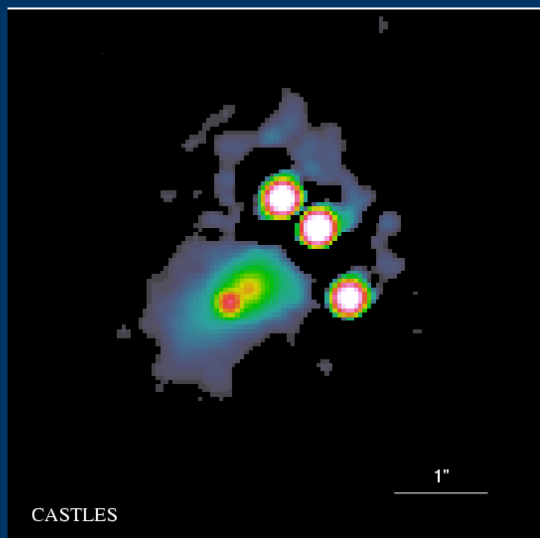
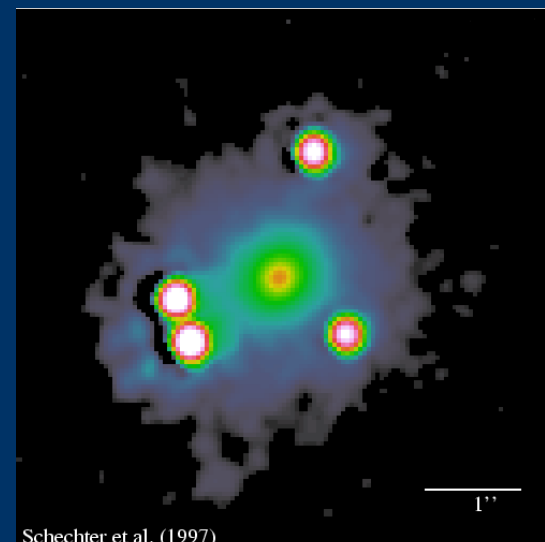
Light Bending and Dark Matter:

Gravitational Lensing as a Probe of Galaxy Structure





Arthur Congdon • JPL

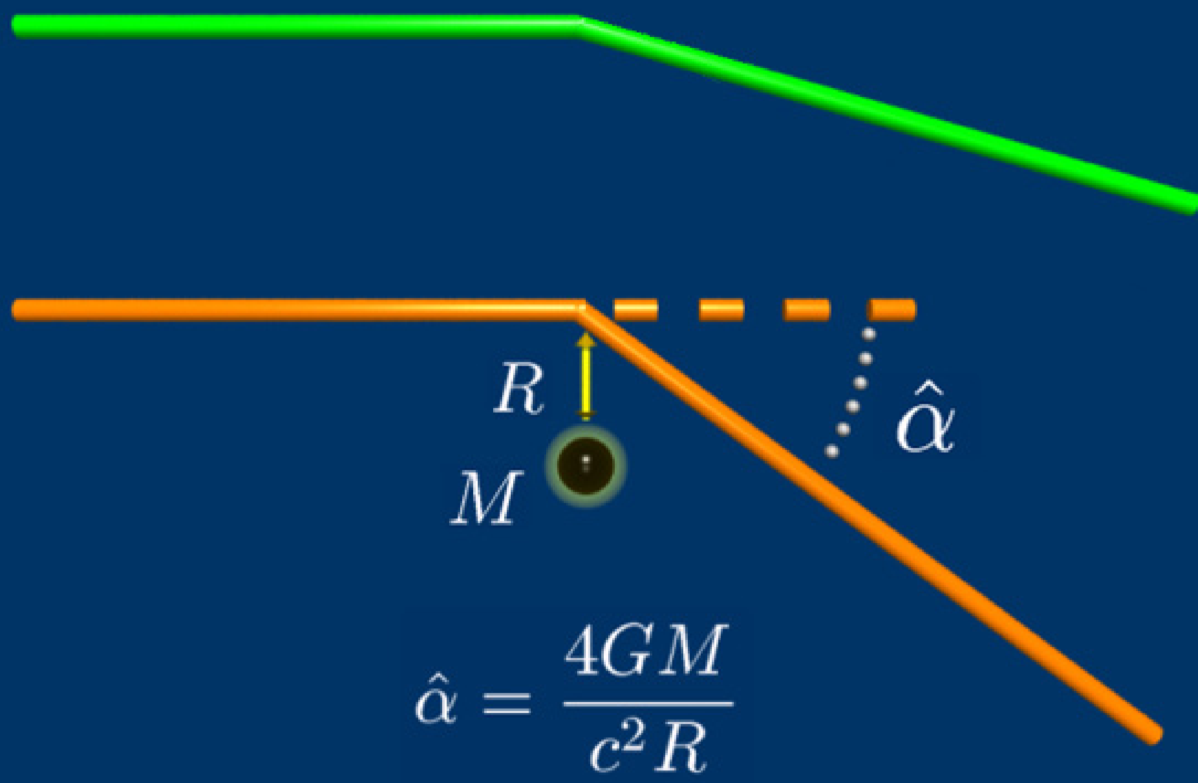
Acknowledgments

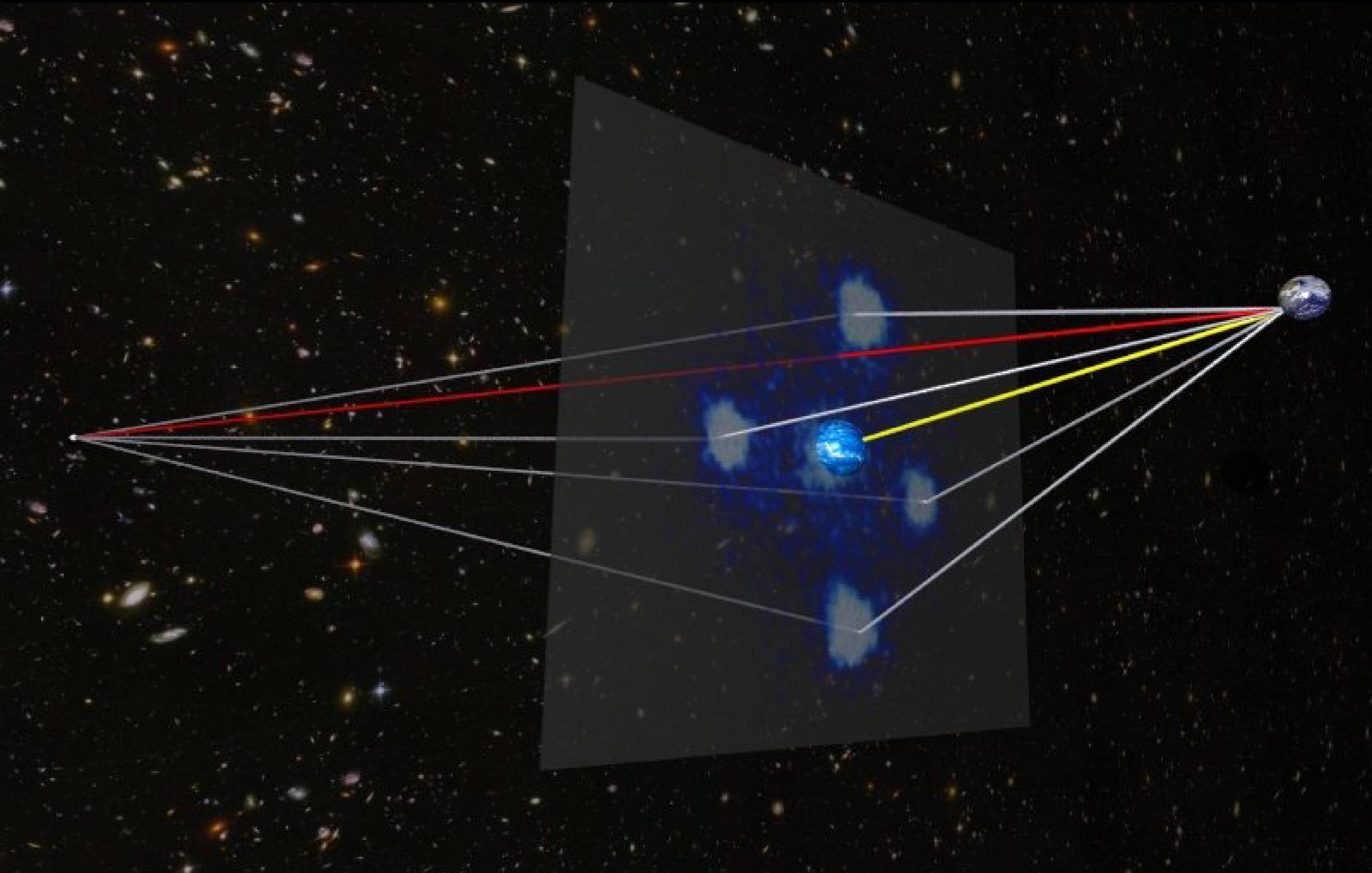
I would like to thank my collaborators,

Chuck Keeton and Erik Nordgren

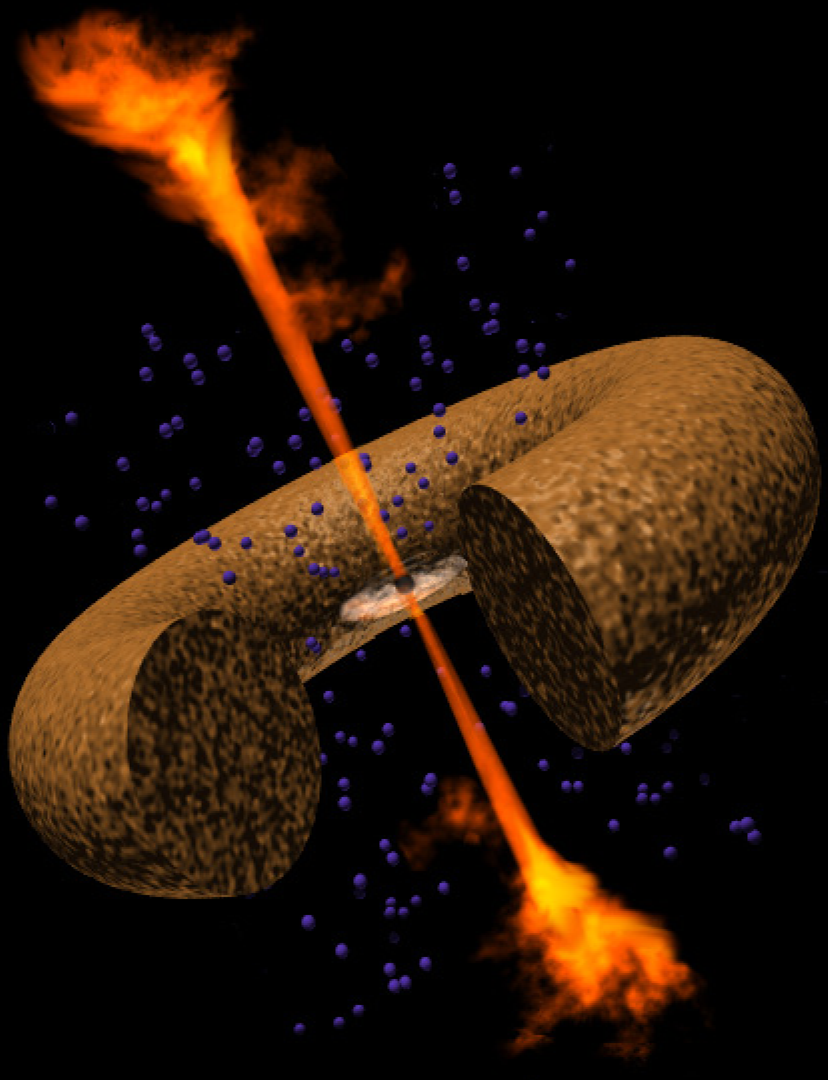
What Is Gravitational Lensing?

