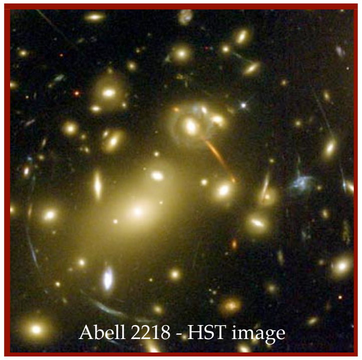
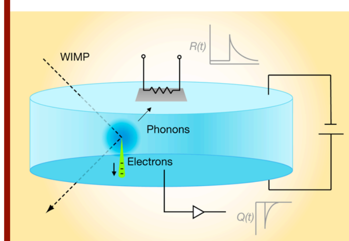
Dark Matter Insights

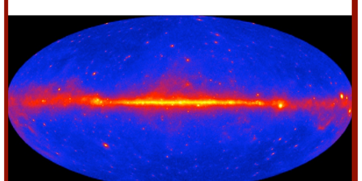
from Cosmological Simulations of Structure Formation

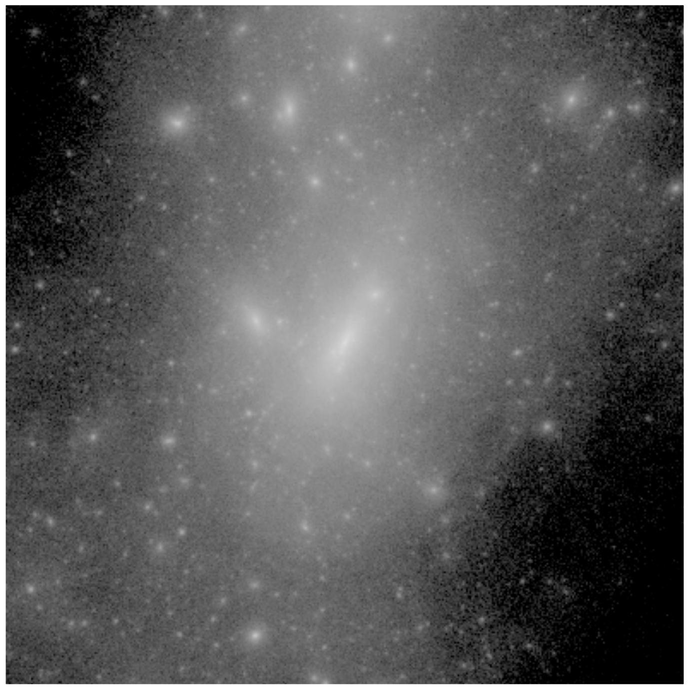
Risa Wechsler

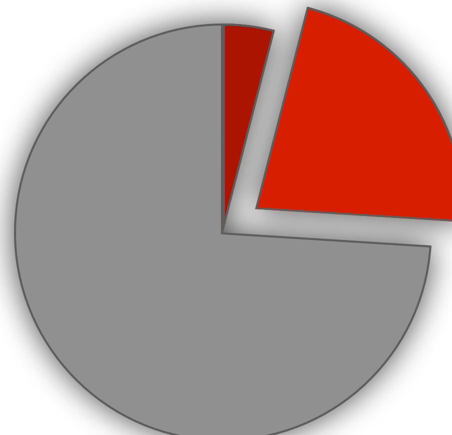

Abell 2218 - HST image



CDMS detector
Illustration: Alan Stonebraker

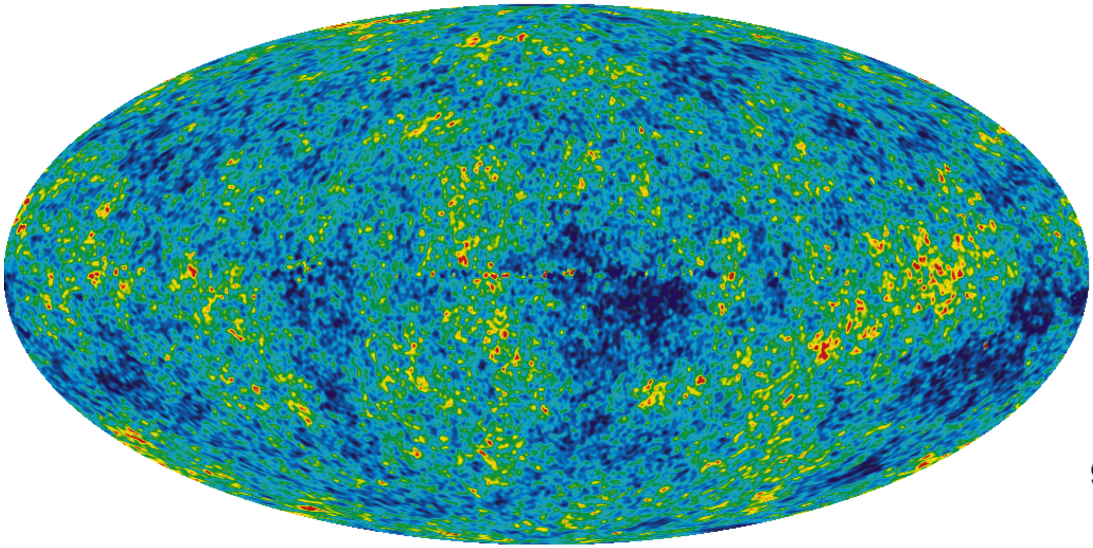

Fermi Space Telescope
Two-Year Data



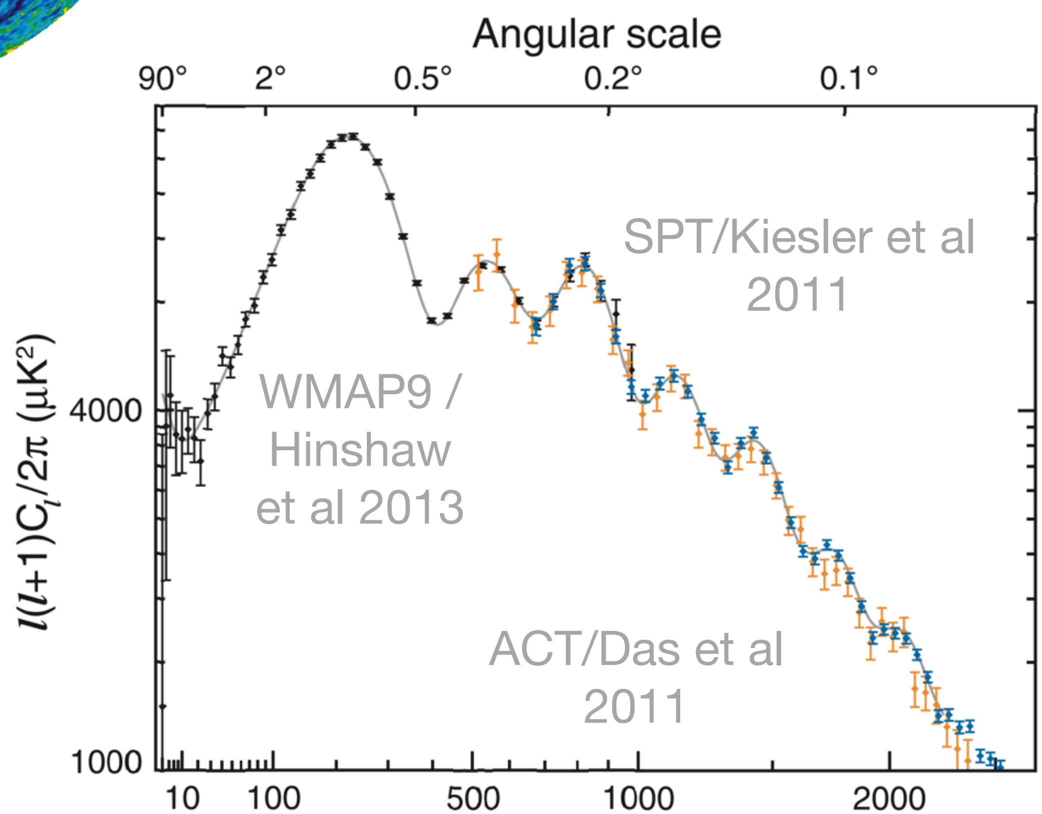


Dark Matter in Aspen
January 29, 2013

CMB alone now provides a ~ 20 sigma detection of dark matter



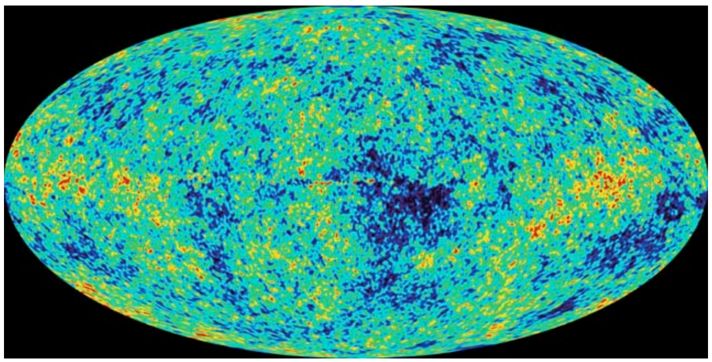
Very well measured CMB power spectrum: 9 measured peaks!



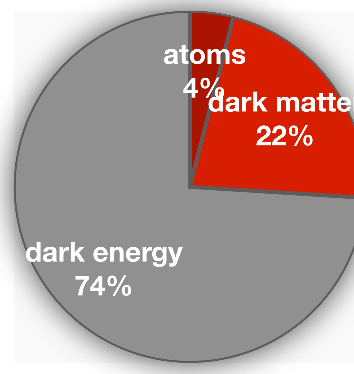
CMB only, 6 parameter ΛCDM:
baryon density 4.5±0.2%
cold dark matter density 23±2%
dark energy density 72± 2%
$n_s = 0.96 \pm 0.01$

Cosmological model constrained by the CMB makes precise predictions for structure formation

