Relating Cluster Galaxies to Cosmological Structure Formation

James Taylor, Jonathan Grossauer, Nicole Drakos
(University of Waterloo)

Jihye Shin (KIAS), Eric Peng (Peking U.)

Pat Cote, Laura Ferrarese, Joel Roediger (NRC)
and the NGVS collaboration

The 7th KIAS Workshop on Cosmology and Structure Formation – Nov 1 2016

Outline:

Part I: Matching Galaxies in the Virgo Cluster to Simulated Subhalos

Jonathan Grossauer + NGVS

(Grossauer et al. 2015)

Jonathan Grossauer

(Most of) the NGVS Collaboration

Part II: Physics of Subhalo Evolution

Nicole Drakos (tidal stripping)

(Drakos, Taylor & Benson in prep.)

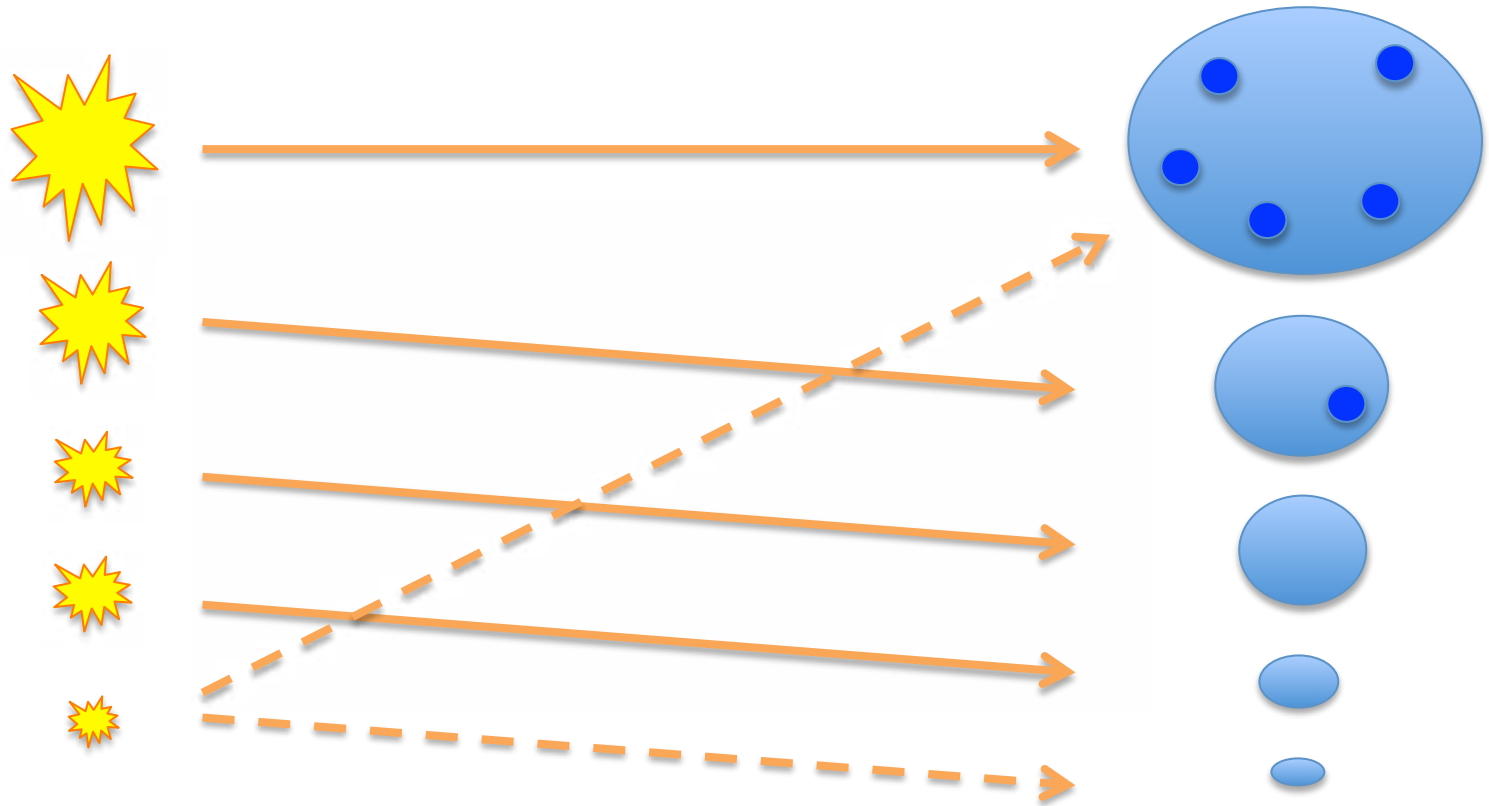
Jihye Shin (hierarchical merging) – see next talk

(Shin, Taylor & Peng in prep.)

Jihye Shin
(KIAS)

Relating Galaxies to Structure : Abundance Matching

Basic Idea: biggest galaxies live in biggest halos

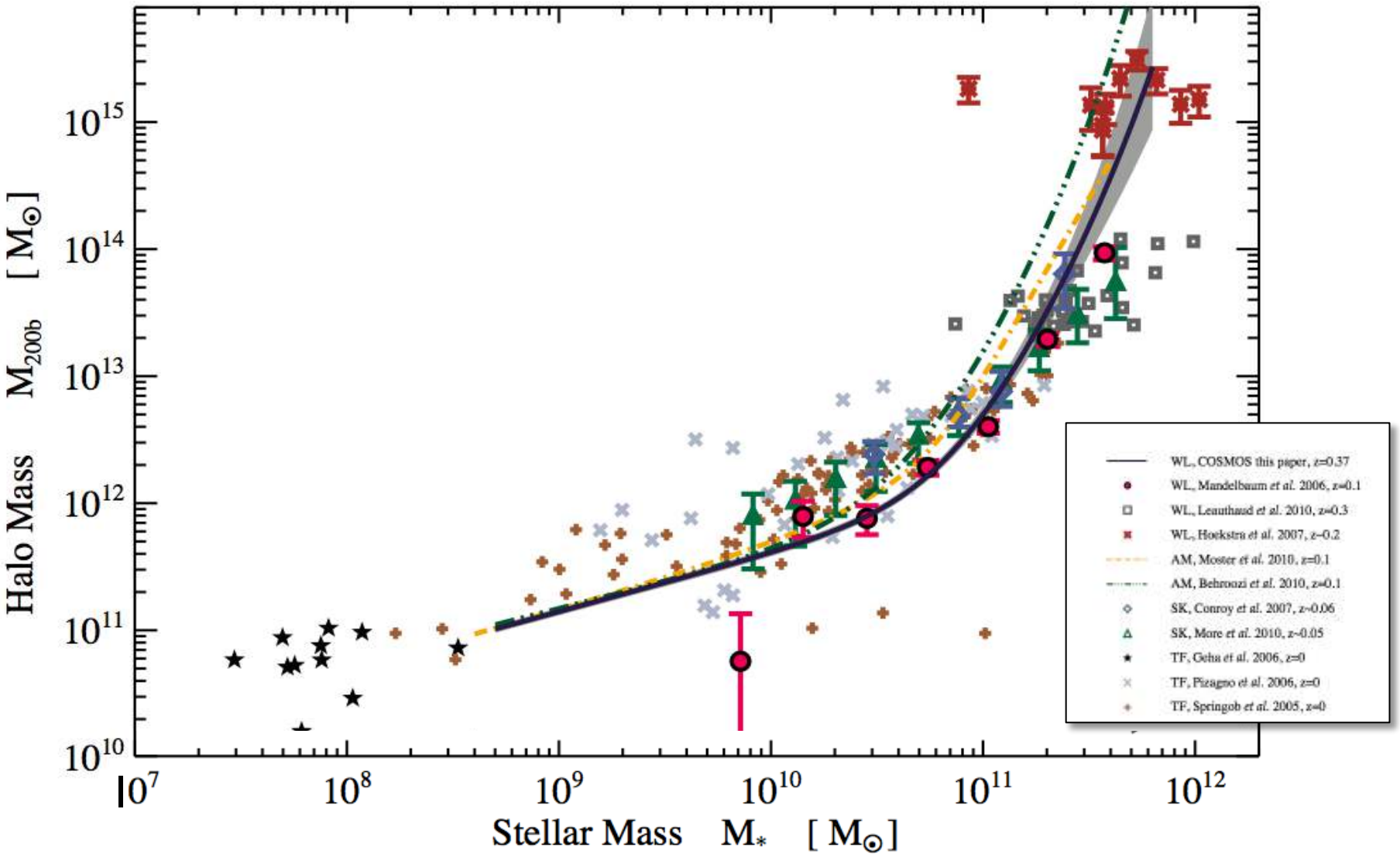


Galaxies from Observation

Halos from Simulation

Match the two to predict the Stellar-to-Halo-Mass Ratio (SHMR)

What we can Observe: The Halo-to-Stellar-Mass-Relation (HSMR)



Leauthaud et al. 2012: HSMR from galaxy-galaxy lensing + clustering in COSMOS (solid curves, including uncertainties) versus HSMRs from other techniques (points)

Approaches to deriving the HSMR/SHMR:

Broadly speaking, two methods:

* more-or-less direct, total mass estimates for individual objects or stacks of objects (from lensing, satellite kinematics, etc.)

* abundance matching, assuming the brightest/greatest stellar mass objects correspond to the most massive halos

Most methods give the HSMR for the one "central" galaxy in each halo.
Unfortunately, many interesting galaxies are "satellites", not "centrals"

So can we determine the HSMR for a satellite population, e.g. cluster members?

