Simulations of Small Scale Structure of Cold Dark Matter with GRACOS

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Outline

- N-body simulation code GRACOS
  - Parallel computing
  - Load balancing techniques
  - Adaptive P3M algorithm
  - Multiple timestepping (in progress)

- Large Scale Structure
  - LCDM universe simulations

- Small Scale structure
  - Caustics
  - Comparison with analytic models
  - Implications on direct detection experiments

P3M N-body algorithm

- Gravitational Force

Total grav. force = Particle-Mesh(PM) + Particle-Particle(PP)
Long Range Force Short Range Force

PM: Long Range component using FFT
PP: Short range component, traditionally
using direct summation over close pairs of particles
Direct summation is extremely time consuming

- Equation of motion

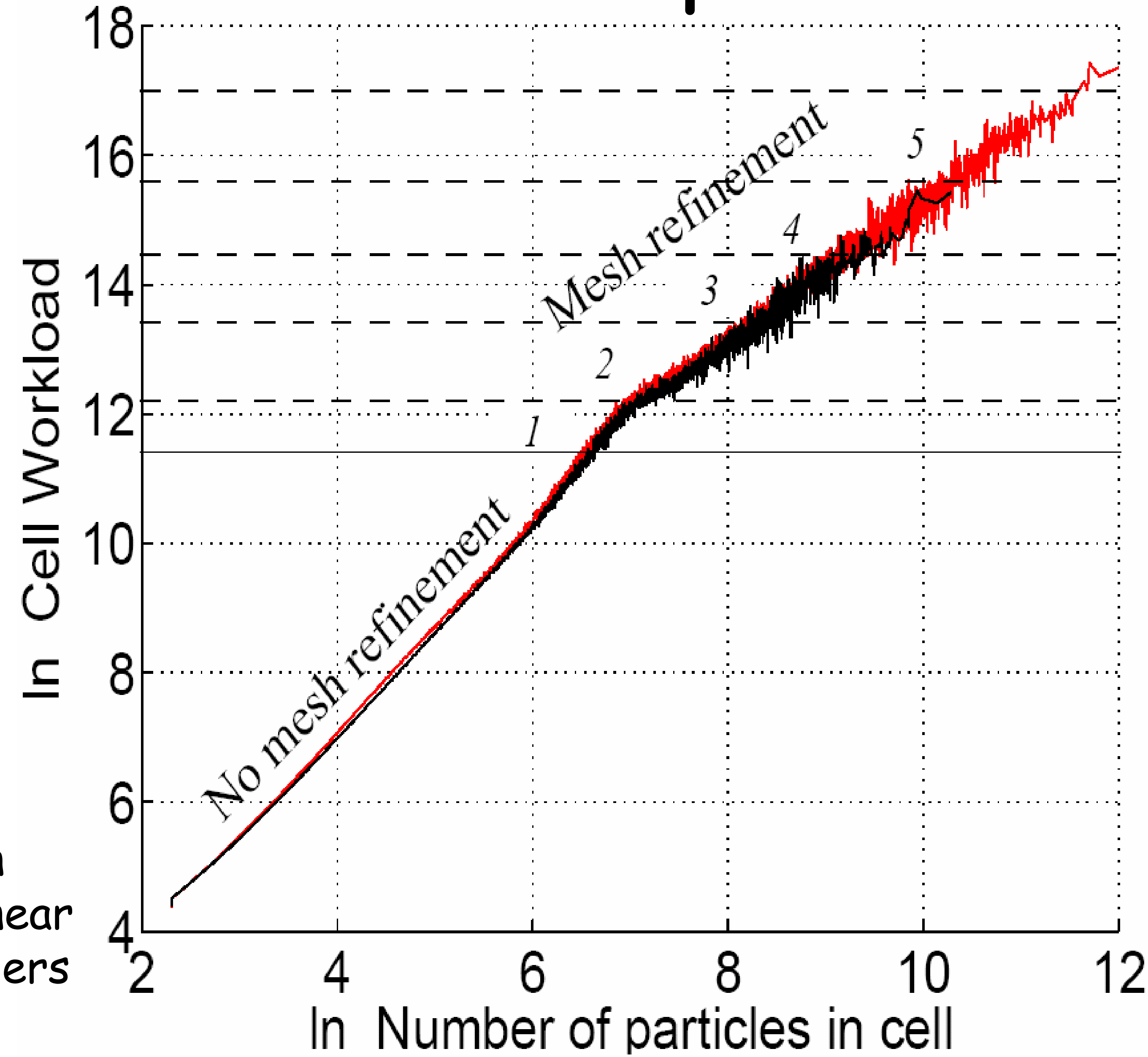
$$\frac{d^2\mathbf{x}}{d\tau^2} + \frac{1}{a}\frac{da}{d\tau}\frac{d\mathbf{x}}{d\tau} = -\nabla_{\mathbf{x}}\phi$$

in code units

$$\frac{d\tilde{\mathbf{x}}}{d\tilde{t}} = \tilde{\mathbf{v}}\ , \quad \frac{d\tilde{\mathbf{v}}}{d\tilde{t}} = \tilde{\mathbf{g}}$$

