On the origin of color anomaly between multiple images of lensed quasars

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1. Color Anomaly in Multiple Quasars

Basic Properties of Lensing

Gravitational lensing has no dependence on wavelength / frequency of observation.

← Such an achromatic feature is included in a strategy of surveys (e.g., MACHO).

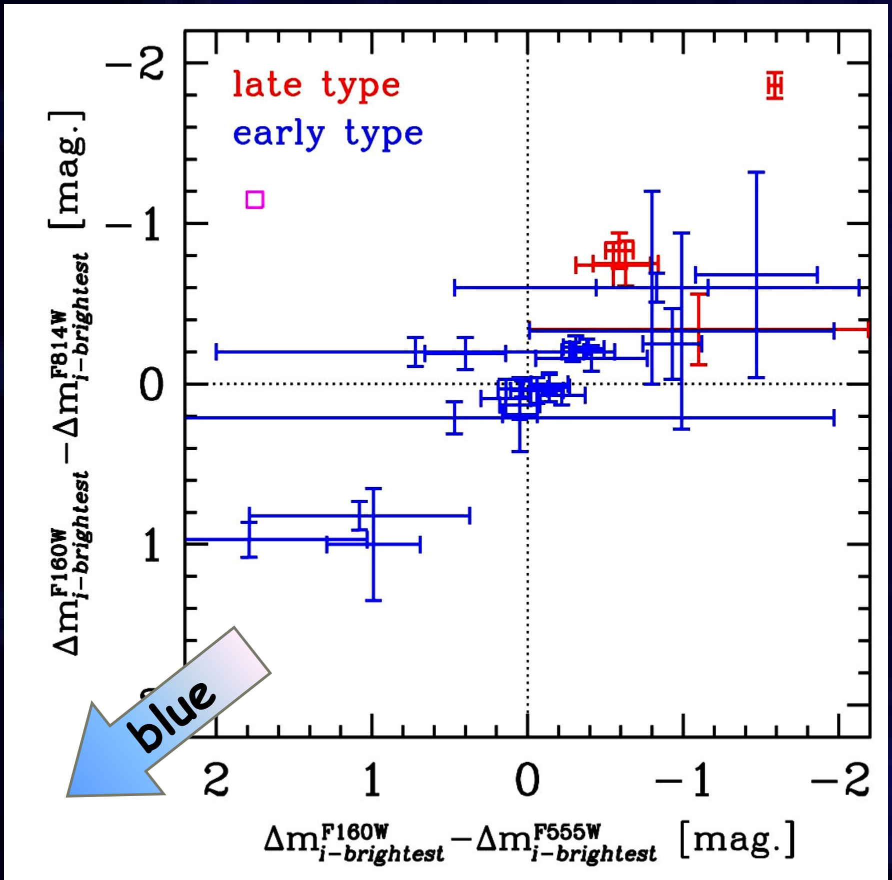
HOWEVER…

Significant chromaticity has been detected in many lensed objects.

⇒ The source structure and/or intervening materials between the source and observer may causes such color change.

Observed Color Change

There are color difference, in part, between multiple images of lensed quasars.



Selection criteria:

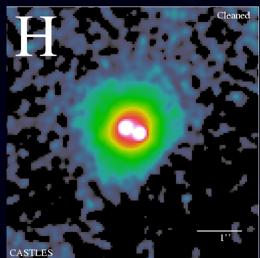
- observed in 3 bands,
  NICMOS2/F160W
  WFPC-2/F555W
  WFPC-2/F814W
- both redshift is known

→15 objects in total

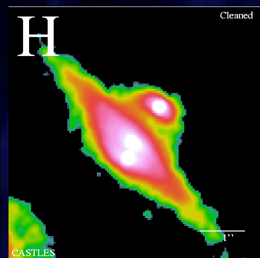
Reference image:

- The brightest image at WFPC-2/F555W

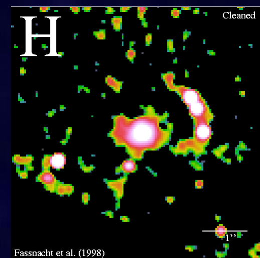
Faces of the samples



[0.68, 0.96]



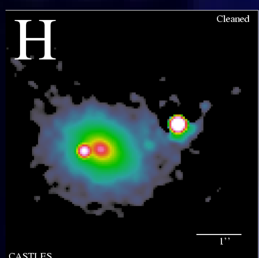
[0.41, 1.59]



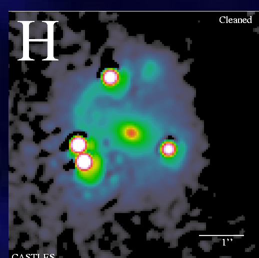
[0.87, 1.28]

