Probing Dark Matter Substructure with Quasar Lensing:

"Beyond Flux Anomalies"

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February 17, 2012

Studying dark matter substructure

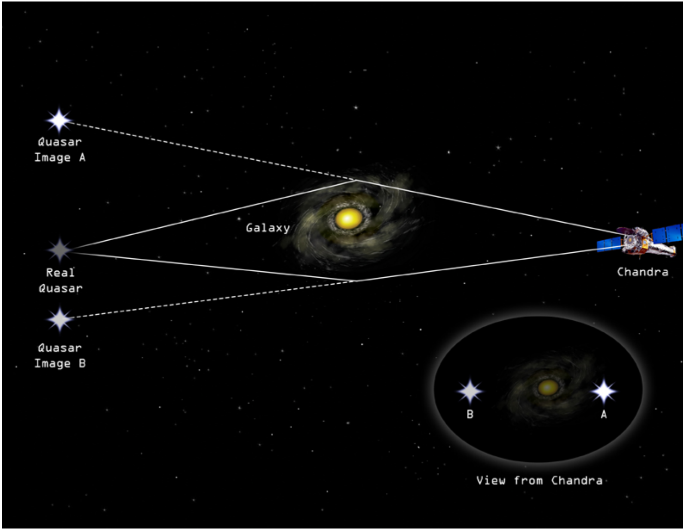
How to solve the (so-called) missing satellites problem?

- blame astrophysics – *substructure exists but is dark*
- blame dark matter – *substructure is suppressed*

Goals for lensing

- Make a census of **"dark dwarfs"**
- Measure mass function, spatial distribution, and even time evolution of clump population
- Work at $z \sim 0.2$–1

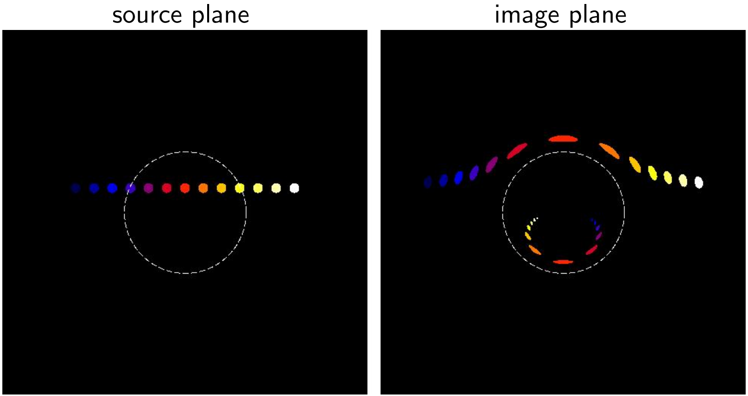
Gravitational lensing



http://chandra.harvard.edu/photo/2003/apm08279/more.html

2-image lensing

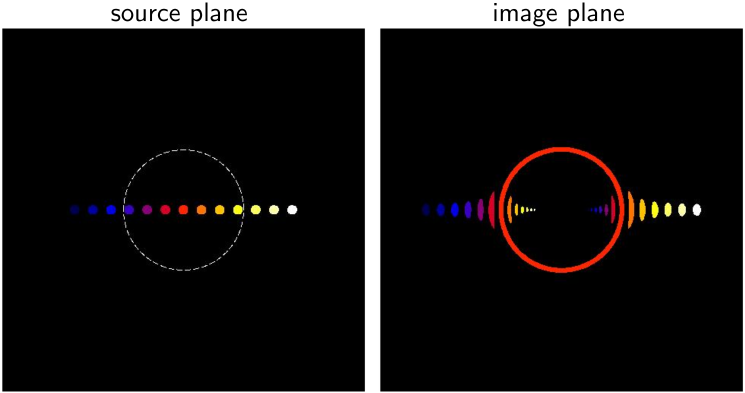
Spherical lens.



Einstein radius: $$\theta_E = \sqrt{\frac{4GM}{c^2}\,\frac{D_{ls}}{D_{ol}D_{os}}}$$

Einstein ring

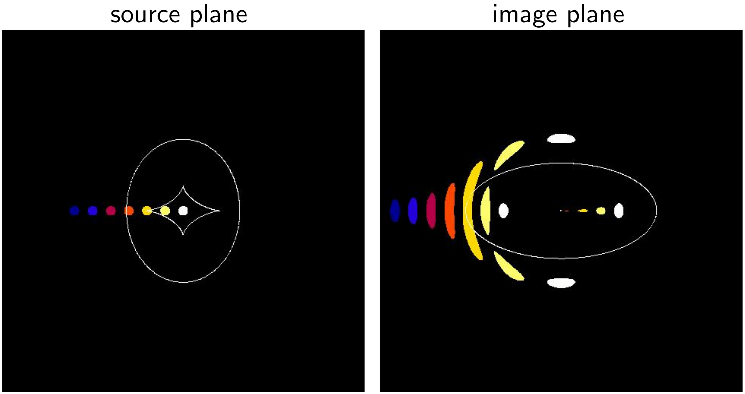
Spherical lens.



