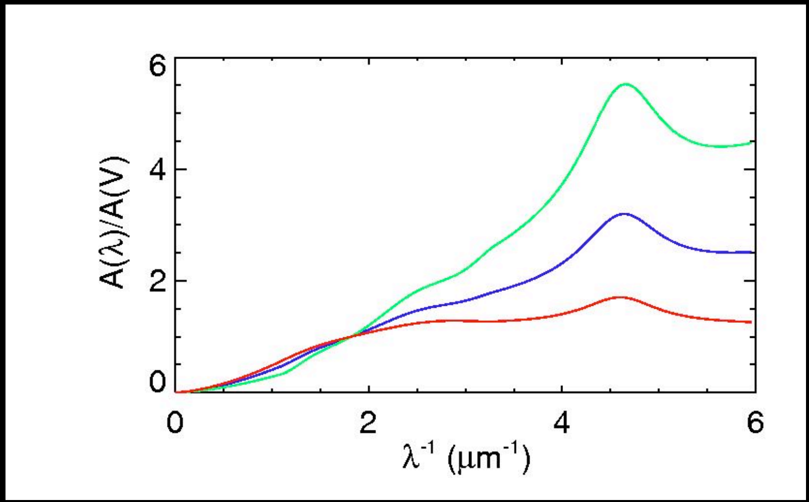
- Measure the difference in emitted and observed light
- Caused by interstellar dust
- Traditionally measured by comparing two stars of the same spectral type

The Galactic Extinction Curve

Galactic Extinction - empirically determined:

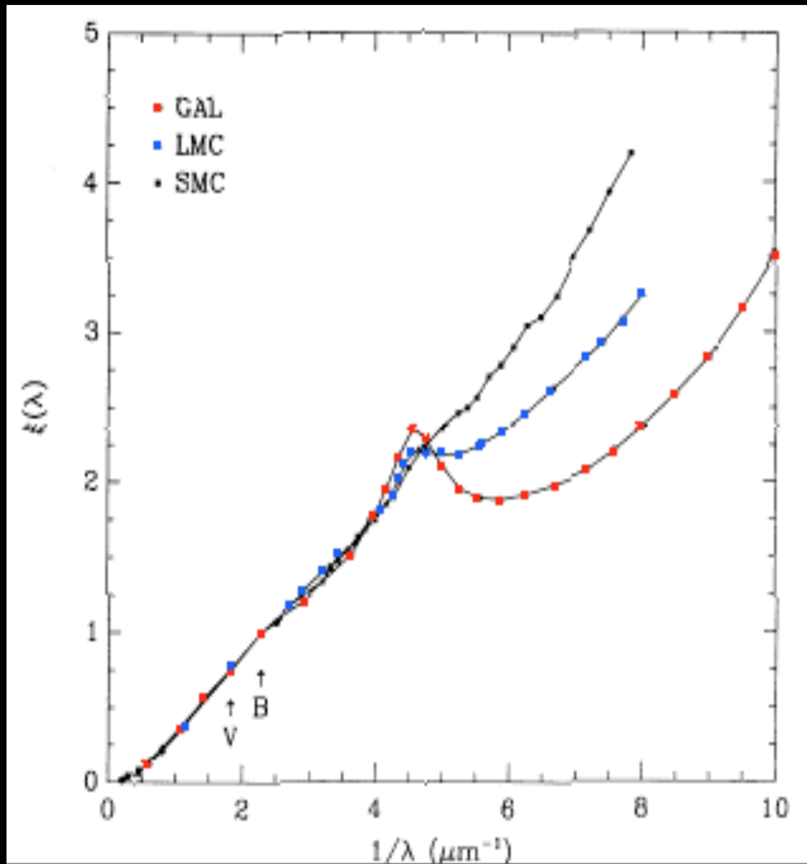
– $\langle A(\lambda)/A(V) \rangle = a(\lambda^{-1}) + b(\lambda^{-1})/R_V$ (Cardelli et al. 1999)

- Bump at 2175 Å (4.6 μm^{-1})
- R_V : Ratio of total to selective extinction in the V band
- Mean value is R_V = 3.1 (blue)
- Low value: R_V = 1.8 (green) (Udalski 2003)
- High value: R_V = 5.6-5.8 (red) (Cardelli et al. 1989, Fitzpatrick et al. 1999)



Other nearby galaxies

- LMC: Smaller bump and steeper rise into the UV (Nandy et al. 1981)
- SMC: No bump, well fitted by A(λ) ∝ 1/ λ (Prevót et al. 1984)
- M31: Average Galactic extinction law (Bianchi et al. 1996)



Graph from Pei (1992)

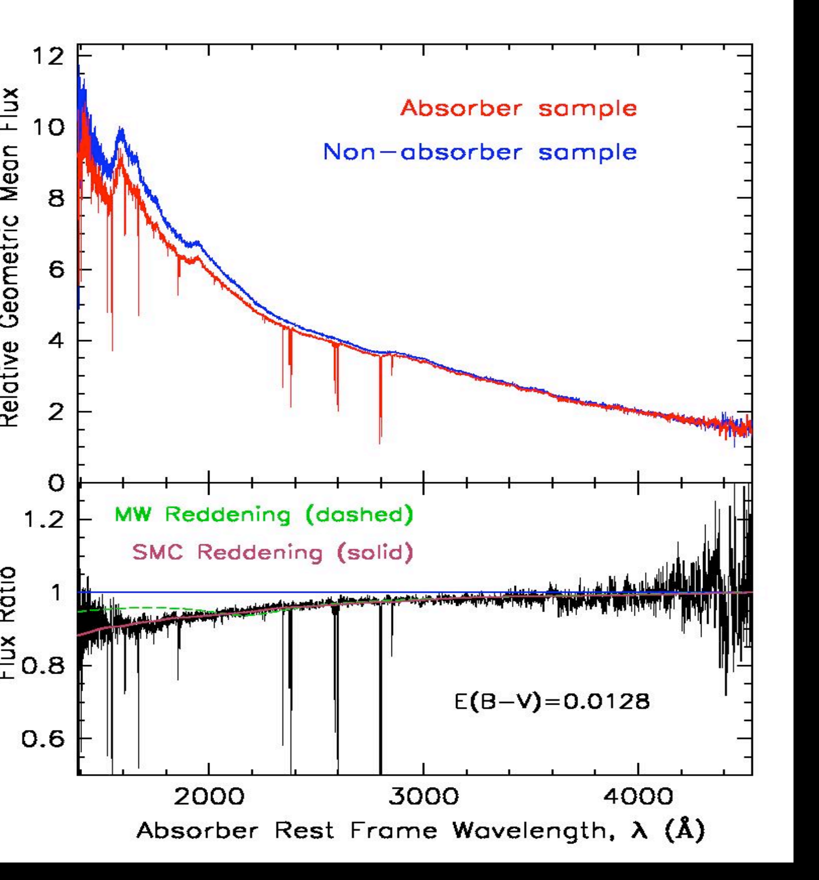
HIGHER REDSHIFT EXTINCTION CURVES

Why measure higher redshift extinction curves?

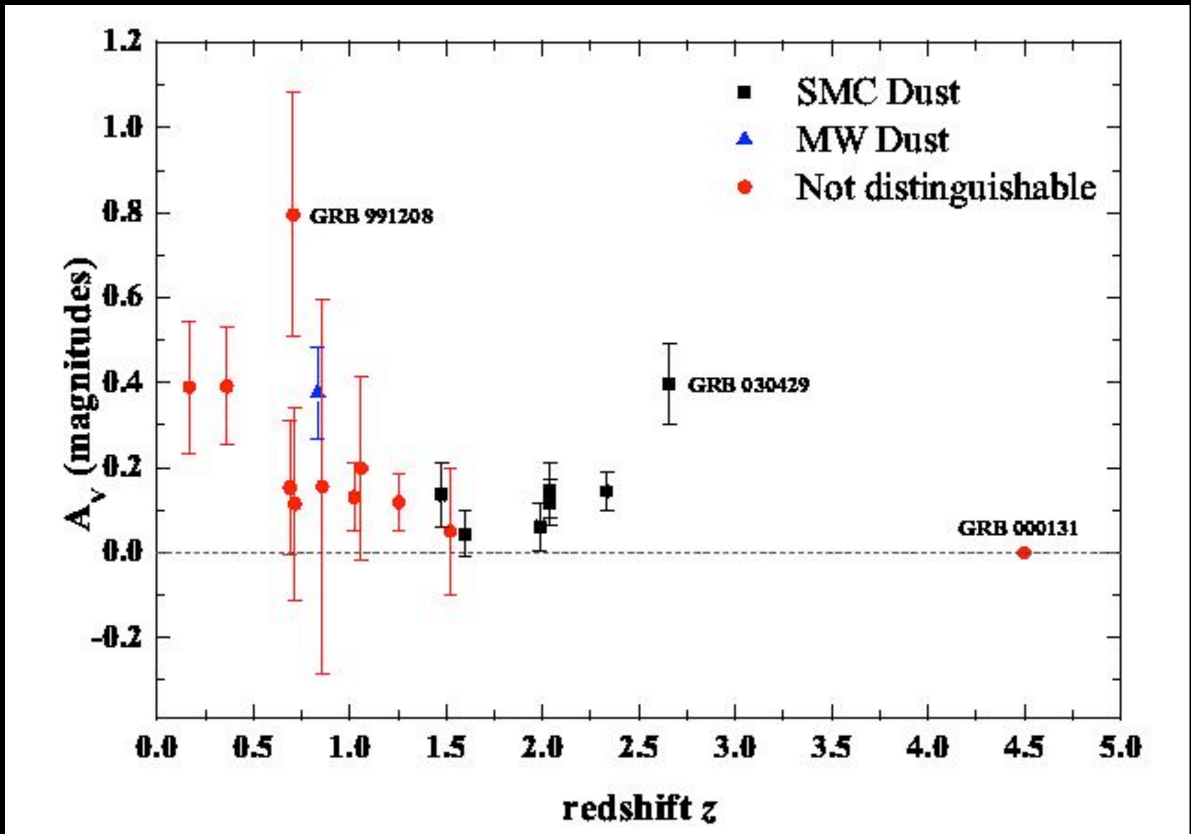
- From the four examples we know, we see that extinction curves can vary greatly
- When analysing data where extinction needs to be accounted for the galactic extinction curve is frequently assumed
- Dust behaviour, and hence extinction, expected to vary with z
- So, how do we do it?

