Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Improve Cosmological Constraints with eFAM

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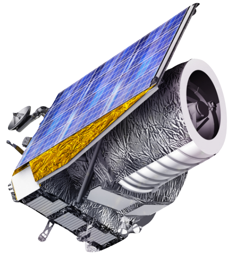
Spoke 3 Technical Workshop, Trieste October 9 / 11, 2023

Big questions in cosmology

- What are the components of our Universe? What is their nature and abundance? (e.g. Dark matter, Dark energy)
- What are the laws of physics describing the Universe evolution? Is General Relativity correct?

A new generation of Data



- **The Euclid Space Mission** (ongoing, ESA, spoke-3 engagement): full-sky galaxy distribution and lensing across 10 billion years
- **The DESI survey** (ongoing) full-sky galaxy distribution, peculiar velocities
- **The Einstein telescope, Lisa** (2030s): Gravitational waves

Our call

High-precision data-analysis

- **Non-linear modelling of cosmological observables**
  - galaxy clustering signal
  - galaxy peculiar motion

Project overview

Technical objectives

1. Deliver a ready-to-use package for the non-linear modelling of the galaxy clustering signal
2. Model the cosmology dependent density-velocity relation
3. Analyse the Euclid clustering signal: improve cosmological constraints (official BAO reconstruction pipeline)

Methodology

eFAM back-in-time reconstruction

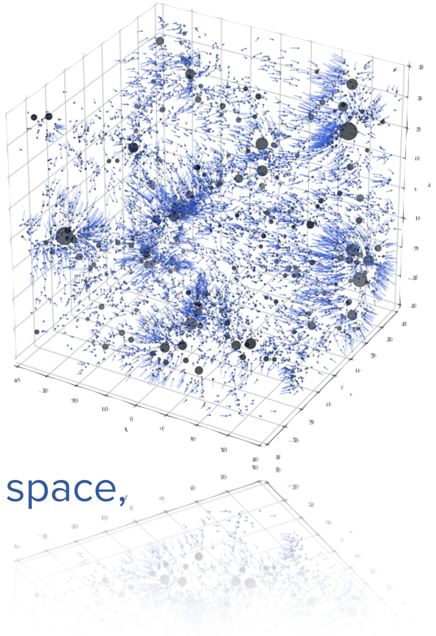
- Multidimensional Optimisation algorithm
- Inputs: observed galaxy positions
- Output: galaxy past positions and velocities as a function of time
- **Novelty:** Introduce non-linear aspects to enhance reconstruction accuracy, versatility (not fine tuned to a specific probe)

State-of-the art & critical points

eFAM in a nutshel

- IDEA: Derives the non-linear trajectories of galaxies by minimising the action of the system

$$S = \int_{t_{\rm int}}^{t_{\rm obs}} dt \sum_{i=1}^{N} \left[\mathrm{Pot}_i(\mathbf{x}, \mathbf{v}) + \mathrm{Kin}_i(\mathbf{x_i}, \mathbf{v_i}) \right]$$



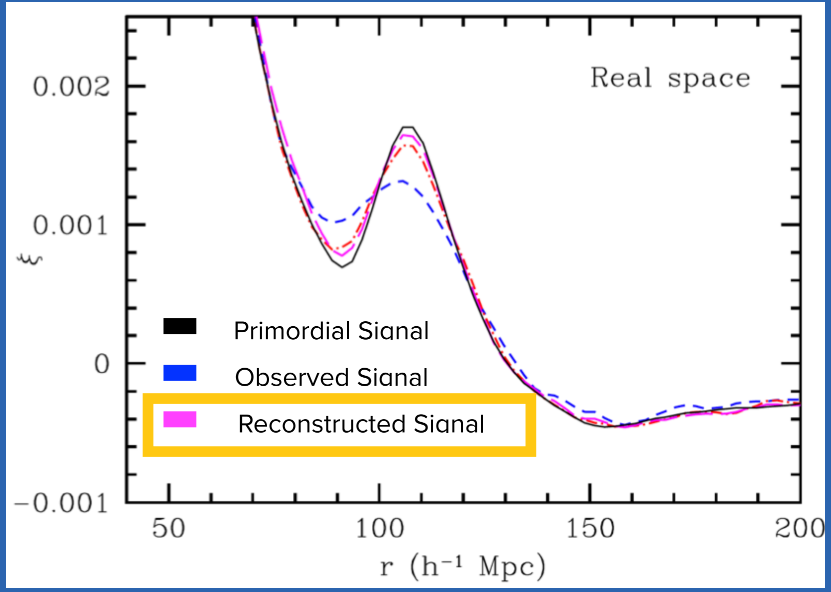
- Parametrises galaxy orbits

$$\mathbf{x}_i(t) = \mathbf{x}_{i,0} + \sum_{n}^{M} \mathbf{C}_{i,n} q_n(t)$$

- Surveys the multidimensional parameter space, $M \times N_{\rm part} \times 3 = \mathcal{O}(10 \times 10^7 \times 3)$, in search of the minima of the action
- **Result:** $\{\mathbf{x}_i(t), \mathbf{v}_i(t)\}_i$ **-> back-in-time galaxy catalogues (with more linear clustering signal)**

Main Application: BAO reconstruction

- Displace galaxies backwards-in-time
- Model velocity distortion
- Obtain a more linear clustering signal
- Improve the extraction of cosmological information