- 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


R
M
$\hat{\alpha}$
$\hat{\alpha} = \frac{4GM}{c^2 R}$

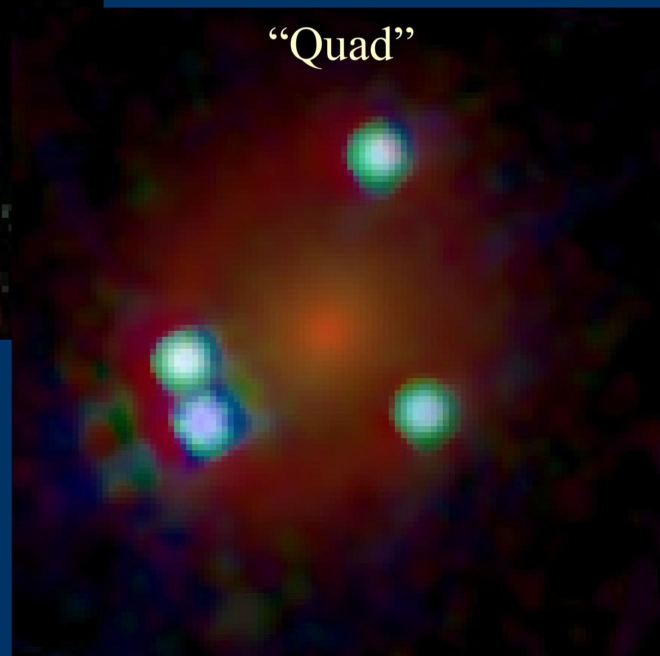


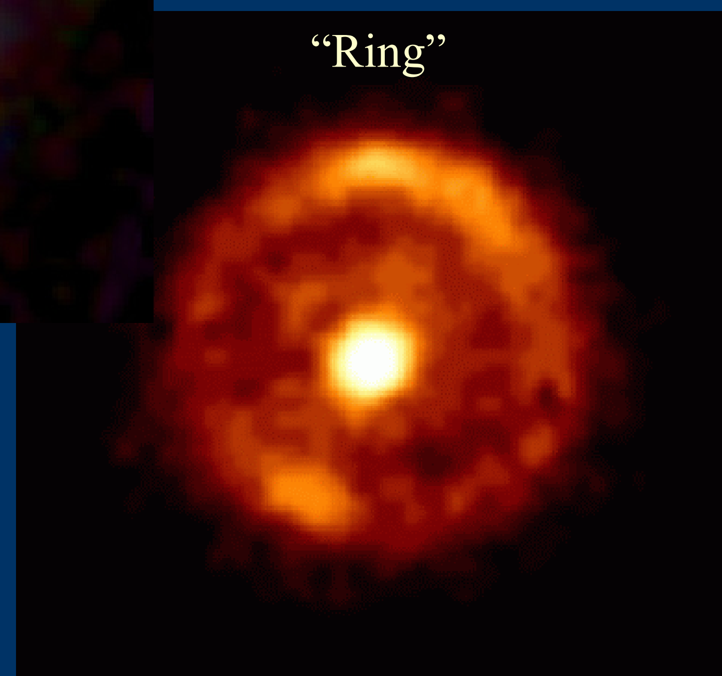
Quasars as Lensed Sources



- 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

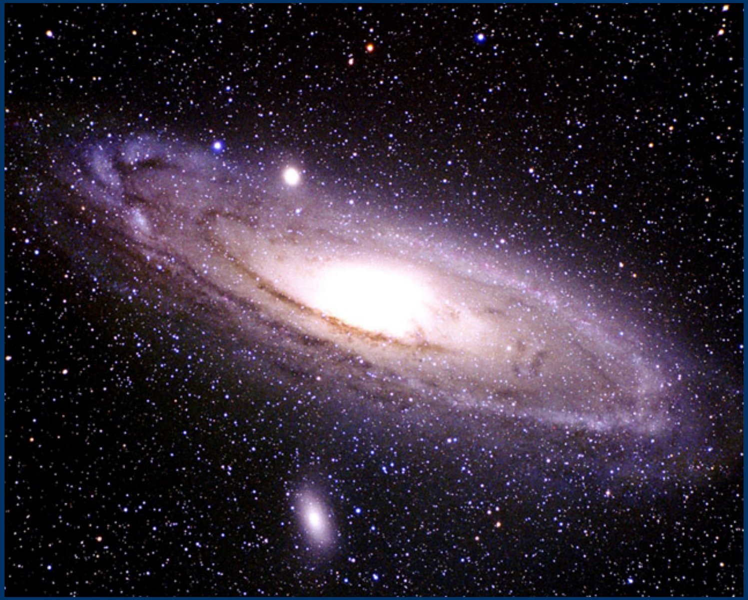




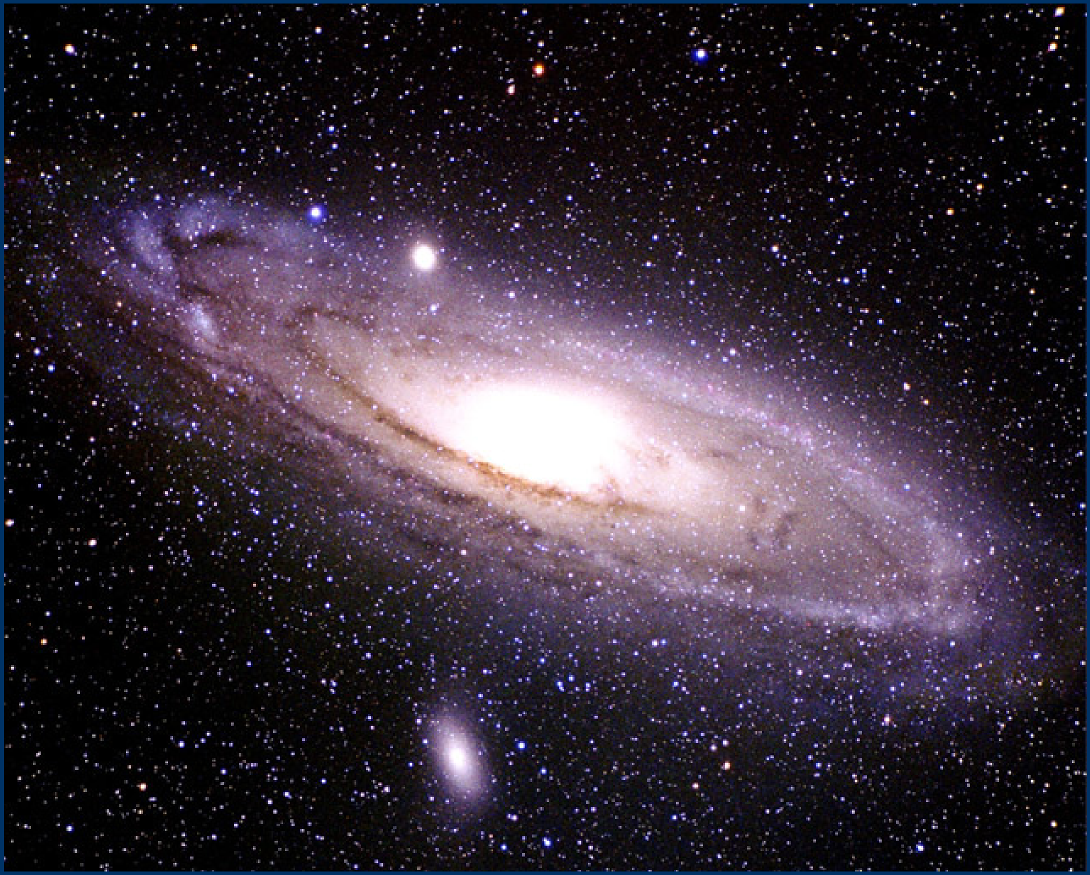
CASTLES ~ www.cfa.harvard.edu/castles

Galaxies as Lensing Objects

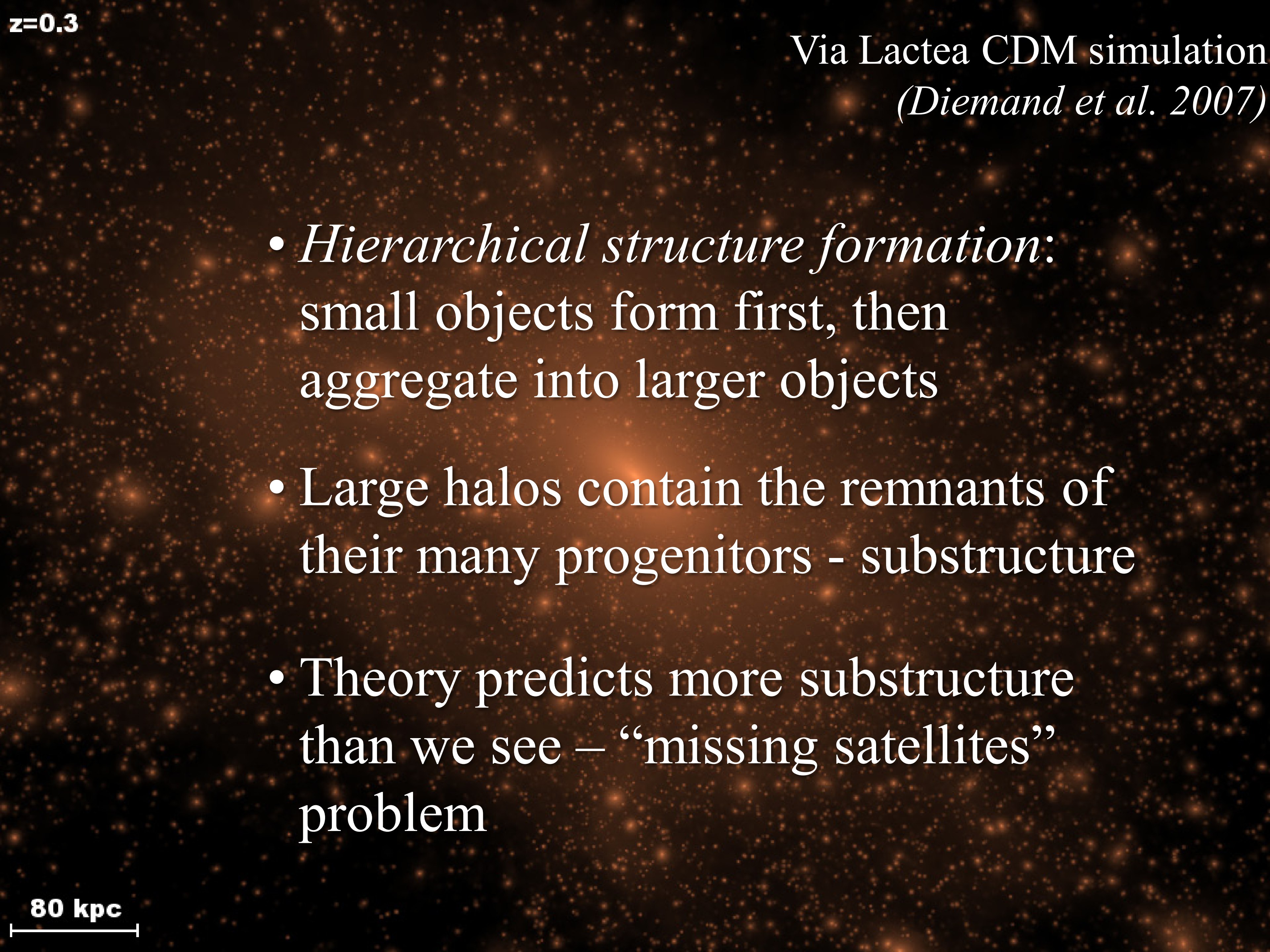
- Two major galaxy types
- Most lens galaxies are elliptical
- Galaxies contain dark matter



