Bright and dark: satellite galaxies as a test of galaxy formation and the nature of dark matter.

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Outline

- Introduction: The missing satellite problem and LCDM
- Part I: Luminous Satellites
  - What do we hope to learn?
  - Previous measurements
  - This work: Measuring the satellite luminosity function since redshift 0.8 with COSMOS
  - Comparison with previous observations
  - Comparison with simulations with Warm and Cold Dark Matter
- Part II: Dark Satellites
  - Gravitational lensing to measure the subhalo mass function
  - Narrow line emission from quasar lenses to obtain a microlensing-free constraint on the subhalo mass function.

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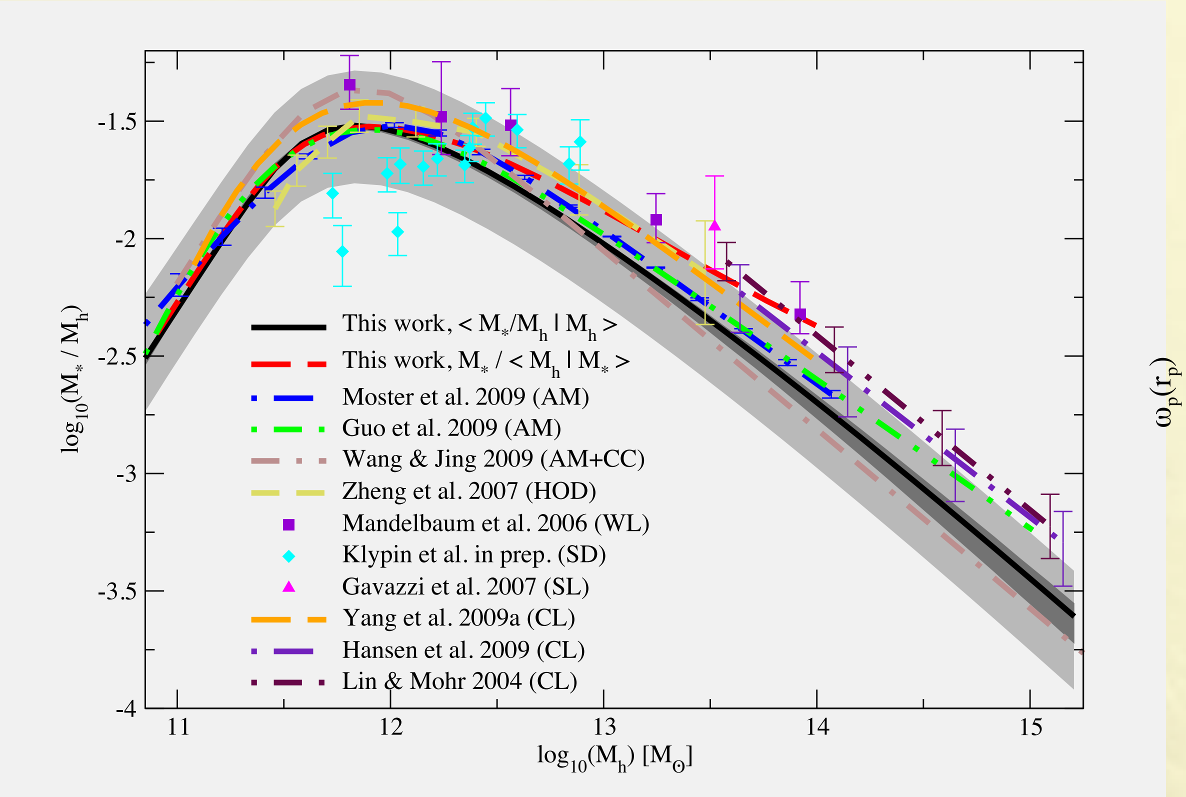
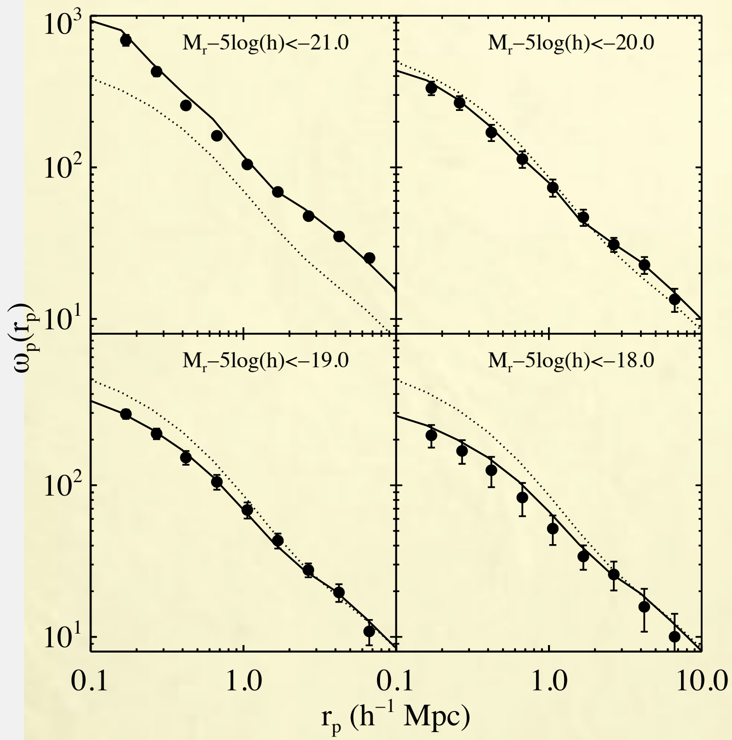
Mapping between halos and galaxies is non-trivial

Kravtsov 2010

Then how do you test ΛCDM?

Abundance Matching



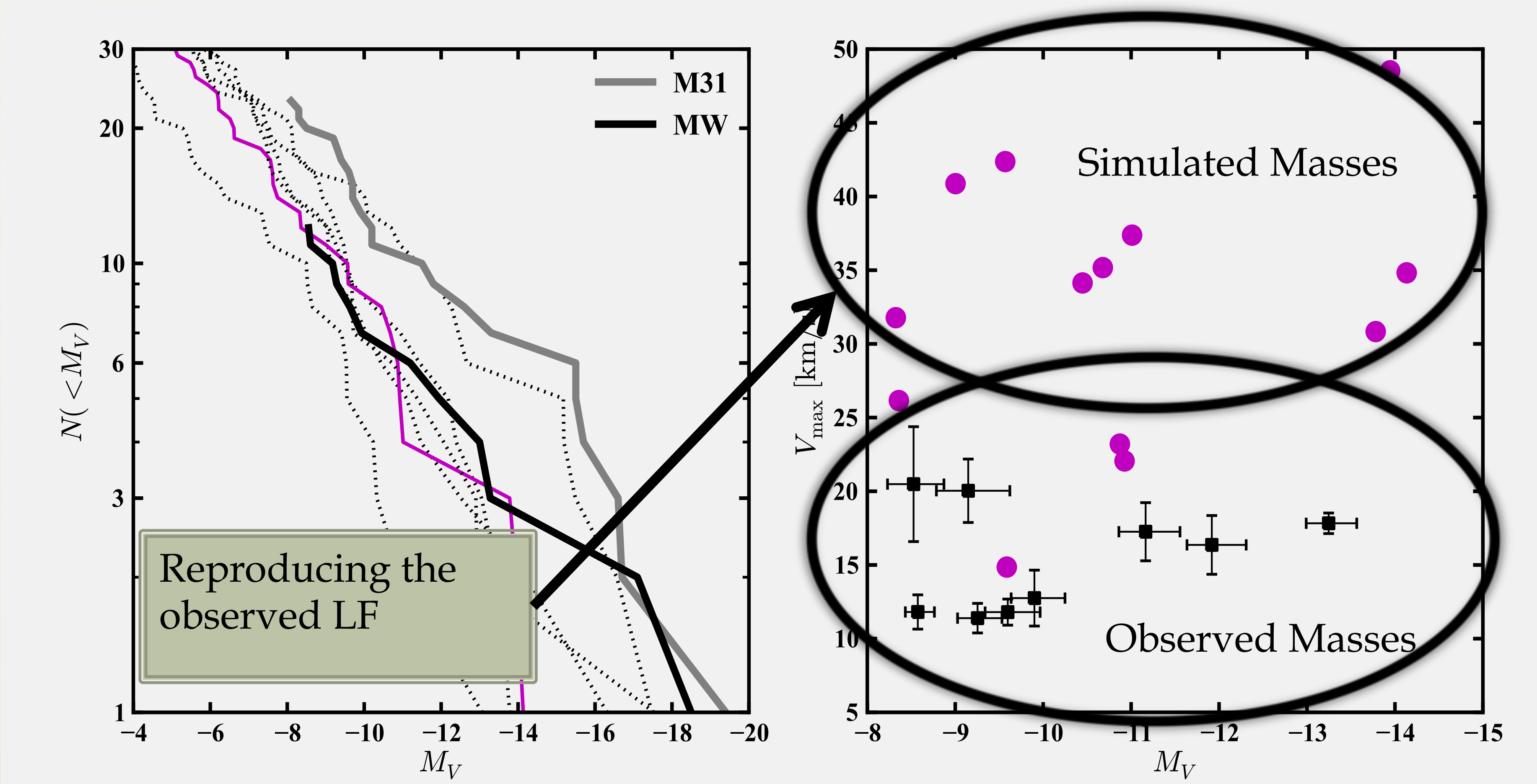


Weak + strong lensing
Satellite kinematics
Stellar kinematics

Behroozi et al. 2010

Conroy, Wechsler, Kravstov 2006

However, at lower masses…

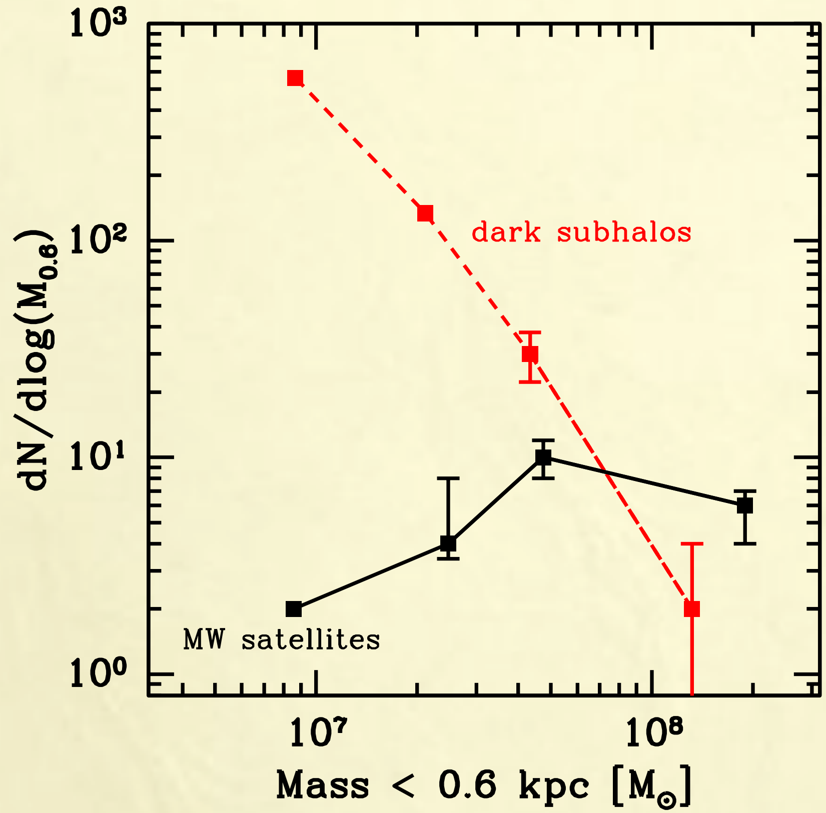


Boylan-Kolchin et al. 2012

This implies that there are a large number of massive satellites around the Milky Way which remain unobserved…

What went wrong?

- The subhalos don’t exist?
- The Milky Way has an abnormal satellite luminosity function?
- We don’t understand star formation in low mass halos



Strigari et al. 2007

Most likely some combination of these

This is a test of the nature of dark matter and of complex star formation processes.

How to make progress

- Form a better understanding of what governs star formation in low mass halos
  - How important are effects such as disruption by the central galaxy?
  - How does the satellite luminosity function evolve over cosmic time.
  - How does the satellite luminosity function depend on the properties of the host galaxy?
- Directly measure the subhalo mass function using an observable which does not depend on star formation.

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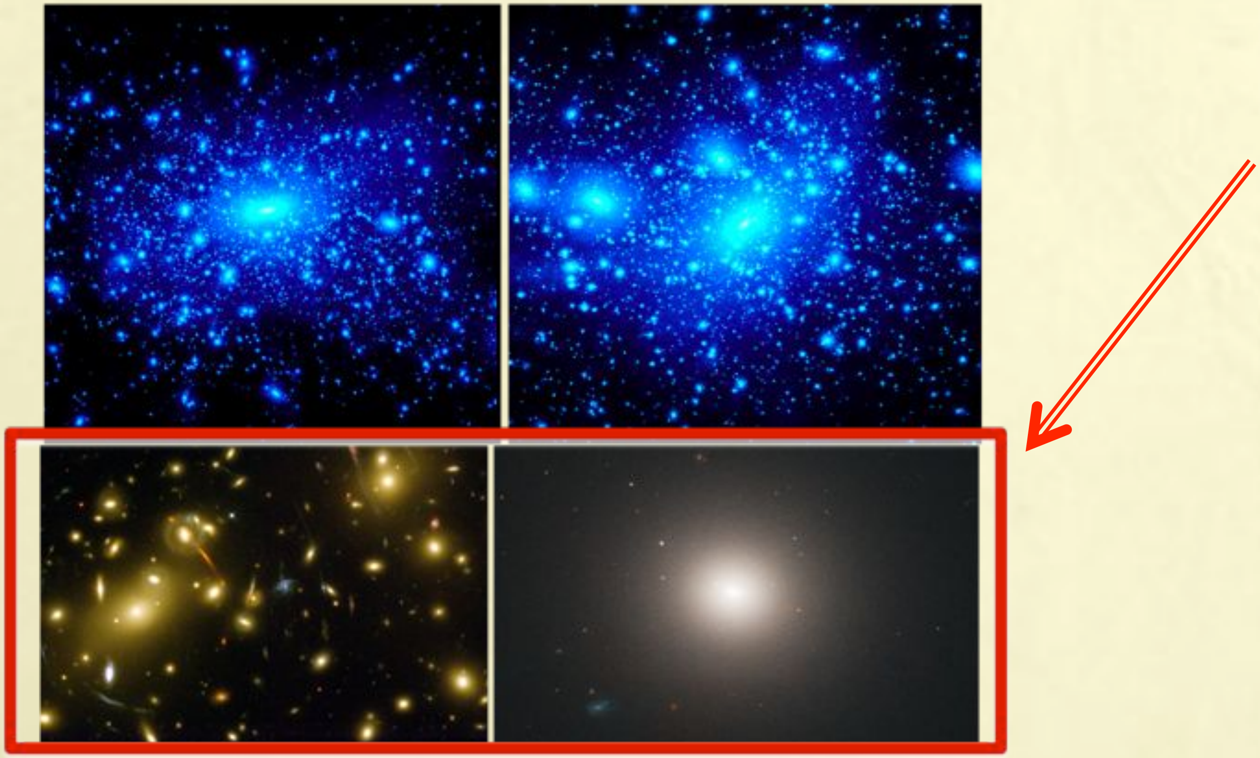
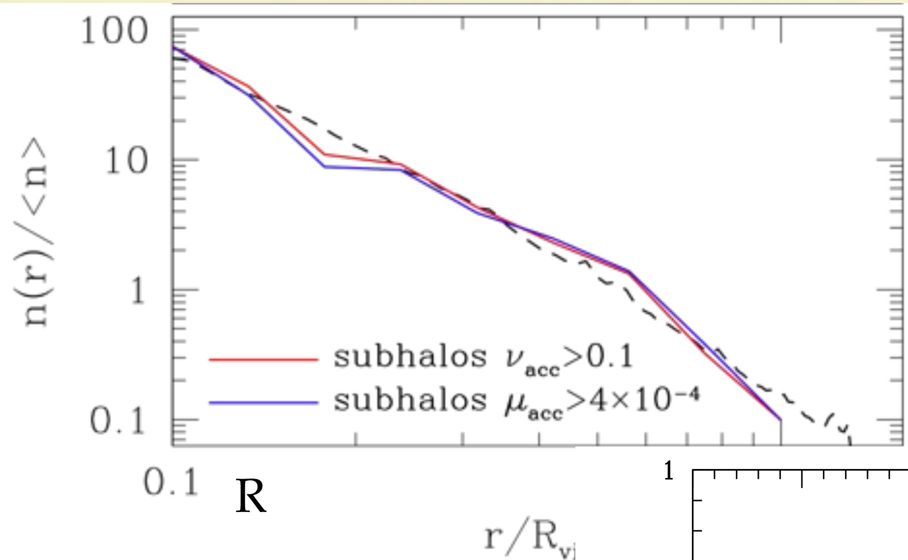
Part I: Characterizing the number and spatial distribution of luminous satellites as a function of environment and redshift.