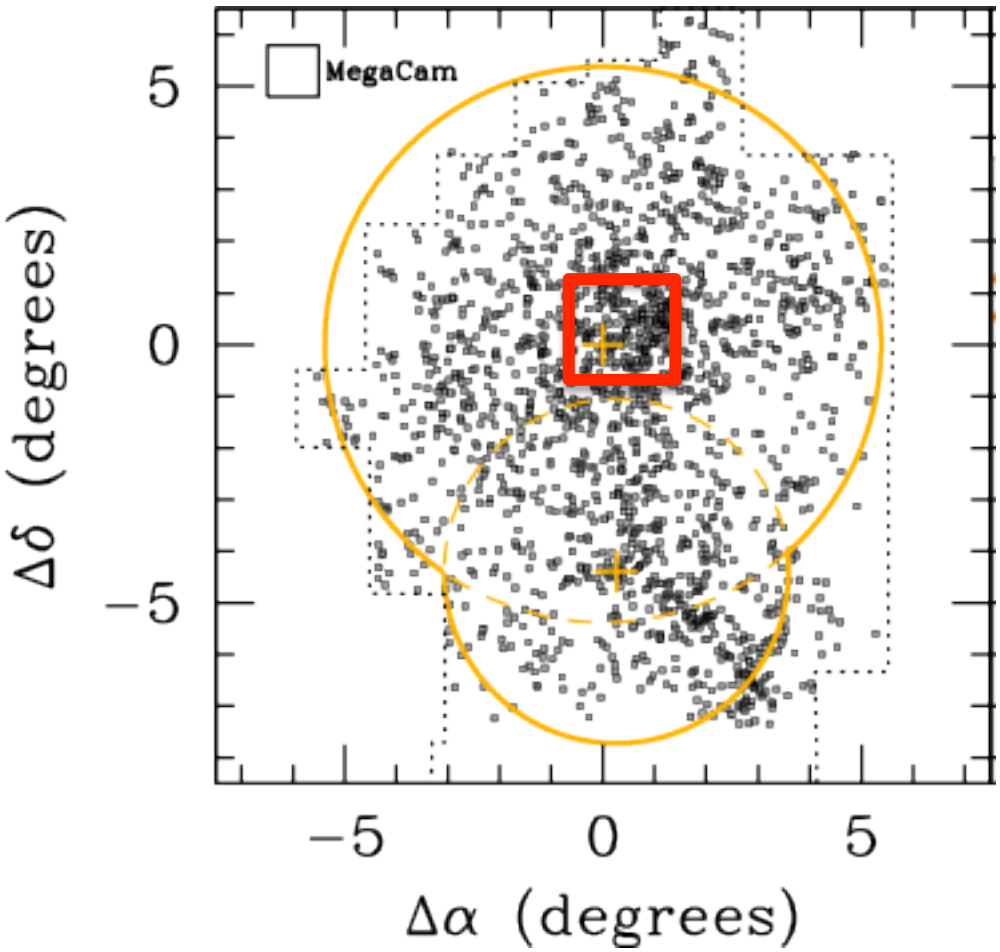
Want to compare observed cluster galaxy population to simulated subhalo population.

Observations: The Next Generation Virgo Survey (NGVS)

(Ferrarese et al. 2012)

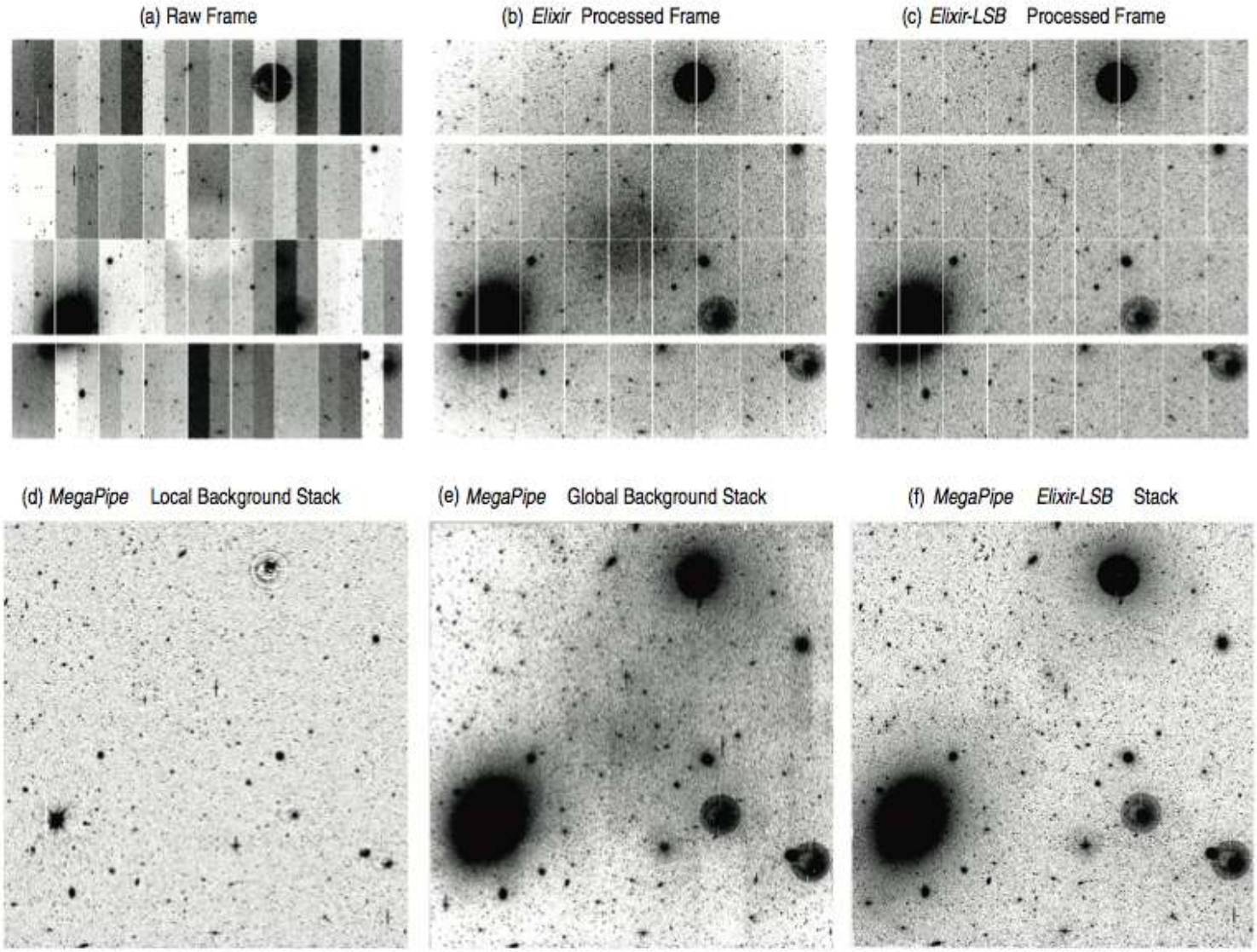
CFHT MegaCam survey of Virgo in 5 bands, + UV, NIR, spectra, etc.

- NGVS provides a complete sample of galaxies to very small stellar masses.
- It provides one of the only complete samples of old galaxies to small masses.
- Virgo is close enough to observe galaxies in detail



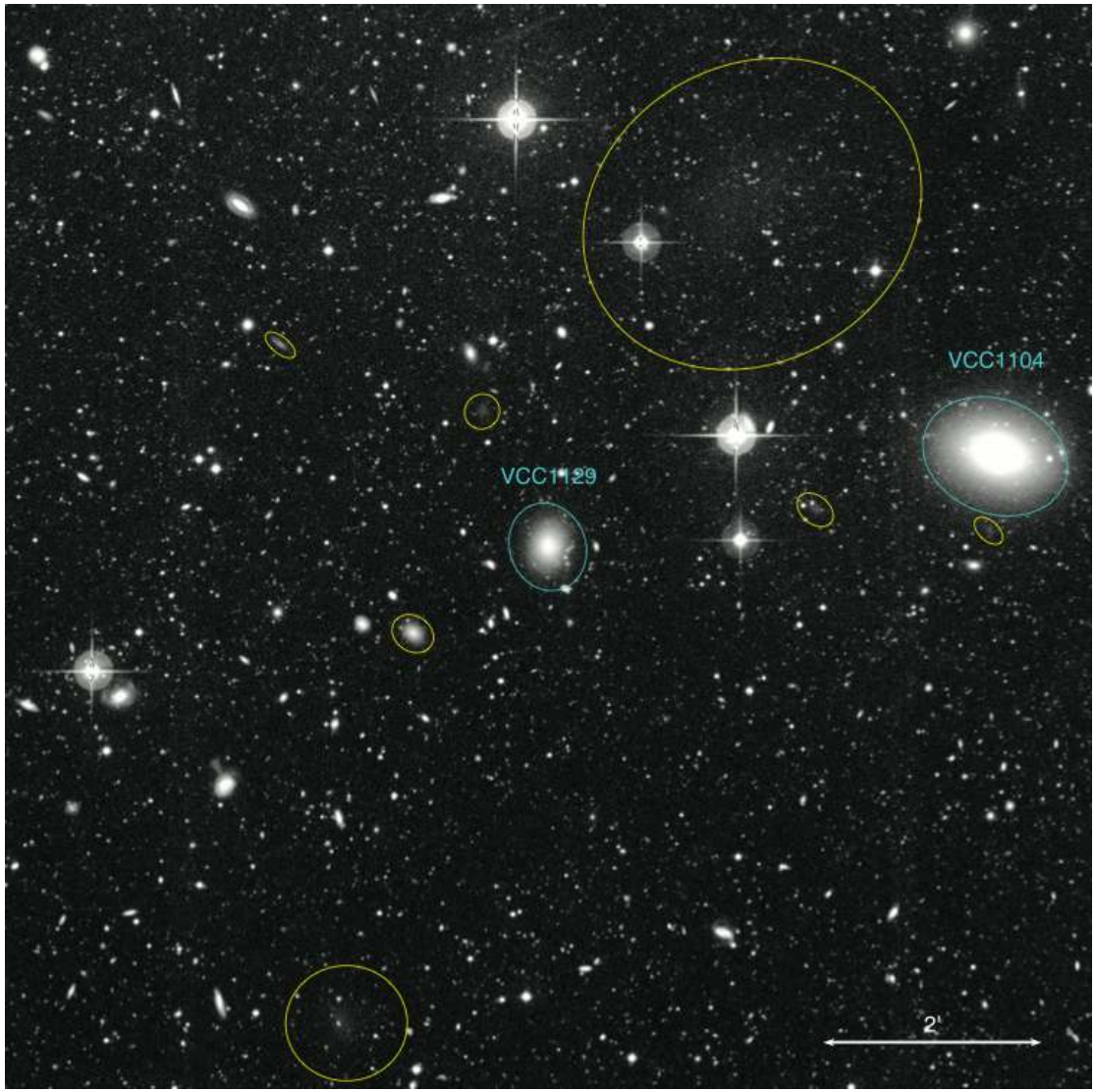
Start with an initial `Pilot' region (central 4 sq. deg.)

