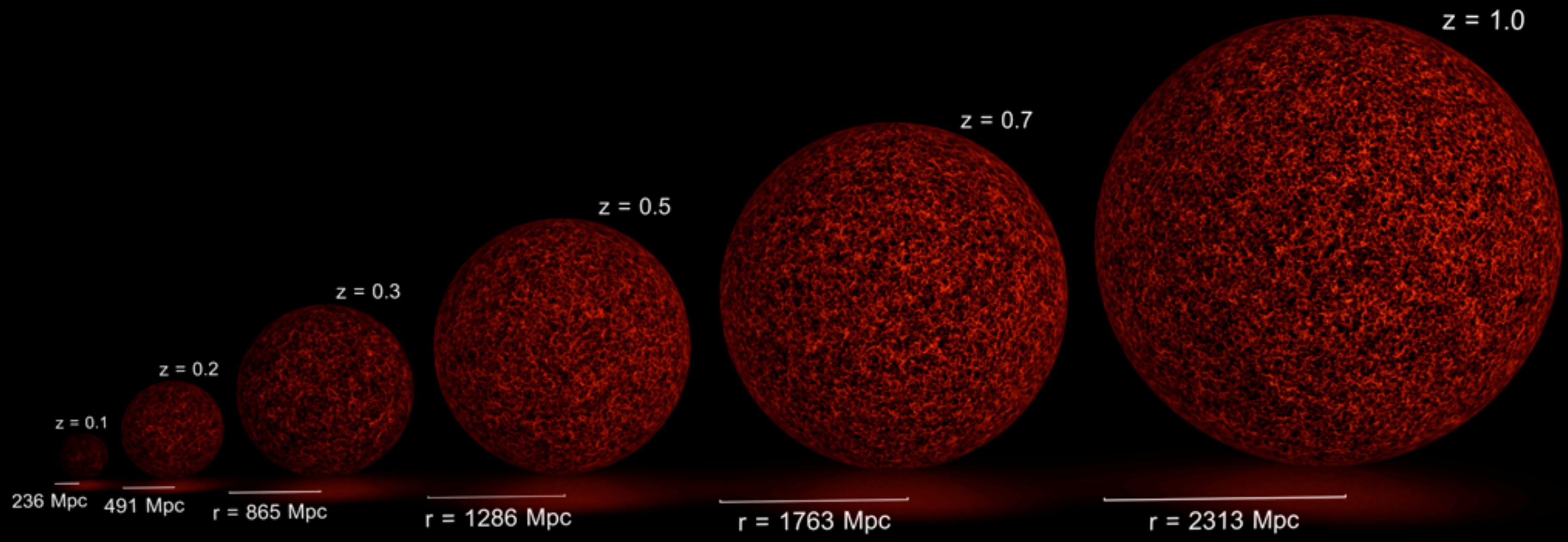
MICE simulations

Abundance of massive clusters and large-scale clustering



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MICE

Marenostrum Institut
de Ciències de l'Espai
Simulations

MICE ⇨ Project to develop very large numerical “cosmological” simulations in the **Marenostrum** supercomputer (Barcelona). Provide future surveys with mocks (DES).

- 10.000 processors, 20 TB RAM , 100 Teraflops
- GADGET N-body simulations with 10^9- ~10^{11} dark-matter particles in volumes 1-500 h^{-3} Gpc^3 ⇨ ***dynamical range of 5-6 orders of magnitude in scale***

People

MICE collaboration : P.Fosalba (PI), F.Castander, M.Crocce, E.Gaztañaga, M.Manera

External : C.Baugh , A.Cabré, A. Gonzalez, V.Springel

project web: www.ice.cat/mice

MICE

Marenostrum Institut
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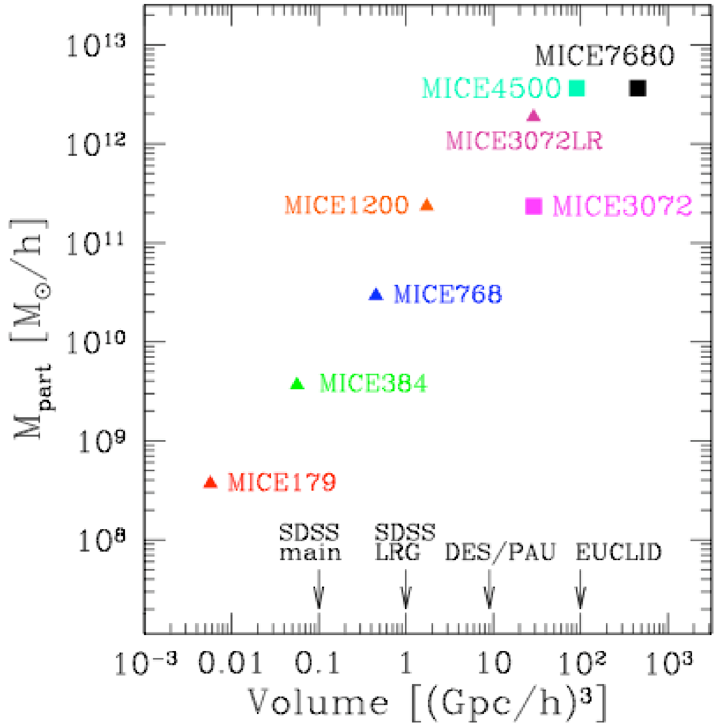
Simulations

Run	N_{part}	L_{box} (h^{-1} Mpc)	m_p (h^{-1} $M_\odot$)
MICE7680	2048^3	7680	3.66×10^{12}
MICE3072	2048^3	3072	2.34×10^{11}
MICE4500	1200^3	4500	3.66×10^{12}
MICE3072LR⋆	1024^3	3072	1.87×10^{12}
MICE768⋆	1024^3	768	2.93×10^{10}
MICE384⋆	1024^3	384	3.66×10^{9}
MICE179⋆	1024^3	179	3.70×10^{8}
MICE1200⋆ (×20)	800^3	1200	2.34×10^{11}



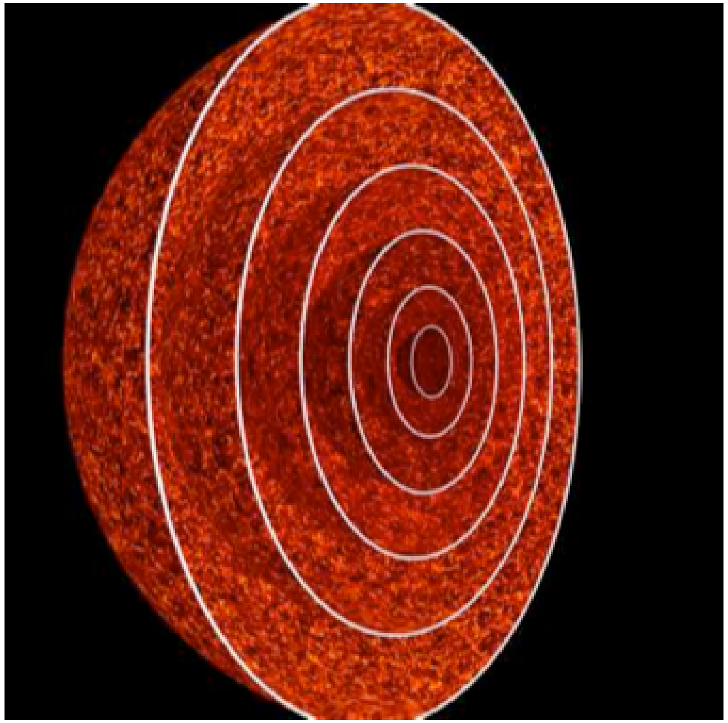
$N_{part} = 4096^3$ - $L_{box} = 3072$ h^{-1}Mpc - $m_p = 3 \times 10^{10}$ $h^{-1}M_O$ *Running* !

