Gravitational lensing as a probe of dark matter on subgalactic scales

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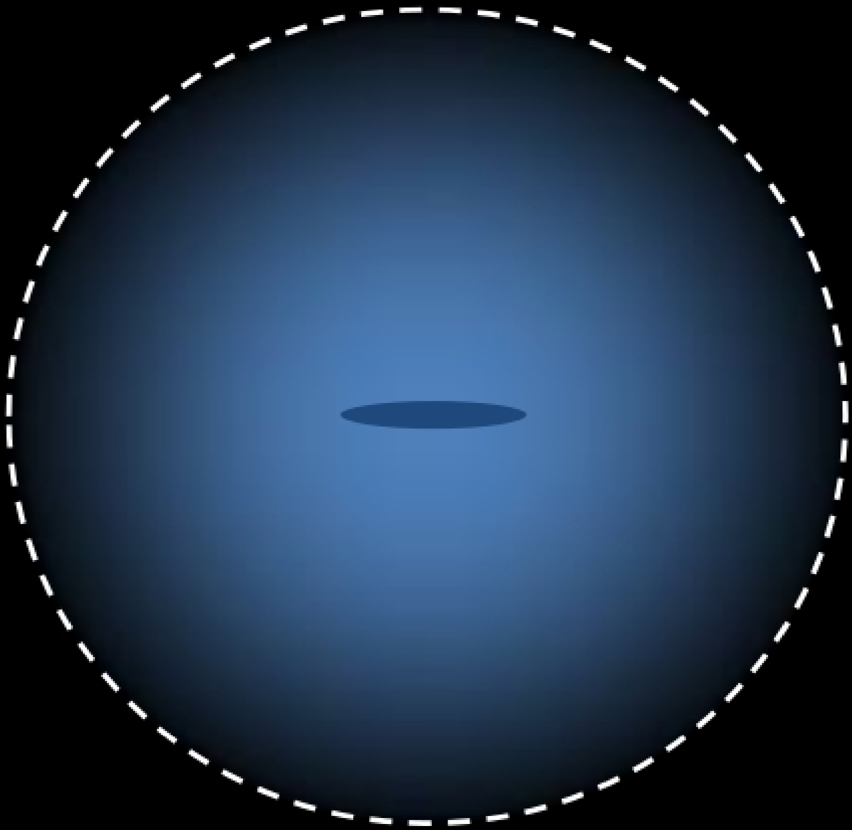
Dark matter halos

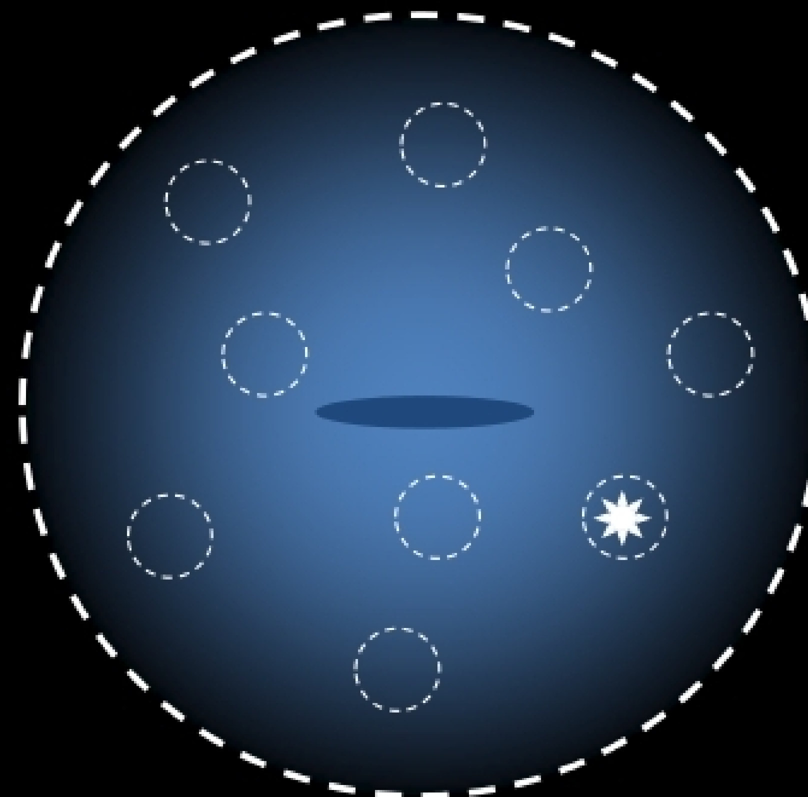


Typical textbook illustration

What they look like in
actual N-body simulations

These subhalos are troublesome!

