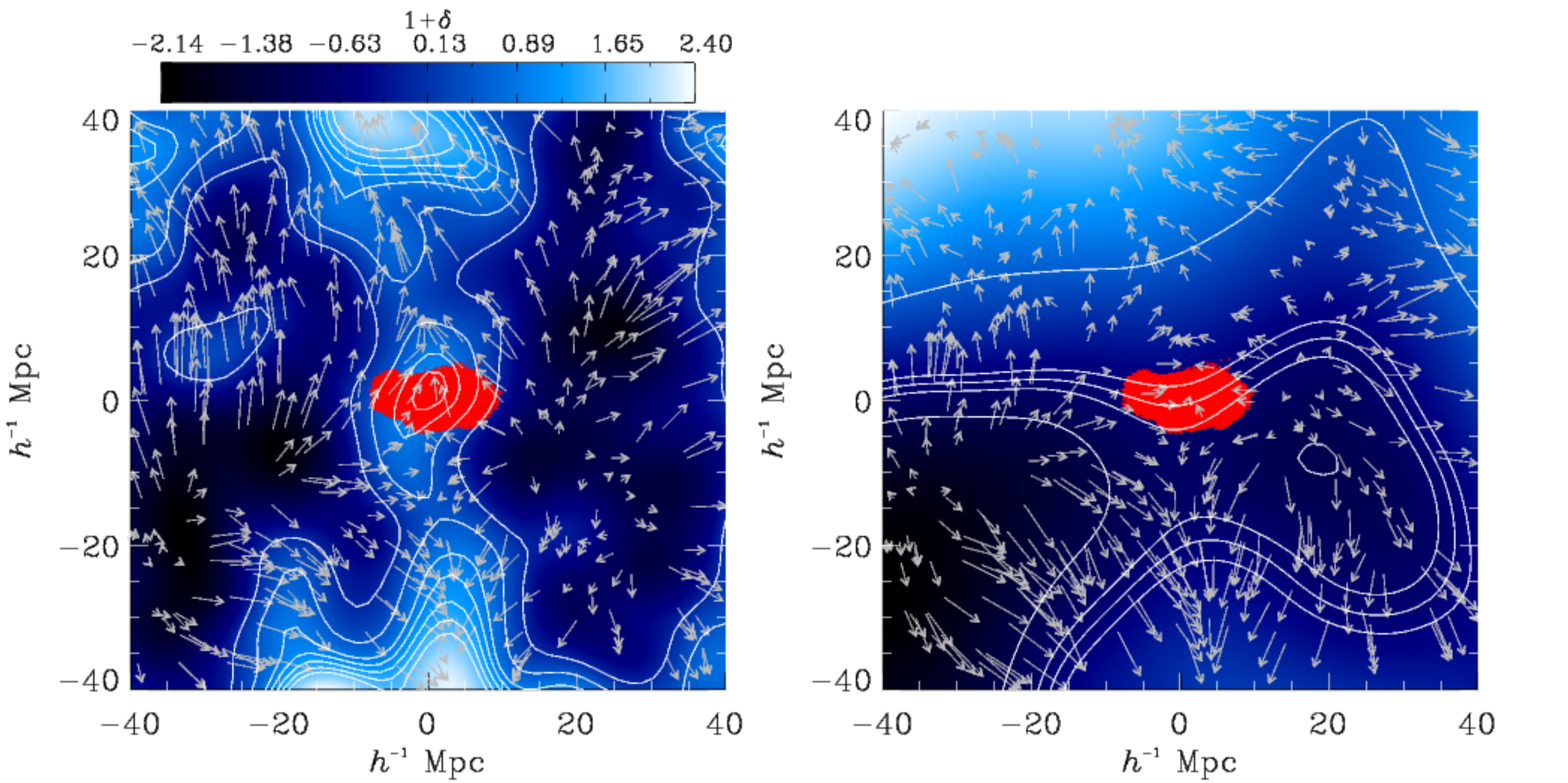
Myth and truth about halo formation in CDM models



Cristiano Porciani

TR 33 The Dark Universe Bonn München Heidelberg
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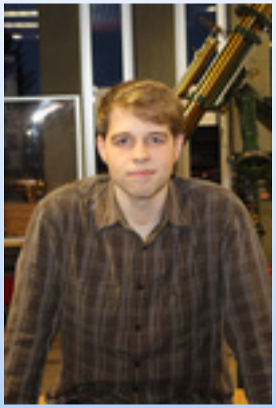
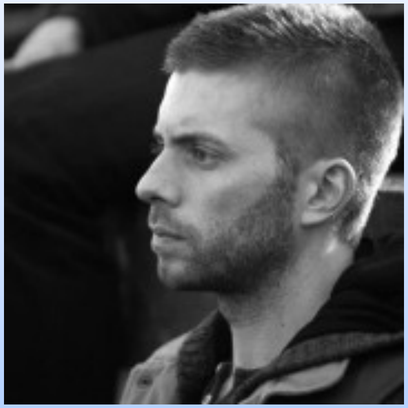


Mikolaj Borzyszkowski
(Bonn)

Aaron D. Ludlow
(Durham)



Borzyszkowski, Ludlow & Porciani, 2014, MNRAS, 445, 4124

Ludlow, Borzyszkowski & Porciani, 2014, MNRAS, 445, 4110

Ludlow & Porciani, 2011, MNRAS, 413, 1961

Preamble

- Contrary to previous speakers I will explore the fully non-linear regime and make heavy use of N-body simulations
- This talk is about understanding halo collapse in CDM models (including some deliberate provocations)
- Although it might sound an academic subject it has applications to survey science and cosmological parameter determination
- Practical relevance (see Ravi's talk):
  - halo mass function (and thus, indirectly survey science)
  - "ton" of halo biases $b(M, z_f, \ldots)$ (and thus, indirectly survey science)
  - assembly bias (and thus, indirectly survey science)
  - galaxy formation

Conventional wisdom

- The virialized part of halos corresponds to a mean overdensity of 200 times the mean density
- Halos form out of linear density peaks at the time in which the linear overdensity smoothed on the halo size is of order unity
- The mass accretion history of the halos reflects the density profile around the peaks out of which they form
- Halos keep accreting matter all the time (new shells fall onto them) and they steadily grow in mass
- The extended Press-Schechter model predicts their accretion history
- The ellipsoidal collapse model à la Bond & Myers describes their formation process

About conventional wisdom (from Wikipedia)

- Conventional wisdom is not necessarily true

- Conventional wisdom is often seen as an obstacle to the acceptance of newly acquired information, to introducing new theories and explanations, and therefore operates as an obstacle that must be overcome by legitimate revisionism

- Despite new information to the contrary, conventional wisdom has a property analogous to inertia that opposes the introduction of contrary belief, sometimes to the point of absurd denial of the new information set by persons strongly holding an outdated (conventional) view.

- This inertia is due to conventional wisdom being made of ideas that are convenient, appealing and deeply assumed by the public, who hangs on to them even as they grow outdated


MAPEI

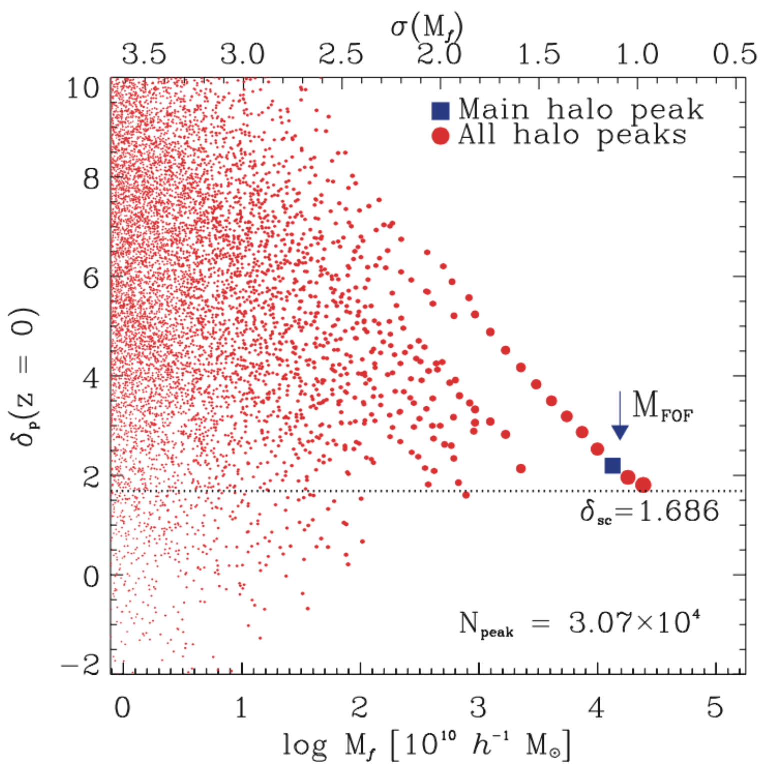



Where do halos come from?

Peaks' theory

- Halos form out of linear density peaks at the time in which the linear overdensity smoothed on the halo size is of order unity
- Difficult to trace back the exact origin of this model: already discussed by Doroshkevich (1970), idea sketched in Peebles (1980, sec. 26, p. 124)
- The formalism gained great popularity after Kaiser (1984) used it to explain the high-clustering amplitude of Abell clusters (e.g. Peacock & Heavens 1985, Bardeen et al. 1986)
- Few direct tests against simulations: Frenk et al. (1998), Katz, Quinn & Gelb (1993), Porciani, Dekel & Hoffman (2002)

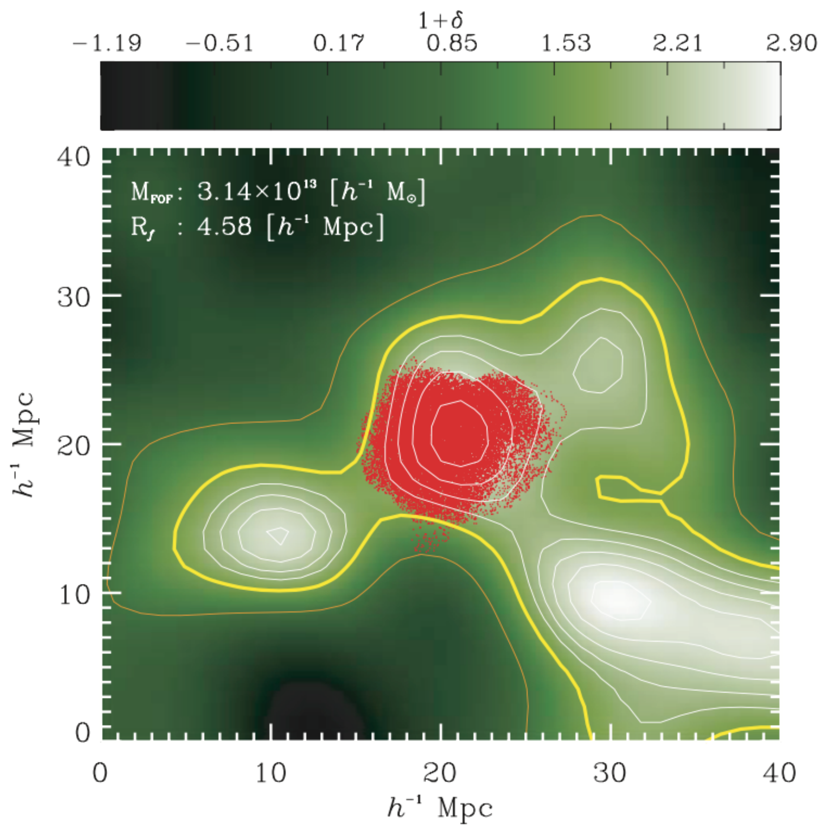
Density peaks in a halo

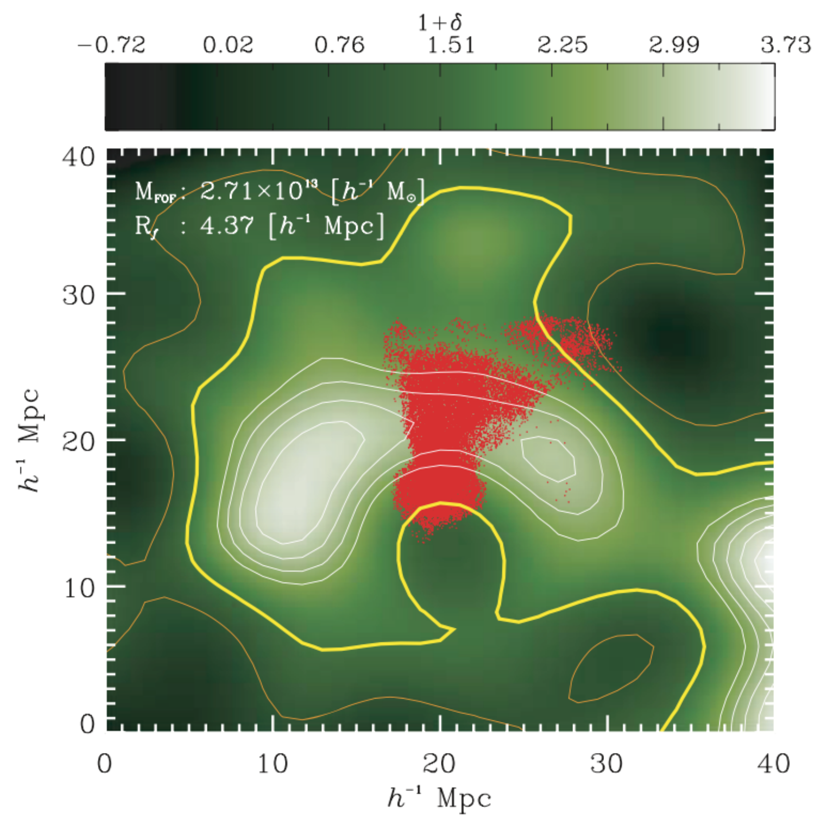


- Fraction of halos that can be associated with peaks on the mass scale of the halo:
  - 98% with $M>10^{15}\ h^{-1}\ M_\odot$
  - 91% with $M>10^{14}\ h^{-1}\ M_\odot$
  - 80% with $M>10^{12}\ h^{-1}\ M_\odot$
  - 70% with $M>5\times10^{11}\ h^{-1}\ M_\odot$
- If one allows a factor of 2 difference between the peak and halo masses, the last fraction increases to 84%
- A significant fraction of halos can only be associated with peaks of mass $M_{pk} << M/4$