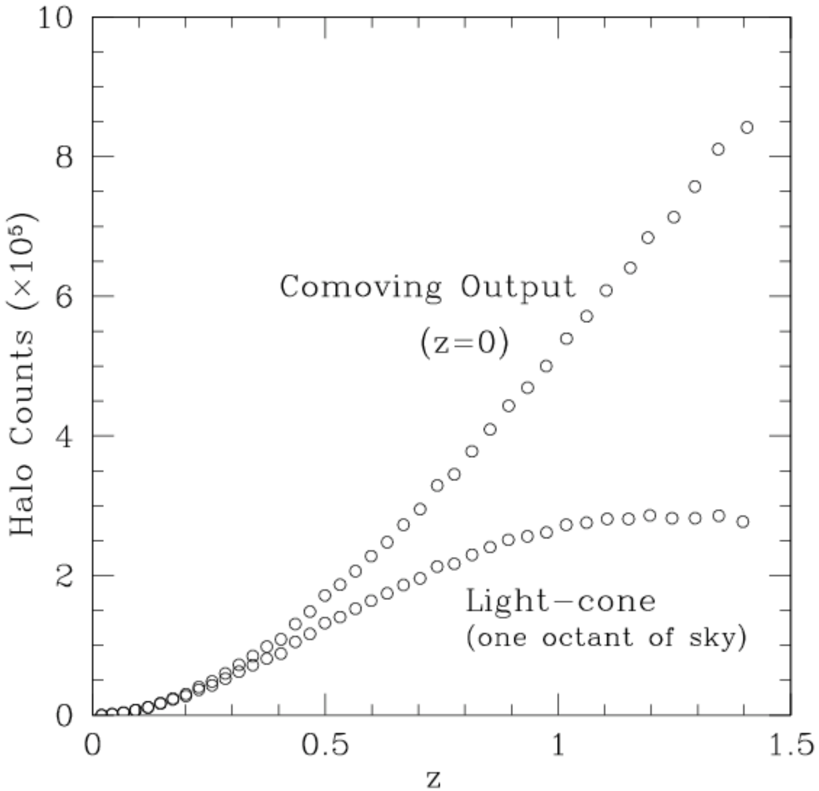
Where do we stand ? Millenniun : N_p 2160^3, m = 9 x 10^8 h^{-1} M_O, L = 500 h^{-1} Mpc (Springel et al. 2006)

MICE 3072 ~ 200 times the volume of Millennium Run (same particle load)

MICE 7680 ~ 20 Hubble Volume Simulations (and 500 times SDSS volume)

MICE light-cone and projected density maps





“ The onion universe: all sky light-cone simulations in spherical shells ”
Fosalba, P. et al , MNRAS 391, 435 (2008)

Lightcone to z =1.4 and proyected density maps :

- *Lensing, Integrated Sachs Wolf Effect, Evolution bias*

Cluster abundance :

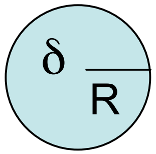
- *Particularly suitable for the most massive and least abundant objects*

"Simulating the Universe with MICE : The abundance of massive clusters"
Crocce, Fosalba, Castander & Gaztanaga, arXiv astro-ph/0907.0019 (2009)

Large Scale Clustering (e.g. BAO to % accuracy) :

- *Large-scale bias (e.g. in LRG type halos)*
- *Angular Clustering in z-slices*
- *Clustering of Clusters*

Quick review ..



$$P_R(\delta) = \frac{e^{-\delta^2/2\sigma^2(R)}}{\sqrt{2\pi\sigma^2(R)}} \qquad \sigma^2(R) \equiv \int d^3k\, P(k)\, W^2(kR)$$

$$M = \rho_b 4\pi R^3/3,$$

filter scale

From spherical collapse it is possible to compute the minimum δ_c that a given region must have in order to expand and then collapse into a virialized structure

For a given filter scale R (or M) we then associate the fraction of points with $\delta > \delta_c$ with the fraction of halos with mass larger than M,

$$F(M) = \int_{\delta_c}^{\infty} P_R(\delta)\, d\delta$$

The number density of halos of mass M is then,

$$n_{ps}(M) = -\frac{2\bar{\rho}}{M} \frac{\delta_c}{\sigma^2} \frac{e^{-\delta_c^2/2\sigma^2}}{\sqrt{2\pi}} \frac{d\sigma}{dM}$$

MICE halo catalogues and mass function

• We built halo catalogues using standard FoF algorithm (b = 0.2 / 0.164)

• Using FoF(0.2) there are (with $N_p > 20$) ~ 25×10^6 halos in MICE3072 ($M > 5 \times 10^{12}$) and ~ 15×10^6 in MICE7680 ($M > 7 \times 10^{13}$) (reaching $M \sim 8 \times 10^{15}$)

• We also built SO catalogues starting from the FoF halos

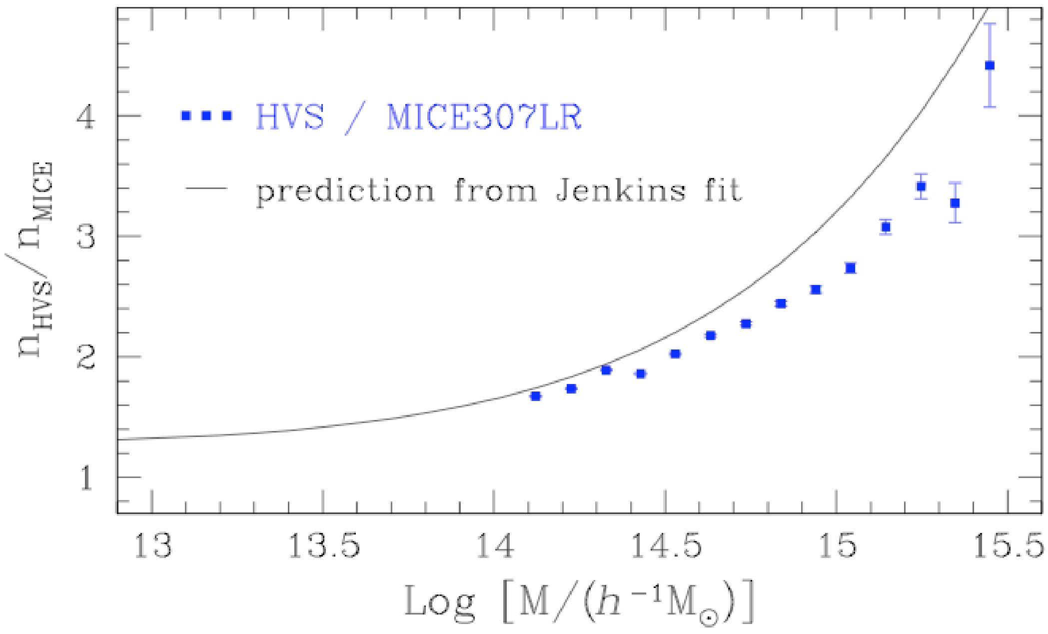
$$f(\sigma, z) = \frac{M}{\rho_b} \frac{dn(M,z)}{d \ln \sigma^{-1}(M,z)}$$

$$f_{\rm Jenkins}(\sigma) = 0.315 \exp\left[-|\log \sigma^{-1} + 0.61|^{3.8}\right]$$

