HIGH Z SATELLITES AND GRAVITATIONAL LENSING AS PROBES OF DARK MATTER

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OUTLINE

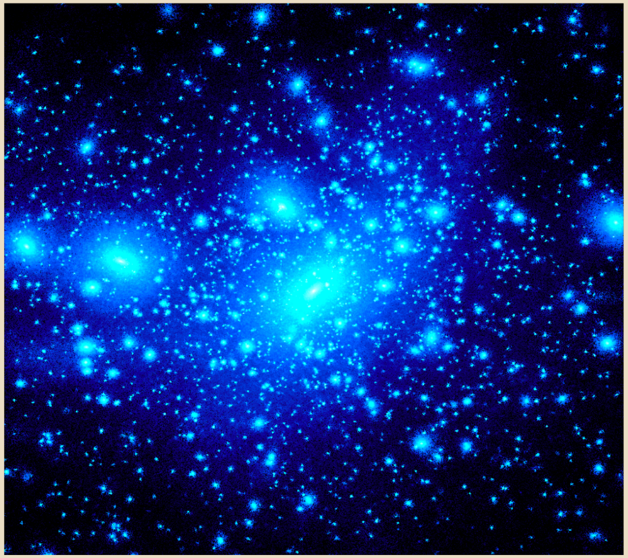
- Motivation (missing satellites?)

- Part I: The properties of luminous satellite galaxies
  - What we can learn by looking outside the Milky Way
  - Brand new preliminary (amazing) results from the CANDELS survey

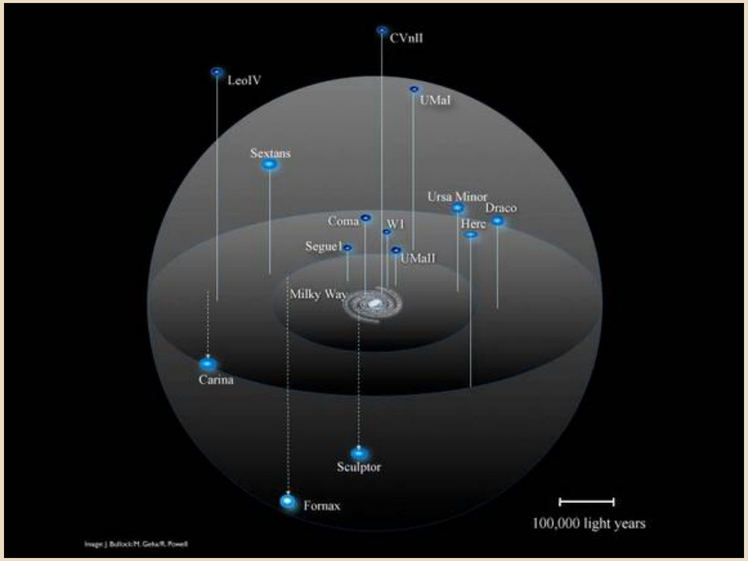
- Part II: Dark satellites with gravitational lensing
  - Reminder about how strong gl works and some of the limitations
  - Using narrow line lensing to increase the lens sample size
  - Sneak peek at some new data…

THE 'TOO MANY SUBHALOS PROBLEM'

Kravtsov 2010



Bullock, Geha & Powell



Satellite galaxies are collections of stars, which we believe to be embedded in a dark matter halos, so there are two solutions:

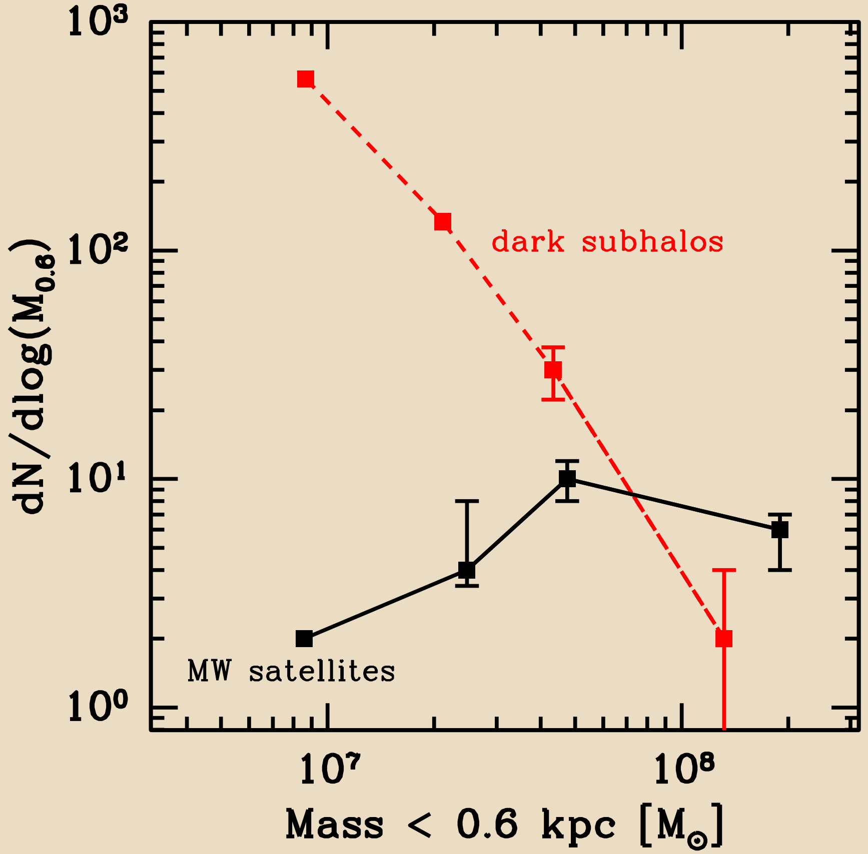
1) There are a large number of dark subhalos which do not contain enough gas or stars for us to see
2) The dark matter theory is incorrect

Satellite galaxies provide important constraints for both astrophysics and the nature of dark matter

PART I: LESSONS FROM LUMINOUS SATELLITES

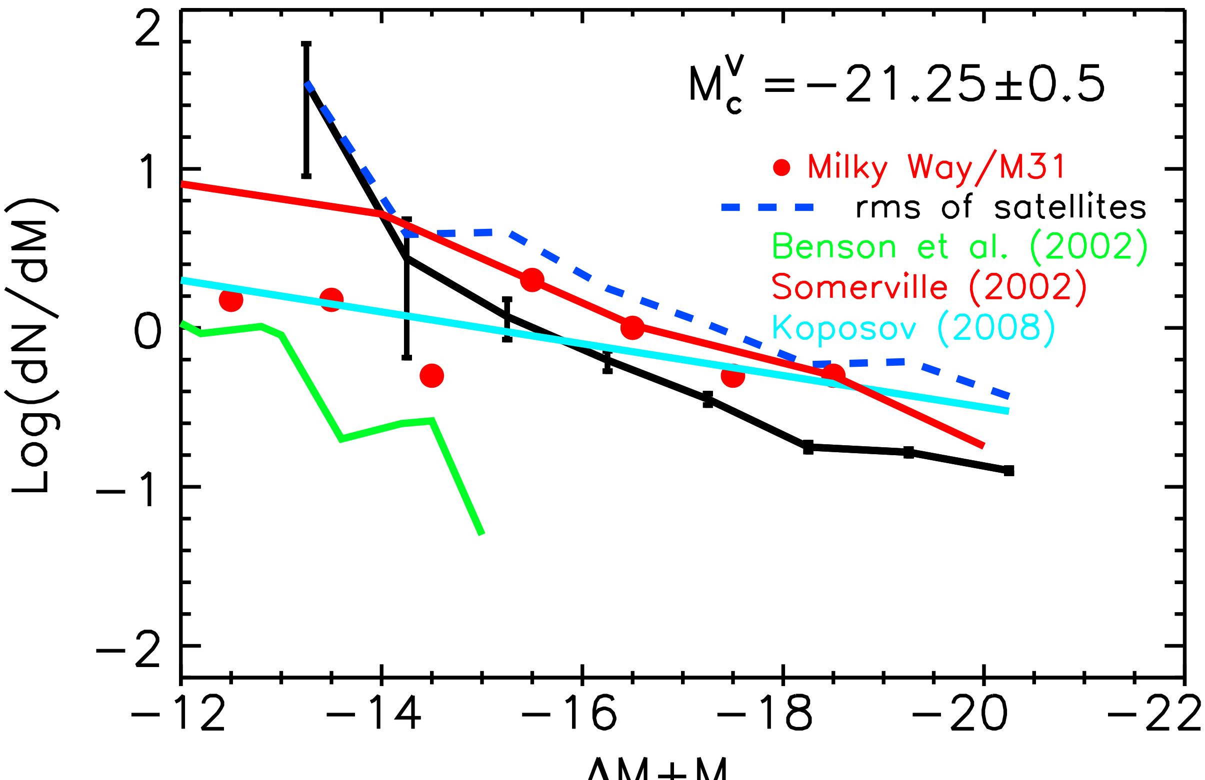
COMPLEX PHYSICS IN SATELLITE GALAXIES

- Internal processes:
  - Supernovae feedback
  - Stellar winds
- External processes:
  - UV heating during re-ionization
  - Tidal interactions with the central halo
  - Ram pressure stripping
- Dark matter temperature?



Strigari et al. 2008

Various combinations of baryonic processes can produce a wide range of predicted luminosity functions for MW satellites at z=0



Guo et al. 2011

HOW DO YOU KNOW WHICH BARYONIC MODEL IS RIGHT?

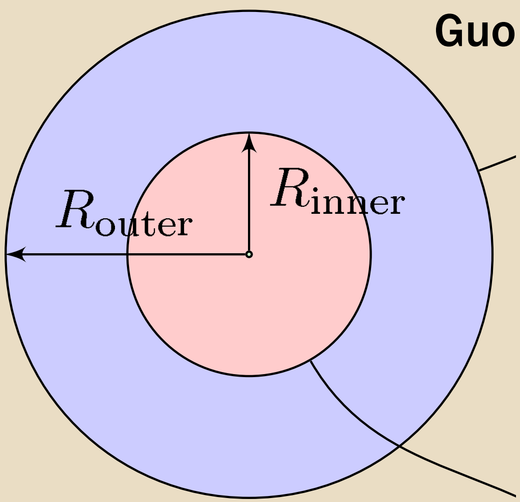
- Look at satellites around different hosts and in different environments to understand the relative importance of environmental processes

- Study satellites at a range of redshifts to separate between time dependent phenomena

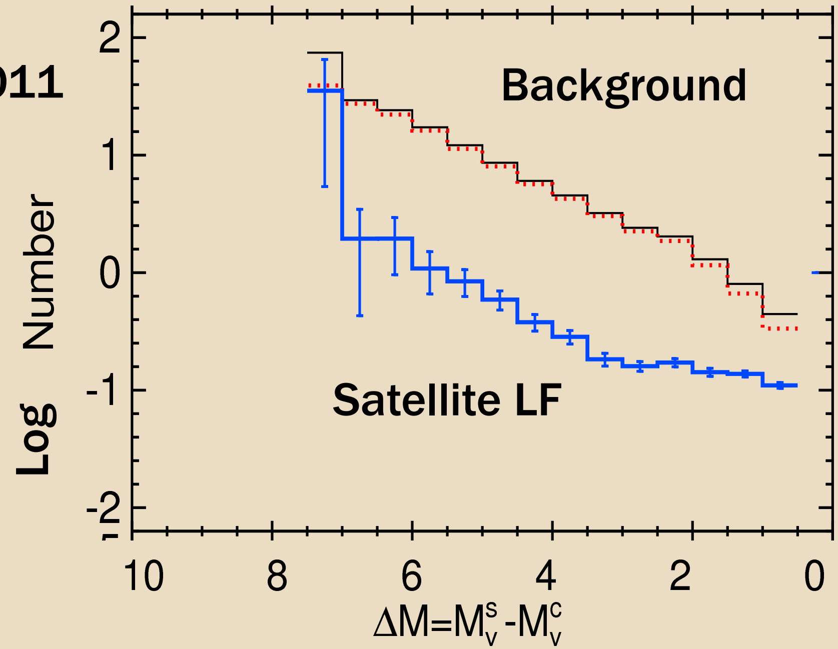
- Look at the spatial distribution of satellites around hosts

HOW TO STUDY SATELLITES OUTSIDE OF THE LOCAL GROUP?

