Strong gravitational lensing and substructure

Shude Mao
NAOC/Manchester

(Nov. 18, 2011, ASIAA)

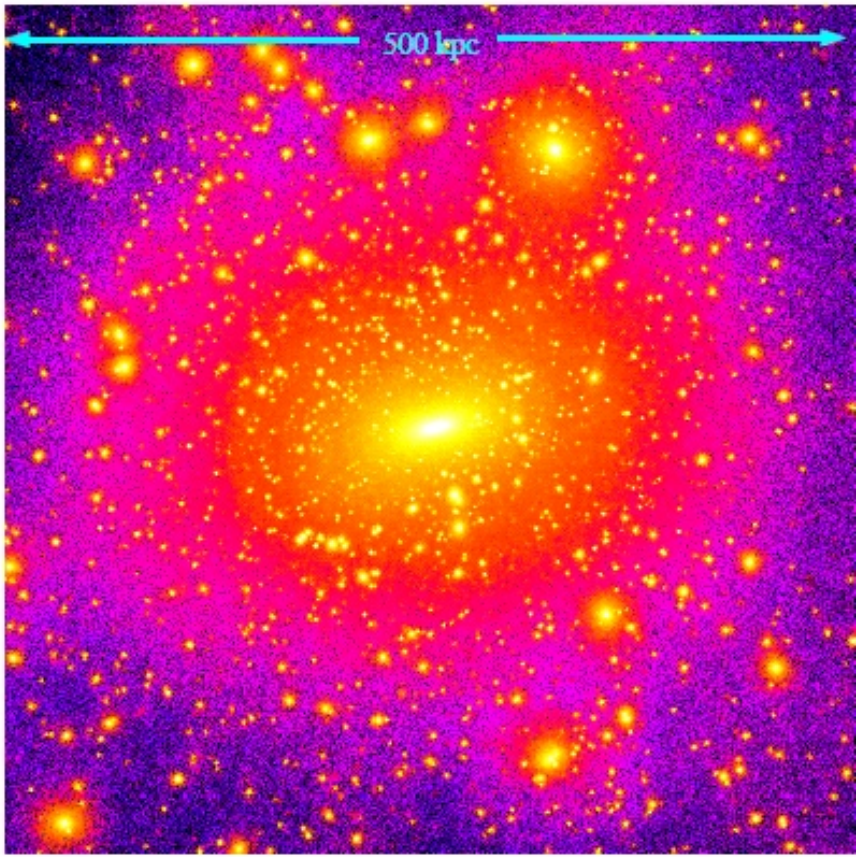
Collaborators:

Dandan Xu, Liang Gao, Volker Springel, Carlos Frenk, Simon White, …

Outline

- Motivations
- Basics of gravitational lensing
- Observational evidence in lenses?
- Theoretical predictions
- Future & summary

Substructure in dark matter haloes

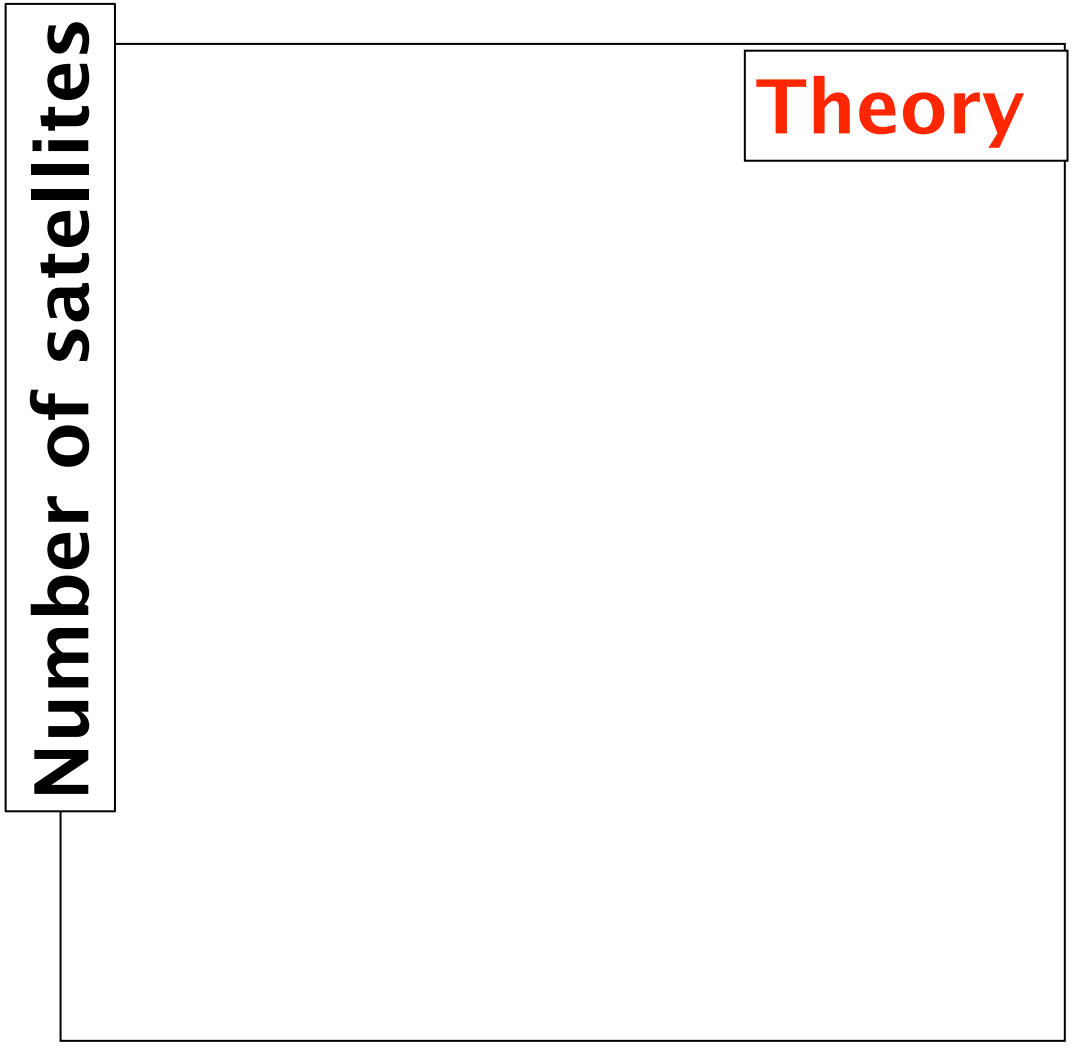


Springel, et al. (see also Diemand, et al.)

Gao et al. (2011, Phoenix simulations)

- 5–10% of halo mass is in substructure within virial radius
- Mass function follows $n(m)dm \sim m^{-1.9}\,dm$

Milky Way Satellite Galaxies



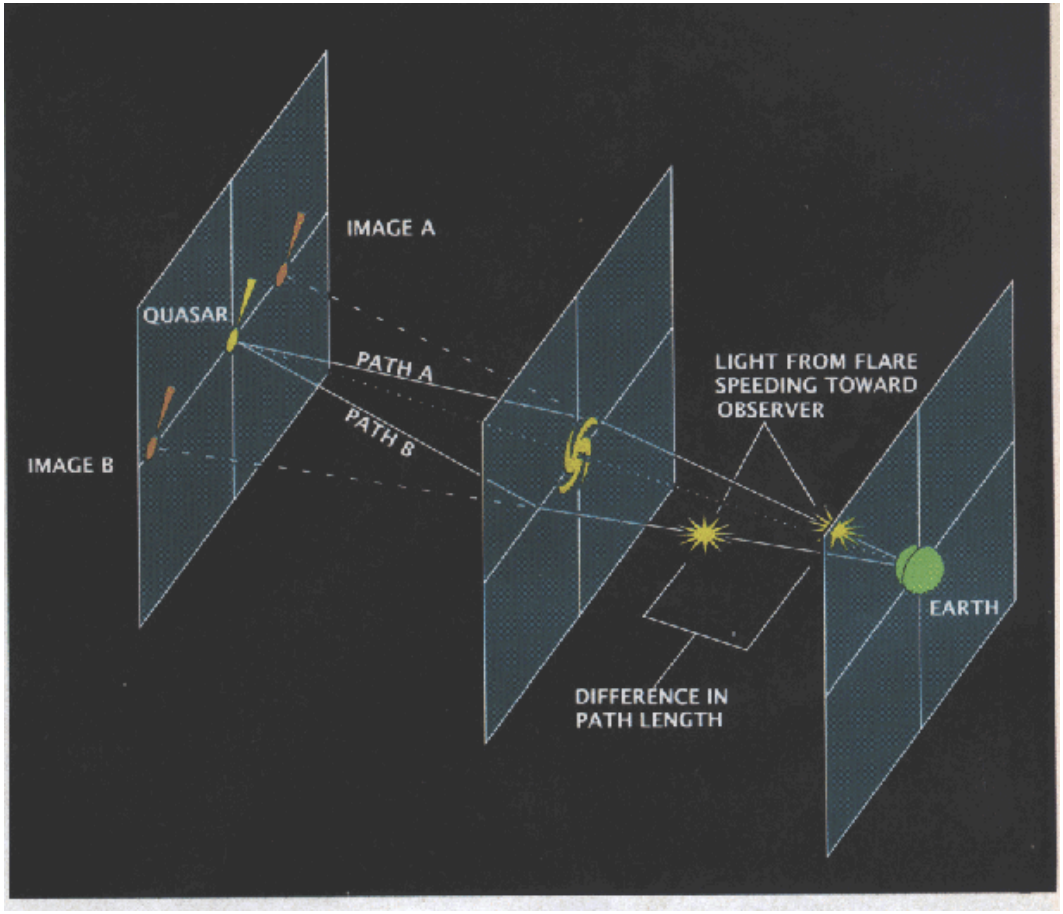
Strigari et al. (2007)

