Effects of the initial conditions on cosmological *N*-body simulations

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Outline

Outline

Structure formation

- Main driver of structure formation: gravity
- The linear regime is well understood, and can be described analytically. The overdensity $\delta \ll 1$ obeys

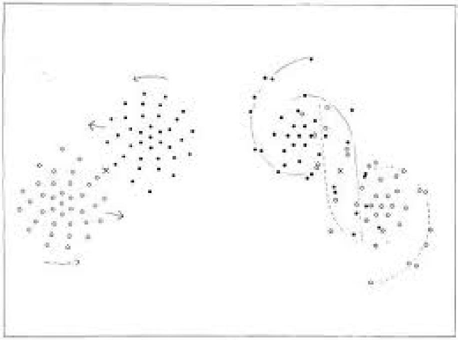
$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} - 4\pi G\bar{\rho}\delta = 0, \qquad (1)$$

  where $a(t)$ is the *expansion factor*.
- However, When $\delta \lesssim 1$, this approximation is not valid anymore: structure formation is a highly non-linear process
- Gas physics is also highly non-linear, and dominant at small scales
- *Cosmological simulations are necessary to understand the detailed physics of structure formation*

Cosmological simulation

History

- First *N*-body simulation: Holmberg (1941)
  - Gravity and electromagnetism are $1/r^2$ laws
  - Simulated 2 galaxies with 37 light-bulbs
  - Gravitational force $\propto$ light received by the light bulb
- First "real" simulation: Von Hoerner (1960, 1963): motions of stars in clusters (16 and 235 stars)

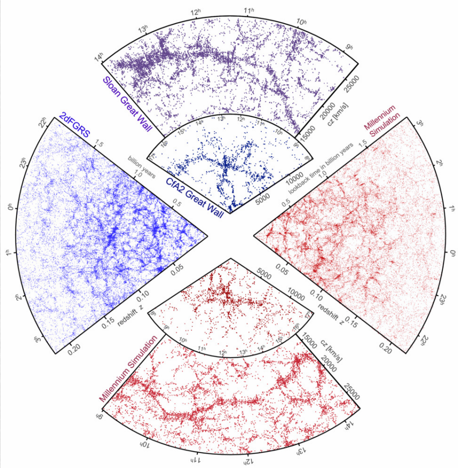


Holmberg (1941)

- First cosmological simulations: Miyoshi & Kiahara (1975): 200 particles
- Horizon run 3 (Kim et al 2011): 7210^3 particles, $10\,h^{-1}\mathrm{Gpc}$

Cosmological simulations

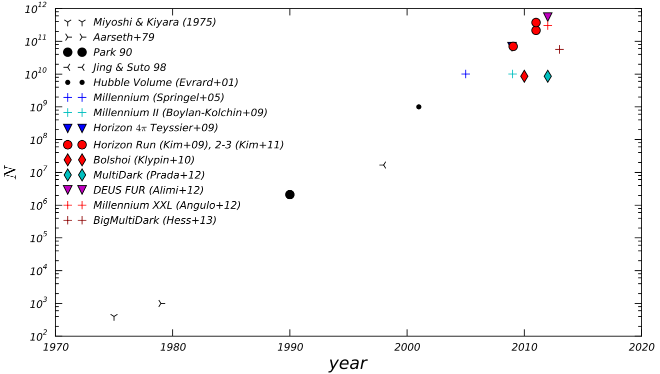
- Remarkably successful in simulating the large-scale structures of the Universe
- Topology of the large-scale structures: Voids, walls, filaments, clusters
- At galactic scales, there are still some unsolved problems



Credit: V. Springel

Cosmological simulations

Large simulations



- Exponential growth
- Need for parallel computation ($\approx$ 1000 cores)

Outline

Gravity

[a]Not in the *elementary* particle sense! Mass of a particle typically $10^{6-8}\,h^{-1}M_\odot$ in cosmological simulations

Gravity

- Gravity is the main driver of structure formation
- It has an infinite range ($\phi(r) \propto 1/r$)
- The cosmological density field is discretised in N *particles*[a] of mass m
- Need for good statistics and low cosmic variance: large box
- Need for good mass and length resolution to accurately describe the small scales: (very) large N

[a] Not in the *elementary* particle sense! Mass of a particle typically $10^{6-8}\, h^{-1} M_\odot$ in cosmological simulations

Gravity

Direct force computation

- Consider a distribution of N point particles of mass m
- A particle i will feel the gravitational force

$$\mathbf{F}_i = -G \sum_{j \neq i} \frac{m_j m_i}{r_{ij}^2} \mathbf{u_{ij}} \tag{2}$$

- Direct computation: $N(N-1)/2 = \mathcal{O}(N^2)$
- Prohibitive for large N (Now (2013): $N \simeq 10^{11-12}$)
- Need for smarter techniques
- Or dedicated hardware (GRAvity piPE, GRAPE, Makino & Funato 1993)

Gravity

Particle mesh (PM) (1)

Hockney et al. (1974); Efstathiou & Eastwood (1981)

Idea:

$$\nabla^2\Phi = 4\pi G\rho \Leftrightarrow \Phi(\mathbf{x}) = \mathcal{G} * \rho(\mathbf{x}), \tag{3}$$

where $\mathcal{G}(\mathbf{r}) = -G/|\mathbf{r}|$ is the Green function of the Laplacian operator.

In Fourier space: just a multiplication

$$\hat{\Phi}(\mathbf{k}) = \hat{\mathcal{G}}(\mathbf{k})\hat{\rho}(\mathbf{k}). \tag{4}$$

Fast Fourier transform (FFT): $\mathcal{O}(N \log N)$, inverse FFT = FFT.