8 double quasars
7 quadruple quasars

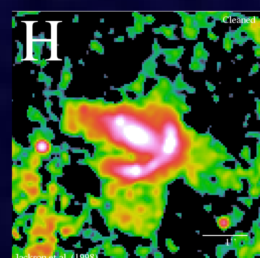
$[z_l, z_s]$



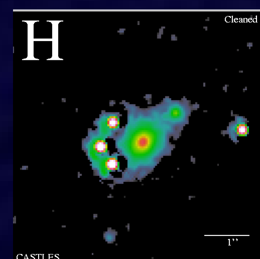
[0.49, 2.72]



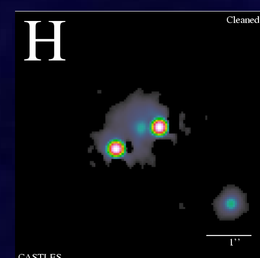
[0.96, 2.64]



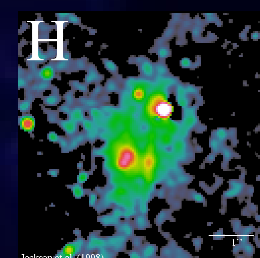
[0.41, 1.34]



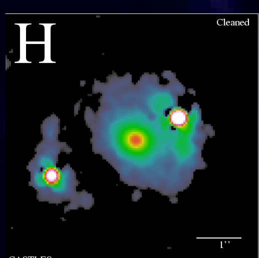
[0.77, 2.80]



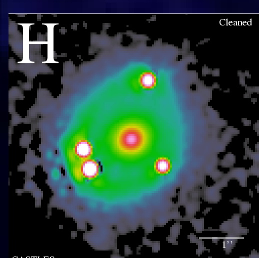
[0.83, 1.38]



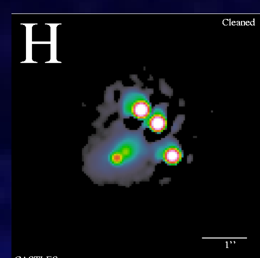
[0.60, 1.54]



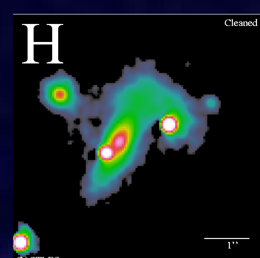
[0.73, 2.32]



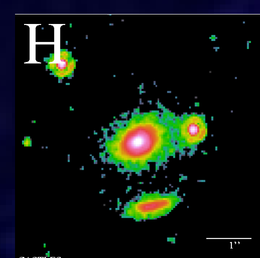
[0.31, 1.72]



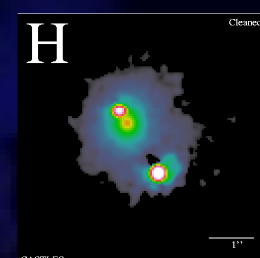
[0.34, 3.62]



[0.72, 1.86]



[1.01, 3.27]



[0.50, 2.03]

from ***CASTLEs*** Web-page

Definition of Obs. Magnitude

Observed magnitude of *i*-th image at time *t* , at wavelength λ ($m_{obs,i}{}^{\lambda}$ [mag.]) is

$$m_{\mathrm{obs},\, i}^{\lambda}(t) = m_{\mathrm{int}}^{\lambda}(t - \tau_i) - 2.5 \log\left[\mu_{\lambda}^{i}(t)\right] + A_{\lambda}^{i}$$

Intrinsic magnitude of quasar

Time delay at image *i*

Magnification at image *i* (include microlensing)

Dust extinction at image *i* due to ISM etc.

We test these possibilities with realistic treatments.

Some Comments, in Advance

- Check all of these three possibility (with optimistic but realistic sence)
- Focus on optical observation (sorry ;_;)
- Focus on only one photometric observations with HST (sorry again ;_;)
- Try to reproduce individual systems, due to wavelength shift by the redshifts *(z)*
  - *z* of lens galaxies for “dust extinction”
  - *z* of source quasars for “microlensing”

2. “Time Delay” Origin

Basic Idea

Quasars :

Generally show intrinsic flux and spectral variation in time (from observation)

$\Rightarrow$ ***Different color in different time***

Gravitational Lensing :

Relative arrival time delay between images should be produced (from theory)

$\Rightarrow$ ***Observed photons at the same time in different images are emitted at different time***

Possible candidate for chromaticity

Estimation

Model of intrinsic quasars variability:

Empirical formula by SDSS (Ivezic et al. 2004)

$$V = (1 + 0.024\, M_i) \cdot \left(\frac{\Delta \tau_{rest}\,[\mathrm{day}]}{\lambda_{rest}\,[\mathrm{\AA}]} \right)^{0.30} \quad [\mathrm{mag.}]$$

Relative time delay :

Realistic assumption; ∼ 1 [month]

[M_i∼-26] ⇒ $V_{555W}=0.076$, $V_{814W}=0.066$, $V_{160W}=0.054$

Less than 0.2 [mag.] color change is expected

Quantitative explanation is difficult

3. “Dust Extinction” Origin

Basic Idea

Dust and/or Gas (ISM):

Spatial distribution of column density is not homogeneous (or smooth) but clumpy

$\Rightarrow$ ***Different extinction at different region***

Gravitational Lensing :

Different image is, of course, formed at different position on the sky (inside the lens galaxy)

$\Rightarrow$ ***Light path of different image passes different region of the lens galaxy***

Again, possible candidate for chromaticity

Part of Previous Studies

- Redshift estimator: Jean & Surdej (1998) etc.
- Study of dust at $z>0$: Falco et al. (1999) etc.
- Reconstruction of dust extinction:
  Munoz et al. (2004) etc.
- Spiral arm on an image of PKS1830:
  Winn et al. (2002) etc.