Does Dark Matter Really Exist?



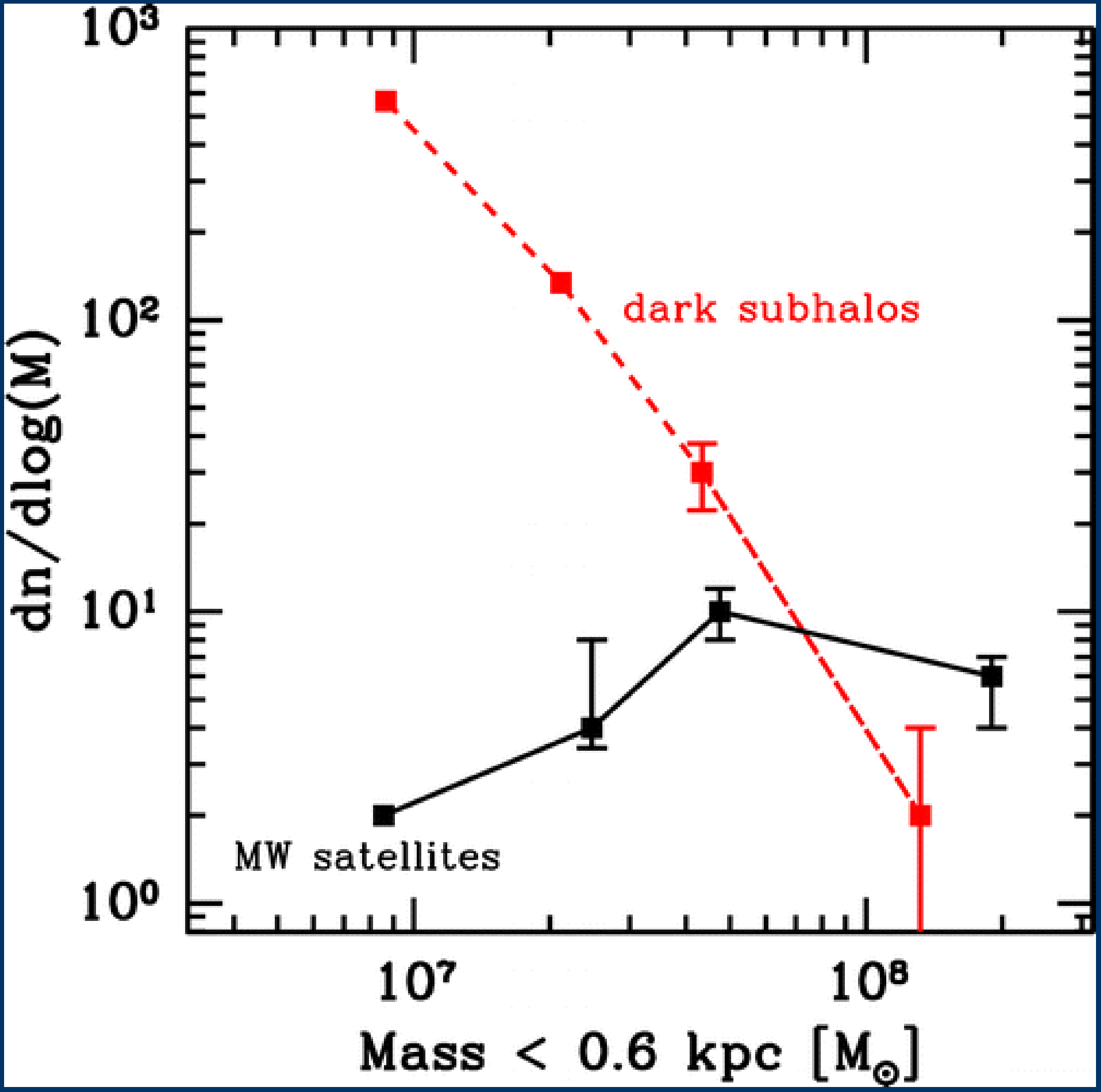
- Use rotation curve to find enclosed mass
- Not enough visible matter to explain observations
- Need more mass – dark matter



Via Lactea CDM simulation
(Diemand et al. 2007)

- *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

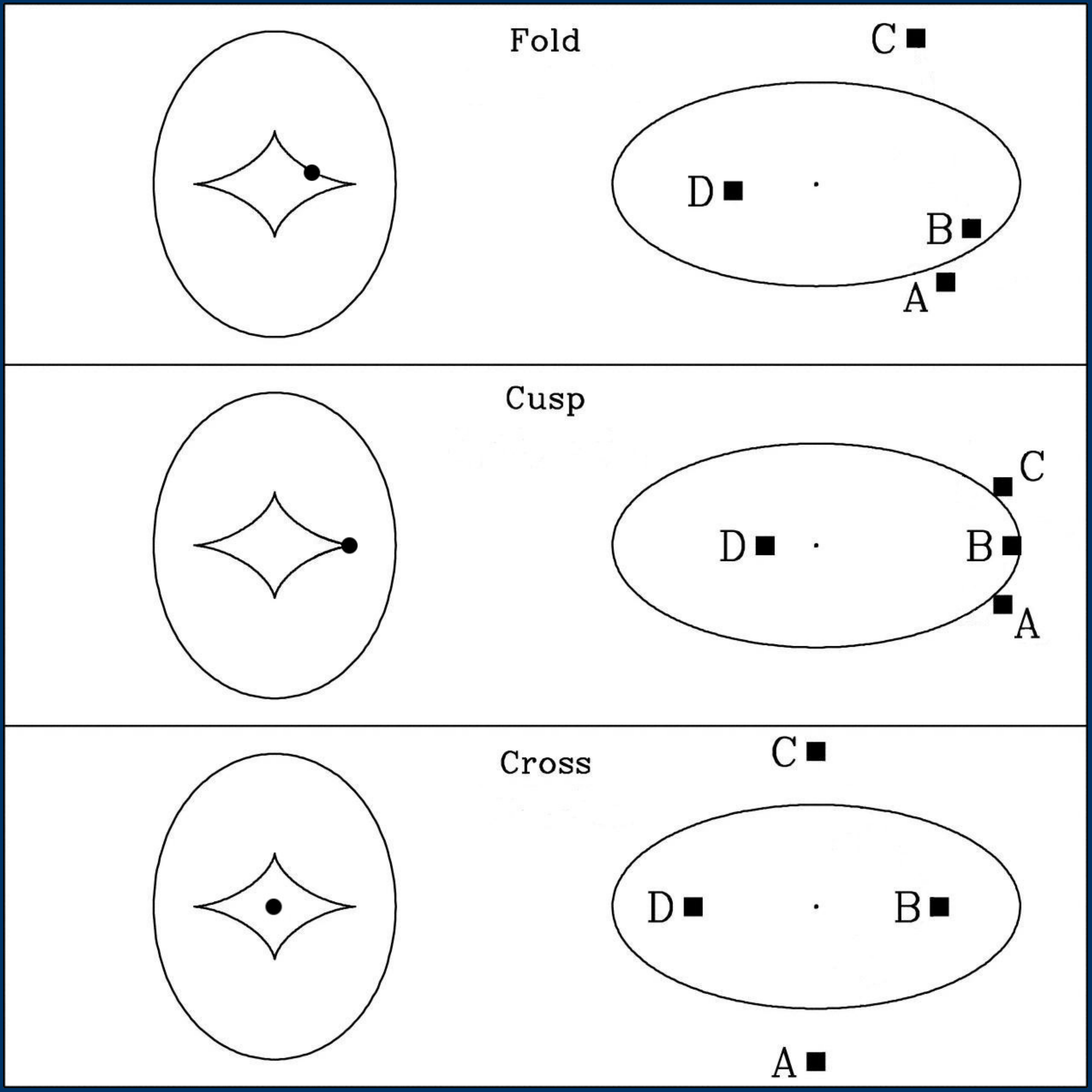


Image plane

Flux Anomalies

- Many lenses require small-scale structure

(Mao & Schneider 1998; Keeton, Gaudi & Petters 2003, 2005)

- Could be CDM substructure

(Metcalf & Madau 2001; Chiba 2002)

