



Osservatorio Astronomico di Trieste  
Astronomical Observatory of Trieste



UNIVERSITÀ  
DEGLI STUDI  
DI TRIESTE



ICSC

Centro Nazionale di Ricerca in HPC,  
Big Data and Quantum Computing

# High-Performance Cosmology: recent developments in the PINOCCHIO code

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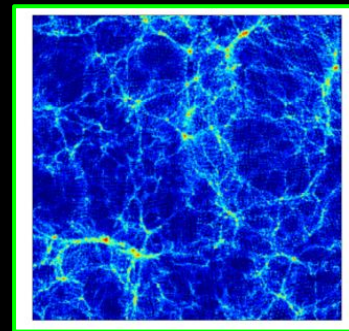
*Trieste, 10 September 2024*

# PINpointing Orbit-Crossing Collapses Hierarchical Objects: PINOCCHIO

PINOCCHIO is an algorithm, based on **Lagrangian Perturbation Theory (LPT)**, **Extended Press & Schechter** approach and **ellipsoidal collapse**, for simulating **Dark Matter halos** in cosmological boxes and past light cones (*Monaco et al. 2017*)

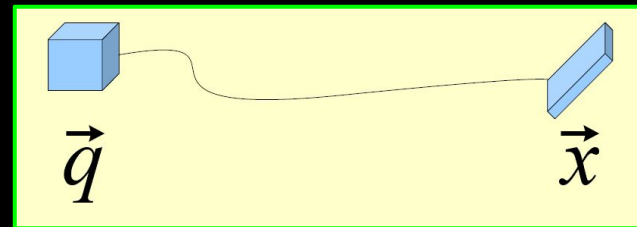
- **N-Body approach:** calculating the **gravitational forces** acting on each particle due to all other particles

Detailed and accurate for **all-scale** structure  
Computationally very expensive



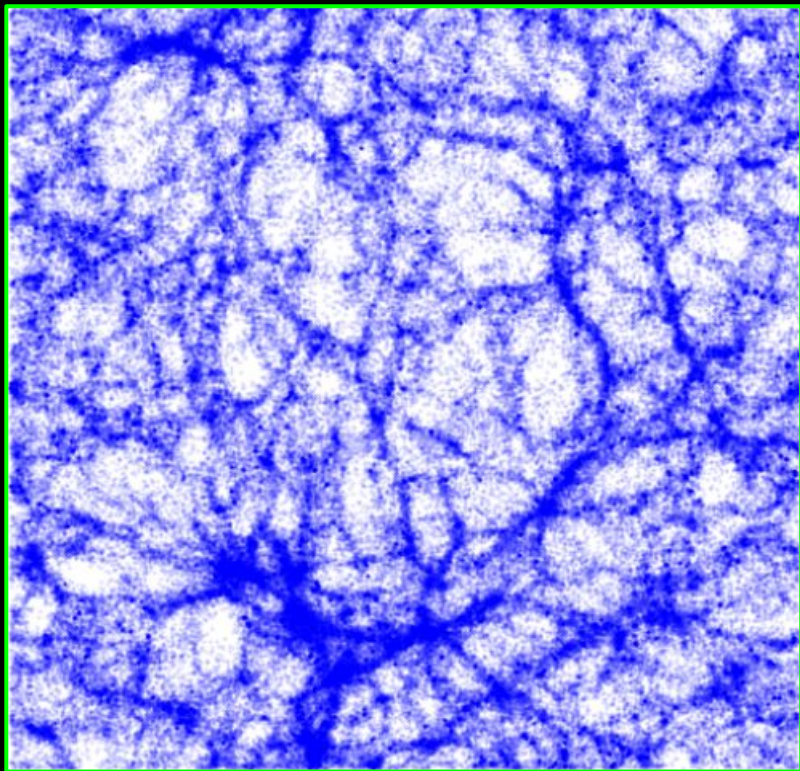
- **LPT approach:** calculating the displacements of particles from their **initial position**

Fast **approximation** for **large-scale** structure

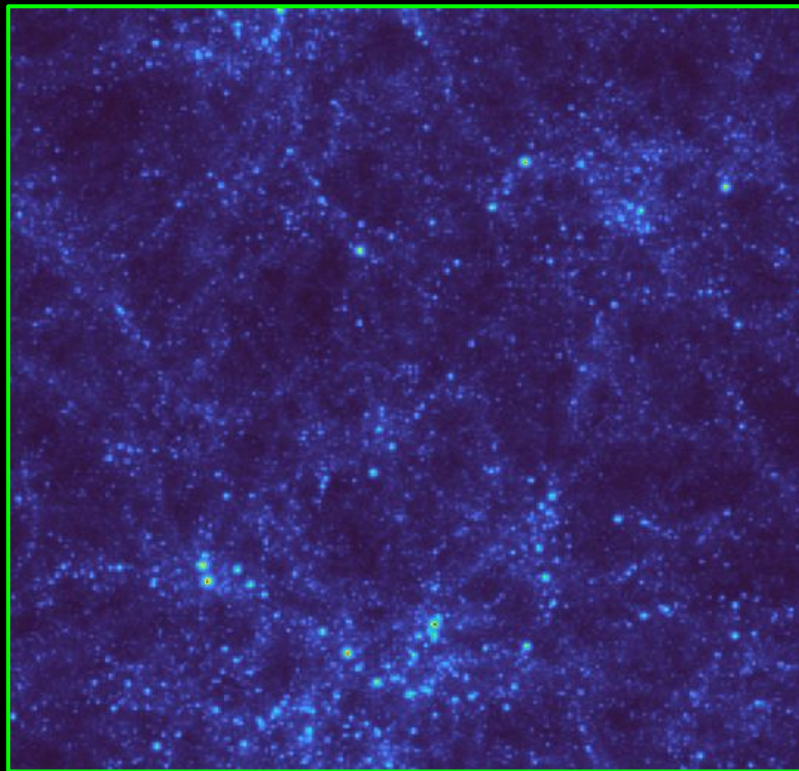


$$\vec{x}(\vec{q}, a) = \vec{q} + \vec{\Psi}(\vec{q}, a)$$

LPT displacement field



Halos



Only the displacements are not enough, we still need to identify halos ...

