Gravitational Microlensing as a Kinematic Probe: Rotation Curves in five Lensed Quasars

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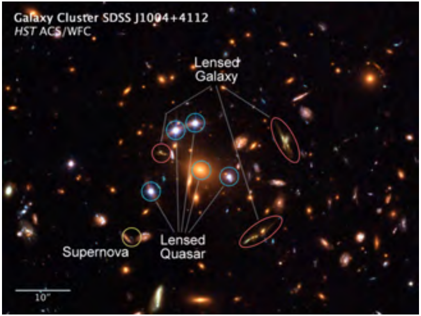
Quadruply Lensed Quasar SDSS J1004+4112

- lensed by galaxy cluster
- 4 bright images
- source redshift: $z_s = 1.734$
- max. image separation: $14''.62$
- time delay: $\Delta t_{AB} = 44$ days

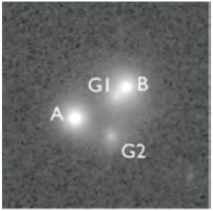


Credit: ESA, NASA, K. Sharon, E. Ofek

Doubly Lensed Quasars

SDSS J1001+5027

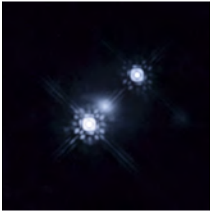
- source redshift: $z_s = 1.838$
- image separation: $2''.86$



Credit: Rusu et al. 2016

HE 1104-1805

- source redshift: $z_s = 2.319$
- image separation: $3''.15$



Credit: NASA, ESA, J.A. Muñoz

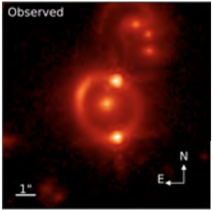
Doubly Lensed Quasars

SDSS J1206+4332

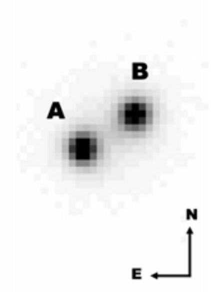
- source redshift: $z_s = 1.789$
- image separation: $2''.90$

SDSS J1339+1310

- source redshift: $z_s = 2.243$
- image separation: $1''.70$

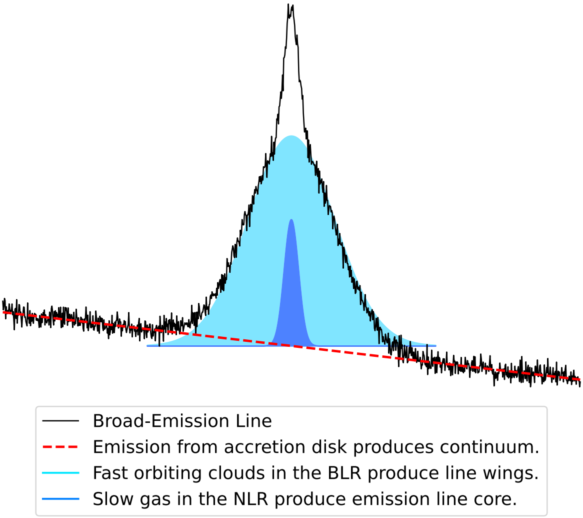


Credit: Birrer et al. 2019



Credit: Shalyapin & Goicoechea 2014

Components - Standard Interpretation

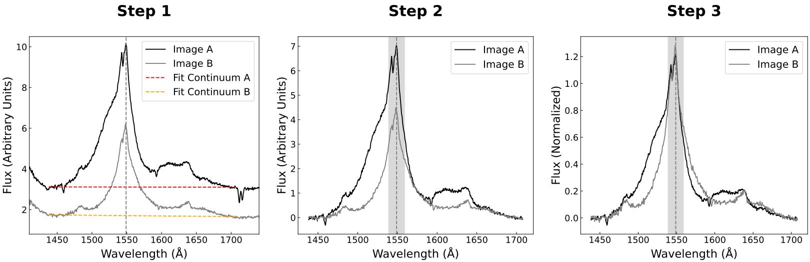


Removing Continuum & Normalization

Step 1: fit straight line to the continuum and subtract it

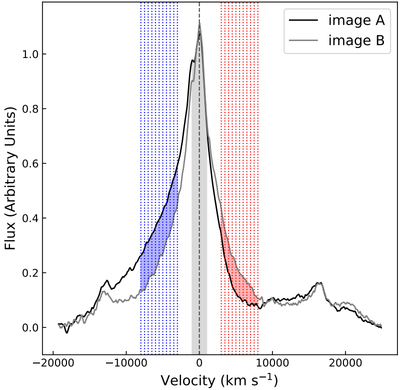
Step 2: define core flux - narrow interval centered at the line peak

