Substructure Lensing

Shude Mao

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Nov. 18, 2014@IPMU

Outline

I. Introduction

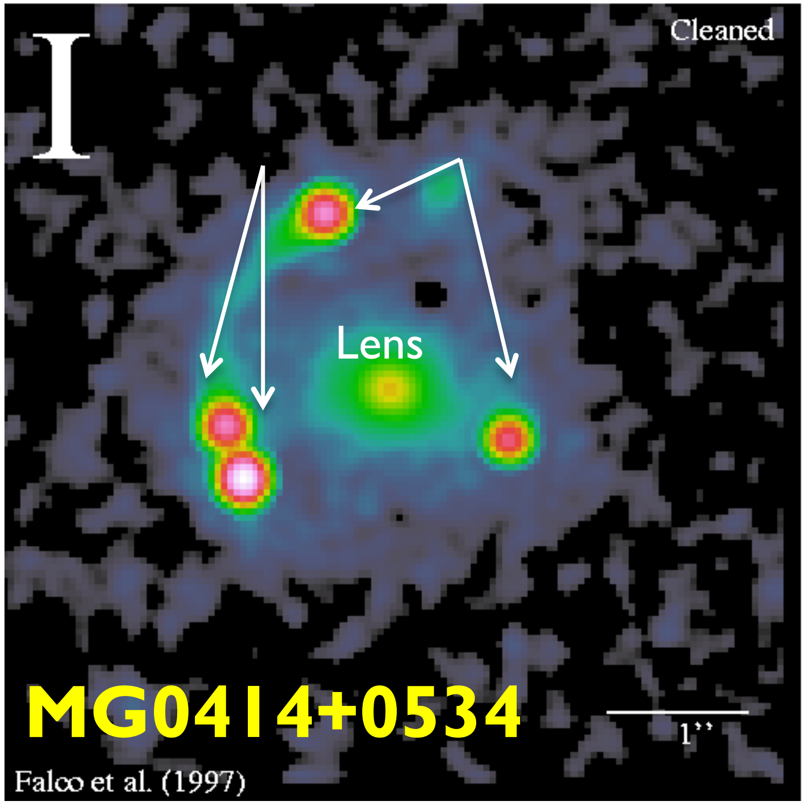
II. Flux ratio Anomalies

– Statistical predictions

– Modelling observed lenses

III. Discussion & future outlook

I. Introduction: Difficulty in modelling lenses

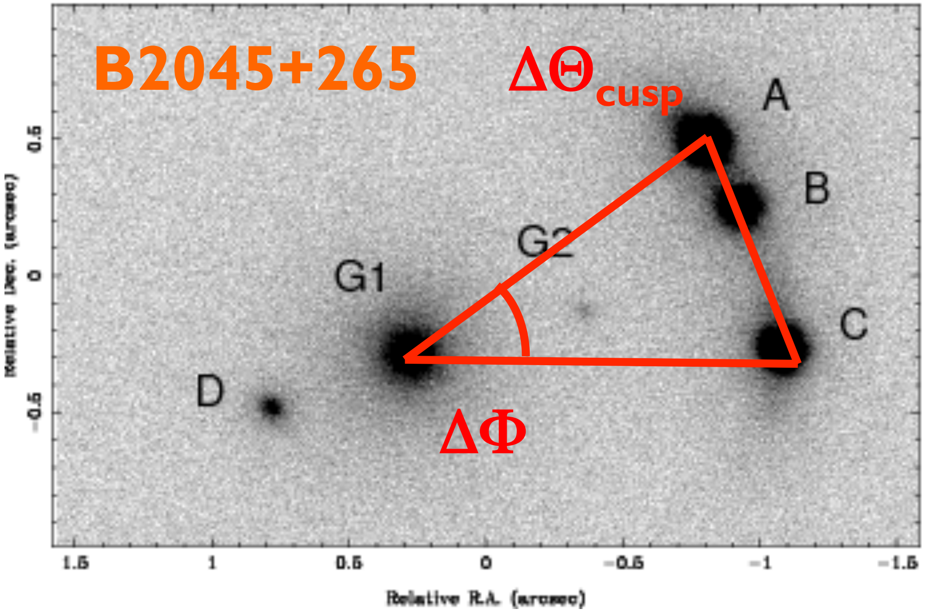


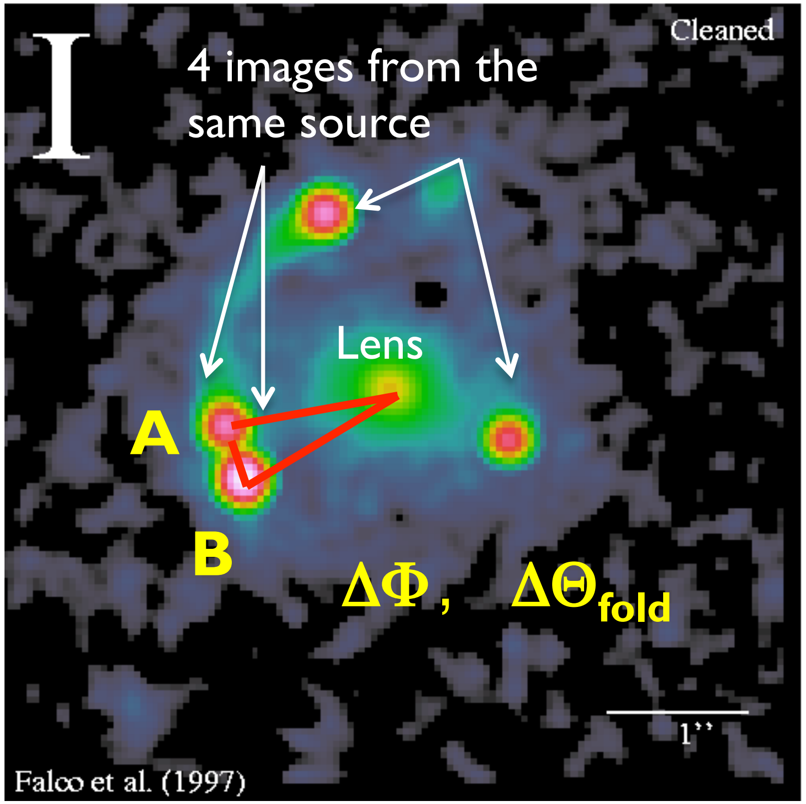
5 quads, 4 doubles, 3 rings

Kochanek (1991) modelled 12 lenses and pointed out:

- It is pretty easy to reproduce the image positions
- But often more difficult to fit the magnifications ("wild fluctuations")

Asymptotic relations for folds & cusps





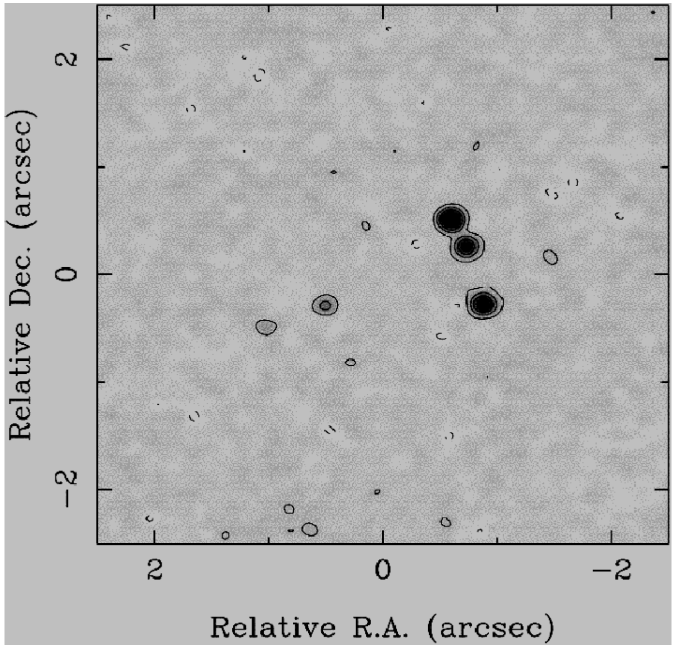
$$R_{cusp} = \frac{\text{Middle-Outer}}{|\text{Middle+Outer}|} \rightarrow 0$$

when $\Delta\Phi \rightarrow 0$

$$R_{fold} = \frac{A-B}{|A+B|} \rightarrow 0$$

Valid for any smooth models!

