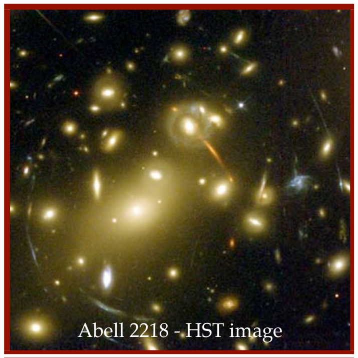
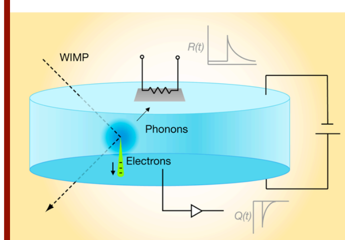
Dark Matter Insights

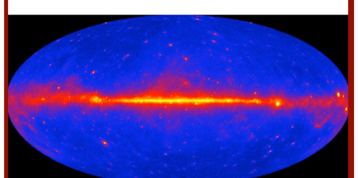
from Cosmological Simulations of Structure Formation

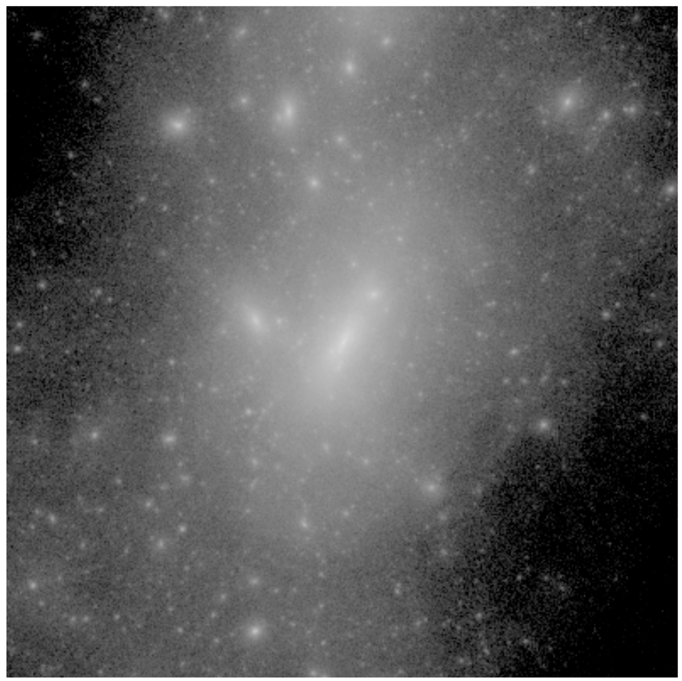
Risa Wechsler

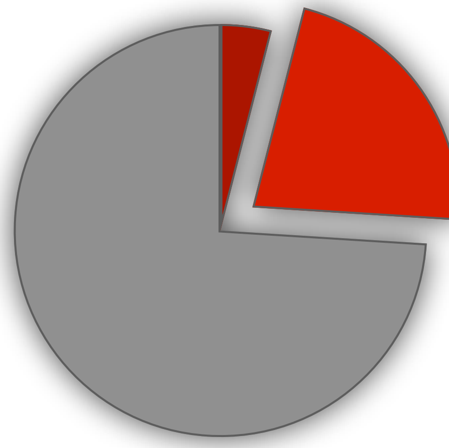

Abell 2218 - HST image



CDMS detector
Illustration: Alan Stonebraker

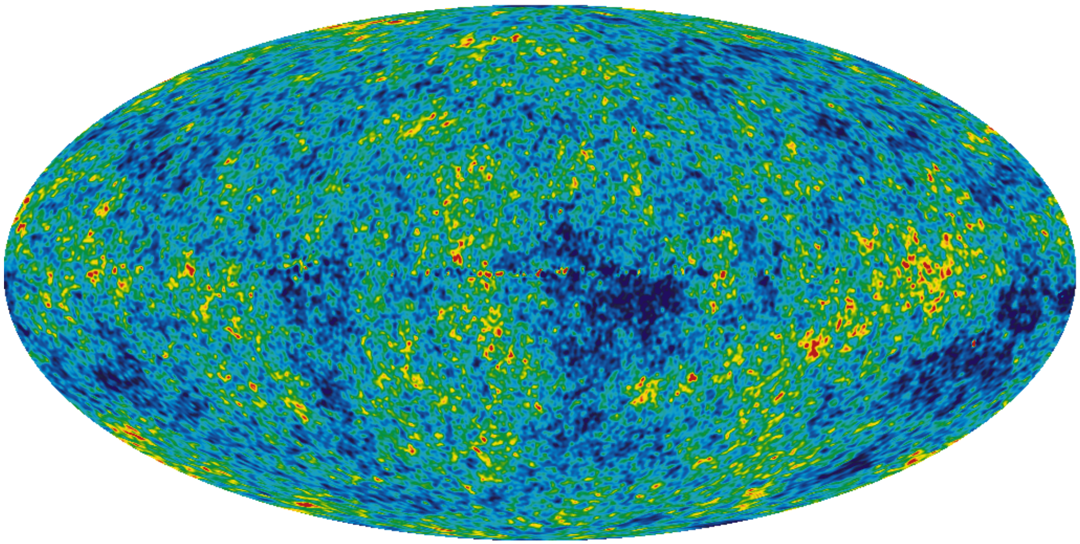

Fermi Space Telescope
Two-Year Data



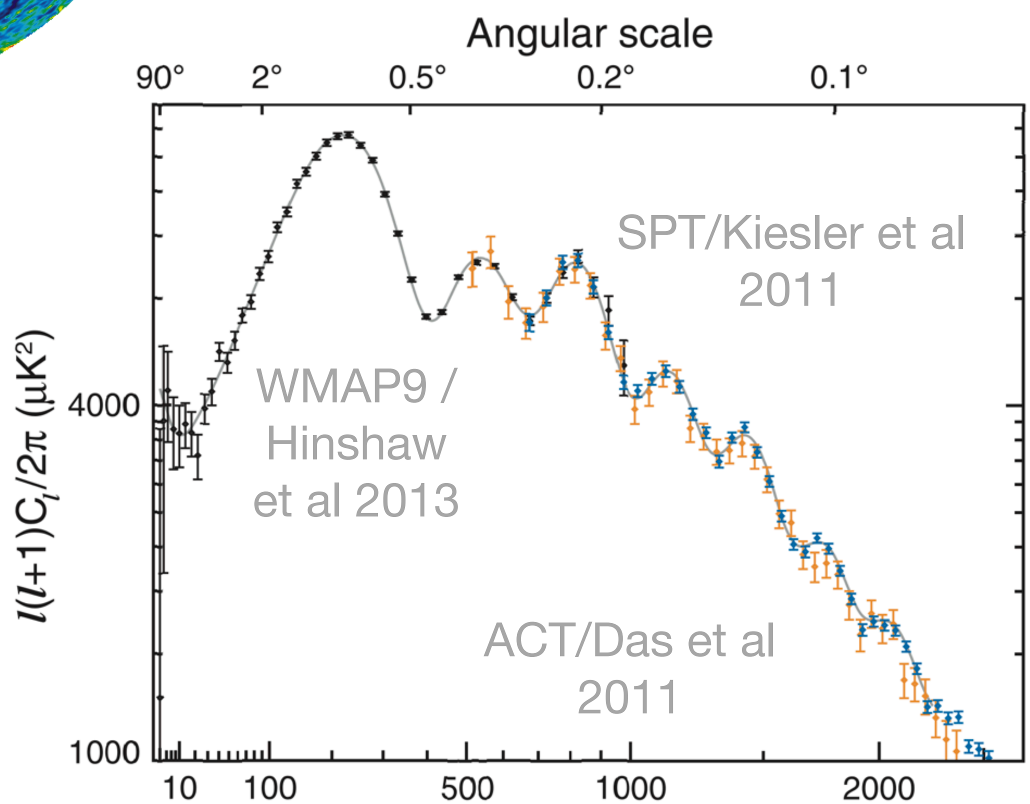


TAUP
September 9, 2013

CMB alone now provides a ~ 50 sigma detection of dark matter



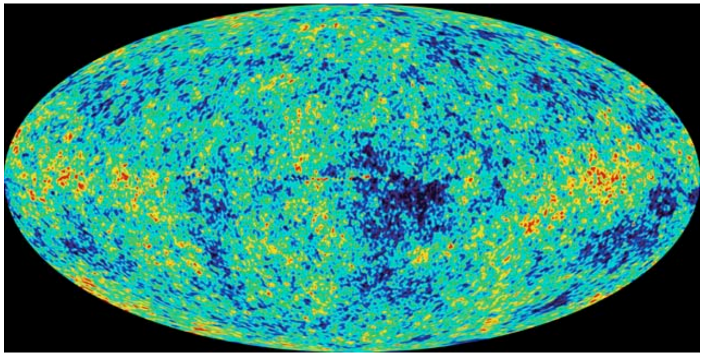
Very well measured CMB power spectrum: 9 measured peaks!



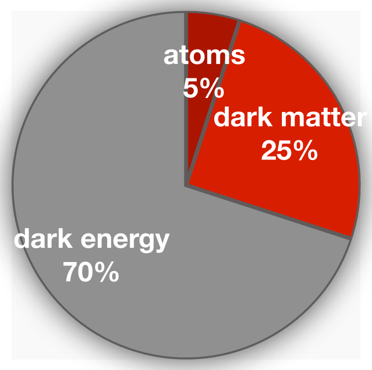
CMB only, 6 parameter ΛCDM:
baryon density 4.8±0.2%
total matter density 31±2%
dark energy density 69 ± 1%
n_s = 0.961 ± 0.006

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

fluctuations are 10^{-5}

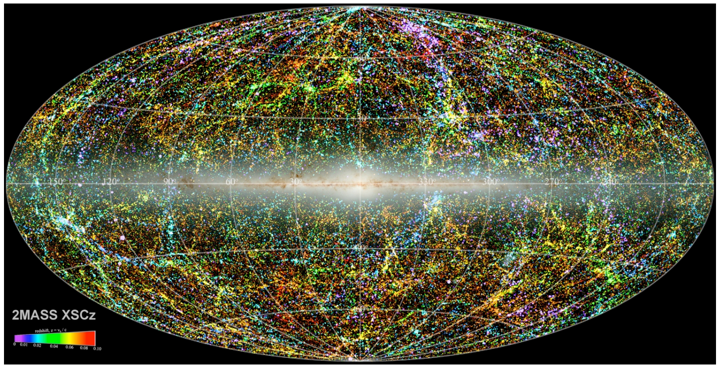


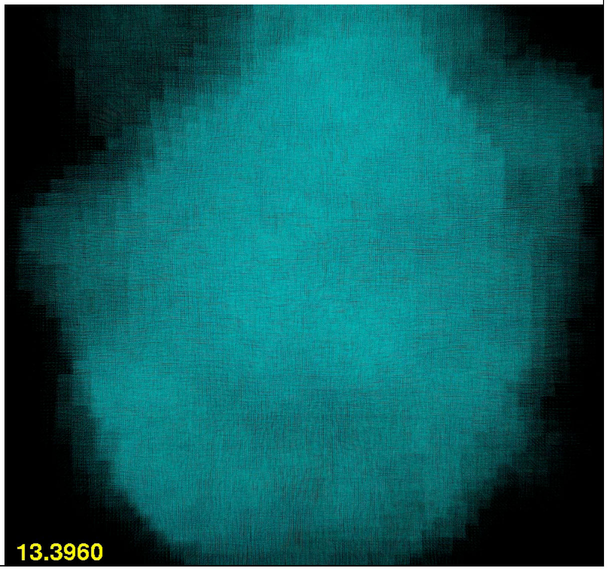
linear fluctuations



non-linear fluctuations

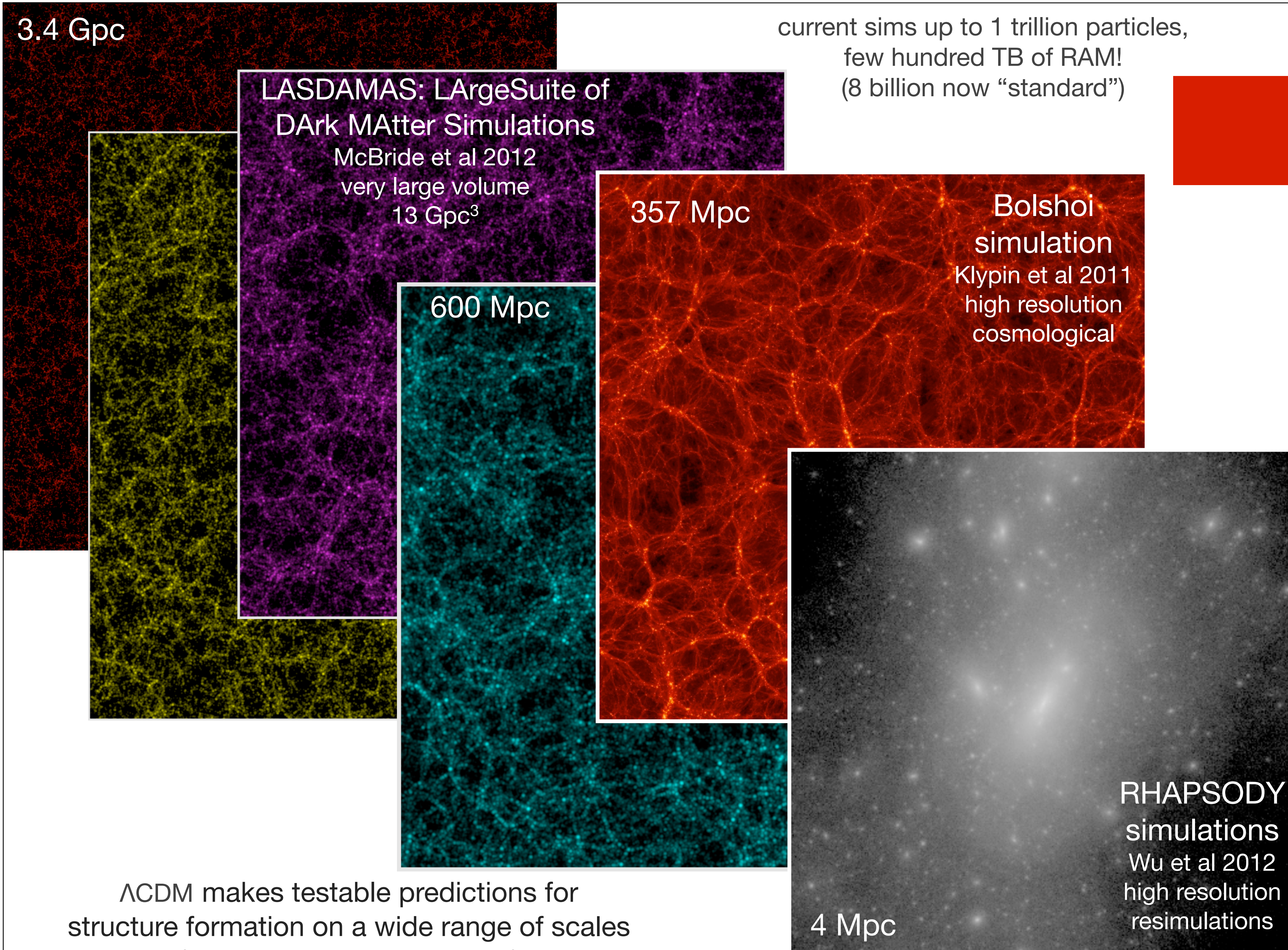
evolution of fluctuations from the CMB to today's distribution of galaxies: highly non-linear, involves baryonic physics. predictions *require* numerical simulations.