Comparison with the

Hubble Volume Simulation

FoF(0.164) halos

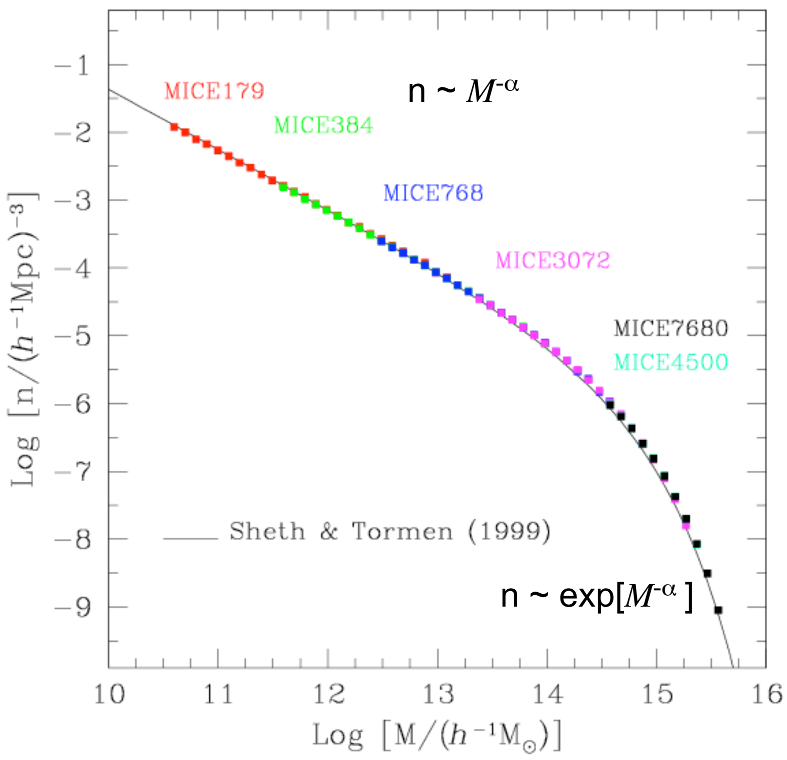


The Mass Function to high-masses

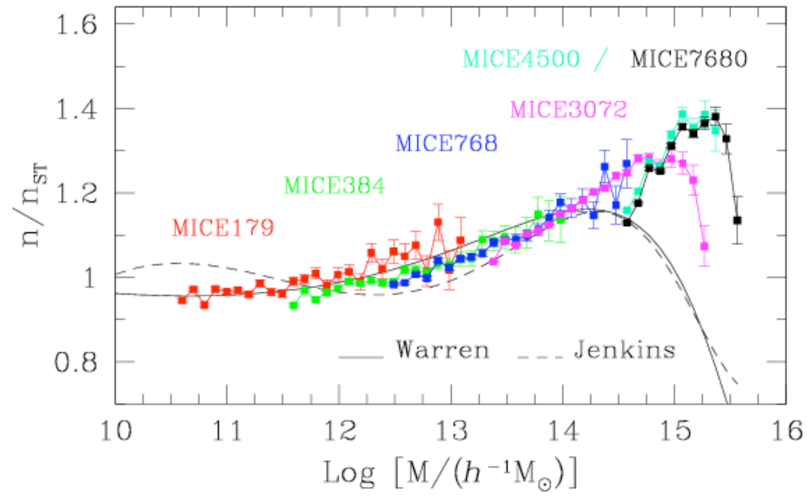
$$f(\sigma, z) = \frac{M}{\rho_b} \frac{dn(M,z)}{d\ln\sigma^{-1}(M,z)} \qquad \sigma^2(M,z) = \frac{D^2(z)}{2\pi^2}\int k^2 P(k) W^2(kR) dk, \quad M = \bar{\rho}_b 4\pi R^3/3,$$

$$\boxed{f_{\rm ST}(\sigma) = A\sqrt{\frac{2q}{\pi}}\frac{\delta_c}{\sigma}\left[1+\left(\frac{\sigma^2}{q\delta_c^2}\right)^p\right]\exp\left[-\frac{q\delta_c^2}{2\sigma^2}\right],}$$

$$P(k) \sim k^{n_{eff}} \qquad \sigma^2 \sim M^{-(1+n_{eff}/3)}$$



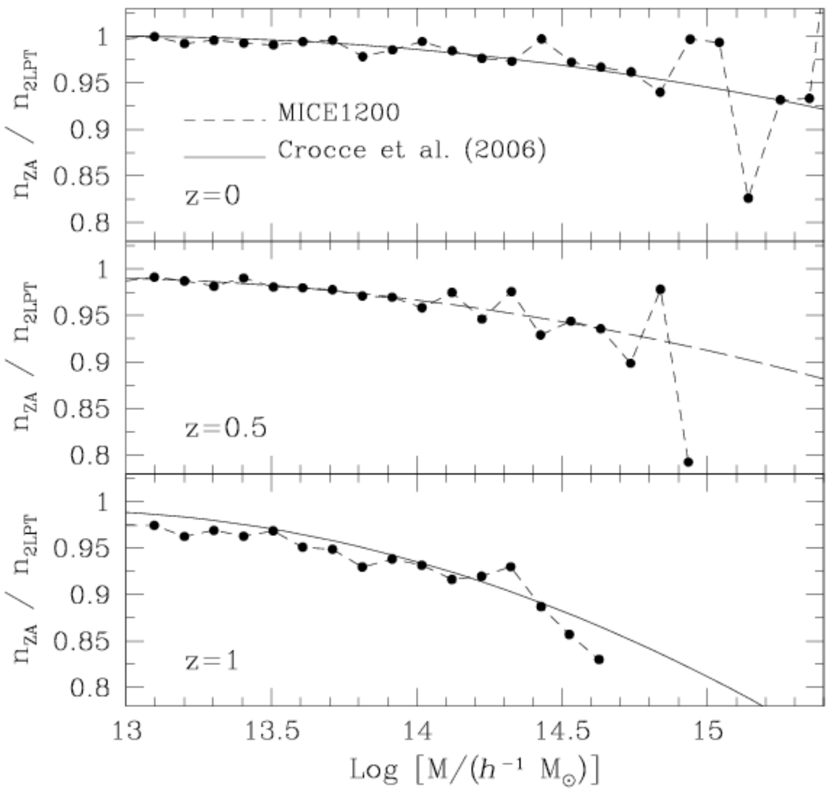
We can cover both the power-law regime at low-mass where n ~ $M^{-\alpha}$ and up to the exponential cut-off regime n ~ exp[- M^{α}]



Sources of Systematic Effects in the abundance of halos I

- Transients from the initial conditions

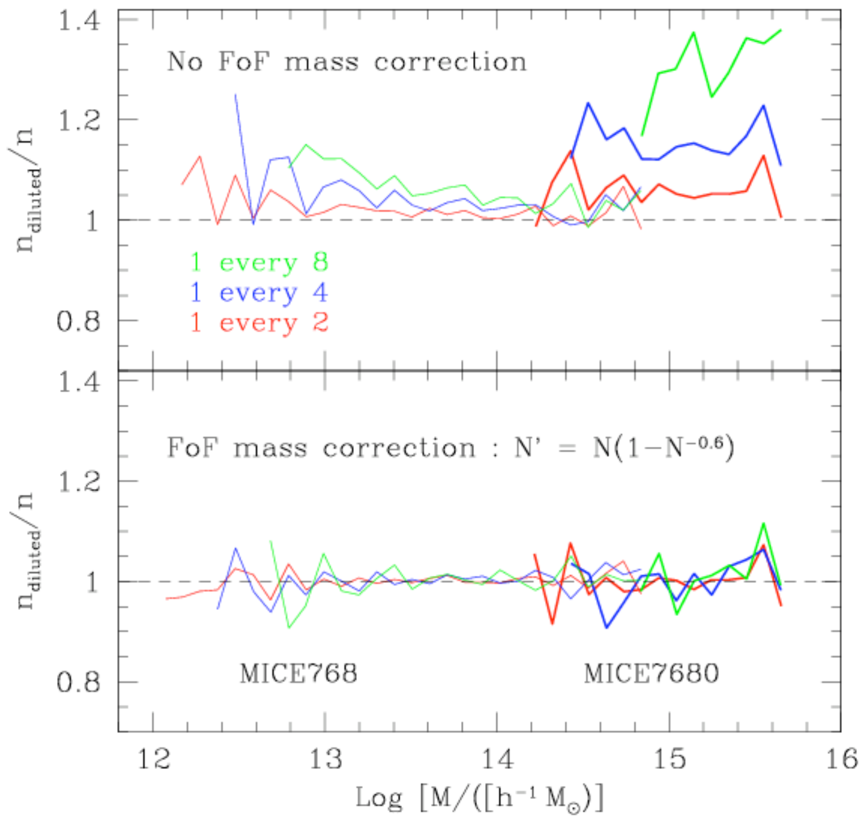
Using ZA and 2LPT at z_i=50



Initial Conditions : starting red-shift and initial dynamics (using Zeldovich vs. 2LPT)