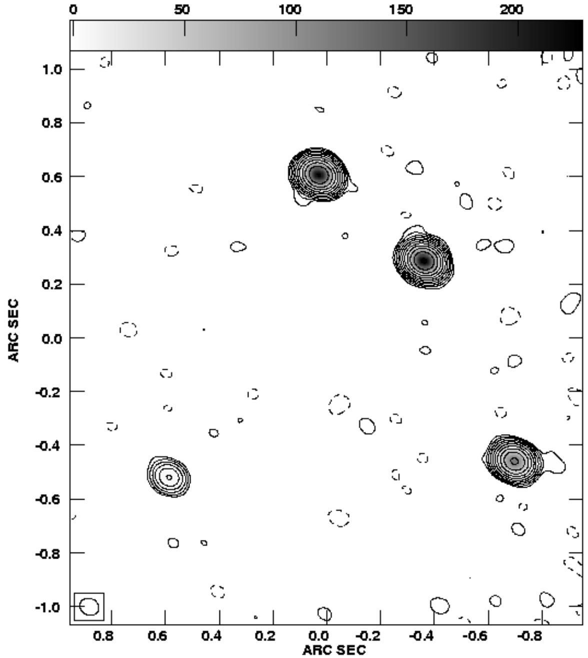
Observed flux ratios in cusp triples



B2045+265

(Fassnacht et al. 1999)

R_{cusp}=0.5



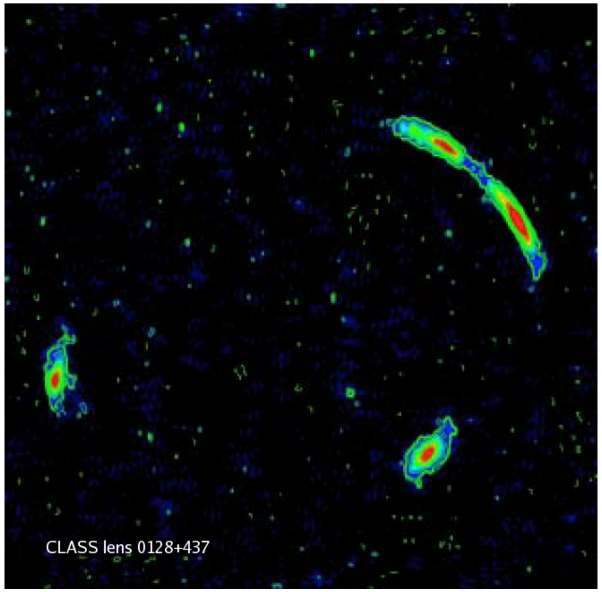
B1422+231

(Patnaik et al. 1992)

R_{cusp}=0.2

- **Substantial deviations from the predicted value (0)**
- **Saddle images are fainter than expected**

Observed flux ratios in fold pairs



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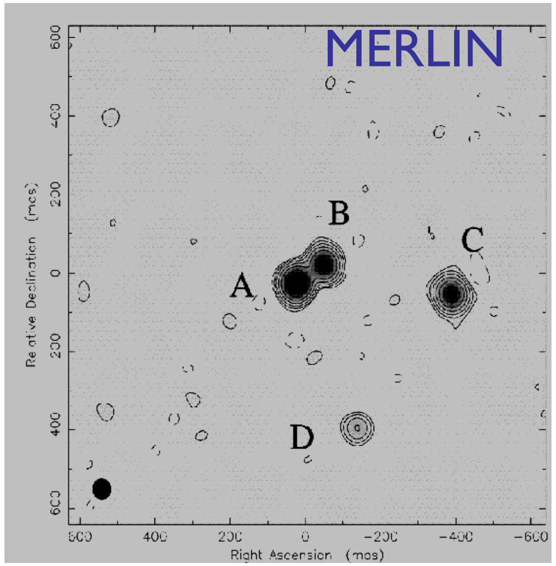
(Phillips et al. 2001)

R_{fold}=0.33



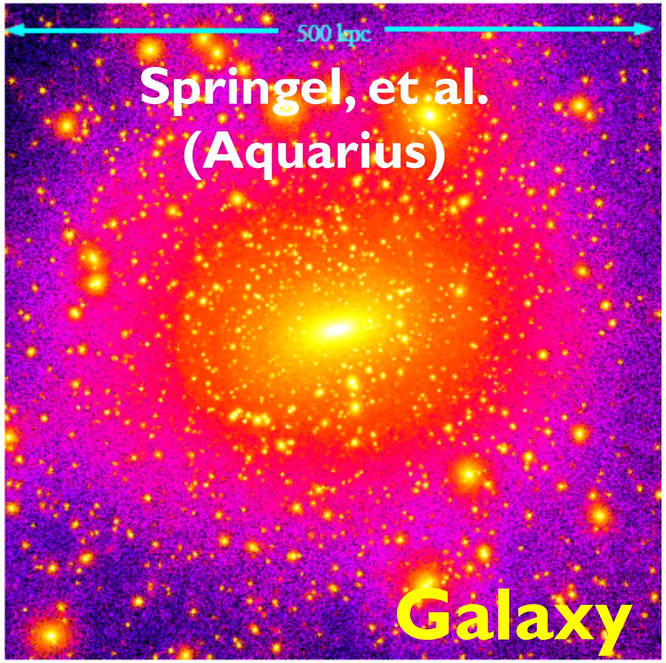
B1555+375

(Marlow et al. 1999)

R_{fold}=0.27

- **Substantial deviations from predicted ratio (~0)**
- **Saddle images are fainter than expected**

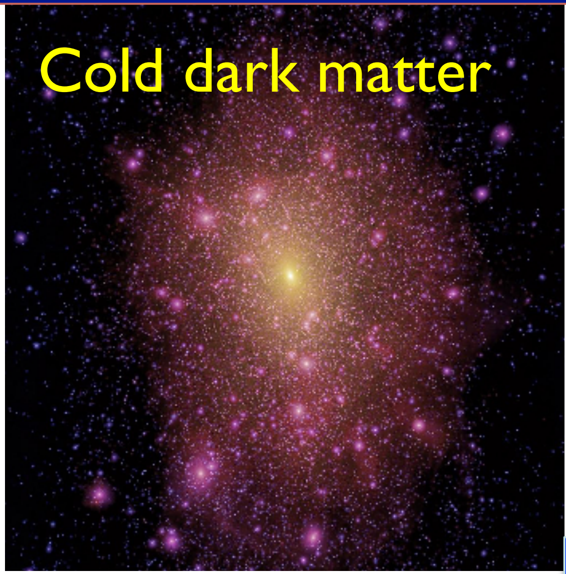
Substructures in CDM models

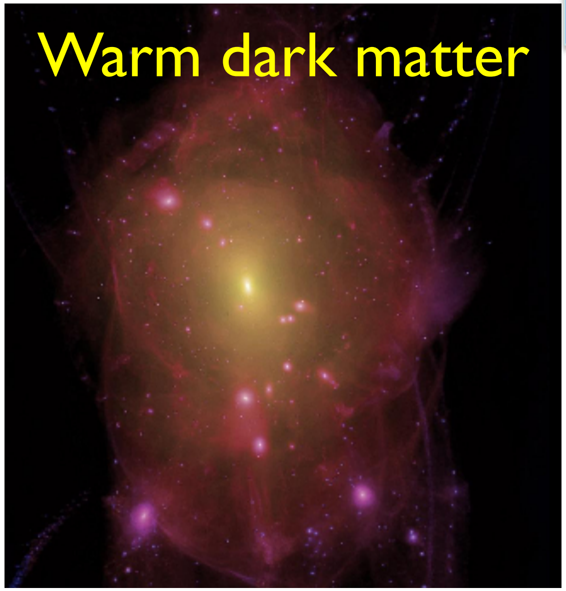


[e.g. Moore et al. 1999; Kauffmann et al. 1993; Klypin et al. 1999; Springel et al.; Kravstov et al.]

