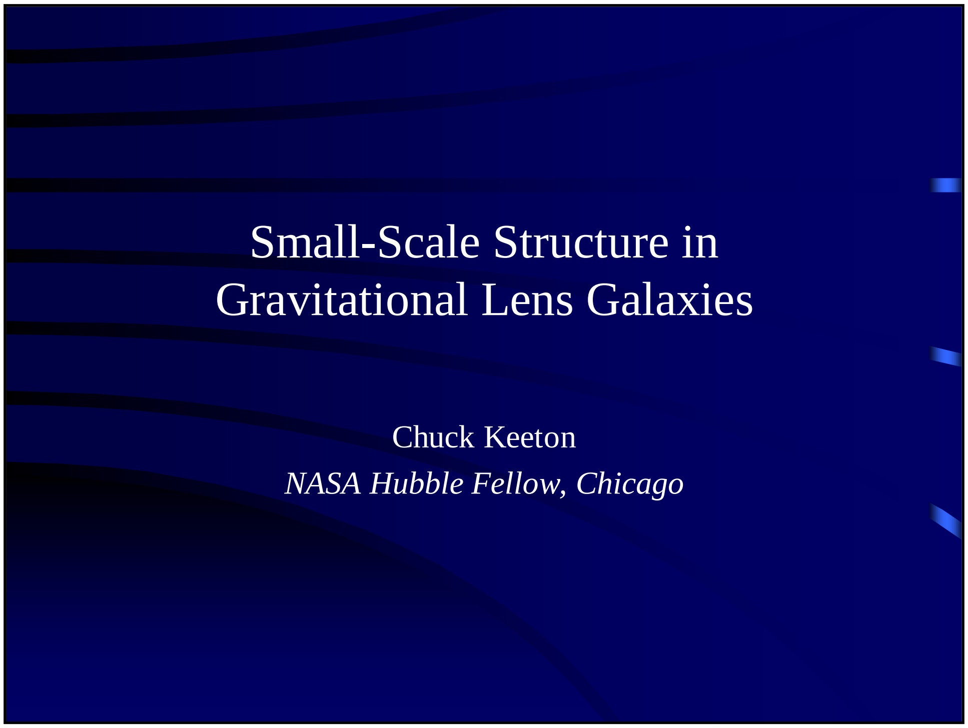
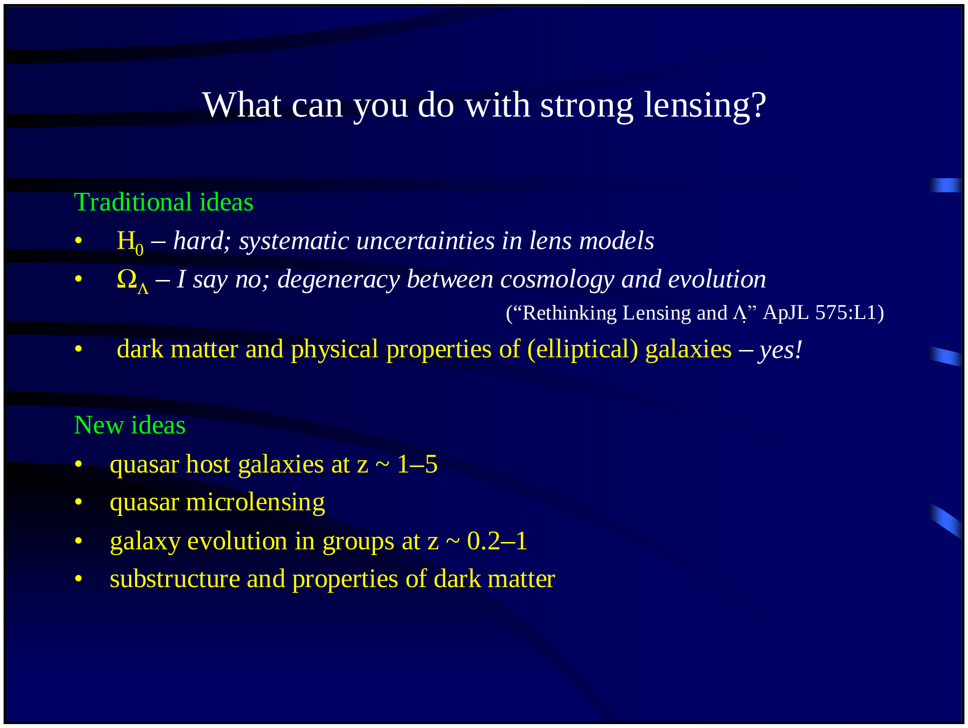


Small-Scale Structure in Gravitational Lens Galaxies

Chuck Keeton

NASA Hubble Fellow, Chicago



What can you do with strong lensing?

Traditional ideas

- H_0 – *hard; systematic uncertainties in lens models*
- Ω_Λ – *I say no; degeneracy between cosmology and evolution*

  (“Rethinking Lensing and Λ” ApJL 575:L1)
- dark matter and physical properties of (elliptical) galaxies – *yes!*

New ideas

- quasar host galaxies at z ~ 1–5
- quasar microlensing
- galaxy evolution in groups at z ~ 0.2–1
- substructure and properties of dark matter

Small-Scale Structure: Two Problems

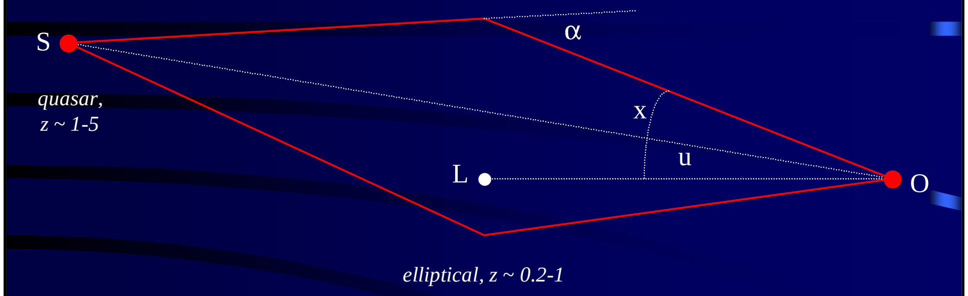
“Missing” core images

- Prediction: a faint image near the center of every lens galaxy
- Not seen!
- Probe of density inside $R < 20$–200 pc

Anomalous flux ratios

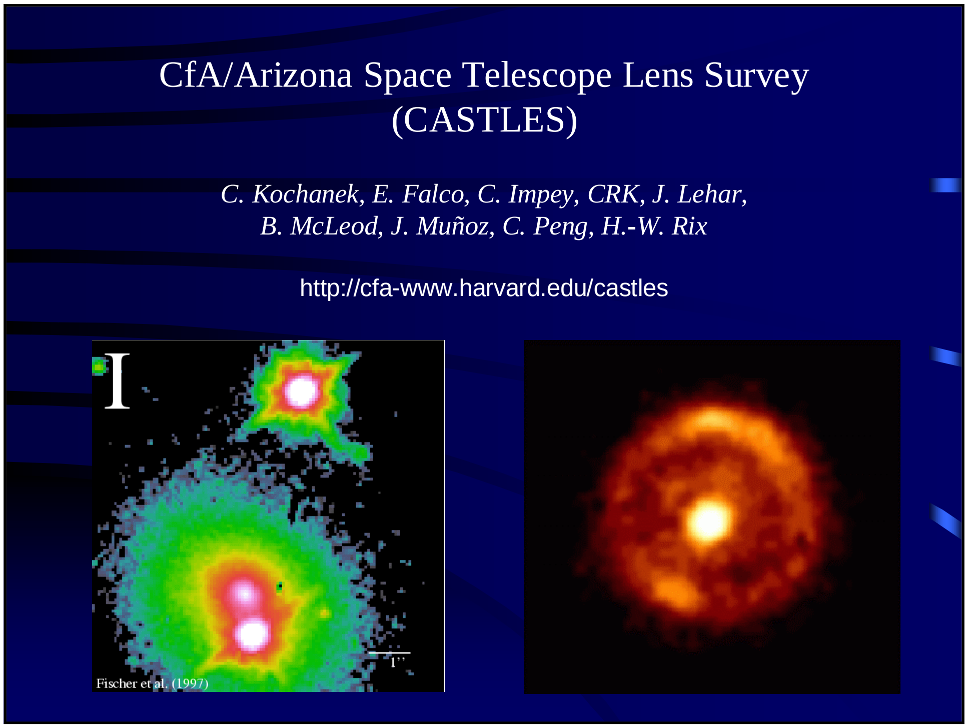
- Flux ratios are notoriously hard to fit
- Due to small mass clumps (10^4–10^8 M_{sun}) in lens galaxies?
- Resolution to CDM “satellite crisis”?

Strong Gravitational Lensing



Lens equation: $u = x - (D_{ls}/D_{os})\,\alpha$

Lensing is sensitive to *all* mass, be it luminous or dark, smooth or lumpy.