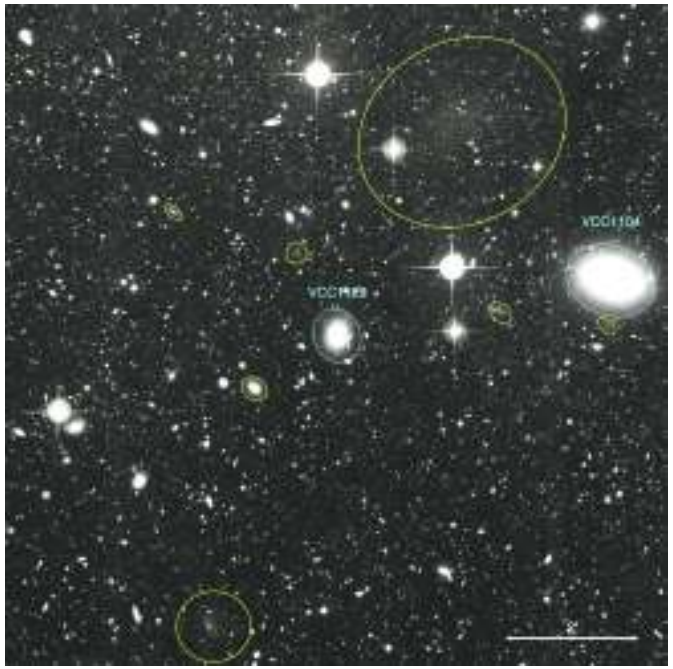
The Next Generation Virgo Survey (NGVS): Scattered Light Corrections



Ferrarese et al. 2012

The Next Generation Virgo Survey (NGVS): The Low Surface Brightness Regime



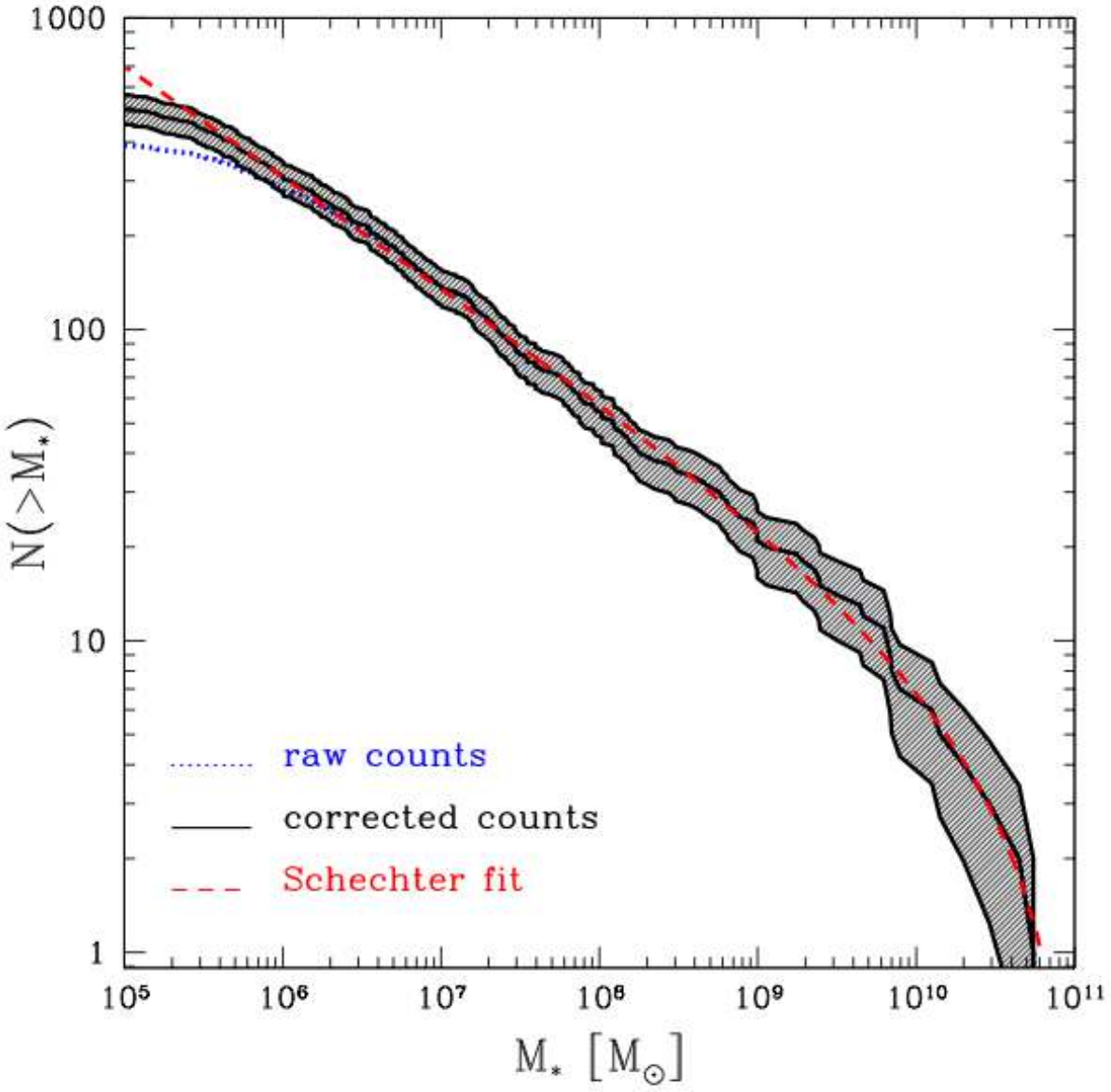


Ferrarese et al. 2012

Observations: Stellar Mass Function for the Pilot Region

For the Pilot region (1/25th of survey), the derived stellar mass function is well fit by a single Schechter function with:

$M^* = 10^{12}\ M_\odot$,
$\Phi^* = 0.87 \pm 0.09$, and
$\alpha = -1.365 \pm 0.01$

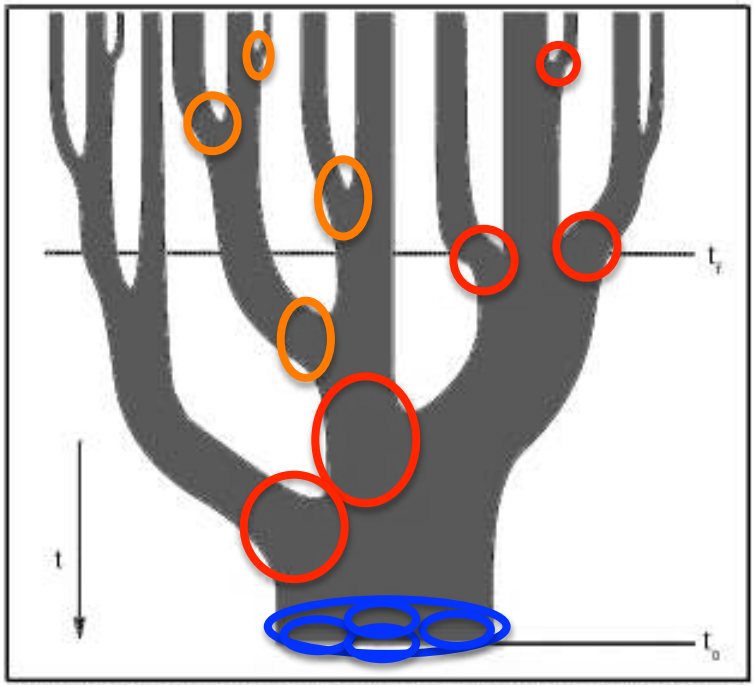


Simulations: Substructure Abundance Matching

Can we use an abundance matching approach to match simulated structures to cluster galaxies?

Clearly, matching to a single final halo gives only the HSMR/SHMR for the one central galaxy

So match to all subhalos or subhalo progenitors? How to define these from the merger sequence?



