Thesis Day 2024

Presented by Giulia Despali (giulia.despali@unibo.it) on behalf of the

Cosmology and Structure Formation group

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Michele Moresco

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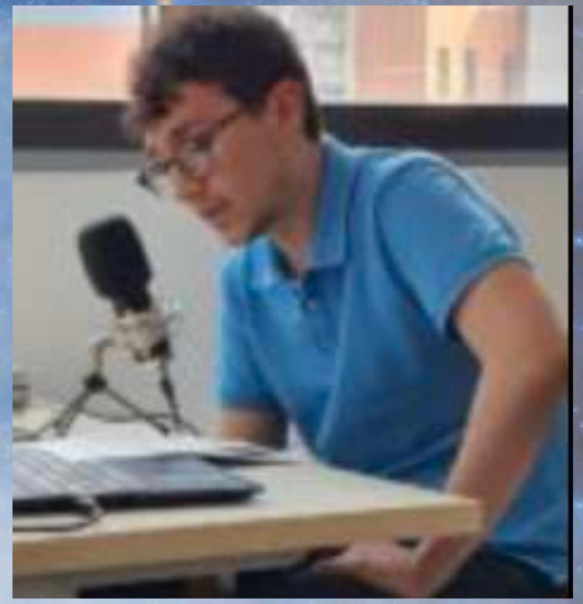


Massimiliano Romanello

To make a long story short…

13.8 billion years of evolution in a single drawing

10^{-32} seconds | 1 second | 100 seconds | 380 000 years | 300–500 million years | Billions of years | 13.8 billion years

Beginning of the Universe

Inflation
Accelerated expansion of the Universe

Formation of light and matter

Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures

Light and matter separate
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter

First stars
The first stars and galaxies form in the densest knots of the cosmic web

Galaxy evolution

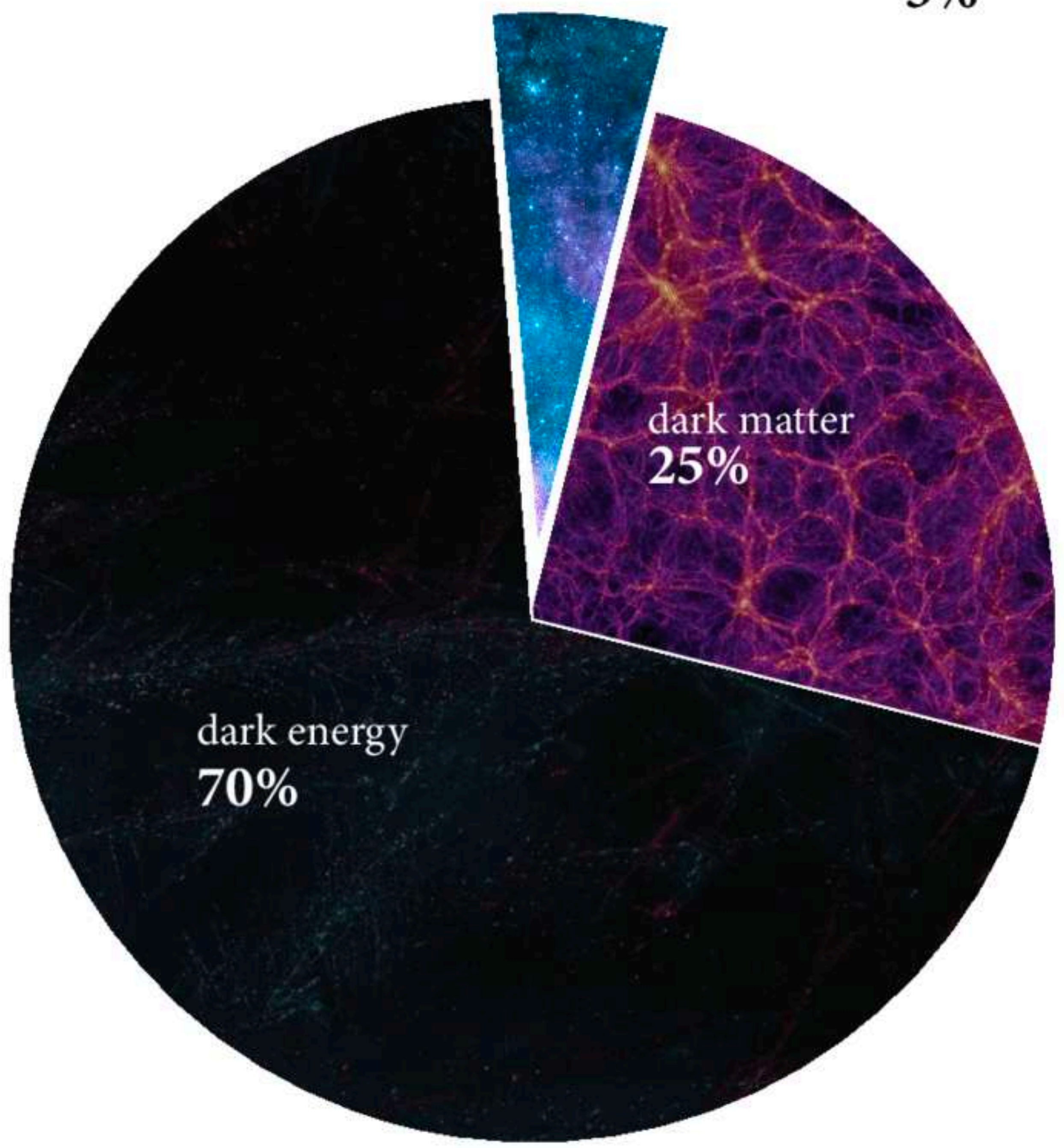
The present Universe

To make a long story short…

13.8 billion years of evolution in a single drawing

Beginning of the Universe

10^{-32} seconds	**Inflation**	Accelerated expansion of the Universe
1 second	**Formation of light and matter**	
100 seconds	**Light and matter are coupled**	Dark matter evolves independently: it starts clumping and forming a web of structures
380 000 years	**Light and matter separate**	• Protons and electrons form atoms • Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
	Dark ages	Atoms start feeling the gravity of the cosmic web of dark matter
300–500 million years	**First stars**	The first stars and galaxies form in the densest knots of the cosmic web
Billions of years	**Galaxy evolution**	
13.8 billion years	**The present Universe**	