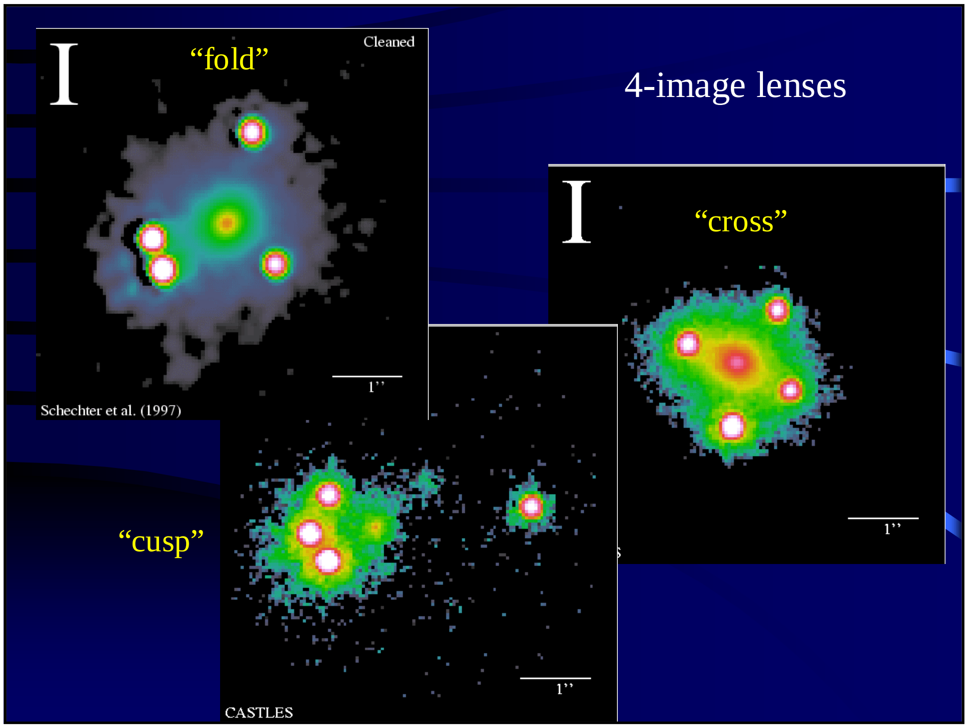


CfA/Arizona Space Telescope Lens Survey (CASTLES)

C. Kochanek, E. Falco, C. Impey, CRK, J. Lehar,
B. McLeod, J. Muñoz, C. Peng, H.-W. Rix

http://cfa-www.harvard.edu/castles

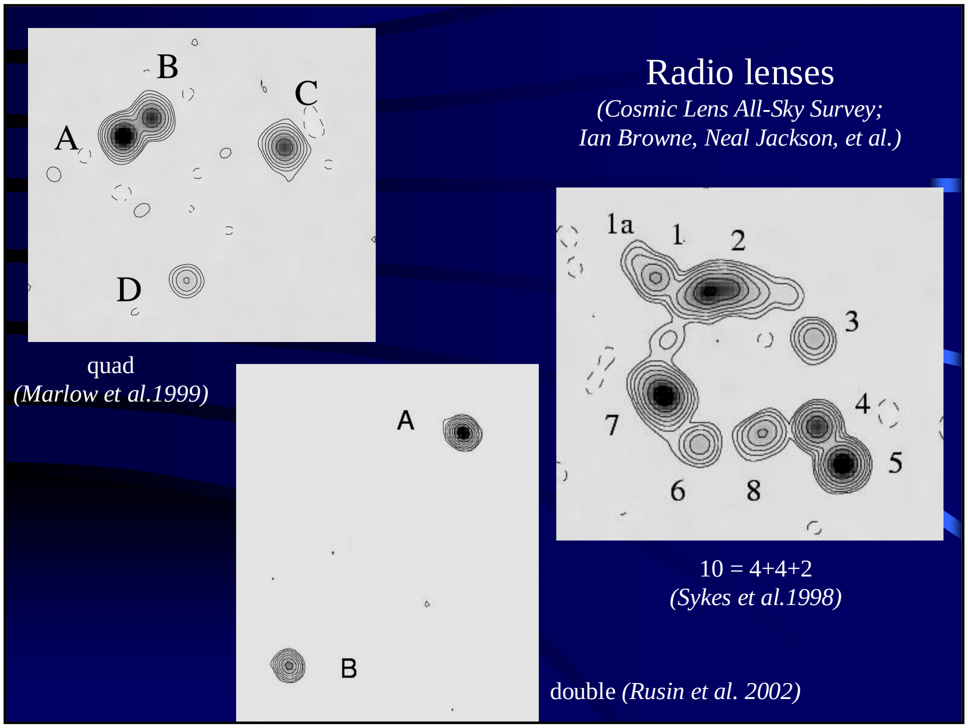
Fischer et al. (1997)



4-image lenses

Schechter et al. (1997)

CASTLES



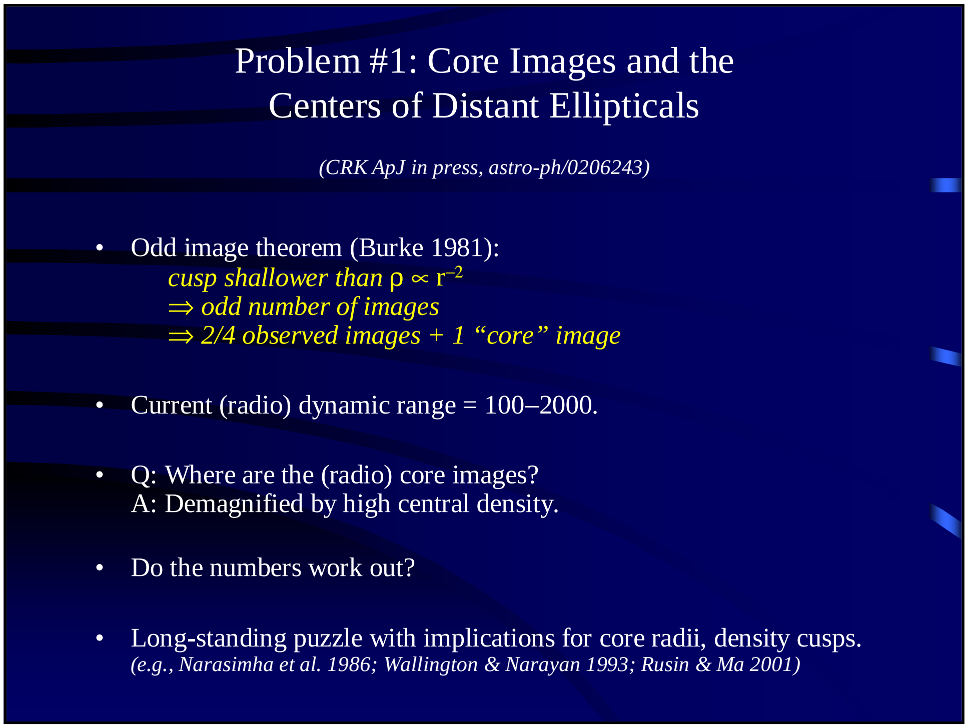
Radio lenses

(Cosmic Lens All-Sky Survey;
Ian Browne, Neal Jackson, et al.)

quad
(Marlow et al.1999)

10 = 4+4+2
(Sykes et al.1998)

double *(Rusin et al. 2002)*



Problem #1: Core Images and the Centers of Distant Ellipticals

(CRK ApJ in press, astro-ph/0206243)

- Odd image theorem (Burke 1981):
  cusp shallower than $\rho \propto r^{-2}$
  $\Rightarrow$ *odd number of images*
  $\Rightarrow$ *2/4 observed images + 1 "core" image*
- Current (radio) dynamic range = 100–2000.
- Q: Where are the (radio) core images?
  A: Demagnified by high central density.
- Do the numbers work out?
- Long-standing puzzle with implications for core radii, density cusps.
  (e.g., Narasimha et al. 1986; Wallington & Narayan 1993; Rusin & Ma 2001)

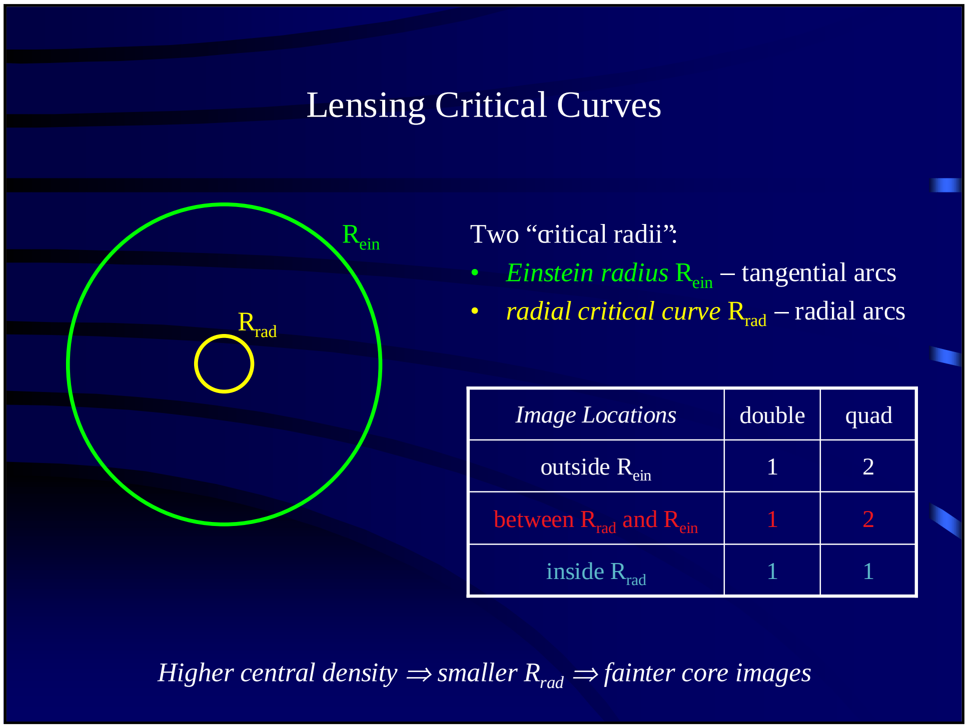
Connections

Galaxy centers are interesting.
  - dynamics
  - remnants of galaxy formation
  - clues to baryon/DM interactions?

CDM concentration problem.