Leapfrog integrator

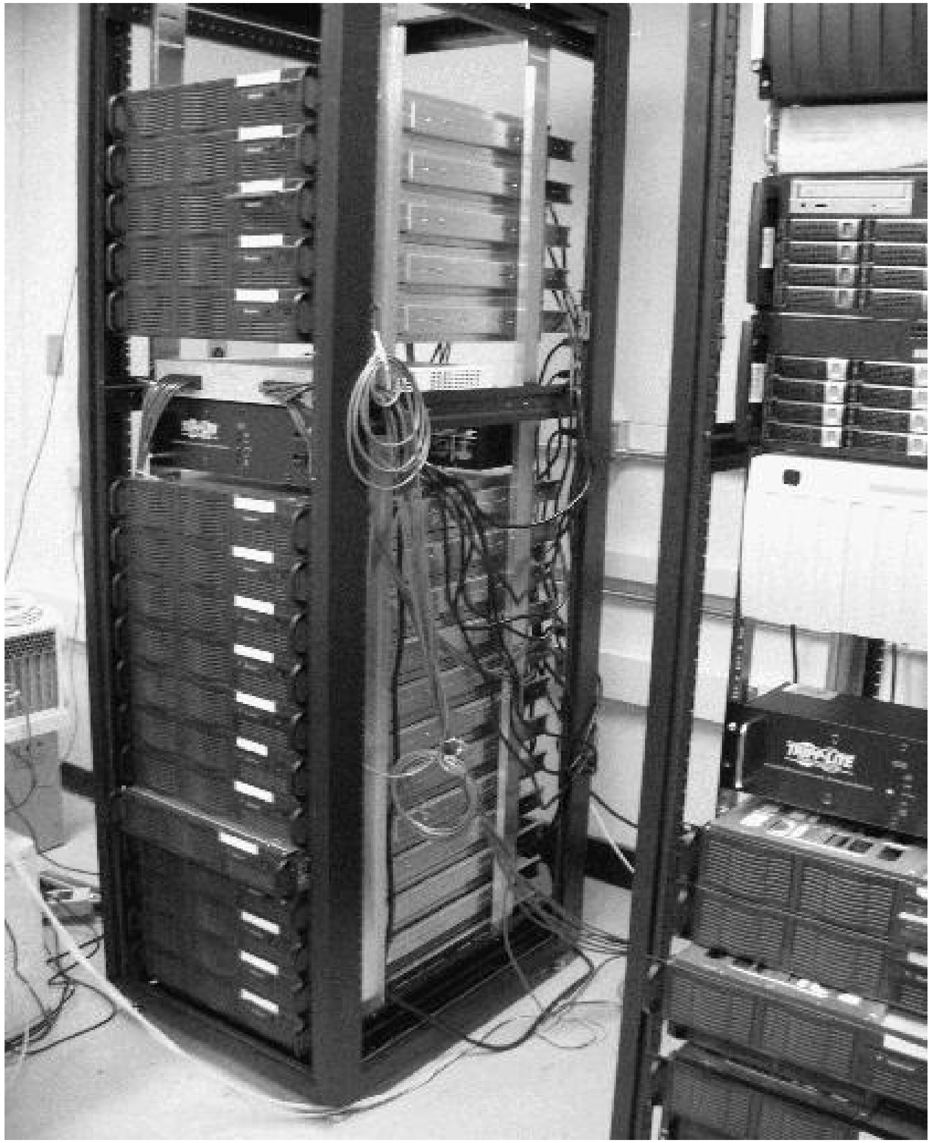
Optimization of PP computation



FFT based solution

The direct summation
Workload becomes linear
At high particle numbers

Beowulf Clusters of Computers



MIT beowulf cluster: assembly and installation by:
O. Scwarz, A. Shirokov, E. Bertschinger, S. Hughes

Parallelization: the problem of separation of task among the processors/nodes

- distribution of the data
- distribution of computation
- distribution of storage

- Must all be close to uniform!

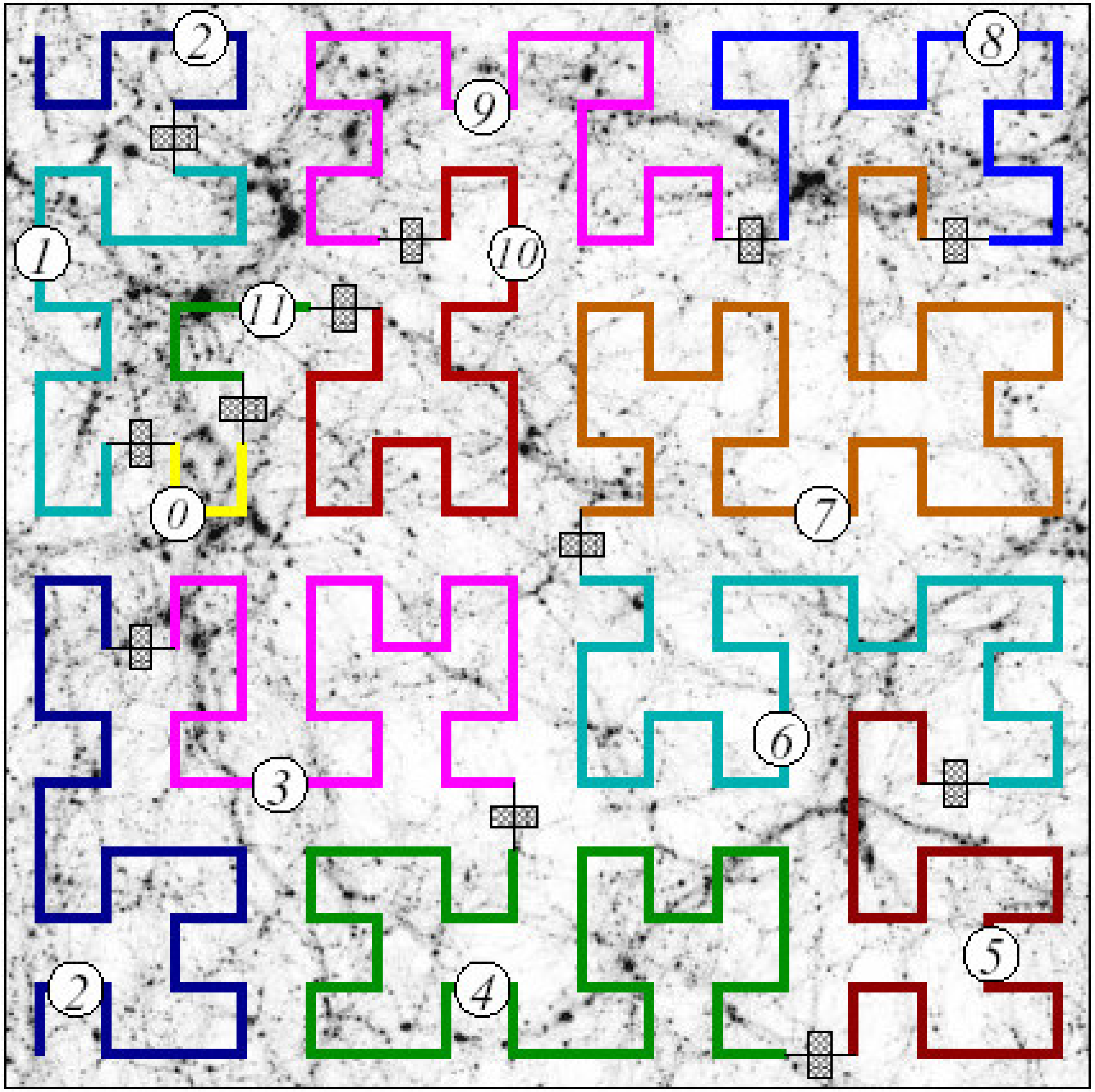
Hilbert Curve Domain decomposition

[Pilkington & Baden (1996)] Pilkington, J. & Baden, S. 1996, IEEE Trans. Par. Dist. Systems, 7, 288