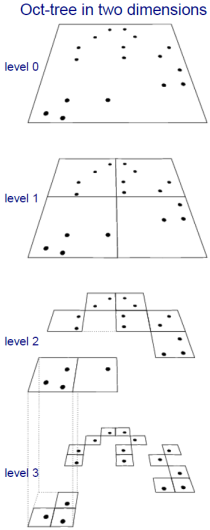
Gravity

Particle mesh (PM) (2)

- Compute the density on the grid from the particles distribution
  - Nearest grid point (NGP): the particle belongs to 1 cell. Piecewise constant.
  - Clouds-in-cell (CIC): particle split into 8 cells. Continuous
  - Triangular shaped cloud (TSC): particle split into 27 cells. Continuous derivative
- Fourier transform the density: get the potential
- Differenciate the potential to get the force: finite differences
- Interpolate the force back to particle (same interpolation scheme as (1))

Gravity

Tree code



Tree algorithms

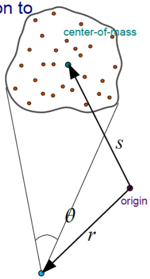
Idea: Use hierarchical multipole expansion to account for distant particle groups

$$\Phi(\mathbf{r}) = -G \sum_i \frac{m_i}{|\mathbf{r} - \mathbf{x}_i|}$$

We expand:

$$\frac{1}{|\mathbf{r} - \mathbf{x}_i|} = \frac{1}{|(\mathbf{r} - \mathbf{s}) - (\mathbf{x}_i - \mathbf{s})|}$$

for $\quad |\mathbf{x}_i - \mathbf{s}| \ll |\mathbf{r} - \mathbf{s}| \qquad \mathbf{y} \equiv \mathbf{r} - \mathbf{s}$



and obtain:

$$\frac{1}{|\mathbf{y} + \mathbf{s} - \mathbf{x}_i|} = \frac{1}{|\mathbf{y}|} - \frac{\mathbf{y} \cdot (\mathbf{s} - \mathbf{x}_i)}{|\mathbf{y}|^3} + \frac{1}{2} \frac{\mathbf{y}^T \left[3(\mathbf{s} - \mathbf{x}_i)(\mathbf{s} - \mathbf{x}_i)^T - \mathbf{I}(\mathbf{s} - \mathbf{x}_i)^2\right] \mathbf{y}}{|\mathbf{y}|^5} + \ldots$$

the dipole term vanishes when summed over all particles in the group

Credits: V. Springel

Gravity

Hybrid methods

- PM: Quick and efficient, intrinsically periodic (FFT)
  - But the resolution is given by the number of grid cells
  - Very expensive for high-resolution
  - Force anisotropies at the cell level
- Tree code: efficient at small distances
- TreePM: combine PM for large-scale forces, and tree for small-scales (Gadget-2,3, GOTPM, ...)
- P^3M: long-range forces computed with PM, short-range with PP
- Adaptive P^3M (AP^3M): P^3M refined in clustered regions
- Adaptive mesh refinement (AMR): PM, refined when needed (ART Kravtsov et al 1997; RAMSES, Teyssier 2002; Enzo, O'Shea et al 2004)

Outline

Cosmological simulations at 1% precision

- Era of precision cosmology: CMB, SN lightcurves, redshift surveys, . . .
- Large upcoming & ongoing surveys (SDSS, (Big)BOSS, LSST, Euclid, DES, . . .): precision of $\approx 1\%$
- Need for massive companion simulations with a 1% level precision
- Can we trust *N*-body simulations? To what extent?
  - How sensitive to the initial conditions are the statisics at a given redshift?

Generating the Initial conditions

- Generate the initial particle positions and velocities
  - Apply a displacement to a pre-initial configuration (preIC)
  - The displacement depends on the cosmology and the starting redshift
- Initial redshift?
- Pre-initial configuration: glass versus grid
- Order of Lagrangian perturbation theory (LPT)?
  - 1LPT or 2LPT? (i.e. Scoccimarro 1998, Crocce et al. 2006)

Generating the Initial Conditions

- Initial redshift (Knebe et al 2005, Heitmann et al 2008, Reed et al 2013)
  - Too high z_i: small displacement, not accurate (numerical noise)
  - Too low z_i: linear regime not valid anymore (shell crossing)
  - Optimum z_i depends on the mean particle separation
- PreICs: Glass versus grid
  - Grid: regular mesh, easy but have preferred directions (x, y, z)
  - Glass (White 1996): isotropic, but need ≈ 200 timesteps to reach the equilibrium, and noise on small scales
    - Start with random positions
    - evolve with negative G
    - reach a state of equilibrium ("glass")

Lagrangian perturbation theory

Mapping the Lagrangian (initial) positions $\mathbf{q}$ into Eulerian (after displacement) positions $\mathbf{x}$

$$\mathbf{x}(\mathbf{q},z) = \mathbf{q} + \Psi(\mathbf{q},z),$$
$$\mathbf{v}(\mathbf{q},z) = \dot{\Psi}(\mathbf{q},z)$$

Ψ: Displacement field.

- LPT:

$$\Psi(\mathbf{q},z) = \overbrace{-D_1(z)\nabla_q\phi^{(1)}(\mathbf{q})}^{\text{1LPT}} + \overbrace{D_2(z)\nabla_q\phi^{(2)}(\mathbf{q})}^{\text{2LPT}}$$

$$\nabla^2\phi^{(1)} = \delta(\mathbf{q}), \qquad D_1(t) = D_+(t),$$
$$\nabla^2\phi^{(2)} = \sum_{i<j}\left\{\partial_i^2\phi^{(1)}\partial_j^2\phi^{(1)} - \left(\partial_{i,j}\phi^{(1)}\right)^2\right\}, \qquad D_2(t) \simeq -\frac{3}{7}D_1^2(t).$$