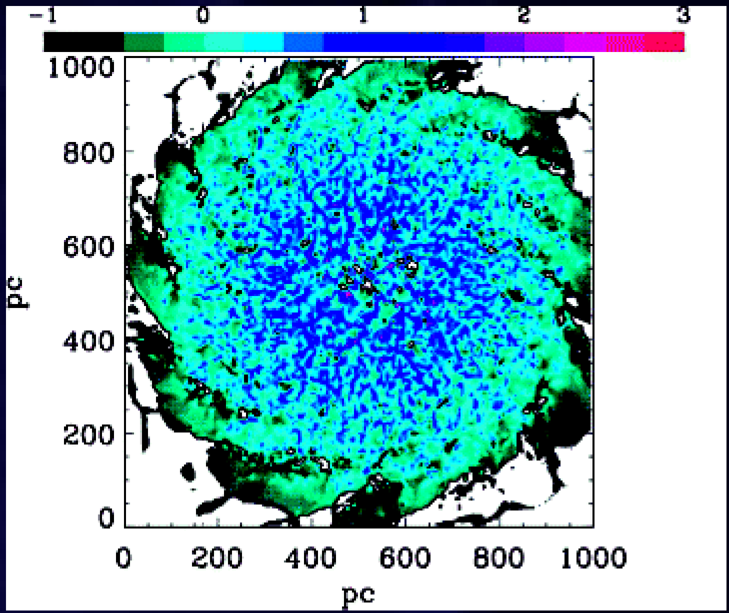
Dust extinction may be a strong candidate to make observed chromaticity

Modeling Clumpy Dust

Gas distribution:

Hydro-dynamical simulation

by Hirashita et al. (2003)

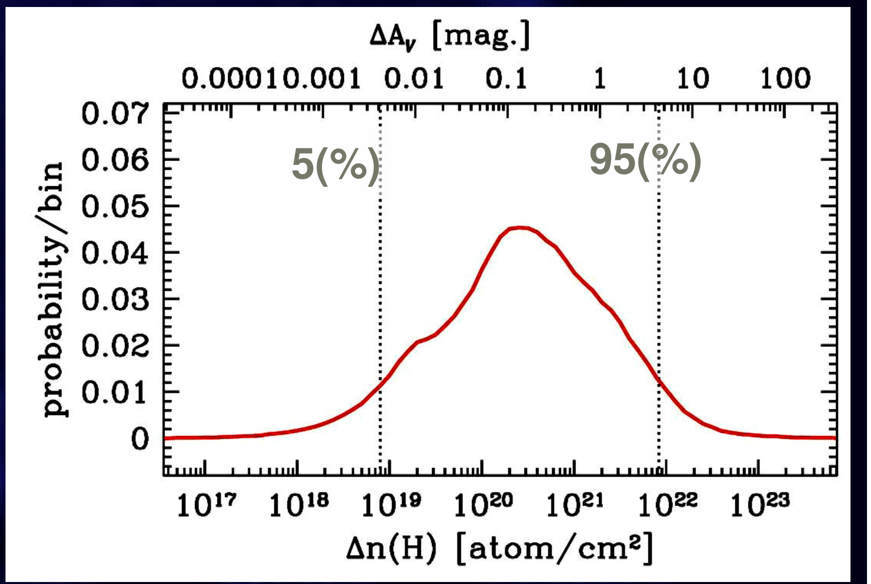


Dust-to-Gas conversion:

Typical value at local

$A_V = 5.3 \times 10^{-22}\, n(H)$

Bohlin et al. (1978)

