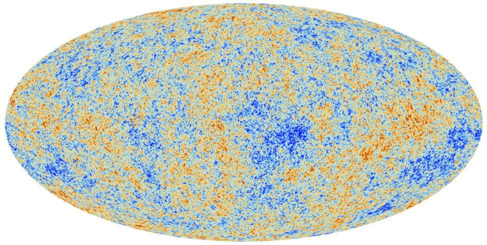
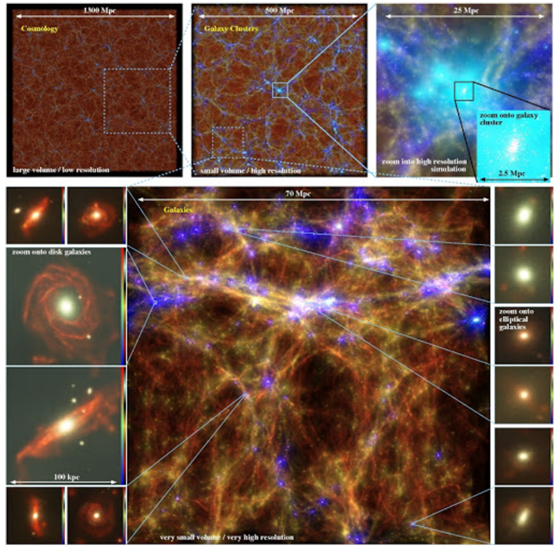
Stefano Borgani (INAF - UNITS - IFPU)
On behalf of **INCC**

Italian Network for Computational Cosmology

aka, Simulations of Cosmic Structure Formation in INAF

What is a Cosmological Simulation?





The problem:

- ➔ Solve the gravitational instability of a self-gravitating collisionless fluid from cosmological scales (~ Gpc) down to the scales relevant for galaxy formation (~100 pc scales), in an expanding background
  - ➔ Approximate methods: Lagrangian Perturbation Theory to speed up computations when dealing with ~ Gpc scales

- ➔ Follow the hydrodynamics of cosmic baryons and astrophysical processes taking place at **sub-pc** scale, but affecting **Mpc** scales (cooling, star formation, SMBH accretion, SN and AGN feedback, …..)
  - ➔ Shortcut: Semi-analytical models of galaxy formation **(see GAEA presentation)**

The solution: *resort to massively parallel codes for cosmological simulations, running on the most advanced HPC infrastructures*

Role of cosmo-simulations in large projects

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It is instrumental !!!!!

Simulation work has to be considered as a fundamental infrastructure activity!

(see presentations of Euclid, LSST, Athena, SKA, X-GALCLU, ZOOMING)

But rarely or never supported by agencies……

→ Generate mock observations (surveys or pointed observations)

- to define scientific case and requirements for telescopes/instruments
- for development/test/validation of analysis pipelines (E2E simulations)

→ Calibrate theoretical/observational systematics of cosmological tools:

E.g. definition of likelihood functions, halo mass function and bias, velocity bias, cluster mass measurements from WL/X-ray/SZ/dynamics, IGM thermal history for Ly-alpha cosmology, RSD & BAO modeling, cosmic shear, cosmic voids, CMB-XC, ….

→ Most important involvement in **Euclid** , with several coordination roles in SWGs, WPs, KPs, ISTs, SGS-OUs

→ In-kind contribution for **LSST**

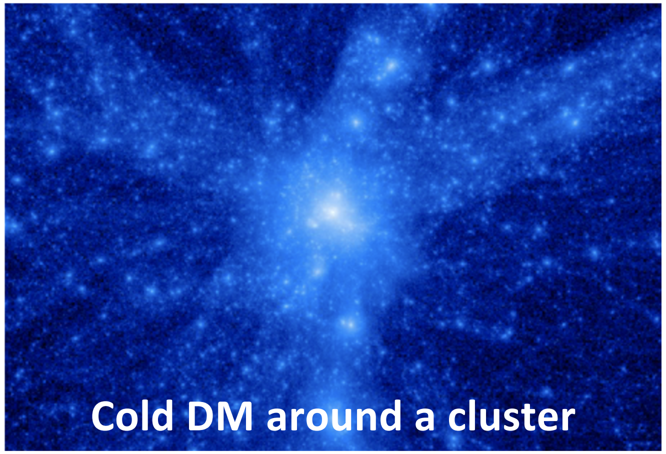
→ But also: **Athena, SKA, WEAVE@WHT, HIRES@E-ELT, ATLASt, eROSITA**

