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

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Outline

1. Initial conditions
2. Simulations and analysis tools
3. Results
4. Summary & Perspectives
Outline

1. Initial conditions
   - Why worry about the ICs?
   - Generating the ICs

2. Simulations and analysis tools

3. Results

4. Summary & Perspectives
Cosmological simulations at 1% precision

- Era of precision cosmology: CMB, SN lightcurves, redshift surveys, ...
- Large upcoming & ongoing surveys (SDSS, 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 statistics 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 $\approx 200$ timesteps to reach the equilibrium, and noise on small scales
    - Start with random positions
    - evolve with negative $G$
    - reach a state of equilibrium (“glass”)
Outline

1 Initial conditions

2 Simulations and analysis tools
   - The simulations
   - Density power spectrum and halo mass function
   - Size distribution of the LSS

3 Results

4 Summary & Perspectives
The simulations

- We used the GOTPM (Dubinksi et al 2004) and TreePM code
- $N$-body only simulations (tests with gas in progress), $N = 512^3$
- WMAP5 cosmology
- Varying the ICs:
  - 4 realisations (with different initial random phases)
  - Initial redshifts: 100, 50, 23
  - Order of LPT: 1 or 2
  - Pre-initial configuration: grid or glass
- Two different box sizes: 256 and 768 $h^{-1}\text{Mpc}$ (aim: LSS)
  - mean particle separation of 0.5 and $1.5 h^{-1}\text{Mpc}$ ($512^3$)
Density power spectrum and halo mass function

- (Density) power spectrum:
  \[ P(k) = P(k) = \frac{1}{V} \left\langle |\delta(k)|^2 \right\rangle \]

- Computed using TSC interpolation, on a \( N_{\text{grid}}^3 = 8N_{\text{part}}^3 \) grid

- Haloes: Friends-of-friends (FOF, Davis et al 1985): groups together particles within \( b = 0.2 \) times the mean interparticle distance.
Maximal extent of LSS

- Apply FoF with varying $b$ to the halo catalogue (Park et al 2012)
- Find $b_{\text{max}}$ that maximises the number of structures
- We found $b_{\text{max}} \approx 0.5–0.6$ (at $z = 0$) for all simulations: apply the same $b_{\text{max}} = 0.55$
- Distribution of the maximal extent of LSS $n(> L_{\text{max}})$
1. Initial conditions

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   - Initial redshift
   - Order of LPT
   - Preinitial configuration

4. Summary & Perspectives
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

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

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

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

Halo mass function & LSS extent

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

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

Redshift evolution of the mass function

\[ z_{ini} = 100 \]

- At \( z > 0 \), the mass function is underestimated in 1LPT simulations
- The underestimation is larger at high mass
- Need for at least \( \approx 100 \) expansion factors
Results: Preinitial configuration

Power Spectrum

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

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

Halo mass function

\& LSS extent \(z_i = 100, \ z_i = 50\) (Gadget)

Mass function

- 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

\[ z_{\text{ini}} = 50 \]

- 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
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Summary & perspectives

Summary

- 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: \( z_{\text{ini}} \approx 100 \) for a mean particle separation of \( 0.5 \, h^{-1}\text{Mpc} \), 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, …
- Study of interaction rate in cosmological simulation (in progress) stay tuned!
Summary & perspectives

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