fluctuations are 10^{-5}

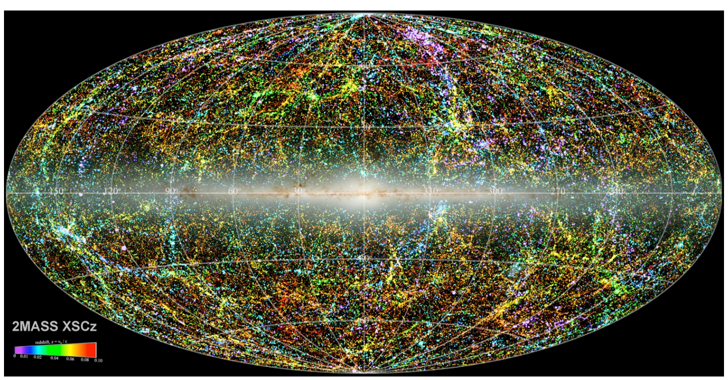


linear fluctuations

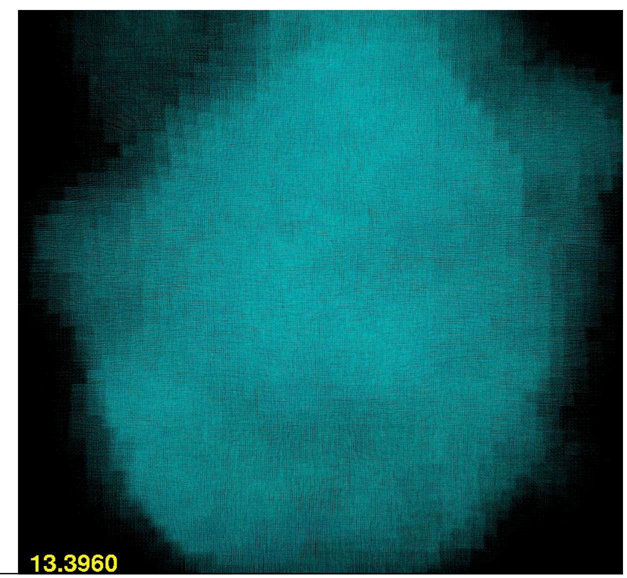


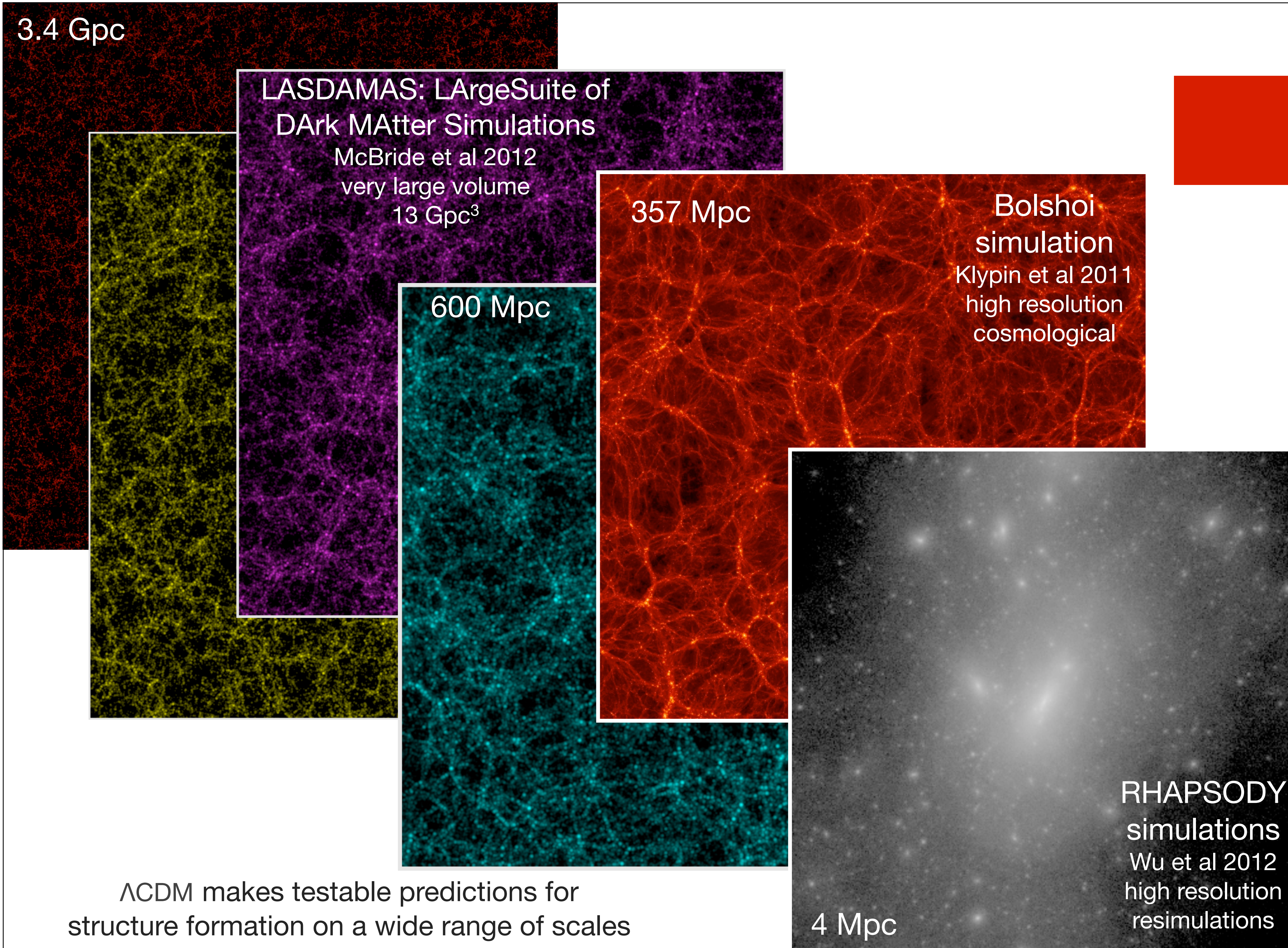
non-linear fluctuations

evolution of fluctuations from the CMB to today's distribution of galaxies: highly non-linear, involves baryonic physics. predictions *require* numerical simulations.



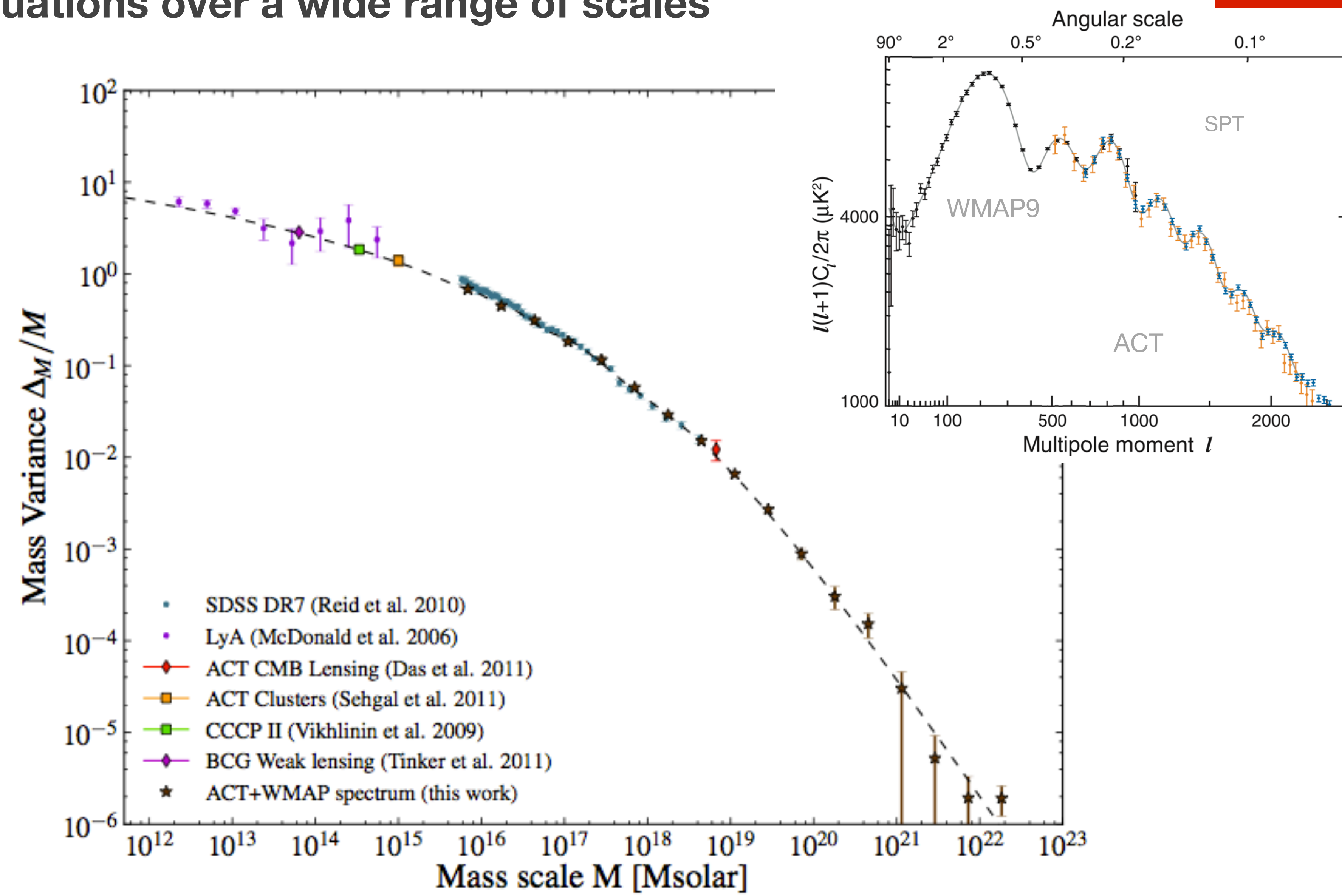
fluctuations are ~200 (gravitationally bound region)
~ 10^{32} (densest regions in the Universe)

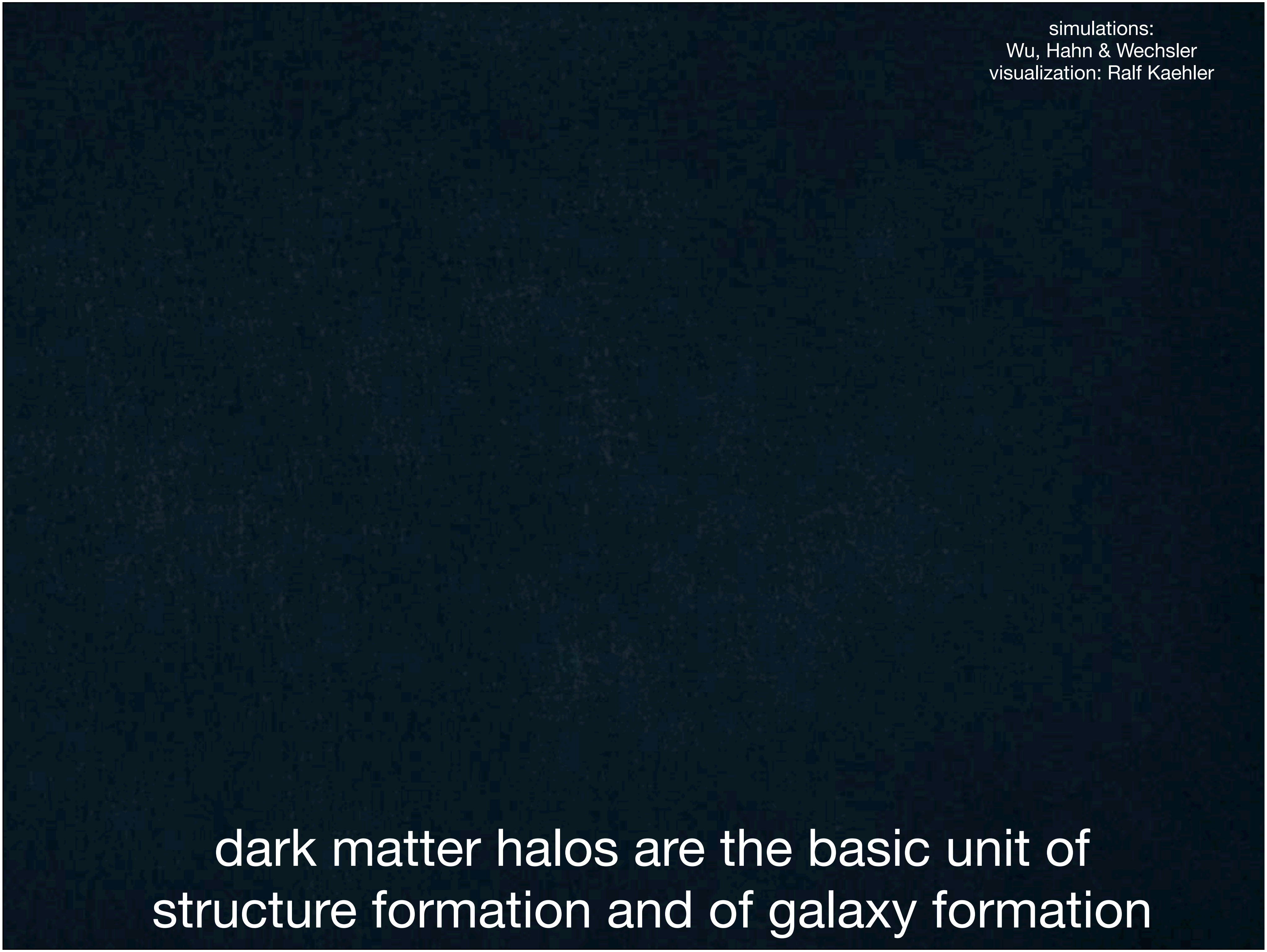




ΛCDM makes testable predictions for structure formation on a wide range of scales (modulo impact of baryons)

Current ΛCDM Model successfully predicts mass fluctuations over a wide range of scales