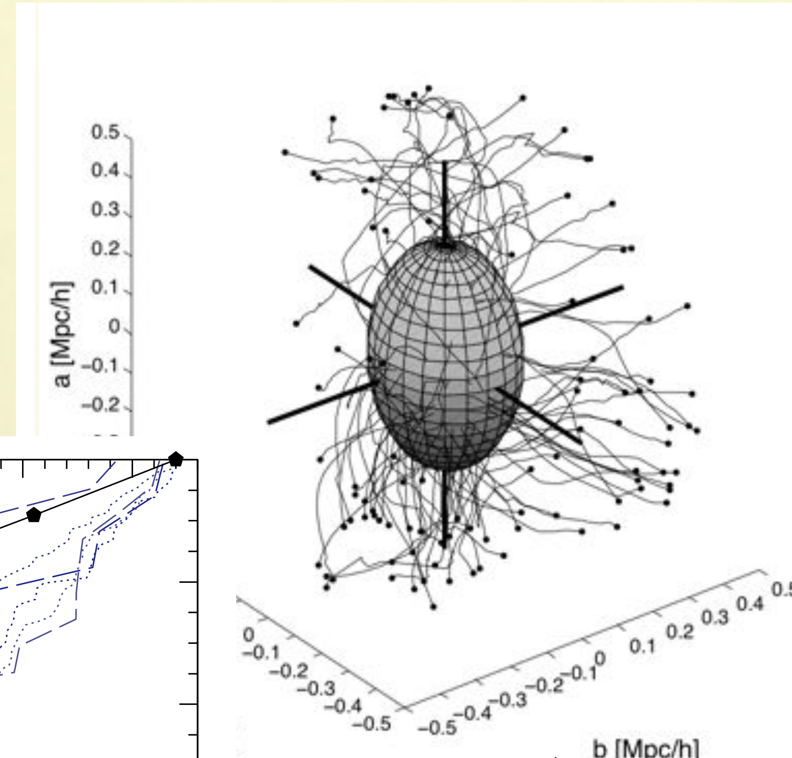
What simulations predict about the satellite spatial distribution:

Radial Distribution



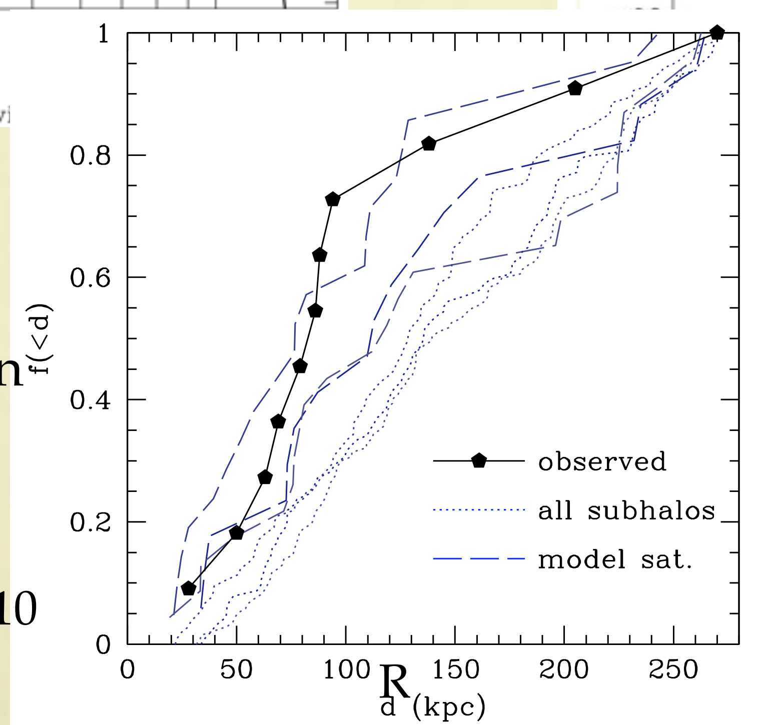
Kravtsov 2010

Angular Distribution



Zentner 2005

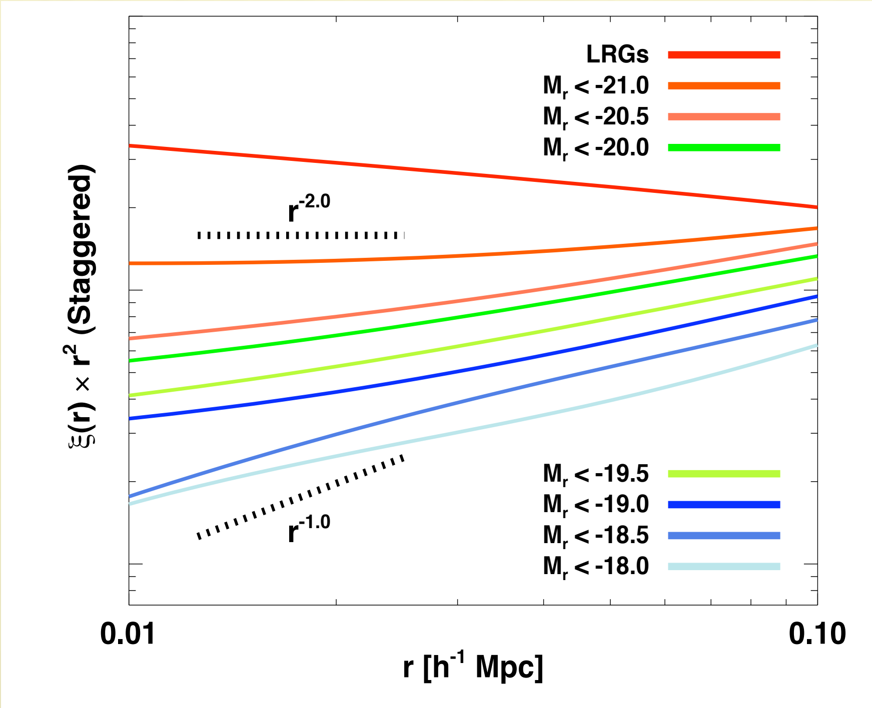
Impact of baryons on survival ?



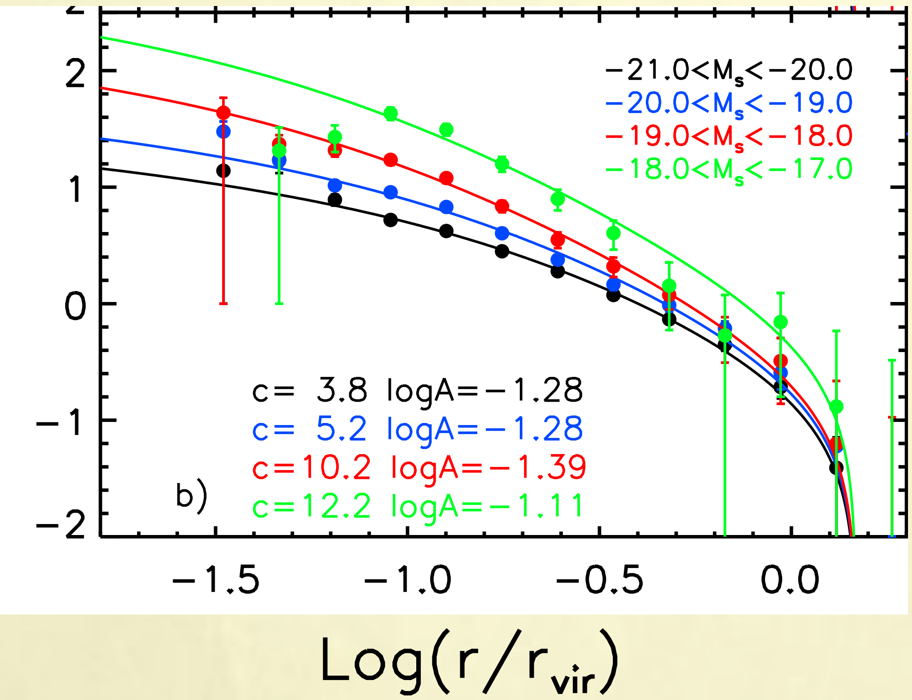
Kravtsov 2010

Radial profile of bright satellites

Watson et al. 2012



Guo et al. 2012



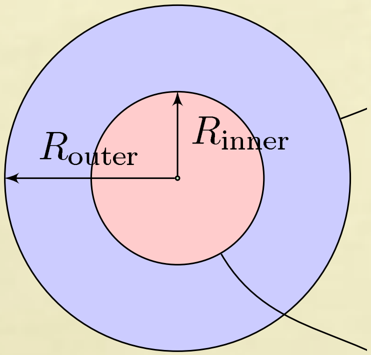
Should see a clearer trend if fainter satellites are studied

Satellite Luminosity function, SDSS

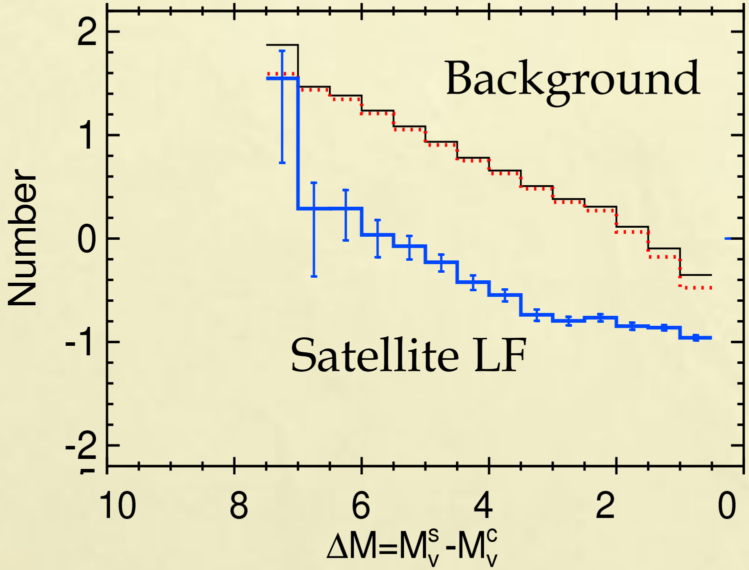
To measure the faint satellite LF cannot rely on spectroscopy.

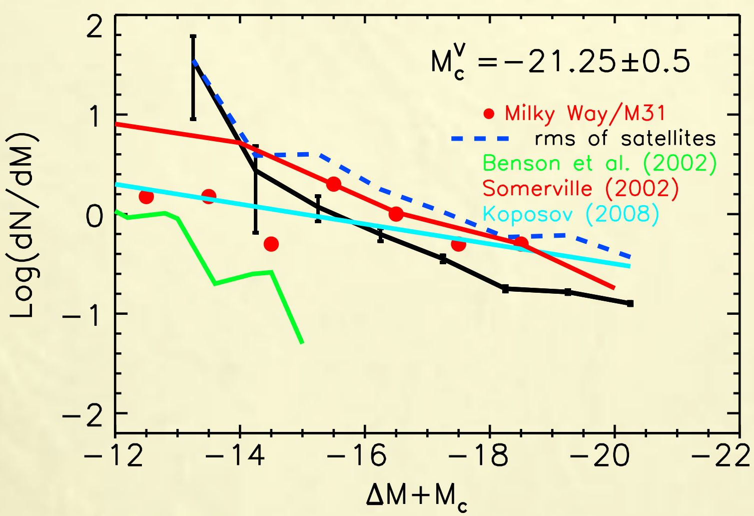
Typically take two annuli, one which is assumed to contain satellites + background/foreground objects, the other which contains only background.

Then subtract to get the satellite luminosity function



Guo et al. 2011





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Goals for this work:

1. Increase the variety of studied luminous satellite populations by:
   i) Increasing the redshift range, in which satellites are studied
   ii) Measure satellite properties as a function of host morphology as well as stellar mass

2. Utilize all available information by performing a self-consistent statistical analysis of all satellite properties of interest
   -Simultaneously infer satellite numbers+ radial+angular distribution and analyze as a function of host properties

Data:

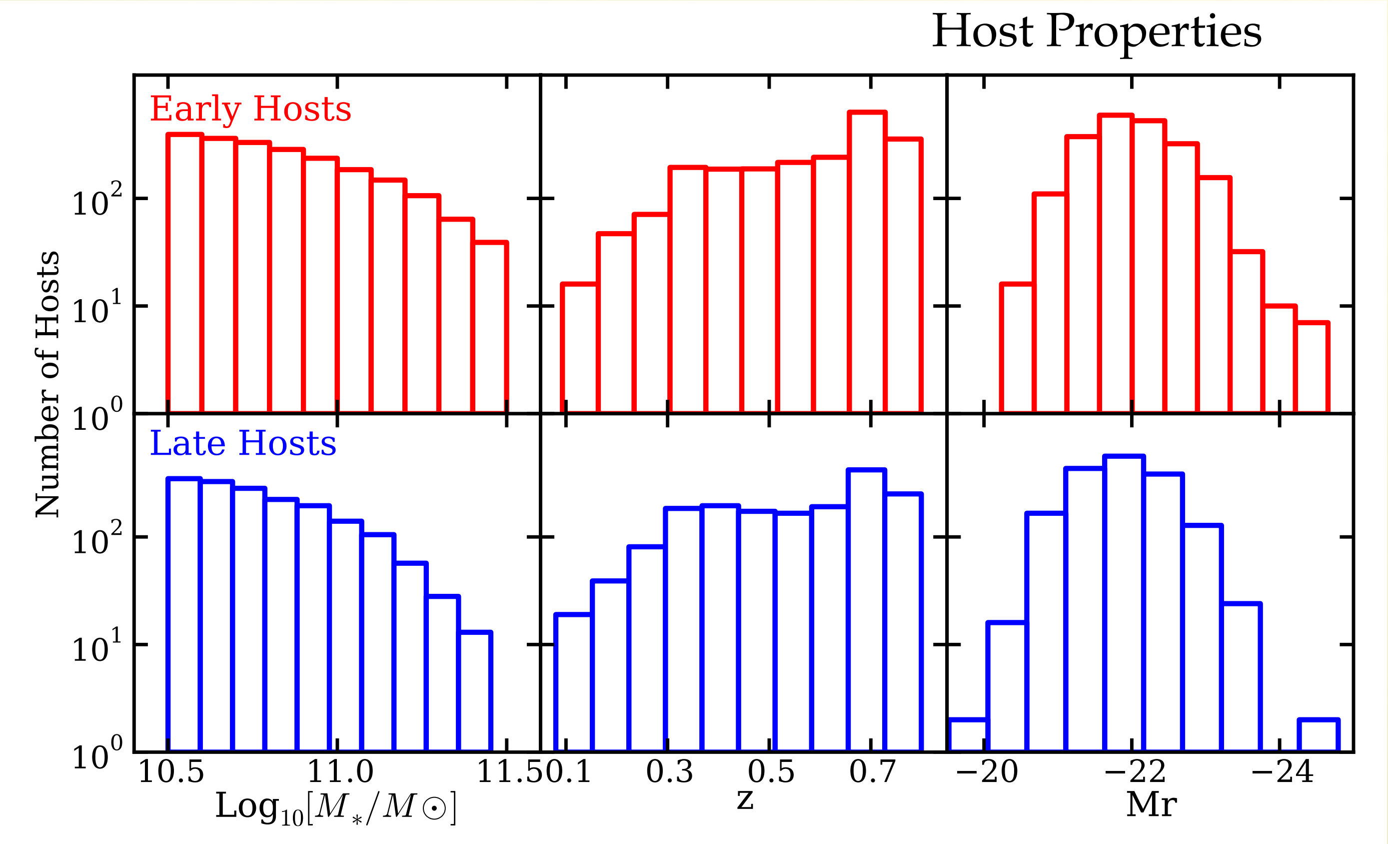
Survey:

COSMOS ACS I814<25.0 + ground based photometry and spectroscopy

Object Selection:

Hosts: 10.5<Log[M*/M⊙]<11.5, 0.1<z<0.8

Everything else: Magnitude limited



Prospective Satellites:

*Up to 1000 times fainter than hosts

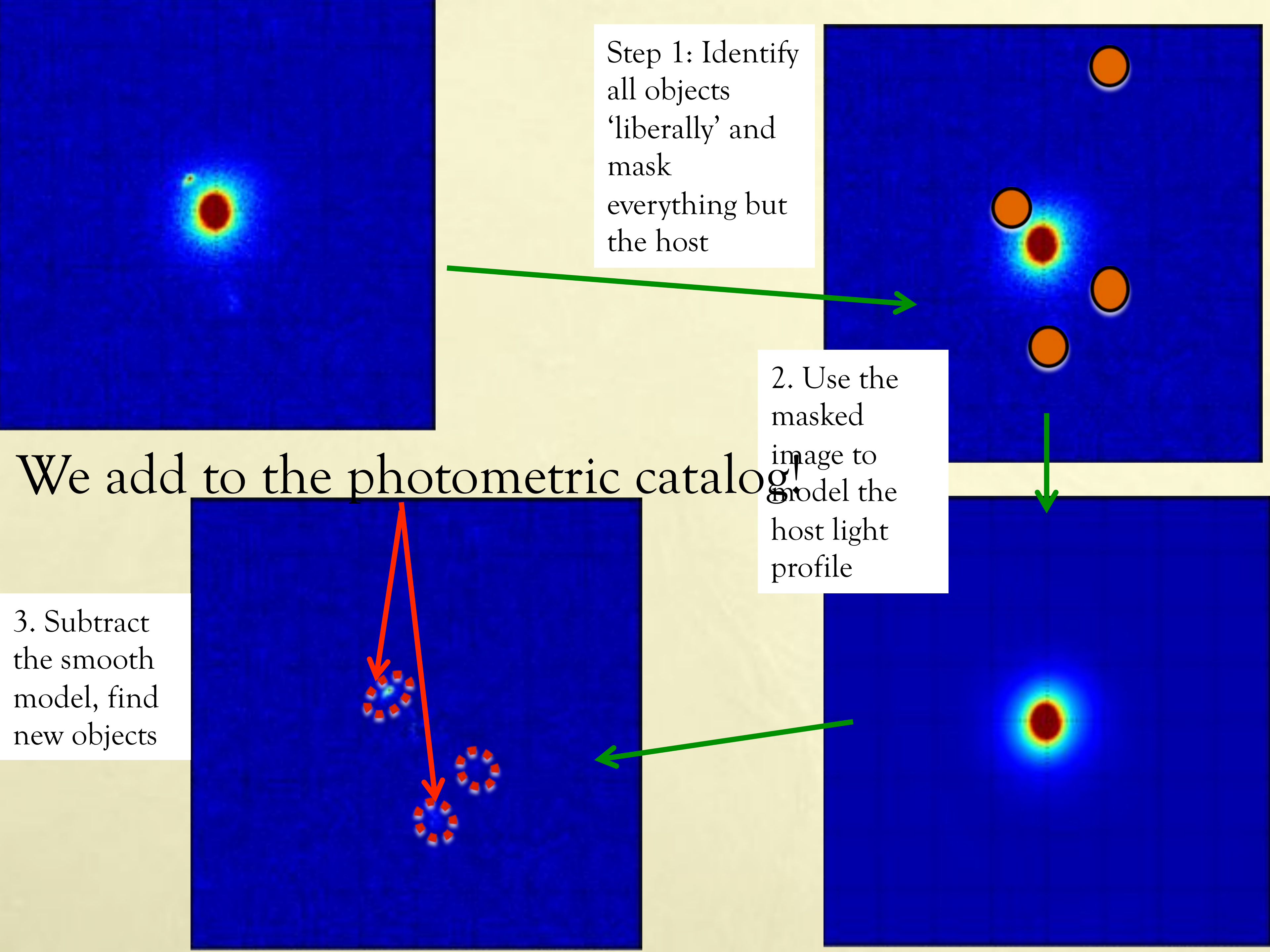
(magnitude limit of 25.0 I814 compare to mr≈ 22 in previous studies outside of the local group)

*SMC-like satellites detectable to redshift 0.8

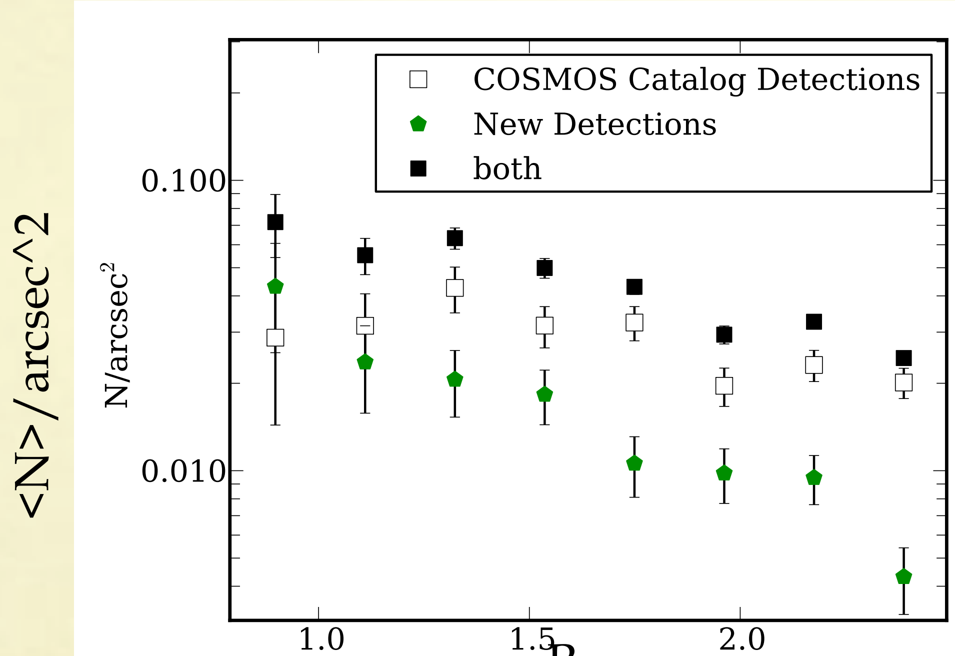
*as close as ≈ 0.”5/2.5 kpc to host centers