- Predicted densities *too high* on kpc scales.
  - rotation curves *(e.g., McGaugh & de Blok 1998)*
  - bars *(Debattista & Sellwood 2000)*
  - strong lensing statistics *(CRK 2001)*
  - microlensing *(Binney & Evans 2001)*
- Core images: densities *too low* on ~100 pc scales? *(CRK 2001)*

Can core images constrain supermassive black holes out to z ~ 1?
(Mao et al. 2001)



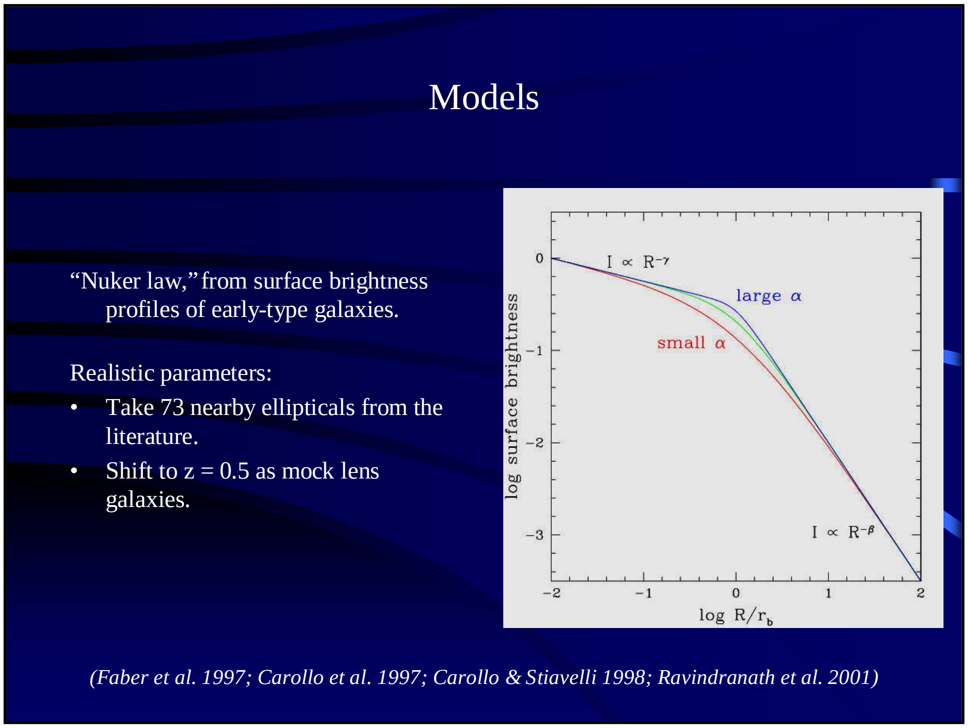
Lensing Critical Curves

Two “critical radii”:

- *Einstein radius* R_{ein} – tangential arcs
- *radial critical curve* R_{rad} – radial arcs

Image Locations	double	quad
outside R_{ein}	1	2
between R_{rad} and R_{ein}	1	2
inside R_{rad}	1	1

Higher central density ⇒ *smaller* R_{rad} ⇒ *fainter core images*



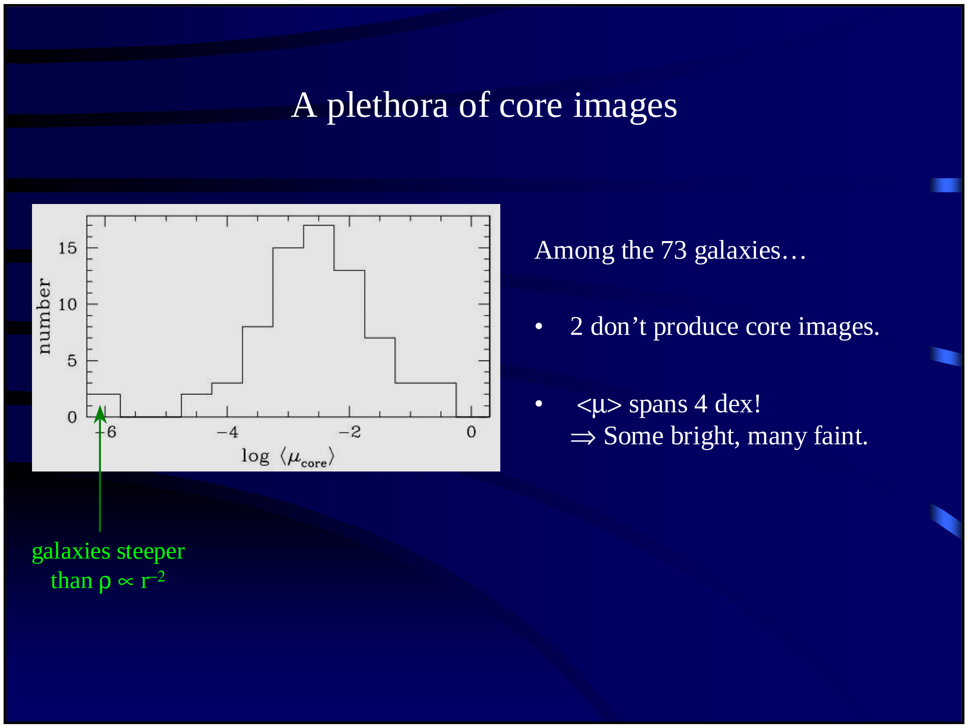
Models

“Nuker law,” from surface brightness profiles of early-type galaxies.

Realistic parameters:

- Take 73 nearby ellipticals from the literature.
- Shift to z = 0.5 as mock lens galaxies.

(Faber et al. 1997; Carollo et al. 1997; Carollo & Stiavelli 1998; Ravindranath et al. 2001)

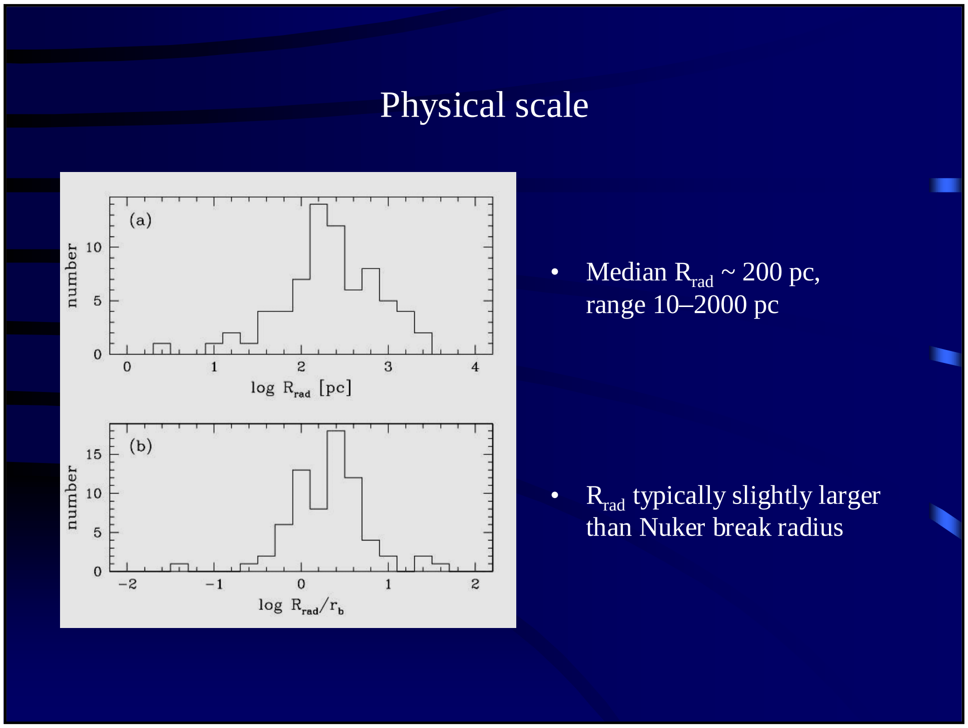


A plethora of core images

galaxies steeper than $\rho \propto r^{-2}$

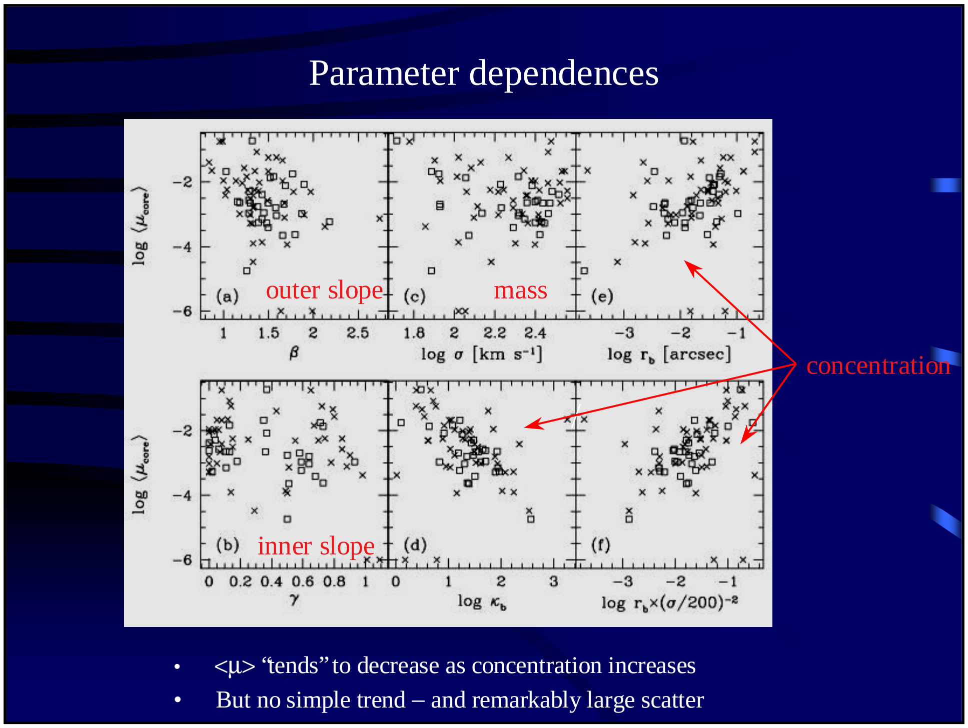
Among the 73 galaxies…

- 2 don’t produce core images.
- <μ> spans 4 dex!
  ⇒ Some bright, many faint.