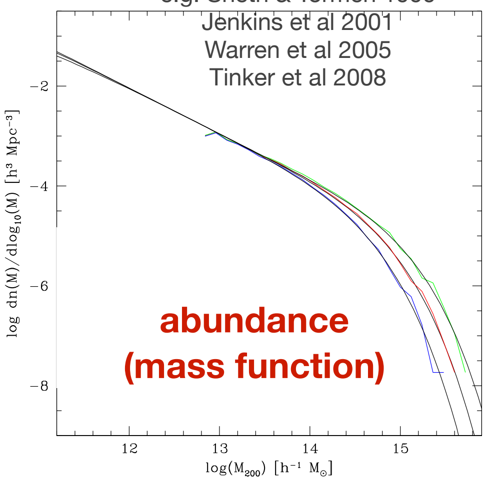



simulations:
Wu, Hahn & Wechsler
visualization: Ralf Kaehler
dark matter halos are the basic unit of
structure formation and of galaxy formation

properties of dark matter halos

halo abundance

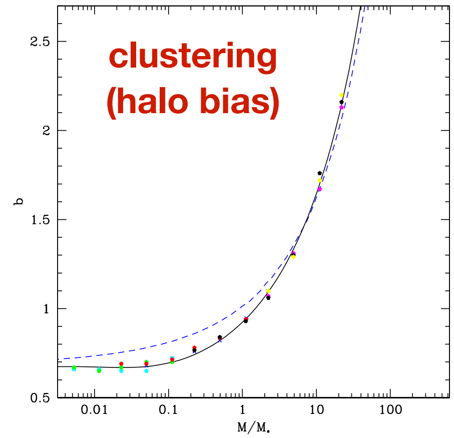
e.g. Sheth & Tormen 1999
Jenkins et al 2001
Warren et al 2005
Tinker et al 2008



halo mass

halo bias

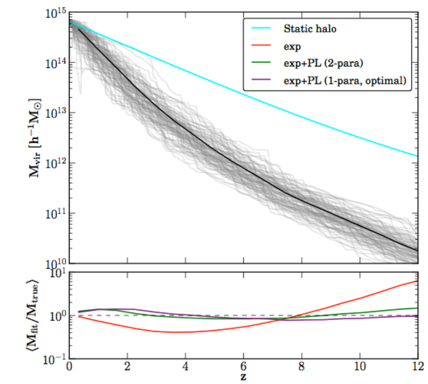
e.g. Mo & White 1996
Seljak & Warren 2004
Tinker et al 2010



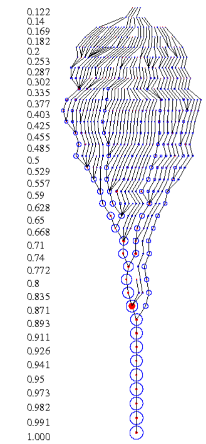
halo mass

mass assembly & merger history

progenitor mass



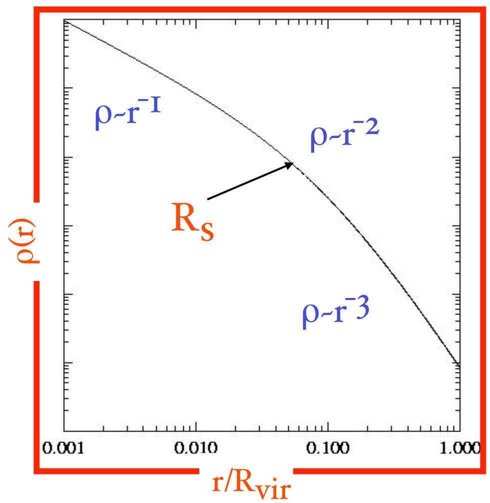
redshift



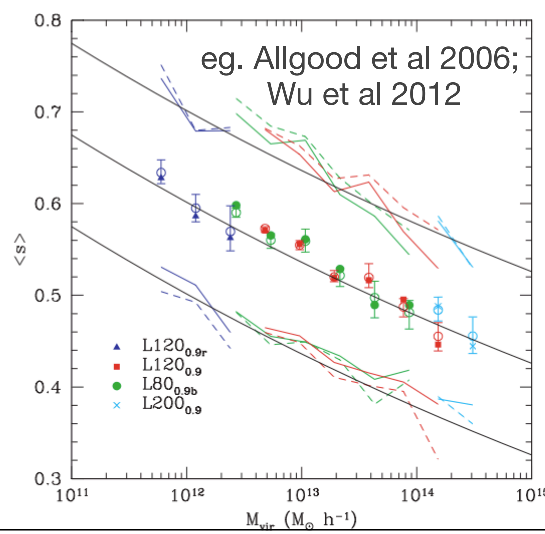
e.g.Wechsler et al 2002;
Wu, Hahn, RW et al 2012

halo density profiles

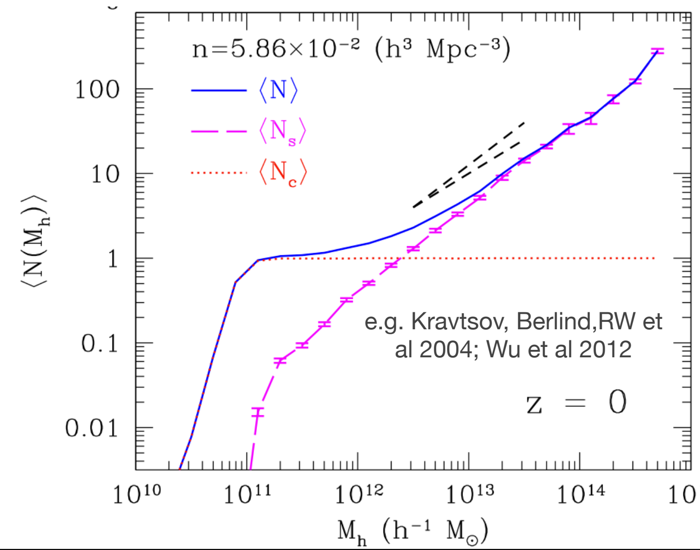
eg. NFW 96,97;
Bullock et al 2001;
RW et al 2002, 2006;
Duffy et al 2008; Wu et al 2012



shapes



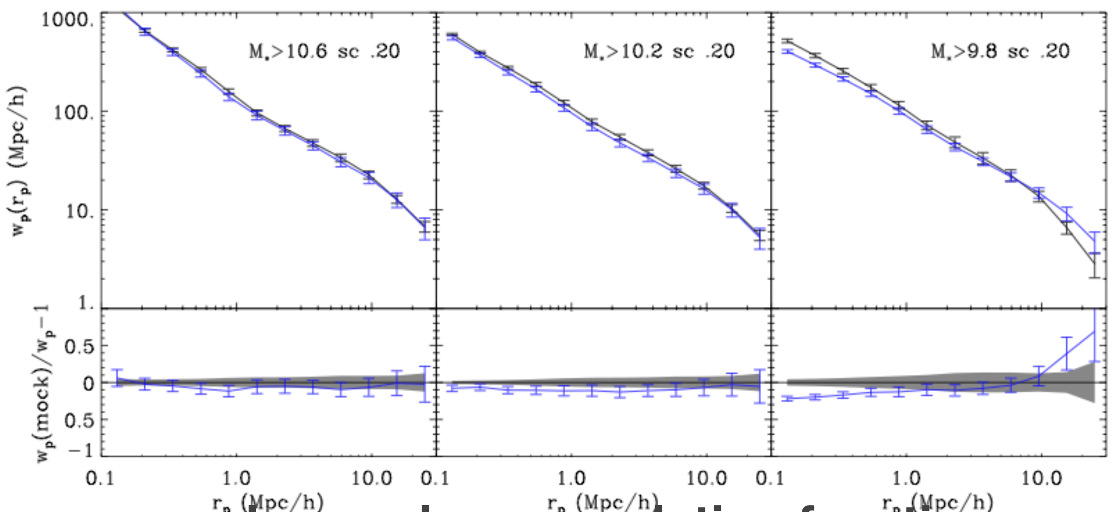
substructures



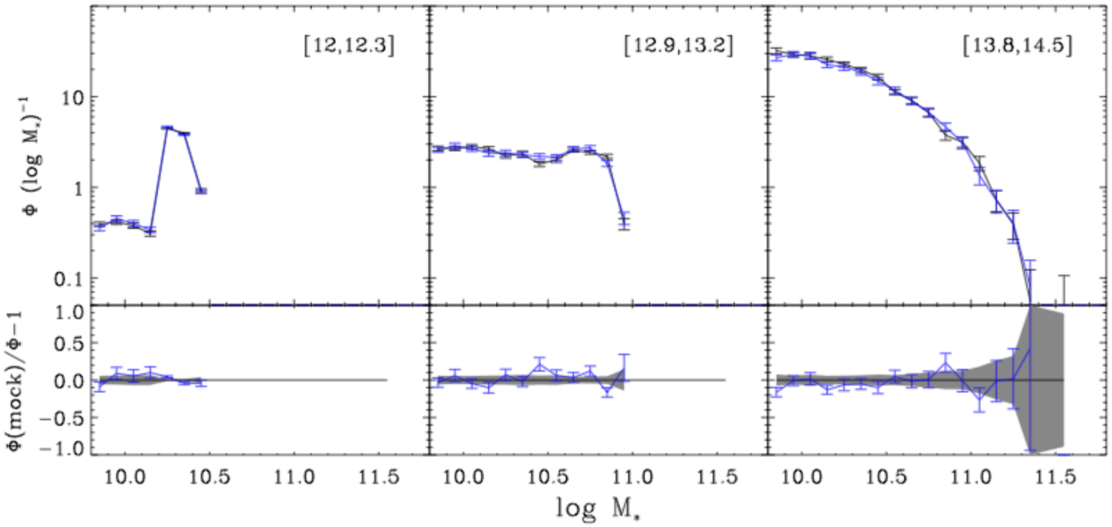
e.g. Kravtsov, Berlind,RW et al 2004; Wu et al 2012

LCDM + simple model for the galaxy-halo connection is in excellent agreement with detailed local measurements of the galaxy distribution

Reddick, RW et al 2012



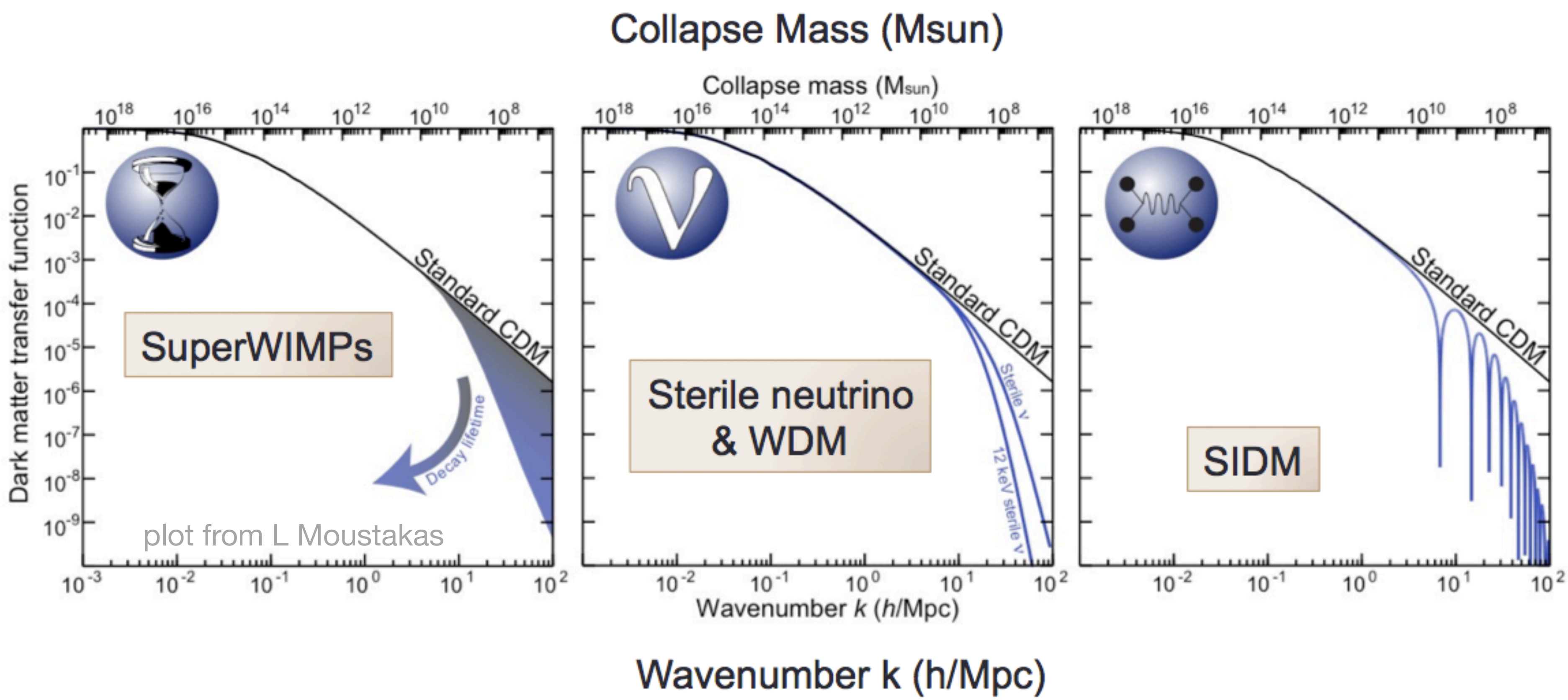
galaxy-galaxy correlation function



Conditional Stellar Mass Function

model:
galaxy luminosities/ stellar masses are tightly correlated to the maximum potential well of the halo over it's history (v_{peak}),
small scatter between galaxy and halo properties
(0.2 dex scatter in M* at a given v_{peak})