# Collapse time for halo identification

The **Lagrangian approach** has a natural limit in the condition **J = 0**

$$\vec{x}(\vec{q}, a) = \vec{q} + \vec{\Psi}(\vec{q}, a)$$

$$J_{ij} = \frac{\partial x^i}{\partial q^j} = \delta_{ij} + \frac{\partial \Psi^i}{\partial q^j}$$

- Before this moment the **Lagrangian-to-Eulerian** mapping is **single-valued**
- When **J = 0** the **q → x mapping** becomes **multi-valued** and the density goes to infinity: orbit crossing or shell crossing

$$1 + \delta = \left| \frac{\partial \mathbf{x}}{\partial \mathbf{x}_i} \right|^{-1} = \frac{1}{(1 - \lambda_1 D)(1 - \lambda_2 D)(1 - \lambda_3 D)},$$

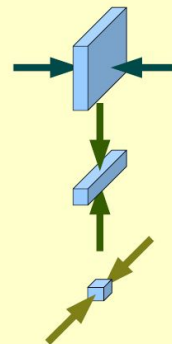


**Eigenvalues  $\lambda_i$**  for calculating **collapse times** of particles

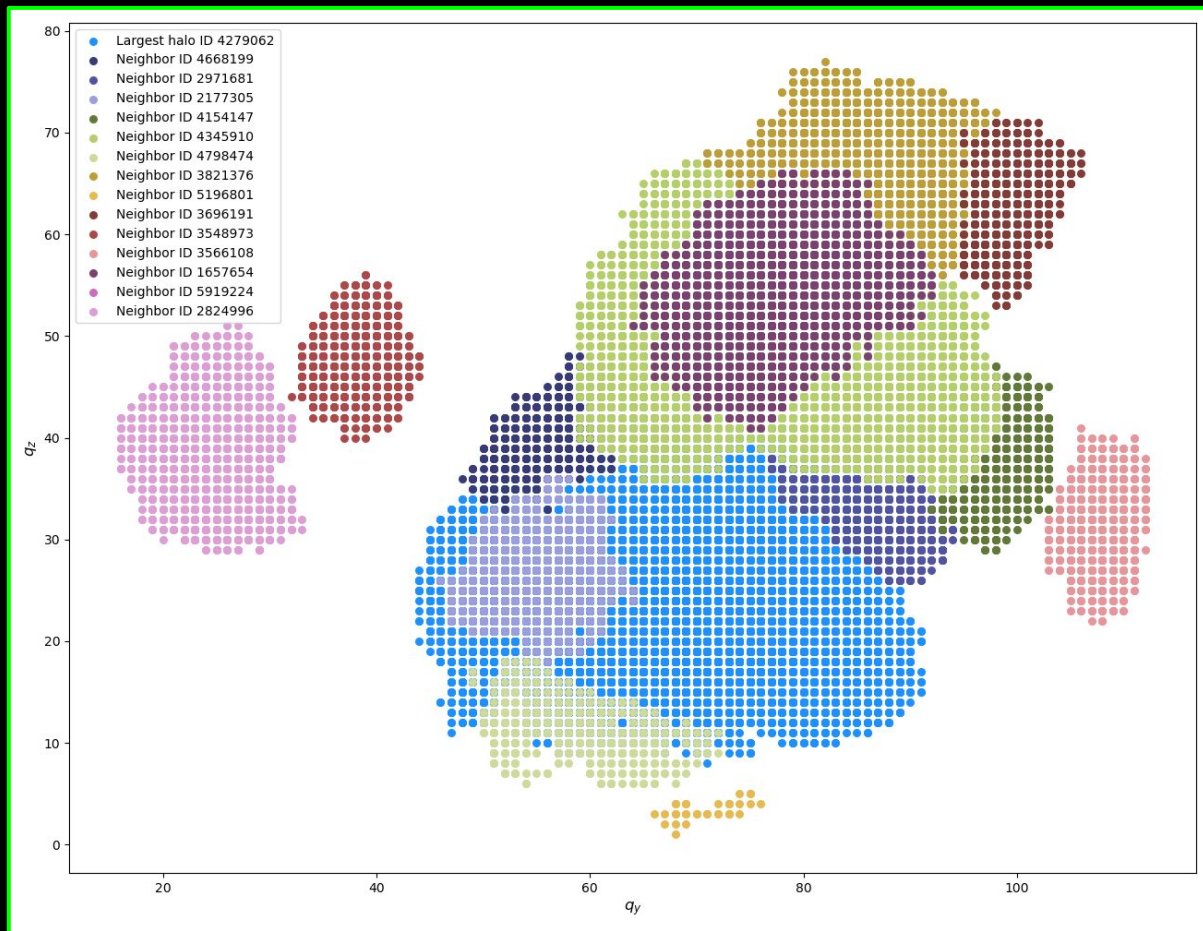
$D(t) = 1/\lambda_1$ : *pancake*  
**(ORBIT CROSSING)**