N-body simulations

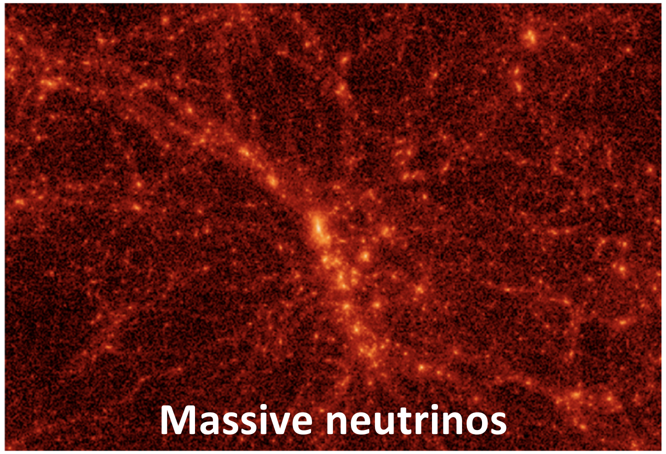
Non-linear gravitational instability of a collisionless self-gravitating fluid in an expanding background

- ➔ Structure of DM halos and statistics of their population
- ➔ Accurate prediction of cosmological observables in LCDM
- ➔ Measurement of cosmic (co-)variances for cosmological applications
- ➔ Effect of non-standard cosmologies:
  - Neutrino masses
  - DE beyond quintessence
  - Warm, Mixed, non-Thermal, Fuzzy, self-interacting, decaying, …. DM
  - Modified Gravity
  - Non-Gaussian perturbations

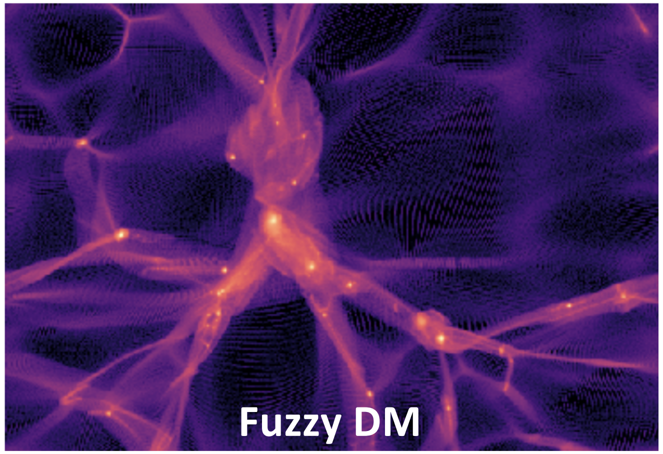
<u>Codes of choice</u>: Gadget-3, Gadget-4, OpenGadget (Tree-PM)