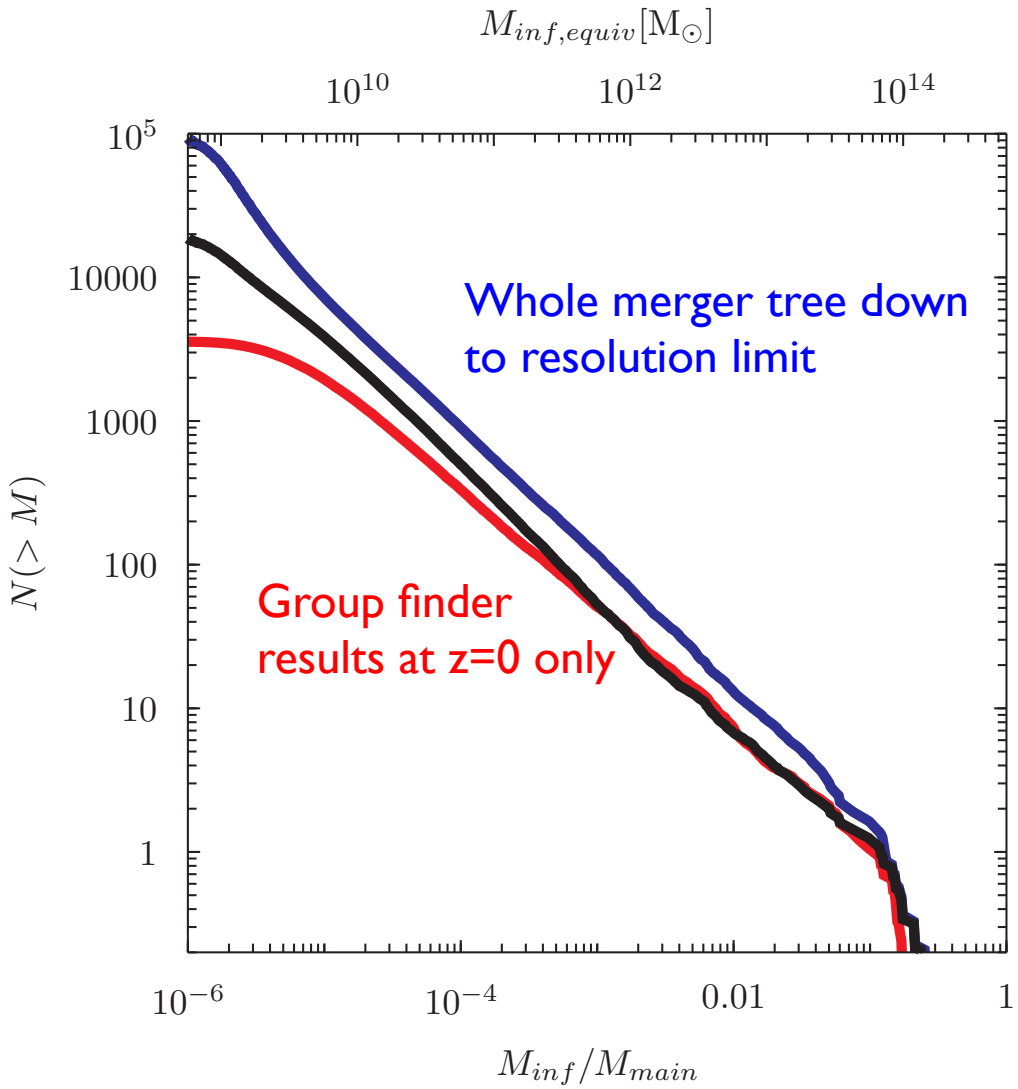
Lacey & Cole 1993

Theory/Simulations: The Subhalo Mass Function

Grossauer et al. 2015:
10 simulations of Virgo-like clusters, each scaled to a fiducial mass & projected 3 ways.

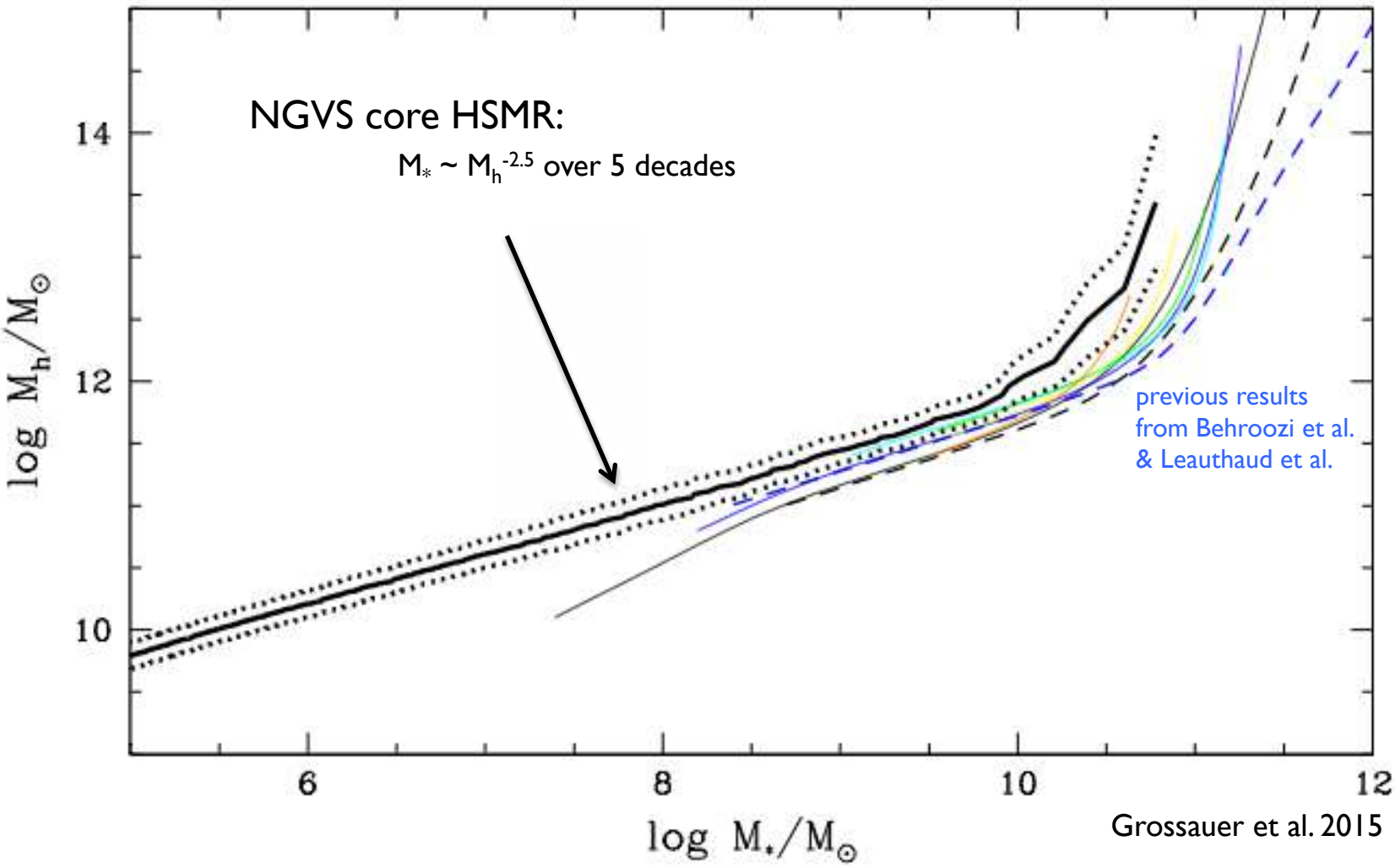
Several ways of identifying substructure in simulated clusters:

cf. Jihye Shin's talk



(Adopting intermediate subhalo model) Results:

The halo-to-stellar-mass ratio (HSMR) measured over 6 decades in M_*



Grossauer et al. 2015

* Initial estimate of the HSMR using the pilot region only
* overall, sensible result; but <u>efficiency 2-3x lower at high-masses, relative to field</u>

Uncertainties and Next Steps

Current Uncertainties:

– (obs.) shot noise/stellar mass function uncertainties (a)

– (obs.) total mass of Virgo (b – red curve)

– (theor.) pruning algorithm (b – black curves)

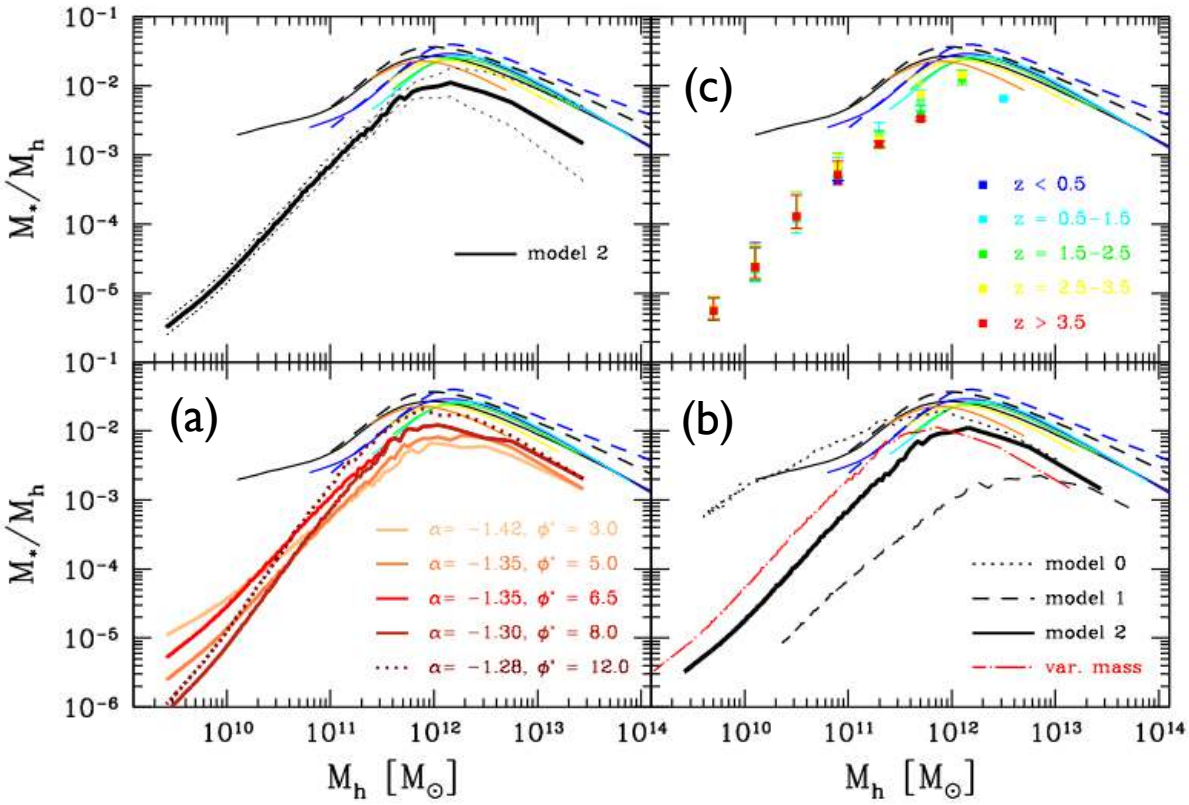
– (both) redshift dependence (c)

Next Steps:

– **theoretical** work on pruning (cf. J. Shin)

– **observational** results for the whole cluster

Grossauer et al. 2015



Abundance Matching in Virgo: Summary

So what else can we get out of this?