Dark matter properties impact the small-scale power spectrum
Does this spectacular agreement hold to small scales?



testable via:

detection of small objects: strong lensing; dwarf satellites

measurements of power spectrum (e.g. Ly-alpha forest, galaxies, etc)

Dark Matter Science Applications

The Domain of DM Simulation

Large scale distribution of DM
- voids, walls, filaments, etc.

Individual isolated halos
- halo mass functions
- concentration-mass relationship
- halo shapes
- evolution with cosmic time
- **DM density profile**
- velocity dispersion profile

Substructure population
- **subhalo mass function**
- **subhalo internal properties**
- **subhalo spatial distribution**

Local DM (at Sun)
- density
- tidal streams, debris flow
- dark disk

Smallest scale structure
- first halos to collapse (at redshift ~50)

Indirect Detection (Annihilation)
- Diffuse extra-galactic gamma-ray background (Fermi)
- Diffuse Galactic (high-l) gamma-ray background (Fermi)
- Clusters (Fermi, ACT's)
- Galactic Center (Fermi, ACT's)
- **Milky Way Dwarfs (Fermi, ACT's)**
- **Dark Subhalos (Fermi)**
- e+/e- from local DM annihilation (Fermi, Pamela, ATIC, ...)
- Neutrinos from Earth and Sun (IceCube)
- “Boost factor” (Everybody)

Direct Detection (Nuclear Recoils)
- standard case: “vanilla” WIMPs
- low mass DM, inelastic DM, etc.
- directionally sensitive experiments

slide from Michael Kuhlen

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slide from Michael Kuhlen

understanding the detailed predictions of cosmological structure formation is essential for determining the nature of dark matter

these predictions require numerical simulations over a huge range of scales.

in many cases they also require an understanding of the connection between dark matter & galaxies, including the impact of galaxy formation on the dark matter distribution.

this is especially hard for probing dark matter physics

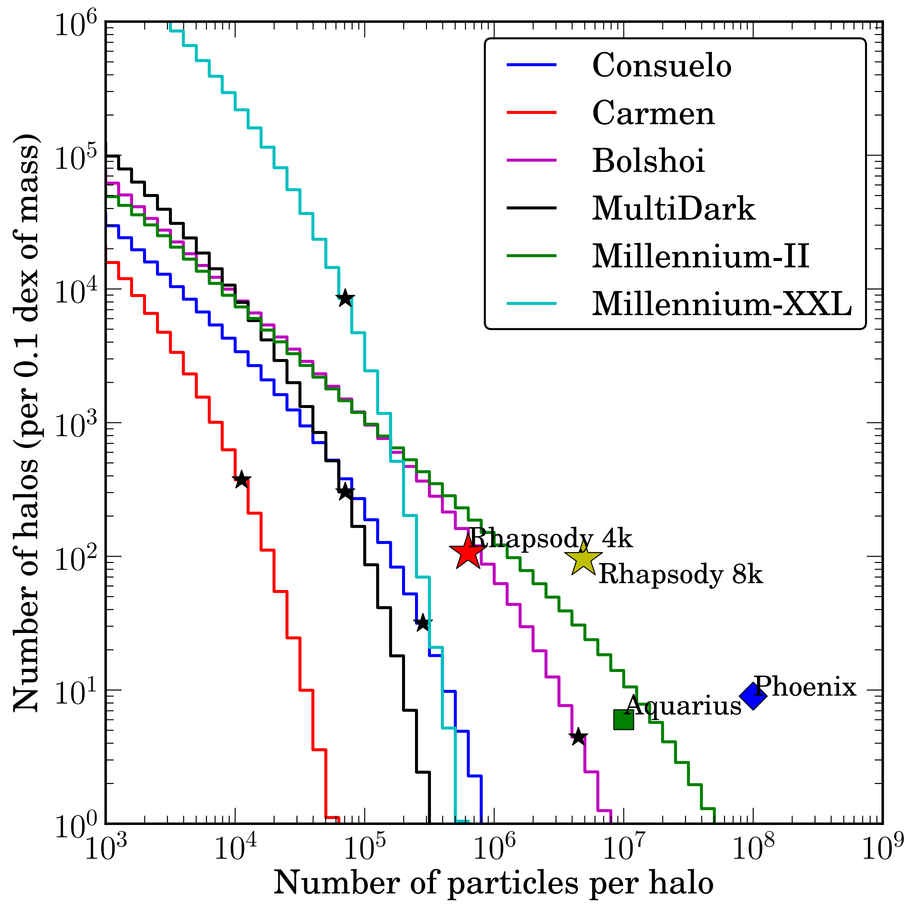
*** differences between CDM and CDM alternatives are on small scales**

*** non-linear physics & the impact of galaxy formation are more important**

This talk:

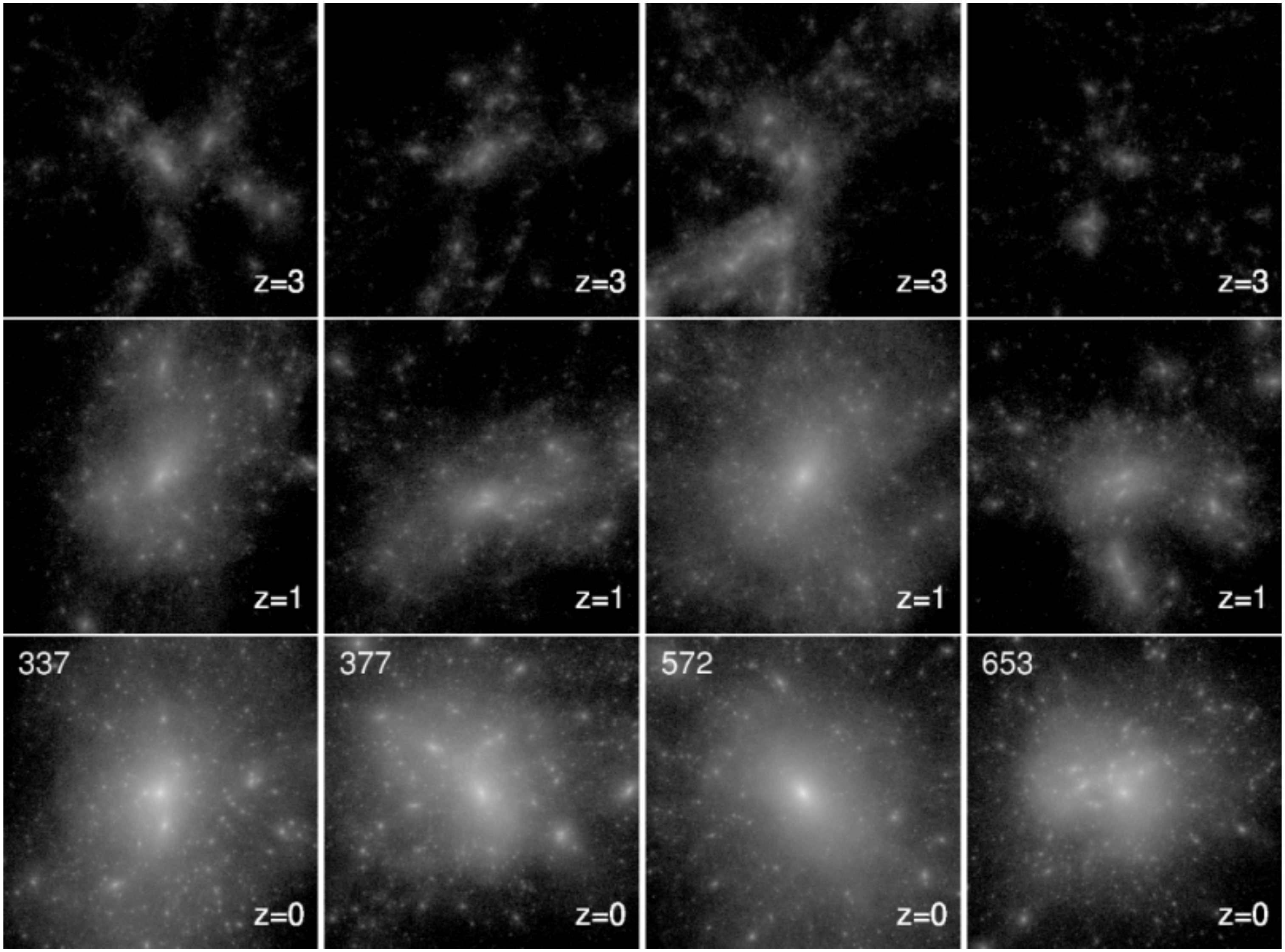
- basic properties of dark matter halos *including scatter*
- the velocity distribution of CDM halos
- inferring the properties of the MW (and other systems) from cosmological simulations
- coming up... Justin Reed: simulations with CDM alternatives and simulations with baryons + Leonidas Moustakas: testing the predictions of DM structure formation on small scales