(compare to ≈ 10 kpc in previous studies outside of the local group)

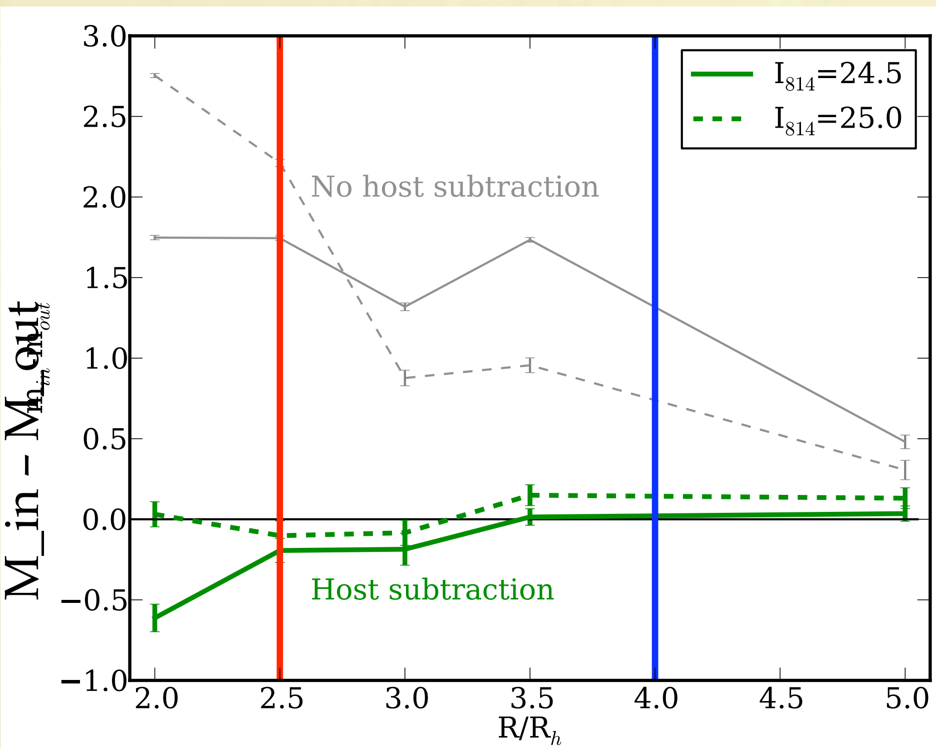
Remove host light from COSMOS images to find close objects

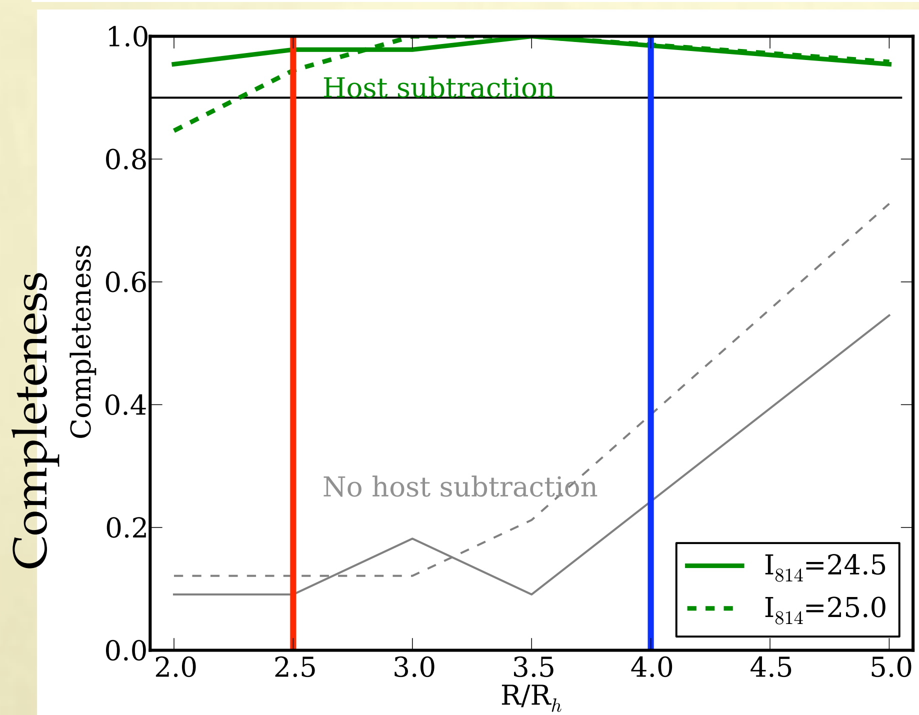

Step 1: Identify all objects 'liberally' and mask everything but the host
2. Use the masked image to model the host light profile
3. Subtract the smooth model, find new objects
We add to the photometric catalog!

Improved sensitivity and completeness

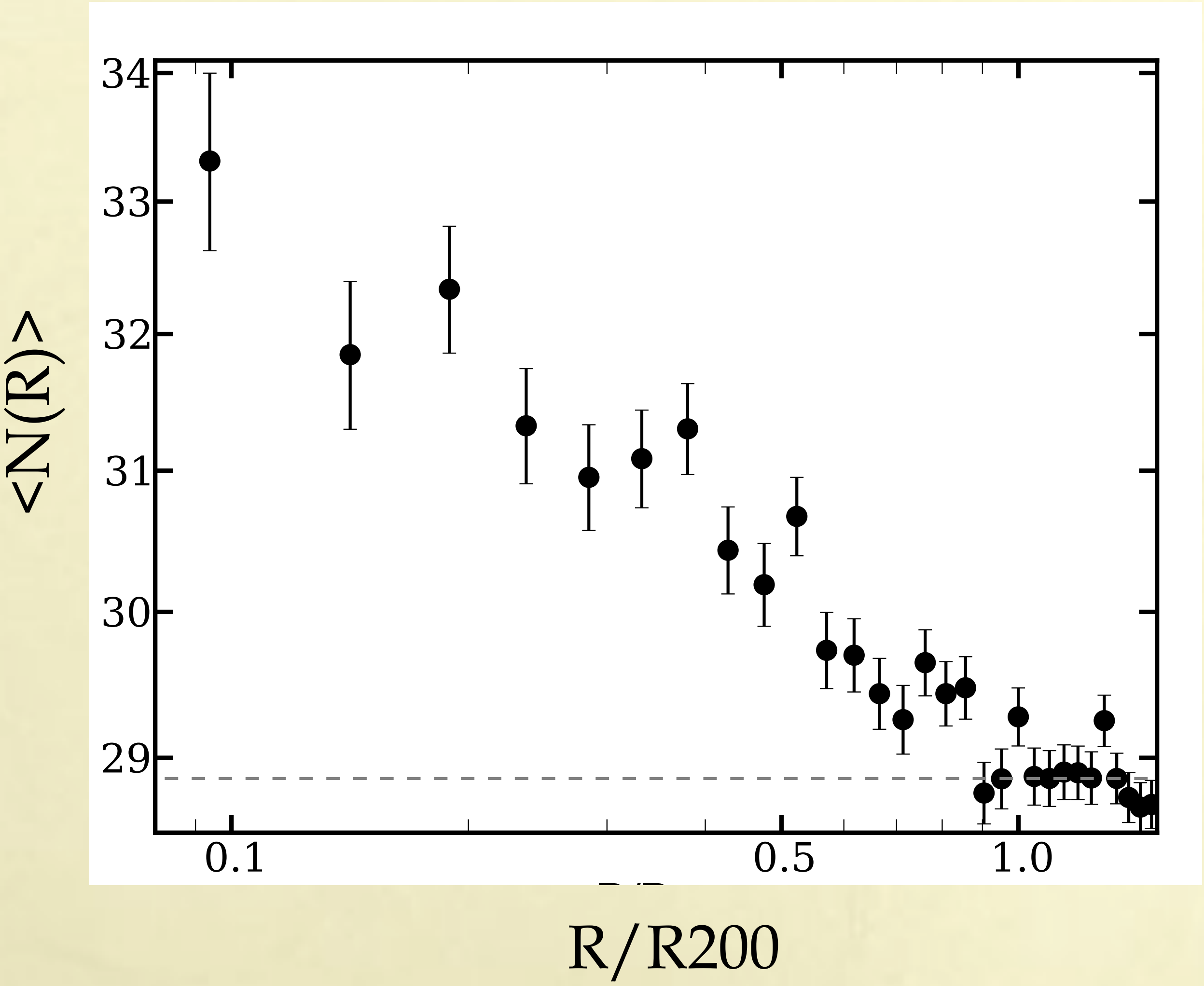


Nierenberg et al 2012



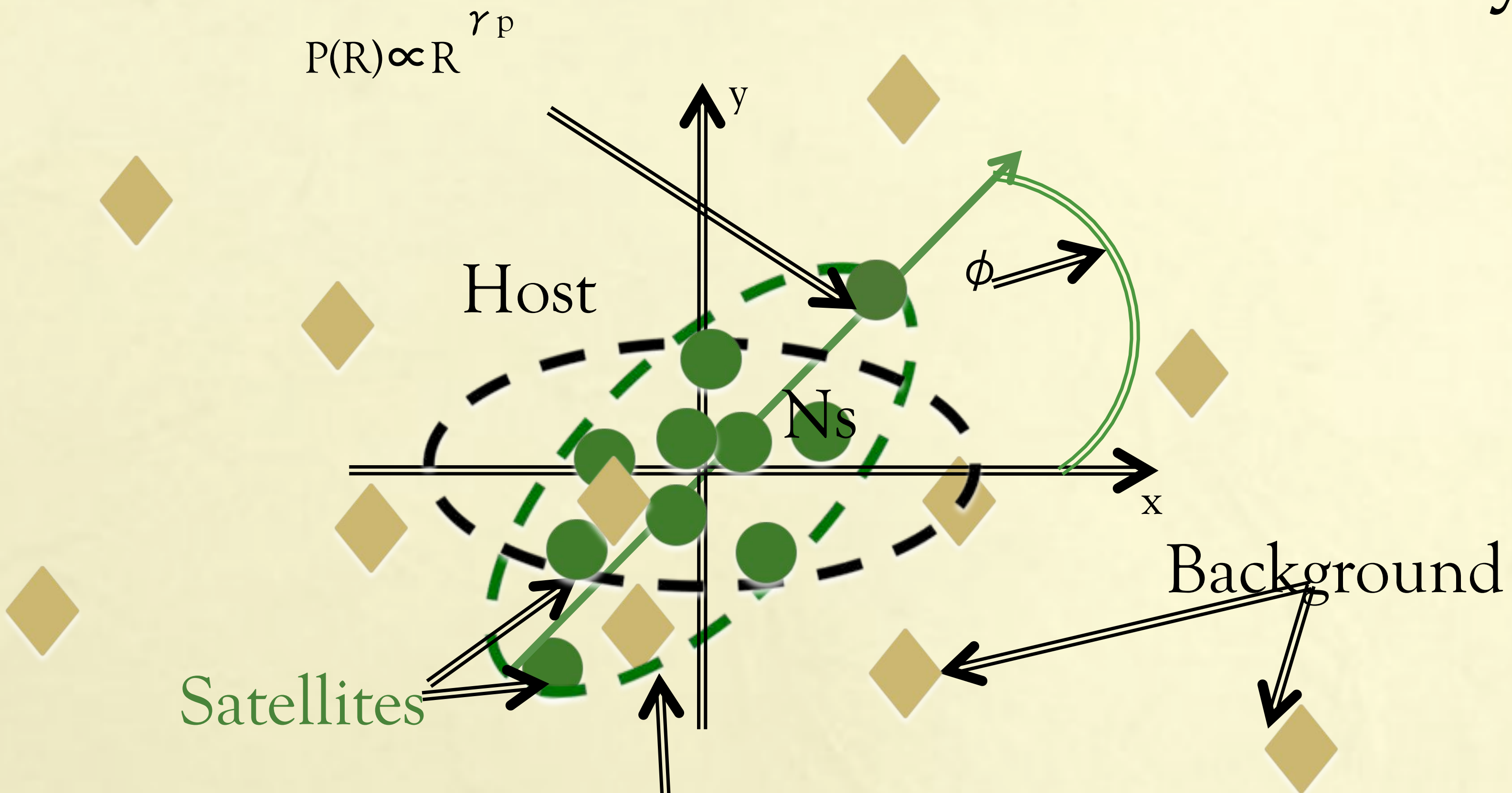


Binned radial distribution of object number density around COSMOS hosts



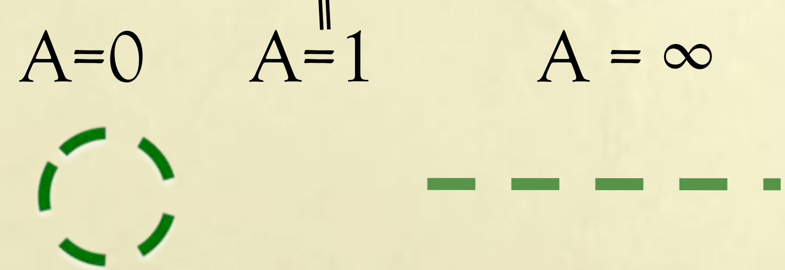
Bayesian inference

Model for the observed number density

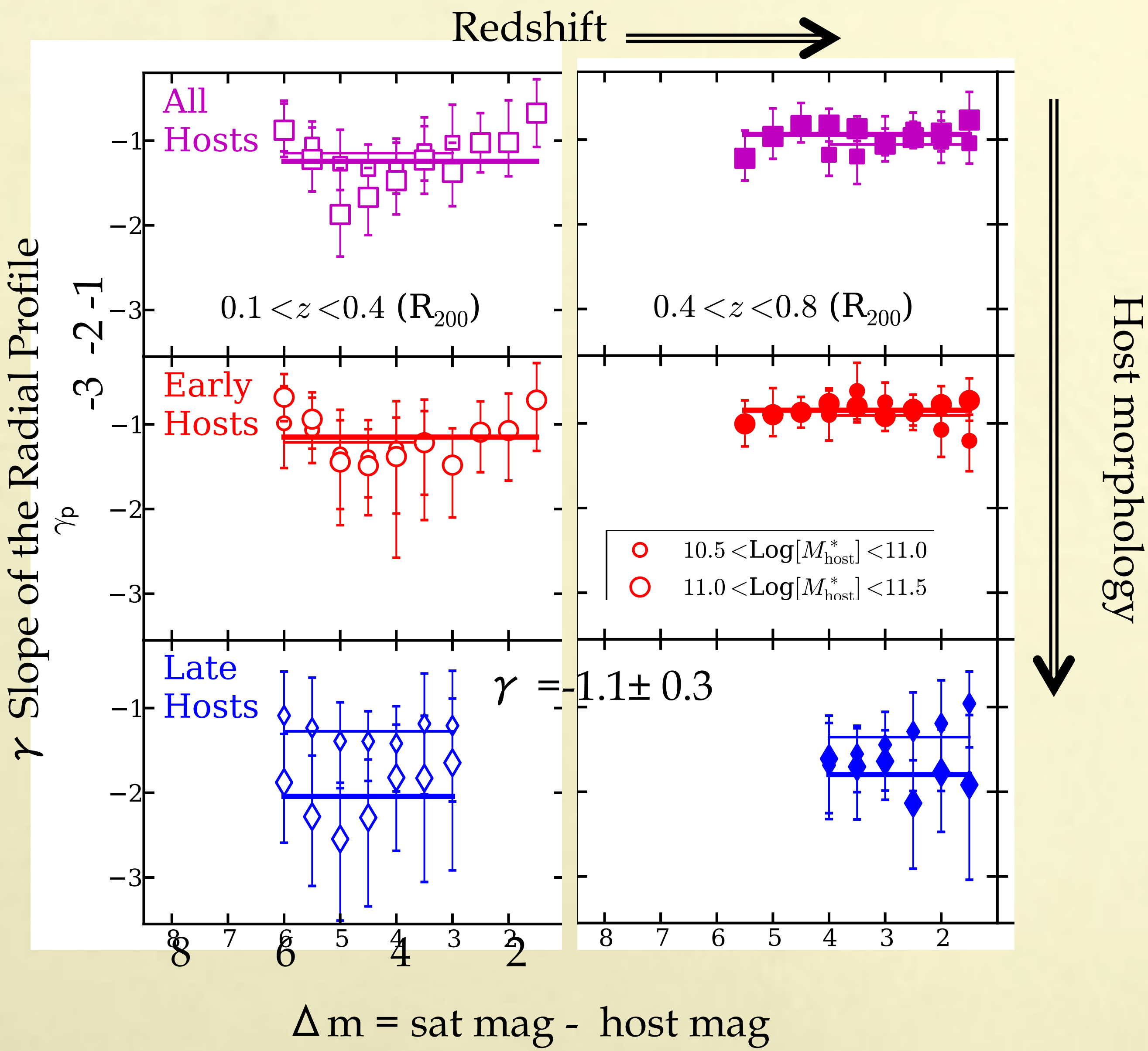


$$\epsilon_s = \frac{A e \epsilon_h}{1 + \epsilon_h - A e \epsilon_h}$$

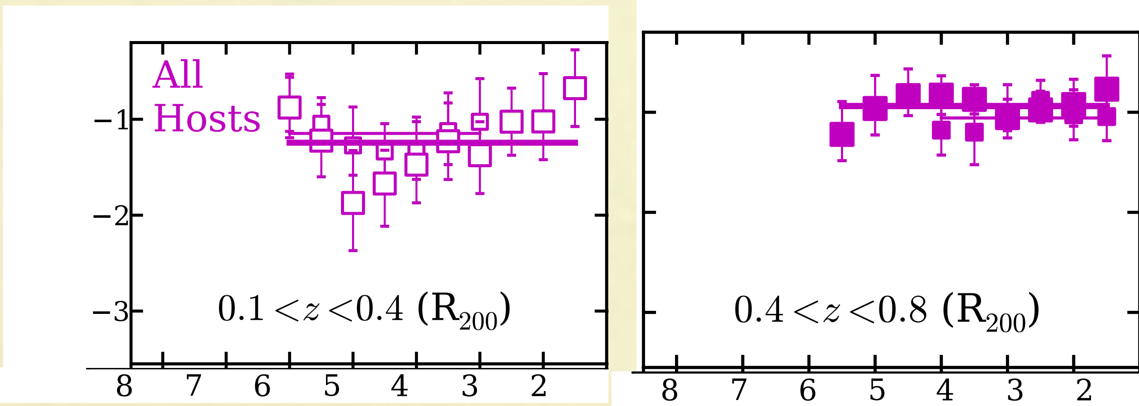
$$\epsilon = \frac{1 - (b/a)^2}{1 + (b/a)^2}$$