Sources of Systematic Effects in the abundance of halos II

• Definition of (FoF) Halo Mass



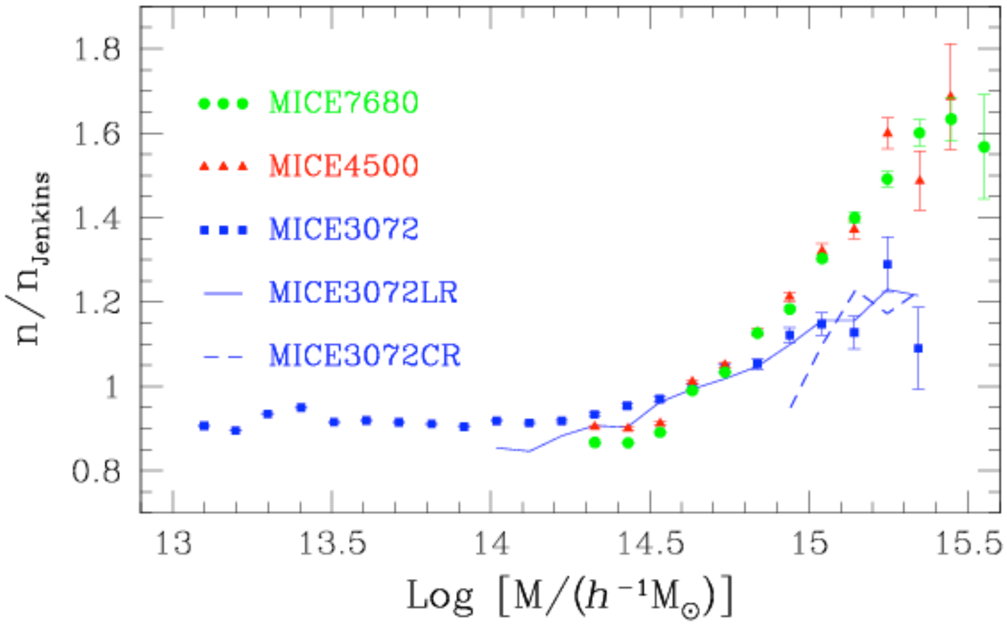
Sub-sampling the particle distribution

FoF mass correction (Warren et al. 2006)

$$N^{corr} = N_p\,(1-N_p^{-0.6})$$

Sources of Systematic Effects in the abundance of halos III

• Mass Resolution



	m_p [M$_\odot$/h]
MICE7680	3.66 x 10^{12}
MICE4500	3.66 x 10^{12}
MICE3072	2.34 x 10^{11}
MICE3072LR	1.87 x 10^{12}
MICE3072CR	1.47 x 10^{13}

• MICE7680 and MICE4500 have completely different random phases, different starting red-shifts and different initial dynamics

• Abundance at high-mass end seems quite robust in front of mass resolution, after correcting the FoF halo mass according to Warren et al (2006)

Estimating errors in the MF : internal, external and analytic methods

(but also for statistical errors in cluster-counts)

Internal :

Poisson and

$$\sigma^{(i)^2}_{Poisson} = 1/N_i$$

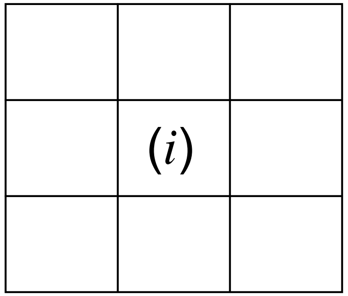
Jack-knife sampling

$$\sigma^{(i)^2}_{JK} = \frac{1}{\bar{n}^{(i)2}} \frac{N_{JK}-1}{N_{JK}} \sum_{j=1}^{N_{JK}} (n_j^{(i)} - \bar{n}^{(i)})^2$$

External :

Sub-volumes, using non-overlapping sub-divisions of larger volume runs.

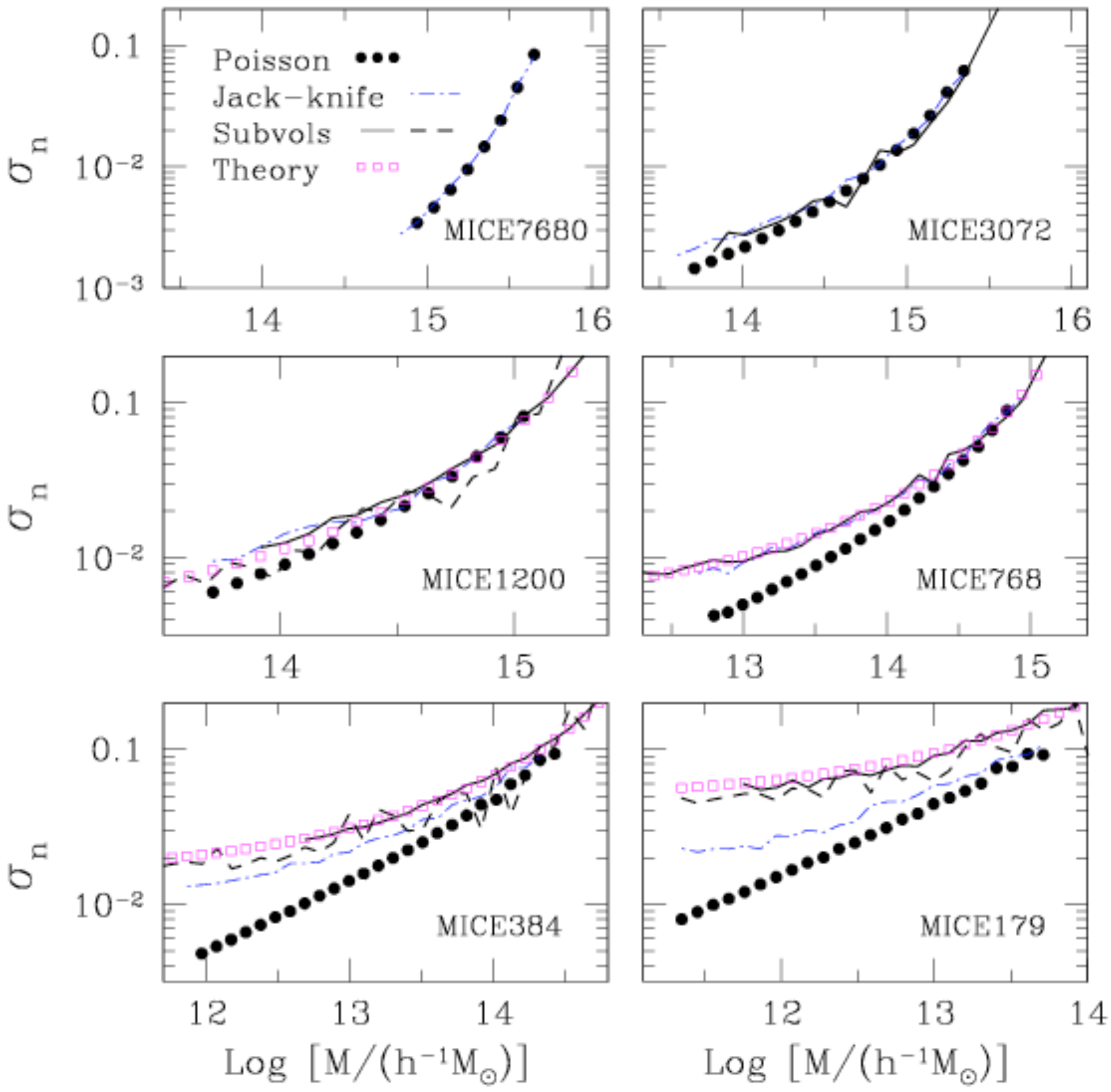
$$\sigma^{(i)^2} = \frac{1}{\bar{n}^{(i)2}} \sum_{j=1}^{N} (n_j^{(i)} - \bar{n}^{(i)})^2$$



Theory :

Accounting for both, sampling variance and shot-noise

$$\sigma_h^2 = \frac{\langle n^2 \rangle - \bar{n}_h^2}{\bar{n}_h^2} = \frac{1}{\bar{n}_h V} + b_h^2 \int \frac{d^3k}{(2\pi)^3} |W(kR)|^2 P(k),$$