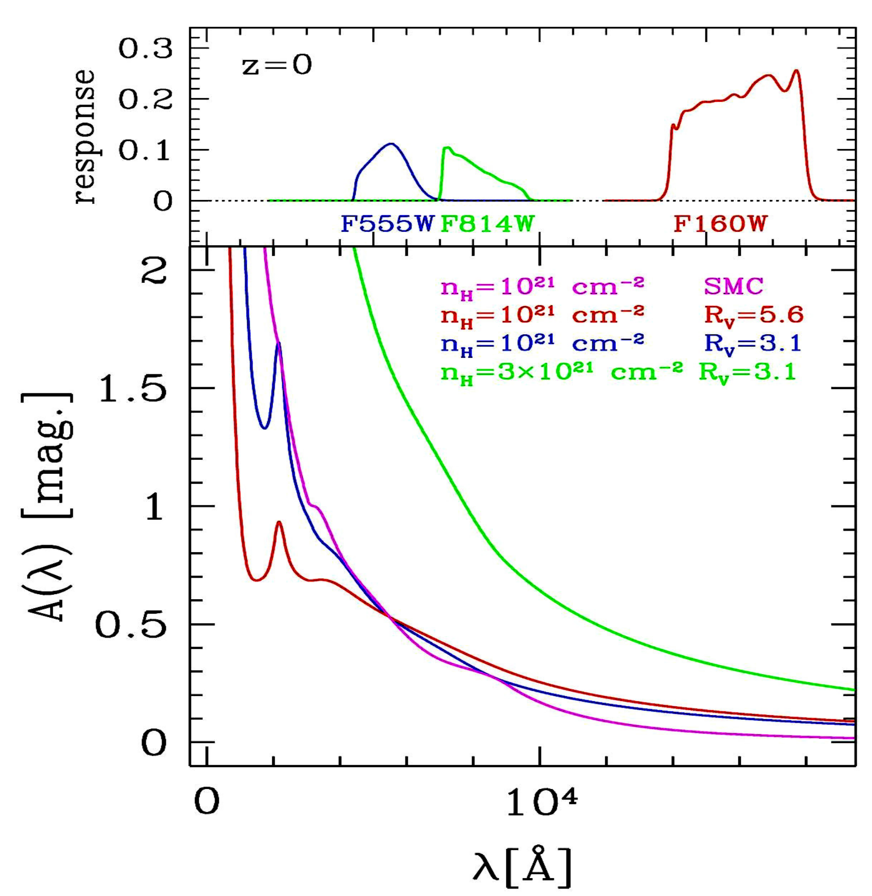


Realistic probability distribution for difference in A_V is obtained

Modeling Extinction Property

Two empirical extinction curves are adopted

- Milky Way (metal rich):
  Cardelli et al. (1989)
- SMC (metal poor):
  Gordon et al. (2003)
  fit by ourselves