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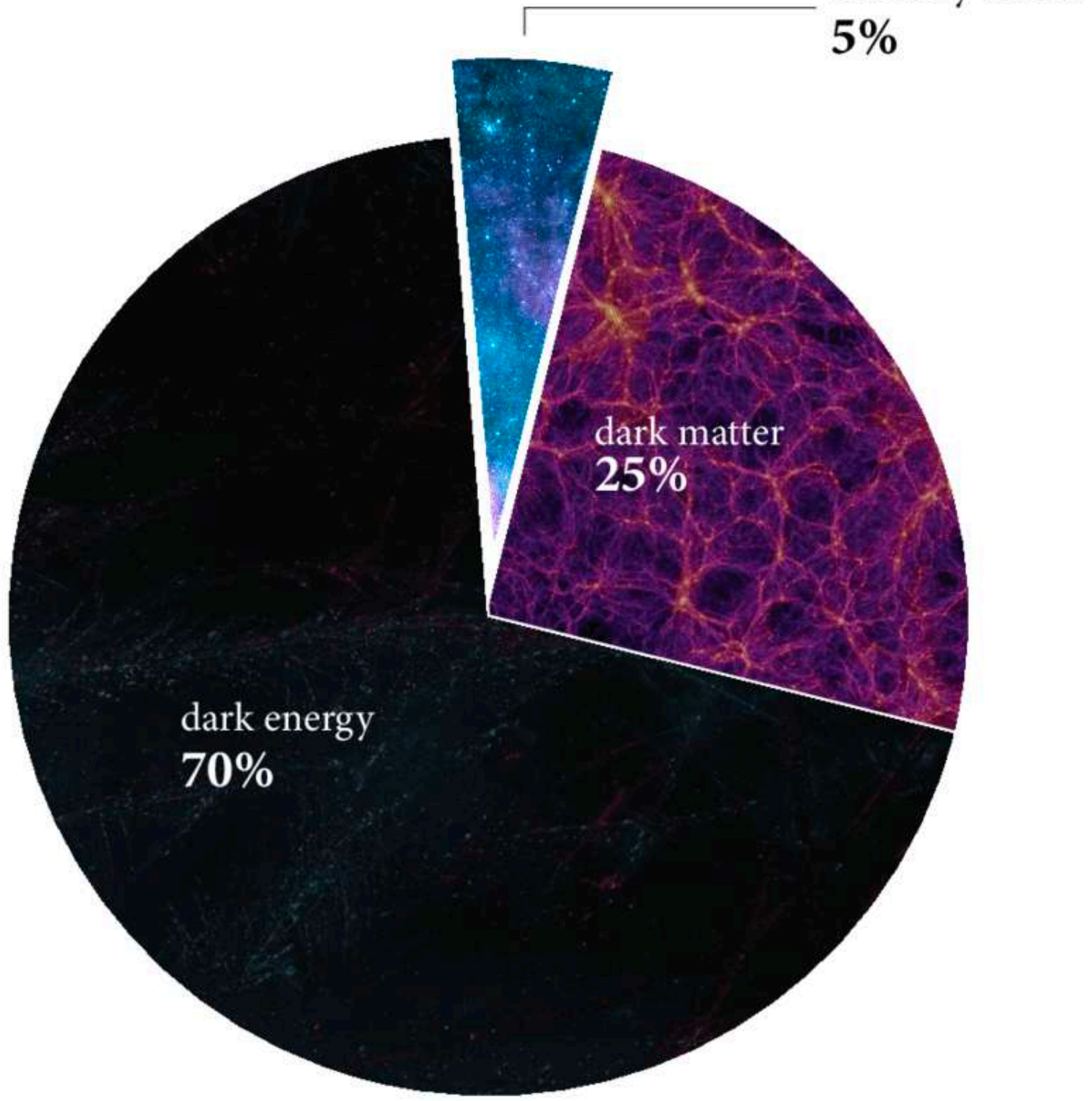

What is Dark Energy?

What is Dark Matter?

Did inflation really happen?

Is General Relativity complete?

How do galaxies form?

An example:

what is dark matter?


we observe clusters, galaxies and their satellites....
JWST


we observe clusters, galaxies and their satellites….
…but their properties depend on the underlying cosmology, dark matter and dark energy
JWST
numerical simulation

THEORY

- Fundamental physics
- Analytical Calculations
- Numerical Analysis
- Supercomputer Simulations

DATA

- Astrophysical observations
- Laboratory experiments
- New observational windows (as e.g. GW)
- Statistical Analysis
- Big Data compression
- Machine Learning

How can we answer the big questions?

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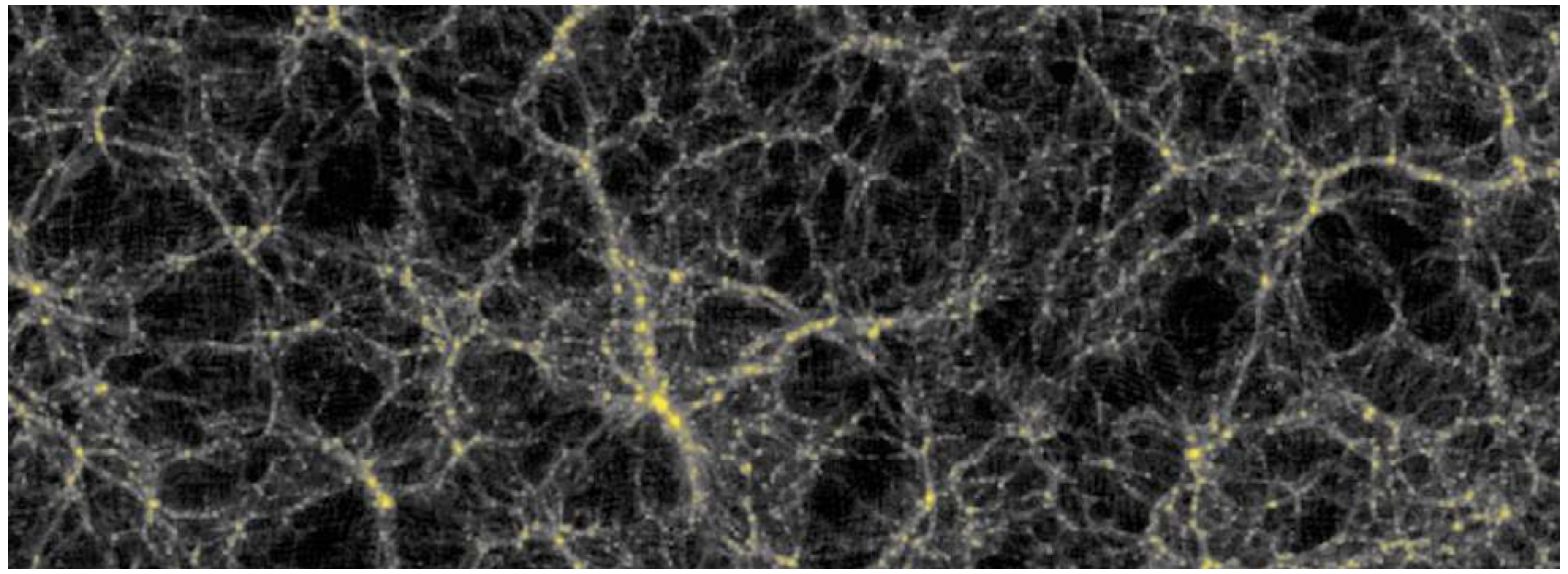
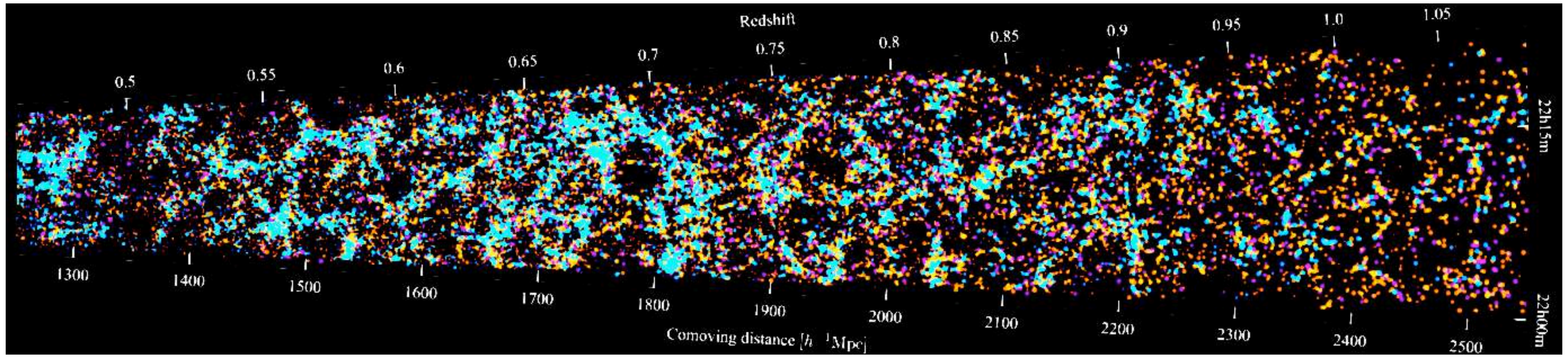
Cosmic web in a simulation