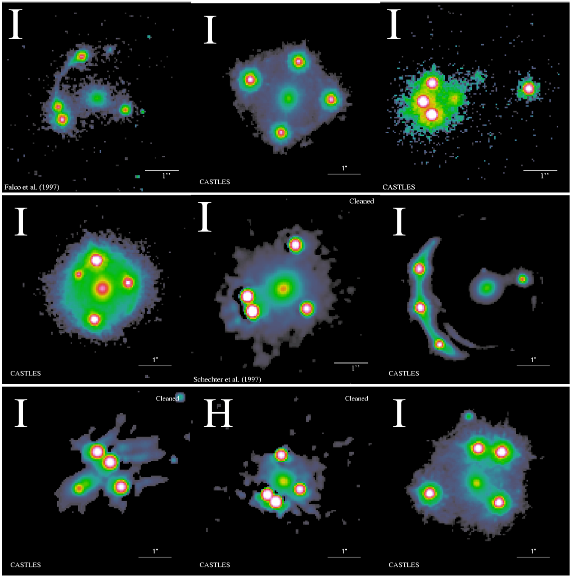
Einstein radius: $$\theta_E = \sqrt{\frac{4GM}{c^2}\,\frac{D_{ls}}{D_{ol}D_{os}}}$$

4-image lensing

Ellipsoidal lens.



Quasar lenses



(CASTLES project, http://www.cfa.harvard.edu/castles)

Key theory

Effectively just 2-d gravity. Projected and scaled potential:

$$\nabla^2\phi = 2\frac{\Sigma}{\Sigma_{\rm crit}}$$

Time delay:

$$\tau(\boldsymbol{x};\boldsymbol{u}) = \frac{1+z_l}{c}\;\frac{D_l D_s}{D_{ls}}\left[\frac{1}{2}\left|\boldsymbol{x}-\boldsymbol{u}\right|^2 - \phi(\boldsymbol{x})\right]$$

Fermat's principle $\nabla_{\boldsymbol{x}}\tau = 0$ gives lens equation:

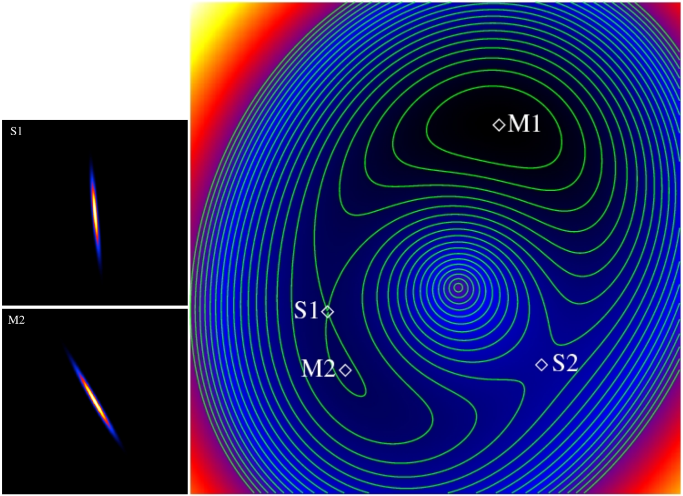
$$\boldsymbol{u} = \boldsymbol{x} - \nabla\phi(\boldsymbol{x})$$

Distortions/magnifications:

$$\mathbf{M} = \left(\frac{\partial\boldsymbol{u}}{\partial\boldsymbol{x}}\right)^{-1} = \left[\begin{array}{cc} 1-\phi_{xx} & -\phi_{xy} \\ -\phi_{xy} & 1-\phi_{yy} \end{array}\right]^{-1}$$

Fermat's principle

Time delay surface: $\tau(\boldsymbol{x};\boldsymbol{u}) = \tau_0 \left[\frac{1}{2} \left| \boldsymbol{x} - \boldsymbol{u} \right|^2 - \phi(\boldsymbol{x}) \right]$



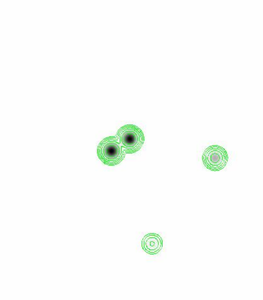
Flux ratio anomalies

"Easy" to explain image positions (even to ∼0.1% precision)

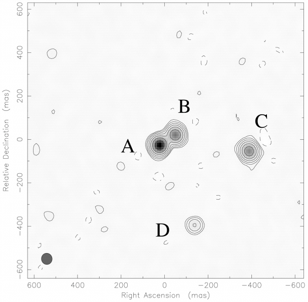
- ellipsoidal galaxy
- tidal forces from environment

But hard to explain flux ratios!