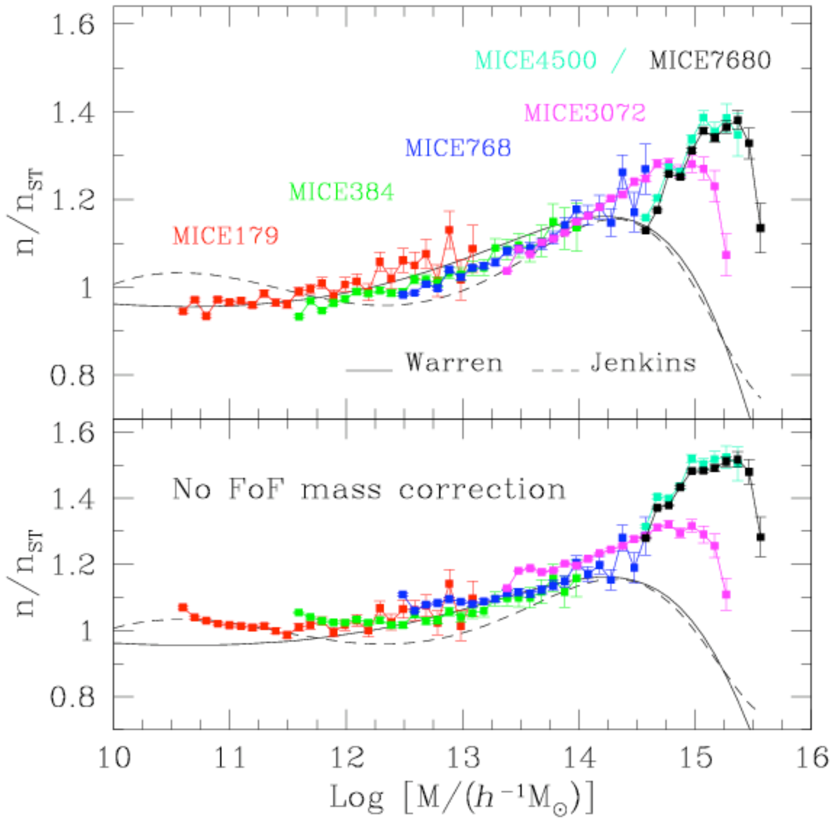
Results

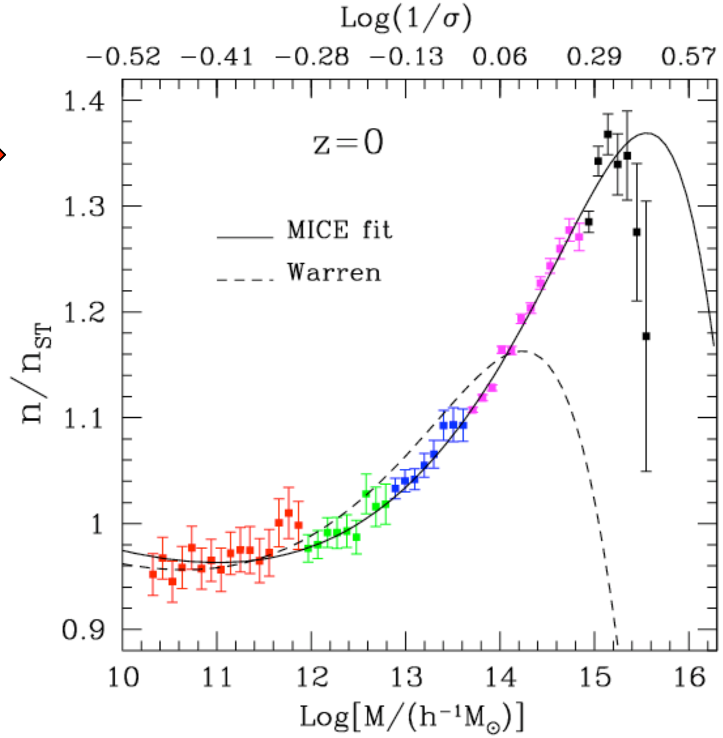
[] Theoretical estimation in very good agreement with sub-vols method

[] Jack-knife re-sampling under-estimates errors at low-mass ($M \leq 10^{13}$ M⊙/h)

[] Poisson shot-noise only good at very high masses ($M \geq 10^{14}$ M⊙/h)

MICE Mass Function Fit @ z = 0





We found that a re-calibration to the Warren MF shape can account for under-estimated high mass abundance

$$f_{\mathrm{Warren}}(\sigma) = 0.7234\,[0.2538 + \sigma^{-1.625}]\,\exp\left[-\frac{1.1982}{\sigma^2}\right]$$

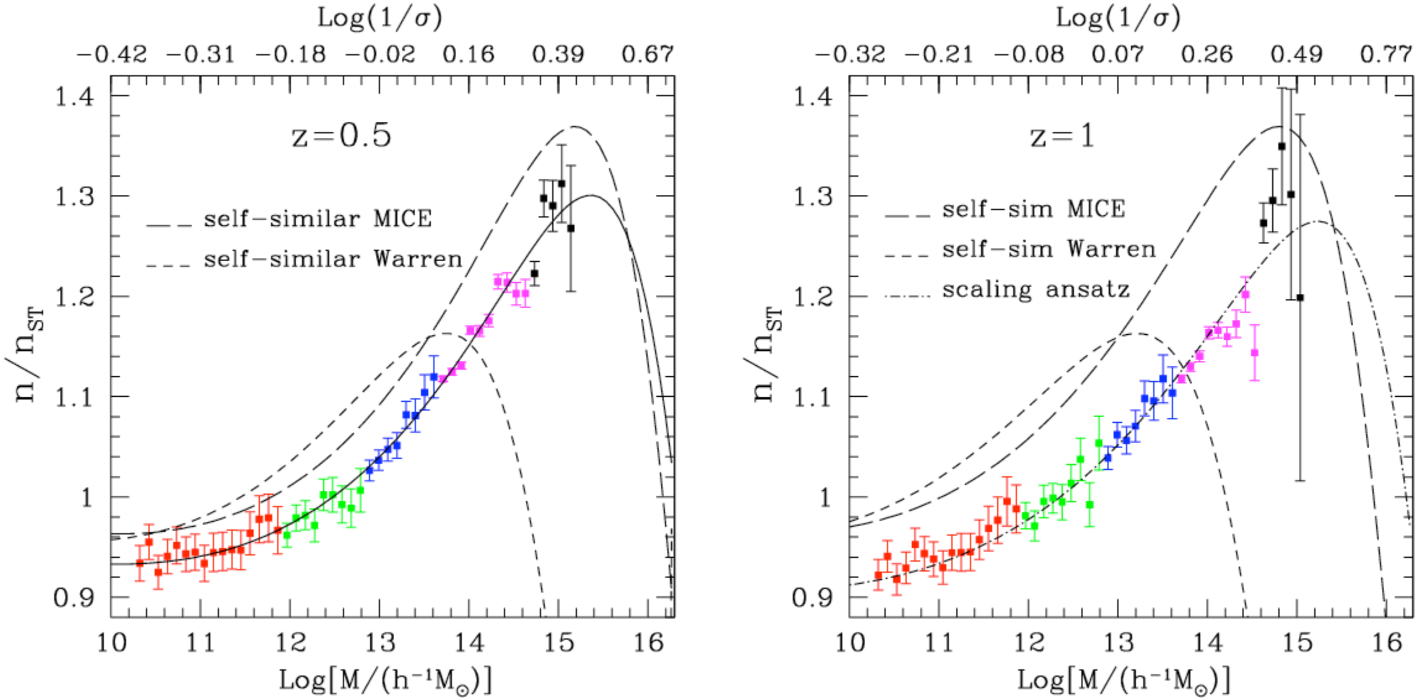
1.036

0.58

0.3

-1.37

Mass Function Universality



$$f(\sigma, \cancel{z}) = \frac{M}{\rho_b} \frac{dn(M,z)}{d \ln \sigma^{-1}(M,z)} \qquad \sigma^2(M,z) = \frac{D^2(z)}{2\pi^2} \int k^2 P(k) W^2(k * R) dk,$$

only through $\sigma(M,z)$ (*self similarity*)

We find the z = 0.5 mass function to be "universal" at ~ 3% at 10^{11} $M_{\odot} h^{-1}$ and 10% at larger masses. Larger departures at higher red-shifts in agreement with previous work.