Physical scale

- Median R_{rad} ~ 200 pc, range 10–2000 pc
- R_{rad} typically slightly larger than Nuker break radius



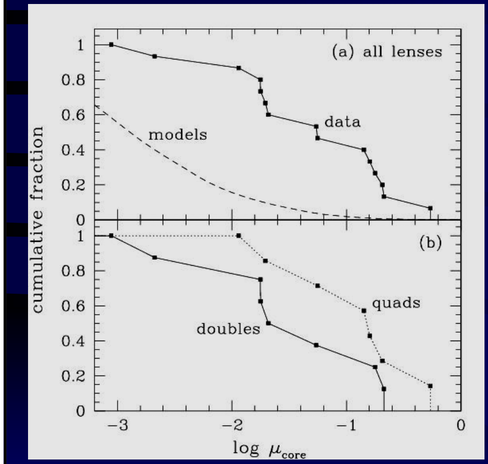
Parameter dependences

- <μ> "tends" to decrease as concentration increases
- But no simple trend – and remarkably large scatter

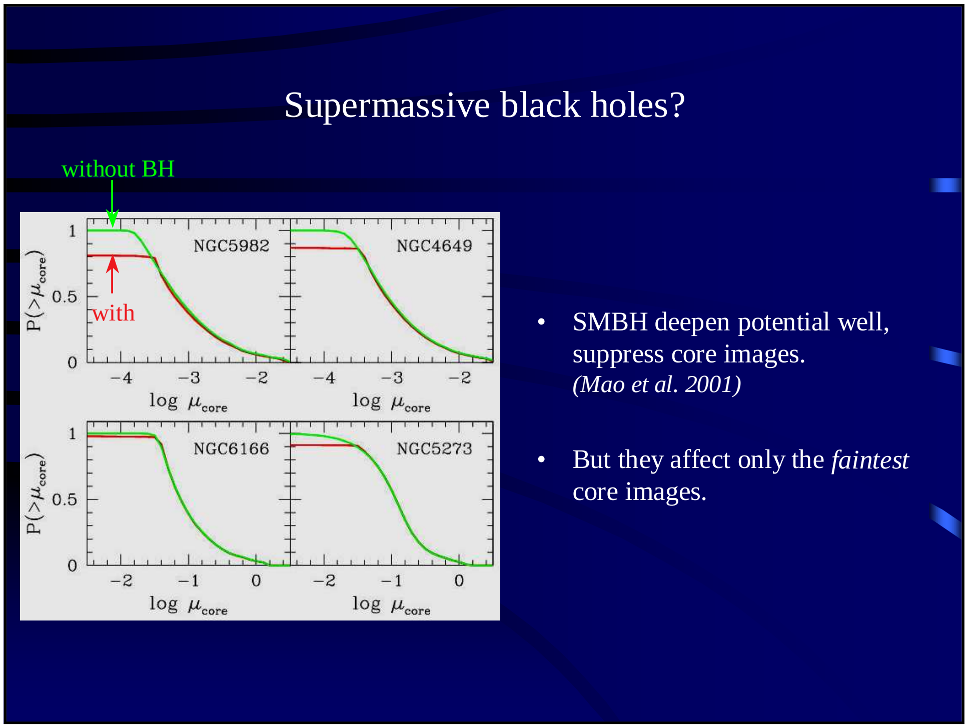
Should we see core images?

- Which galaxies have <μ> > 0.1?
  - NGC 4239 and 5273: dwarf galaxies – *poor lenses*
  - NGC 6166: brightest cluster galaxy; most distant and least concentrated galaxy in Faber et al. (1997) sample – *atypical*
- Such galaxies are likely to be rare in lens samples.
- Thus, bright core images are likely to be rare.

Comparison to data

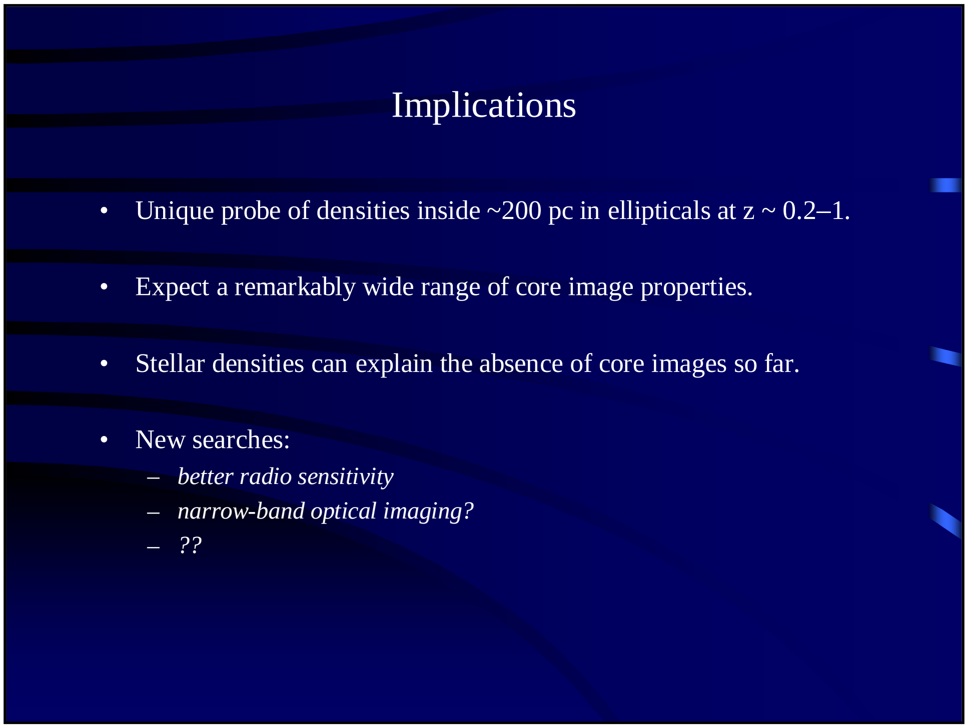


- Data from CLASS – only *upper limits* on μ.
  (Norbury et al., in prep.)
- Models do not predict core images brighter than observed.
- Doubles yield stronger limits, better targets for follow-up.



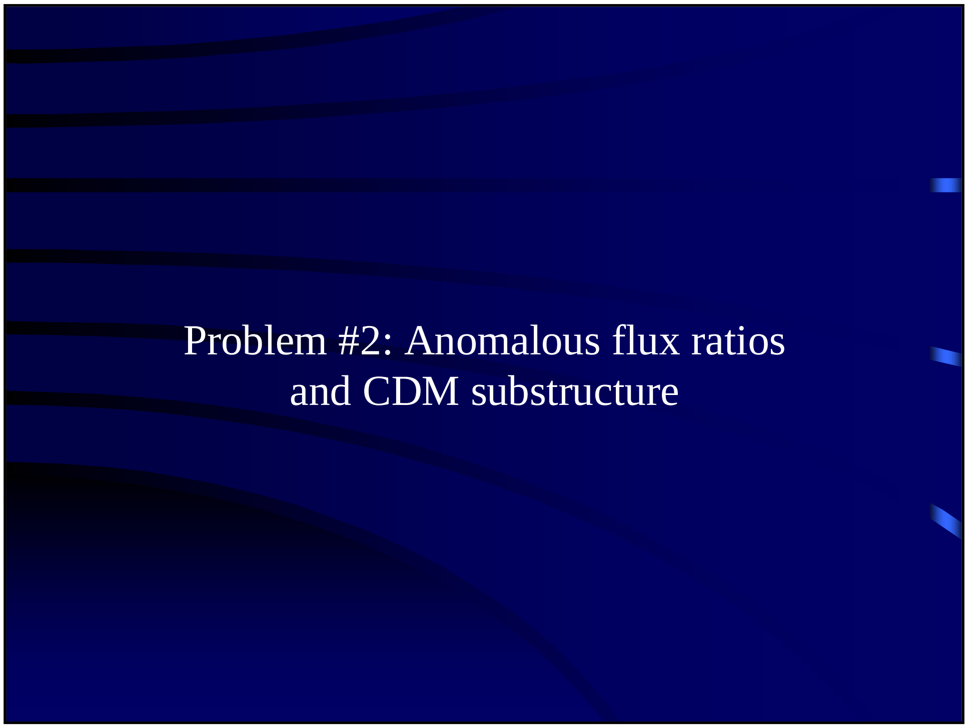
Supermassive black holes?

- SMBH deepen potential well, suppress core images. *(Mao et al. 2001)*
- But they affect only the *faintest* core images.

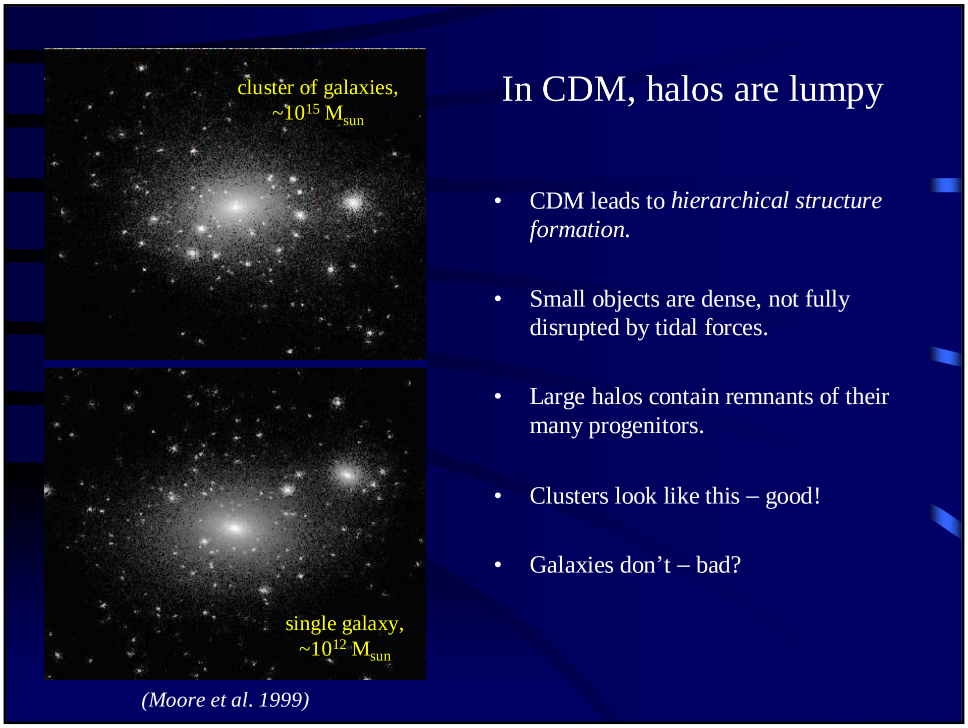


Implications

- Unique probe of densities inside ~200 pc in ellipticals at z ~ 0.2–1.
- Expect a remarkably wide range of core image properties.
- Stellar densities can explain the absence of core images so far.
- New searches:
  - *better radio sensitivity*
  - *narrow-band optical imaging?*
  - *??*