- **5-10% of halo mass is in substructures**
- **Mass function follows $n(m)dm \sim m^{-1.9}\,dm$**
- **$\sim 10^4$ subhaloes are predicted with $V_c > 3$ km/s**

Nature of dark matter & Small scale power-spectrum





If we can determine the mass function and spatial distribution of subhaloes

- **Constrain the nature of dark matter (cold or warm?)**
- **Small-scale matter power spectrum on ~kpc scale**

Lensing anomalies due to substructures

- **Magnification: Φ_{xx}, Φ_{yy}, Φ_{xy} [Φ: lens potential]**

(Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002; Keeton 2001

Bradac et al. 2001; Moustakas & Metcalf 2003; Moller, Hewitt, & Blain 2003; Metcalf & Zhao 2002; Keeton, Gaudi & Petters 2002; Evans & Witt 2003;

Dalal & Kochanek 2002; Chen, Kravtsov, & Keeton 2003; Metcalf & Amara 2012)

- **Position (astrometry): Φ_x, Φ_y**

(e.g., Chen et al. 2007; Vegetti et al. 2010, 2012, 2014)

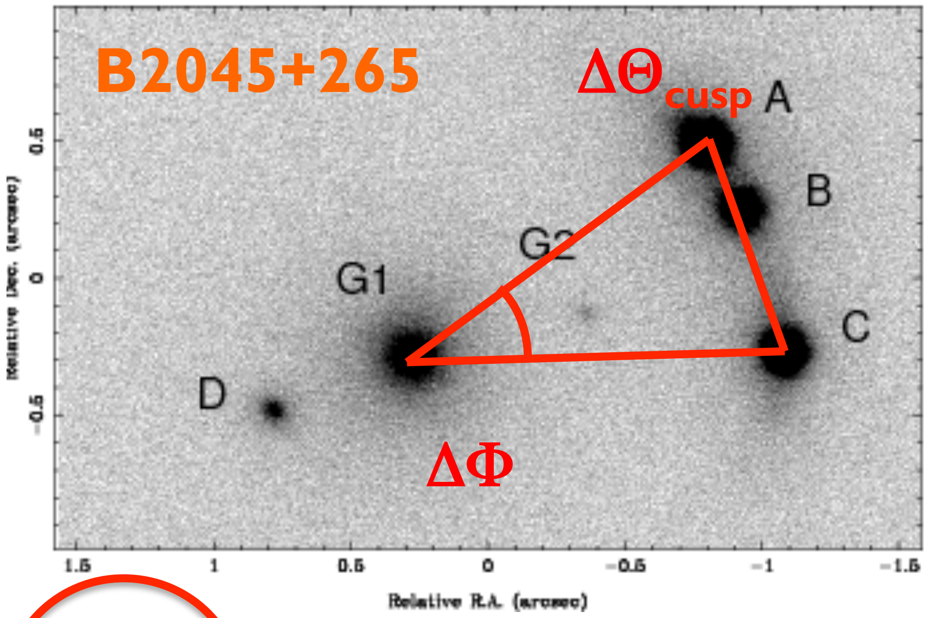
- **Time delay: Φ, Φ_x, Φ_y**

(e.g., Keeton & Moustakas 2009)

- **Flexions: third order derivative**

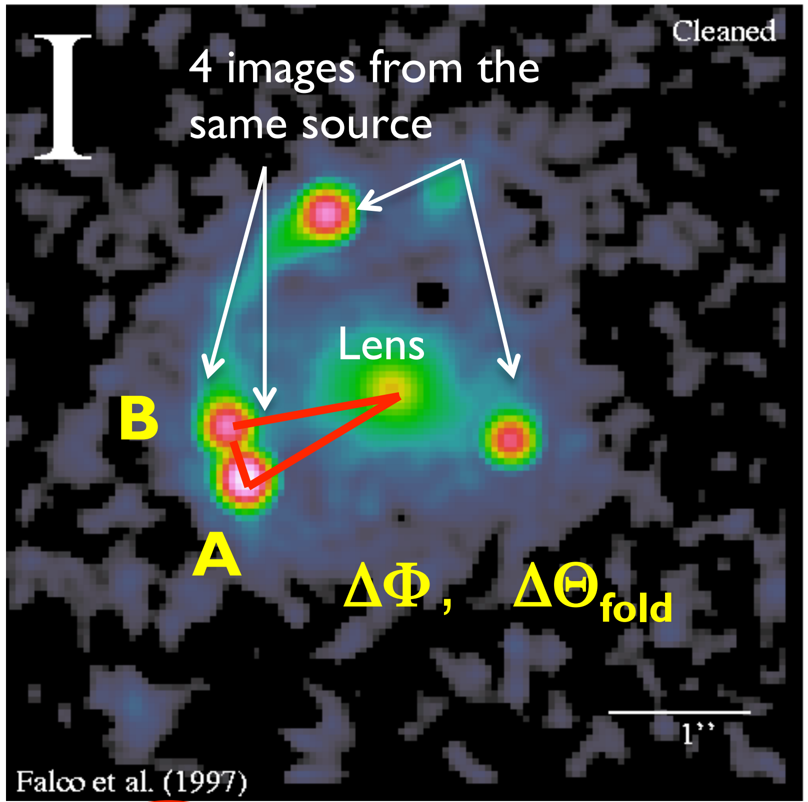
(e.g., Bacon et al. 2006; Er, Ismael, Mao 2012)

Asymptotic relations for folds & cusps



$$R_{cusp} = \frac{|Middle-Outer|}{|Middle+Outer|} \longrightarrow 0$$

when $\Delta\Phi \longrightarrow 0$



$$R_{fold} = \frac{|A-B|}{|A+B|} \longrightarrow 0$$

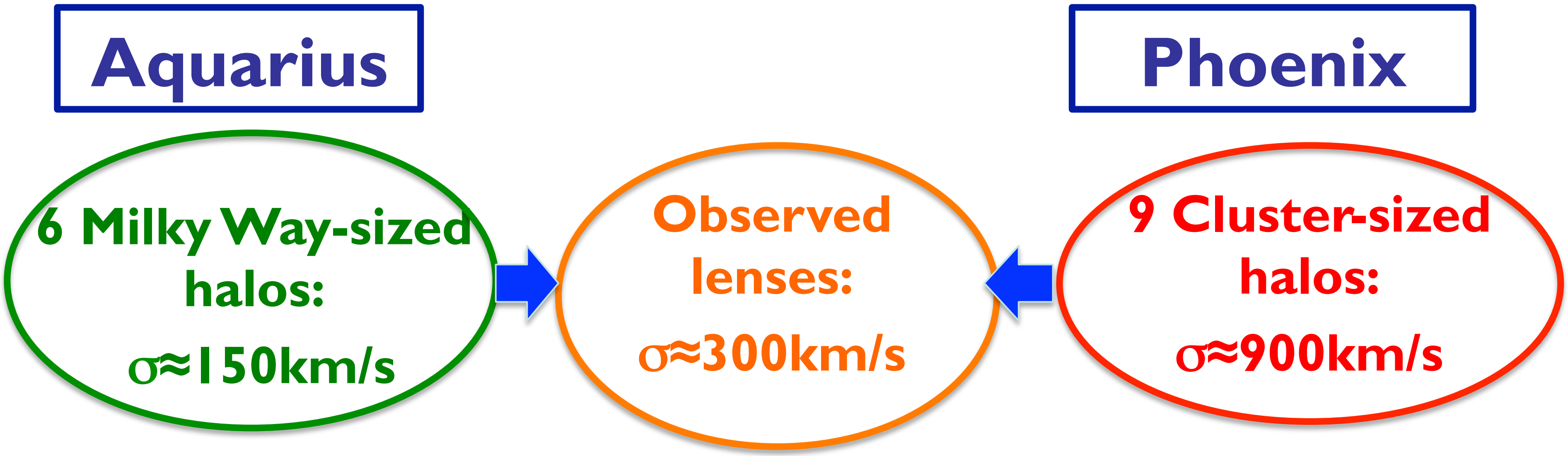
II. R_{cusp} & R_{pair} : statistical predictions

- **Singular isothermal ellipsoid (SIE)**
  + higher-order multipole amplitudes (a3, a4):
  - ✓Einstein radius = 1 arcsecond
  - ✓shape parameters are drawn from SDSS galaxies (Hao, Mao et al. 2006)

- **Adopt randomly orientated external shear**
  - ✓ amplitude is assumed to be a lognormal distribution