- <u>Long-standing problem</u>
  Too few satellite galaxies compared to subhalos in CDM simulations (Moore et al. 99, Klypin et al. 99)



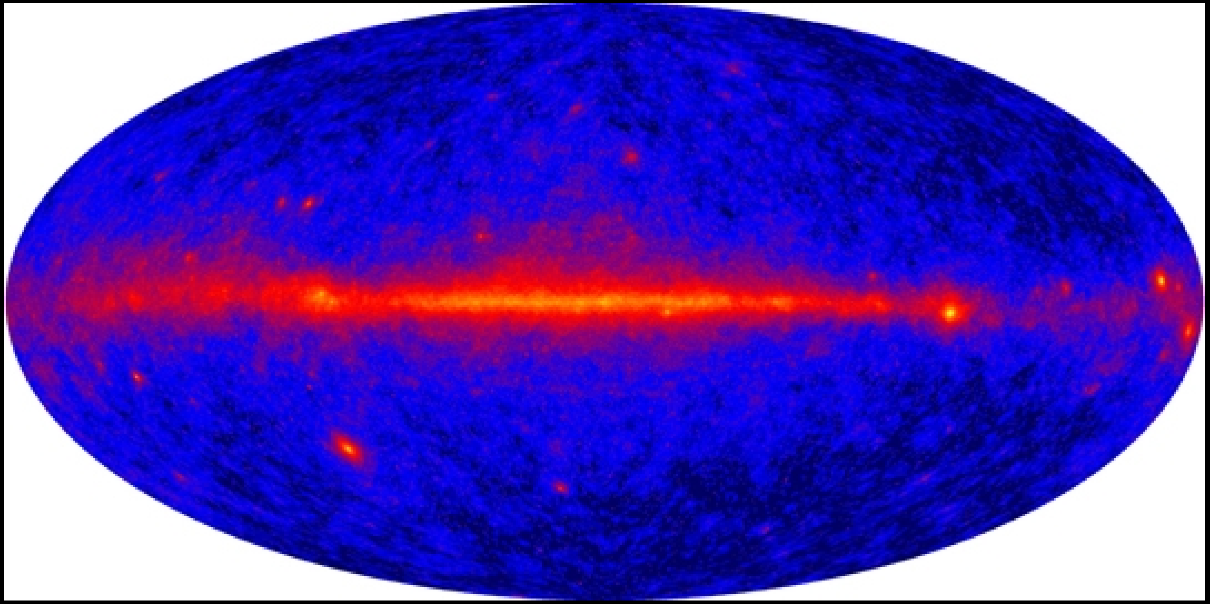
- <u>Possible solutions</u>
  - Vanilla CDM not correct! Try warm, fuzzy, light, self-interacting or super-WIMPy dark matter…
  - Star formation quenched in all but the most massive subhalos

Large numbers of completely dark subhalos awaiting detection!