Observed distribution of galaxies



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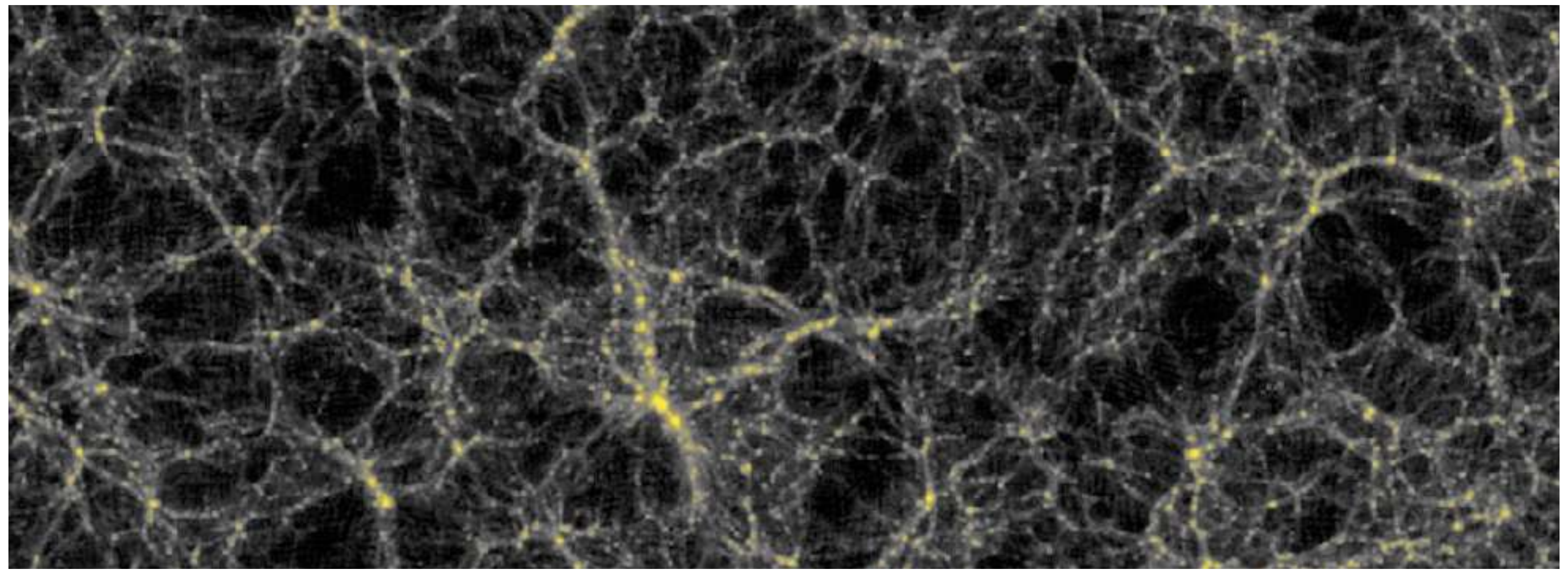

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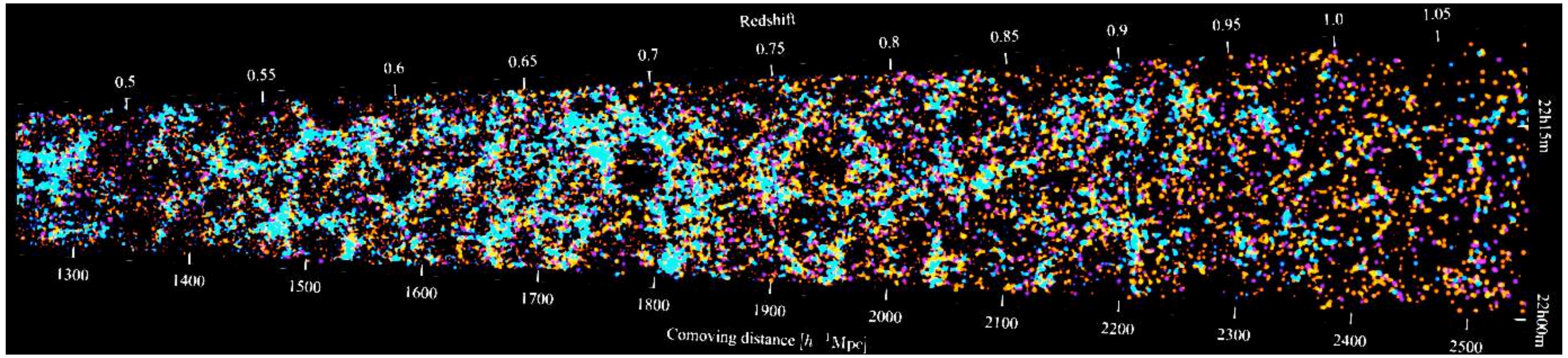
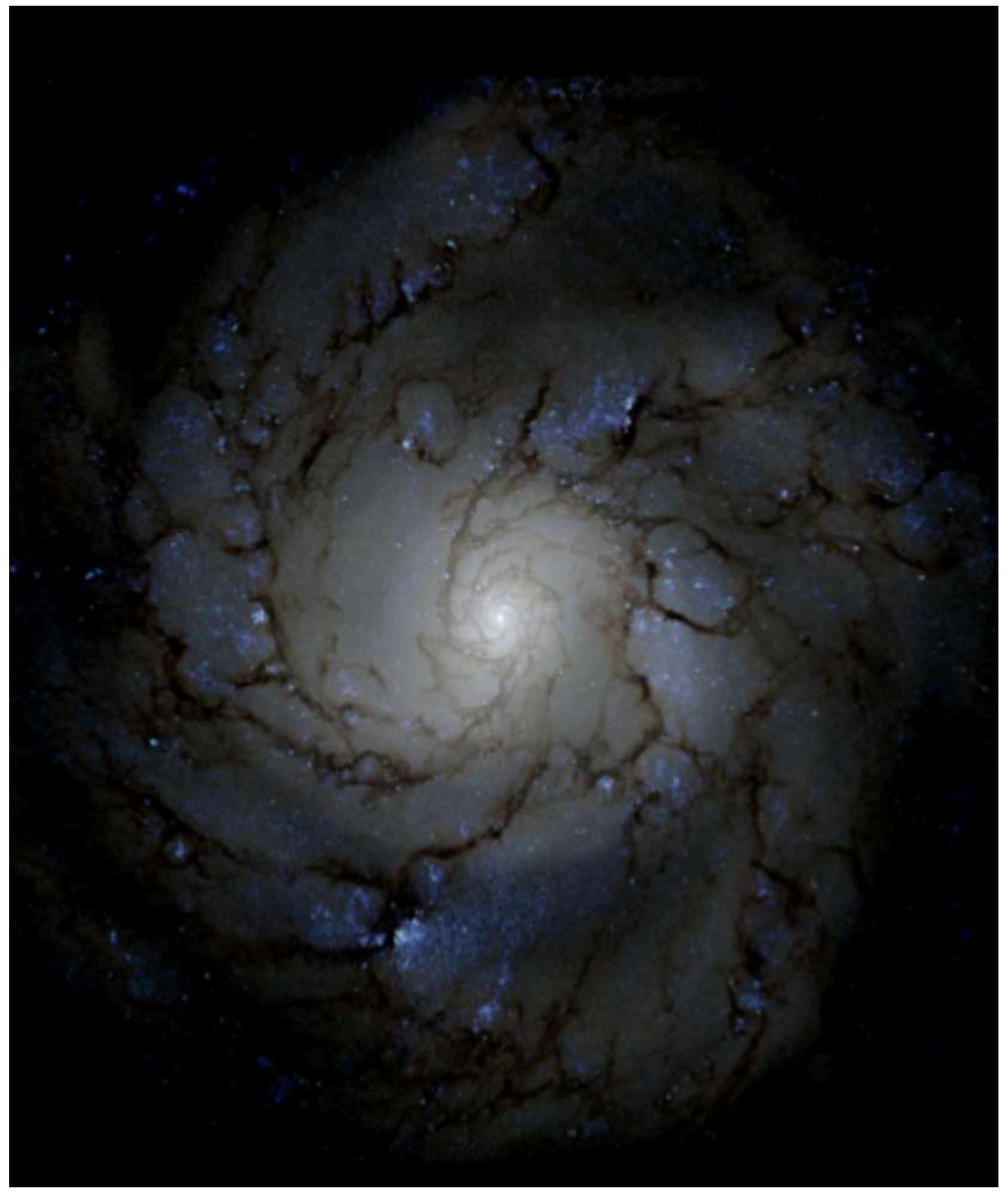