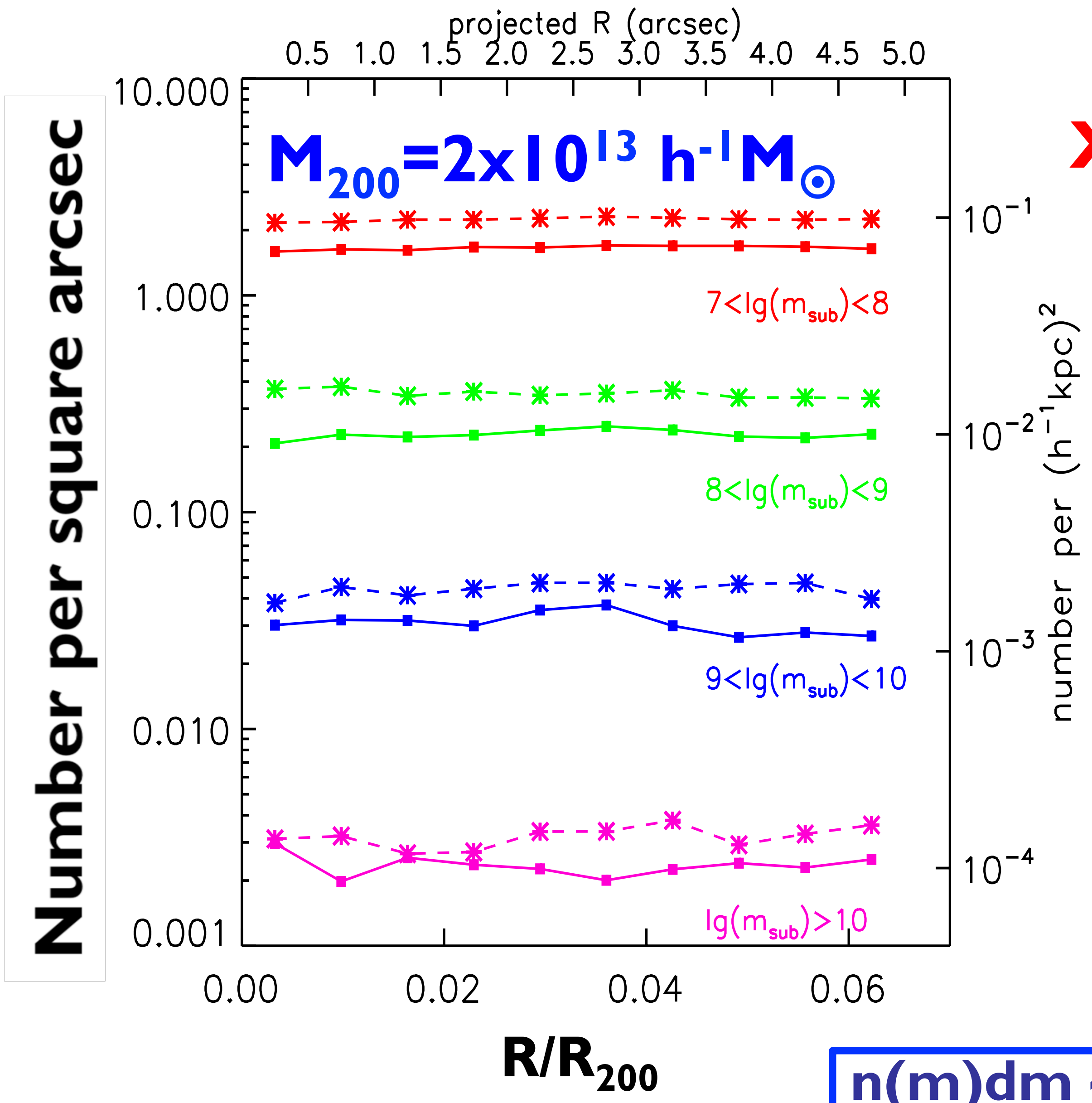
- **Adding in a subhalo population**

Rescaling the subhalo population



- **Rescale subhalo properties: r ~ $M_{200}^{1/3}$, v ~ $M_{200}^{1/3}$; characteristic over-density unchanged**
- **For each rescaled halo, we assume an Einasto density profile**

