Gravitational lensing as a probe of dark matter on subgalactic scales

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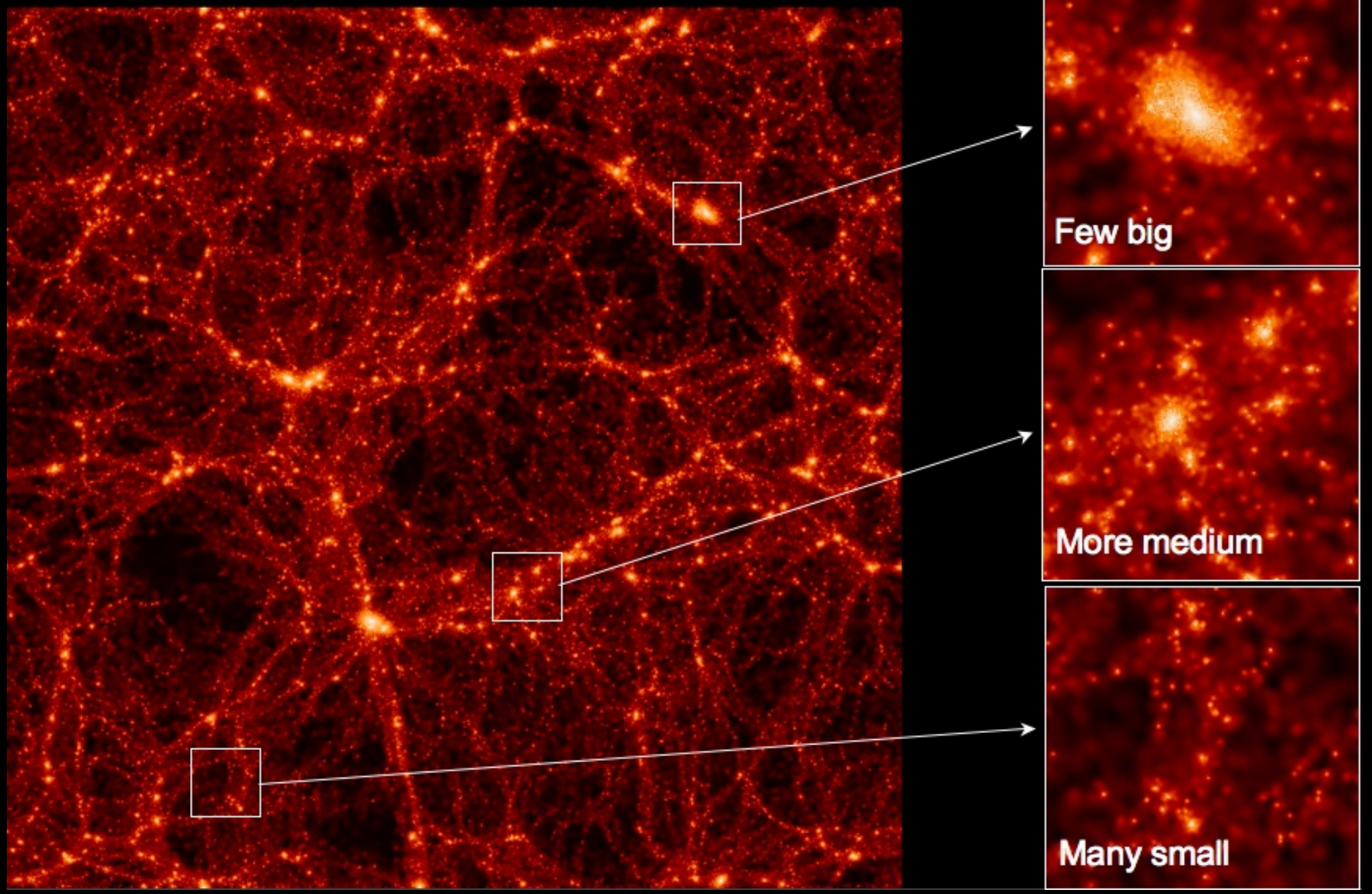
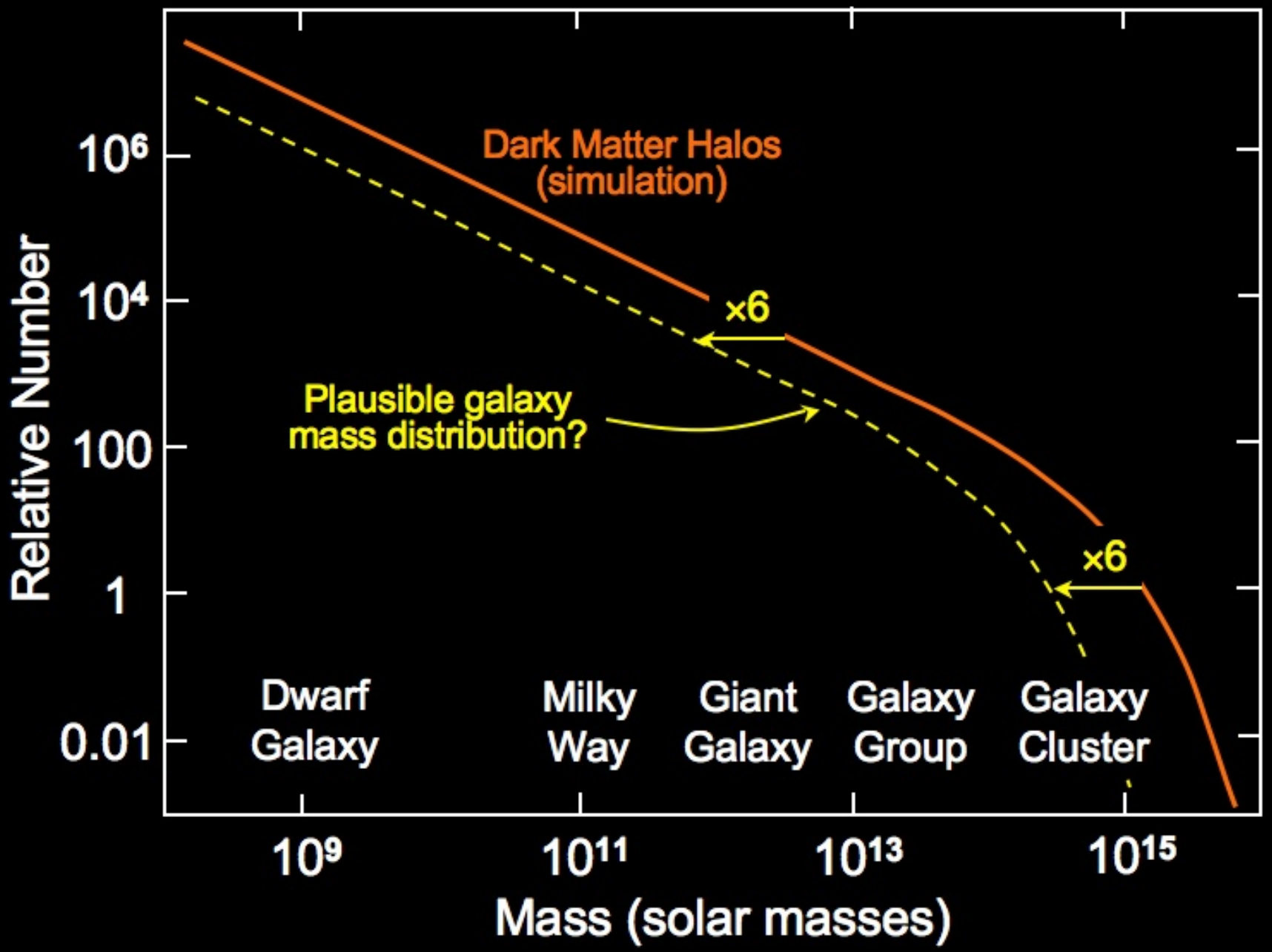
Outline

- Small-scale ΛCDM and its challenges
- Role of Gravitational lensing
- Different probes, different constraints
- Strong-lensing systems with VLBI
- Further questions
- Work in progress

The web of cold dark matter halos



Halo and galaxy mass functions



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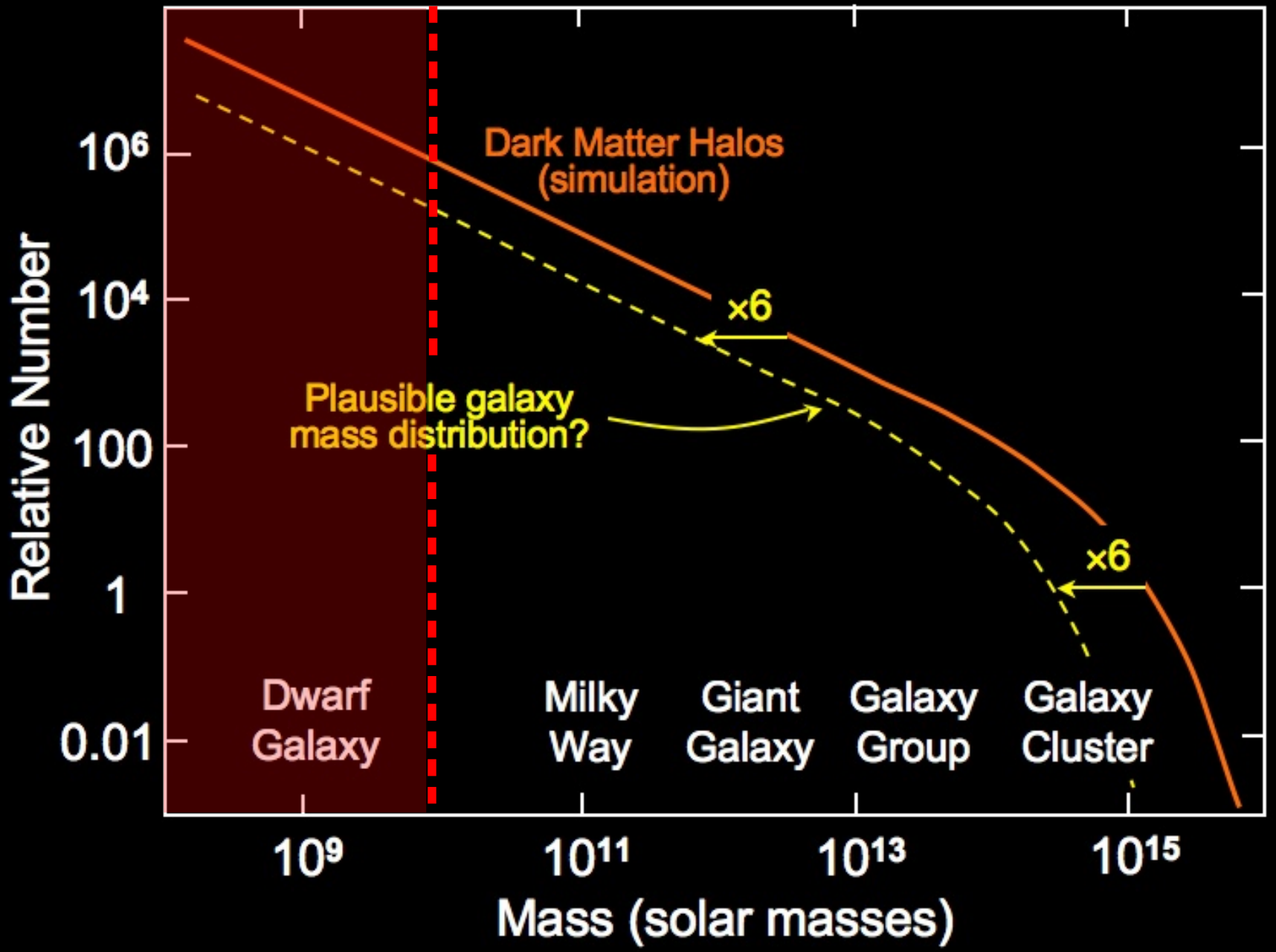

Where is the trouble ?

- Abundance matching → the missing-satellite problem
  (Moore et al. 99, Klypin et al. 99)

  "Galactic luminosity is a monotonic function of halo mass"

- Central slope → the core-cusp problem
  (Moore 1994, Navarro et al. 1996, 1997)

  Is there a universal halo density profile? What is that?

- Normalization → the too-big-to-fail problem
  (Boylan-Kolchin et al. 2011)

  At which z most massive subhalos correspond to brightest dSphs?

- Spatial distribution → the disk of dSphs arounf MW and Andromeda
  (Metz et al. 2009)

  Can collisionless/dissipationless matter form disk?

Where is the trouble ?