Extinction curves from QSOs

- Compare the composite spectra of quasars (DLAs, absorbers, galaxies) to a standard spectra
- Varying results
  - DLAs
    - Extinction (Pei et al. 1992)
    - No extinction (Murphy & Liske 2004, Ellison et al. 2005)
  - Mg II absorbers
    - Galactic extinction (Malhotra 1997)
    - SMC extinction (York et al. 2006)
  - Foreground galaxies
    - Galactic type extinction (Östman et al. 2005)



Extinction curves from GRBs

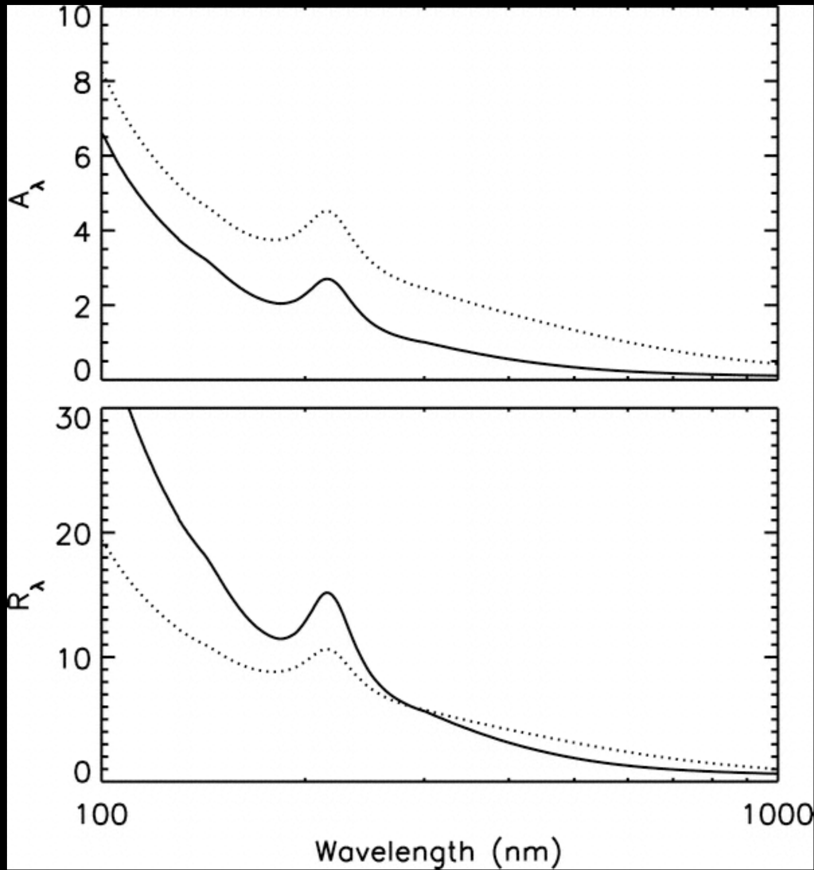


(Kann et al. 2005)

- Found by studying the spectral energy distribution
- Seem to favour SMC type extinction (Jakobsson et al. 2004, Kann et al. 2005)

Extinction curves from SNe Ia

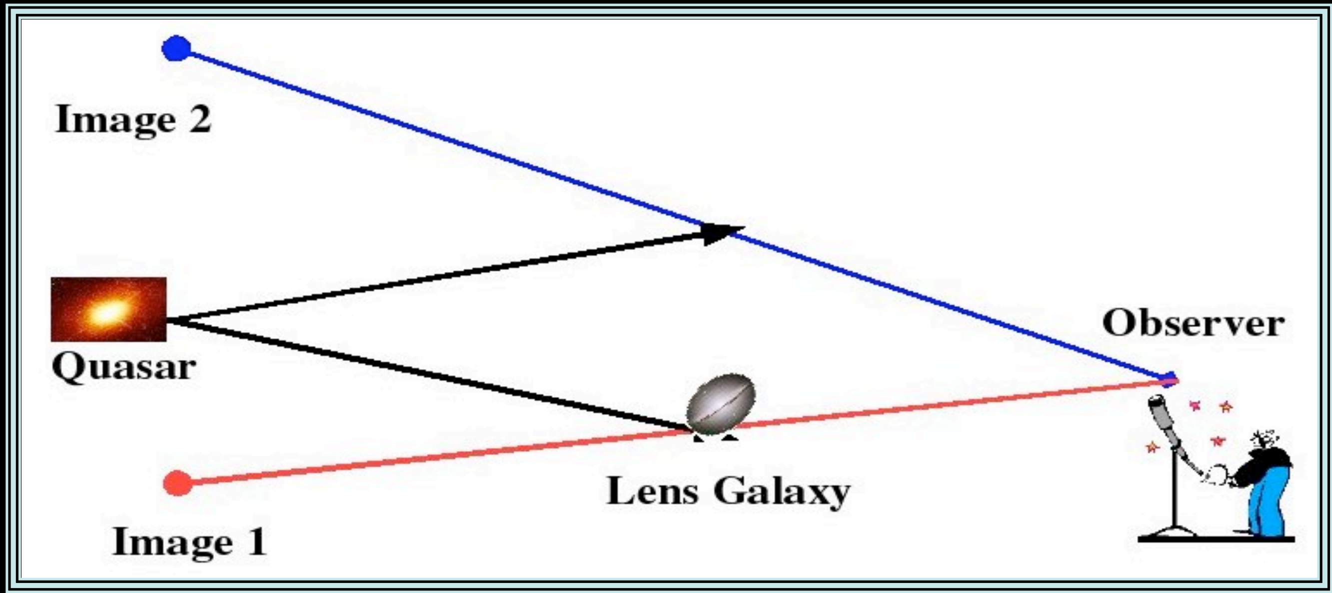
- Consistent with Galactic extinction (Riess et al. 1996)
- Lower R_V values - SNe Ia environments systematically different? (Branch & Tammann 1992, Krisciunas et al. 2000)
- Extinction estimates might be affected by circumstellar dust (Wang 2005)



(Wang 2005)

EXTINCTION CURVES FROM LENSED QSOs

The Method



- Compare two images, where ideally one should suffer no extinction and the other go through the galaxy
- For more than doubly imaged quasars have the possibility of getting more than one curve for the lensing galaxy

Extinction along both lines of sight

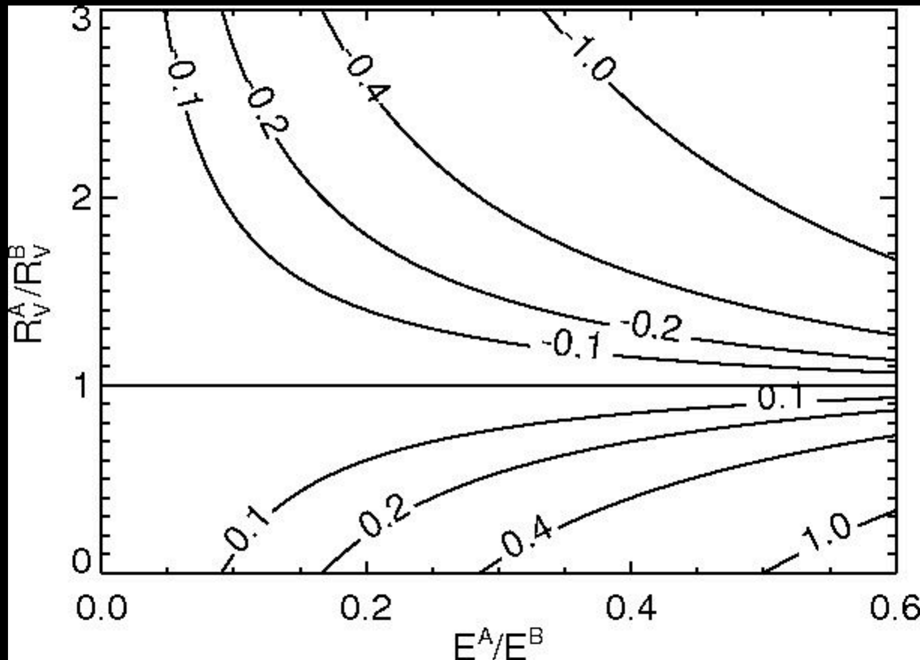
Galactic extinction:

$$\begin{aligned} A^{diff}(\lambda) &= A^{B}(\lambda) - A^{A}(\lambda) \\ &= \left(E^{B} - E^{A}\right)\left[R_V^{diff}\, a(\lambda^{-1}) + b(\lambda^{-1})\right] \end{aligned}$$