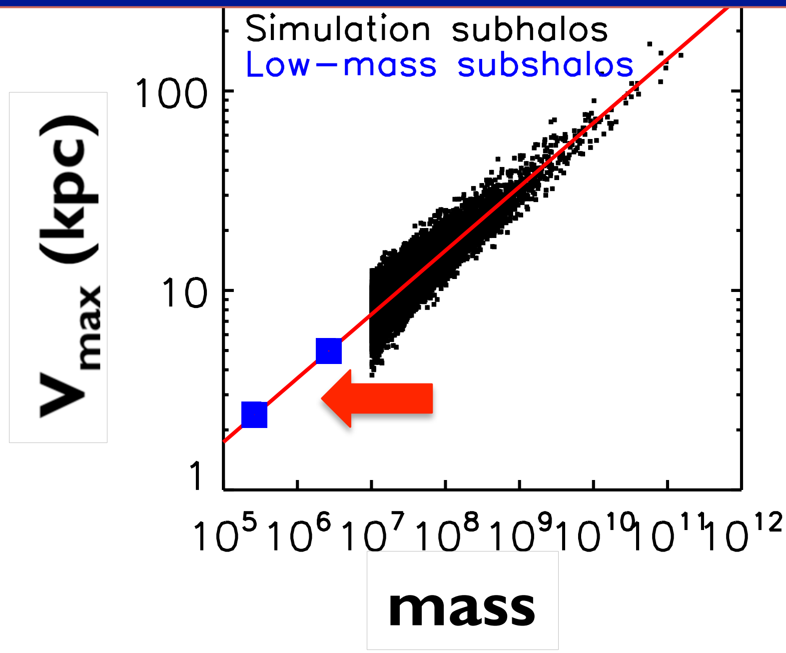
Projected number of subhaloes



X10/dec

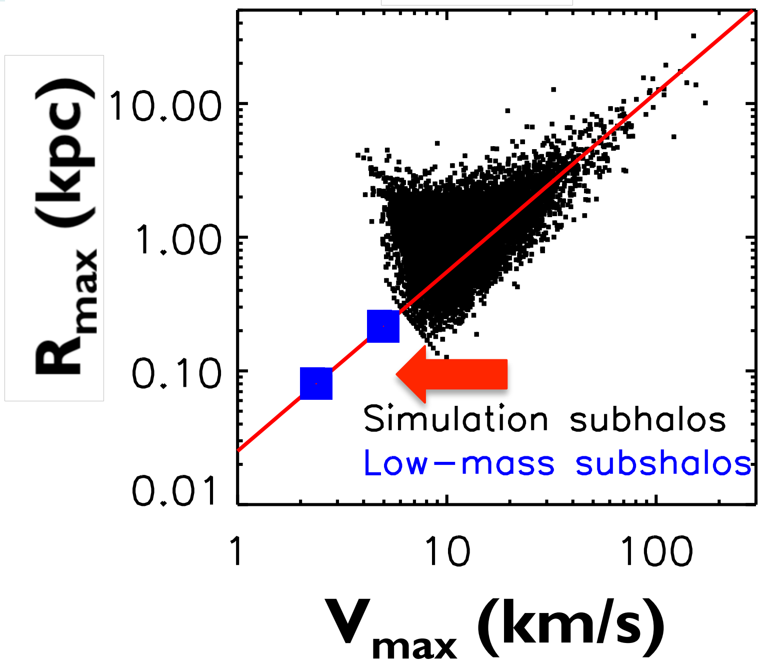
$n(m)dm \sim m^{-0.9}\ d\ logm$

Treating unresolved subhaloes



$V_{max} \sim m^{1/3}$

subhaloes below $10^7 M_\odot$ are unresolved



$R_{max} \sim v_{max}^{4/3}$

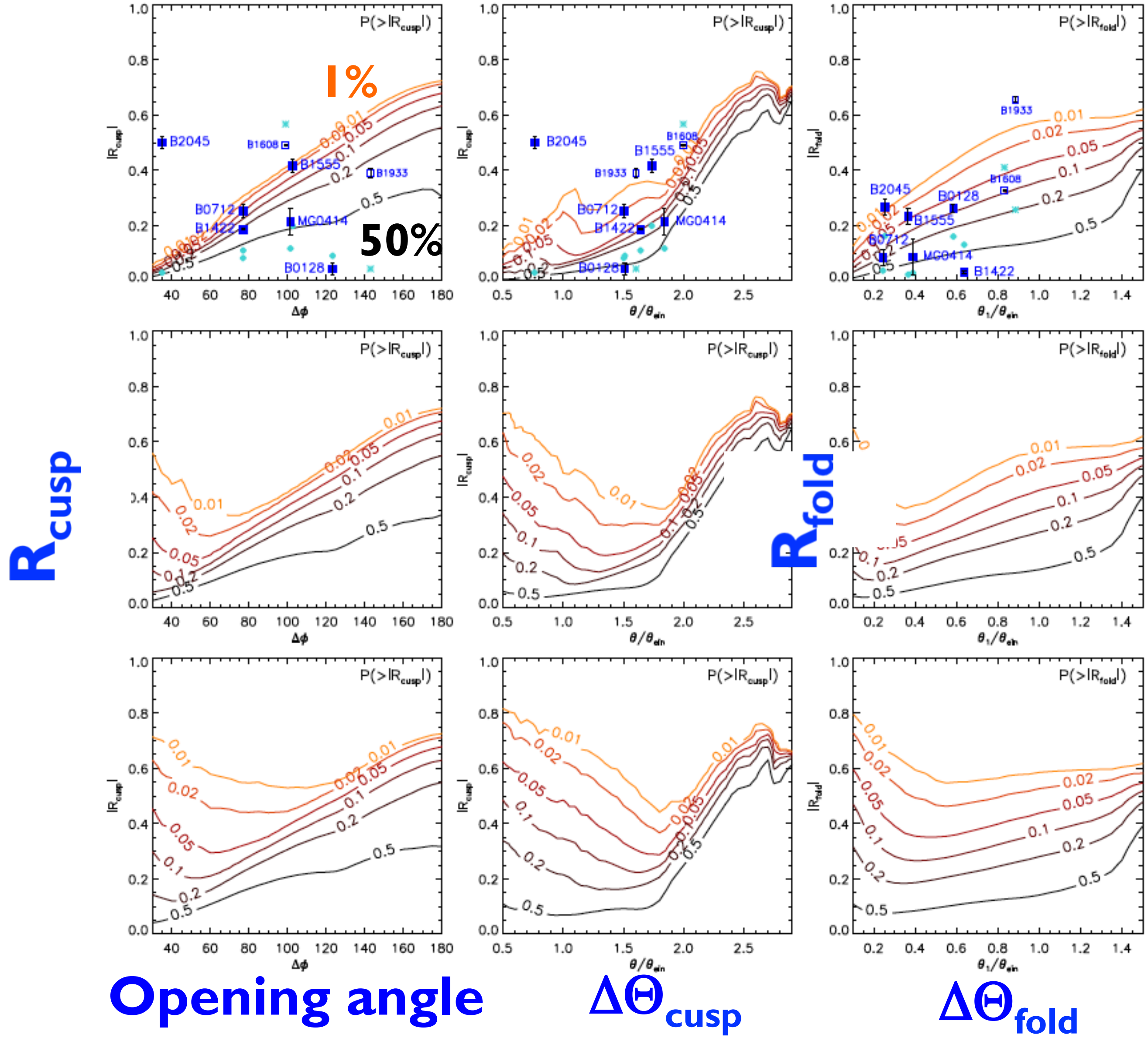
Substructures contribute <~1% around typical Einstein radius

Statistical predictions

Smooth haloes

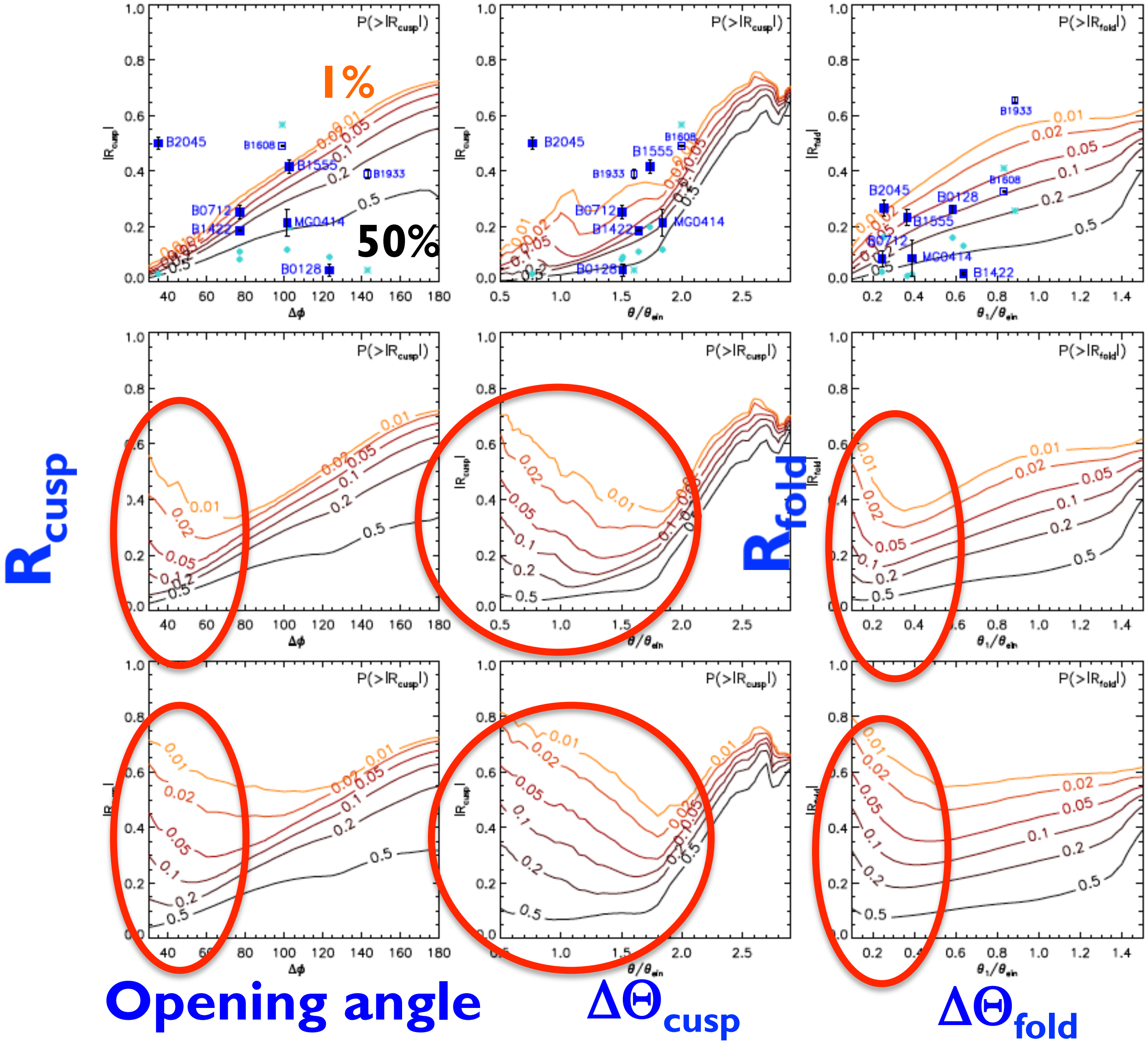
+ subhaloes in Milky Way-sized haloes

+ subhaloes in group-sized haloes ($5x10^{13}$ $M_\odot$)



Statistical trends

- **Subhaloes induce much larger scatters.**
- **close pairs and triples show more deviations**



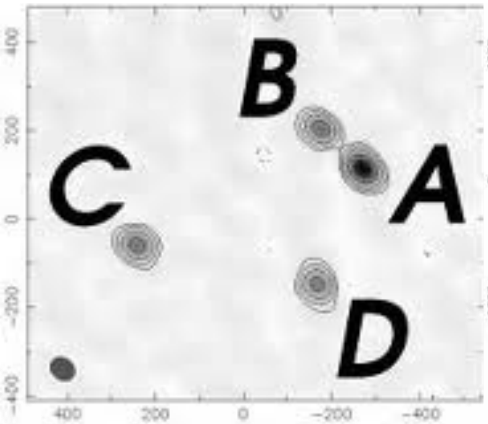
Limitations

The above statistical study does not take into account

- ➢ Lens populations
- ➢ Envionmental effects
- ➢ Selection effects
- ➢ Magnification bias