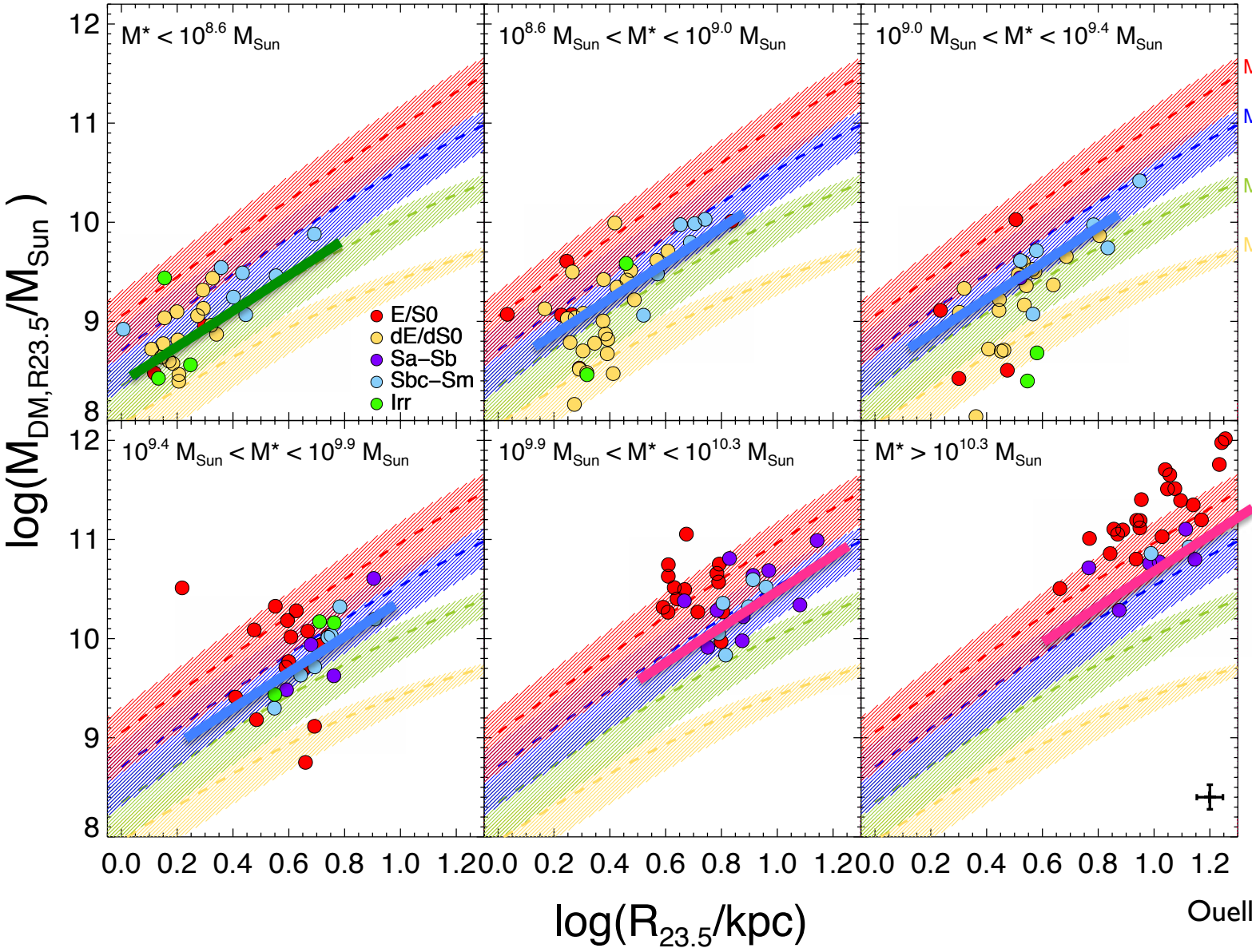
* The derived SHMR should give halo mass estimates for all Virgo members based on their stellar masses, valid in an average sense

⇔ can compare to, e.g. galaxy dynamics (cf. SHIVir results)

* More generally, matching to substructure gives an indication of the infall redshift, based on the current phase-space position

* Should also be able to make statistical statements about tidal stripping

Results from the "Spectroscopic and H-band Imaging of the Virgo cluster" (SHIVir) survey (Ouellette et al. 2016) – dynamics for 190 Virgo Galaxies

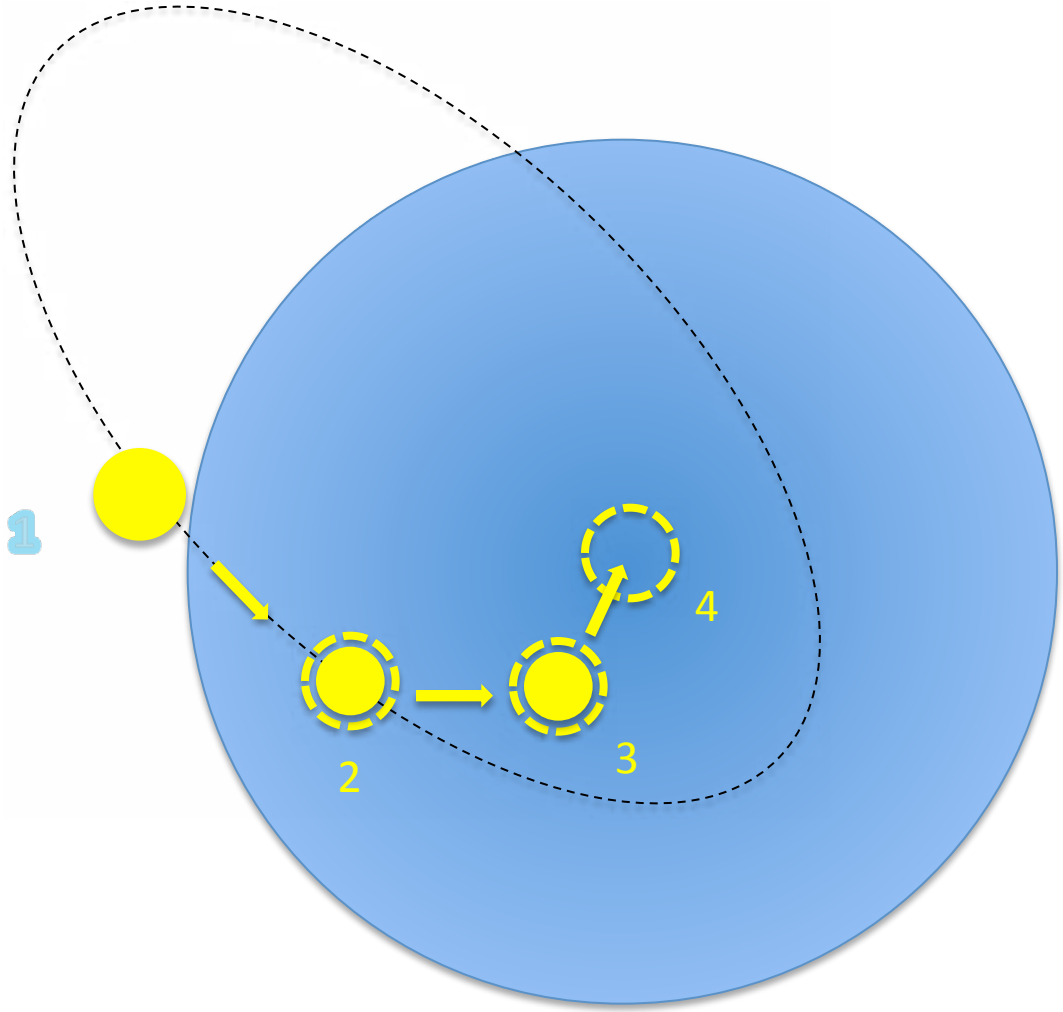


Thick lines: prediction from G15 HSMR

Ouellette et al. 2016

Part II: The Physics of Subhalo Evolution

(cf. Drakos, Taylor & Benson submitted)



Stages of Evolution

1: Infall

2: Tidal Stripping

3: Dynamical Friction

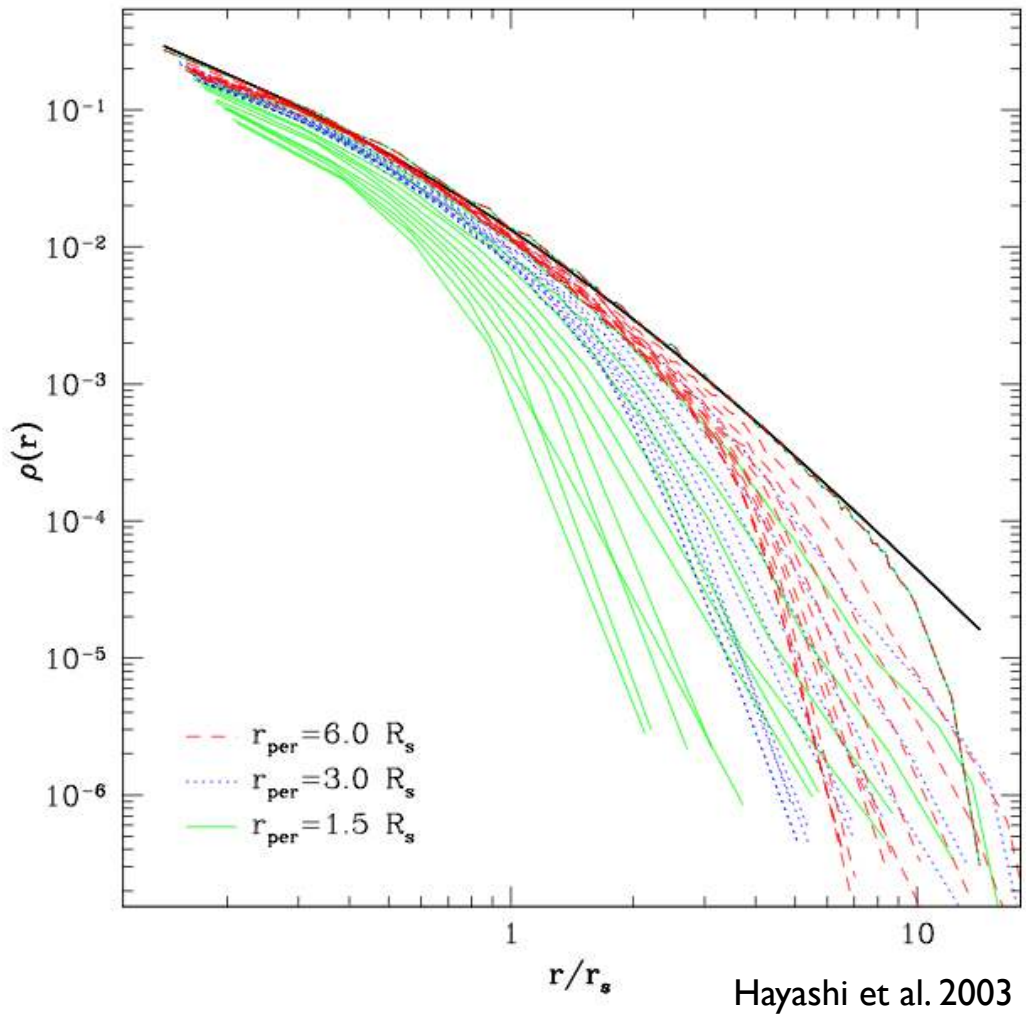
4: Disruption

Effect of Tidal Stripping on the Density Profile

An unexplained result from 13 years ago: the density profile of tidally stripped subhalos (Hayashi et al. 2003)

$$\rho(r) = \frac{f_t}{1 + (r/r_{te})^3} \rho_{\rm NFW}(r)$$

can we explain the origin of this form?