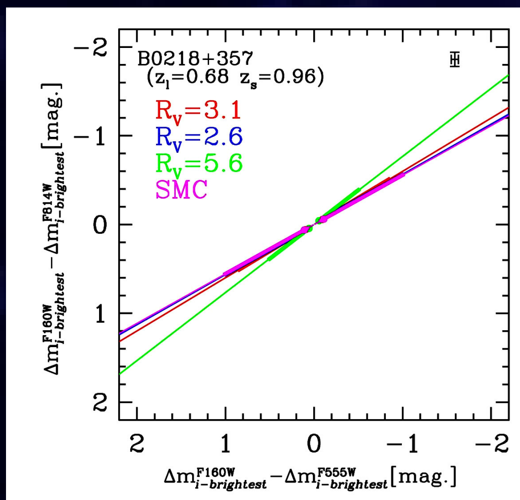


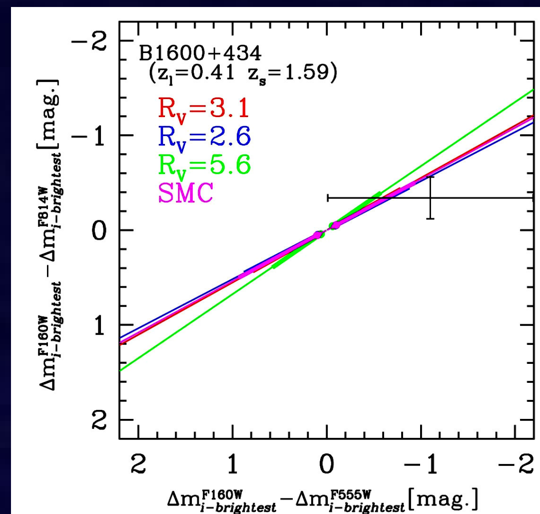
Filter responses are taken into account

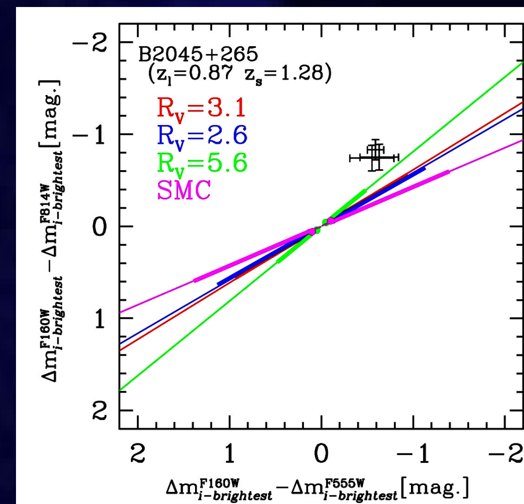
Calculate expected values

Case studies

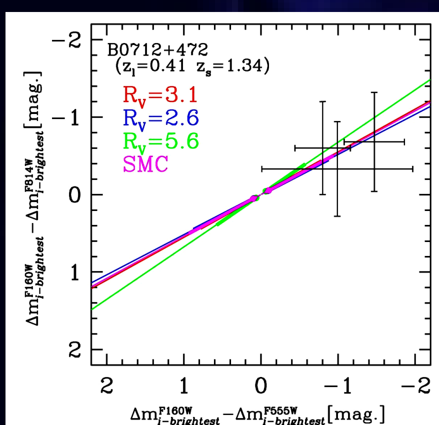
① "late type galaxy" lens

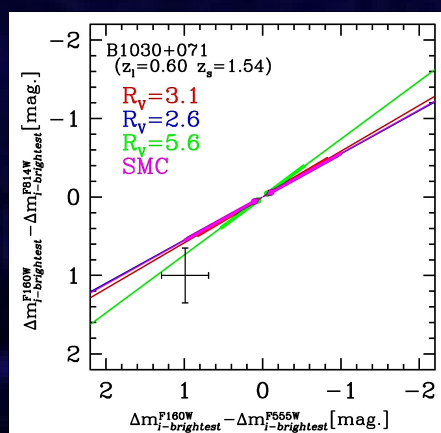


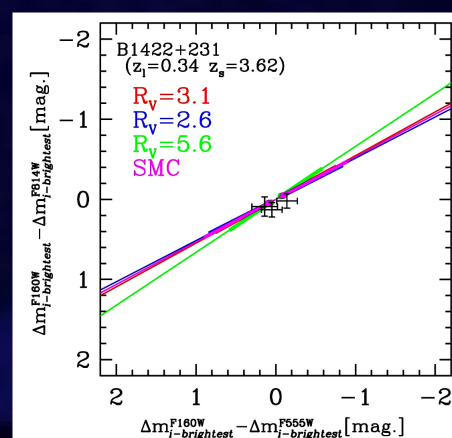


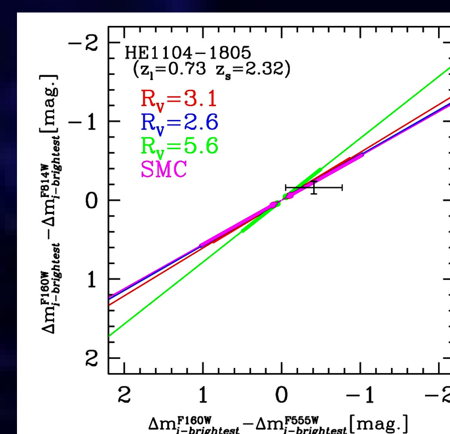


② "early type galaxy" lens

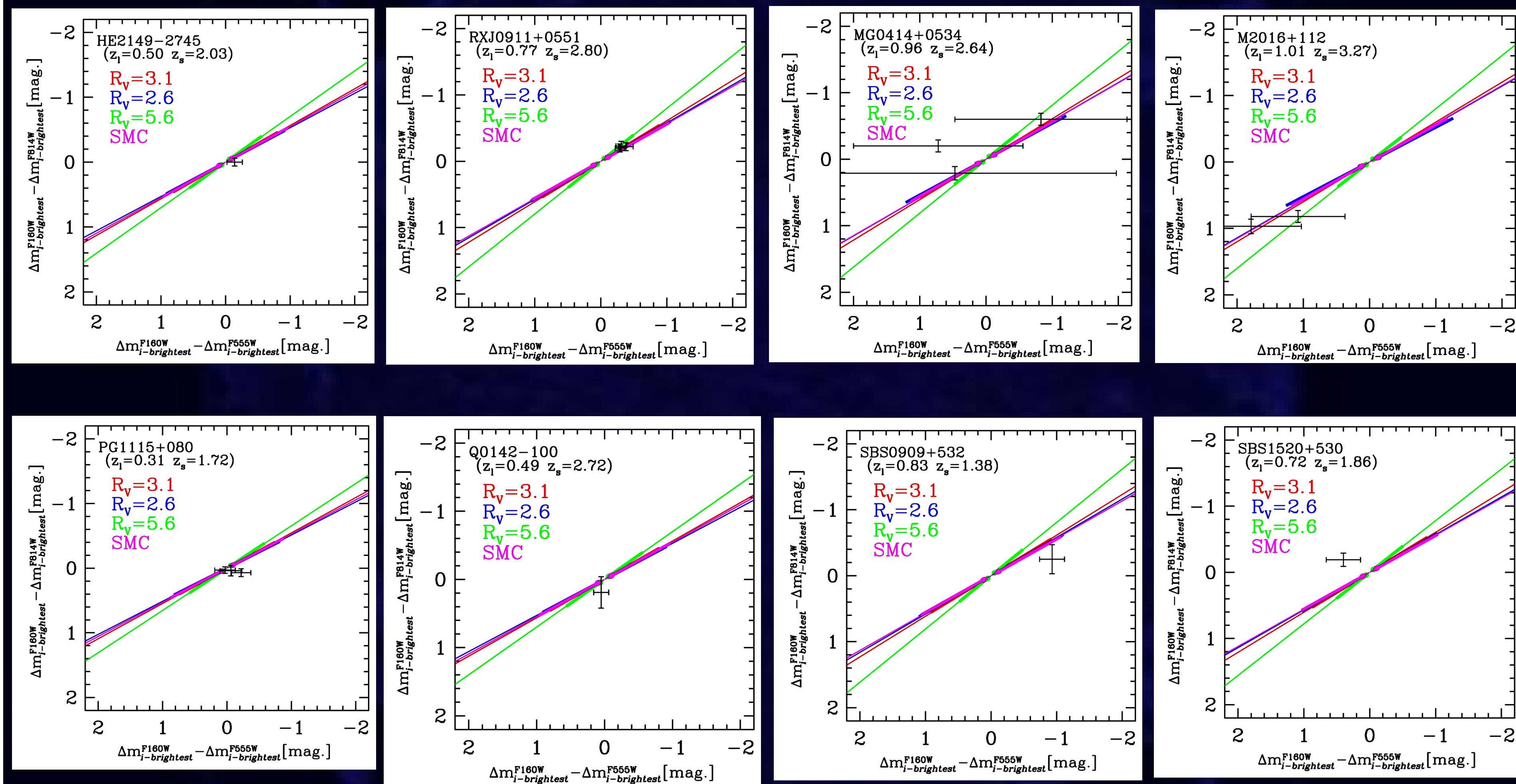








Case studies (2)



Chromaticity is nicely reproduced in all object

4. “Microlensing” Origin

Basic Idea

Quasar Central Engine (Accretion Disk):

Standards accretion model shows different effective temperature at different radius

⇒ ***Different size at different waveband***

Gravitational Lensing :

Amplitude of magnification depends on the source size ($\kappa \sim 1$ is expected from macrolens models; typically $\sim$10 yr duration except Huchra's lens)