- Fitting the lenses requires $0.006 < f_{\rm sub} < 0.07$

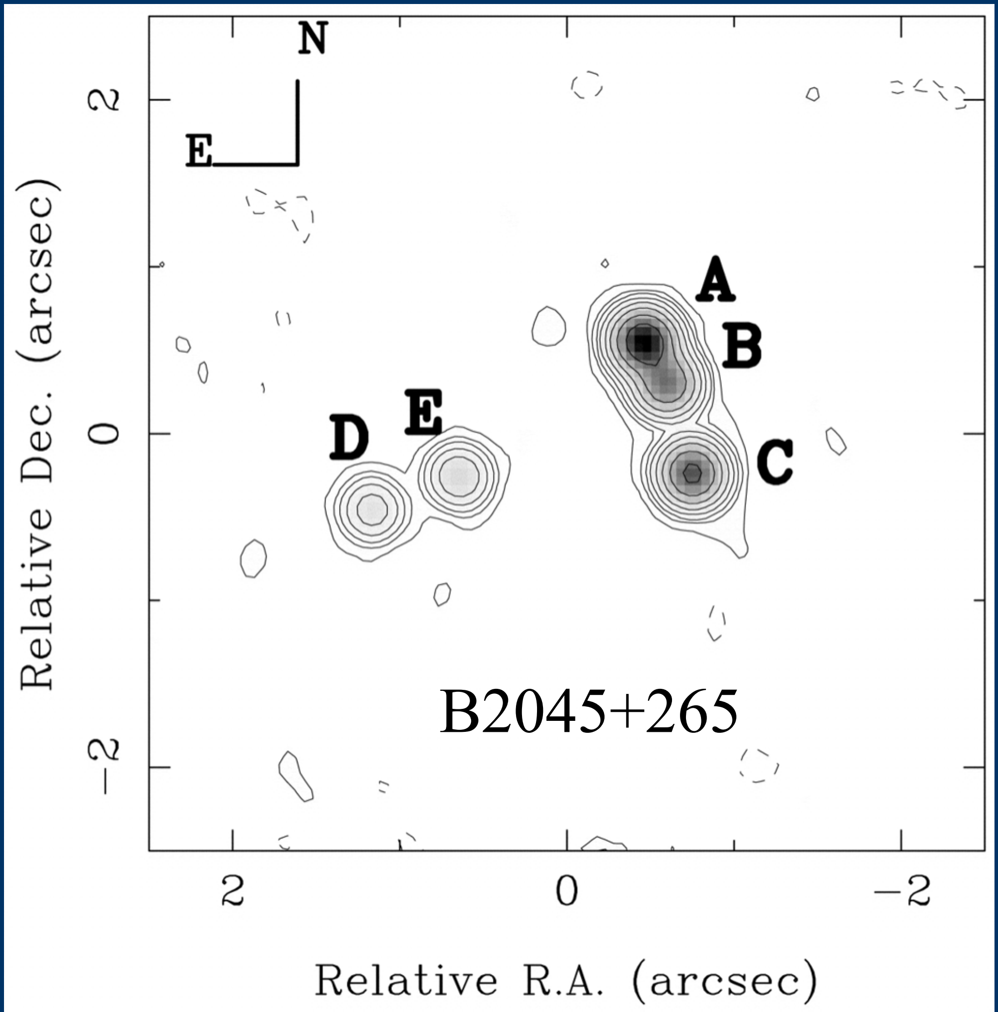
(Dalal & Kochanek 2002)

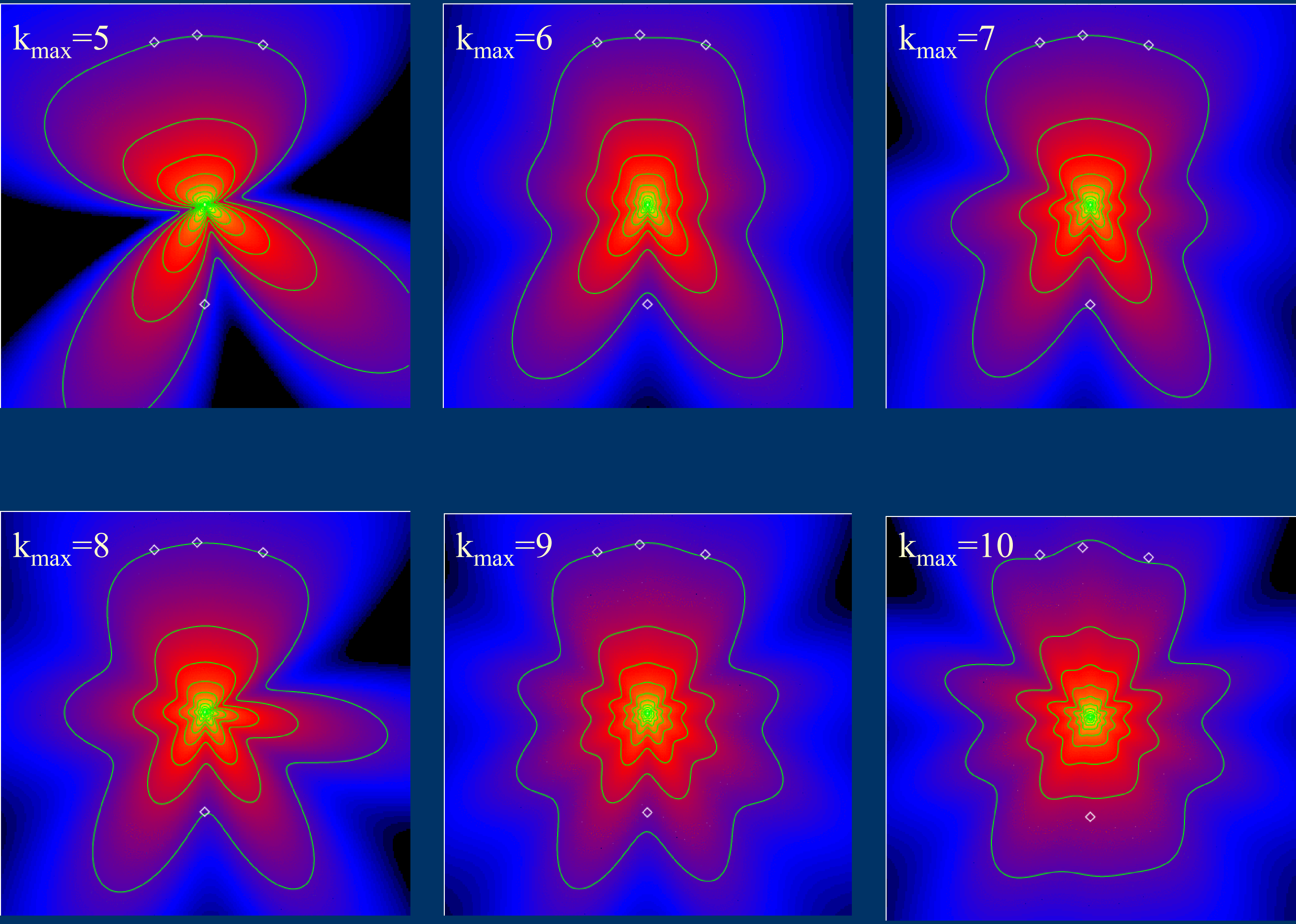
- Broadly consistent with CDM

- Is substructure the only viable explanation?

"Minimum Wiggle" Model

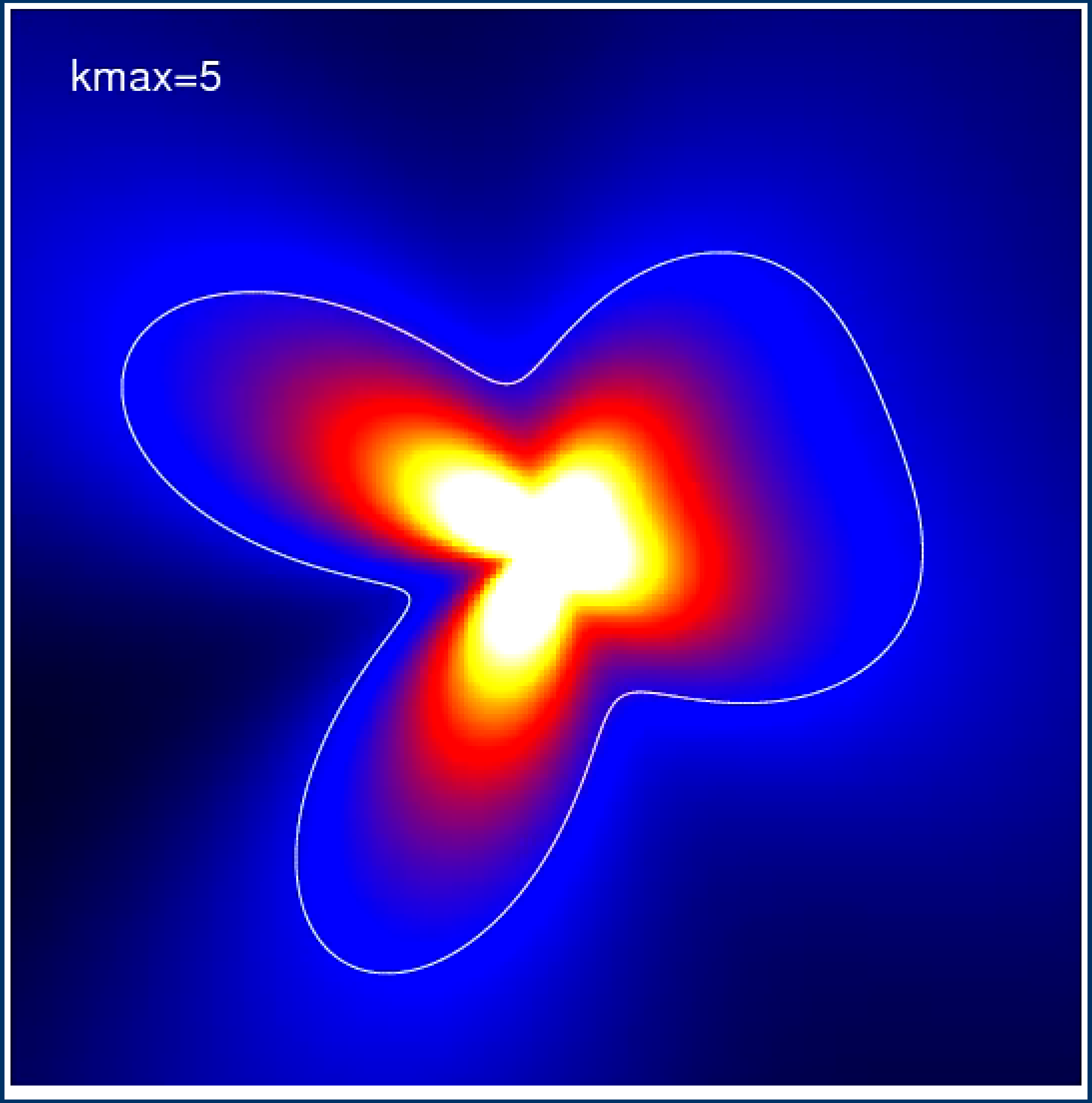
- Allow many multipoles, up to mode k_{max}
- Models underconstrained ⇒ large solution space
- Minimize departures from elliptical symmetry