Cold DM around a cluster



Massive neutrinos



Fuzzy DM

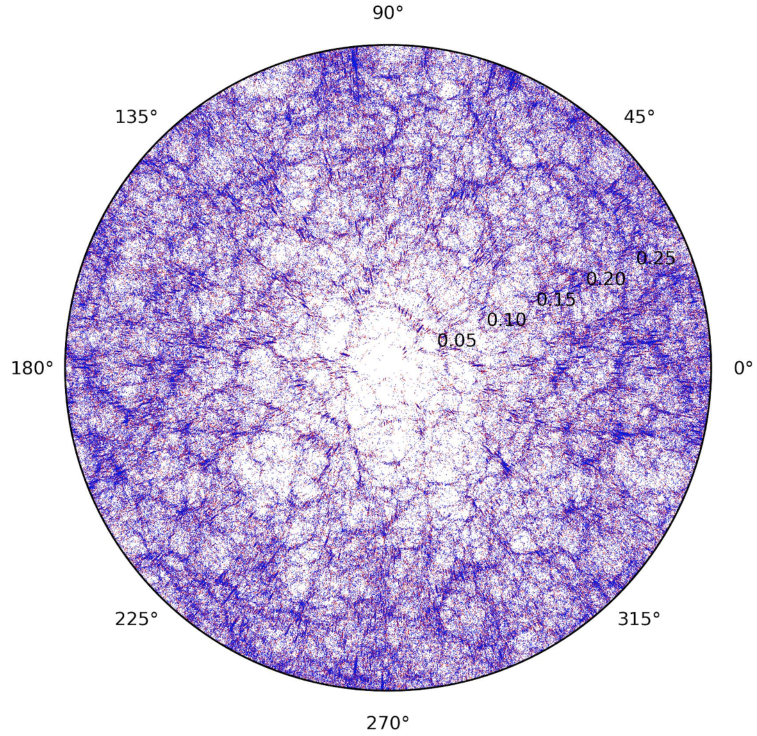
Approximate simulation methods

Fast and flexible generation of large ensembles of large-scale distribution of collapsed halos

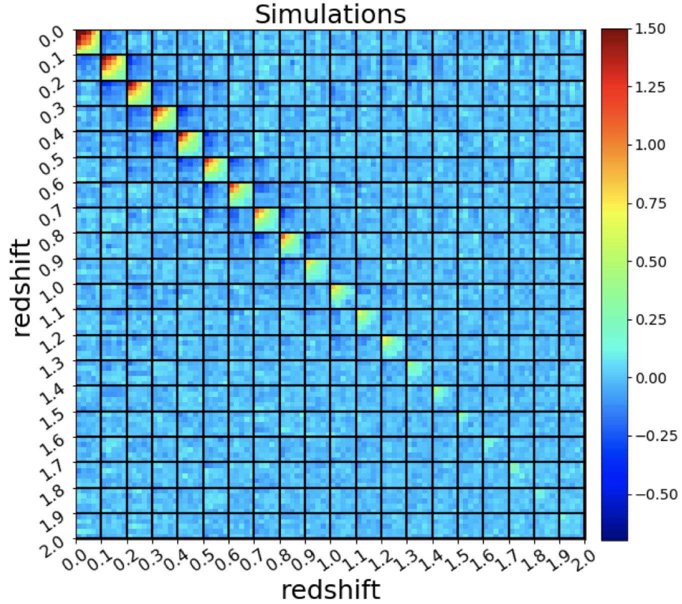
- ➔ Generate large ensembles of past-light cones for mock surveys
  - Precise measurement of covariances
  - Exploration of parameter space of cosmological models
- ➔ Interface with HOD to paint galaxies for optical/near-IR and HI surveys
- ➔ Now included different non-minimal LCDM extensions

Code of choice: Pinocchio (LPT-based)