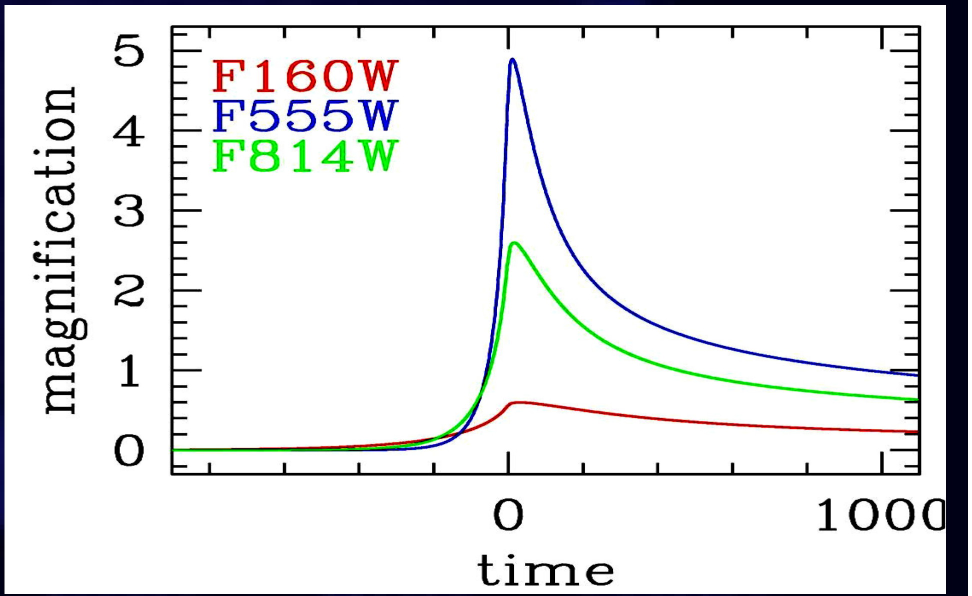
⇒ ***Magnification is different for the source with different finite size (time scale is too long)***

Again, possible candidate for chromaticity

Part of Previous Studies

- Chromaticity in quasar microlensing:
  Wambsganss et al. (1991) etc.
- Quasar microlensing with realistic sources:
  Yonehara et al. (1998) etc.
- Monitoring: GLITP, Ostensen et al. (1996) etc.

Quasar microlensing is also a strong candidate for chromaticity



Microlensing Calculation

Accretion disk model:

Standard accretion disk model with $dM=dM_{Edd}$

Shakura & Sunyaev (1973)

Magnification:

$$\mu_{\lambda}^{i} \approx \mu^{i,macro} + \mu_{\lambda}^{i,micro}$$

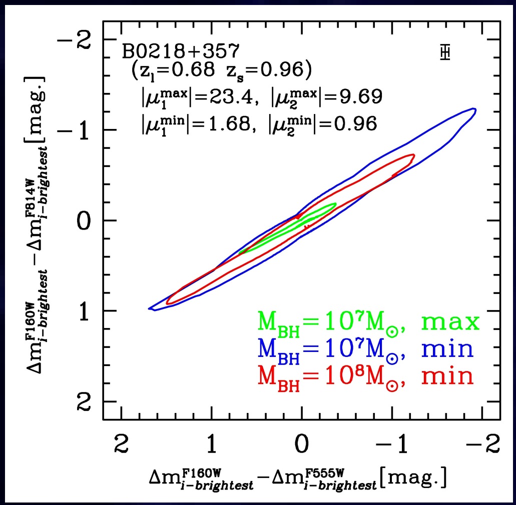
Estimate from lens model fitting (PEMD+external shear)