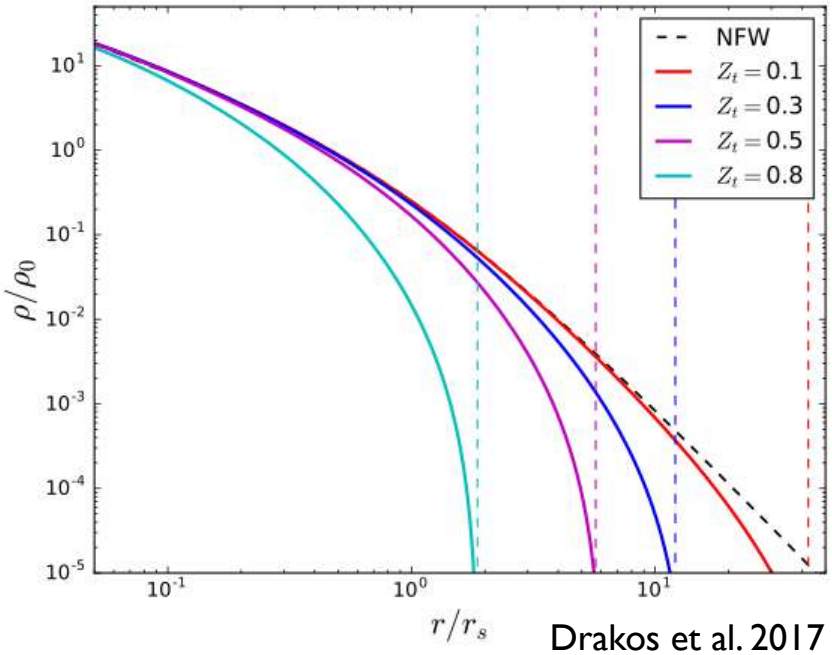
Hayashi et al. 2003

A separate problem: how to model isolated, NFW-like systems?

1) Empirical approach: remove all material outside some radius; then iteratively remove unbound particles until convergence

2) Alternately, a King-like approach: truncate f(E) at some E_t , then shift so $f(E_t) = 0$

➔ Results very similar

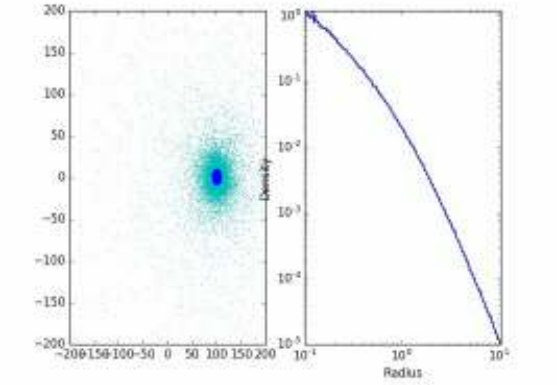


Drakos et al. 2017

Profiles in terms of $Z_t = E_t/\Phi_0$

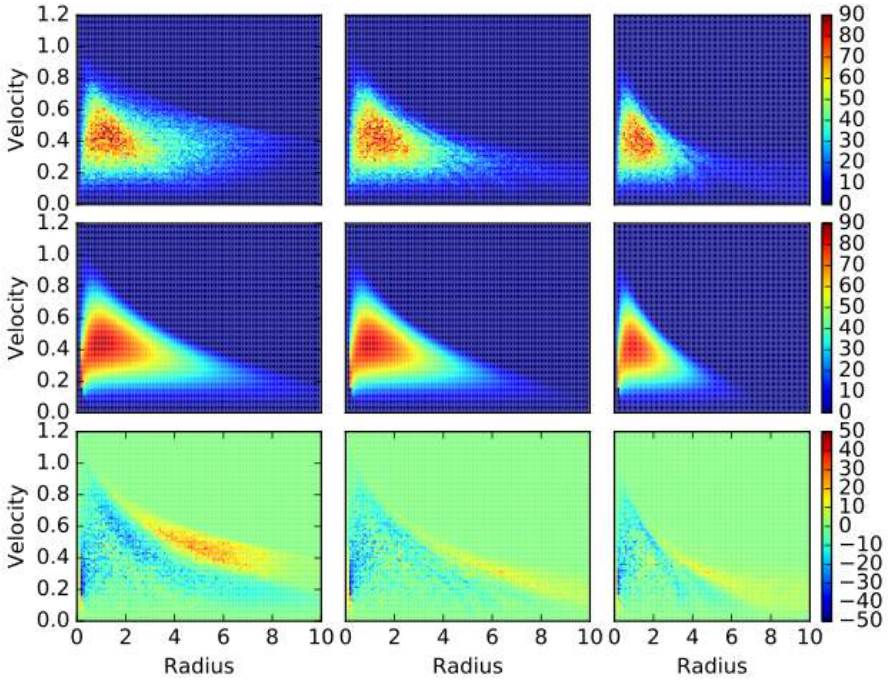
A good model for the phase-space of tidally stripped systems?

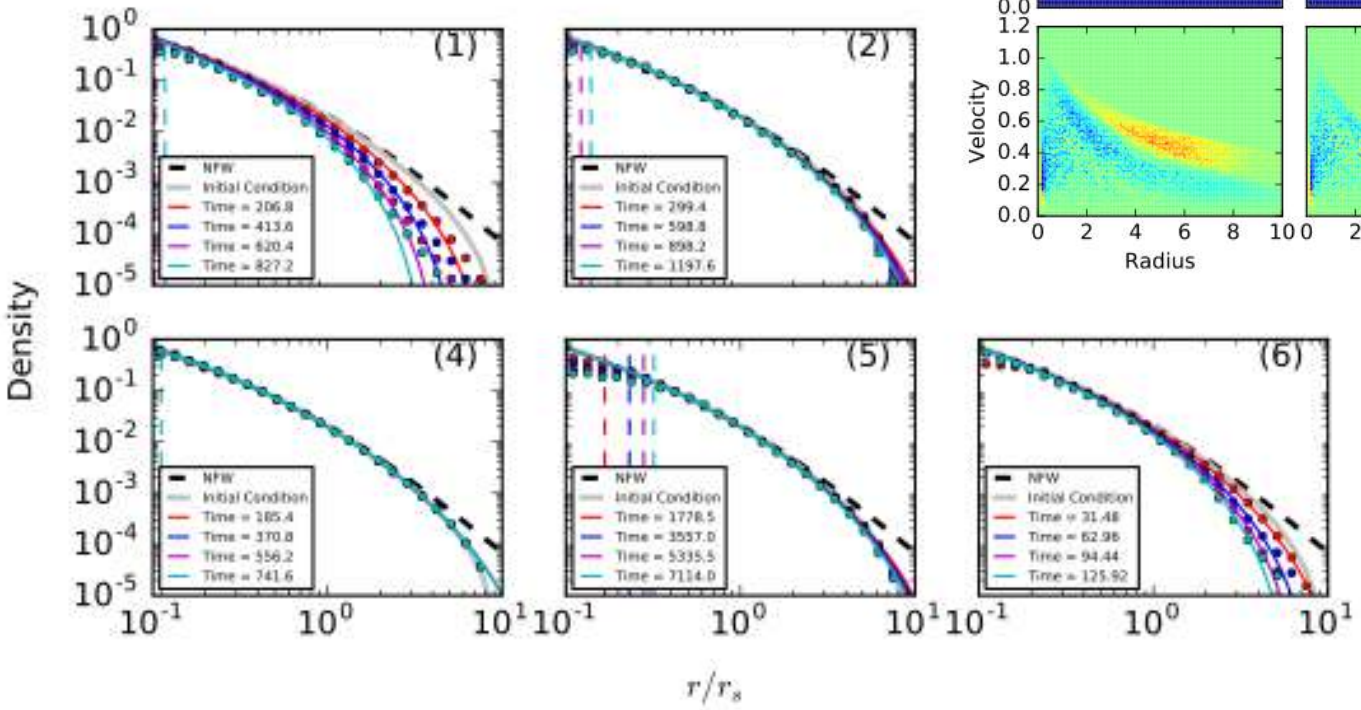
* Comparing to simulations of tidal stripping of subhalos on various orbits, get a very good match to density profile and phase-space distribution of stripped remnant