Step 3: normalize the continuum-subtracted spectra

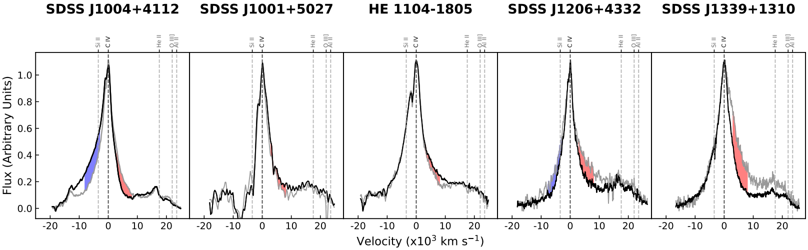


Calculation Δm

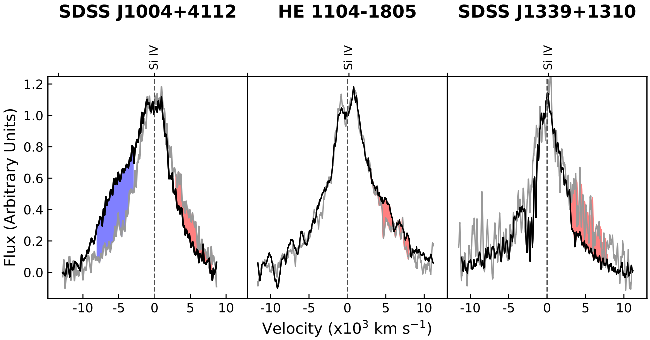
- use cores as baseline for no microlensing
- fit spline to line wings
- velocity interval: 500 km s^{-1}
- velocity range: 3000 – 8000 km s^{-1}