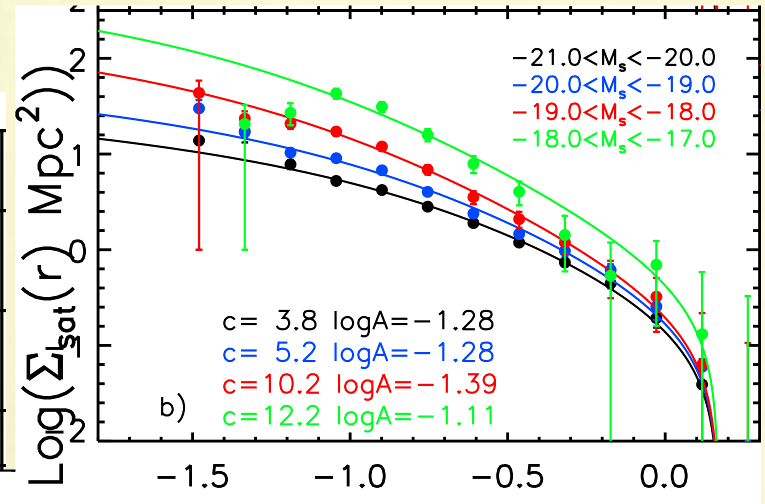


Radial Distribution



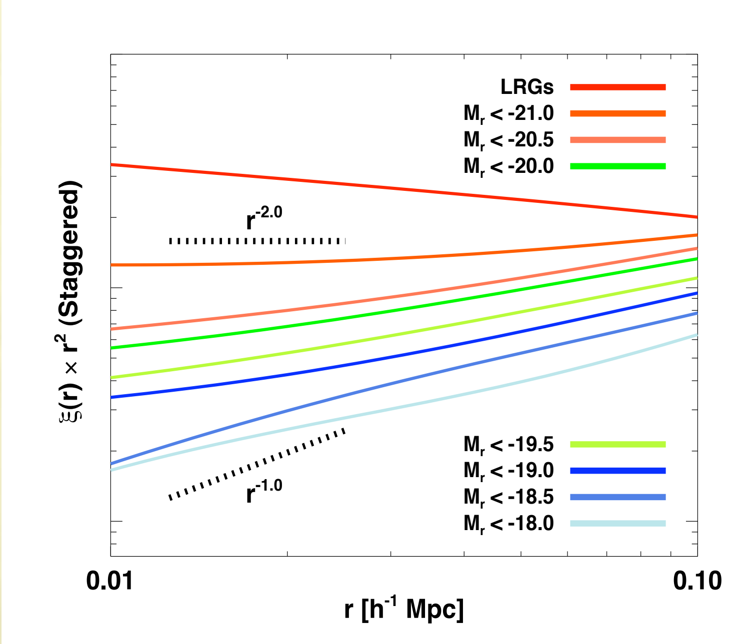
Comparison of radial dist with other work



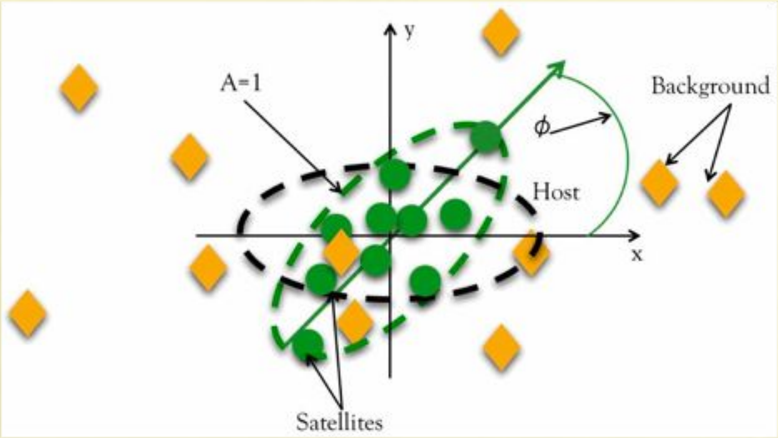


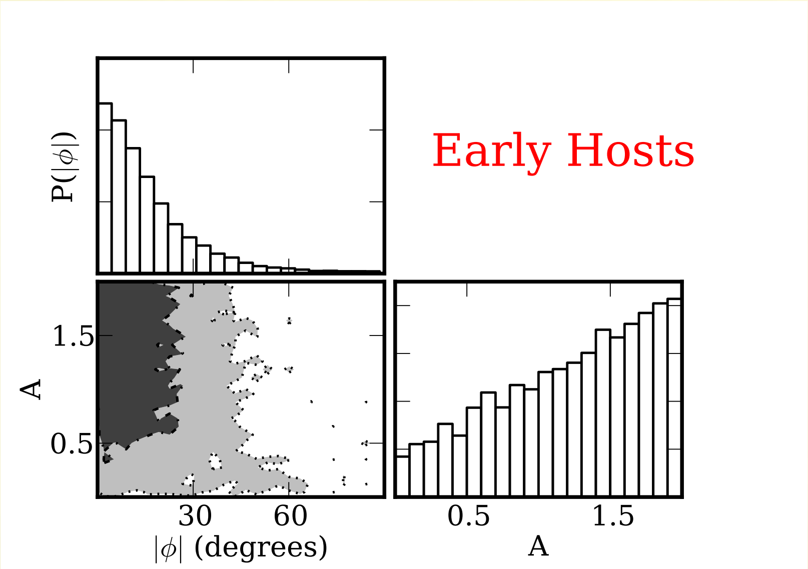
-We find no trend in the radial profile with host mass, redshift, morphology or satellite luminosity

-Slightly shallower than Chen 2008, consistent with Watson 2010

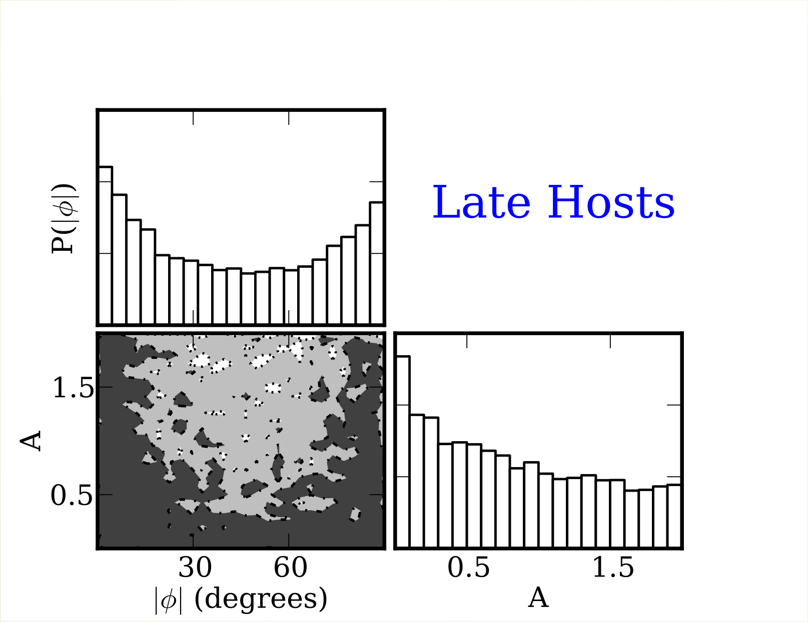


Angular Distribution

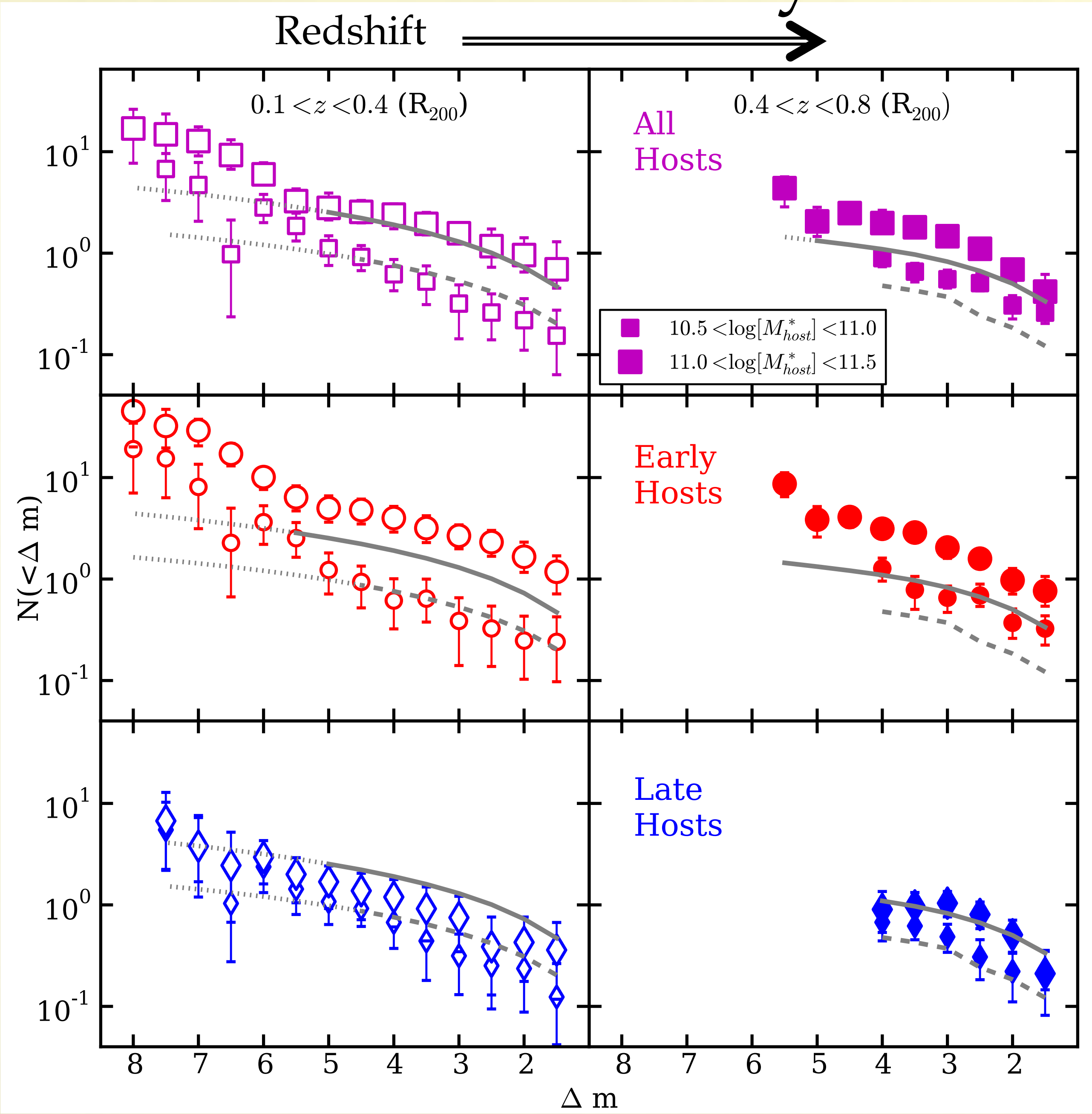




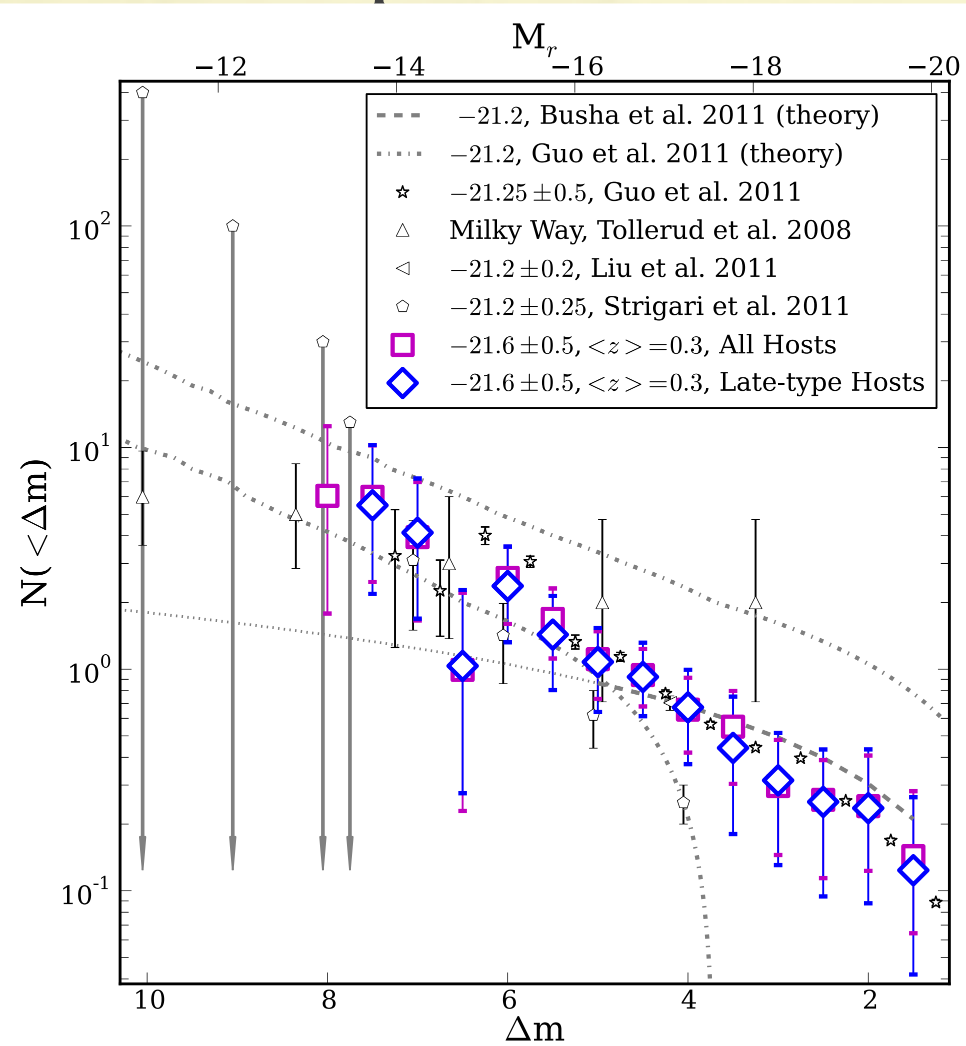
Results consistent with
Bailin 2008, Brainerd 2005 and
results from galaxy formation
modeling