$$\left(E \equiv E(B-V) = A(B) - A(V)\right)$$

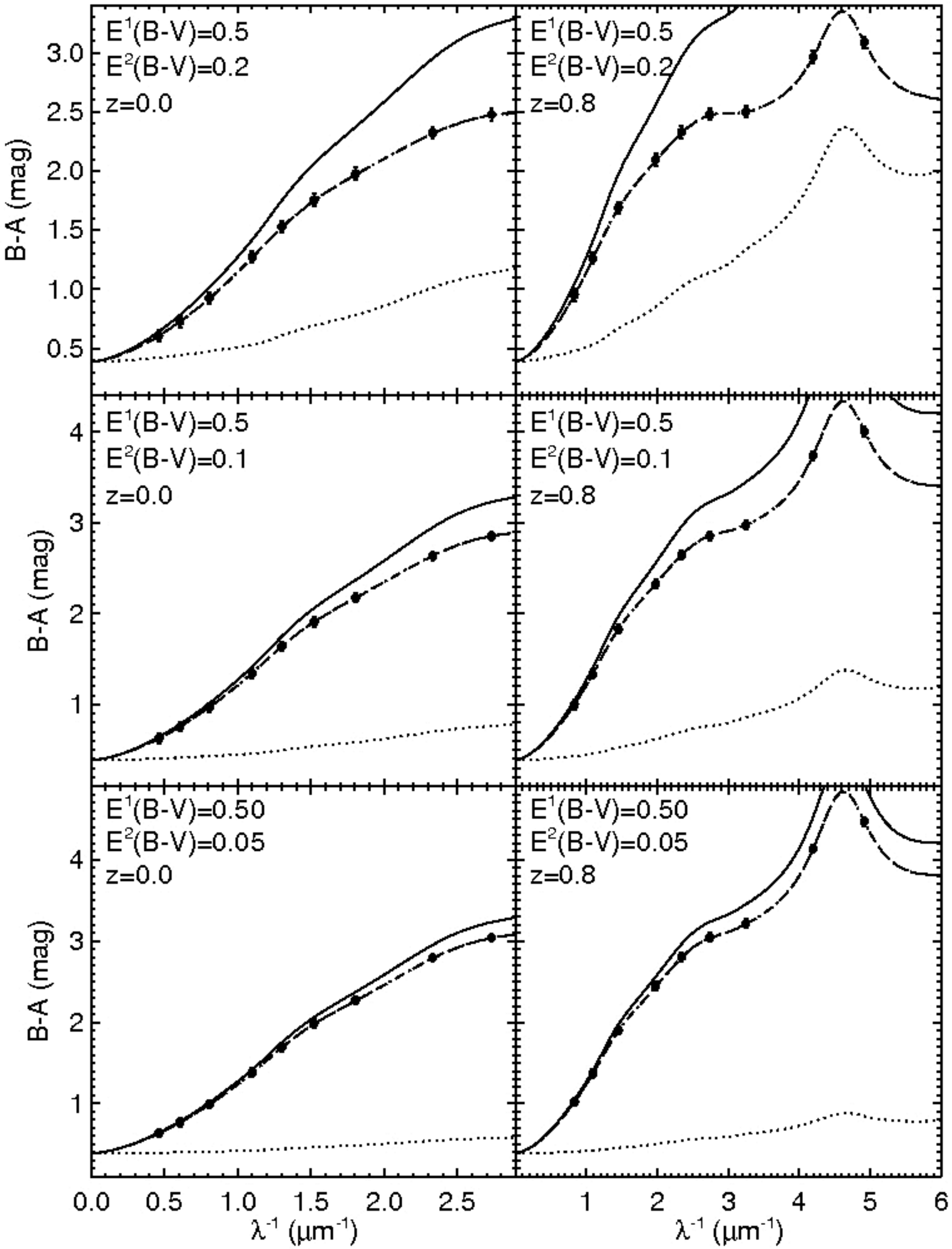
The deviation of the real R_V to the deduced R_V^{diff} is given by η, where:

$$\begin{aligned} \frac{R_V^{diff}}{R_V^{B}} &= 1 + \frac{E^{A}/E^{B}}{1 - E^{A}/E^{B}}\left(1 - \frac{R_V^{A}}{R_V^{B}}\right) \\ &\equiv 1 + \eta \end{aligned}$$



Dark Cosmology Centre

Extinction along both lines of sight



R_V=2.0 (lower E(B-V))

R_V=4.0 (higher E(B-V))

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Microlensing

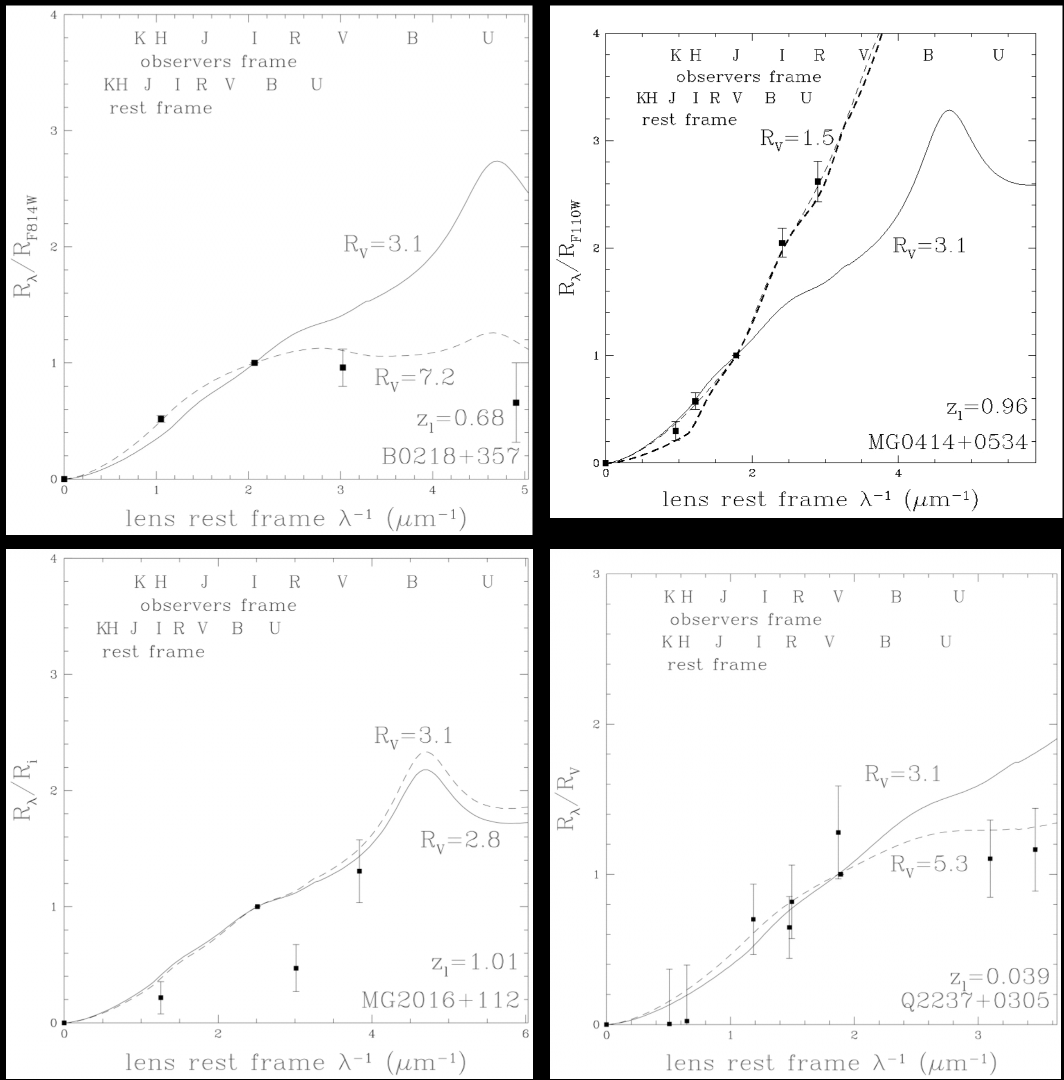
- The lensing by stars or other objects in the lens galaxy
- Affects the continuum part of the emission
- Effects can look like 'extinction'
- If the data are taken on a timescale smaller than that of the microlensing signal, then any achromatic microlensing signal should, to first order, only affect the estimate of the intrinsic magnitude ratio
- For chromatic microlensing, it is necessary to study the spectra of the quasars to separate it from the extinction signal

Time delays

- Travel path for different images differs ⇒ intrinsic variations show up at different times
- Ideally one should take data with a time difference corresponding to the time delay
- Alternatively, if data are taken simultaneously, then the intrinsic variations should only affect the estimated intrinsic brightness ratio of the images

PREVIOUS STUDIES

Falco et al. 1999



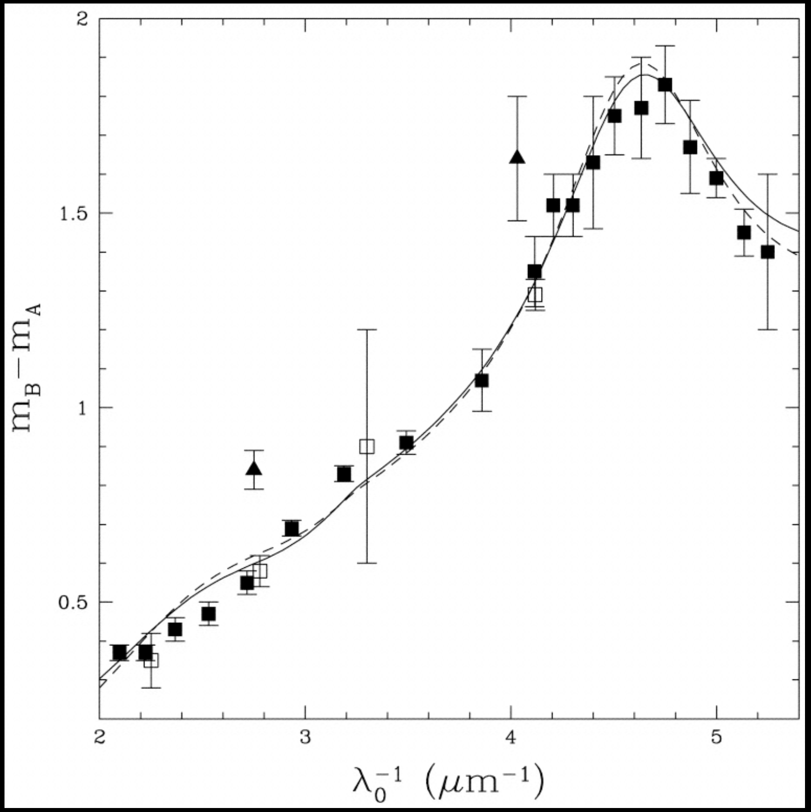
- Studied the extinction of 23 lensing galaxies with 0<z<1 by assuming a mean Galactic extinction law