- In CDM, theory predicts many more than observed satellites in a Milky-

Missing "satellites"

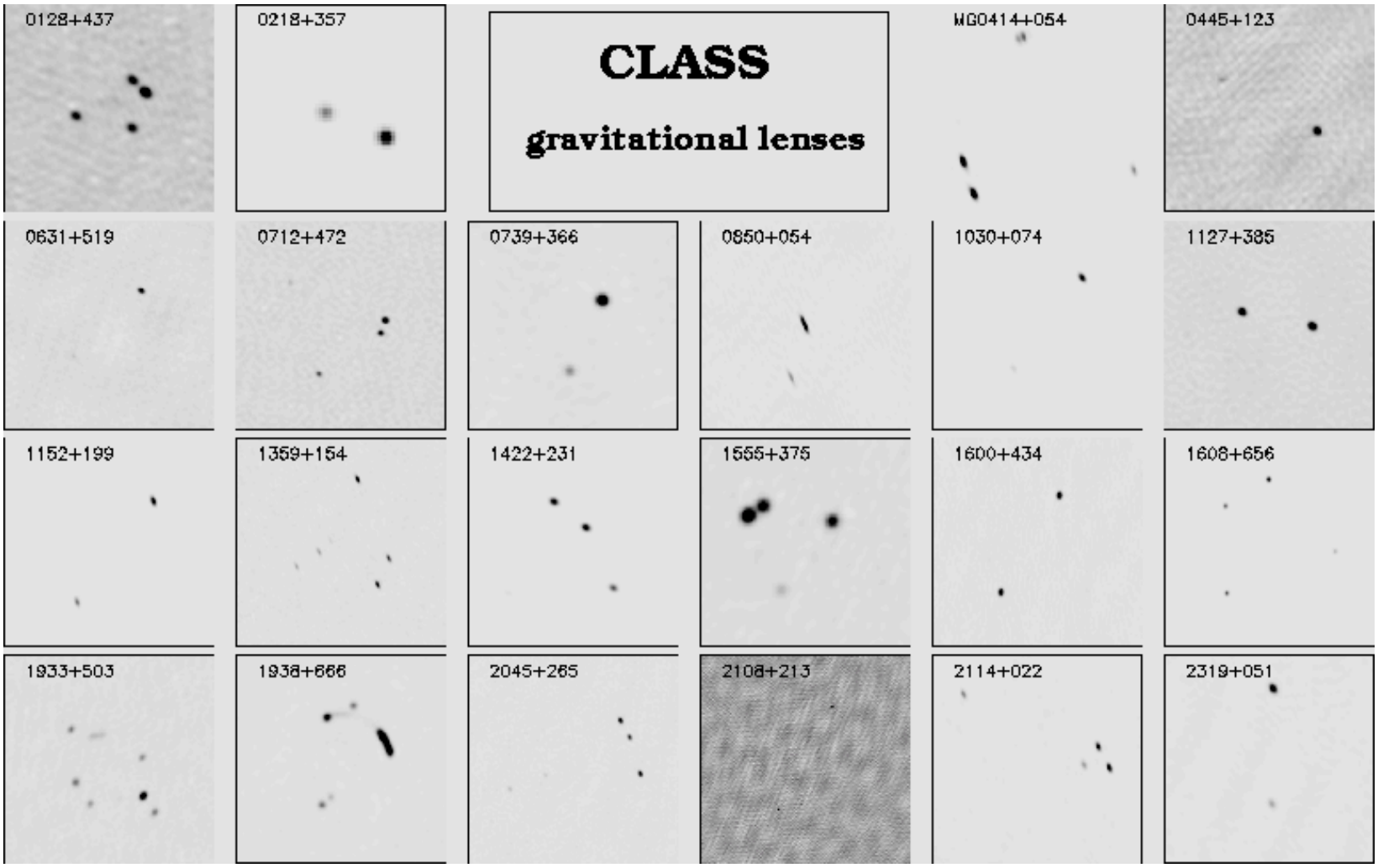
- Are the satellites predicted by theory non-existent or just dark?
- If they do not exist, what's wrong with the standard cosmological model?
  - Their number and spatial distributions depends on the nature of DM (WDM??)
- If they exist and are dark, why are they not forming stars?
- How do we detect the "missing satellites"?

Gravitational lensing



Lensing magnifies, deflects, and distorts background sources

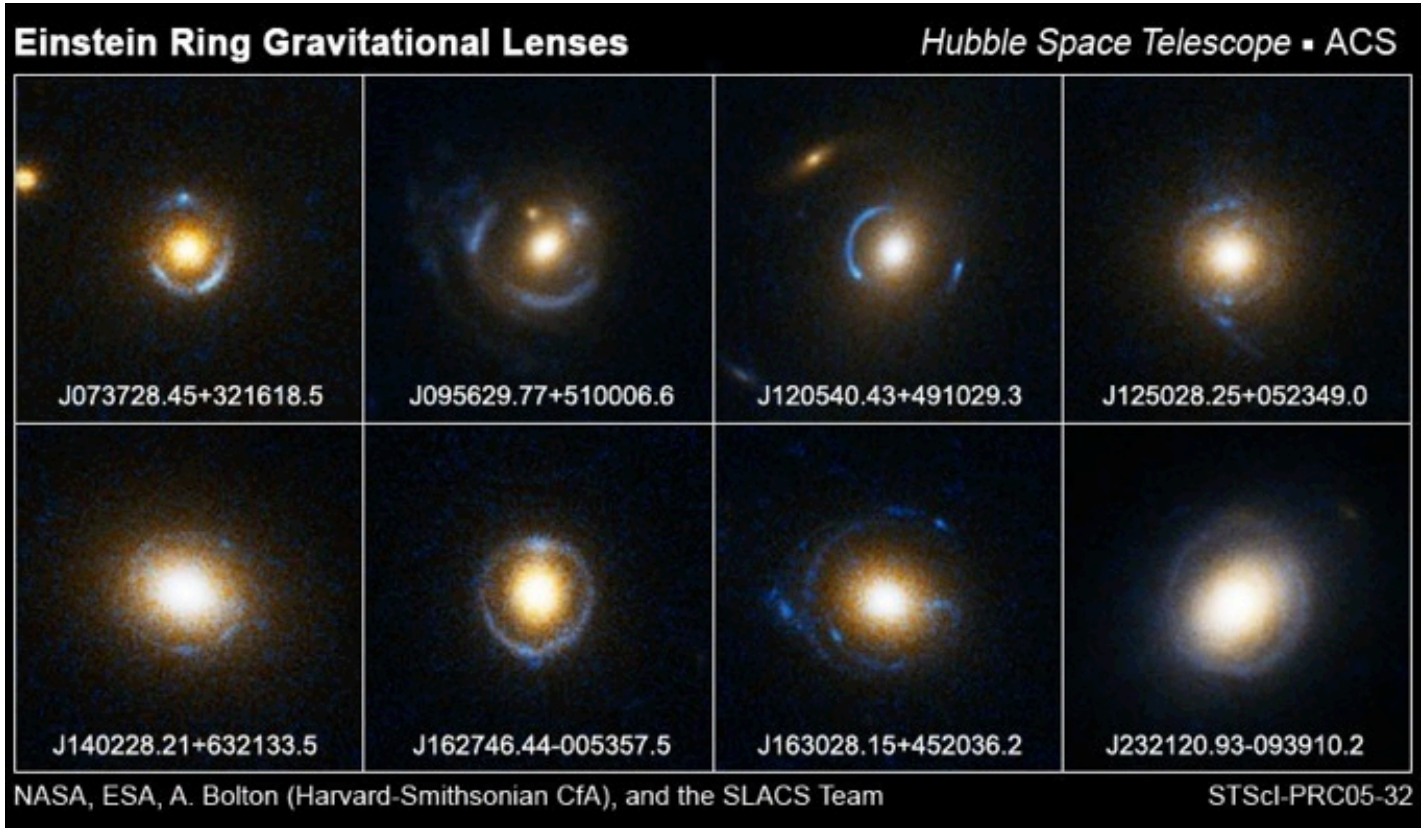
Gravitationally lensed



~100 AGN lenses known

CLASS radio lens survey: 22 lenses (No dust effects, no stellar microlensing)

