Cosmic evolution of faint satellites as a test of cold and warm dark matter

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Many thanks to:

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- **Matthew Auger (IoA)**
- Chris Fassnacht (UCD)
- Michael Busha (Zurich)
- **Phil Marshall (Oxford)**
- Nicola Menci (Rome)

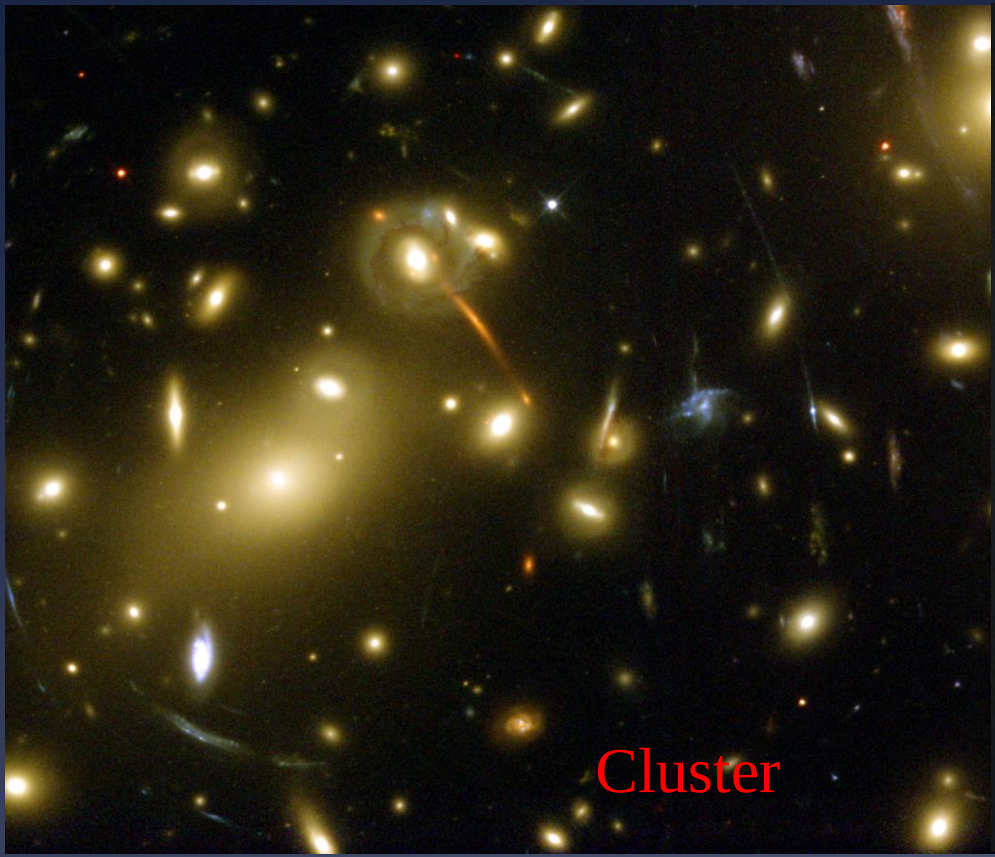
Outline

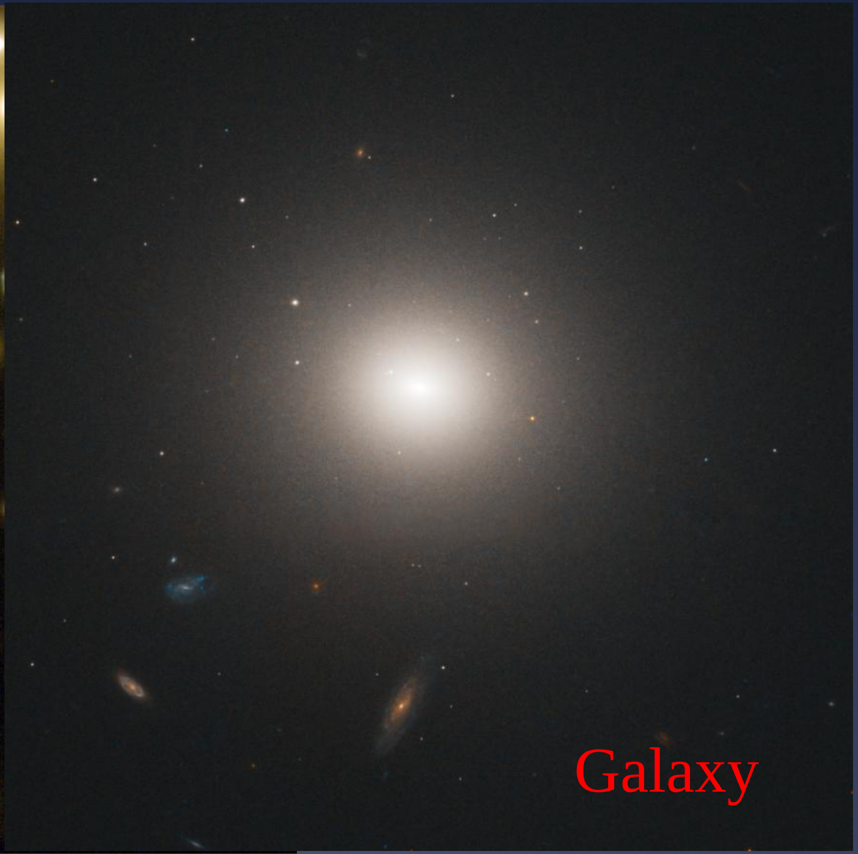
- Introduction: why are there more subhalos in simulations of galaxies than MW satellites?
- Measuring the cosmic evolution of satellites
- Comparison with CDM
- What about altering the properties of DM?Comparison with WDM models
- Breaking the degeneracy: prospects for direct measurements of the mass function of subhalos with gravitational lensing and insights from luminous satellites

Substucture: Theory

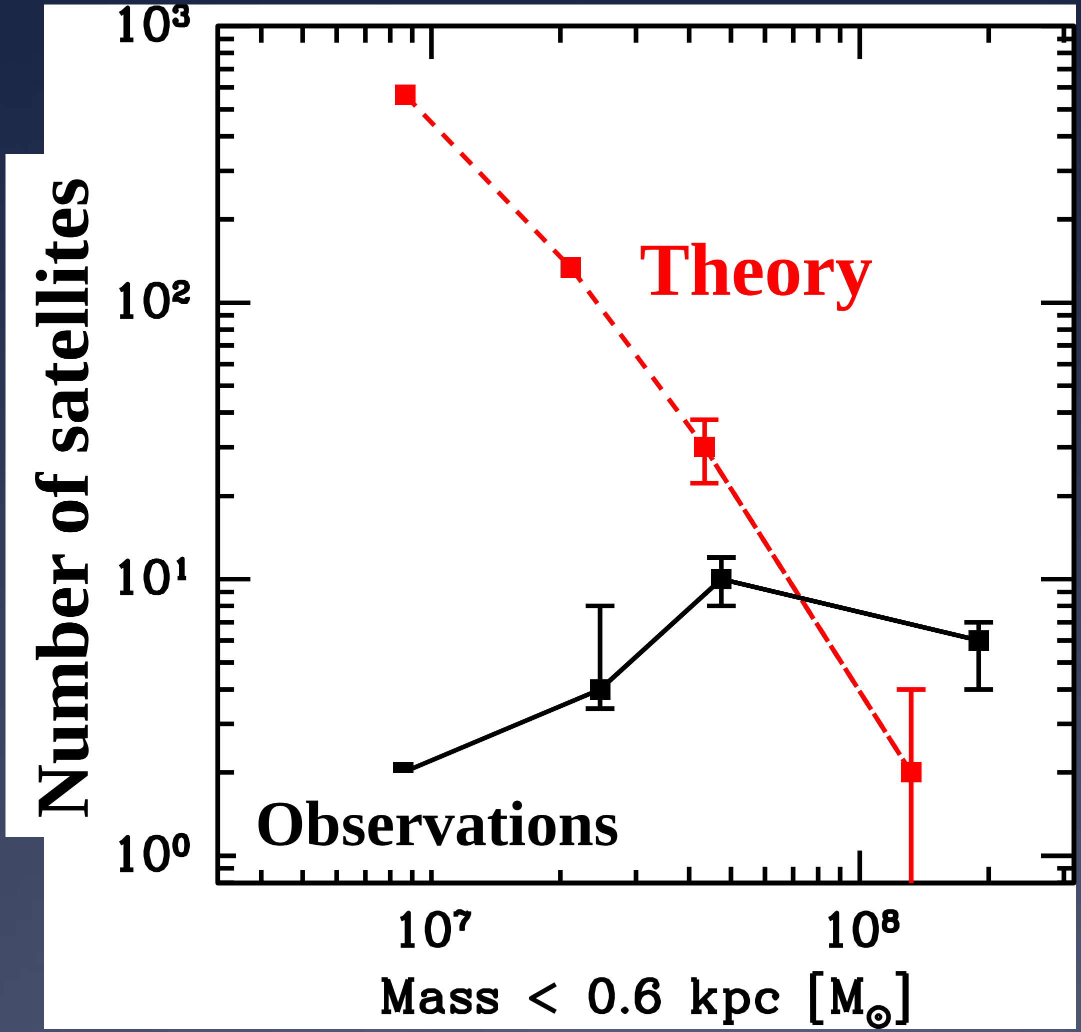
Kravtsov 2010

Substructure: Observations





Milky Way Satellites



Strigari et al. 2007

The missing satellites problem: big questions

- Are the satellites predicted by theory non-existent or just dark?
- If they don't exist, what's wrong with the standard cosmological model?
- If they exist and are dark, why are they not forming stars?