Scaling ansatz

$$f_{\mathrm{MICE}}(\sigma, z) = A(z)\left[\sigma^{-a(z)} + b(z)\right] \exp\left[-\frac{c(z)}{\sigma^2}\right]$$

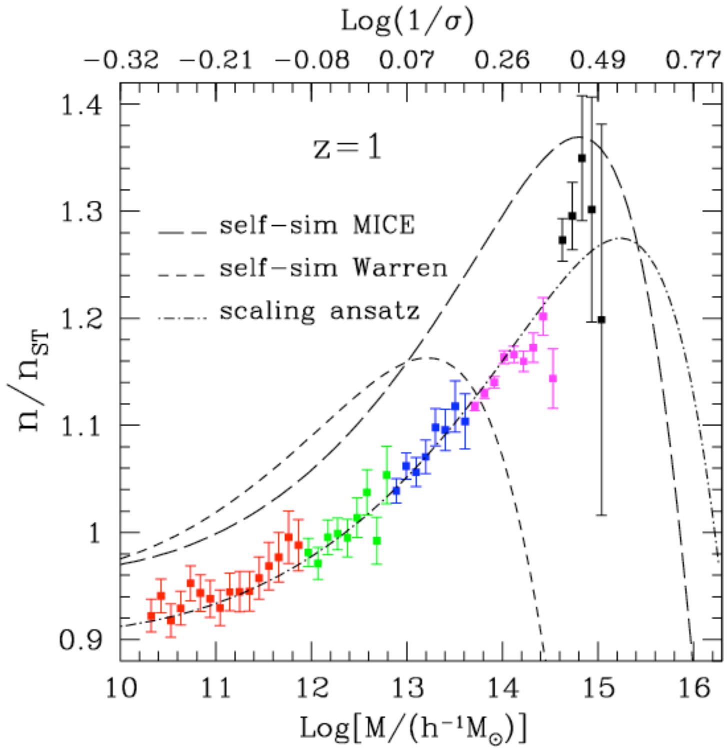
$$P(z) = P(0)(1+z)^{-\alpha_i} \;; P = \{A, a, b, c\} \;; \alpha_i = \{\alpha_1, \cdots, \alpha_4\}$$

➲ Using z = 0 and 0.5 we can compute the slope and then, *predict* the abundance at higher red-shifts

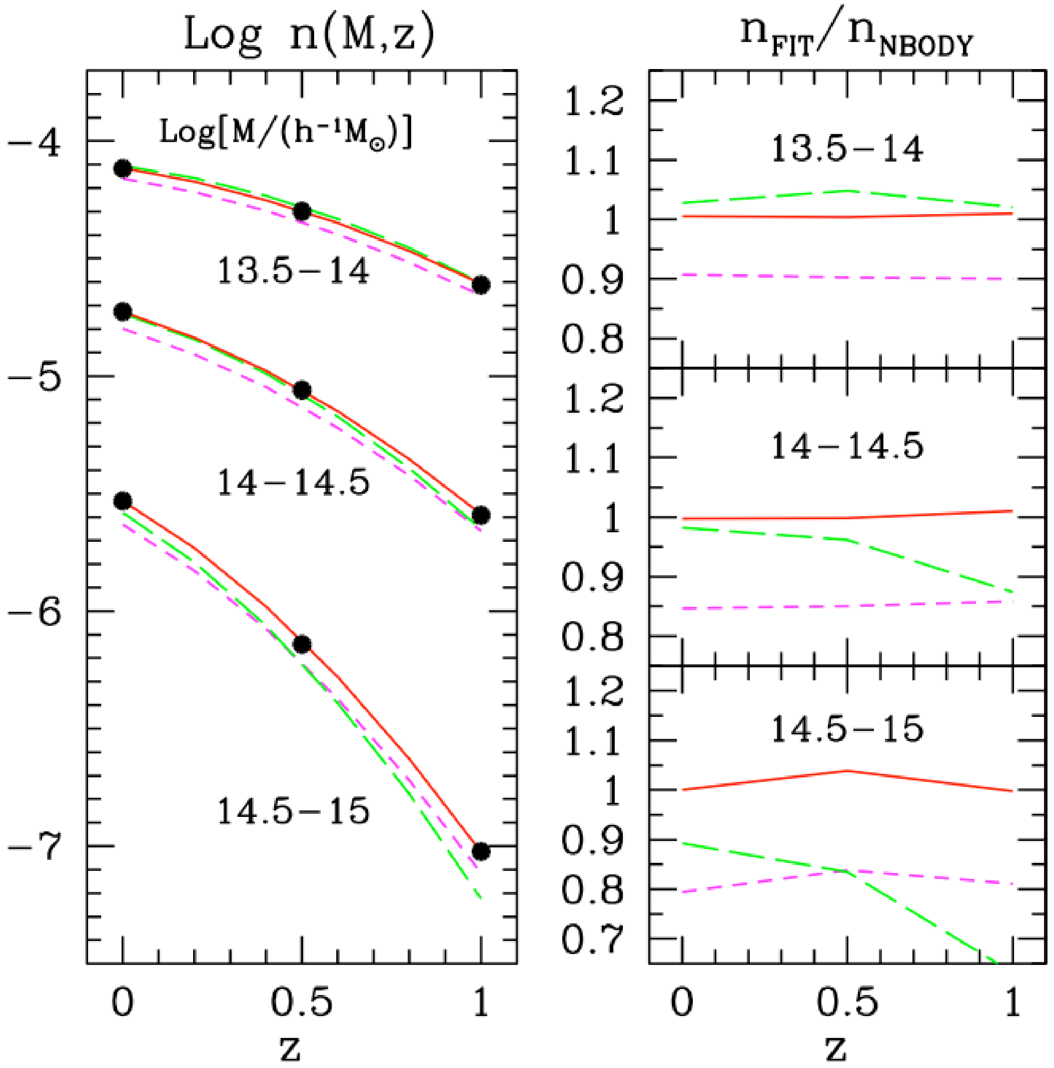
$$\alpha_1 = 0.13,\ \alpha_2 = 0.15,$$

$$\alpha_3 = 0.084,\ \alpha_4 = 0.024.$$

(see also Tinker et al 2008 for SO halos)



Halo Growth Function



Scaling ansatz in Red,
Self Similarity in Magenta
(Sheth & Tormen 1999)
and Green (Warren 2006)

Cosmological Implications

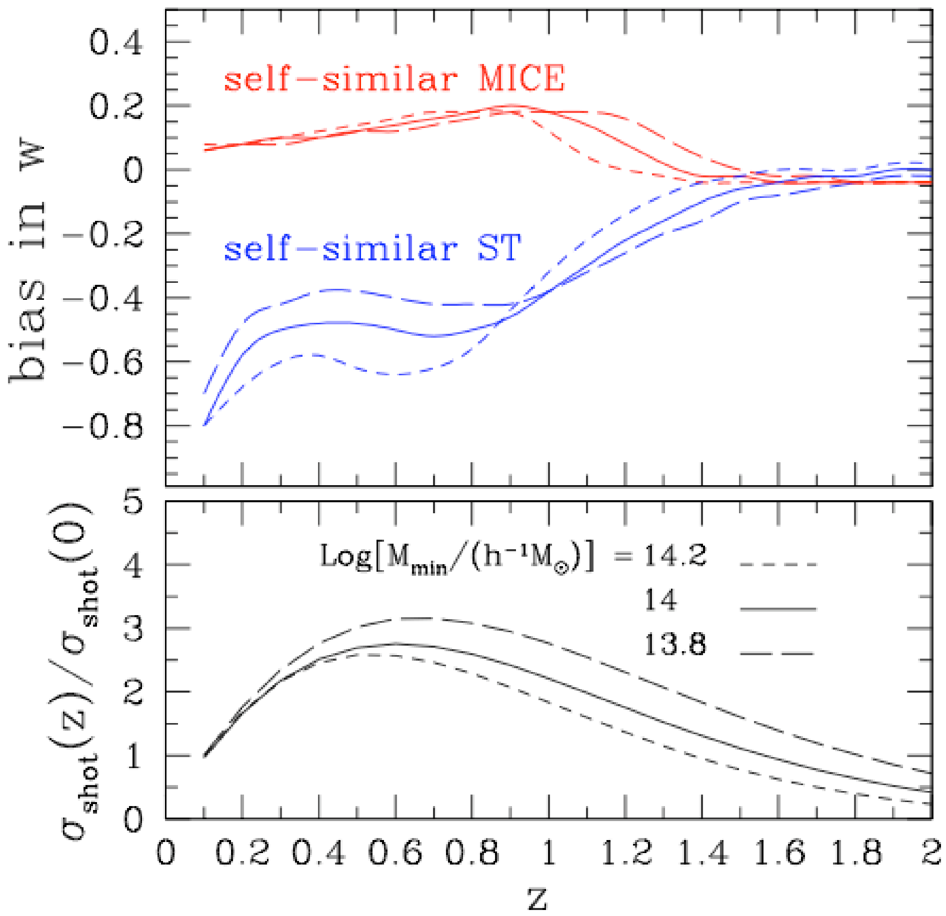
Bias on w induced by a self similar prior on the MF