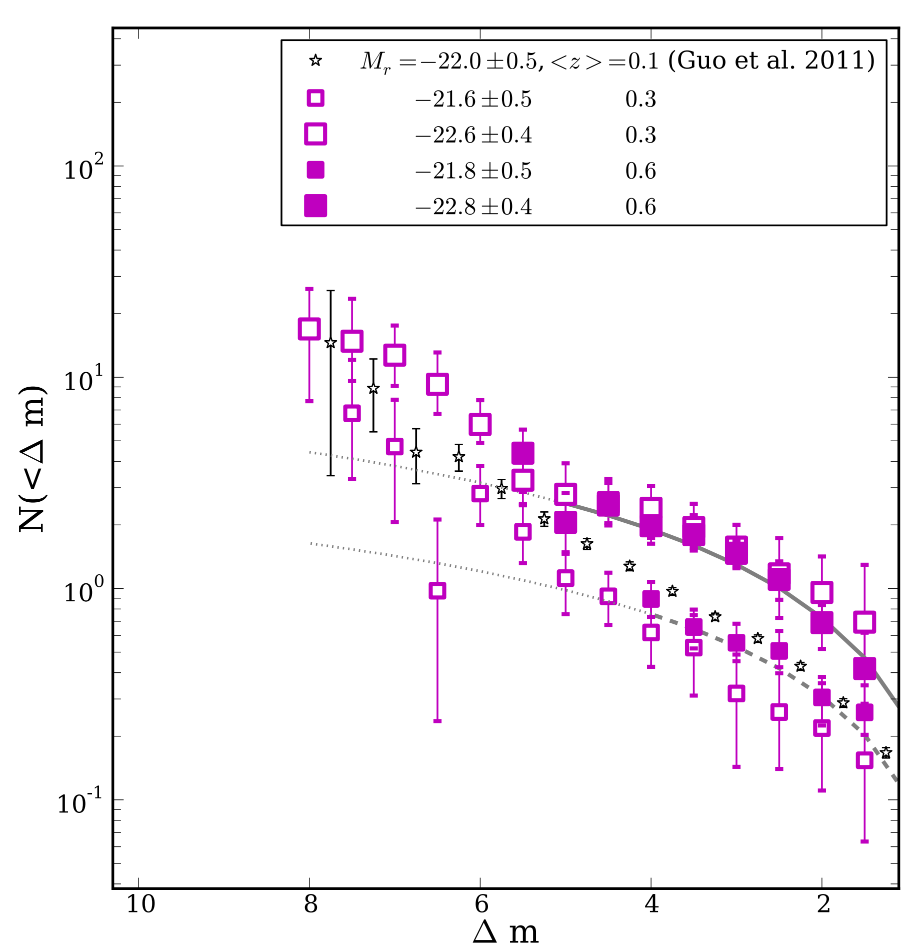
Cumulative Luminosity Function



Comparison of CLF with low z work

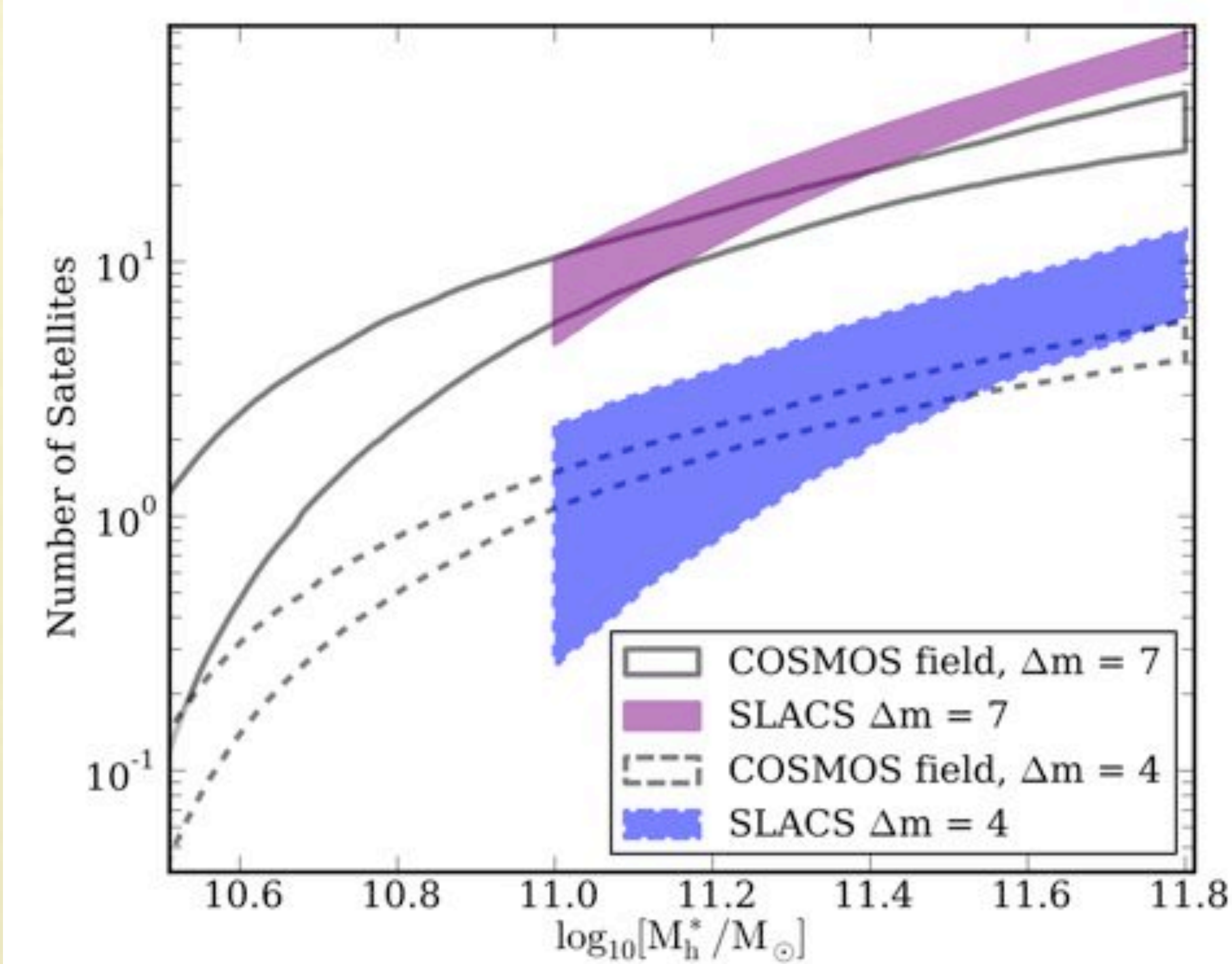


Milky Way Mass Hosts



Varying Mass Hosts

Dependence of satellite numbers on host stellar mass



Nierenberg et al. 2013 b

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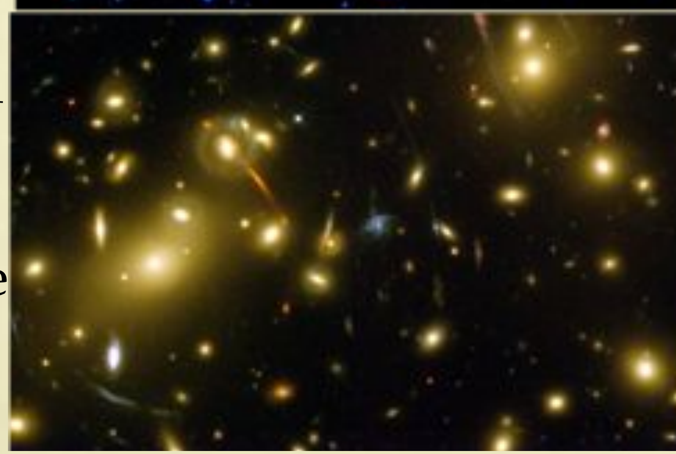
The satellite luminosity function depends on:

Cluster-Mass Halo **Galaxy-Mass Halo**

The halo mass function- dynamical friction, density profile, dark matter particle mass

Star formation- a function of halo mass, metallicity, UV heating, sNae feedback, ect.



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Simulations

We compare the data with predictions from four different models:

- Guo et al. 2011- SAM applied to Millenium I (Springel et al. 2005) and II (Boylan-Kolchin et al. 2009) Msub, min = 10^8 $M_\odot$ (Tuned to match the field LF)
- Lu et al. 2012- SAM applied to Bolshoi-like EPS merger trees, Msub min = 10^ 9$M_\odot$ (Tuned to match the field LF)
- Menci et al 2012- the same SAM applied to two different EPS merger trees- one CDM, one WDM with cutoff scale Msubmin = 10^7 $M_\odot$ (Tuned to match the color magnitude relation)

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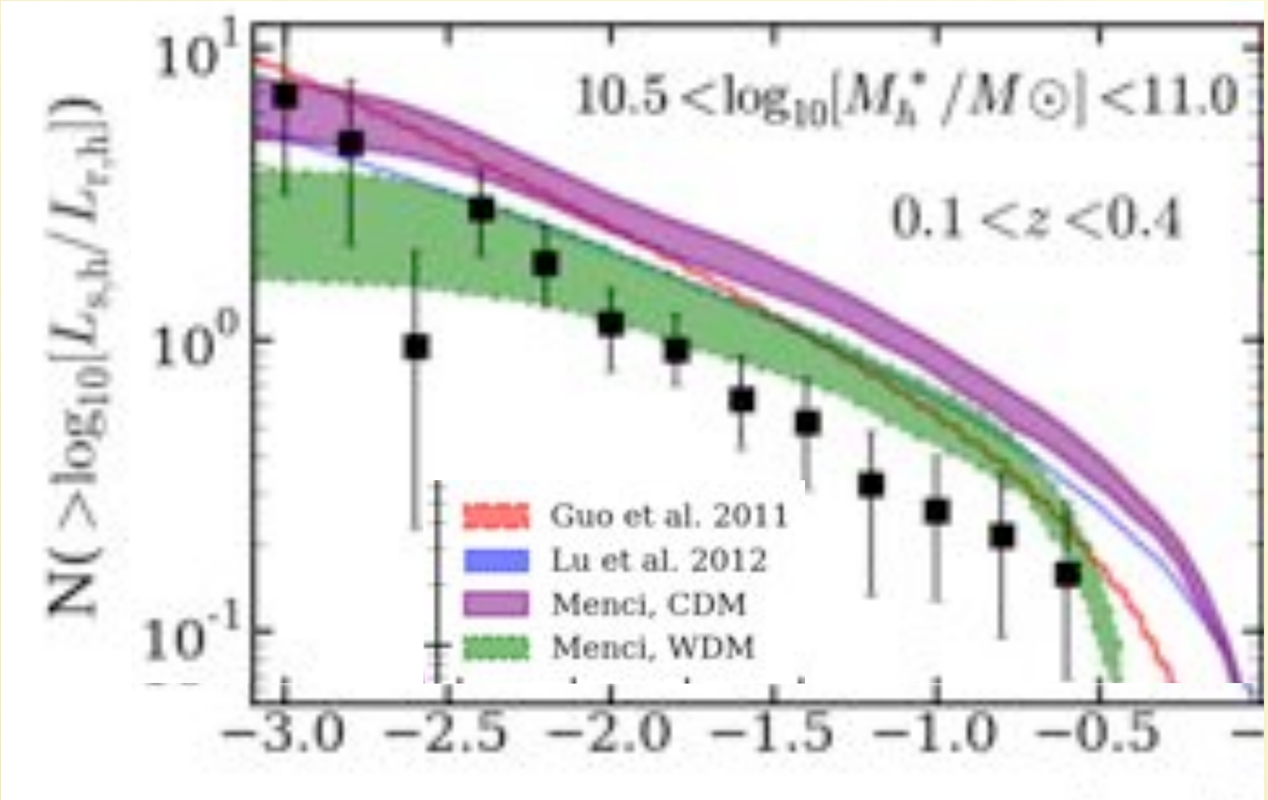
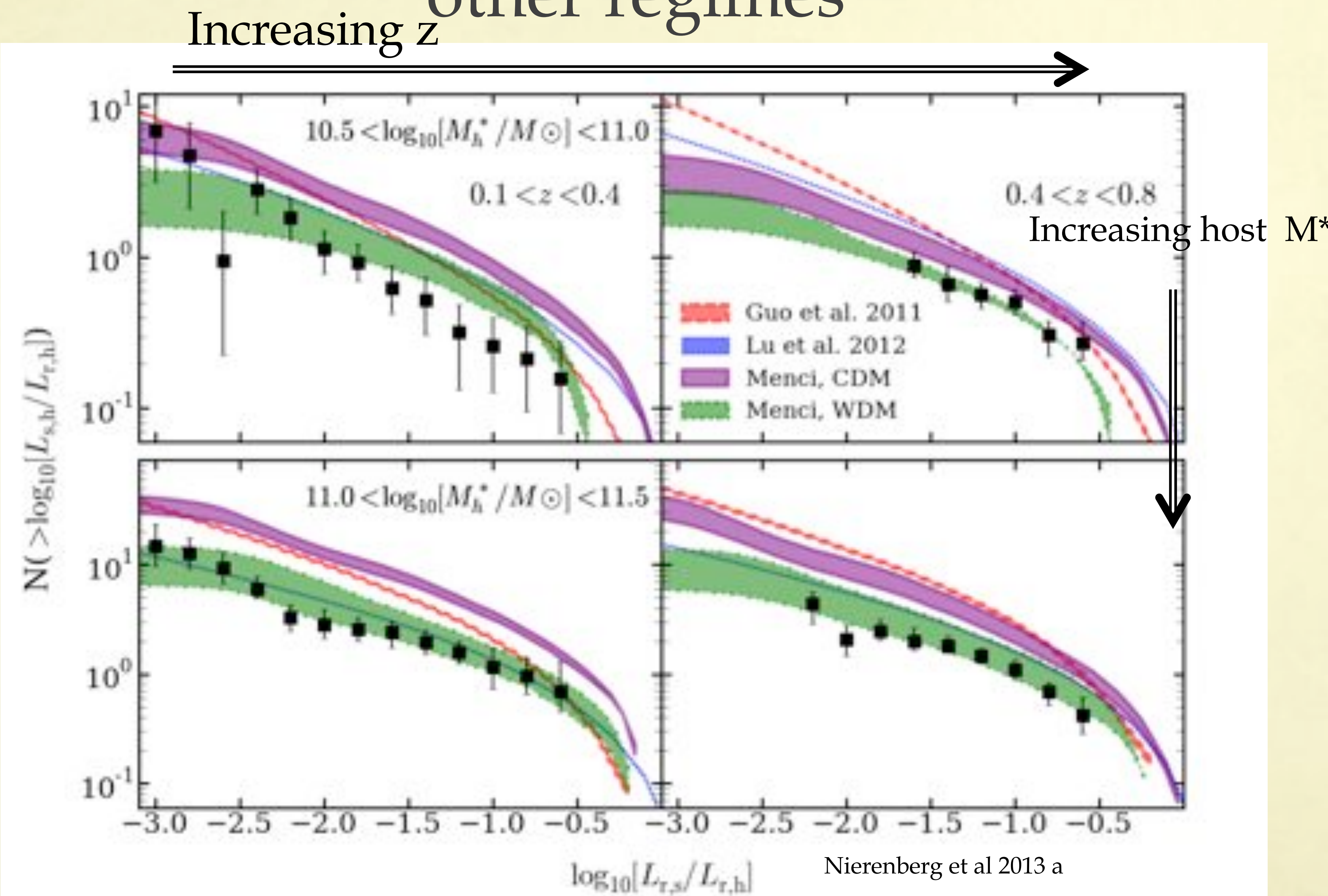
Comparison with our observations-MW mass, low redshift hosts



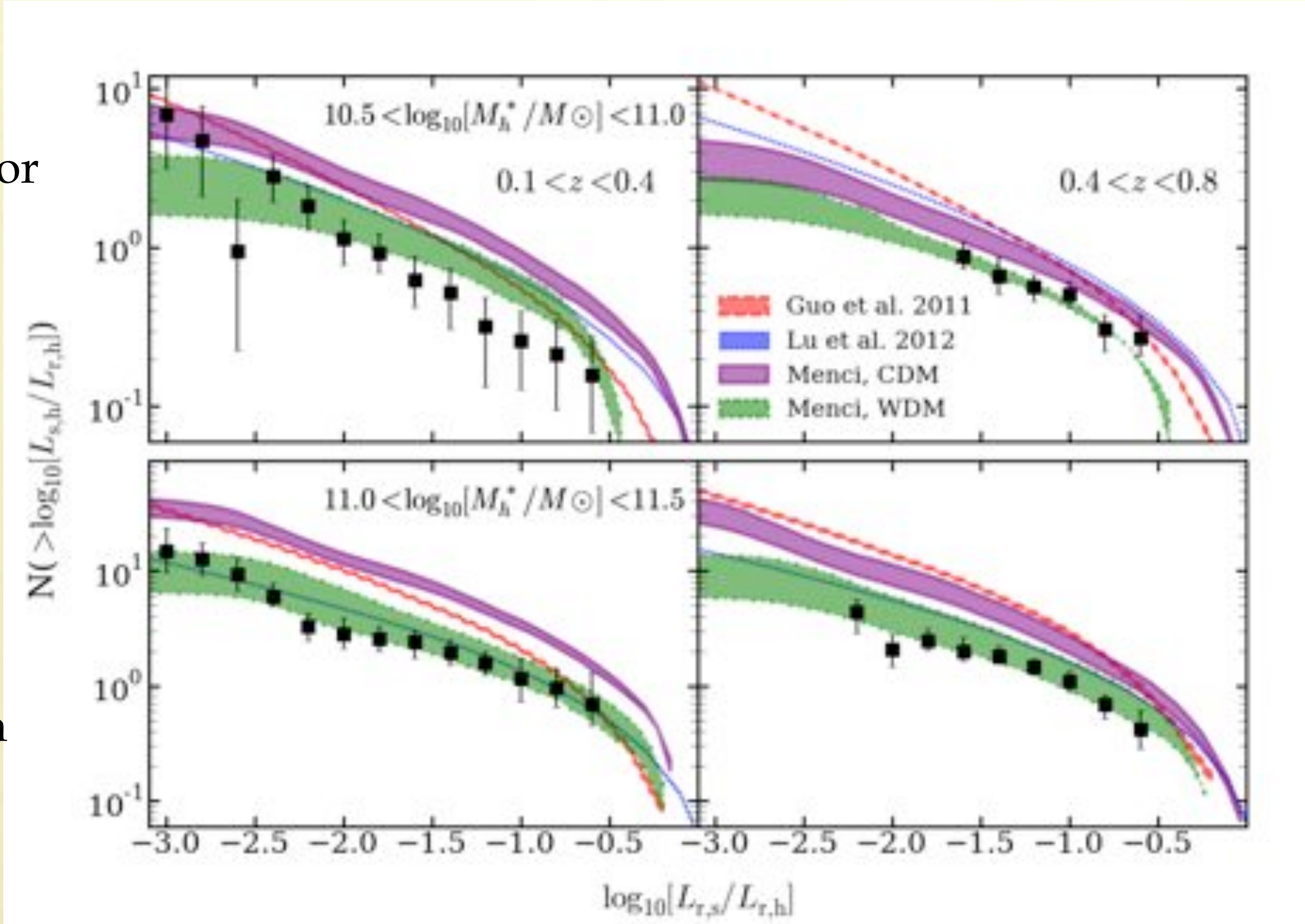
Comparison with our observations, other regimes



Nierenberg et al 2013 a

Main Points

- All models do well for MW mass, low redshift hosts
- CDM models show more redshift evolution than WDM
- CDM models show more dependence on the host mass



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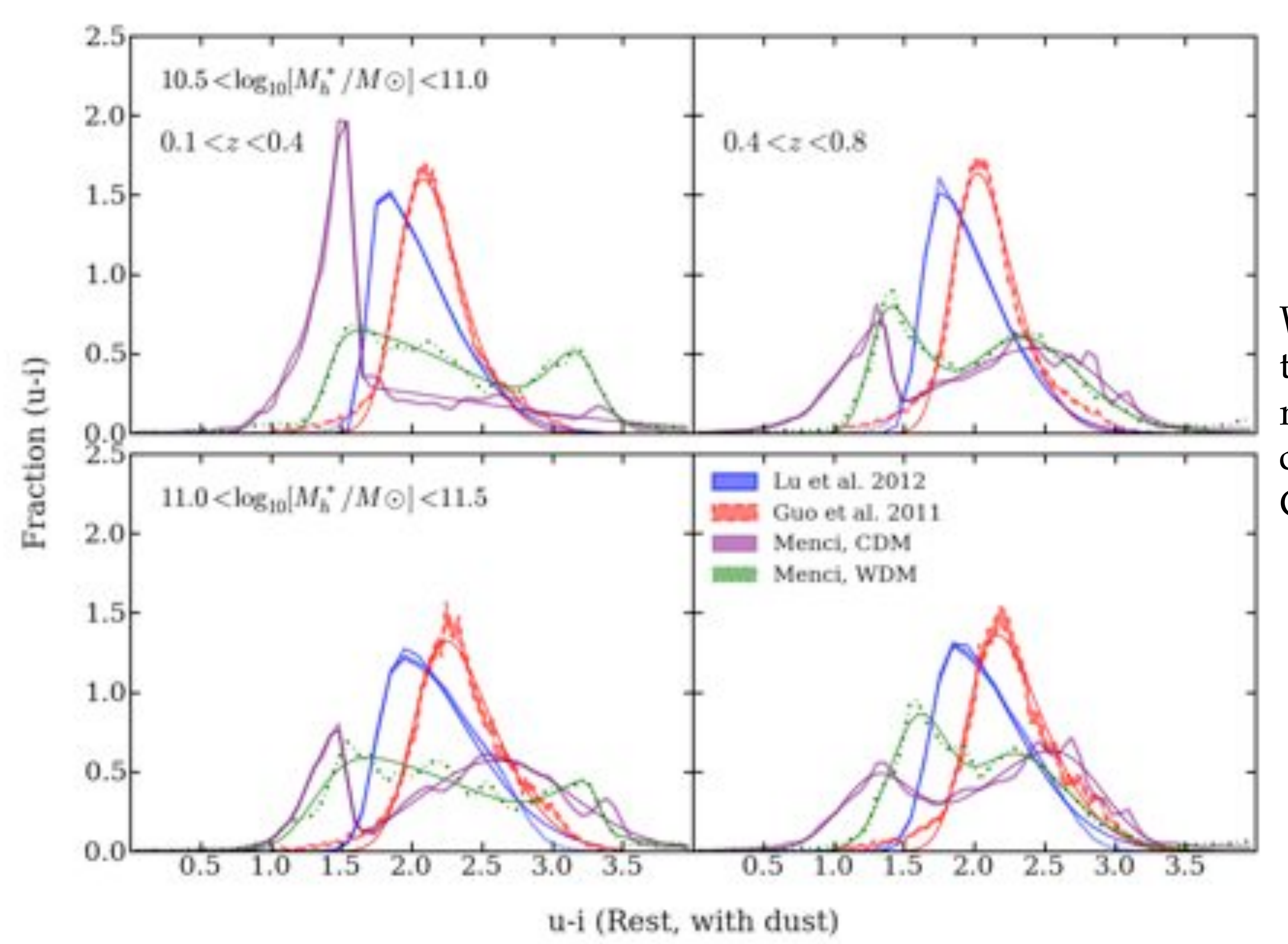
Prediction for Satellite Colors (same SPS)



We can test this by measuring colors in CANDELS

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Conclusions

- Measurements of satellite galaxies at a variety of redshifts and environments provide important constraints on the physics governing star formation and the nature of dark matter

- Among these models, WDM seems to most closely match the observed redshift evolution and host mass dependence of the satellite luminosity function, however future improvements to SAMS may change this.