Satellites of MW like hosts are too faint for redshift measurements



Guo et al. 2011

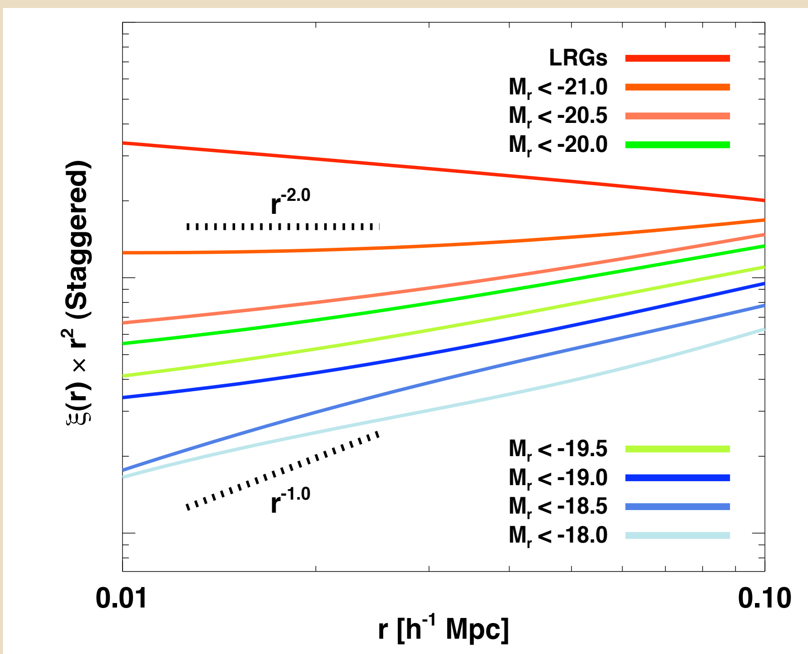


Subtract background/foreground numbers from numbers in the inner region to get satellite numbers

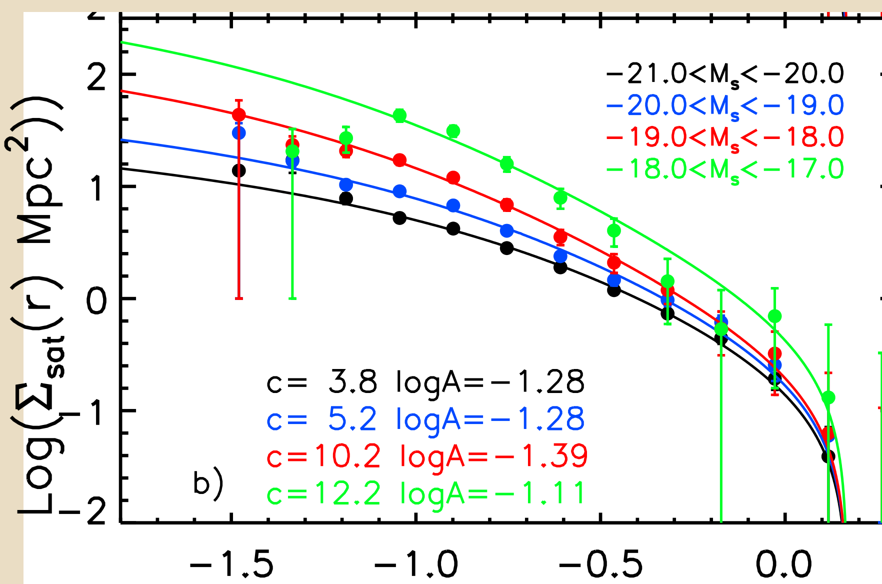
RESULTS FROM SDSS

- The Milky Way has a typical satellite population for its stellar mass (e.g. Guo et al. 2011, Strigari & Wechsler 2011, Lares et al. 2011)
- Faint satellites have steeper (or shallower?) number density radial profiles around hosts than bright satellites

Watson et al. 2012



Guo et al. 2012



HOW TO MAKE PROGRESS

- Go to space!
  - Higher resolution and increased sensitivity allows for more accurate measurement of the satellite spatial resolution
  - Depth makes it possible to go to higher redshifts
- More statistics
  - Build a model which simultaneously fits the properties of the satellite spatial distribution and the satellite luminosity function (and whatever else you care about

SATELLITES IN COSMOS AND CANDELS

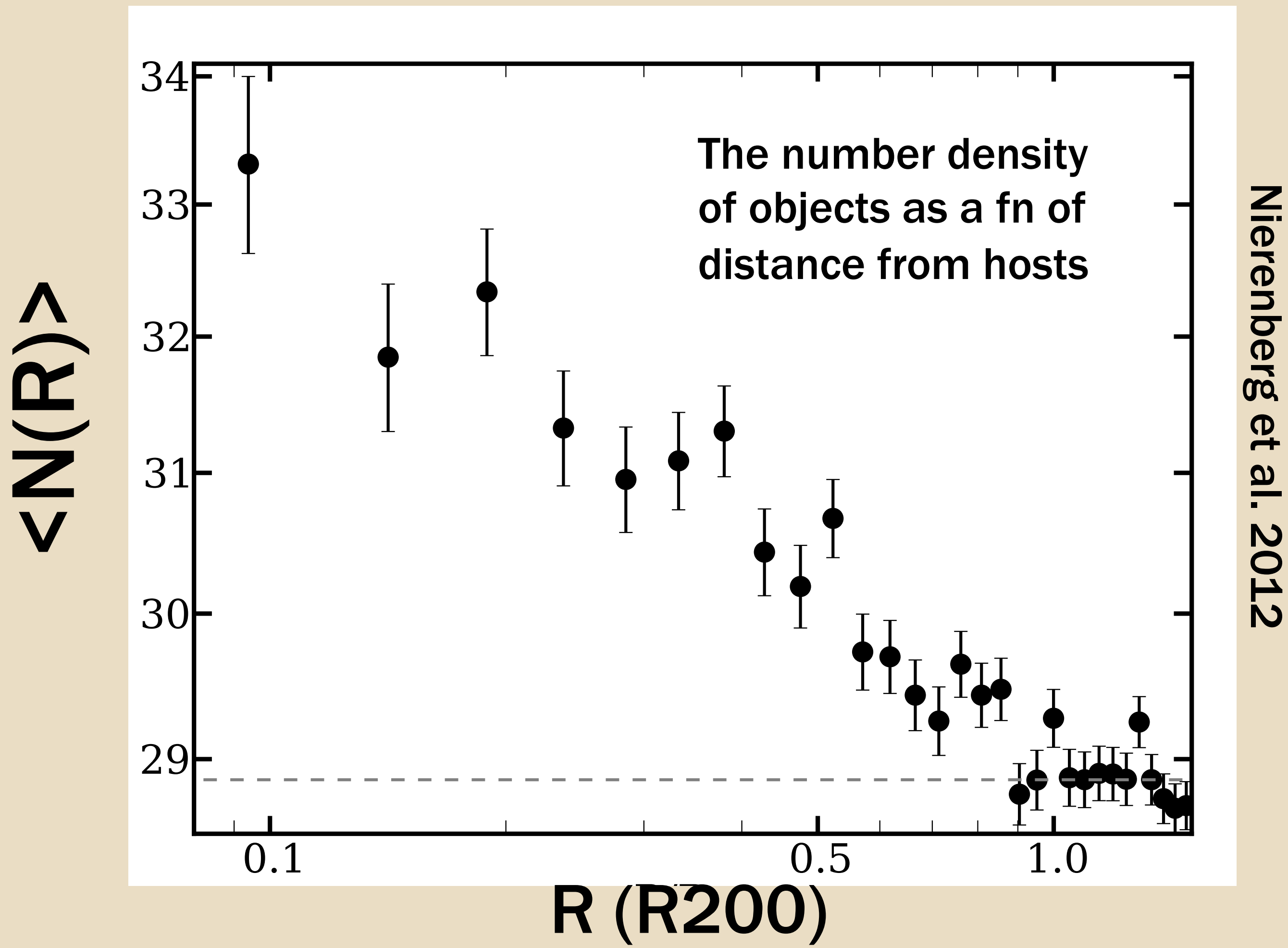
- COSMOS – 1.7 square degree HST survey with i 814 imaging (Scoville et al. 2007)
  - mag
  - Sub

Spatial Distribution, host props, and lower z stats

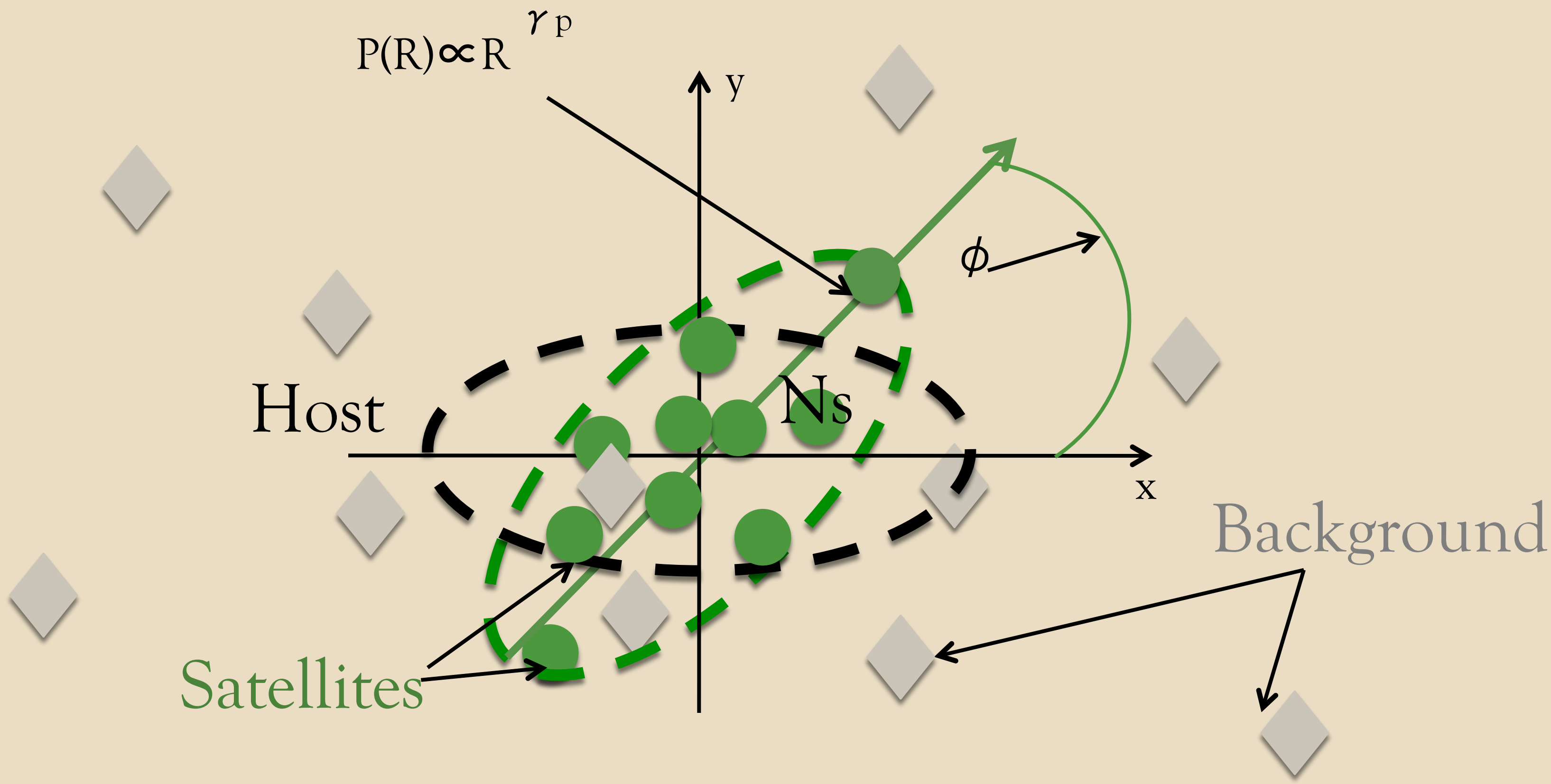
- CANDELS - 0.25 square degrees HST survey with F125W, F140W, F160W and F606W photometry (Koekemoer et al. 2011, Grogin et al. 2011)
  - Mag limit ~2
  - Satellites 10 edshift 1.5!

Deeper, higher z stats, satellite colors

THE SATELLITE SIGNAL

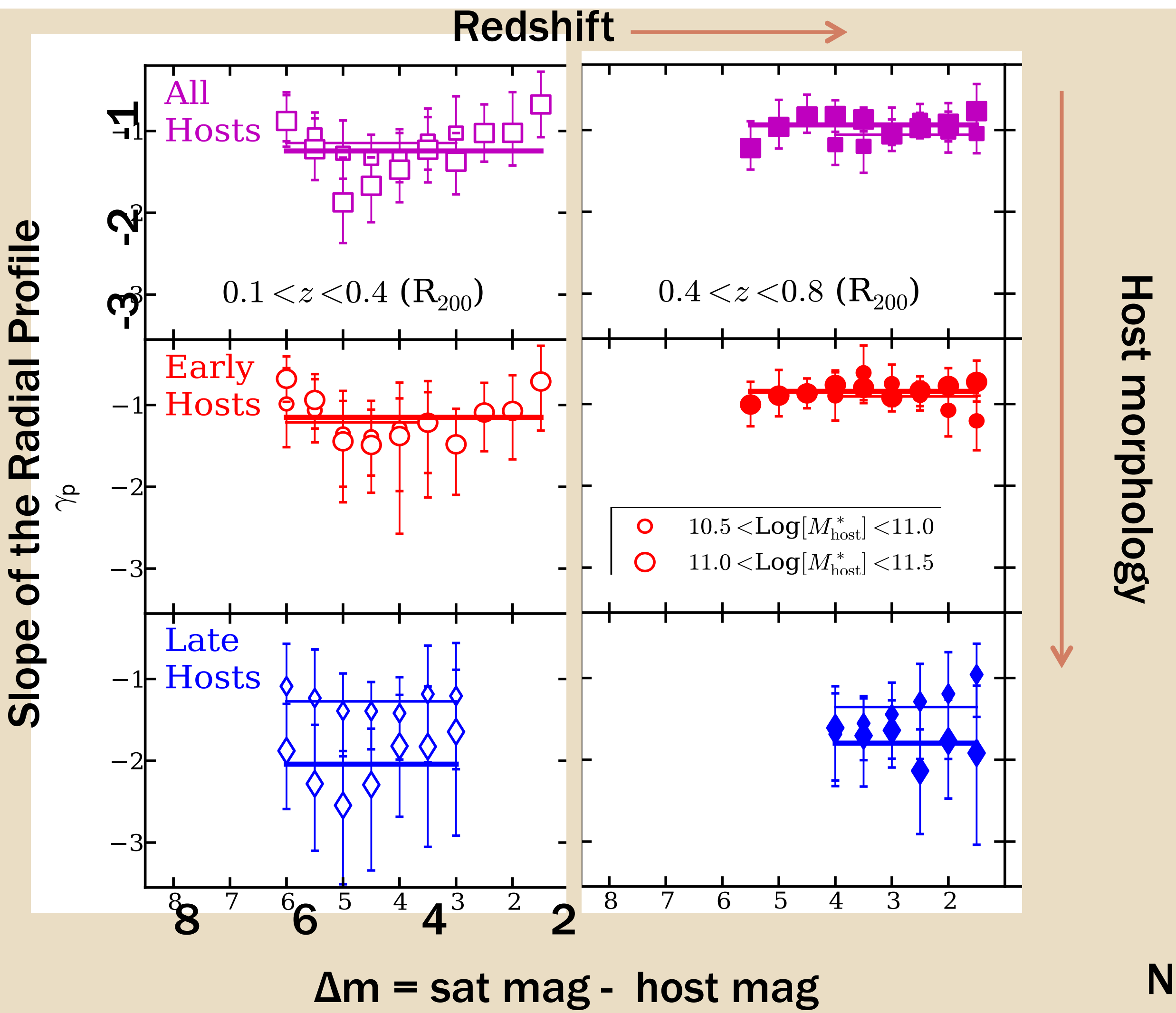


A MODEL FOR THE OBSERVED NUMBER DENSITY



The number and positions of objects around the hosts is determined by the number of satellites, the radial and angular distribution of satellites, the number of background/foreground objects…ect….