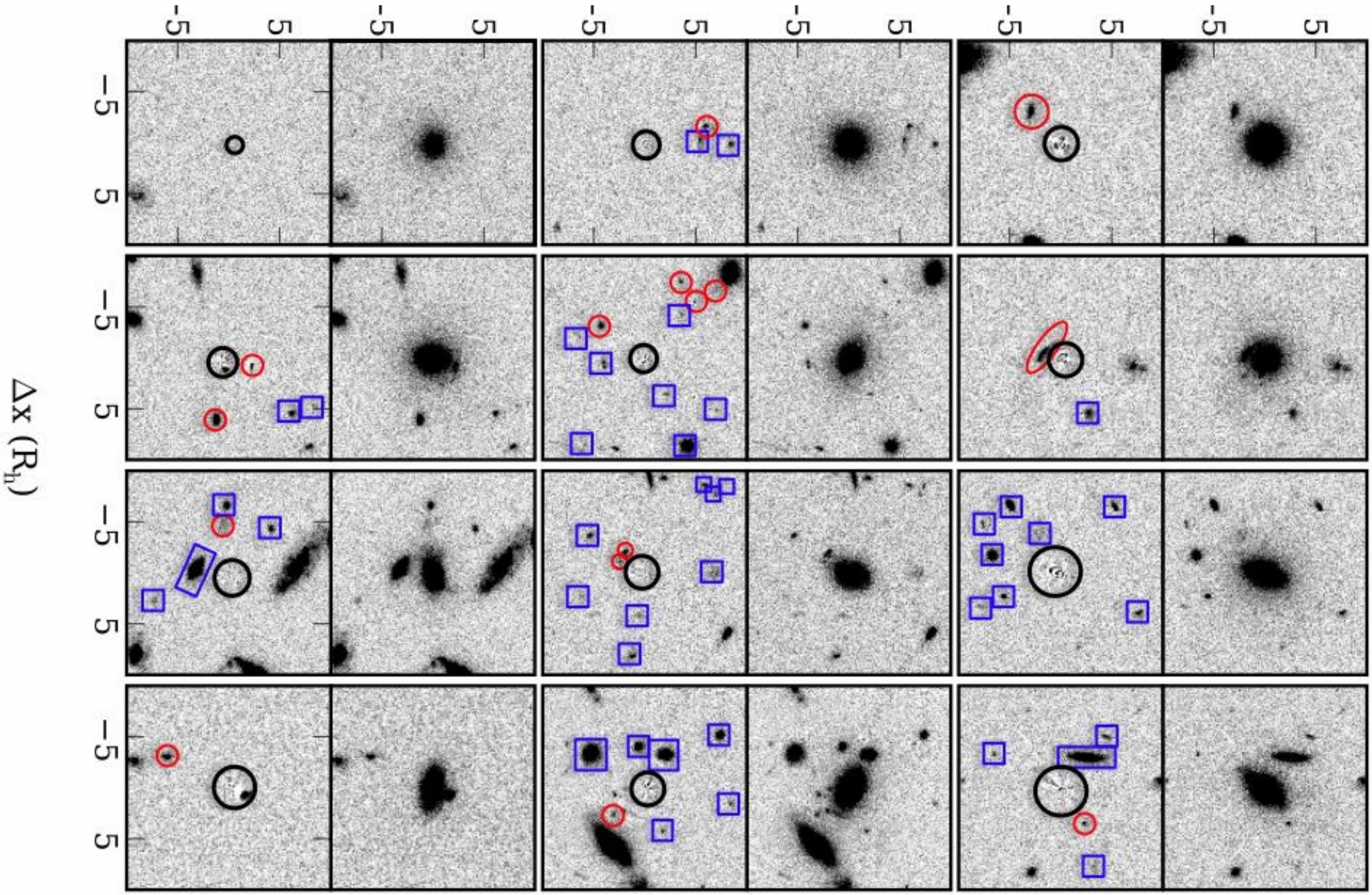
Measuring the Cosmic

Evolution of Satellites

Motivations

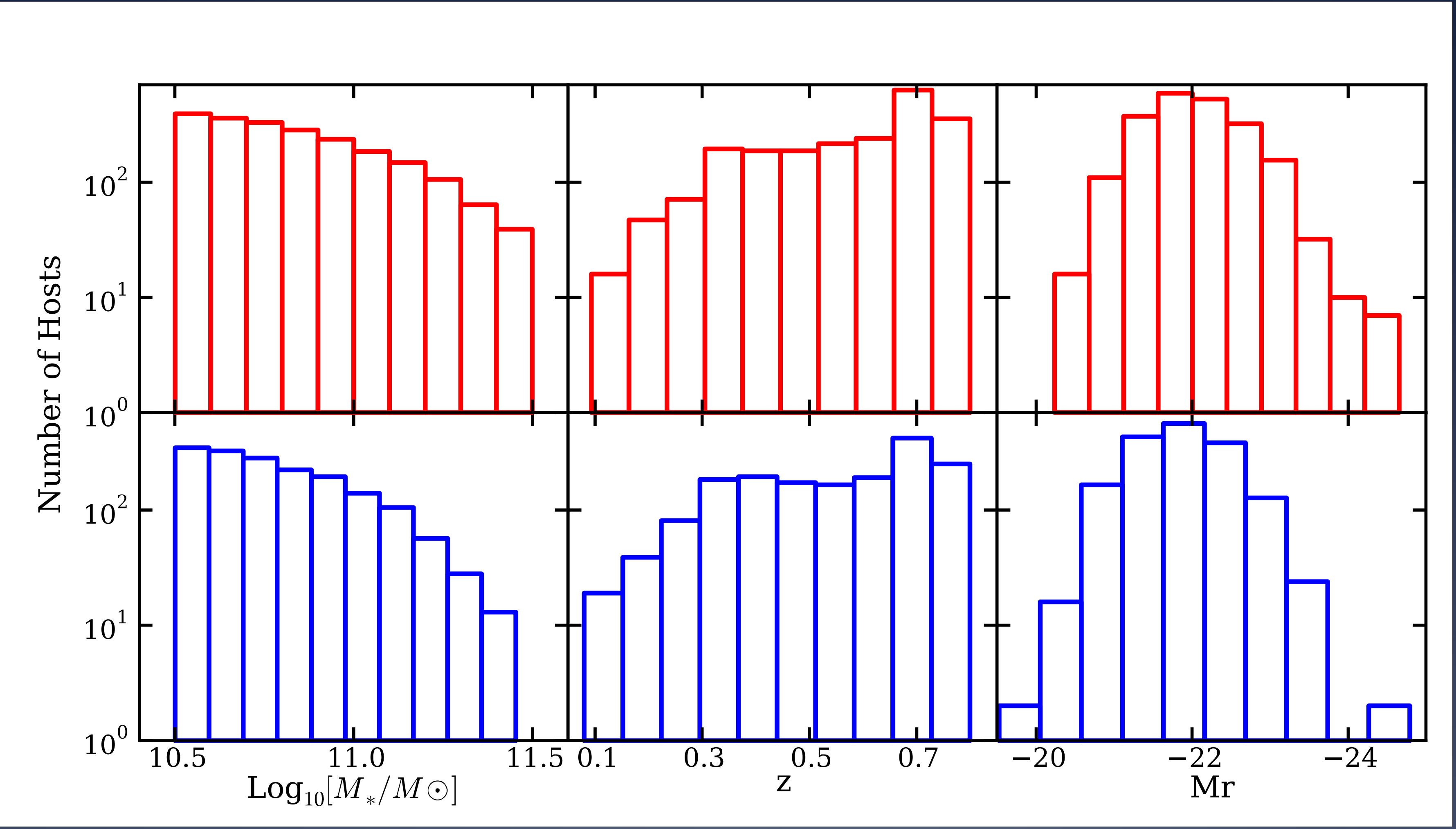
- New observational benchmark for galaxy evolution models
- Hosts comparable to massive lens galaxies. Combining subhalo mass function and luminosity function one can infer physics of star formation at low masses (Treu 2010)

The power of HST: detecting satellites at z>0.1



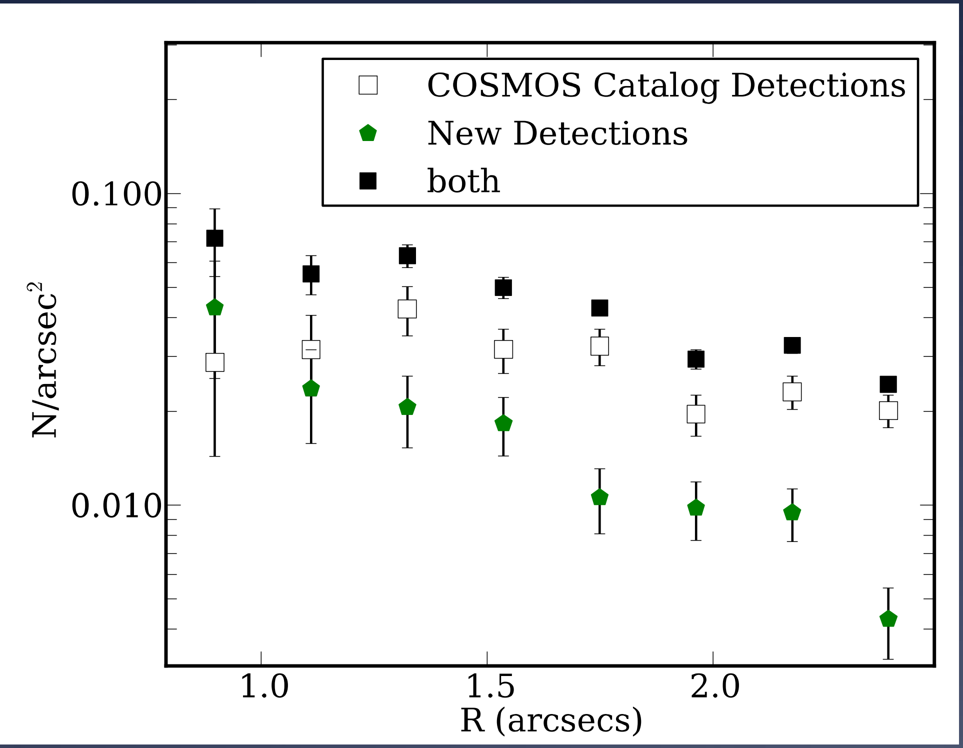
Nierenberg et al. 2011

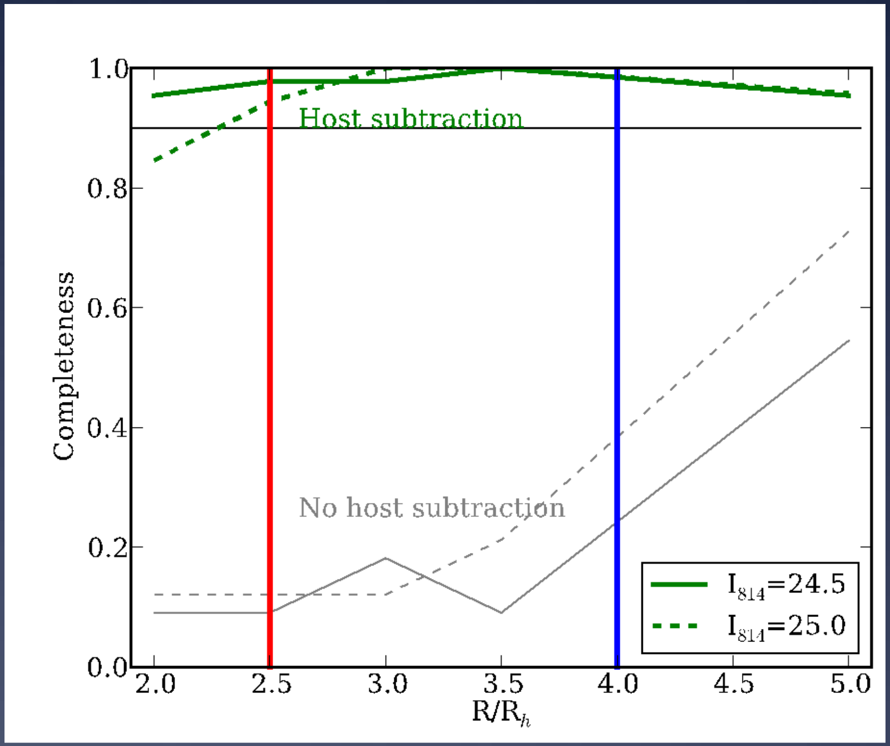
COSMOS: 1000s of hosts, 1000s of satellites