- Future measurements of faint satellite colors will provide significantly increased leverage in understanding the physics of star formation.

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Part II: Constraining the subhalo mass function using OSIRIS NIR Flux ratio anomalies

With: Tommaso Treu (UCSB), Shelley Wright (U. Toronto), Chris Fassnacht (UC Davis), Matthew Auger (Cambridge IOA), Greg Dobler (UCSB)

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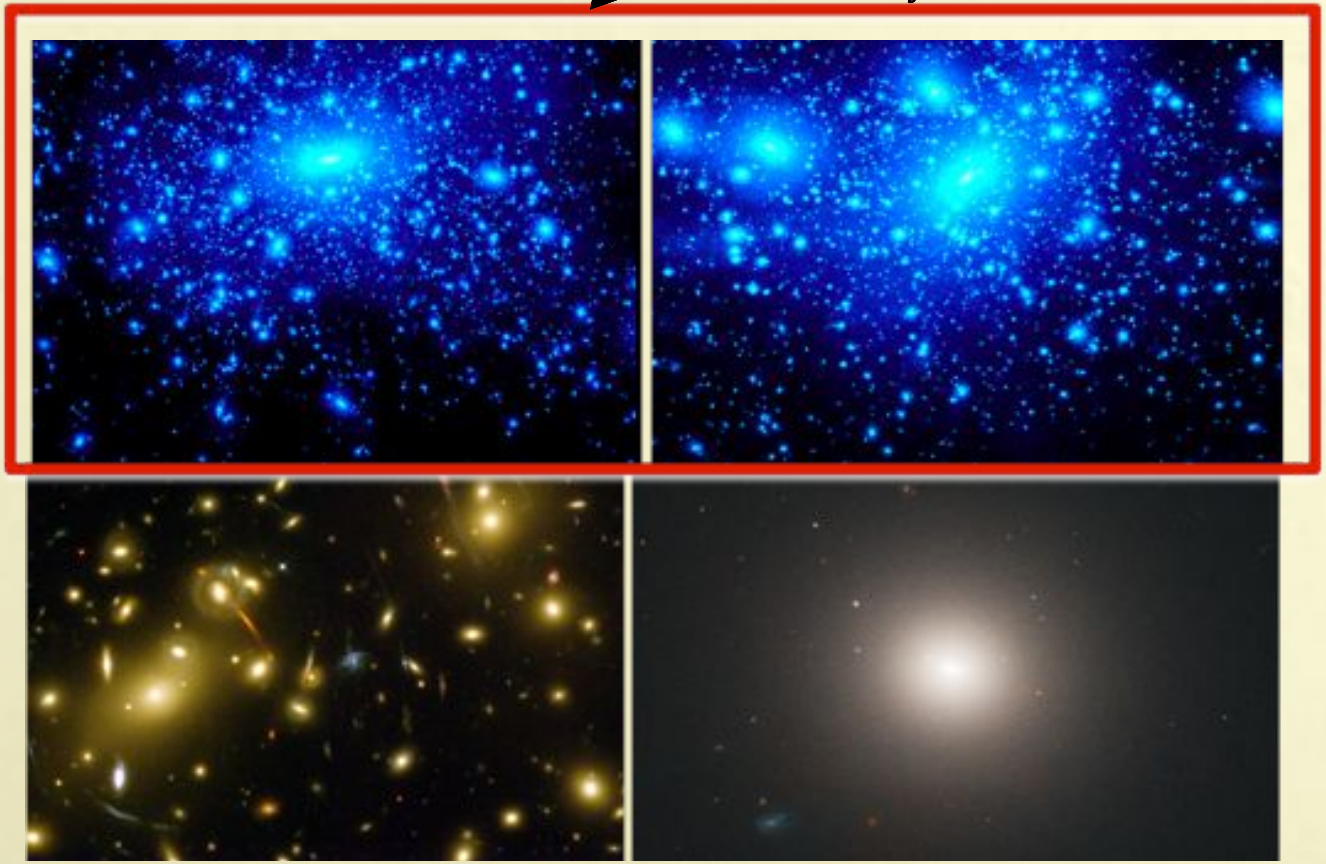
This part, directly measure the subhalo mass function

Cluster-Mass Halo

Galaxy-Mass Halo

Simulation

Observation



Kravtsov 2010

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Outline

* Gravitational lensing as a means of measuring the satellite galaxy mass function
* How to avoid unwanted microlensing
* Using OSIRIS to obtain spatially resolved spectra to obtain a microlensing- free signal
* Preliminary results for two systems
* Future prospects

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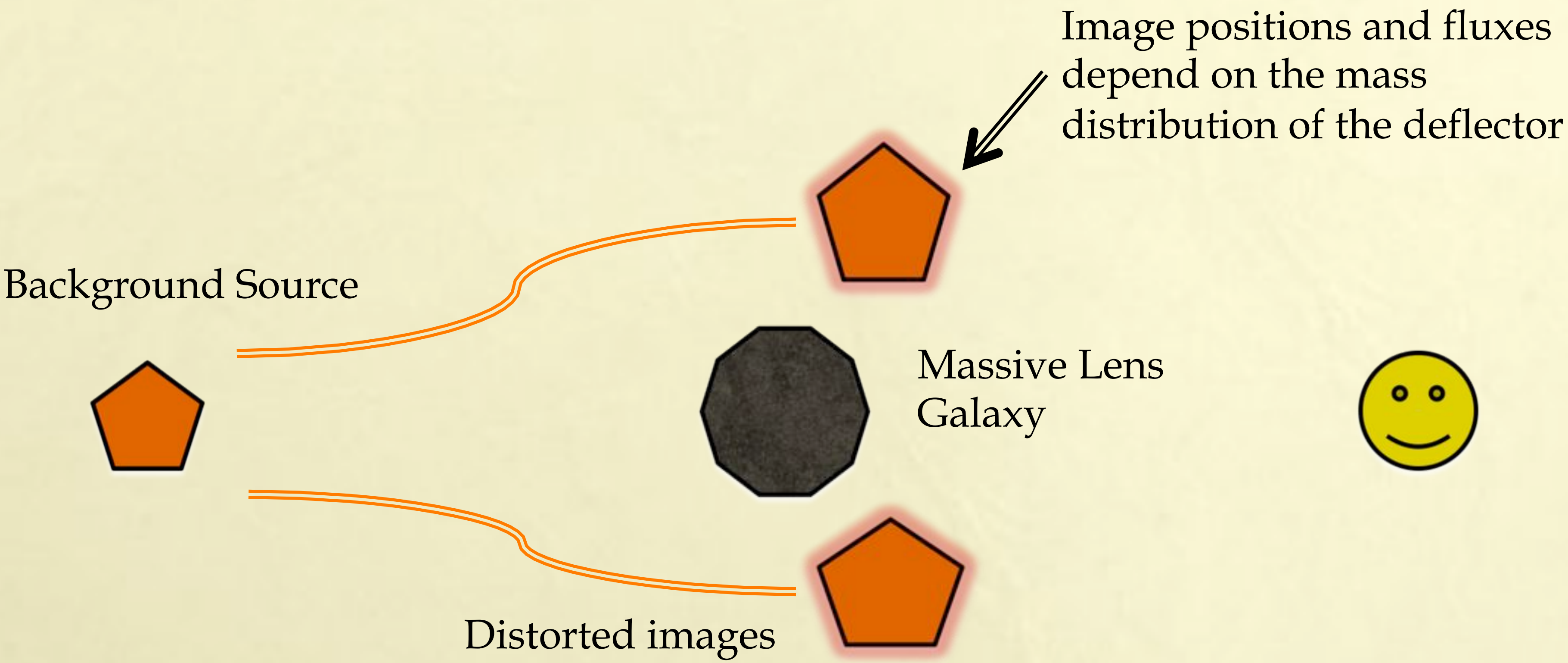
Gravitational lensing is sensitive to the presence of subhalos regardless of their star formation efficiency



In strong lensing, light from a background source is deflected enough that multiple images appear

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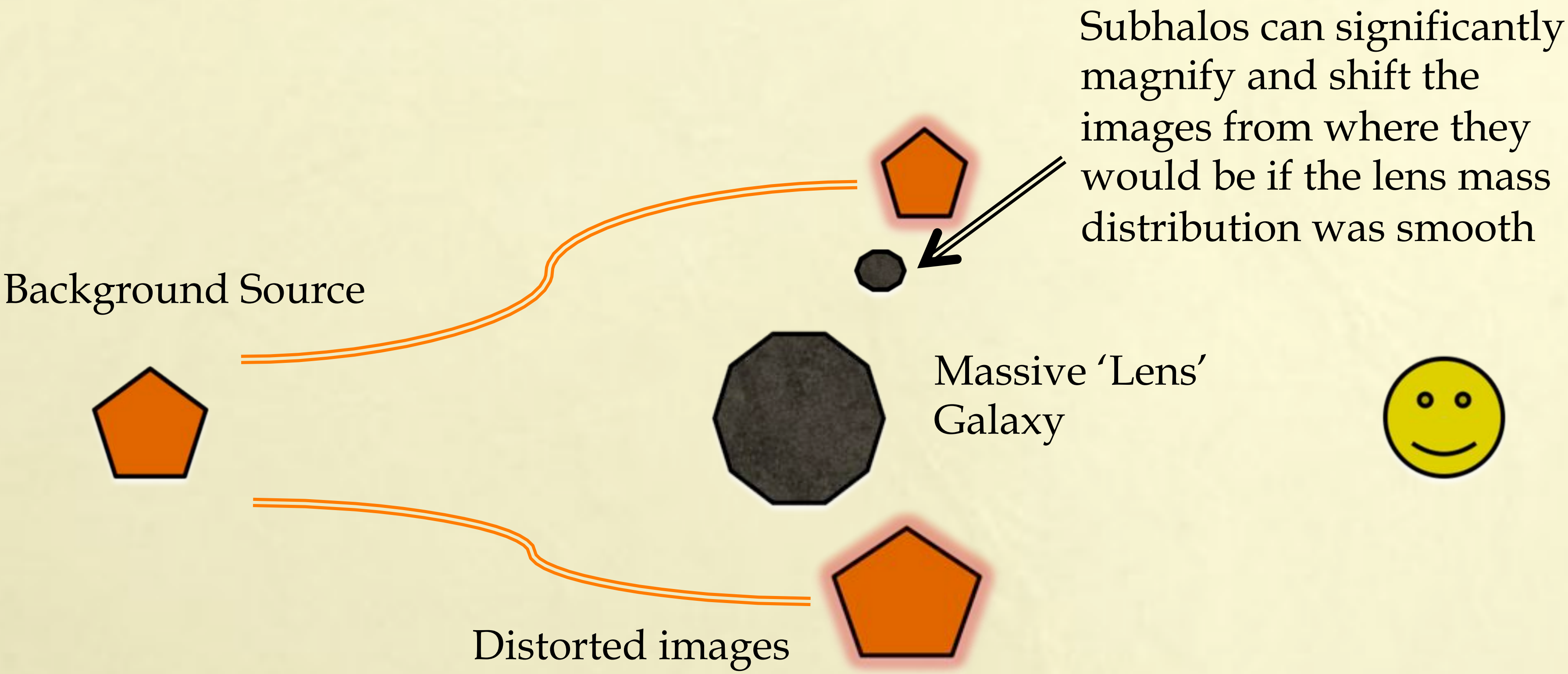
Gravitational lensing is sensitive to the presence of subhalos regardless of their star formation efficiency



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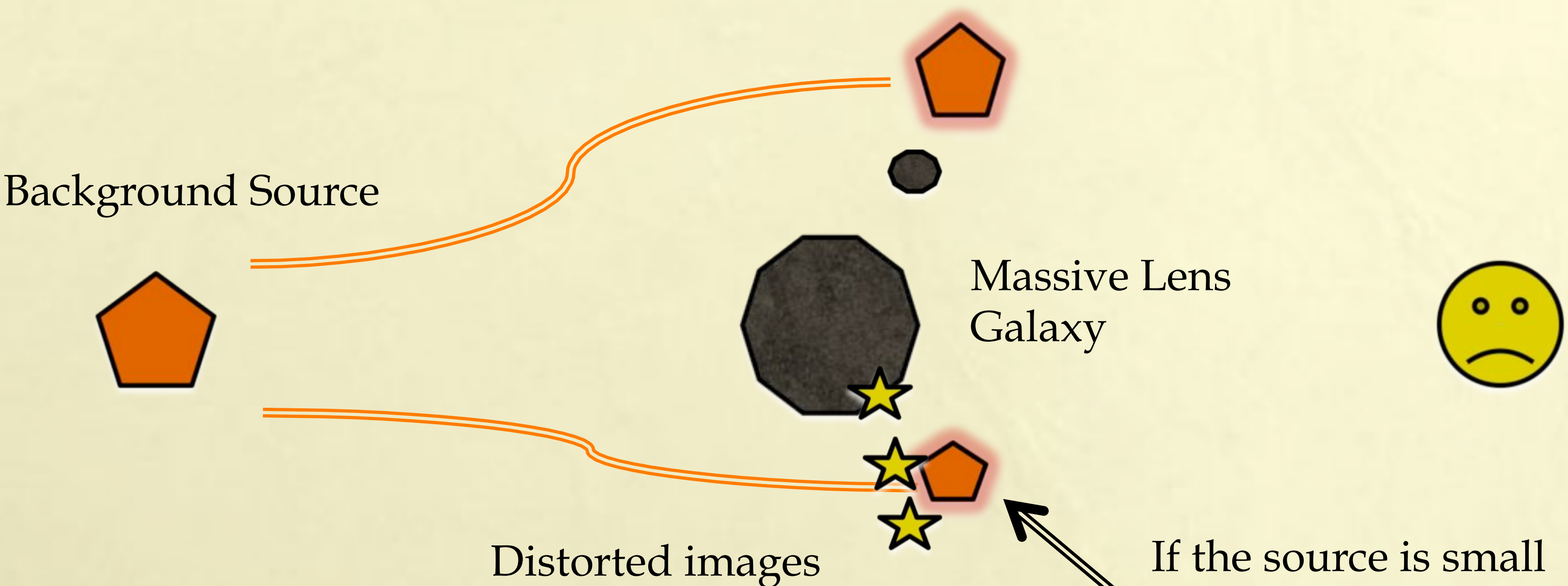
Beware of microlensing by stars if the source is small



If the source is small enough, stars in the lens galaxy can significantly affect the lensing

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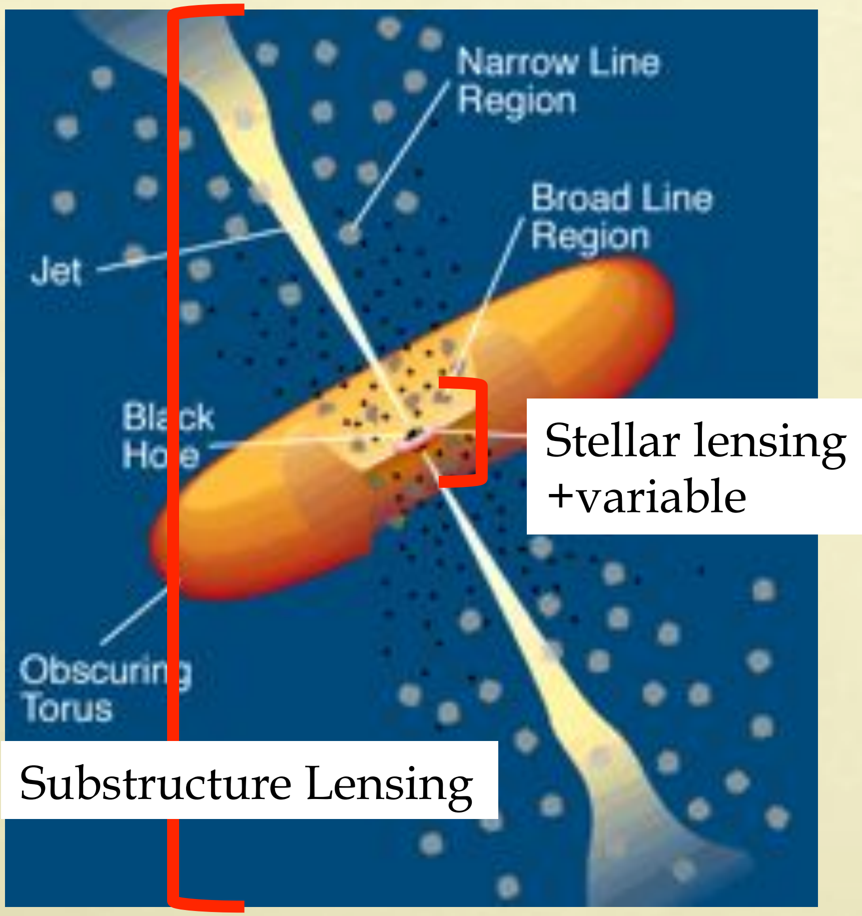
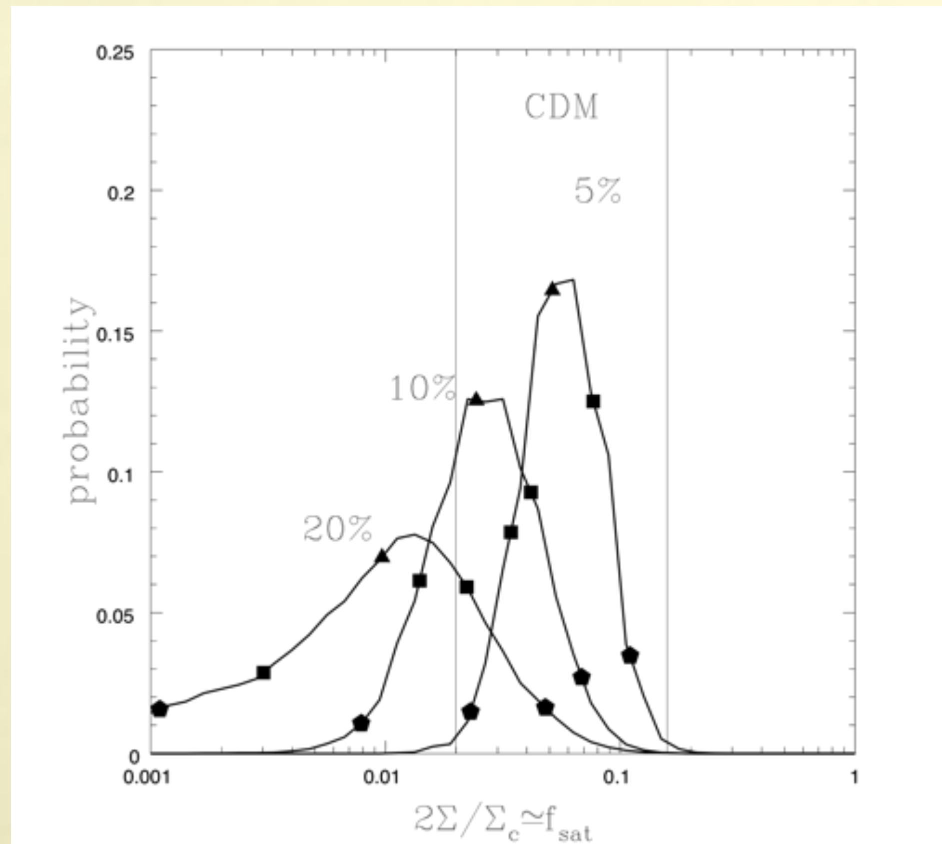
To use lensing to measure subhalo mass function, need large, constant sources- e.g. radio emission from an AGN