Ludlow & Porciani (2011)

Peak-halos and "peakless" halos

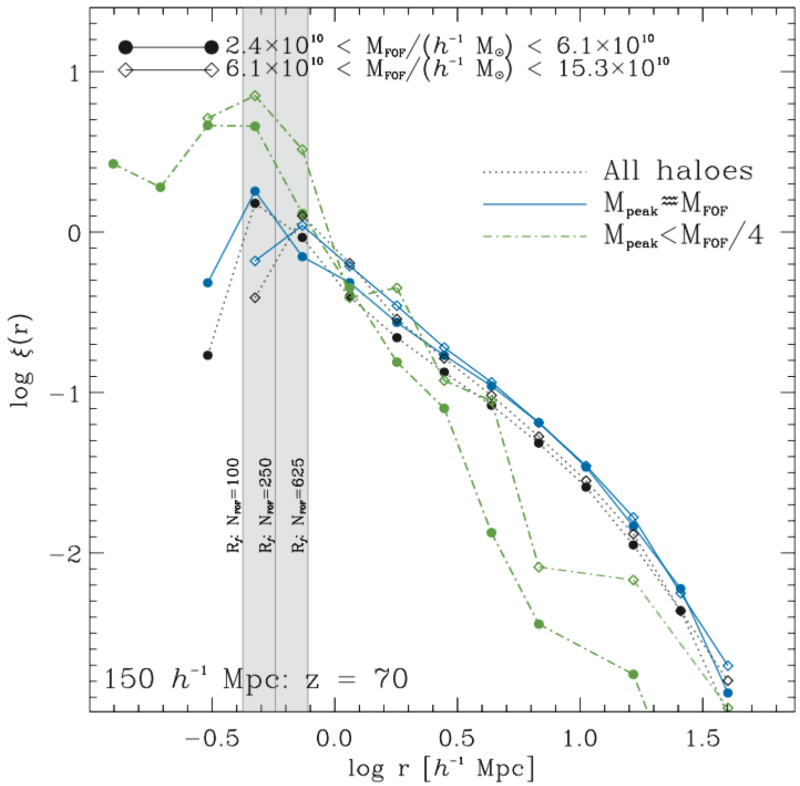


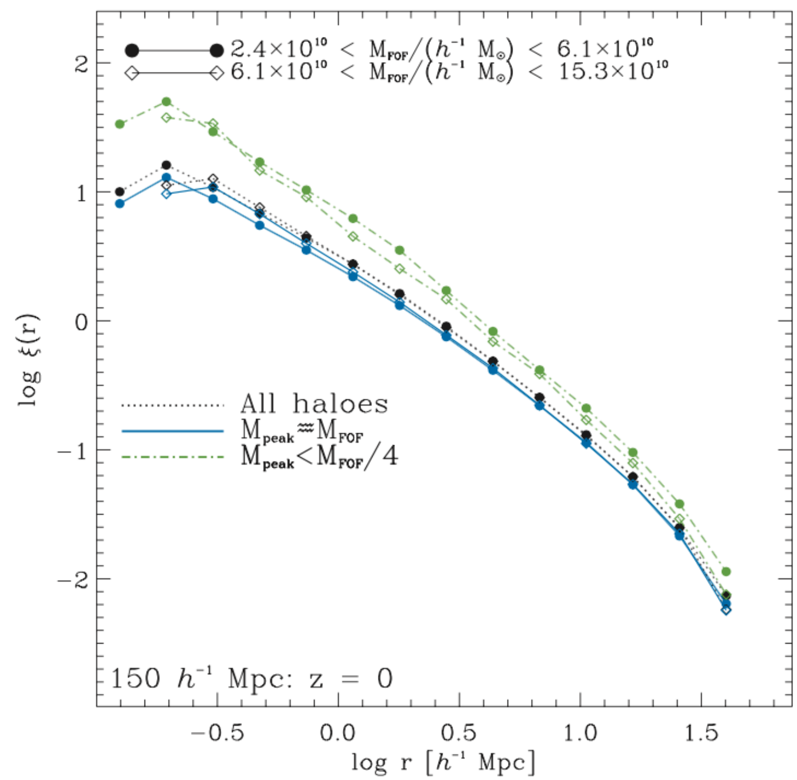


Ludlow & Porciani (2011)

Peak vs “peakless” halos

Ludlow & Porciani (2011)

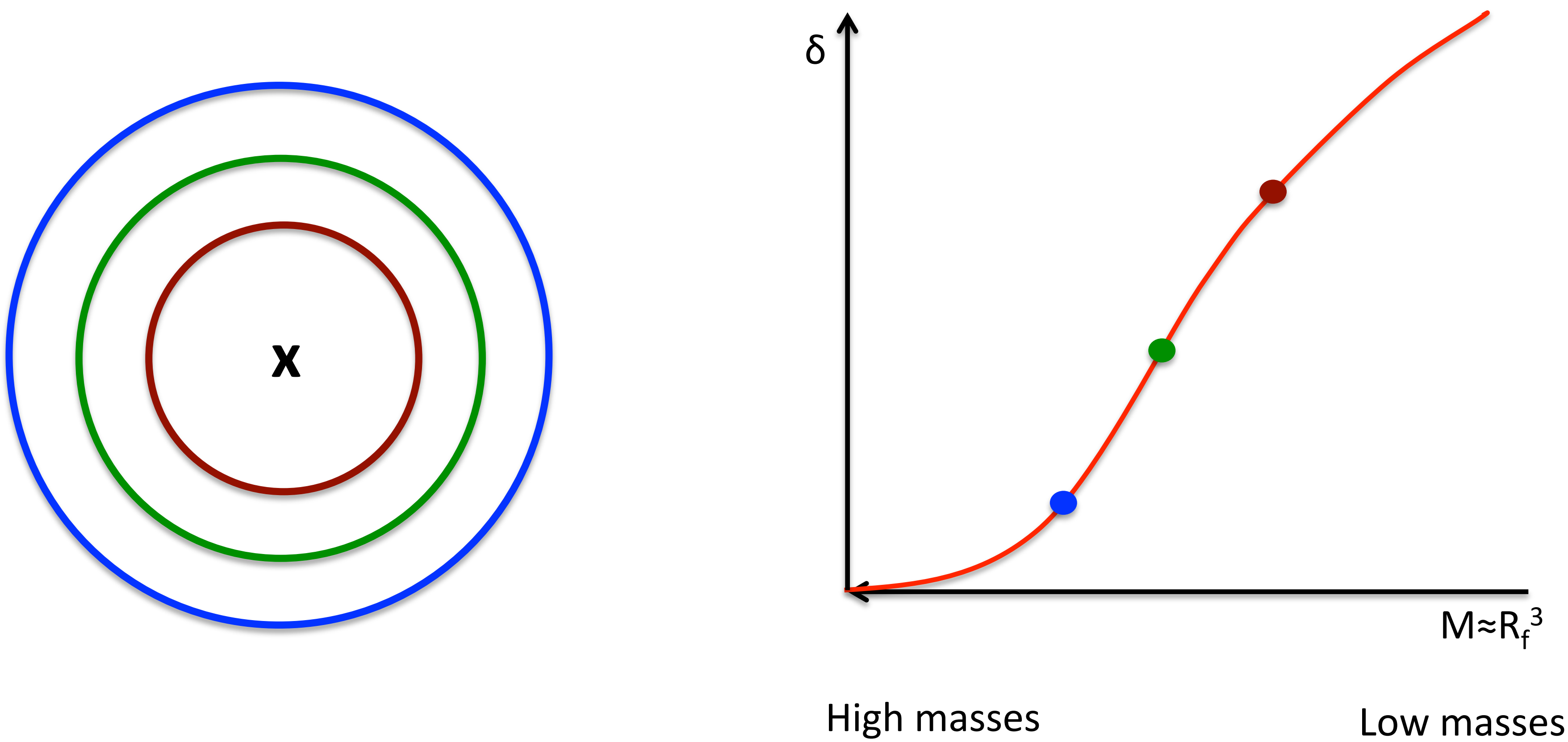




“Peakless” halos cluster more strongly than peak halos of the same mass. No other difference could be detected in terms of their internal properties.

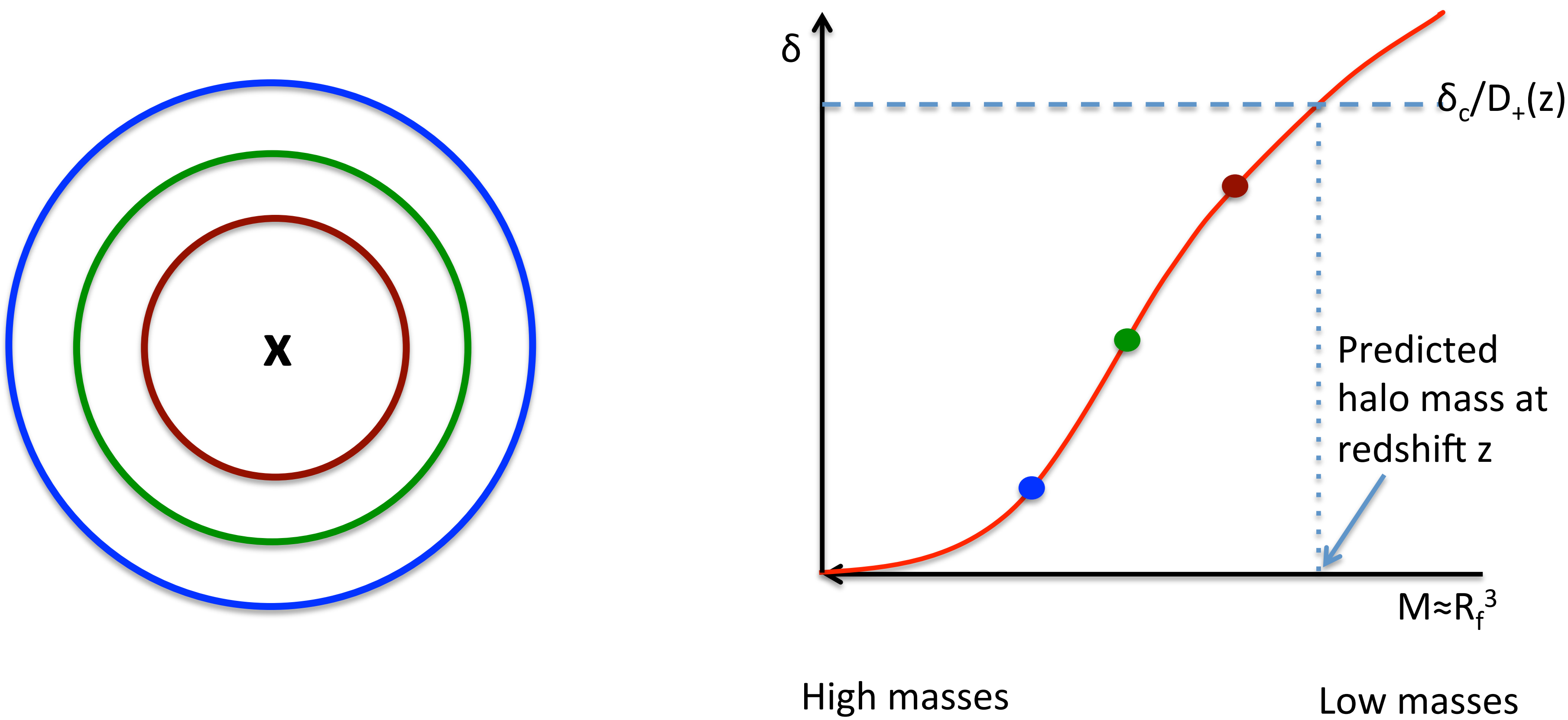
How do halos form?