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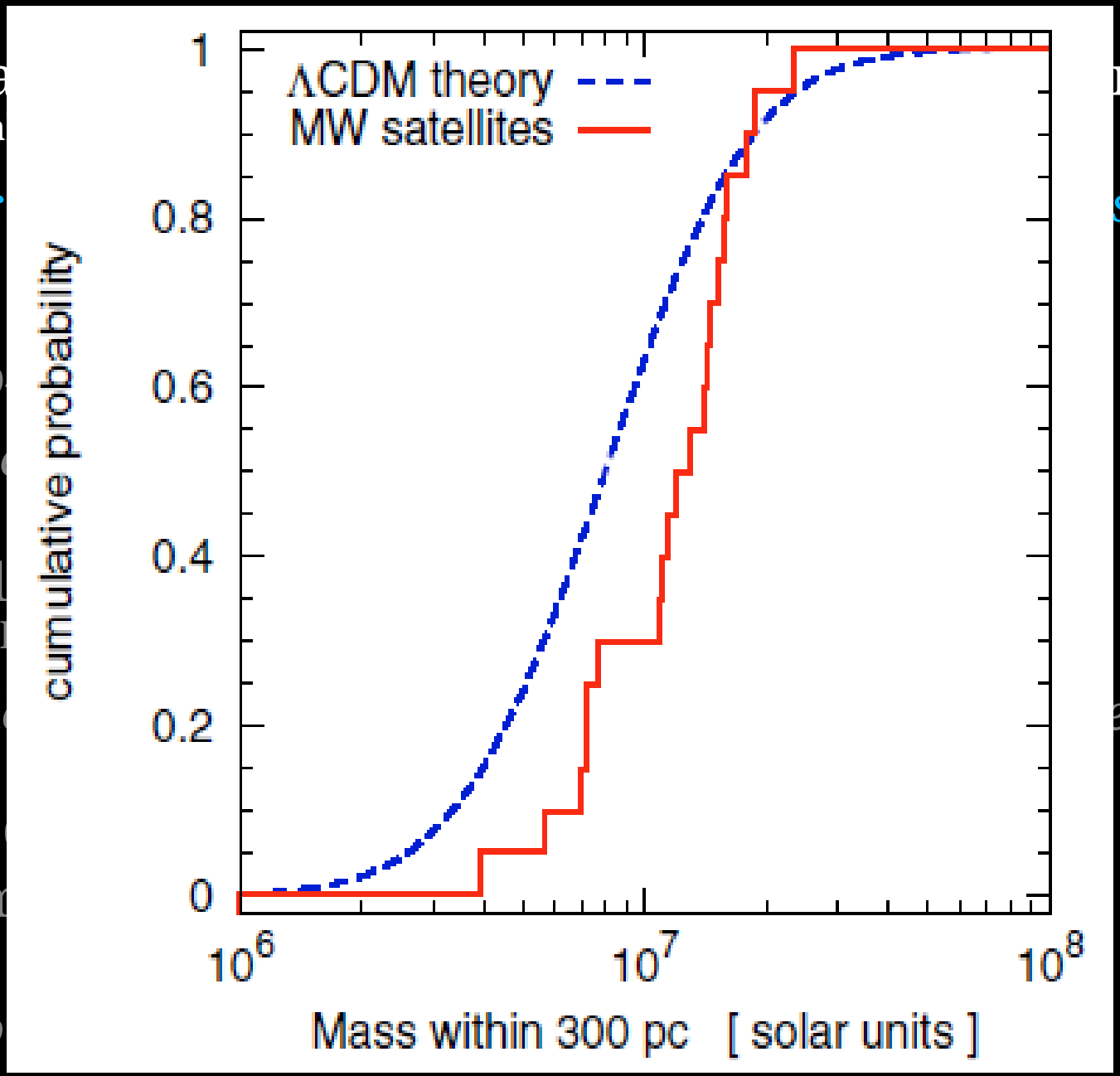

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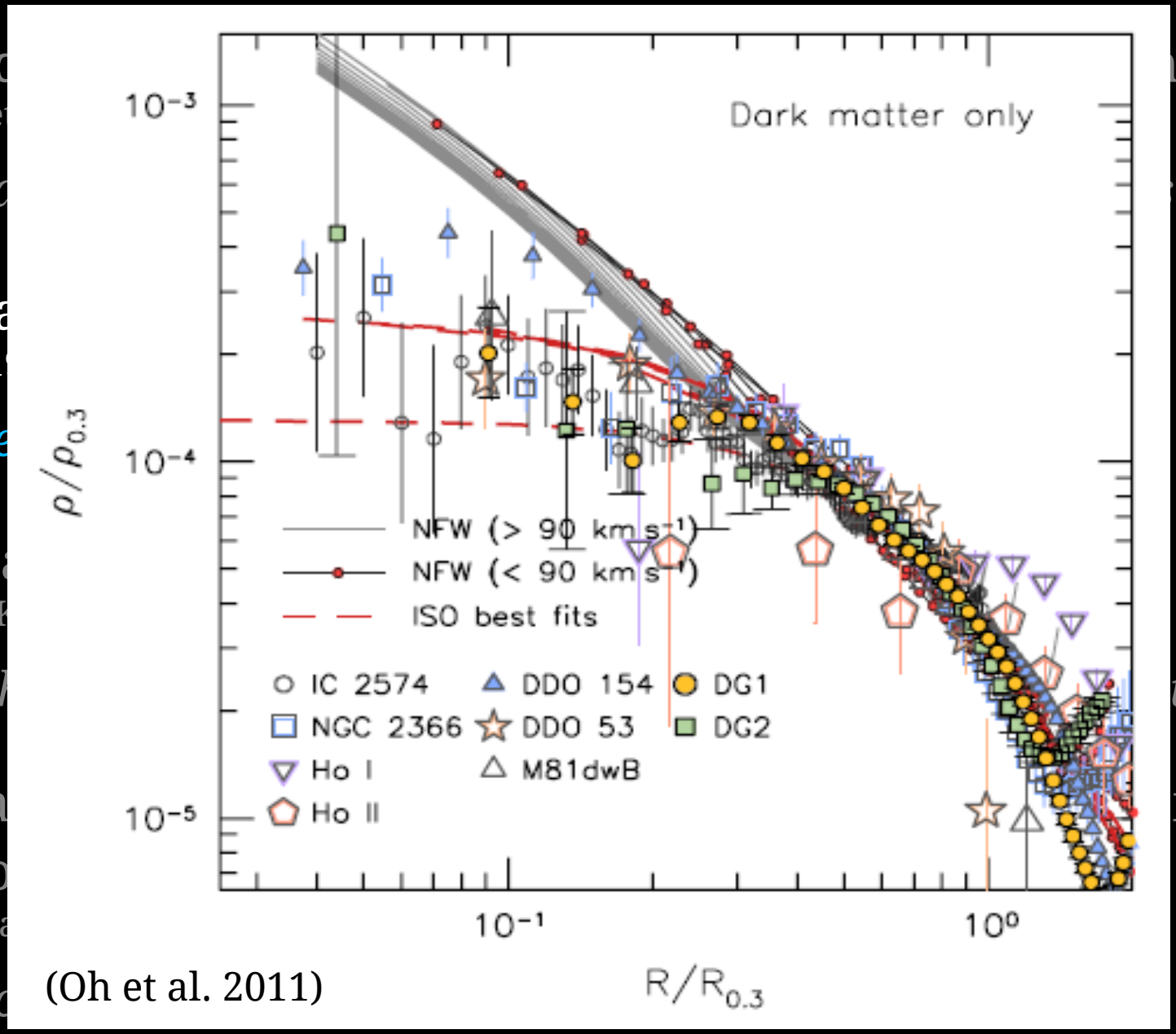

(Oh et al. 2011)

Where is the trouble ?

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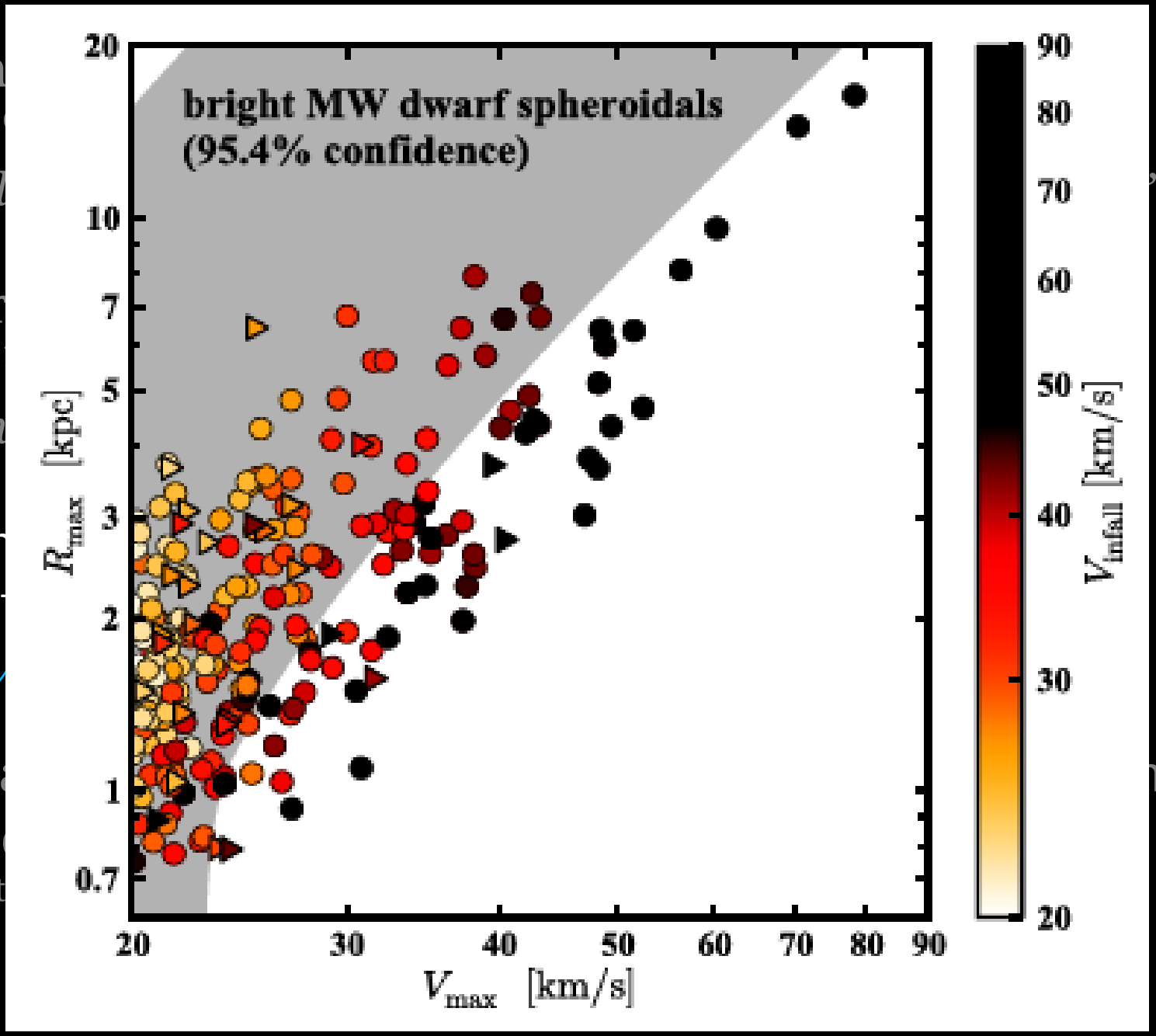

dSphs?