COSMOS RESULTS I : RADIAL PROFILE

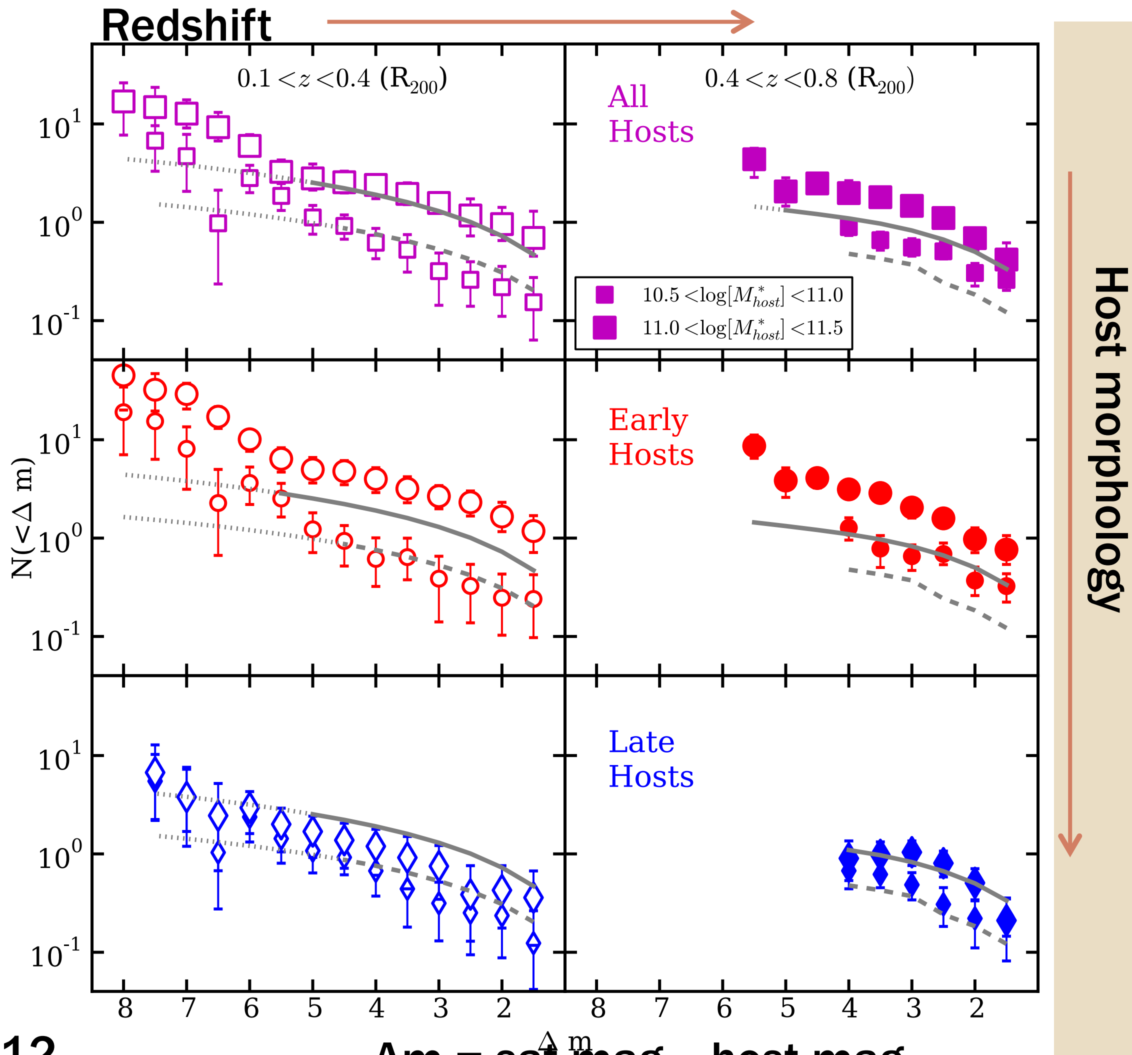


No dependence on host morphology, host stellar mass, satellite luminosity or redshift (to fainter than prev studies)

Nierenberg et al. 2012

COSMOS RESULTS II: LUMINOSITY FUNCTION

The satellite LF depends on the host stellar mass, and host morphology at fixed stellar mass



Δm = sat mag - host mag

Nierenberg et al. 2012

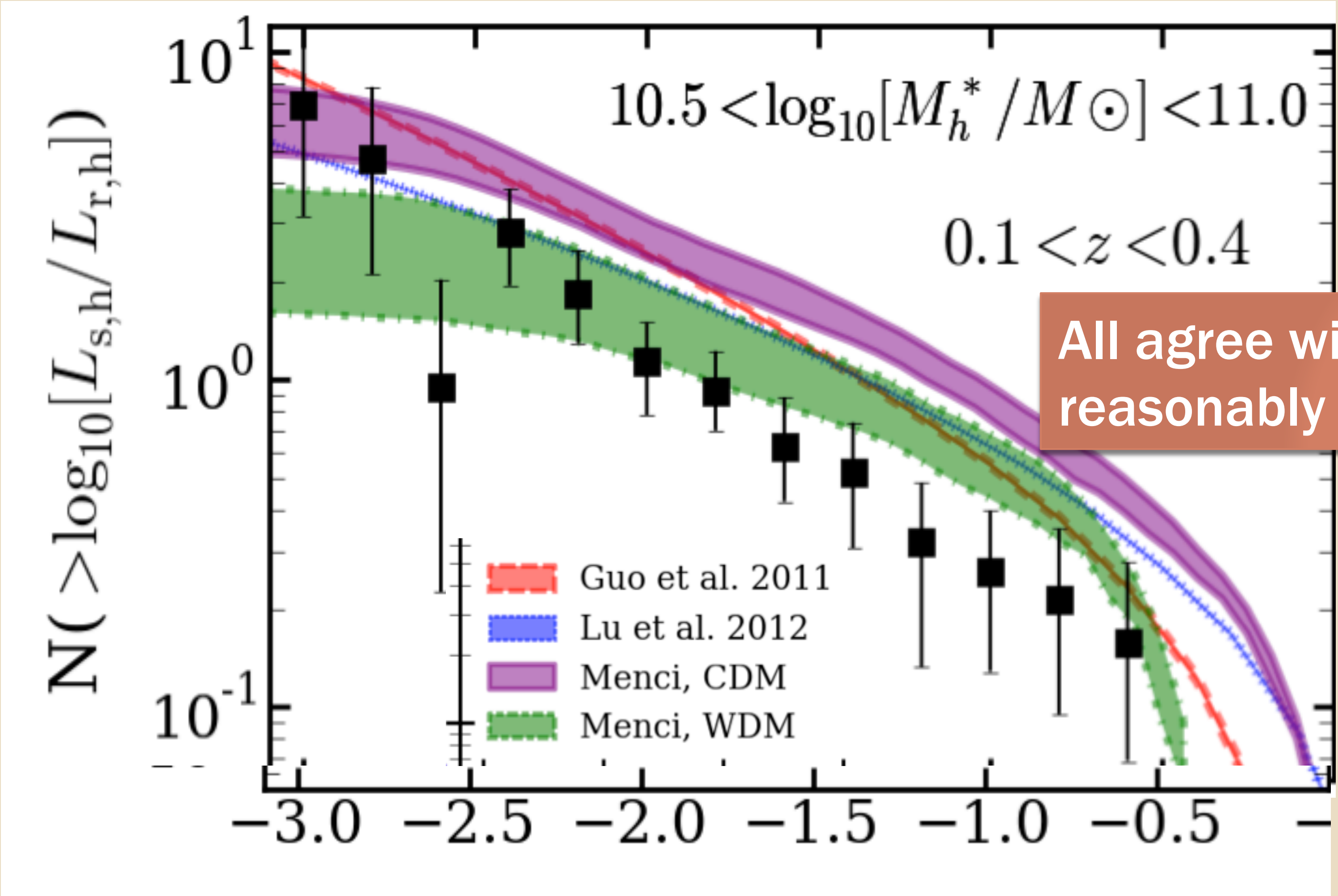
COSMOS COMPARISON WITH THEORY

- 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)

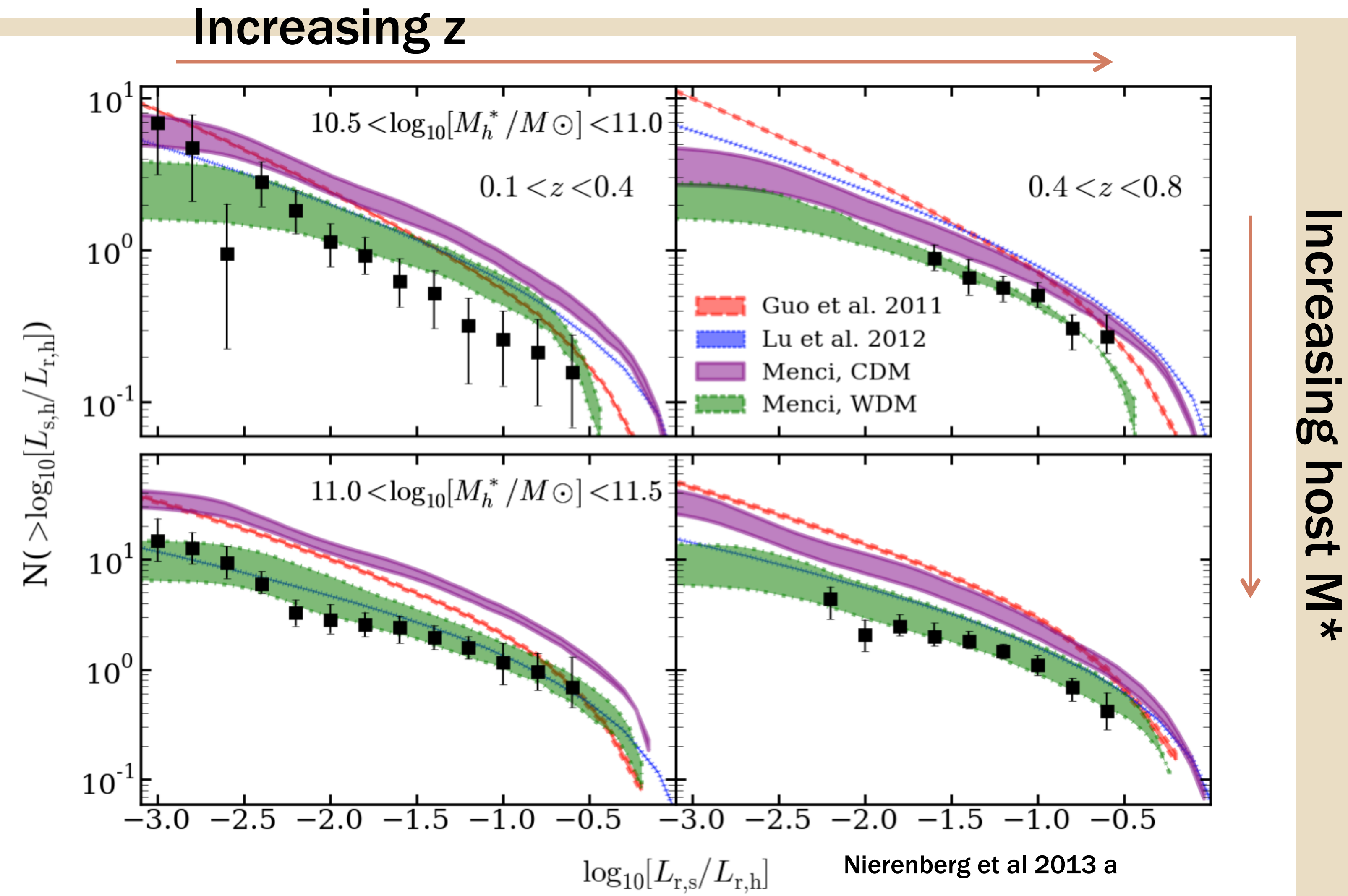
- Menci et al 2012- the same SAM applied to two different EPS merger trees- one CDM, one WDM with cutoff scale Msubmin = 10^7 $M_\odot$ (Tuned to match the color magnitude relation)

