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

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

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KOREA INSTITUTE FOR ADVANCED STUDY

# Outline

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# 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 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 $\approx$ 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")

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# The simulations

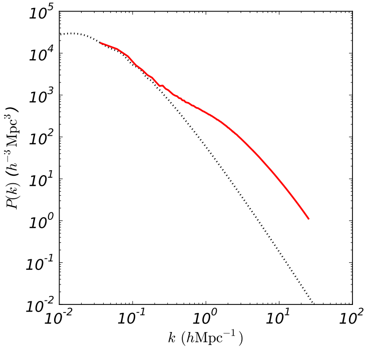
- We used the GOTPM (Dubinksi et al 2004) and TreePM code
- $N$-body only simulations (tests with gas in progress), $N = 512^3$
- WMAP5 cosmology
- Varying the ICs:
  - 4 realisations (with different initial random phases)
  - Initial redshifts: 100, 50, 23
  - Order of LPT: 1 or 2
  - Pre-initial configuration: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

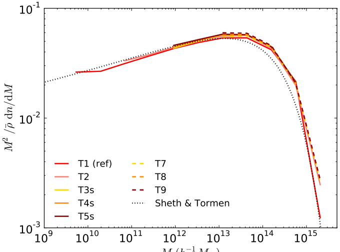
# Density power spectrum and halo mass function

- (Density) power spectrum:

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

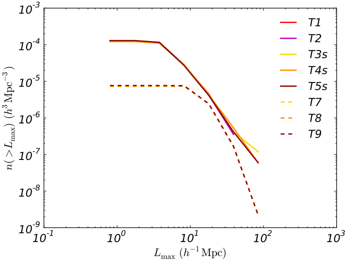
- Computed using TSC interpolation, on a $N_{\rm grid}^3 = 8N_{\rm part}^3$ grid
- Haloes: Friends-of-friends (FOF, Davis et al 1985): groups together particles within $b = 0.2$ times the mean interparticle distance.

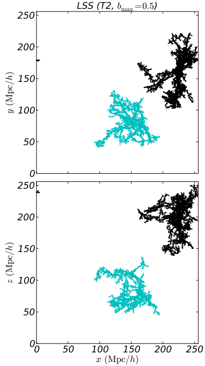


# Maximal extent of LSS

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



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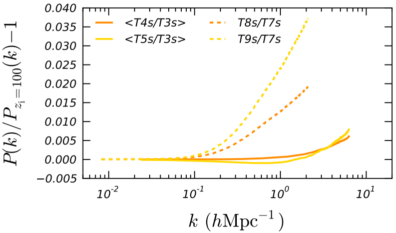
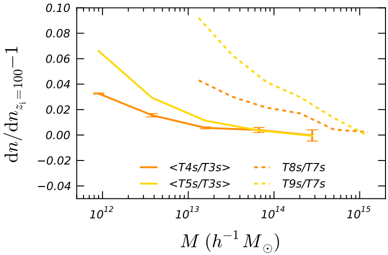
# Results: Initial Redshift

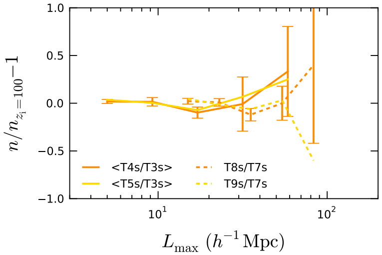
Power spectrum, mass function & LSS extent

$N = 512^3$

Initial redshifts: 100 (ref), 50, 23



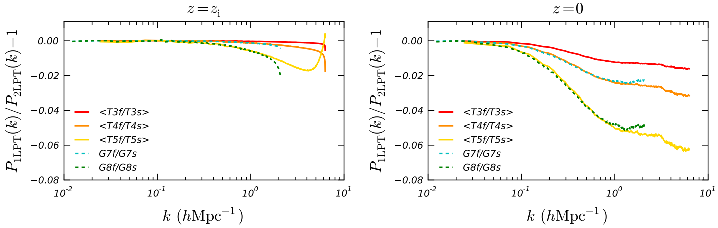

- Lower starting redshifts yield more *low-mass haloes* and *extra small-scale power*
- No clear effect for the size distribution of LSSs