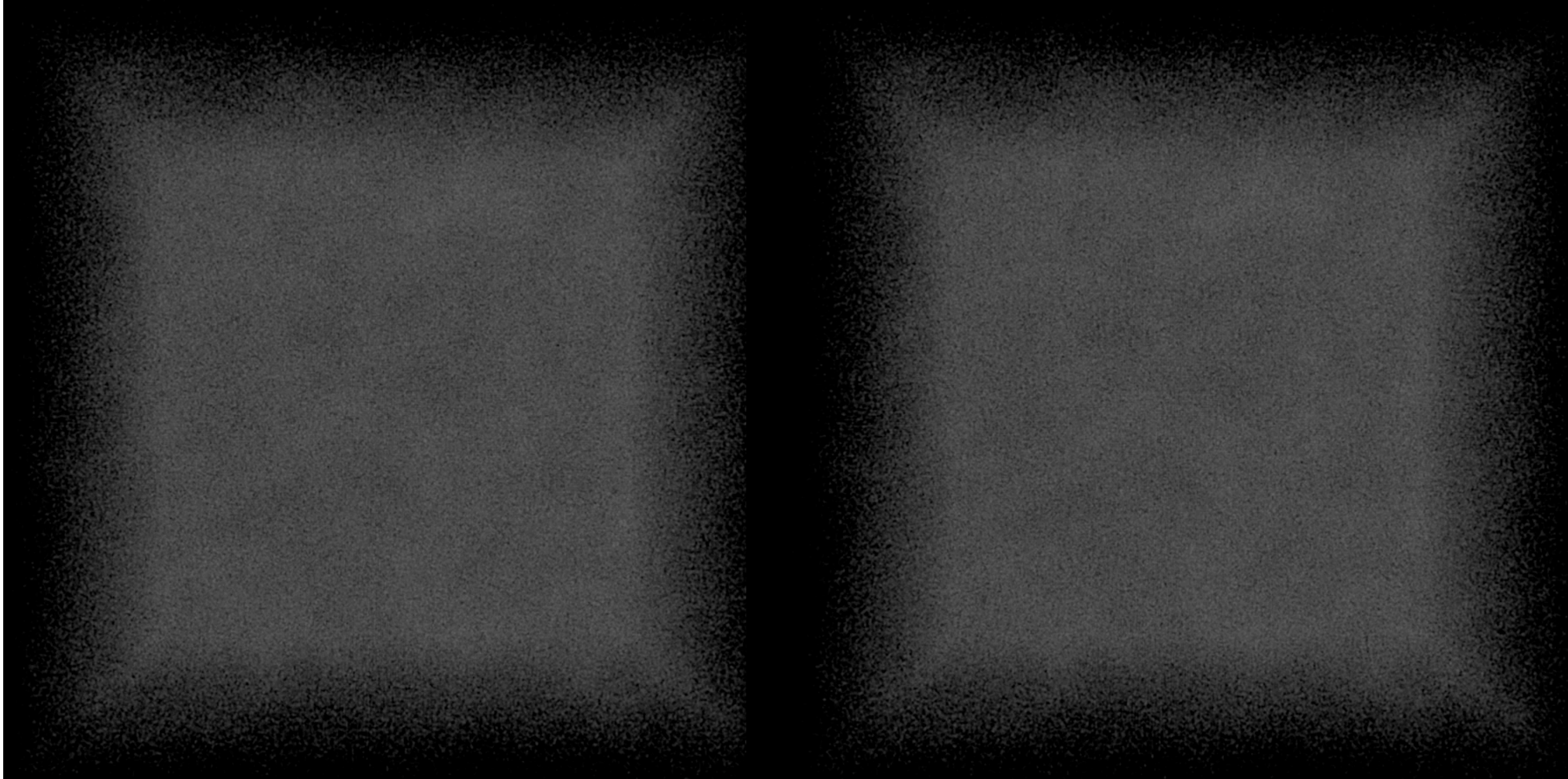
fluctuations are ~200 (gravitationally bound region)
~ 10^{32} (densest regions in the Universe)

current sims up to 1 trillion particles,
few hundred TB of RAM!
(8 billion now “standard”)



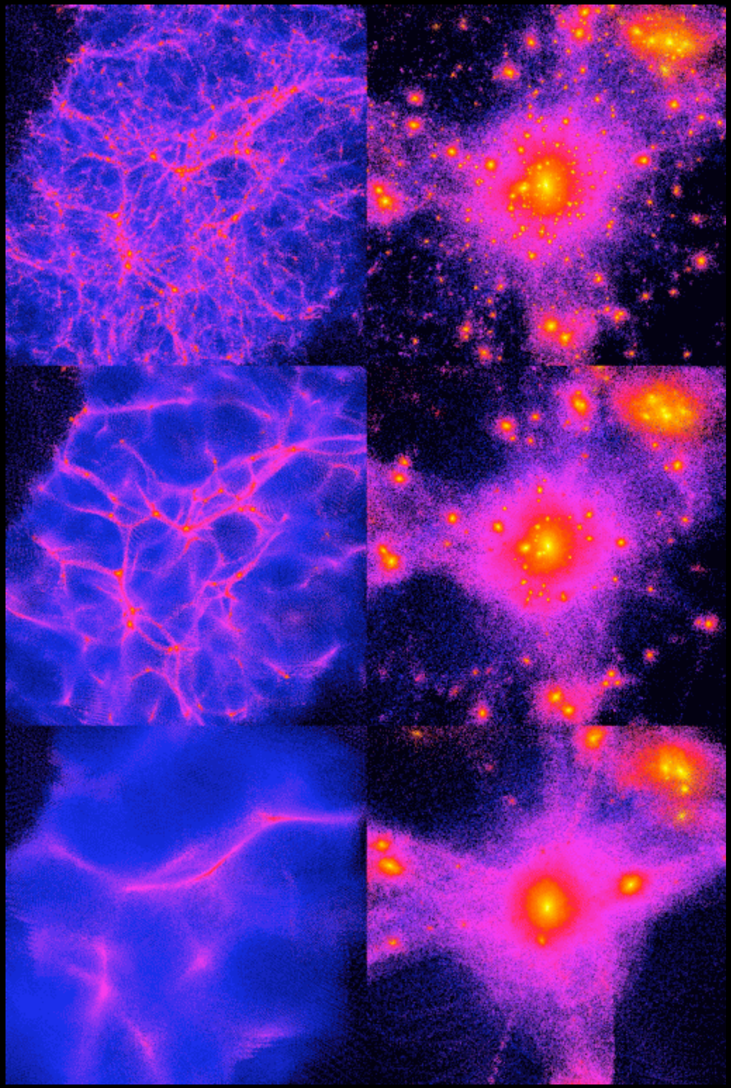
ΛCDM makes testable predictions for
structure formation on a wide range of scales
(modulo impact of baryons)

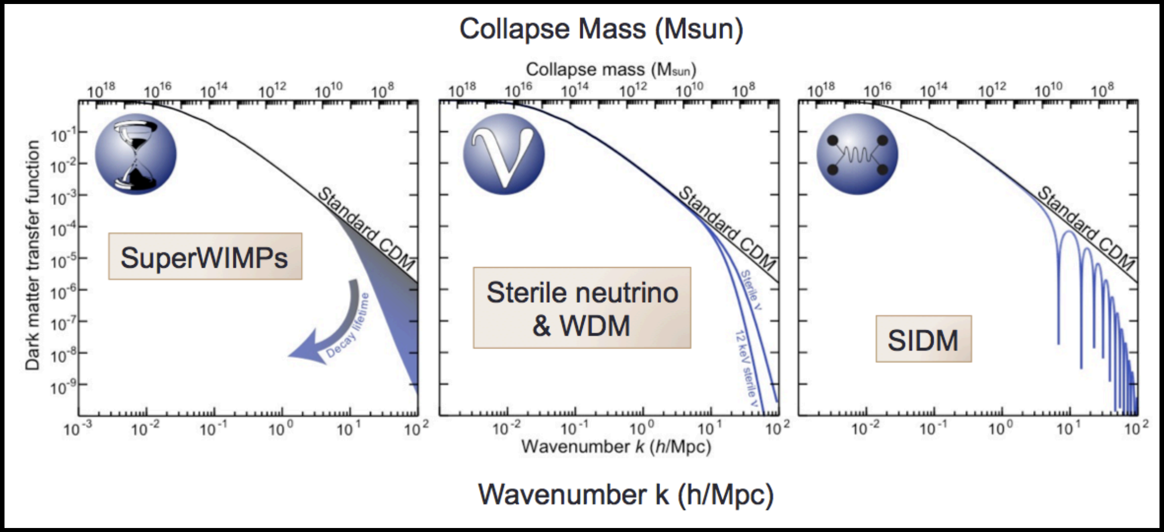
this distribution depends on cosmological parmaters
& the nature of dark matter



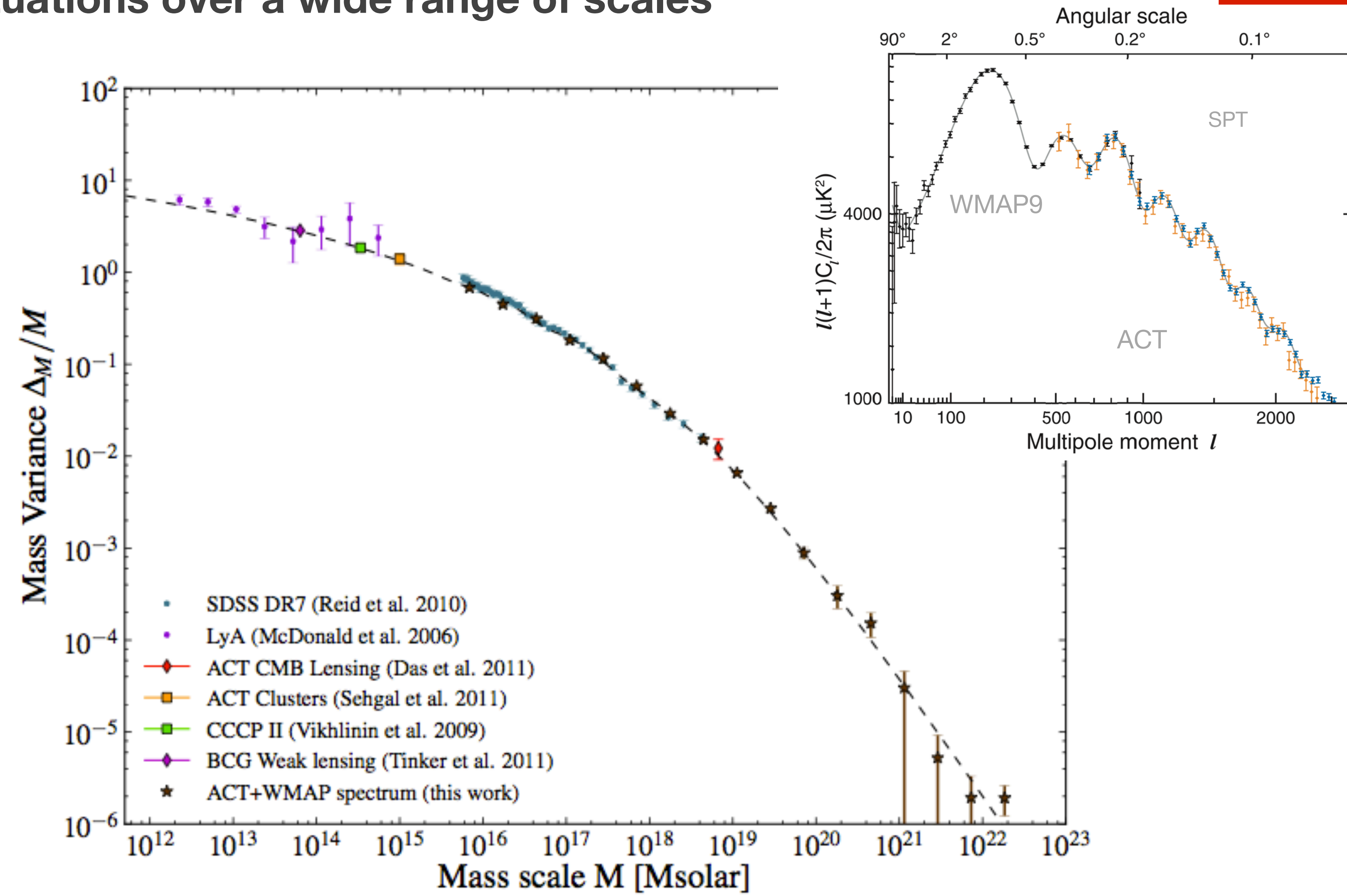
movie, simulation: Ralf Kaehler, Yao-Yuan Mao (Stanford/SLAC)

