Revealing the Structure of the Lensed Quasar Q 0957+561

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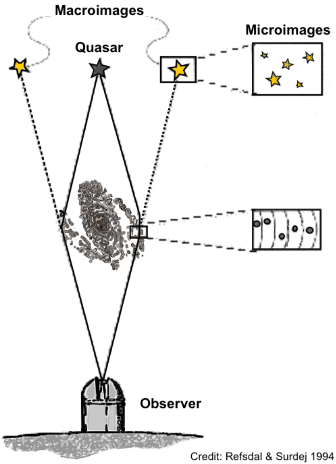
Quasar Microlensing - Phenomenology

- stars behave like small lenses
- affect light curves
- image separation too small to be resolved
- whole galaxy: smooth potential, produces macro-images
- stars: introduce graininess, produce additional magnification
- information about size



Credit: Refsdal & Surdej 1994

Motivation

- use microlensing to reveal structure of AGN:
    - broad-line region (BLR)
    - accretion disk
    - supermassive black hole (SMBH)
- in other words: **study AGN structure at 3 different scales**

Accretion Disk Size Q 0957+561

Revealing the Structure of the Lensed Quasar Q 0957+561:
I. Accretion Disk Size

Fian et al. (submitted)

Objective:

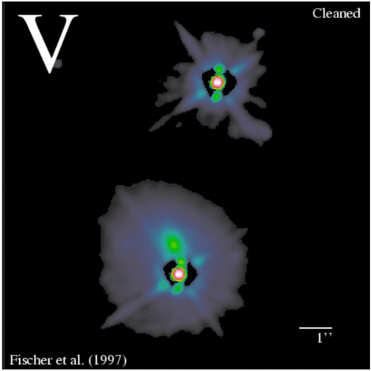
- calculate the size of the accretion disk
- evaluate impact of uncertainties

Method:

- relation between disk-size and microlensing
- use microlensing in the light curves to study size

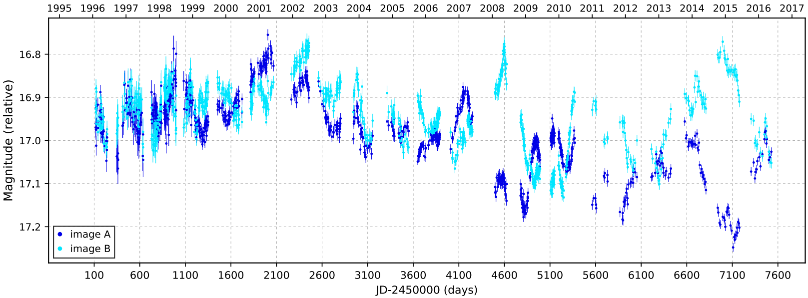
Q 0957+561 Overview

- first identified gravitationally lensed object
- discovered in 1979
- double quasar
- $z = 1.41$
- image separation: 6"
- $\Delta t_{AB} = 417$ days



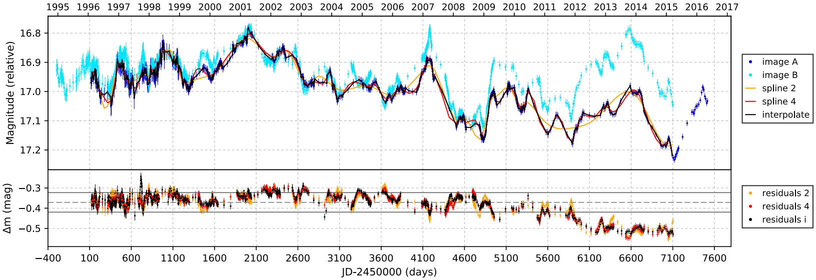
Light Curves of A and B

- r-band observations from 1996 to 2016 (21 yr)
- IAC 80 (Tenerife) during the first observing period (1996-2005)
- Liverpool Telescope (La Palma): 2005 to 2016
- in total: 1067 epochs