expected



observed *(Marlow et al. 1999)*

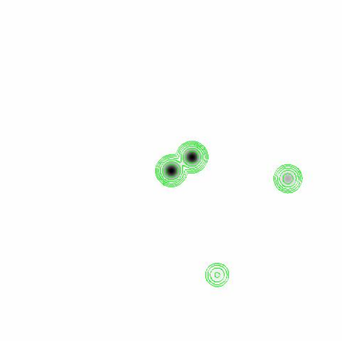


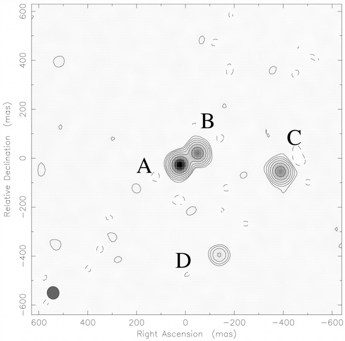
Anomalies are generic

Close pair of images: Taylor series expansion yields

$$A - B \approx 0$$

Universal prediction for smooth models. *(CRK, Gaudi & Petters 2005)*





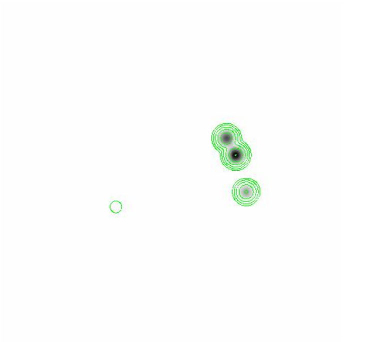
(models, CRK et al. 2005; B1555+375, Marlow et al. 1999)

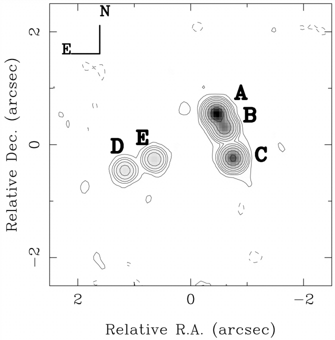
Anomalies are generic

Close triplet of images: Taylor series expansion yields

$$A - B + C \approx 0$$

Universal prediction for smooth models. *(CRK, Gaudi & Petters 2003)*

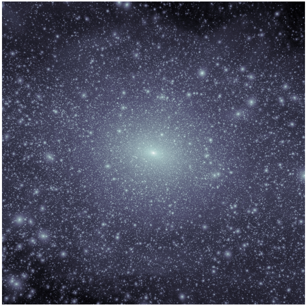




(models, CRK et al. 2003; B2045+265, Fassnacht et al. 1999)

Can also apply to lens time delays. *(Congdon, CRK & Nordgren 2008, 2010)*

Substructure

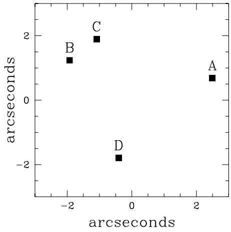


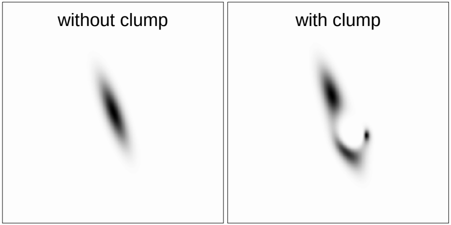
(Diemand et al. 2008; Springel et al. 2008)

Substructure and lensing

Q) What happens if lens galaxies contain mass clumps?

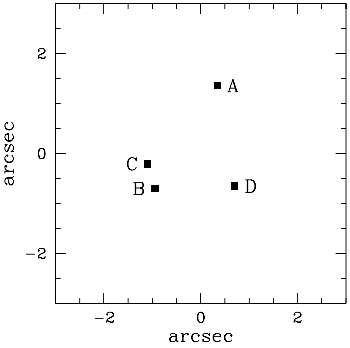
A) The clumps distort the images on small scales.

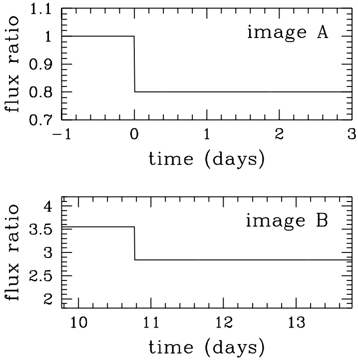




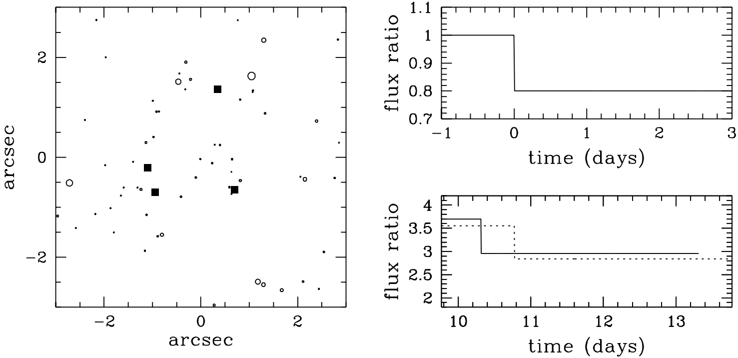
(cf. Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002)

(CRK & Moustakas 2009)





(CRK & Moustakas 2009)