Problem #2: Anomalous flux ratios and CDM substructure



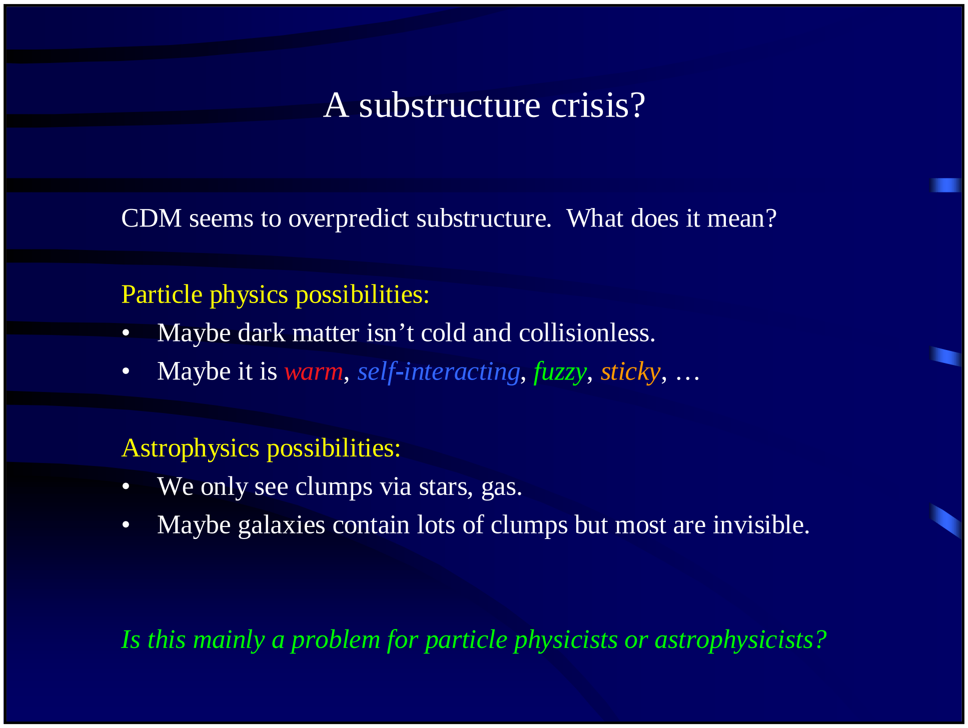
In CDM, halos are lumpy

cluster of galaxies, ~10^{15} M_{sun}

single galaxy, ~10^{12} M_{sun}

(Moore et al. 1999)

- CDM leads to *hierarchical structure formation.*
- Small objects are dense, not fully disrupted by tidal forces.
- Large halos contain remnants of their many progenitors.
- Clusters look like this – good!
- Galaxies don’t – bad?



A substructure crisis?

CDM seems to overpredict substructure. What does it mean?

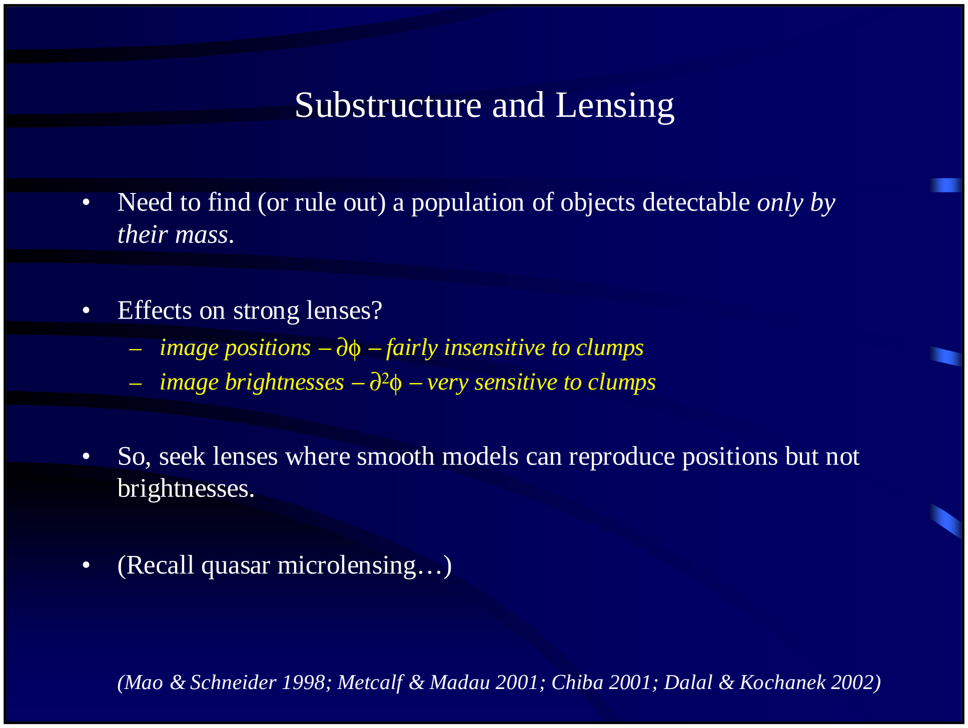
Particle physics possibilities:

- Maybe dark matter isn't cold and collisionless.
- Maybe it is *warm*, *self-interacting*, *fuzzy*, *sticky*, …

Astrophysics possibilities:

- We only see clumps via stars, gas.
- Maybe galaxies contain lots of clumps but most are invisible.

Is this mainly a problem for particle physicists or astrophysicists?



Substructure and Lensing

- Need to find (or rule out) a population of objects detectable *only by their mass*.
- Effects on strong lenses?
  - *image positions – $\partial\phi$ – fairly insensitive to clumps*
  - *image brightnesses – $\partial^2\phi$ – very sensitive to clumps*
- So, seek lenses where smooth models can reproduce positions but not brightnesses.
- (Recall quasar microlensing…)

(Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2001; Dalal & Kochanek 2002)

Typical Numbers

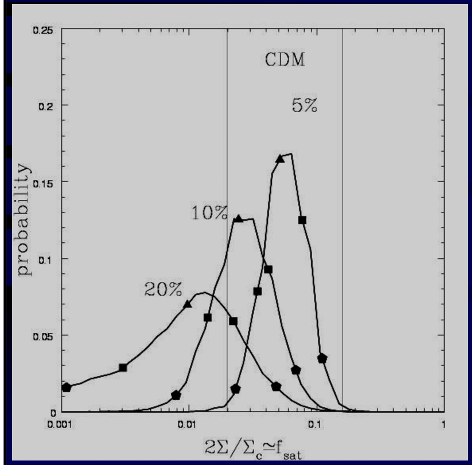
	Stars	*Satellites*
mass	$1\ M_{sun}$	$10^6\ M_{sun}$
R_{ein}	2 μas	1 mas
time delays	δ□ ≈ 0	δ□ ≈ 0
positions	δx ≈ 2 μas	δx ≈ 1 mas
fluxes	δf ~ arbitrary	δf ~ arbitrary

From lensing to dark matter physics

- Observe lenses.
- Find systems inconsistent with smooth lens models.
- Infer amount of substructure. (Add substructure until the models are *statistically* consistent with the data.)
- Connect to CDM predictions.
- Constrain physics of dark matter.

Dalal & Kochanek: "Detection of CDM Substructure"

(2002 ApJ 572:25)



satellite mass fraction, f_{sat}

- Bayesian analysis of substructure parameters.
- Main result is lower limit on f_{sat}.
- f_{sat}~2% (0.6–7% at 90% confidence)
- A detection of substructure!

Implications?

Appears to be a major success for the CDM paradigm:

- Confirms predictions on very small spatial scales.
- Rules out alternatives like warm or self-interacting dark matter.

But recall the assumptions:

- The need for substructure is inferred from the failure of models to fit observed fluxes..
- The substructure is assumed to be the granular stuff predicted by CDM.

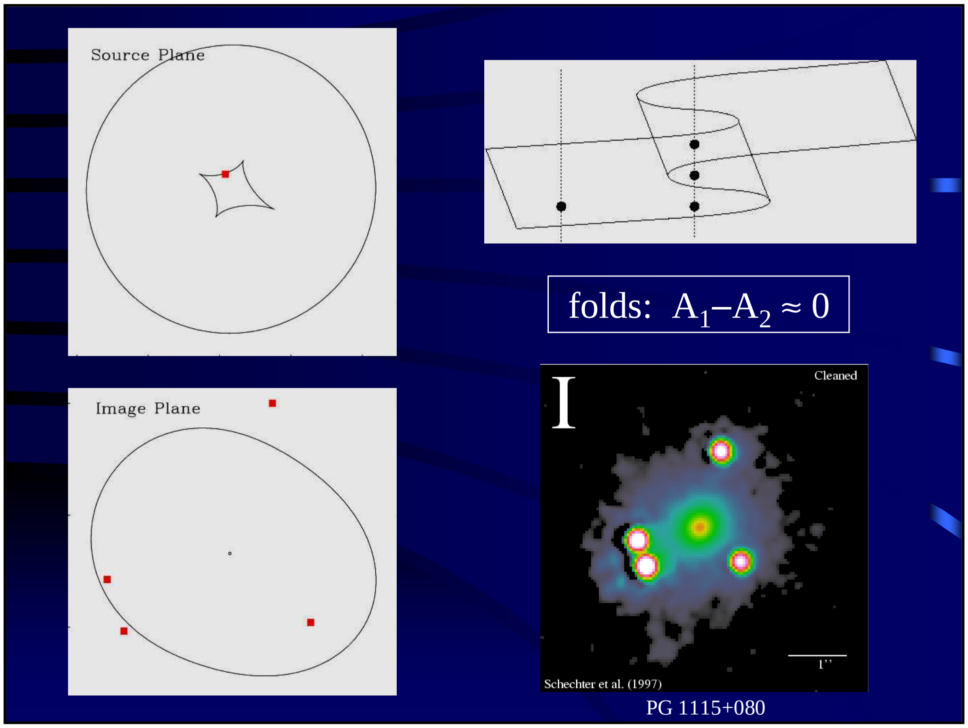
We need to rebuild the chain of logic, link by link…

Link #1: Finding the Anomalies

(CRK, Gaudi & Petters, astro-ph/0210318)