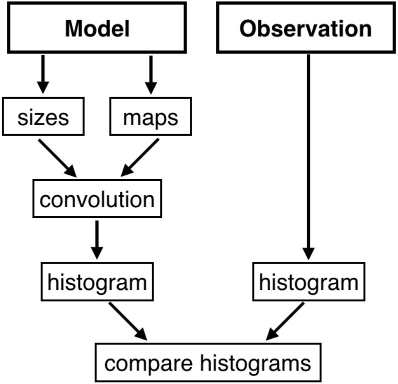
Intrinsic + Microlensing Variability

- shift light curve of B by -413 days
- correct for Δm between A and B using radio data
- flux variations in A mainly intrinsic
- subtract intrinsic variability $\rightarrow$ residuals



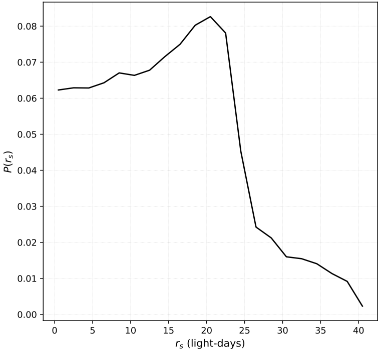
Disk Size Estimation

- microlensing is sensitive to the size
- **Bayes' theorem:** $P(r,p|\Delta m_{obs}) \propto P(\Delta m_{obs}|r,p)\ P(r,p)$
- source: circular Gaussian
- magnification = convolution of source profile and magnification map



Accretion Disk Size

- $R_{1/2} = 17.6 \pm 2.7 \sqrt{M/0.3M_{\odot}}$ ld
- significantly greater than average size
- consistent within errors with result of Hainline et al. 2012 ($R_{1/2} = 12.2^{+26.4}_{-8.3}$ ld)
- maybe large source size because of low transverse velocity $\Rightarrow$ future work



Broad Line Region Size Q 0957+561

Revealing the Structure of the Lensed Quasar Q 0957+561:
II. Constraints on the Broad-Line Region Size

Fian et al. (to be submitted)

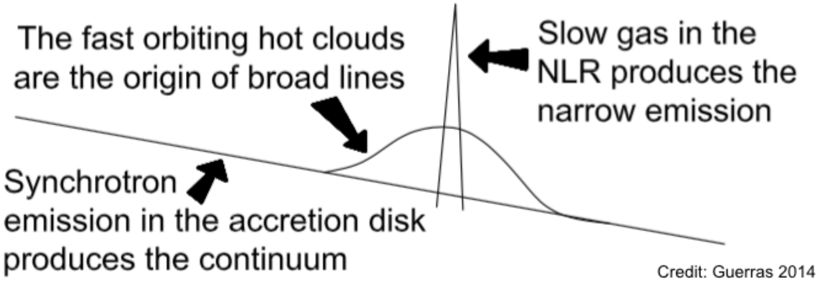
Objective:

- study impact of microlensing on different wavelength regions
- study size, kinematics, and geometry of the BLR

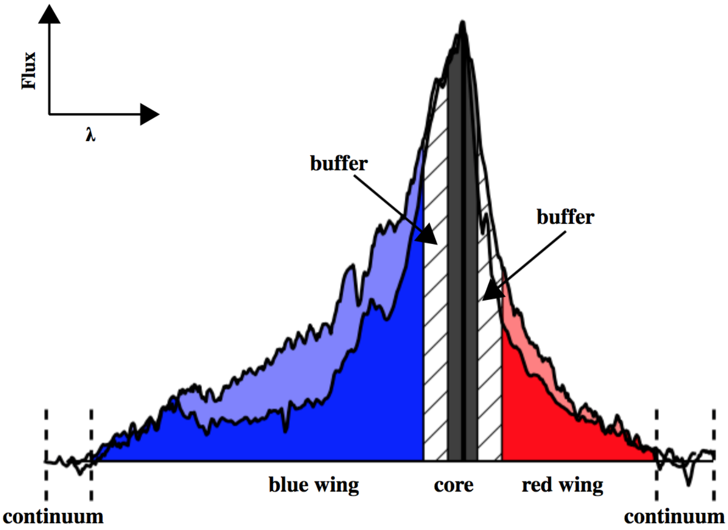
Method:

- analyze different emission lines in several epochs
- estimate Δm for different line components
  (broad, very broad, underlying continuum)