Excursion-set method

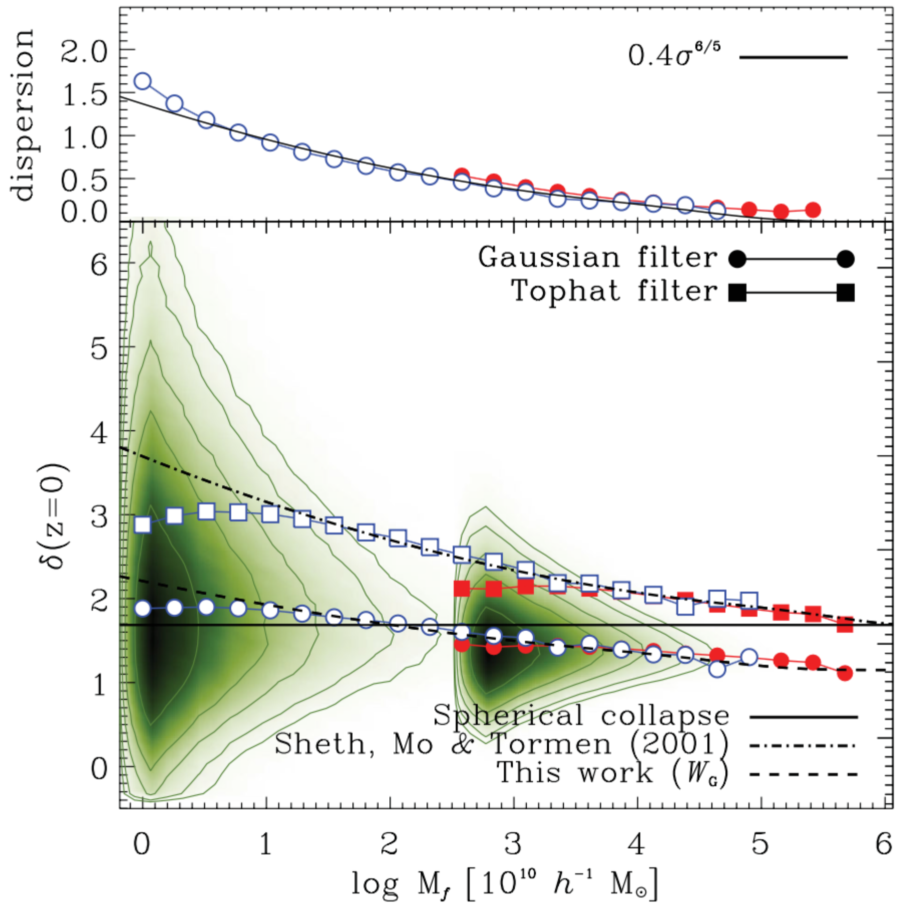


Press & Schechter (1974), Bond et al. (1991)

Add a collapse criterion



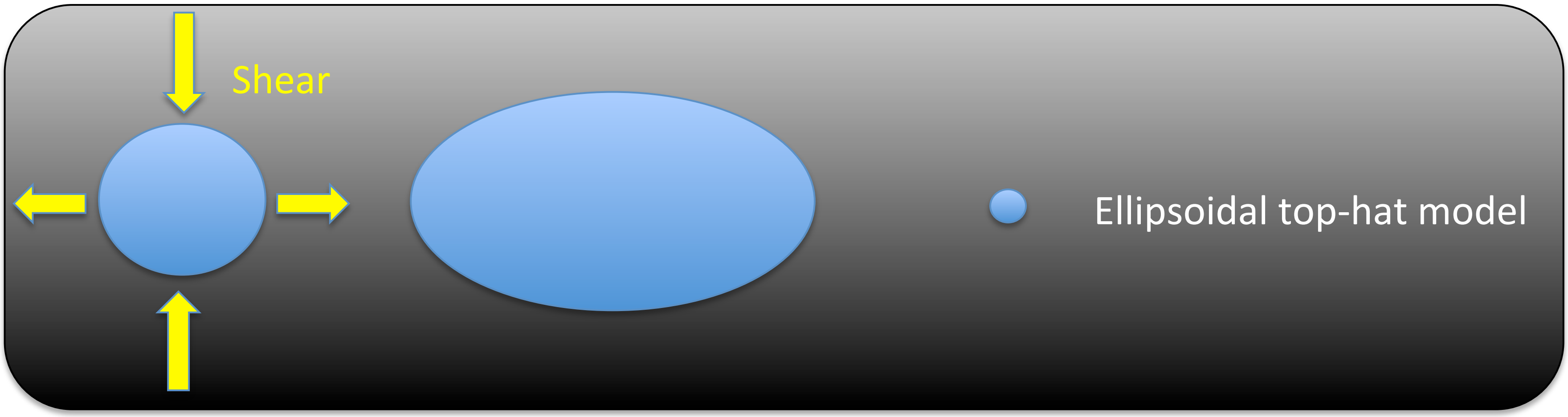
Collapse threshold from N-body



SMT: fit to GIF n(M,z)

Sheth & Tormen 1999, Sheth, Mo & Tormen 2001, Robertson et al. 2009, Elia, Ludlow & Porciani 2012

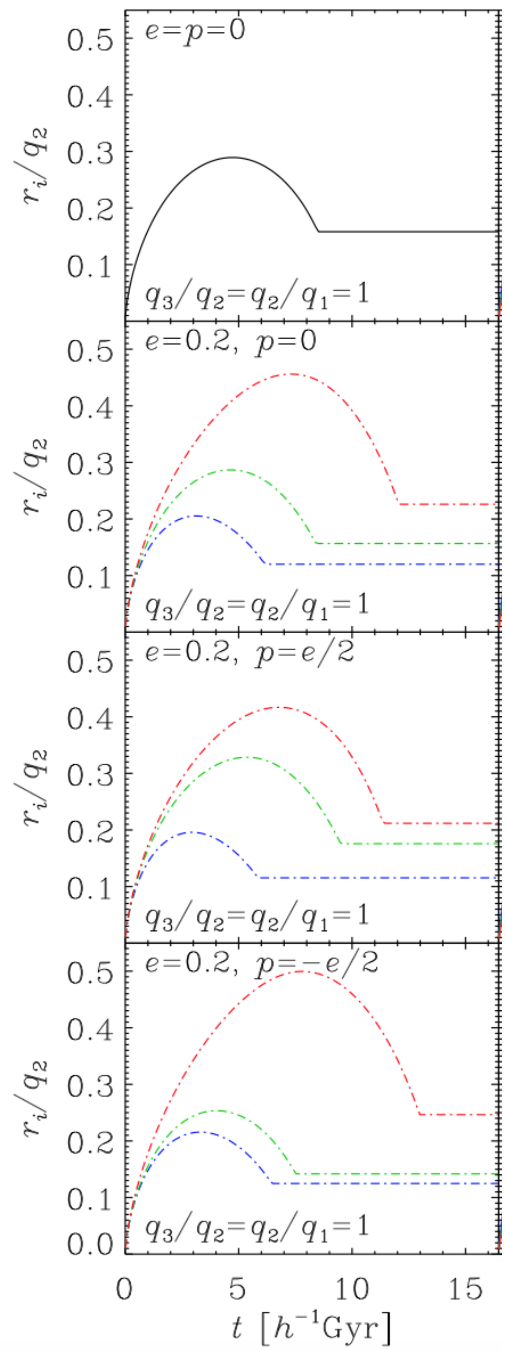
The Sheth-Mo-Tormen explanation



Eisenstein & Loeb (1995), Bond & Myers (1996)

- Random points in a Gaussian random field experience stronger shear when the filter size is reduced (Doroshkevich 1970)

- More strongly sheared perturbations require higher initial density contrasts to overcome the tidal stretching and collapse by a particular time (Sheth, Mo & Tormen 2001)

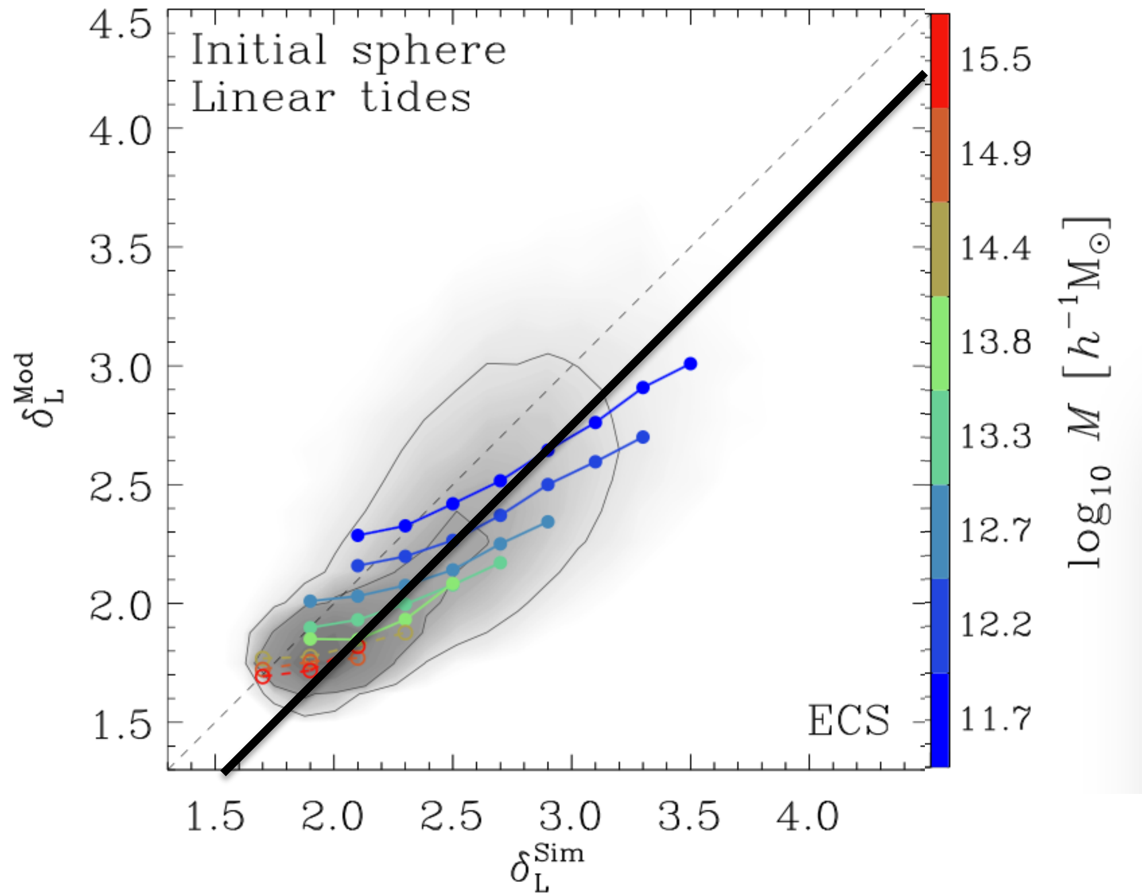


e=p=0
q3/q2=q2/q1=1
e=0.2, p=0
q3/q2=q2/q1=1
e=0.2, p=e/2
q3/q2=q2/q1=1
e=0.2, p=−e/2
q3/q2=q2/q1=1
ri/q2
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
t [h−1Gyr]

How well does the EC work?