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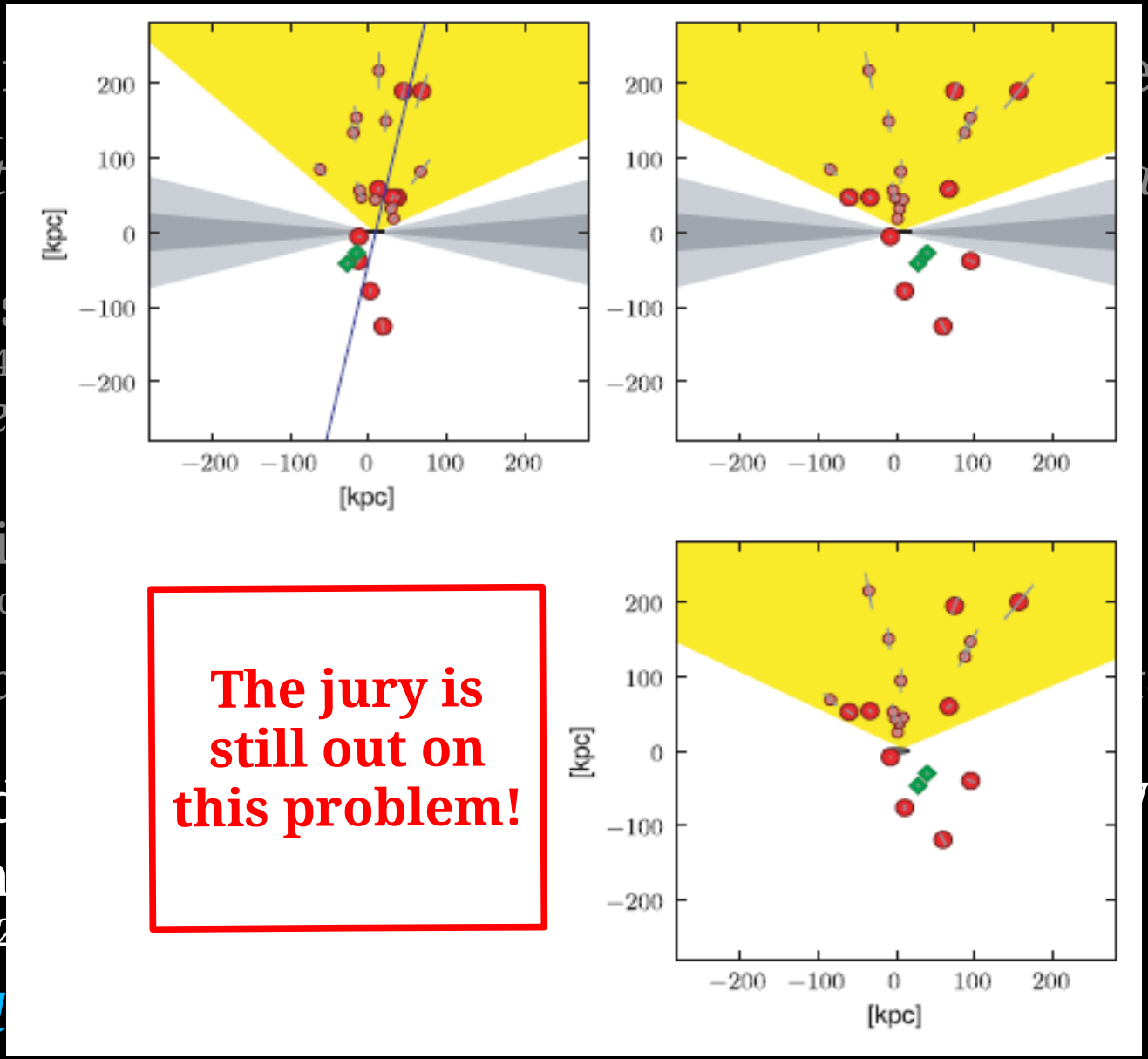
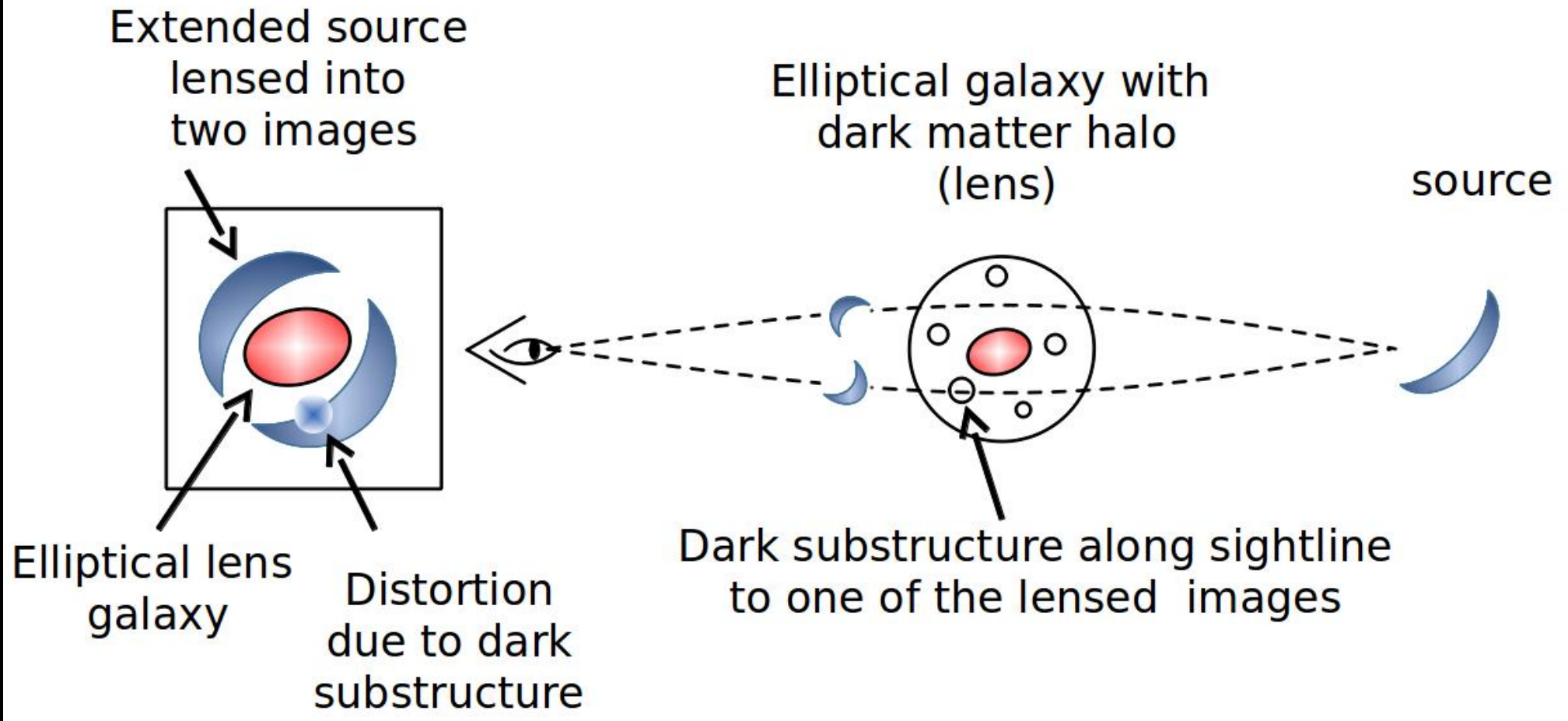
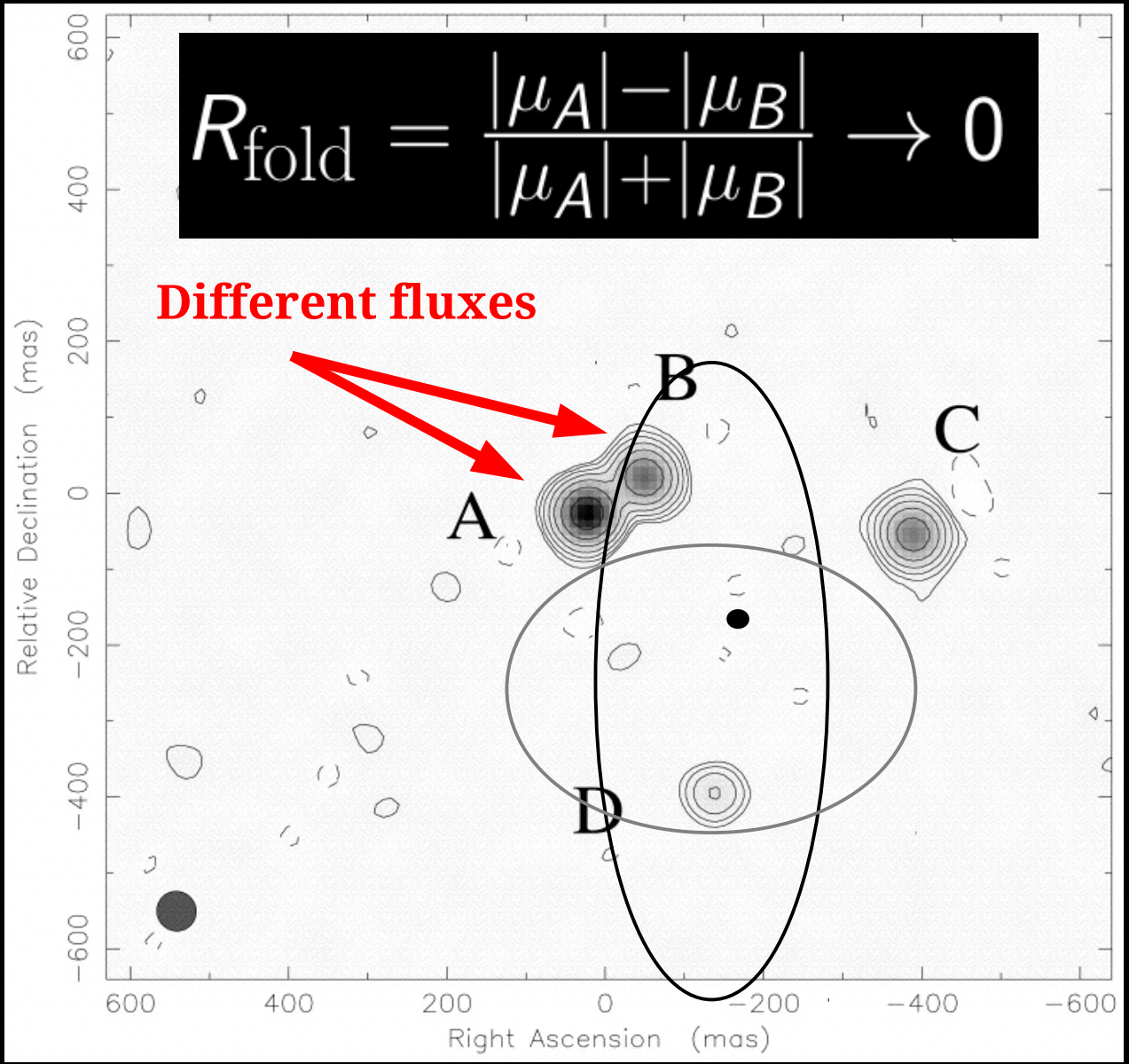


Gravitational lensing at help...



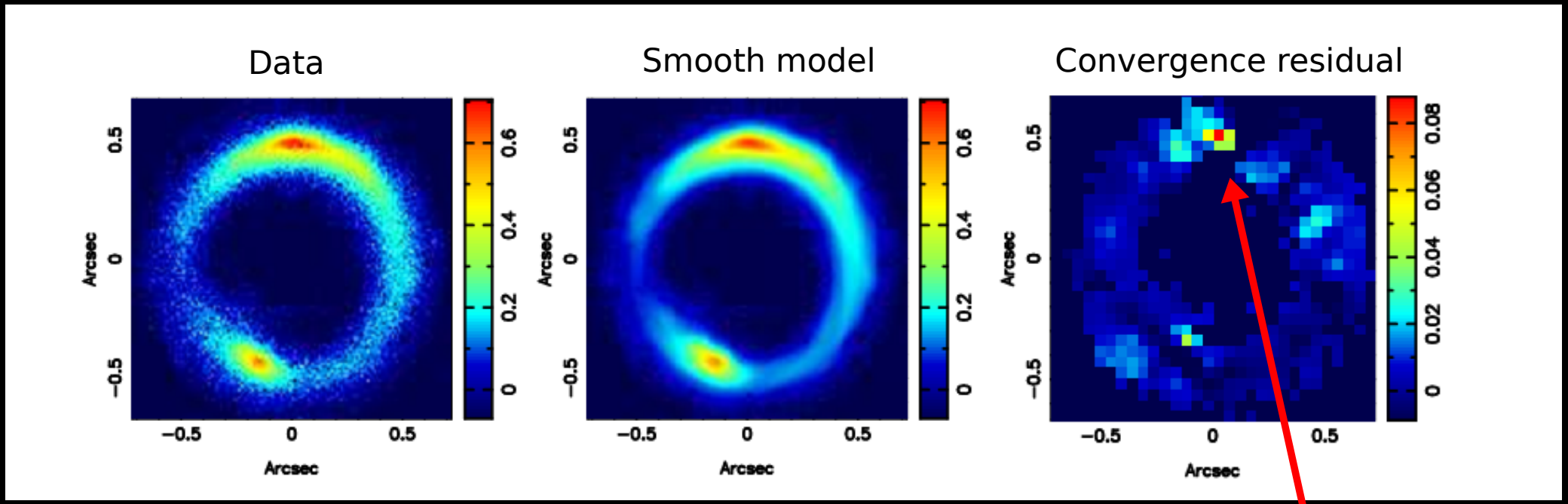
Any supporting observations?



(Marlow et al. 1999)

Any supporting observations?