Simulation



Real image

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How can we answer the big questions?

the Euclid mission (ESA)
to explore the dark universe

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first images

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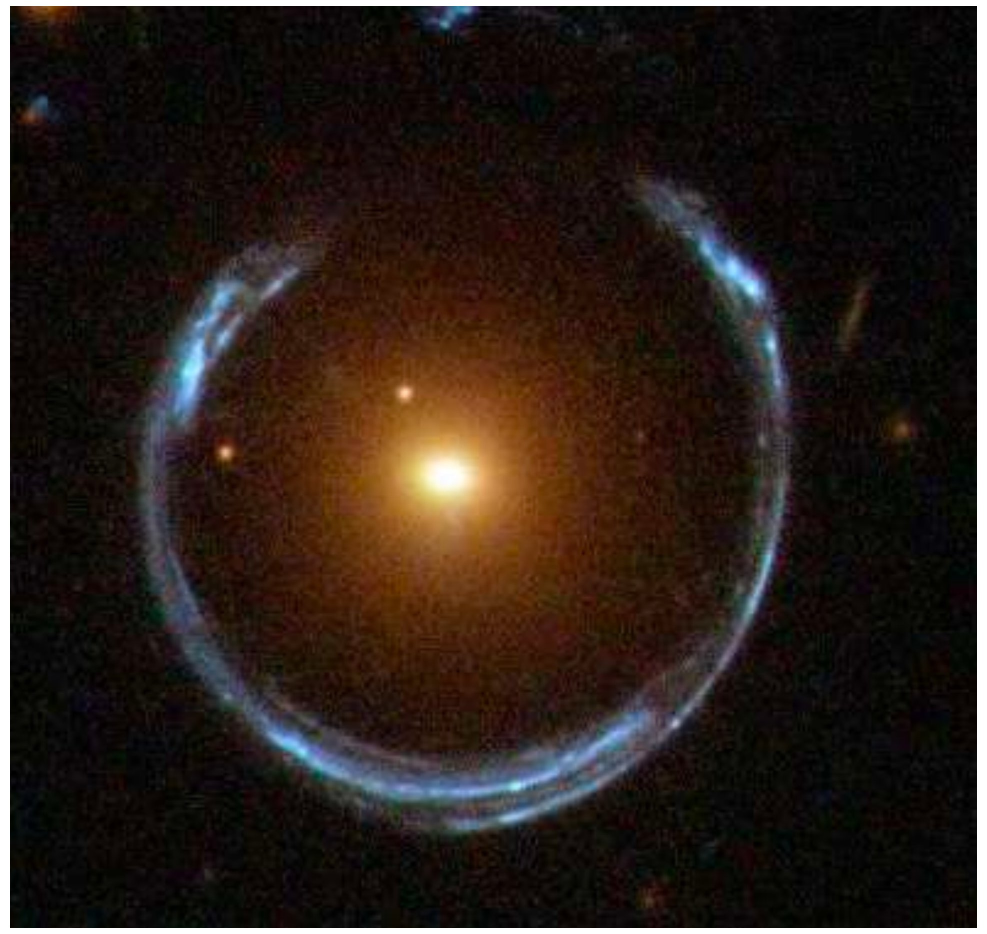
gravitational lenses