SLOAN Lenses ACS survey



~100 lenses

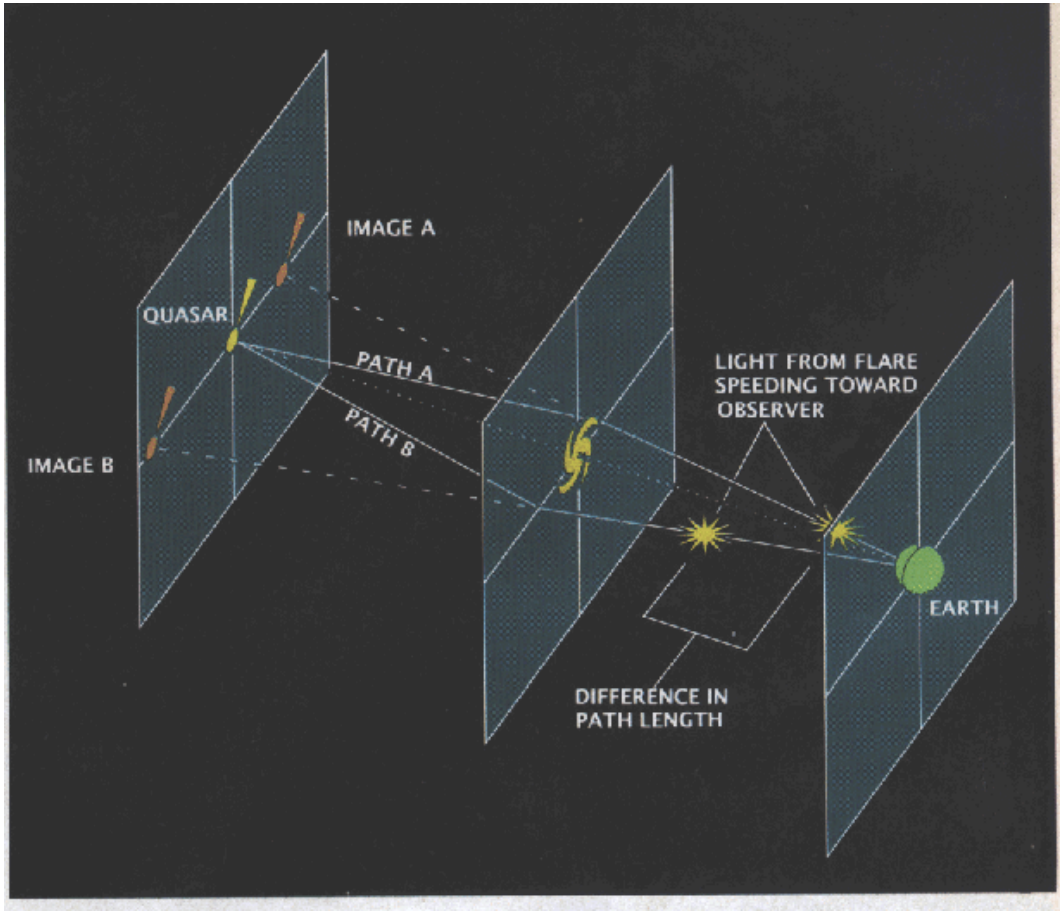
Bolton, Burles, Gavazzi, Koopmans, Moustakas, Treu

- Lens population at z~0.2 from SDSS
- They can also be used to detect

Basic theory of gravitational

- Observables:
  - Astrometry: Ψ'
  - Flux ratios: ψ''
  - Time delay: ψ', ψ
  - Flextions: ψ'''
- $\Psi = \Psi_{smooth} + \delta\Psi$
  - Substructures perturb the observables, particularly those that depend on higher-order derivatives.
- Critical curves and caustics play a crucial role.

Lensing mathematics

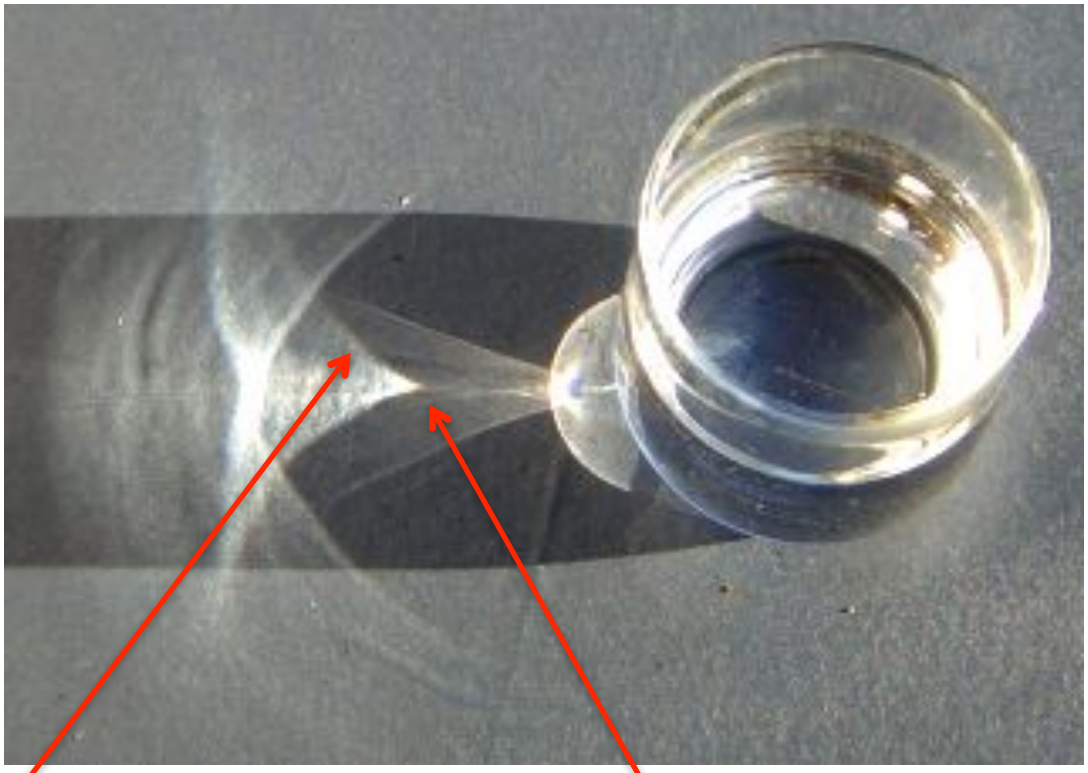


- Lensing is a mapping from the source to lens plane
- Jacobian singularities: Critical curves /

Caustics in the real world

Parallel rays from the Sun are piled into bright optical caustics by waves.