- They did further analysis on a few systems where they allowed R_V to vary

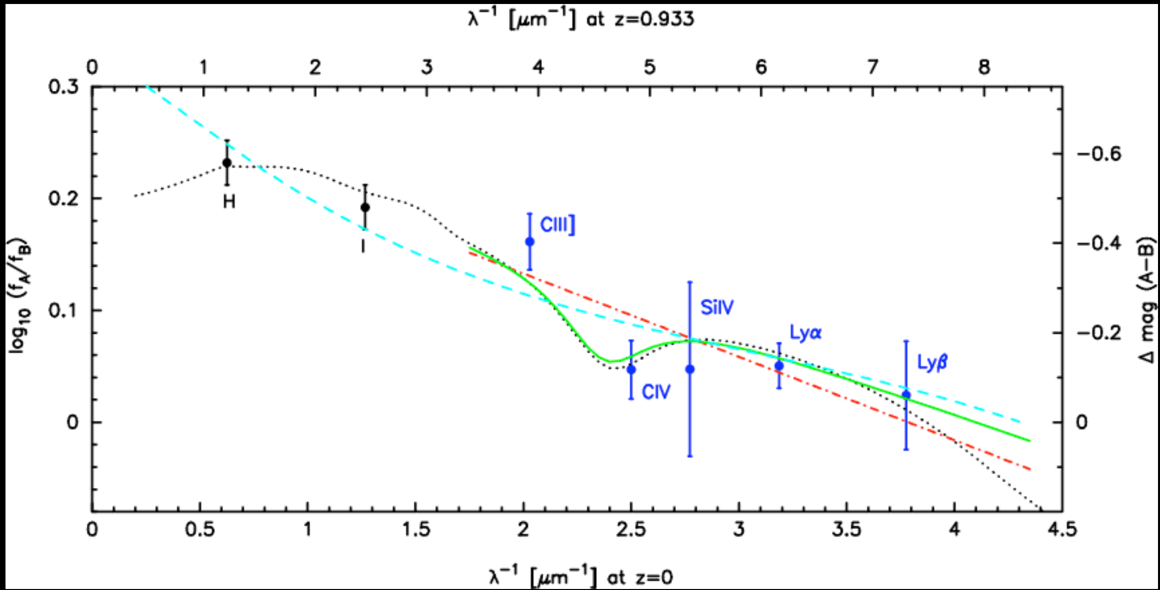
- Note: Their data is combined from epochs spanning several years

Motta et al. (2002)

- SBS 0909+532
- z_l = 0.83
- Strong detection of the 2175 Å bump
- R_V = 2.1 ± 0.9
- E(B-V) = 0.21 ± 0.02



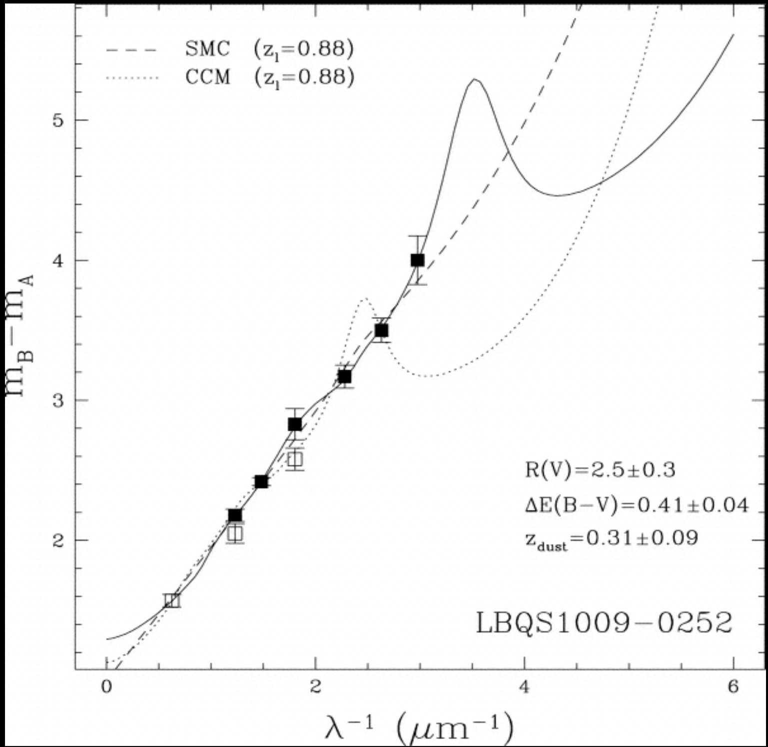
Wucknitz et al. 2003

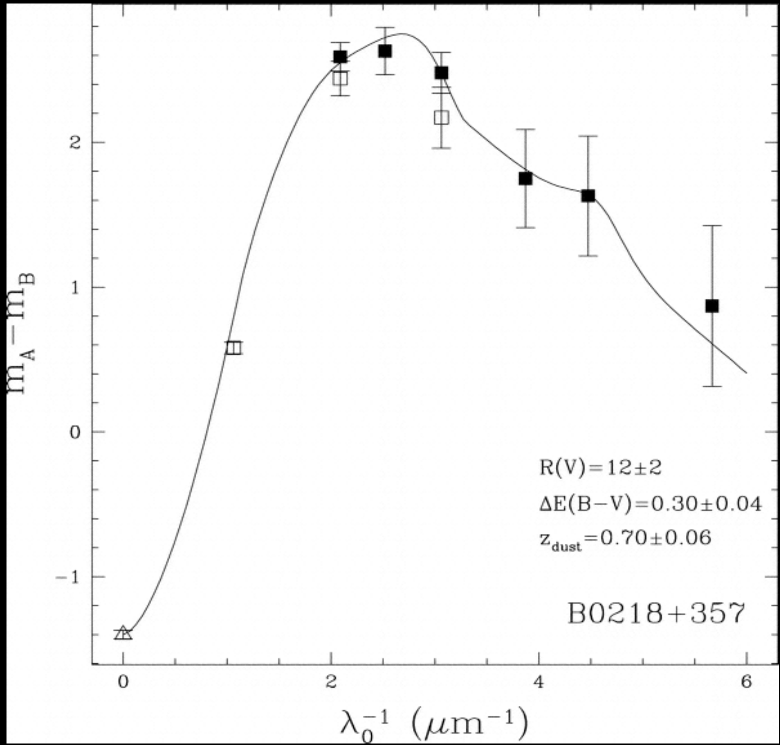


- HE 0512-3329
- z = 0.93
- Double

- Galactic extinction marginally preferred
- R_V = -2.0
- A(V) = 0.07

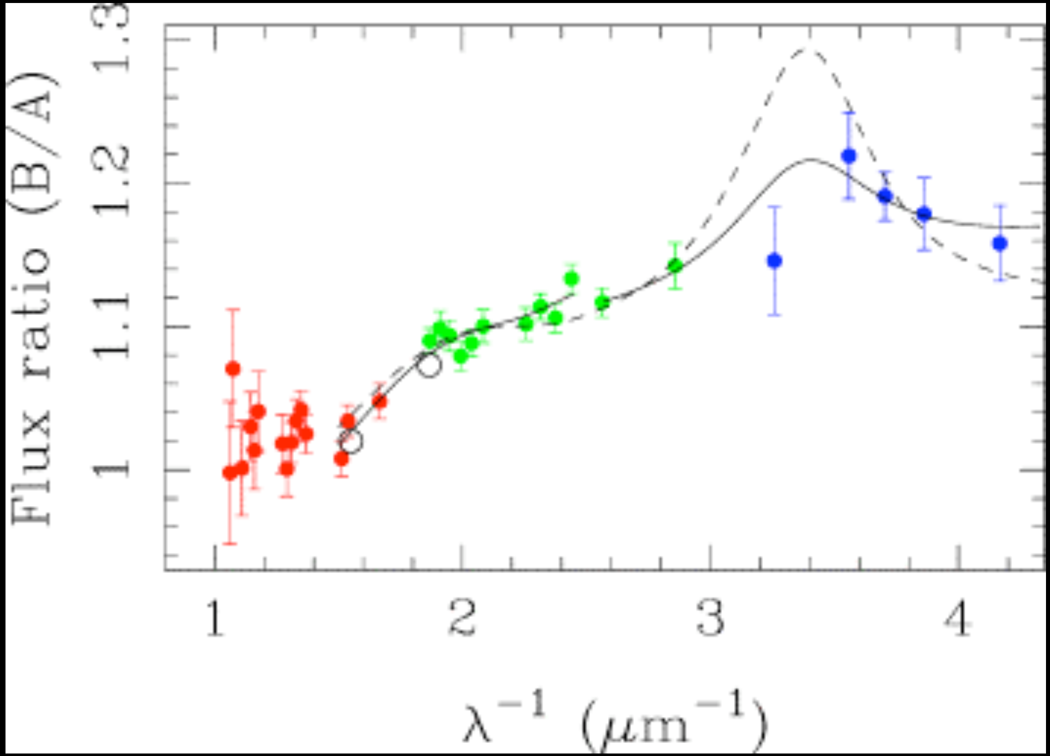
Muñoz et al. (2004)





