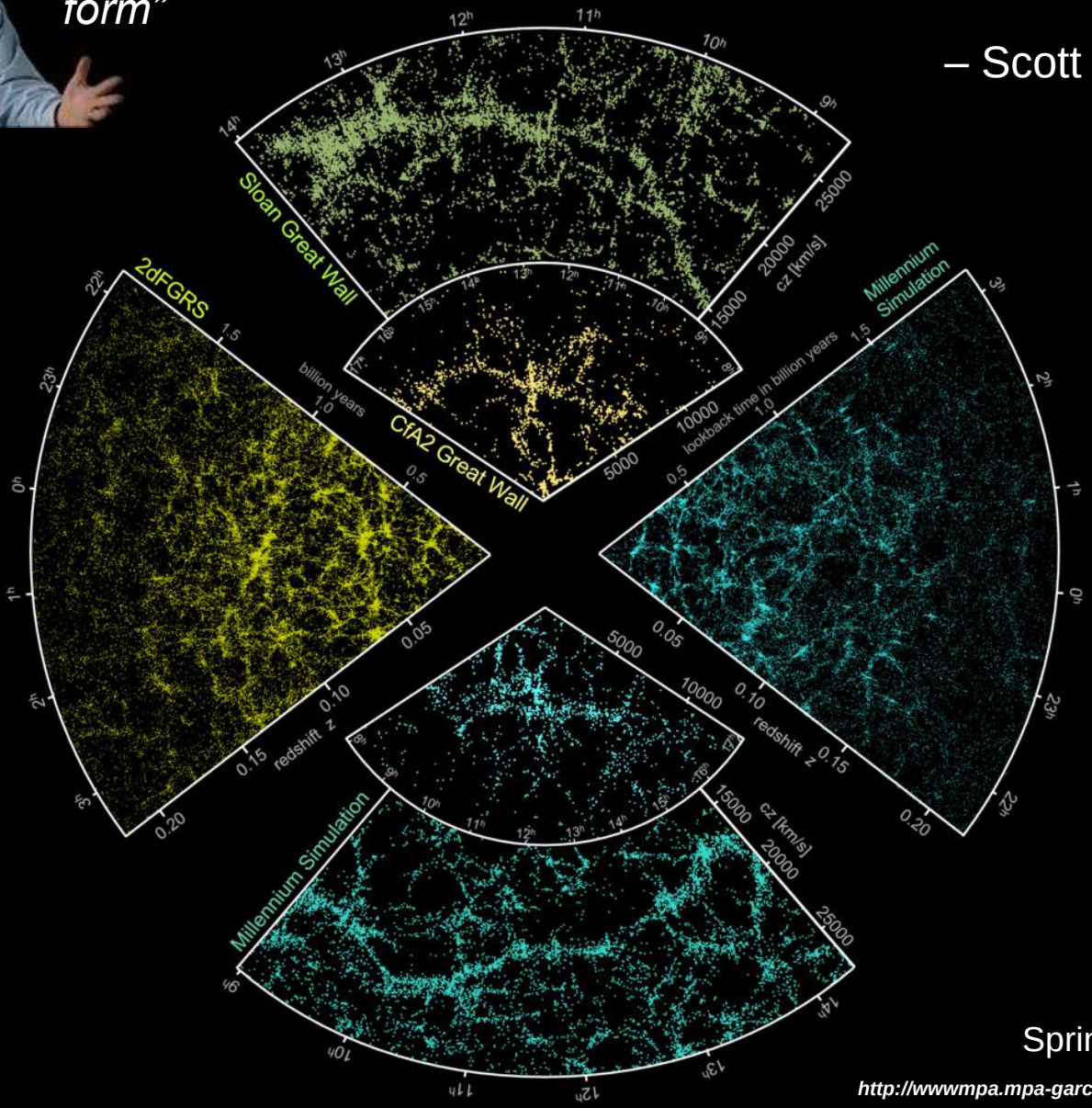
The future of structure formation

Andrey Kravtsov

It’s difficult to make predictions, especially about the future
- Yogi Berra (or Niels Bohr)

“One of key contributions of our generation to human knowledge is mapping structures in the universe and understanding how they form”

– Scott Dodelson



Springel et al. 2005

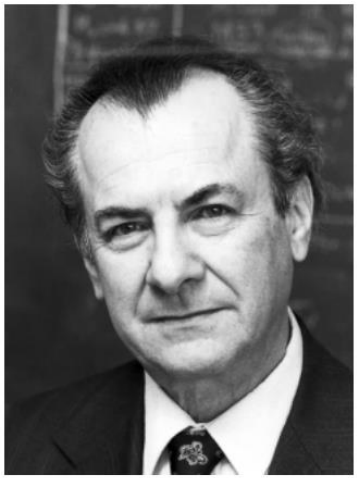
http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/

27 February 1970, Volume 167, Number 3922 **SCIENCE**

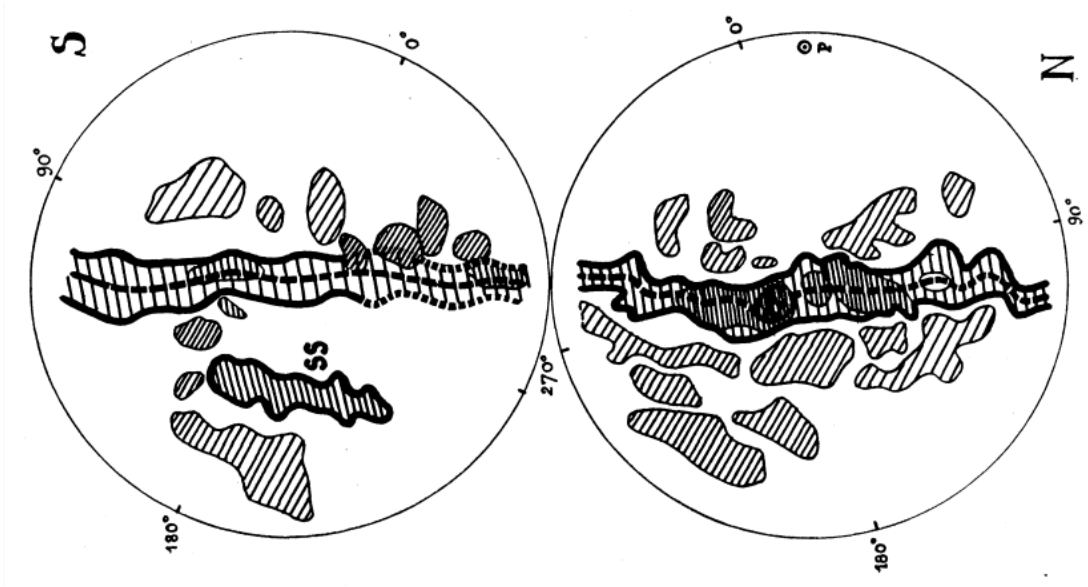
The Case for a Hierarchical Cosmology

Recent observations indicate that hierarchical clustering is a basic factor in cosmology.

G. de Vaucouleurs



G. de Vaucouleurs



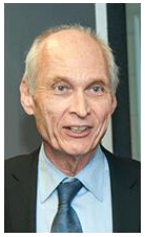
Local Supercluster
de Vaucouleurs 1953

The real hierarchical cosmology

VOLUME 48, NUMBER 23 PHYSICAL REVIEW LETTERS 7 J

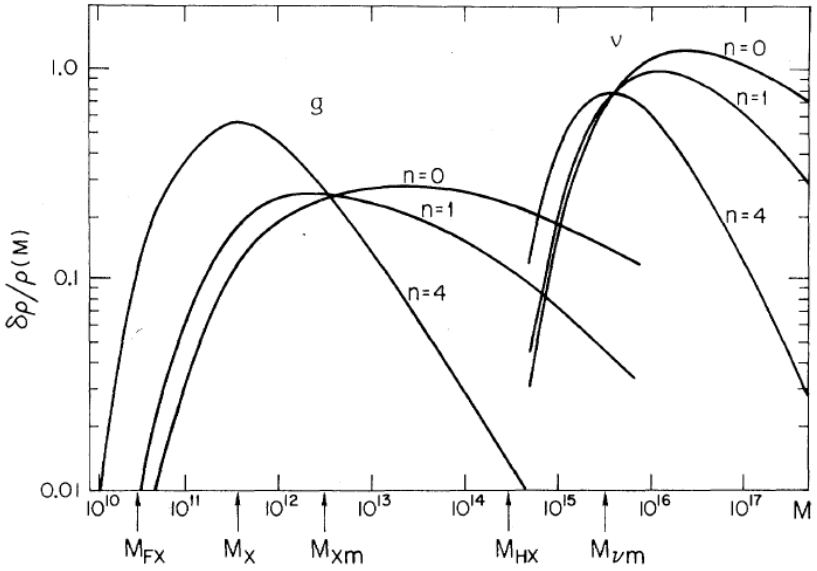
Formation of Galaxies in a Gravitino-Dominated Universe

J. R. Bond
Physics Department, Stanford University, Stanford, California 94305
and
A. S. Szalay
Astronomy and Astrophysics Center, University of Chicago, Chicago, Illinois 60637, and Astronomy Department, University of California, Berkeley, California 94720
and
M. S. Turner
Astronomy and Astrophysics Center, University of Chicago, Chicago, Illinois 60637



(Received 4 December 1981; revised manuscript received 8 April 1982)

If gravitinos of mass 1 keV (or similar particles) dominate the mass of the universe, a critical scale of galactic size arises due to their collisionless phase mixing. It is shown that density perturbation spectrum of gravitinos is relatively flat between galactic and cluster scales, unlike the massive neutrino case. If gravitinos form the dark matter, initial adiabatic fluctuations lead to a hierarchical picture of clustering. Galaxies form first, but dissipation is necessary for their survival.



THE ASTROPHYSICAL JOURNAL, 263:L1–L5, 1982 December 1
© 1982. The American Astronomical Society. All rights reserved. Printed in U.S.A.

LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

Nature Vol. 299 2 September 1982

LETTERS

Galaxy formation by dissipationless particles heavier than neutrinos

George R. Blumenthal*, Heinz Pagels†
& Joel R. Primack‡

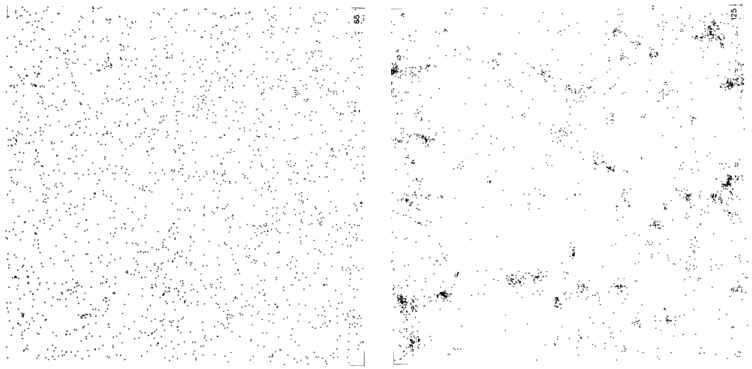
Richard Miller

early simulations of structure formation in hierarchical models

THE ASTROPHYSICAL JOURNAL, **270**:390–409, 1983 July 15

NUMERICAL EXPERIMENTS ON THE CLUSTERING OF GALAXIES

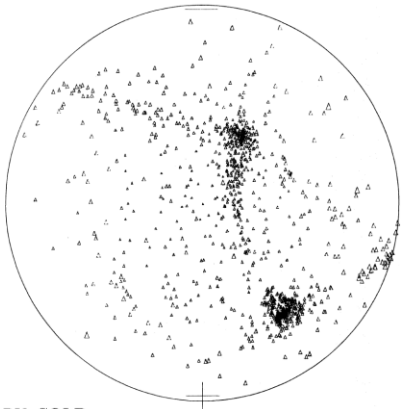
R. H. MILLER
University of Chicago; and Theoretical and Planetary Studies Branch, NASA Ames Research Center
Received 1981 August 10; accepted 1983 January 4



Mon. Not. R. astr. Soc. (1983) **204**, 891–907

Three-dimensional numerical model of the formation of large-scale structure in the Universe

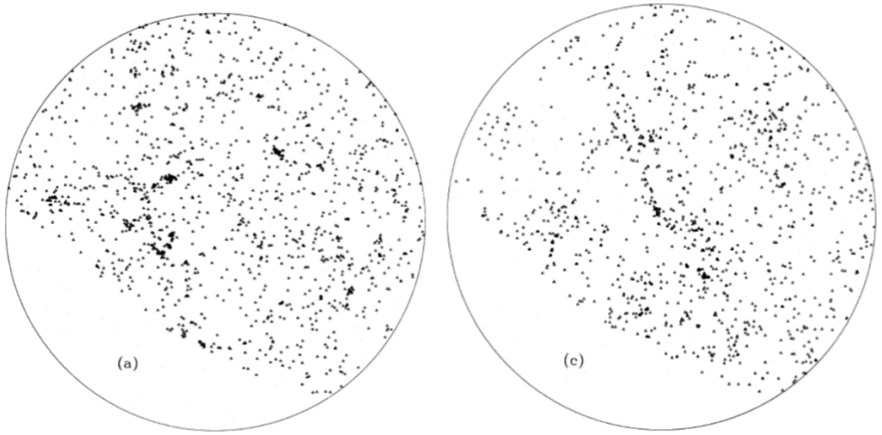
A. A. Klypin and S. F. Shandarin *The Keldysh Institute of Applied Mathematics, Academy of Sciences of USSR, Miusskaja Sq. 4, Moscow 125047, USSR*
Received 1982 November 15; in original form 1982 April 28



THE ASTROPHYSICAL JOURNAL, **292**:371–394, 1985 May 15

THE EVOLUTION OF LARGE-SCALE STRUCTURE IN A UNIVERSE DOMINATED BY COLD DARK MATTER

MARC DAVIS,[1,2] GEORGE EFSTATHIOU,[1,3] CARLOS S. FRENK,[1,4] AND SIMON D. M. WHITE[1,5]
Received 1984 August 20; accepted 1984 November 30



Princeton University
DEPARTMENT OF PHYSICS: JOSEPH HENRY LABORATORIES
JADWIN HALL
POST OFFICE BOX 708
PRINCETON, NEW JERSEY 08544

Rec'd 8/5/80

July 31, 1980

Professor Dick Miller
Department of Astronomy & Astrophysics
University of Chicago
1100 - 14 East 58th Street
Chicago, Illinois 60637

Dear Dick:

I quote Ed Groth on your movie: "It really does look like the universe!"

.....

I very much hope you will keep up the work on expanding N-body models and we can get together to discuss what might be done with them. Meanwhile, have fun with the ILLIAC!

Cheers,

P. J. E. Peebles

PJEP:mrf

the role of numerical models

Physics Today (Nov. 2004)

Reference Frame

Computational Scenarios

Leo P. Kadanoff

Numerical simulations can

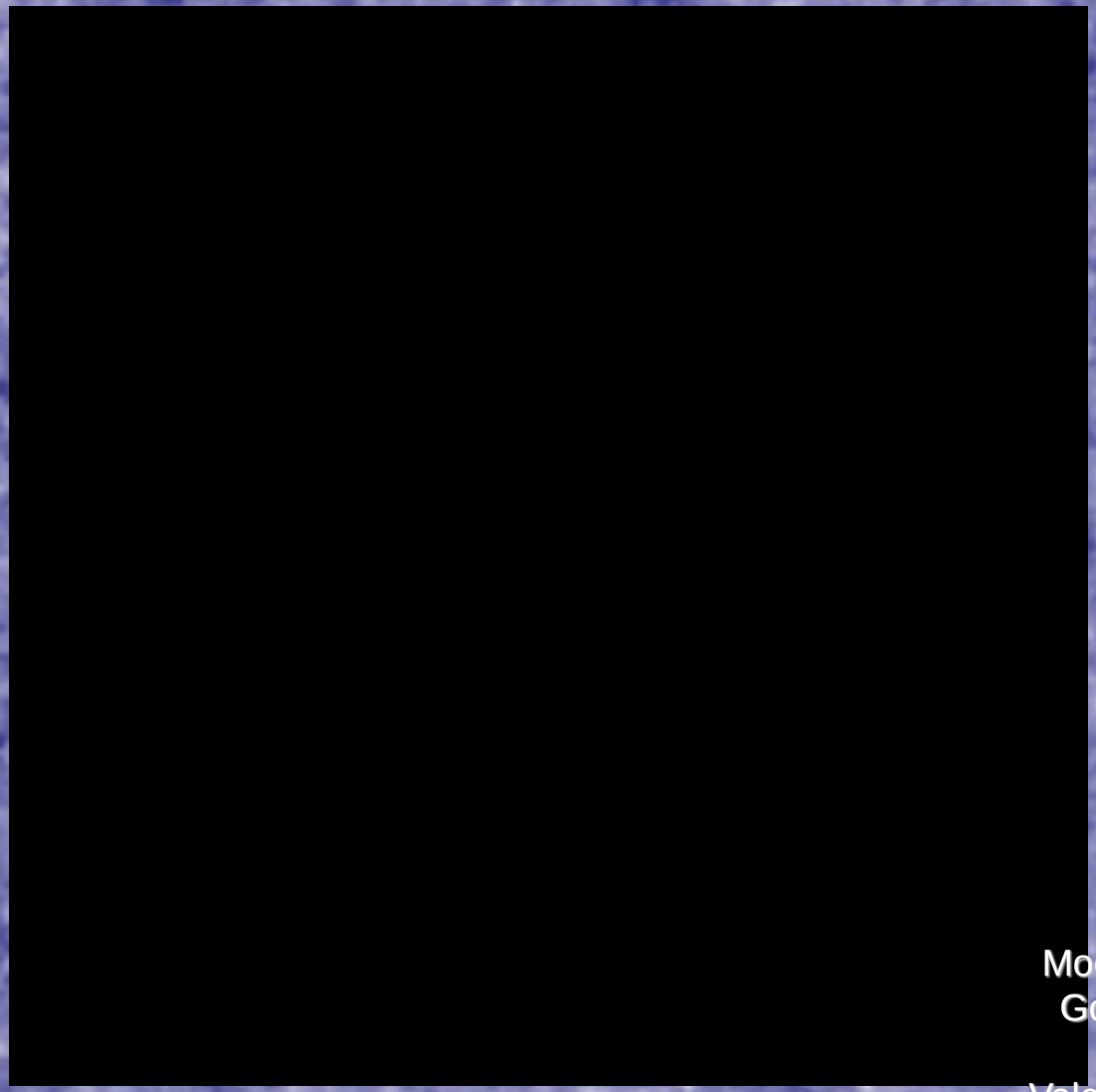
- make accurate quantitative predictions and can thus prove or disprove a model
- can reproduce a correct qualitative behavior of a physical system, but not quantitative details.

In computational science most simulations are actually of the 2nd kind.
"Computation is about insight, not numbers" – Richard Hamming.

Computer simulation shows a bubble rising through a model star. The bubble was started in a slightly off-center position in a spherically symmetrical environment. This completely asymmetrical structure was a surprising outcome and has an important influence on the subsequent history of the star and its transition to supernova behavior. Another simulation (see Plewa et al., reference 1) shows that after the bubble surfaces, material flies over the star surface and dredges up material from the surface. Image was constructed by the ASC center at the University of Chicago and Argonne National Laboratory.

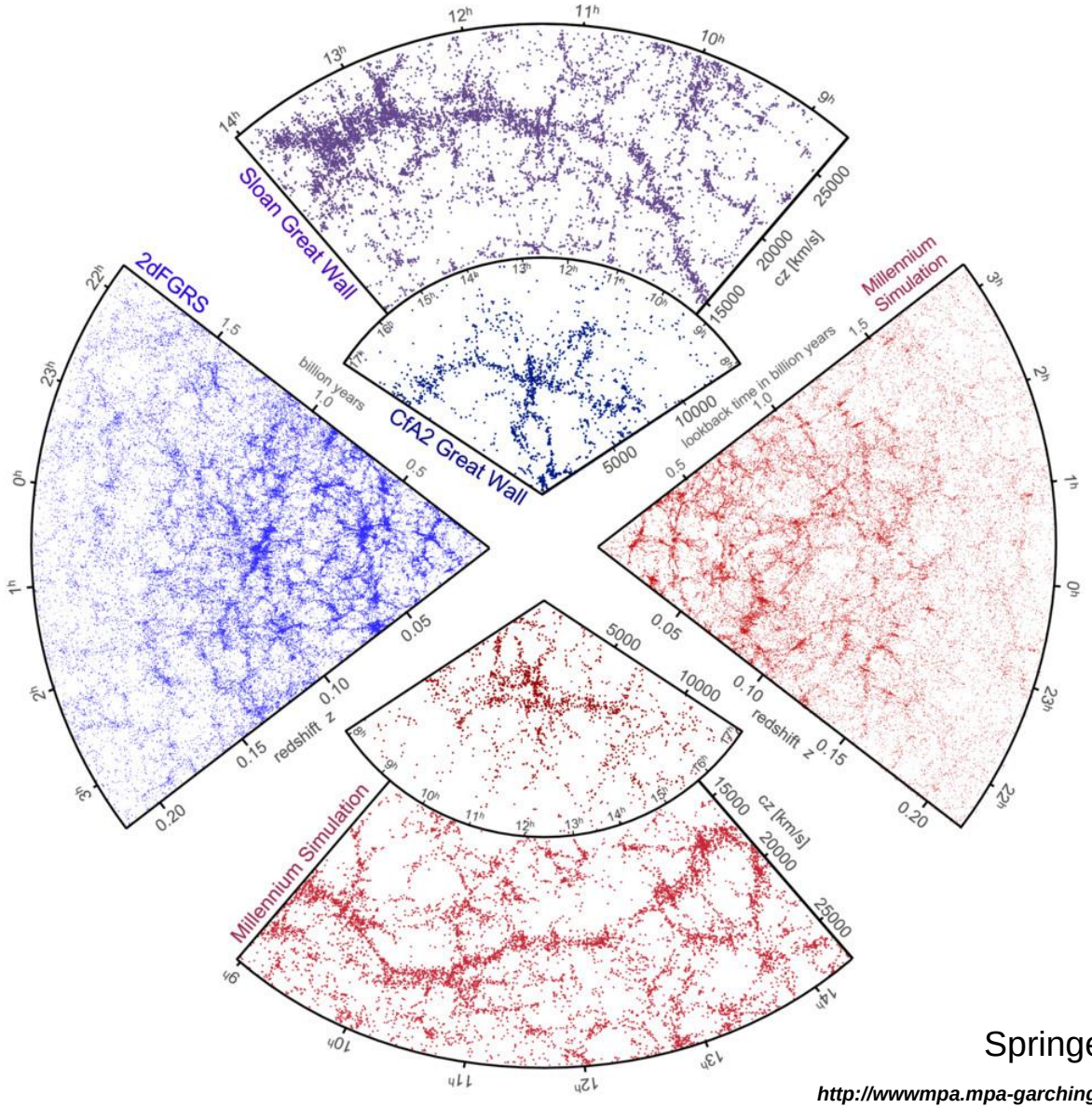
Qualitative insight from simulations: survival of substructure

hierarchical collapse of a peak in the initial Gaussian perturbation field
(here you see only dark matter)