Outline

The simulations

- We used the `GOTPM` (Park et al 2005) and `Gadget-3` (Springel 2005) TreePM codes
- N-body only simulations (tests with gas in progress)
- WMAP5 (and 7) cosmology
- 1 $N_{\mathrm{part}} = 2048^3$ (high res.) simulation, 2 1024^3, many 512^3
- Varying the ICs:
  - 4 realisations (different random phase)
  - Initial redshift: 500, 100, 50, 23
  - Order of LPT: 1 or 2
  - Pre-initial configuration: grid or glass
- Two different box sizes: 256 and 768 $h^{-1}\mathrm{Mpc}$ (aim: LSS)
  - mean particle separation of 0.5 and 1.5 $h^{-1}\mathrm{Mpc}$ (512^3)

Simulation parameters

ID	N_p	$L_{\rm box}$ (h^{-1}Mpc)	$z_{\rm ini}$	rms Ψ	LPT	PreIC
Set 1:						
T2s	1024	256	100		2	mesh
T3s	512	256	100		2	mesh
T3f	512	256	100		1	mesh
T4s	512	256	50		2	mesh
T4f	512	256	50		1	mesh
T5s	512	256	23		2	mesh
T5f	512	256	23		1	mesh
T7	512	768	100		2	mesh
T8	512	768	50		2	mesh
T9	512	768	23		2	mesh

Outline

Power spectrum

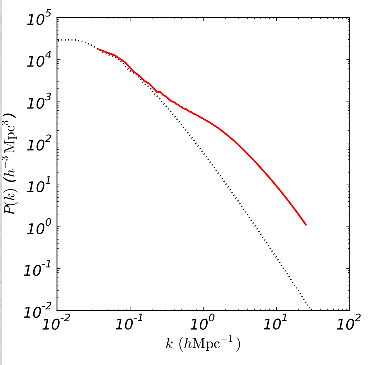
- Overdensity field:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}},$$
$$\delta(\mathbf{k}) = \frac{1}{(2\pi)^3} \int \delta(\mathbf{x}) \mathrm{e}^{i\mathbf{k}\mathbf{x}} \mathrm{d}^3\mathbf{x}$$

- Power spectrum:

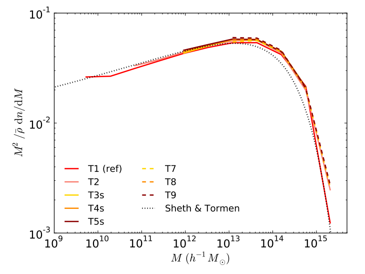
$$P(\mathbf{k}) = P(k) = \frac{1}{V} \left\langle \left|\delta(\mathbf{k})\right|^2 \right\rangle$$

- Power spectrum computed using TSC interpolation, on a $N_{\mathrm{grid}}^3 = 8N_{\mathrm{part}}^3$ grid



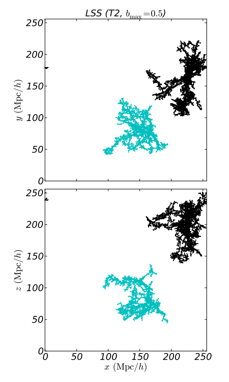
Mass function

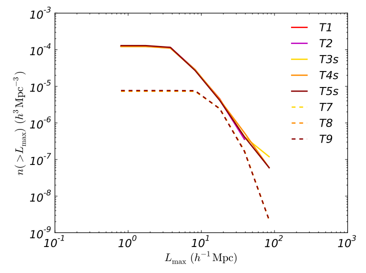
- Halo: non-linear, virialised object
- Halo mass function: $\frac{dn}{dM}$, number of haloes dn with mass between M and $M + dM$
- Friends-of-friends (FOF, Davis et al 1985): groups together all particles within b times the mean interparticle distance.
- $b \approx 0.2$ (linking length) gives a "correct" mass function



Maximal extent of LSS

- Apply FoF with varying b to the halo catalogue (Park et al 2012)
- Find b_{max} that maximises the number of structures
- We found $b_{\mathrm{max}} \approx 0.5$–$0.6$ for all simulations: apply the same $b_{\mathrm{max}} = 0.55$
- Distribution of the maximal extent of LSS $\mathrm{d}n/\mathrm{d}L_{\mathrm{max}}$





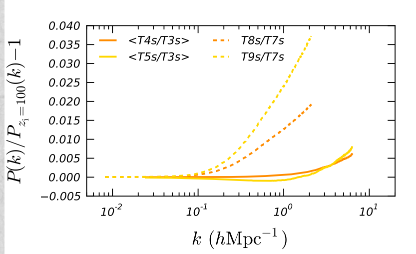
Outline

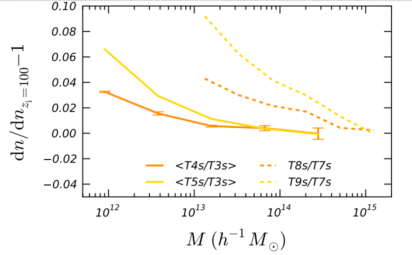
Results: Initial Redshift

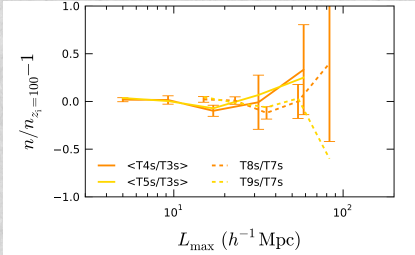
Power spectrum, mass function & LSS extent

$N = 512^3$

Initial redshifts: 100 (ref), 50, 23







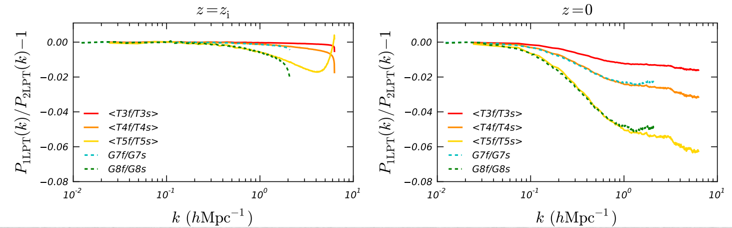
- Lower starting redshifts yield more low-mass haloes and extra small-scale power
- No clear effect for the size distribution of LSSs