Density Profiles

Phase-space distributions



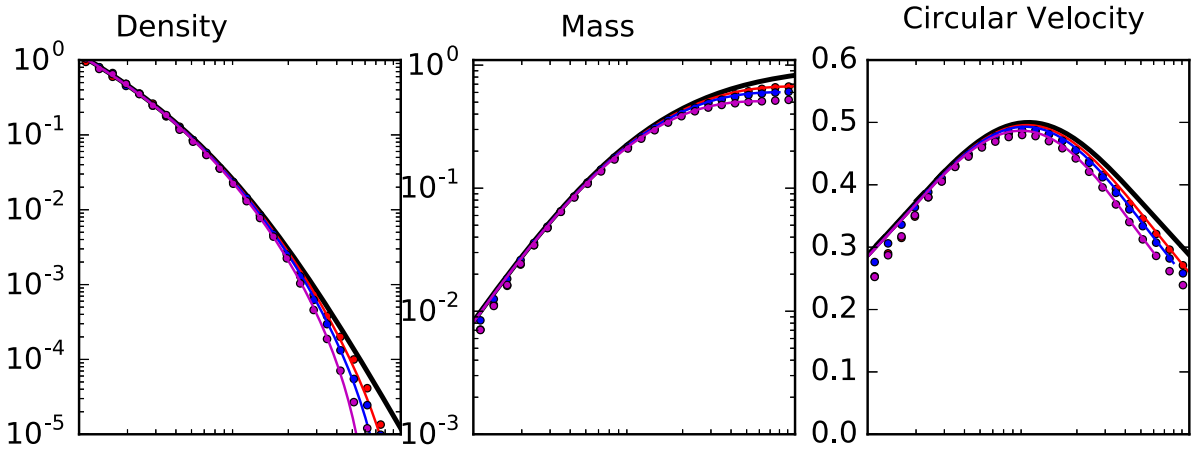


Drakos et al. 2017

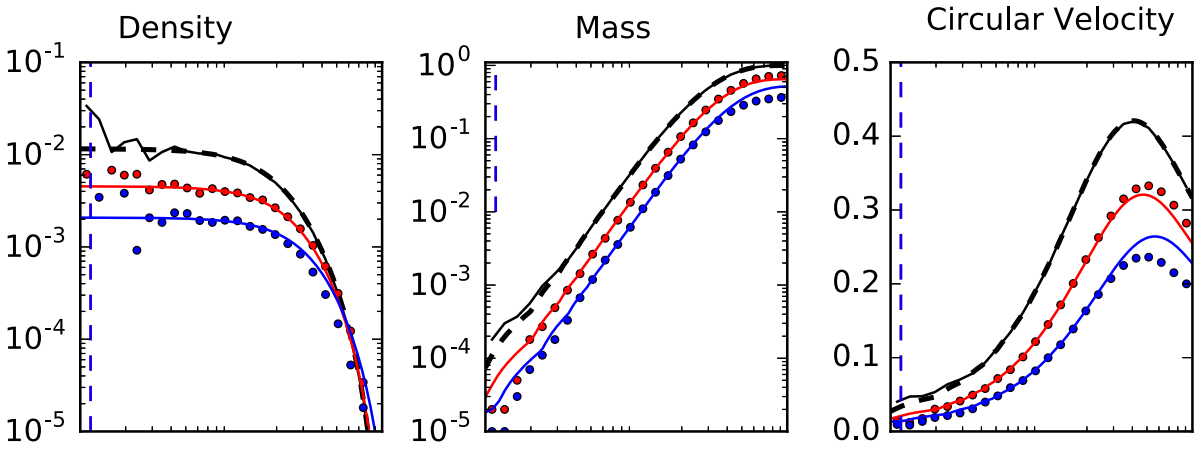
A good model for the phase-space of tidally stripped systems?

* Same approach seems to work for other DFs, e.g. Hernquist profile (+ King model)

Hernquist profile



King model



Drakos et al. in prep.

Summary

Part I: Abundance matching between cluster galaxies and subhalos

– simple power law trend in HSMR: $M_* \sim M_h^{-2.5}$
– slight offset from field values at large M_*? (N.B. should also treat ICL?)
– relative to Local Group, the "missing satellites" are not actually missing in Virgo
– halo mass estimates agree with average dynamical masses for indiv. galaxies

Part II: Towards a better model for tidal stripping

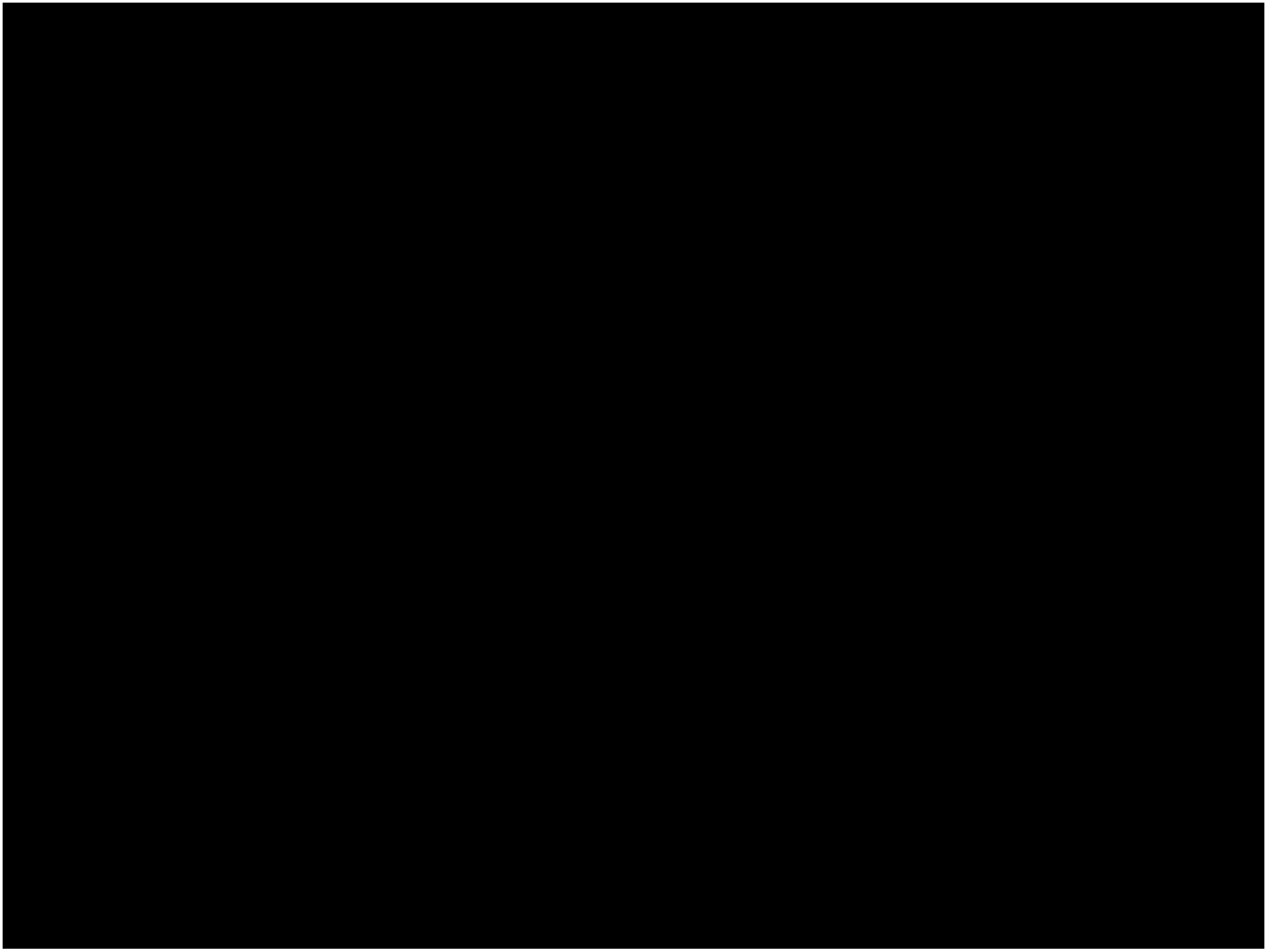
– a King-like truncation of the DF in binding energy can explain the `Hayashi' profile of tidally stripped subhaloes
– this approach seems to work ~ universally
– provides a rough model for the phase-space distribution in stripped systems

Up next:

– extend abundance matching to whole Virgo cluster
– combine these results to study the profiles of tidally stripped galactic systems in Virgo, e.g. the phase-space distribution of tracers such as GCs, PNe, etc.

감사합니다

Kamsahamnida!
Thanks to the Organizers!



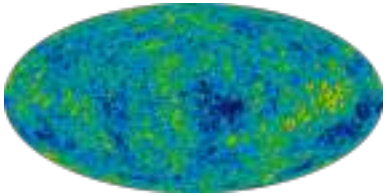
(Extra Slides)

Progress in Cosmology from Structure Formation

# Crossings	Fluctuation Regime
<<1	Linear

(CMB)

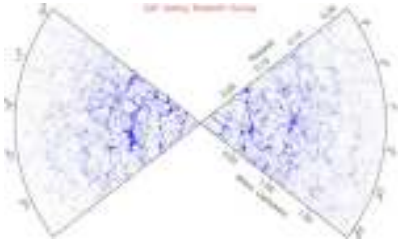
multiple, percent-level constraints on power spectrum P(k), equation of state H(z), growth factor D(z)



~1	Non-linear

(Weak lensing, cluster number counts, LSS)

potential precision constraints, but systematics?