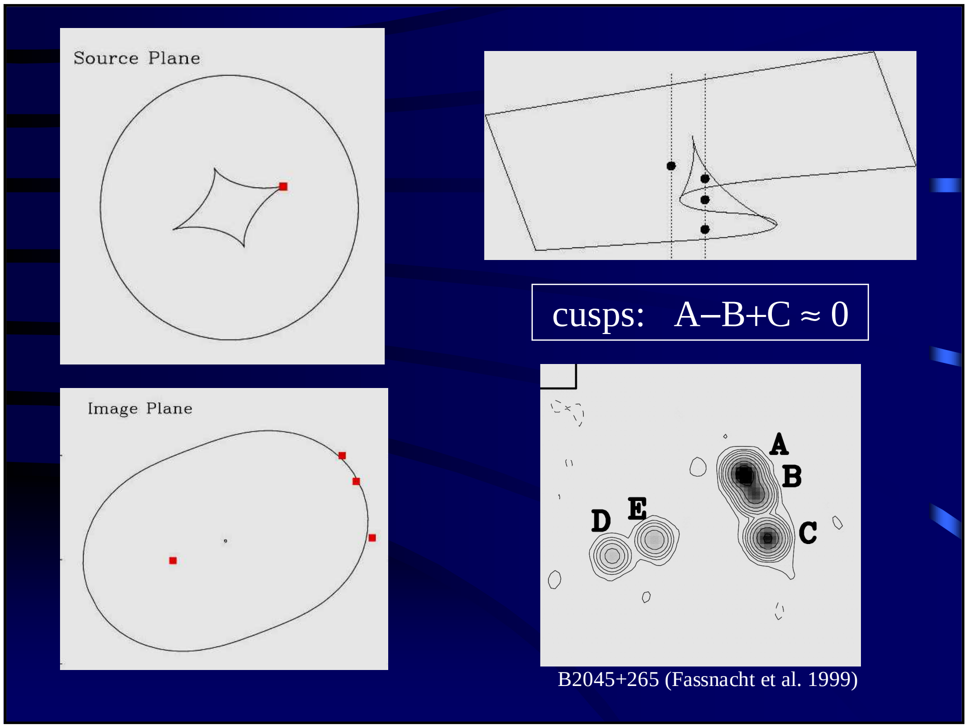
- Do the “anomalies” really indicate substructure? Or just a failure of imagination in the models?
- Proving a negative is hard!
- Fortunately, strong generic statements can be made about certain combinations of fluxes…

(Forget about the causes or implications of the anomalies; for now let’s just focus on finding them.)



folds: $A_1 - A_2 \approx 0$

PG 1115+080

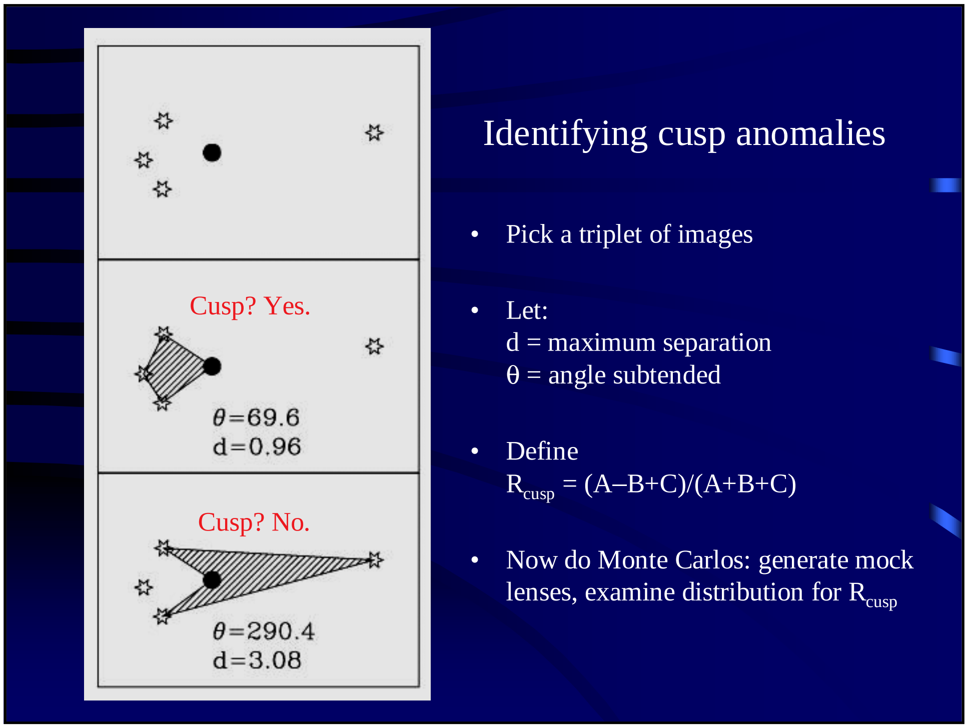


cusps: $A - B + C \approx 0$

B2045+265 (Fassnacht et al. 1999)

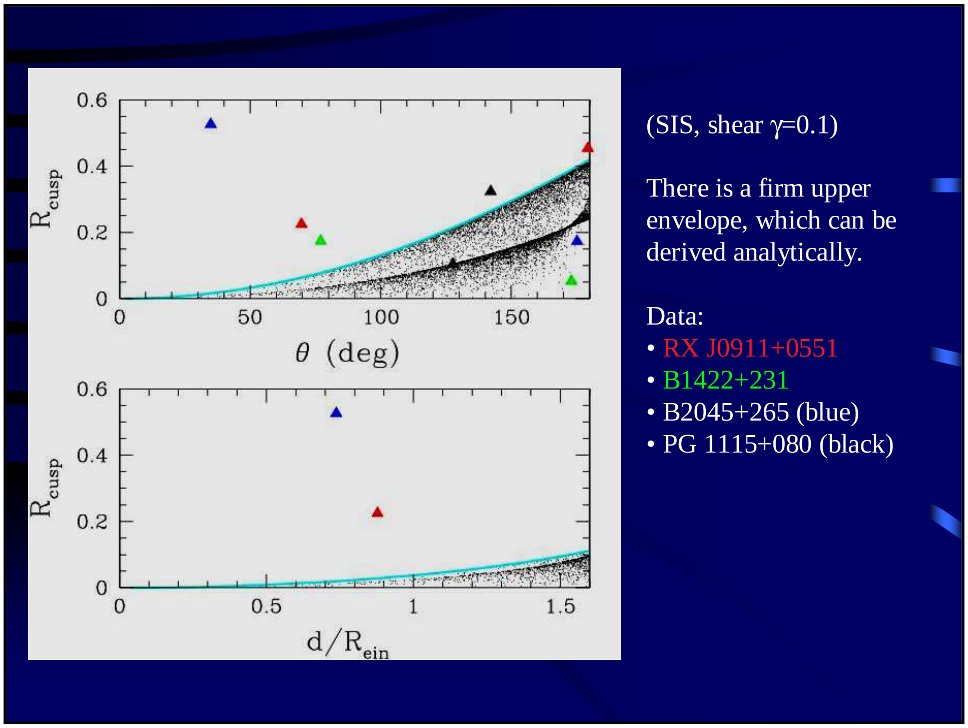
Robustly Identifying Flux Ratio Anomalies

- The fold and cusp relations are strong model-independent statements.
- Violating them requires structure on scales smaller than the separation.
- But they require a source asymptotically close to the fold/cusp.
- How well do they hold in practice?
  Can we identify flux ratio anomalies directly from the data?



Identifying cusp anomalies

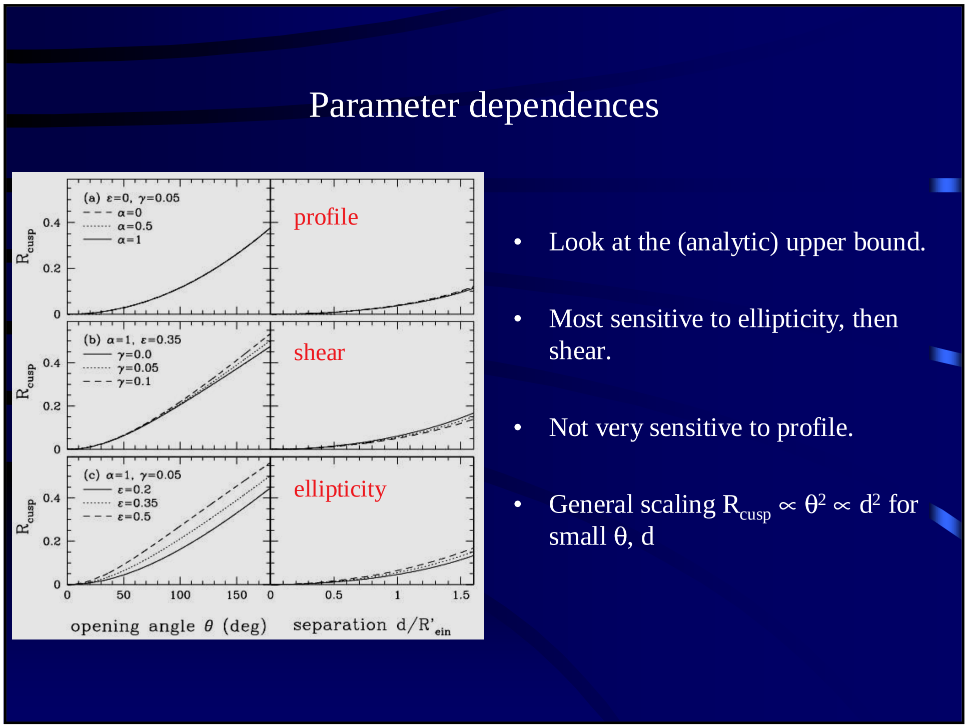
- Pick a triplet of images
- Let:
  d = maximum separation
  θ = angle subtended
- Define
  $R_{cusp} = (A-B+C)/(A+B+C)$
- Now do Monte Carlos: generate mock lenses, examine distribution for R_{cusp}



(SIS, shear γ=0.1)