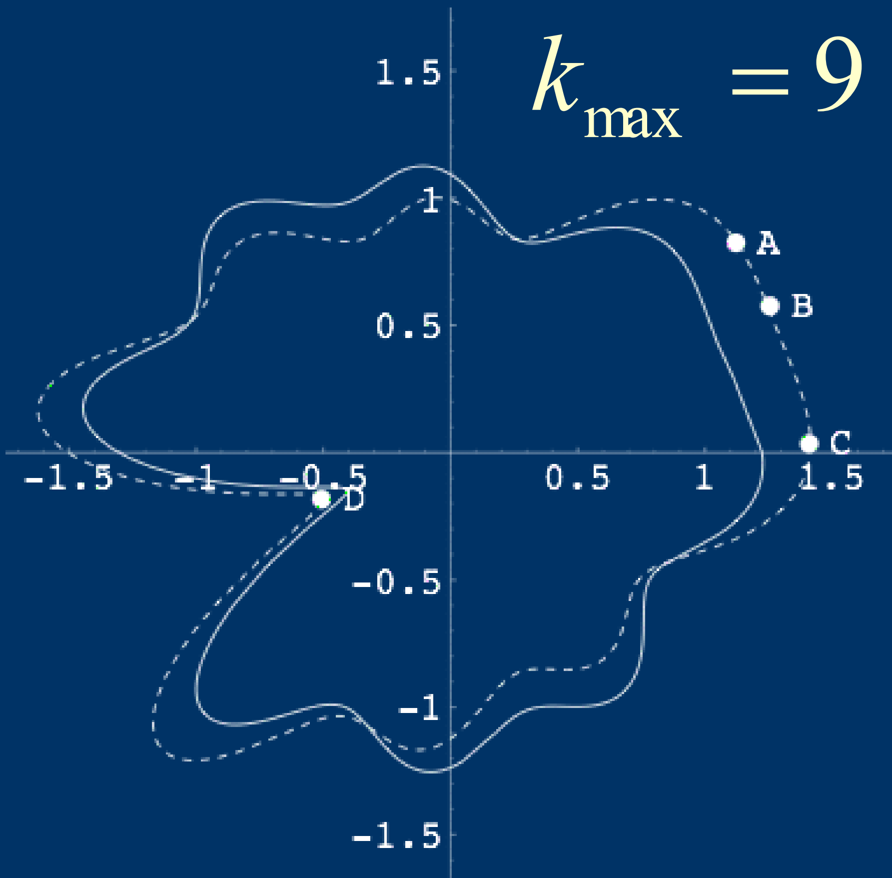


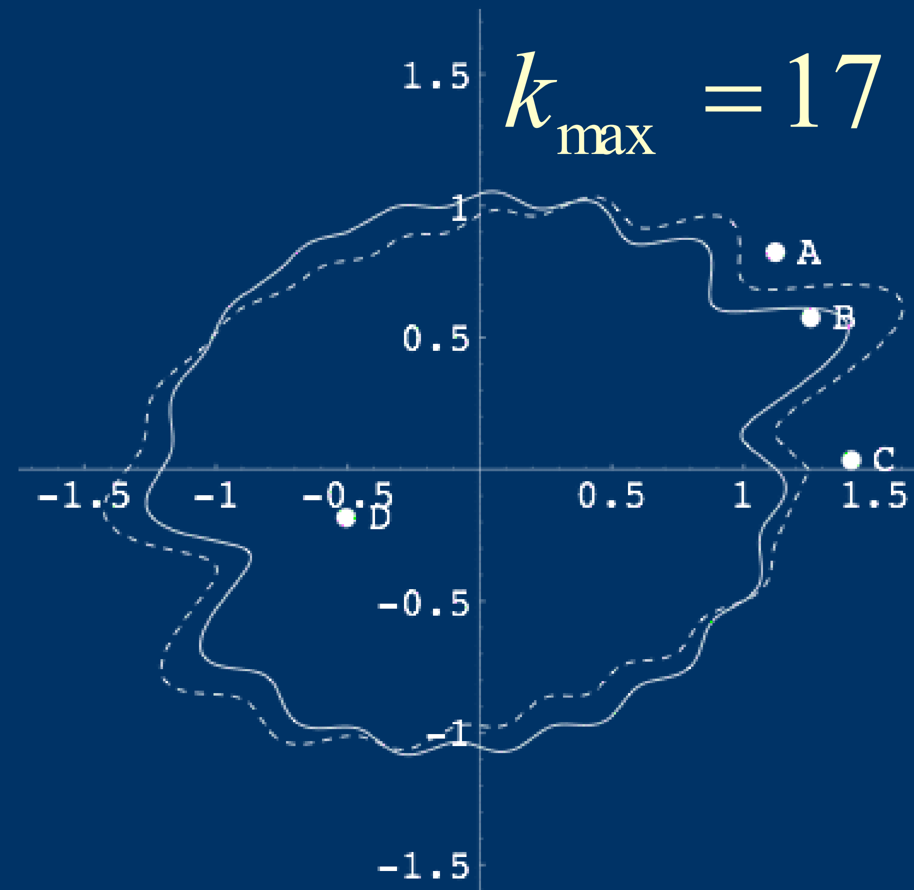
k_{max}=5
k_{max}=6
k_{max}=7
k_{max}=8
k_{max}=9
k_{max}=10

Solution for B2045+265



Solution for B2045+265

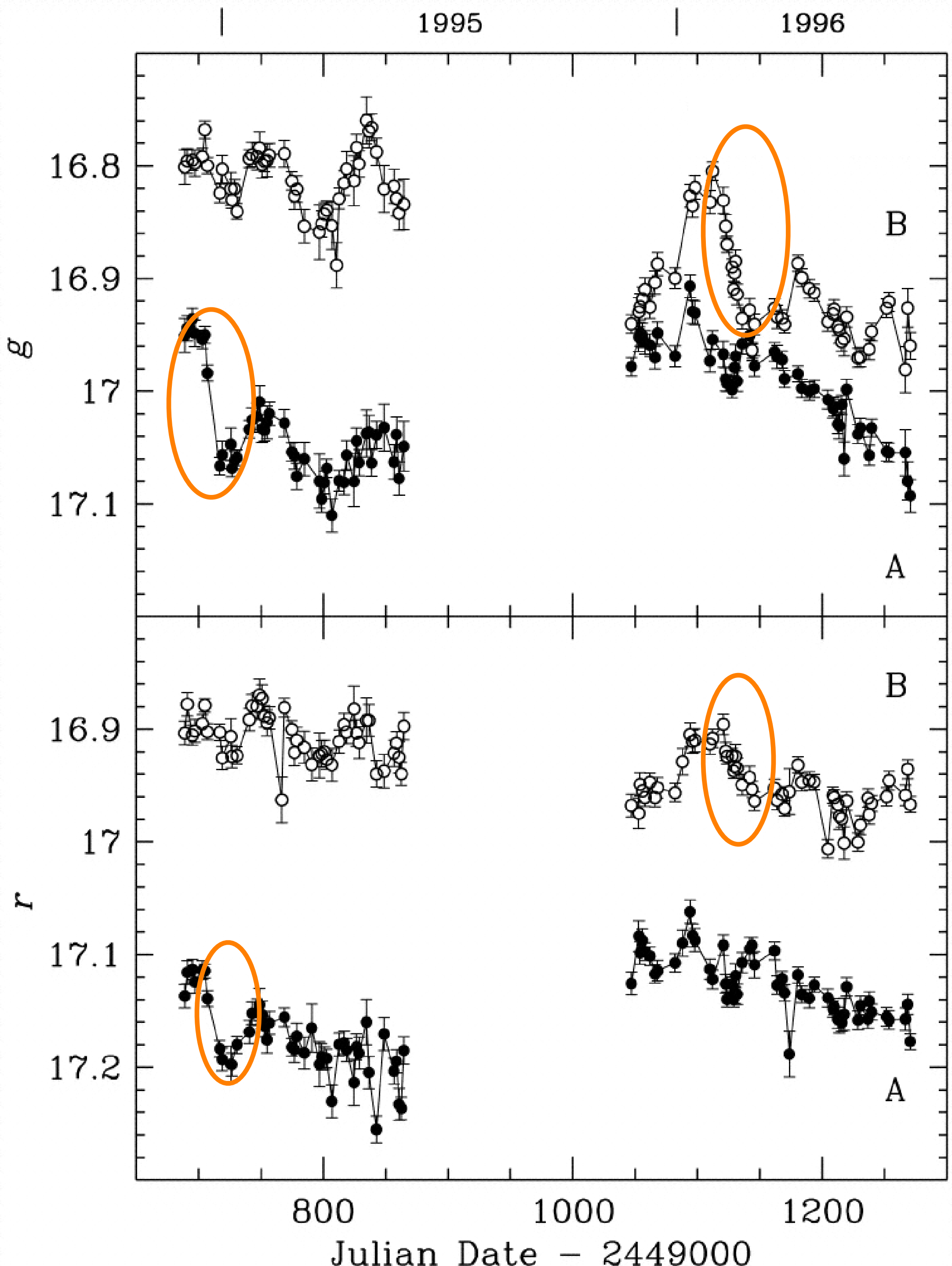




Isodensity contours (solid)
and critical curves (dashed)

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

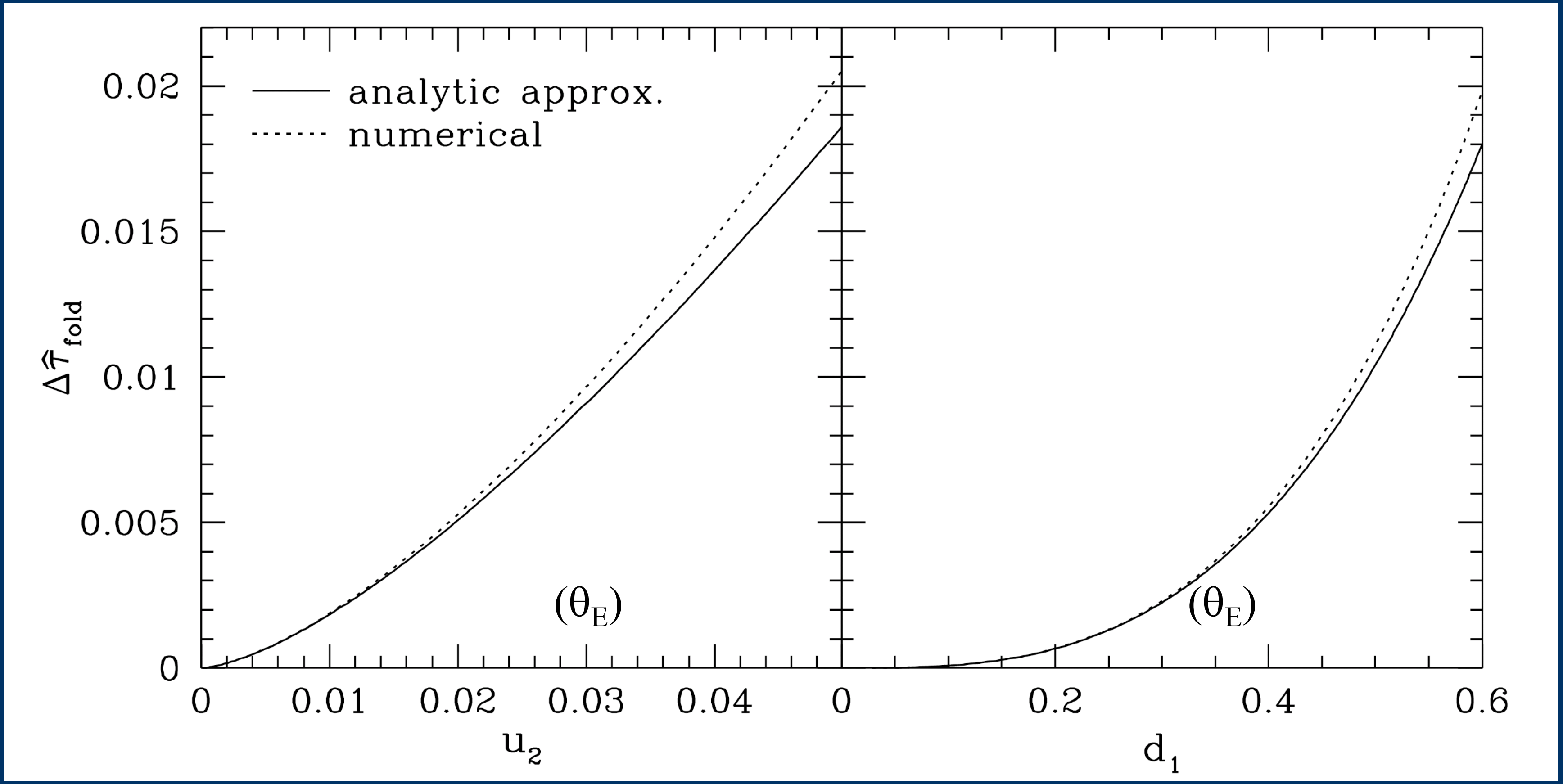
Robust probe of dark matter substructure?