$D(t) = 1/\lambda_2$ : *filament*

$D(t) = 1/\lambda_3$ : *knot*

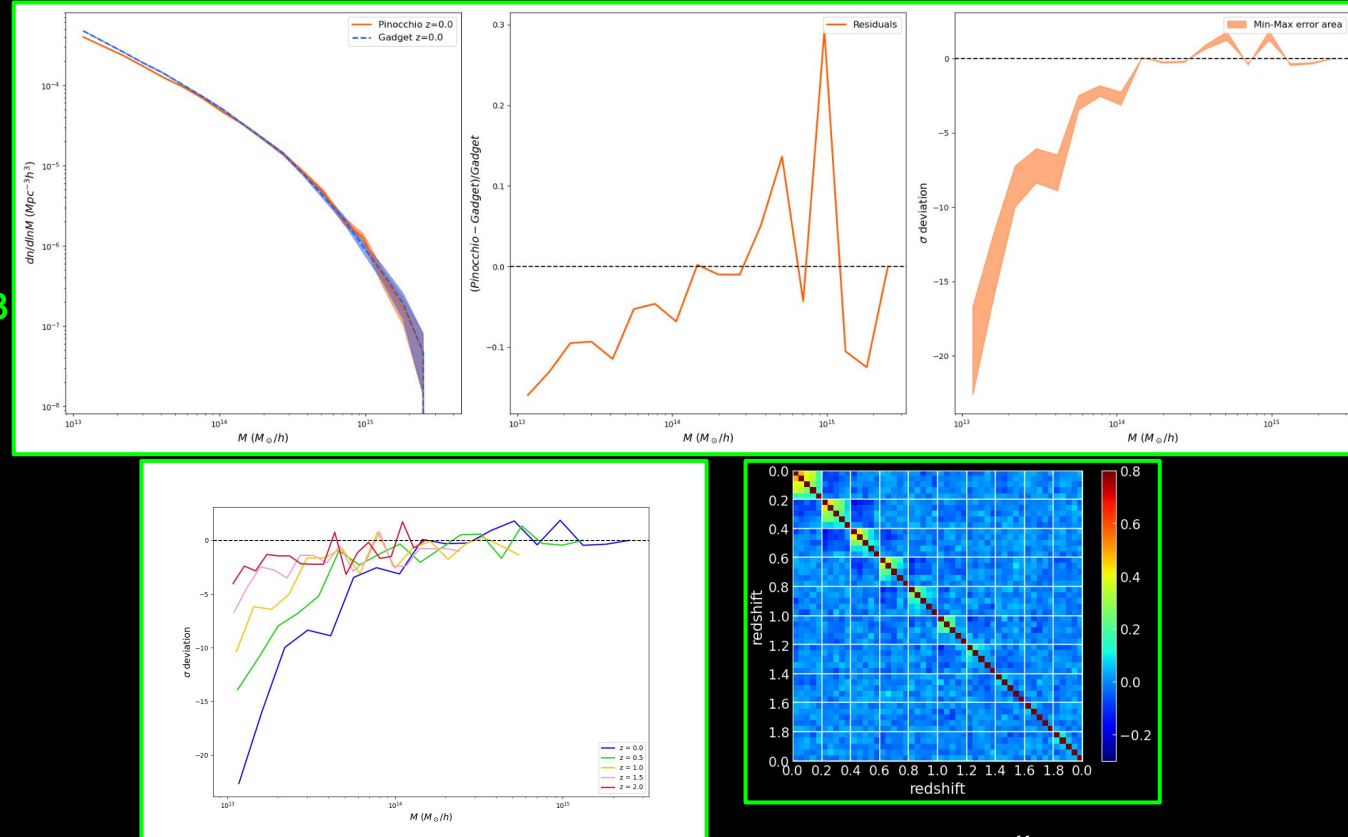


# Halo identification directly on the grid: Fragmentation



# PINOCCHIO vs N-body: DM halos

- **~1000 faster**
- **5 – 10% accuracy** in reproducing 2-point statistics ( $k < 0.3$  h/Mpc), halo mass function and bias
- For sufficiently massive halo (**~100 particles**) most **FOF** halos (**> 80%**) unambiguously associated with a corresponding **PINOCCHIO** halo

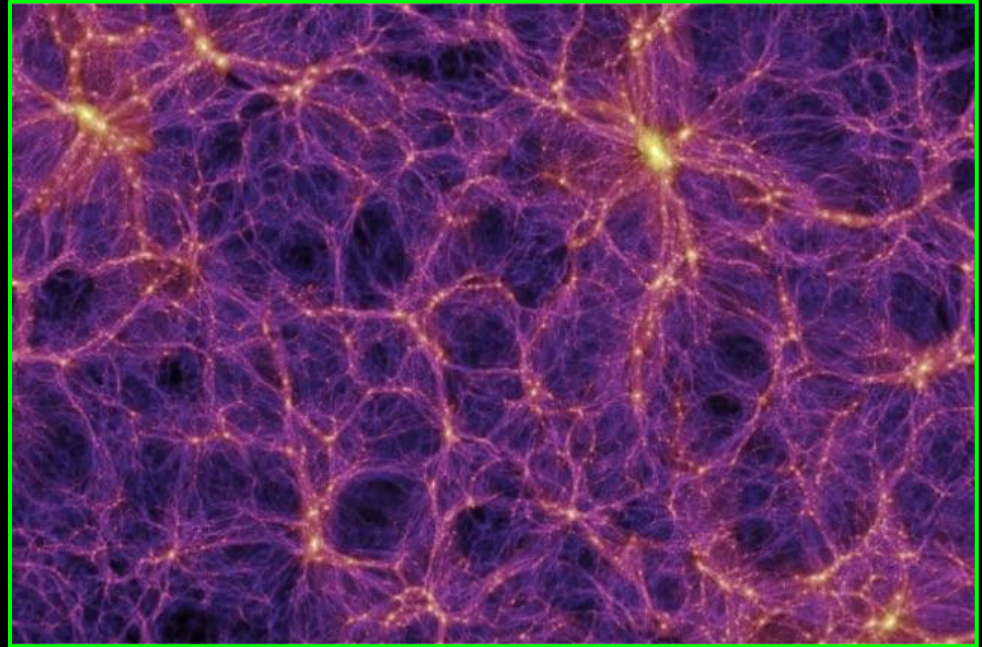


(From Fumagalli+21)