Borzyszkowski, Ludlow & Porciani (2014)

linear δ required in the EC model for the perturbation to collapse at $z = z_{id} = 0$

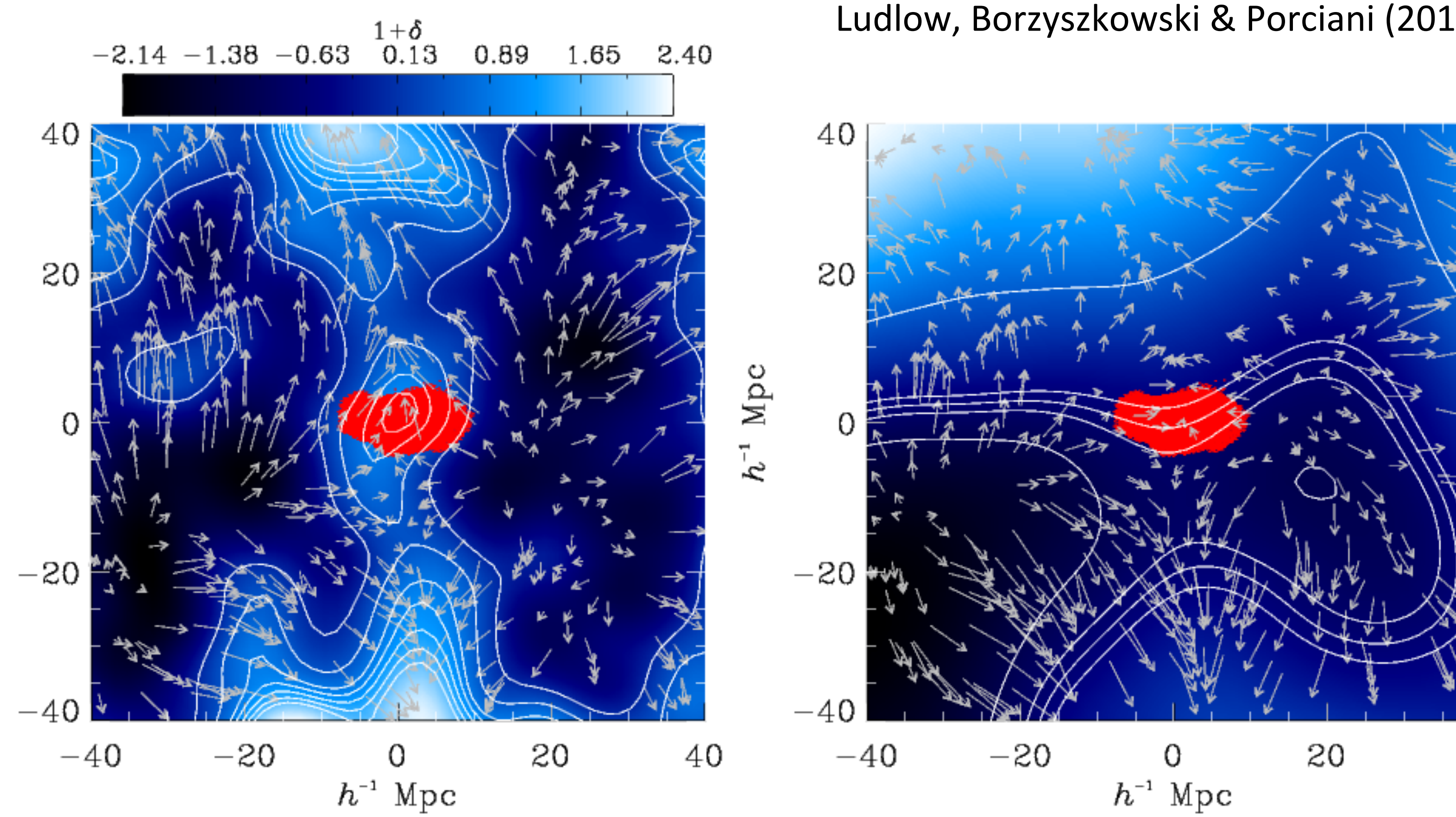


SMT01 rescaled the EC barrier by a factor 0.84

linear δ of protohalos in simulations

Halos in Lagrangian space

Ludlow, Borzyszkowski & Porciani (2014)

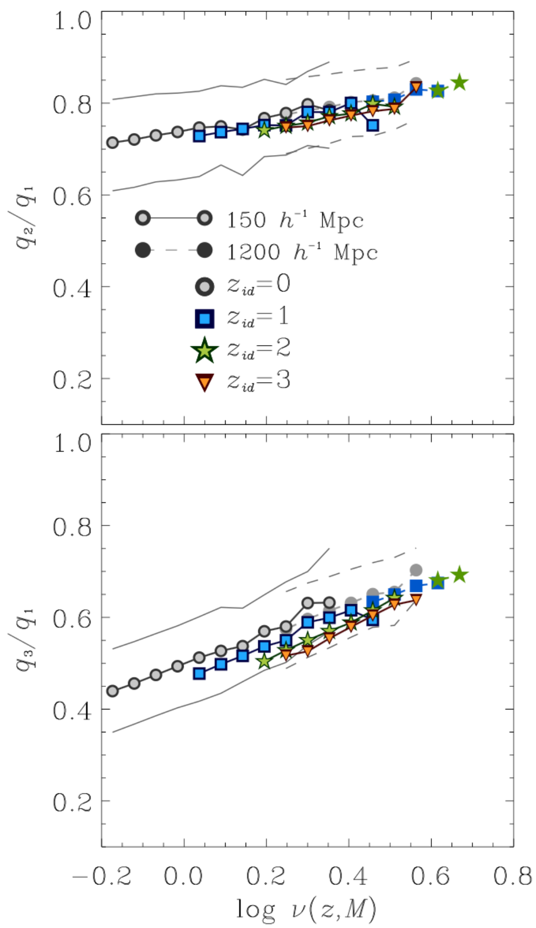


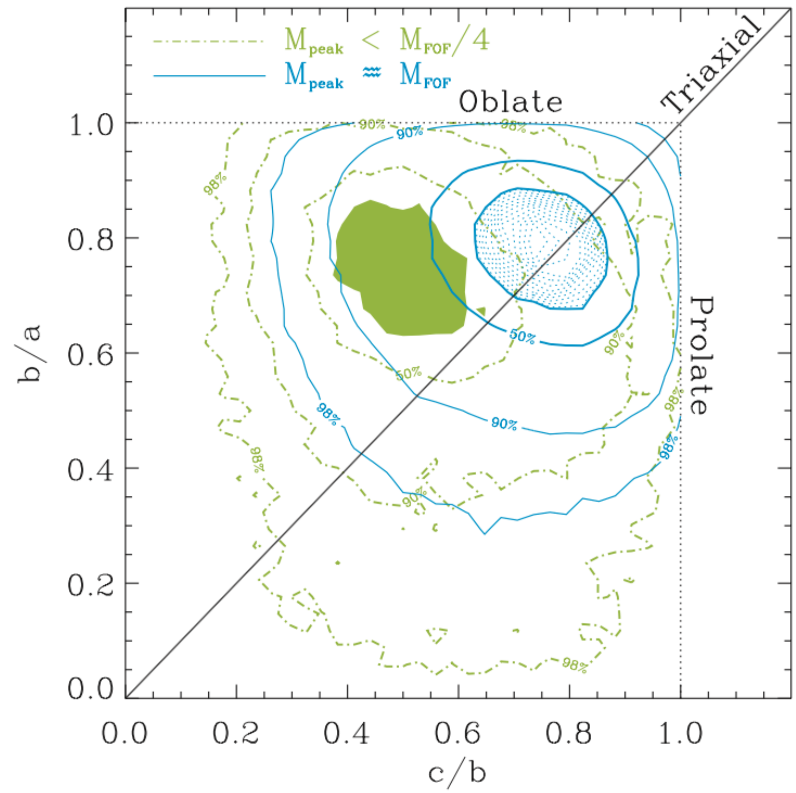
Linear overdensity field

Linear peculiar potential

Although halos form at the locations of linear peaks,
their Lagrangian shape does not follow isodensity contours!

Protohalos are not spherical



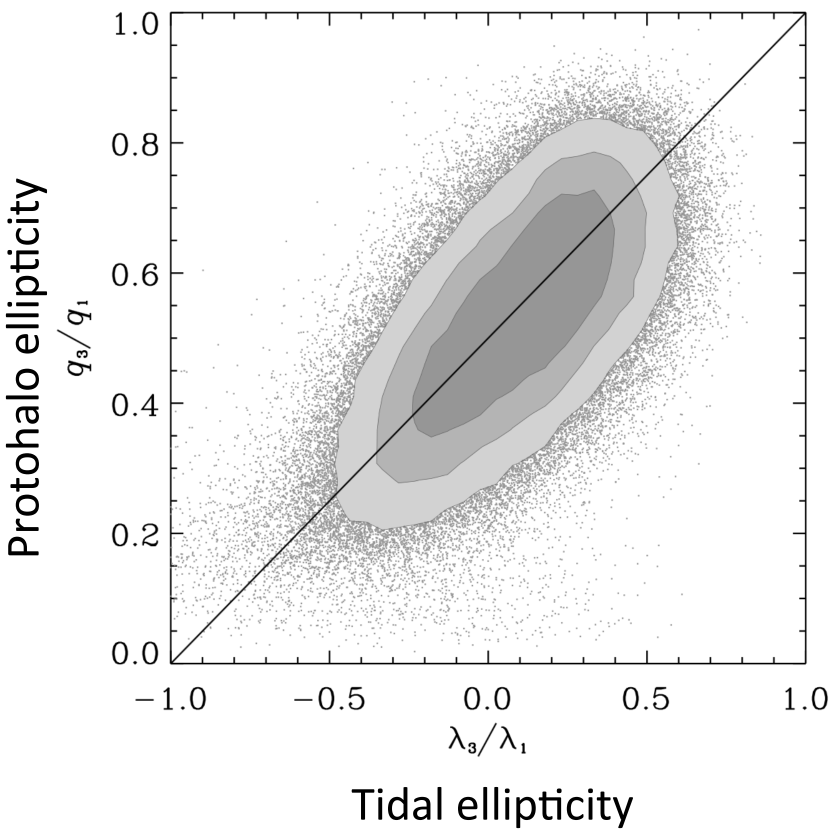


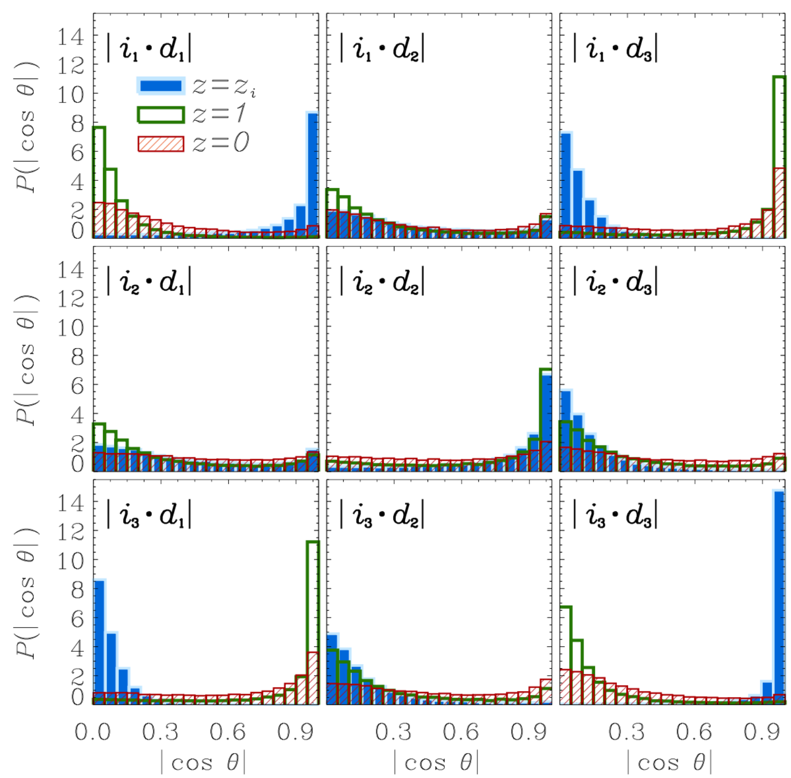
Ludlow, Borzyszkowski & Porciani (2014)

Borzyszkowski, Ludlow & Porciani (2014)