Nierenberg et al. 2012, astro-ph/1202.2125

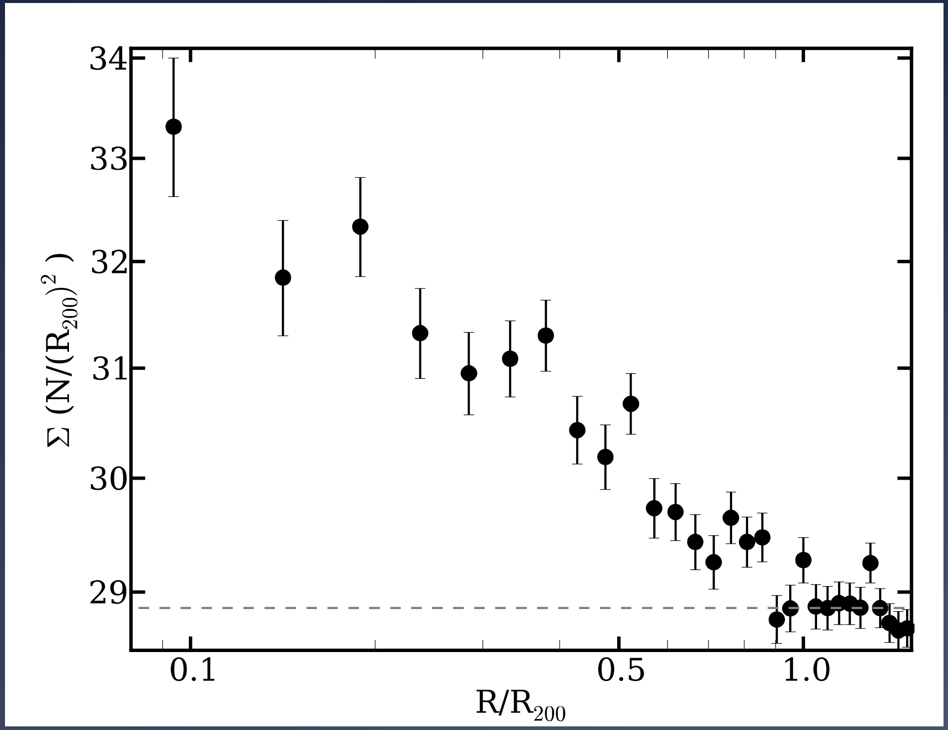
The power of HST and bspline

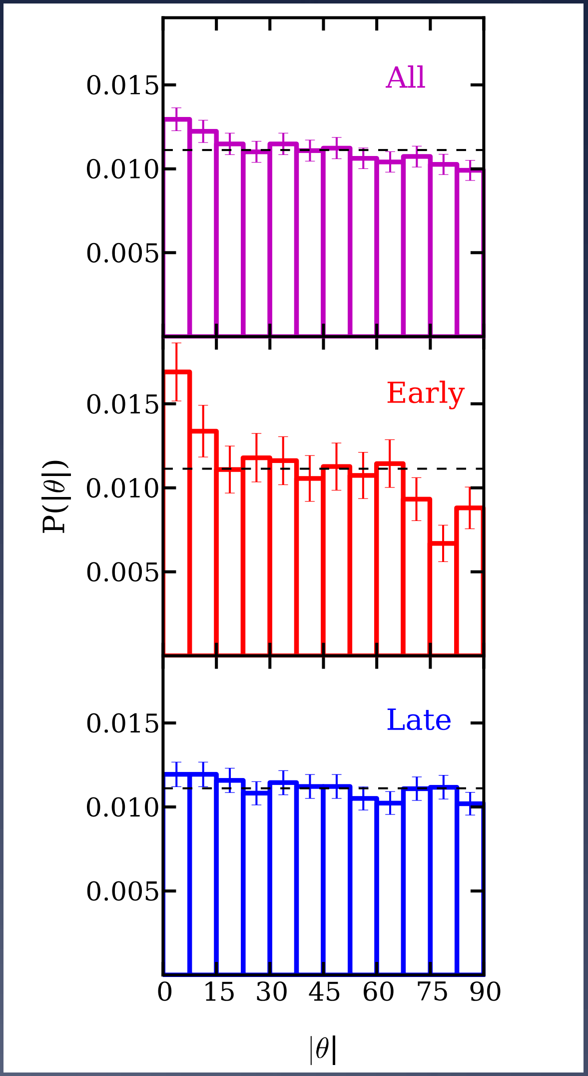




Nierenberg et al. 2012

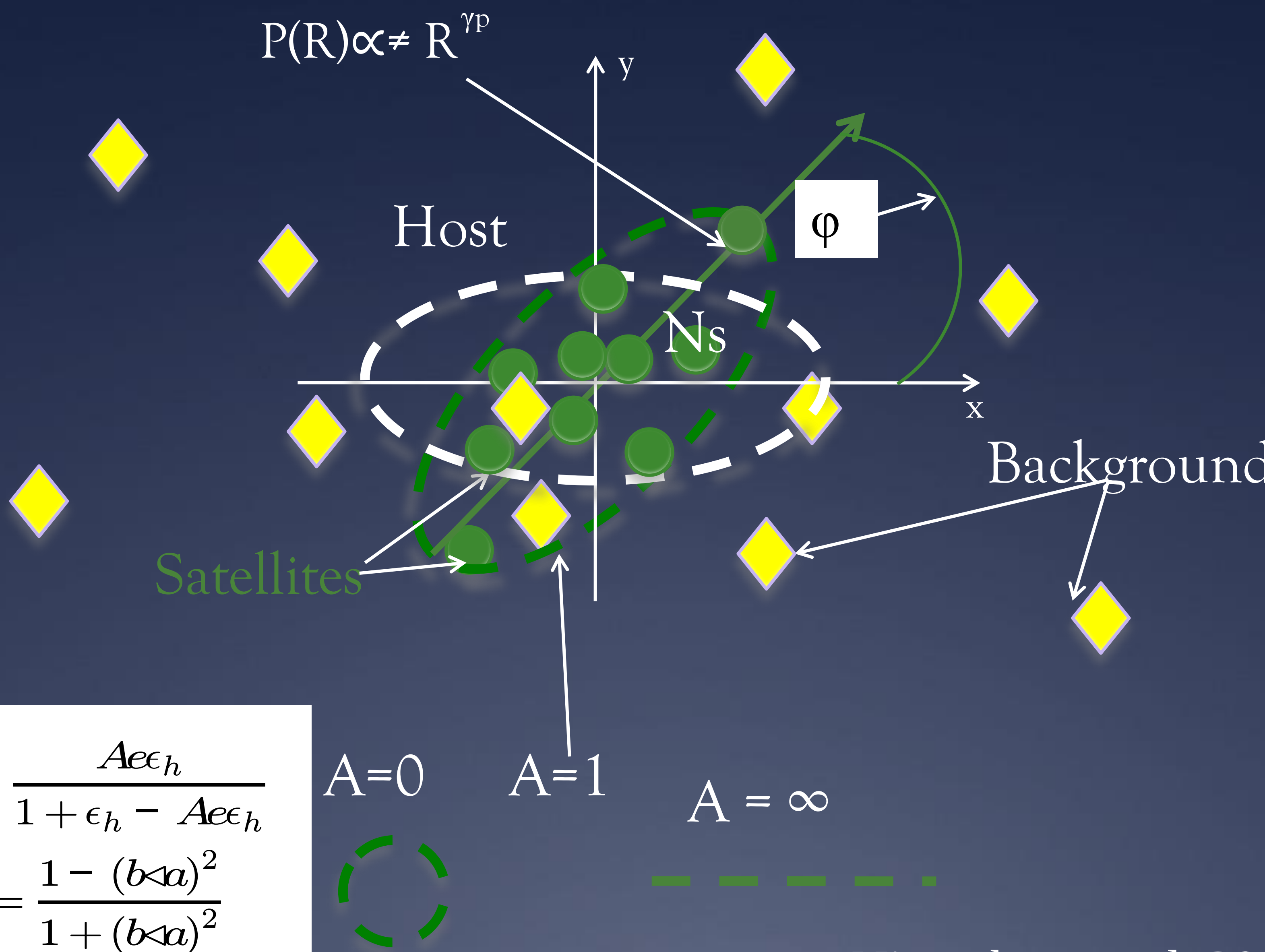
Observational signal visible with "naked eye"





Nierenberg et al. 2012

More rigorously: Spatial Distribution Model



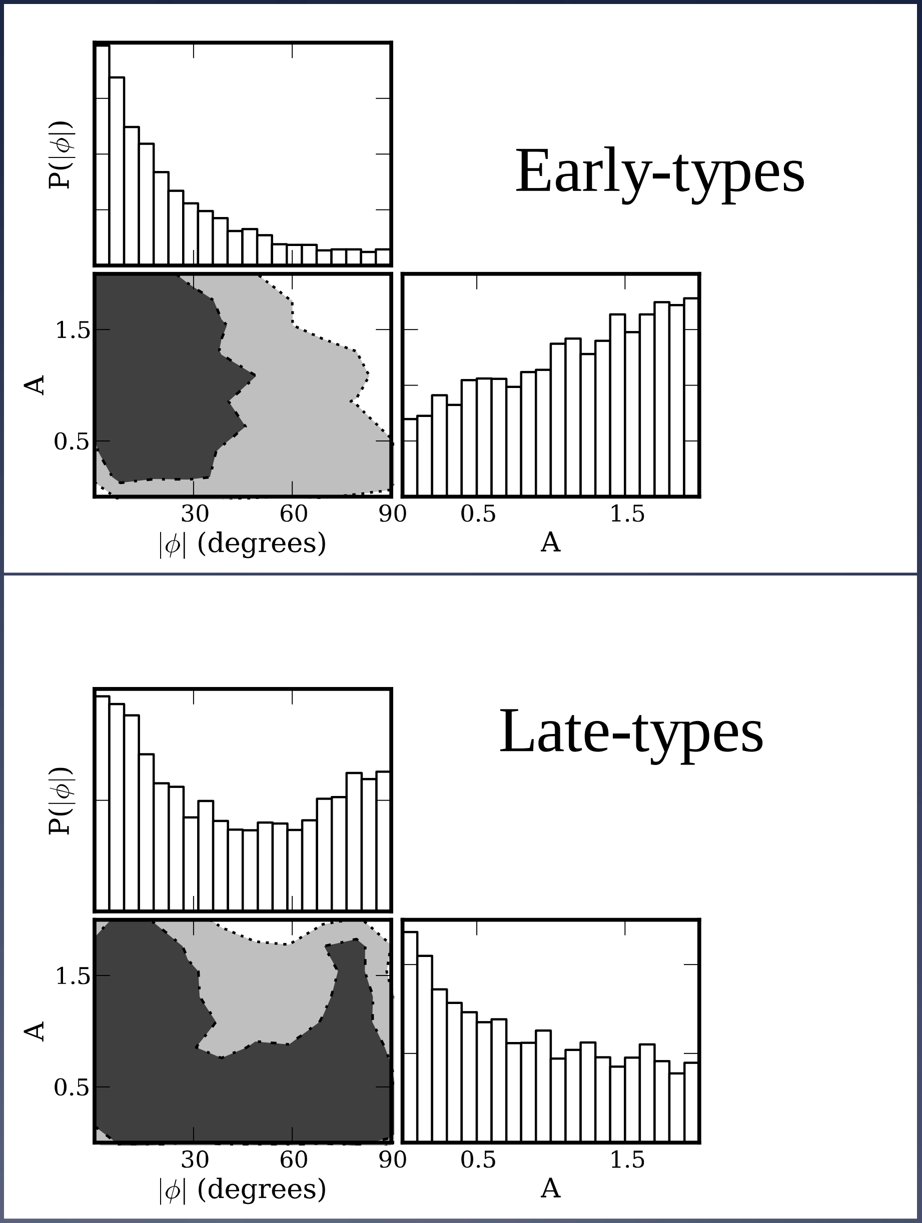
$$\epsilon_s = \frac{A\epsilon\epsilon_h}{1+\epsilon_h - A\epsilon\epsilon_h}$$