# PINOCCHIO vs N-Body: Cosmic Voids

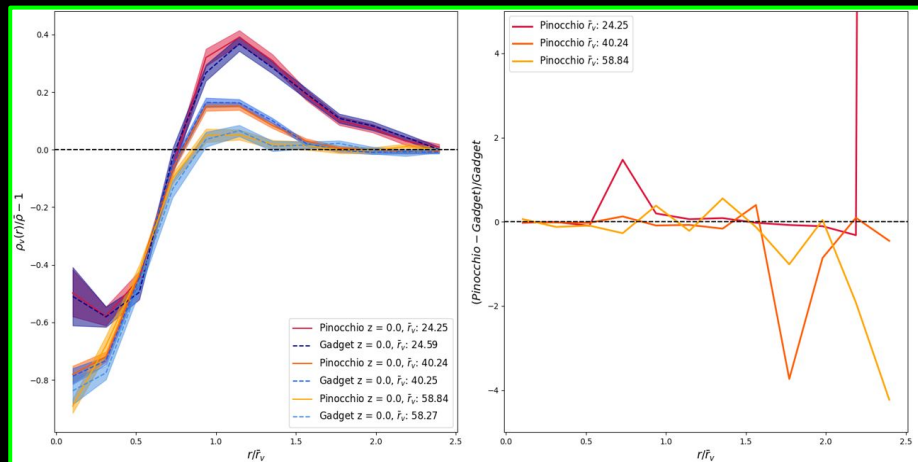
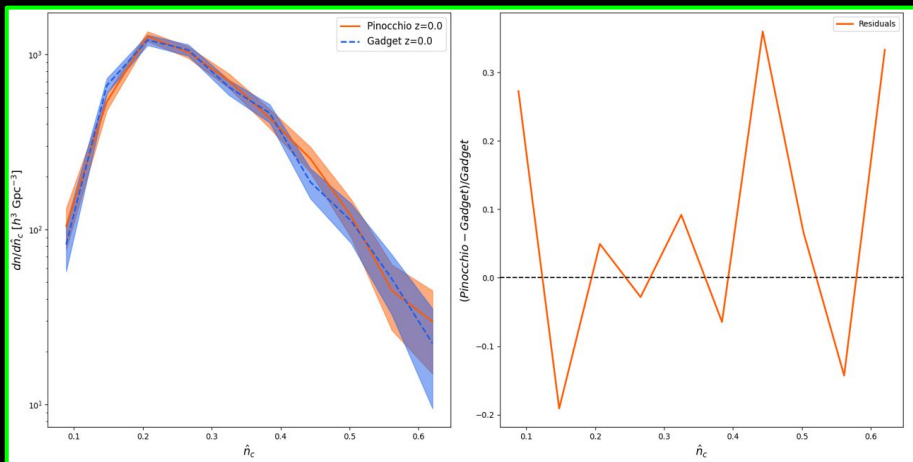
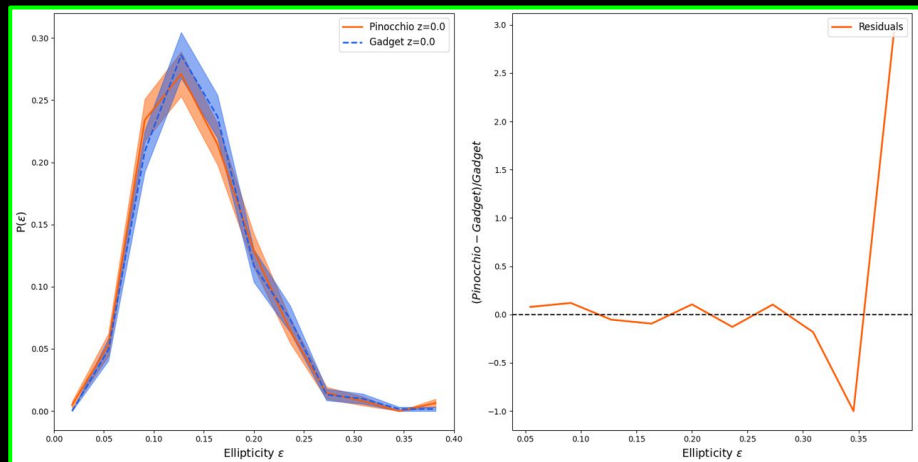
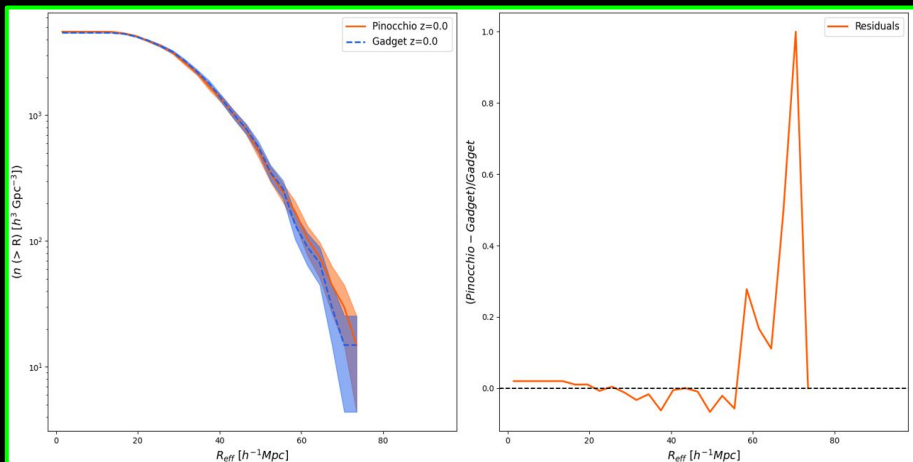
**Voids** are vast **underdense regions** that encode key information about the **expansion history** and **geometry** of the Universe

- Their **dynamic** is **less affected** by **non-linearities**
- We expect (**and demonstrate**) that PINOCCHIO can produce **competitive void statistics** compared to an N-body with respect of **halos statistics**

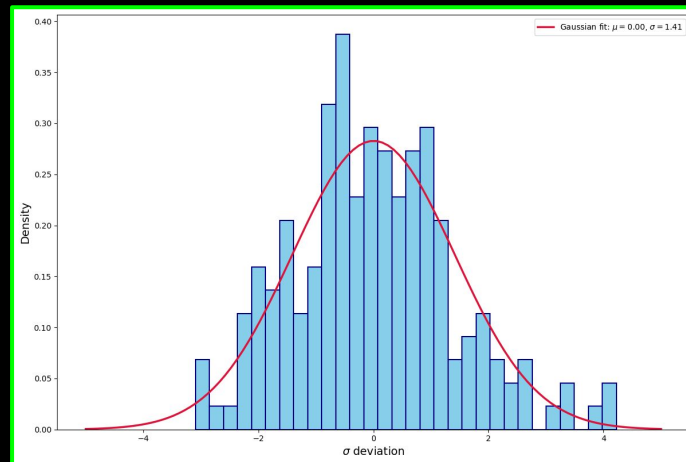
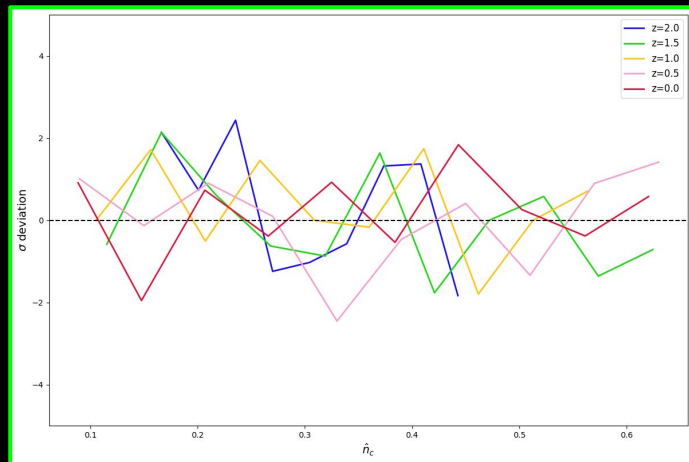
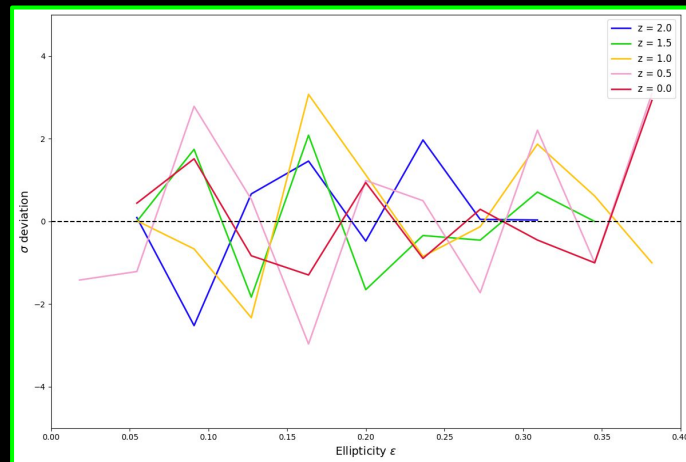
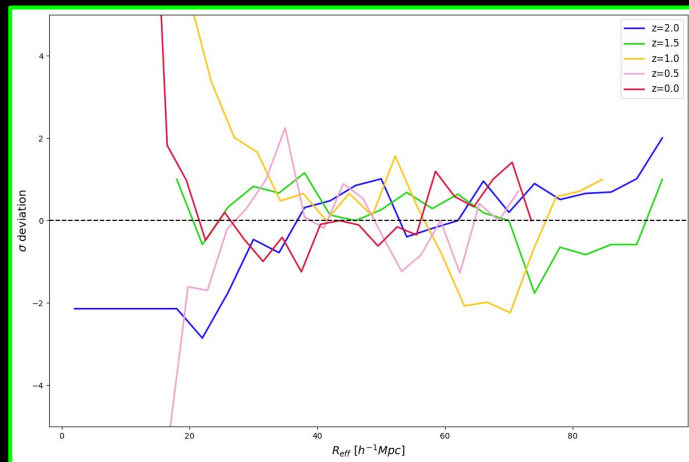