Dalal and Kochanek 2002, 7 radio-loud lens systems

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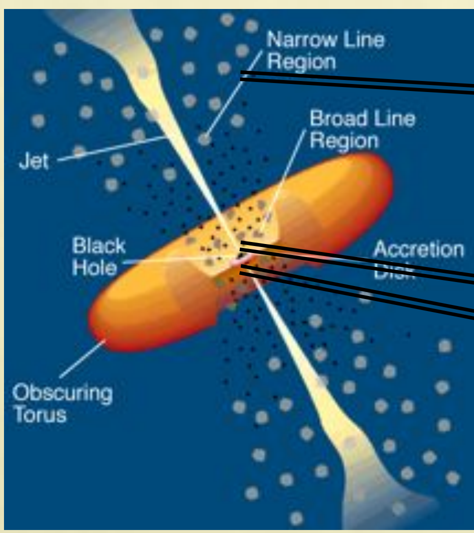
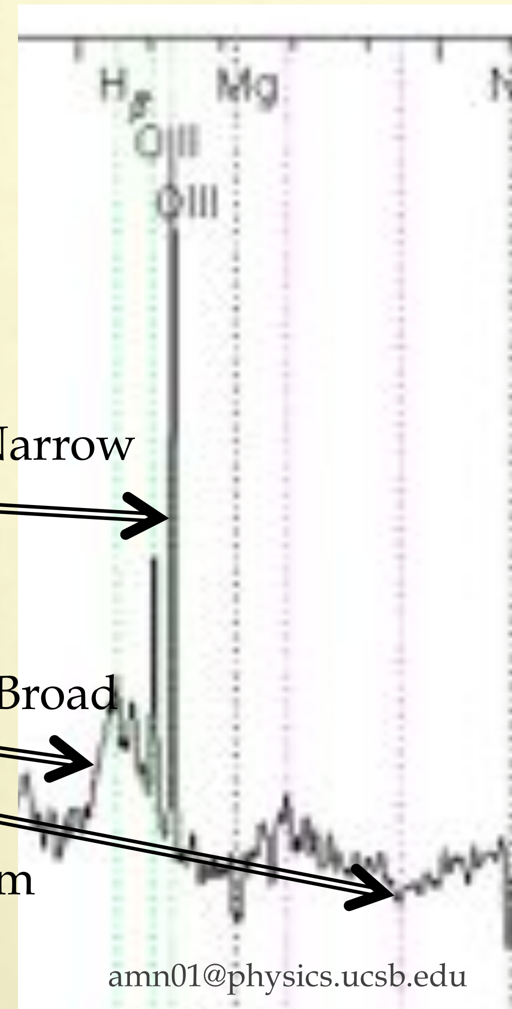
This project: Using narrow line flux ratios to constrain substructure lensing

Originally suggested by Moustakas and Metcalf 2003

Benefits:

- All quasars show strong narrow line emission (unlike radio emission)
- Not variable and not affected by micro-lensing





Narrow

Broad

Continuum

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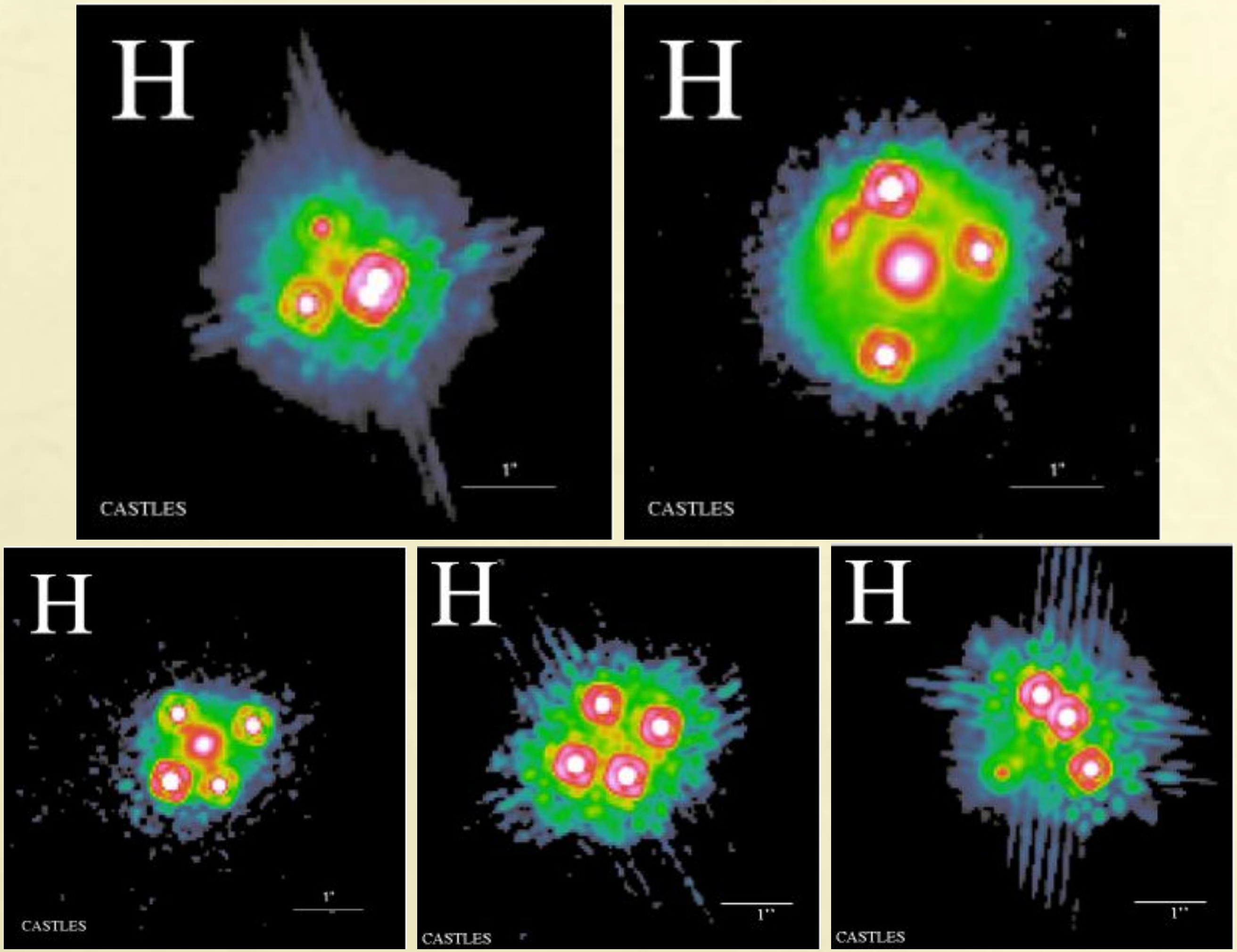
Initial experiment: Measure N-L flux ratios in 5 four image quasar lenses



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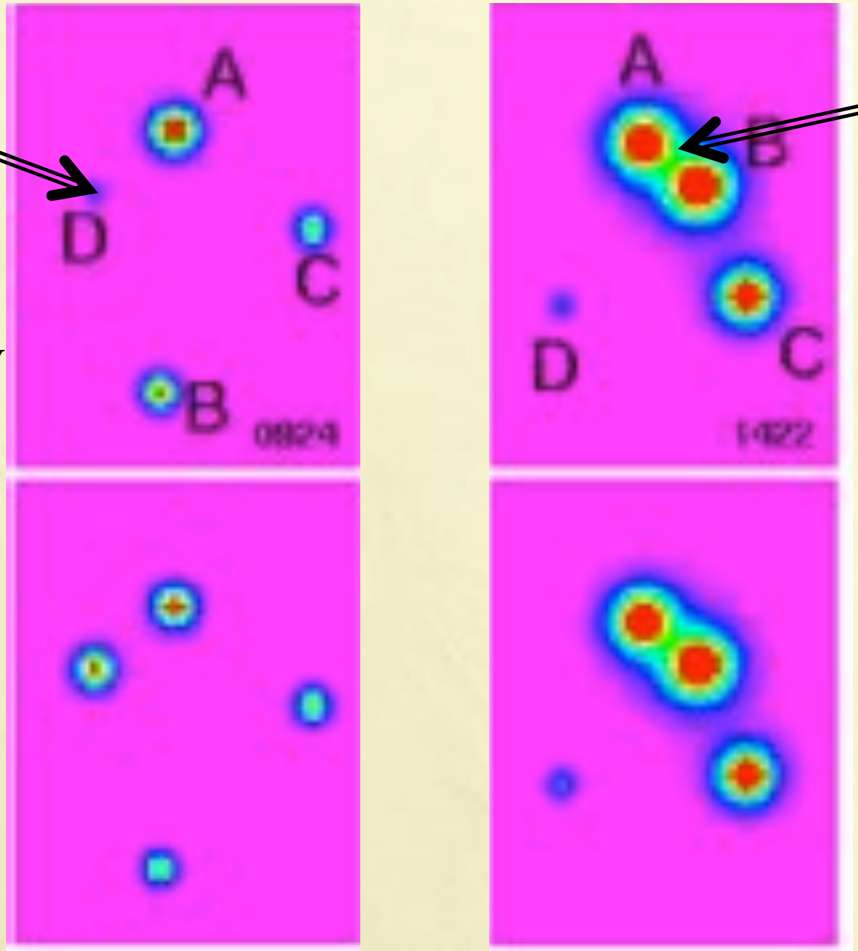
0924 and 1422 as test cases

D/A is 10x lower than the smooth prediction

A/B is ~10% lower than the smooth prediction

Observed continuum fluxes from HST (potentially affected by stellar lensing)

Smooth mass distribution prediction



The experiment: Measure the flux ratios in the narrow-line emission and use to constrain the substructure fraction.

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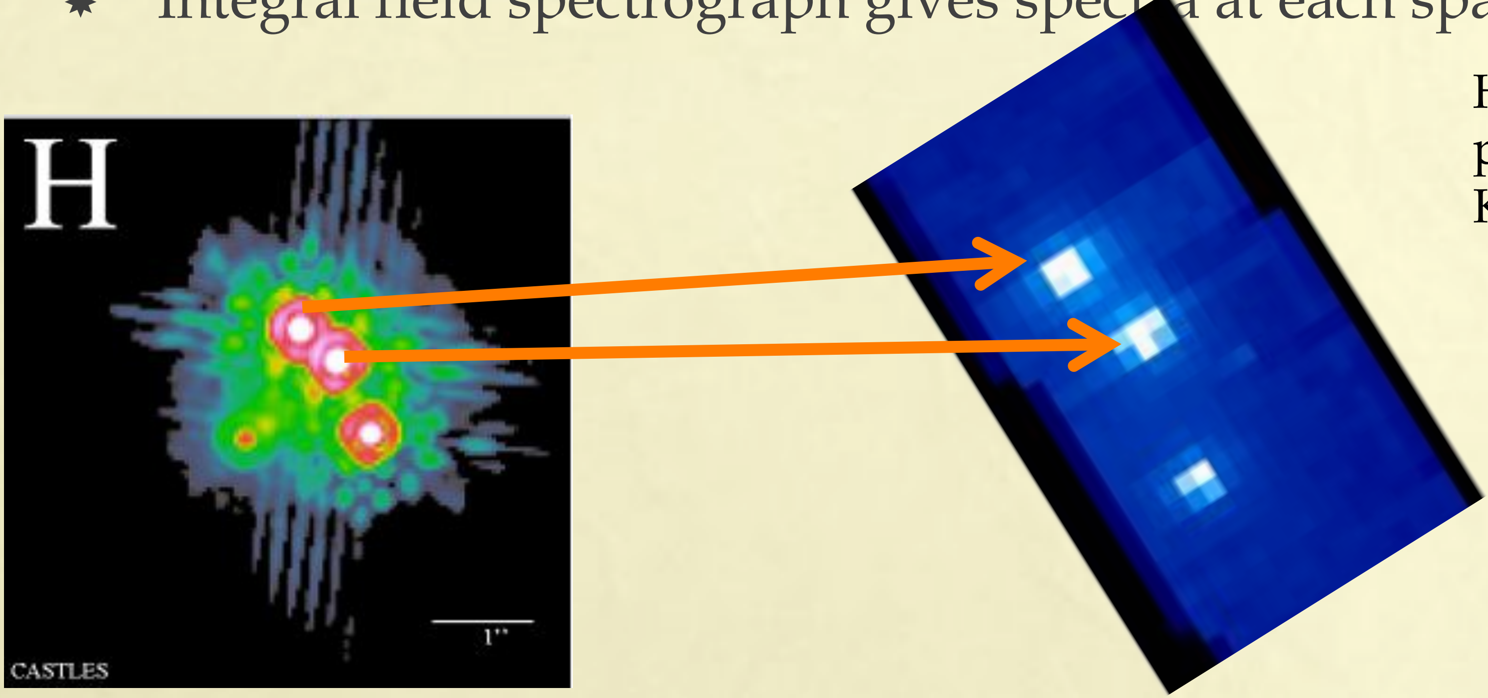
Use OSIRIS to get spatially resolved spectra of the lensed images

- Adaptive optics gives ~mas spatial resolution
- Integral field spectrograph gives spectra at each spatial pixel



Hbb, 100 mas pixels with Keck II

B1422+231

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Optimal Spectral Extraction

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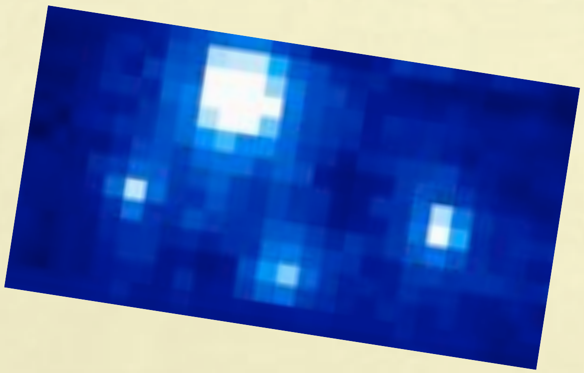
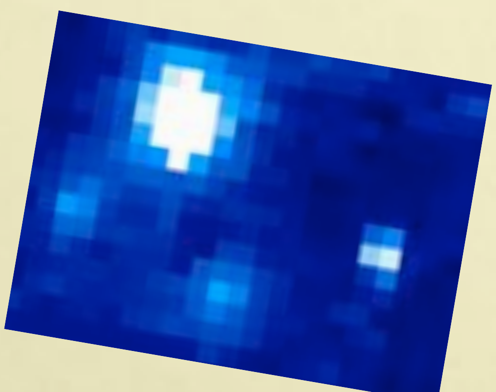
How to Extract Image Spectra

Part I: Use the white image, integrated over wavelengths near broad emission features, to infer the PSF properties and image positions for each exposure separately



Global Parameters- same for each exposure

(dxB, dyB), (dxC, dyC), (dxG, dyG), fB/fA, fC/fA, fG/fA



Local Parameters- vary with exposure

(xA, yA), fA, fBack, psfWidth, psfPA, psfQ, strehl

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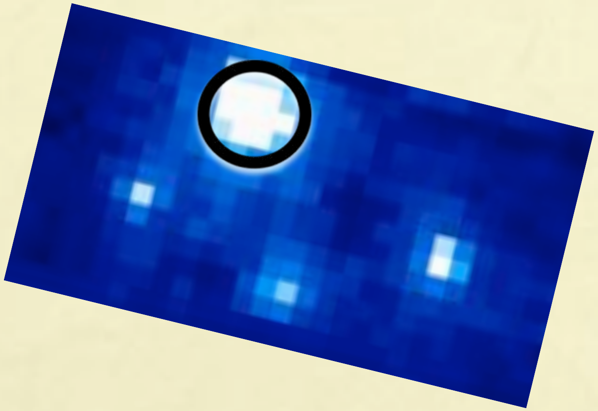
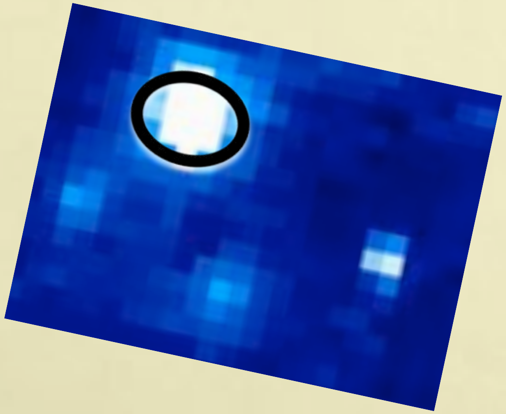
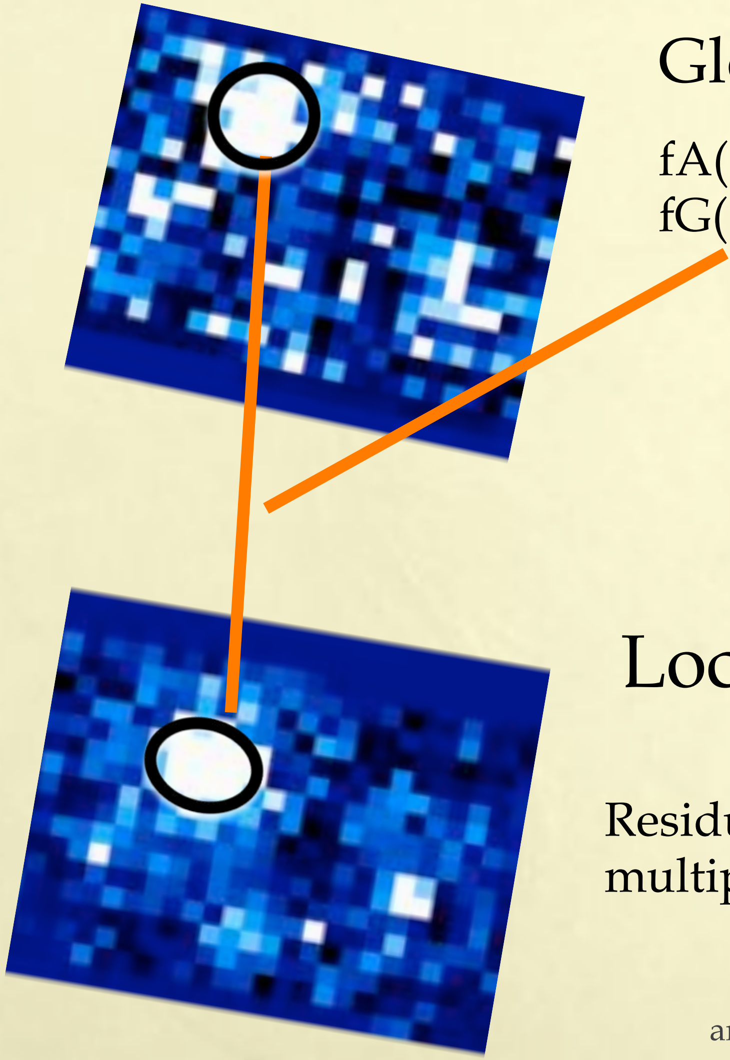
Part II - Use the PSF, image position, and sky throughput parameters inferred from the first step and do a xi-squared optimization at each wavelength slice to get the image fluxes







Global Parameters

$fA(\lambda)$, $fB(\lambda)$, $fC(\lambda)$, $fG(\lambda)$

Local Parameters

Residual sky, multiplicative factor

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Bonus

Can infer the FWHM of [OIII] source size to 3 mas accuracy- find it's about 15 mas, or ~100 pc at (redshift 3.6 !)