$$\epsilon = \frac{1-(b/a)^2}{1+(b/a)^2}$$

Nierenberg et al. 2011

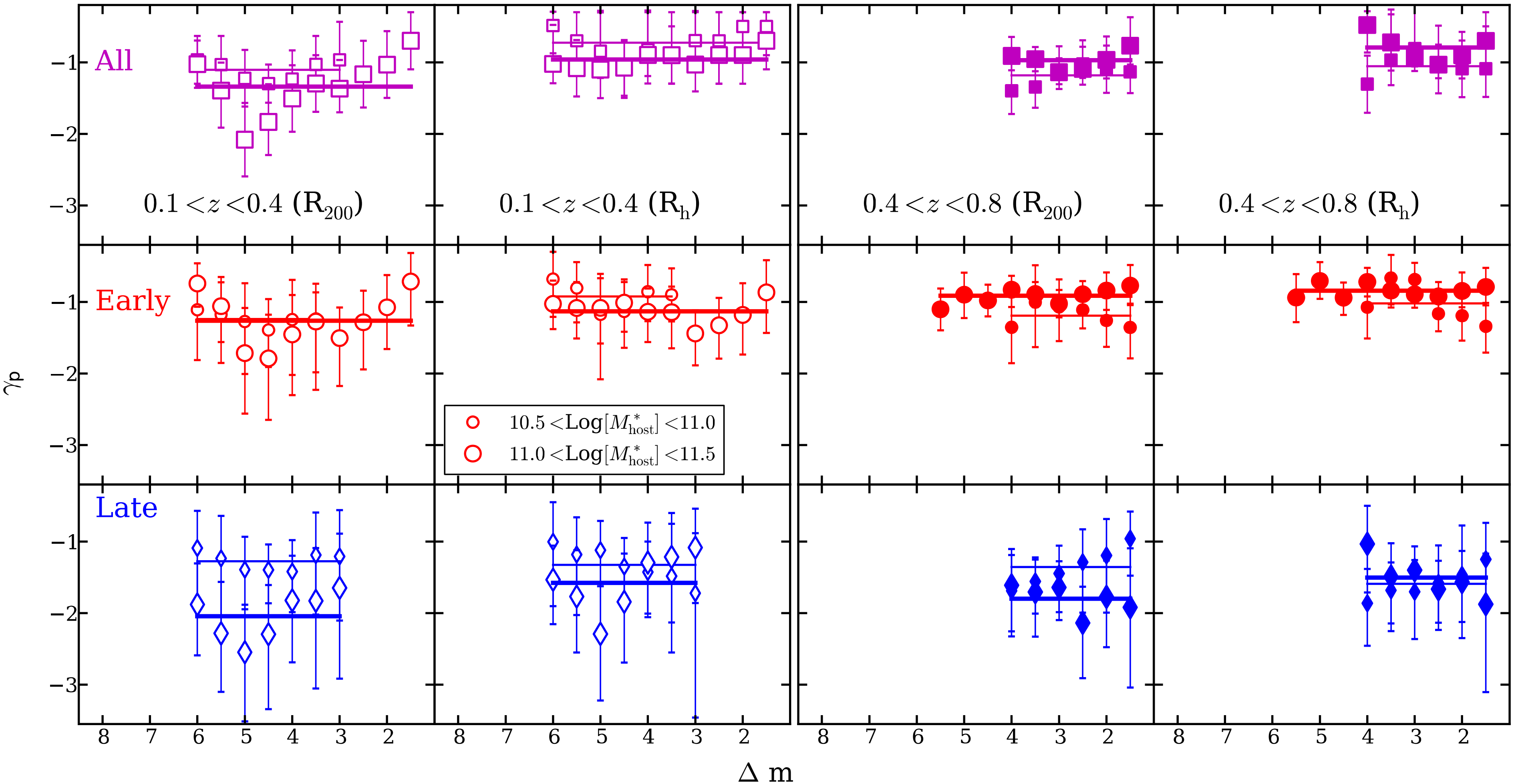
Angular distribution of satellites

Aligned with major axis =more efficient for lensing anomalies?
(Zentner 2005)