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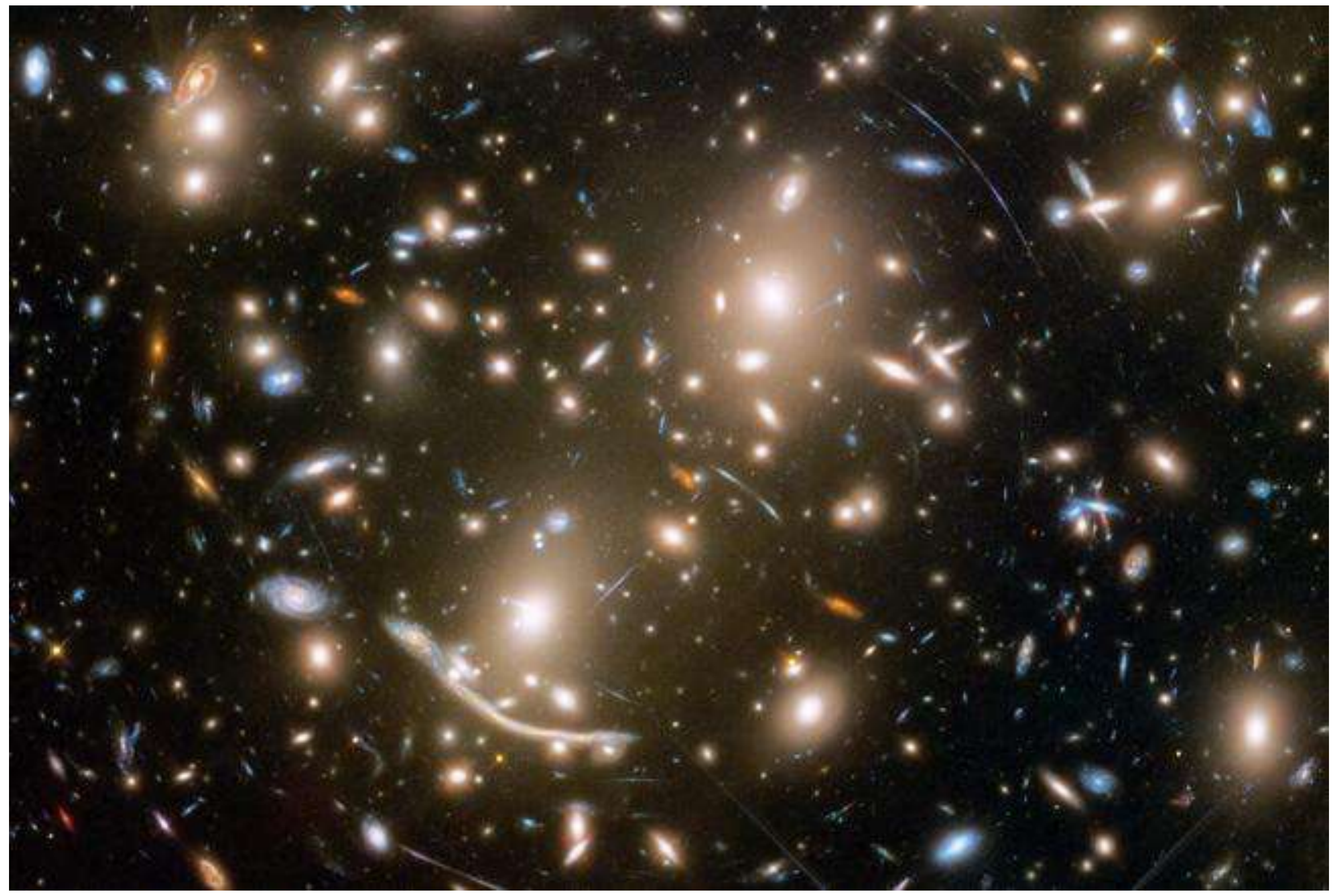
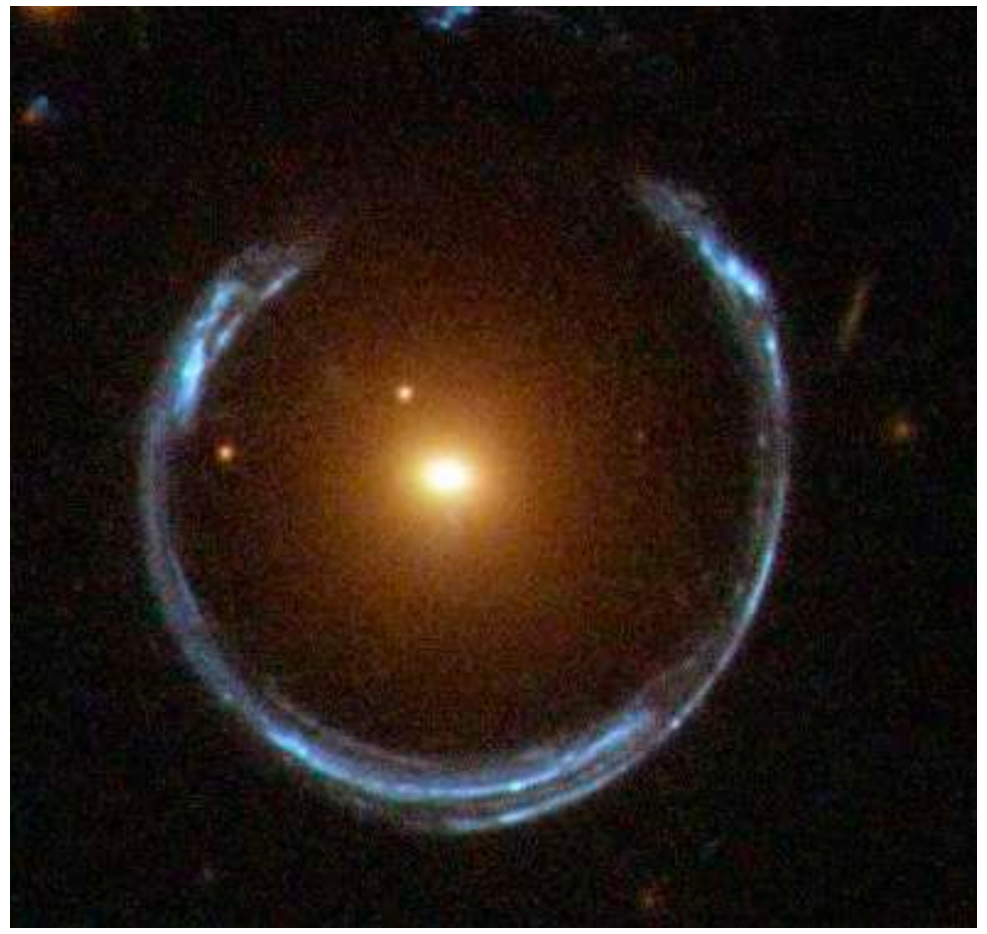
galaxies and clusters



gravitational lenses



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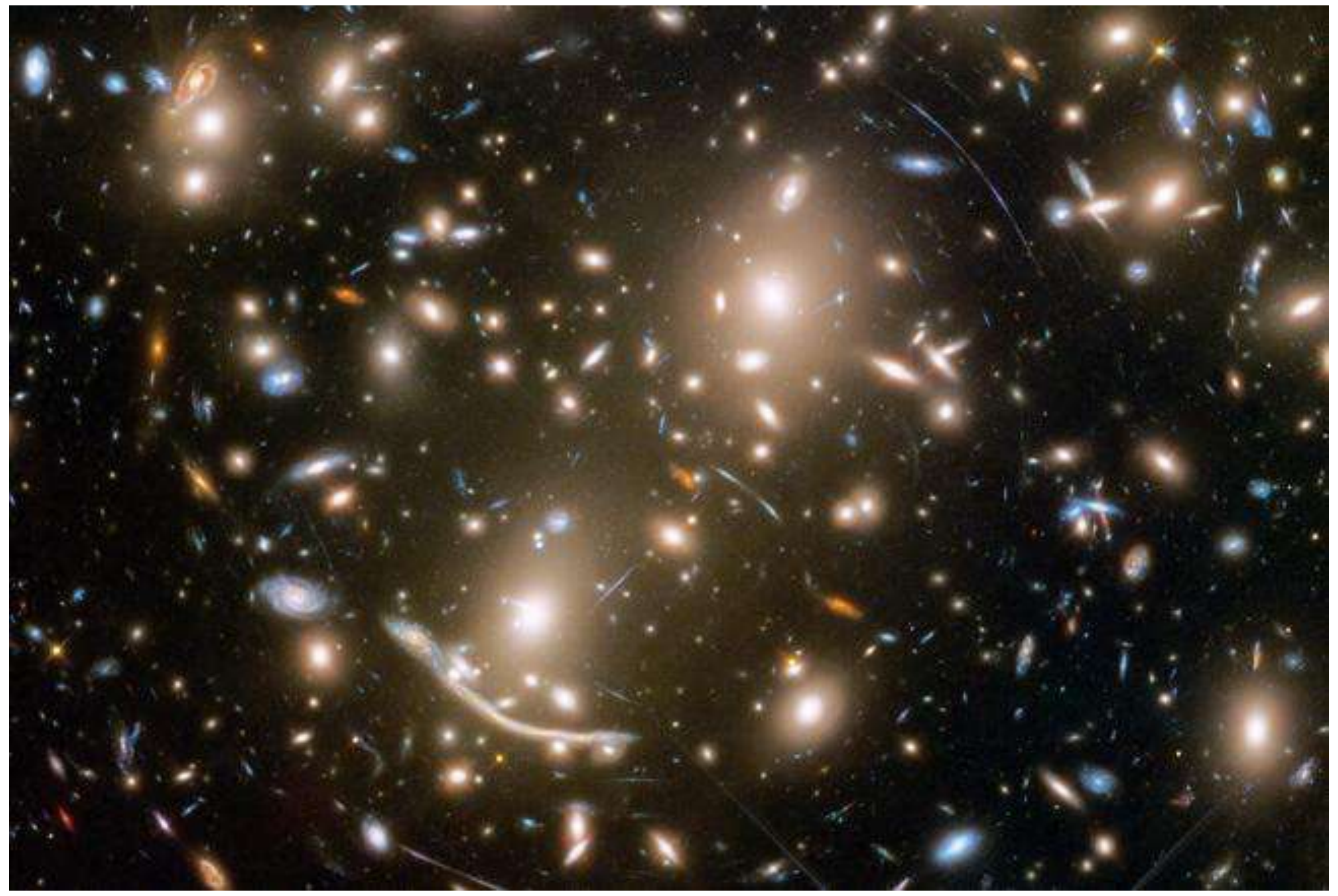