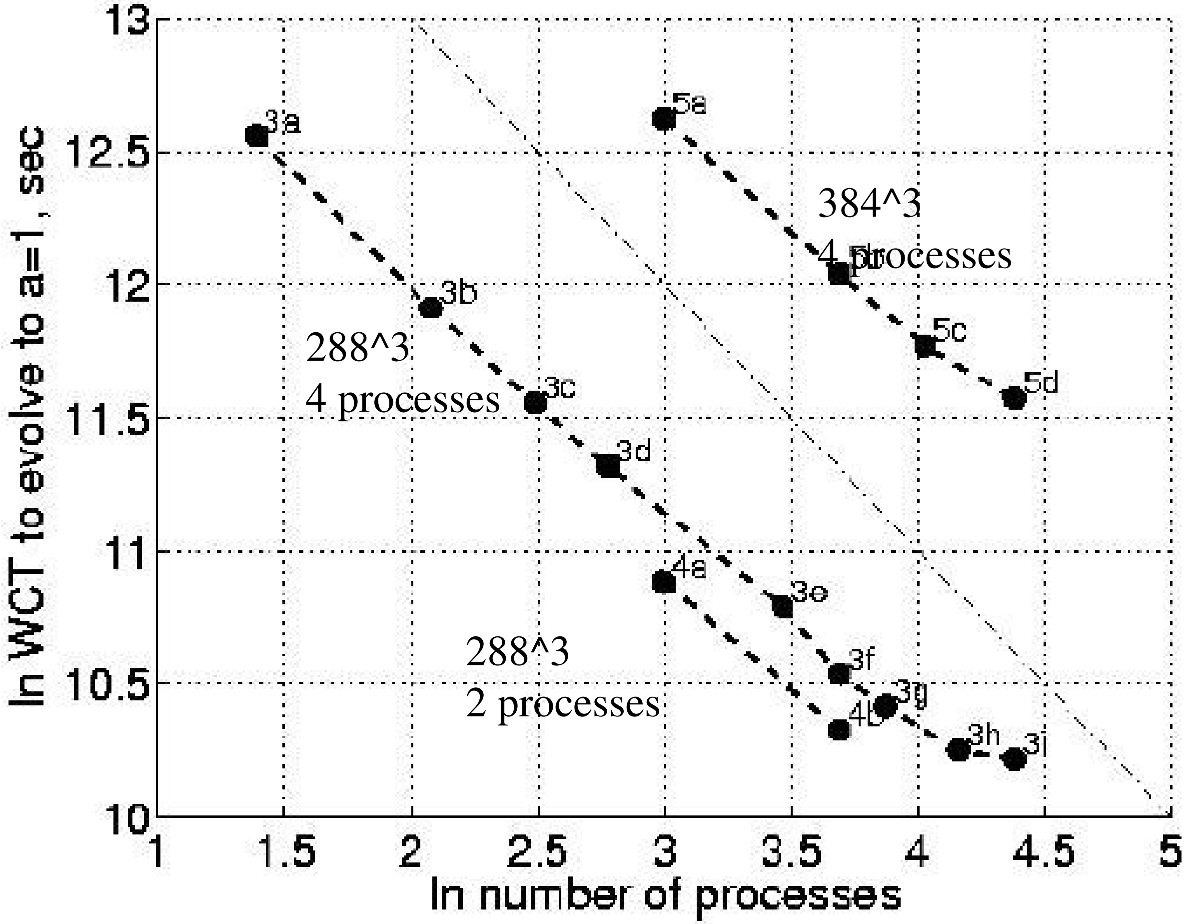
The solution:
(independently adopted
by gadget2)

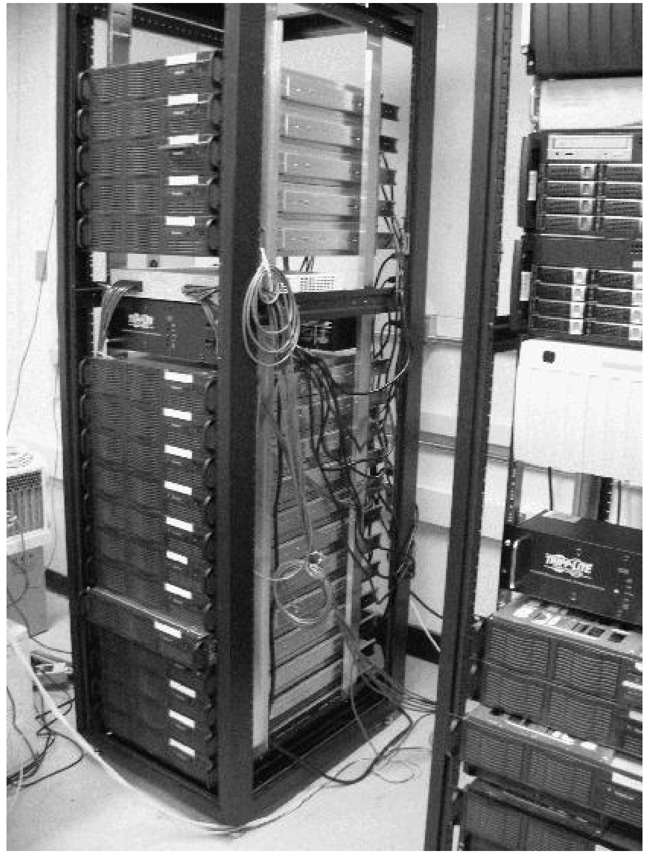
Introduce a curve
And the partitions

Partitions are moving
along the curve to adjust for change in particle distribution