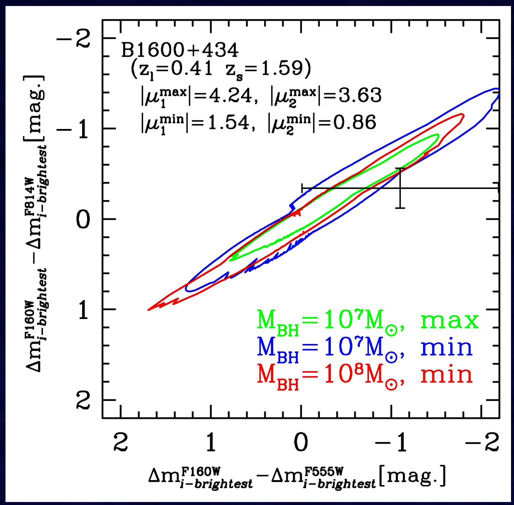
Calculate by using simple approximation, i.e., $\mu \propto r^{-0.5}$

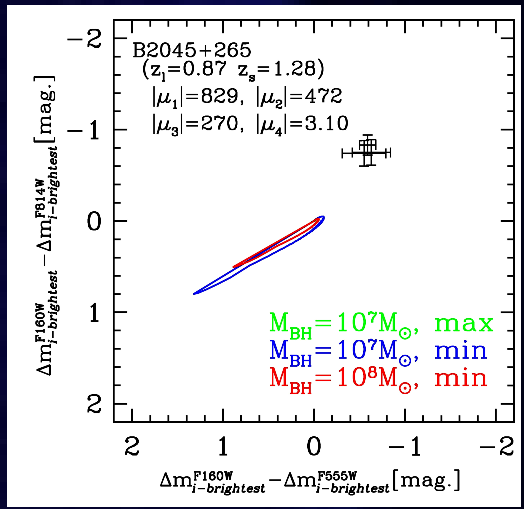
Filter responses are taken into account, again