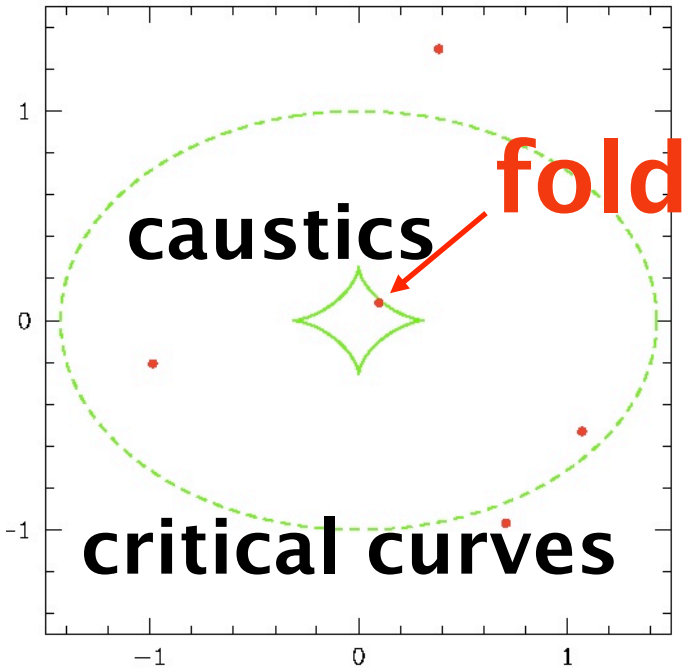
Caustics in the real world

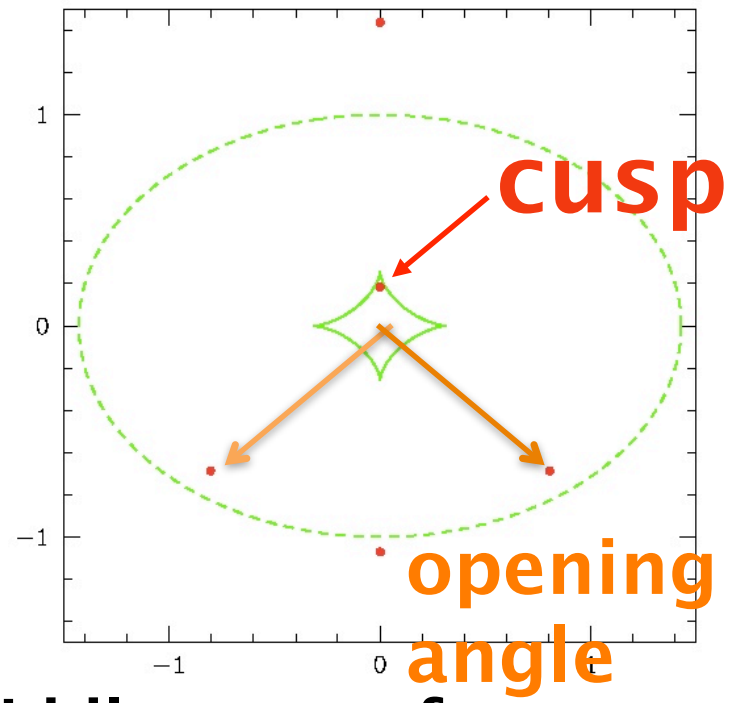


CUSP

FOLD

Images near fold and cusp caustics





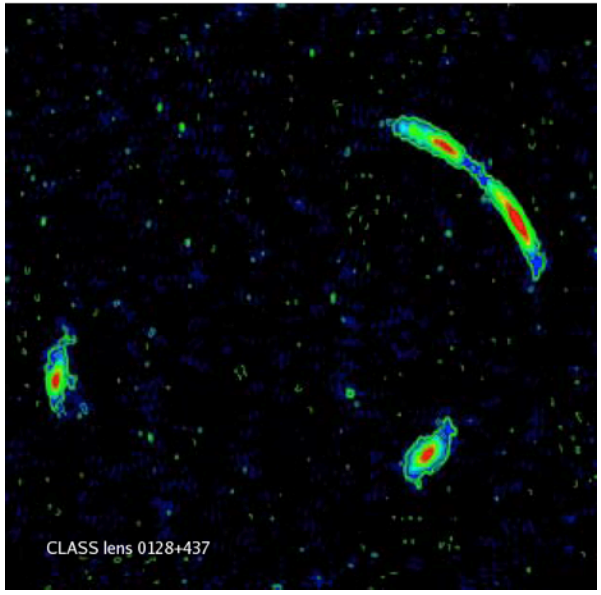
Pairs have equal brightness

middle=sum of two outer images

$$R_{\rm cusp} \equiv \frac{|\mu_A + \mu_B + \mu_C|}{|\mu_A| + |\mu_B| + |\mu_C|}$$

These relations are valid for any smooth potential, independent of radial and angular profiles (Mao & Schneider 1998)!

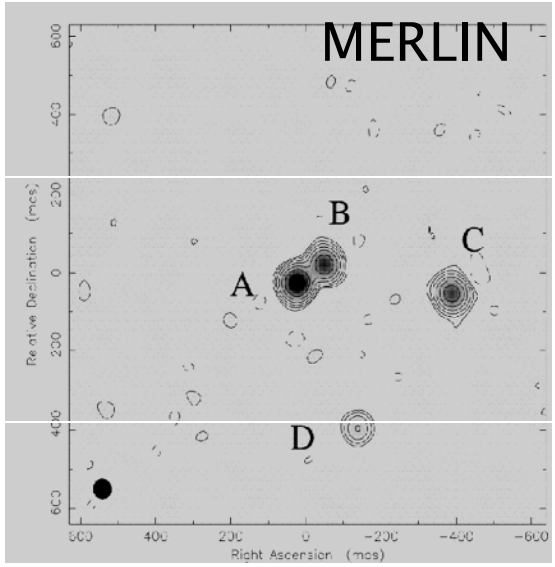
Observed flux ratios in close



B0128+437

(Phillips et al. 2001)

R_{pair}=0.5



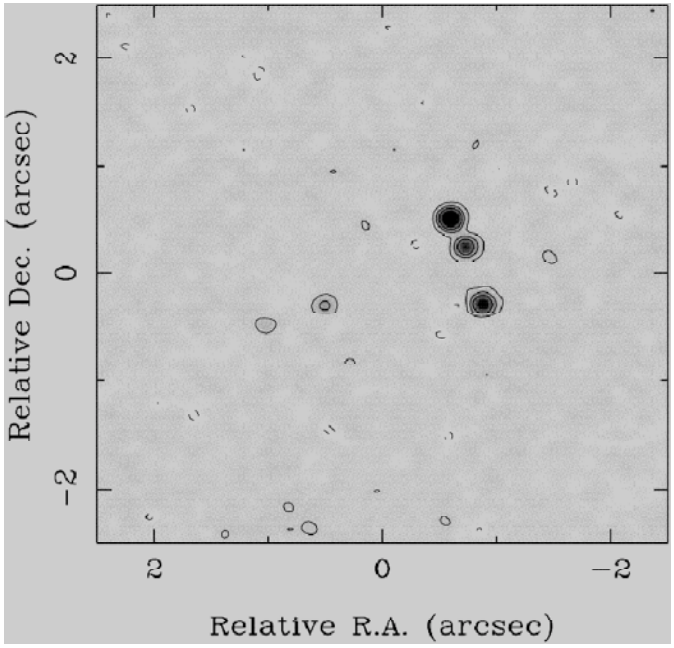
B1555+375

(Marlow et al. 1999)

R_{pair}=0.57

- Substantial deviations from the predicted ratio (~1)
- Saddle images are fainter than expected

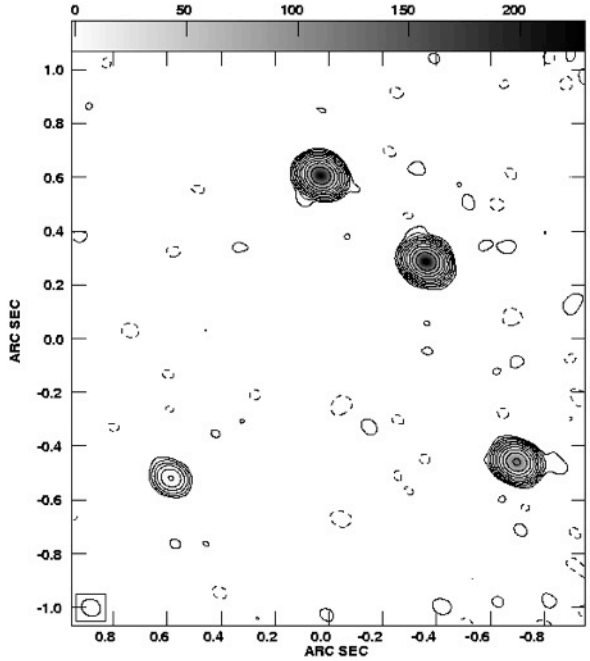
Observed flux ratios in cusp



B2045+265

(Fassnacht et al. 1999)

Middle/(Outer Pair) =0.3



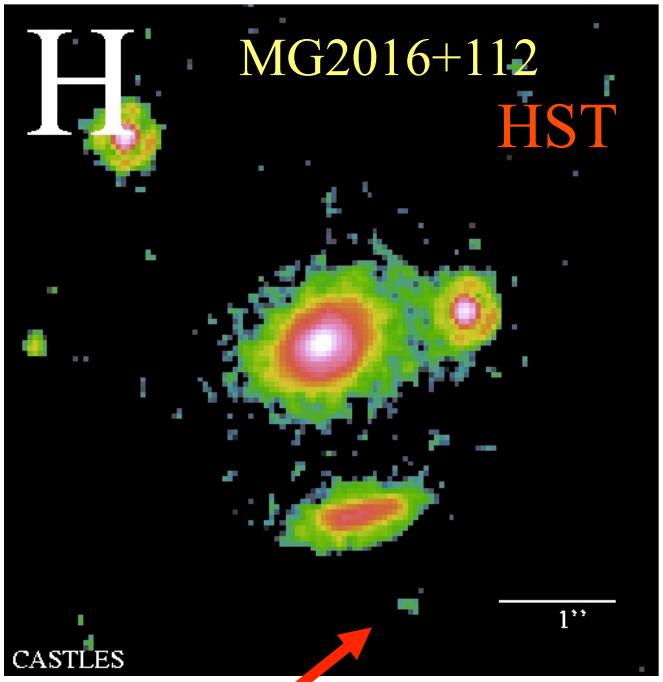
B1422+231

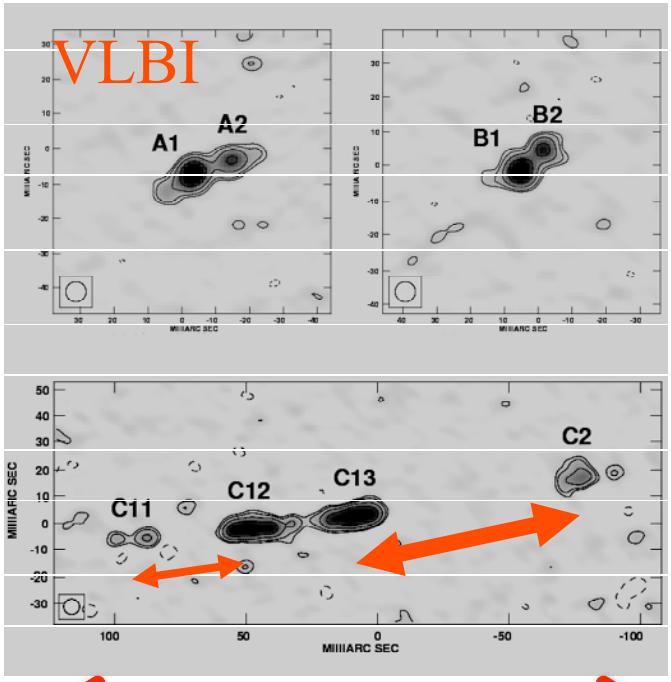
(Patnaik et al. 1992)