Scalability





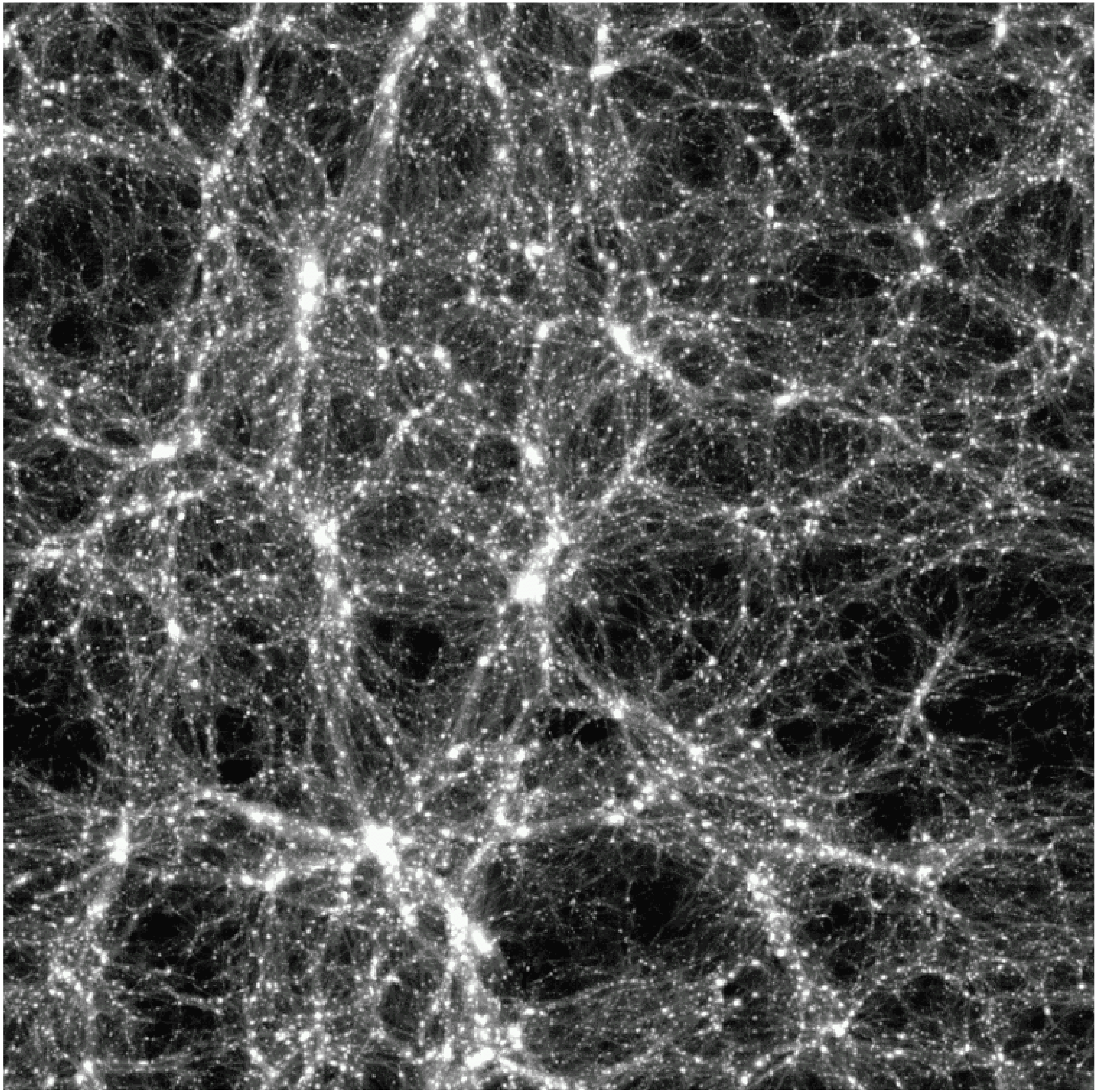
The maximum optimal number of processes increases with the problem size

Large Scale Structure

LCDM universe

GRACOS (GRAvitational COSmology) Code

z = 0
L = 200Mpc



P3M simulation

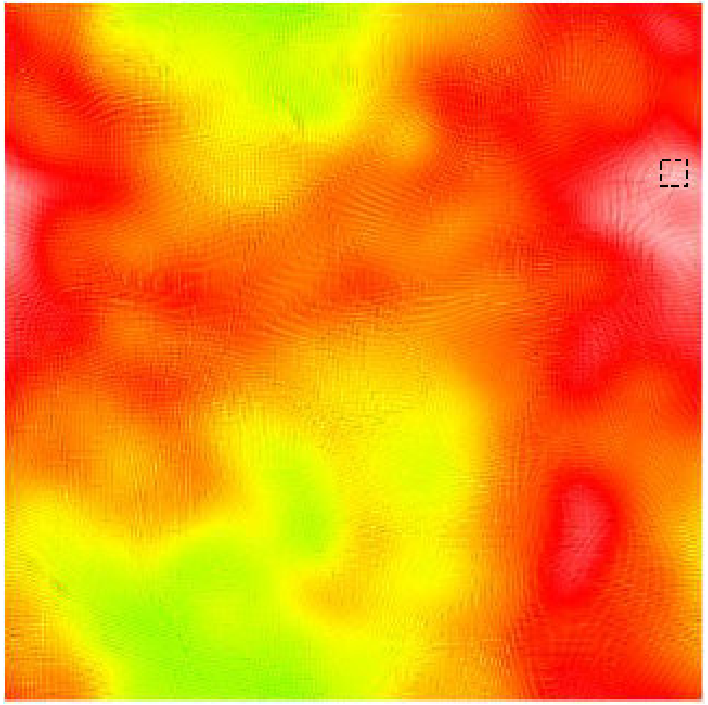
800^3 particles

Initial conditions *n=-3*

$$P(\mathbf{k}) = P_0 k^n \left[\frac{D_+(a)}{D_+(1)}\right] \exp(-k^2 l_s^2)$$

$z_i = 350$

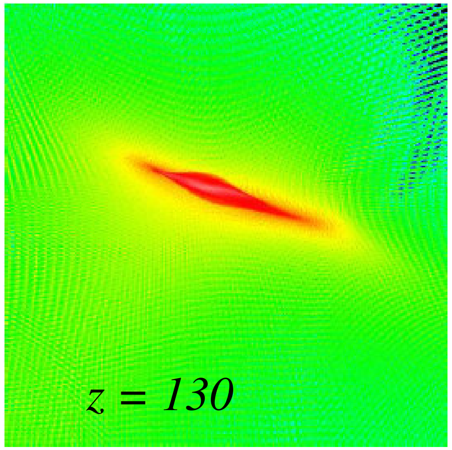
particle weighs $3.1 \times 10^{-12} M_\odot$



$k_c \approx 1.7 \times 10^6 \ \mathrm{Mpc}^{-1}$

The First Caustic to Form

z <~ 350
L = 20pc



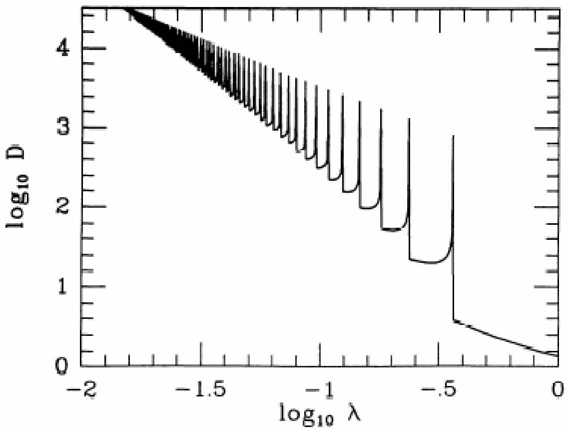
PM 512^3 particle simulation: physical space