Moore et al. 1998, 1999
Gottloeber et al. 1998
Klypin, Kravtsov,
Valenzuela & Prada 1999

modern structure formation simulations reproduce observed large-scale structures qualitatively



Springel et al. 2005

http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium

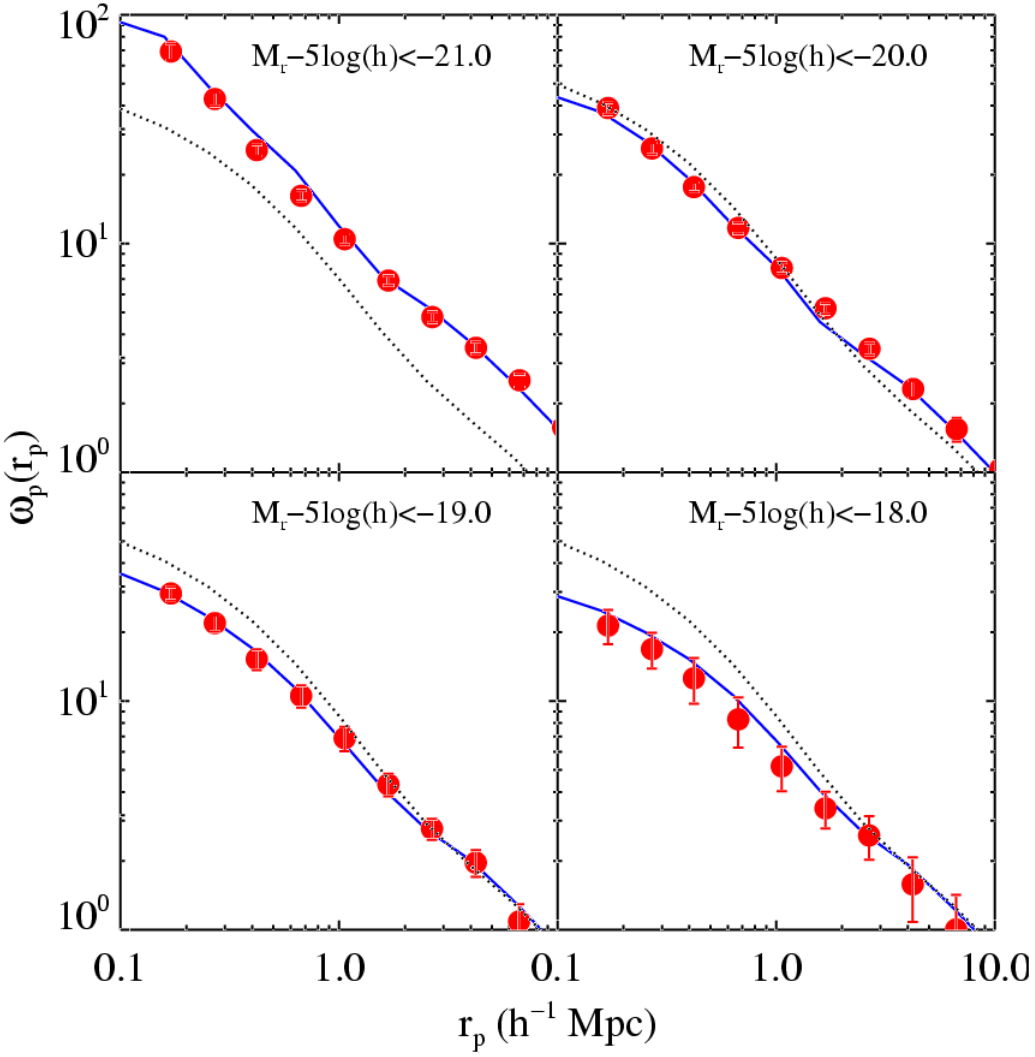
former
KICP summer
Student
-> faculty @ Harvard

and quantitatively…

galaxy clustering in the SDSS at z~0 and its luminosity dependence are well reproduced by simulations

Risa Wechsler
(former KICP fellow
-> Stanford faculty)

projected 2-point correlation function



projected separation (chimps)

abundance matching:

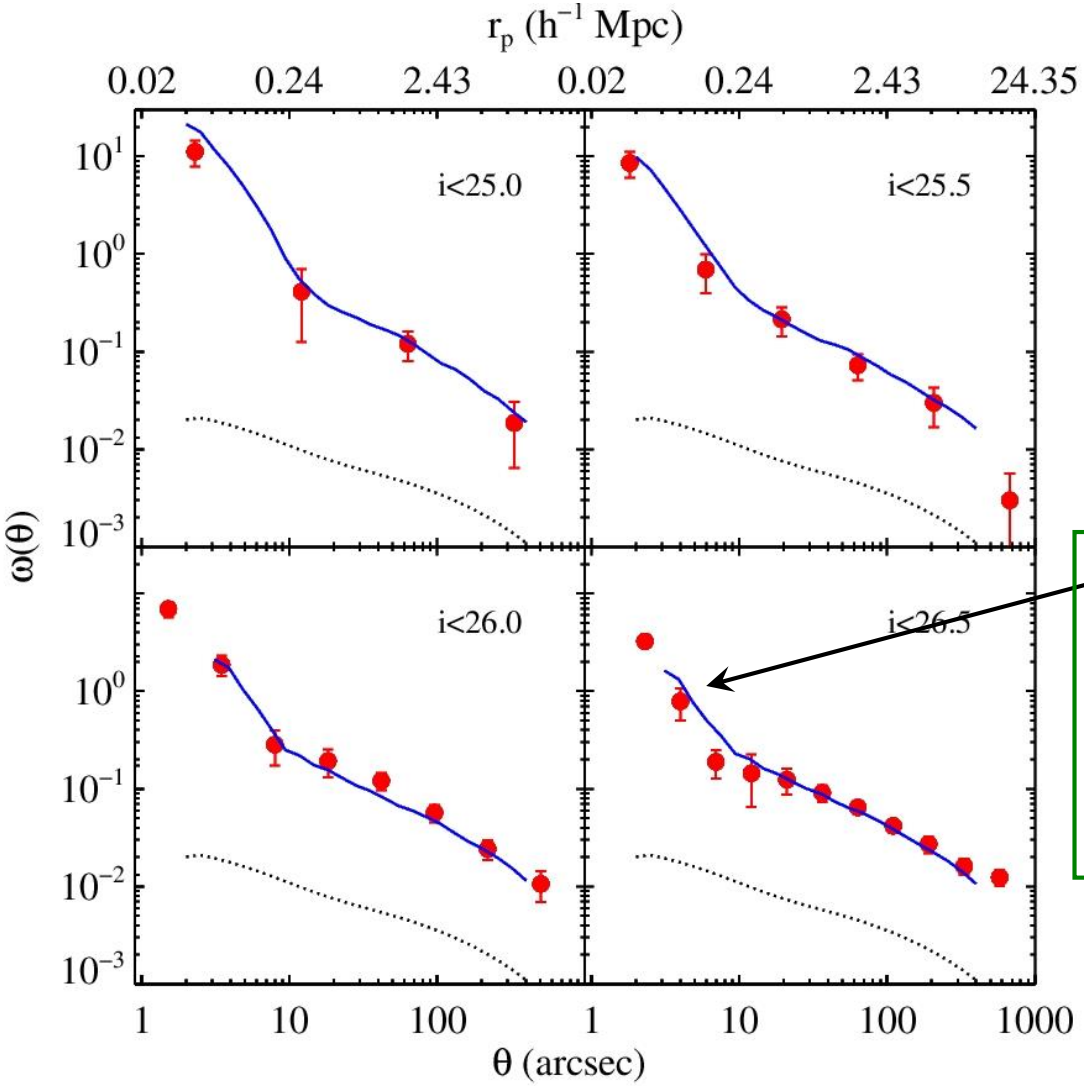
$n(>V_{max,acc})=n(>L)$

Conroy, Wechsler, Kravtsov 2006

Kravtsov et al. 2004
Kravtsov & Klypin 1999

halo clustering vs Subaru Deep Field (z~4)

angular
2-pt correlation
function



angular separation

dotted line: dm
solid lines: halos
circles: Subaru data
(Ouchi et al. 2005; Kashikawa et al. 2005)

strong deviation from power law at rp~0.3h^{-1} Mpc at z~3 was predicted by simulations

(Zheng 2004; Kravtsov et al. 2004)

Conroy, Wechsler & Kravtsov 2006

cosmology from galaxy clustering

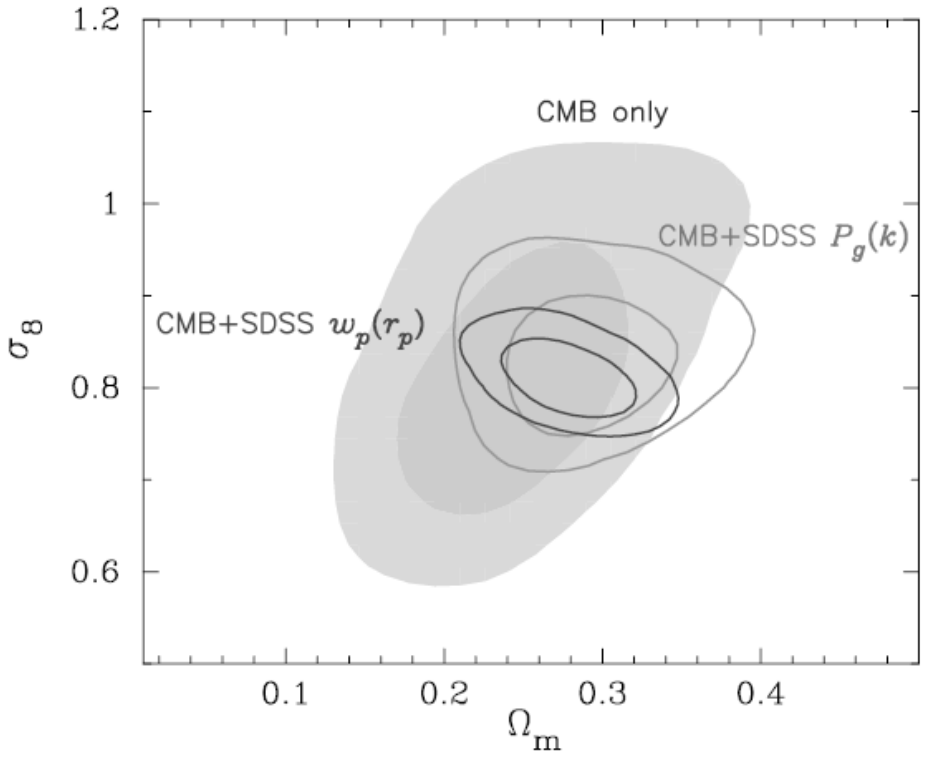
using input from simulations to model halo occupation distribution of galaxies