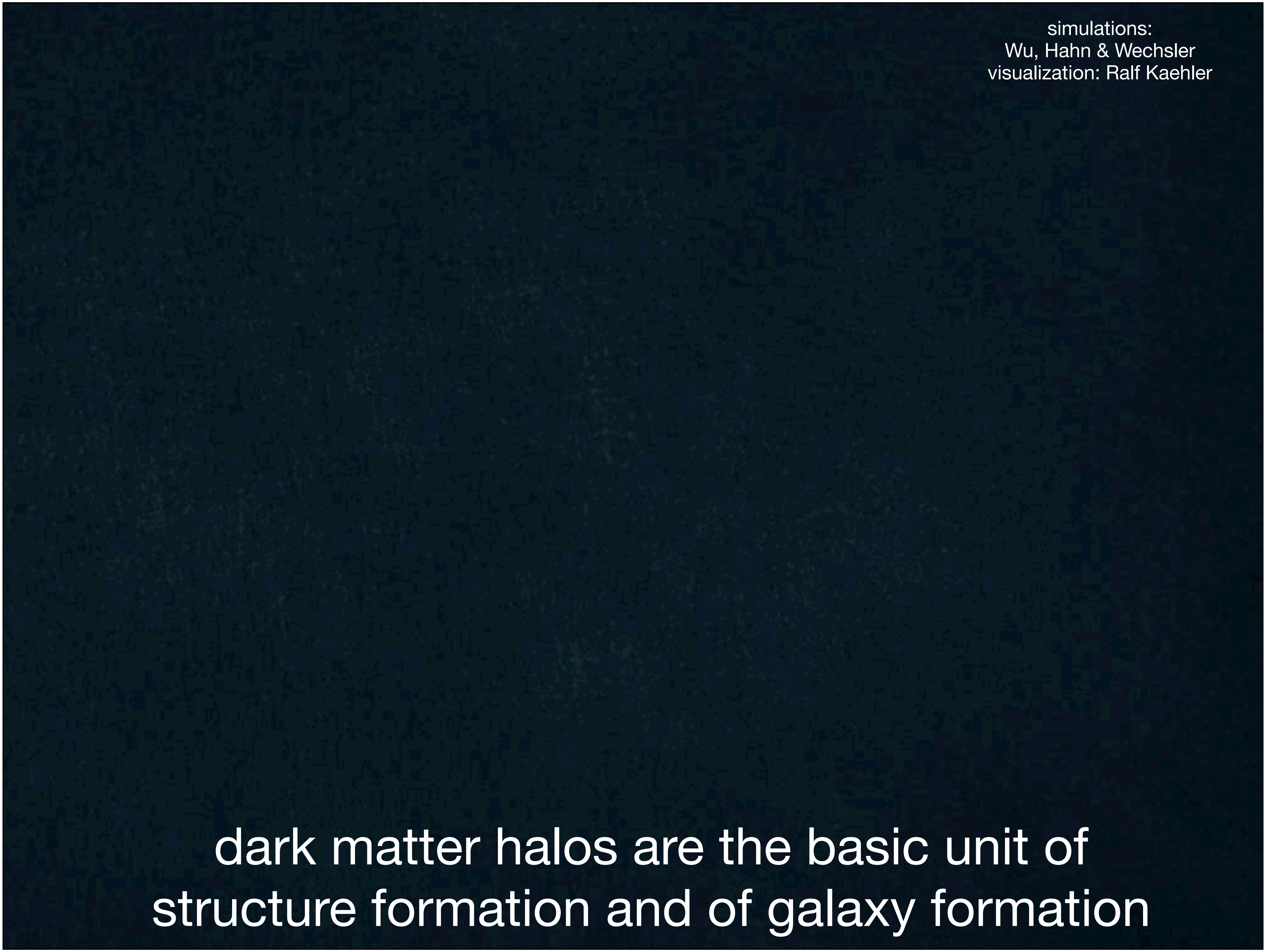
this distribution depends on cosmological parmaters & the nature of dark matter



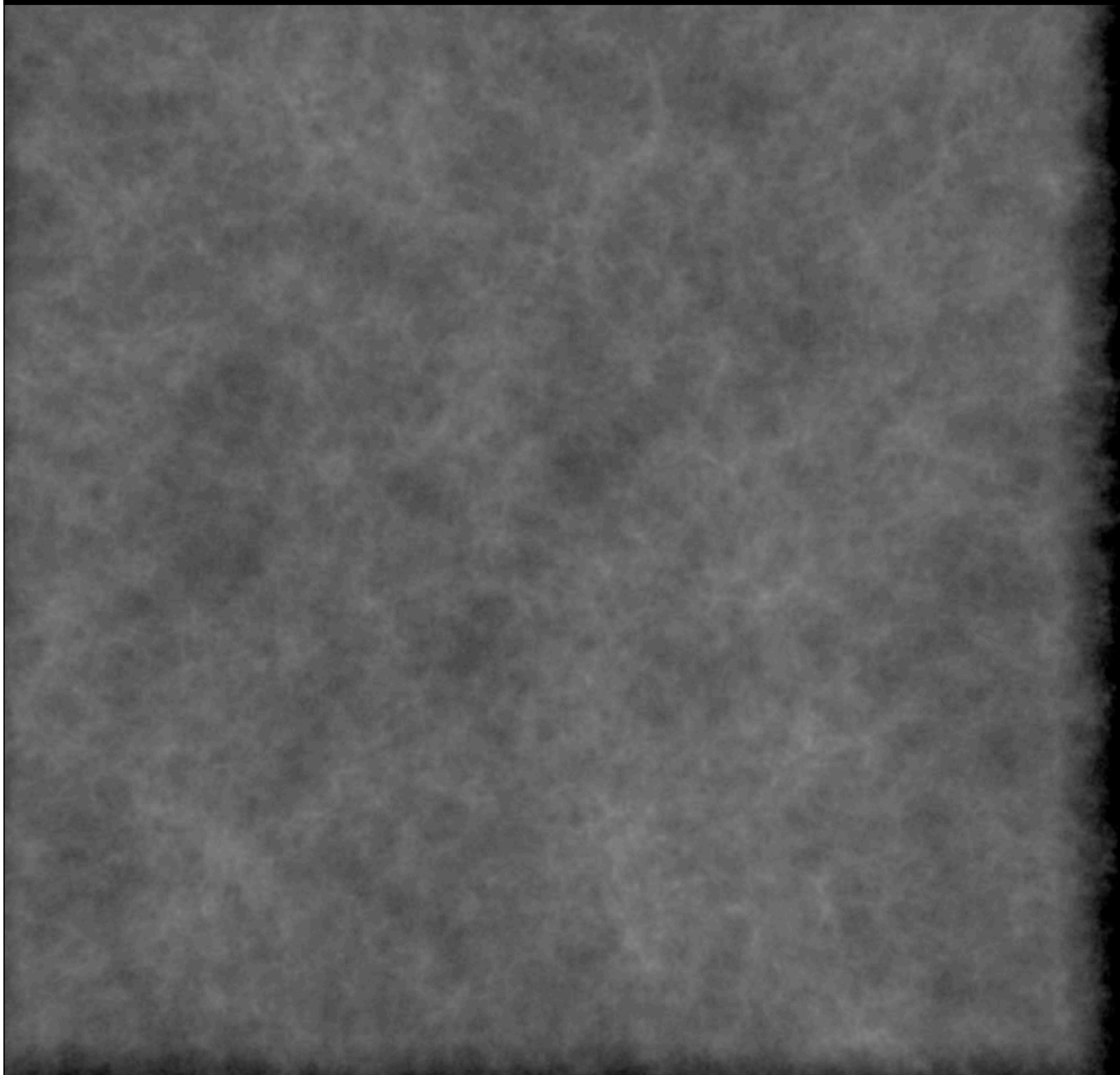


Current ΛCDM Model successfully predicts mass fluctuations over a wide range of scales



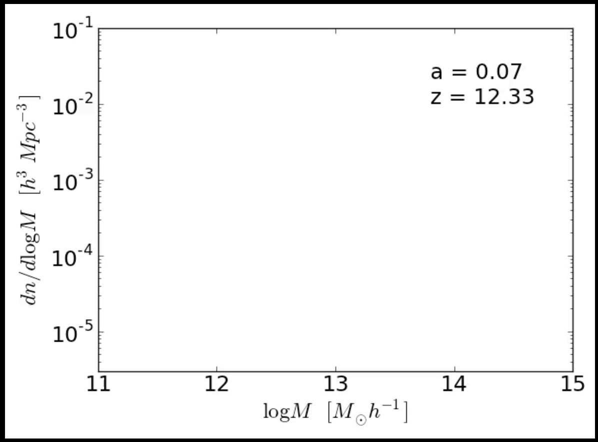

simulations:
Wu, Hahn & Wechsler
visualization: Ralf Kaehler
dark matter halos are the basic unit of
structure formation and of galaxy formation

matter distribution (180 Mpc)

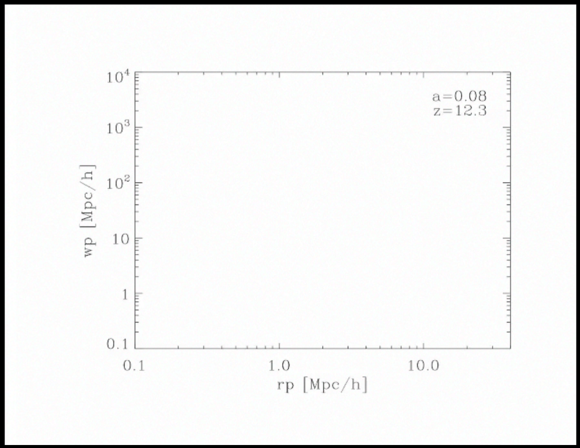


example statistics:

halo mass function

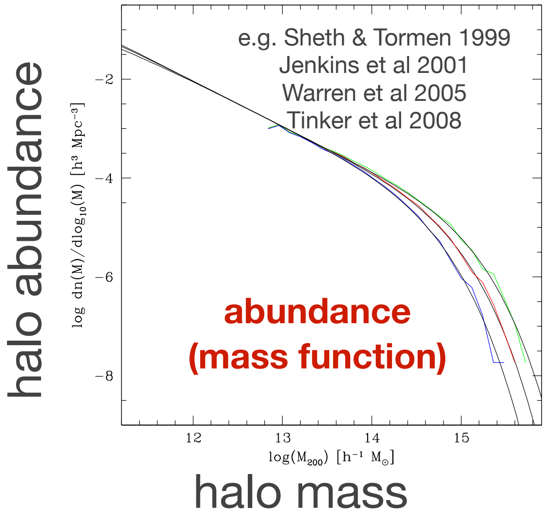


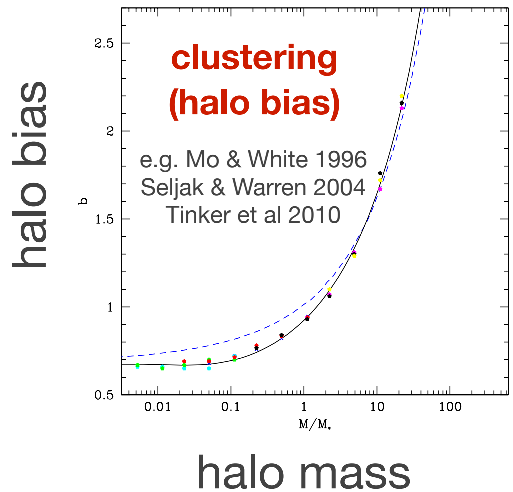
halo correlation function



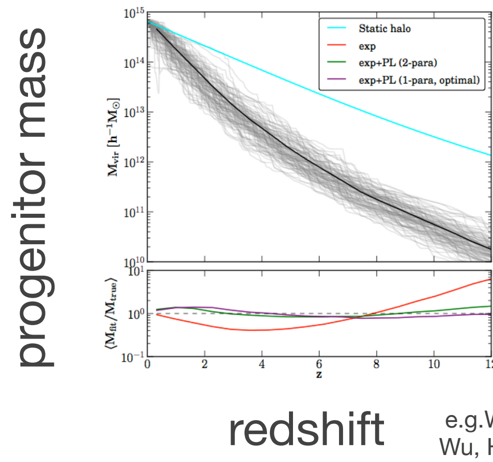
movie, simulation, statistics: Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Risa Wechsler (Stanford/SLAC)