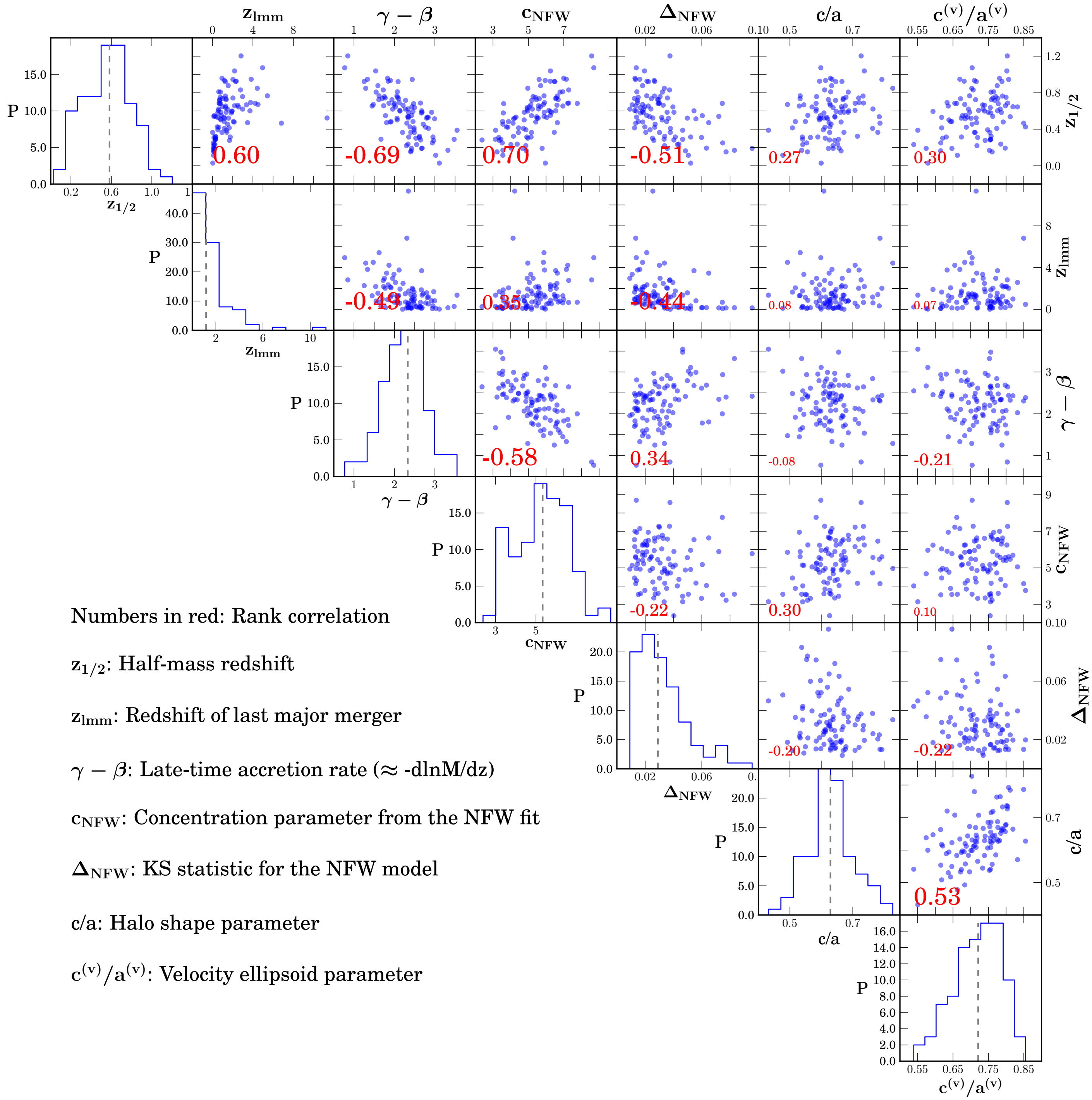
various high resolution simulations



- Want statistics, to understand scatter between systems.
- Want high resolution for various studies (e.g. substructure, density profiles, velocity distribution)
- Currently only a handful of very high resolution systems
- Rhapsody simulations
  - ~100 cluster-size halos
  - several x 10^6 M_{sun} particles.
  - resolve ~100 substructures in ~100 halos
  - expansion (number, mass range) in progress

halos have a diversity of formation histories & internal properties





Numbers in red: Rank correlation

$z_{1/2}$: Half-mass redshift

z_{lmm}: Redshift of last major merger

$\gamma - \beta$: Late-time accretion rate ($\approx$ -dlnM/dz)

c_{NFW}: Concentration parameter from the NFW fit

Δ_{NFW}: KS statistic for the NFW model

c/a: Halo shape parameter

$c^{(v)}/a^{(v)}$: Velocity ellipsoid parameter

Wu, Hahn, RW, Mao, Behroozi 2013

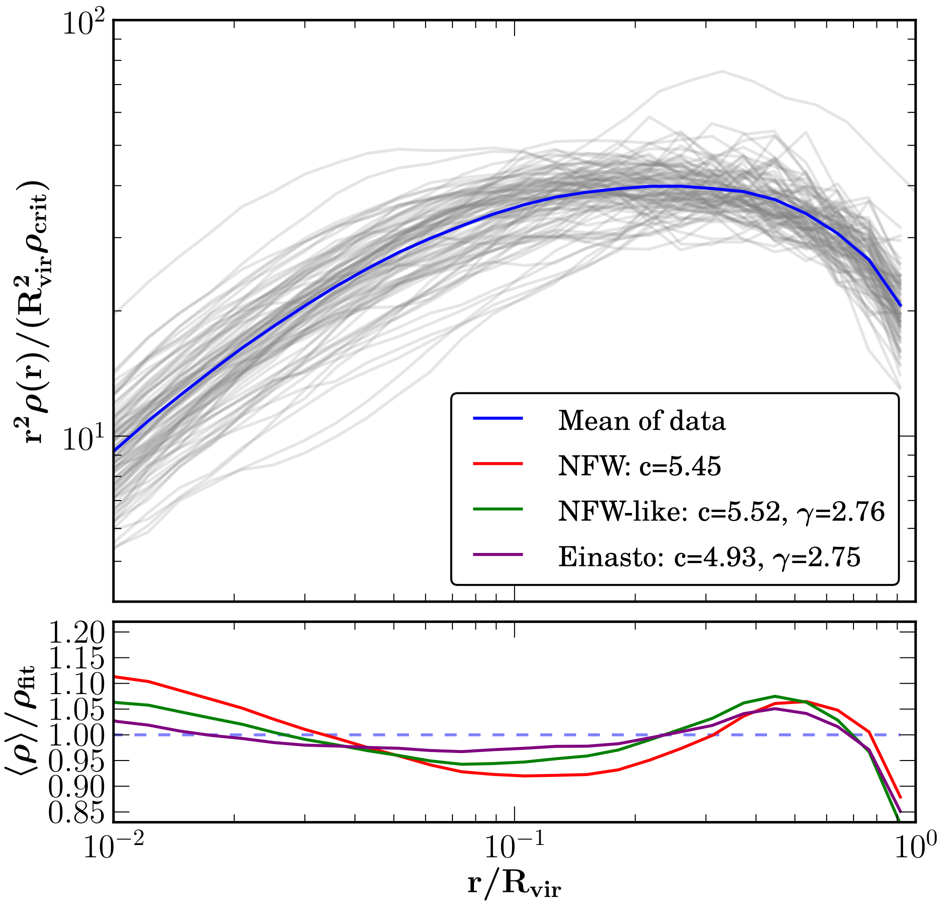
This diversity can matter in interpreting various results

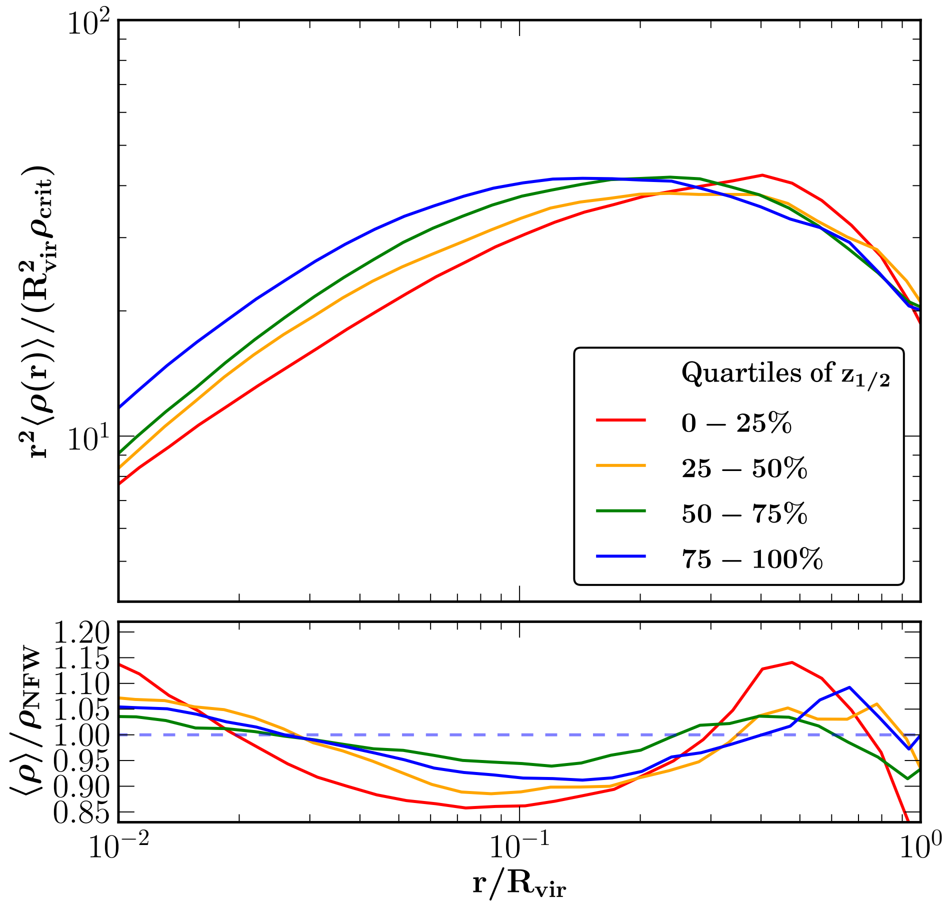
- e.g. in the Milky Way
  - some things we can only measure here.
  - is the dark matter distribution, satellites, etc perfectly typical, or does it depend on other properties of the halo environment / formation history

- e.g. in interpreting strong lensing systems
  - substructures in lensing systems may not be representative
  - density profile of lensing-selected systems may not be typical

example: impact of formation time on the density profile

Wu, Hahn, RW, Mao, Behroozi 2013





example: the velocity distribution of dark matter particles

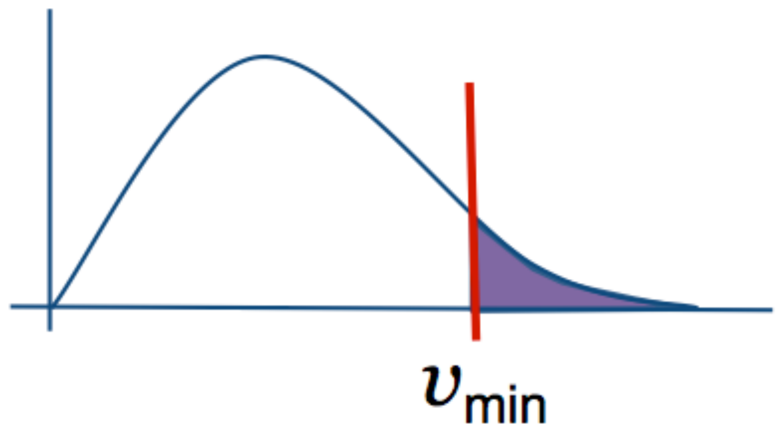
What is the velocity distribution of dark matter for our own galaxy?

(assuming we live in CDM, what is the range of possibilities for halos consistent with the Milky Way?)