THE ASTROPHYSICAL JOURNAL, 625:613–620, 2005 June 1

COSMOLOGY AND THE HALO OCCUPATION DISTRIBUTION FROM SMALL-SCALE GALAXY CLUSTERING IN THE SLOAN DIGITAL SKY SURVEY

KEVORK ABAZAJIAN,[1,2] ZHENG ZHENG,[3] IDIT ZEHAVI,[4] DAVID H. WEINBERG,[3] JOSHUA A. FRIEMAN,[2,5] ANDREAS A. BERLIND,[6] MICHAEL R. BLANTON,[6] NETA A. BAHCALL,[7] J. BRINKMANN,[8] DONALD P. SCHNEIDER,[9] AND MAX TEGMARK[10,11]

rms overdensity fluctuations on the scale of 8/h Mpc



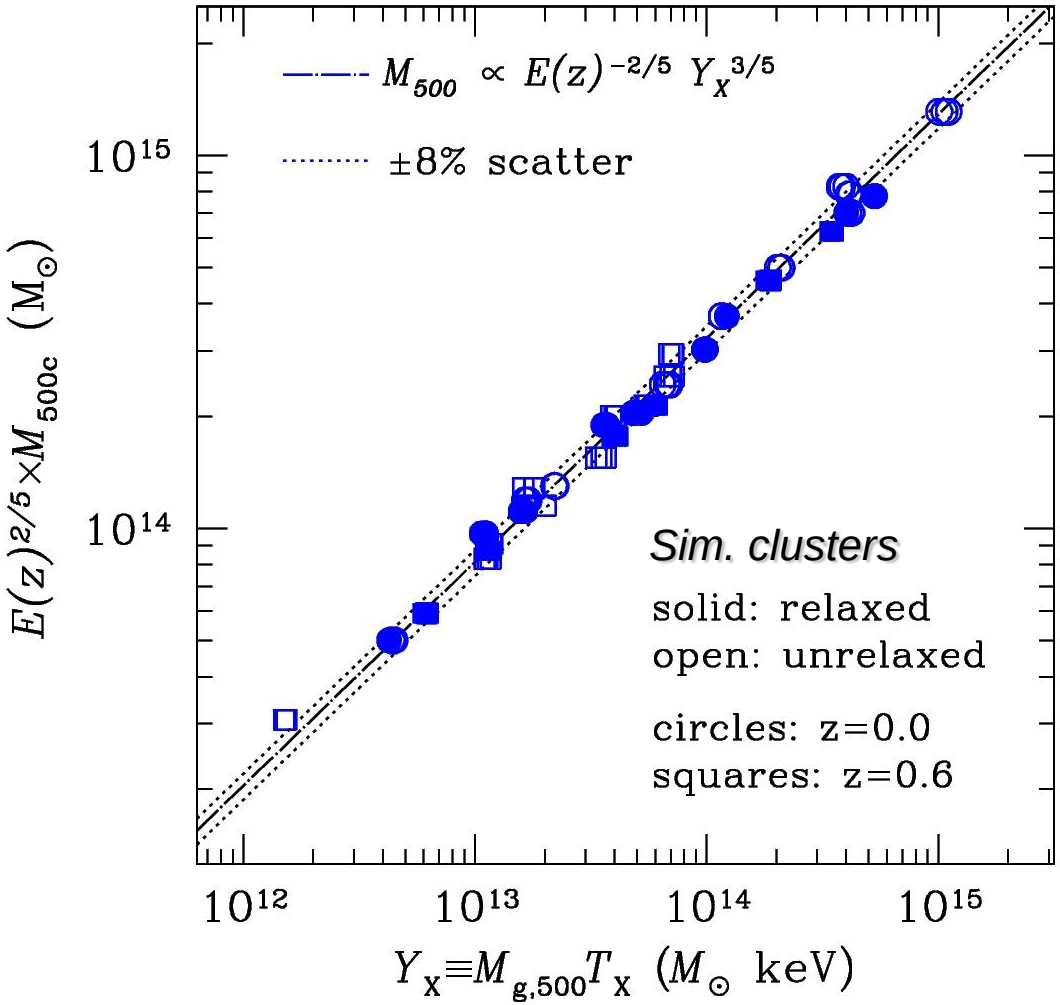
mean matter density in units of critical density

Josh Frieman
Fermilab/KICP

Daisuke Nagai
(KICP student
-> faculty @ Yale)

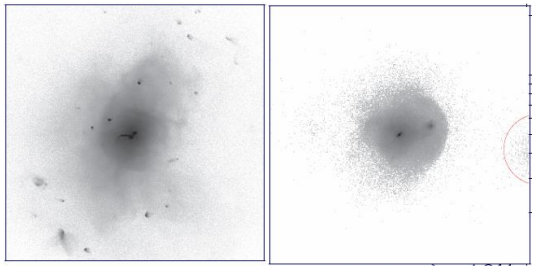
$Y_x = M_{gas} \times T_x$ as a cluster mass proxy

Kravtsov, Vikhlinin, Nagai 2006
Nagai, Kravtsov & Vikhlinin 2007; Nagai 2007



Total mass M500 scaled to z=0

cosmological simulations show that Y_x is an excellent mass proxy. scatter in Yx-M is <~8% for both relaxed and unrelaxed systems and for both low and high z



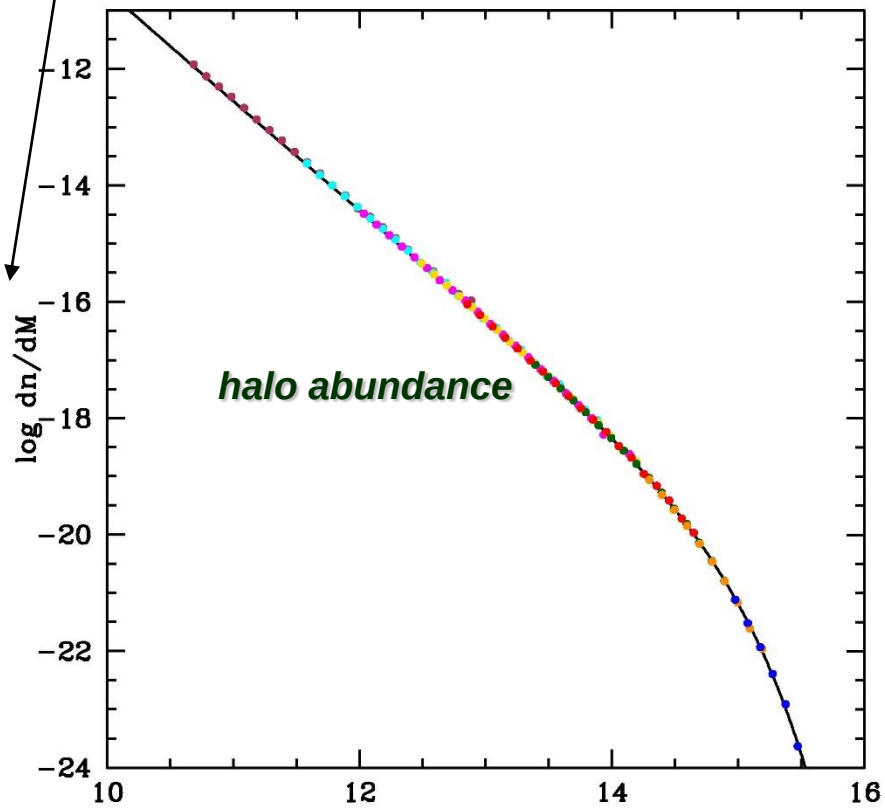
X-ray "pressure" = Y_x = gas mass x temperature
where T_x is measured excluding inner $0.15r_{500}$

Jeremy Tinker
(assoc. KICP fellow
-> NYU)