Results: Order of LPT

Power Spectrum (L'Huillier, Park & Kim 2014, New A 30, 79)

Initial redshift: 100, 50, 23 (256 $h^{-1}\mathrm{Mpc}$)

50, 23 (768 $h^{-1}\mathrm{Mpc}$)

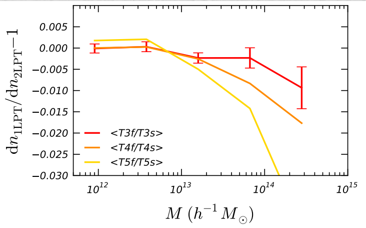


- 1LPT simulations have lower initial power on small scales
- This lack of power increases with starting redshift
- Independant of the resolution and code (G vs T simulations)
- Even $z_{\mathrm{ini}} = 100$ yields more than 1% difference: *need for 2LPT ICs*

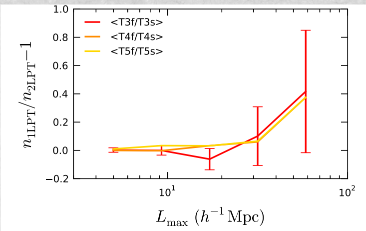
Results: Order of LPT

Halo mass function & LSS extent (L'Huillier, Park & Kim 2014, New A 30, 79)

Initial redshift: 100, 50, 23 (256 h^{-1}Mpc)



Mass function



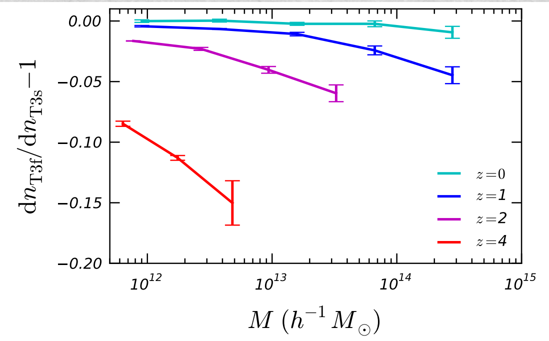
LSS size distribution

- Mass function: within 1% at low masses
- High masses underestimated in 1LPT simulations
- The underestimation is larger at lower starting redshifts
- LSS distribution: independant of the LPT order

Results: Order of LPT

Redshift evolution of the mass function (L'Huillier, Park & Kim 2014, New A 30, 79)

$z_{\rm ini} = 100$

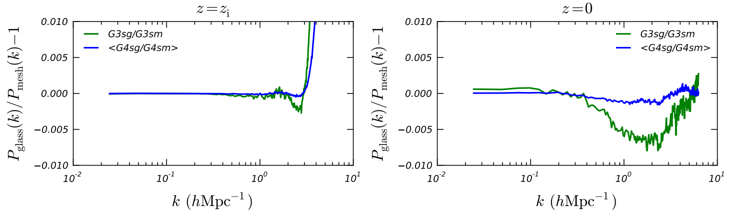


- At $z > 0$, the mass function is underestimated in 1LPT simulations
- The underestimation is larger at high mass
- Need for at least ≈ 100 expansion factors

Results: Preinitial configuration

Power Spectrum (L'Huillier, Park & Kim 2014, New A 30, 79)

$z_i = 100$, $z_i = 50$ (Gadget)

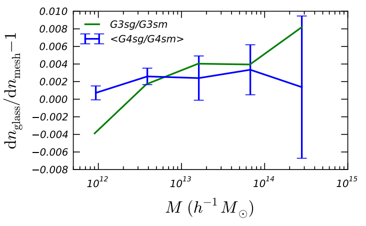


- Extra power on very small scales at initial redshift
- Vanishes by $z = 0$
- At a given LPT order, initial power is independant of $z_{\rm ini}$
- At $z = 0$, all within 1%

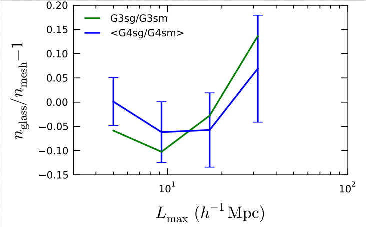
Results: Preinitial configuration

Halo mass function & LSS extent (L'Huillier, Park & Kim 2014, New A 30, 79)

$z_i = 100$, $z_i = 50$ (Gadget)



Mass function



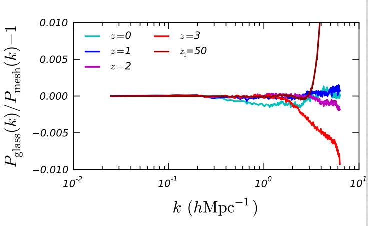
LSS size distribution

- Mass function: within 1% at low masses, large fluctuation at high masses
- No significant differences for the LSS size distribution

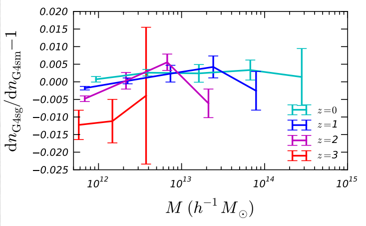
Results: Preinitial configuration

Redshift evolution (L'Huillier, Park & Kim 2014, New A 30, 79)

$z_{\text{ini}} = 50$



Power spectrum



mass function

- No significant difference after $z = 2$
- At $z = 3$: underestimation of the grid small scale power and the low-mass end of the mass function

Outline

Outline

Horizon run 4

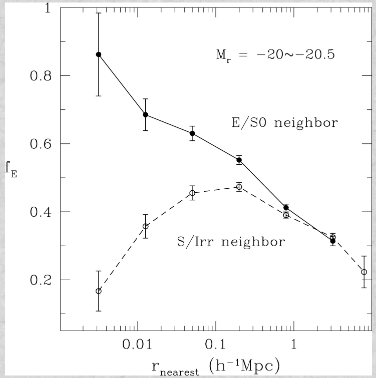
Some propaganda

Horizon run 4 (this background image)