360 deg. survey slice



Covraance matrix of cluster counts

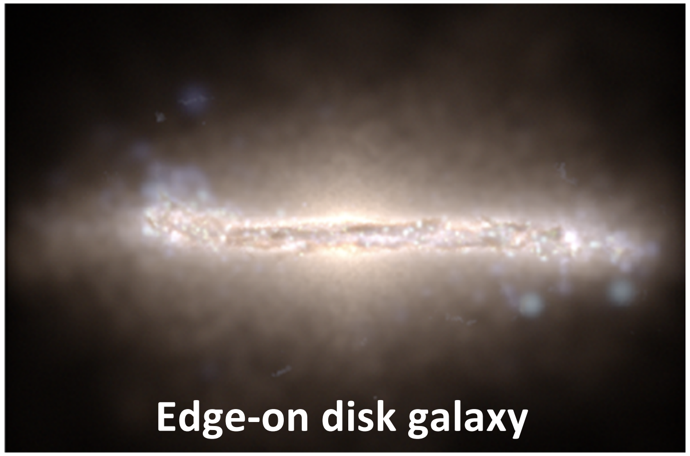


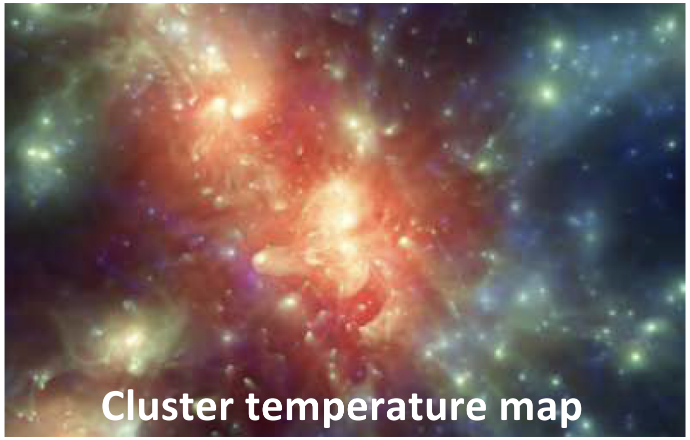
Hydrodynamical simulations

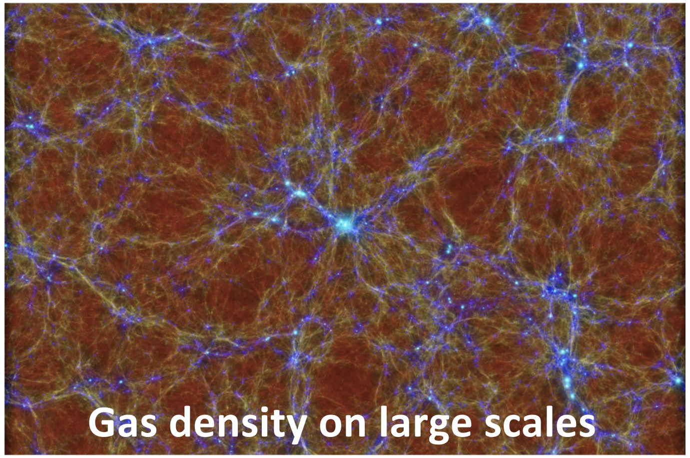
Evolution of cosmic baryons under the action of gravity and astrophysical processes driving galaxy formation from early epochs (z>10) to the nearby universe

- ➔ Predicting morphologies and morphological mix of galaxies
- ➔ Understand the eco-system of galaxies and IGM/CGM/ICM
- ➔ Role of different feedback sources (SN, AGN, etc)
- ➔ Production and circulation of cosmic metals
- ➔ Predictions of multi-lambda properties of galaxies, clusters, IGM/ICM/CGM
- ➔ Impact of baryons on cosmological observables
- ➔ Calibration of cosmological probes

<u>Codes of choice</u>: Gadget-3, OpenGadget (SPH), AREPO (Eulerian moving mesh)


Edge-on disk galaxy


Cluster temperature map


Gas density on large scales

Who are we?

Team Summary

15. Personale INAF coinvolto

Numero di partecipanti INAF al progetto: 16

Struttura	Nfte	N0	TI 21	TI 22	TI 23	TD 21	TD 22	TD 23	Nex	Extra
OAS BOLOGNA	2	1	0.6	0.6	0.6	0	0	0	1	0.1
O.A. TRIESTE	10	1	3.3	3.3	3.2	1.1	0.9	0.4	1	0.15
IASF MILANO	1	0	0.4	0.4	0.4	0	0	0	0	0
O.A. BRERA	1	0	0.3	0.3	0.3	0	0	0	0	0
Totali	14	2	**4.6**	**4.6**	**4.5**	**1.1**	**0.9**	**0.4**	2	**0.2**

16. Personale Associato INAF coinvolto

Numero di partecipanti Associati INAF: 13

#	Struttura	TI 2021	TI 2022	TI 2023	TD 2021	TD 2022	TD 2023
1	Università degli Studi di Trieste	0.5	0.5	0.5	0	0	0
2	OATs	0.8	0.8	0.8	2.1	2.1	0.3
3	OAS Bologna	0.1	0.1	0.1	0	0	0
4	UNITS	0.3	0.3	0.3	0	0	0
5	IASF Milano	0	0	0	0.7	0.7	0.0
6	OAS	0	0	0	0.0	0.1	0.1
7	UNIBO	0	0	0	0.4	0.4	0.4
	Totali	**1.7**	**1.7**	**1.7**	**3.2**	**3.3**	**0.8**

Who are we?