HST + Keck (2.2 & 1.6 micron) observations



(Vegetti et al. 2012)

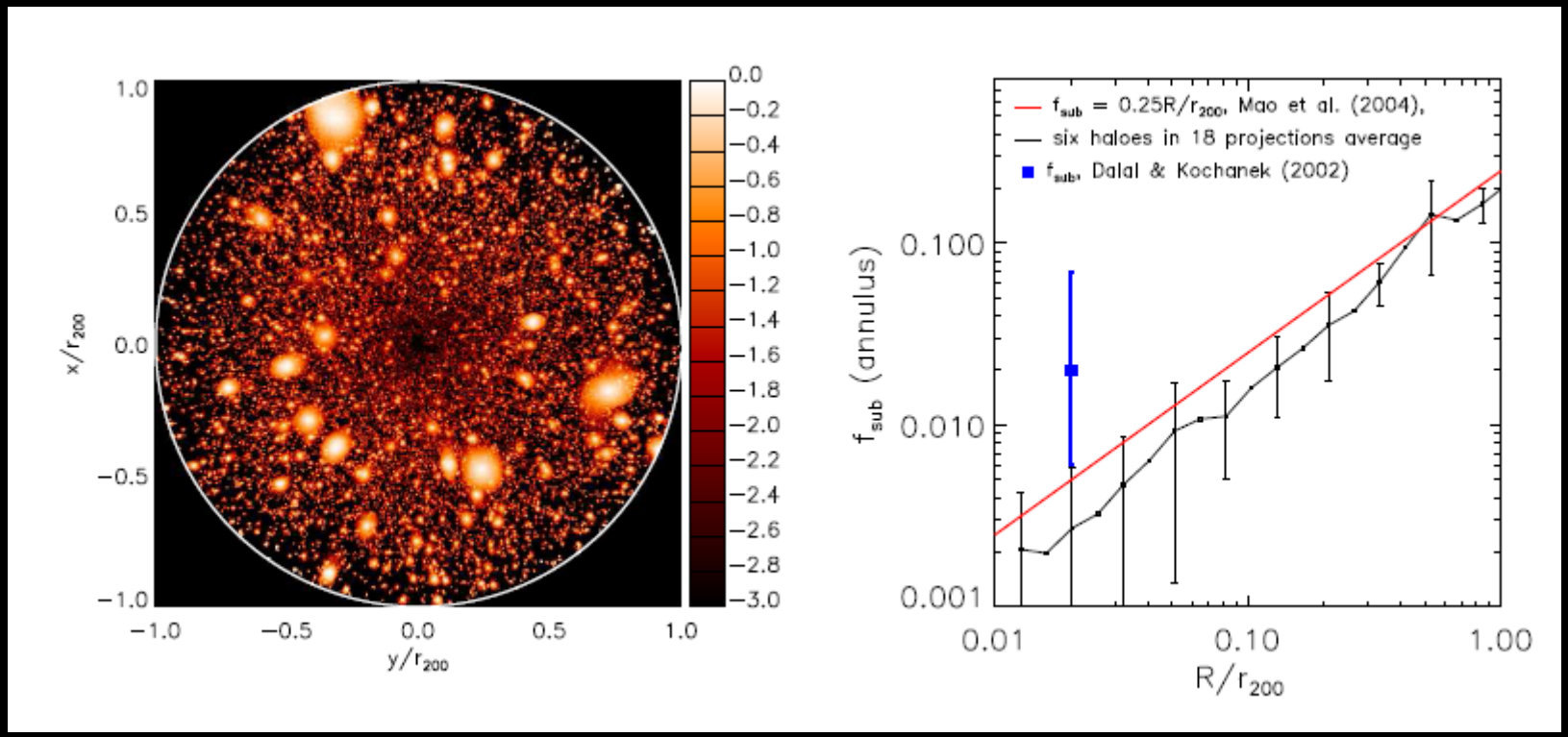
10^8 M_{solar} subhalo

Weird: Detections give tentative evidence for *more* substructure than predicted by CDM, and a flatter subhalo mass function

N-body simulations vs. detections

Relative substructure surface mass fraction:

Aquarius N-body simulation



(Xu et al. 2008)

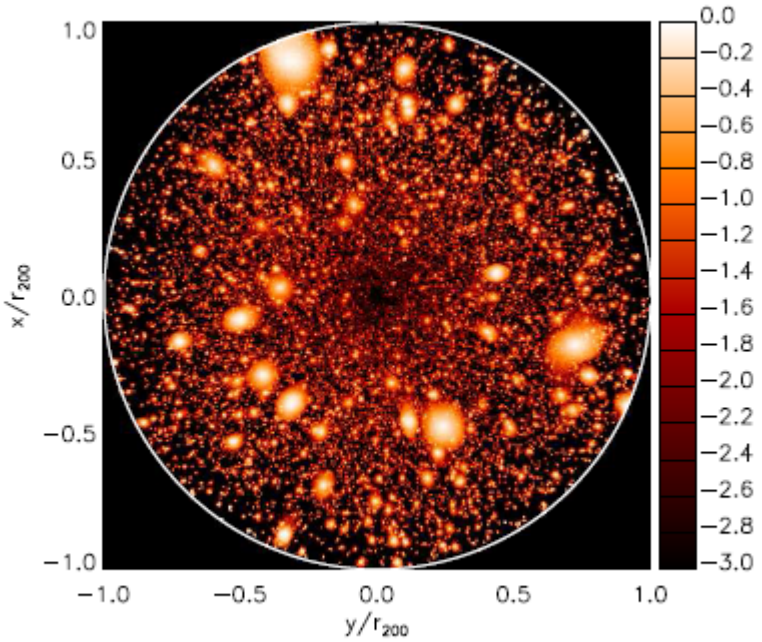
$$f_{\rm sub} \equiv \frac{\Omega_{\rm sub}}{\Omega_{\rm CDM}}$$

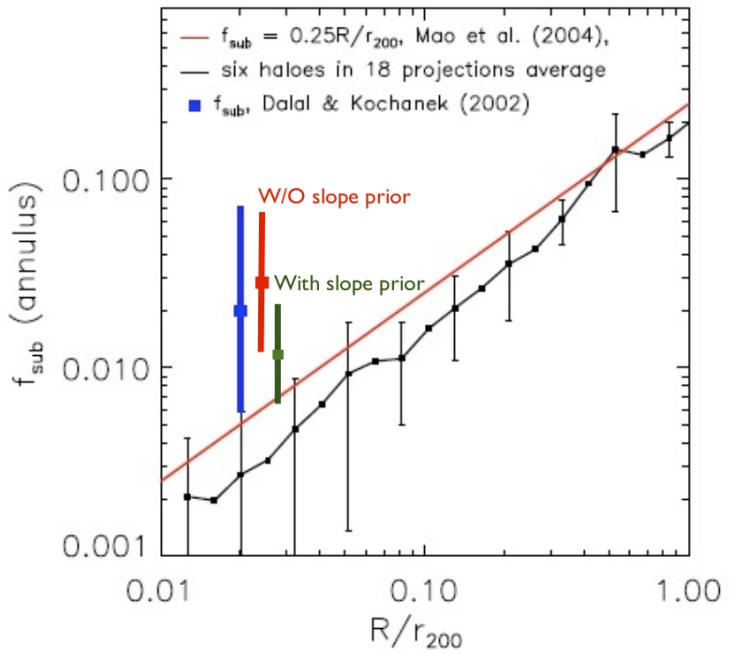
$$f_{\rm sub} \approx 0.002$$

N-body simulations vs. detections

Relative substructure surface mass fraction:

Aquarius N-body simulation





(Vegetti et al. 2010 & 2012)

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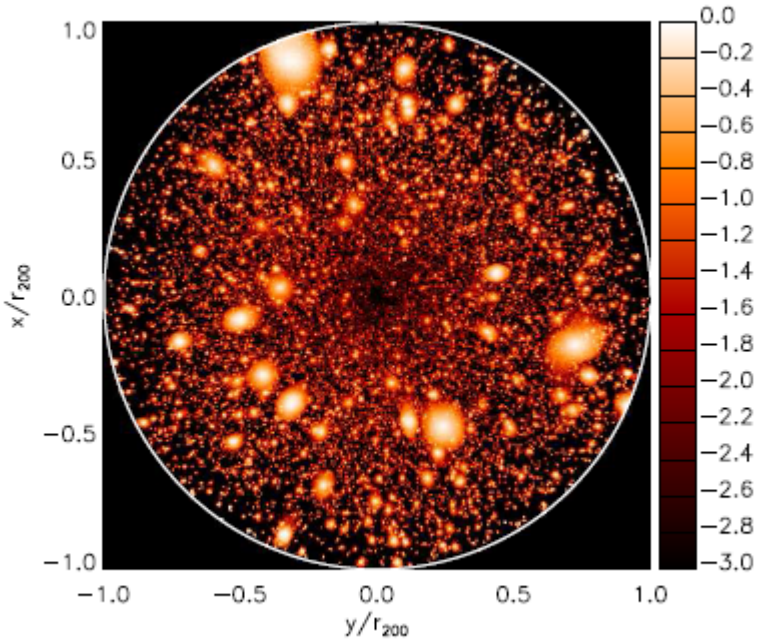

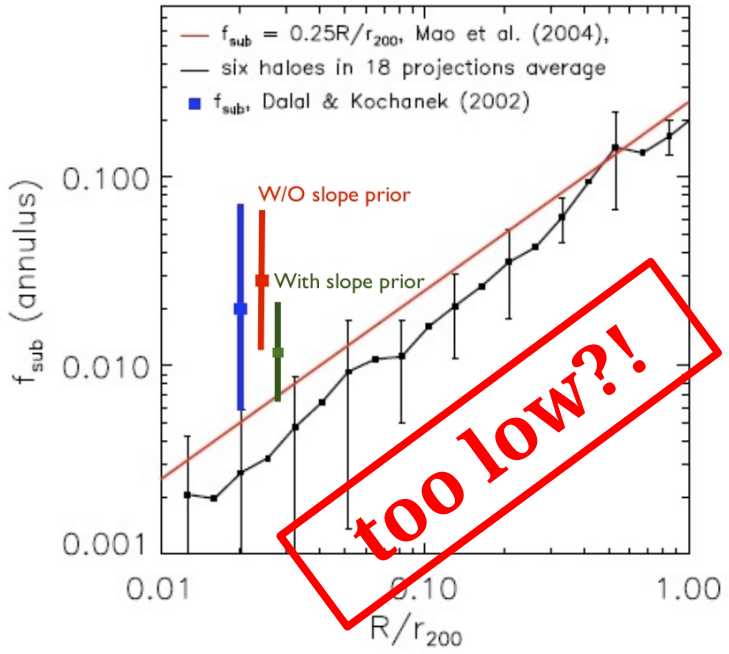

(Vegetti et al. 2010 & 2012)

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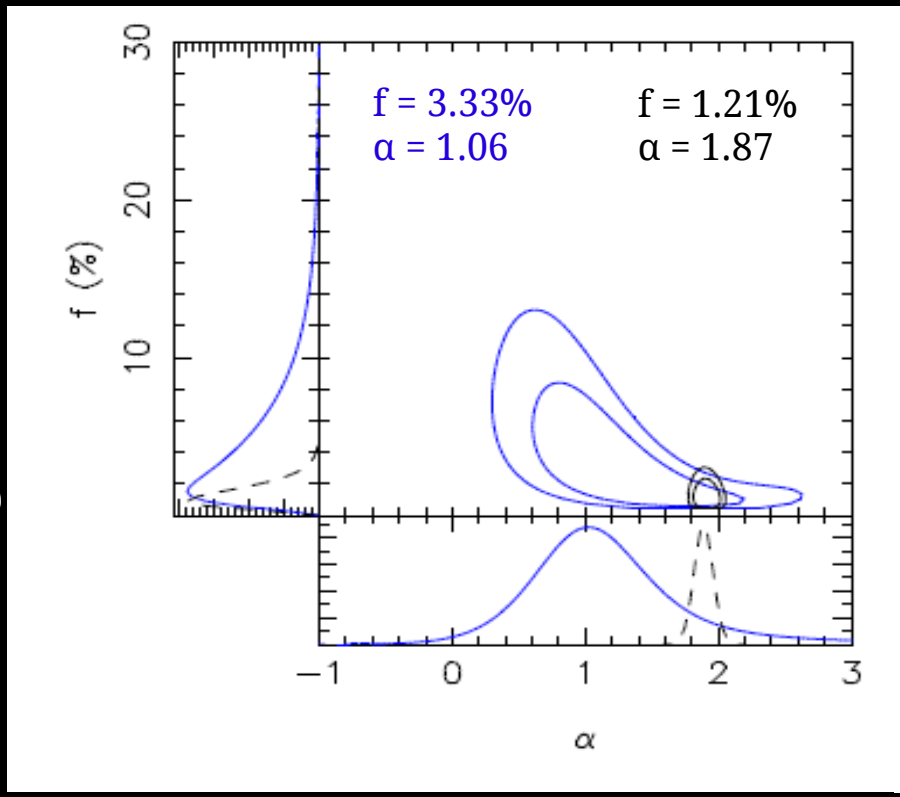
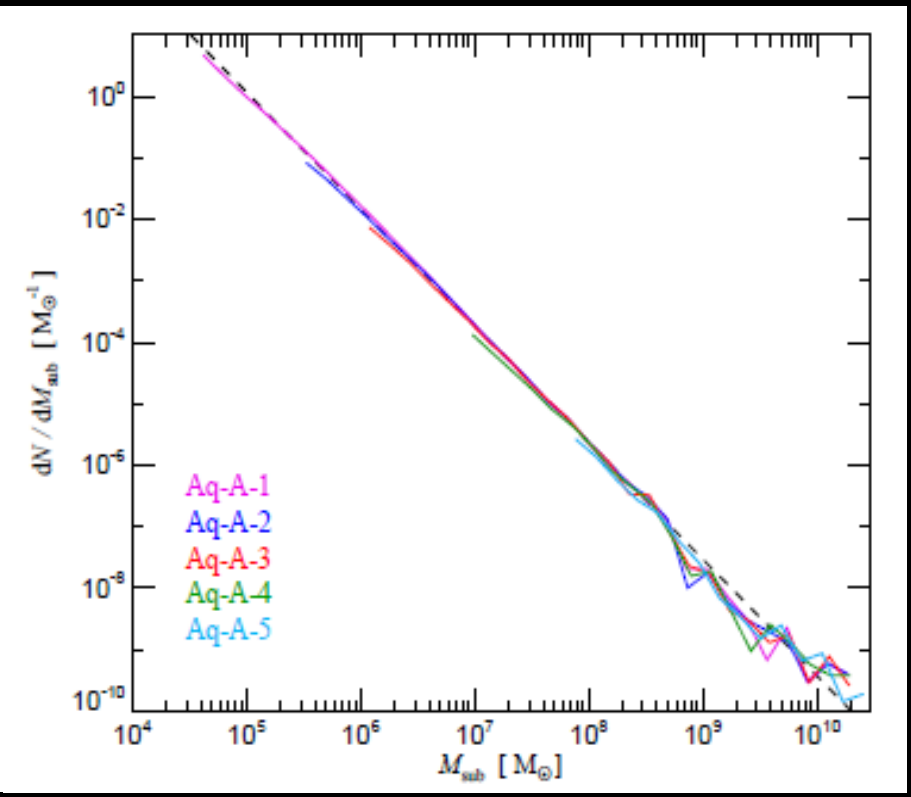
N-body simulations vs. detections