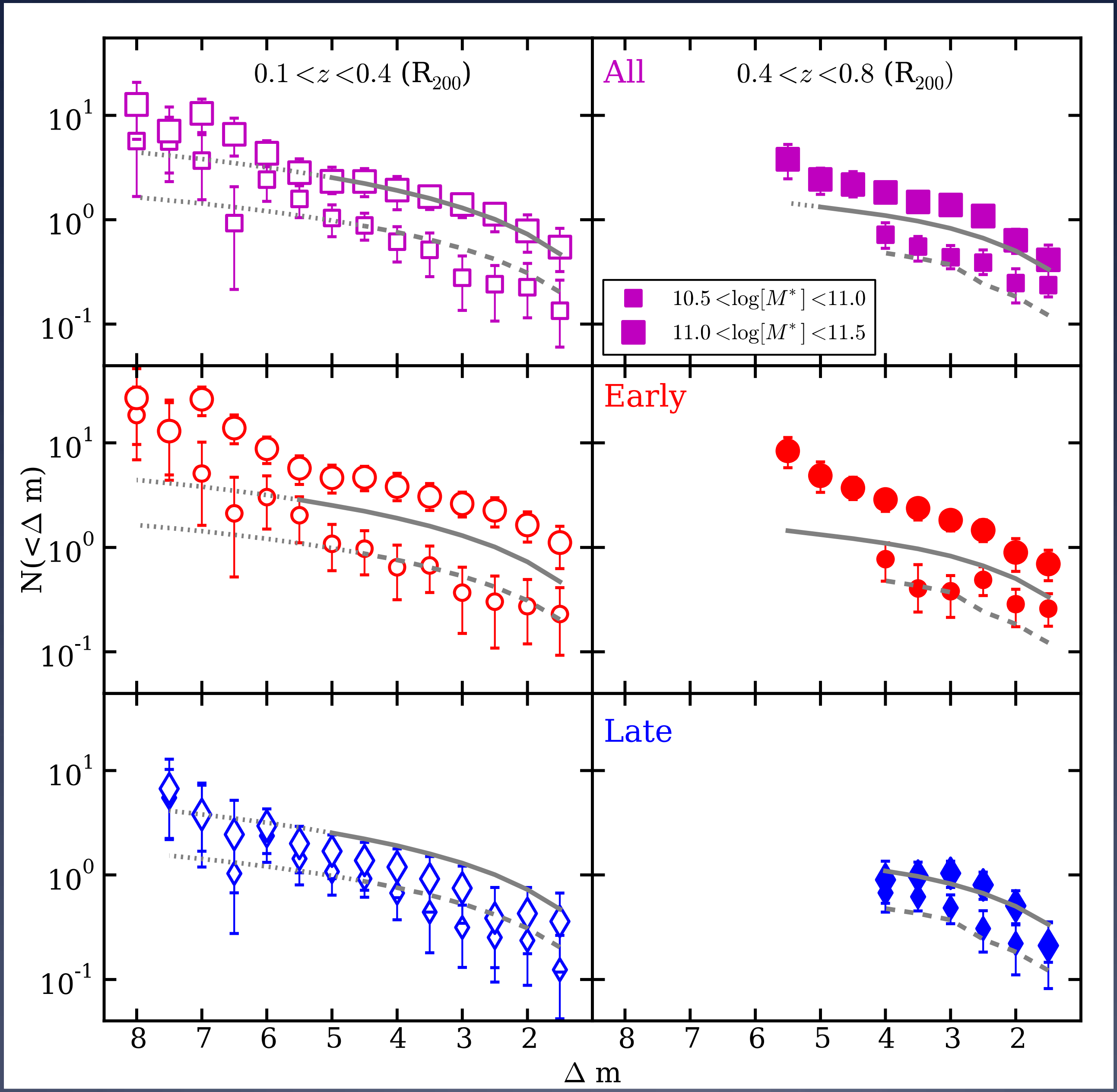
Nierenberg et al. 2012

Projected slope of the satellite number density is -1.1+-0.3 for every subsample

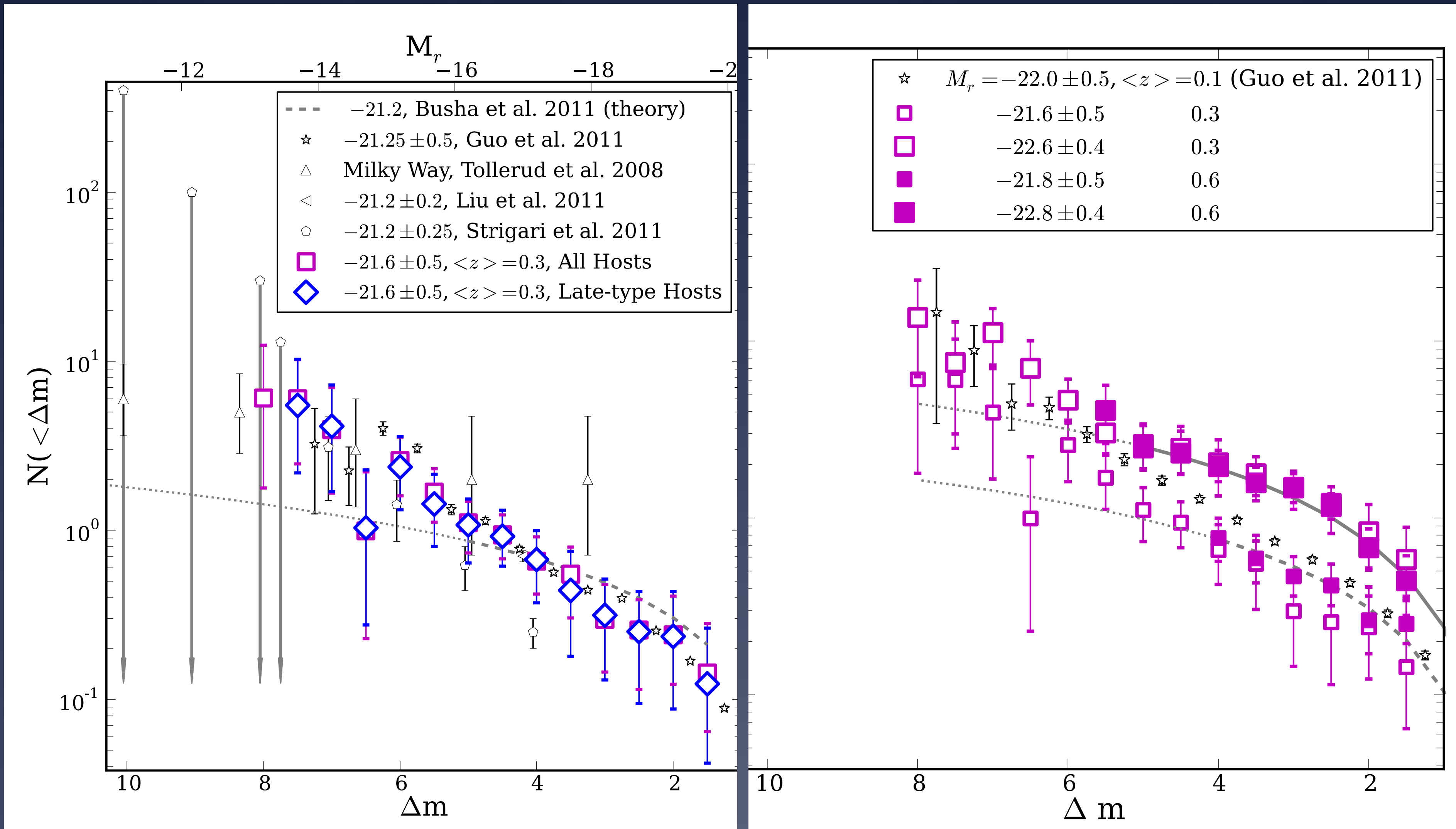


At variance with previous work claimed strong dependency on host mass

Satellite cumulative luminosity function

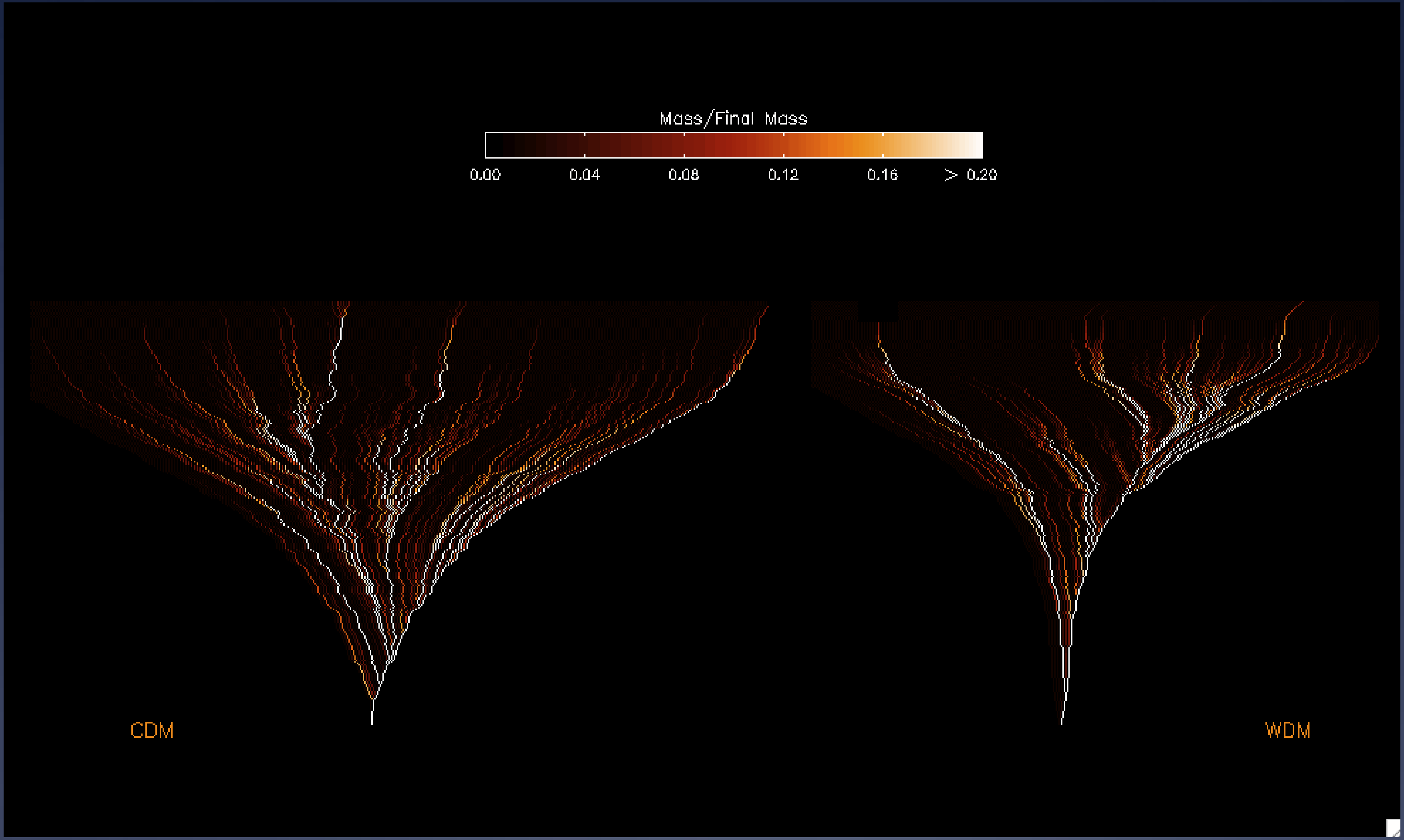


Comparison with MW/SDSS



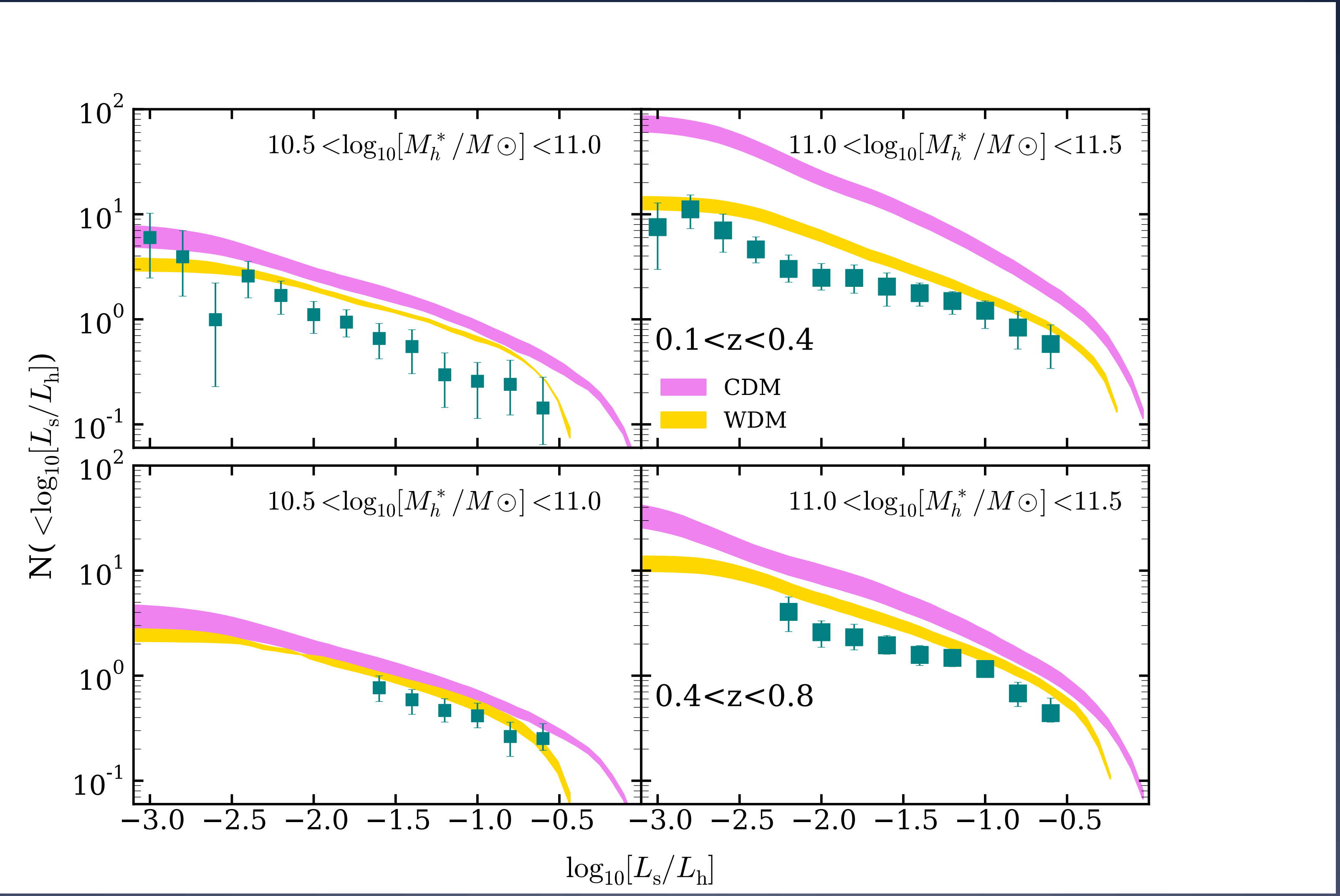
A curious coincidence

Warm or Cold Dark Matter?



Nierenberg, Menci & Treu 2012

Warm or Cold Dark Matter?

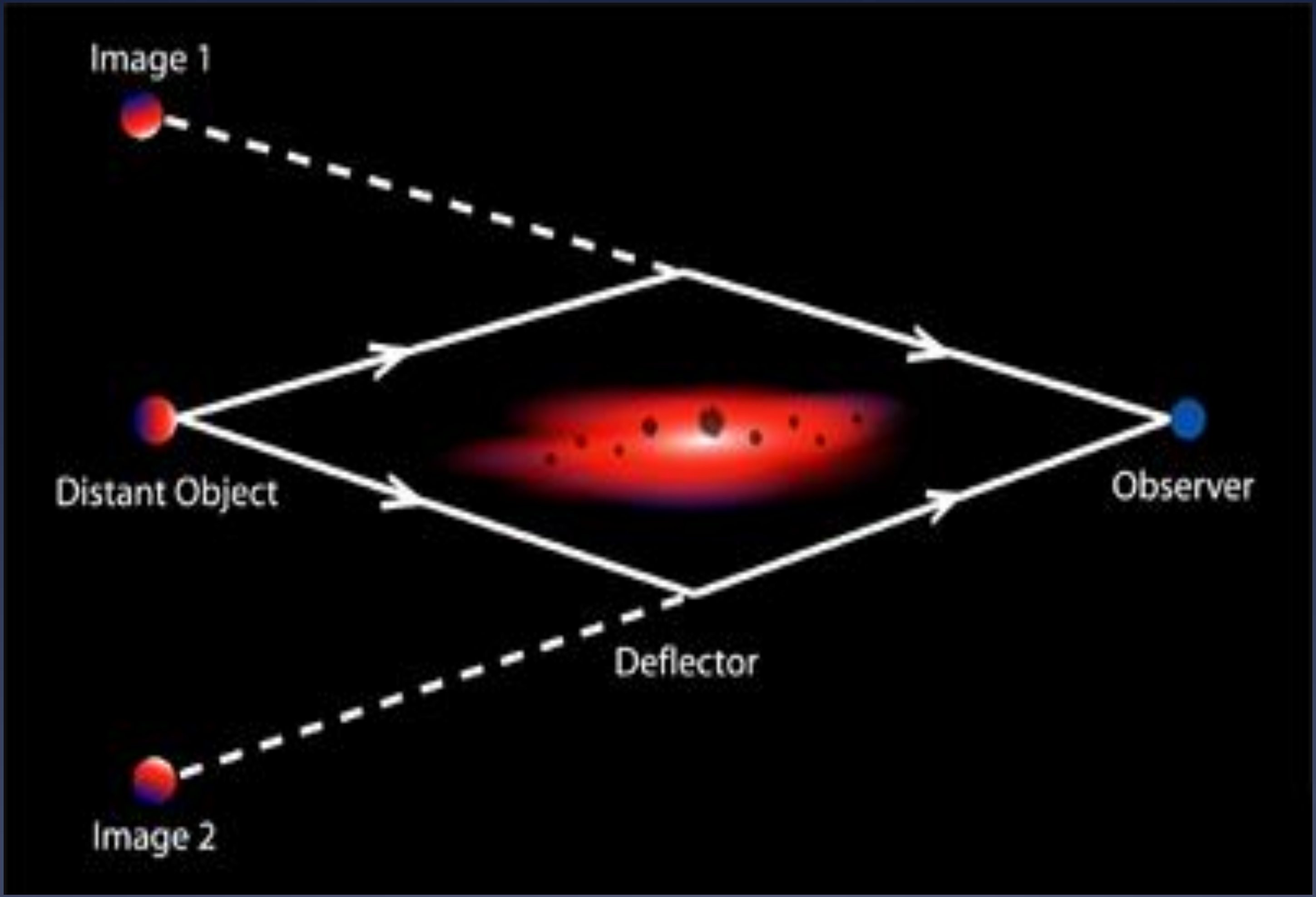


Nierenberg, Menci & Treu 2012

Dark substructure

and strong lensing

Strong gravitational Lensing



Light ray deflection is a direct measurement of mass, luminous or dark!