Direct detection of dark matter

- the differential event rate depends on velocity distribution function (VDF) of dark matter particles that go through the detector

$$\int_{v_{\min}(Q)} d^3v \, \frac{f(\mathbf{v}+\mathbf{v_e})}{v}$$



$$\left.\frac{dR}{dQ}\right|_Q = \frac{\rho_0}{m_{\text{dm}} m_N} \int_{v_{\min}(Q)} d^3v \, v f(\mathbf{v}+\mathbf{v_e}) \frac{d\sigma}{dQ}$$

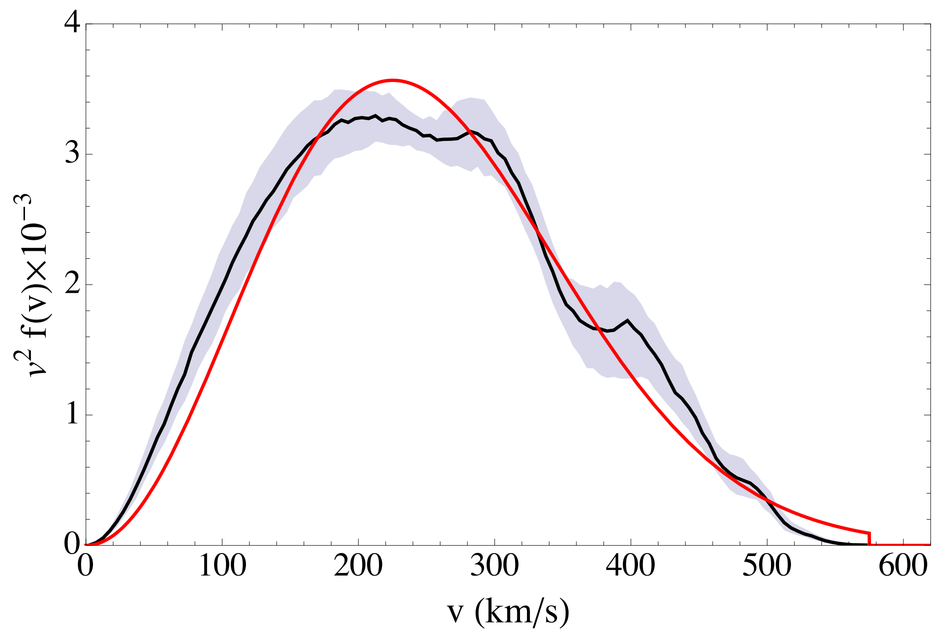
$$= \frac{\rho_0 \sigma_0}{2\mu^2 m_{\text{dm}}} A^2 |F(Q)|^2 \int_{v_{\min}(Q)} d^3v \, \frac{f(\mathbf{v}+\mathbf{v_e})}{v}$$

The “Standard Halo Model”

- standard model assumes that the VDF is given by an isothermal, isotropic Maxwell-Boltzmann distribution

$$f_{\rm shm}(v) \propto e^{v^2/v_0^2}\ \Theta(v_{\rm esc} - v)$$

- model is commonly used to convert limits from a given experiment into a mass and cross section



Doesn’t agree with predictions of CDM halos

Over predicts events at high velocities

Unphysical cutoff

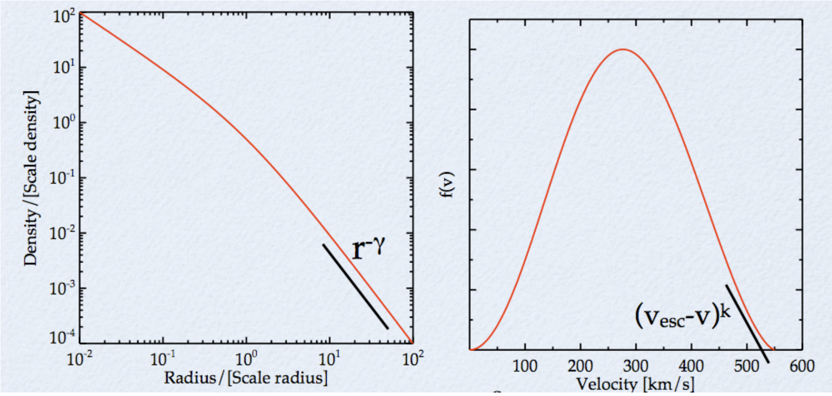
M. Kuhlen et al (2009)
Fairbairn and Schwetz (2009)
Vogelsberger (2008)
Lisanti et al (2011)

Method 1: Analytic Calculation

- Eddington's formula

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2 M}\left[\int_0^{\mathcal{E}} \frac{d\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{d^2\rho}{d\Psi^2} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{d\rho}{d\Psi}\right)_{\Psi=0}\right]$$

- Directly connects the density profile and the VDF



Lisanti, Strigari, Wacker & RW; PRD 2011:
model that is consistent with NFW halos in the tail
(unlike SHM)

- Assumptions:
  - system is in equilibrium
  - spherically symmetric
  - isotropic (small number of anisotropic models can be analytically solved)

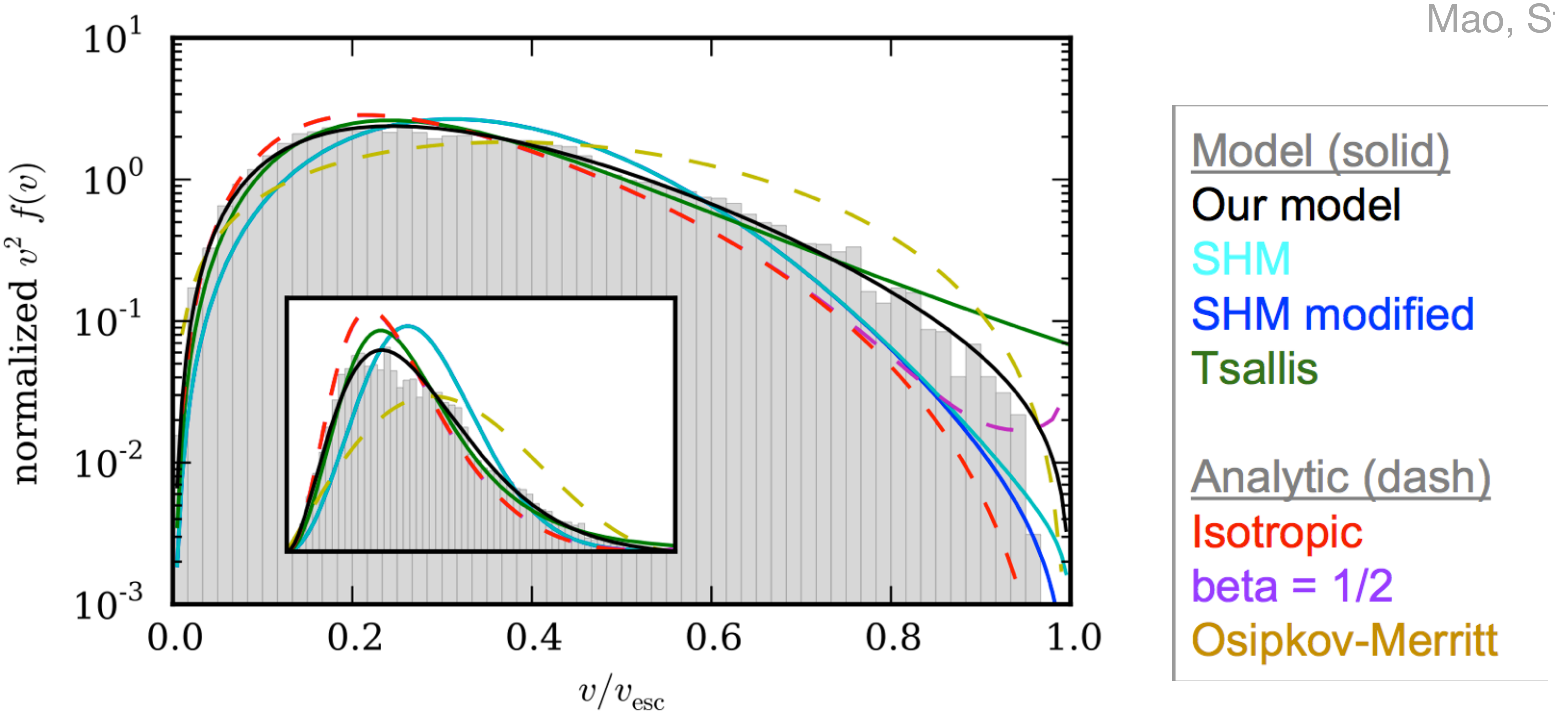
- But, **none of these assumptions appear to be true for CDM halos.**

Method 2: Cosmological Simulations

- measure the VDF directly in simulations
- Tricky part:
  - dark matter particles are probably $\ll 100\ M_{sun}$
  - dark matter particles in simulations are ~ 10^3 -- $10^{11}\ M_{sun}$
- Second tricky part:
  - baryons might impact the dark matter distribution
  - simulations with baryons are significantly more expensive, and we don't understand galaxy formation well enough to believe that any specific implementation is correct
- nevertheless, we can make a good start... we have a good idea of what halos look like in CDM.
- what is the largest source of uncertainty?
  - scatter from halo to halo
  - radial position in the halo
  - scatter from one region in a halo to another (e.g., due to substructure)
  - uncertain impact of baryons

A new model for the VDF based on CDM halos

Mao, Strigari, RW et al 2013



$$f(v) \propto \exp\left(-\frac{v}{v_0}\right)\left(v_{\rm esc}^2 - v^2\right)^p, \quad v \in [0, v_{\rm esc}]$$

$$f_{\rm shm}(v) \propto e^{v^2/v_0^2}\ \Theta(v_{\rm esc} - v)$$

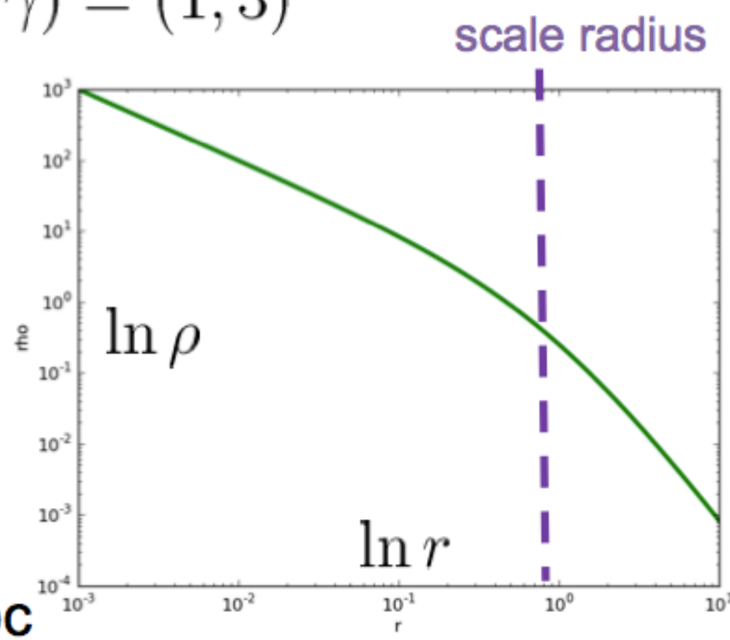
- not a Maxwell-Boltzmann distribution
- two parameters, v0 and p
- tail modified by a power-law cutoff in energy

Density profile of the Milky Way

- Density profiles of simulated halos are well described by the Navarro–Frenk–White (NFW) profile.

$$\rho(r) = \frac{\rho_s}{(r/r_s)^{\alpha}(1 + r/r_s)^{\alpha-\gamma}} \qquad (\alpha, \gamma) = (1, 3)$$