- J. Kim, C. Park, S.W. Hong, H.S. Hwang, B. L'Huillier
- 8000 CPU cores, 50 days.
- Aim at creating mock catalogue for HectoMAP
- $L = 3.15\, h^{-1}\mathrm{Gpc}$, $N = 6300^3$ ($\bar{d} = 0.5\, h^{-1}\mathrm{Mpc}$)
- 2LPT, $z_{\mathrm{ini}} = 100$, 2000 timesteps
- 70 outputs, lightcone up to $z = 1.39$
- Simulation achieved, haloes detected and (preliminary) merger tree built
- Applications: Galaxy interactions, clustering, semi-analytic models, lensing, ...

Outline

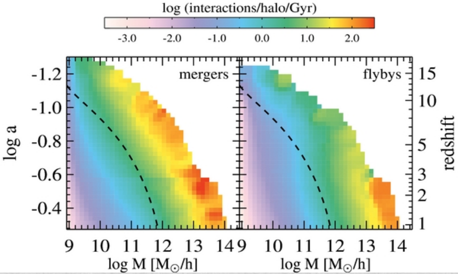
Morphological transformation

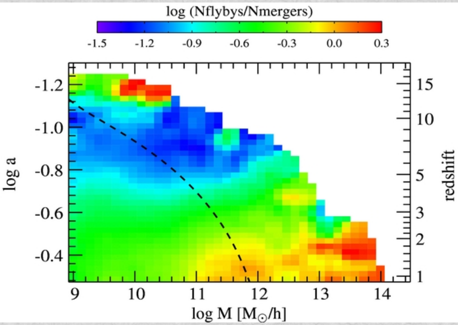


Park, Gott & Choi (2008)

- SDSS DR4plus (LSS-DR4plus), $15.5 < r_{\mathrm{Pet}} < 17.6$, $0.001 < z < 0.5$
- Fraction of elliptical (ETG) versus distance to nearest neighbour
- If the neighbour is an ETG: decreases with increasing distance
- If the neighbour is a LTG:
  - outside of $R_{\mathrm{vir,N}}$: same trend
  - Within $R_{\mathrm{vir,N}}$: the probability to be an ETG decreses with decreasing distance: *reversed morphological transformation?*
- Role of distant interactions

Flybys in cosmological simulations





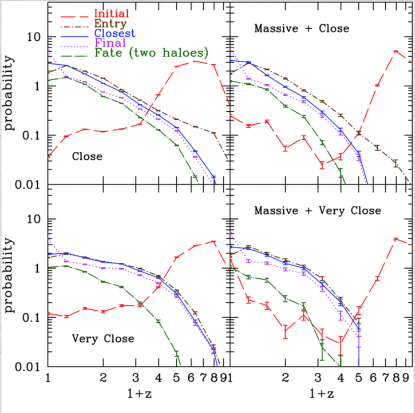
- Sinha & Holley-Bockelmann (2012): importance of flybys?
- N-body simulation:
- Merger dominant at high z
- For massive haloes ($> 10^{11}$) and $z < 2$, flybys important
- Small box ($50\,h^{-1}\mathrm{Mpc}$: large-scale effects?)
- Down to $z = 1$
- Observationally: close pairs as a proxy for merger rate. What about flybys? (cf. Tonnensen & Cen 2012)

Pair interactions

Moreno (2012) using the Millennium simulation (Springel et al 2005): Interacting pairs: within $d_{\text{crit}} = 0.2$ or $1\,h^{-1}\mathrm{Mpc}$ (comoving). Introduced a 5-steps interaction scheme:

- Initial: when the two haloes are first detected
- Entry: when their separation is closer than d_{crit}
- Closest: when the distance is the smallest
- Final: last time the 2 haloes are identified
- Fate: what happens to the pair: merges, absorbed by third party, or survives

Pair interactions



Moreno et al (2012)

- $M > 8.6 \times 10^{10}\, h^{-1} M_{\odot}$
- Close: $d < 0.2\, h^{-1}\mathrm{Mpc}$
- Very close: $d < 1\, h^{-1}\mathrm{Mpc}$
- Massive: $M > 8.6 \times 10^{11}\, h^{-1} M_{\odot}$
- Also: separation, total mass, mass ratio, lifetime

The rates and types of halo interactions

L'Huillier, C. Park and J. Kim, in prepatation

Means of galaxy evolution:

- Secular evolution: isolated galaxies
- Major merger have a dramatic impact (morphology transformation, significant mass increase) (Toomre & Toomre 1972)
- Minor mergers also matter: more frequent (Bournaud et al 2007)
- How about flybys? Not much studied (notable exception: Sinha & Holley-Bockelmann 2012)
- Role of the environment: field, groups and cluster

The rates and types of halo interactions

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Main questions

- How and how often do haloes interact?
- How does it change with redshift and with other properties (mass ratio, impact factor, environment)?