Hunting for the dark

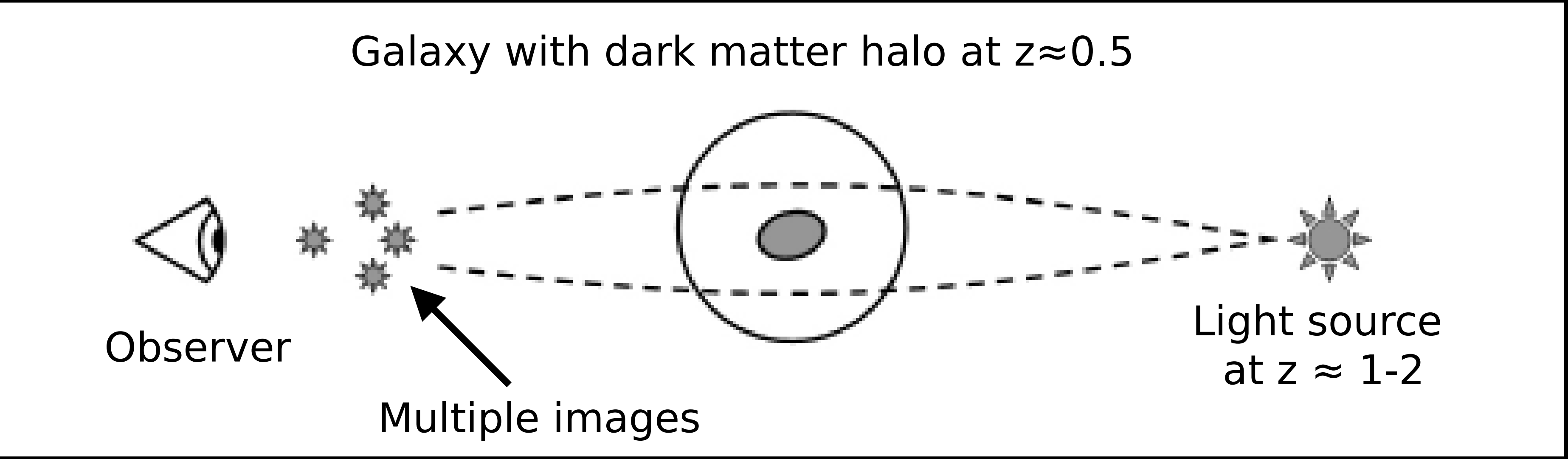
- If CDM is WIMPs → Subhalos detectable with Fermi due to WIMP sefl-annihilation
No clear-cut detections so far…

- Subhalos may also be detectable through gravitational lensing effects – regardless of the microphysics of the dark matter particles