Slope of the galactic subhalo mass fucntion:

(Vegetti et al. 2010 & 2012)





(Springel et al. 2008)

$$\frac{dN}{dM}_{\text{vir}} \propto M_{\text{vir}}^{-\alpha}$$

$$\alpha = 1.9$$

N-body simulations vs. detections

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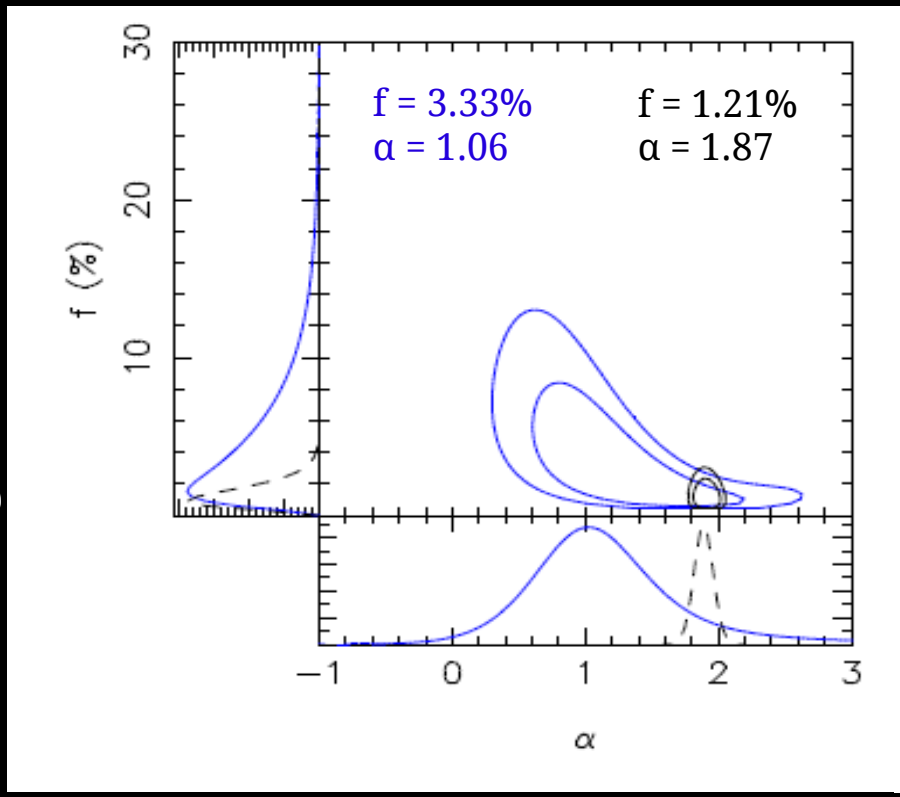

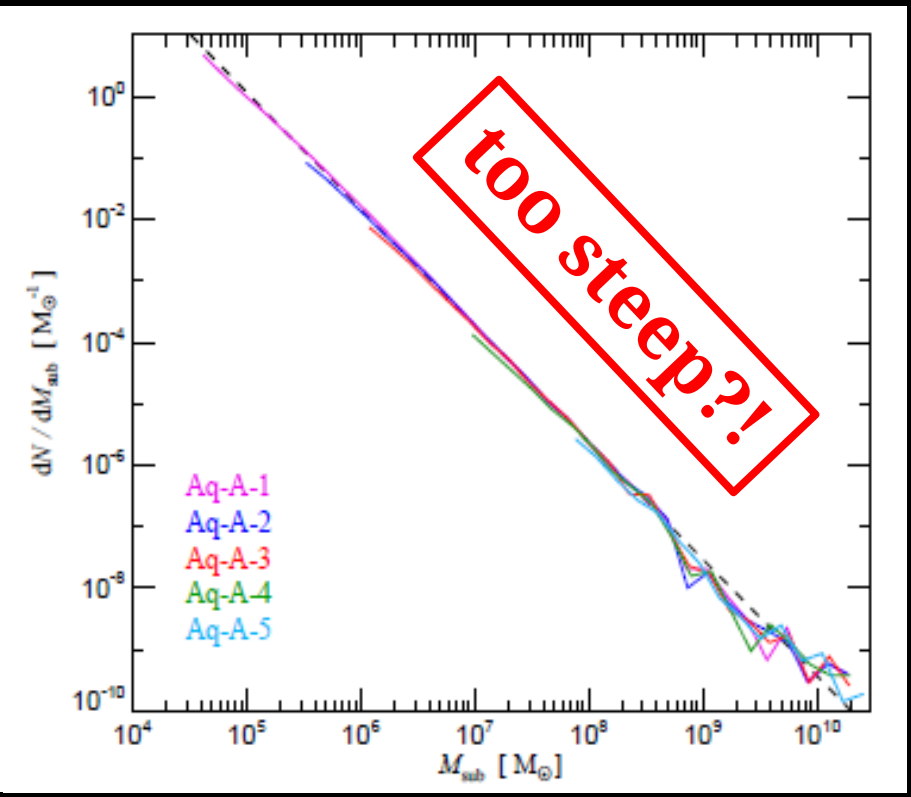

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Resolution effects

Small-scale distortions get washed out by poor observational resolution → Detecting low-mass subhalos requires very high angular resolution

Problem:
You cannot have both large sources and great resolution!

- Hubble Space Telescope → 0.1" resolution
  ~ 1 kpc sources (galaxies, stellar continuum)

- ALMA (with 10 km baseline) → 0.01" resolution
  ~ 100 pc sources (galaxies, dust contiuum, CO)

- European VLBI Network (EVN) → 0.0003" (0.3 milliarcsecond)
  ~ 1-10 pc sources (AGN jets)

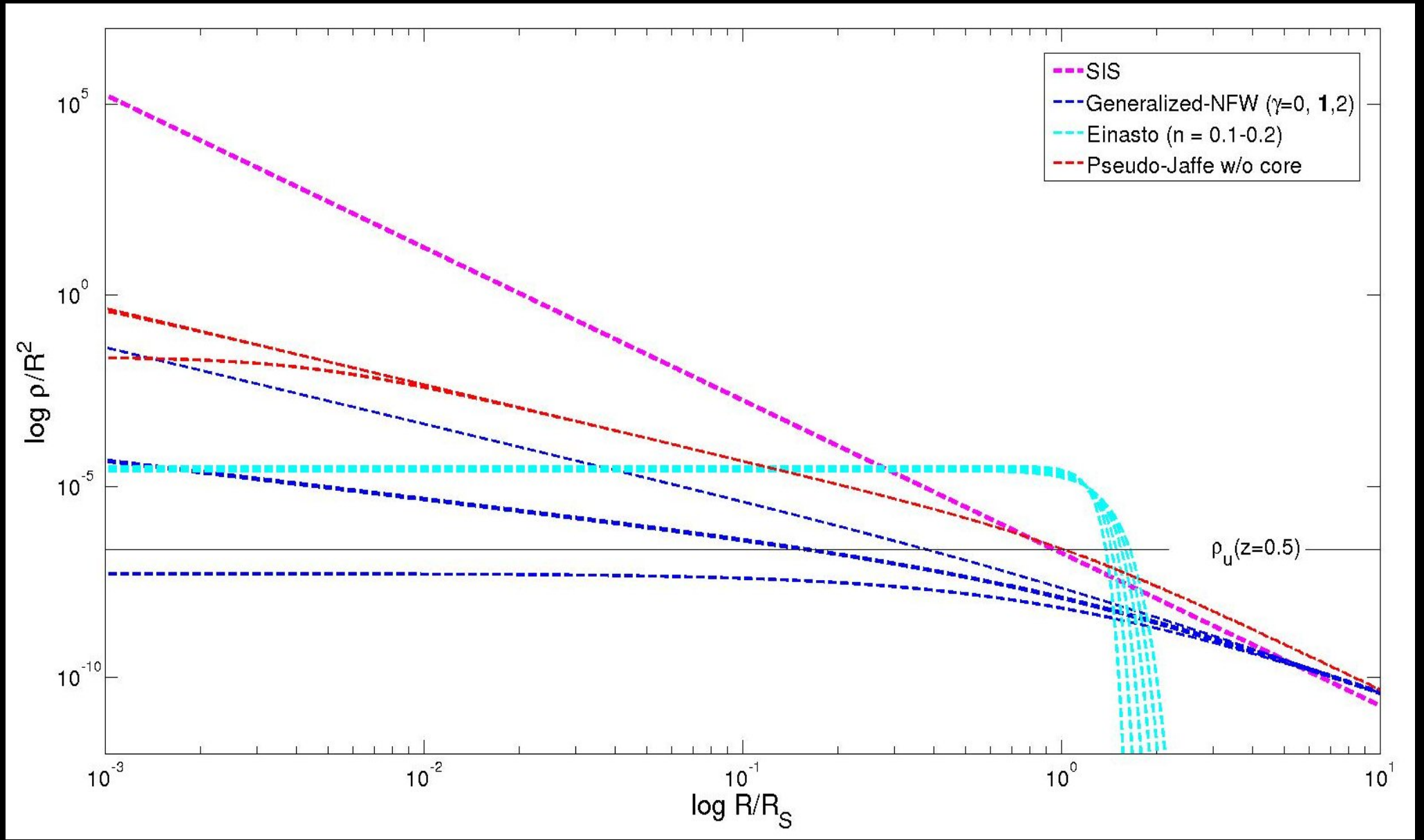
Inner density profile of subhalos

- Compact dark objects are there, but do they have N-body simulations-favored universal density profile?

- Central subhalo densities can vary a lot, but how big is the difference in lensing signature?

- Slope of mass function on subgalactic scale is related to inner slope of subhalo mass profile.

Inner density profile of subhalos



How many lenses are needed to quantify the substructure mass fraction with quasar jets?

1. Compact dark objects (IMBHs & UCMHs)

(surveying N = 5 systems, with larger than 95% confidence)

$$\frac{\Omega_{\rm UCMH}}{\Omega_{\rm CDM}} \geq 0.1$$

$$\frac{\Omega_{\rm IMBH}}{\Omega_{\rm CDM}} \geq 0.01$$

2. “Standard” CDM subhalos (NFWs)

- Low number density
- Shallow inner density profile

→ Source area too small, negligibly small probability of proper alignment

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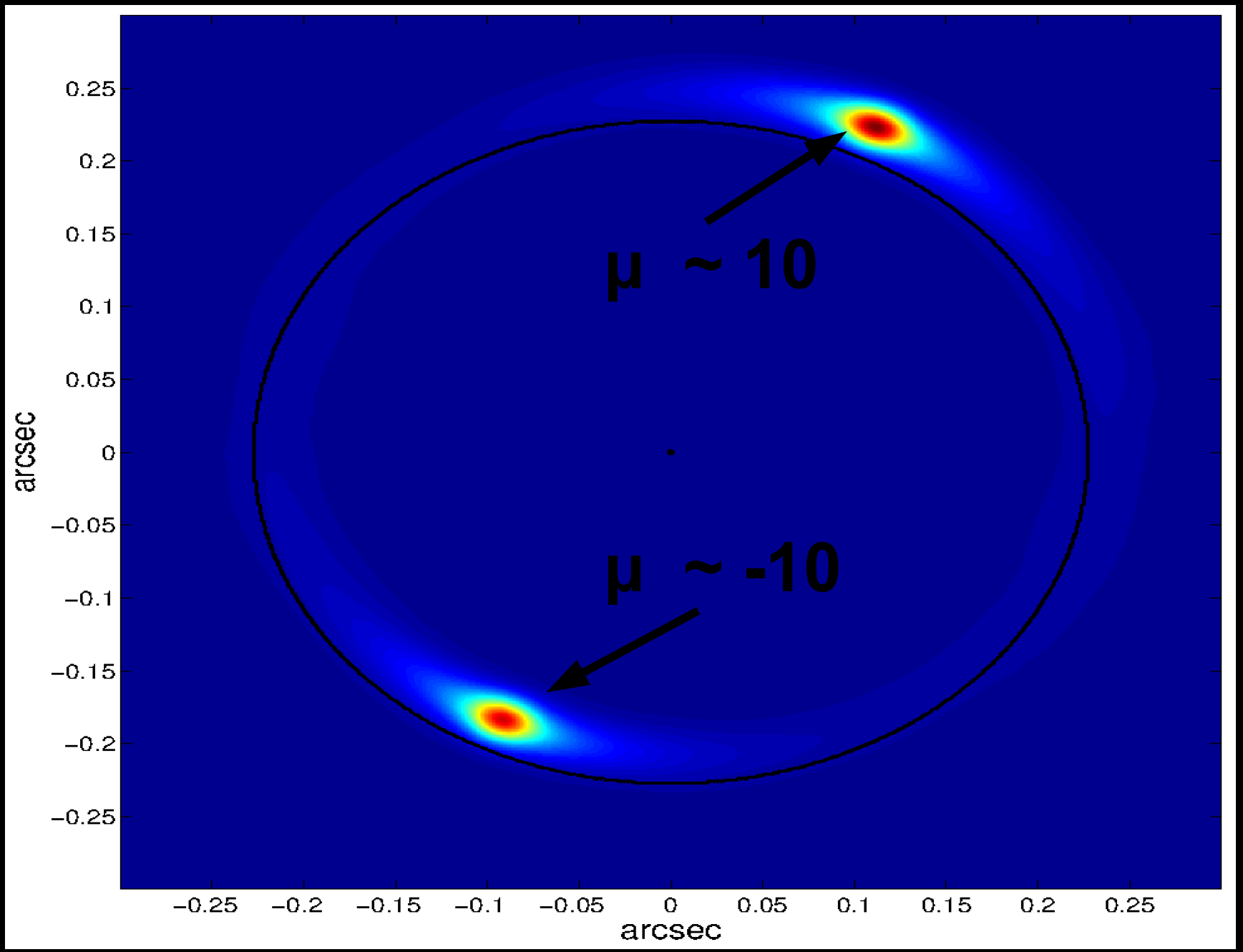
Smooth lens model