Halo catalogues

Catalogues

- Two catalogues of target and neighbour haloes defined by a mass cut
- Catalogue of target haloes (T): $M > M_0 = 5 \times 10^{11}\, h^{-1} M_\odot$
- Catalogue of neighbour haloes (N): $M > fM_0 = 2 \times 10^{11}\, h^{-1} M_\odot$; $f = 0.4$ sets the minimum mass ratio
- Both catalogues are complete (more massive than the mass resolution)

Method

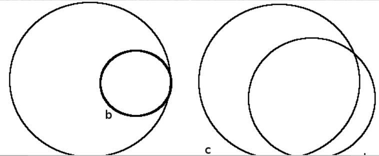
Interactions

We define interactions pairs of targets and neighbours such as

- the target halo lies within the virial radius of its (closest) neighbour
- the neighbour satisfies: $M_{\mathrm{N}} > fM_{\mathrm{T}}$ ($f = 0.4$)

Notes:

- At the moment, we don't consider multiple interactions: only the closest neighbour is considered
- An interaction may counted twice if the neighbour is also in the Target catalogue, and if the target is the closest neighbour of the neighbour satisfying the mass condition

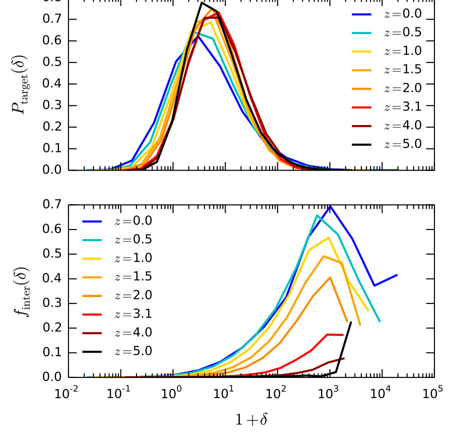


Method

To quantify the environment: ρ_{20}: density over 20 neighbours

$$\rho_{20} = \sum_{i=1}^{20} M_i W(r_i, h),$$

where r_i is the distance to the i^{th} neighbour, M_i its mass, W the SPH spline kernel, and h the smoothing length.

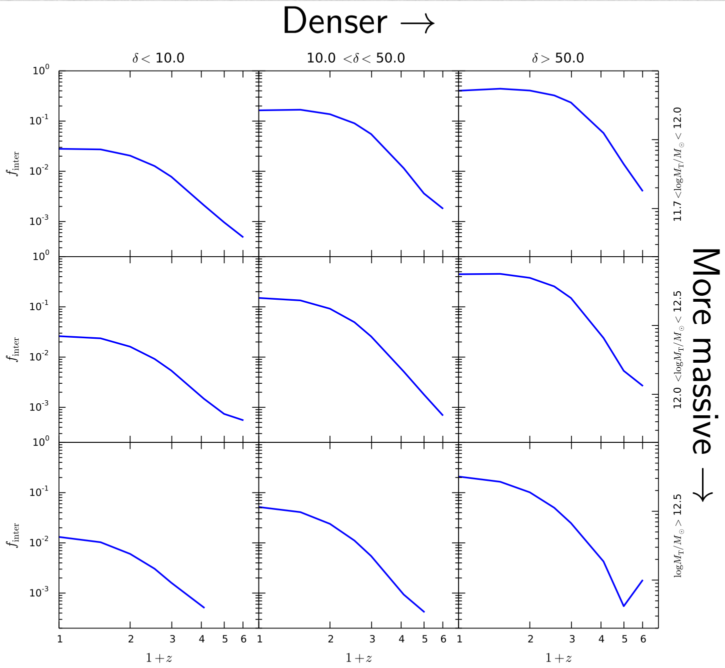


We are interested in the distribution $\mathrm{d}N = f(M_\mathrm{T}, p, q, \delta, z)\mathrm{d}M_\mathrm{T}\,\mathrm{d}p\,\mathrm{d}q\,\mathrm{d}\delta\,\mathrm{d}z$, where

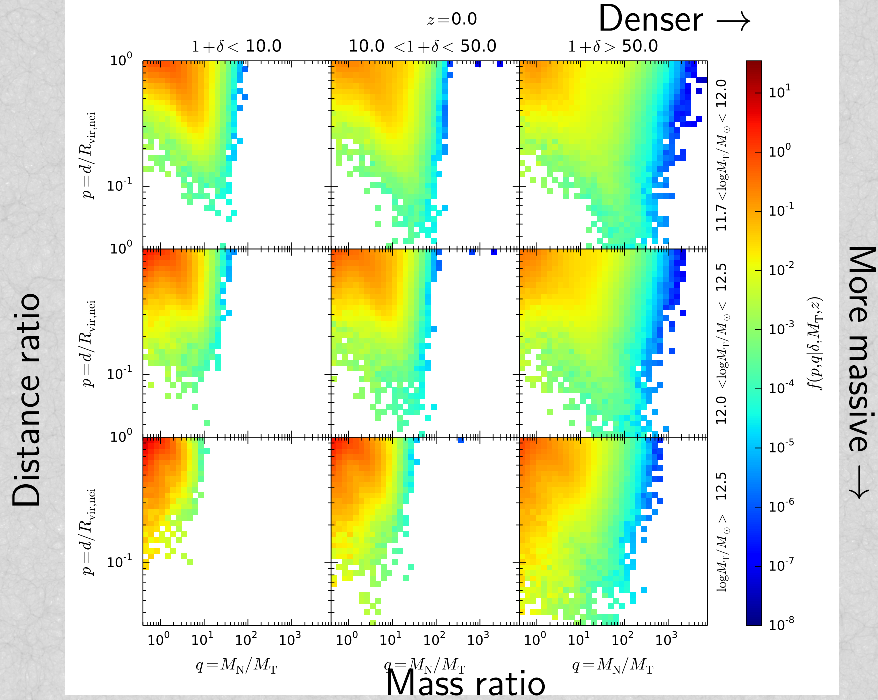
$p = d/R_{\mathrm{vir,N}}$; $q = M_\mathrm{N}/M_\mathrm{T}$; $\delta = \rho_{20}/\bar{\rho} - 1$

5 parameters: we use different bins of ρ_{20} and M_T, at different z, and study the distribution of p and q.