Protohalos vs tides

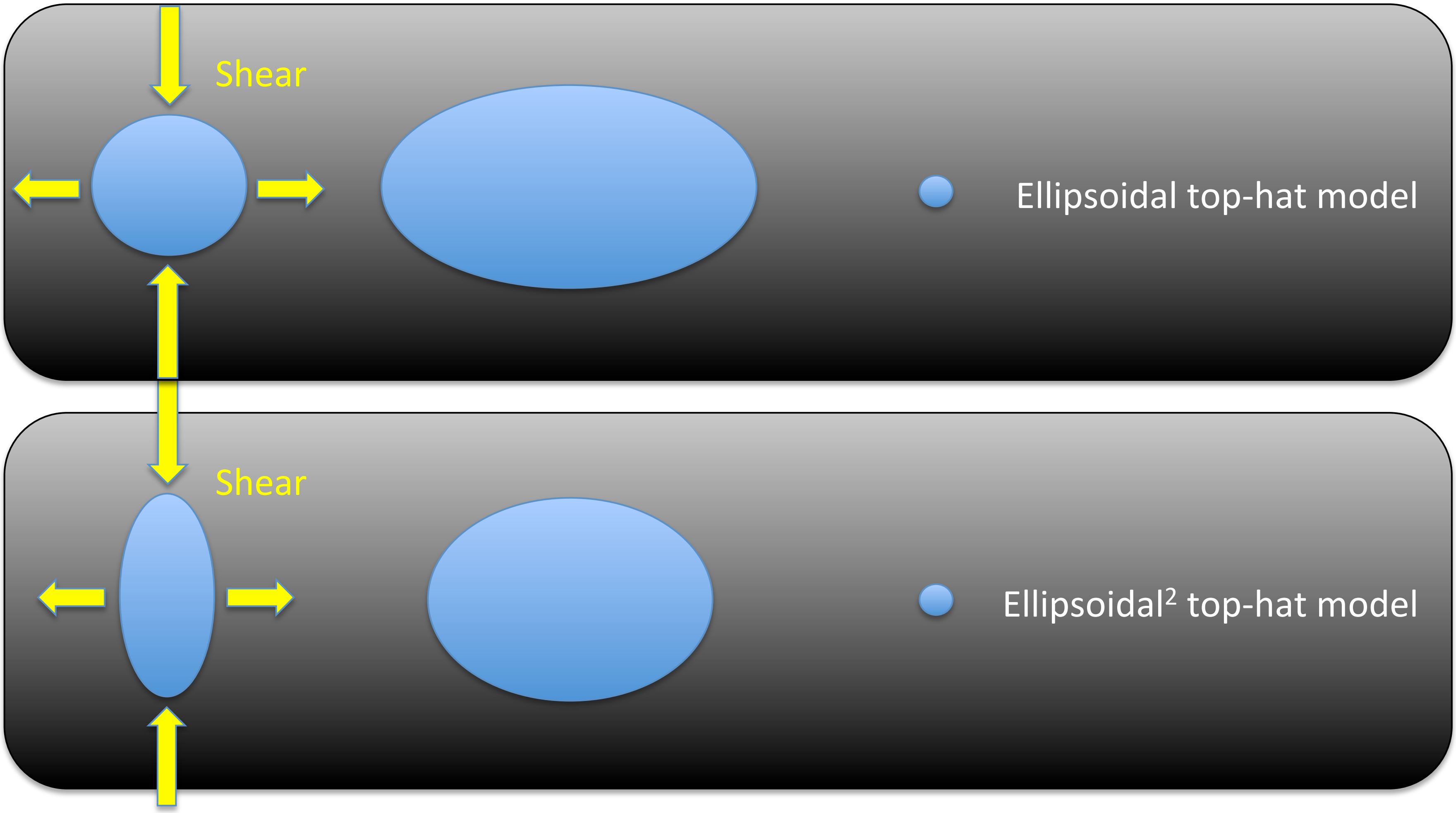
Porciani, Dekel & Hoffman (2002), Lee & Pen (2000), Ludlow, Borzyszkowski & Porciani (2014)



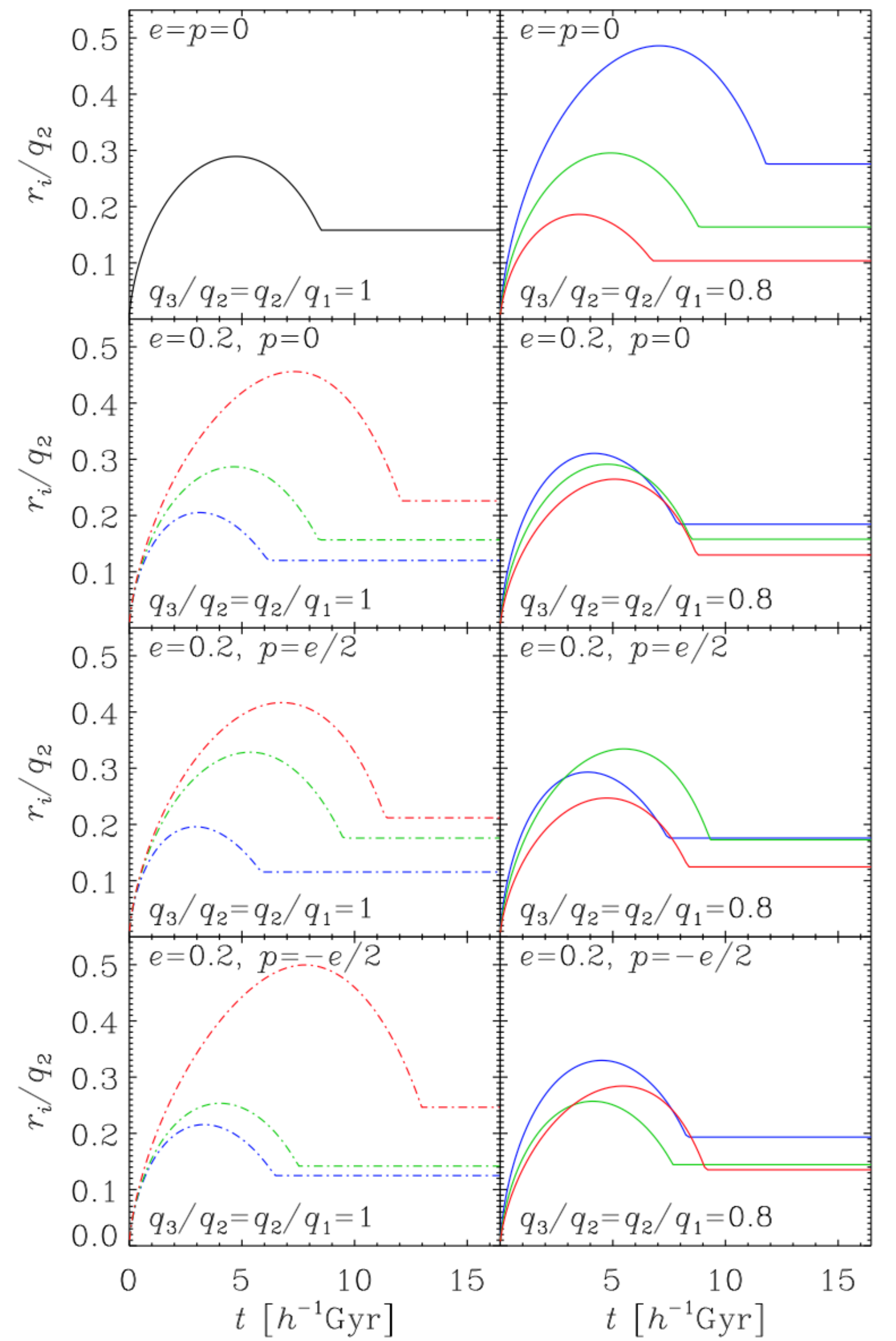


The shape and orientation of protohalos strongly correlates with the tidal field.
This explains why halos have low spin parameters.

A new collapse model

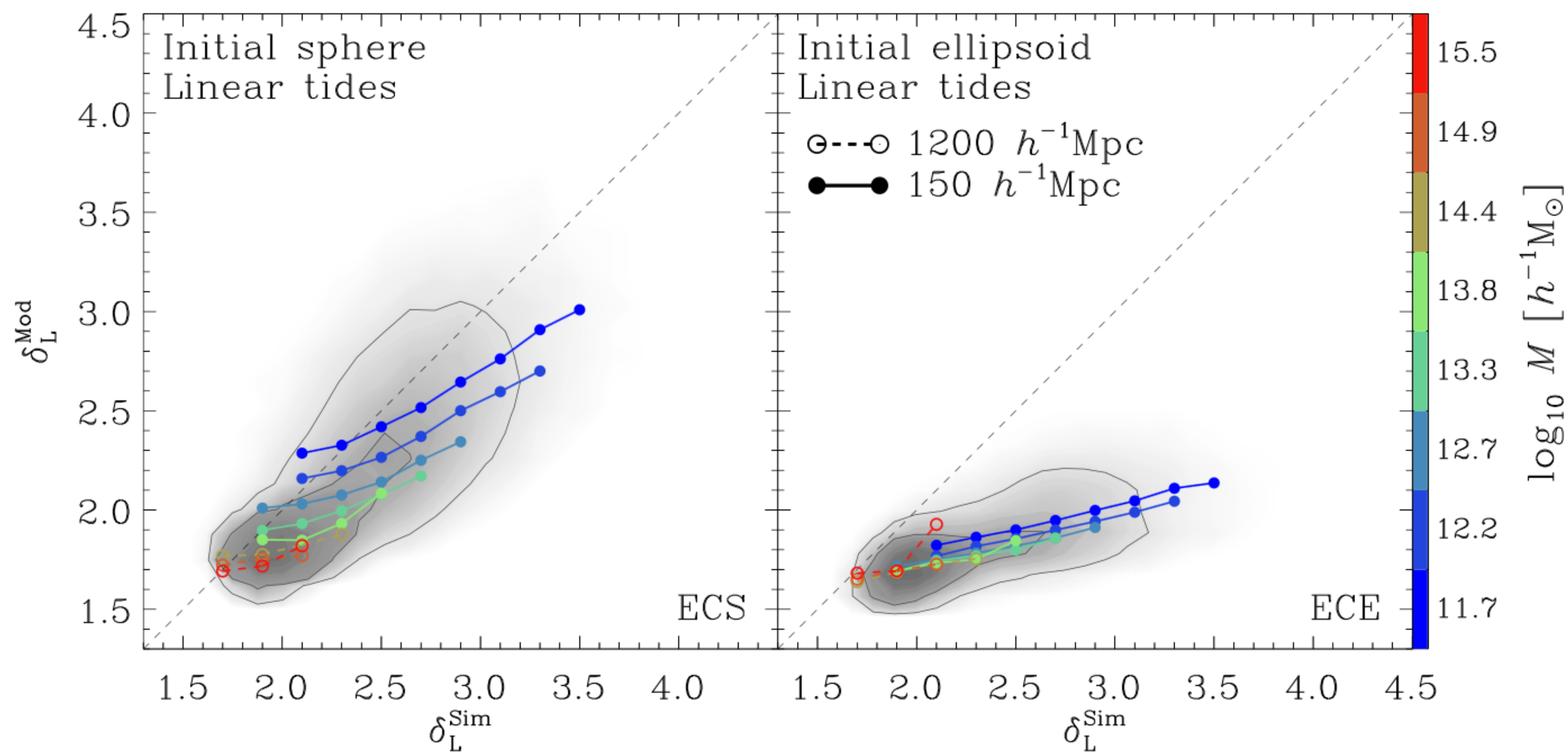


Ludlow, Borzyszkowski & Porciani (2014), Borzyszkowski, Ludlow & Porciani (2014)



In the E^2 model all axes collapse approximately at the same time

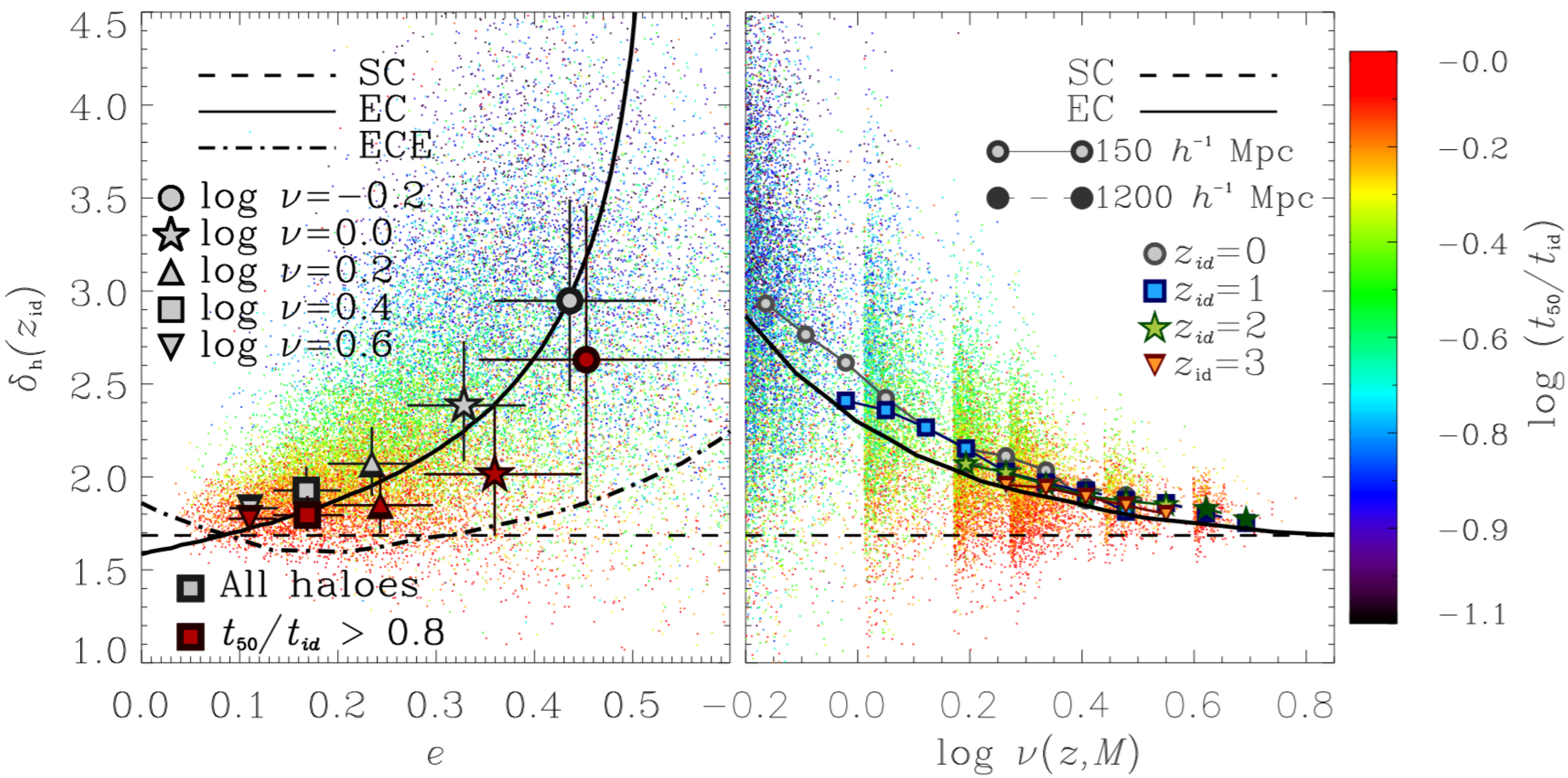
How well does the E^2 model do?