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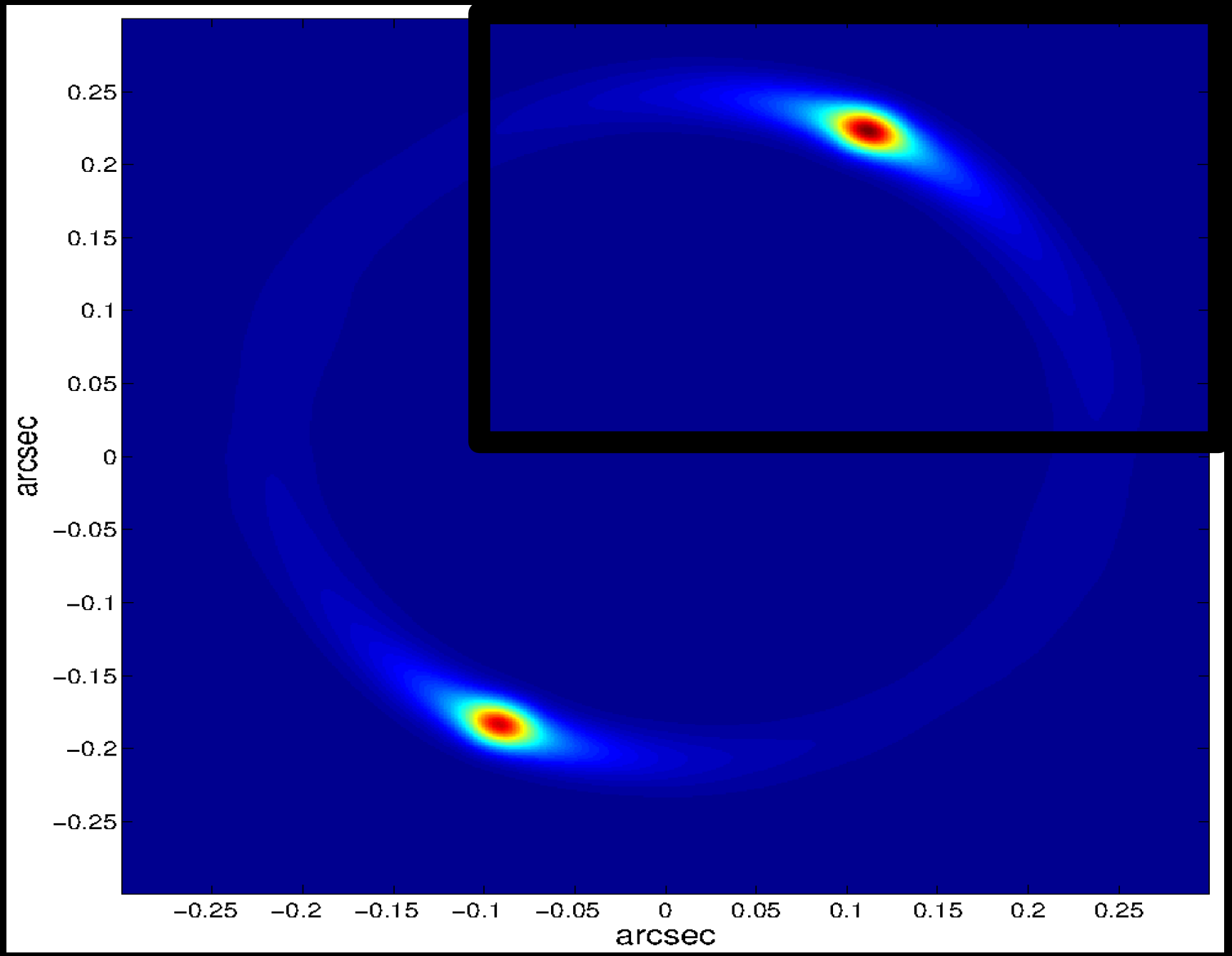
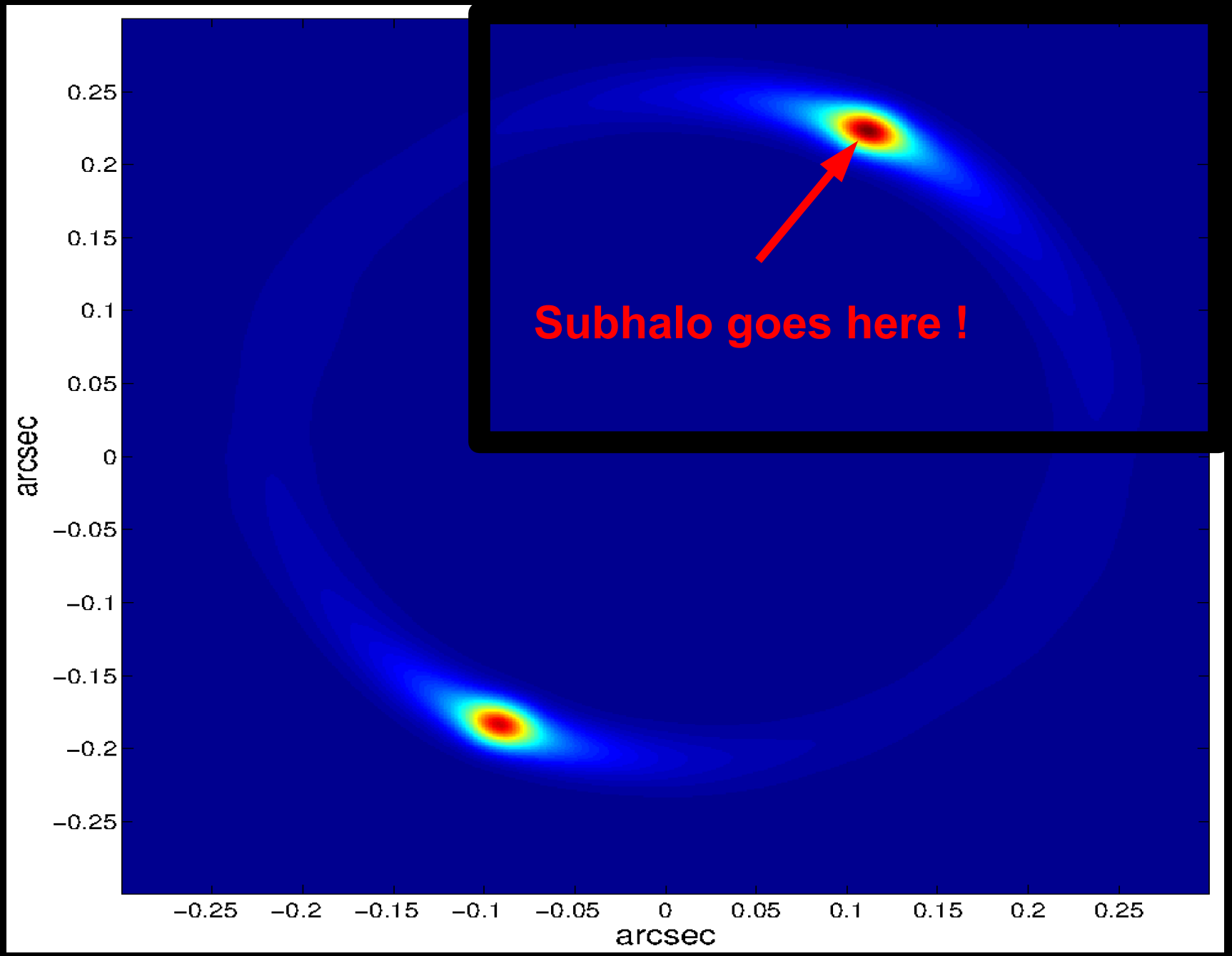
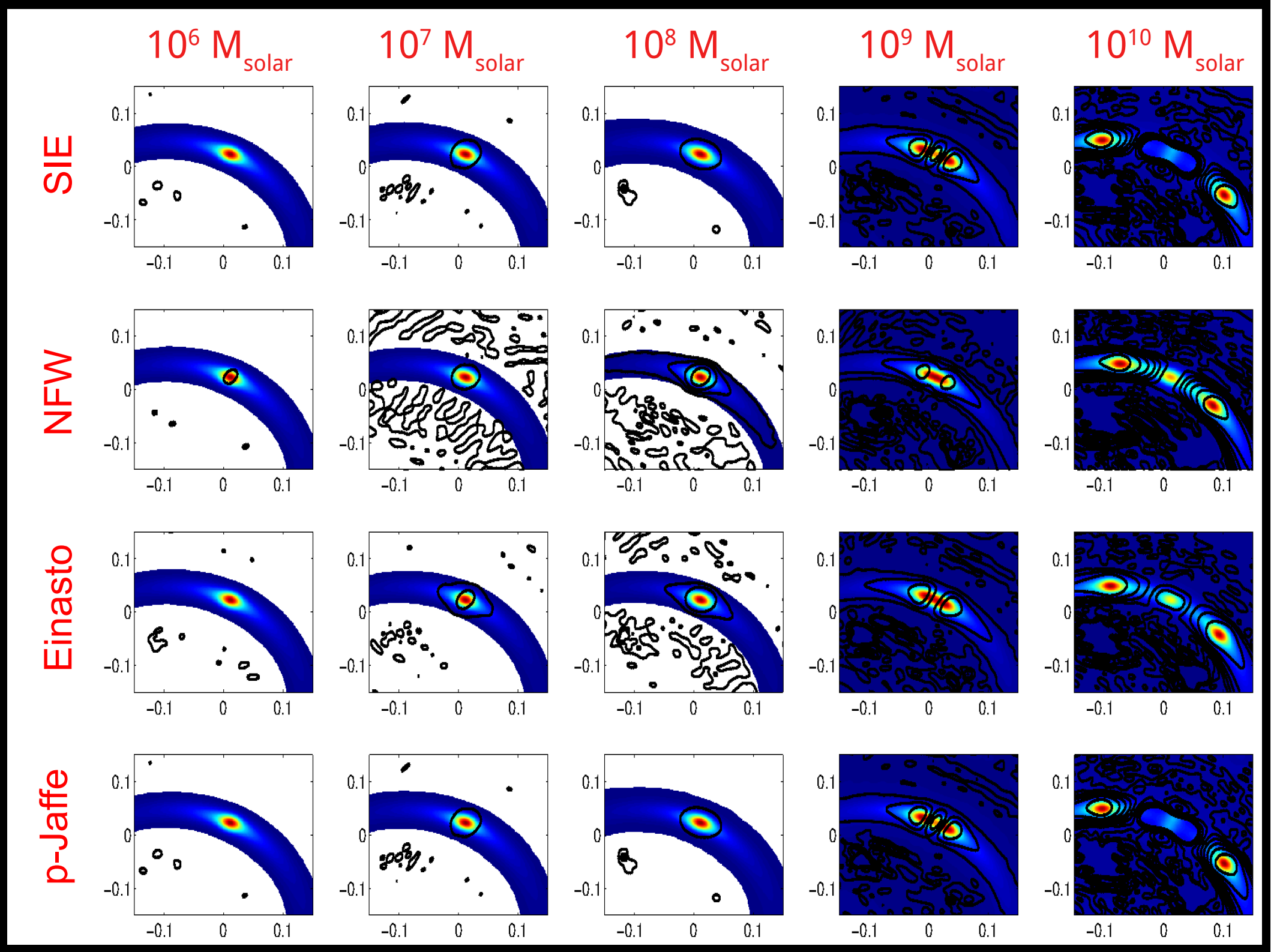