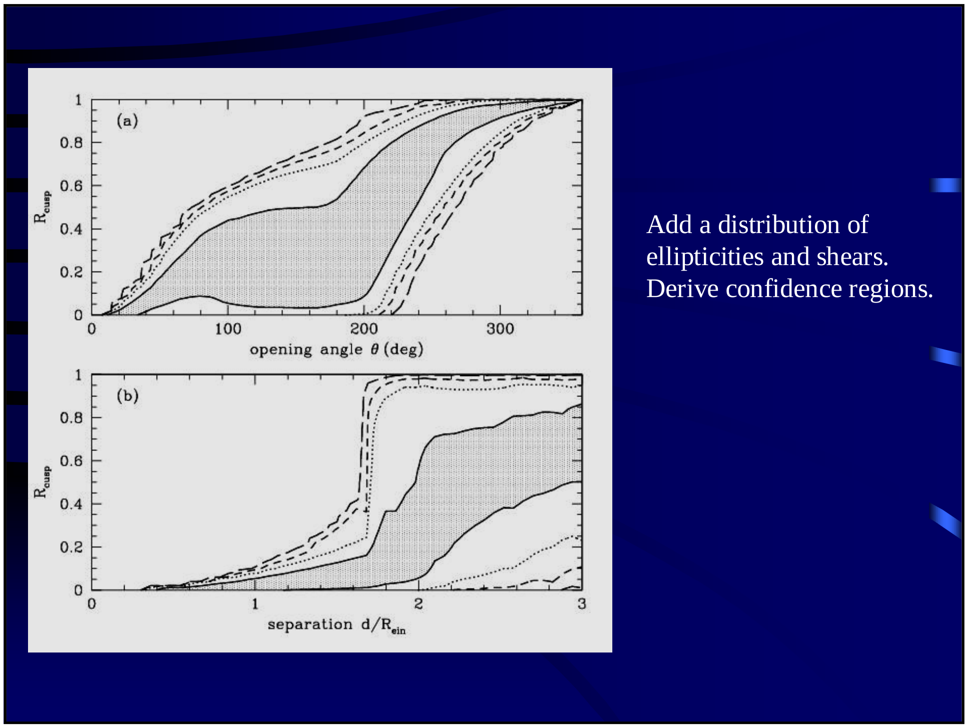
There is a firm upper envelope, which can be derived analytically.

Data:
- RX J0911+0551
- B1422+231
- B2045+265 (blue)
- PG 1115+080 (black)

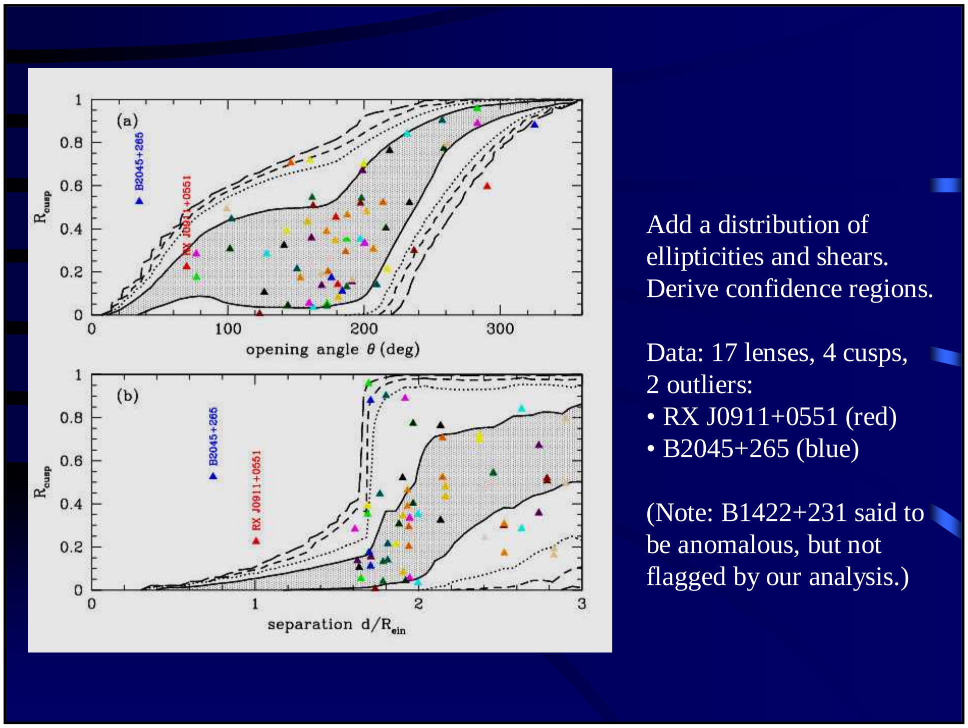


Parameter dependences

- Look at the (analytic) upper bound.
- Most sensitive to ellipticity, then shear.
- Not very sensitive to profile.
- General scaling $R_{cusp} \propto \theta^2 \propto d^2$ for small θ, d



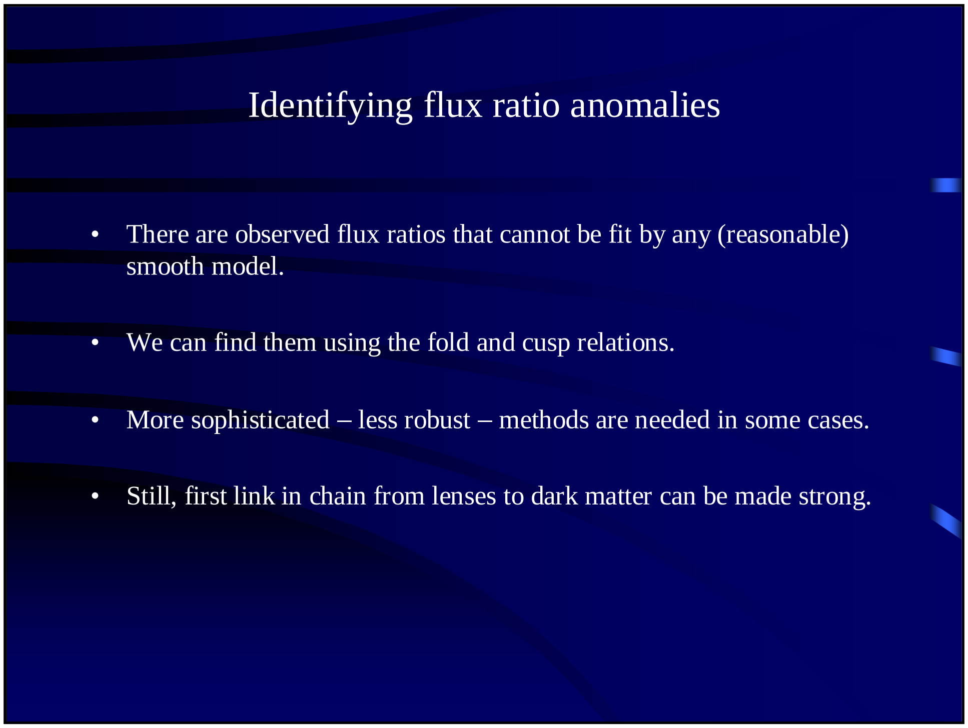
Add a distribution of ellipticities and shears. Derive confidence regions.



Add a distribution of ellipticities and shears. Derive confidence regions.

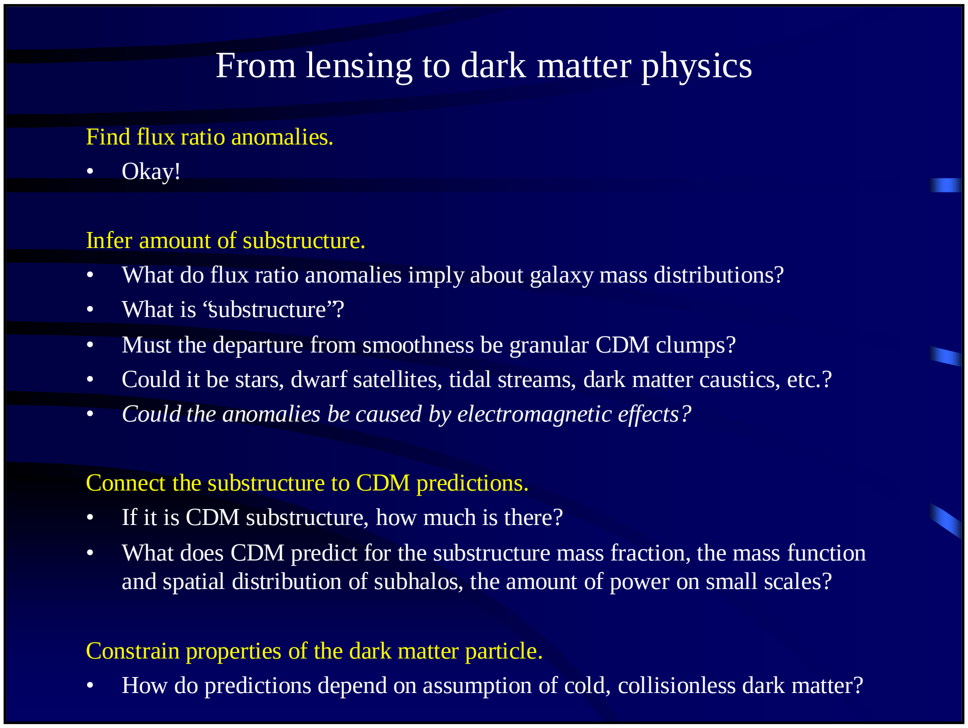
Data: 17 lenses, 4 cusps, 2 outliers:
- RX J0911+0551 (red)
- B2045+265 (blue)

(Note: B1422+231 said to be anomalous, but not flagged by our analysis.)



Identifying flux ratio anomalies

- There are observed flux ratios that cannot be fit by any (reasonable) smooth model.
- We can find them using the fold and cusp relations.
- More sophisticated – less robust – methods are needed in some cases.
- Still, first link in chain from lenses to dark matter can be made strong.



From lensing to dark matter physics

Find flux ratio anomalies.

- Okay!

Infer amount of substructure.