Strong lensing in terms of Fermat's principle

Fermat distance

Shapiro delay

$$t(\vec{\theta}) = \frac{(1+z_{\rm d})}{c}\frac{D_{\rm d}D_{\rm s}}{D_{\rm ds}}\left[\frac{1}{2}(\vec{\theta}-\vec{\beta})^2 - \psi(\vec{\theta})\right]$$

Excess time delay

geometric time delay

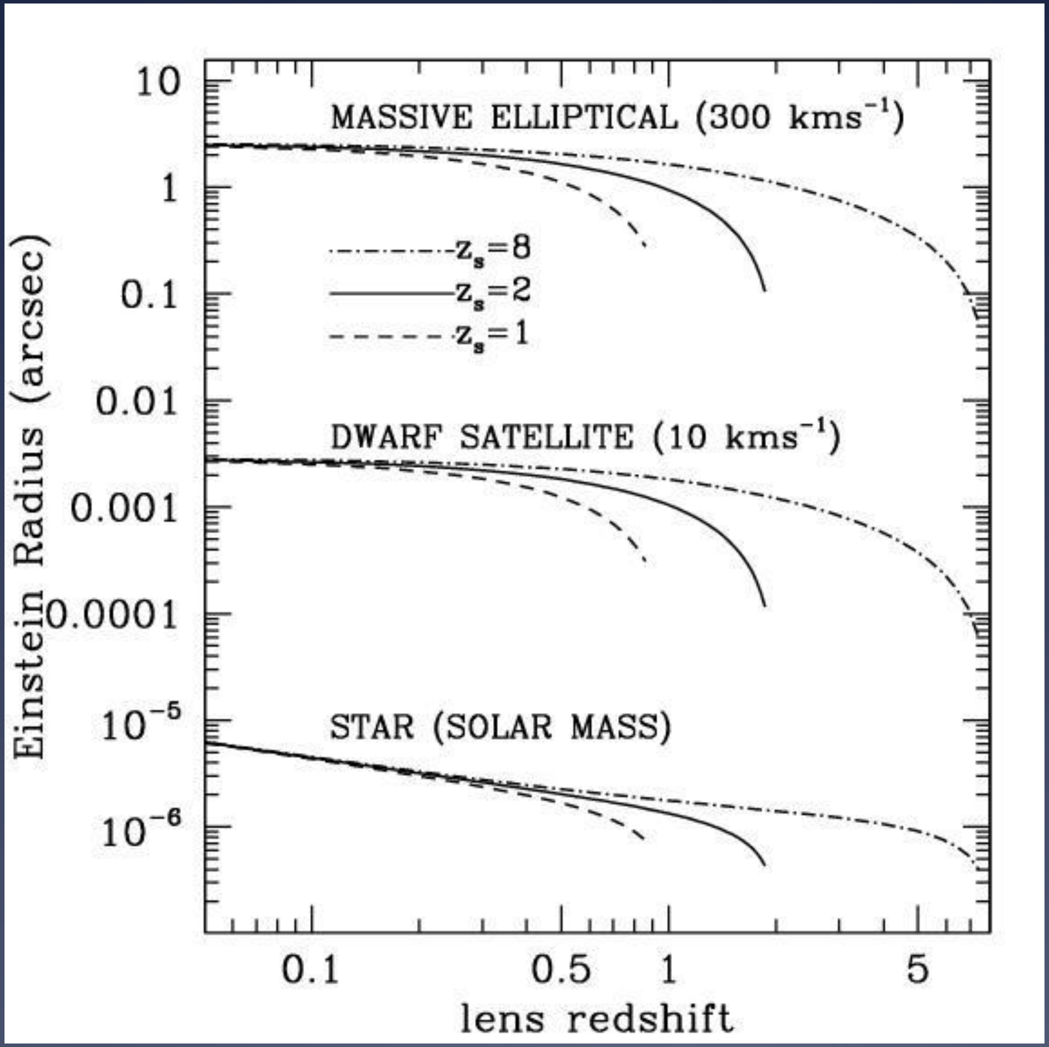
Observables: flux, position, and arrival time of the multiple images

“Missing satellites” and lensing

- Strong lensing can detect satellites based solely on mass!
- Satellites are detected as “anomalies” in the gravitational potential ψ and its derivatives
  - ψ'' = Flux anomalies
  - ψ' = Astrometric anomalies
  - ψ = Time-delay anomalies

– **Natural scale is a few milliarcseconds.**

“Missing satellites” and lensing



Treu 2010

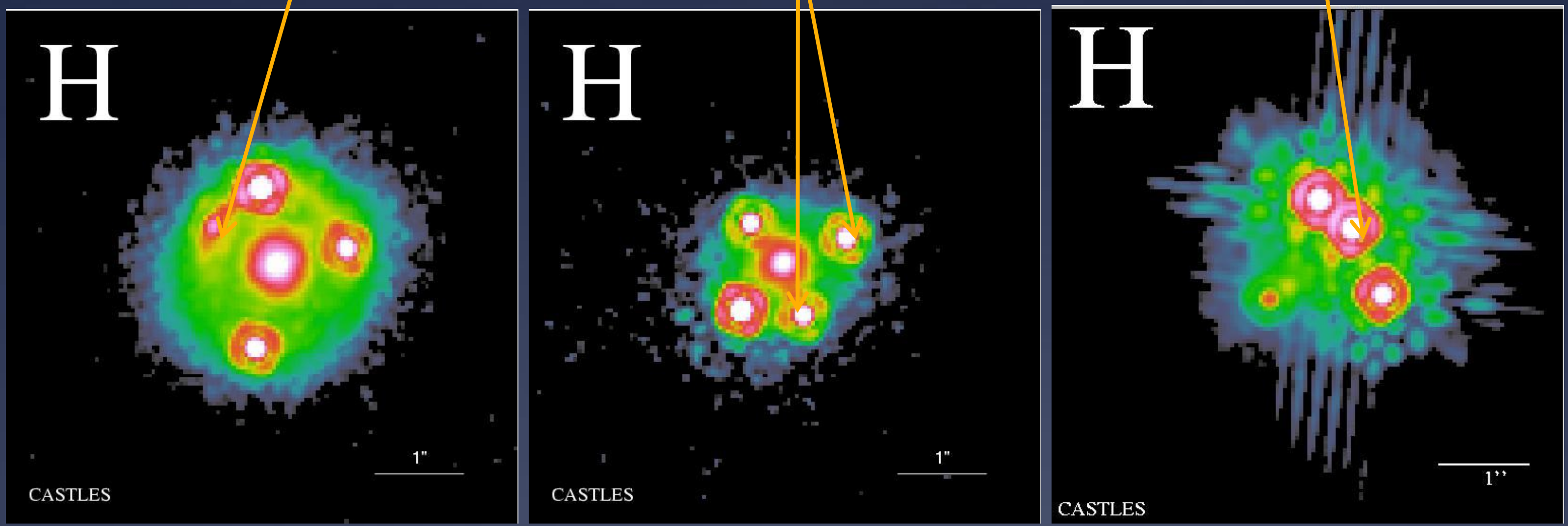
Flux Ratio Anomalies

A smooth mass distribution would predict:

This to be 100x brighter

These to be 2x brighter

This to be 10% brighter



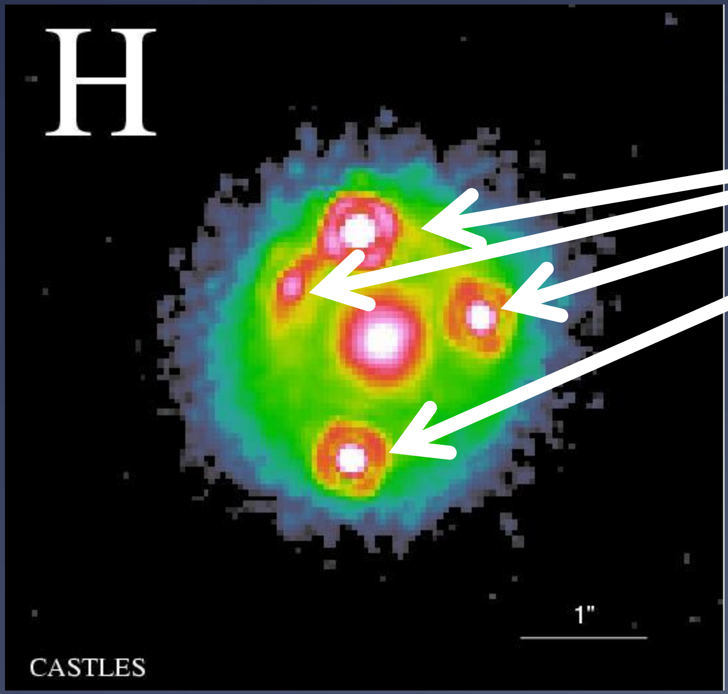
What causes this the anomaly?

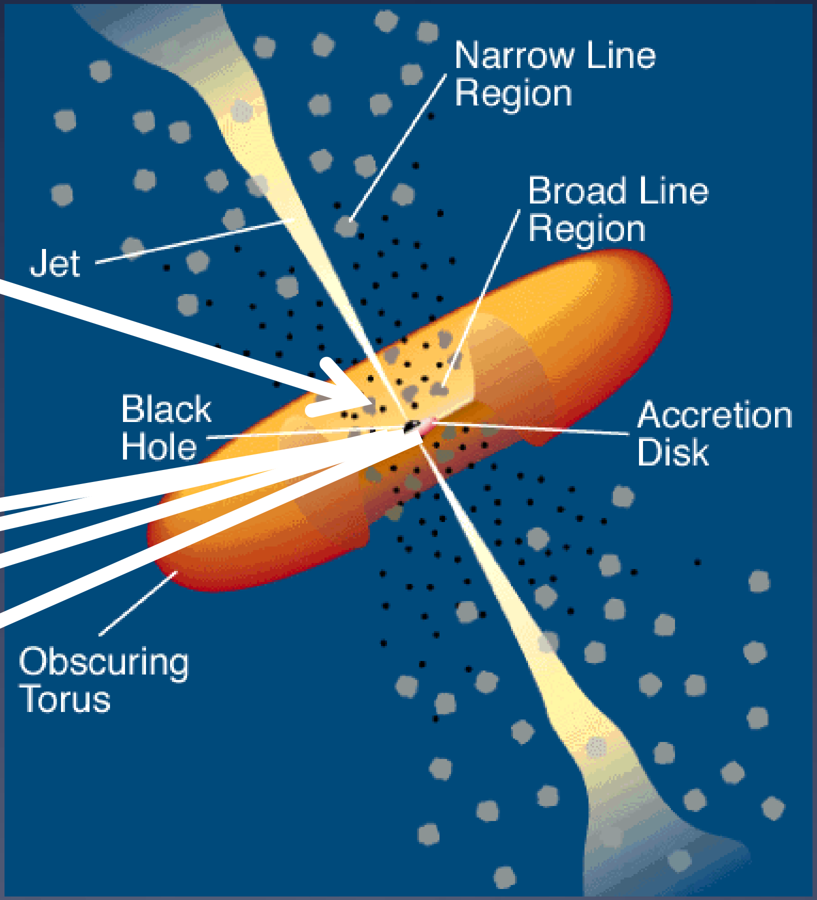
1.Dark satellites?

2.Astrophysical noise (i.e. microlensing and dust)?