COMPARE WITH SATS OF LOW Z MW MASS HOSTS



All agree with data reasonably well

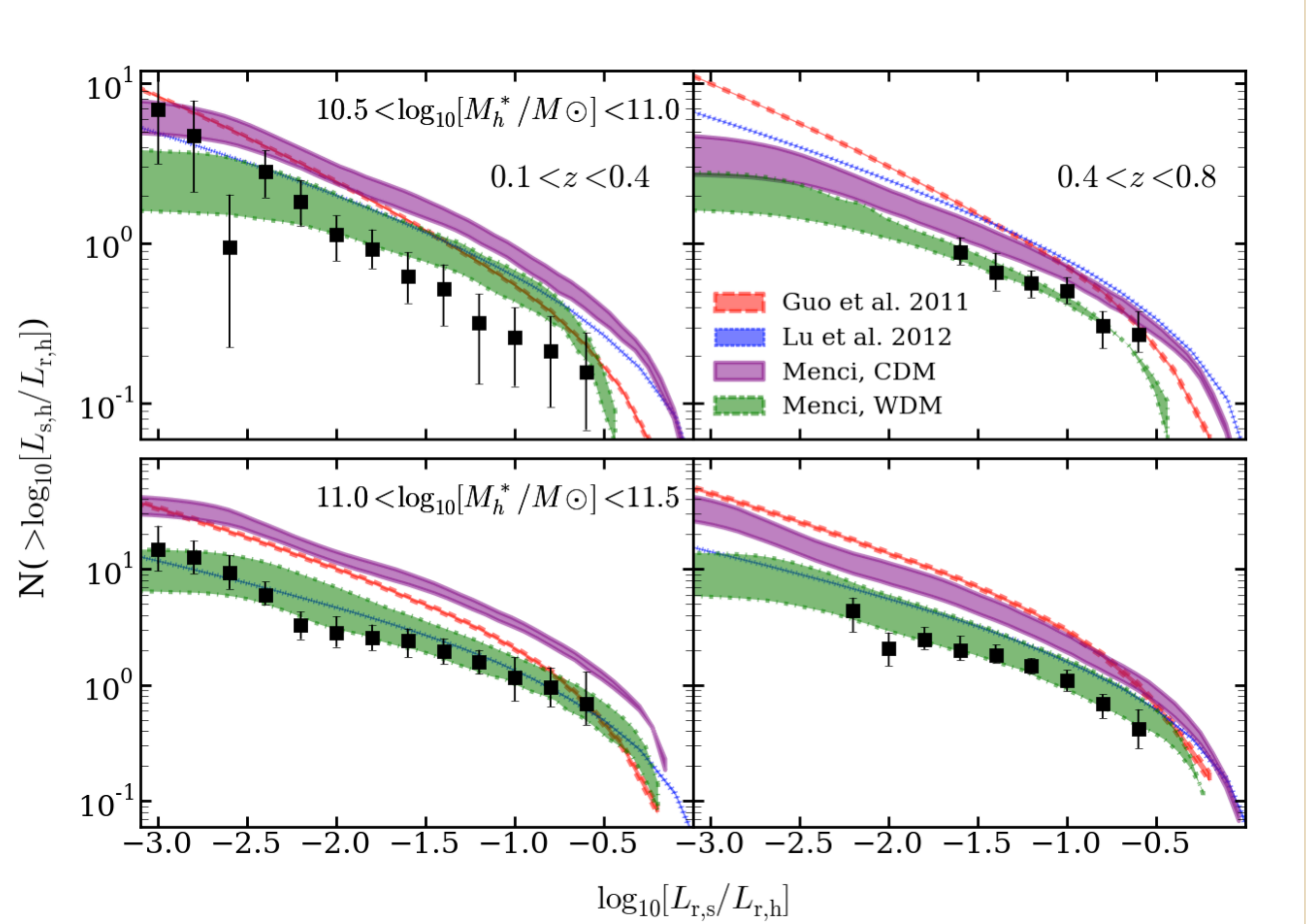
NEW REGIMES



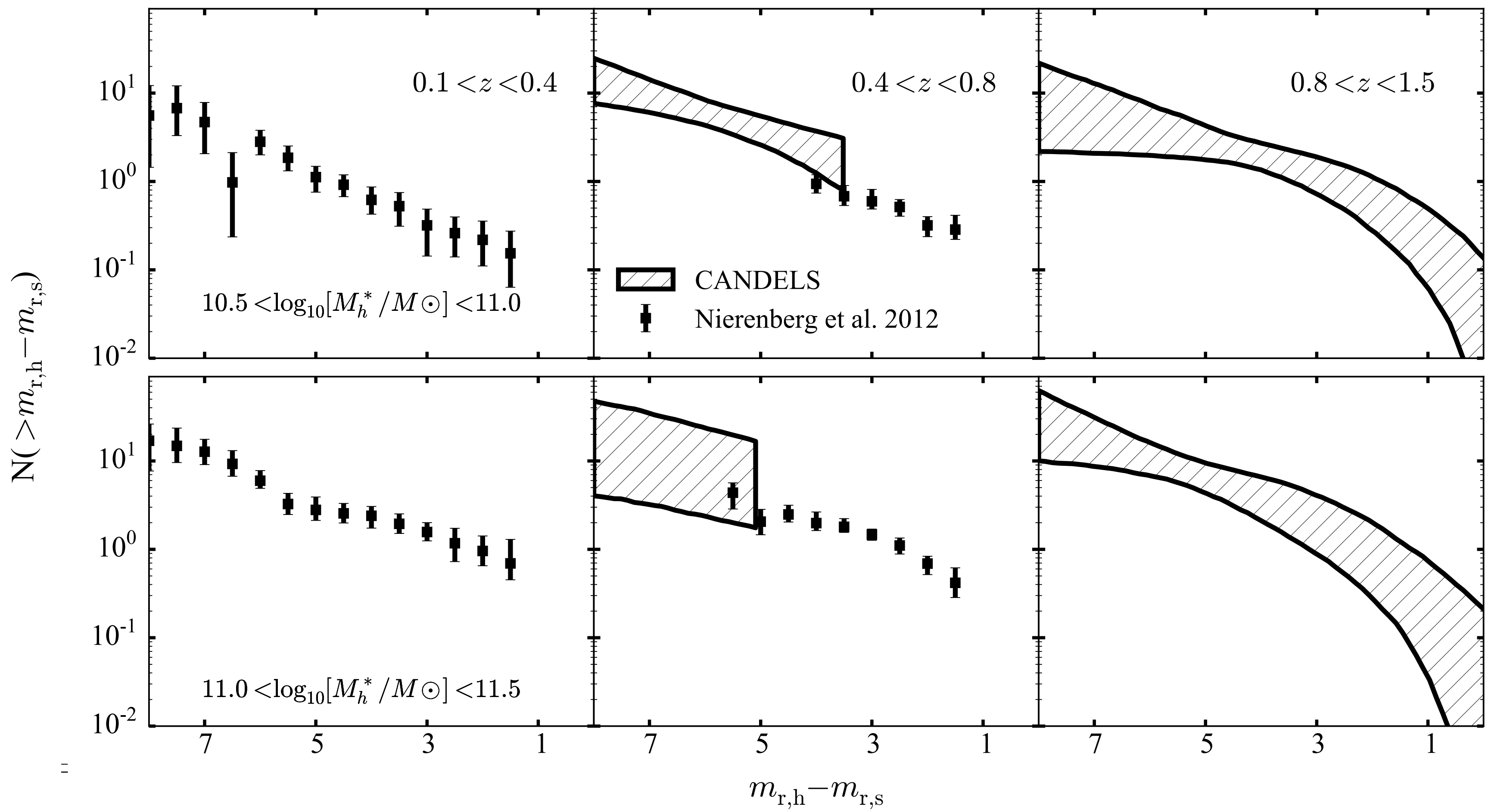
Nierenberg et al 2013 a

MAIN POINTS

- All models do well for MW mass low z hosts
- Of these models, WDM model did the best

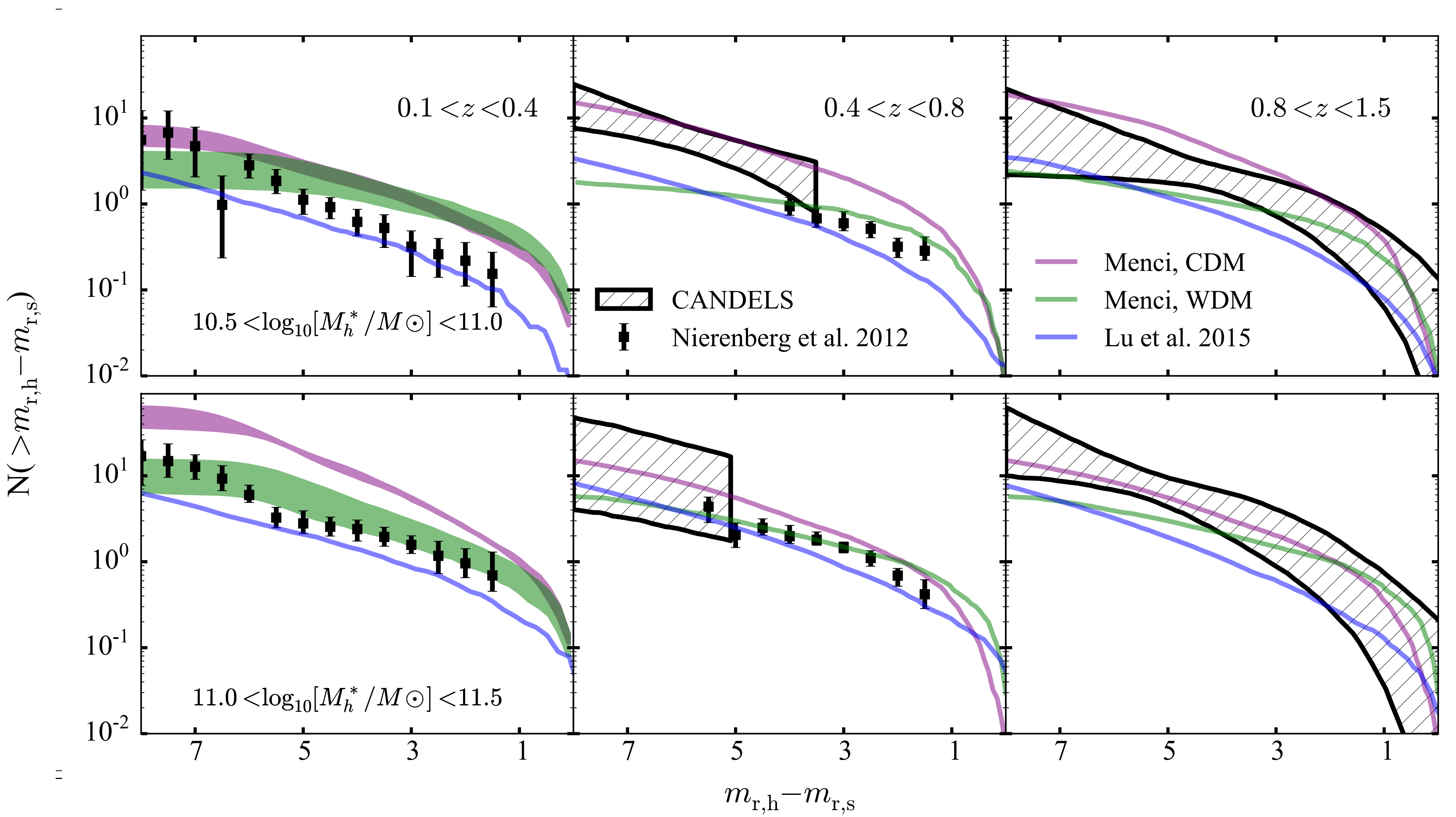


ADD NEW CANDELS DATA



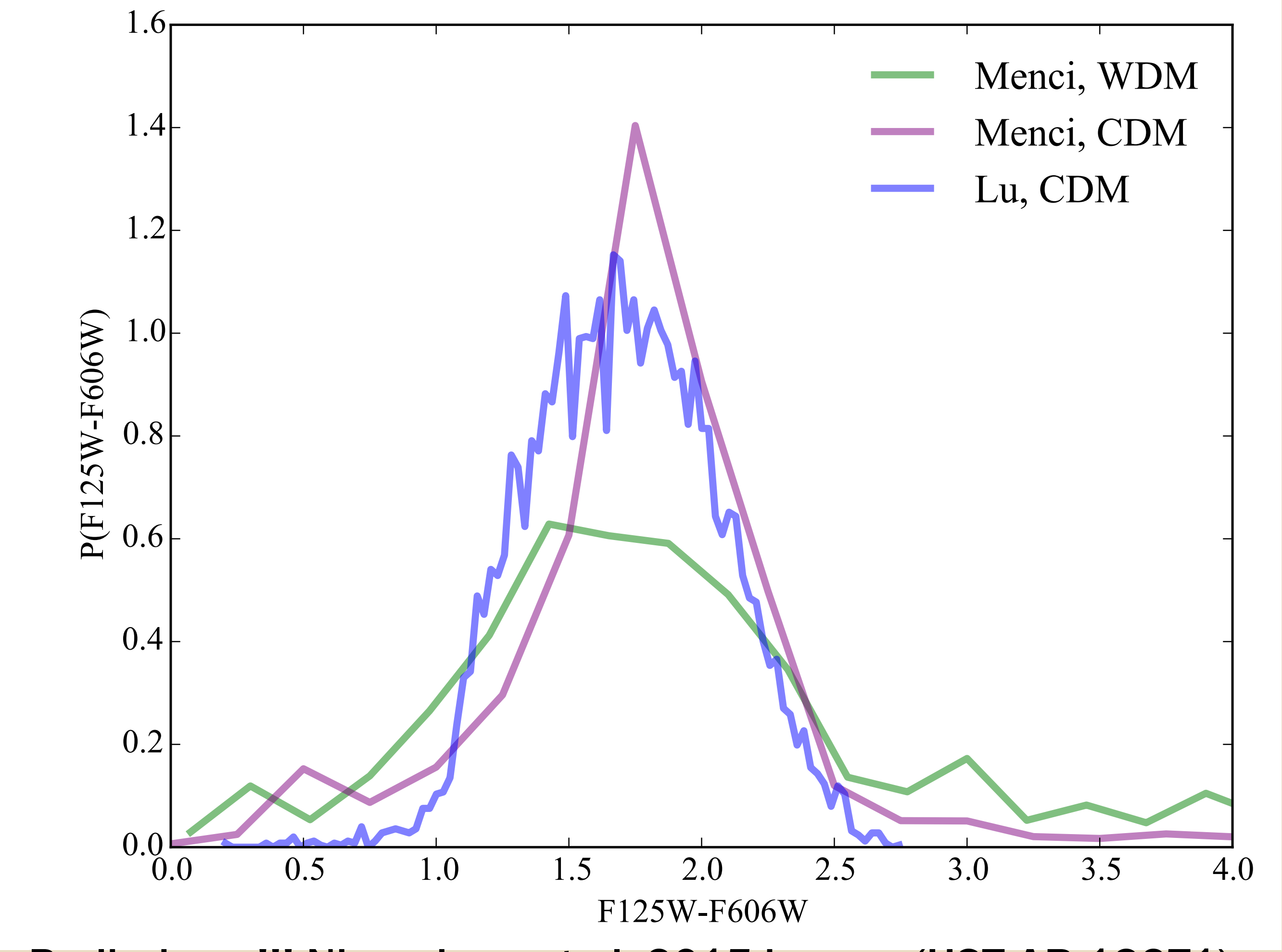
Preliminary!!! Nierenberg et al. 2015 in prep (HST-AR-13271)

COMPARE WITH THEORY



Preliminary!!! Nierenberg et al. 2015 in prep (HST-AR-13271)

SATELLITE COLOR DISTRIBUTION PREDICTIONS



Preliminary!!! Nierenberg et al. 2015 in prep (HST-AR-13271)