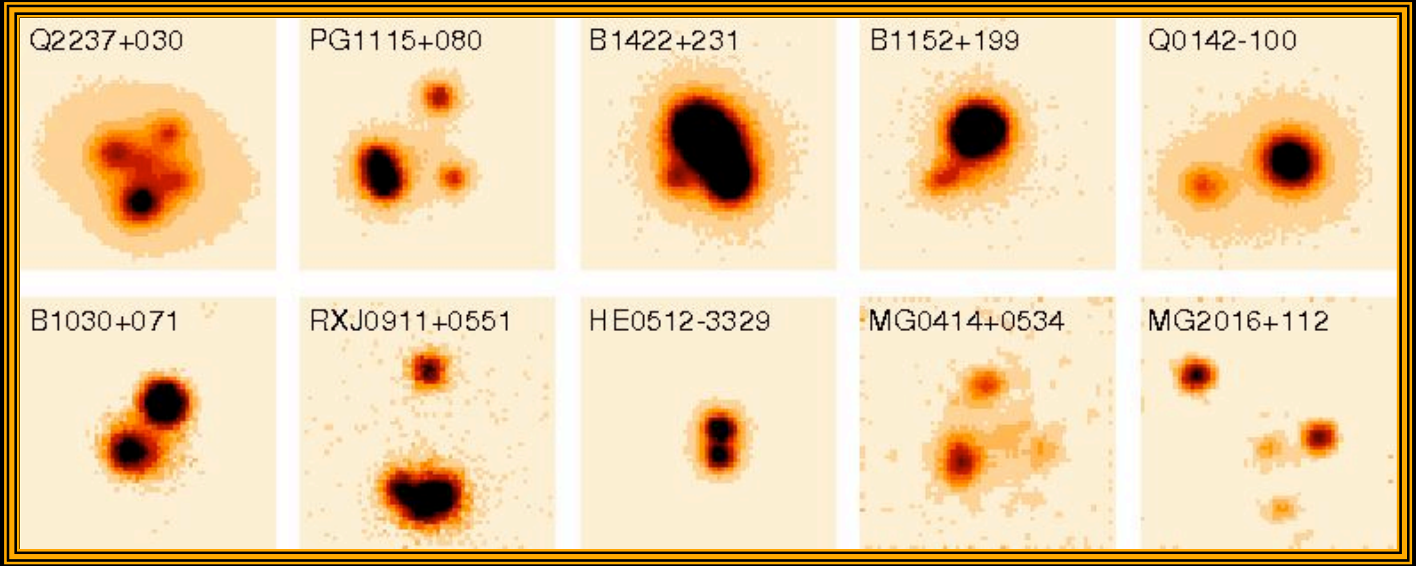
Goicoechea et al. 2005

- QSO 0957 +561
- z_l = 0.36
- Combination of extinction laws
- $R_V = 4.4 \pm 0.5$



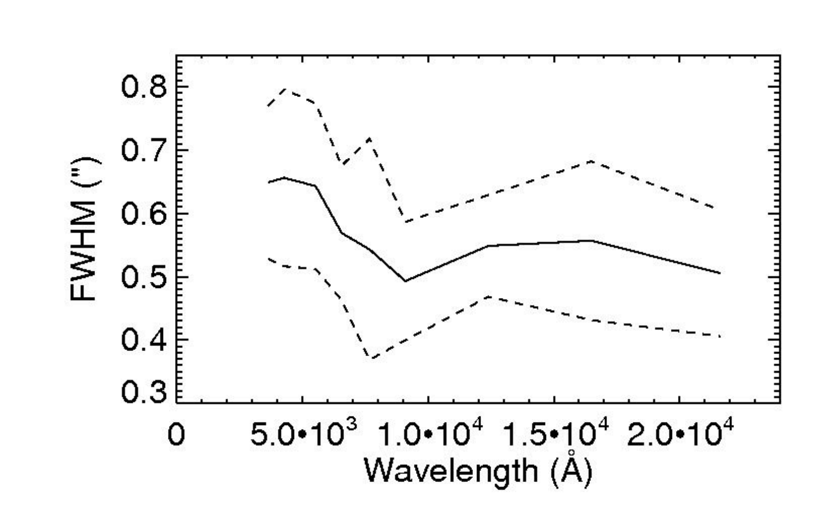
VLT SURVEY

VLT Survey



- 10 systems, (5 doubles and 5 quads)
- Image separation > 0.4"
- Redshift known for both the lens and the quasar
- Redshifts of the lensing galaxies range from z=0.04-1.01

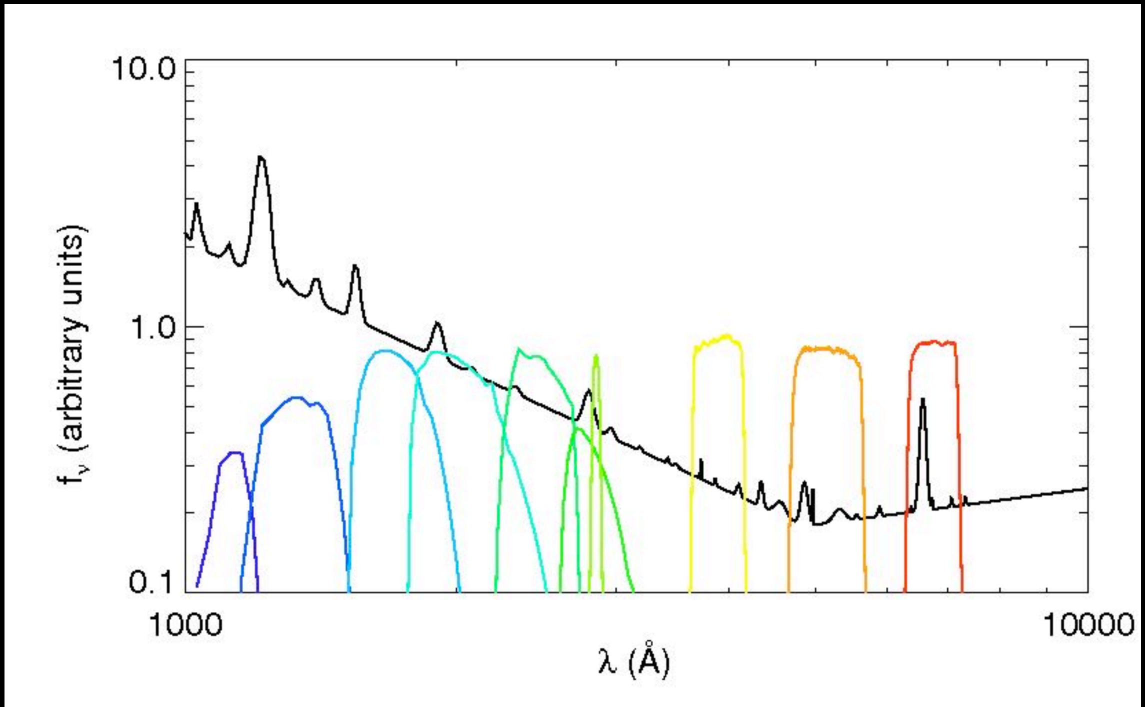
Data



Excellent seeing conditions
Broad wavelength coverage (U,B,V,R,I,z’,J,H,Ks)

Effort made to minimize time delay between observations

Correcting for microlensing



- Calculate the proportion of the continuum part to the the full emission for each band
- Introduce a correction due to microlensing which is proportional to this ratio