Borzyszkowski, Ludlow & Porciani (2014)

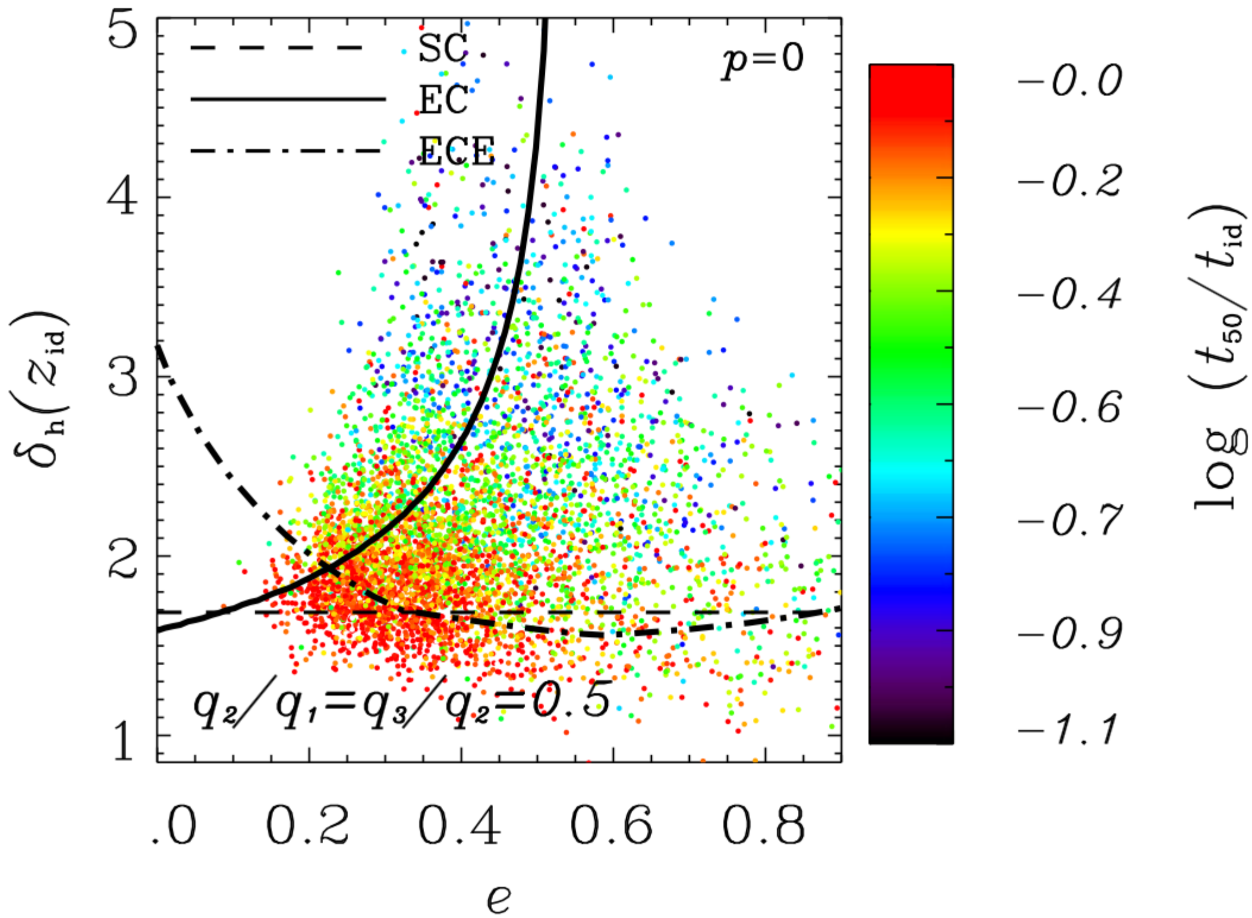
What is the origin of the scatter?

Ludlow, Borzyszkowski & Porciani (2014)



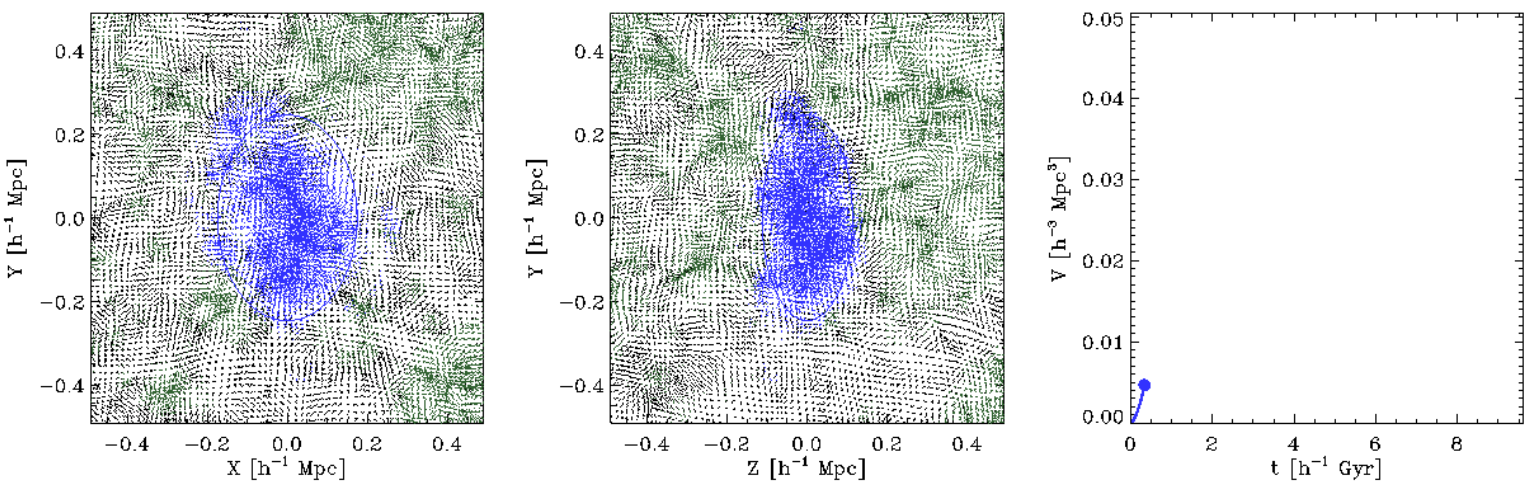
The linear density threshold strongly depends on the half-mass formation time (natural origin of assembly bias at low halo mass!!!)

Morevoer…



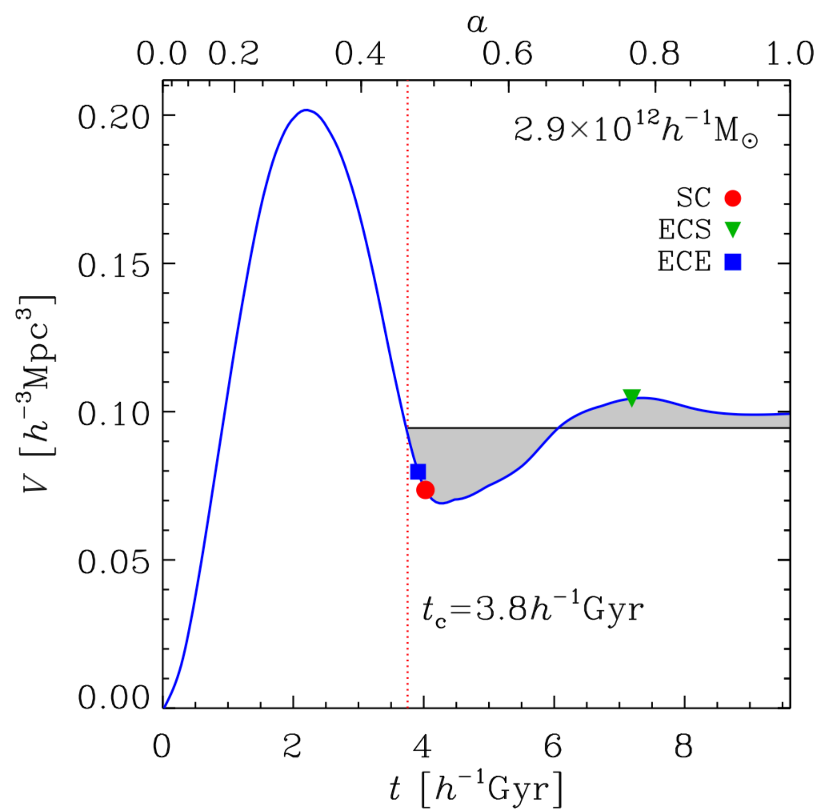
Ludlow, Borzyszkowski & Porciani (2014)

How do halos form in simulations?

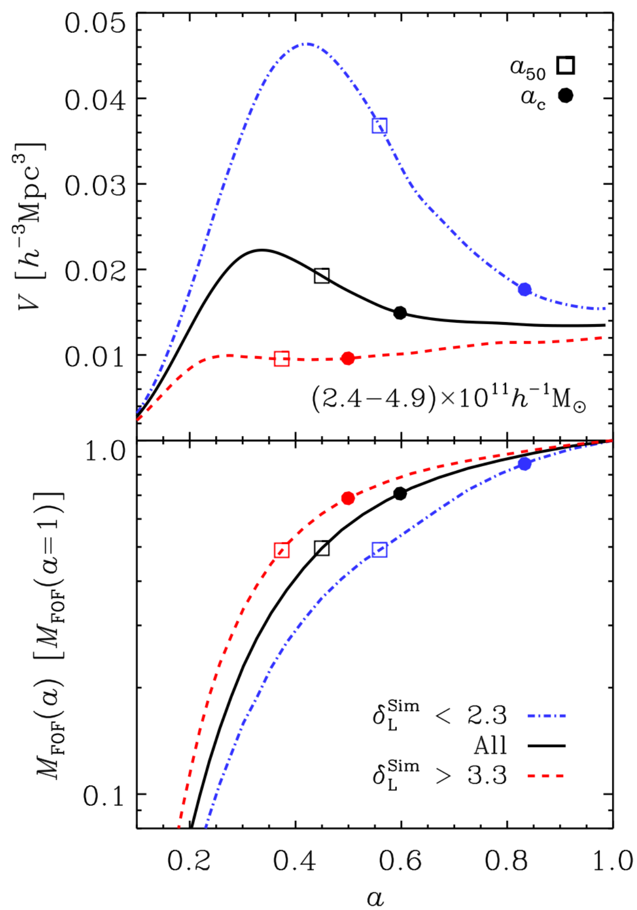


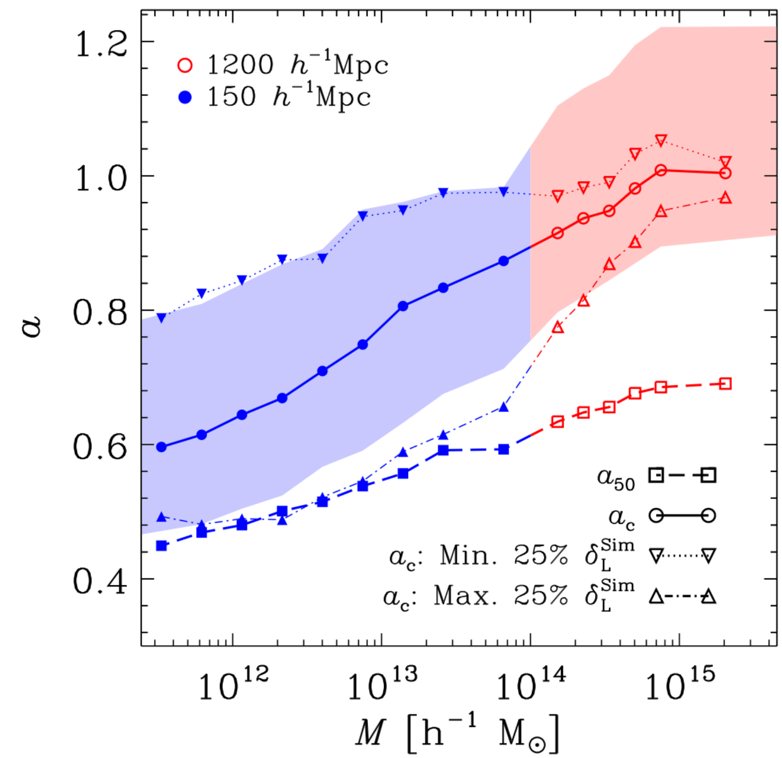
Defining the “collapse time”