Visiting period at LMU working with Chris Davies, Joe Mohr (and Tiago Castro)

# PINOCCHIO for Cosmic Voids: first order statistics



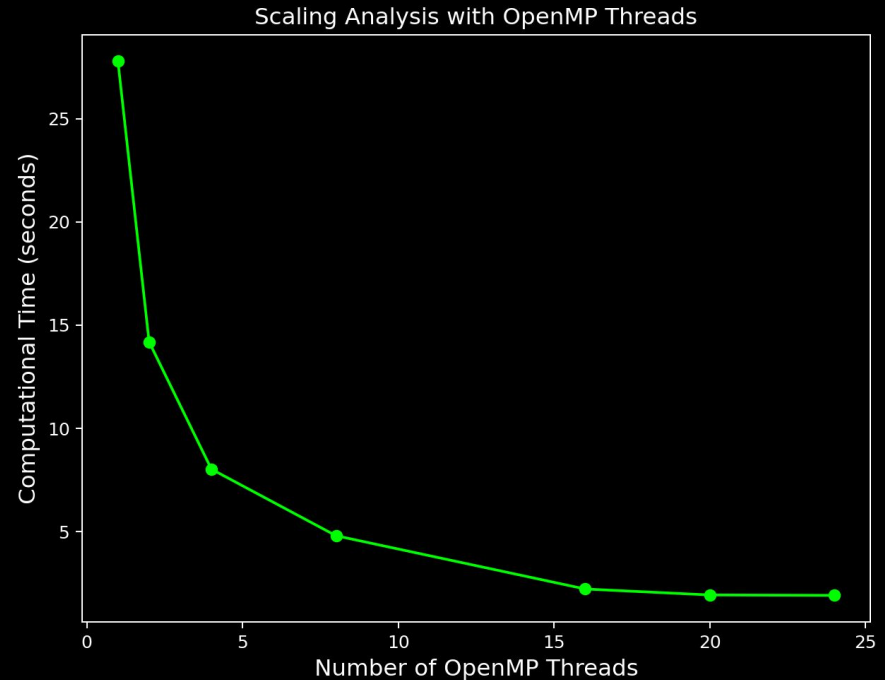
# PINOCCHIO for Cosmic Voids: sigma deviations



# PINOCCHIO: massively parallel codes

**Extension** of the existing **parallel computing paradigm** by integrating **OpenMP** alongside the already-established **MPI framework** for the calculation of collapse times

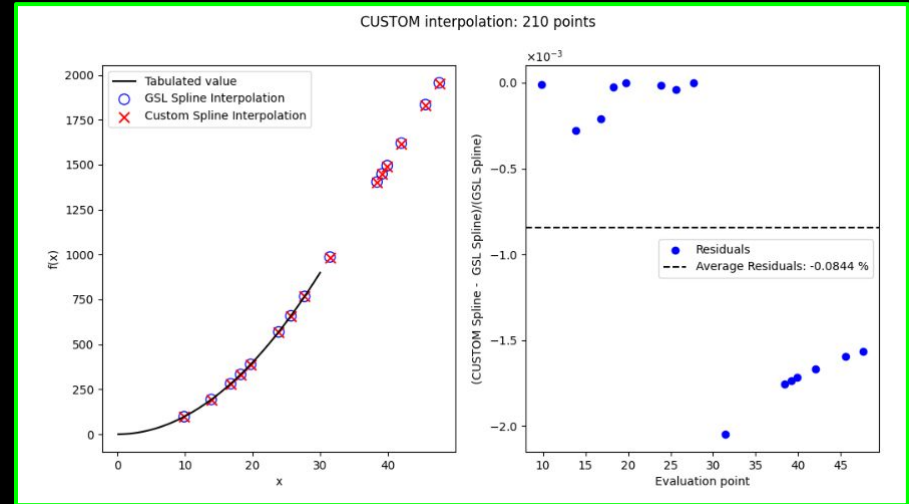
- Nearly **ideal** scaling up to **~20 threads** per single MPI Task
- Large Euclid Box ( box  $\sim 4$  Gpc,  $4096^3$  particles ) **computational time**: **~8%** out of **~40 minutes**
- Computational time **improvement**: **~9x speed-up**
- Thousands of mocks: **~50 hours less**



# PINOCCHIO: massively parallel code

Extension of the existing parallel computing paradigm by integrating GPU offloading with OpenMP for the calculation of collapse time