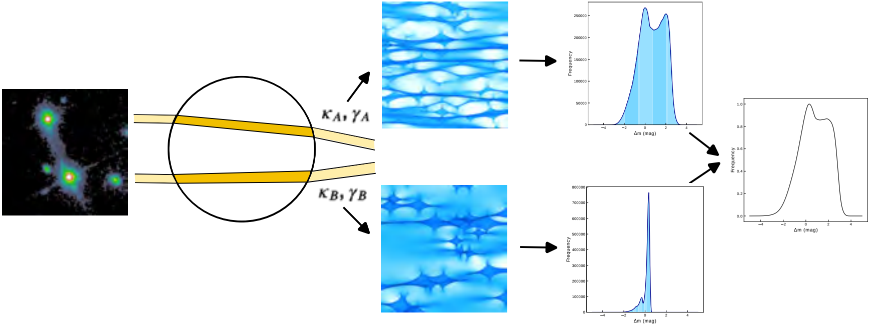
C IV Emission Line



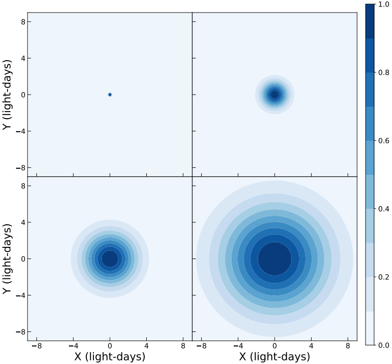
Si IV Emission Line

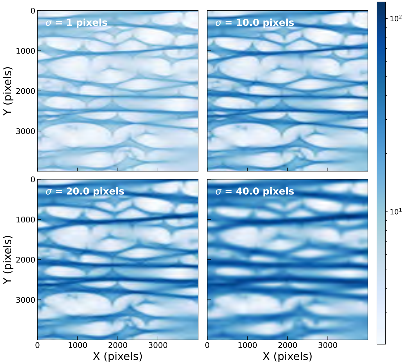


Theoretical Model



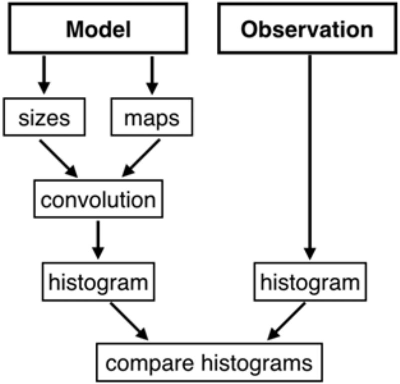
Effect of Extended Sources



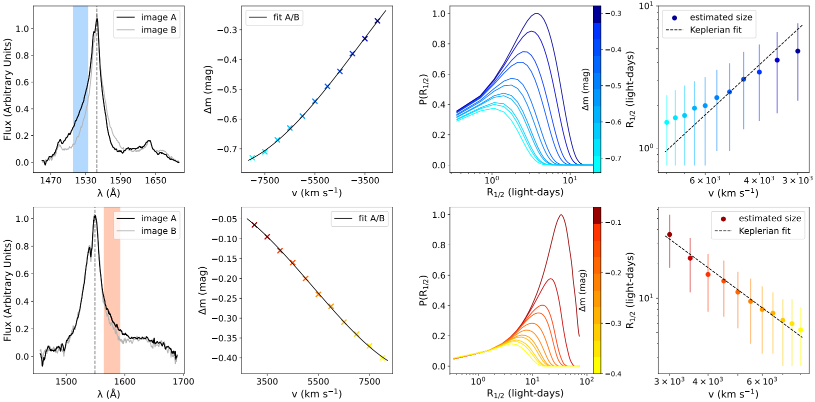


Size Estimation of Emission Region

- 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

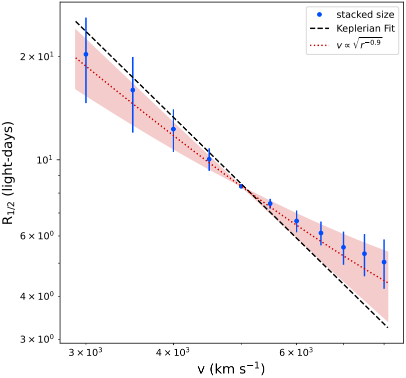


Initial Findings: 2 Examples



Average Size-Wavelength Trend

- **blue points**:
  average sizes of the emission regions vs. wavelength
- **dashed black line**:
  Keplerian fit; fixed power-law index of 4/3
- **dotted red line**:
  best fitting model; power-law index of ~ 0.9



SMBH Masses via Kinematic Responses

$$M_{BH} \sin^2 i = \frac{R\ v^2}{G}$$

M_{BH} .... SMBH mass
i .... inclination
R .... distance
v .... velocity
G .... gravitational constant

Object (1)	Line (2)	Wing (3)	$M_{BH}\ sin^2 i\ (M_\odot)$ (4)
SDSS J1001+5027	C IV	red	$6.6^{+1.0}_{-0.5} \times 10^7$
SDSS J1004+4112	C IV	blue	$1.2^{+1.0}_{-0.5} \times 10^7$
		red	$1.0^{+0.8}_{-0.4} \times 10^7$
	Si IV	blue	$0.6^{+0.8}_{-0.3} \times 10^7$
		red	$1.0^{+0.9}_{-0.5} \times 10^7$
HE 1104-1805	C IV	red	$5.8^{+1.9}_{-1.4} \times 10^7$
	Si IV	red	$7.1^{+2.1}_{-1.6} \times 10^7$
SDSS J1206+4332	C IV	blue	$2.8^{+1.4}_{-0.9} \times 10^7$
		red	$3.2^{+1.5}_{-1.0} \times 10^7$
SDSS J1339+1310	C IV	red	$2.2^{+1.3}_{-0.8} \times 10^7$
	Si IV	red	$2.3^{+1.1}_{-0.7} \times 10^7$

Virial SMBH Masses

$$M_{BH} = f \, \frac{R_{1/2} \, \sigma^2}{G}$$

M_{BH} .... SMBH mass
f .... virial factor
$R_{1/2}$ .... BLR size
σ .... velocity dispersion
G .... gravitational constant

Object (1)	Line (2)	$R_{1/2}$ (light-days) (3)	M_{BH} ($M_{\odot}$) (4)
SDSS J1001+5027	C IV	12 ± 7	$(15 \pm 9) \times 10^7$
	Mg II	45 ± 14	$(25 \pm 9) \times 10^7$
SDSS J1004+4112	C IV	2 ± 1	$(3 \pm 2) \times 10^7$
	Mg II	3 ± 2	$(1 \pm 1) \times 10^7$
HE 1104-1805	C IV	10 ± 6	$(11 \pm 7) \times 10^7$
	Mg II	87 ± 37	$(16 \pm 7) \times 10^7$
SDSS J1206+4332	C IV	6 ± 4	$(9 \pm 6) \times 10^7$
	Mg II	28 ± 10	$(12 \pm 5) \times 10^7$
SDSS J1339+1310	C IV	5 ± 3	$(11 \pm 7) \times 10^7$
	Mg II	32 ± 11	$(8 \pm 3) \times 10^7$

Conclusions & Most Important Findings

(1) unexpected chromatic enhancement within broad-line wings

(2) we resolved structure of inner, disk-like BLR

(3) for two systems: kinematic agreement with Keplerian fit

(4) for remaining systems: slightly flatter trend

(5) remarkable kinematic coincidence between rotation curves derived from blue and red wings

(6) SMBH mass estimates via spectral responses

(7) mean BLR inclination $\sim 37^\circ$

Thank you for your attention!