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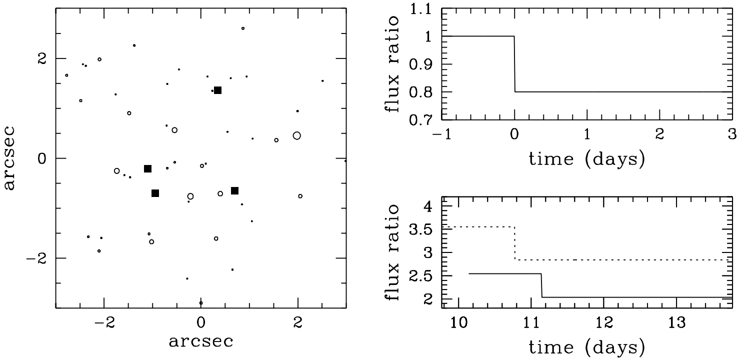

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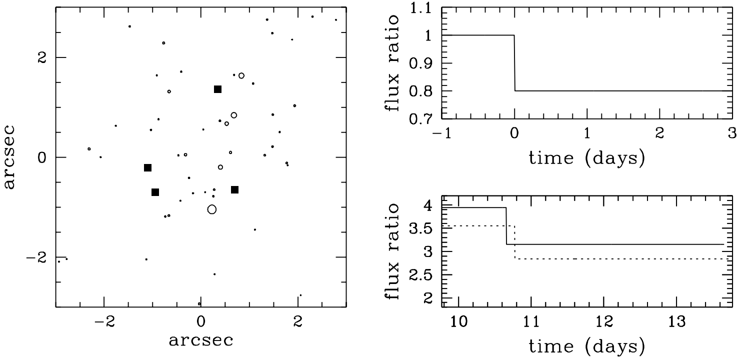
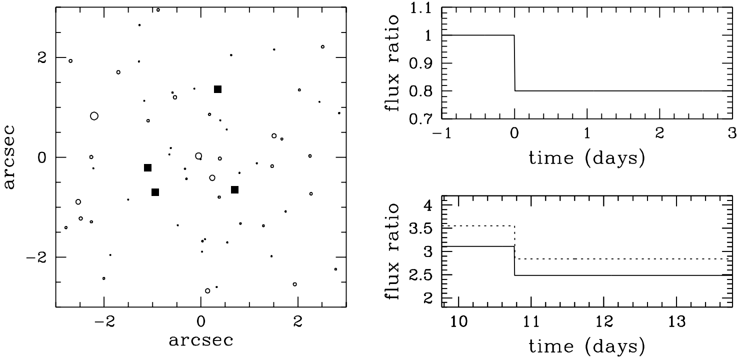
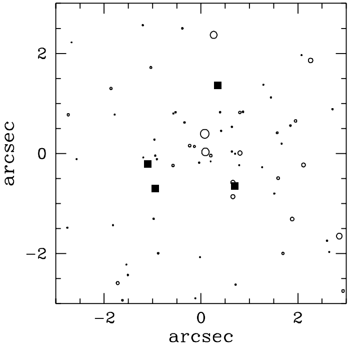
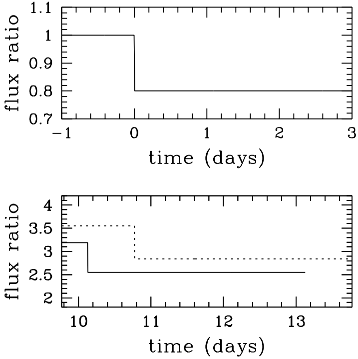


(CRK & Moustakas 2009)

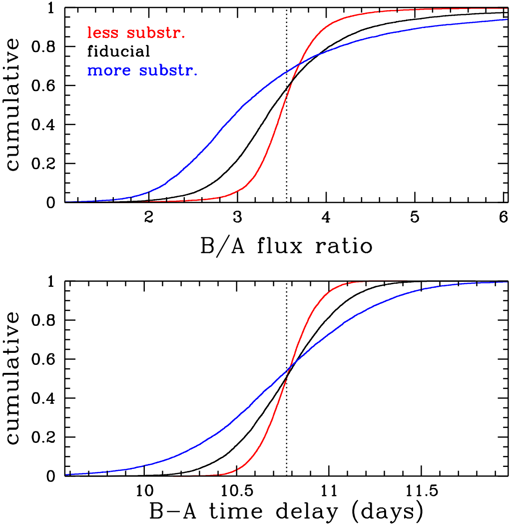


(CRK & Moustakas 2009)





Stochasticity

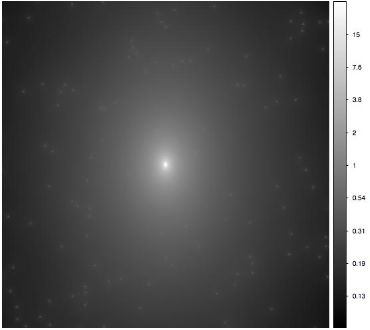


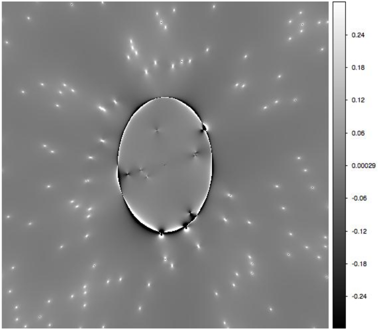
Parity dependence

Data: often see suppressed saddle images.
Theory: generally expect magnified minima, suppressed saddles.