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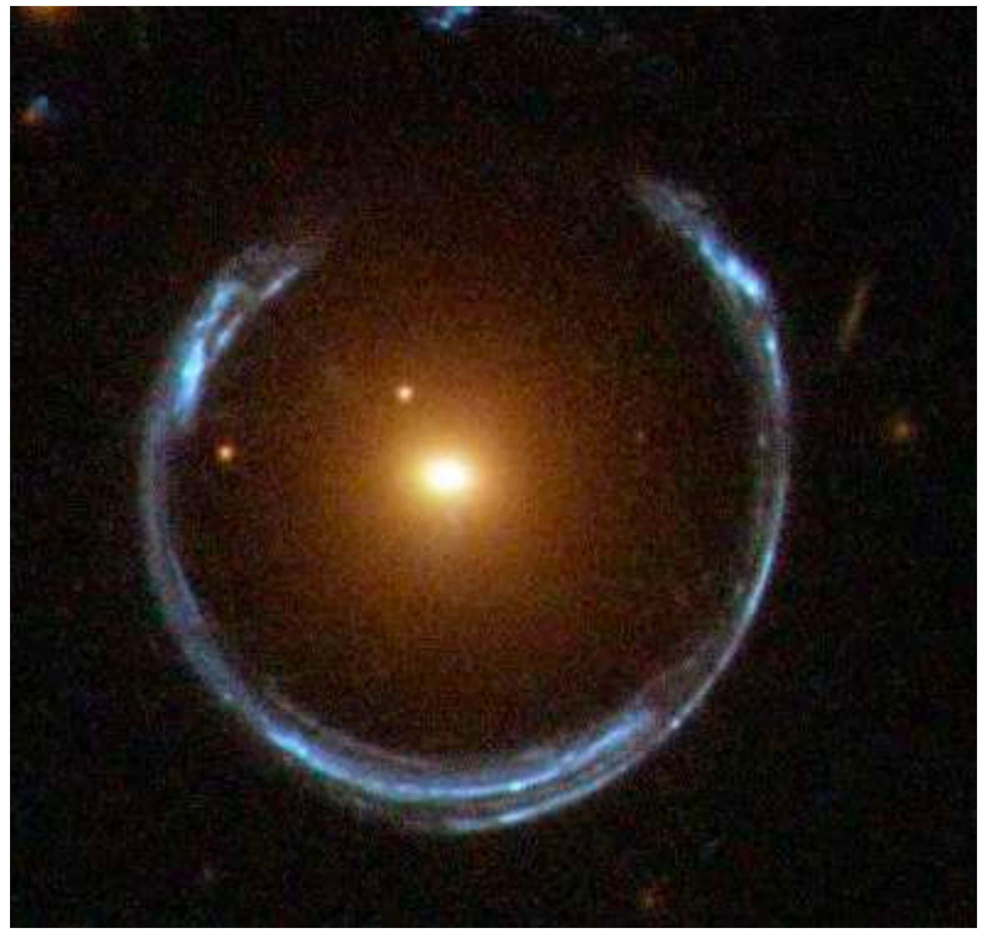
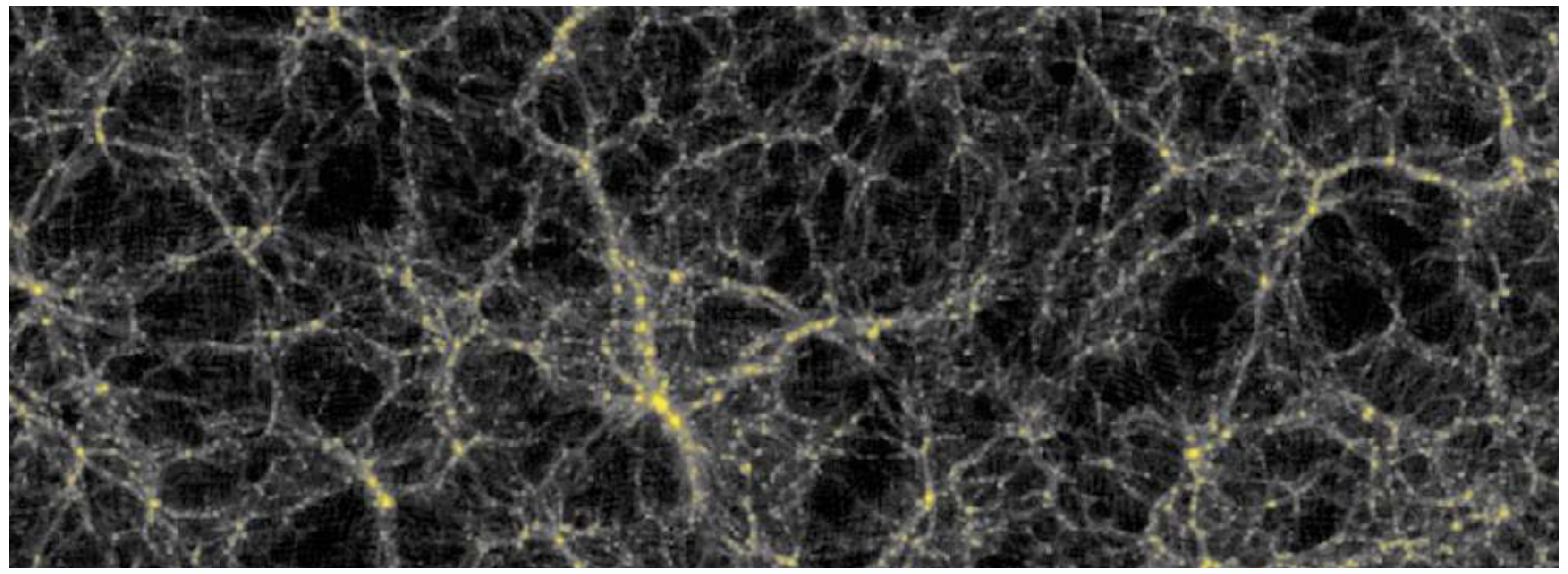