Q0957+561

Kundić et al. (1997)

Time-Delay Relation for Fold Pairs

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

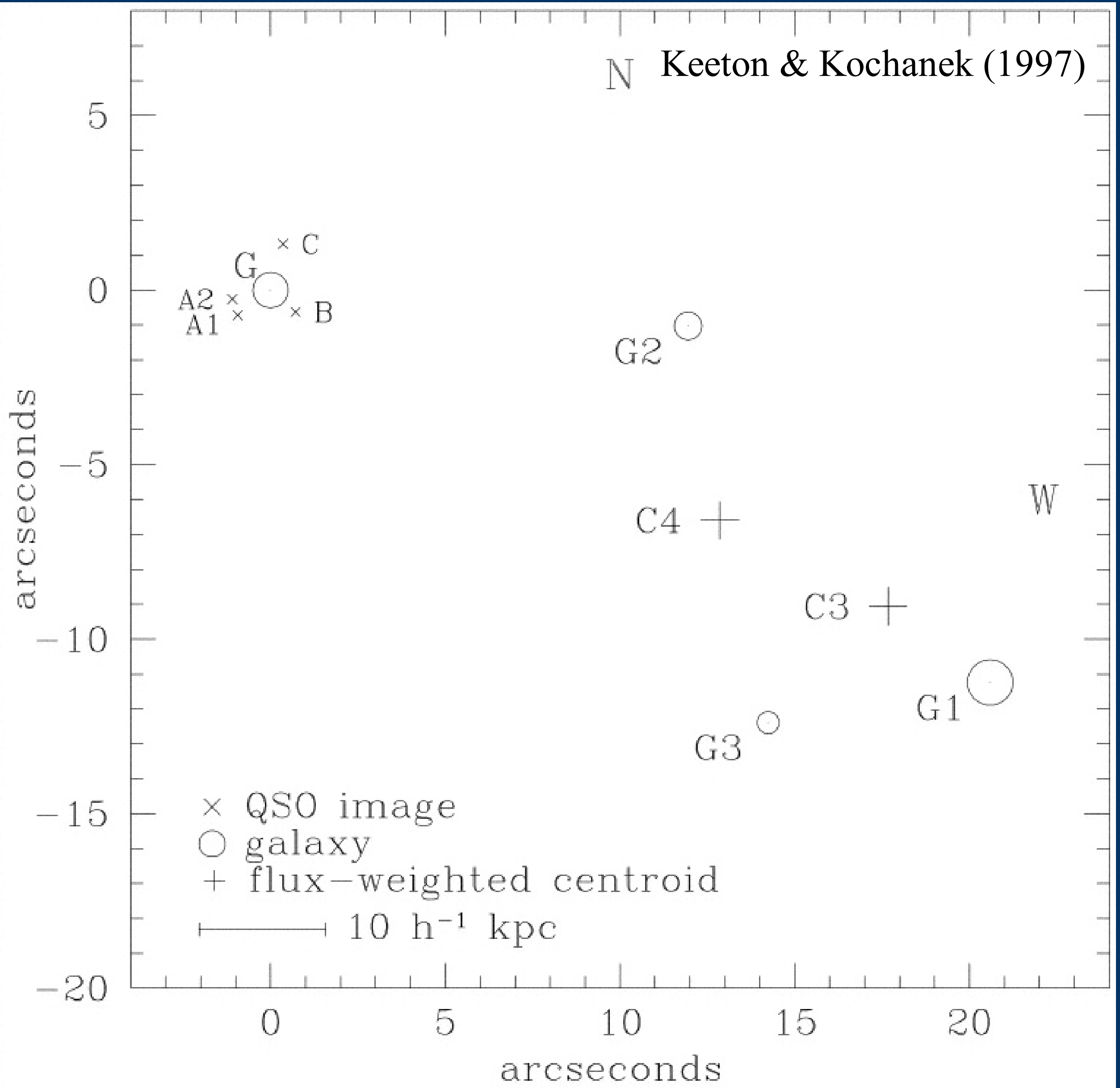


Analytic scaling is astrophysically relevant

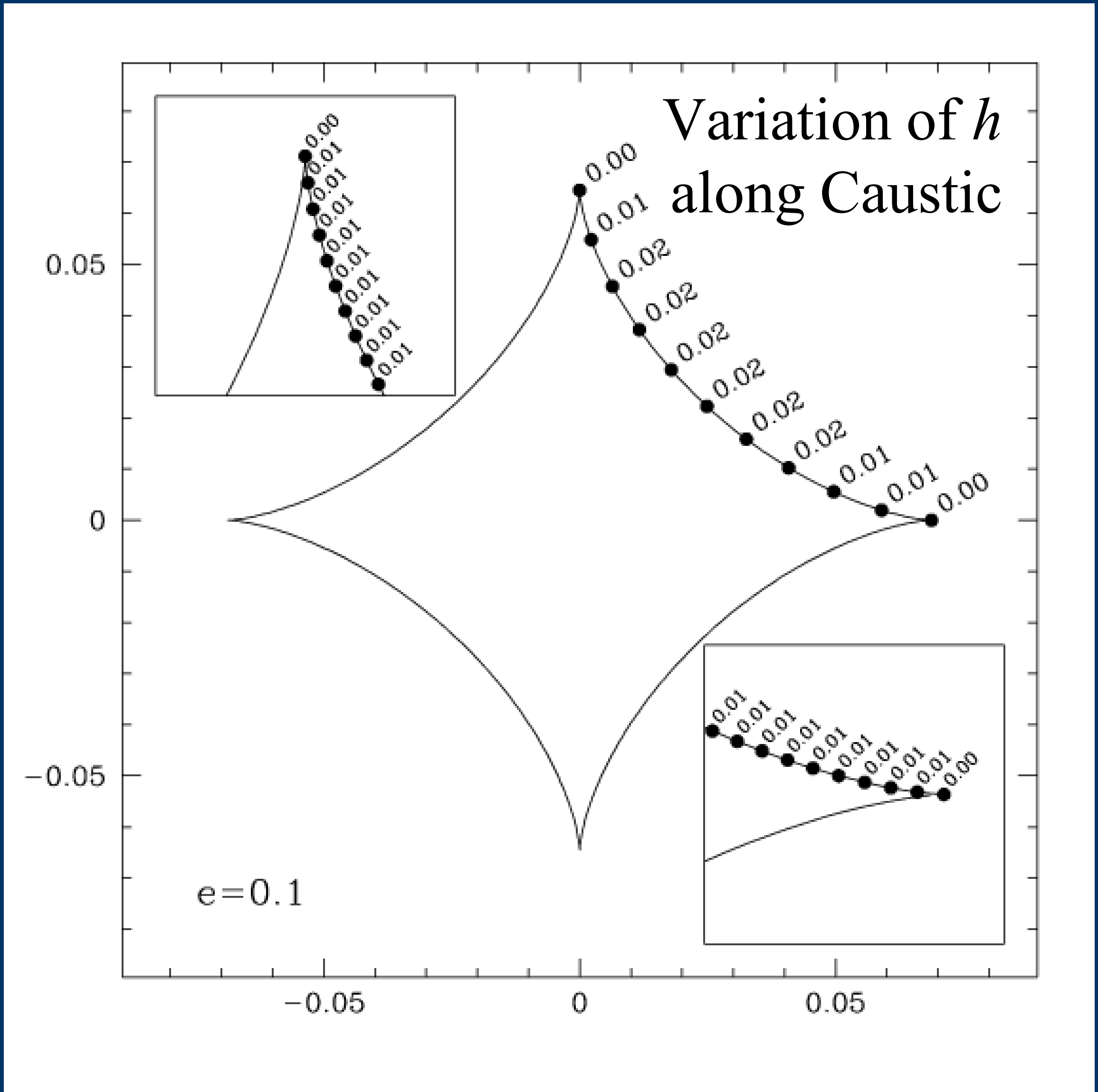
Dependence of Time Delay on Lens Potential

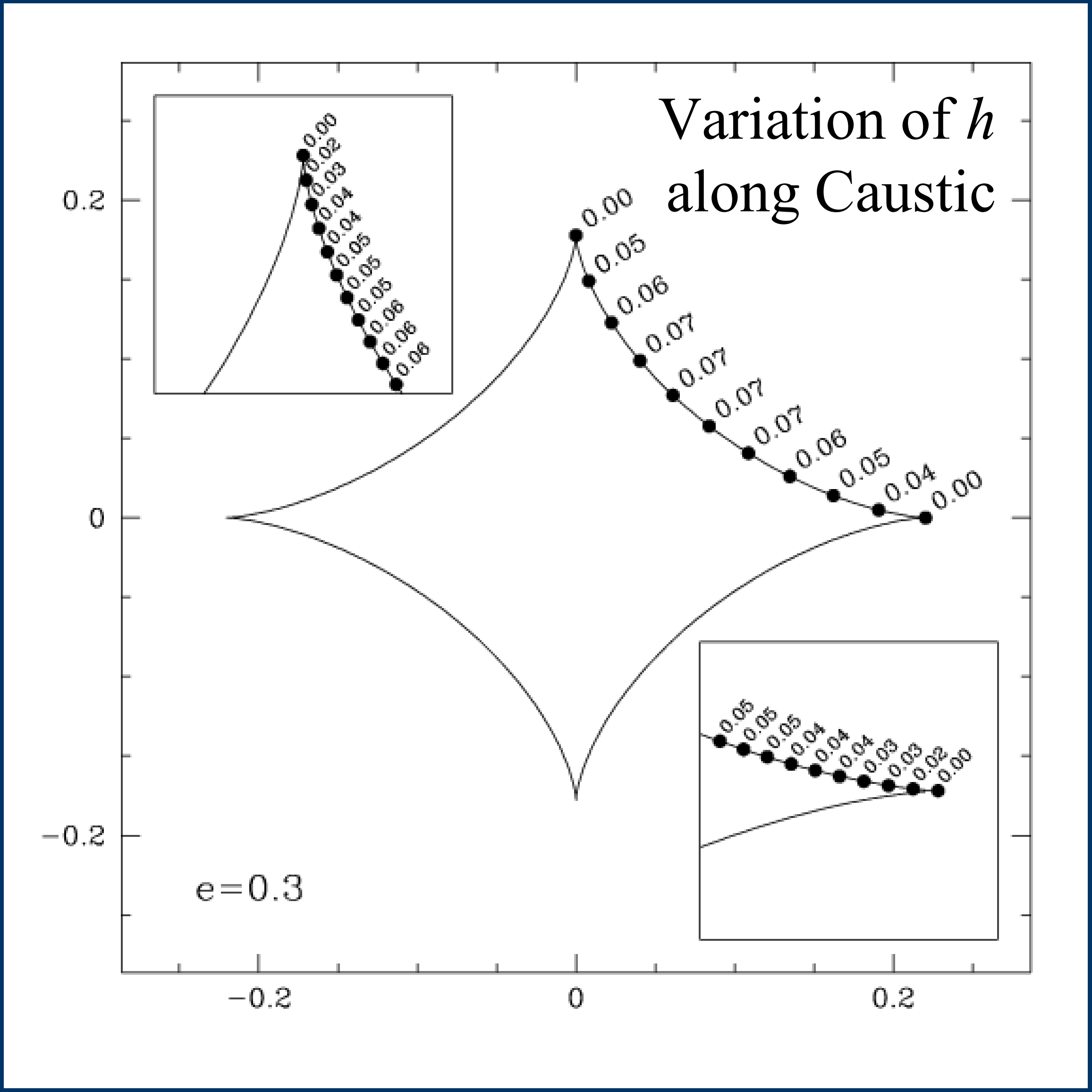
- Use *h* as proxy for time delay
- Model lens as elliptical galaxy with shear
- Higher-order multipoles are not so important here