SUMMARY OF PART I

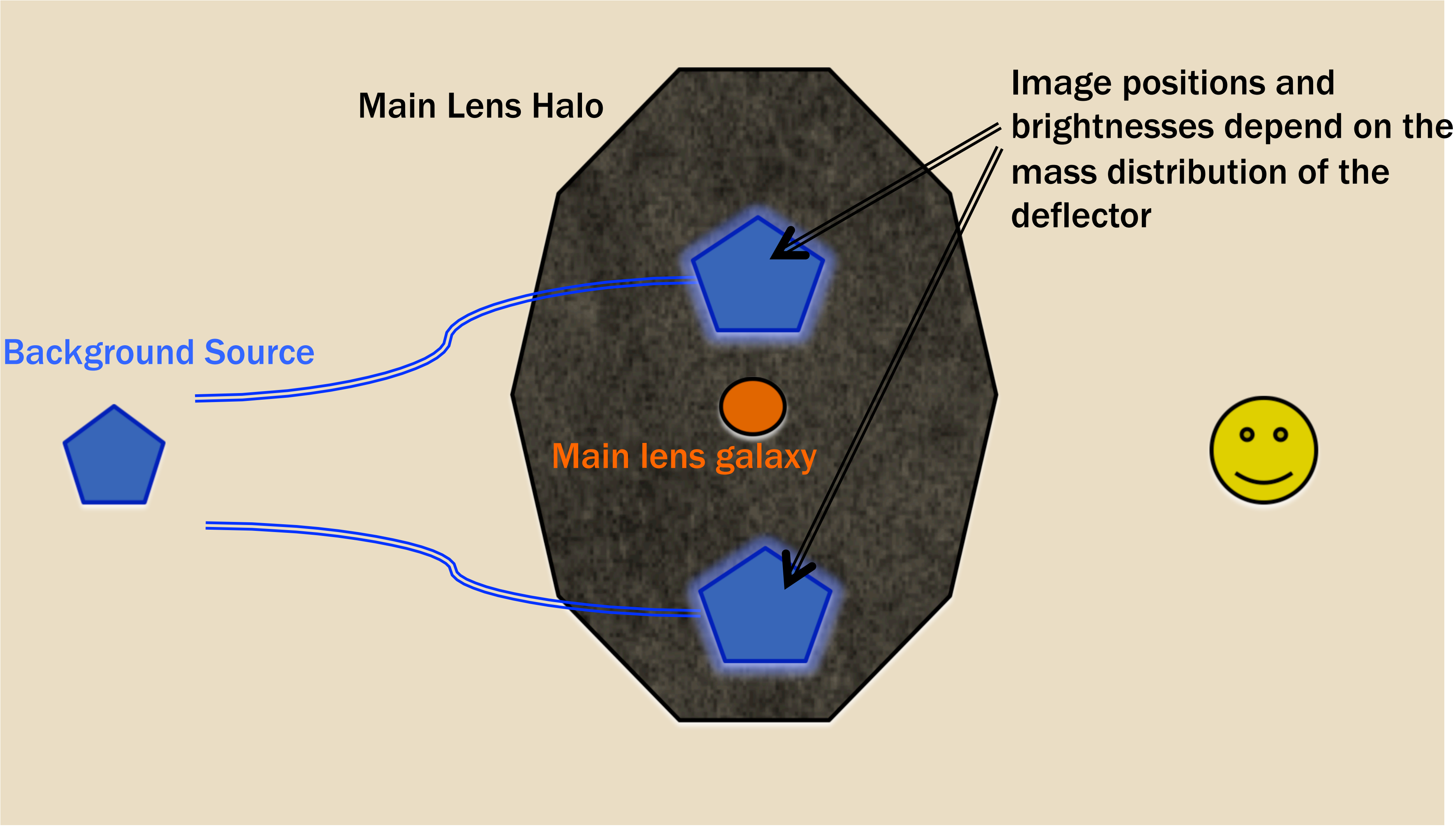
1) It's important to test models in a range of regimes!!

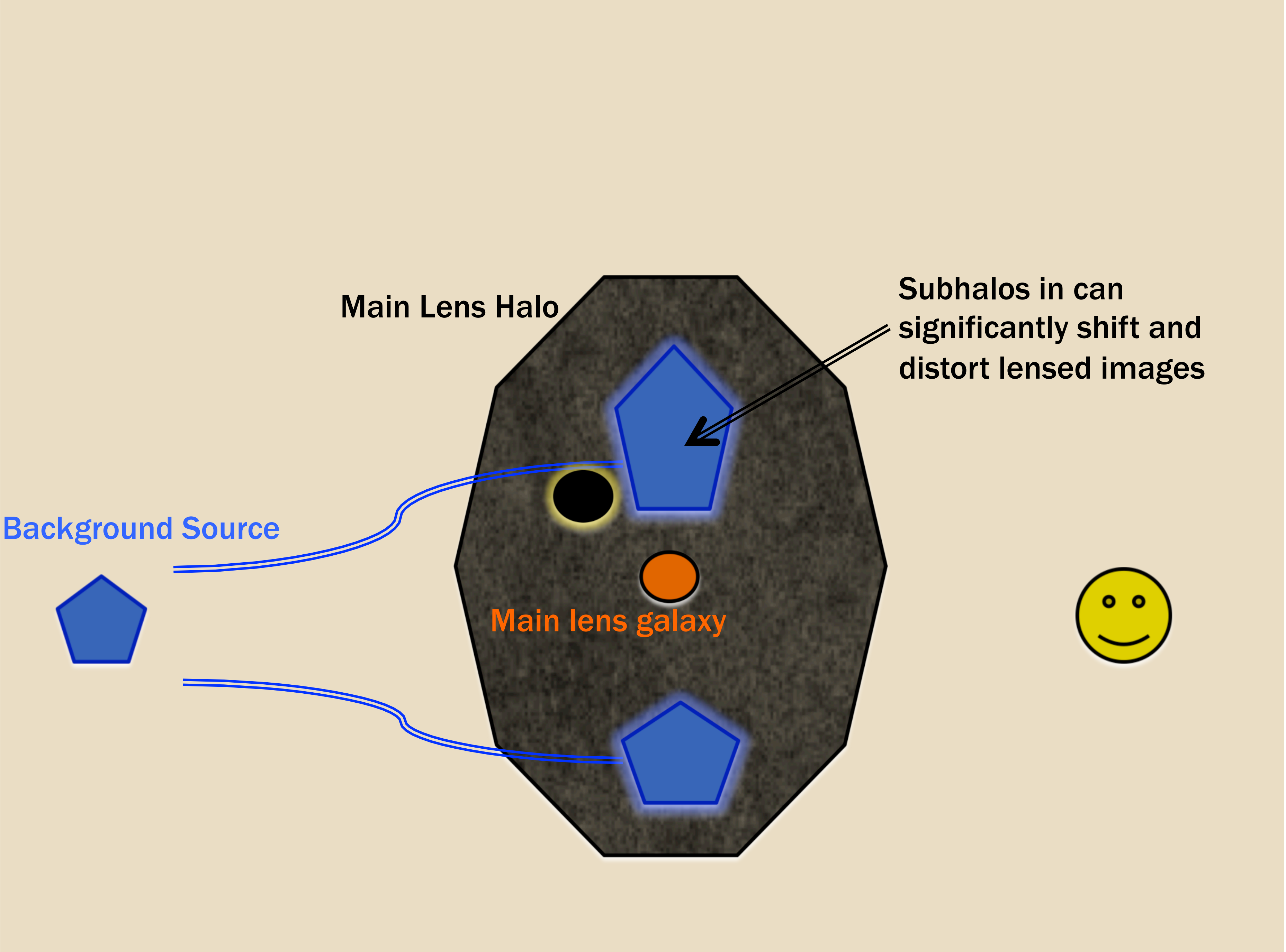
2) Luminous satellites provide new information about astrophysics and dark matter physics.

PART II: A DIRECT MEASUREMENT OF THE SUBHALO MASS FUNCTION

Kravtsov 2010

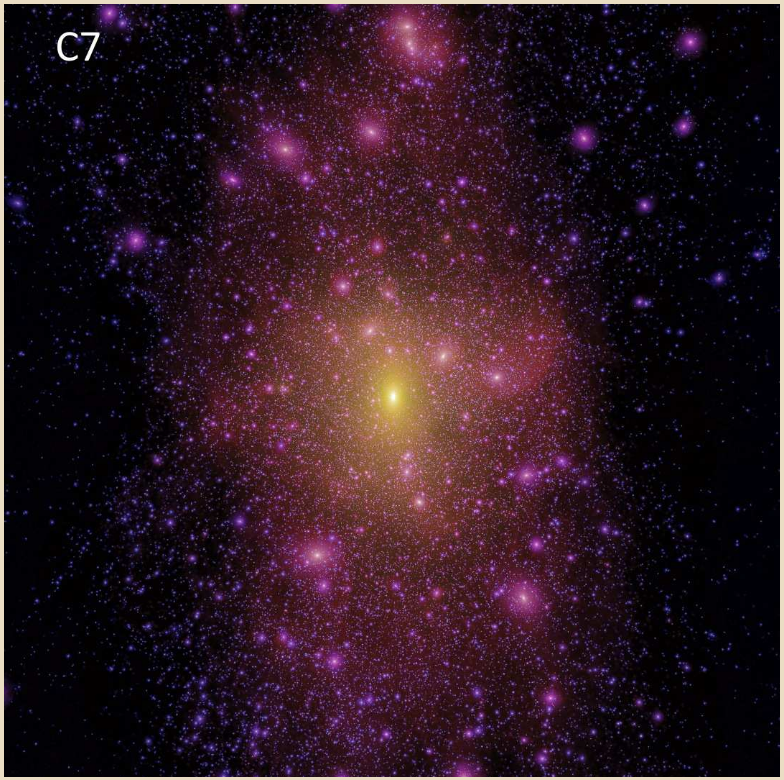
STRONG GRAVITATIONAL LENSING



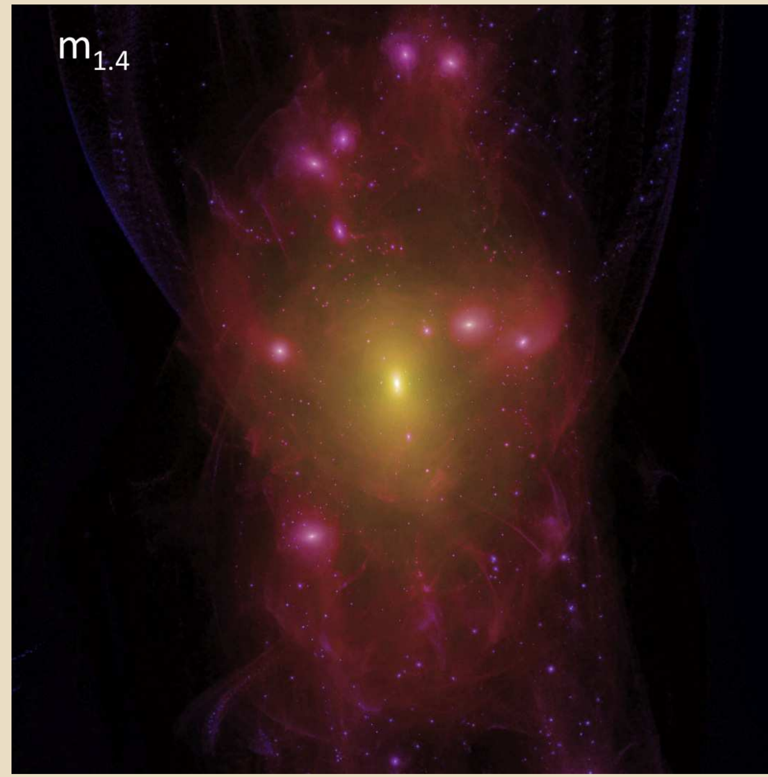


Main Lens Halo
Subhalos in can significantly shift and distort lensed images
Background Source
Main lens galaxy