The lensing situation

Zackrisson & Riehm (2009)



Strong lensing (a.k.a. macrolensing)

Resolution effects

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

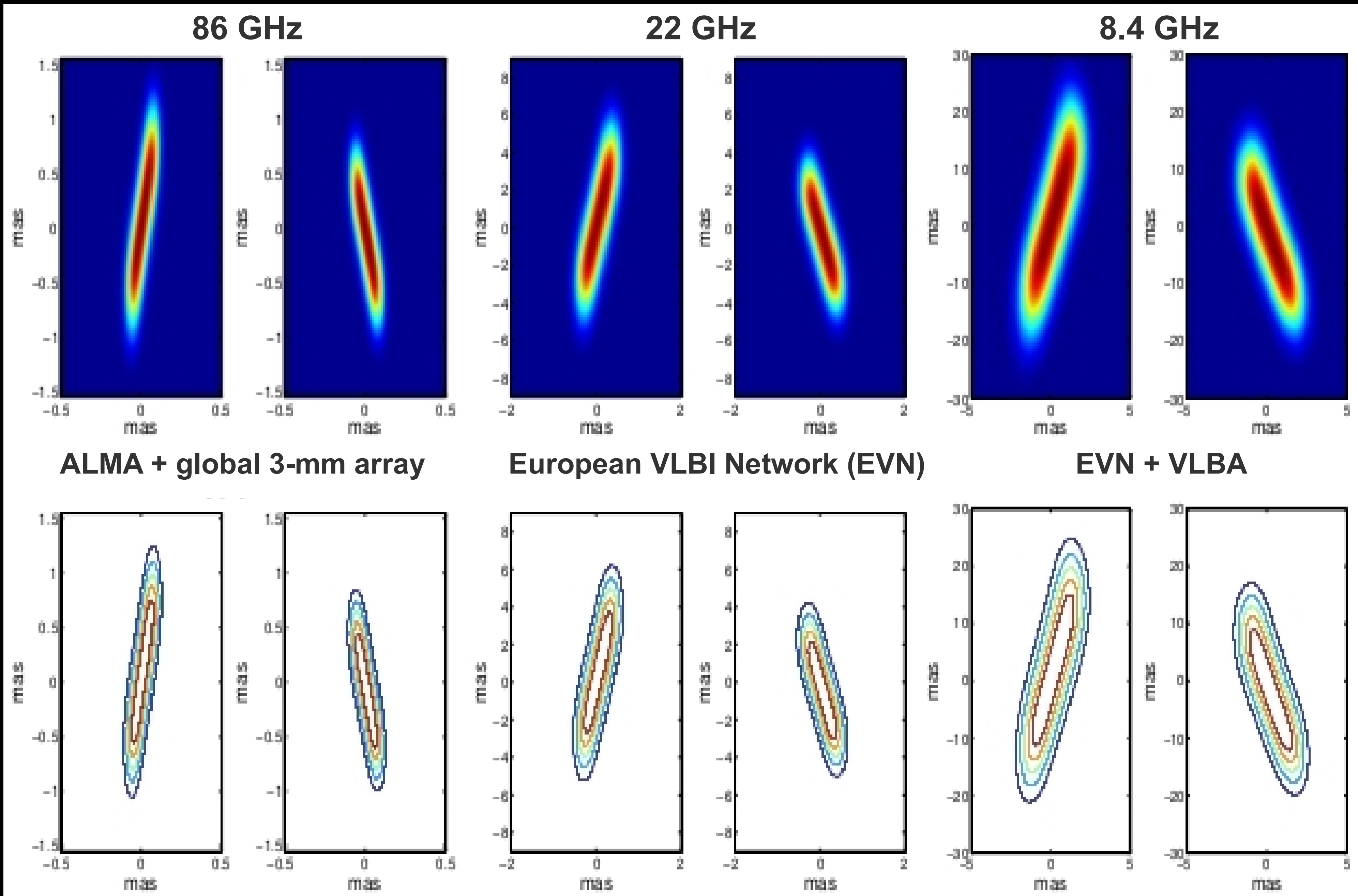
Problem:
You cannot have both large sources and great resolution!