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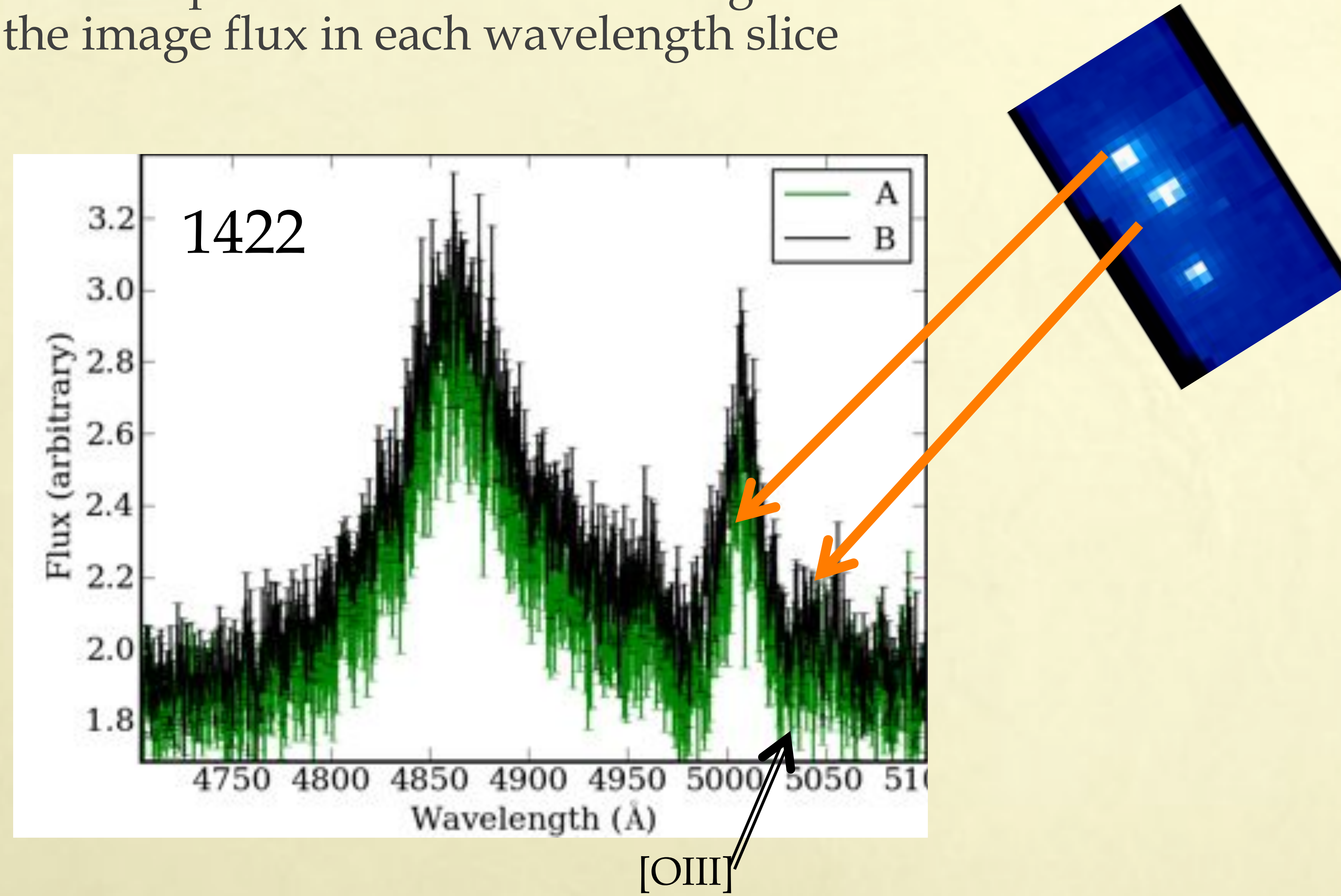
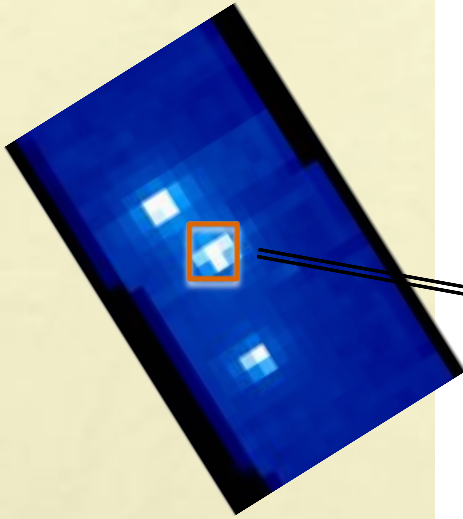
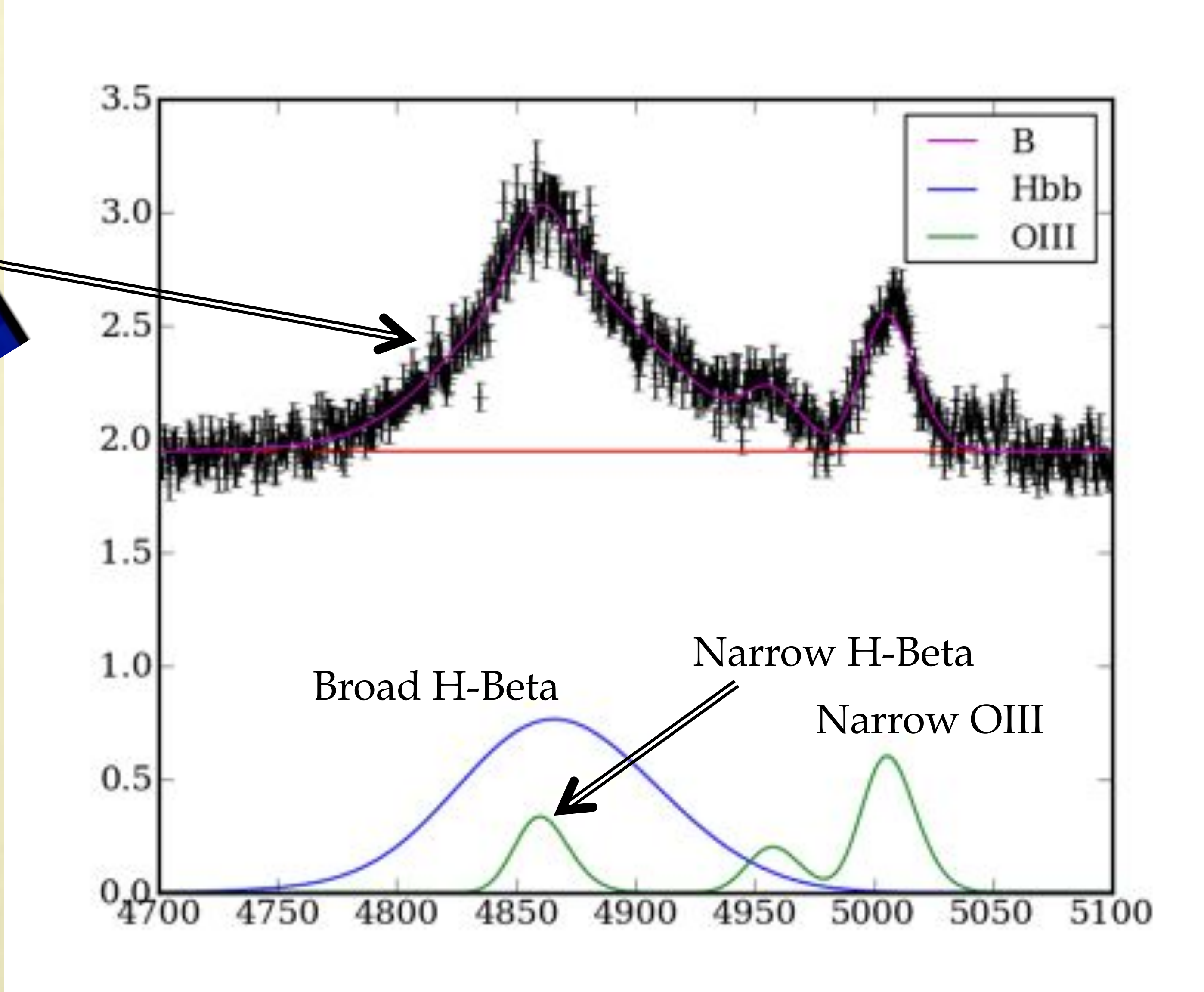
Extracted Spectra

Model the image positions and PSF properties simultaneously for all exposures in the ‘white images’ and use this to calculate the image flux in each wavelength slice



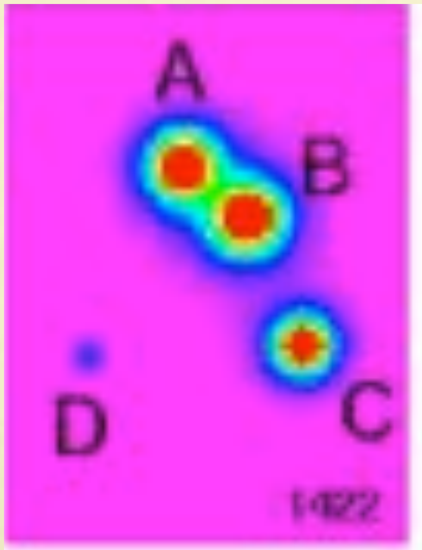
Model Narrow and Broad Fluxes

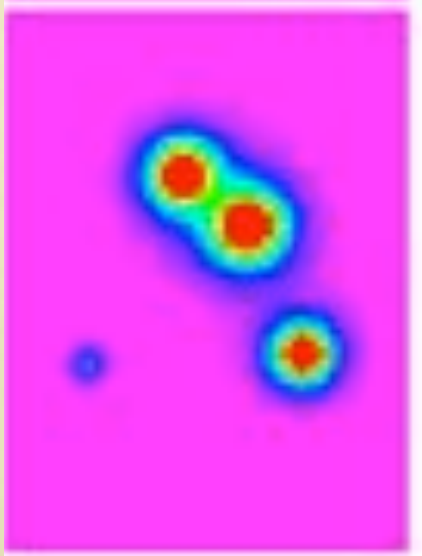




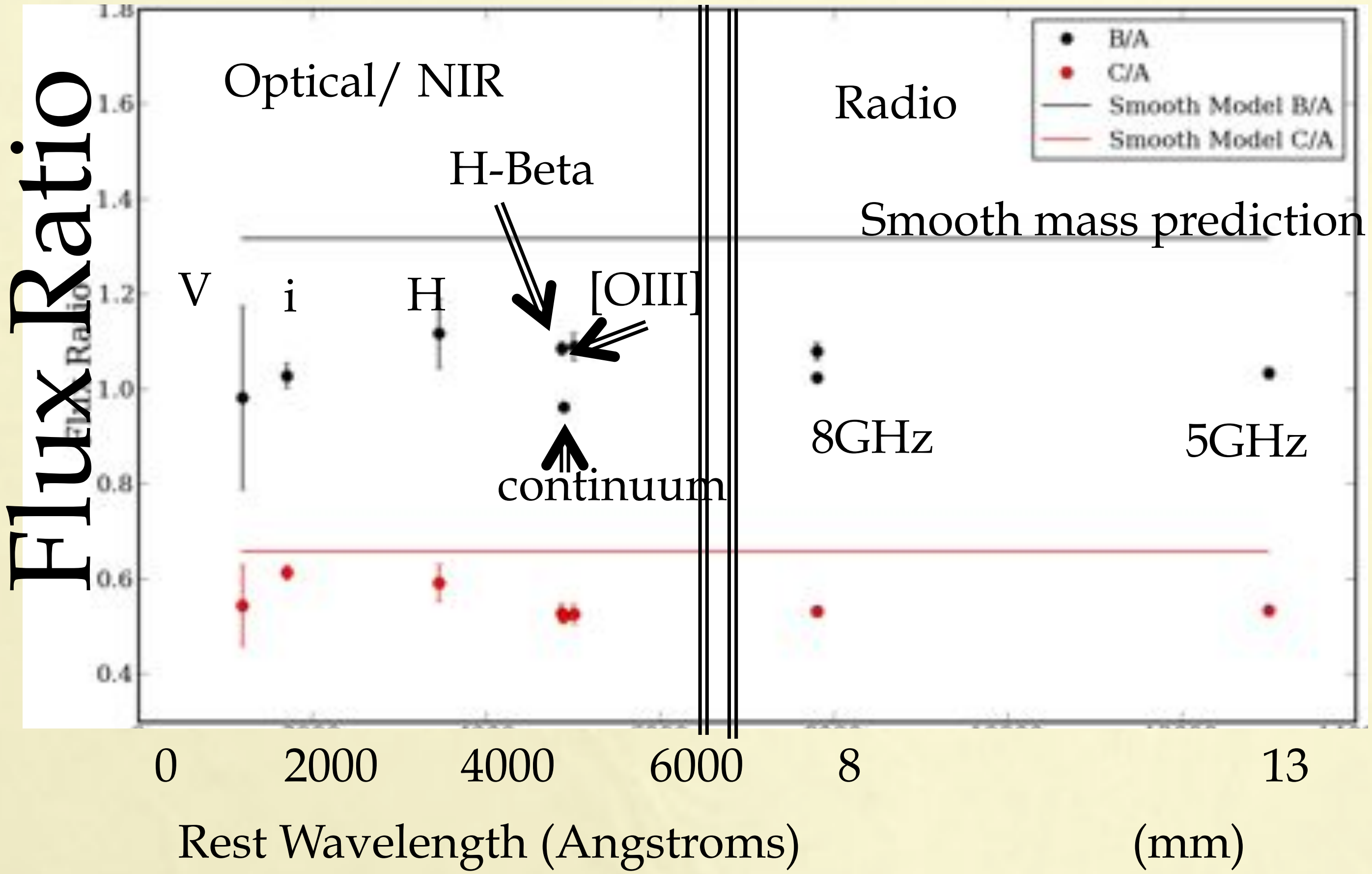
Results for 1422

Observed continuum fluxes

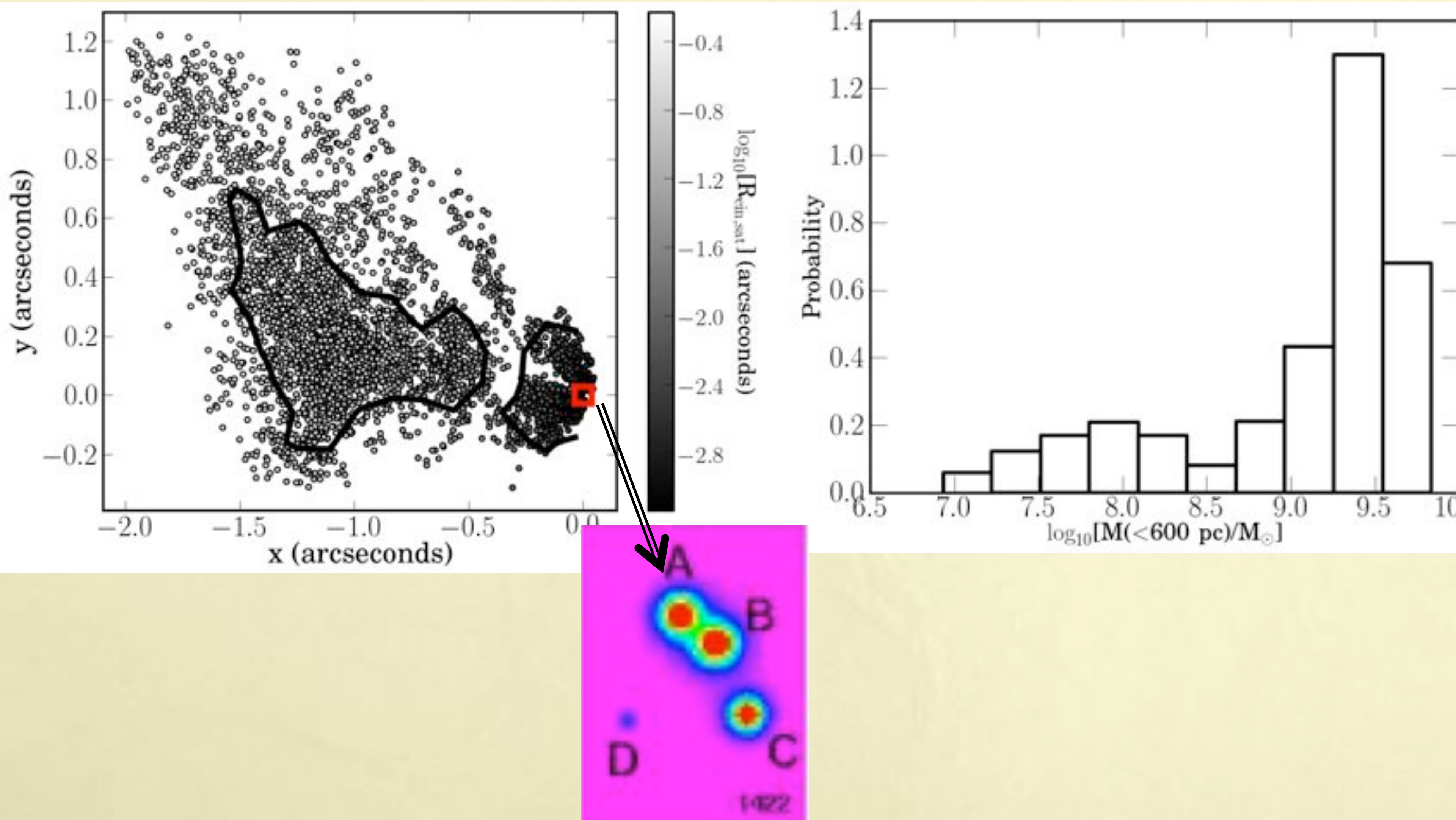




Smooth lens prediction



Subhalo mass assuming an SIS mass profile



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Conclusions (Thanks for listening!)

- OSIRIS + Adaptive optics give sufficient spatial and spectral resolution to study narrow line flux ratios in quasar lenses
- Results from the lenses 0924 and 1422 show that this method can be used to distinguish between the effects of microlensing by stars and millilensing by substructure.
- Coming up soon: Analysis of the rest of the set and gravitational lens modelling of narrow line flux ratios.
- For the future: New surveys (PANSTARRS, DES, LSST, …) will discover thousands of new quasar lenses, and short integration times with TMT will make this method feasible for a large number of systems.

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