Extinction laws considered

- Galactic extinction law

$$A(\lambda) = A(V)\left[a(\lambda^{-1}) + R_V b(\lambda^{-1})\right]$$

$$R_V \equiv \frac{A(V)}{E(B-V)}$$

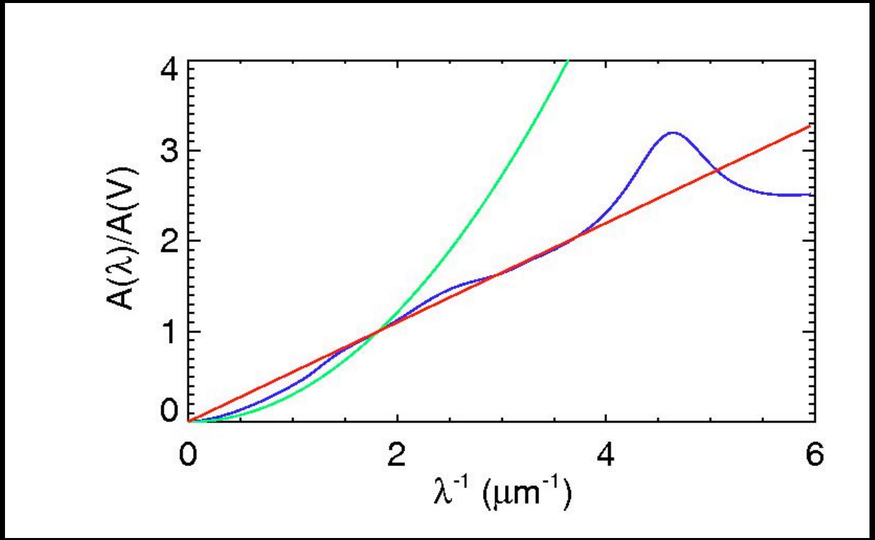
$$E(B-V) = A(B) - A(V)$$

- Linear SMC type extinction

$$A(\lambda) = A(V)\left(\frac{\lambda}{5500\,\text{Å}}\right)^{-1}$$

- Power law

$$A(\lambda) = A(V)\left(\frac{\lambda}{5500\,\text{Å}}\right)^{-\alpha}$$



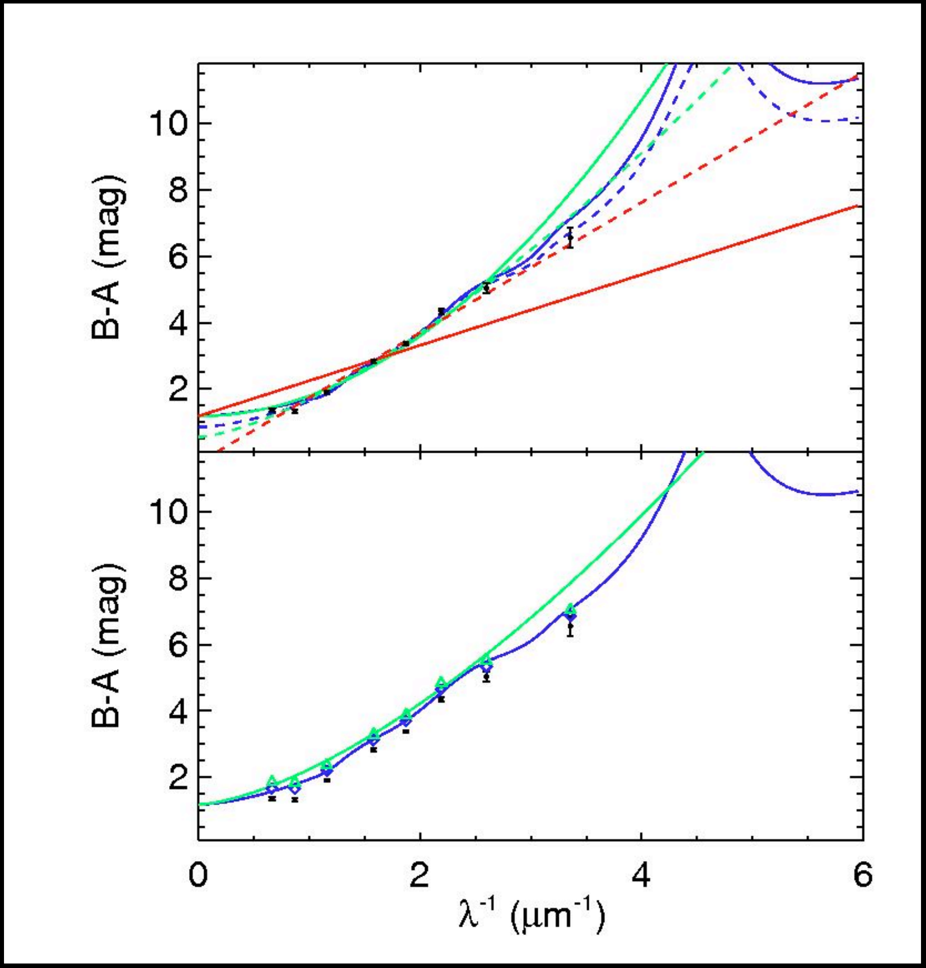
RESULTS - INDIVIDUAL SYSTEMS

B1152+199

- Lens system
  - Double
  - Late type galaxy
  - $z_l = 0.44$
  - $z_Q = 1.02$

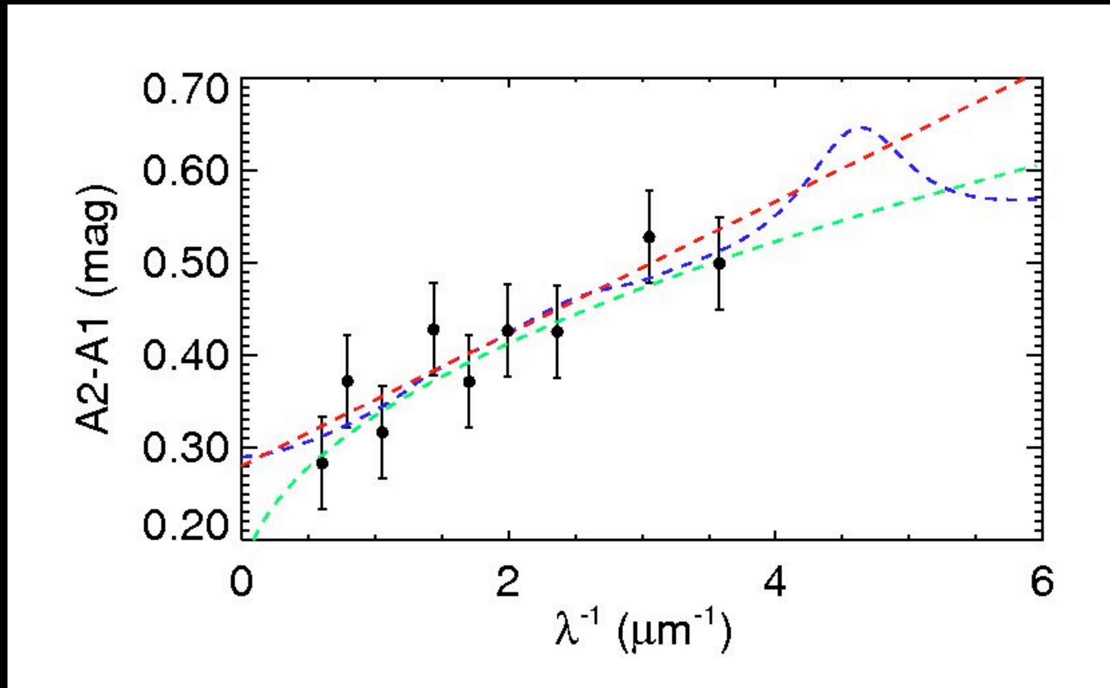
- Best fit from a Galactic extinction law with
  - $R_V = 2.1 \pm 0.1$
  - $A(V) = 2.43 \pm 0.09$

- When the intrinsic ratio is fixed, the best fit gives
  - $R_V = 2.0 \pm 0.1$
  - $A(V) = 2.41 \pm 0.09$
  - $s = 0.32 \pm 0.07$



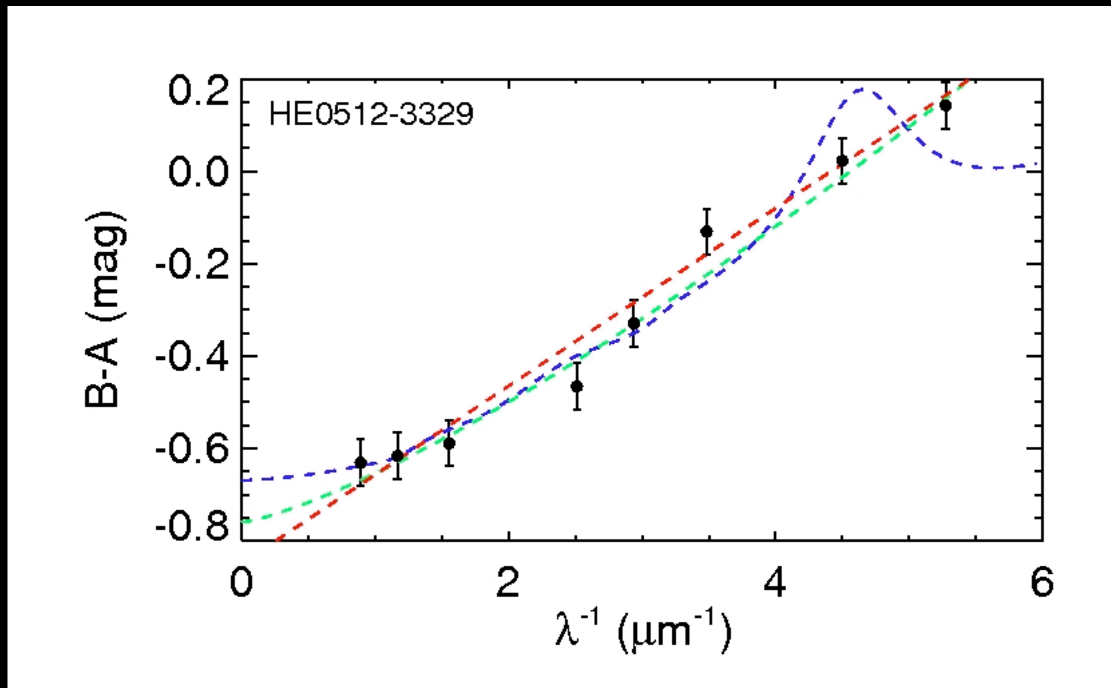
PG1115+080

- Lens system
  - Quad
  - Early type
  - $z_l = 0.31$
  - $z_Q = 1.72$
- Weak extinction
  - Equally good fits
  - A(V) = 0.12 ± 0.06
  - $R_V = 3.3 \pm 1.9$

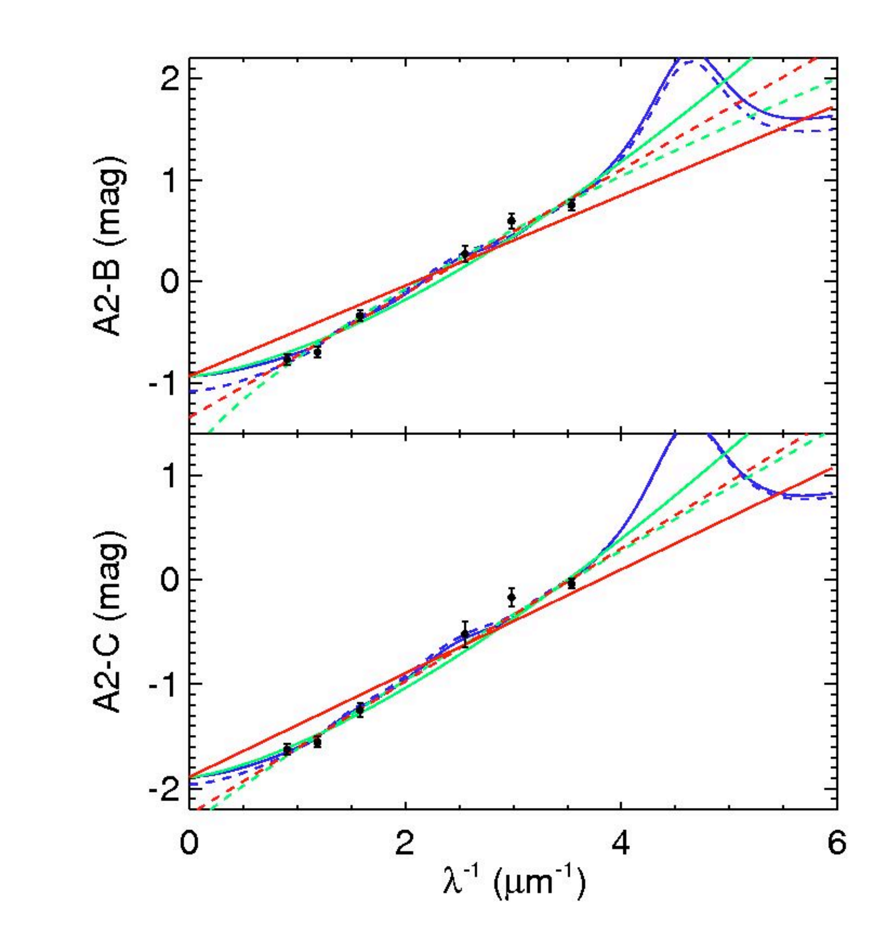


HE0512-3329

- Lens system
  - Double
  - Late type galaxy
  - $z_l = 0.93$
  - $z_Q = 1.57$
- Linear extinction
  - Best fit
  - A(V) = 0.35 ± 0.02
- Galactic fit
  - A(V) = 0.14 ± 0.04
  - $R_V = 1.7 \pm 0.4$