An alternative is to add substructures directly into observed radio lenses

Fold and cusp radio lenses



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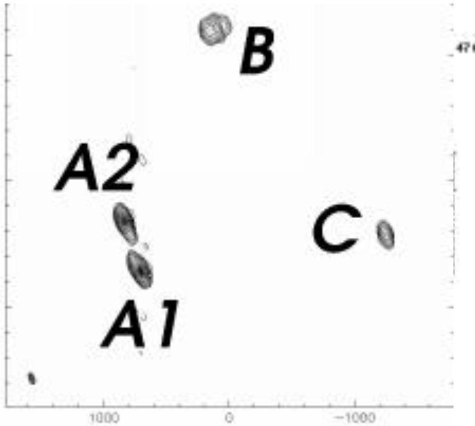
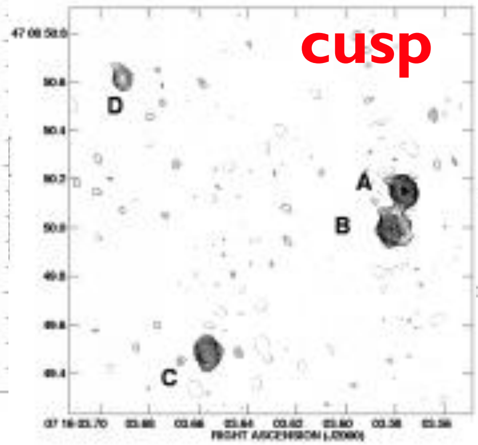
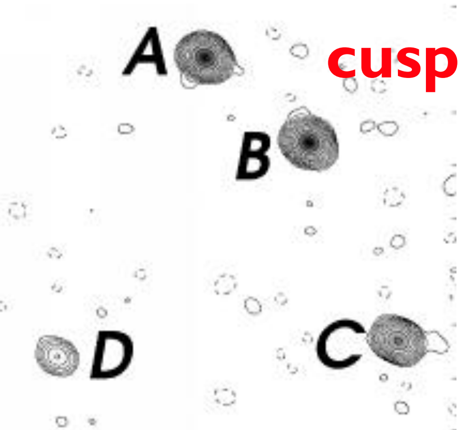