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

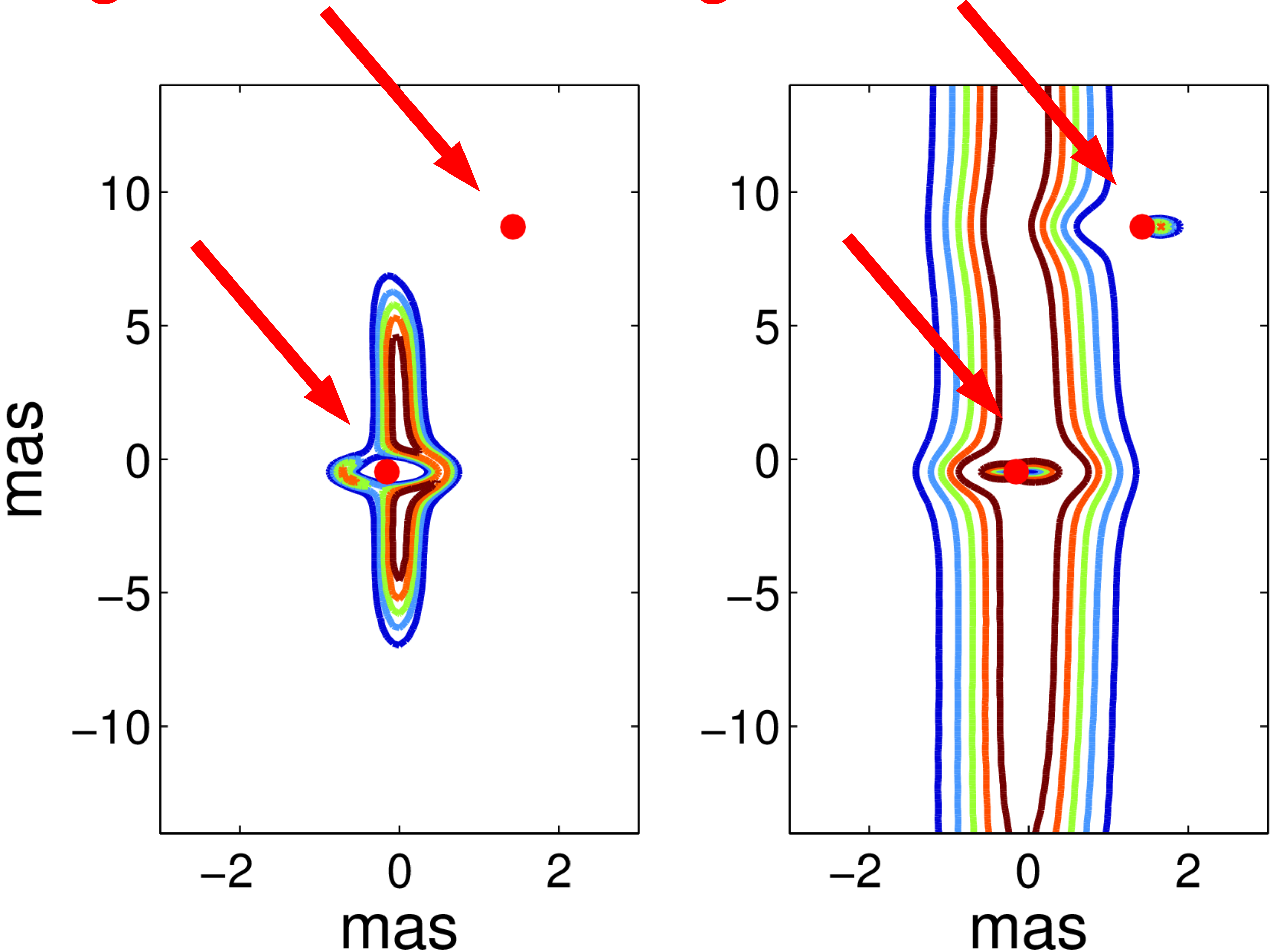
- ALMA (with 10 km baseline) → 0.01" resolution
  ~ 100 pc sources (galaxies, dust contiuum, CO)