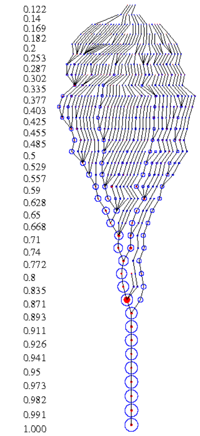
the properties of dark matter halos can be used to describe large-scale structure evolution in terms of a “halo model”





mass assembly & merger history

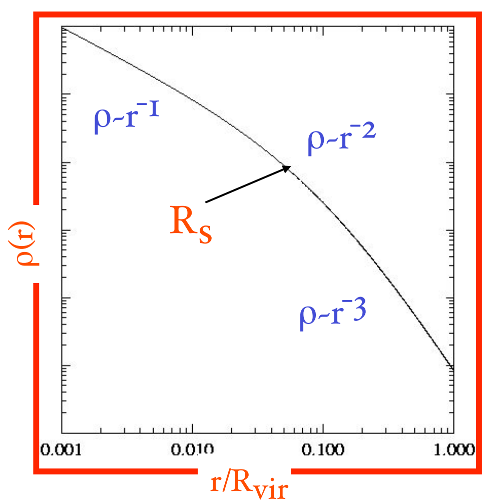




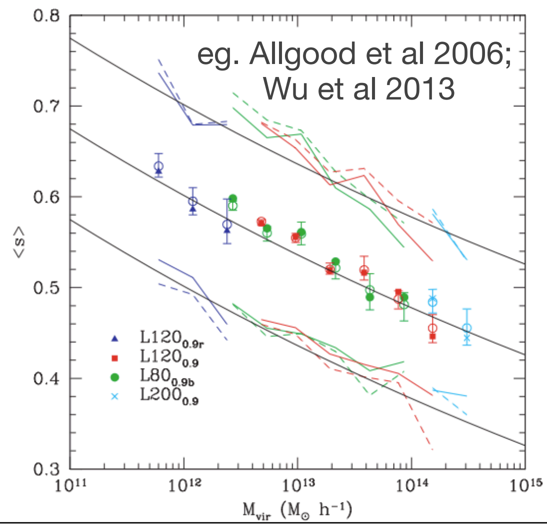
e.g.Wechsler et al 2002;
Wu, Hahn, RW et al 2012

halo density profiles

eg. NFW 96,97;
Bullock et al 2001;
RW et al 2002, 2006;
Duffy et al 2008; Wu, RW et al 2013

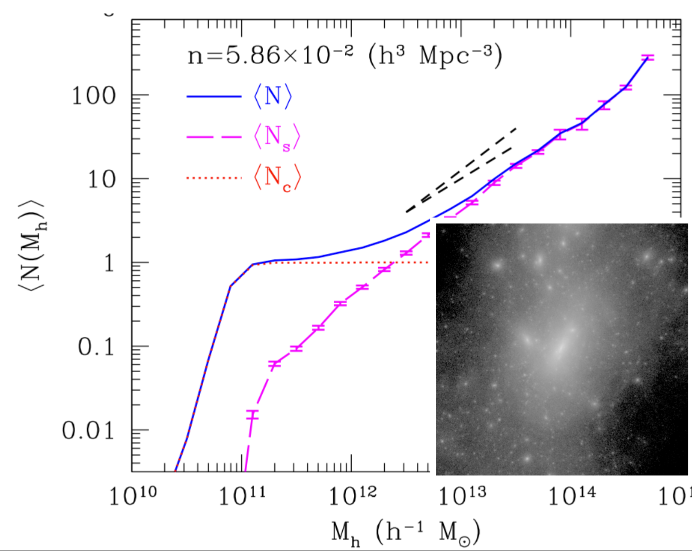


shapes



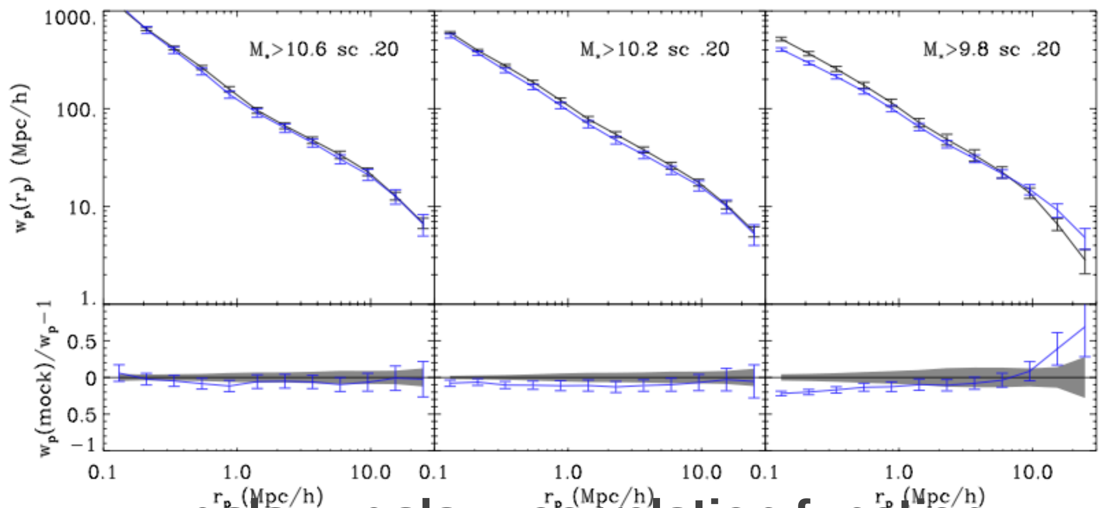
substructures

e.g. Kravtsov, Berlind,RW et al 2004; Wu, RW et al 2013b

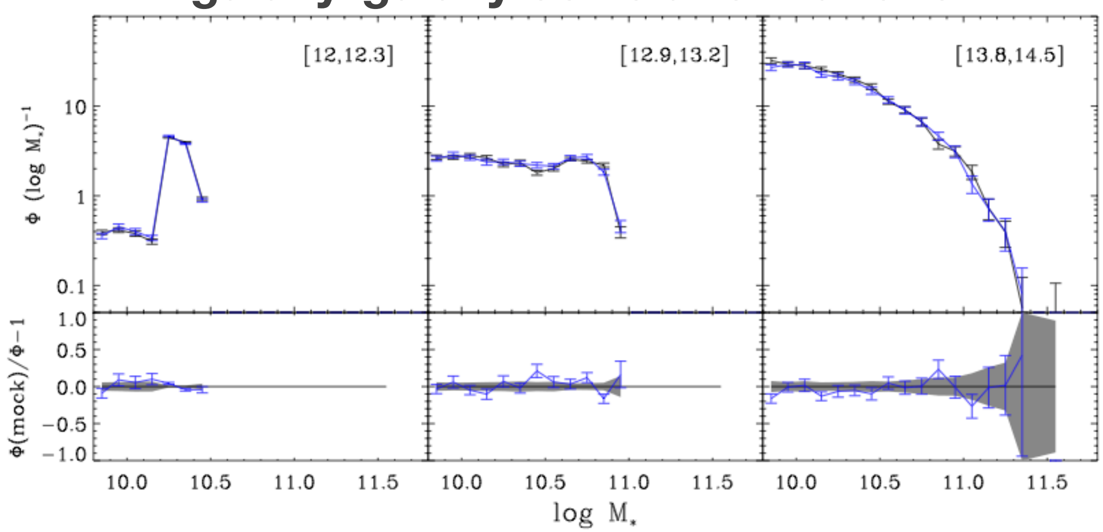


LCDM (e.g. from CMB) + simple model for the galaxy-halo connection is in excellent agreement with detailed local measurements of the galaxy distribution

Reddick, RW et al 2013



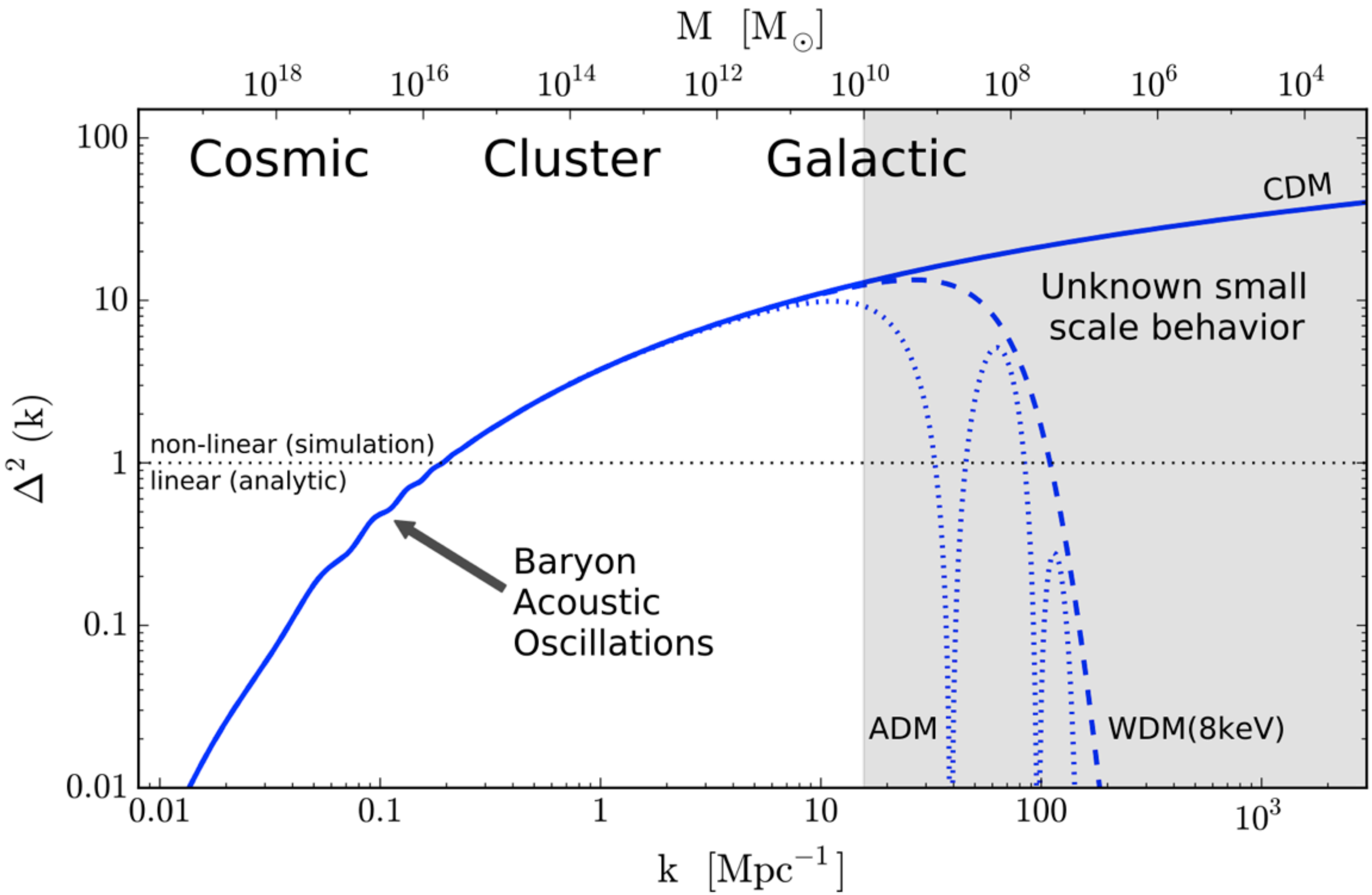
galaxy-galaxy correlation function



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})