Smooth lens + low-mass perturber




10^6 M_{solar}
10^7 M_{solar}
10^8 M_{solar}
10^9 M_{solar}
10^{10} M_{solar}
SIE
NFW
Einasto
p-Jaffe
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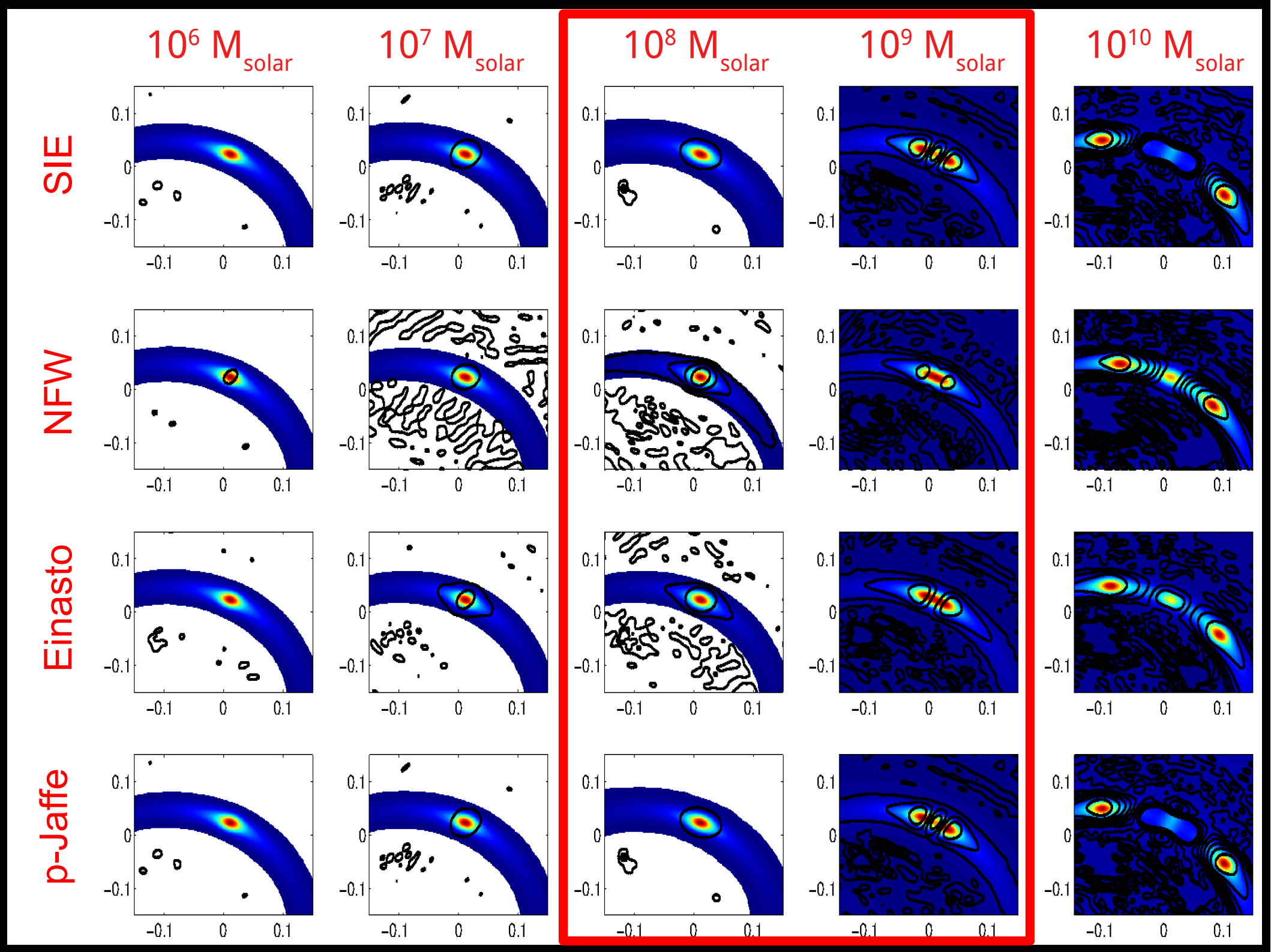
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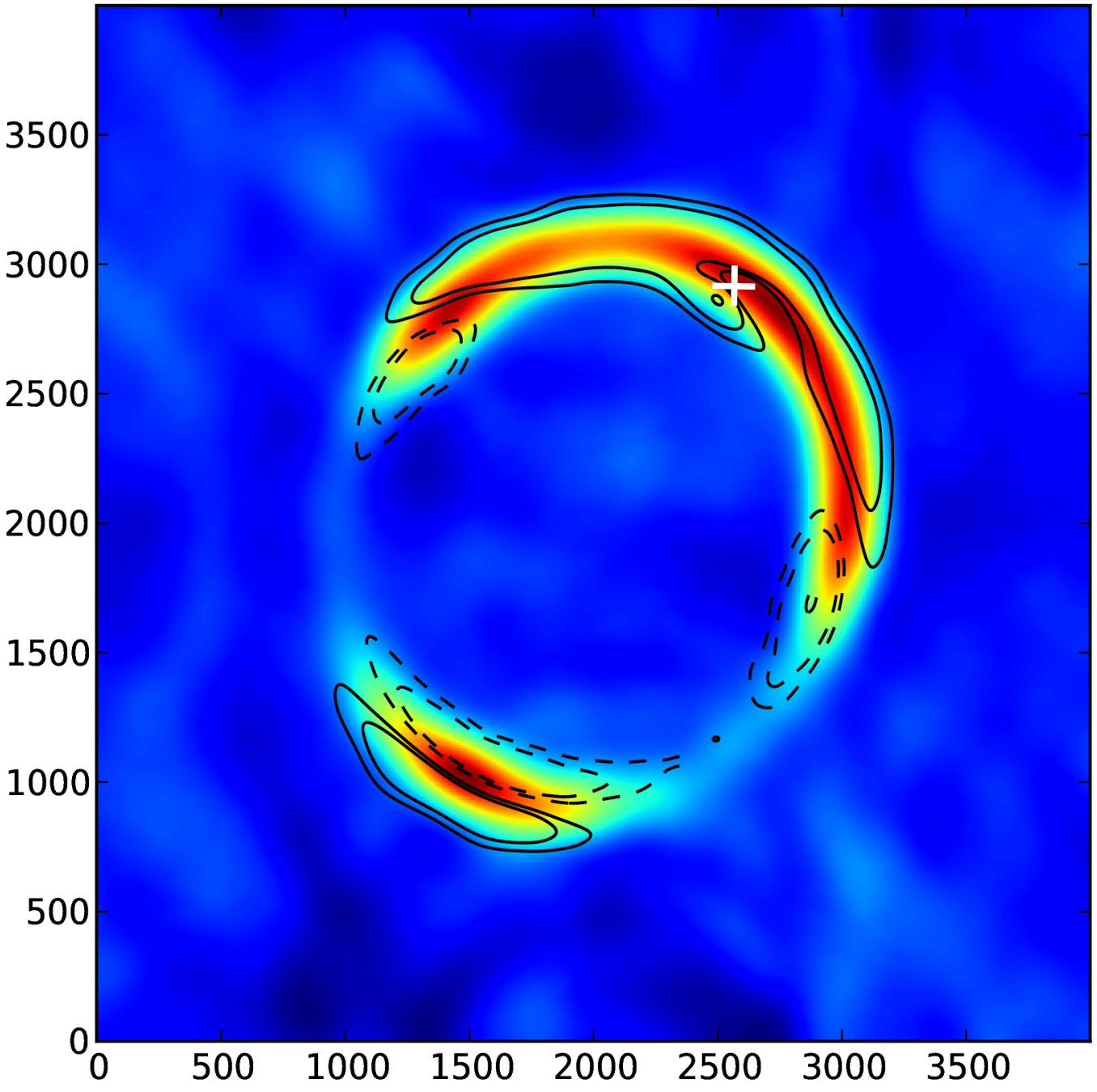
Astrometric shift and other global effects...

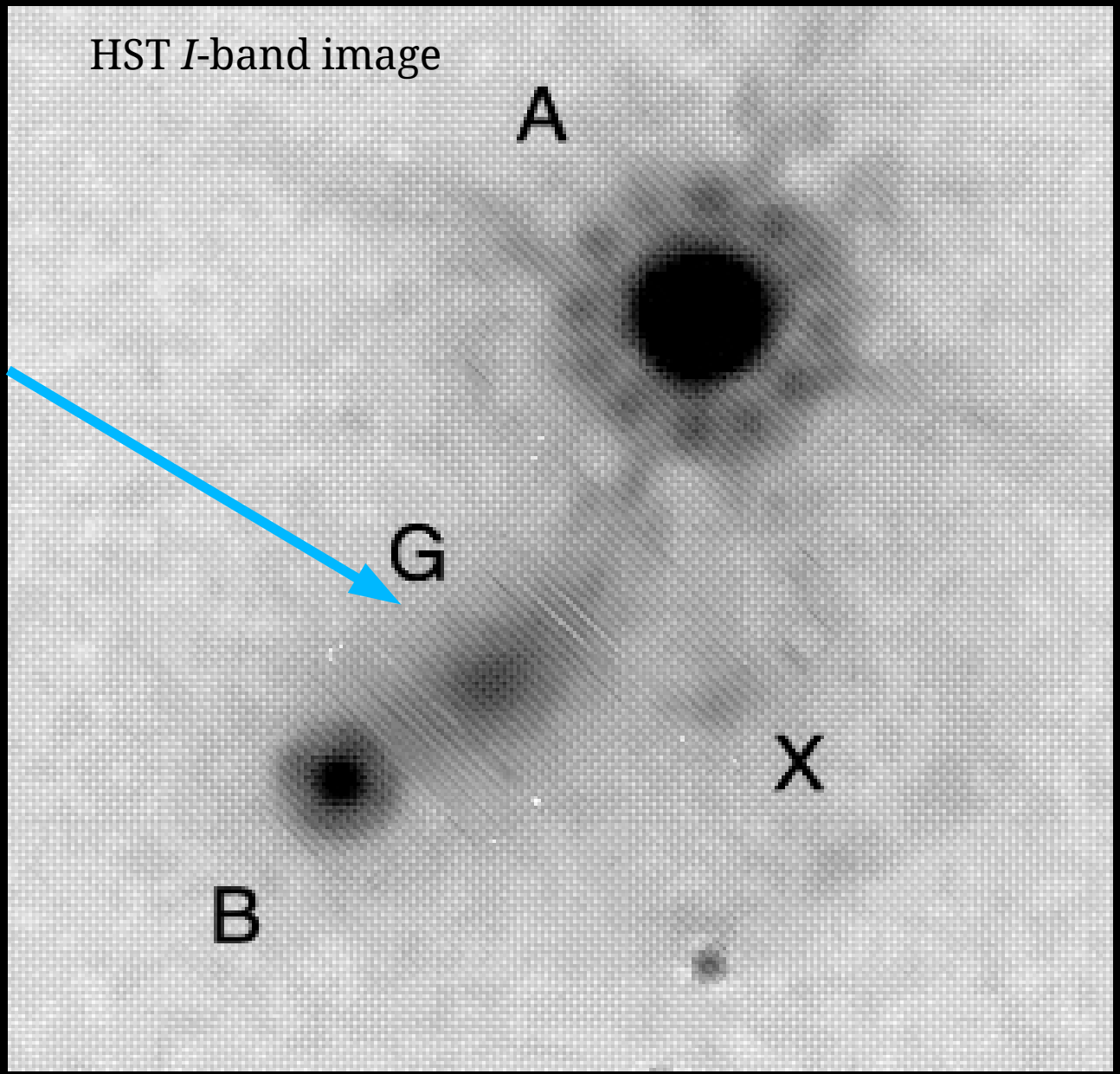


Further questions…

- What is the statistical situation considering predicted galactic subhalo mass function and relative substructure mass fraction?
  (in progress…)
  - Any (non)detection with subhalo mass/type estimate puts constraints on these two, therefore the nature of dark matter…
- How sensitive is single-lens detection to source internal structure?
- How does the probability depend on source model/magnification distribution of sources, etc.?

  (in progress…)
- On which scale line-of-sight contaminants become significant?