What Is Shear?



Neighboring galaxies perturb lensing observables


Variation of *h*
along Caustic
e=0.1
0.05
0
−0.05
−0.05
0
0.05
0.00
0.01
0.02
0.02
0.02
0.02
0.02
0.02
0.01
0.01
0.00


Variation of *h*
along Caustic
e=0.3
0.2
0
−0.2
−0.2
0
0.2
0.00
0.05
0.06
0.07
0.07
0.07
0.07
0.06
0.05
0.04
0.00
0.00
0.02
0.03
0.04
0.04
0.05
0.05
0.05
0.06
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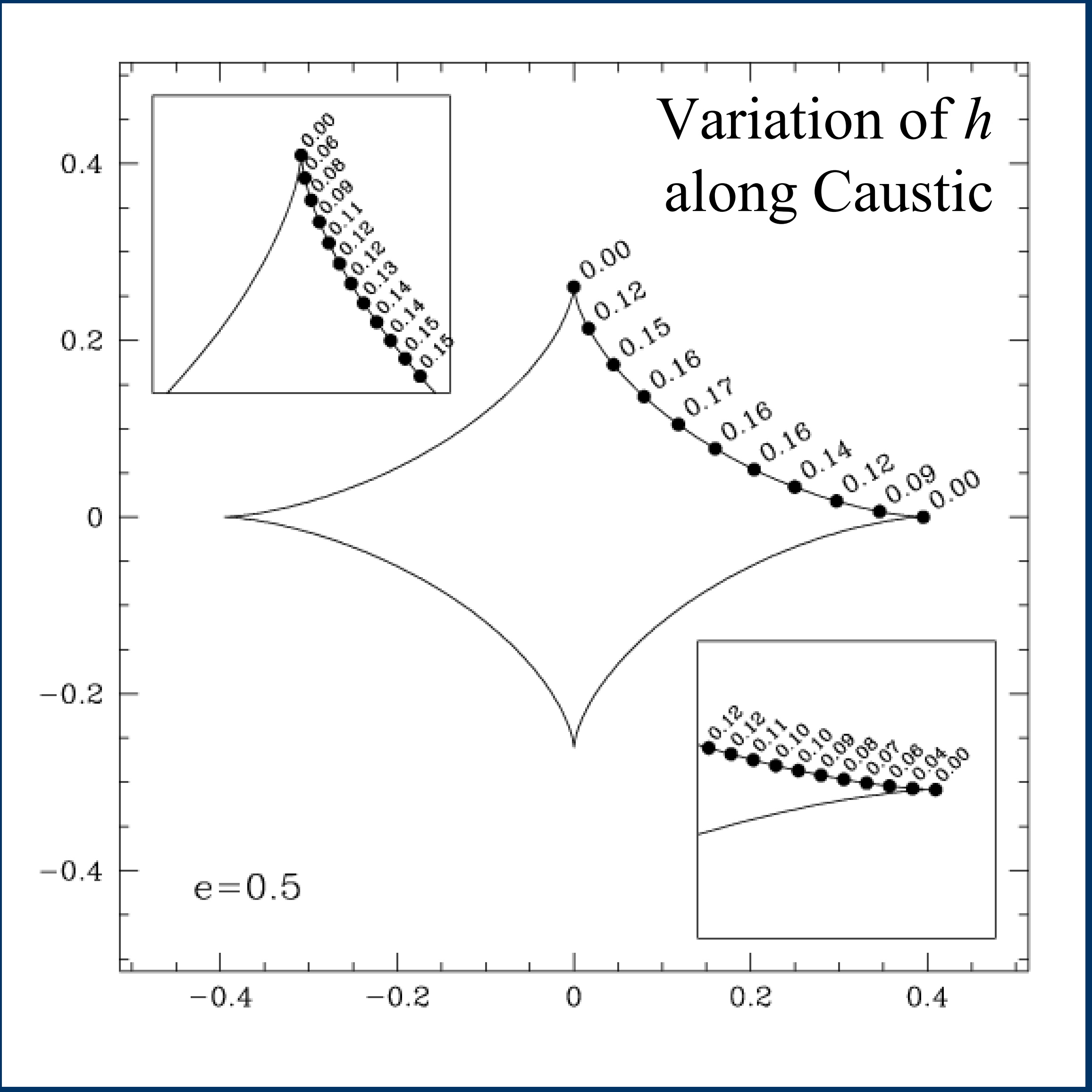
0.04
0.03
0.03
0.02
0.00

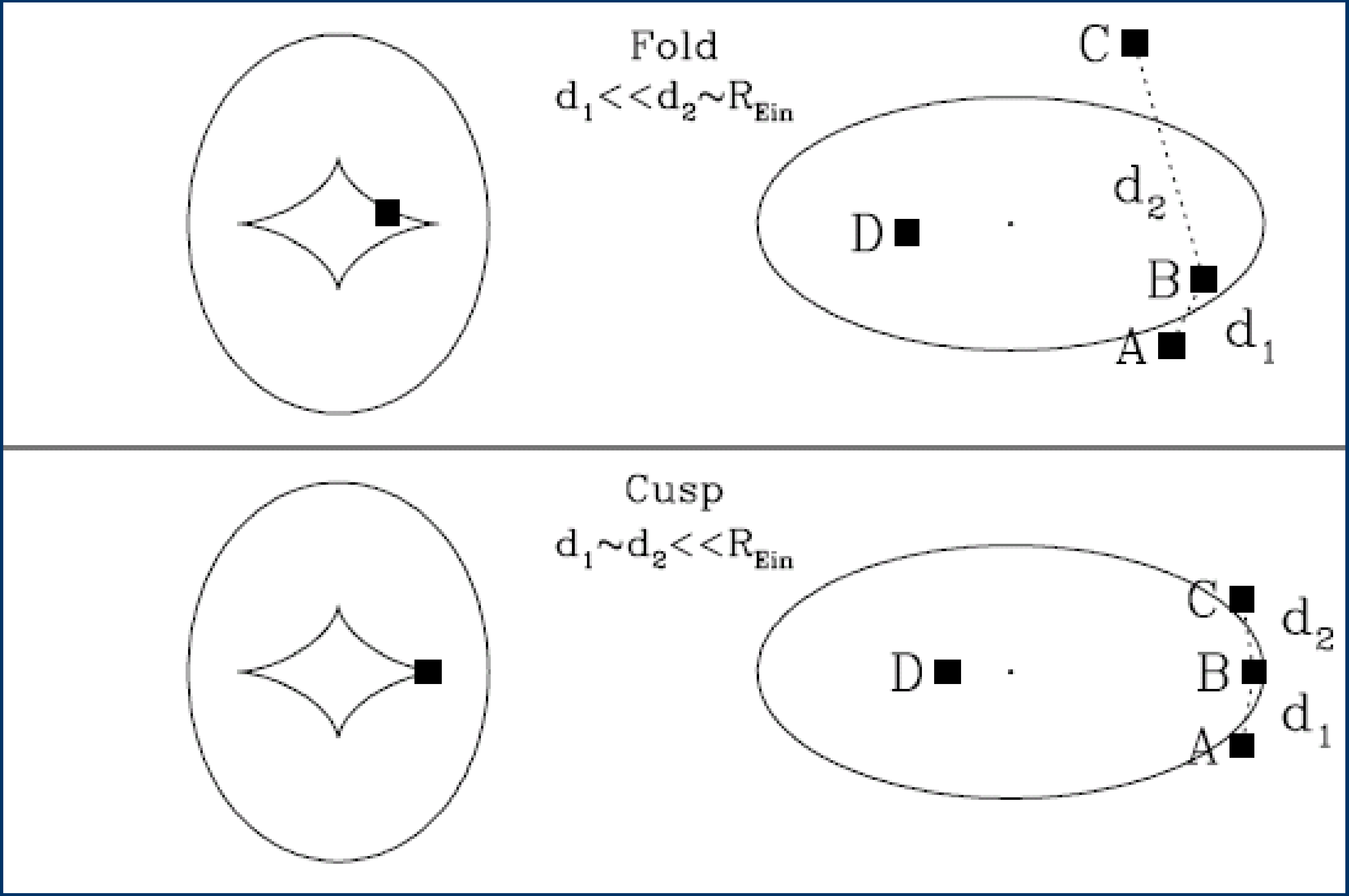


Variation of h along Caustic
e=0.5
0.00
0.12
0.15
0.16
0.17
0.16
0.16
0.14
0.12
0.09
0.00