Middle/(Outer pair) =0.67

- **Substantial deviations from the predicted ratio (~1)**
- **Saddle images are fainter than expected**

Anomalous astrometric signals





(Koopmans et al. 2002; Kochanek 2003)

200 mas

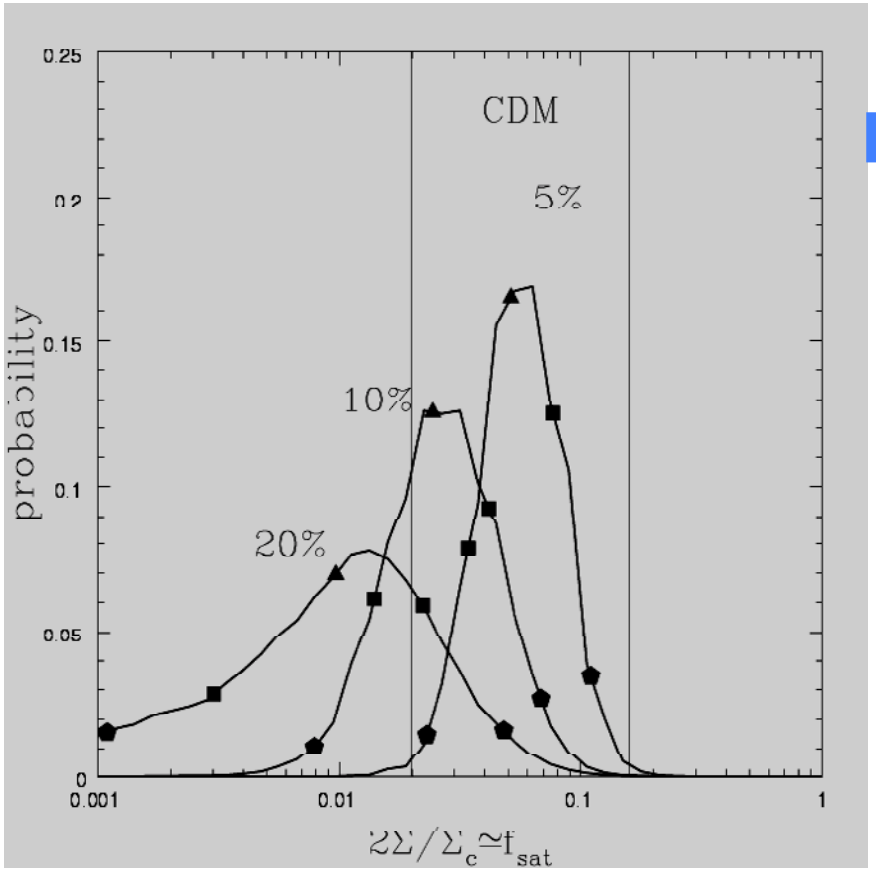
Astrometry affected by a satellite galaxy 1% of the primary lens

C11-C12 and C13-C2 should have the same separation

What causes the "flux ratio

- Dust? No, does not affect radio lenses
- Other propagation effects?
  - Somewhat unlikely as no frequency dependency of flux ratios is obvious
  - Saddle images are most affected – consistent with substructure lensing but not with other effects
- Microlensing by stars?
  - Radio source sizes are usually too large
  - Observed radio microlensing in B1600+434: amplitude is ~5% on the timescale of days
  - Observed deviations in flux ratios are too

Theoretical requirement



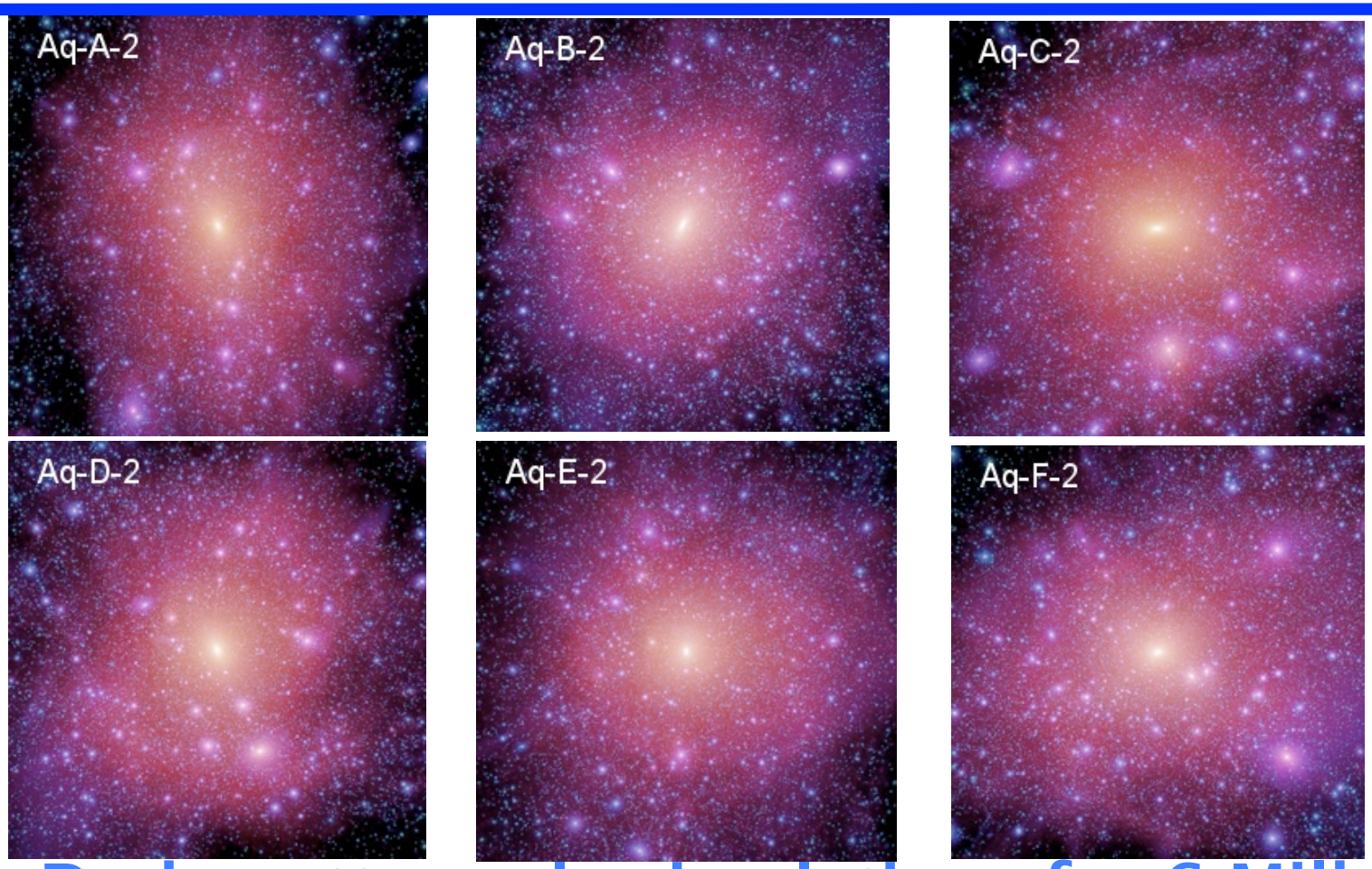
Dalal & Kochanek (2002)

- **Used a sample of 7 four-image lenses (6 radio)**
- **6 show poor fits to image flux ratios**
- **Substructure fraction depends on the systematic flux errors**

- **For 10% flux errors, 90% confidence limit: $0.6\% < f_{sub} < 7\%$**
- **$\delta x \sim 1$ mas $(M/10^6\ M_{sun})^{1/2}$ at mass scale: $10^6 M_{sun} < M < 10^9\ M_{sun}$**

Roughly consistent with ΛCDM!?