WITH ENOUGH LENSES CAN DISTINGUISH BETWEEN DM MODELS



Cold Dark Matter

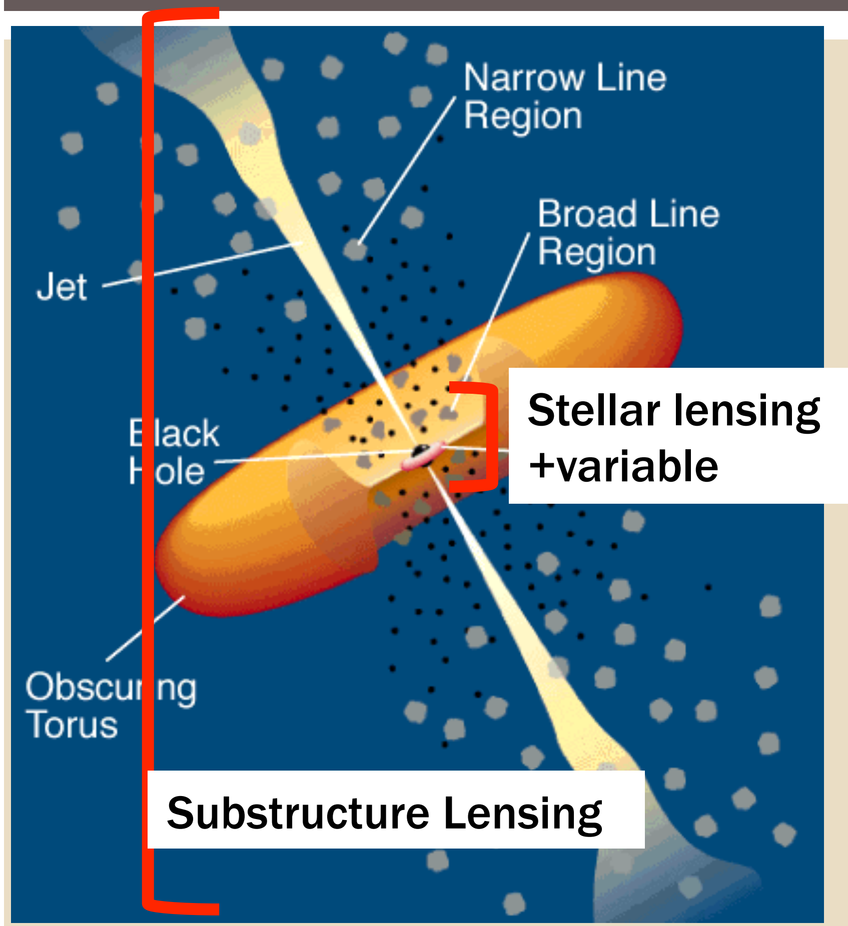


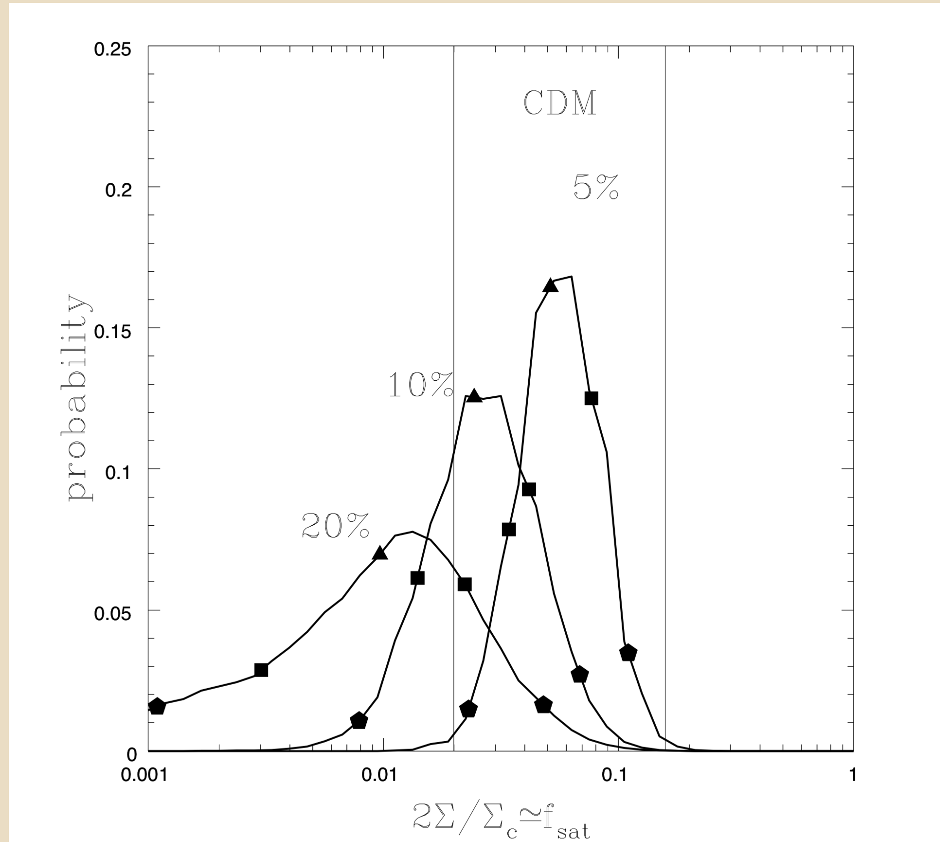
Warm Dark Matter

Lovell et al. 2013

CAVEAT: IF THE BACKGROUND SOURCE IS SMALL, STARS CAN ALSO LENS

NEED LARGE BACKGROUND SOURCE- E.G. AGN RADIO EMISSION



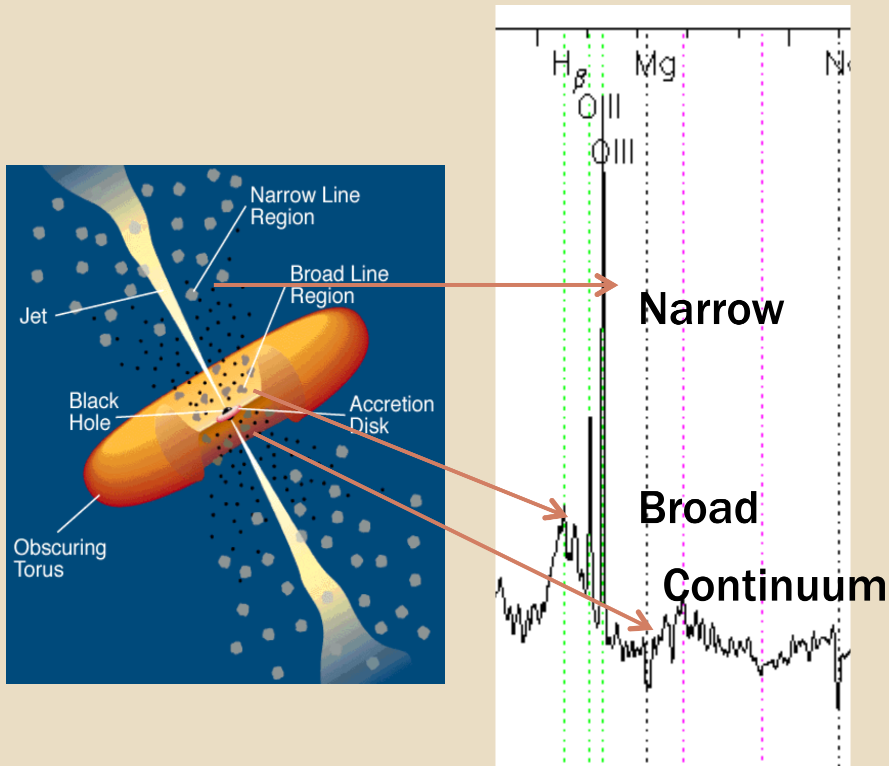


Dalal and Kochanek 2002, 7 radio-loud lens systems

Other large sources include background galaxies (see e.g. Vegetti et al., Hezaveh et al.)

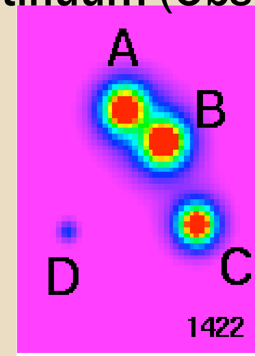
INCREASE THE SAMPLE OF LENSES WITH LENSED AGN NARROW LINE EMISSION

- All quasars show significant narrow line emission (unlike radio)
- Narrow-line is not variable and not microlensed

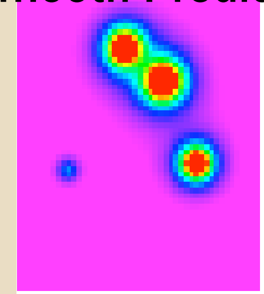


Example: 1422

Continuum (Observed)