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

Simulations

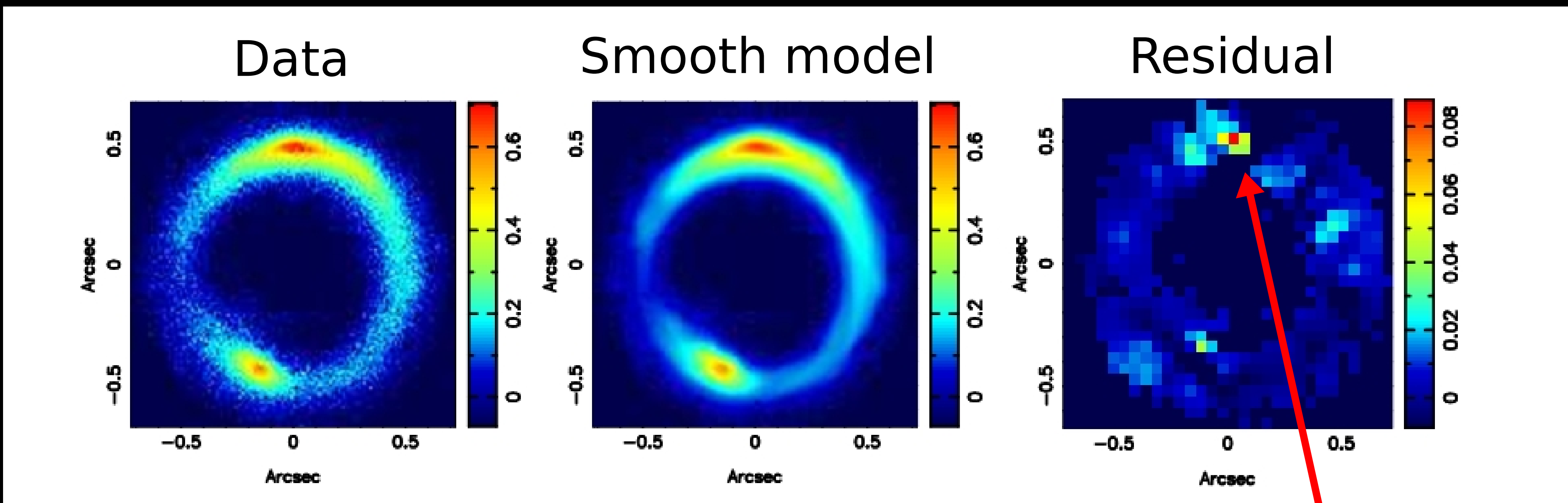


Larger source area → Higher chance of detection



Detections so far

Vegetti et al. (2012, Nature): HST observations

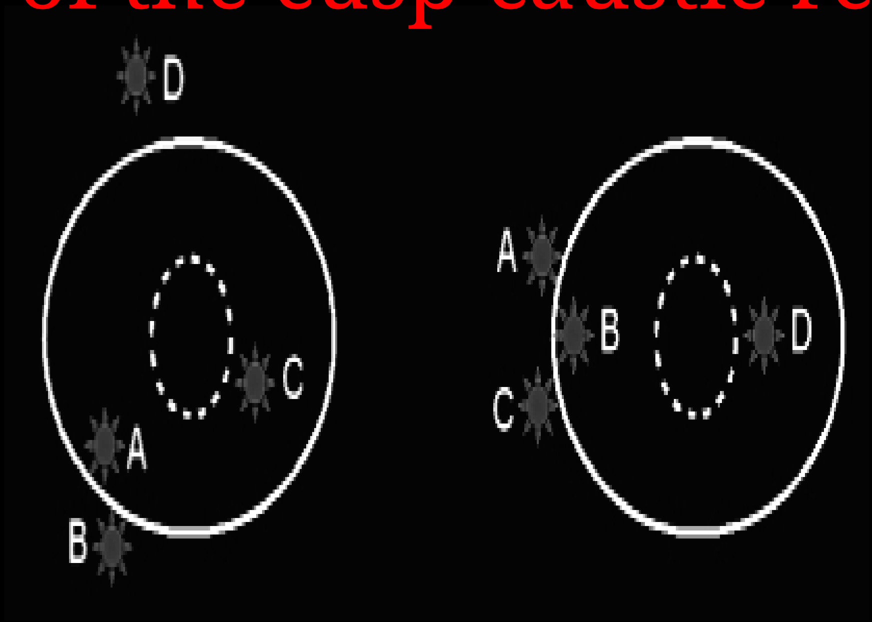


10^8 M_{solar} subhalo

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

Other supporting observations?

“The amount of substructure in the central regions of the Aquarius halos is *insufficient* to explain the observed frequency of violations of the cusp-caustic relation.” (Xu et al. 2009)



fold cusp

$$R_{\rm fold} = \frac{|\mu_A| - |\mu_B|}{|\mu_A| + |\mu_B|} \rightarrow 0$$

$$R_{\rm cusp} = \frac{|\mu_A| - |\mu_B| + |\mu_C|}{|\mu_A| + |\mu_B| + |\mu_C|} \rightarrow 0$$

N-body simulations vs. detections

- Galactic subhalo mass fucntion: $\frac{dN}{dM} \propto M^{-\alpha}$

Aquarius N-body simulation :
(Springel et al. 2008)

$\alpha = 1.9$

too steep?!

- Relative substructure mass fraction: $f_{\rm sub} \equiv \frac{\Omega_{\rm sub}}{\Omega_{\rm CDM}}$

Aquarius N-body simulation :
(Springel et al. 2008)

$f_{\rm sub} \approx 0.002$

too low?!