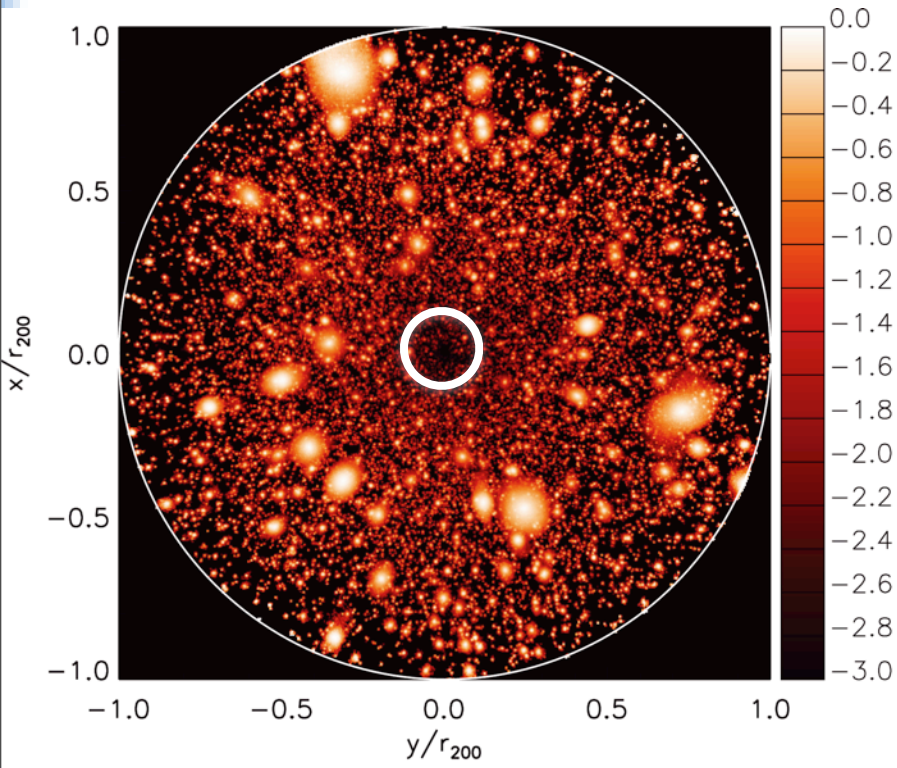
Aquarius simulations

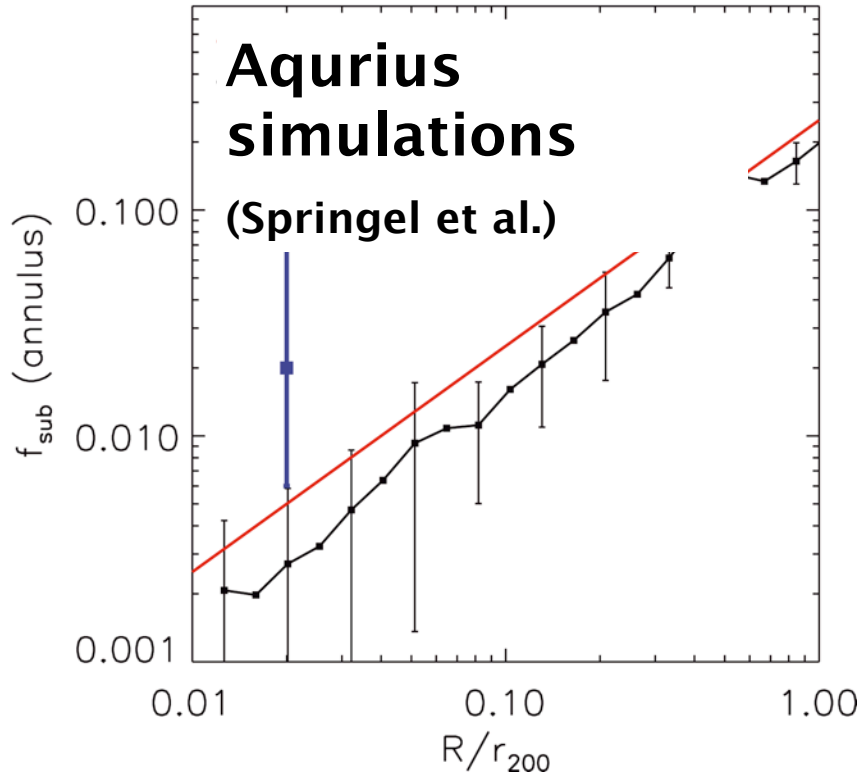


Springel et al. (VIRGO)

- Dark matter only simulations for 6 Milky Way sized haloes with ~200 million particles. Haloes down to ~ 10^6 solar masses are resolved.

CDM predictions

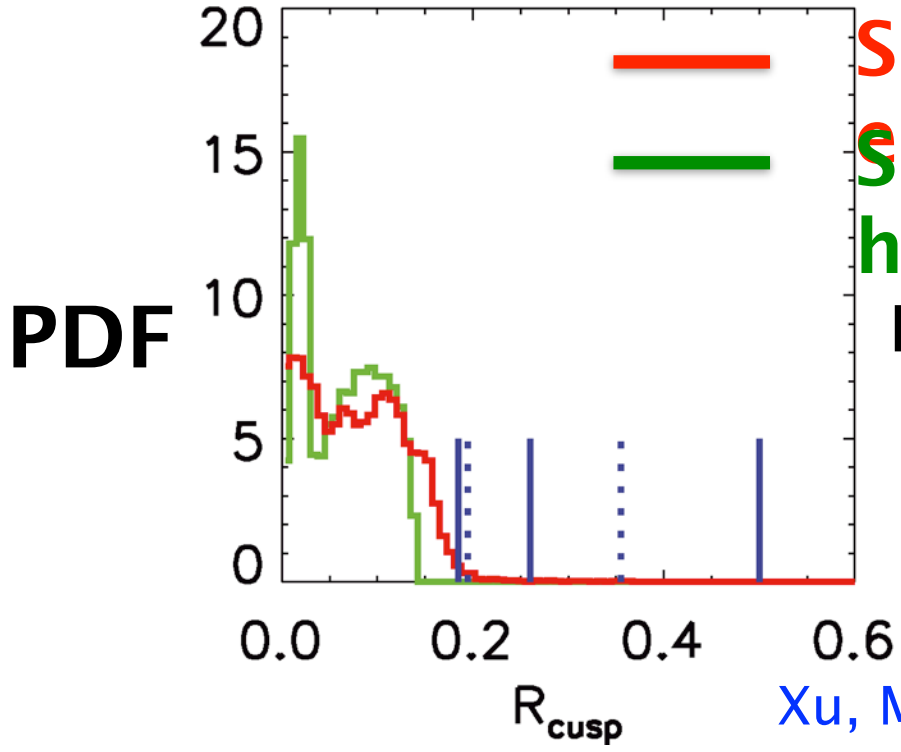




Xu, Mao + VIRGO collaboration (2009, 2010, 2011)

- <1% of dark matter is in substructures at typical lens positions
- Fraction is low because most substructure is in the outer parts

Predicted cusp violations

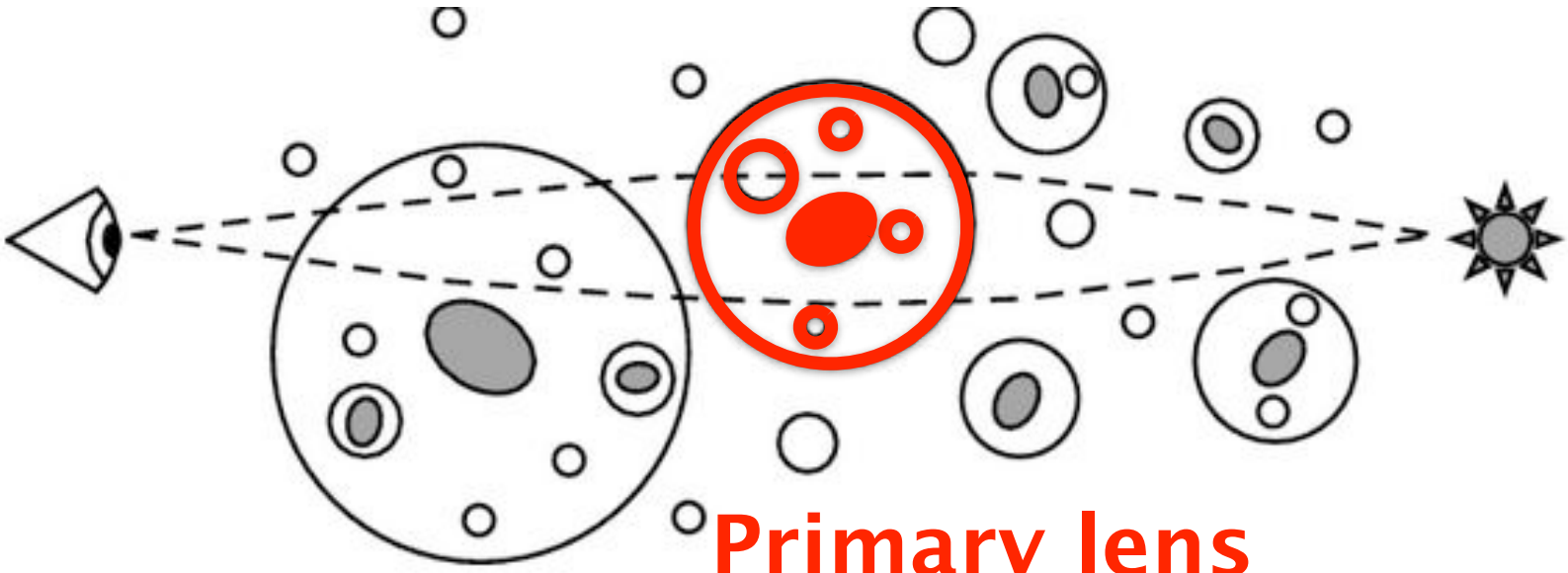


R_{cusp}=(middle−outer)/(middle+outer)

Xu, Mao, Gao et al. (2009, 2010)

- Difficult to reproduce the observed cusp violations using substructures within lens galaxies
- Adding globular clusters and luminous

Line of sight lensing



- In principle, any (sub)haloes along the line of sight can cause flux anomalies (Metcalf 2002)
- Calculations much more involved!