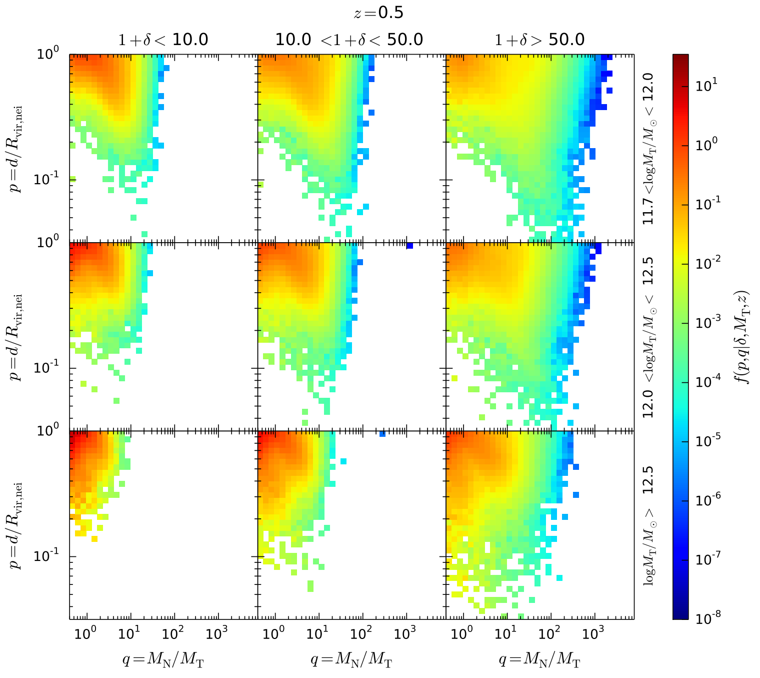
Preliminary results!



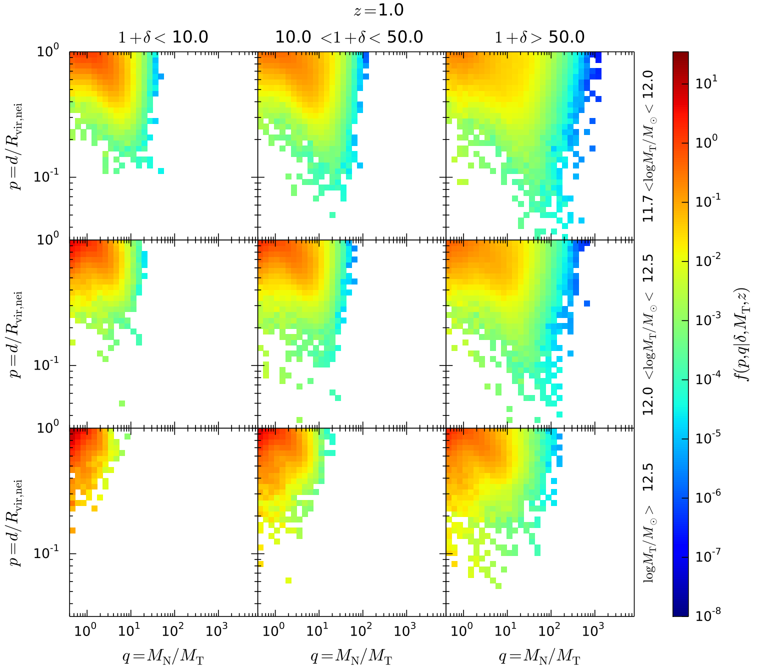
Denser →
$\delta < 10.0$
$10.0 < \delta < 50.0$
$\delta > 50.0$
More massive →
$11.7 < \log M_T/M_\odot < 12.0$
$12.0 < \log M_T/M_\odot < 12.5$
$\log M_T/M_\odot > 12.5$
f_{inter}
$1+z$



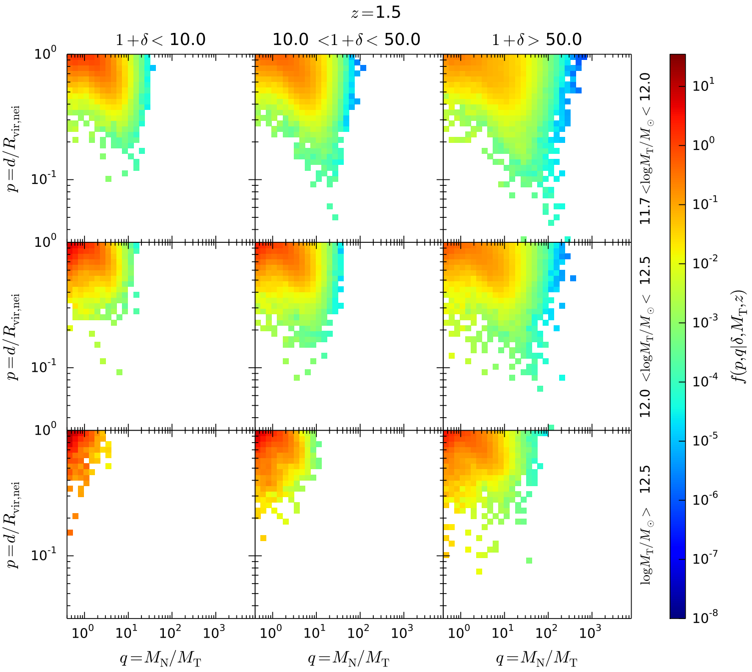
$z = 0.0$
Denser →
$1+\delta < 10.0$
$10.0 < 1+\delta < 50.0$
$1+\delta > 50.0$
$p = d/R_{\rm vir,nei}$
$q = M_{\rm N}/M_{\rm T}$
$11.7 < \log M_{\rm T}/M_\odot < 12.0$
$12.0 < \log M_{\rm T}/M_\odot < 12.5$
$\log M_{\rm T}/M_\odot > 12.5$
$f(p,q|\delta, M_{\rm T}, z)$
Distance ratio
Mass ratio
More massive →



$z = 0.5$
$1+\delta < 10.0$
$10.0 < 1+\delta < 50.0$
$1+\delta > 50.0$
$11.7 < \log M_{\rm T}/M_\odot < 12.0$
$12.0 < \log M_{\rm T}/M_\odot < 12.5$
$\log M_{\rm T}/M_\odot > 12.5$
$p = d/R_{\rm vir,nei}$
$q = M_{\rm N}/M_{\rm T}$
$f(p,q|\delta,M_{\rm T},z)$
10^0
10^{-1}
10^1
10^2
10^3
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