accurate calibration of the halo SO mass function

Tinker, Kravtsov et al. 2008, ApJ 688, 709

$$\frac{dn}{dM} = f(\sigma)\frac{\bar{\rho}_m}{M}\frac{d\ln\sigma^{-1}}{dM}$$

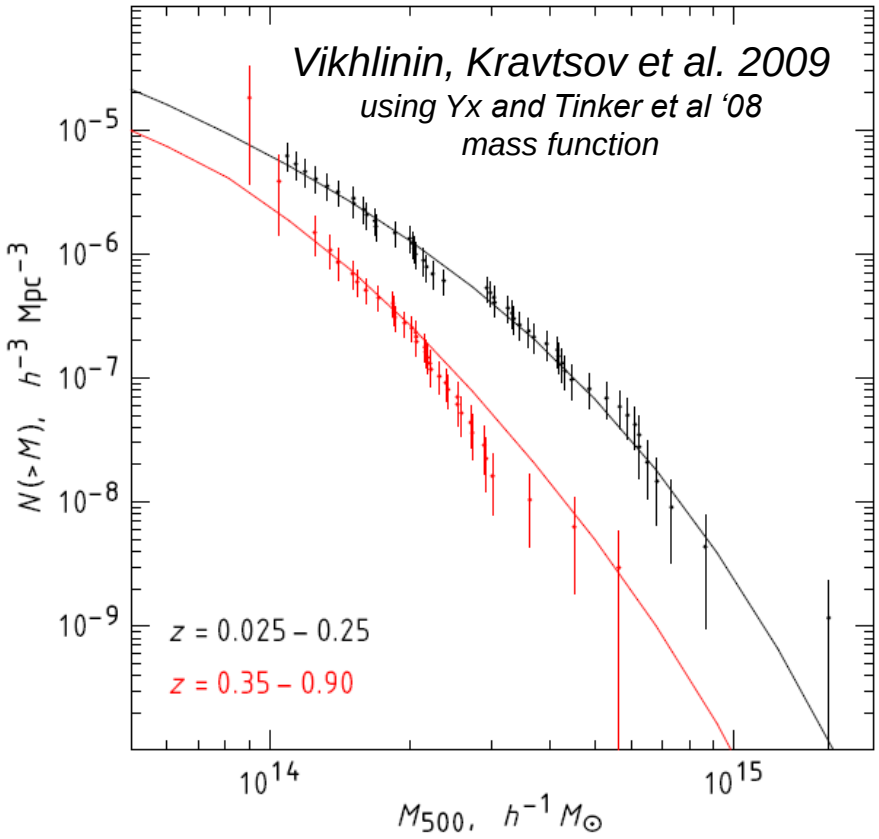


$$\Delta = \frac{M_\Delta}{(4/3)\pi R_\Delta^3 \bar{\rho}_m}$$

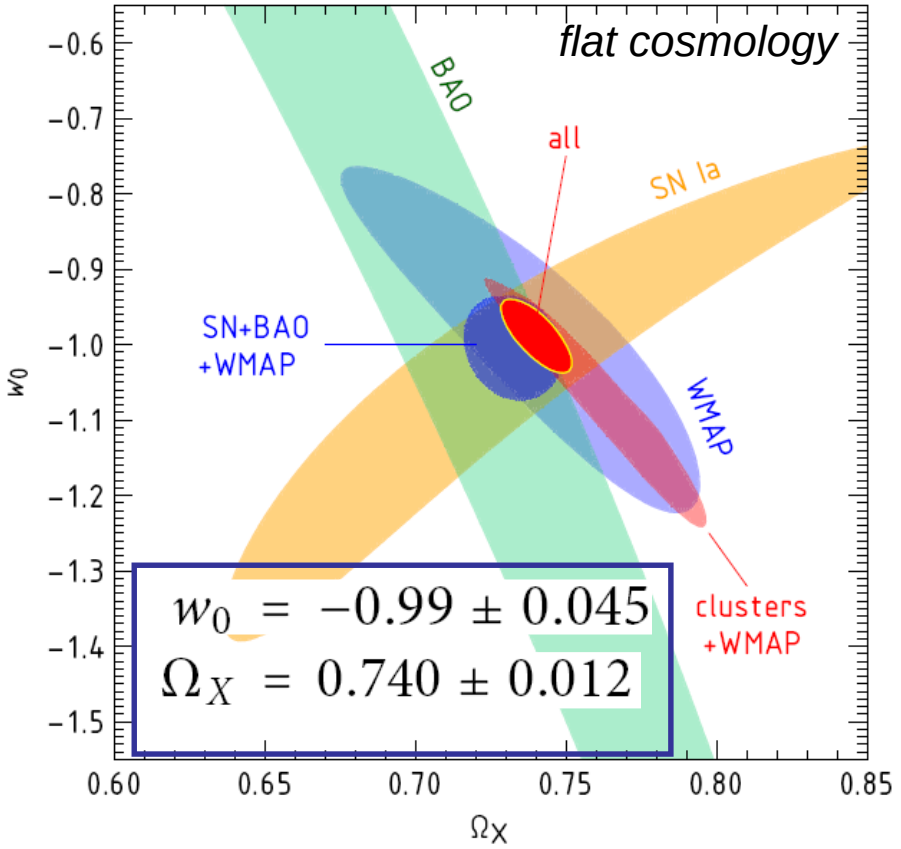
$$\bar{\rho}_m(z) \equiv \Omega_m(z)\rho_{\rm crit}(z) = \bar{\rho}_m(0)(1+z)^3$$

Complementary constraints on w-Ω_x from the evolution of cluster abundance

equation of state of dark energy: $p = w_0\rho$



mass within radius enclosing overdensity of 500 times the critical density $\rho_{crit}(z)$



contribution of dark energy to the energy-density of the universe in units of the critical density

Brad Benson

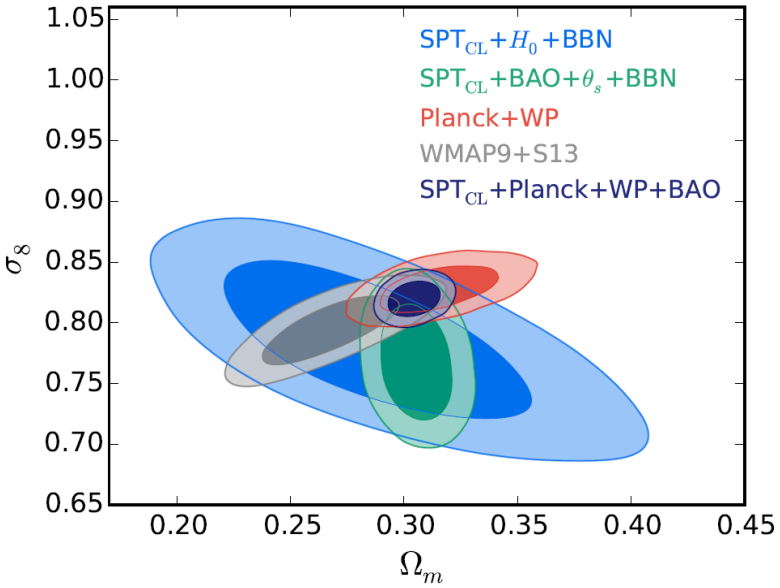
complementary constraints from the evolution of cluster abundance

Lindsey Bleem

the main source of uncertainty for cluster cosmology is uncertainty in mass calibration of clusters:

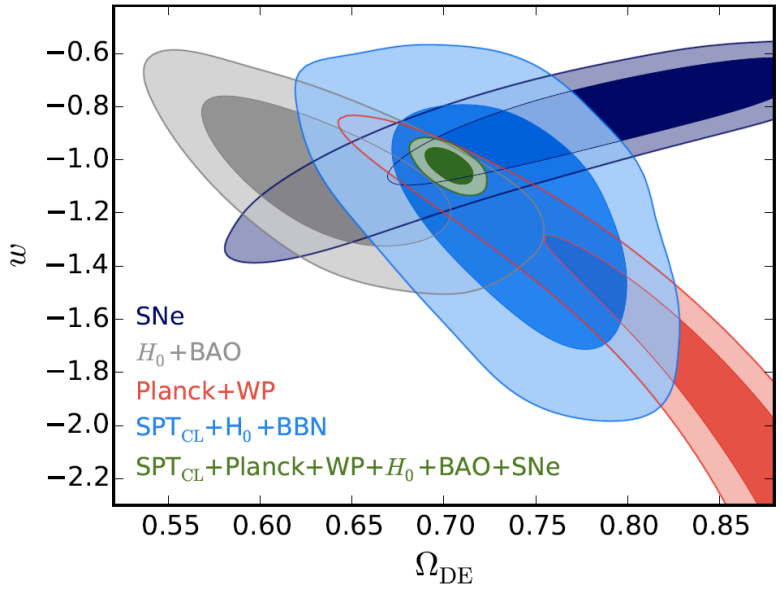
- simulations cannot predict observable-mass correlations due to uncertainties in baryonic physics
- current observations have only a limited ability to self-calibrate

rms overdensity fluctuations on the scale of 8/h Mpc



mean matter density in units of critical density

equation of state of dark energy: $p = w\rho$



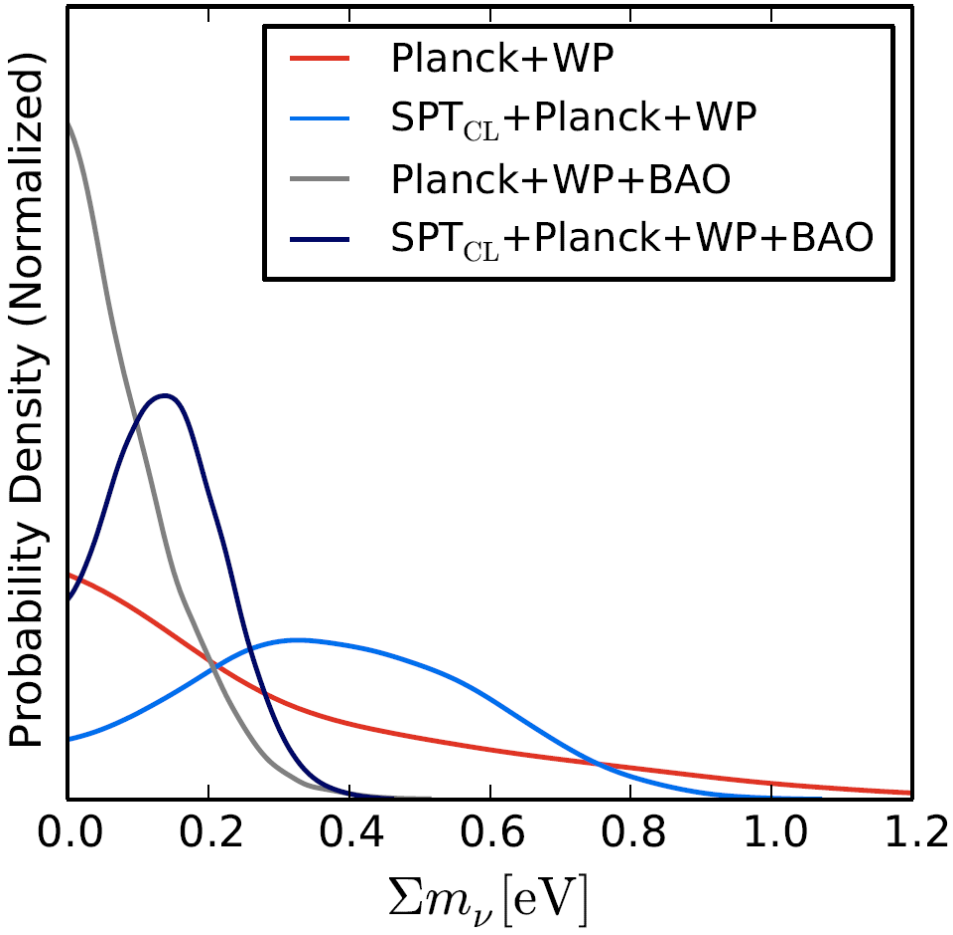
dark energy density in units of critical density

de Haan et al.
(the SPT collaboration)
arXiv/1603.06522

potential for constraining neutrino masses

the main source of uncertainty for cluster cosmology is uncertainty in mass calibration of clusters:

- simulations cannot predict observable-mass correlations due to uncertainties in baryonic physics
- current observations have only a limited ability to self-calibrate



de Haan et al.
(the SPT collaboration)
arXiv/1603.06522

critical problem to solve: mass calibration of observational mass proxies

(or develop robust ways to self-calibrate)

CMB lensing

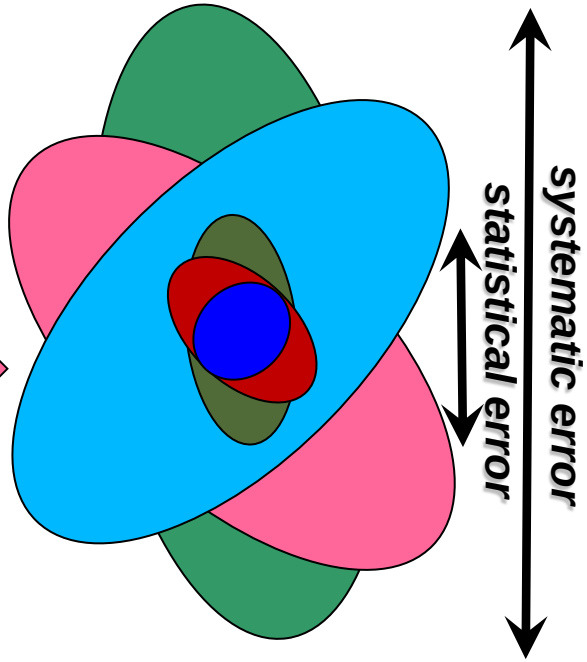
Baxter et al. '15

weak galaxy lensing

example: improved modelling of cluster mass profile and observables to avoid biases