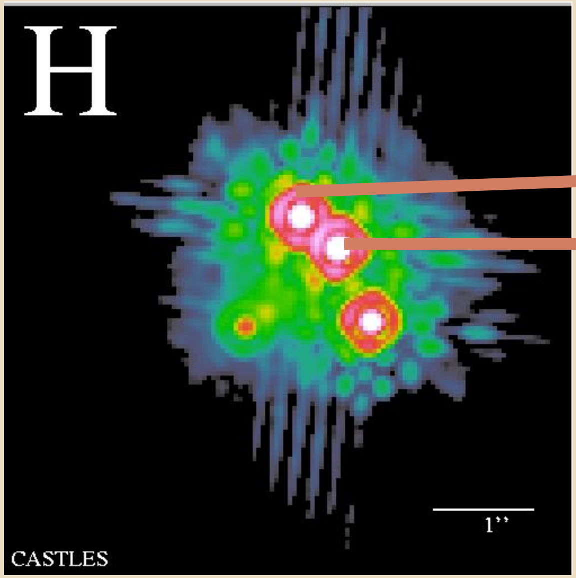
Smooth Prediction



Need high res, spatially resolved spectroscopy

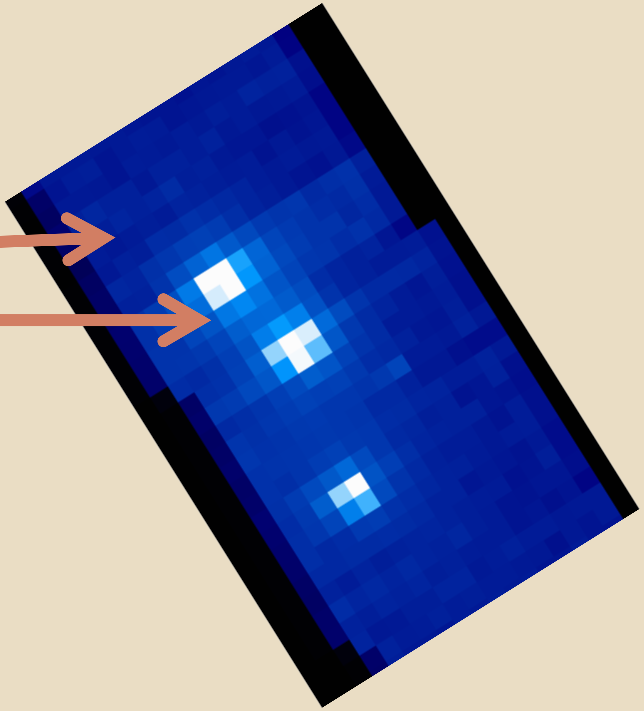
METHOD 1: KECK OSIRIS

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



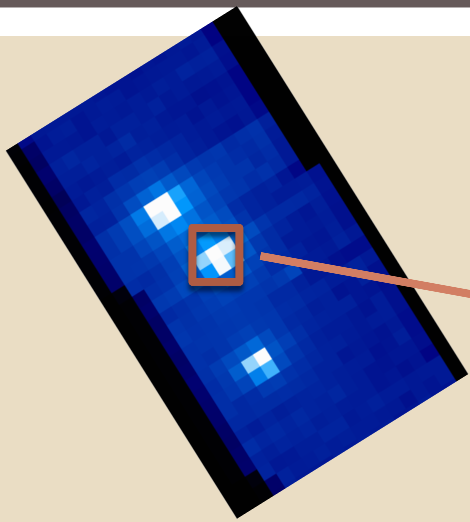
HST NICMOS, CASTLES

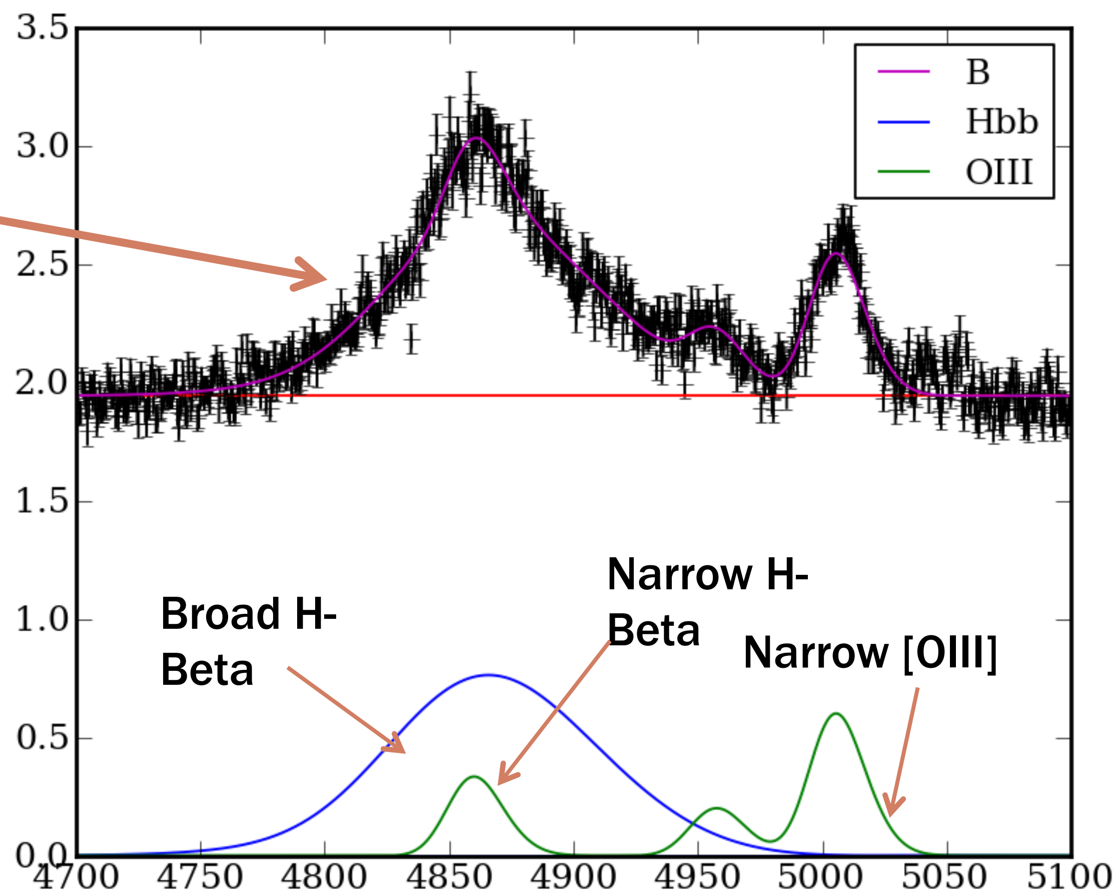
B1422+231



OSIRIS Hbb,
Nierenberg et al. 2014

EXTRACT AND MODEL LINE FLUXES IN EACH IMAGE

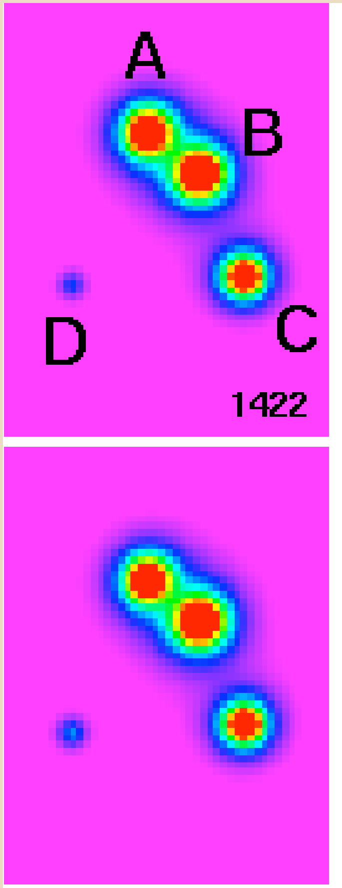


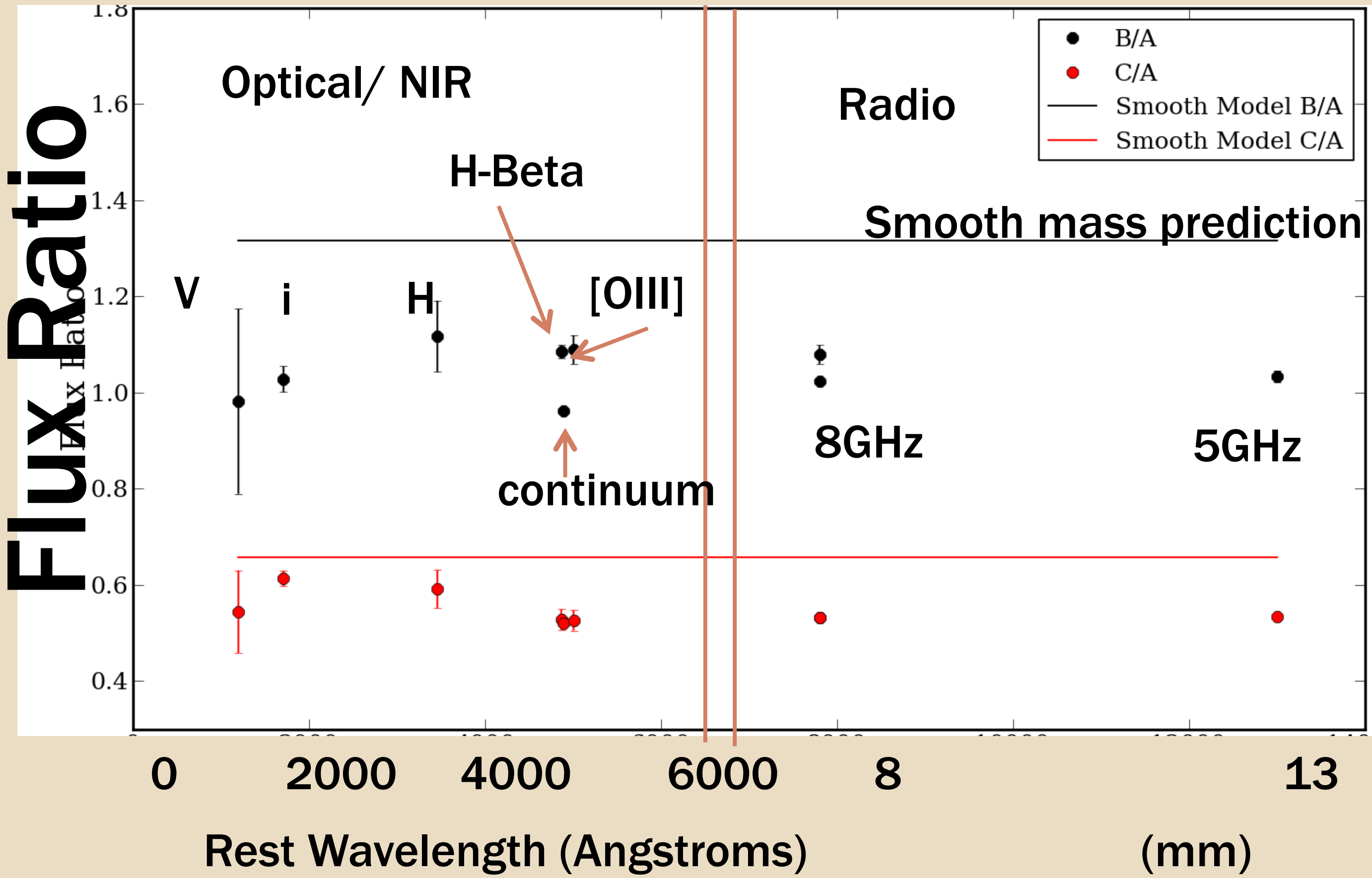


Nierenberg et al. 2014

FLUX MEASUREMENT RESULT FOR 1422

Observed continuum

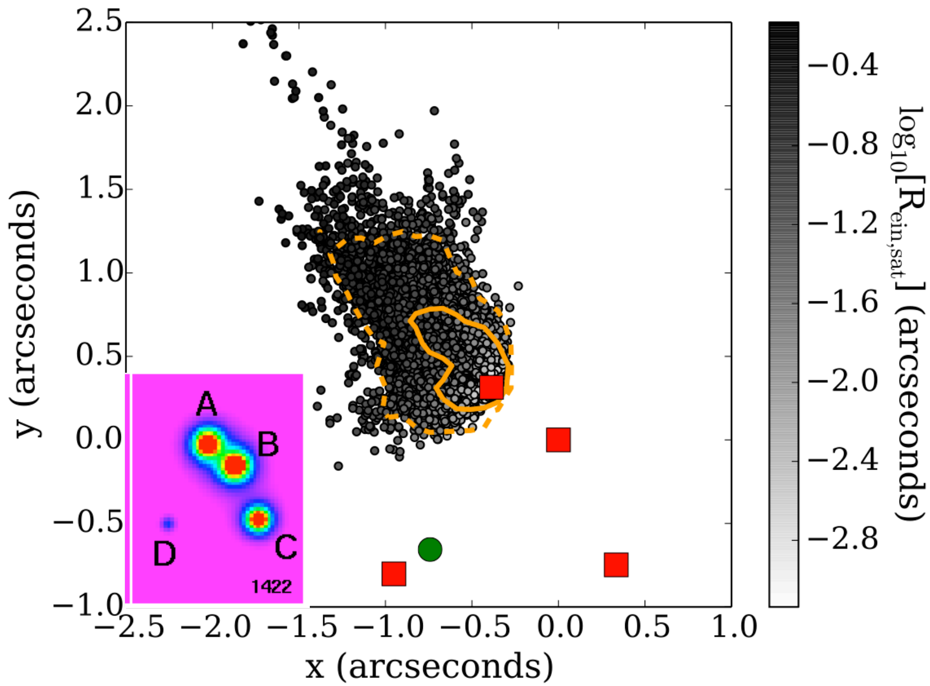




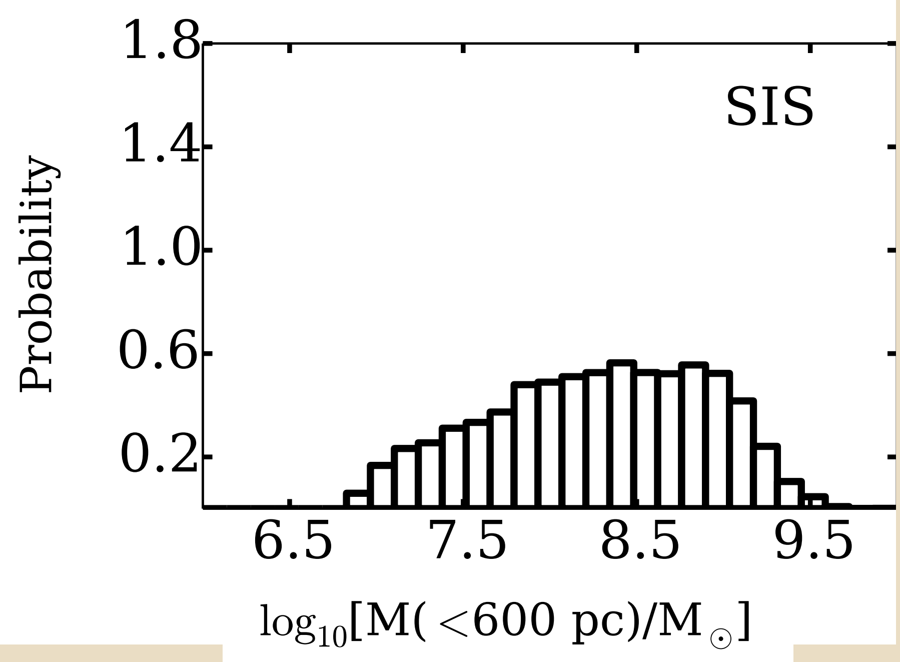
Smooth lens prediction

ASSUMING A SINGLE PERTURBING SUBHALO

MCMC accepted positions and masses



Posterior mass distribution

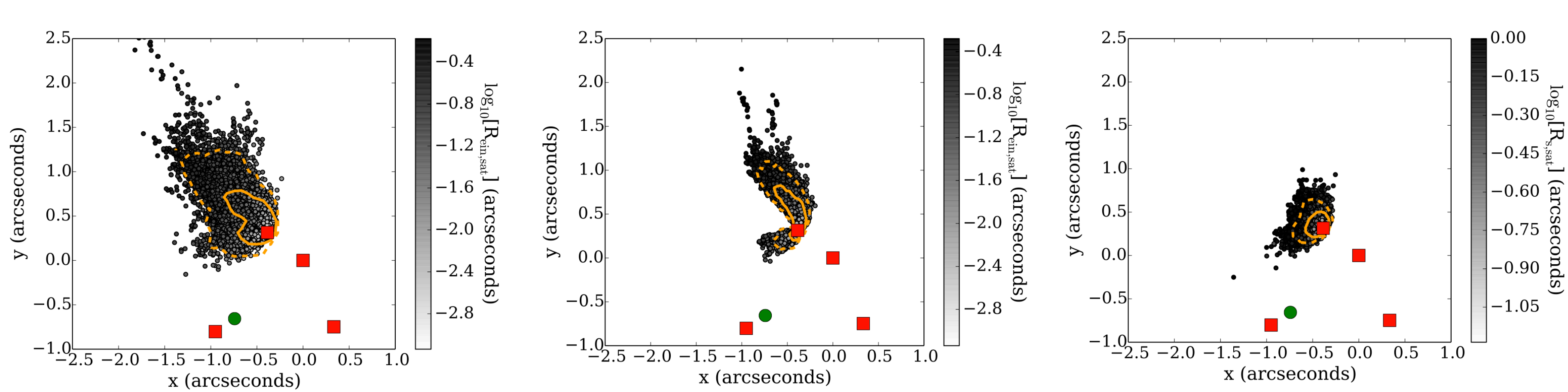


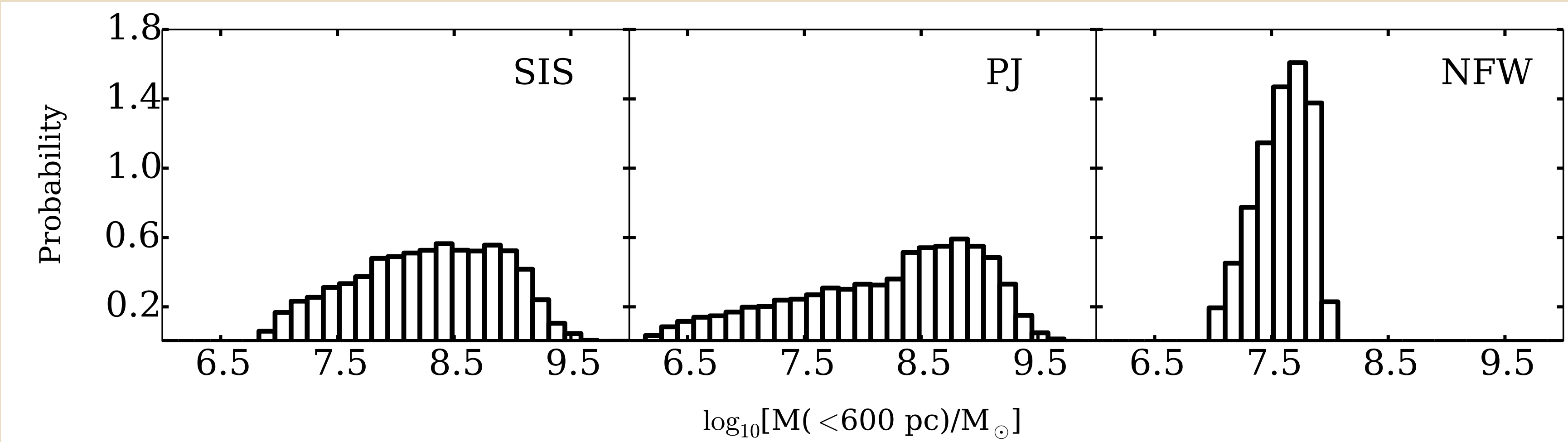
Nierenberg et al. 2014

SIS~r^-2

SIS~r^-2, with truncation

NFW

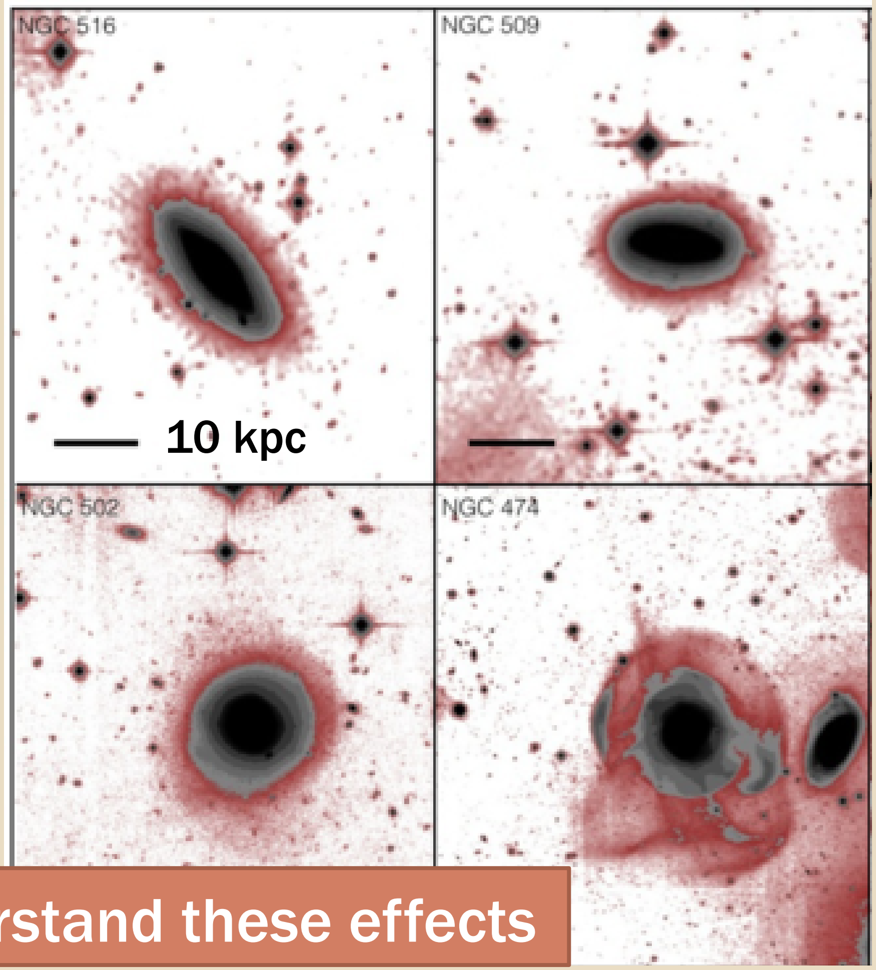




The inferred perturber masses and positions depends on the halo profile -> with more systems, we will be able to learn about both the subhalo mass function and the subhalo profile

HOW TO IMPROVE THE ANALYSIS

- Consider real distributions of realistic subhalos with 3D spatial distributions (Kim, Nierenberg, Peter et al….in prep)
- Include effects of line of sight structure
- ‘Structure’ vs. subhalo?