different dark matter models primarily impact on small scales

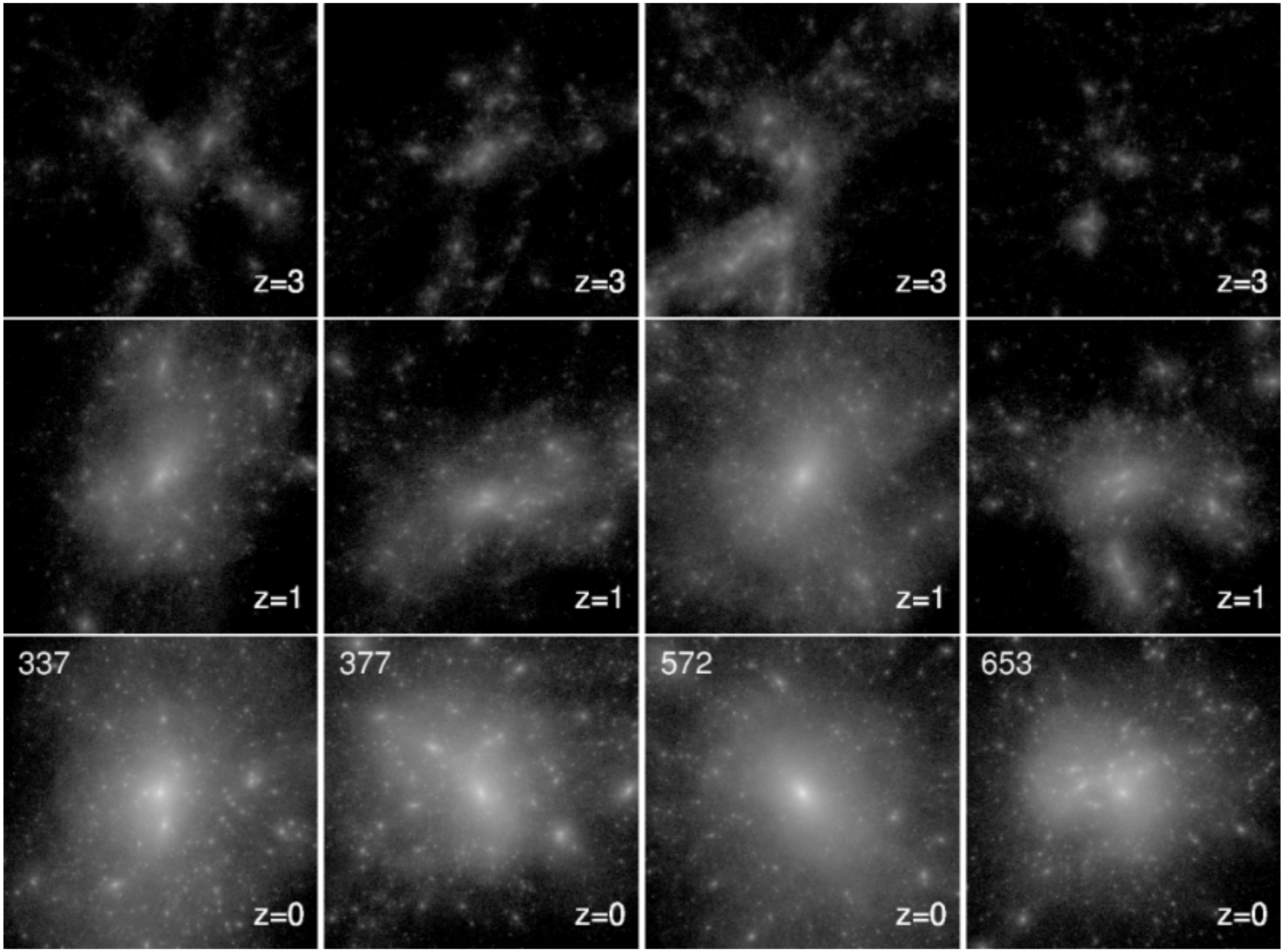


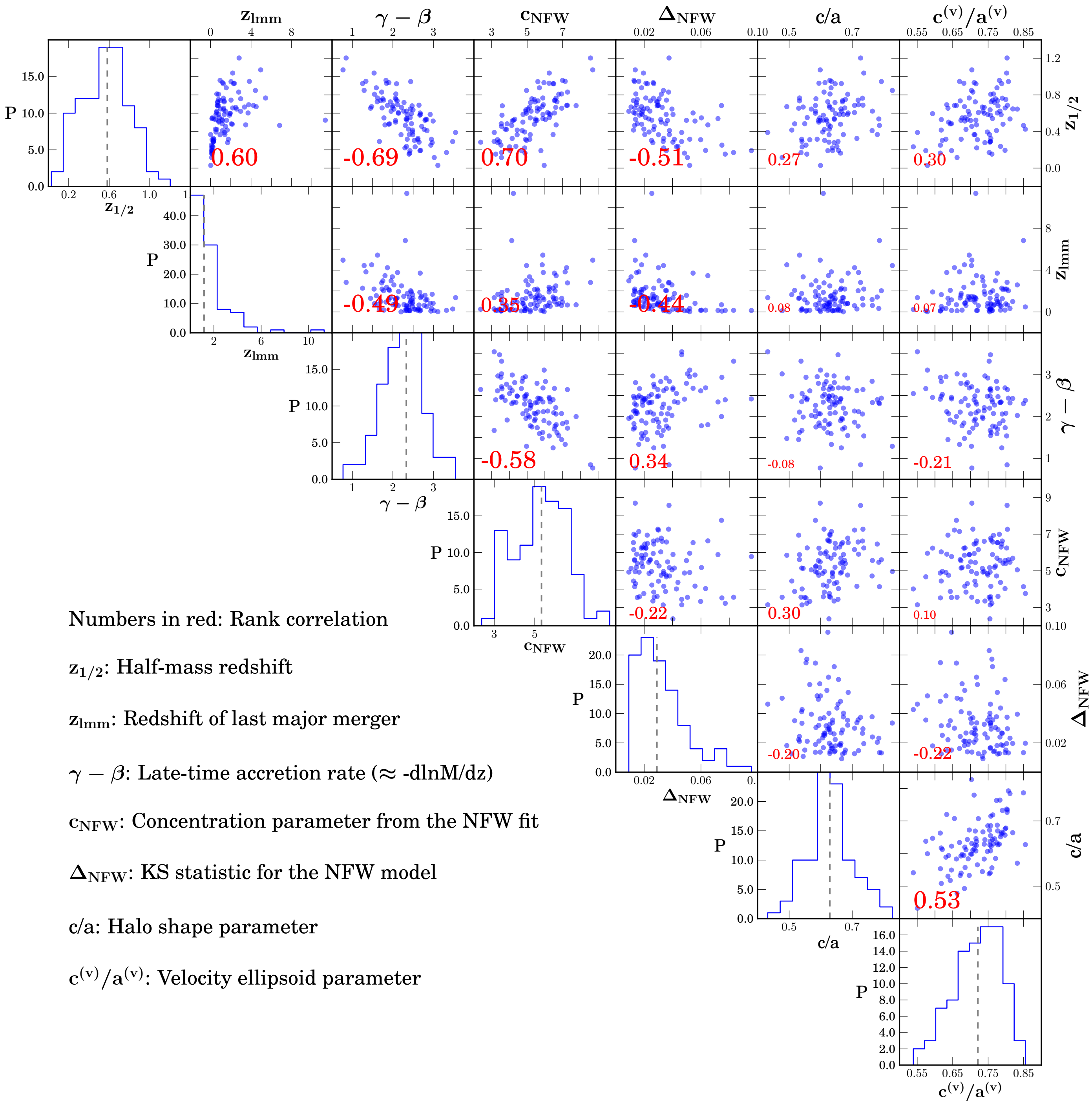
Impact of structure formation on probes of dark matter

		LSS		Halos				Substructure						Local		
		voids, walls, filaments	halo mass functions	concentration-mass relation	halo shapes	density profiles	pseudo-phase-space density	mass (or V_{max}) functions	density profiles	central density	spatial distribution	streams	folds & caustics	local density	tidal streams	dark disk
Astrophysical	Dwarf galaxy abundance				■	■		■	■	■	■				■	■
	Dwarf galaxy kinematics							■	■	■						
	Stellar streams				■	■		■			■	■				
	Gravitational lensing	■	■	■	■	■		■	■		■					
Indirect Detection	Extra-galactic DGRB	■	■	■		■		■	■							
	Galactic DGRB				■	■		■	■		■					
	Clusters			■	■	■		■	■							
	Galactic Center					■										
	Milky Way Dwarfs			■		■			■	■						
	Dark Subhalos			■		■		■	■	■	■					
	Local anti-matter													■		
	Neutrinos from Earth & Sun													■	■	■
	Substructure boost							■	■		■		■			
	Sommerfeld boost						■					■	■		■	■
Direct	"Vanilla" ~100 GeV DM													■		
	light / inelastic DM													■	■	■
	axions												■	■	■	■
	directionally sensitive experiments													■	■	■

Kuhlen, Vogelsberger & Angulo 2012

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

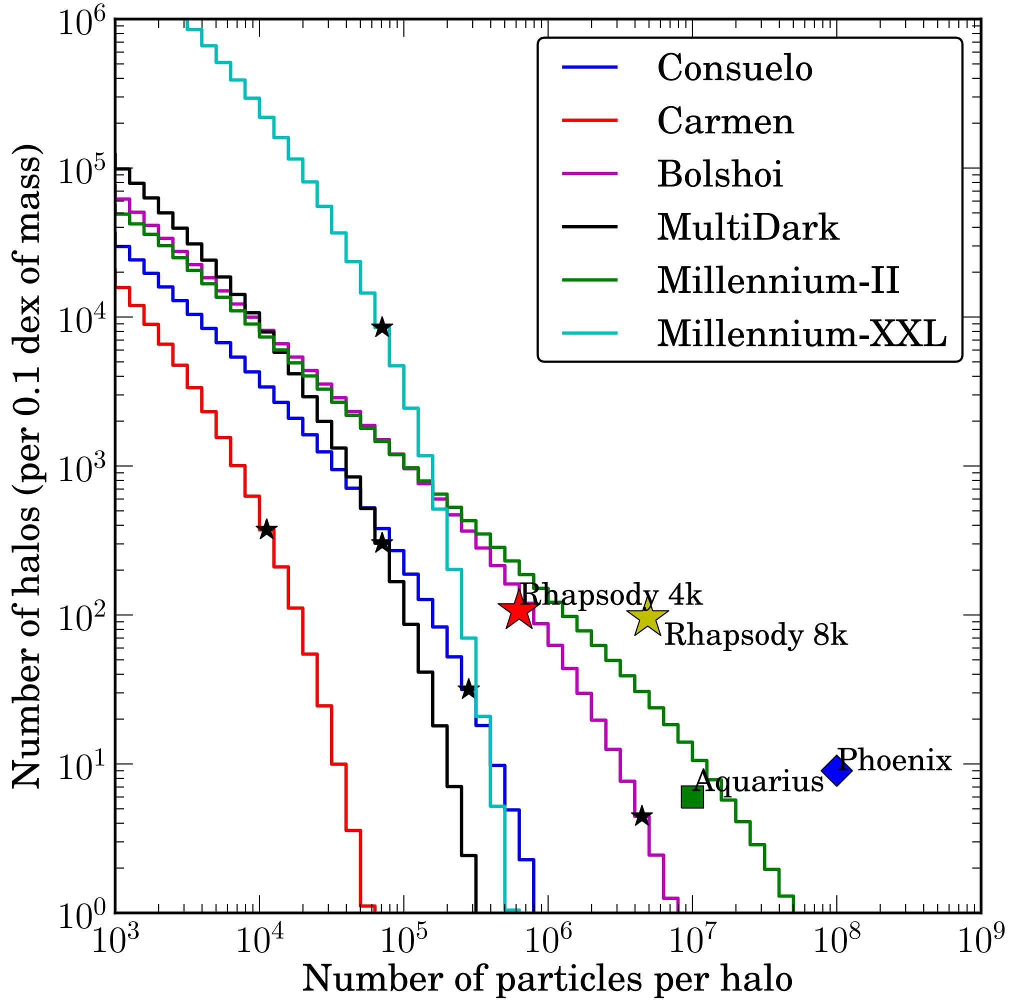
Wu, Hahn, RW, Mao, Behroozi 2013

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

Still hard to get both statistics & resolution



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

for the rest of the talk I will focus primarily on one statistic as an example:

velocity distribution of dark matter in halos

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?)

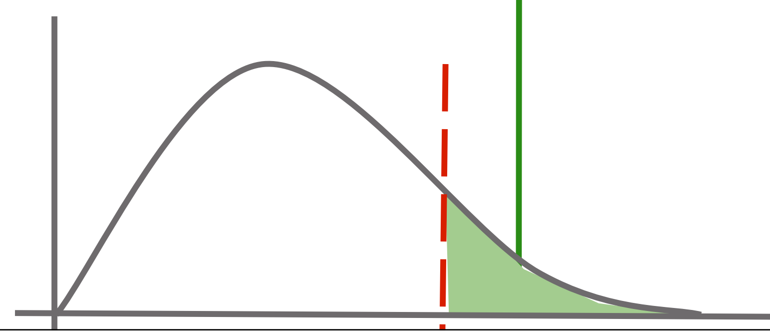
Direct detection of dark matter

- the differential event rate of the dark matter -- nucleon collision depends on the **Galactic velocity distribution function** (VDF) of dark matter particles that go through the detector
- The relevant quantity:

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

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

$$g(v_{\rm min}, \mathbf{v_e}) =$$

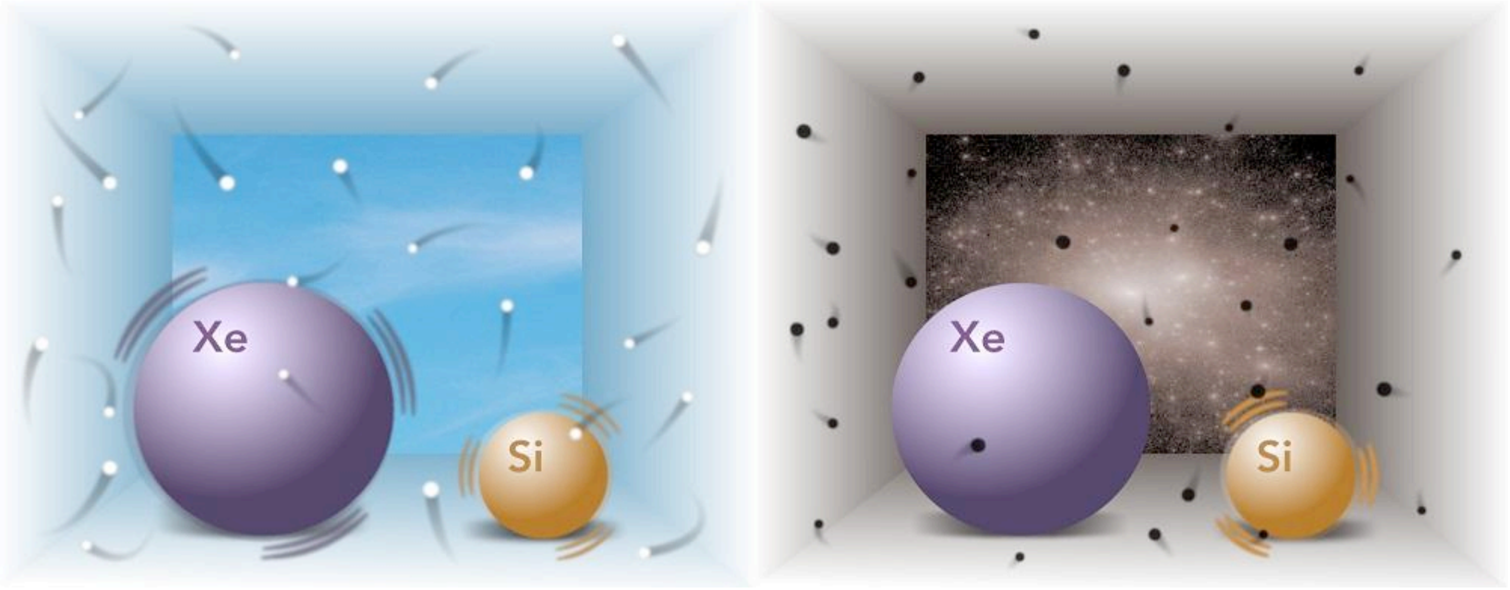


Does the VDF really matter?

Yes, especially for larger v_{min} & especially for comparing experiments.