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N-body simulations	Approximate Methods	Hydrodynamical Simulations	Code Development
Marco Baldi **Stefano Borgani** **Carmelita Carbone** **Elisabetta Carella** **Tiago Castro** Gabriella De Lucia Fabio Fontanot **Carlo Giocoli** Ben Granett **Valerio Marra** Lauro Moscardini **Matteo Viel**	**Stefano Borgani** **Tiago Castro** **Alessandra Fumagalli** **Carlo Giocoli** **Pierluigi Monaco** Alex Saro	**Veronica Biffi** **Stefano Borgani** Max Gaspari **Carlo Giocoli** **Gianluigi Granato** **Umberto Maio** Federico Marinacci **Ilaria Marini** **Massimo Meneghetti** **Giuseppe Murante** **Antonio Ragagnin** **Cinthia Ragone** **Elena Rasia** Alex Saro **Luca Tornatore** **Matteo Viel**	**Marco Baldi** **Gianluigi Granato** **Umberto Maio** Federico Marinacci **Pierluigi Monaco** **Giuseppe Murante** **Eduardo Quintana** **Antonio Ragagnin** Giuliano Taffoni **Luca Tornatore**

<u>Trieste (OATs + UNITs + SISSA + IFPU)</u>: 14 staff + 2 postdocs + 3 PhD students
<u>Bologna (OAS + UNIBO)</u>: 5 staff + 2 postdocs
<u>Milano (IASF + OAMi + UNIMi)</u>: 2 staff + 1 PhD student

Funds & Resources

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<u>At present:</u> 1 ERC-StG (partially), 2 H2020-FET-HPC, 1 Levi-Montalcini, INFN-InDark

→ No post-doc supported by ASI, so far, for Euclid-related simulations

Access to computing infrastructures:

- CHIPP & INAF-CINECA MoU
- Local clusters @ OATs and @ UniBO
- ISCRA @ CINECA
- PRACE
- SUPERMUC @ LRZ-Garching
- INFN cluster and storage @ CNAF for Euclid activities
- Tianhe-2 @ Guangzhu
- Small local clusters/servers for postprocessing and code development
- CINECA and IA2 support for long-term storage

~ 10^7 core hours secured over the last 2-3 years through (highly successful) applications to competitive calls

Criticalities

→ Collaboration with CINECA:
- Provider of services or scientific partner for collaborative research projects?
- CINECA computer scientists working on astrophysical applications?

→ Flexible access to HPC facilities for code development and testing
- In-house (i.e. INAF) facilities

→ Medium and long-term storage:
- Crucial for a more efficient exploitation of simulations and dissemination
- Proximity to computing nodes
- Archival and VO-like data publication

Significant benefits from CHIPP and INAF-CINECA MoU that go beyond the allocation of computational resources

Competences to be (further) developed

→ Code development and HW/SW co-design for exa-scale applications (ExaNest, EuroEXA, EuPEX, …; **see EXACT presentation**)
Parallelization as of today: MPI/OpenMP/OpenACC

→ Machine-learning methods
- Run-time & post-processing analyses
- Exploration of parameter space of simulations

→ Visualization / data exploration and navigation
- Much more than fancy movies and images → **VisIVO**

→ Postprocessing tools for simulated mock observations, from radio (interferometry and single dish) to X-ray satellites

→ Quantum computing: a game changer or a risky path?
- Ongoing discussion with IBM Research Center in Zurich for the development of a Quantum Simulation Code
- Partner in a QuantERA proposal submitted for the development of applications in astrophysics