Light Bending and Dark Matter:
Gravitational Lensing as a Probe of Galaxy Structure

Arthur Congdon • JPL
Acknowledgments

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What Is Gravitational Lensing?

- Bending of light by mass
- Larger deflection for larger mass or smaller distance from lens
- Multiple images if source and lens are nearly aligned – strong lensing
- Positions, fluxes and/or arrival times of images constrain properties of source and lens
\[ \hat{\alpha} = \frac{4GM}{c^2 R} \]
Quasars as Lensed Sources

- Radio emission comes from extended jets
- Optical, UV and X-ray emission comes mainly from the central accretion disk
Lensing by Galaxies: Hubble Space Telescope Images

“Double”

“Quad”

“Ring”

CASTLES ~ www.cfa.harvard.edu/castles
Galaxies as Lensing Objects

- Two major galaxy types
- Most lens galaxies are elliptical
- Galaxies contain dark matter
Does Dark Matter Really Exist?

- Use rotation curve to find enclosed mass
- Not enough visible matter to explain observations
- Need more mass – dark matter
• **Hierarchical structure formation**: small objects form first, then aggregate into larger objects

• Large halos contain the remnants of their many progenitors - substructure

• Theory predicts more substructure than we see – “missing satellites” problem
Missing Satellites Problem

Strigari et al. (2007)
Four-Image Lenses

Source plane

Fold

Cusp

Cross

Image plane
Flux Anomalies

- Many lenses require small-scale structure 
  \cite{Mao1998, Keeton2003, Keeton2005}

- Could be CDM substructure 
  \cite{Metcalf2001, Chiba2002}

- Fitting the lenses requires \[ 0.006 < f_{\text{sub}} < 0.07 \] 
  \cite{Dalal2002}

- Broadly consistent with CDM

- Is substructure the only viable explanation?
“Minimum Wiggle” Model

- Allow many multipoles, up to mode $k_{\text{max}}$
- Models underconstrained $\Rightarrow$ large solution space
- Minimize departures from elliptical symmetry

- B2045+265
Solution for B2045+265

kmax=5
Solution for B2045+265

$\kappa_{\text{max}} = 9$

$\kappa_{\text{max}} = 17$

Isodensity contours (solid) and critical curves (dashed)
What Have We Learned from Multipoles?

- Multipole models with shear cannot explain anomalous flux ratios
- Isodensity contours remain wiggly, regardless of truncation order
- Wiggles are most prominent near image positions; implies small-scale structure
- Ruled out a broad class of alternatives to CDM substructure
Lens Time Delays

Robust probe of dark matter substructure?

Q0957+561

Kundić et al. (1997)
Time-Delay Relation for Fold Pairs

\[ \Delta \tau_{fold} \approx \sqrt{-\frac{16u_2^3}{27h}} \approx -\frac{h}{2} d_1^3 \]

Analytic scaling is astrophysically relevant
Dependence of Time Delay on Lens Potential

- Use $h$ as proxy for time delay
- Model lens as elliptical galaxy with shear
- Higher-order multipoles are not so important here
What Is Shear?

Neighboring galaxies perturb lensing observables

Keeton & Kochanek (1997)
Variation of $h$ along Caustic

e = 0.1
Variation of $h$ along Caustic

$e=0.3$
Variation of $h$ along Caustic

$e=0.5$
Time Delays for a Realistic Lens Population

• Perform Monte Carlo simulations:
  – use galaxies with distribution of ellipticity, shear and multipoles
  – use random source positions to create mock four-image lenses
  – use Gravlens software (Keeton 2001) to obtain image positions and time delays
  – create time delay histogram for each image pair
Matching Mock and Observed Lenses
Histograms for Scaled Time Delay: Folds

PG 1115+080

SDSS J1004+4112
Histograms for Scaled Time Delay: Cusps

RX J0911+0551

RX J1131-1231
Nature of Dark Matter

- Various explanations of dark matter
  - sterile neutrino
  - lightest supersymmetric particle
  - extra dimensions

- Signatures of dark matter
  - particle annihilation at galactic center or elsewhere
  - strong lensing?

\[ \Lambda \text{CDM} \quad m_X = 350 \text{ eV} \quad m_X = 175 \text{ eV} \]

Constraining Dark Matter with Strong Lensing

- Different models give different mass functions
- Use lensing observables to constrain mass function and hence particle properties
- Keeton and Moustakas (2008) have shown that time delays are sensitive to substructure
What Have We Learned from Time Delays?

- Time delay of the close pair in a fold lens scales with the cube of image separation.
- Time delay is sensitive to ellipticity and shear, but not higher-order multipoles.
- Monte Carlo simulations reveal strong time-delay anomalies in several lenses.
- We can use time delays to understand the nature of dark matter.