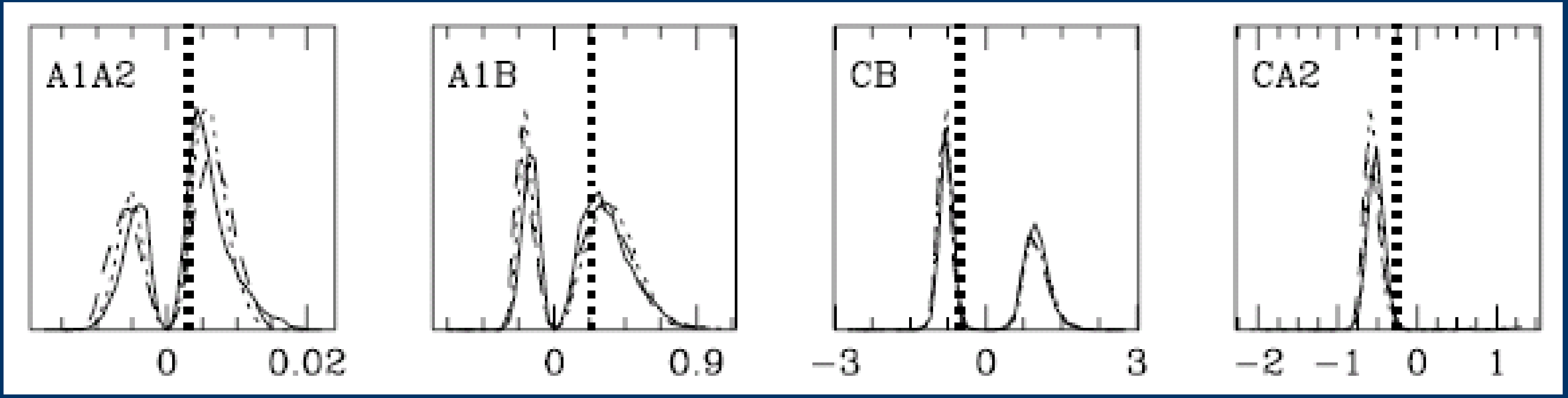
Time Delays for a Realistic Lens Population

- 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

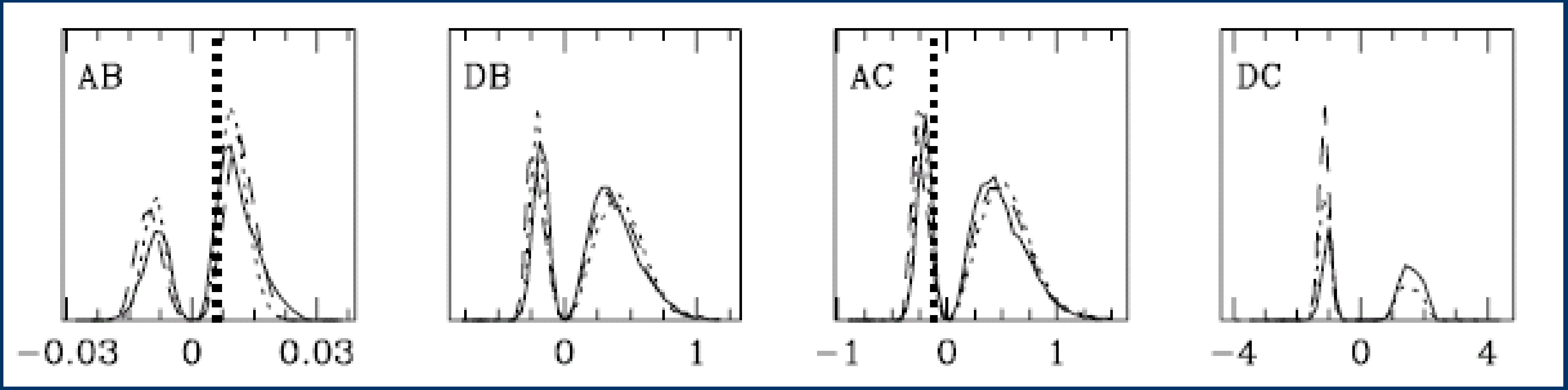
Matching Mock and Observed Lenses



Histograms for Scaled Time Delay: Folds

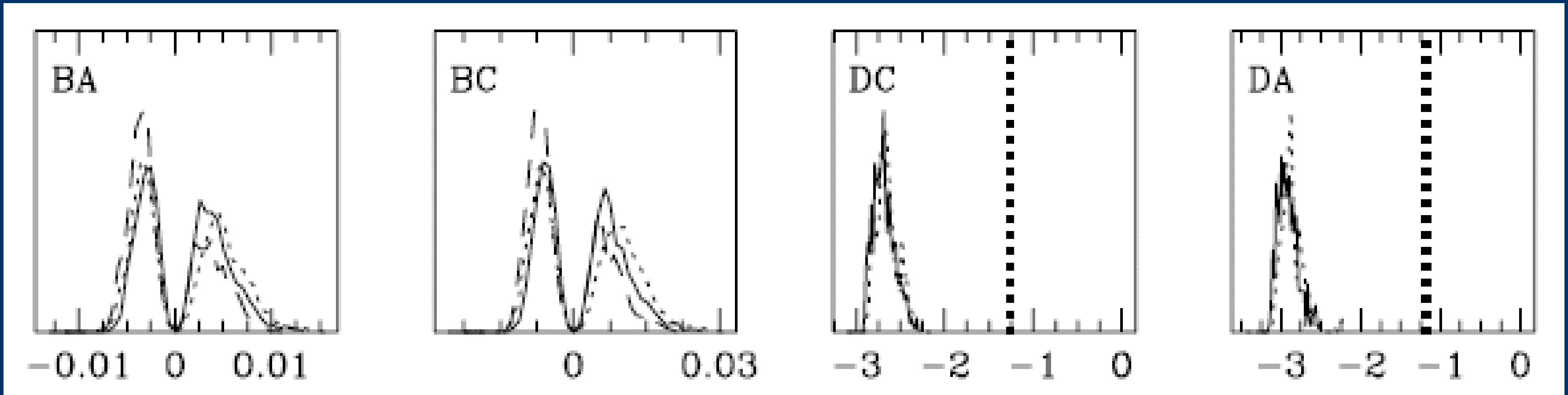


PG 1115+080

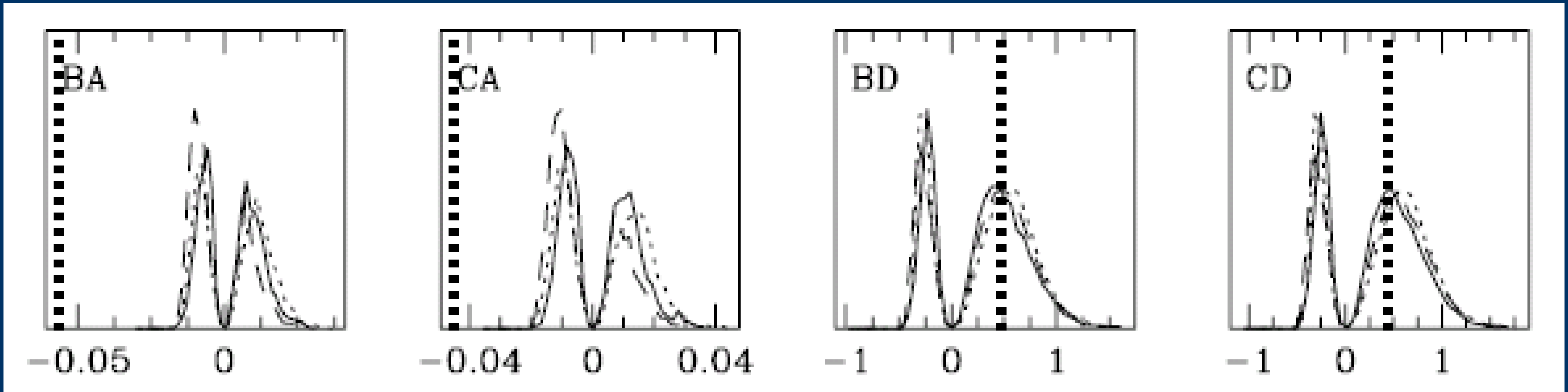


SDSS J1004+4112

Histograms for Scaled Time Delay: Cusps



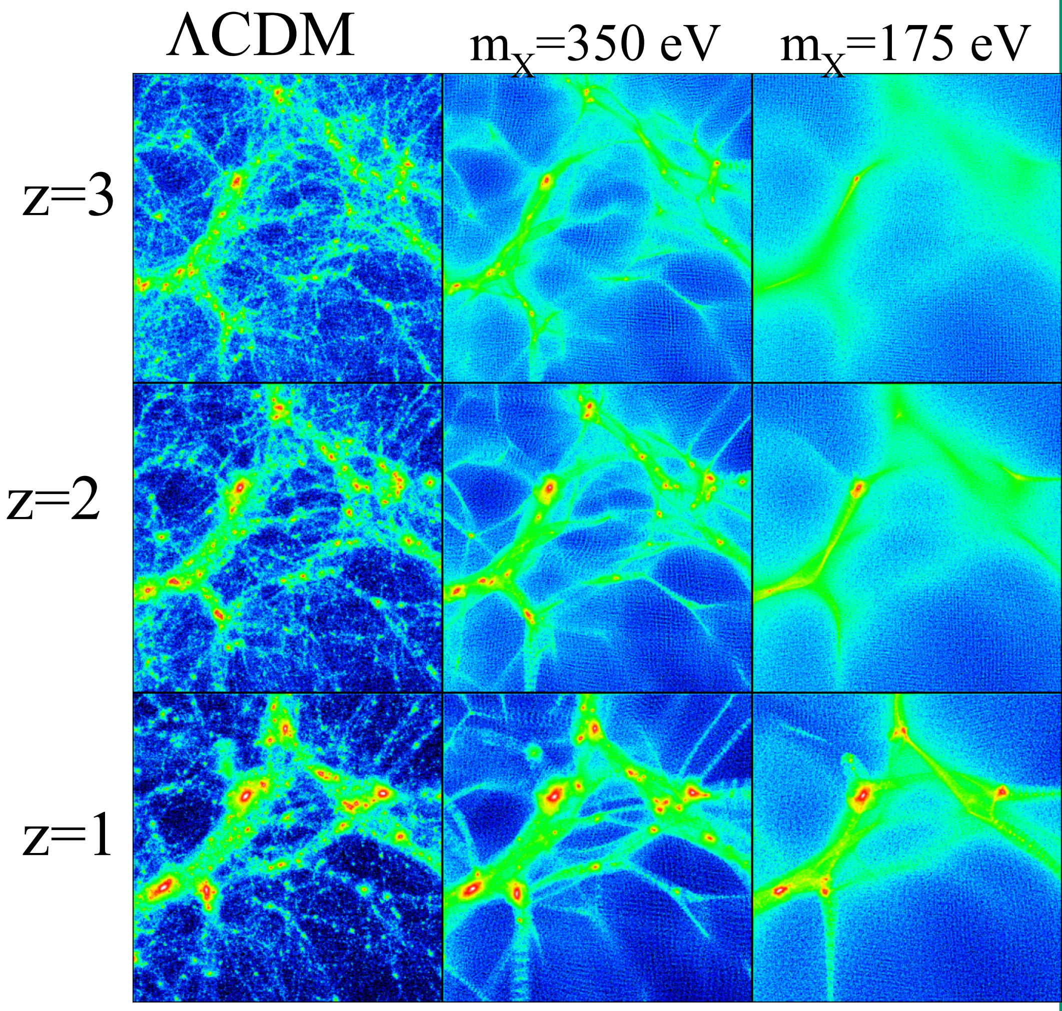
RX J0911+0551



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?



Bode et al. (2001, ApJ, 556, 93)

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