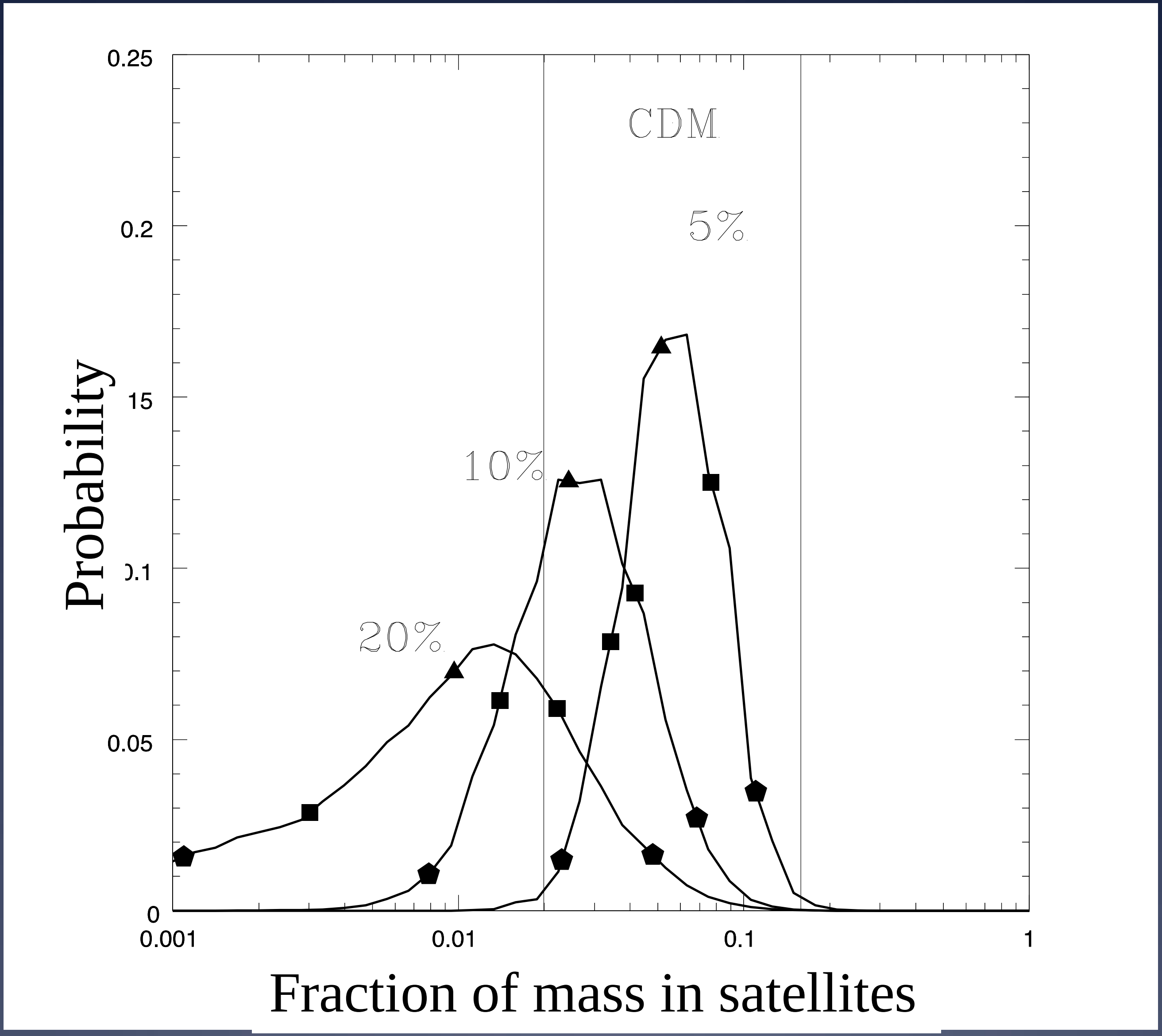
(Micro)lensing of active galactic nuclei

The accretion disk is so small that can be lensed by a single star in the foreground galaxy (microlensing)



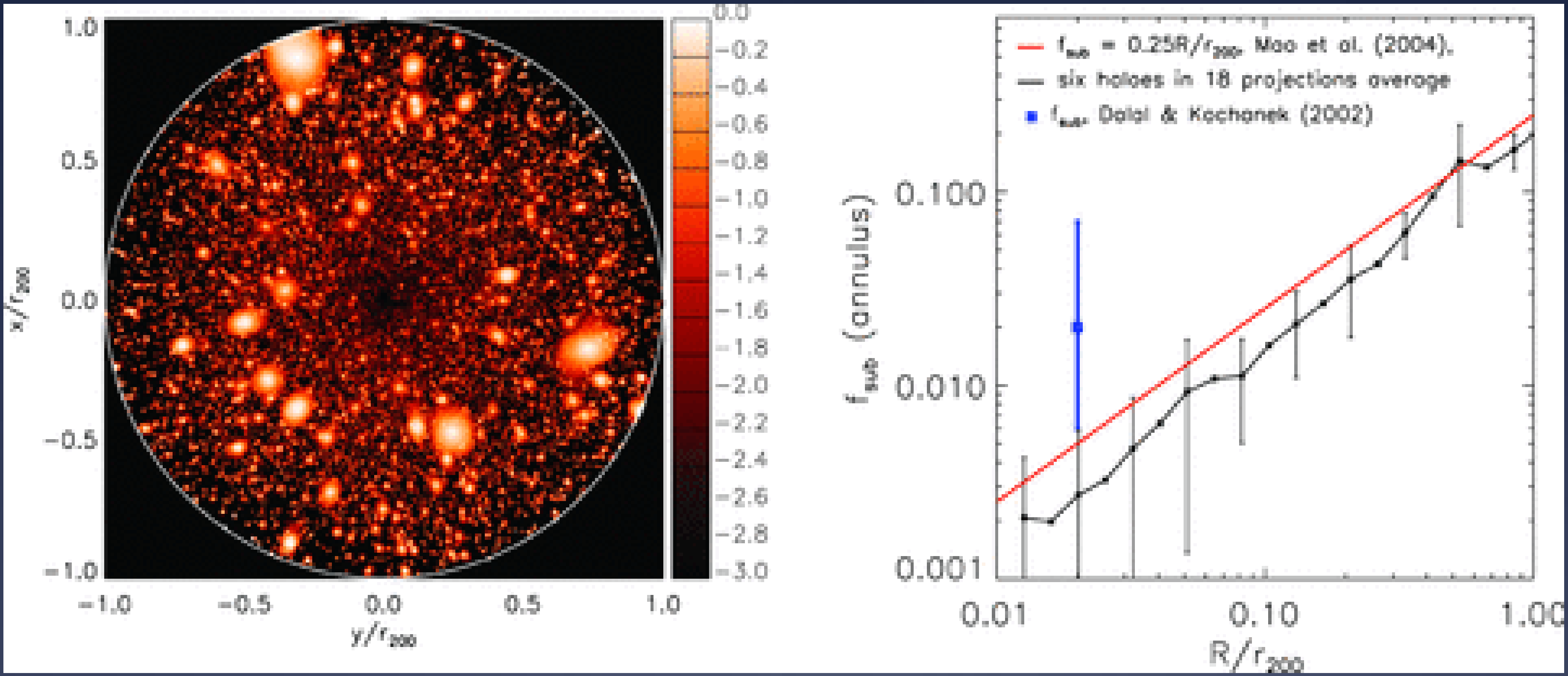


Radio Anomalies. Are they enough?



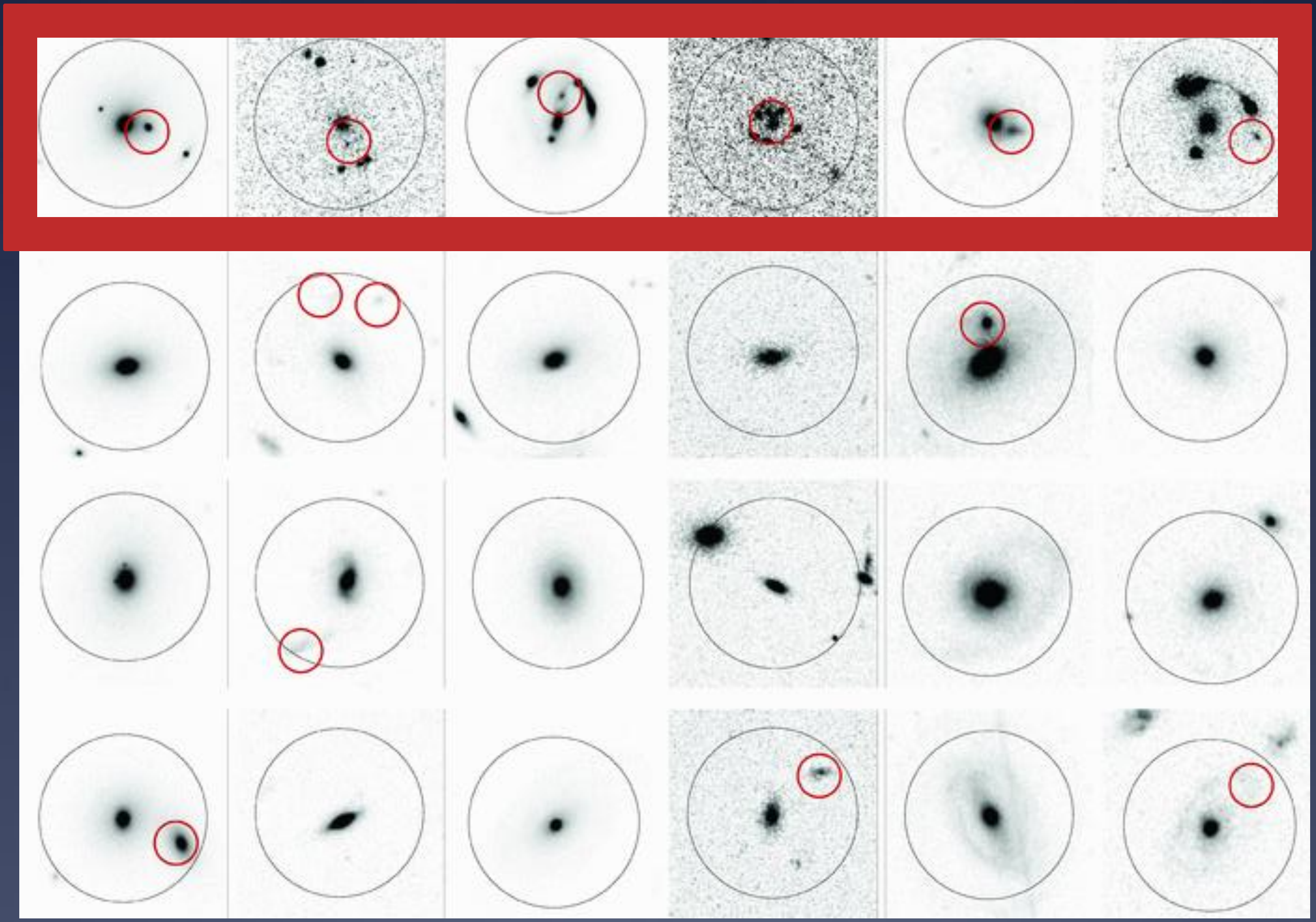
Dalal and Kochanek 2002

Or perhaps too many?



Xu et al. 2009

Is CLASS Unbiased wrt substructure?



Jackson et al. 2010

How do we make progress?

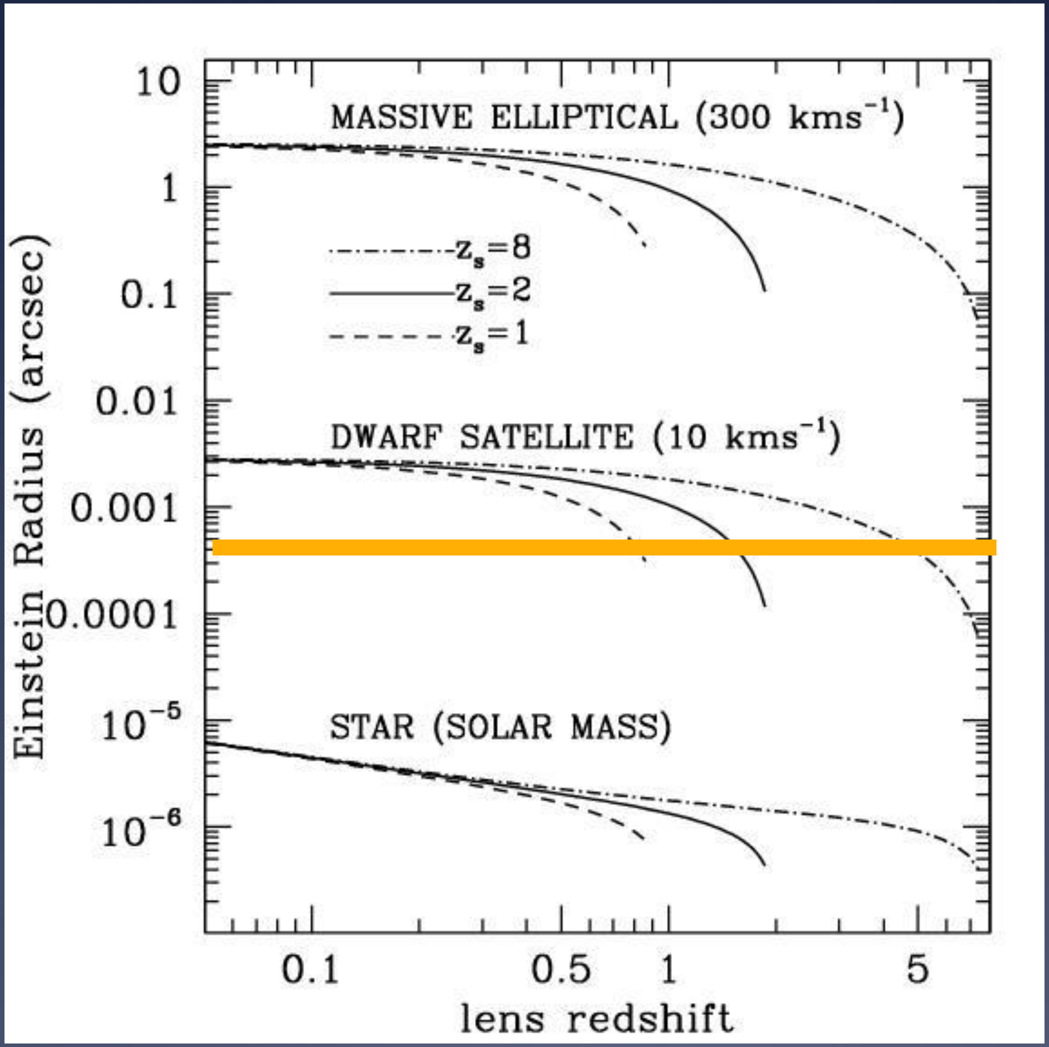
1. Direct detection a.k.a. "gravitational imaging" (Vegetti's talk)
2. Larger samples (Dalal & Kochanek used only 7 lenses); need more lenses..
3. Avoid microlensing (e.g. mid-IR; Keeton's talk)
4. Take into account spatial information from luminous satellites