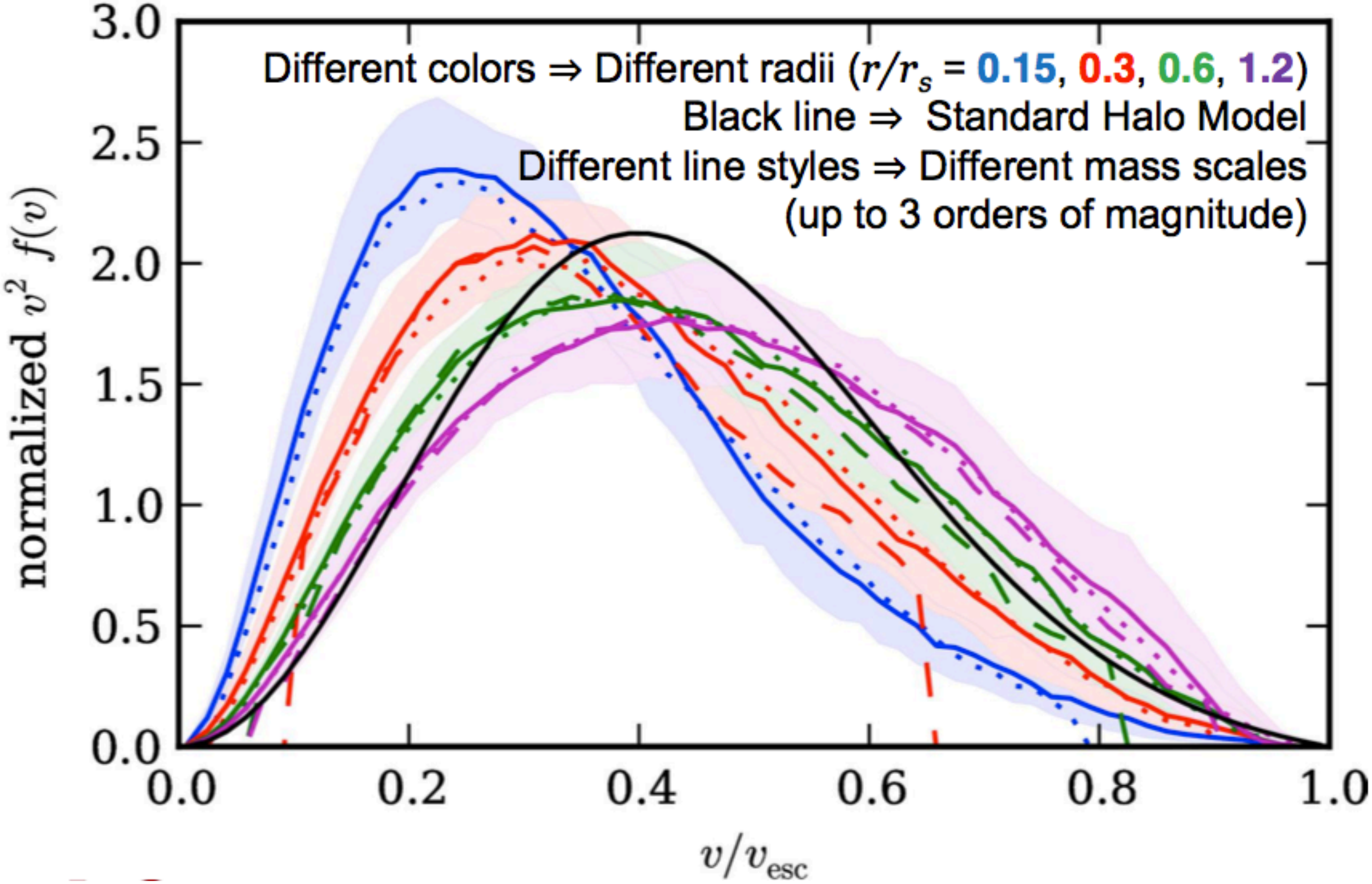
- Universality in VDFs
  if radii normalized by scale radius
  - r/r_s : most important quantity determining potential



- Solar system at r = 8 kpc
  Current constraints on r_s ~ 13 – 55 kpc
  ⇒ r/r_s ~ 0.15 – 0.6

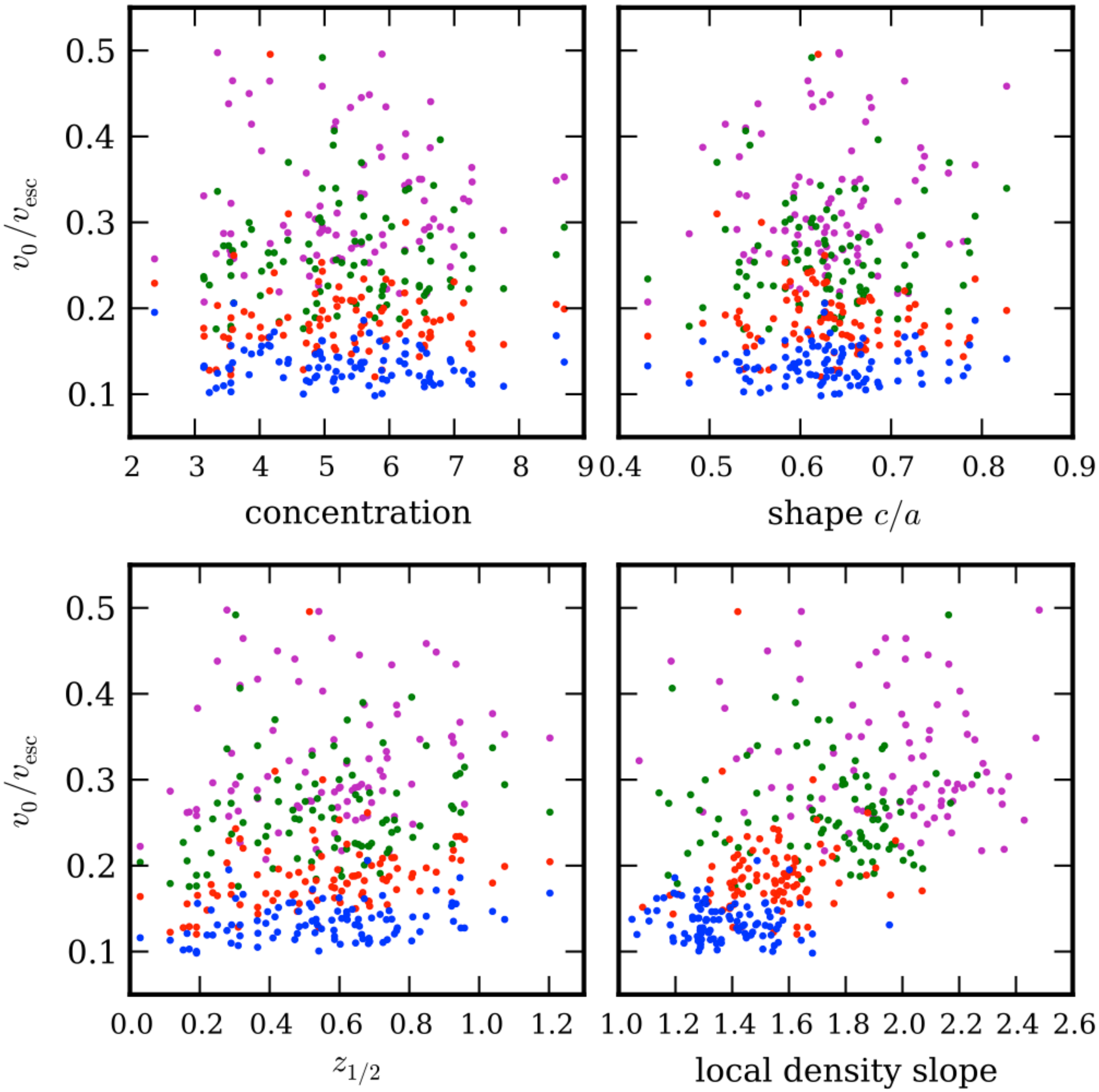
Measured VDF in cosmological halos

Mao, Strigari, RW et al 2013



r/rs has the most impact on the VDF

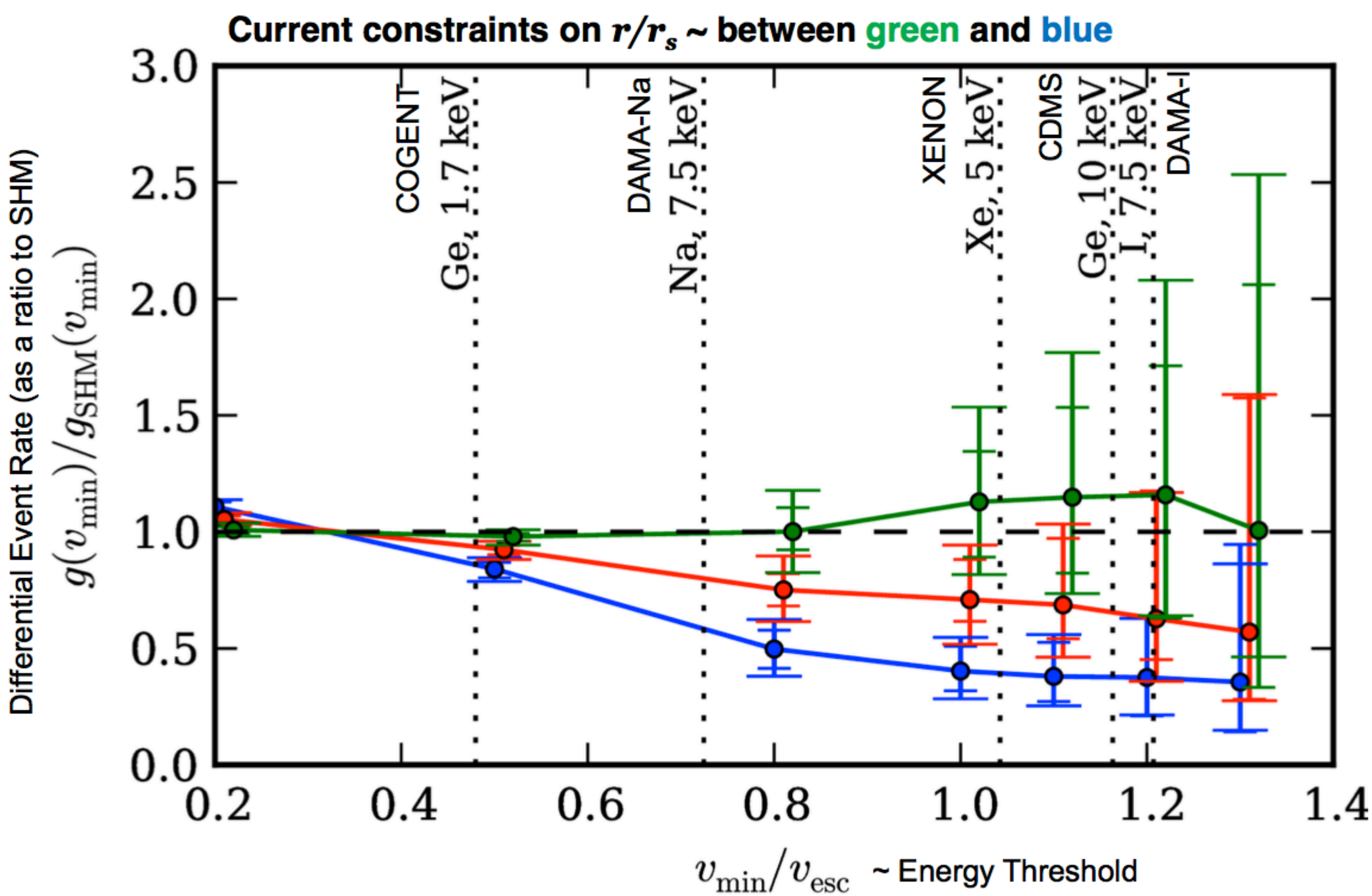
Mao, Strigari, RW et al 2013



at fixed r/rs, little to no trend with other halo properties

impact on direct detection experiments

Mao, Strigari, RW et al 2013



inside error bars:halo-to-halo scatter

outside error bars: addition scatter from multiple regions

which part of the VDF matters depends on mass and target
(v_{min} is higher / tail matters more for lighter WIMPs and heavier targets)

VDF summary

- shape of the VDF is universal over a wide range of halo masses, environments
- we have identified a useful analytic model that is relevant for CDM halos
- most important quantity for direct detection is the location of the Earth in the Milky Way with respect to its density profile
- difference from SHM has impact for rates and in particular when comparing once DM experiment to another!

- additional sources of scatter / impact:
  - halo-to-halo scatter
  - variation of the VDF in various directions at fixed radius (including streams & substructures)
  - quality of the fit
  - impact of baryons (still very uncertain!)

biggest uncertainty:
our location with respect to the density profile of the MW

how do we learn more?

more generally...

- How typical is the Milky Way?
  - if dark matter is detected, it will likely be from interactions *in the MW*
  - some measurements (e.g. faintest satellites) only possible in the MW
- Is the Milky Way a typical halo?
  - what is its mass?
  - what is its density profile?
  - what is its formation history?
  - how much dark matter substructure does it have and with what properties?
  - what is its velocity structure?
  - how do its visible satellite galaxies compare to other systems?
  - which aspects of its environment (e.g. presence of M31, Virgo, etc...)matter for its internal properties?

What is the mass, density profile, formation history of the Milky Way?