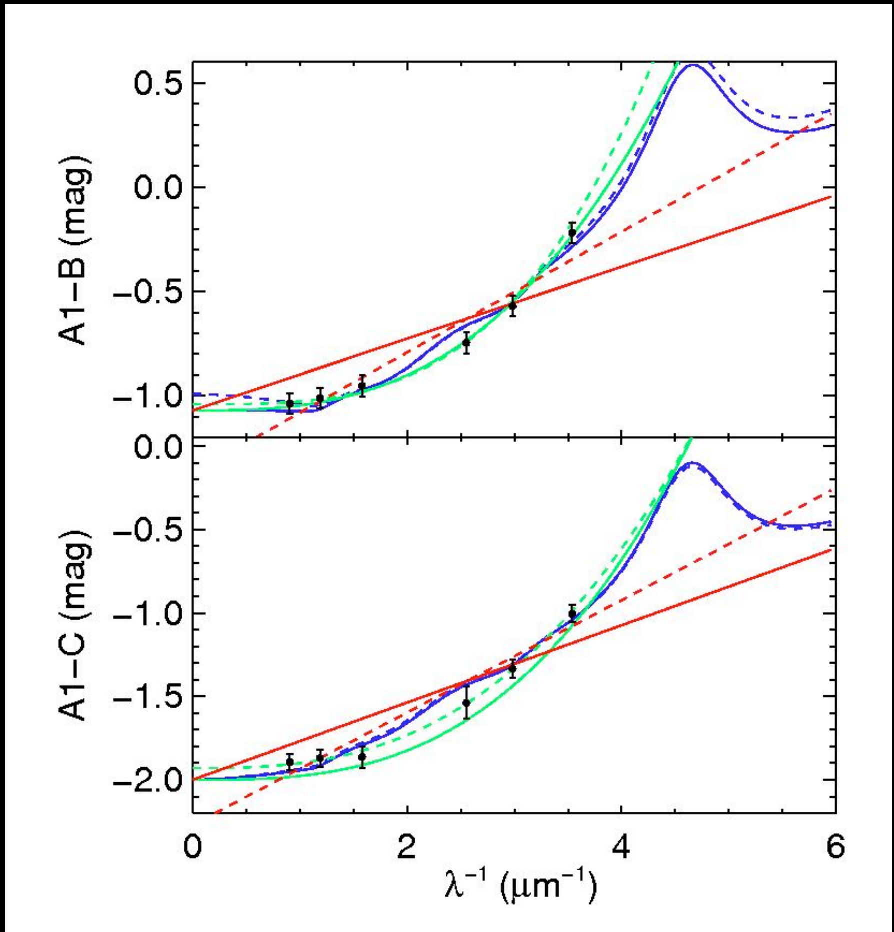


MG0414+0534



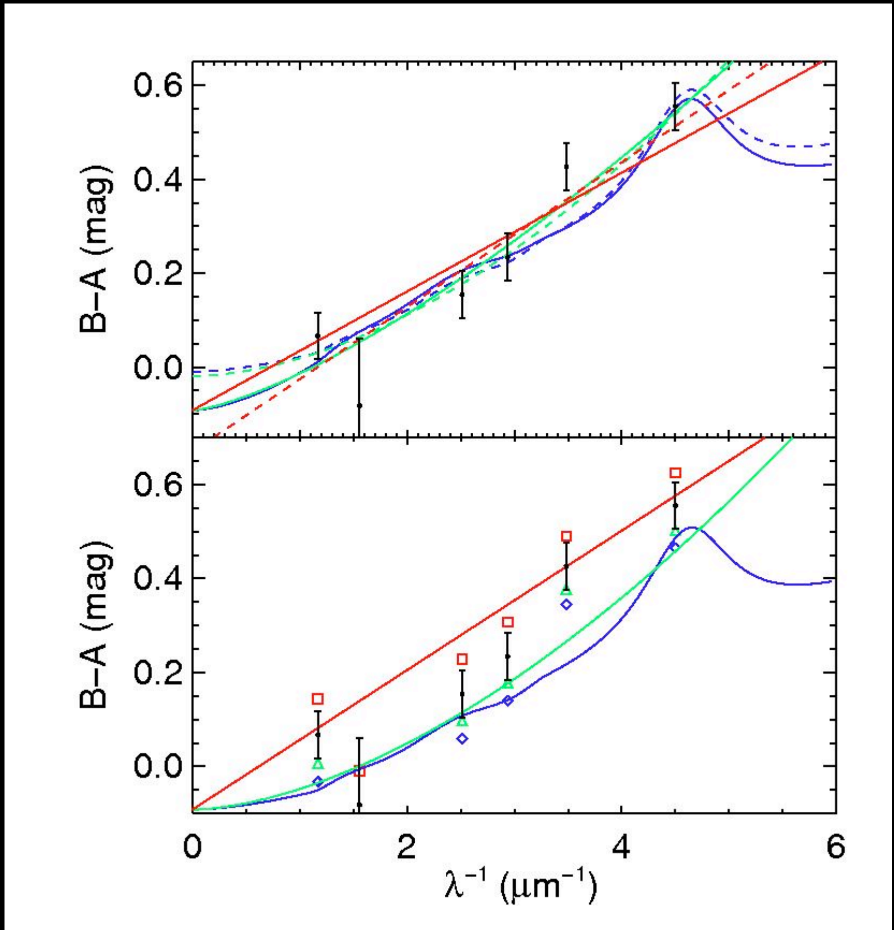
- Lens properties
  - Quad
  - Early type galaxy
  - $z_l = 0.96$; $z_Q = 2.64$
- Similar goodness of fits
- Galactic extinction - A2-B:
  - $A(V) = 0.87 \pm 0.05$
  - $R_V = 2.7 \pm 0.2$
- Galactic extinction - A2-C:
  - $A(V) = 0.91 \pm 0.04$
  - $R_V = 2.6 \pm 0.1$
- The similar properties derived from comparing to B and C suggest that their extinction does not affect the result

MG0414+0534



- Lens properties
  - Quad
  - Early type galaxy
  - $z_l = 0.96$; $z_Q = 2.64$
- Best fit for a power law
- Power law extinction - A1-B:
  - A(V) = 0.10 ± 0.05
  - α = 3.1 ± 0.6
- Power law extinction - A1-C:
  - A(V) = 0.15 ± 0.07
  - α = 2.7 ± 0.6
- Possible that B and C are affecting the extinction properties

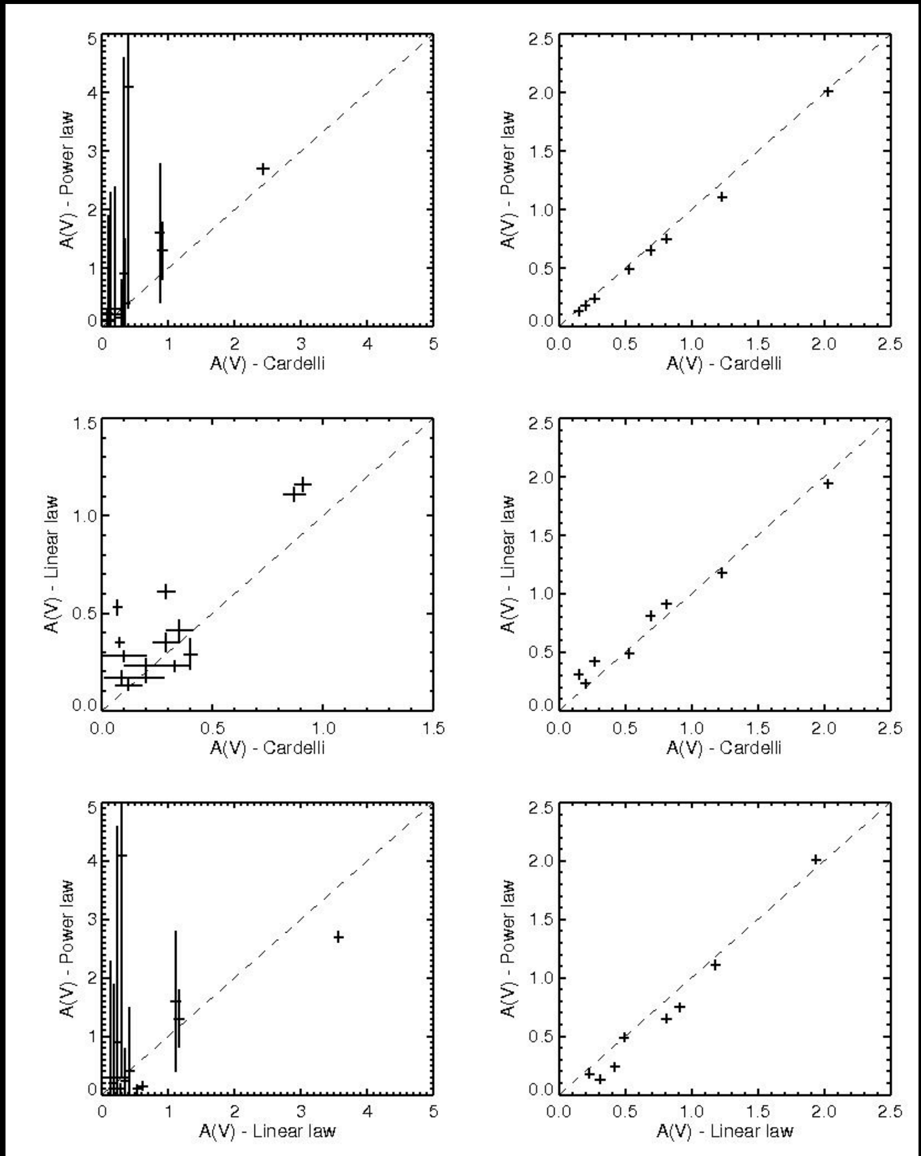
MG2016+122



- Lens properties
  - Double
  - Early type galaxy
  - $z_l = 1.01$; $z_Q = 3.27$
- Power law marginally best
- Microlensing correction zero within two sigma
- Best fit for free intrinsic ratio
  - $A(V) = 0.11 \pm 0.09$
  - $\alpha = 1.8 \pm 0.6$
- Best fit for fixed intrinsic ratio
  - $A(V) = 0.18 \pm 0.03$
  - $\alpha = 1.4 \pm 0.2$