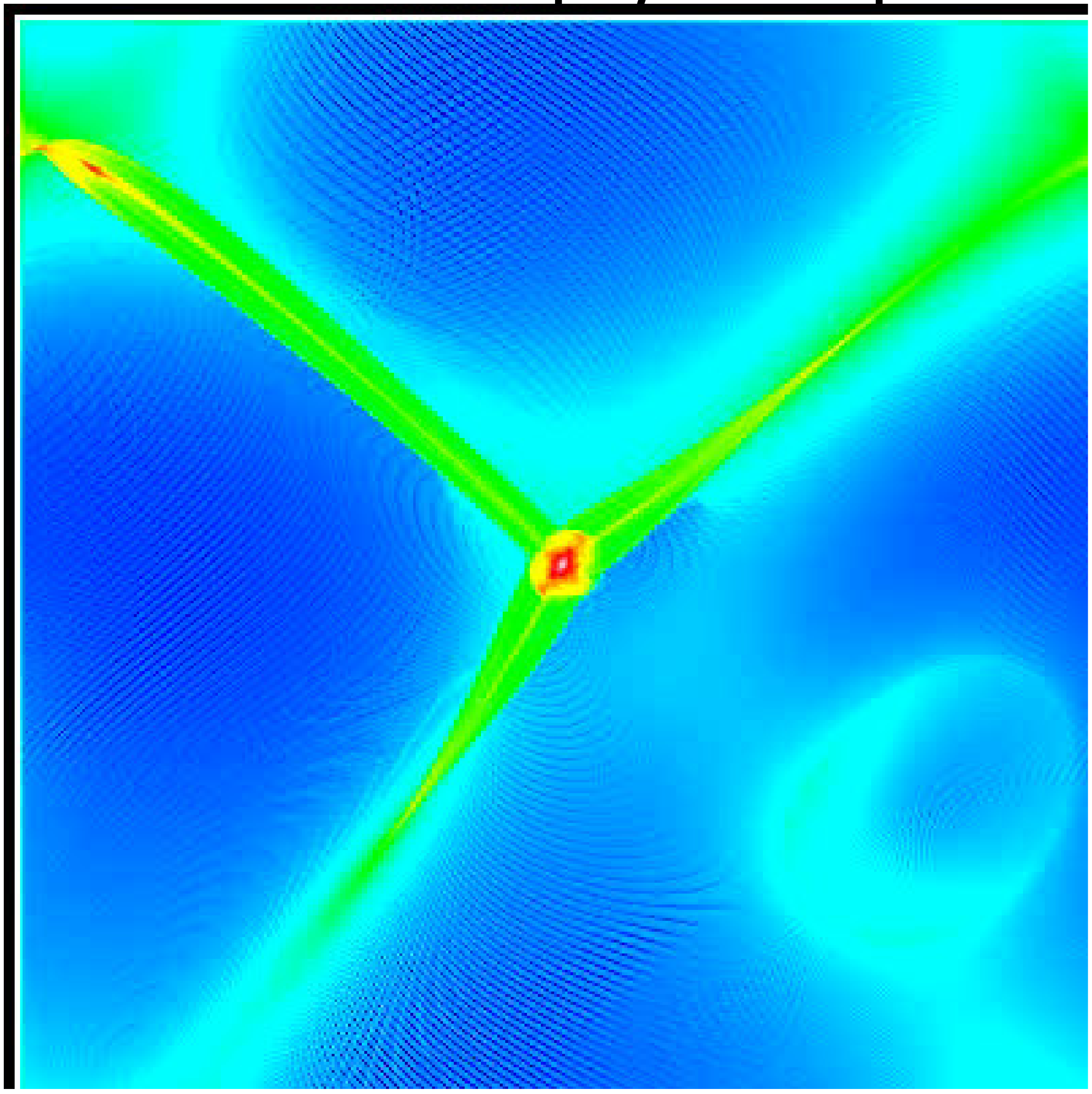
4 smoothing lengths per sidelength in ICs