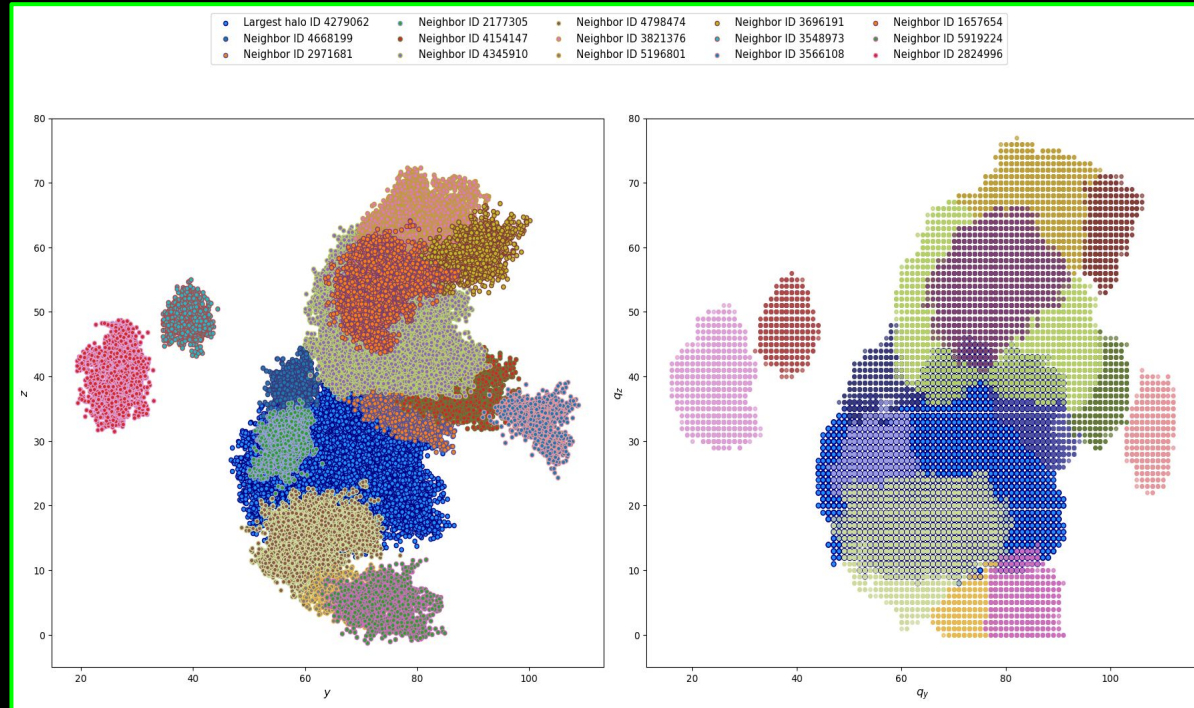
- Implementation of a custom cubic spline interpolation
- GPU offloading test out of PINOCCHIO and comparison with GSL
- Integration in PINOCCHIO and test on CPU
- Offloading tested successfully up to  $128^3$  particles in a box of  $256 \text{ Mpc}/h$  size



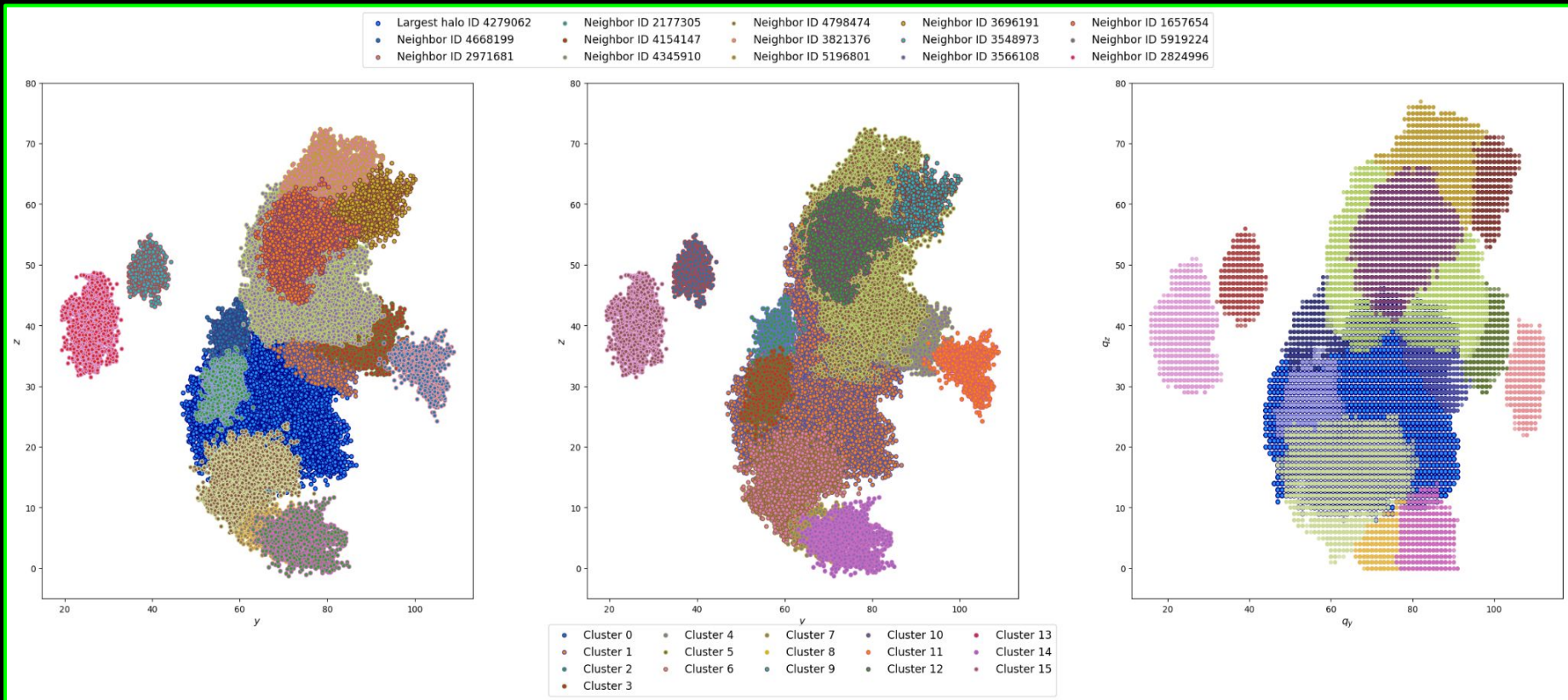
# New methodology for the Fragmentation

Investigating the possible application of a density-based clustering algorithm called Advanced Density Peak Advanced Density Peak (ADP)

- Clustering for a domain decomposition: to identify Eulerian patches that will end up in halos according to PINOCCHIO
- Apply the current algorithm for fragmentation on every independent domain