(Becker & Kravtsov '11; Diemer & Kravtsov '14; Shirasaki, Nagai & Lau '16)

improved hydrostatic masses



Doug Rudd
former KICP student/consultant
-> data science industry

Baryonic effects

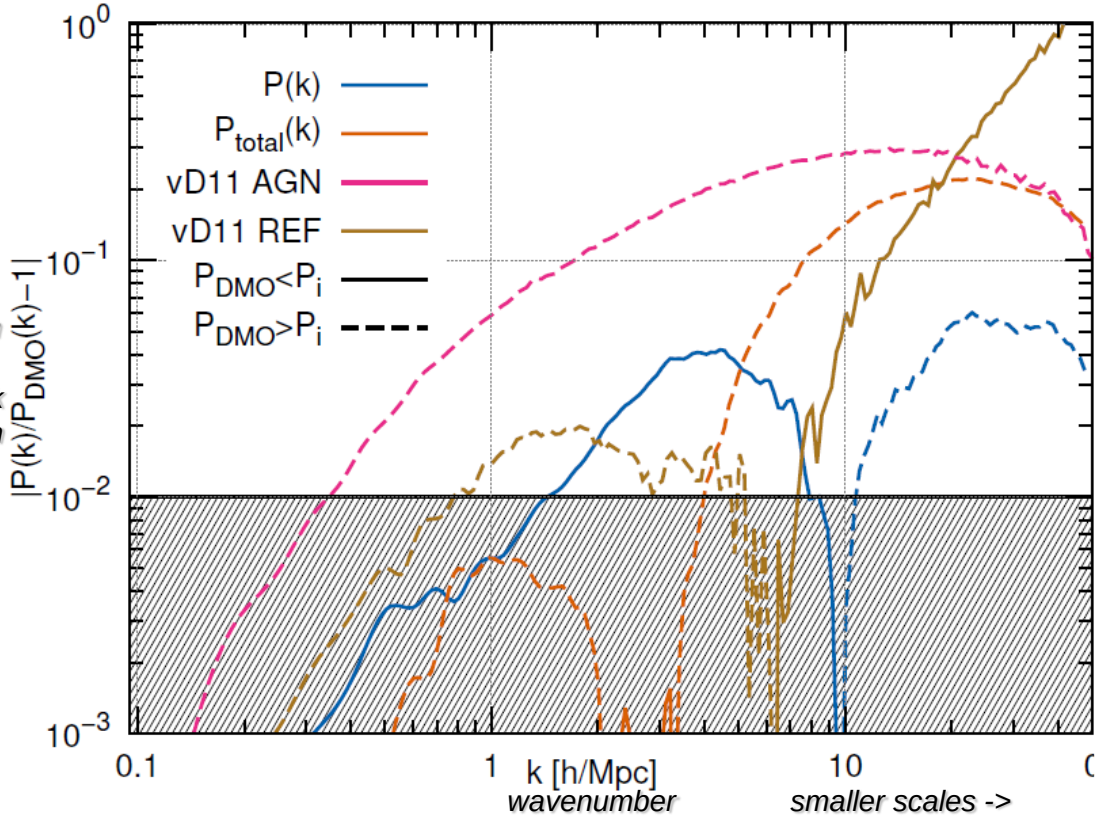
Dealing with the baryonic effects is unavoidable
even one probes the total mass distribution directly

Andrew Zentner
former KICP fellow
-> faculty at U.Pittsburgh

Jing et al. 2008; Rudd, Zentner & Kravtsov 2008
Guillet et al. 2010; van Daalen 2011, 2015; Velliscig et al. 2014; Mohammed et al. 2014

Zentner, Hu, Rudd 2015, Eifler et al. 2015: biases can be controlled via careful modelling but at the expense of increased statistical uncertainties

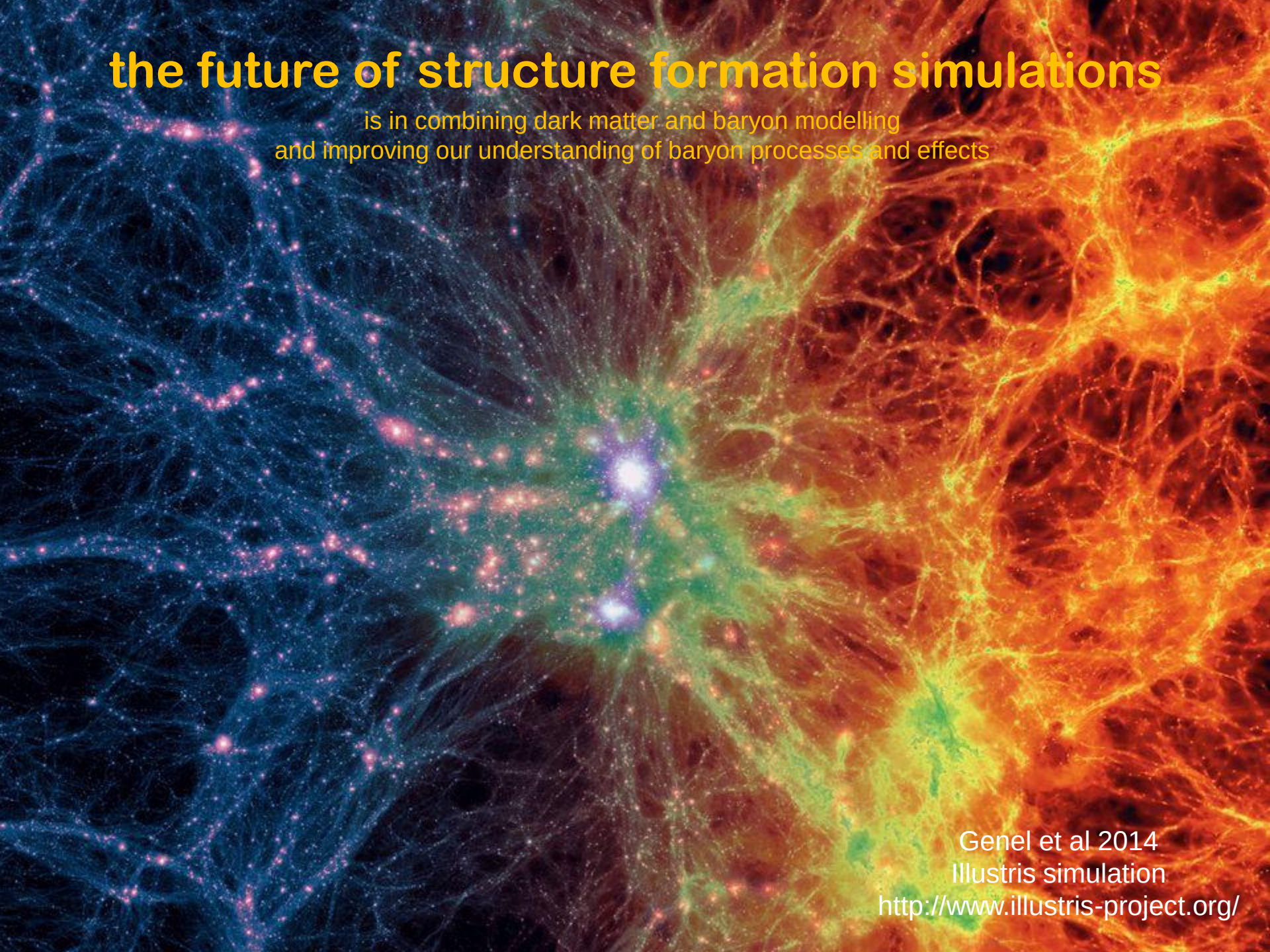
power spectrum of density fluctuations in sims with baryons relative to P(k) in dark matter only simulation



Baryonic effects on P(k) in the EAGLE simulation
Hellwing et al. 2016
arXiv/1603.03328

the future of structure formation simulations

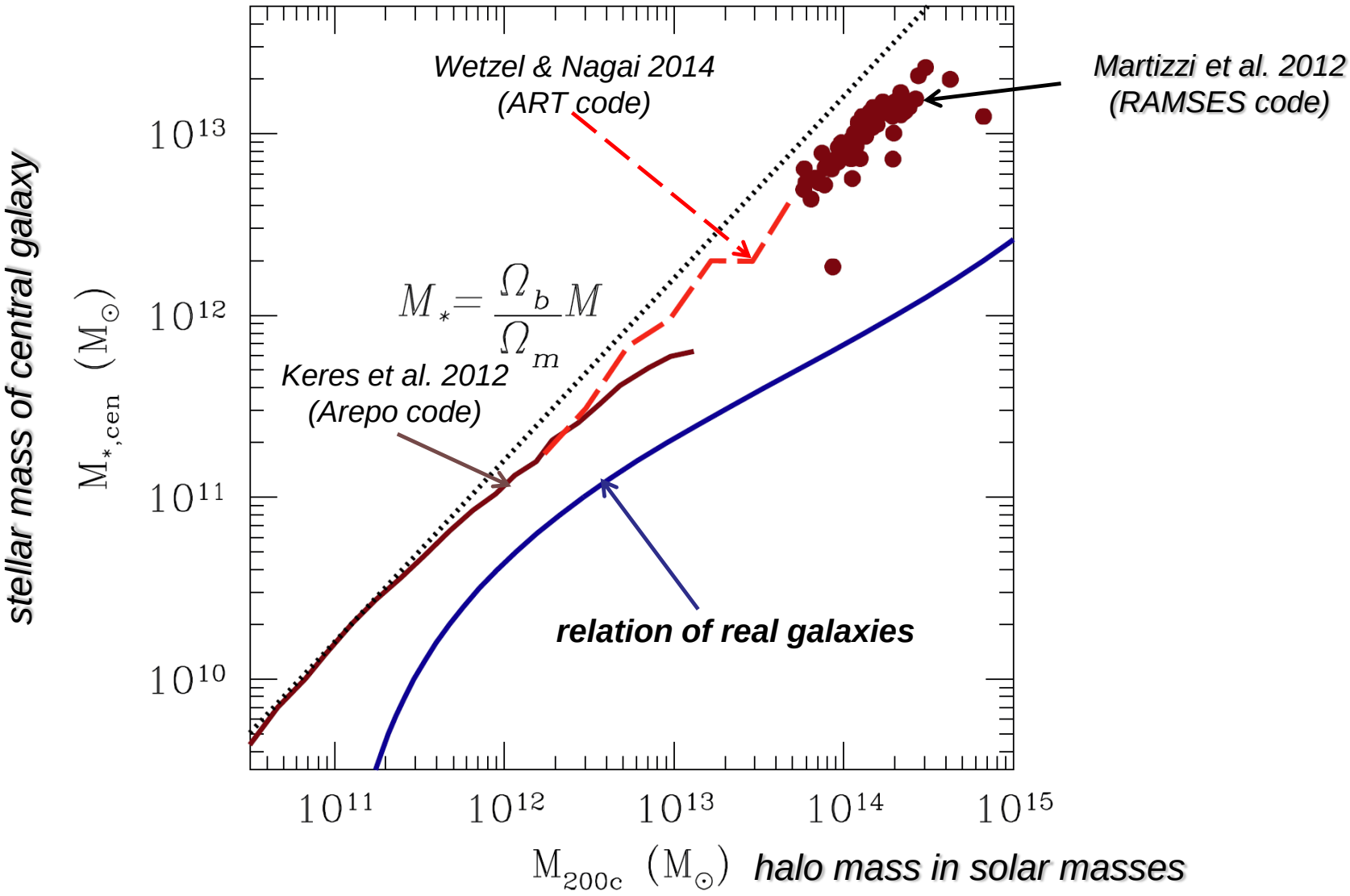
is in combining dark matter and baryon modelling
and improving our understanding of baryon processes and effects