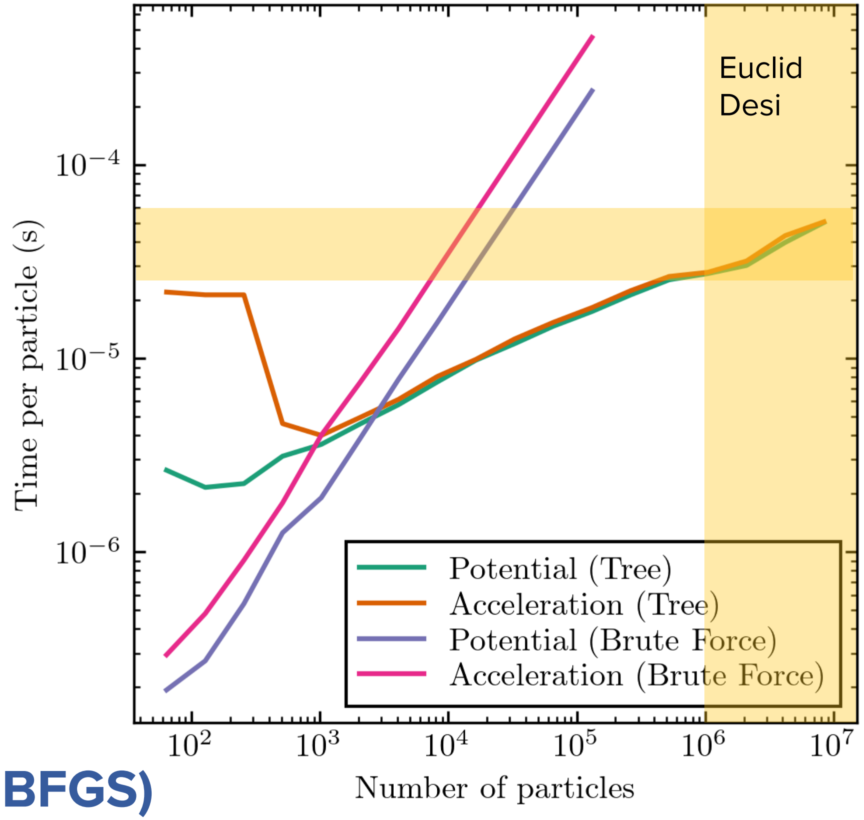


Credits: Eisenstein et al 2017b

State-of-the art & critical points

Critical point

- **Computational time:**
  - Gravitational potential calculation, Treecode (pytreegrav*), CPU time $\propto Nlog(N)$,
  - one Action evaluation: 3' on 40cores
- **Local Solution:**
  - Local optimisation algorithm: Conjugate gradient method **(L-BFGS)**
- **Cosmology dependence:**
  - Retrieved trajectories depend on assumed background cosmology



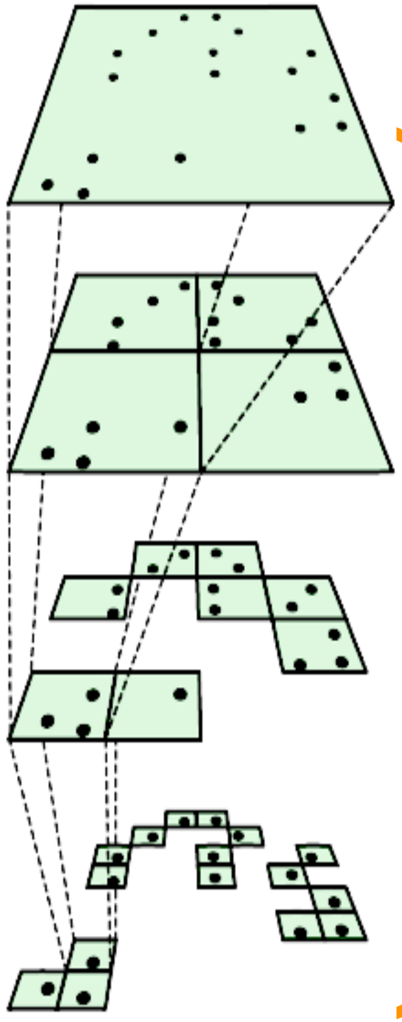
Credits: https://github.com/mikegrudic/pytreegrav

- https://github.com/mikegrudic/pytreegrav)

State-of-the art & critical points

Solutions

- **Computational time:**
  Implementation of a Machine Learning based Poisson Solver
  - Expected time-scaling: 50cpu h per training + 1ms model evaluation
  - Perfect for mock analysis
  - **Beneficial for cosmological simulations (WP2/WP3)**
- **Cosmology dependence:**
  - Enabling iterative reconstruction, loop on cosmological parameters



White & Springel 1999

Roadmap

	Time-scale	Milestones	KPIs
Aug-Sept 2023 **Completed**	**Development of eFAM 2.0:** - Migration to python form C++ - Integration of new poisson solver - Parallelisation openMp	**Successful development and validation of eFAM 2.0: 15x speedup**	**Algorithm accuracy** eFAM velocities vs. "True" velocities in N-body simulations
Oct-Dec 2023 **Euclid Phase**	**Application to Euclid mock data:** - Apply eFAM to Euclid mock galaxy catalogs (Cubic simulation) - Measure the reconstructed clustering signal - Extract cosmological information from the reconstructed signal	**Completion of Euclid DR1 forecast**	**Algorithm efficiency:** compare eFAM cosmological constraints with standard analysis
Jan 2023-Feb 2024	**Preparation of Euclid BAO reconstruction paper**	**Paper ready for submission**	**Paper accepted for publication**
Feb-Apr 2024	**Development of eFAM 3.0:** - Development of ML Poisson solver - Validation of new solver agains pytreegrav	**Successful development and validation of eFAM 3.0**	**Algorithm efficiency & accuracy** eFAM 3.0 vs eFAM 2.0 cpu time and accuracy challenge

Thank you !