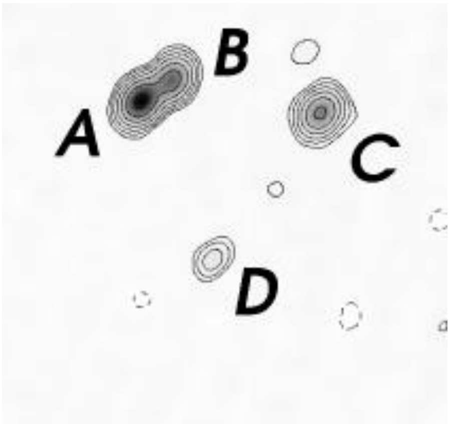
MG0414+053



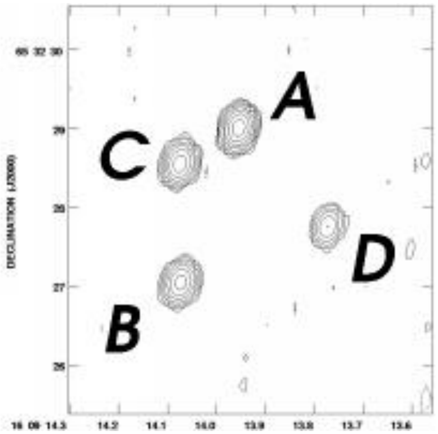
B0712+231



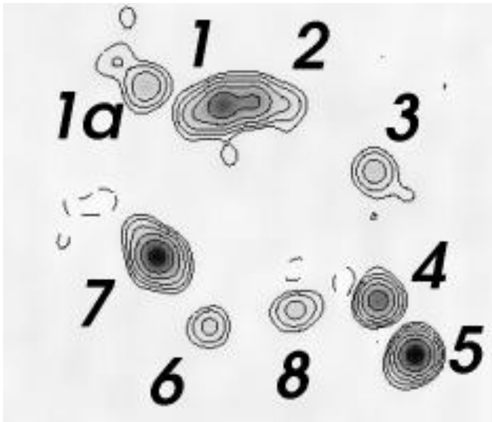
B1422+231



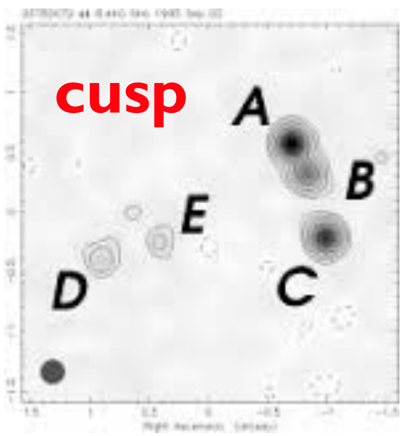
B1555+375



B1608+656



B1933+503



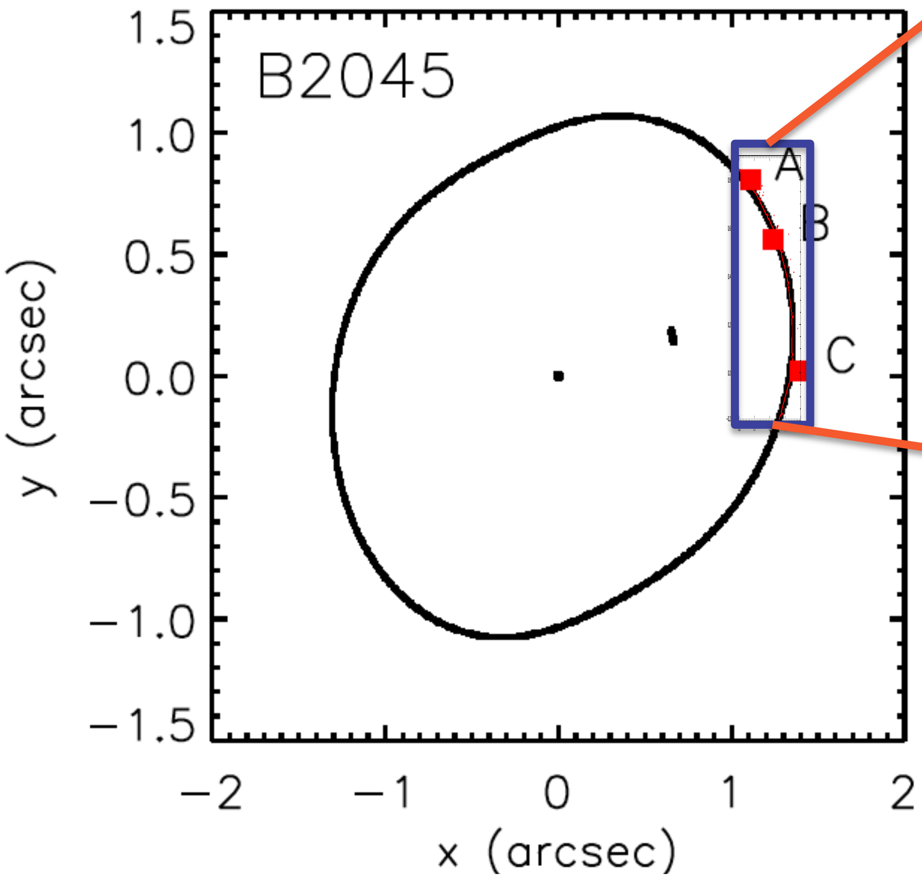
B2045+265

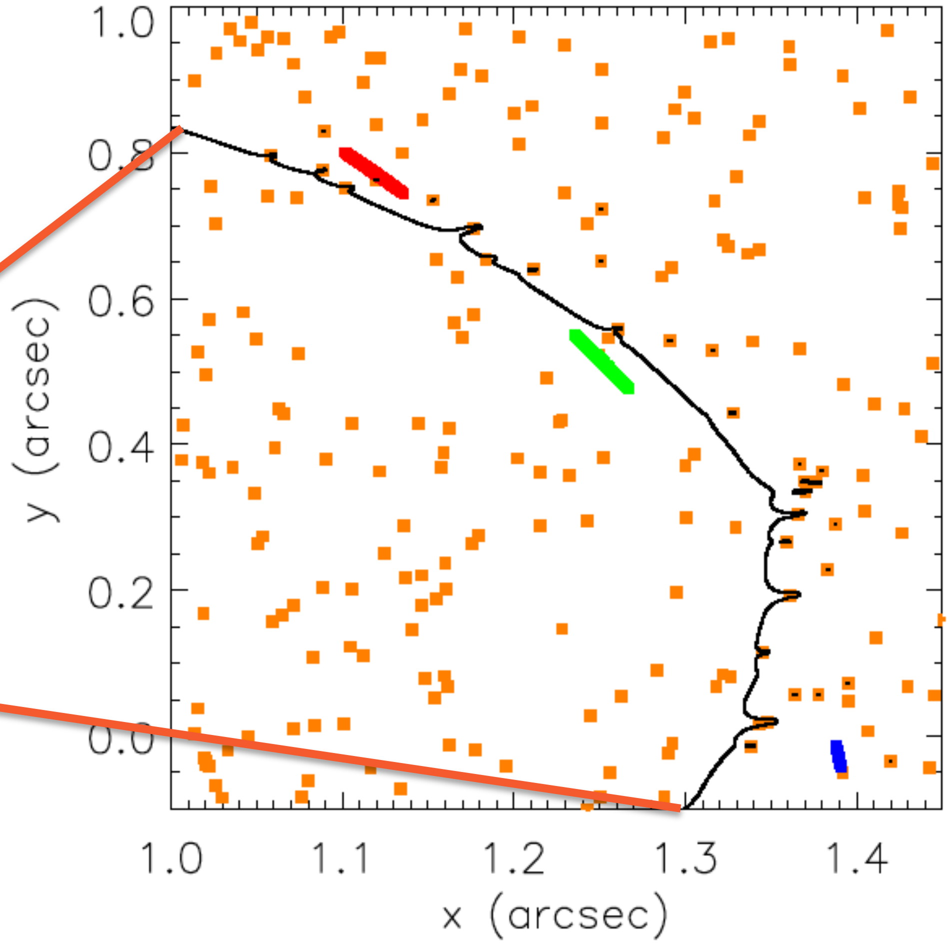
Studying substructure effects in observed radio lenses

- **Macro-model for each observed lens:**
  SIE (main lens)+γ_{ext}+SIS (secondary lens)
- **Adopt rescaled subhalo population from Aquarius and Phoenix simulations**
  observed velocity dispersion → halo $v_{max}=2^{1/2}\,\sigma$
- **Selecting similar lens systems**
  - Opening angle, Einstein radius and close pair (triple) image separations are within 10% of the observed values