Many shells, - caustics

- No implied symmetry
- Inner caustic survives

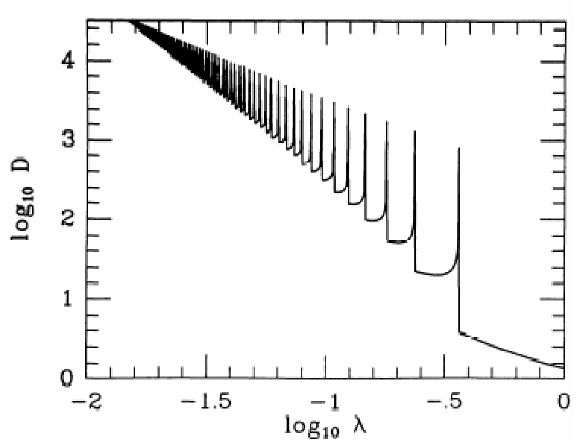
Bertschinger 1985

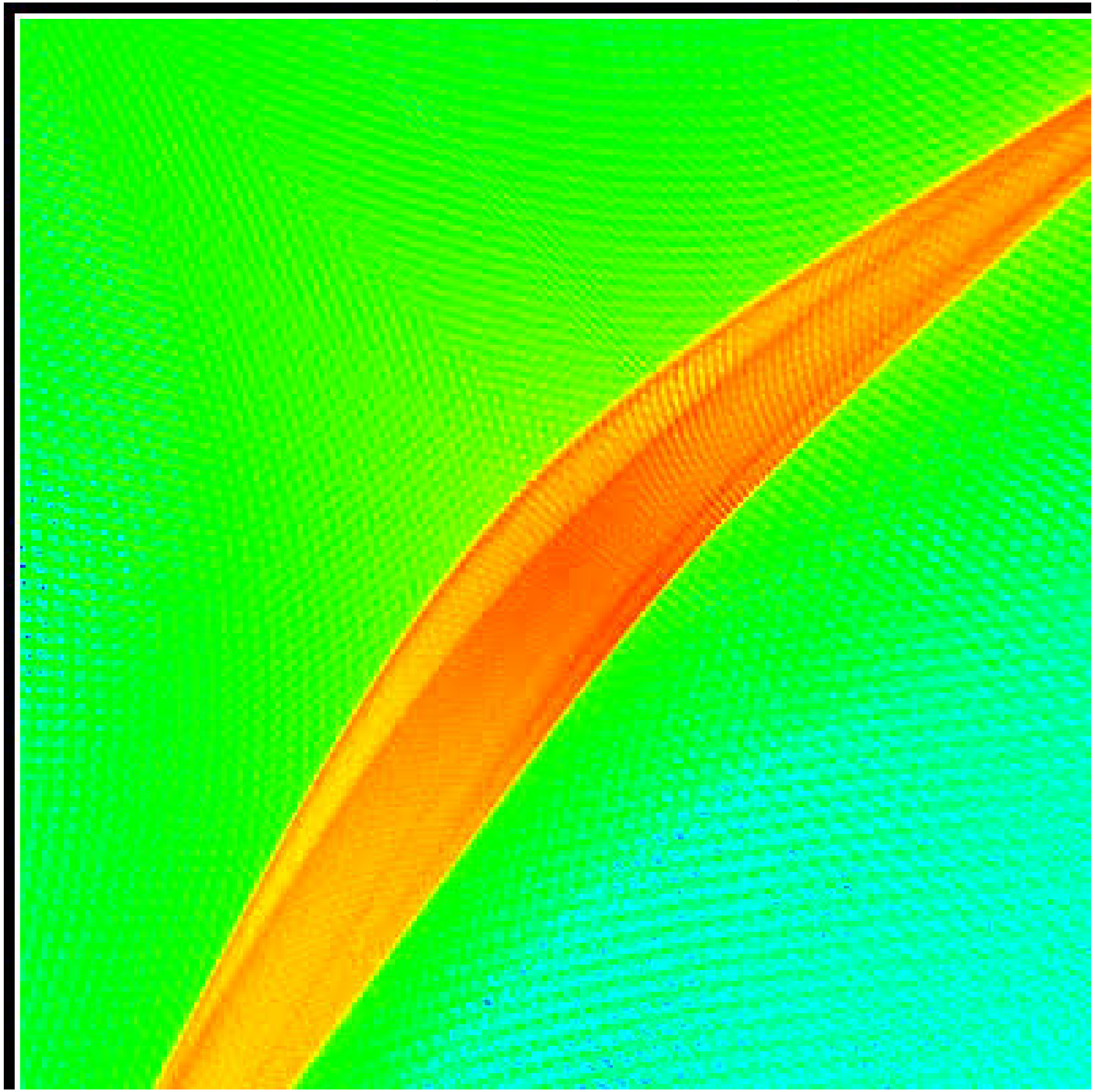




PM 512^3 simulation: physical space

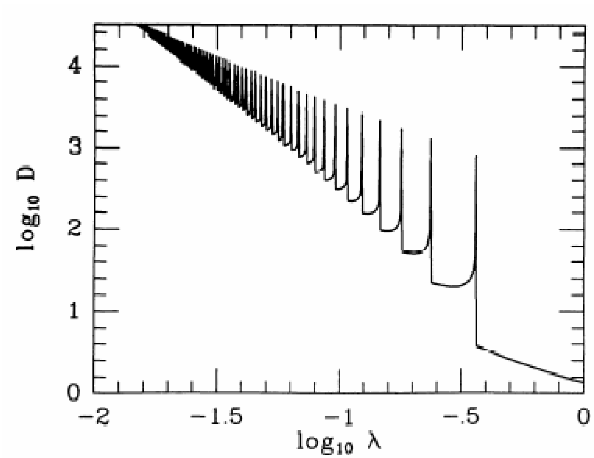
Analytical model
Bertschinger 1985

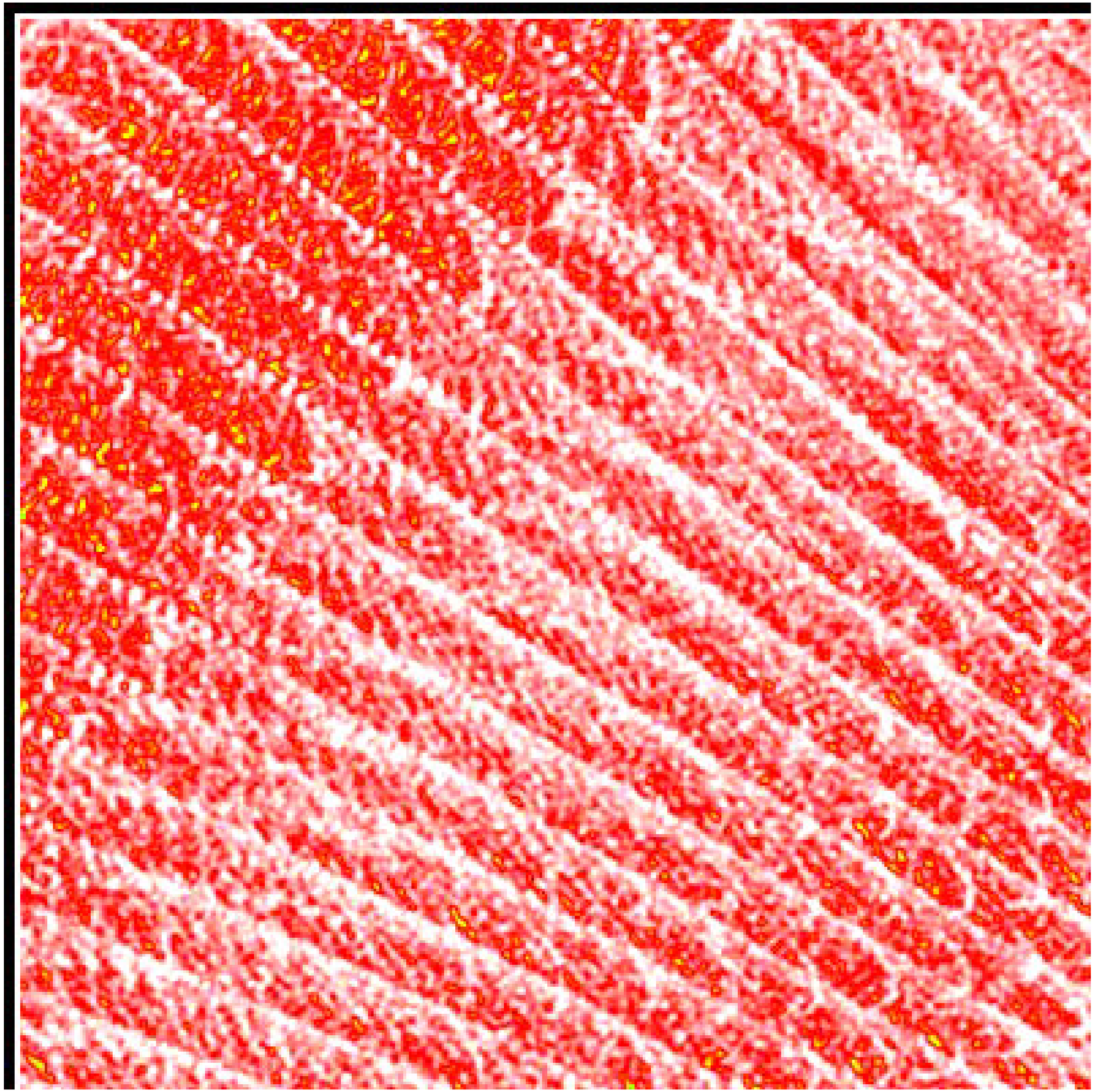