>> 1	Strongly Non-linear

i.e. halo structure (density profile, shape, conc., spin), subhalo properties

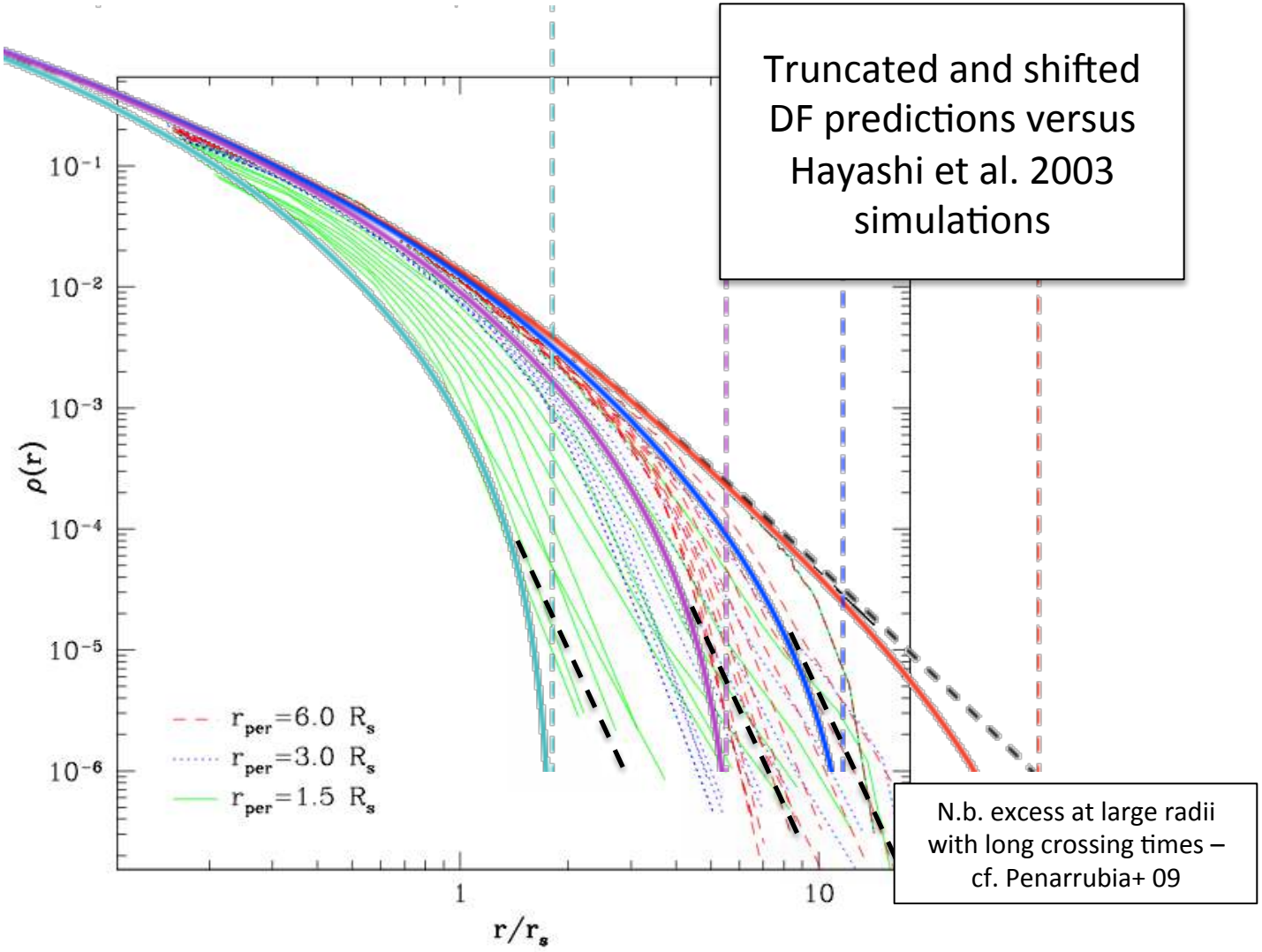
(weak + strong lensing? galaxy dynamics?)

precision tests still a distant prospect?

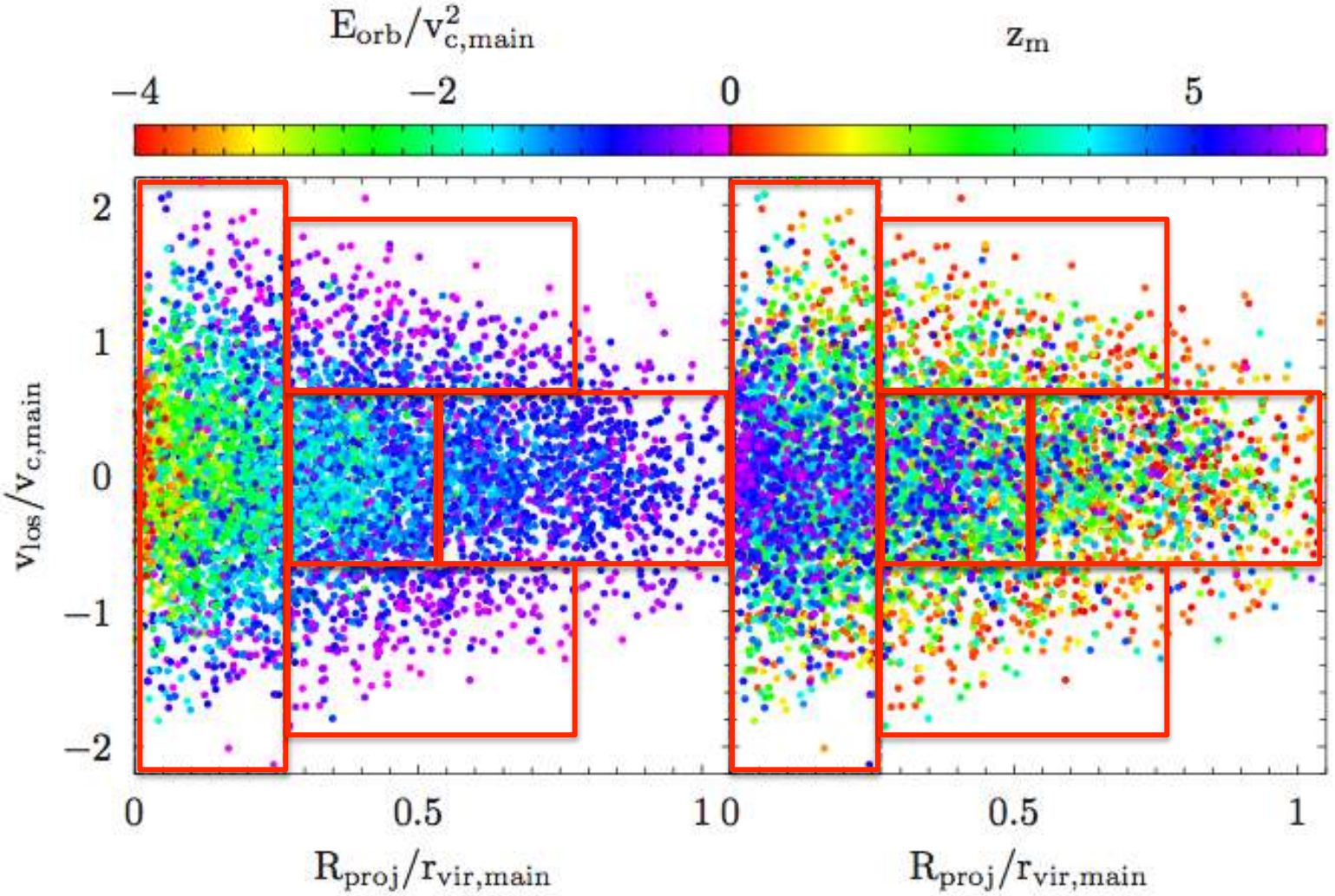
➔ Will need this eventually, to get power spectrum on small scales, test gravity in larger field regime

A good model for the phase-space of tidally stripped systems?

* Comparing to simulations, get a very good match to density profile and phase-space distribution of tidally stripped halos

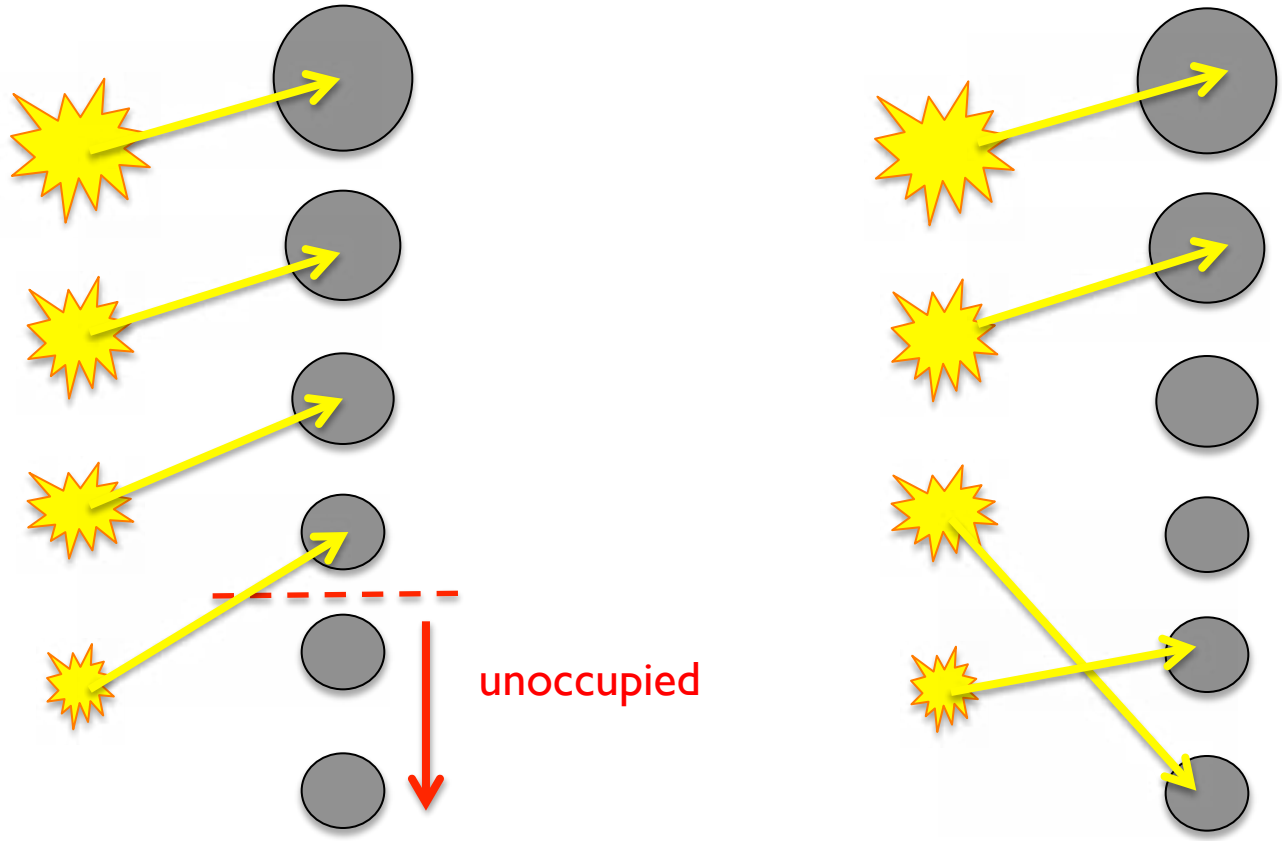


Next Step: using position and velocity information to test for redshift dependence



By selecting objects at different radii and velocity offsets, we can sample different ranges of z_m

N.B.: "Stochasticity"



deterministic/one-to-one

stochastic

But if halo mass doesn't control galaxy formation, what does?

Results from other surveys and simulations ...
a deterministic relationship, or a stochastic one?