# Results: Order of LPT

Power Spectrum

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

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

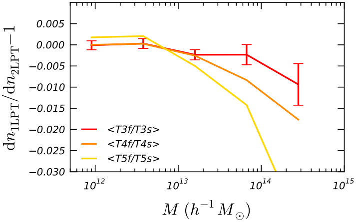



- 1LPT simulations have lower initial power on small scales
- This lack of power increases with starting redshift
- Independant of the resolution and code (G vs T simulations)
- Even $z_{\text{ini}} = 100$ yields more than 1% difference: *need for 2LPT ICs*

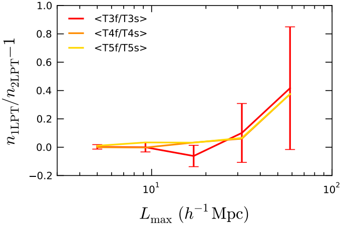
# Results: Order of LPT

Halo mass function & LSS extent

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




Mass function



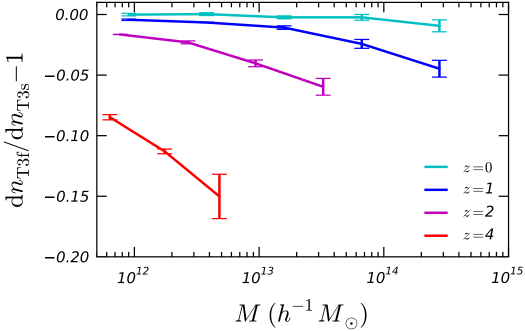

LSS size distribution

- 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

$z_{\text{ini}} = 100$

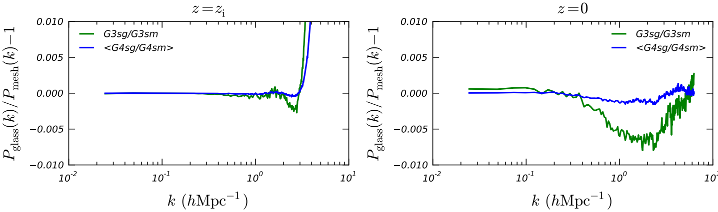



- At $z > 0$, the mass function is underestimated in 1LPT simulations
- The underestimation is larger at high mass
- Need for at least $\approx 100$ expansion factors

# Results: Preinitial configuration

Power Spectrum

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

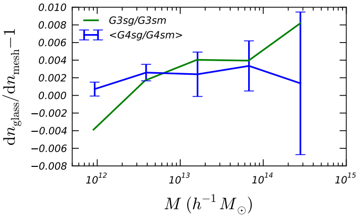



- Extra power on very small scales at initial redshift
- Vanishes by $z = 0$
- At a given LPT order, initial power is independant of $z_{\mathrm{ini}}$
- At $z = 0$, all within 1%

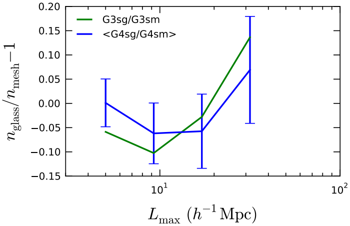
# Results: Preinitial configuration

Halo mass function

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




Mass function



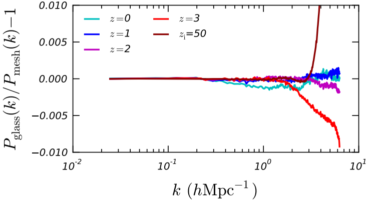

LSS size distribution

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

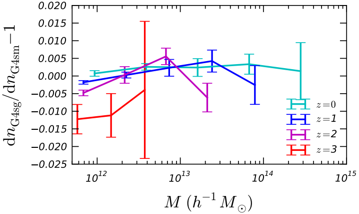
# Results: Preinitial configuration

Redshift evolution

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




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

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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: $z_{\mathrm{ini}} \approx 100$ 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, ...
- Study of interaction rate in cosmological simulation (in progress) stay tuned!

# Summary & perspectives

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감사합니다!