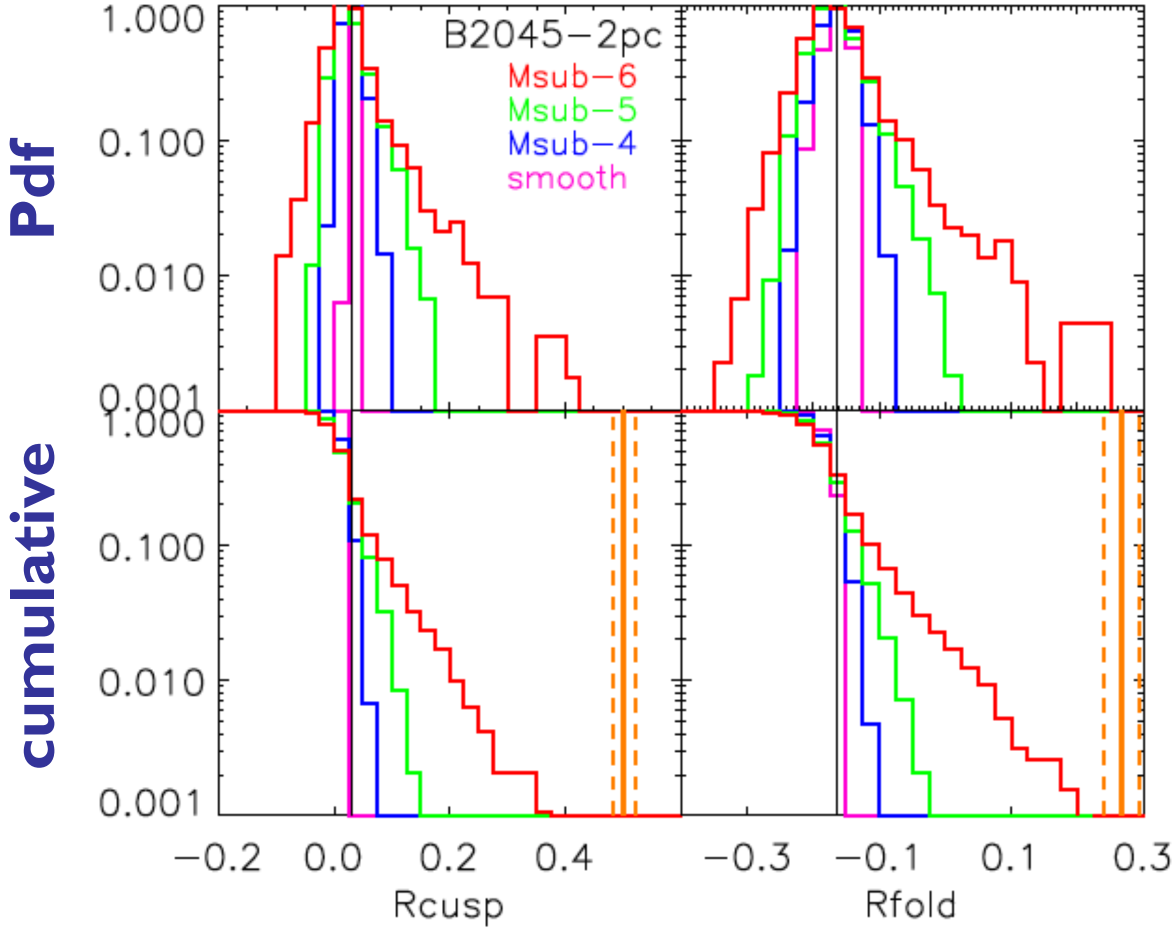
Critical curves with substructures

case study B2045





Contributions from low mass subhaloes



Purple: smooth

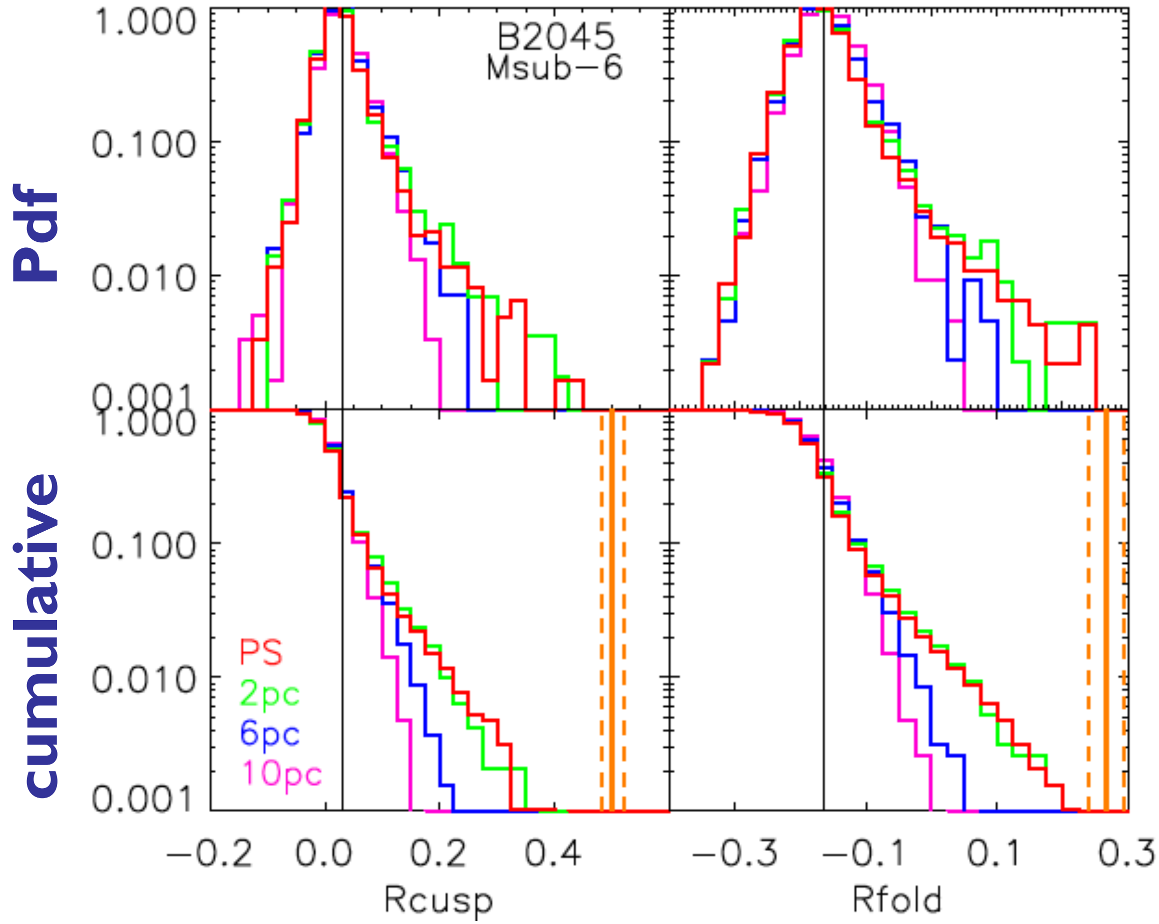
red: 10^6 $M_\odot$

green: 10^5 $M_\odot$

blue: 10^4 $M_\odot$

- **Large subhaloes cause most deviations**
- **We can ignore subhalos below 10^5 solar masses**

Dependence on source size



Source size:

red: point

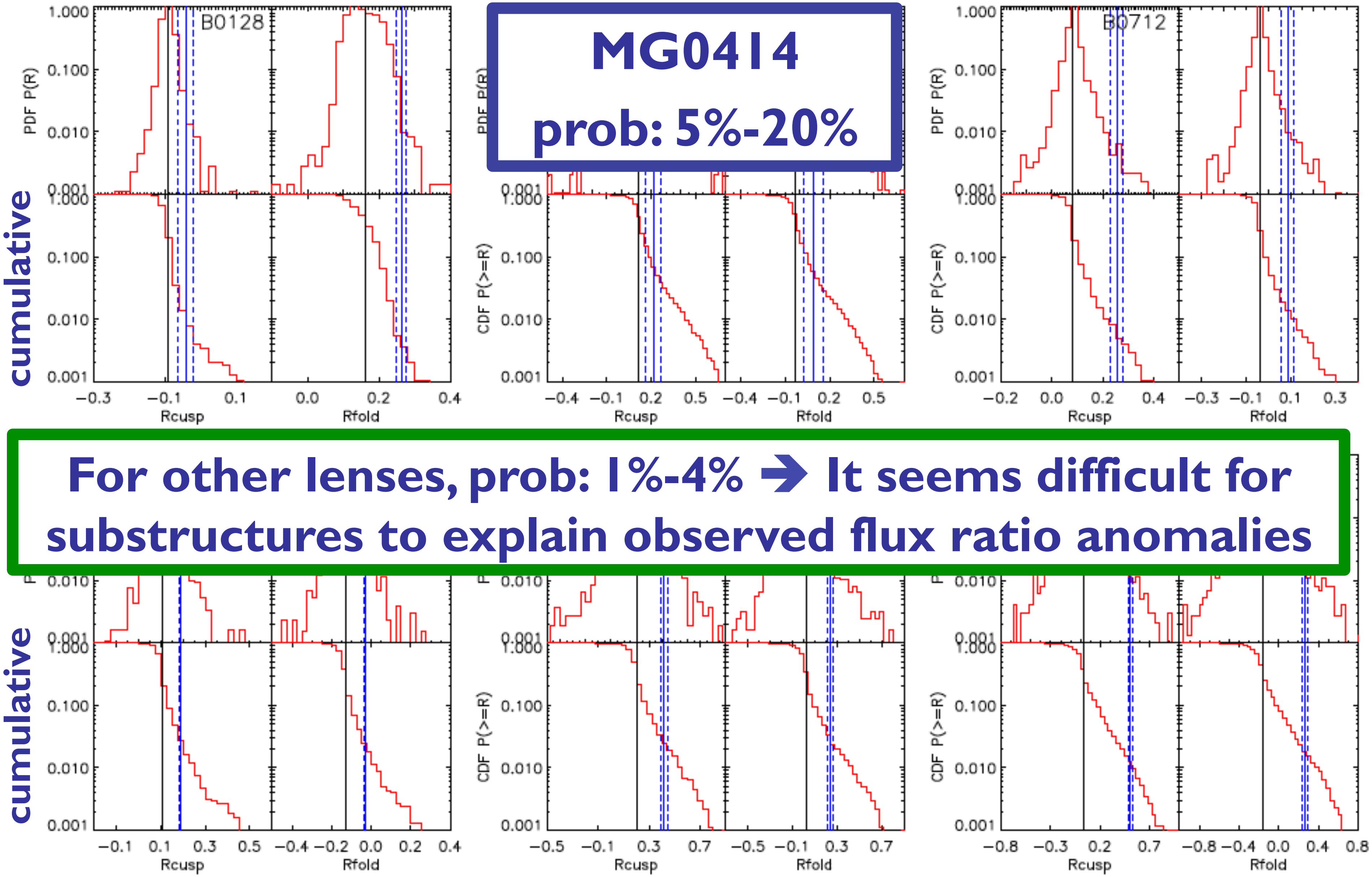
green: 2pc

blue: 6pc

Purple: 10pc

- ➢ **The smaller the source size, the more significant the deviations**
- ➢ **Assume point source for maximum deviations**

Main results



MG0414

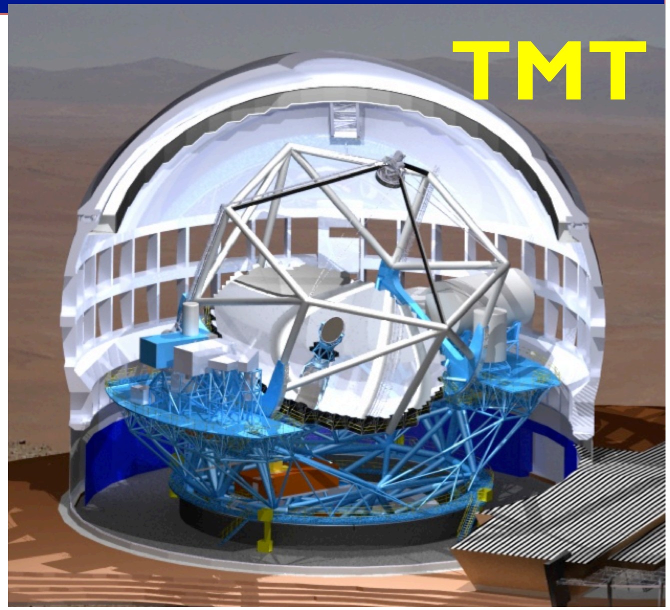
prob: 5%-20%

For other lenses, prob: 1%-4% → It seems difficult for substructures to explain observed flux ratio anomalies

Discussions

- **CDM substructures appear to under-predict the observed radio flux ratio anomalies**
- **Line of sight effects? (Xu et al. 2012; see talks by Inoue & Takahashi)**
- **Oversimplifications in the macro-model**
  - ✓ **Environment?**
  - ✓ **SIE too simplistic (isophotal twists, deviations from ellipses, non-concentricity)?**
- **Why are saddle images always fainter than expected?**

Future outlook: observations



- **higher resolution and deeper images and more kinematical data**
- **Astrometric lensing (Vegetti's talk): more promising? More codes?**
- **Time delay anomaly?**
- **Narrow-line flux ratios (talk by Nierenberg)**
- **TMT can probe substructures with mass lower by a factor of 100**

Future outlook: theory

- Theoretically, better hydro-simulations are needed
  - ✓ to assess subhalo abundance and spatial distribution: importance of baryons
  - ✓ High-resolution group simulations needed?
  - ✓ particle number sufficient?
- better smoothing algorithm (Augulo et al. 2013)? Tracking?
- We need to better assess the line of sight effect