Components - Standard Interpretation



Sketch Calculation

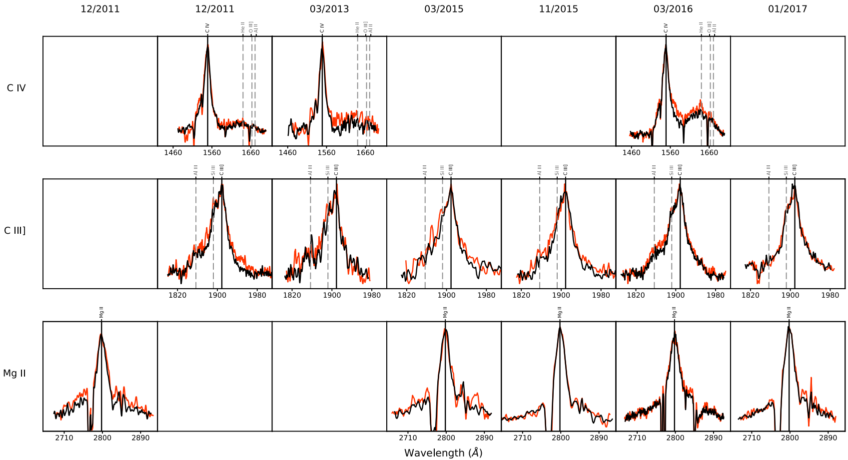


Spectroscopic Data Q 0957+561

- 14 epochs of observation
- data covering a period of 18 years
- from April 1999 to January 2017
- data from: HST, MMT, NOT, LT, WHT

Date	Emission Line	Facility	Reference
04/1999	C IV, C III], Mg II	HST	Goicoechea et al. 2005
06/2000	C IV, C III], Mg II	HST	Goicoechea et al. 2005
01/2008	C IV, C III], Mg II	MMT	Motta et al. 2012
01/2009	C III]	NOT*	GLENDAMA
03/2010	C IV, C III]	NOT*	GLENDAMA
10/2010	Mg II	LT*	GLENDAMA
03/2011	Mg II	LT*	GLENDAMA
04/2011	Mg II	LT*	GLENDAMA
12/2011	Mg II	LT*	GLENDAMA
12/2011	C IV, C III]	NOT*	GLENDAMA
03/2013	C IV, C III]	NOT*	GLENDAMA
03/2015	C III], Mg II	LT	GLENDAMA
11/2015	C III], Mg II	LT*	Gil-Merino et al. 2018
03/2016	C IV, C III], Mg II	WHT	Fian et al. (in prep.)
01/2017	C III], Mg II	LT	Gil-Merino et al. 2018

Example BELs: C IV, C III], and Mg II



BLR Size and Geometry

- wings of Mg II, low velocity bins of C IV + C III]: large, spherically symmetric region
- high velocity bins of C IV + C III]: compact region, non-spherical geometry, probably following motion of accretion disk

Line	Feature	$R_{1/2}$
C IV	continuum	$8.3^{+13.6}_{-2.9}$
	wing	$36.7^{+6.4}_{-5.4}$
	bin 1	$53.2^{+6.4}_{-3.1}$
	bin 2	$15.1^{+18.5}_{-5.1}$
C III]	continuum	$20.9^{+19.8}_{-6.1}$
	wing	$45.8^{+9.1}_{-7.4}$
	bin 1	$55.8^{+3.8}_{-3.3}$
	bin 2	$18.8^{+19.6}_{-6.4}$
Mg II	continuum	$36.7^{+11.1}_{-5.4}$
	wing	$52.6^{+4.7}_{-4.8}$
	bin 1	$80.7^{+9.6}_{-9.3}$
	bin 2	$51.3^{+3.5}_{-3.5}$

SMBH Masses from Fe III Redshift (Q 0957+561)

Revealing the Structure of the Lensed Quasar Q 0957+561
III. SMBH Mass via Gravitational Redshift

Fian et al. (to be submitted)

Objective:

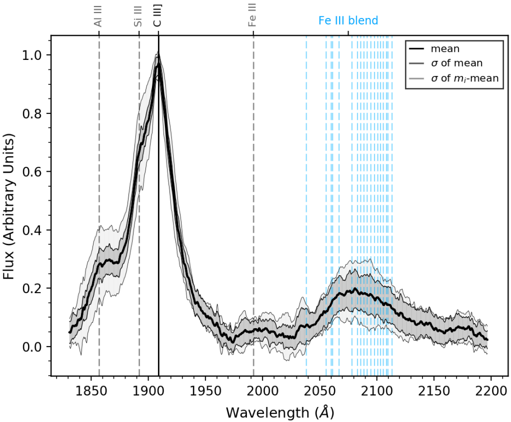
- infer SMBH mass of Q 0957+561

Method:

- study size of the Fe III emitting region
- calculate gravitational redshift and the line broadening
- kinematics + estimation of redshift $\rightarrow$ size + M_{BH}

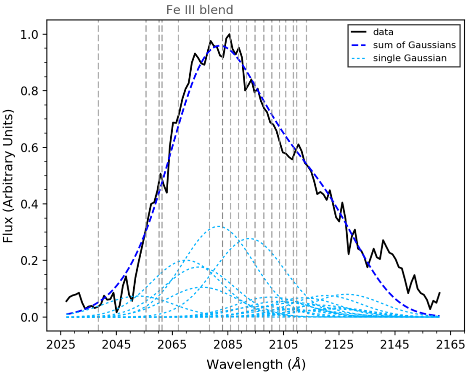
Fe III Blend

- formed by many emission lines
- relatively isolated
- very variable
- originates from small region (few light-days)
- redshifted

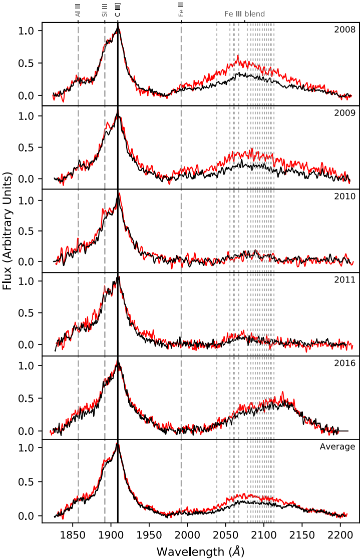


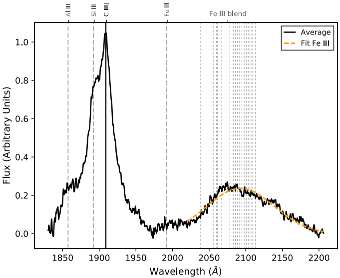
Perform Fit to Fe III Blend

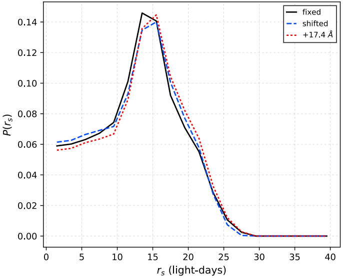
- fit: sum of 18 Gaussians
- fixed parameters: position and flux
- free parameters:
  - shift (position)
  - factor f (flux)
  - σ (broadening)



Fe III blend, Fit, and PDF







Fe III Emitting Region Size and SMBH Mass

- in agreement within errors with:
  - virial determinations from Assef et al. 2011 ($M_{SMBH} \sim 1.0 \times 10^9 M_\odot$ using C IV)
  - average SMBH mass from Mediavilla et al. 2018 ($M_{SMBH} \sim 0.8 \times 10^9 M_\odot$)
- affected by relatively small errors ($\leq 30\%$)
  $\rightarrow$ significant improvement in mass measurements

Interval	$R_{1/2}$ (lt-days)	M_{BH} ($\times 10^9 M_\odot$)
Fixed	$15.0^{+6.8}_{-9.7}$	$1.47^{+0.24}_{-0.31}$
Shifted	$15.0^{+6.8}_{-9.7}$	$1.47^{+0.24}_{-0.31}$
+17.4Å	$15.5^{+6.4}_{-10.1}$	$1.52^{+0.24}_{-0.32}$

Conclusions + Most Important Findings

Study structure of Q0957 at 3 different scales via microlensing:

1. new (and fast) method to estimate accretion disk size
   $\rightarrow r_s$ of $\sim$ 18 light-days
2. use microlensing in wings of BELs to reveal structure of BLR
   $\rightarrow$ existence of 2 regions:
   - **(a)** LIL: arise from large region insensitive to ML
   - **(b)** HIL: compact region (inner part of BLR), sensitive to ML
3. huge microlensing differences in the Fe III lines
4. redshift of $\sim$ 17Å for Fe III
5. new method to estimate SMBH mass: size+redshift of Fe III

Thank you for your attention!