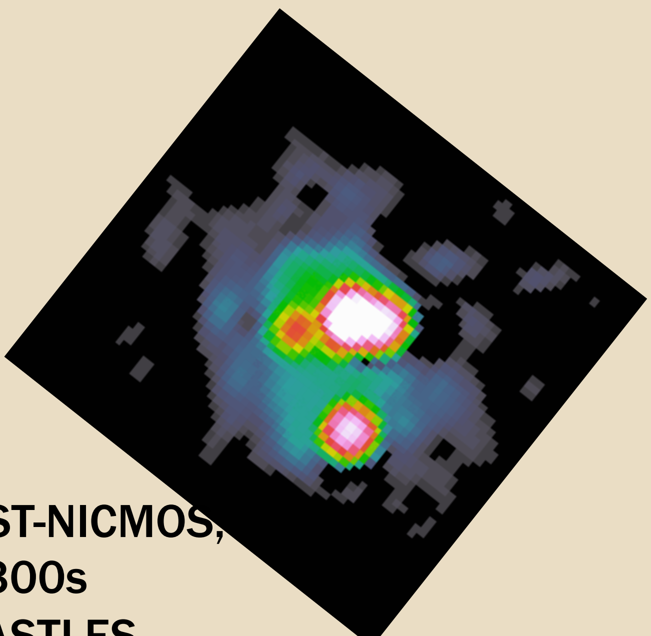
Need many systems to understand these effects

Duc, P.A. et al. 2014

FUTURE PROSPECTS WITH OSIRIS

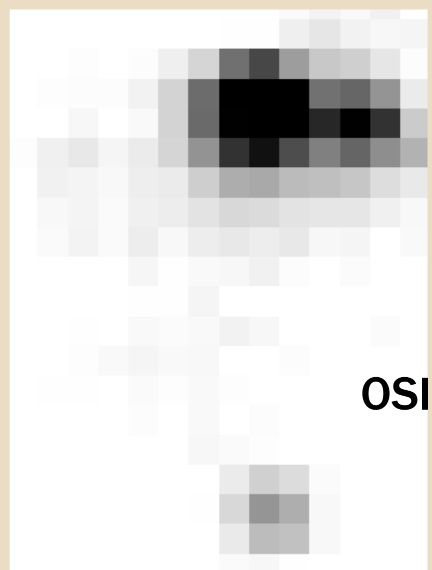
- Three more systems with data from OSIRIS, analysis underway (an additional three to be collected)

- Improved Tip-Tilt sensor grating, and detector will allow for measurement of additional narrow-lines

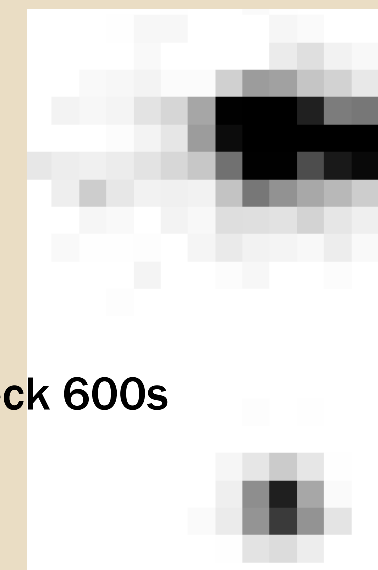


HST-NICMOS, 5300s CASTLES

Old tip-tilt sensor



New tip-tilt sensor



OSIRIS, Keck 600s

METHOD II: HST GRISM

HST GO-13732, Five more systems with HST!

Gravitational lens WFI 2033

H-Beta, [OIII]

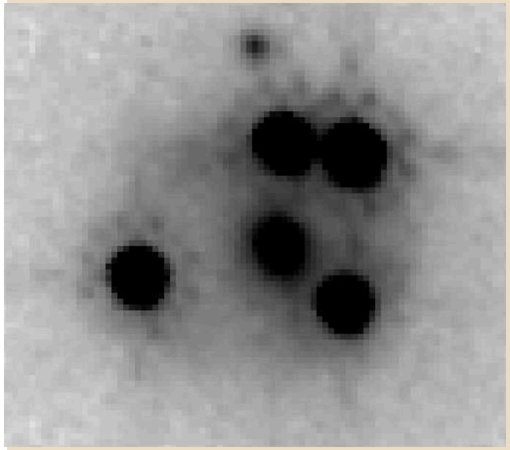
Pros:

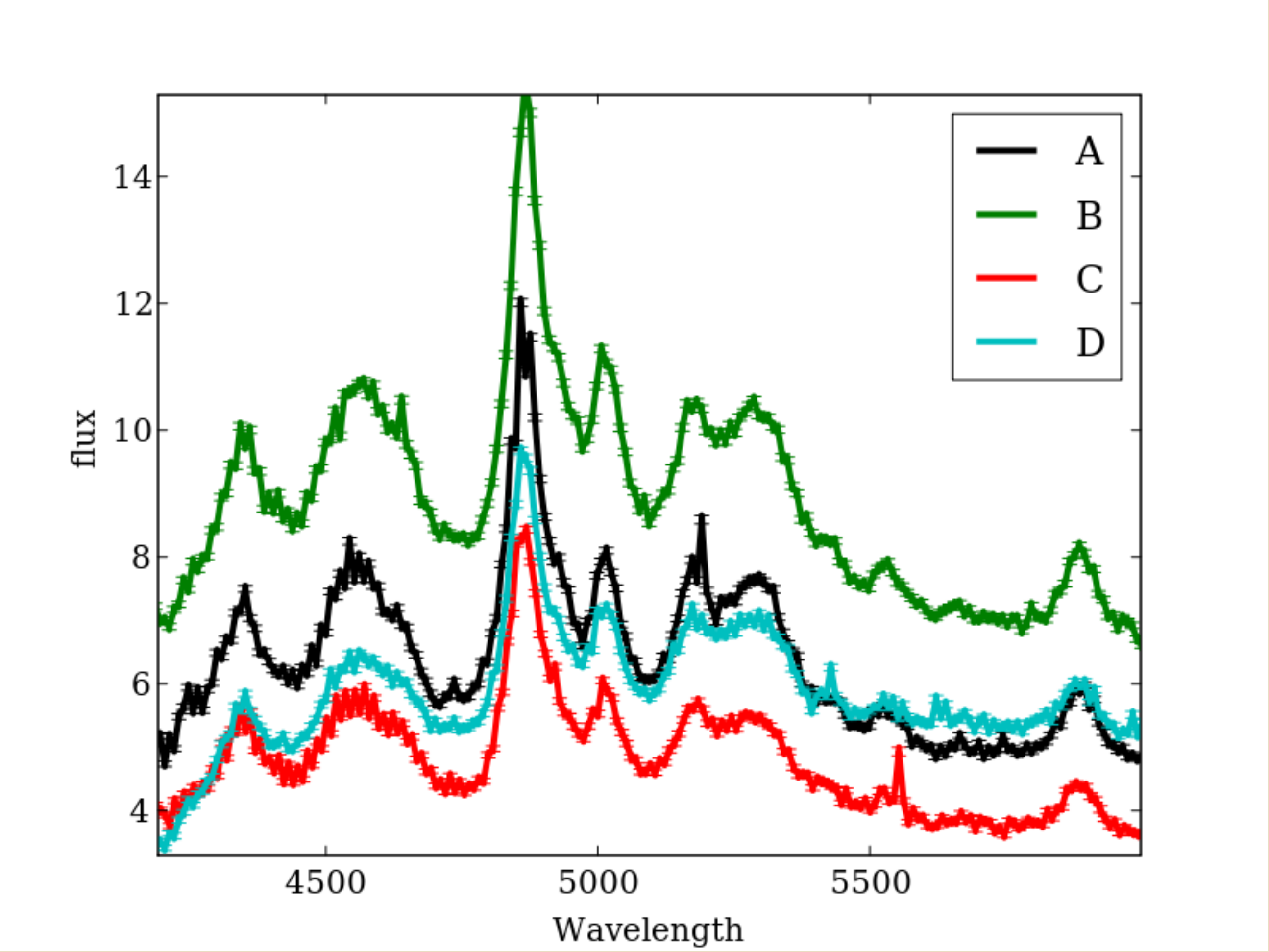
- More declinations available
- High spatial resolution
- No atmosphere!!
- 1-2 orbits only per object

Cons:

- Grism data

PRELIMINARY SPECTRAL EXTRACTION FOR WFI 2033





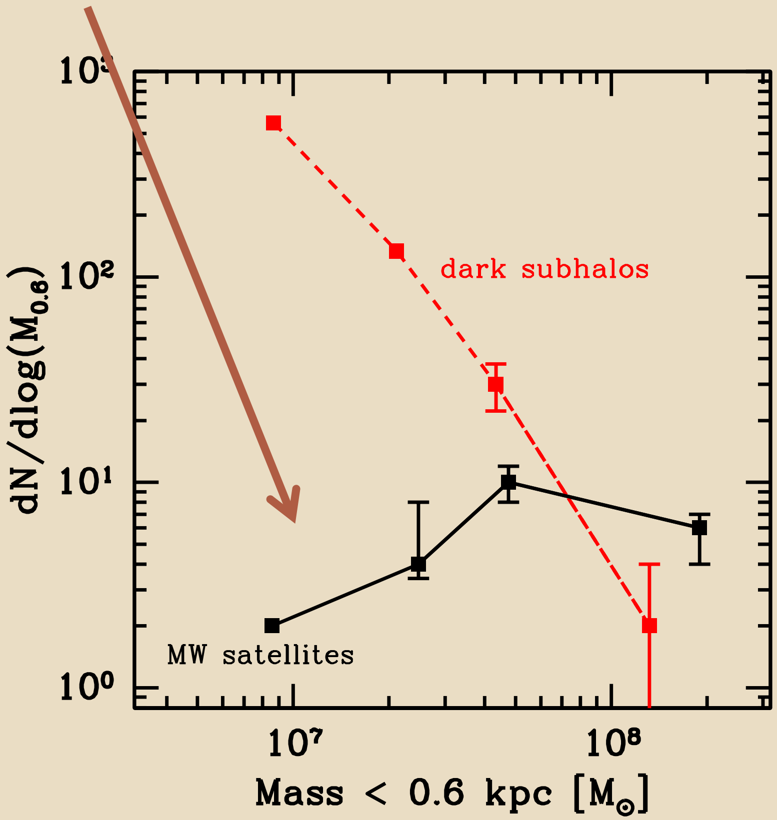
N++ in prep

FINAL SAMPLE OF 17 SYSTEMS

Lens	KECK	HST GRISM	Radio/mid IR (D+K)
0134	✔		
0414			✔
0435		✔	
0712			✔
0810	✔		
0911		✔	
0924	✔		
1115			✔
1138	✔		
1330	✔	✔	
1413	✔		
1422	✔		✔
1608			✔
1933			✔
2026		✔	
2033		✔	
2045	✔		✔

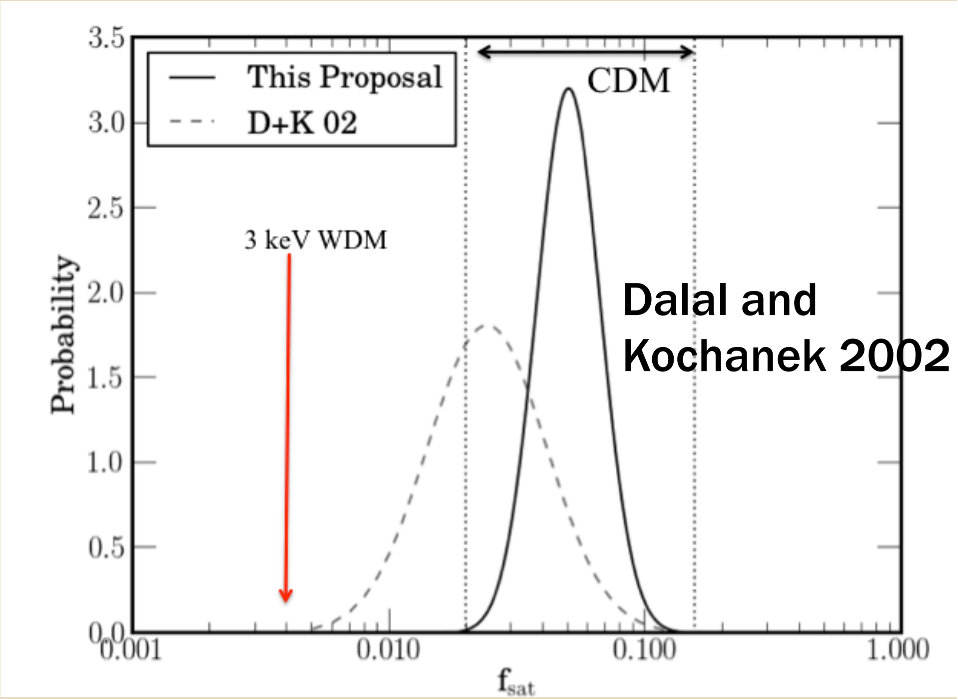
MORE THAN DOUBLE THE PREVIOUS SAMPLE

We are sensitive to these masses!



Strigari et al. 2008.

Tentative constraint forecast



Dalal and Kochanek 2002

EVEN MORE SYSTEMS!

- Combine these results with gravitational lensing results from lensed background galaxies (Vegetti, Hezaveh…)

- Extend analysis to hundreds of quad quasar lenses to be discovered in DES, PAN-STARRS and LSST!

CONCLUSIONS (THANKS FOR LISTENING!)

- OSIRIS + Adaptive optics give sufficient spatial and spectral resolution to study narrow line flux ratios in quasar lenses
- Results from 1422 show that this method can be used to detect 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.