Genel et al 2014
Illustris simulation
http://www.illustris-project.org/

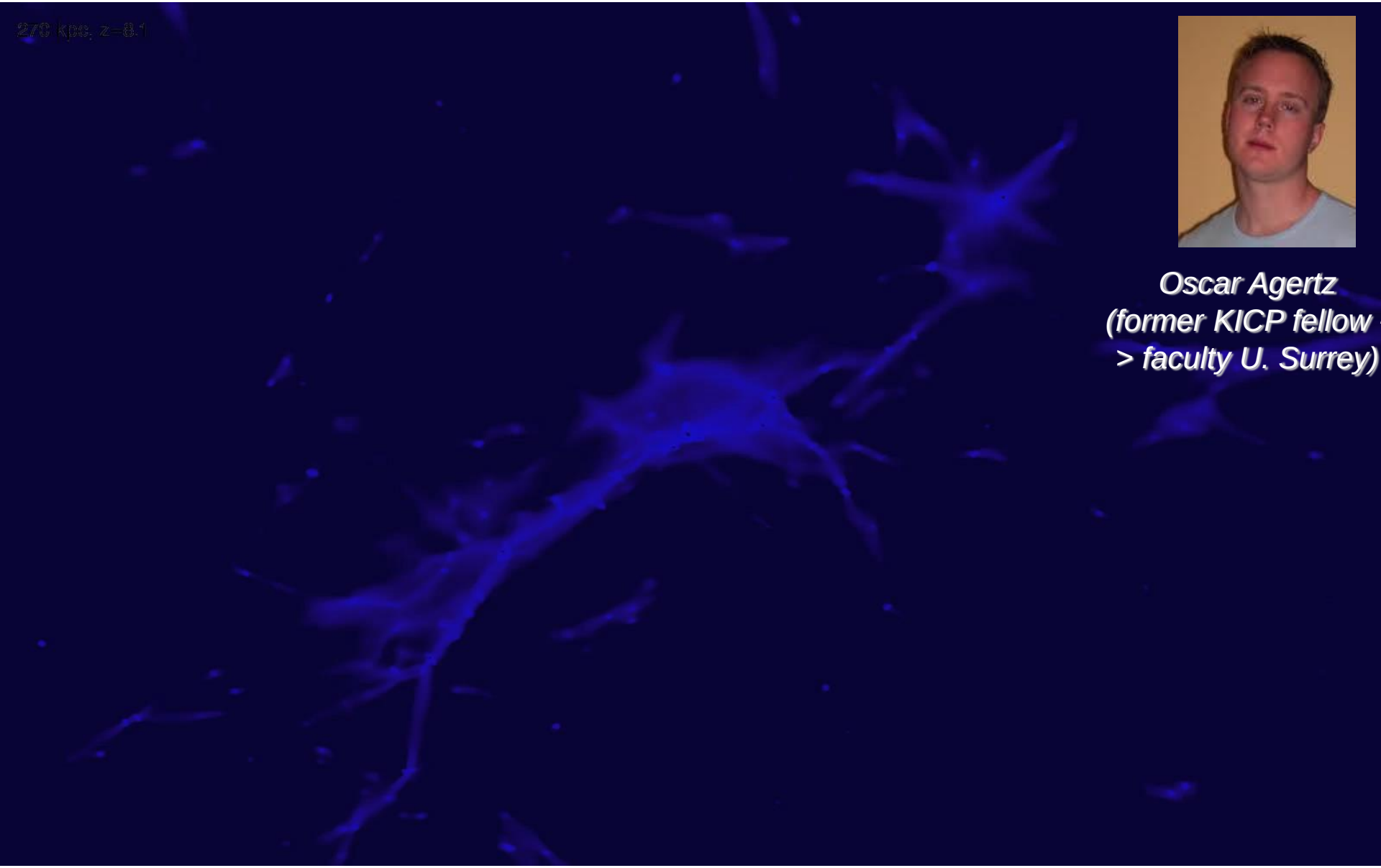
M_*-M_{halo} relation of galaxies in simulations with inefficient feedback

Most simulations prior to ~2011 included basic thermodynamic processes and a recipe for stellar/AGN, but failed to reproduce a pronounced characteristic mass at M~10^{12} Msun indicated by observations



galaxy formation simulation with efficient feedback

temperature distribution of baryonic matter in a region around forming galaxy



Oscar Agertz
(former KICP fellow
> faculty U. Surrey)

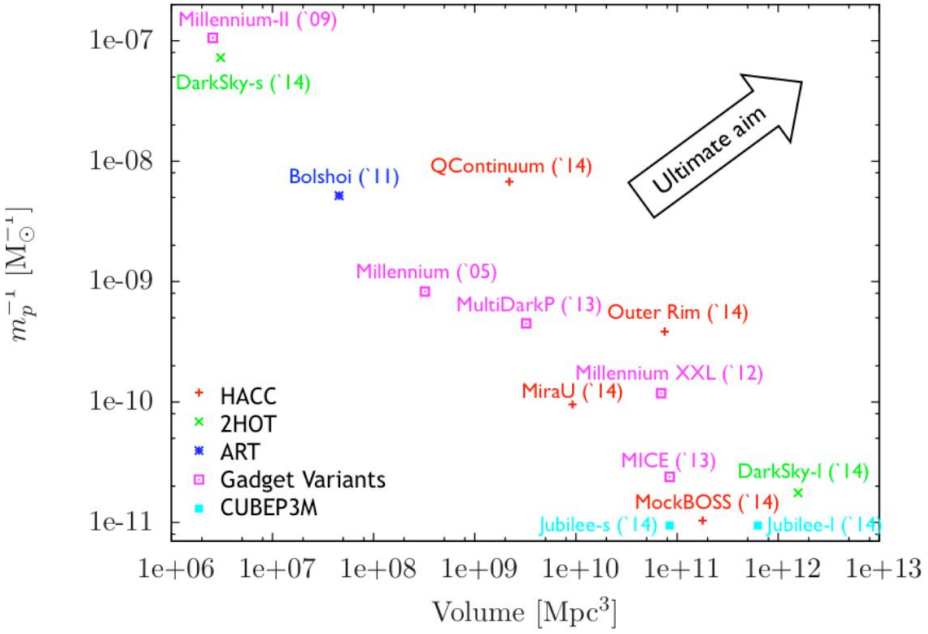
Agertz & Kravtsov 2015, 2016

mocking the universe

Dark matter simulations will continue to hold advantage in size and volume

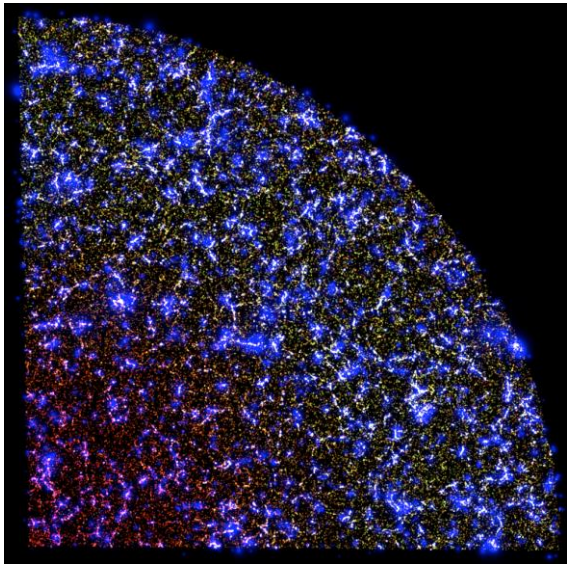
If robust models for mapping galaxies onto dark matter distribution can be developed (i.e., developing good understanding the galaxy-halo connection) many involving just positions and velocities of galaxies can be addressed with large N-body simulations

Salman Habib, Katrin Heitmann
(Argonne)



Heitmann et al. 2015, ApJS

Li, Gladders et al. 2015, arXiv/1511.03673



Wechsler et al. DES mock catalogs

Risa Wechsler
(former KICP fellow
-> Stanford faculty)

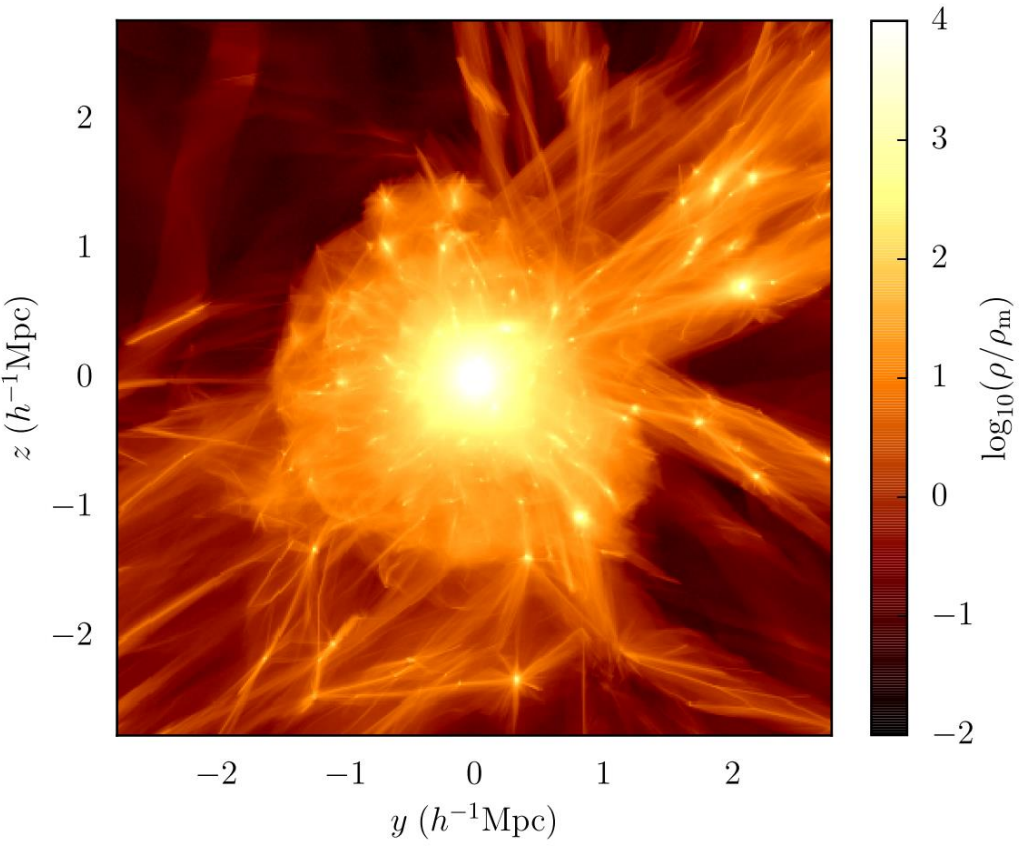
Flender, Bleem et al. 2015, arXiv/1511.02843