4. Luminous satellites

1. Radial number density profile well measured and close to isothermal
2. Angular distribution highly anisotropic
3. This should be accounted for in comparing statistics of flux ratio anomalies
4. And we can combine the inferences to figure out M/L!

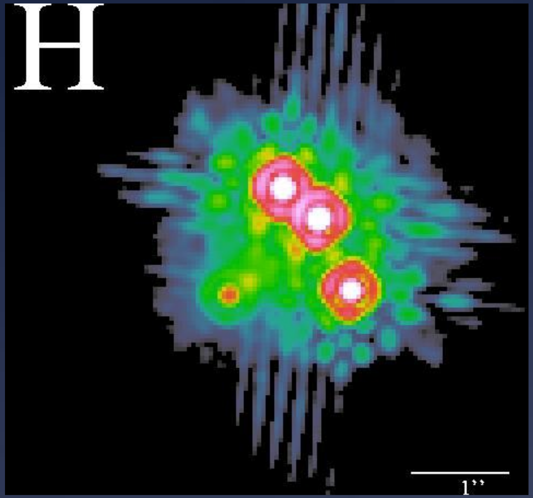
Future Prospects

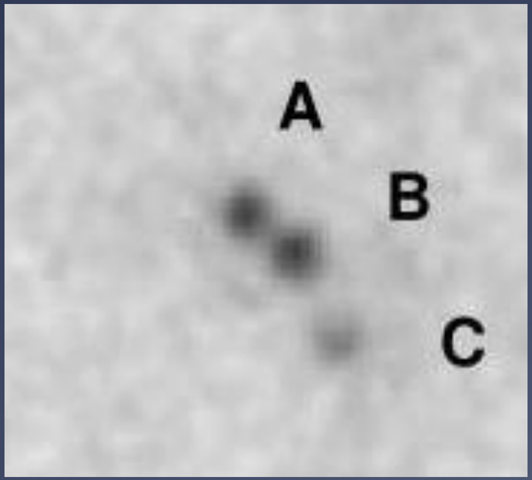
Dusty torus is "immune" to microlensing



Treu 2010

Dusty Torus: mid-IR fluxes





Sensitivity at 11μms:

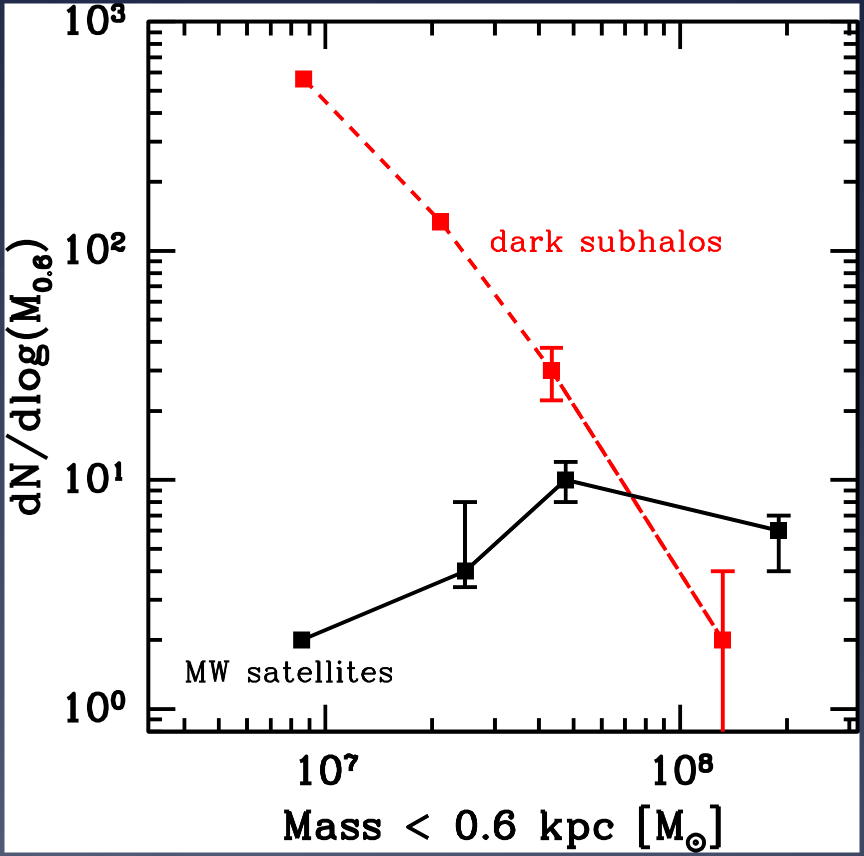
- D ~0.2-0.3mJ:
  - Undetected by Subaru
  - S/N~40-60 in 28s of JWST-MIRI
- B 10mJ:
  - S/N~5 in 3.1 hrs of Subaru
  - S/N~700 in 28s of JWST-MIRI

Flux (mJ)	MIRI Exptime (S/N=10)
0.02	100s
0.006	1000s
0.002	9500s

Chiba et al. 2005; 3.1hrs of Subaru

Gravitational imaging: Future Prospects

- Gravitational imaging can now reach $2x10^8$ solar mass sensitivity, limited by resolution and S/N (Vegetti et al. 2012)
- With Next Generation Adaptive Optics and then TMT we should reach 10^7 solar masses, that is where the discrepancy with theory is strongest
- Also, for more massive galaxies than MW we should think in terms of mass ratio



Flux ratio anomalies: Future Prospects

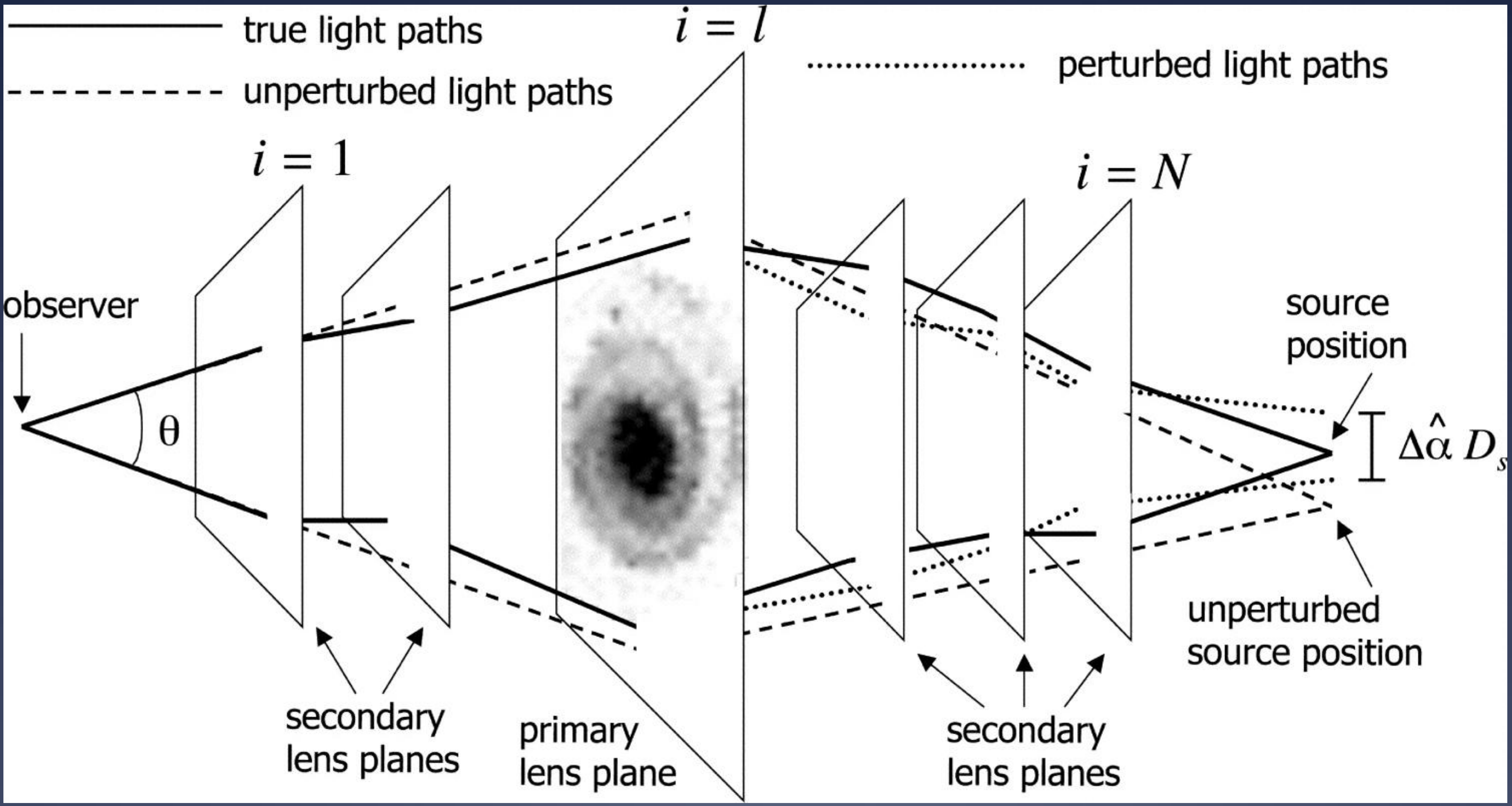
- Future surveys (DES/LSST) will discover thousands of systems, mostly fainter than those currently known
- High resolution follow-up (and spectra!) will be needed to make sense of them
- JWST will be able to measure flux ratios in the mid-IR in snapshot mode

Summary

- Satellites as faint as 1/1000 of the host can be detected up to z=1 with HST images
- The angular distribution of satellites is anisotropic for early-type hosts and Isotropic for late-type hosts
- The radial profile of satellites is consistent with isothermal
- The number of satellites is a very strong function of galaxy mass and morphology, not so much of redshift
- Observations can be matched by properly rescaling M/L in CDM. However… WDM does surprisingly well!
- We need lensing observations to disentangle luminosity and mass function. Currently limited by small number statistics and selection effects, need JWST and AO (Keck and TMT). We should not forget the lessons learned from luminous satellites

The end

Where is the substructure? cosmological simulations



Metcalf 2005; Chen; Xu et al. 2009, 2010