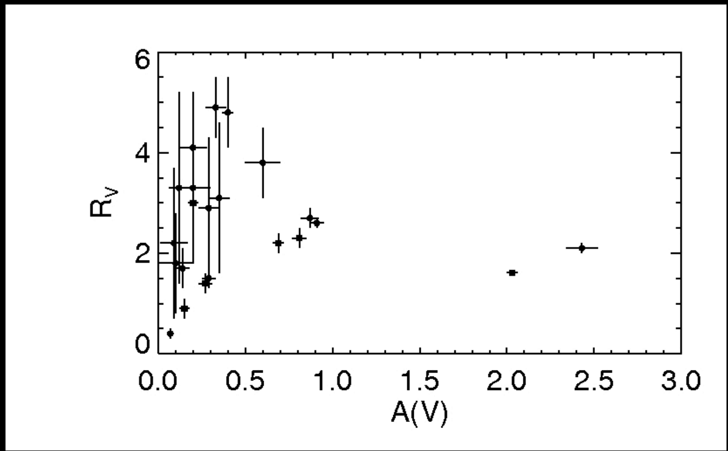
RESULTS - FULL SAMPLE

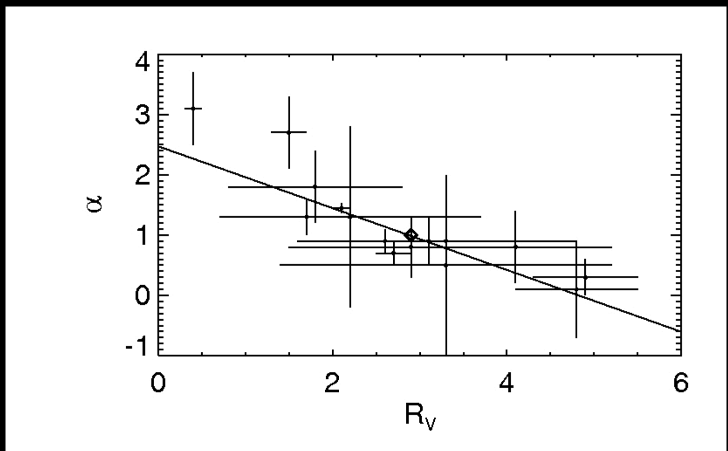
Parameters of the fits



- Power law extinction overestimates A(V) compared to other fits when intrinsic ratio is free
- Better correlation when intrinsic ratio is held fixed
- Mean A(V) = 0.54 (Galactic extinction)

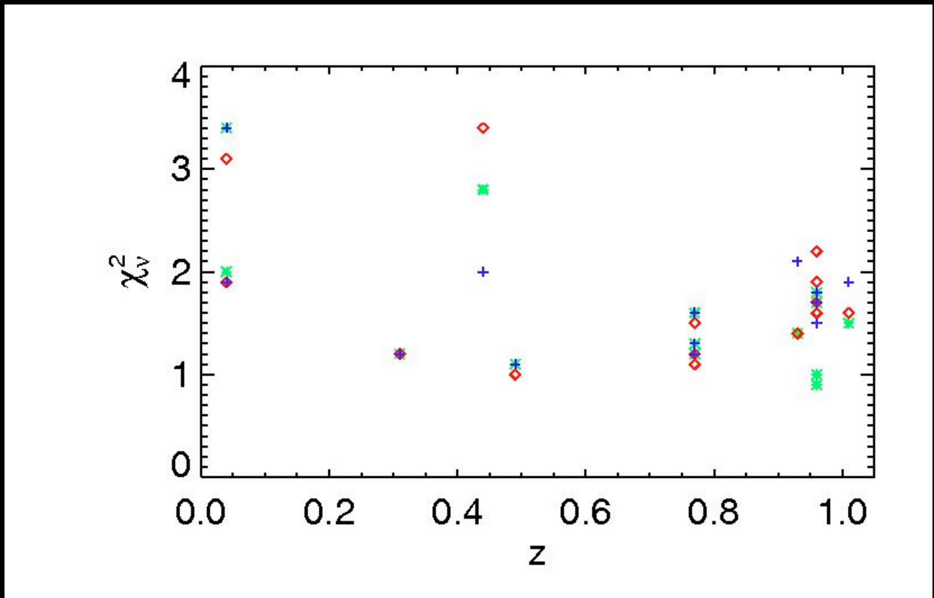
Parameters of the fits





- See no correlation between A(V) and R_V
- Strong anti-correlation between R_V and α

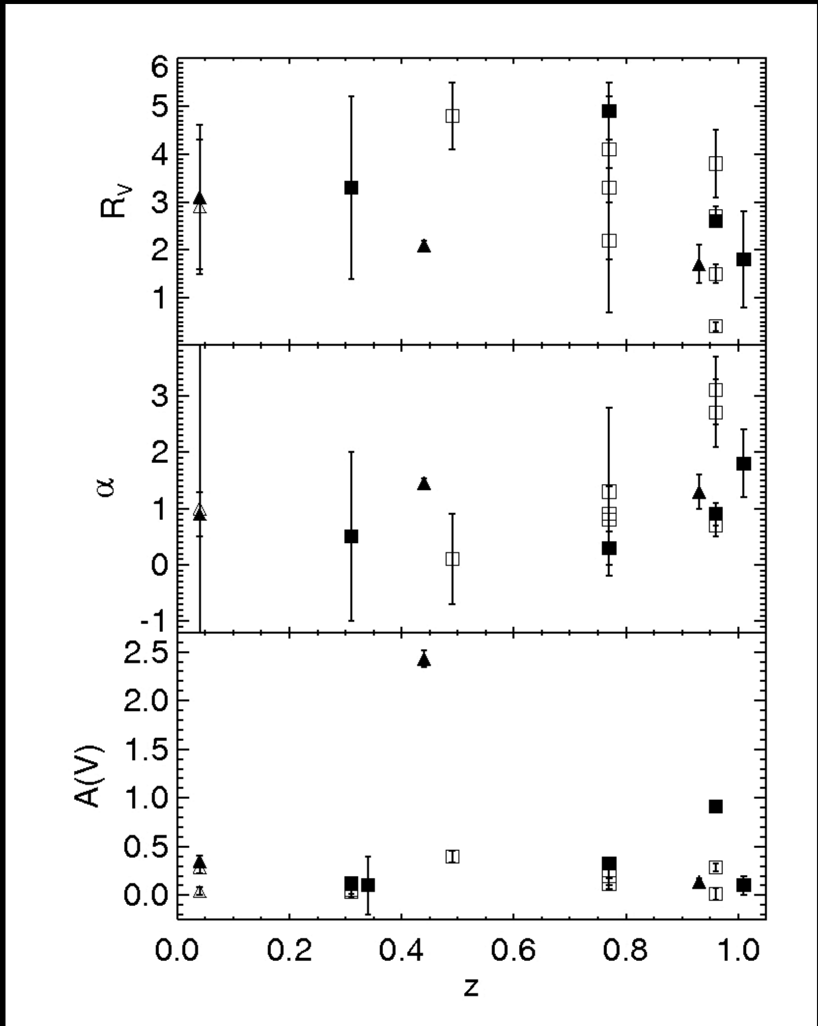
Preferred extinction



Galactic: blue cross
Power law: green star
Linear law: red diamond

- The sample as a whole does not show a preference for a certain extinction law
- Individual systems can show a strong preference

Extinction vs. redshift and type



- See no strong correlation between extinction properties and redshift in our sample

- Mean R_V is:
  - $R_V = 2.8 \pm 0.3$ (full sample)
  - $R_V = 2.8 \pm 0.4$ ('golden' sample)

FUTURE PROSPECTS

Future prospects

- Method is ideal for studying dust extinction of high redshift galaxies
- Can complement various cosmological probes, where dust correction is crucial (e.g. SN Ia studies)
- Ideal for studying evolution of dust properties in the redshift range of $0 < z < 1$
- Need a larger sample to make statistically robust claims

What’s required?

- To increase sample size, need higher resolution -> space based observations
- Effects of extinction along both lines of sight reduced for a large sample
- Want multiband observations in the optical and the infrared
- A simultaneous radio survey, to constrain the intrinsic ratio, would be very useful
- Can SNAP be of use?

Summary

- Multiply imaged quasars can be used to study the extinction curves of lensing galaxies
- Extinction along both lines of sight can affect single systems, but partially cancels out in a large sample
- Our mean $R_V = 2.8 \pm 0.3$ is slightly lower than, but consistent with, that of the Galaxy ($R_V = 3.1$)
- We see no strong correlation between extinction properties and redshift
- A larger sample size is needed to make statistically robust claims -> space based survey of great interest