(Schechter & Wambsganss 2002; CRK 2003)

Left: κ map
Right: fractional change in magnification due to substructure





Types of substructure

"Microlensing" by stars

- $R_{\rm ein} \sim 10^{-6}$ arcsec
- optical and shorter wavelengths
- may be chromatic (due to source size)
- variable over months/years

"Millilensing" by mass clumps

- $R_{\rm ein} \sim 10^{-3} (M/10^6\,M_\odot)^{1/2}$ arcsec
- (mostly) achromatic
- effectively constant in time

Some results

Dalal & Kochanek (2002)

- flux ratios in 7 quad lenses
- $f_{\rm sub} = 2.0^{+5.0}_{-1.4}$ percent (90% CL)
- little constraint on clump mass scale

Vegetti, Koopmans, et al.

A theory of stochastic lensing

Back of the envelope.

- clump mass, m
- number density, n – distance to nearest clump, $d \sim n^{-1/2}$
- surface mass density, $\kappa_s = mn$

Flux perturbation, mediated by shear: *(cf. Mao & Schneider 1998)*

$$\delta\gamma \sim \frac{m}{d^2} \sim mn \sim \kappa_s$$

Position perturbation, mediated by deflection: *(cf. Chen et al. 2007; CRK 2009)*

$$\delta\alpha \sim \frac{m}{d} \sim (\kappa_s m)^{1/2}$$

Time delay perturbation, mediated by potential: *(cf. CRK & Moustakas 2009)*

$$\delta\phi \sim m \ln d$$

Lensing complementarity

Full theory: treat substructure lensing as a stochastic process, use probability theory. *(CRK 2009; Petters, Rider & Teguia 2009ab)*

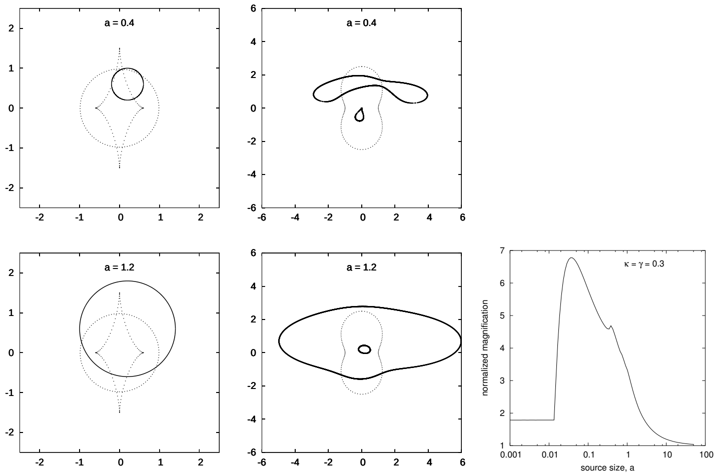
How do different lensing observables depend on the mass function and spatial distribution of clumps?

observable	mass scale	spatial scale
fluxes	$\int m \frac{dN}{dm} dm$	quasi-local
positions	$\int m^2 \frac{dN}{dm} dm$	intermediate
time delays	$\int m^2 \frac{dN}{dm} dm$	long-range

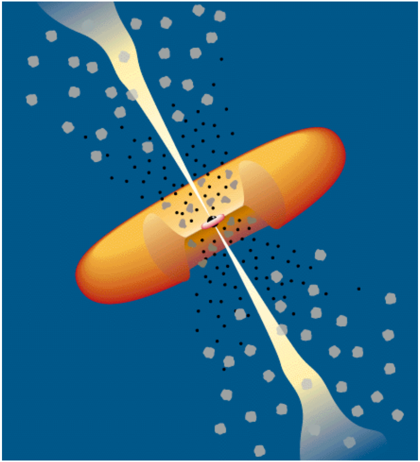
Beyond flux anomalies: "Multi-messenger" lensing.

Multi-scale lensing

Signal depends on size of source relative to clump ⇒ combine different source sizes to probe different mass scales. *(Dobler & CRK 2006)*



Quasars as multi-scale sources



(Credit: C. Meg Urry, Yale)

X-ray / optical continuum, emission lines / infrared / radio

Multi-wavelength observations

Microlensing

- X-ray, optical continuum, optical emission lines
- probe relative abundances of stars and (smooth) dark matter in lens galaxies, also structure of source quasars

(e.g., Kochanek et al. 2007; Sluse et al. 2007, 2010; Eigenbrod et al. 2008; Morgan et al. 2008, 2010; Pooley et al. 2009; Dai et al. 2010; Bate et al. 2011; Blackburne et al. 2011; Mosquera et al. 2011; Muñoz et al. 2011; Jimenez-Vicente et al. 2012)

Millilensing

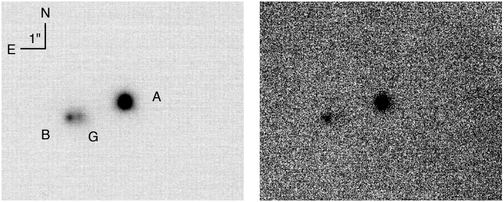
- optical, IR, radio
- suppress microlensing, look for features that reveal mass scale

(e.g., Chiba et al. 2005; Agol et al. 2009; MacLeod et al. 2009; Minezaki et al. 2009; More et al. 2009)