Rudolf Julius Emmanuel Clausius (1822-1888)



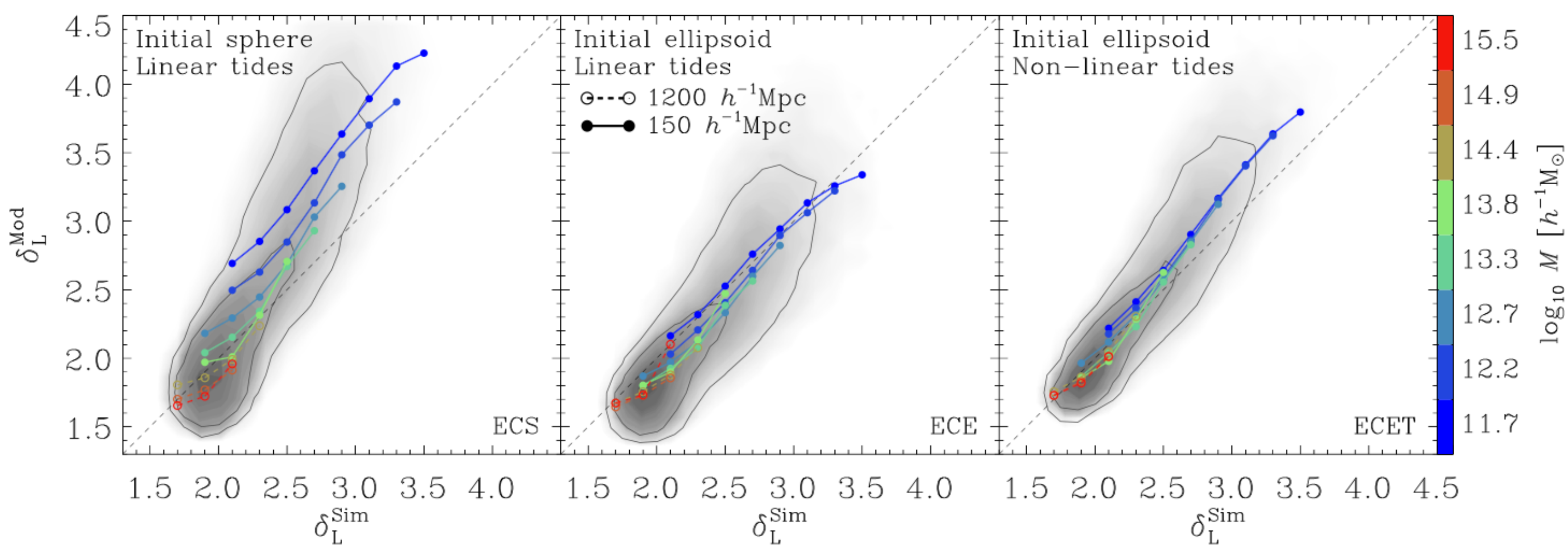
The halo “collapse” time



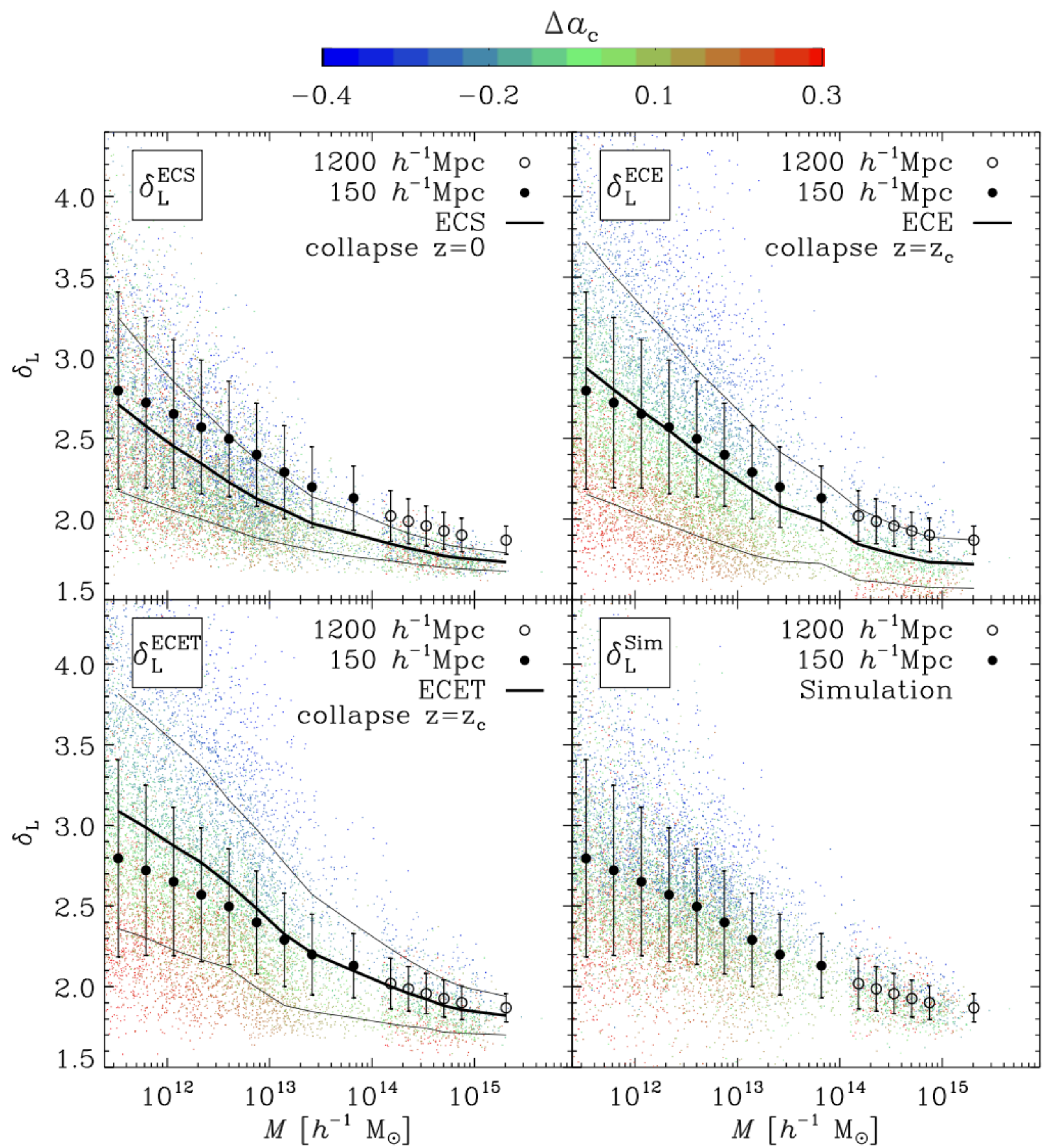


Borzyszkowski, Ludlow & Porciani (2014)

Putting all together (aka achieving self-consistency)

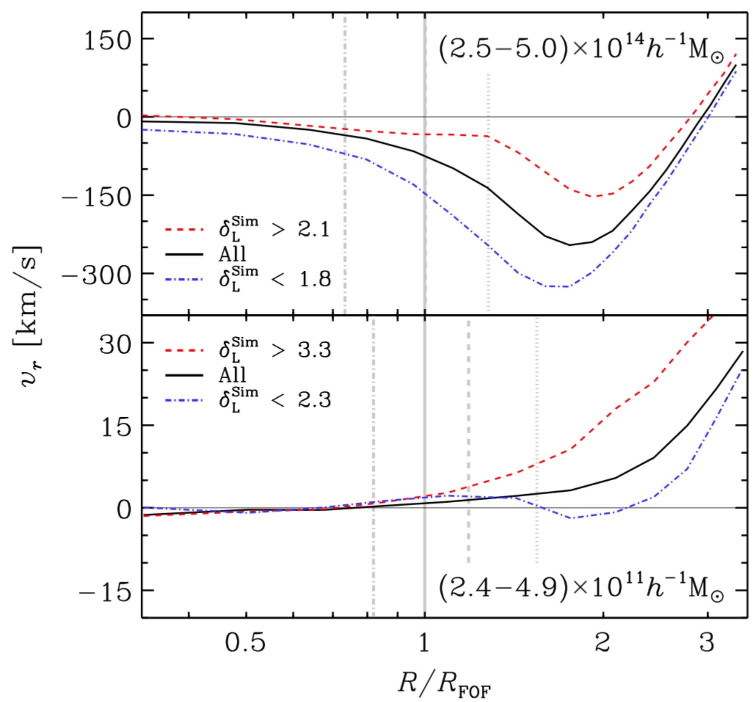


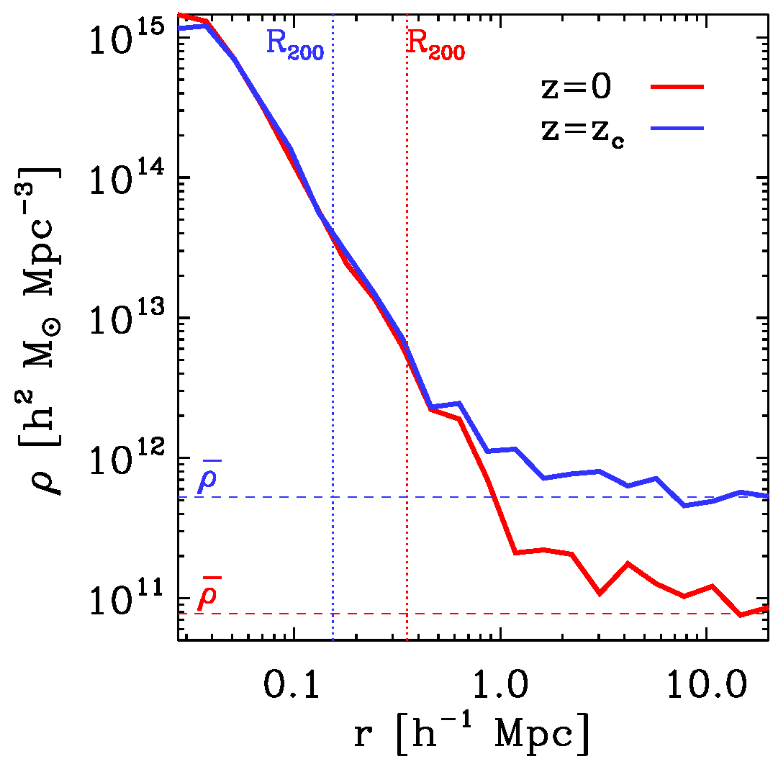
Borzyszkowski, Ludlow & Porciani (2014)



Δa_c
−0.4
−0.2
0.1
0.3
δ_L^{ECS}
1200 h^{-1}Mpc
150 h^{-1}Mpc
ECS
collapse z=0
δ_L^{ECE}
1200 h^{-1}Mpc
150 h^{-1}Mpc
ECE
collapse z=z_c
δ_L^{ECET}
1200 h^{-1}Mpc
150 h^{-1}Mpc
ECET
collapse z=z_c
δ_L^{Sim}
1200 h^{-1}Mpc
150 h^{-1}Mpc
Simulation
δ_L
4.0
3.5
3.0
2.5
2.0
1.5
10^{12}
10^{13}
10^{14}
10^{15}
M [h^{-1} $M_\odot$]

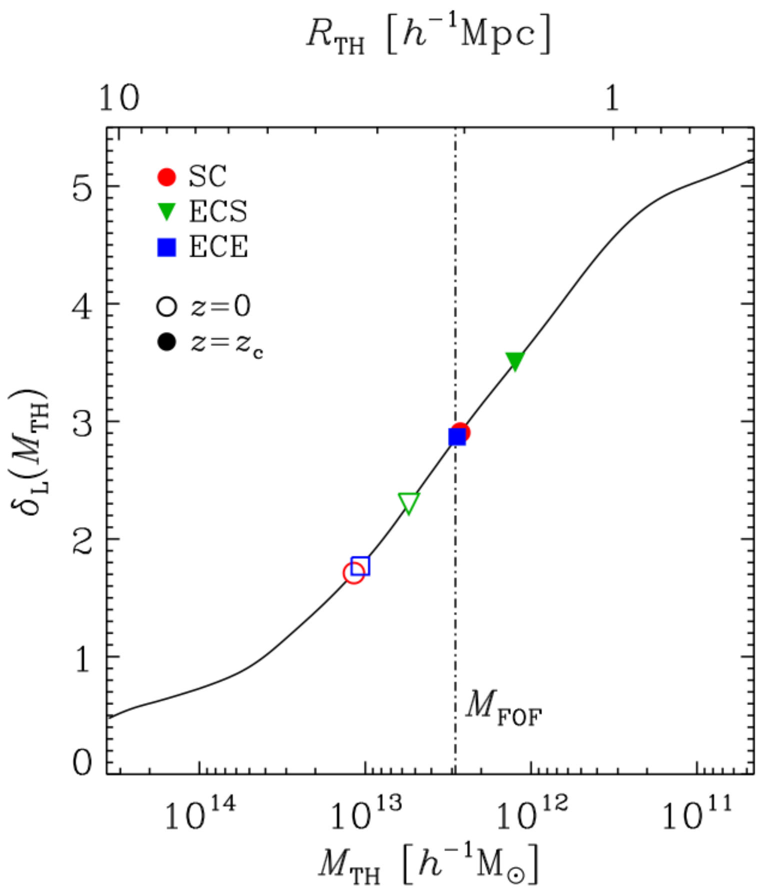
Do halos steadily grow in mass?