(relevant for a light WIMP, heavy target, or a high recoil energy)

$$v_{\rm min} = \sqrt{\frac{E_{nr} m_n}{2\mu^2}}$$



[Greg Stewart/SLAC National Accelerator Laboratory]

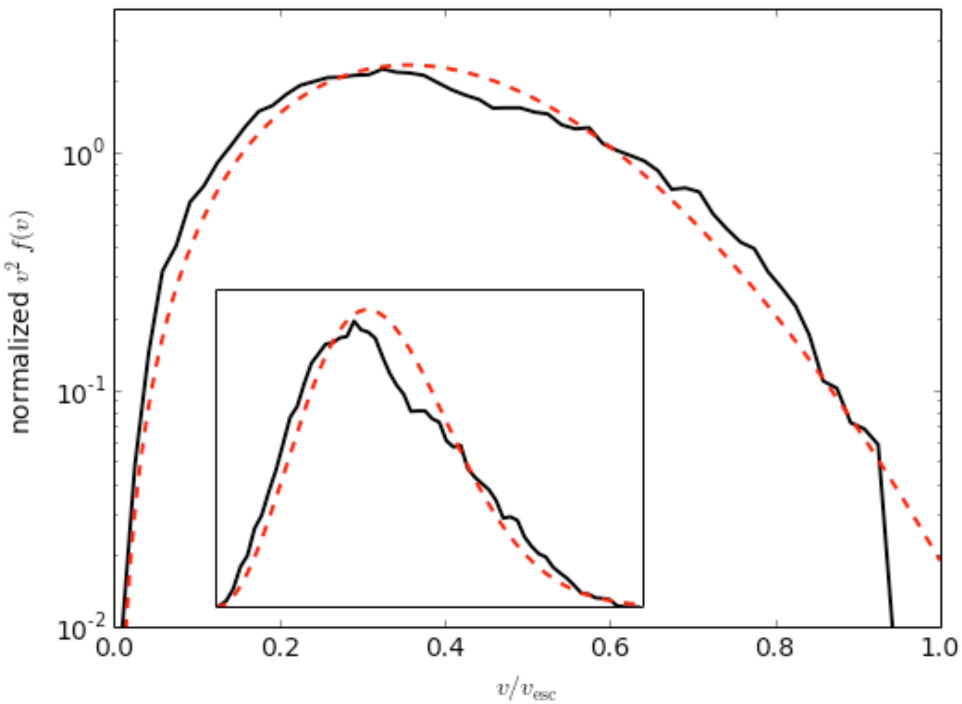
Analytic Calculation of VDF

$$f(v) \propto \exp\left(-\frac{v^2}{v_0^2}\right)$$

- "Standard Halo Model"
  (Maxwell-Boltzmann distribution with a cutoff at escape velocity)

- Assumptions:
  - steady-state
  - spherically symmetric
  - isotropic
  - isothermal

$$\rho(r) \propto r^{-2}$$

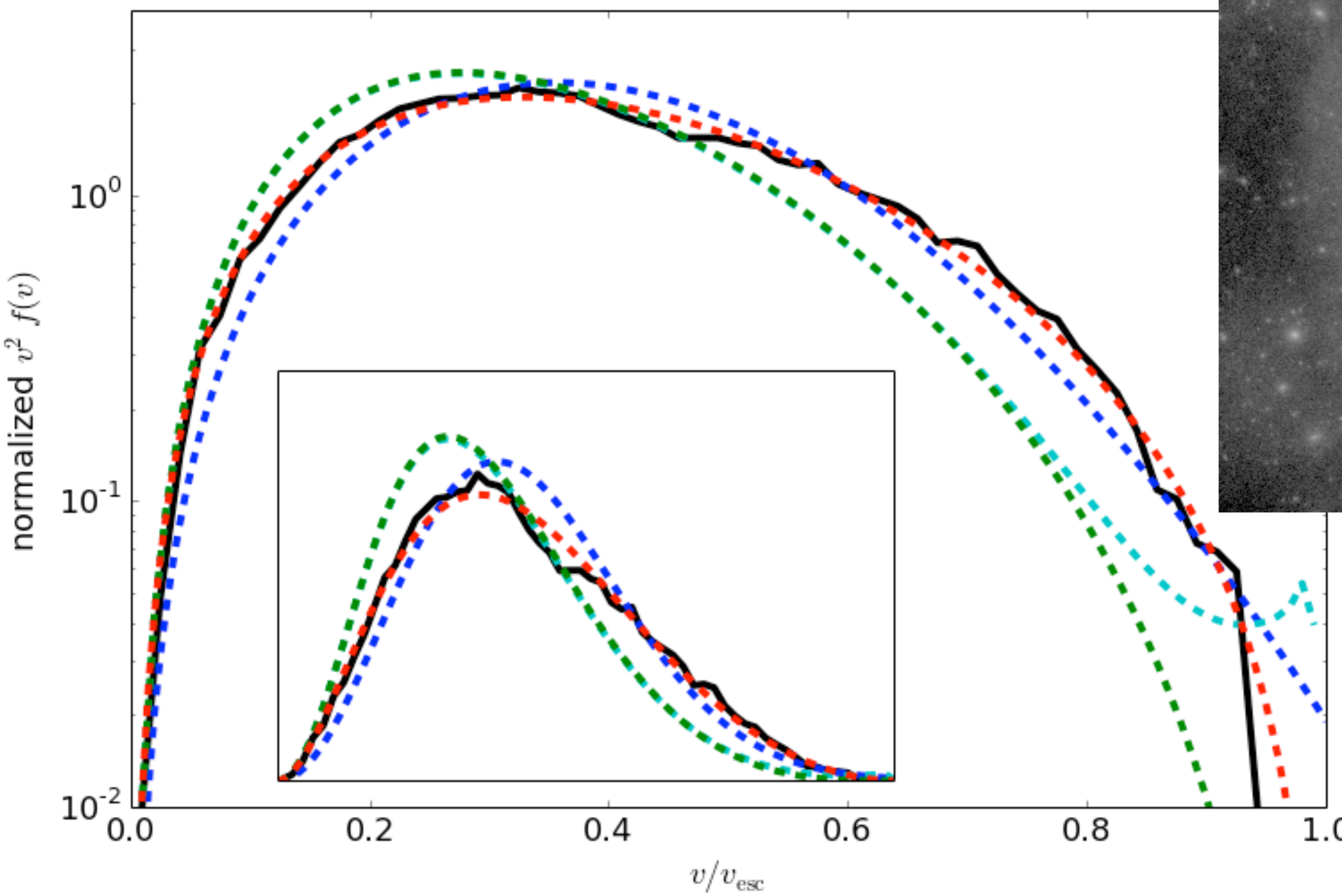


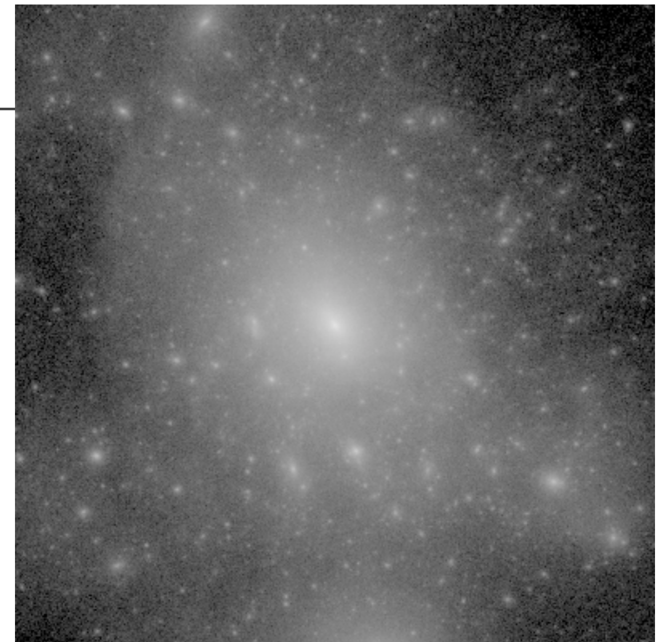
The assumptions of isotropic and isothermal can be removed, but the VDF still does not match simulations.

[Mao, Strigari, RW, Wu, Hahn, ApJ (2013)]

New VDF Model

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





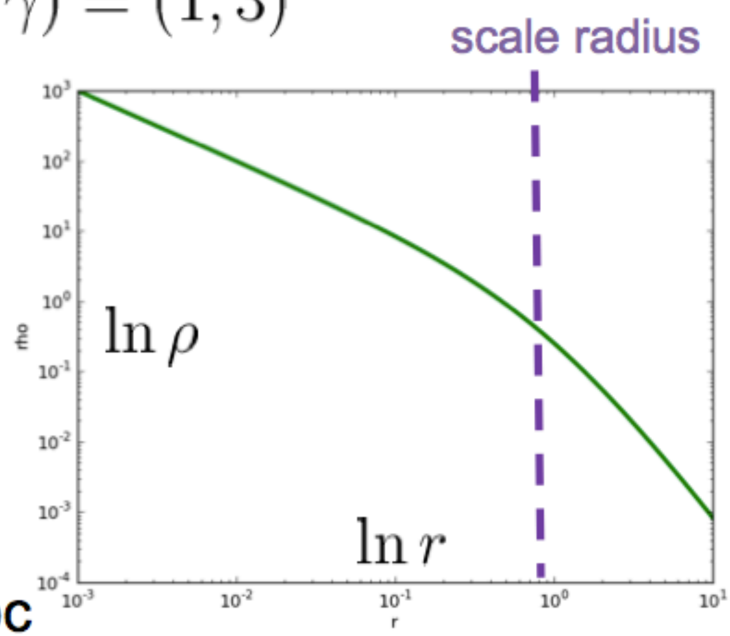
Simulation
Our Model
Standard Halo
Eddington (Isotropic)
Osipkov--Merritt

Density profile of the Milky Way

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

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

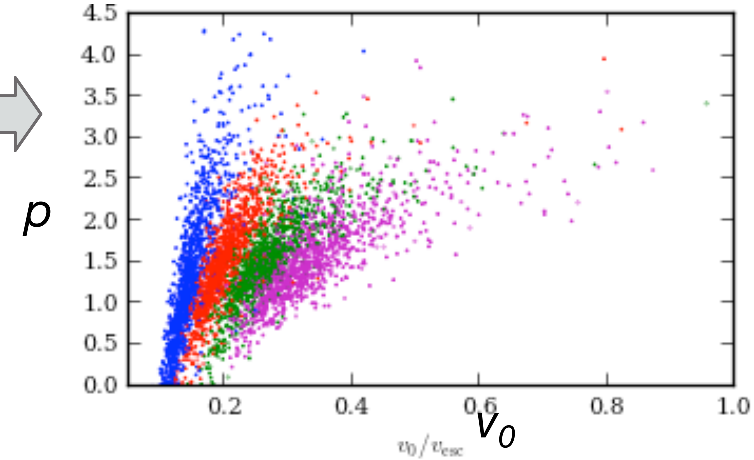
- Universality in VDFs
  if radii normalized by scale radius
  - r/r_s : most important quantity determining potential



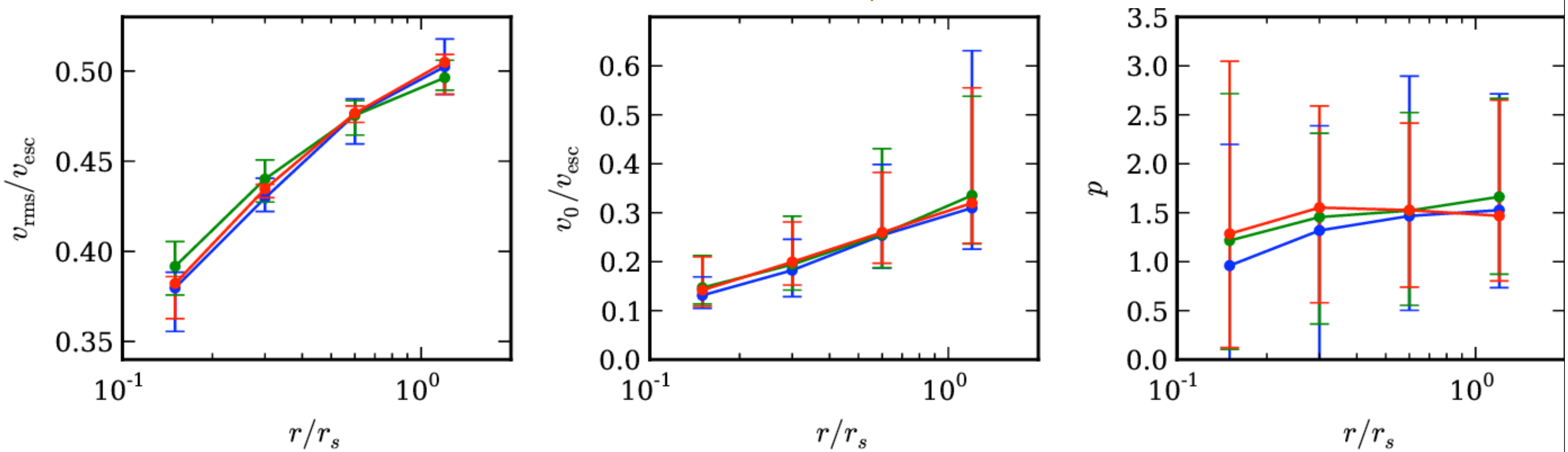
- Solar system at r = 8 kpc
  Current constraints on r_s ~ 13 – 55 kpc
  ⇒ r/r_s ~ 0.15 – 0.6

peak of the VDF is set by position of earth wrt density profile. tail set by disrupted satellites?