map large scale structures



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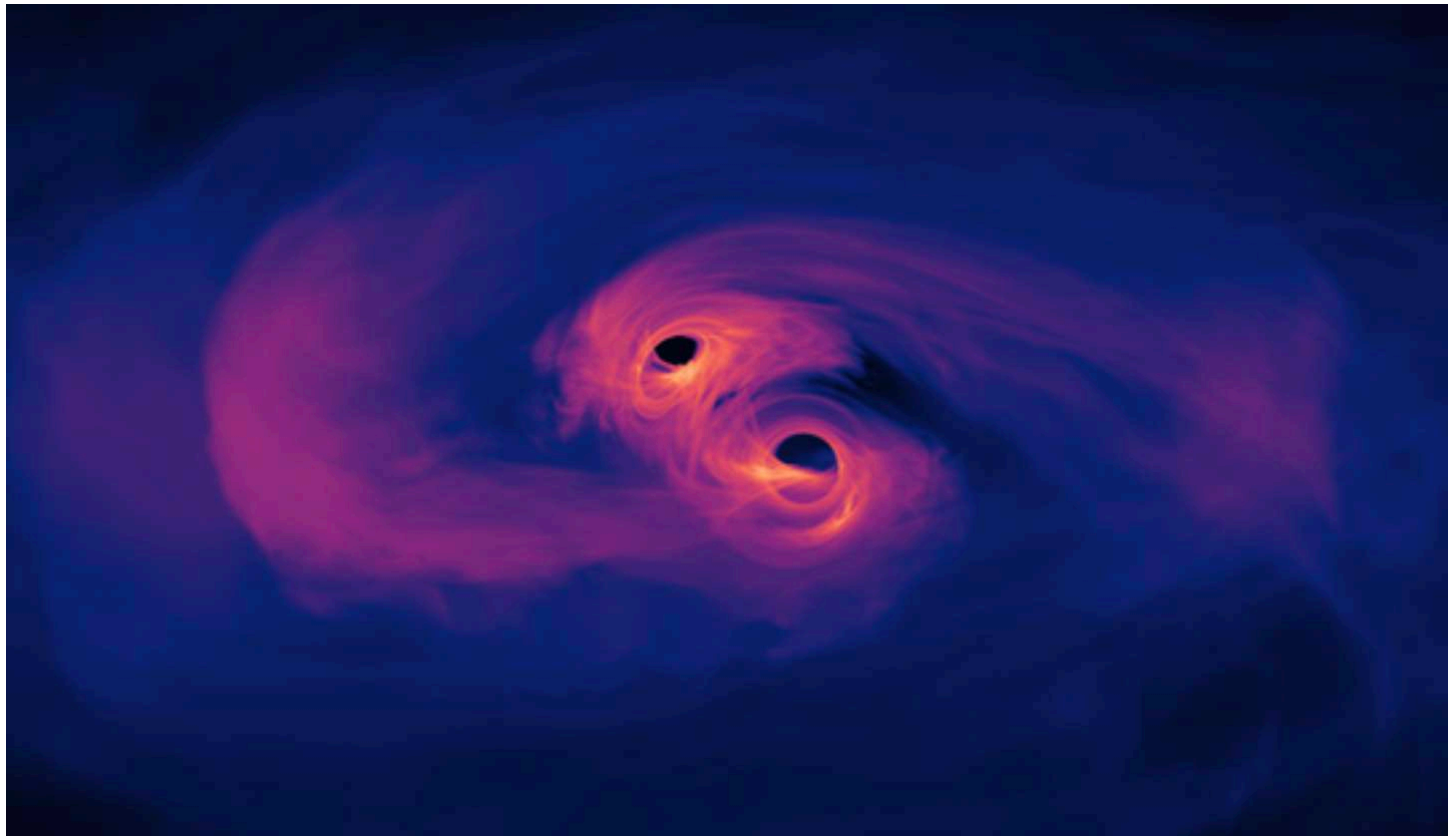
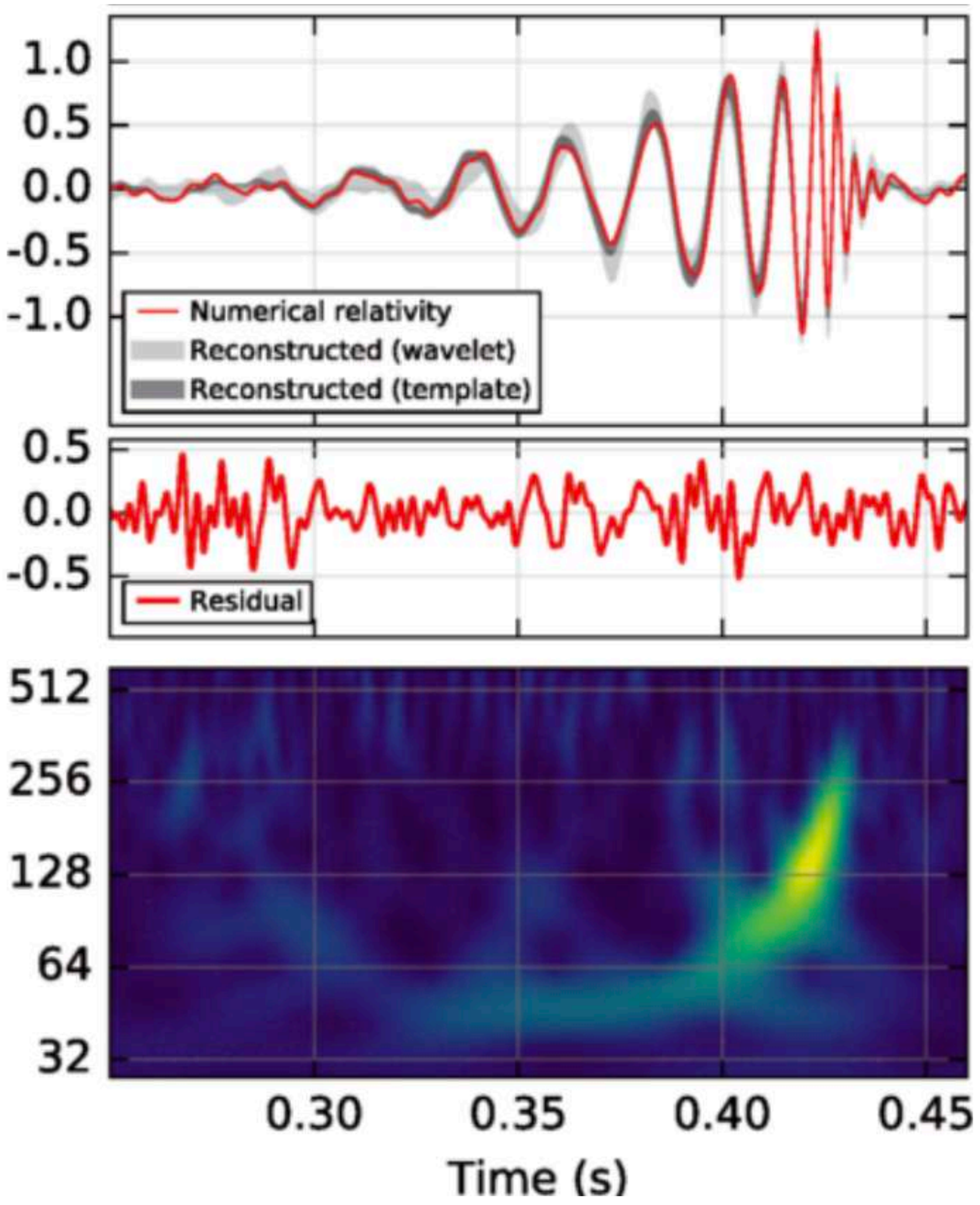
How can we answer the big questions?