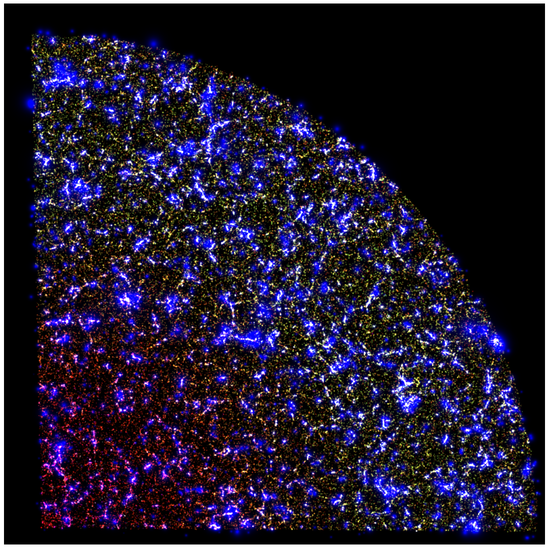
Various observables

- the rotation curve, as traced by gas or stellar halo stars
- the properties of the MW satellites: positions, masses, proper motions
- motion with respect to Andromeda
- etc...

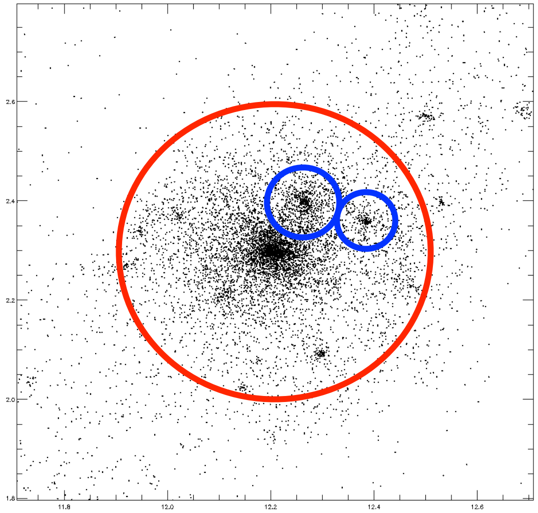
these all require a model to get to the physical properties of interest

Busha, Marshall, RW et al (2011); Marshall, Busha, RW 2012 in prep

large cosmological simulations provide an informative prior for these variables of interest



- Instead of simplified models, model the dynamics of halos in their true cosmological context; dynamics generated by an LCDM universe
- Large cosmological simulations contain millions of dark matter halos
- We know the position, mass, velocity, motions, internal properties of each one at every output time, plus their assembly histories
- Halos catalogs from this cosmological simulation can be thought of as the prior probability density function for galaxy halos in a given cosmological model
- Importance sample this prior PDF with your observed data, to get the posterior PDF of some intrinsic property of the object in question.



What can the MCs teach us about the MW?

- Observational Constraints on the Milky Way
  - Not a satellite of a larger structure
  - Has exactly two satellites galaxies with v_{max} > 55 km/s
  - No other substructures within 300 kpc with v_{max} > 25km/s

Sagittarius is next brightest with v_{max} ~ 20 km/s (Strigari et al 10)

	LMC	SMC
v_{max}	~65 km/s	~60 km/s
r_0	50 kpc	60 kpc
Speed	378 ± 18 km/s	301 ± 52 km/s

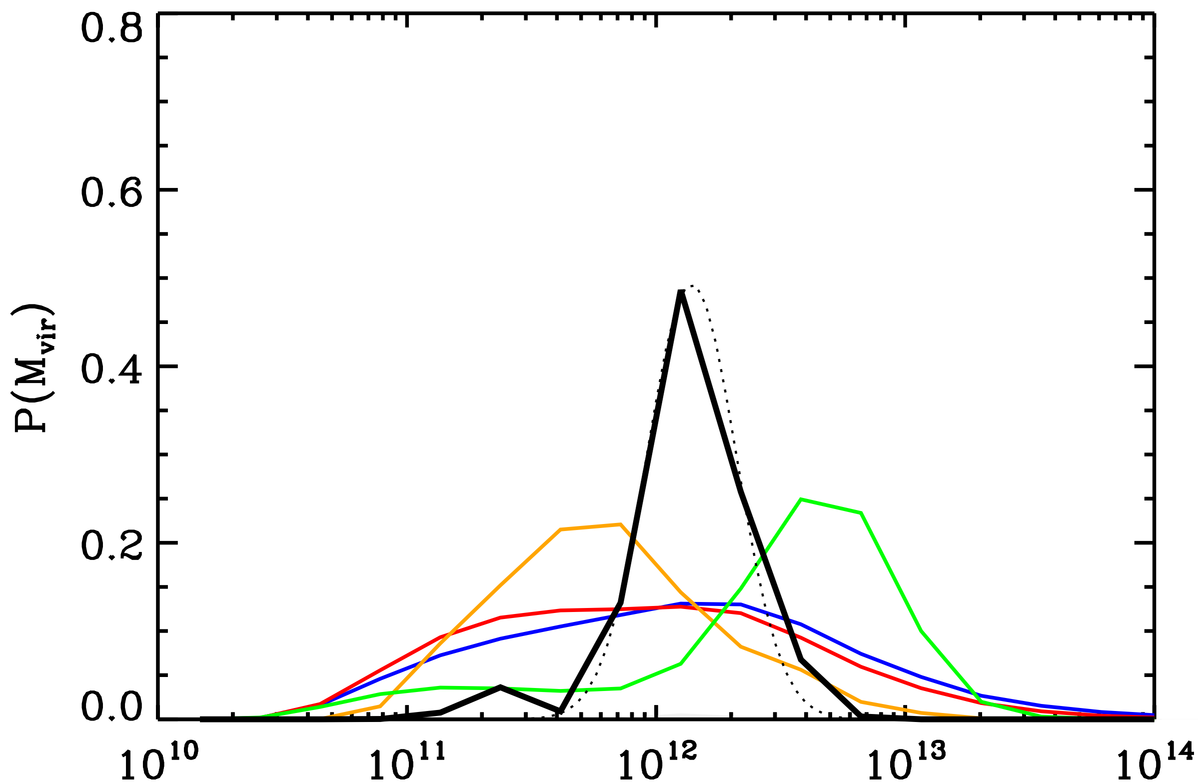
Watkins et al 2010; Kallivayalil et al 06, 12; Krachentsev et al 04; van der Marel et al 02

1. calculate the likelihood that each halo with two satellites (~36000 halos at z=0) has satellites with v_{max}, r_0, and speed of the LMC and SMC.

2. calculate posterior PDF for the properties of the MW using these likelihoods.

Busha, Marshall, RW, Klypin, Primack 2011

Weighing the MW with the properties of its satellites

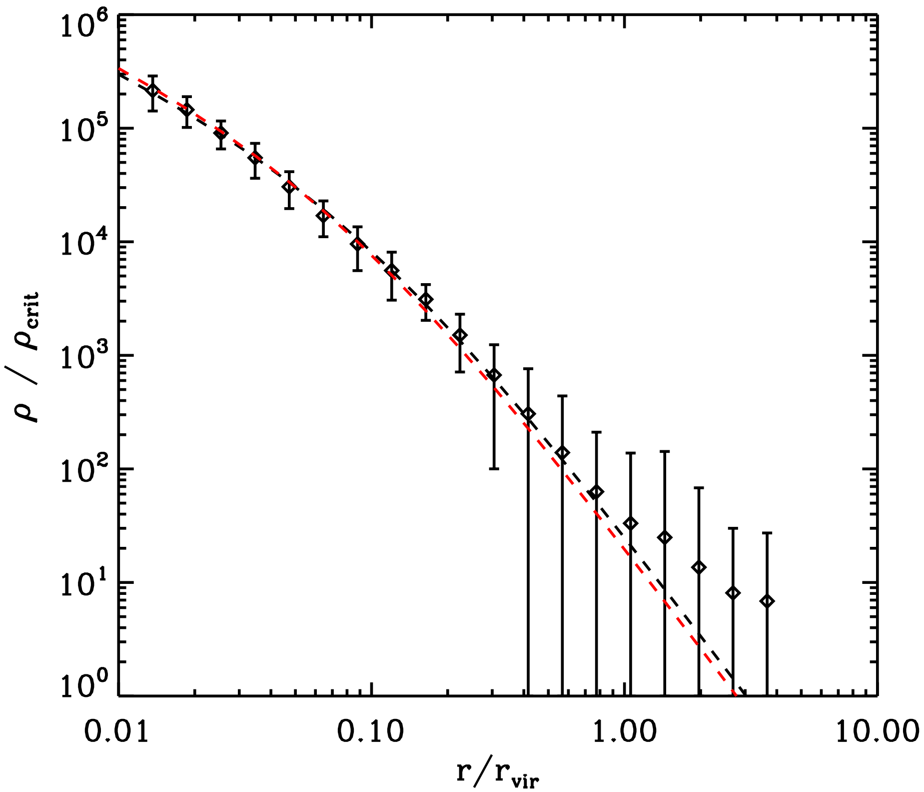


blue: all halos with $N_{sats} = 2$
red: $N_{sats} + v_{max}$
orange: $N_{sats} + r_0$
green: N_{sats} + speed
black: combined constraints

$$1.2^{+0.7}_{-0.4}\,(\text{stat.})^{+0.3}_{-0.3}\,(\text{sys.}) \times 10^{12} M_\odot$$

Busha, Marshall, RW et al 2011

The density profile of dark matter in the MW



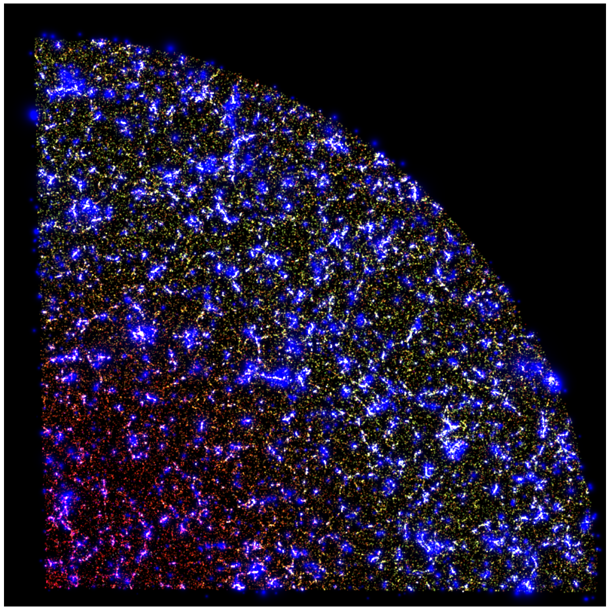
- halos with properties similar to these satellites have slightly higher concentrations than halos selected only by mass
- c = 11 +/- 2 for halos with MC-like satellites vs. c = 8.7 +/- 3.5 for halos with MW-like masses
- satellite analogs have ~60% higher central densities within 8 kpc.
- implications for the VDF (because it primarily depends on r/r_s) and direct detection rates

Busha, Marshall, RW et al 2011

Many possible applications!
Large cosmological simulations allow you to do many analyses in new ways.

- In this case:
  - apply more/tighter priors (e.g. new precise measurements of the LMC proper motions dynamics of the local group)
  - look at the posterior distribution of other intrinsic properties, and learn more about the MW (e.g. density profiles satellite population, distribution and speeds of dark matter particles, merger history, etc.)

- Many other interesting examples!
  - properties of the MW satellites
  - e.g. dynamics of bullet clusters



Summary

- LCDM incredibly successful (at least down to the scale of ~ 10^{11} M_{sun})
- predictions for the detailed statistics of high resolution halos, but full resolution range of interest for the full variety of halos is still beyond computational capabilities
- New analytic form for the velocity distribution for realistic DM halos which is in good agreement with the *measured VDF* in cosmological simulations
- Key uncertainty in direct detection rates from VDF is the position of the earth wrt the density profile of the MW
- new method to infer properties of systems based on selecting from large volume simulations, e.g. can infer the mass distribution and formation history of the Milky Way using the properties of the Magellanic Clouds or the properties of the Local Group
  - from MCs, $M_{MW} = 1.45{\times}10^{12}{\pm}0.4M_{\odot}$, consistent with detailed kinematic studies of the MW; MW has slightly higher concentration than typical.
- important first step in using all available observations to place the MW in larger cosmological context, and make detailed predictions for *our* halo (density profile, substructures, velocity structure) as relevant to dark matter probes