Distribution of VDF Parameters (v_0, p)
Colors labels different r/r_s



v_{rms}, v_0, and p as a function of r/r_s
Colors labels different halo masses



[Mao, Strigari, RW, Wu, Hahn, ApJ (2013); Mao, Strigari, RW, arXiv:1304.6401]

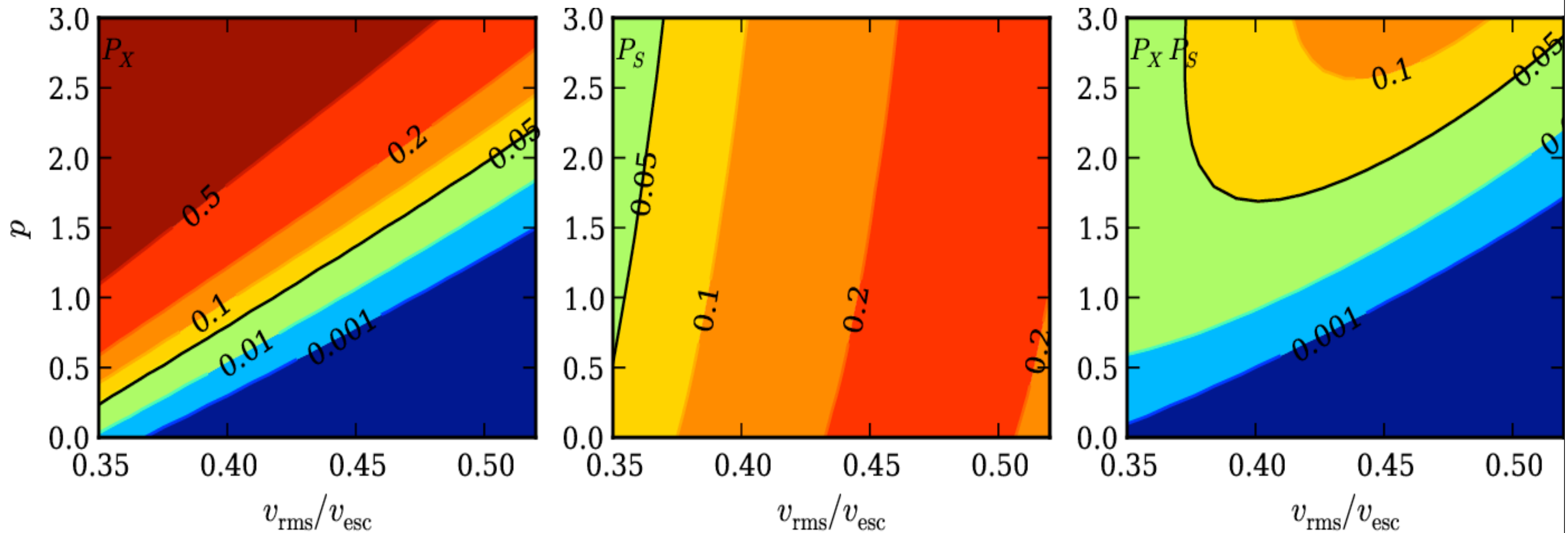
The Impact of VDF on Experiments

[Mao, Strigari, RW, arXiv:1304.6401]

Contours of probabilities on the parameter space:

- Ranges of parameters from DM simulations.
- Two *mock* experiments set up; SHM completely ruled out their compatibility.
- Assuming sharp energy thresholds: 6 keVnr for target Xe; 7 keVnr for target Si

Px = target Xe sees 0 event   Ps = target Si sees 3 event   Px Ps = joint probability

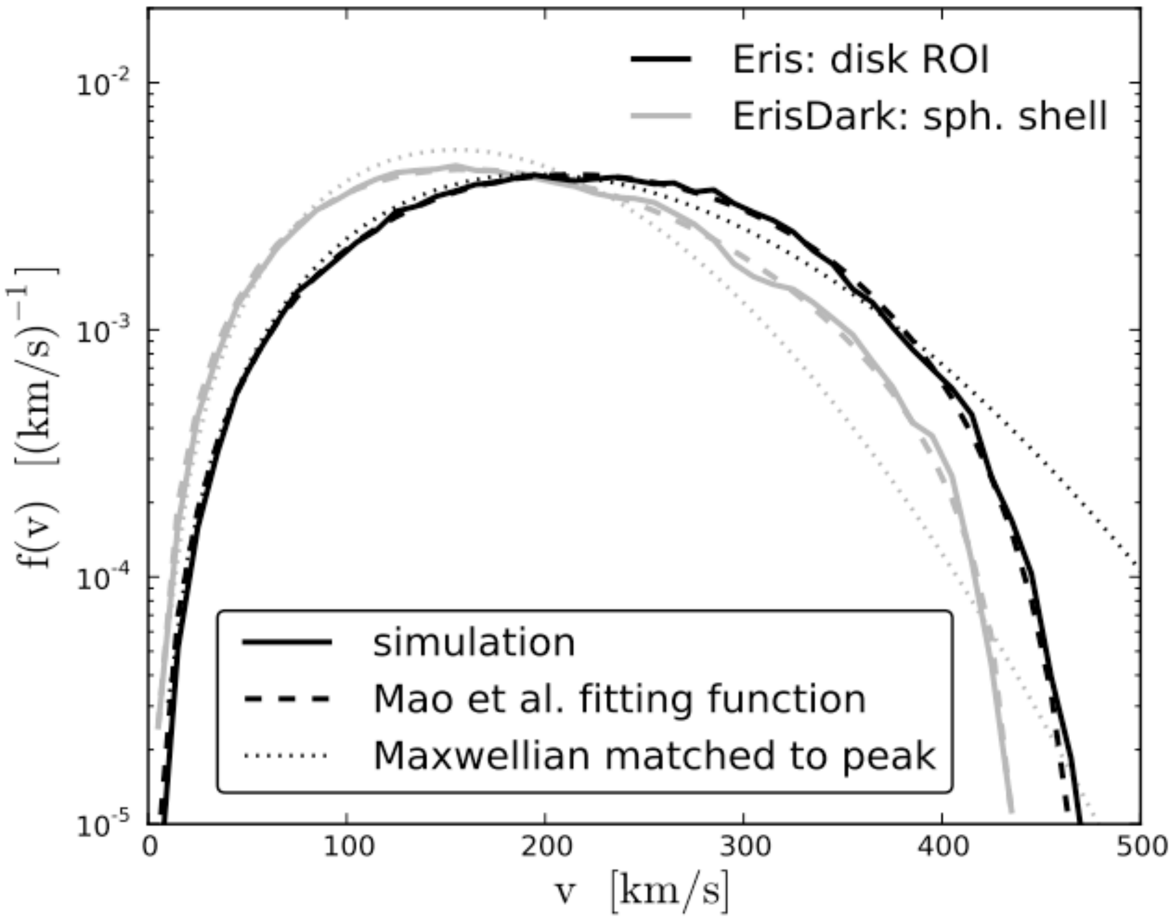


[Mao, Strigari, RW, Wu, Hahn, ApJ (2013)]

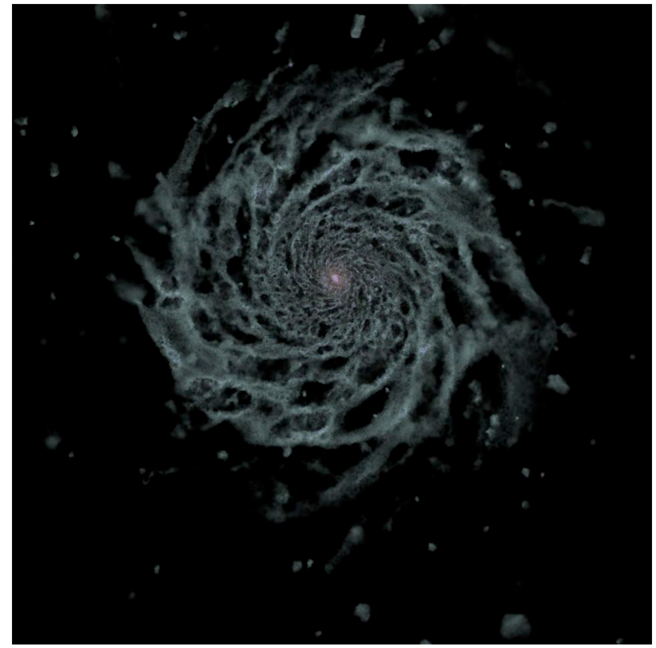
New VDF Model

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

with and without baryons



[Kuhlen, Pillepich, Guedes, & Madau, arXiv:1308.1703]



[Eris Simulation: Guedes, Callegari, Madau, Mayer (2011)]

The Impact of VDF on Experiments

[Mao, Strigari, RW, arXiv:1304.6401]

Crosses indicate the parameter fits from Eris (upper) and ErisDark (lower)

Contours of probabilities on the parameter space:

- Ranges of parameters from DM simulations.
- Two *mock* experiments set up; SHM completely ruled out their compatibility.
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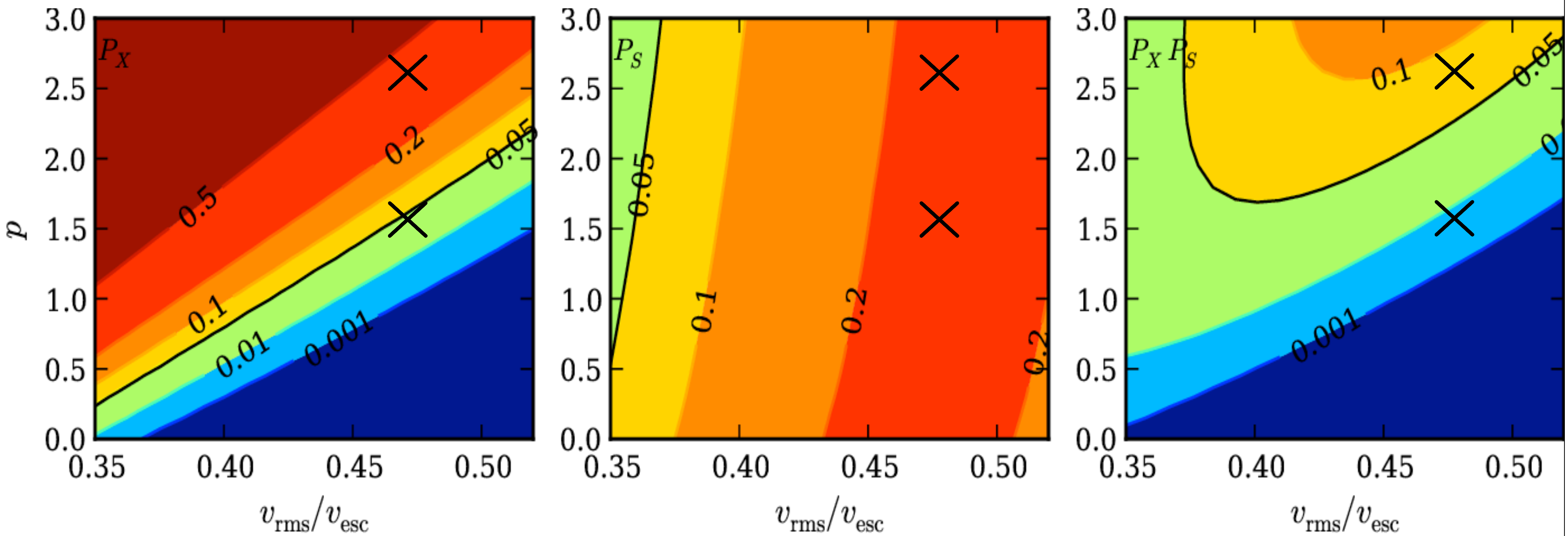
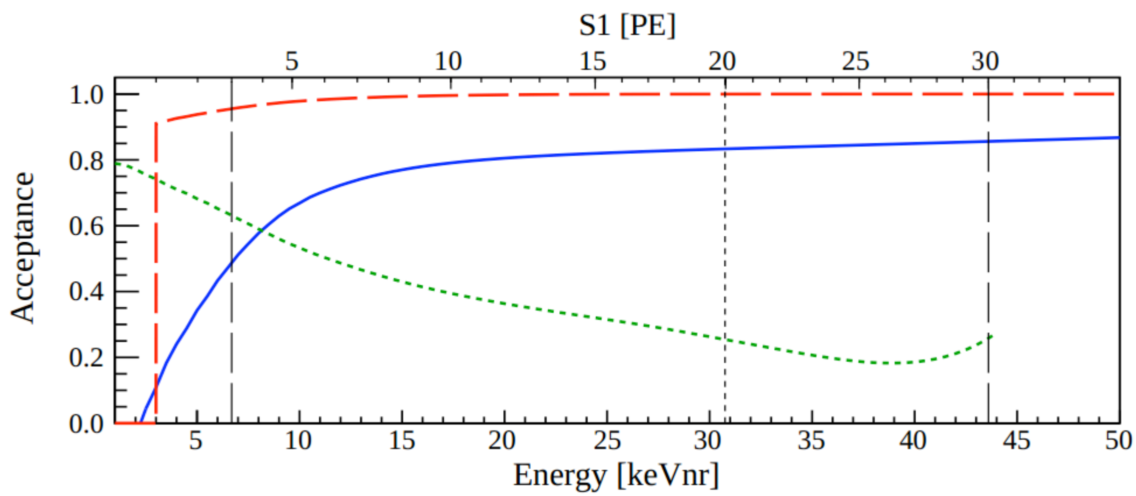


Not the end of the story...