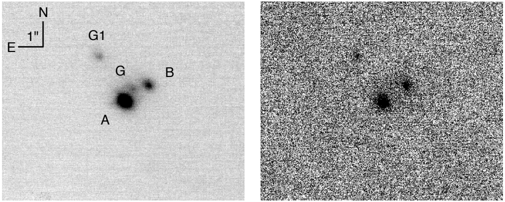
Gemini observations

- K = mostly from accretion disk
- L' = mix of accretion disk and dusty torus

Q0142−100



SDSS 0246−0825



(Fadely & CRK 2011)

Gemini observations

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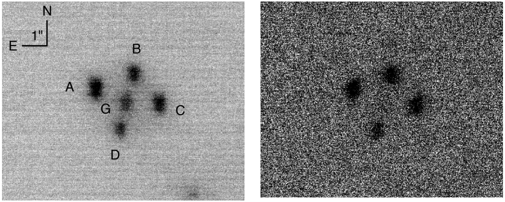
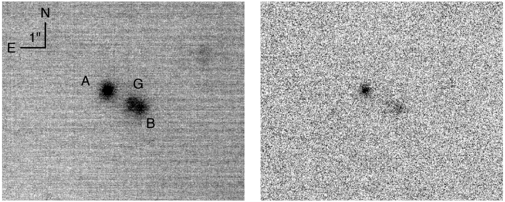
HE 0435−1223

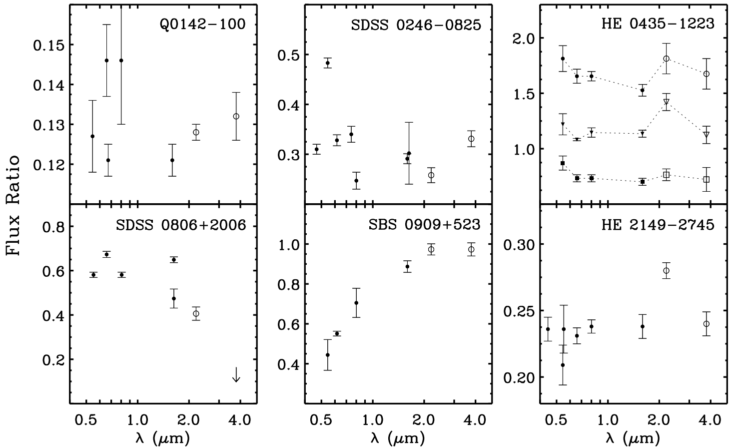


SDSS 0806+2006



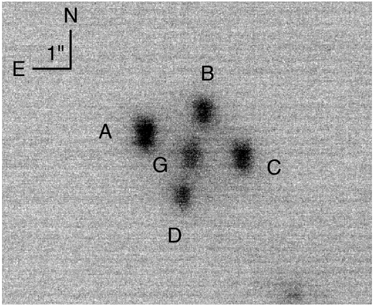
(Fadely & CRK 2011)

Multi-wavelength flux ratios



(Fadely & CRK 2011)

HE 0435−1223



(Fadely & CRK 2011)

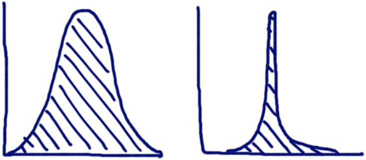
Constraints

- HST positions, $\sigma = 3$–5 mas
- optical/IR fluxes, $\sigma \sim 5\%$
- (time delays, $\sigma = 0.8$ d)

Interlude: Bayesian statistics

$$\text{"Posterior"} \qquad P(\theta|d,M) = \frac{\mathcal{L}(d|\theta,M)\,P(\theta,M)}{\mathcal{E}(M)}$$

$$\text{"Evidence"} \qquad \mathcal{E}(M) = \int \mathcal{L}(d|\theta,M)\;P(\theta,M)\;d\theta$$



"Nested sampling" (Skilling 2004, 2006)

- variants: Shaw et al. (2007), Feroz & Hobson (2008), Brewer et al. (2009), Betancourt (2010)
- statistical uncertainties: CRK (2011)

Comparing models

Bayesian evidence allows objective model comparison, even with different numbers of parameters.

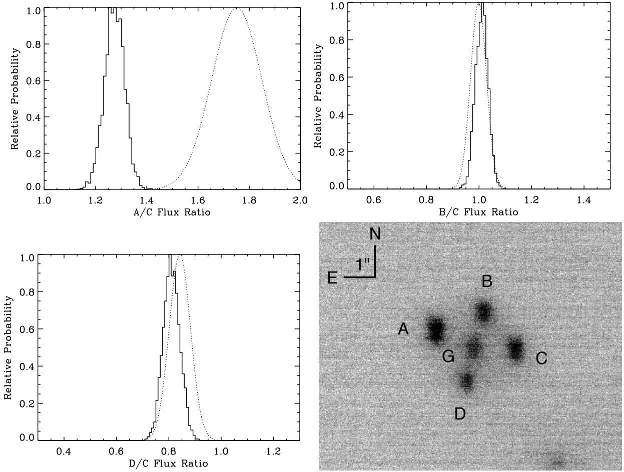
Compare two models via $\mathcal{E}_2/\mathcal{E}_1$ or $\log_{10}(\mathcal{E}_2/\mathcal{E}_1) = \Delta\log_{10}(\mathcal{E})$.