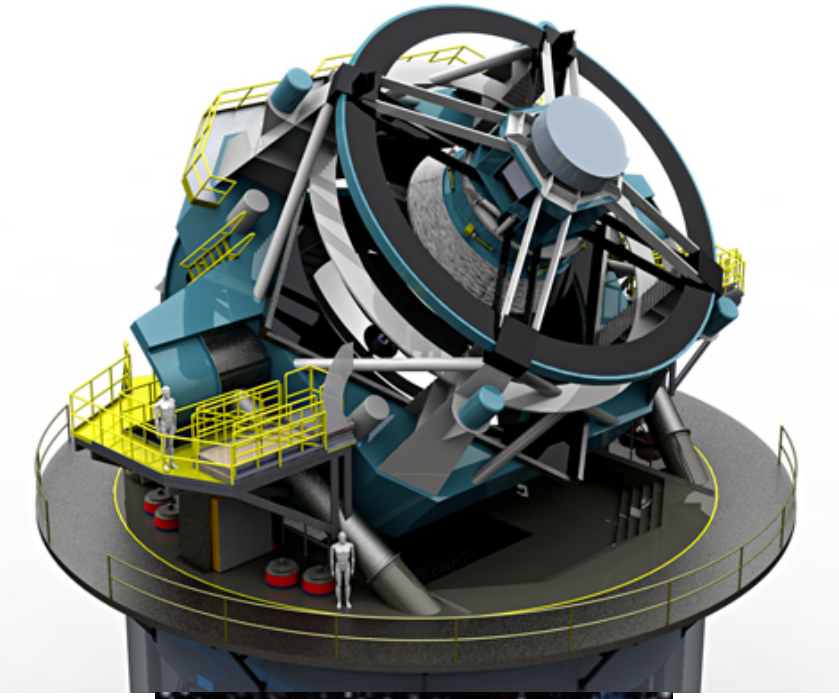
Line of sight haloes

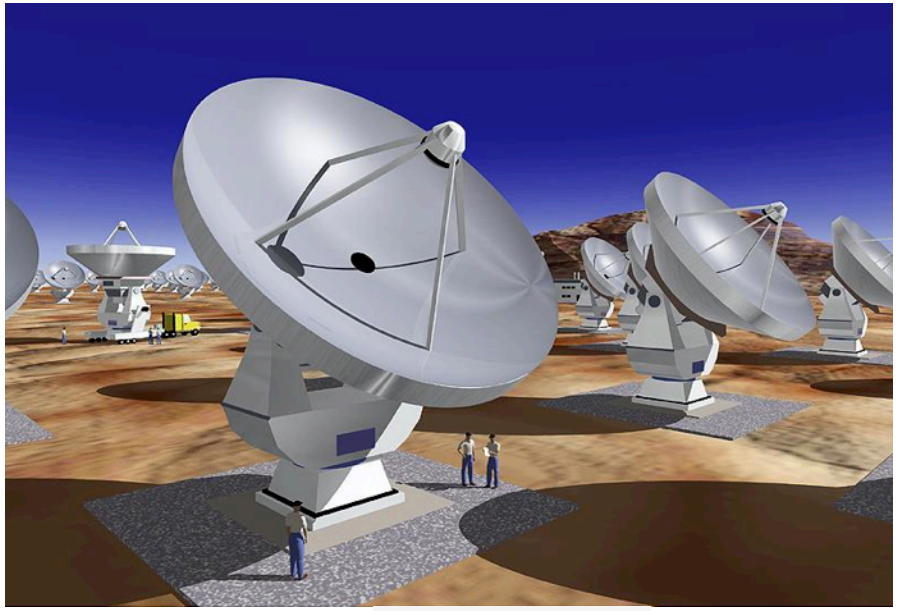
- Depends on the source redshift, separation of lenses & substructure density profiles (Xu et al. 2011). **Testable predictions!**

- Equally important as substructures in lenses

- Probabilities are marginally consistent with data.

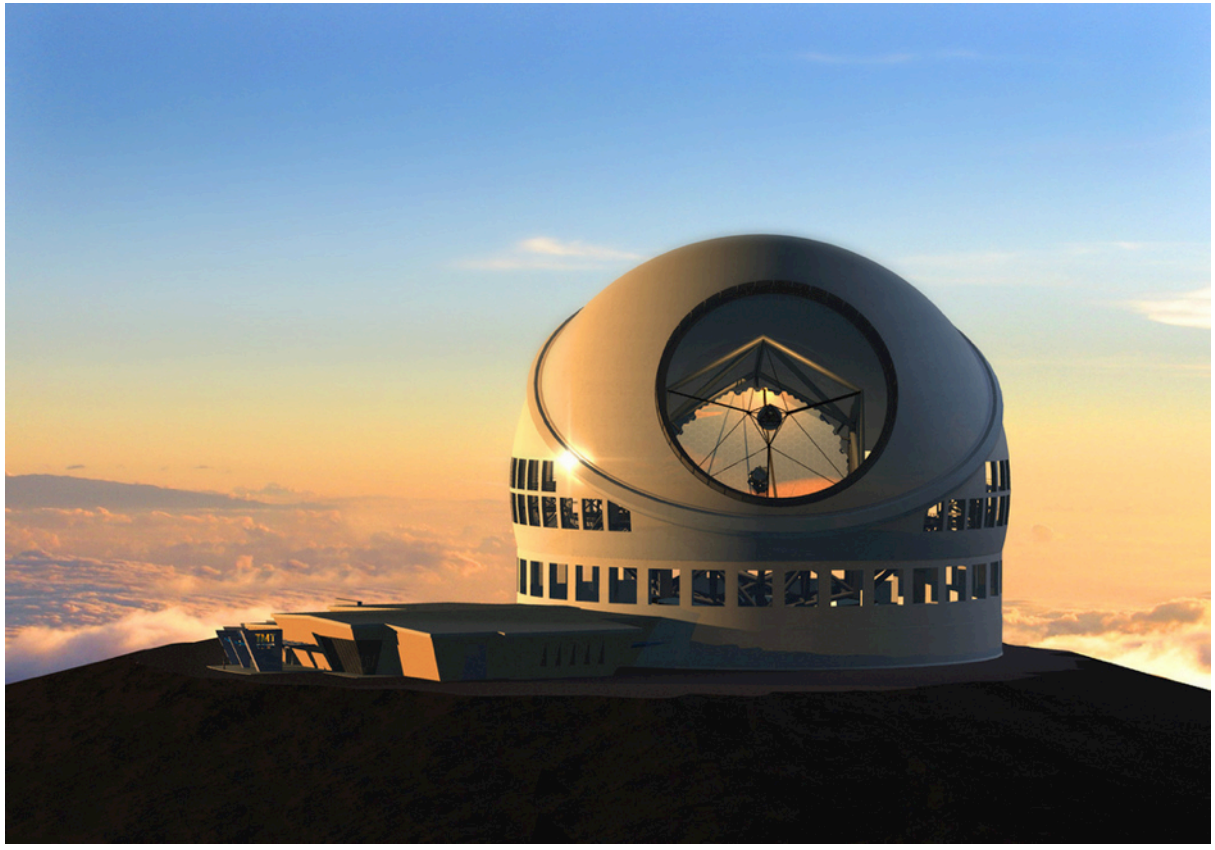
Future surveys of strong





- Discovery of many gravitational lenses with SKA, LSST
- LSST will discover ~8000 lensed AGNs, and

Thirty Meter Telescope (TMT)