Where to look for answers?
strongly-lensed blazar B1152+199



Lens galaxy

(Rusin et al. 2002)

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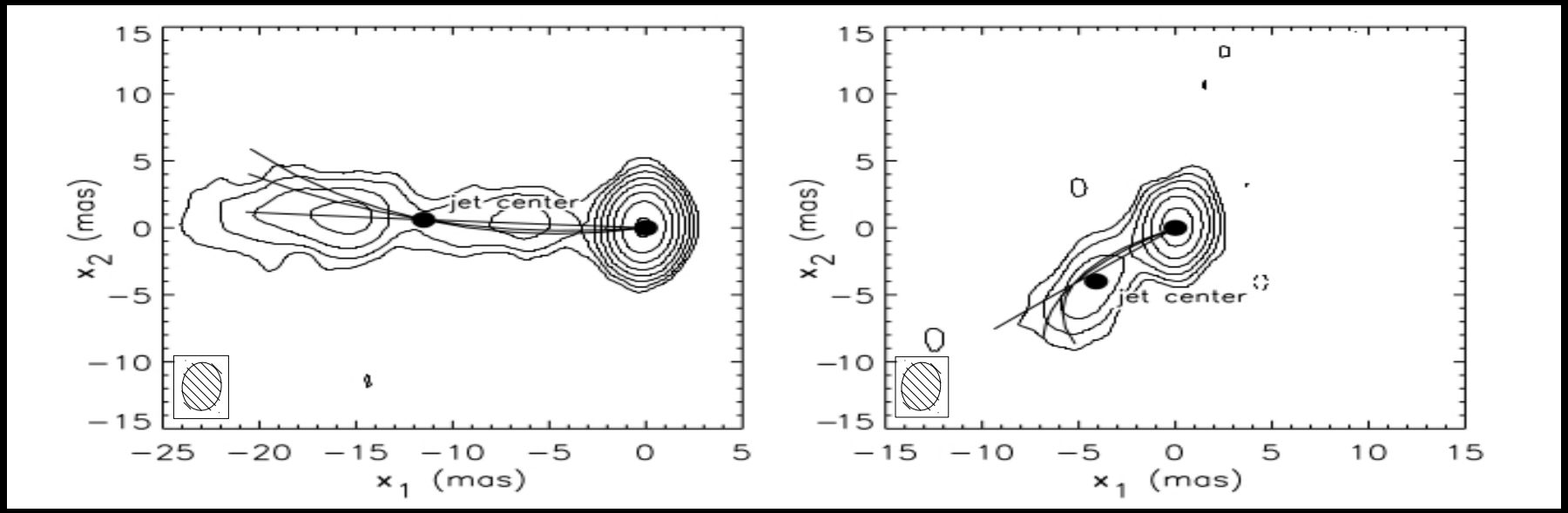
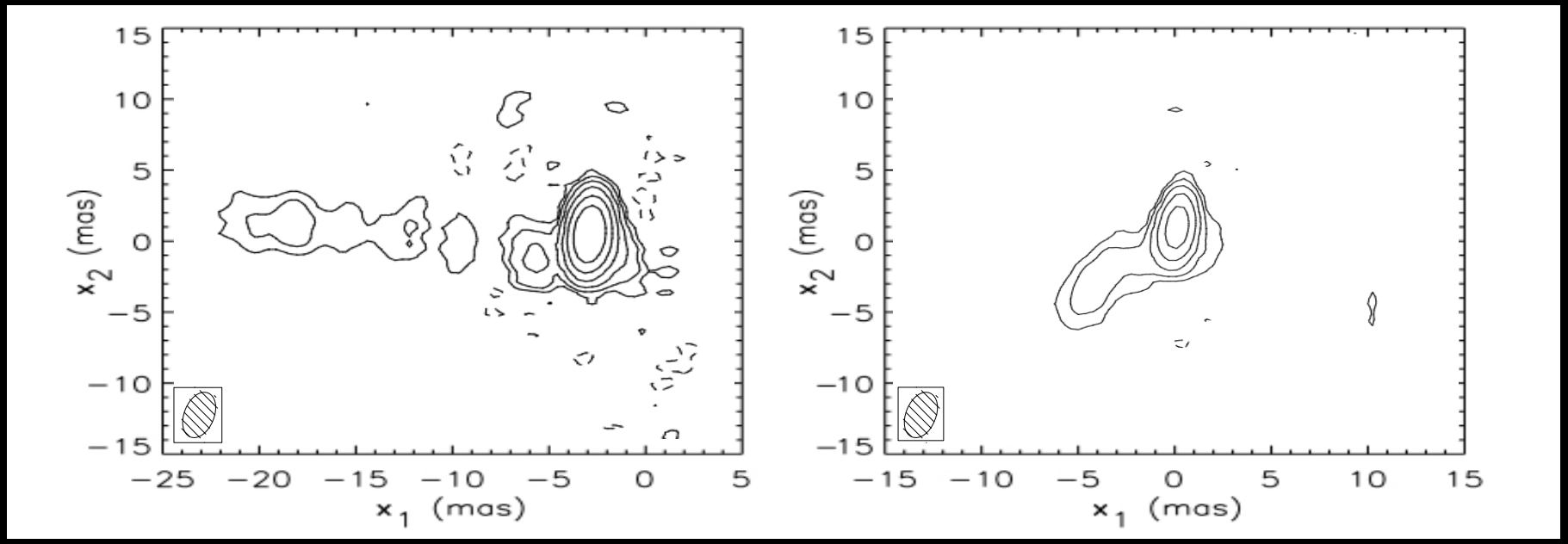
strongly-lensed blazar B1152+199

VLBA maps @ 5GHz

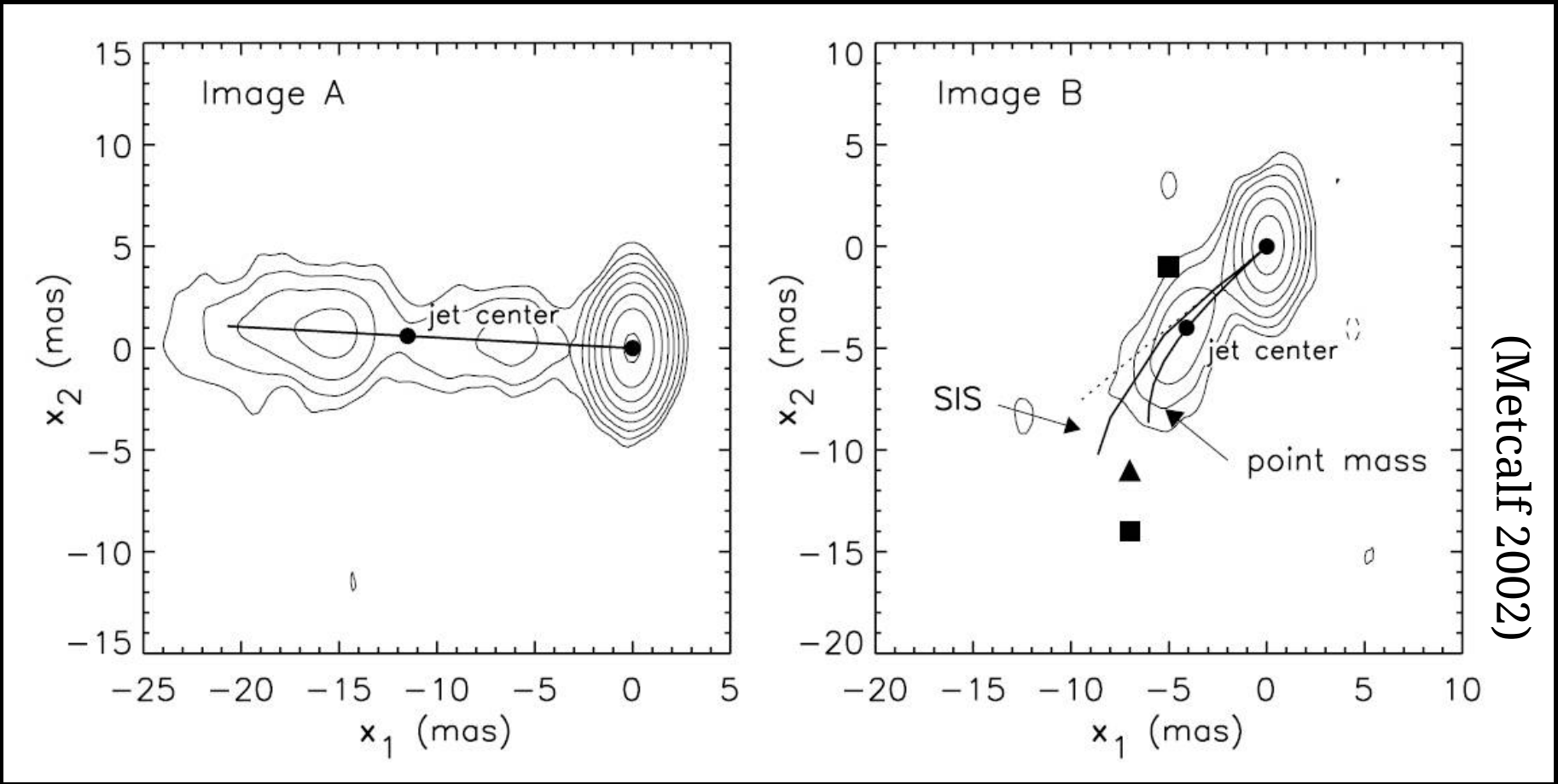


2001



2012

Work in progress...



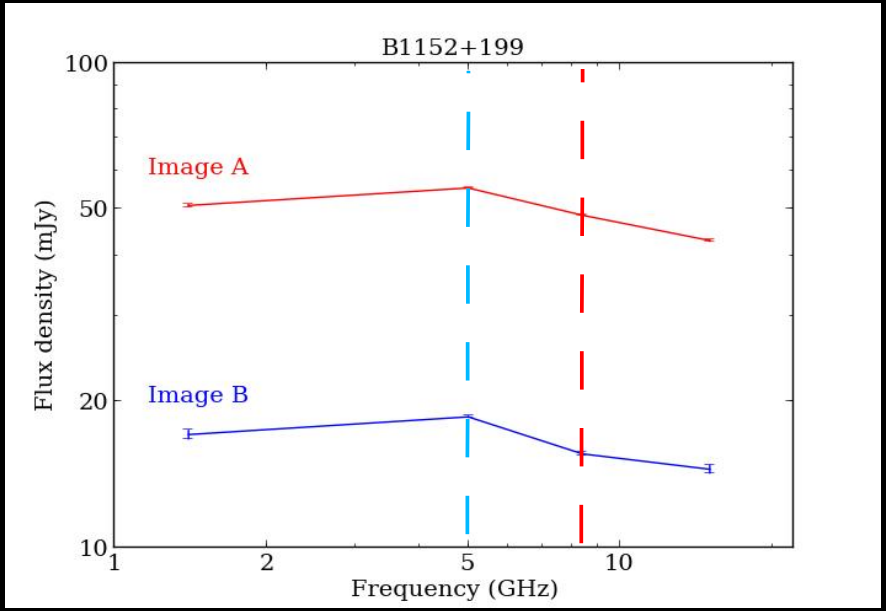
(Metcalf 2002)

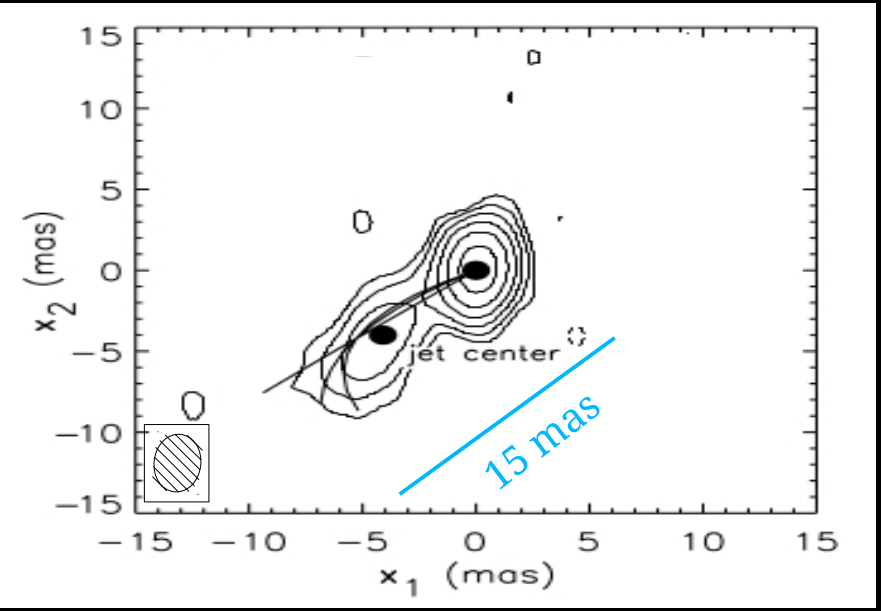
- Possible to reproduce the curvature with CDM subhalos?

- How massive the subhalo needs to be?

- What are the odds?

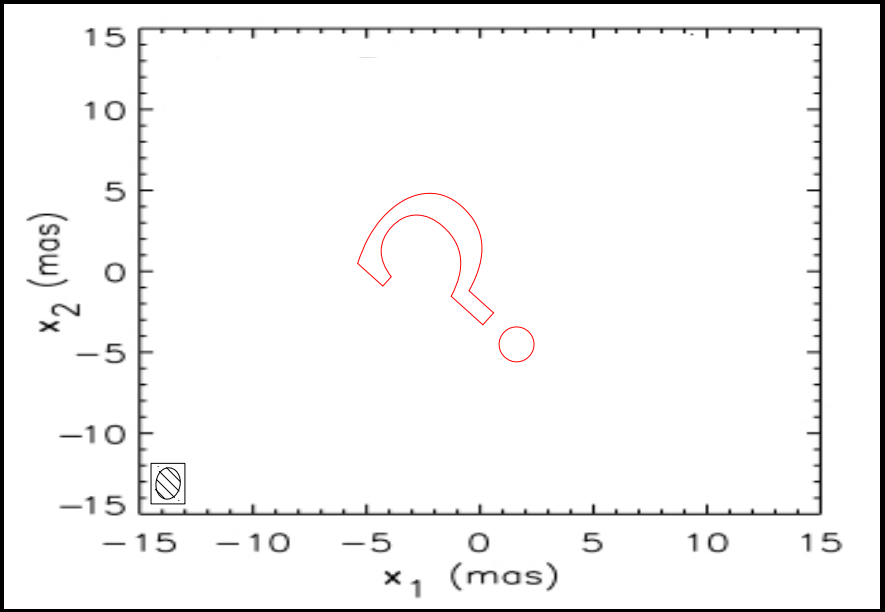
Where to look for answers?
strongly-lensed blazar B1152+199





5 GHz

Proposal under revision…



8.4 GHz