Jeffreys (1961) scale:

$\Delta\log_{10}(\mathcal{E})$	Significance
0–0.5	Barely worth mentioning
0.5–1.0	Substantial
1.0–1.5	Strong
1.5–2.0	Very strong
> 2.0	Decisive

HE0435: Smooth mass models

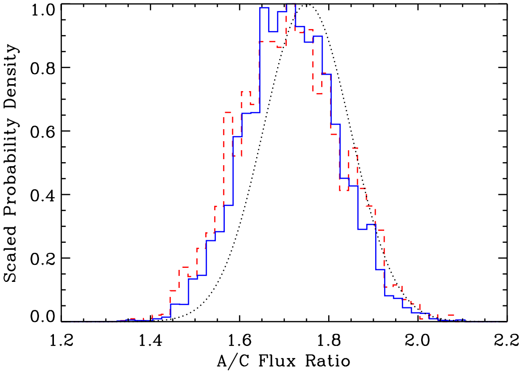
16 constraints, 17 parameters $\Rightarrow N_{\rm dof} = -1$
But best $\chi^2 = 24.6$ (!)



(Fadely & CRK 2012)

With mass clump(s)

Add one clump near image A.
Add three clumps near images A, B, D.
Clumps are truncated isothermal spheres.



(Fadely & CRK 2012)

Statistical significance of clump(s)

Use Bayesian evidence to compare different models.

model	$\Delta \log_{10}(\mathcal{E})$
smooth	$\equiv 0$
clump A	3.83 ± 0.12
clumps AD	3.90 ± 0.13
clumps AB	4.46 ± 0.12
clumps ABD	4.35 ± 0.13

Decisive evidence for a clump near image A.

$$\log_{10}(M^A_{\rm ein}) = 7.65^{+0.87}_{-0.84} \qquad \log_{10}(M^A_{\rm tot}) = 9.31^{+0.44}_{-0.42}$$

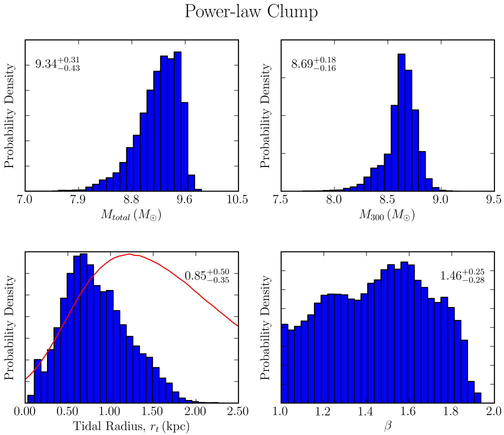
Intriguing evidence for a second clump near image B.

$$\log_{10}(M^B_{\rm ein}) = 6.55^{+1.01}_{-1.51} \qquad \log_{10}(M^B_{\rm tot}) = 8.76^{+0.50}_{-0.77}$$

First constraints from a quasar lens on masses of subhalos with no visual counterparts. From joint flux and position constraints.

Clump internal structure

- power law profile (Fadely poster); also NFW (not shown)
- M_{total} vs. M_{300}, tidal radius, profile index $M(r) \propto r^{\beta}$



Full population of clumps

It seems unlikely that the lens galaxy contains one or two clumps that are (almost) perfectly aligned with the quasar images.

More likely: they are "special" representatives of a larger pop'n.

Statistical arguments: use the representatives to constrain the full population. *(cf. Vegetti talk)*

Or try to constrain the population directly

- assume truncated isothermal spheres with mass function

$$\frac{dN}{dm} \propto m^{-1.9}, \qquad m \in 10^7\text{–}10^{10}\, M_\odot$$

- see whether models make sense, constrain $\kappa_s = \Sigma_s / \Sigma_{\rm crit}$

Statistical inference

Parameters

- $q =$ smooth model
- $s =$ substructure *population* (abundance, mass function, etc.)
- $c =$ individual clumps (position, mass, etc.)

Most interested in marginalized posterior for substructure population parameters:

$$P(s) \propto \int \mathcal{L}(c,q)\ P(c|s)\ P(s,q)\ dc\ dq$$

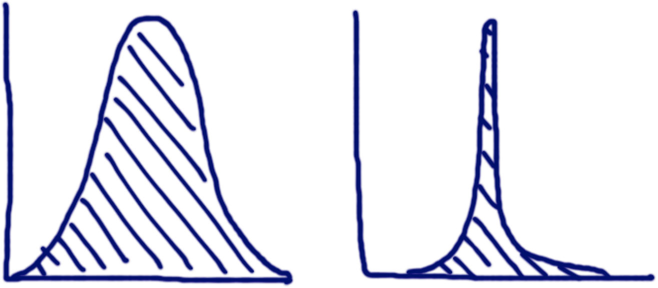
Handle clumps using Monte Carlo integration: let c_j be a realization of the clump population, drawn from $P(c|s)$. Then