insight from N-body simulations: the halo splashback radius

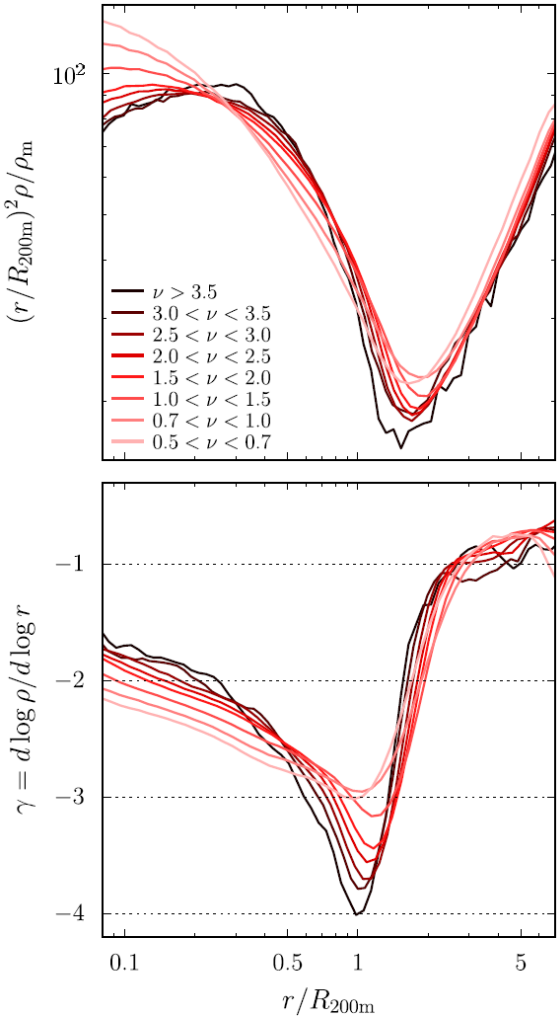
Benedikt Diemer
(former KICP student
-> ITC fellow, Harvard)

Diemer & Kravtsov 2014, ApJ 789, 1
More, Diemer & Kravtsov 2015, ApJ 810, 36

Surhud More
(former KICP fellow
-> IPMU faculty)



dark matter density map through a cluster-sized halo
in a slice through the center of thickness =0.15 Rvir
(density is reconstructed using phase-space sheet, Phil Mansfield)



splashback radius detected!

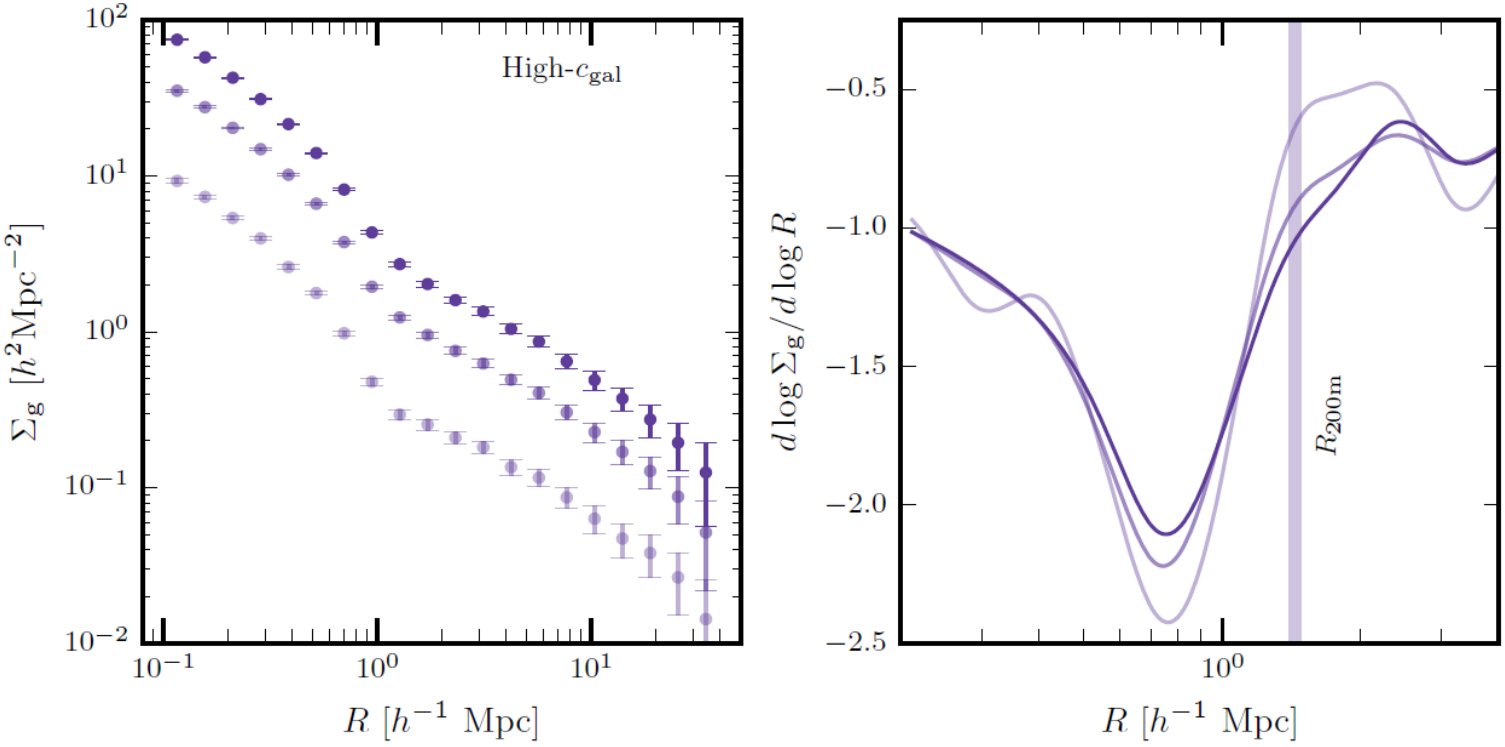
DETECTION OF THE SPLASHBACK RADIUS AND HALO ASSEMBLY BIAS OF MASSIVE GALAXY CLUSTERS

Surhud More [1], Hironao Miyatake [2,3,1], Masahiro Takada [1], Benedikt Diemer [4], Andrey V. Kravtsov[5,6,7], Neal K. Dalal [8, 1], Anupreeta More [1], Ryoma Murata [1,9], Rachel Mandelbaum[10], Eduardo Rozo[11], Eli S. Rykoff[12], Masamune Oguri[9,13,1], David N. Spergel[3,1]

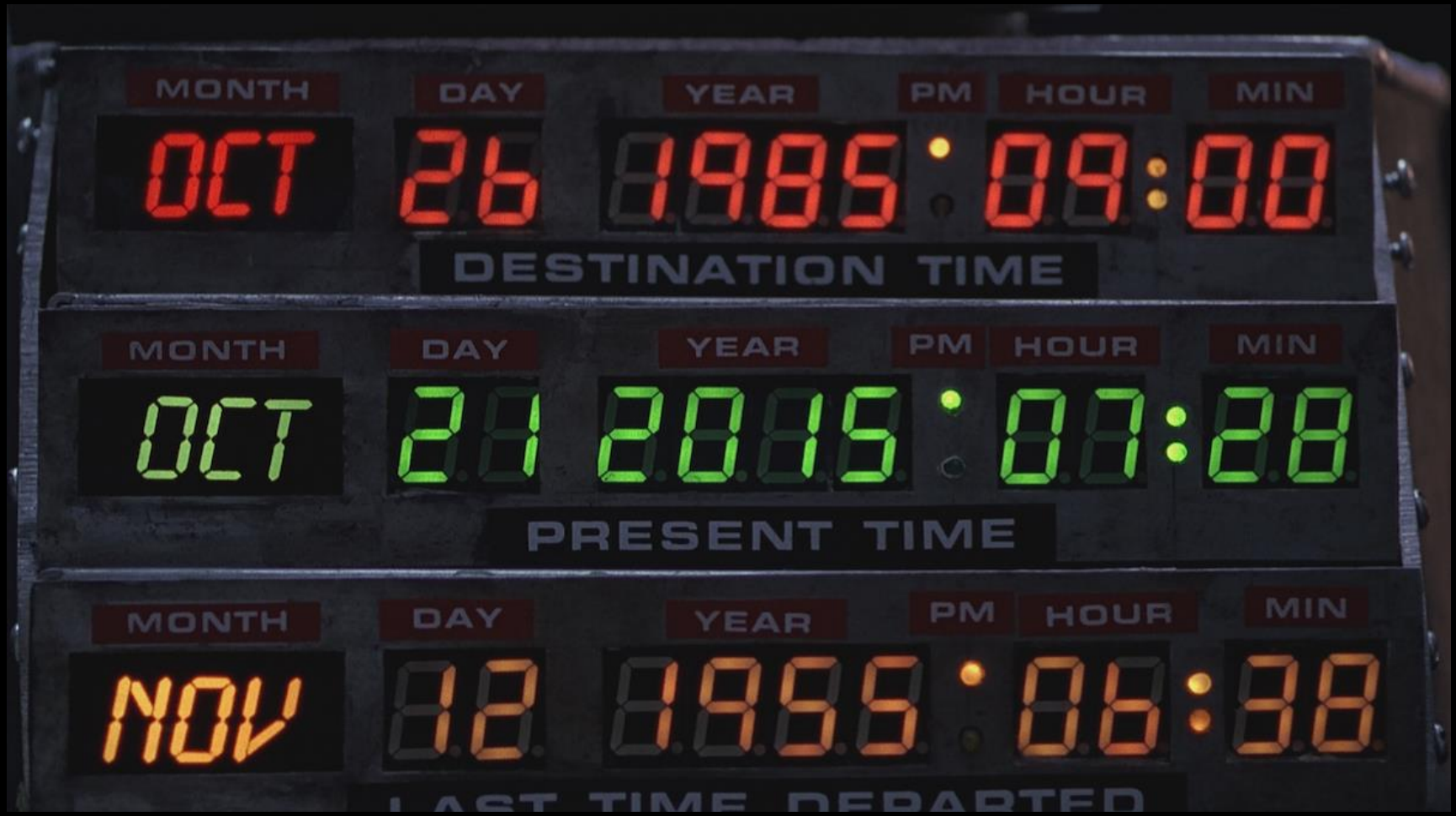
arXiv:1601.06063

Surhud More
(former KICP fellow
-> IPMU faculty)

…but at a different radius???
(self-interacting dark matter anyone?)



the future is now…



the future is now…

- the future of structure formation modelling is in simulations of both baryonic and dark matter components and their effects on each other

- progress is being made in modelling baryons and feedback in structure formation simulations

  Simulations should provide useful brackets for analyses of future observations, including self-calibration and marginalization of model uncertainties

- novel hydro and N-body schemes for exascale computing need to be developed

- mock catalogs built on large N-body simulations will continue to be a workhorse of theoretical analyses of large surveys and, likely, will continue to provide valuable insights and guidance!

  Data volume is a challenge for analyses. New approaches needed.

- deriving robust cosmology constraints from structure growth will require work at the intersection of theory, structure formation modelling, and observational analyses

  KICP has a strong track record in such work!