[] Cluster counts in red-shift shells $\Delta z = 0.1$ up to $z = 2$ (full sky)

[] Assume red-shift independent mass threshold, $M = 10^{14}\ M_{\odot} / h$

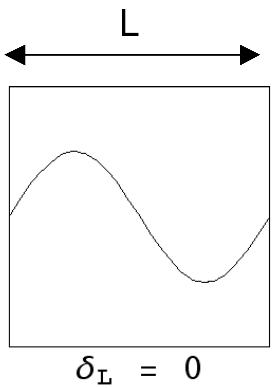
$$\chi^2 = \sum_{z_i} \frac{\left(n(w)^{(i)} - n(z)^{(i)}_{Nbody}\right)^2}{{\sigma^{(i)}}^2}$$

[] At low z mass function shape and the geometric volume have relatively small and comparable sensitivity to changes in *w*

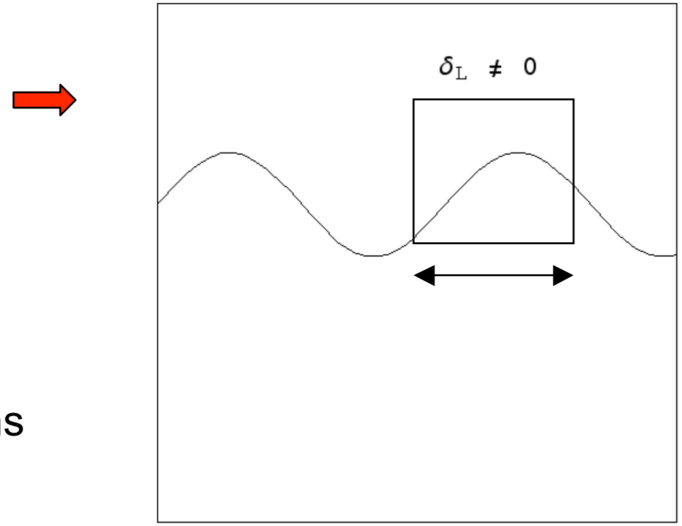


A tentative explanation for the high-mass excess,

work in progress



δ_L denote fluctuations in the mean density



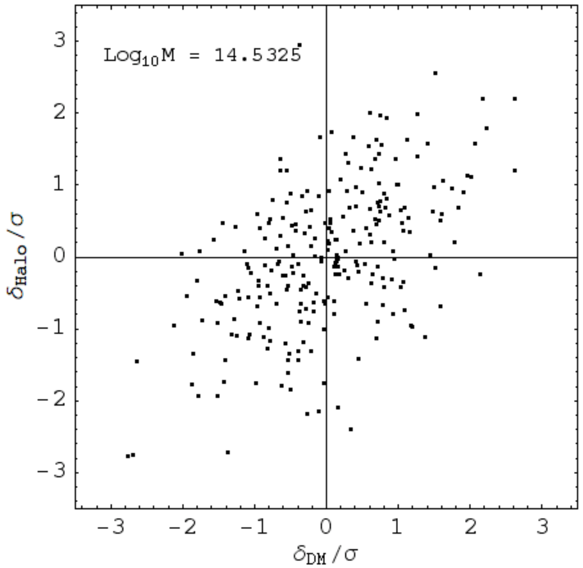
Within the larger volume δ_L will not be zero but very small (with Gaussian PDF) due to the long-wavelength modes

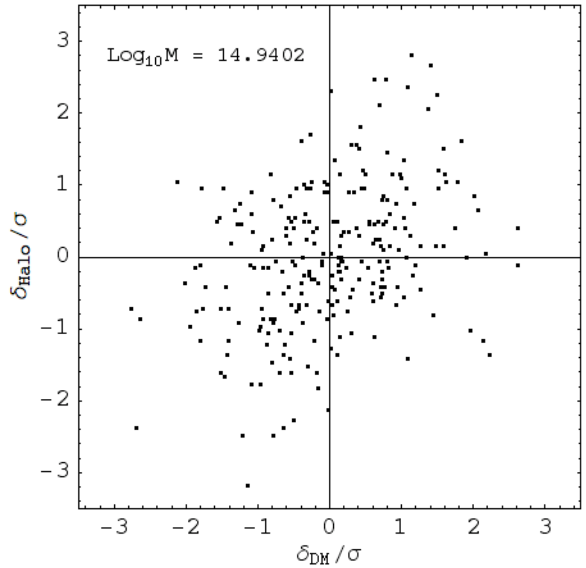
$$\bar{\rho} \longrightarrow \delta_c \longrightarrow \nu = \frac{\delta_c}{\sigma(M)} \qquad \delta_c \longrightarrow \delta_c(1 - \#\delta_L)$$

A tentative explanation for the high-mass excess,

work in progress

- We divided the largest box-size in 252 sub-volumes of L ~ 1200 h^{-1} Mpc



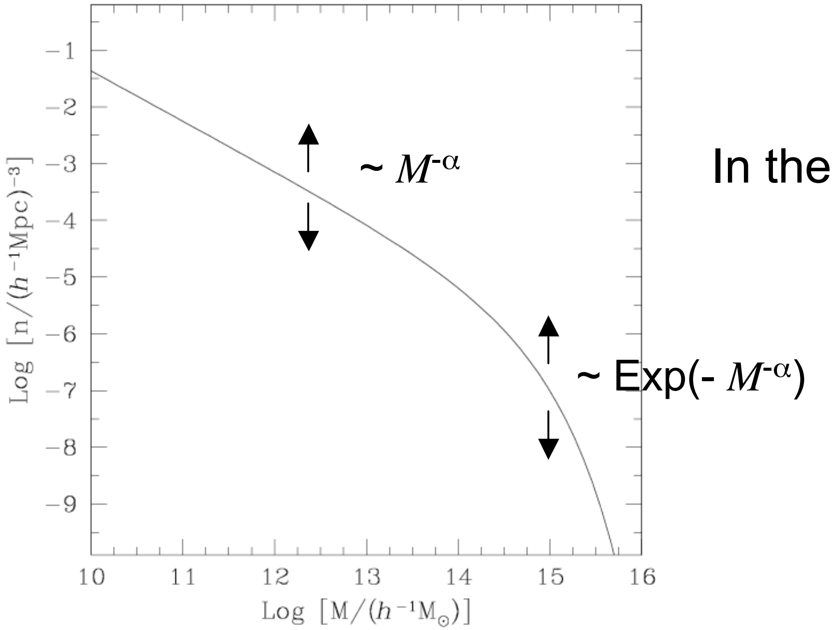


$$\bar{\rho} \longrightarrow \delta_c \longrightarrow \nu = \frac{\delta_c}{\sigma(M)} \qquad \delta_c \longrightarrow \delta_c(1 - \#\delta_L)$$

A tentative explanation for the high-mass excess,

work in progress

$$f(M) = \int d\delta_L \, f(M, \delta_L) \, \mathrm{Prob}(\delta_L)$$



In the power law regime $f(M) \approx f(M, \delta_L = 0)$

But in the exponential tail this is not true anymore

$$\bar{\rho} \longrightarrow \delta_c \longrightarrow \nu = \frac{\delta_c}{\sigma(M)} \qquad \delta_c \longrightarrow \delta_c(1 - \#\delta_L)$$

Conclusions

* MICE Consortium : developing a set of large N-body simulations, largest halo catalogues publicly available (http://www.ice.cat/mice)

* Combine big volumes (10-100 $Gpc^3\, h^{-3}$) with good mass resolution ($\sim 10^{10}\, M_o h^{-1}$)

* Accurately sampling the mass function in more than 5 decade in mass, we find a departure from standard FoF fit of Warren at large masses, with 10-30% larger abundance

* Result is robust in front of several possible systematic effect. Maybe is the effect of long-wavelength modes?