Large aperture

Diffraction limit

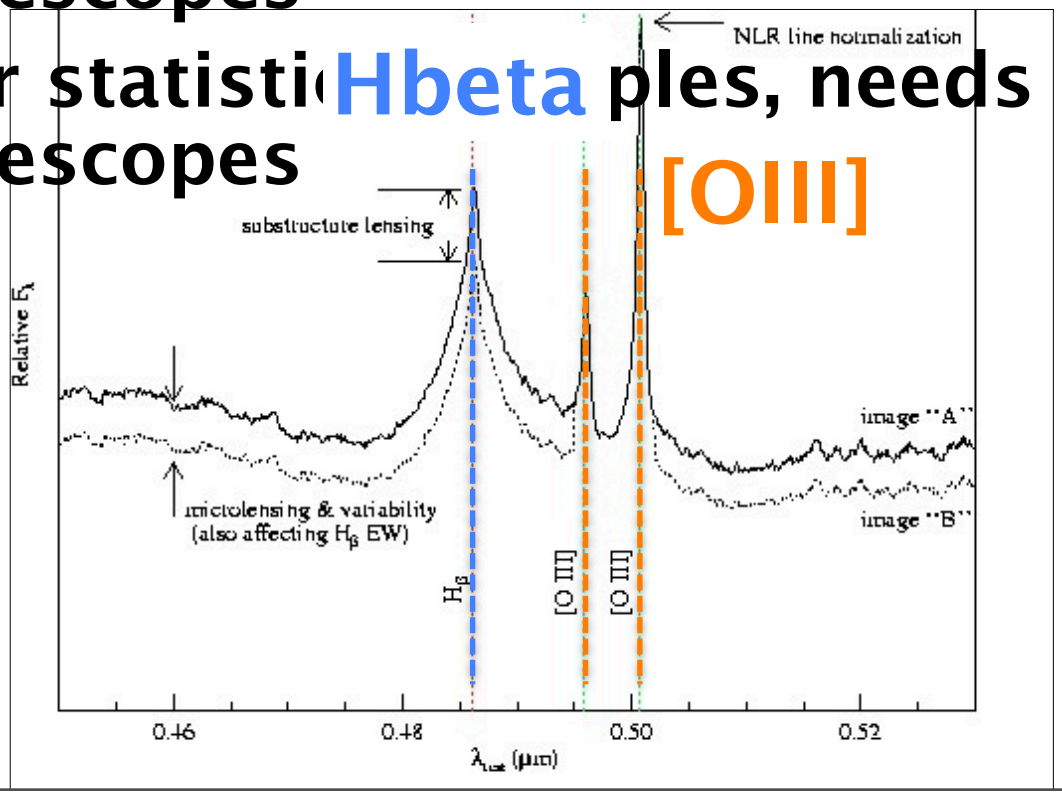
IR optimised

- All three features will be important for studying gravitational lenses
- TMT will be able to study faint lensing galaxies statistically.

IR spectroscopy

Infrared emission line spectroscopy (Moustakas & Metcalf 2003)

- difference among images reveals the presence of substructures
- Accessible with current 8-10m class telescopes
- For statisti Hbeta ples, needs 30m class telescopes

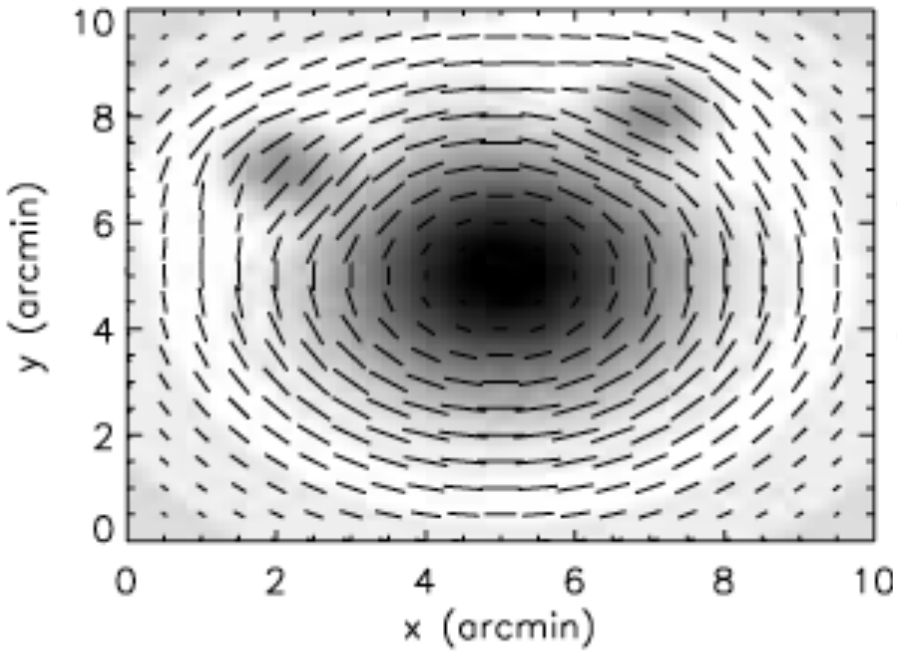


[OIII]

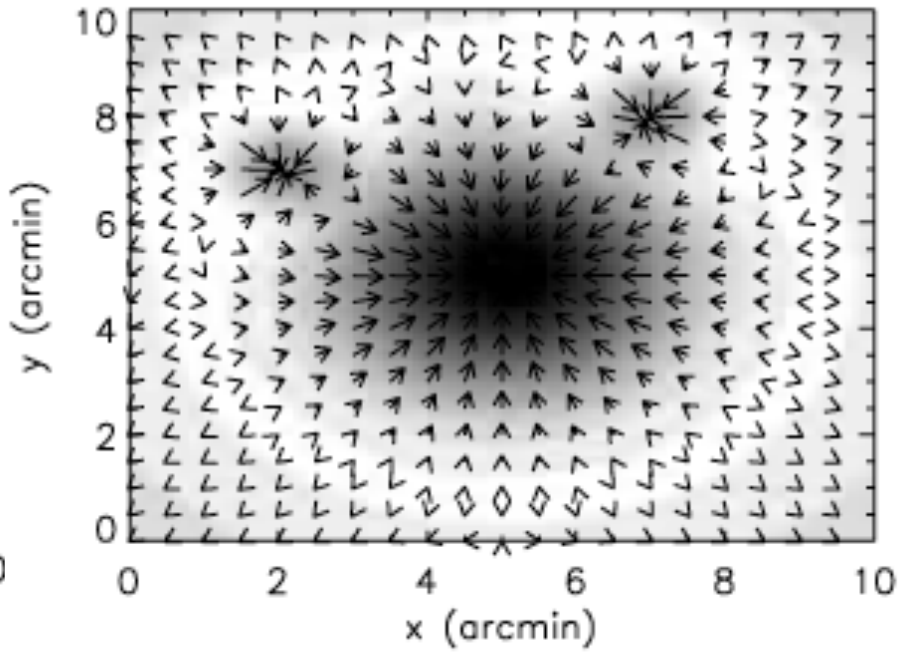
For a source at z ~ 2, Hbeta and [OIII] are redshifted into IR

Detecting substructures with

shear



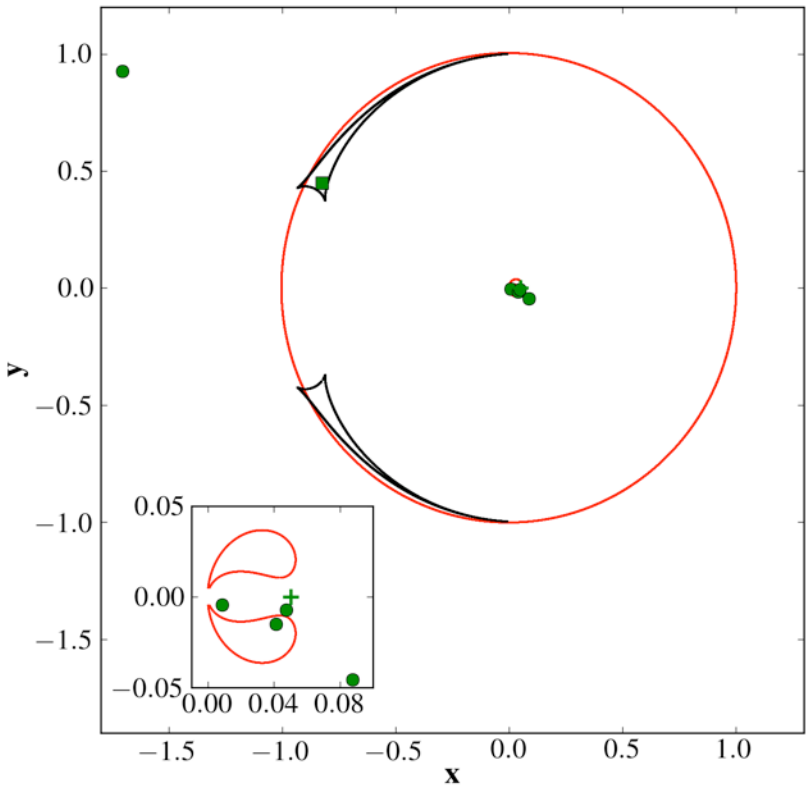
flexion F



From Bacon et al. 2006

- Flexions have potential to detect substructures
- Not yet demonstrated since noise

Central supermassive black



Caustics and critical curves by an offset black hole.

Li, Mao et al. (2011); Mao & Witt (2011)

- Black holes can create extra central images
- Usually too faint to be seen, but may be

Summary

- Gravitational lensing is a useful probe for substructures on all scales.
- CLASS lenses show more significant deviations than CDM predictions
  - Wrong DM properties? Effects of baryons?
  - Small number statistics?
- More lenses are needed to understand small-scale substructures in CDM
  - PanSTARRS/SKA//LSST will provide more lenses