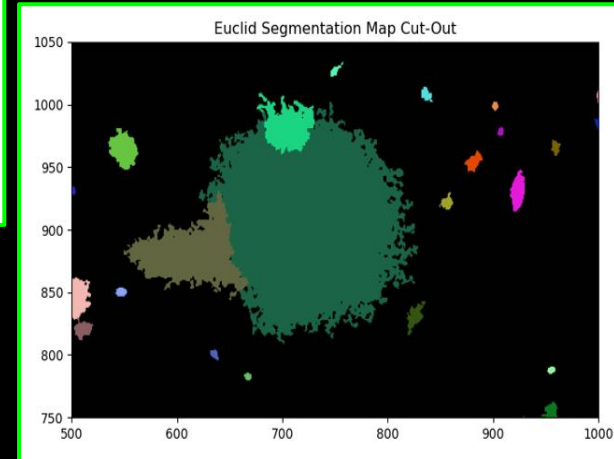
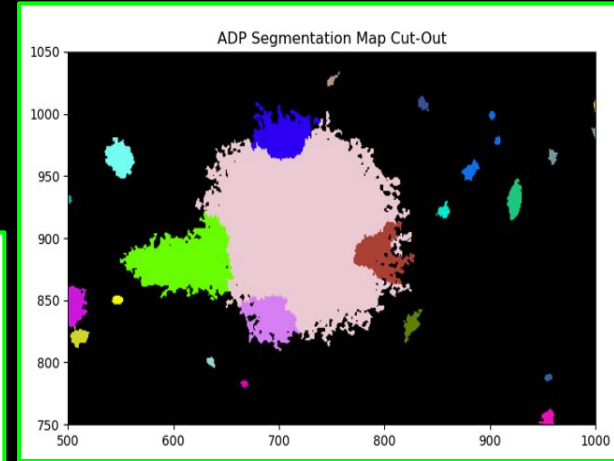
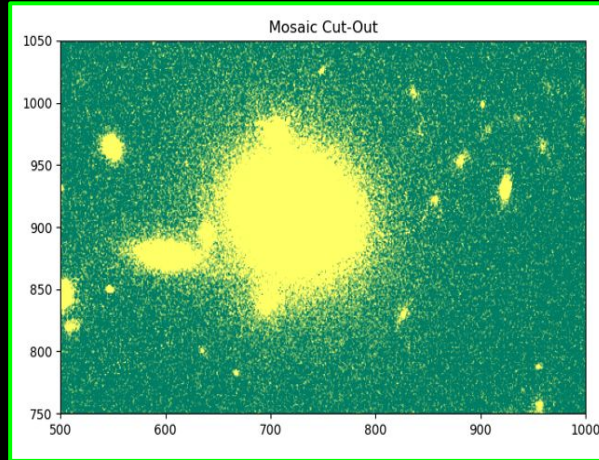
# New methodology for the Fragmentation: preliminary results



# New methodology for the Fragmentation: Deblending-like

Investigating the possible application of a density-based clustering algorithm called Advanced Density Peak Advanced Density Peak (ADP)

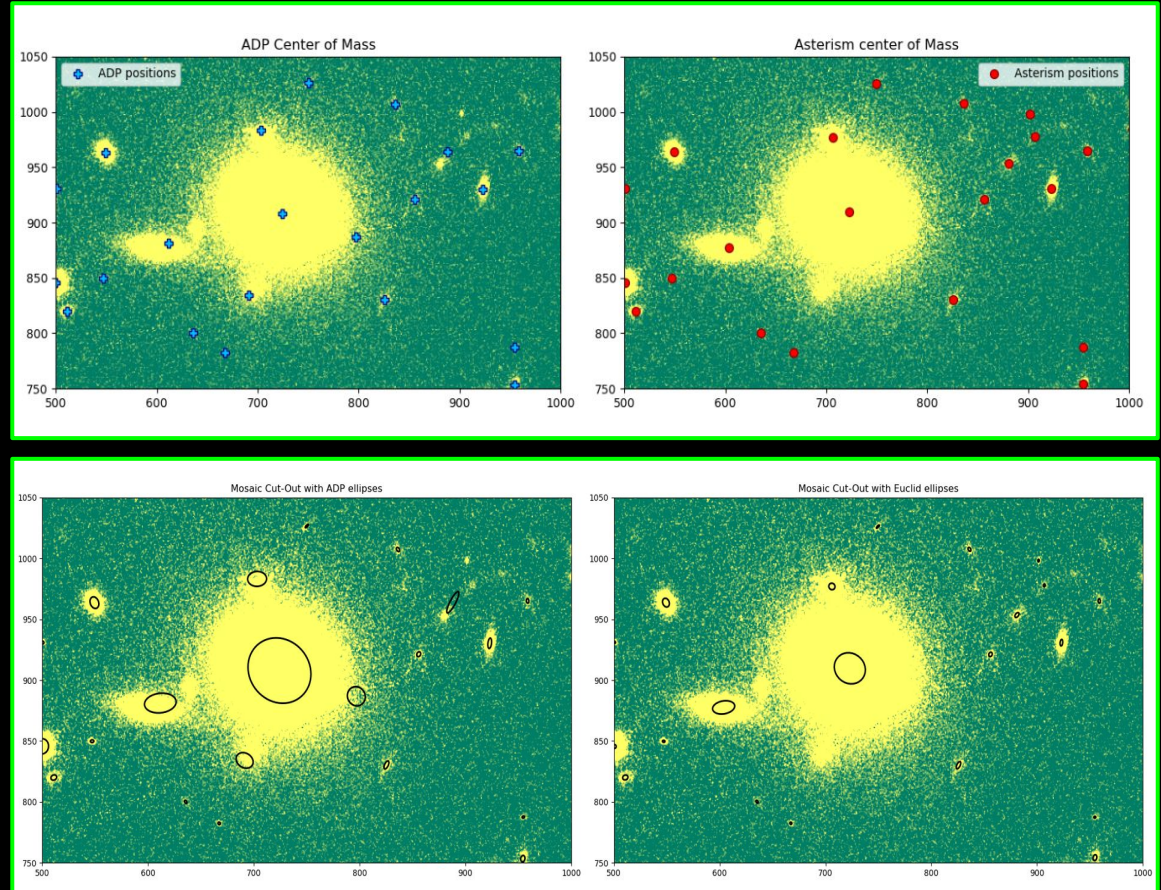
- Bypass the Eulerian space and apply the clustering algorithm directly to a regular 3D grid of points, using the collapse time for each particle provided by PINOCCHIO



## ADP: Deblending for *Euclid*

2D version of ADP already implemented and tested for source Deblending on a simulated image of True Universe (TU) against official *Euclid* algorithm

- Source positions
- Position Angle (PA)
- Ellipticity



# Conclusions and future developments

## Conclusions:

- **Agreement** within  $2\sigma$  at all considered redshift for **first order void statistics**
- **Offloading** tested successfully up to  $128^3$  particles in a box of  $256 \text{ Mpc}/h$  size
- Computational time **improvement**:  $\sim 9x$  speed-up with **OpenMP** parallelization
- **New fragmentation** with a density-based **clustering (ADP)** algorithm looks **promising**
- **Deblending** with a density-based **clustering (ADP)** algorithm **successful**

## Future developments:

- **Extension** to a **3D** grid-based version of **ADP** is ongoing
- **Extension** of **GPU** of **collapse times** calculation to **larger grid/resolution** is ongoing
- **Extension** to  $f(R)$  modified gravity for **void statistics** is planned
- **Testing** of **Deblending** on **newly simulated images** and application to **real data** is planned

**Backup slides**

# Collapse time in PINOCCHIO: approximation

The calculation of the collapse time is straightforward once the eigenvalues of the second derivatives of the potential are given