Case studies

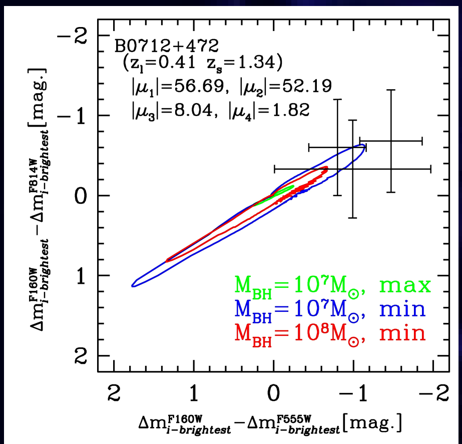
① "late type galaxy" lens

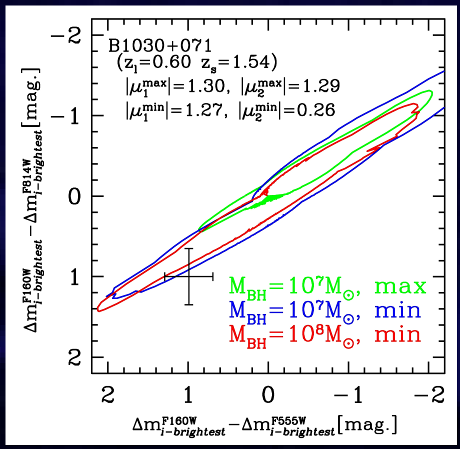


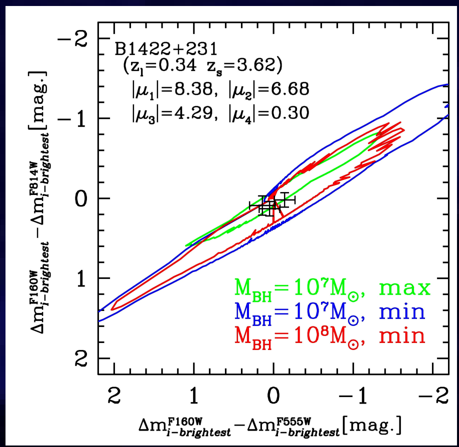


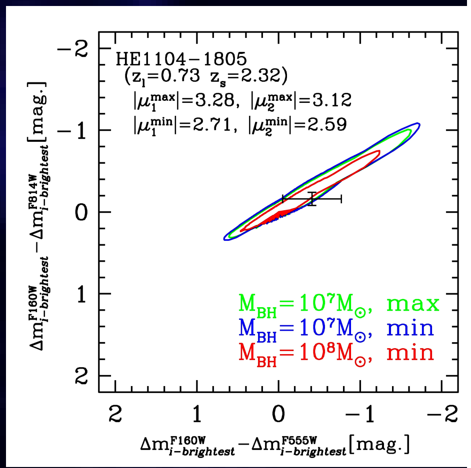


② "early type galaxy" lens

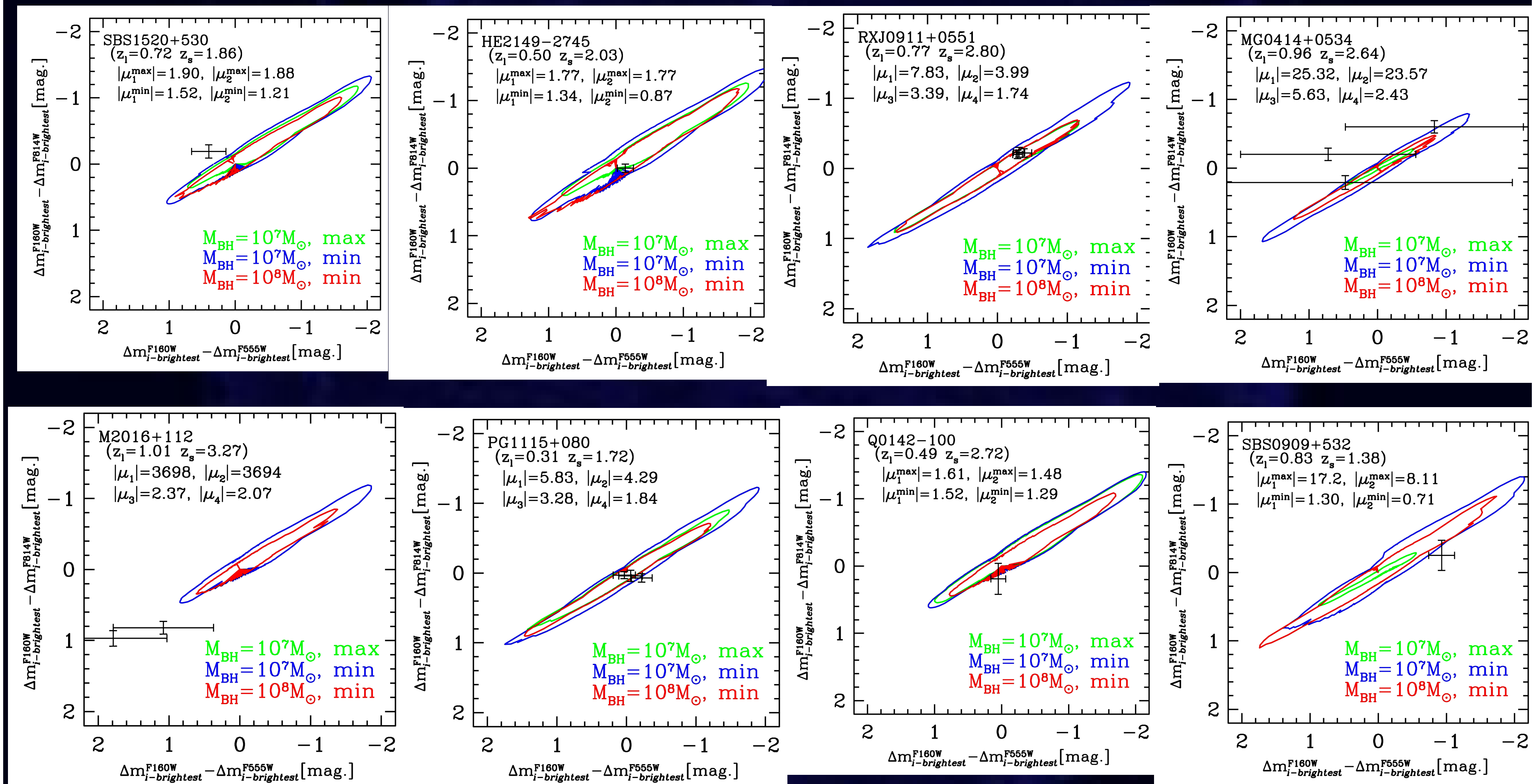








Case studies (2)



Broadly consistent with this scenario

5. Summary

Results

- Possibility of “time delay+intrinsic variability” is statistically rejected.
- “dust extinction” and “quasar microlensing” nicely reproduce the observed chromaticity.
- Late type galaxies may contain plenty of dust, and the chromaticity can be explained by dust rather than microlensing.
- Even in a case of so-called “early type” lens galaxy, the chromaticity is explained by dust.
- Long-term monitoring with multi-waveband will discriminate remaining two possibilities.

Prospects

- Lens model fitting for some systems is somewhat poor, and further modeling will be required for more robust conclusion.
- Consistency check for “dust extinction” with lens model (& possibly with “microlensing”) should be done.
- Of course, comparison between other waveband (radio, X-ray) is also important.
- If the origin becomes clear or the two effects are clearly separated, the color anomaly will provide practical information about
  - Dust at distant galaxies
  - Structure of quasar central engine