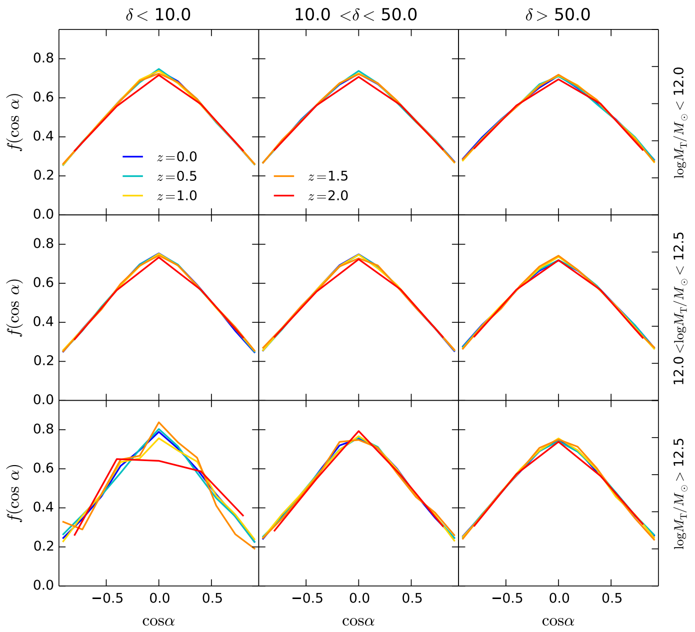


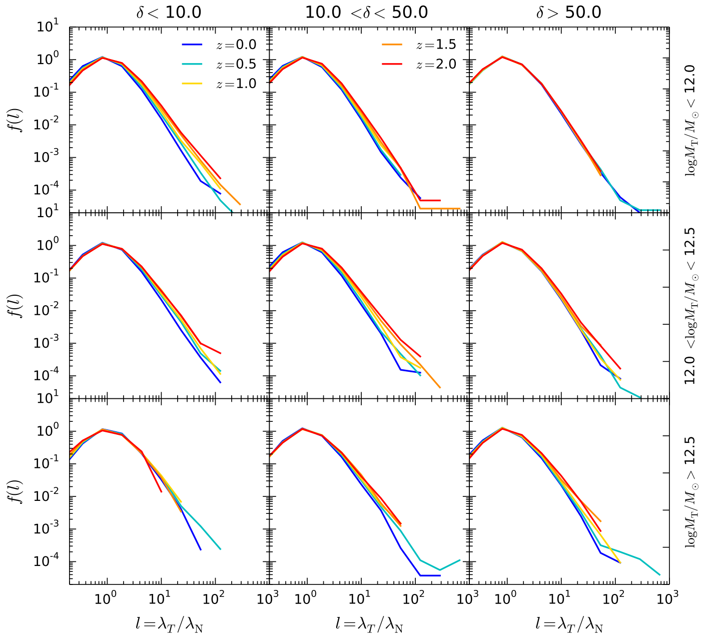
$z = 1.0$
$1+\delta < 10.0$
$10.0 < 1+\delta < 50.0$
$1+\delta > 50.0$
$p = d/R_{\rm vir,nei}$
$q = M_{\rm N}/M_{\rm T}$
$11.7 < \log M_{\rm T}/M_\odot < 12.0$
$12.0 < \log M_{\rm T}/M_\odot < 12.5$
$\log M_{\rm T}/M_\odot > 12.5$
$f(p,q|\delta,M_{\rm T},z)$
10^{0}
10^{-1}
10^{1}
10^{2}
10^{3}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}



$z = 1.5$
$1+\delta < 10.0$
$10.0 < 1+\delta < 50.0$
$1+\delta > 50.0$
$11.7 < \log M_{\rm T}/M_\odot < 12.0$
$12.0 < \log M_{\rm T}/M_\odot < 12.5$
$\log M_{\rm T}/M_\odot > 12.5$
$p = d/R_{\rm vir,nei}$
$q = M_{\rm N}/M_{\rm T}$
$f(p,q|\delta,M_{\rm T},z)$

$\alpha = (\mathbf{J}_N, \mathbf{r})$





$\delta < 10.0$
$10.0 < \delta < 50.0$
$\delta > 50.0$
$z=0.0$
$z=0.5$
$z=1.0$
$z=1.5$
$z=2.0$
$f(l)$
$l=\lambda_T/\lambda_N$
$\log M_T/M_\odot < 12.0$
$12.0 < \log M_T/M_\odot < 12.5$
$\log M_T/M_\odot > 12.5$

Outline

Outline

Summary & perspectives

Summary (1): ICs

- Choice of the ICs important to reach 1% precision *even for the pure N-body case!*
- Size distribution of LSS not very sensitive to the ICs (small box)
- Glass pre-ICs have an excess of power at small scales at initial times, but vanishes with time
- 2LPT and high initial redshift are necessary to reach 1% accuracy: $z_{\mathrm{ini}} \approx 100$ for a mean particle separation of $0.5\,h^{-1}\mathrm{Mpc}$, at least 50 expansion factors
- Important for high-redshift studies

Next

- ICs for the hydro case (in progress)
- Use of accurate large *N*-body simulations for galaxy evolution, study of the LSS, ...

Summary (2): halo interactions

Halo interaction

- Horizon run 4 provides very good statistics and allow for study of environmental effects

Next

- Use of merger trees to distinguish the types (mergers vs. flybys)
- Need to quantify the strength of interactions in addition to the frequency
- Study of galaxy interaction in clusters
- Inclusion of hydrodynamics
- Formation of the large-scale structures
- Work in progress. . . stay tuned!

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Halo interaction

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감사합니다!