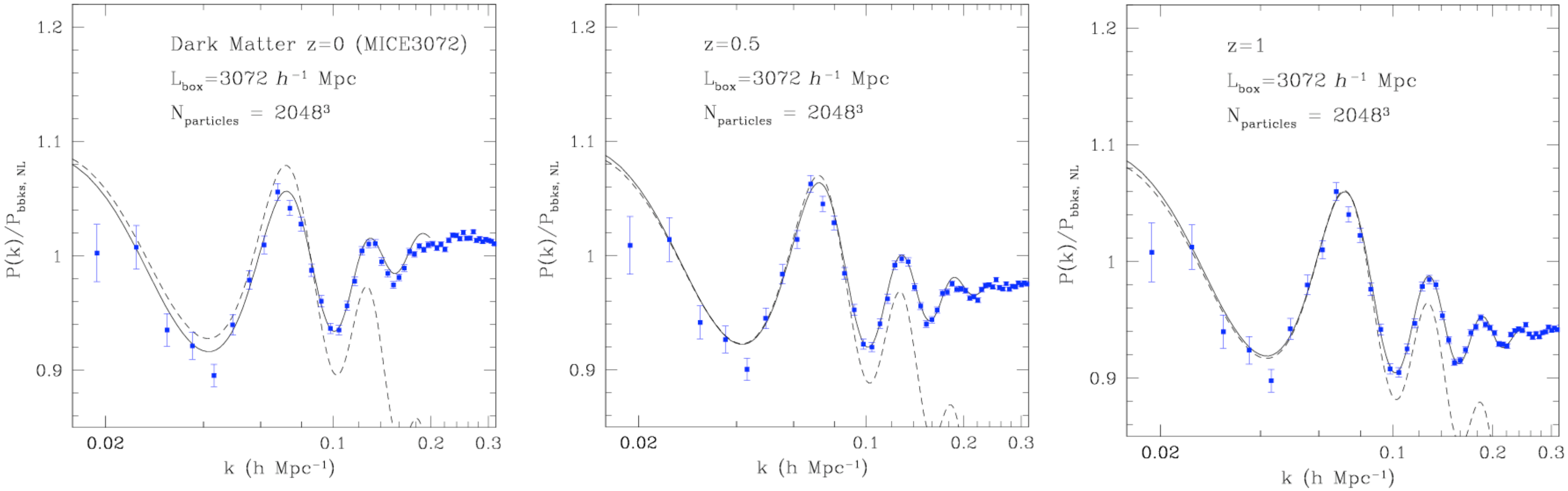
* We quantified to what extent the FoF mass function is universal and found scaling law for the parameters that account accurately for the high-z masss function

* Assuming self-similarity can bias estimates of dark-energy

MICE - Large Scale Clustering

Dark Matter

Probing the baryon acoustic oscillations (BAO)



Nonlinear Model : Renormalized Perturbation Theory

$$P(k,z) = G_\delta^2(k,z) \times P_{\rm Linear}(k) + P_{\rm ModeCoupling}(k,z)$$

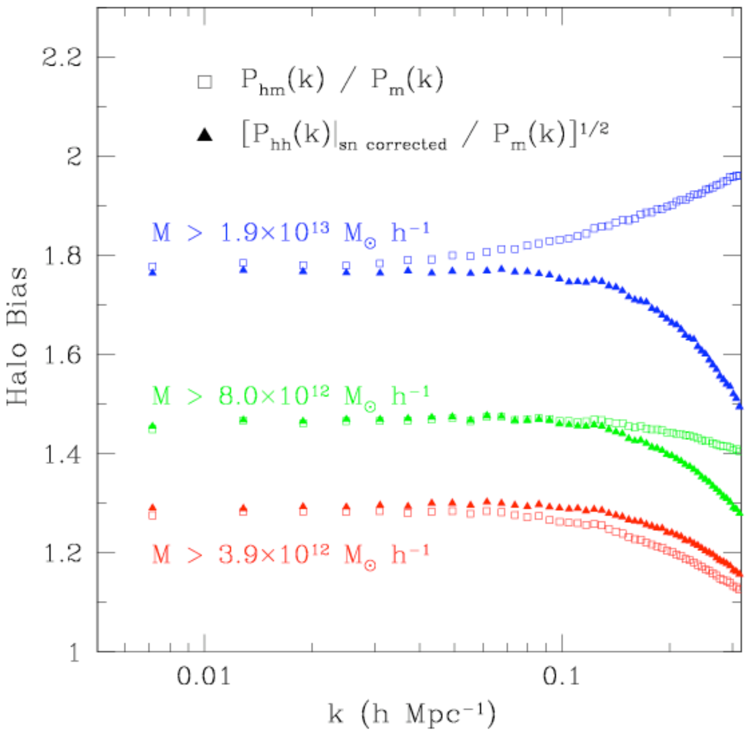
$$\xi(r) = [\xi_{\rm L} \otimes G_\delta^2](r) + \xi_{\rm MC}(r)$$

Crocce & Scoccimarro, PRD 73, 063520 (2006) & PRD 73, 063519 (2006)

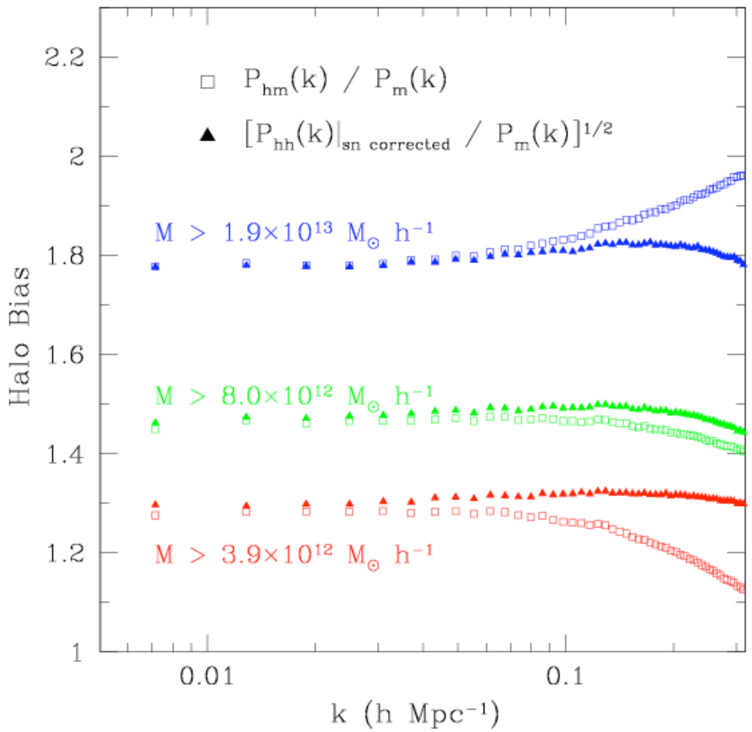
Halo Bias - scale dependence at BAO regime

Fourier Space : *non-trivial shot-noise correction*

$$P_{\rm true}(k) = P_{\rm obs}(k) - P_{\rm shot}\ ;\quad P_{\rm shot} = 1/\bar{n}\ .$$



Accounting for halo exclusion effects (Smith et al 2007)



- ✓ Halo bias with respect to the *nonlinear* matter distribution
- ✓ Strong dependence on halo mass

Halo Bias - scale dependence at BAO regime

Real Space : *from cross-correlation function*