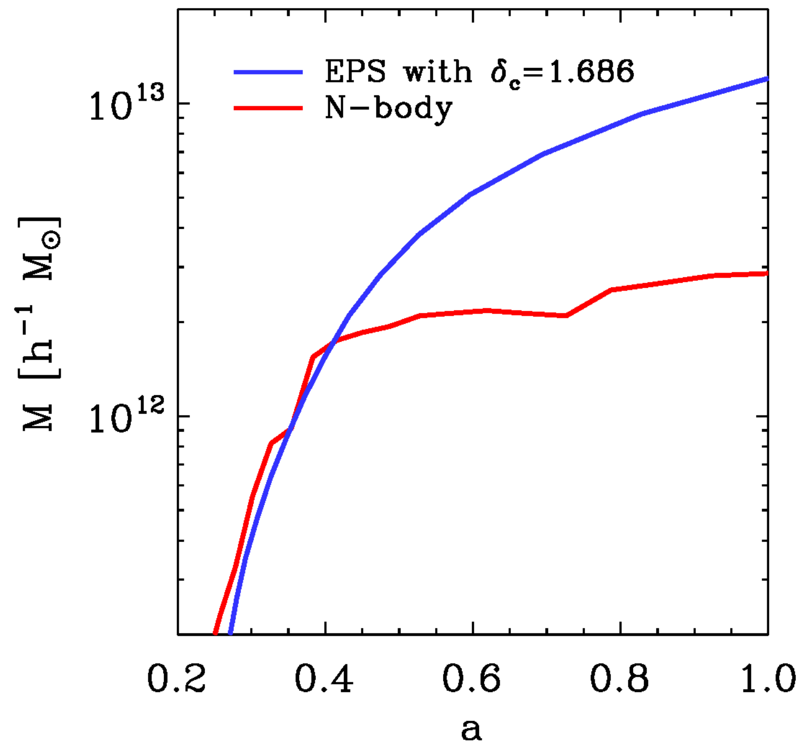




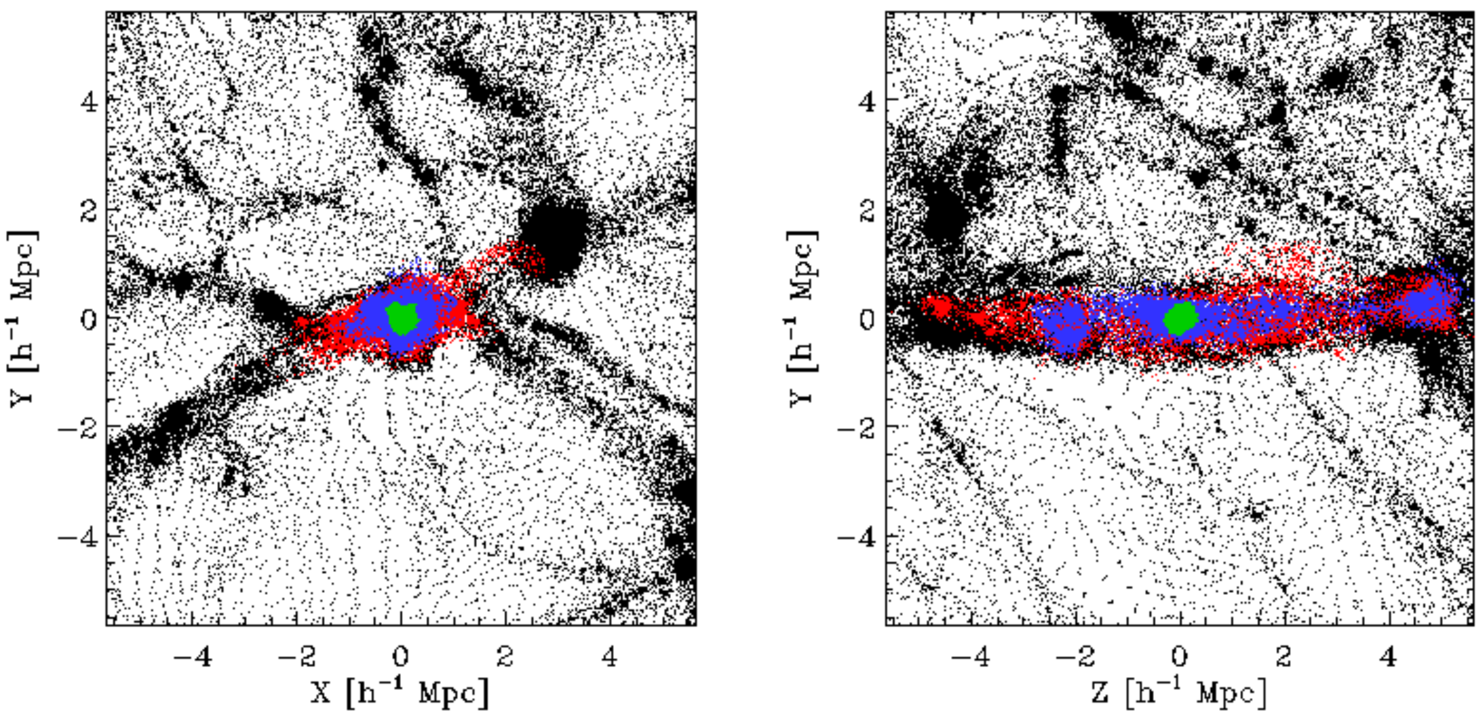
Borzyszkowski, Ludlow & Porciani (2014)
See also Prada et al. (2006)

Back to EPS

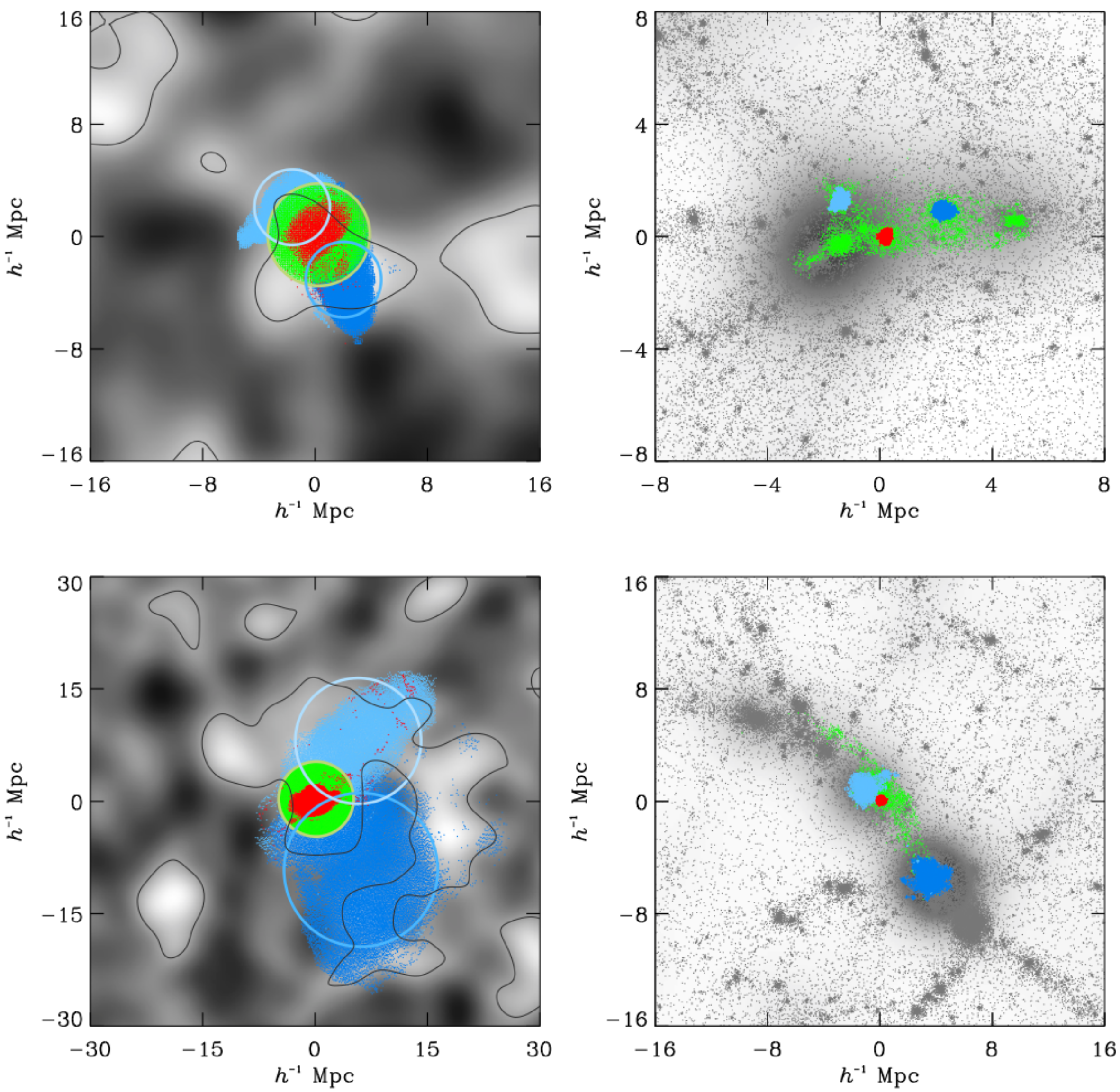




Borzyszkowski, Ludlow & Porciani (2014)


Y [h⁻¹ Mpc]
X [h⁻¹ Mpc]
Y [h⁻¹ Mpc]
Z [h⁻¹ Mpc]
4
2
0
−2
−4

Ludlow, Borzyszkowski & Porciani (2014)



Lagrangian space

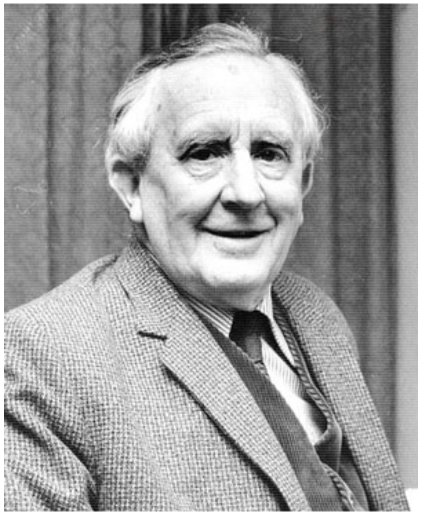
Eulerian space

Conclusions

Cluster-sized halos Galaxy-sized halos

- The virialized part of halos corresponds to a mean overdensity of 200 times the mean density FACT MYTH
- Halos form out of linear density peaks at the time in which the linear overdensity smoothed on the halo size is of order unity FACT FACT (approximately)
- The mass accretion history of the halos reflects the density profile around the peaks out of which they form FACT MYTH
- Halos keep accreting matter all the time (new shells fall onto them) and they steadily grow in mass FACT MYTH
- The extended Press-Schechter model predicts their accretion history FACT MYTH
- The ellipsoidal collapse model à la Bond & Myers describes their formation process FACT MYTH

I believe that legends and myths are largely made of truths



The great enemy of the truth is very often not the lie, deliberate, contrived and dishonest, but the myth – persistent, persuasive and unrealistic