$$P(s) \propto \sum_j \int \mathcal{L}(c_j,q)\ P(s,q)\ dq$$

Marginalizing vs. optimizing

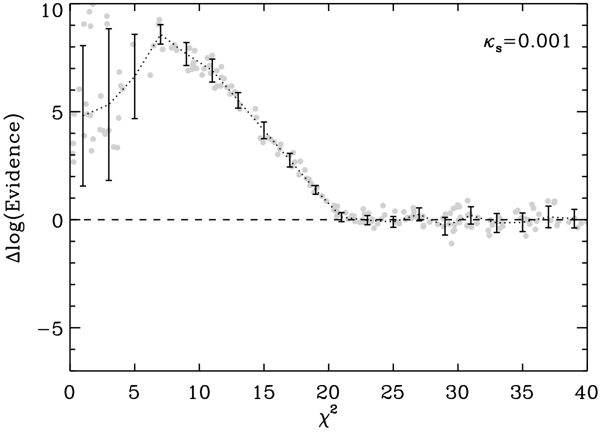
- Optimizing = finding the peak ($\mathcal{L} = e^{-\chi^2/2}$)
- Marginalizing = finding the area

They are not necessarily equivalent!



Marginalizing vs. optimizing

Each point is one realization of the clump population.



(Fadely & CRK 2012)

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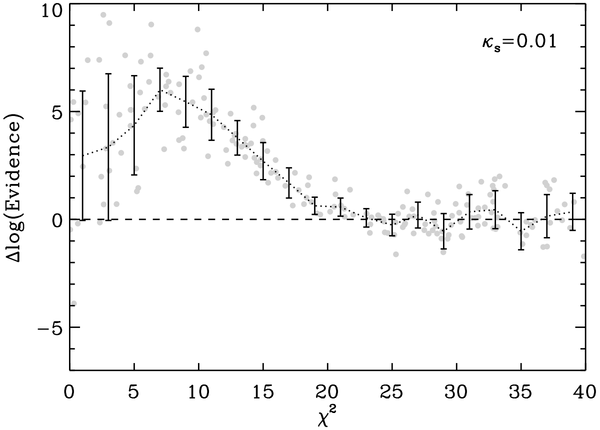

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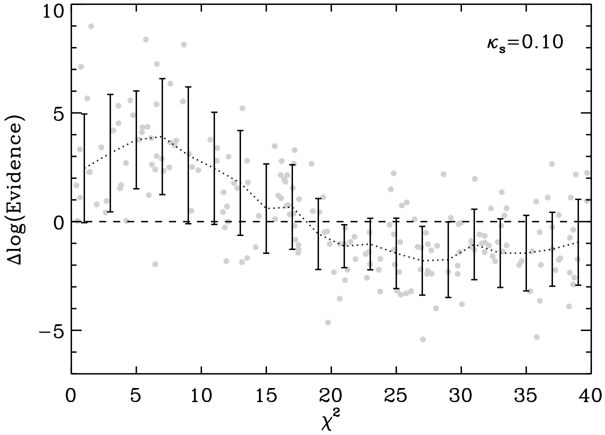
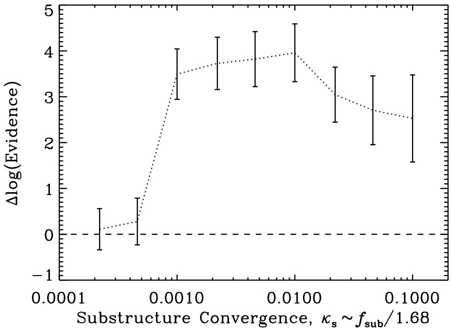


(Fadely & CRK 2012)

Results

Recall: $dN/dm \propto m^{-1.9}$ for $m \in 10^7$–$10^{10}\ M_\odot$



(Fadely & CRK 2012)

$\Rightarrow$ $f_{\rm sub} > 0.00077$ at Einstein radius

Outstanding questions

Q) Can we distinguish. . .

- detecting a few clumps that (presumably) trace a pop'n
- detecting a full population

A) Time delays (I think)

Q) How far down the mass function can we probe?
A) New simulations to examine different shapes, cut-offs, etc.

(Moustakas, Fadely, et al.)

Q) Could clumps be along the line of sight?

(e.g., CRK 2003; Chen et al. 2003; Metcalf 2005ab; Miranda & Macciò 2007; Xu et al. 2012)

A) We need to look at this for real lenses

Outstanding questions

Q) Does lensing require **more** substructure than CDM predicts?

(e.g., Mao et al. 2004; Amara et al. 2006; Macciò et al. 2006; Xu et al. 2009, 2010; Chen et al. 2011)

Possibilities:

- luck of the draw?
- biases? (natural or human)
- environment?
- line of sight?
- any effects from baryons?

A) Need predictions that are better tuned to lensing!

Conclusions

Beyond flux anomalies

- "multi-wavelength" – probe different scales
- "multi-messenger" – complementarity between fluxes, positions, time delays

Learning to probe…

- individual clumps – internal structure
- clump populations – mass function
- *mass clumps in distant galaxies*

Best times are ahead

- theory/observation synergy
- more/better data in sight *(ask Phil Marshall!)*