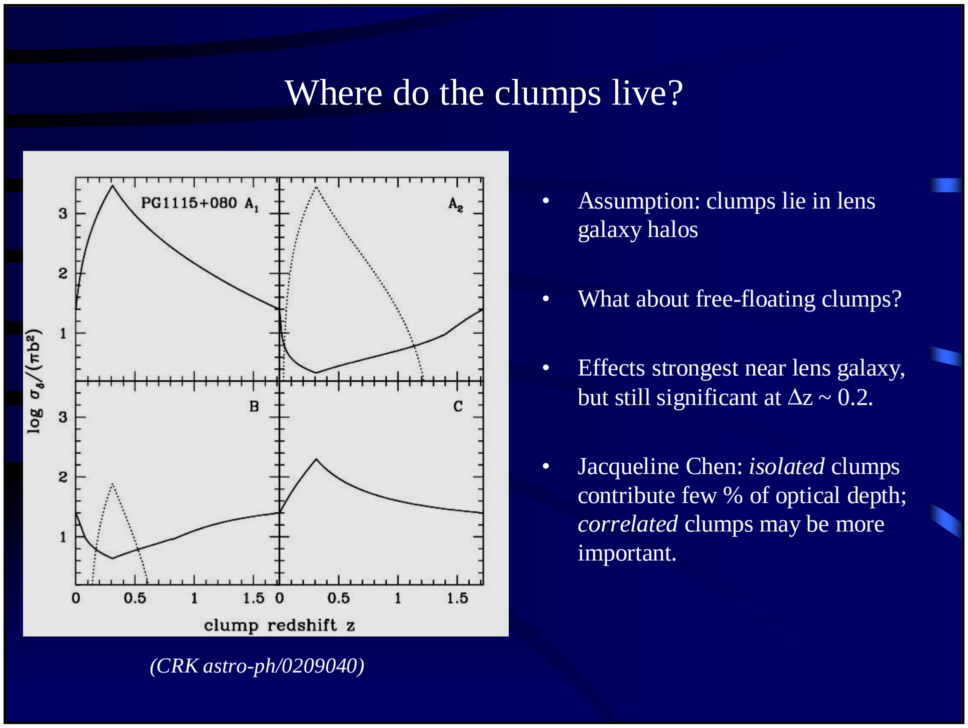
- What do flux ratio anomalies imply about galaxy mass distributions?
- What is “substructure”?
- Must the departure from smoothness be granular CDM clumps?
- Could it be stars, dwarf satellites, tidal streams, dark matter caustics, etc.?
- *Could the anomalies be caused by electromagnetic effects?*

Connect the substructure to CDM predictions.

- If it is CDM substructure, how much is there?
- What does CDM predict for the substructure mass fraction, the mass function and spatial distribution of subhalos, the amount of power on small scales?

Constrain properties of the dark matter particle.

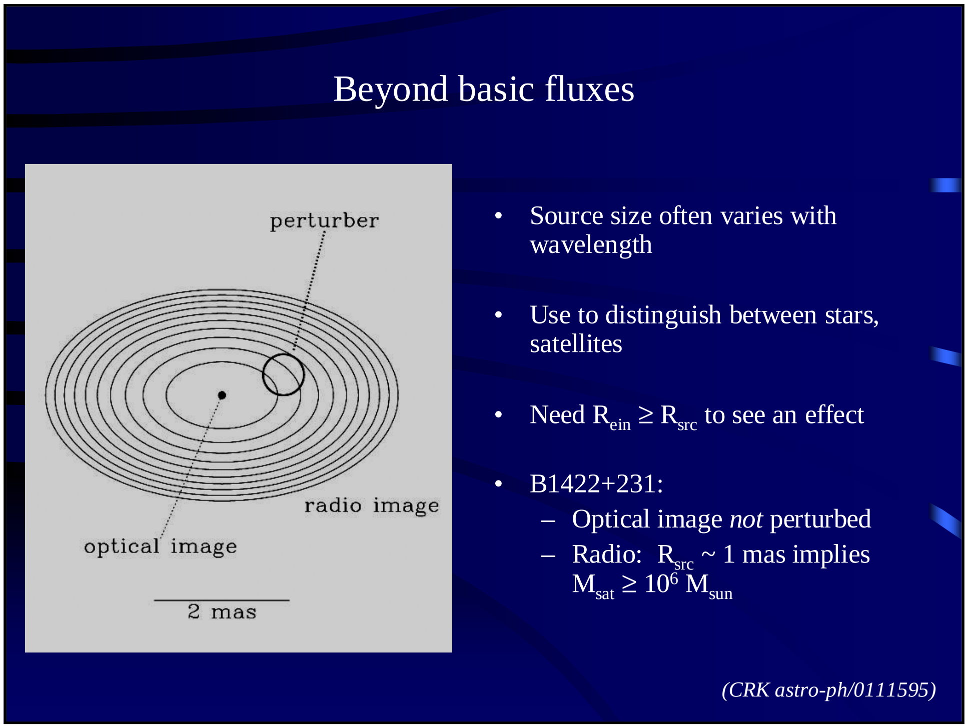
- How do predictions depend on assumption of cold, collisionless dark matter?



Where do the clumps live?

(CRK astro-ph/0209040)

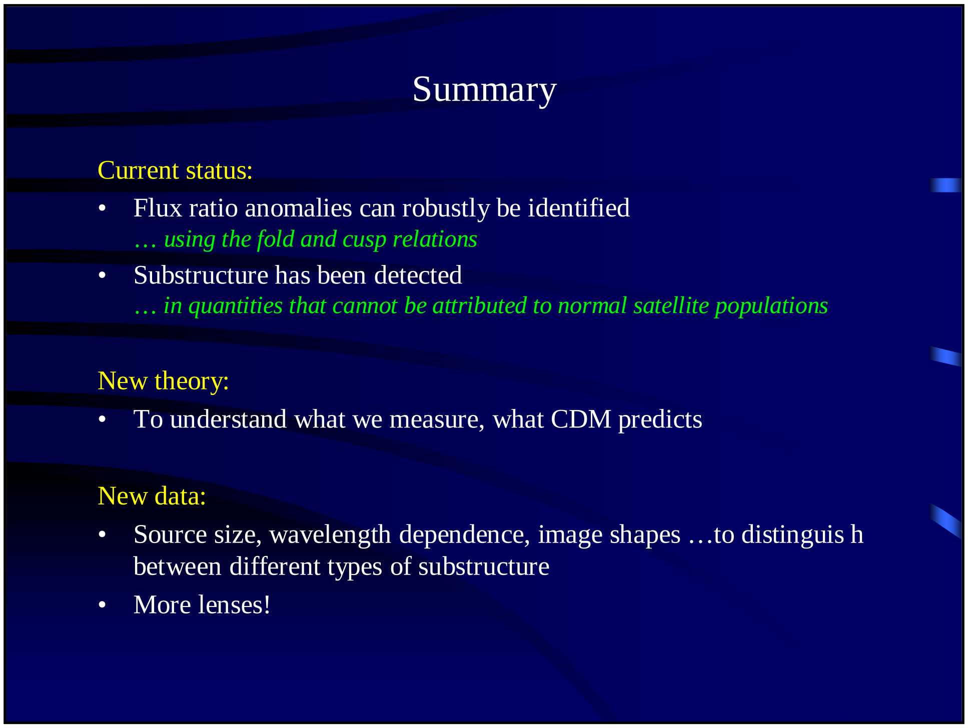
- Assumption: clumps lie in lens galaxy halos
- What about free-floating clumps?
- Effects strongest near lens galaxy, but still significant at $\Delta z \sim 0.2$.
- Jacqueline Chen: *isolated* clumps contribute few % of optical depth; *correlated* clumps may be more important.



Beyond basic fluxes

- Source size often varies with wavelength
- Use to distinguish between stars, satellites
- Need $R_{ein} \geq R_{src}$ to see an effect
- B1422+231:
  - Optical image *not* perturbed
  - Radio: $R_{src} \sim 1$ mas implies $M_{sat} \geq 10^6\ M_{sun}$

(CRK astro-ph/0111595)



Summary

Current status:

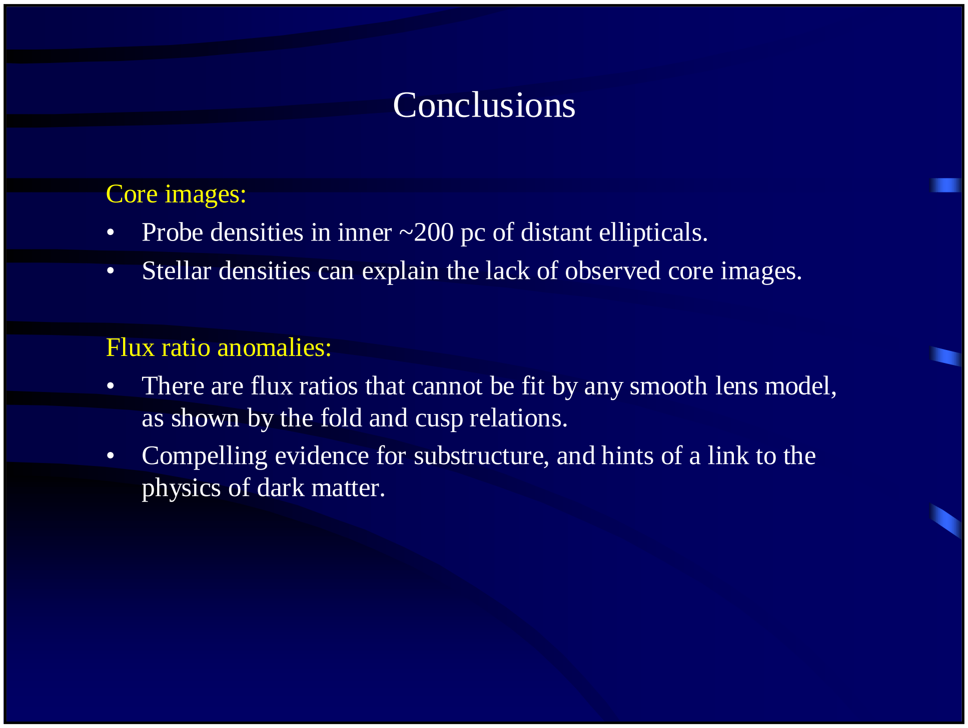
- Flux ratio anomalies can robustly be identified
  … using the fold and cusp relations
- Substructure has been detected
  … in quantities that cannot be attributed to normal satellite populations

New theory:

- To understand what we measure, what CDM predicts

New data:

- Source size, wavelength dependence, image shapes …to distinguish between different types of substructure
- More lenses!



Conclusions

Core images:

- Probe densities in inner ~200 pc of distant ellipticals.
- Stellar densities can explain the lack of observed core images.

Flux ratio anomalies:

- There are flux ratios that cannot be fit by any smooth lens model, as shown by the fold and cusp relations.
- Compelling evidence for substructure, and hints of a link to the physics of dark matter.