Detectability limits

1. Compact dark objects (IMBHs & UCMHs)

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

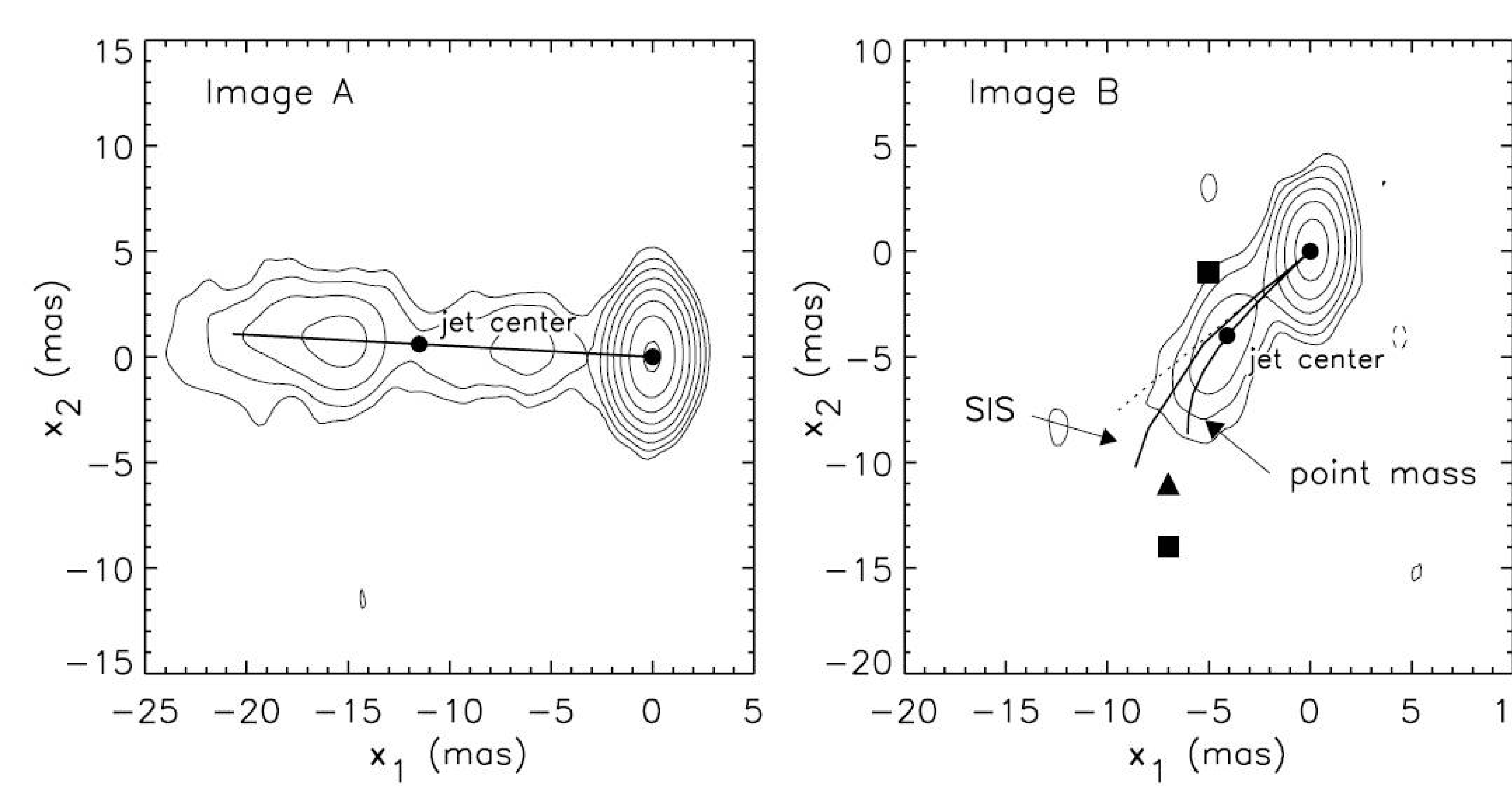
$$\frac{\Omega_{\mathrm{UCMH}}}{\Omega_{\mathrm{CDM}}} \geq 0.1$$

2. “Standard” CDM subhalos (NFWs)

- Low number density
- Shallow inner density profile

→ Negligibly small probability of proper alignment

EVN observations (Feb 2013)



Metcalf (2002)

Rusin et al. (2002), Metcalf (2002): B1152+199
Anomalous bending in lensed AGN jet
VLBA observations @ 5 GHz (3.6 × 1.9 mas beam)

<u>Our observations:</u> 0.3 mas resolution @ 22 GHz →

First robust detection of millilensing?

<u>Team</u>: Erik Zackrisson (PI), Saghar Asadi,
Emily Freeland, Hannes Jensen,
John Conway, Kaj Wiik

B1152+199 (Expectations)