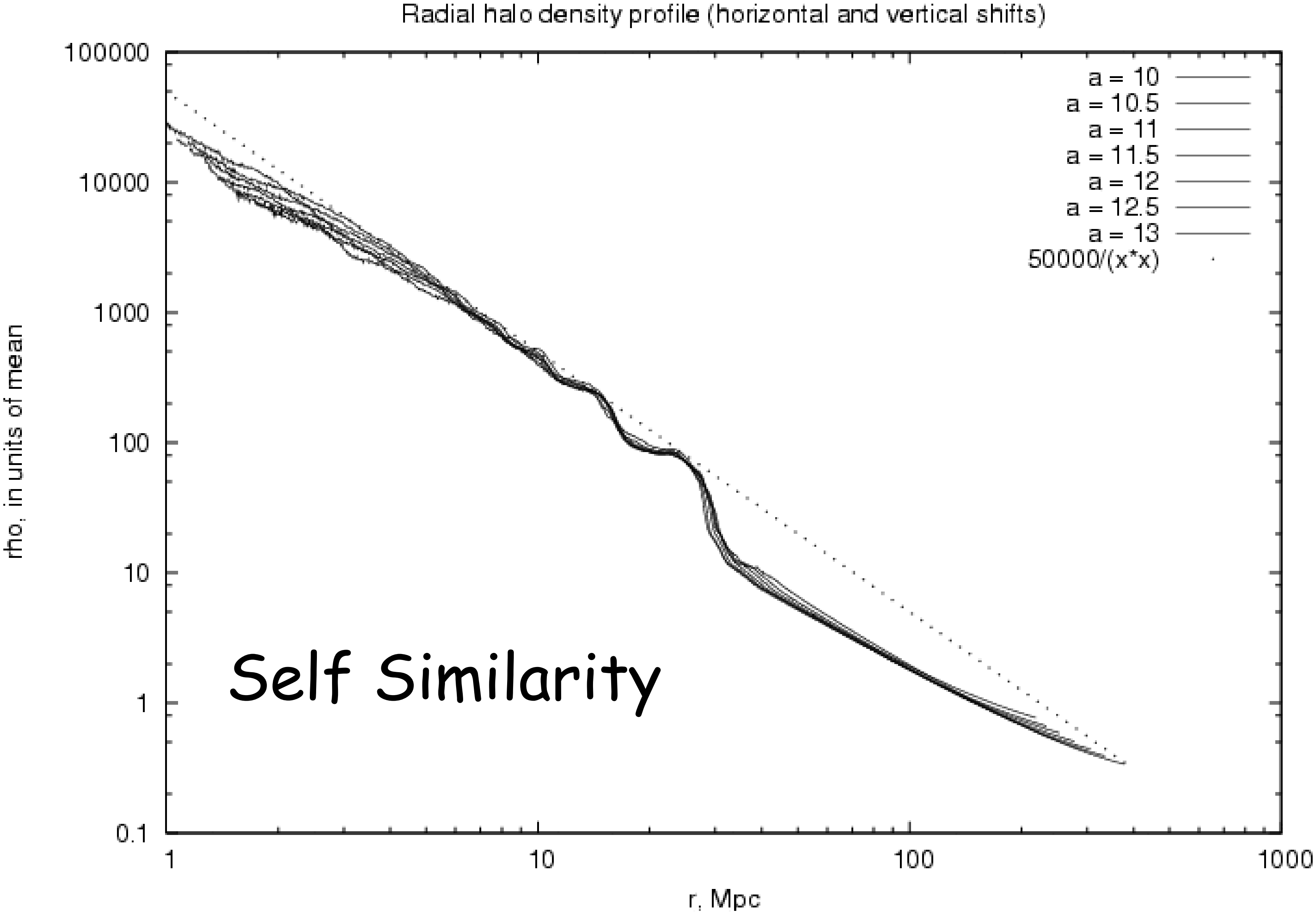
PM 512^3 particle simulation

Bertschinger 1985

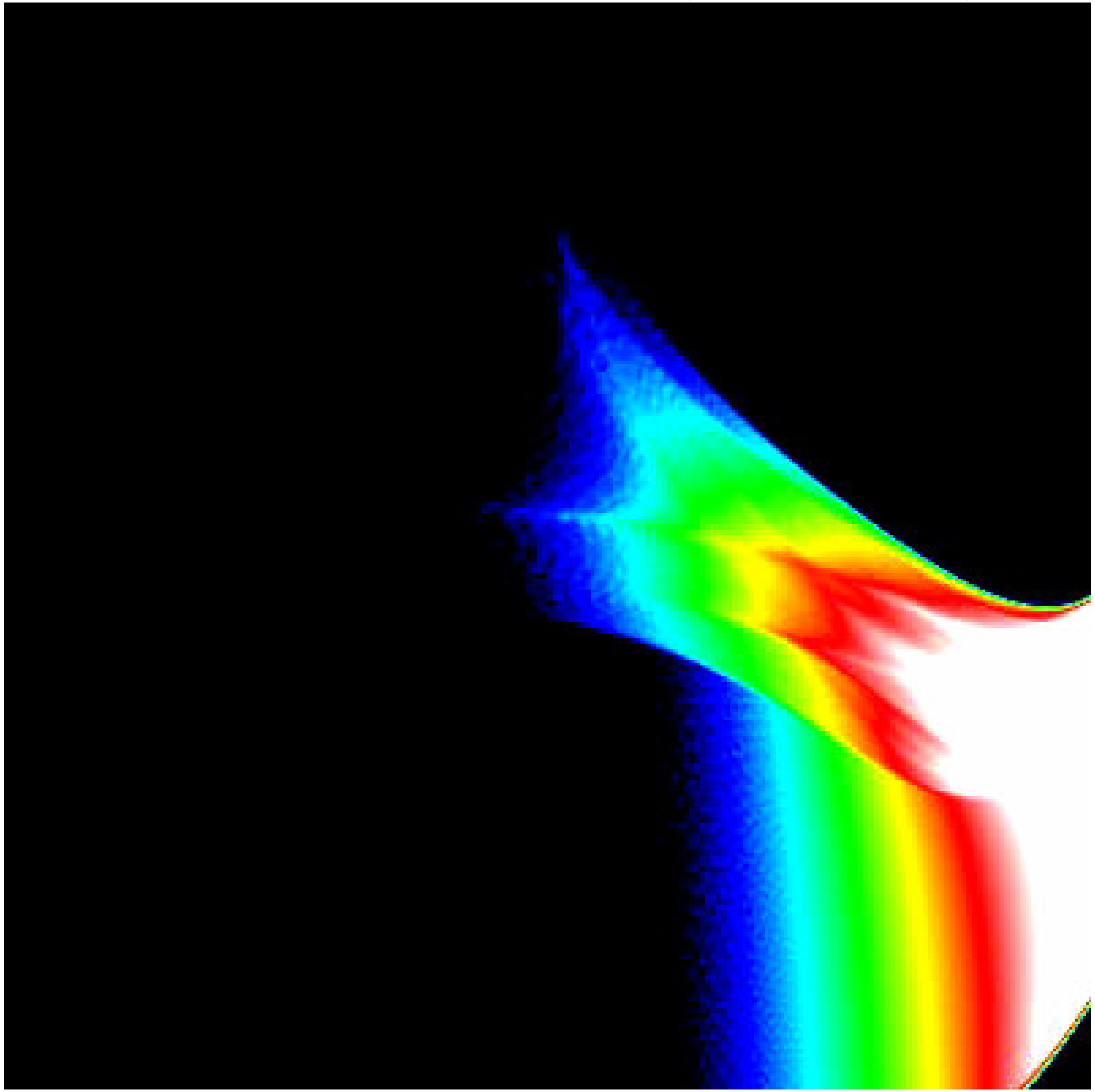




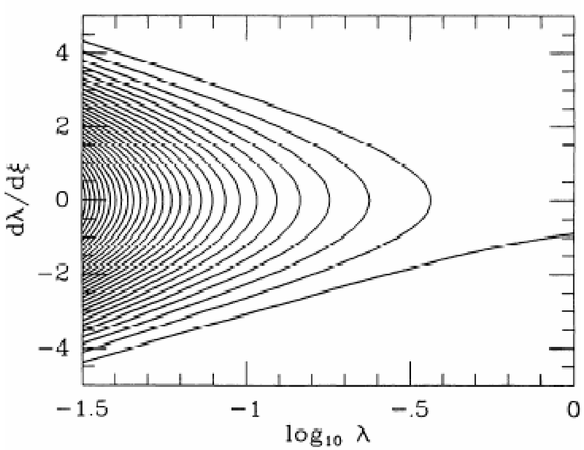
PM 512^3 particle simulation: radial profile



PM 512^3 particle simulation: phase space



Bertschinger 1985



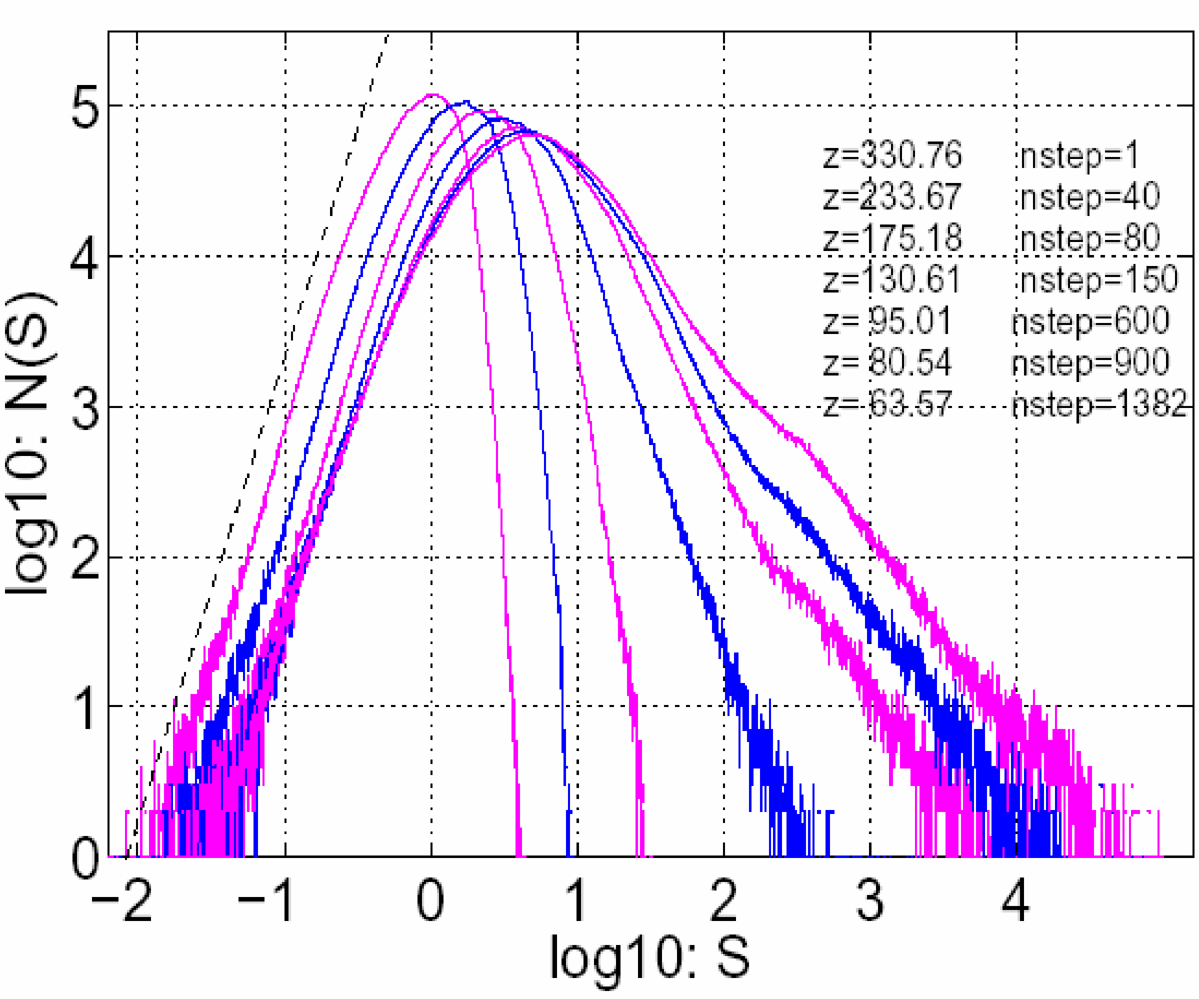
Measuring the Detection Rate Distribution Function

$$f(v) = 4\pi v^2 f(\mathbf{v}) = \frac{4\pi v^2 e^{-v^2/2\sigma^2}}{(2\pi\sigma^2)^{3/2}}$$

$$N(\Gamma) \propto \begin{cases} \Gamma^3, & \Gamma \ll \Gamma_0 \\ \exp(-\frac{\Gamma^2}{2\sigma^2 n_\chi^2 \sigma_\chi^2}) & \Gamma \gg \Gamma_0 \end{cases}$$

$$N(\Gamma) \propto \Gamma^{-2.7\pm0.3}$$

Power law tail



Summary