- Calculation of invariants of the 3x3 tensor of second derivatives of the gravitational potential
- Diagonalization of the tensor if needed

$$J(q, b_c) = 0$$

$$1 - \lambda_i b_c - \frac{3}{14} \lambda_i (\delta_l - \lambda_i) b_c^2 - \left( \frac{\mu_3}{126} + \frac{5}{84} \lambda_i \delta_l (\delta_l - \lambda_i) \right) b_c^3 = 0$$

First order solution:

$$b_c^{(1)} = 1/\lambda_1$$

Second order solution:

$$b_c^{(2)} = \frac{7\lambda_1 - \sqrt{7\lambda_1(\lambda_1 + 6\delta_l)}}{3\lambda_1(\lambda_1 - \delta_l)}$$

Third order solution:

$$1 - \lambda_1 b_c^{(3)} - \frac{3}{14} \lambda_1 (\delta_l - \lambda_1) (b_c^{(3)})^2 - \left( \frac{\mu_3}{126} + \frac{5}{84} \lambda_1 \delta_l (\delta_l - \lambda_1) \right) (b_c^{(3)})^3 = 0$$

# Collapse time in PINOCCHIO: exact solution

Dynamics of ellipsoidal collapse is completely described by the evolution of the three main axes of the ellipsoid (*Bond & Mayers 1996*)

- Computational **expensive** prescription
- **PINOCCHIO**: ellipsoid evolution following *Nadkarni-Ghosh & Singhal 2016*

$$\begin{aligned}\frac{d\lambda_{a,i}}{d\ln a} &= -\lambda_{v,i}(1-\lambda_{a,i}) \\ \frac{d\ln\lambda_{v,i}}{d\ln a} &= -\frac{3}{2}\mu\Omega_m\lambda_{d,i}-\lambda_{v,i}\left(2+\frac{\dot{H}}{H^2}\right)-\lambda_{v,i}^2 \\ \frac{d\lambda_{d,i}}{d\ln a} &= -(1+\delta)\left(\delta+\frac{5}{2}\right)^{-1}\left(\lambda_{d,i}+\frac{5}{6}\right)\sum_{j=1}^3\lambda_{v,j}+ \\ &\quad \left(\lambda_{d,i}+\frac{5}{6}\right)\sum_{j=1}^3(1+\lambda_{v,j})-(\delta+\frac{5}{2})(1+\lambda_{v,i}) \\ &\quad +\sum_{j\neq i}\frac{[\lambda_{d,j}-\lambda_{d,i}][\lambda_{a,i}^2(1+\lambda_{v,i})-\lambda_{a,j}^2(1+\lambda_{v,j})]}{(1-\lambda_{a,i})^2-(1-\lambda_{a,j})^2}\end{aligned}$$

Collapse time

$$\lambda_{a,i} \rightarrow 1$$

# Fragmentation

**Collapsed particles** may become part of **dark matter halos** or of the **filament network** that connects them

- A **particle** that **collapses before** its **neighbours** becomes a **1-particle halo**
- A **collapsing particle** may **accrete** on a **halo** if it "touches" it in **Lagrangian space**
- **Halo mergers** are checked each time a **collapsing particle** "touches" two halos
- **Halos** and **particles** are moved with **2LPT**

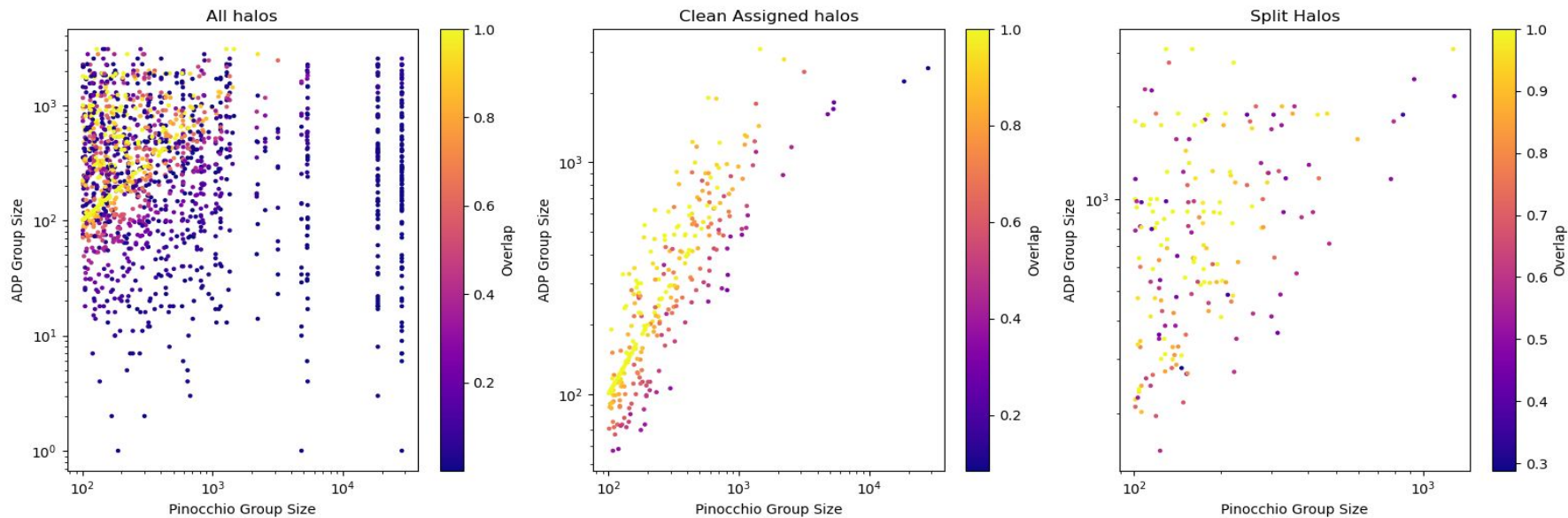
## Particle accretion

$$d_{\text{thr}}^2 = \begin{cases} (f_a R^e)^2 + (f_{200} R)^2, D'_1 \sigma \leq \sigma' \\ \left\{ f_a R^e [1 + f_{ra} (D'_1 \sigma - \sigma')] \right\}^2 + (f_{200} R)^2, D'_1 \sigma > \sigma' \end{cases}$$

## Halo merging

$$d_{\text{thr}}^2 = \begin{cases} (f_m R_{\text{lar}}^e)^2 + (f_{200} R_{\text{lar}})^2, D'_1 \sigma \leq \sigma' \\ \left\{ f_m R_{\text{lar}}^e [1 + f_{rm} (D'_1 \sigma - \sigma')] \right\}^2 + (f_{200} R_{\text{lar}})^2, D'_1 \sigma > \sigma' \end{cases}$$

# New methodology for the Fragmentation: preliminary results



## ADP: Deblending for *Euclid*