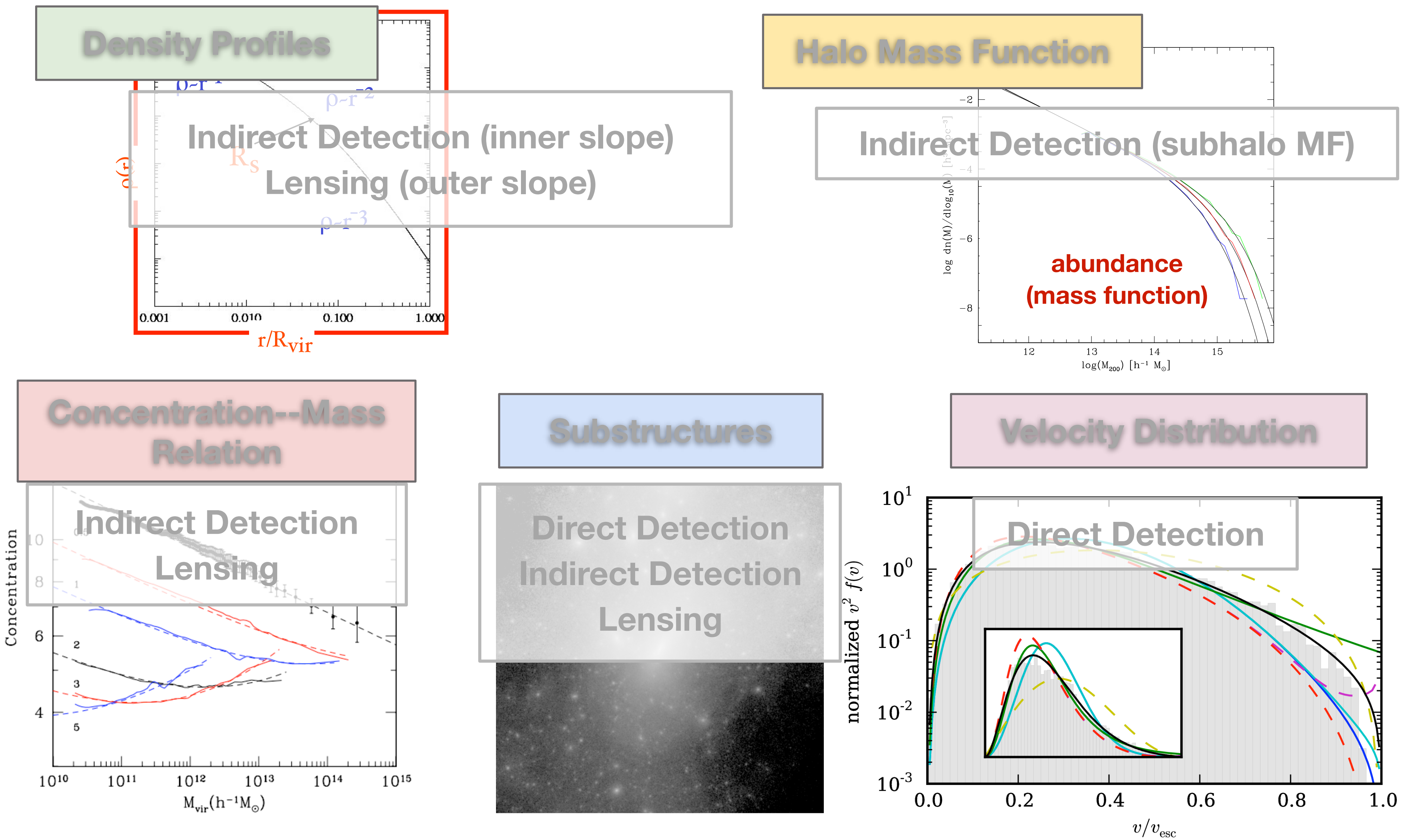
Here I have discussed a cosmologically motivated VDF, along with the priors on the parameters. **Future experiments should include the uncertainty in VDF in the analysis**! Similar things are true for other predictions from structure formation!

In this case, the tension between XENON100 and CDMS-II comes ONLY from the results at 2 to 6 keVnr of XENON100



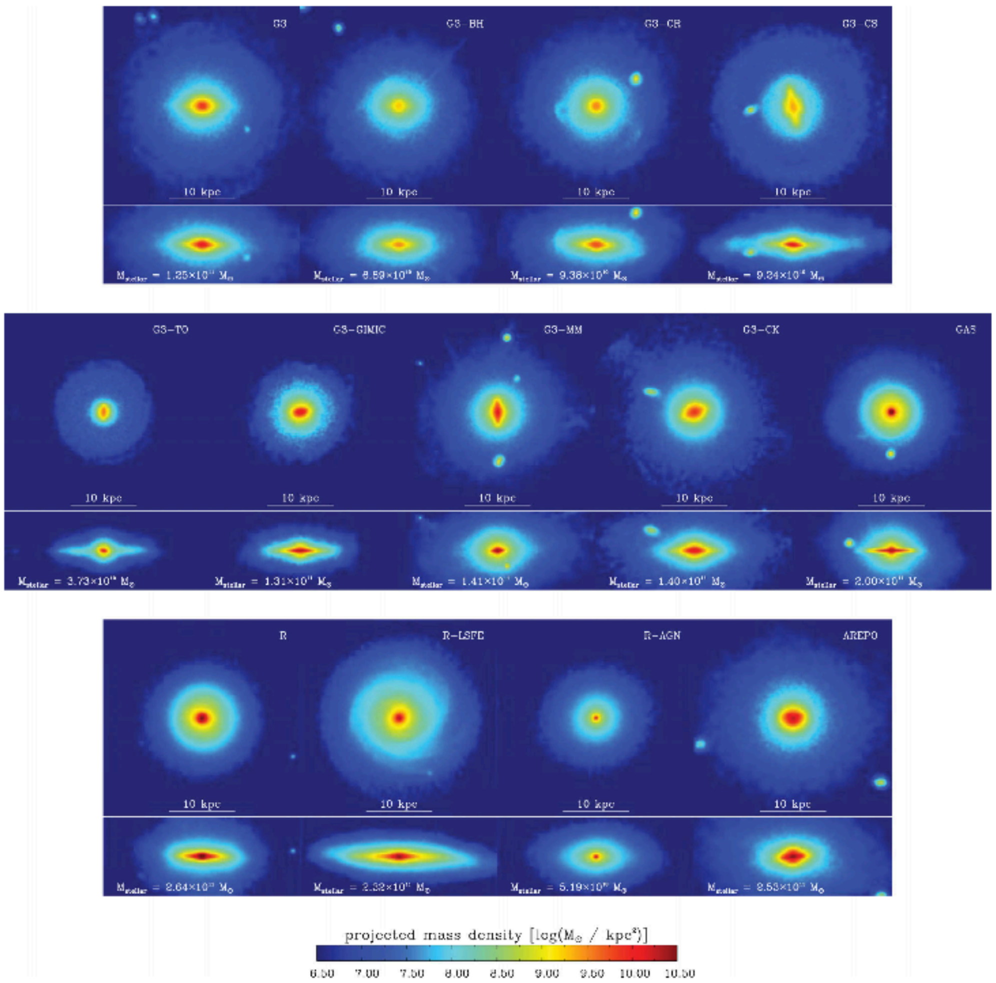
[XENON100 Collaboration, PRL (2012)]

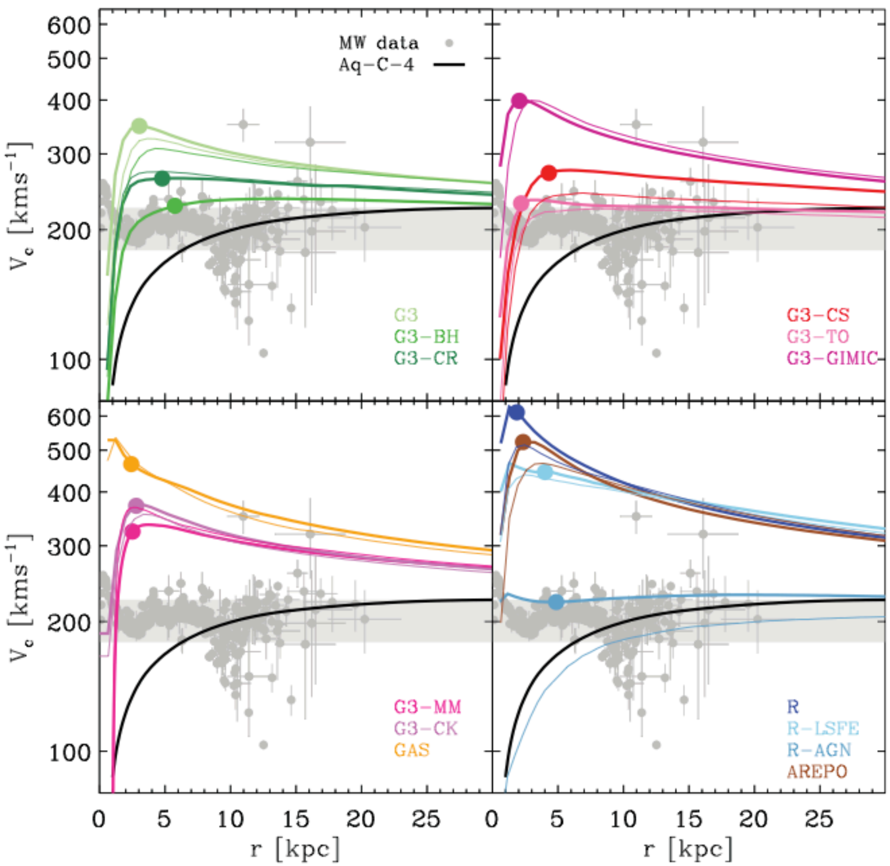
Just scratched the surface here...



uncertainty in impact of baryon physics

Scannapieco et al 2012, comparison of 13 Milky Way runs with same DM history

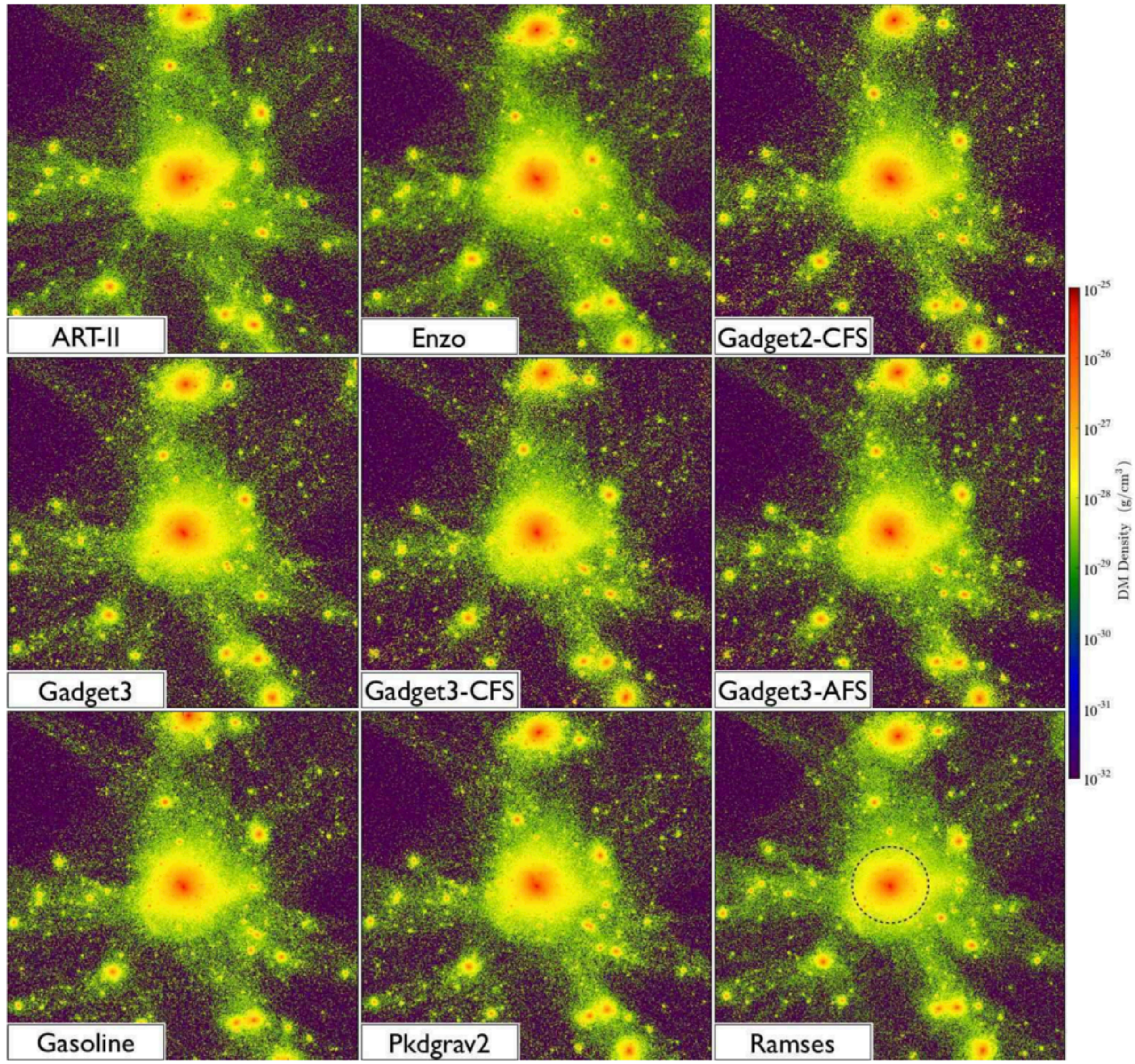




comparison of multiple codes with high res baryonic physics: AGORA project

Kim et al 2013

(project just getting started)



Summary

- LCDM incredibly successful (at least down to the scale of ~ 10^{11} M_{sun})
- Below this scale viable and interesting dark matter models can make different predictions
- Predictions of dark matter structure formation are essential for understanding constraints on dark matter from direct detection, indirect detection, and numerous astrophysical probes (e.g. lensing, rotation curves)
- These measurements are becoming more precise and require halo models:
  - that are more precise and accurate
  - in which we can characterize their uncertainties
  - where we understand the impact of baryons and of diversity between systems
- Velocity distribution function as an example:
  - New analytic form for the VDF for realistic DM halos which is in good agreement with the measured VDF in cosmological simulations
  - difference from SHM has impact for rates and in particular when comparing once DM experiment to another!
- What's next?
  - full resolution range of interest for the full variety of halos is still beyond computational capabilities, but this is progressing
  - lots to do to investigate alternative dark matter models (WDM, SIDM, etc etc)
  - significant progress in understanding impact of baryons, but lots to do here!