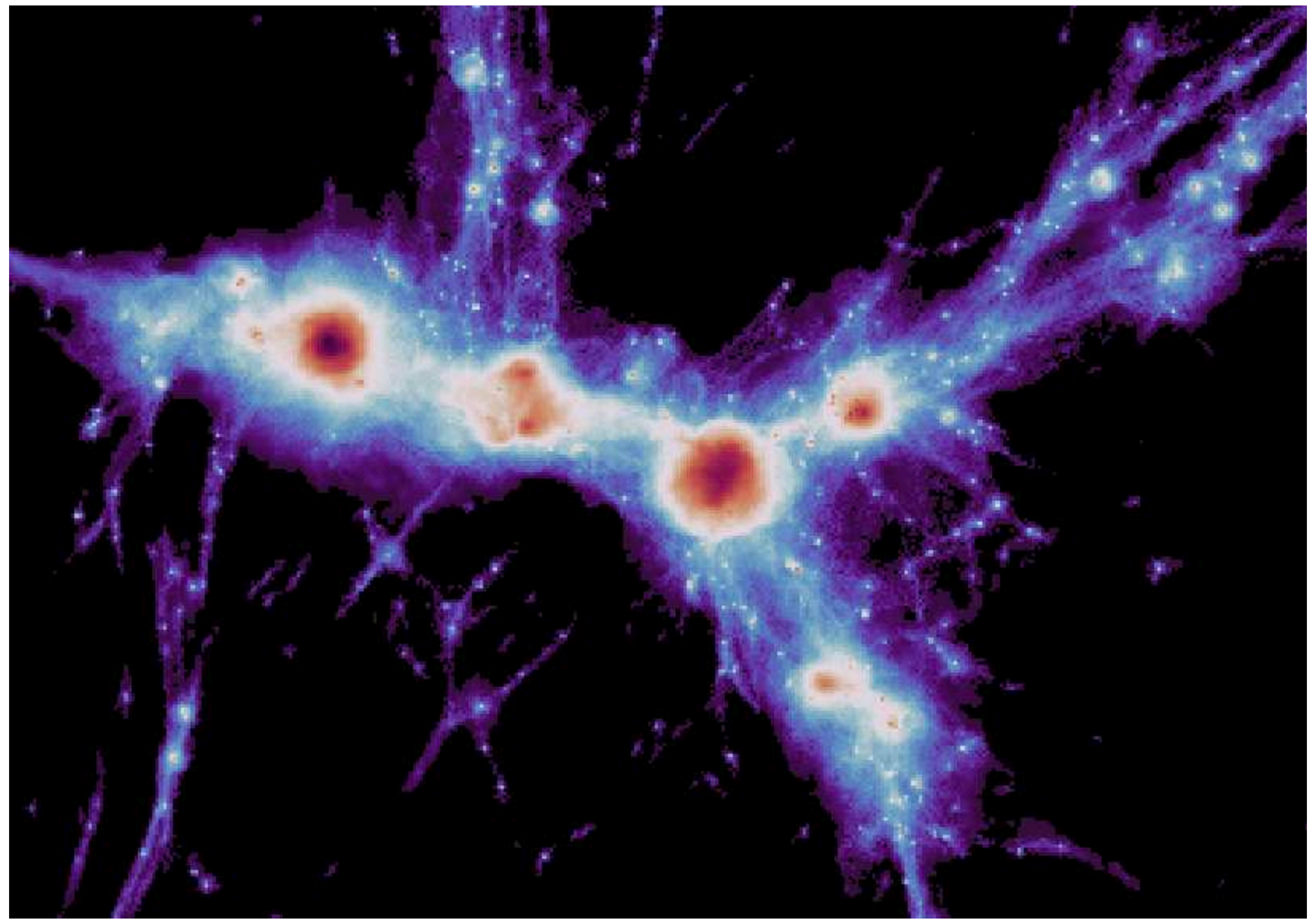
Gravitational waves - multimessenger astrophysics



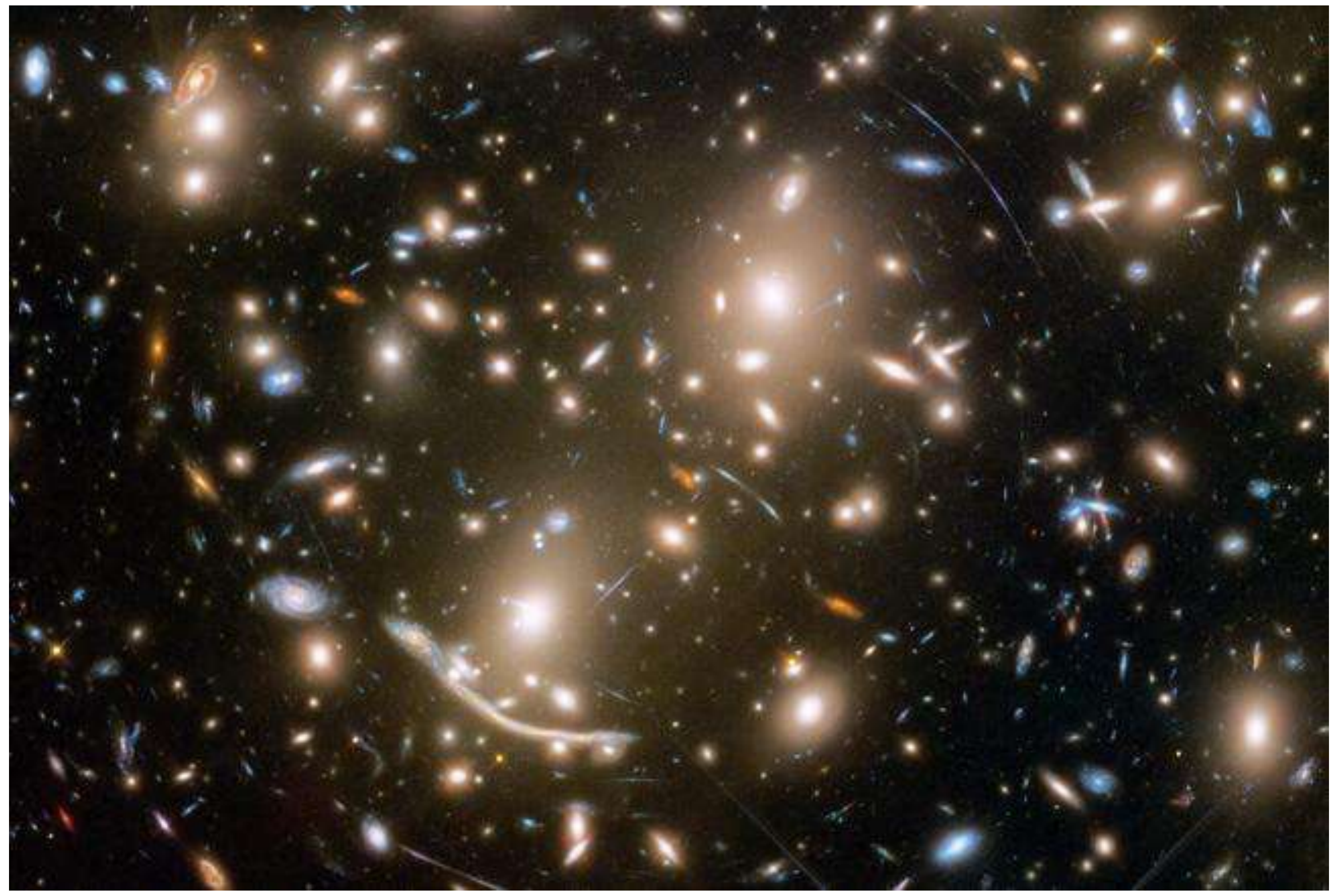


what we do

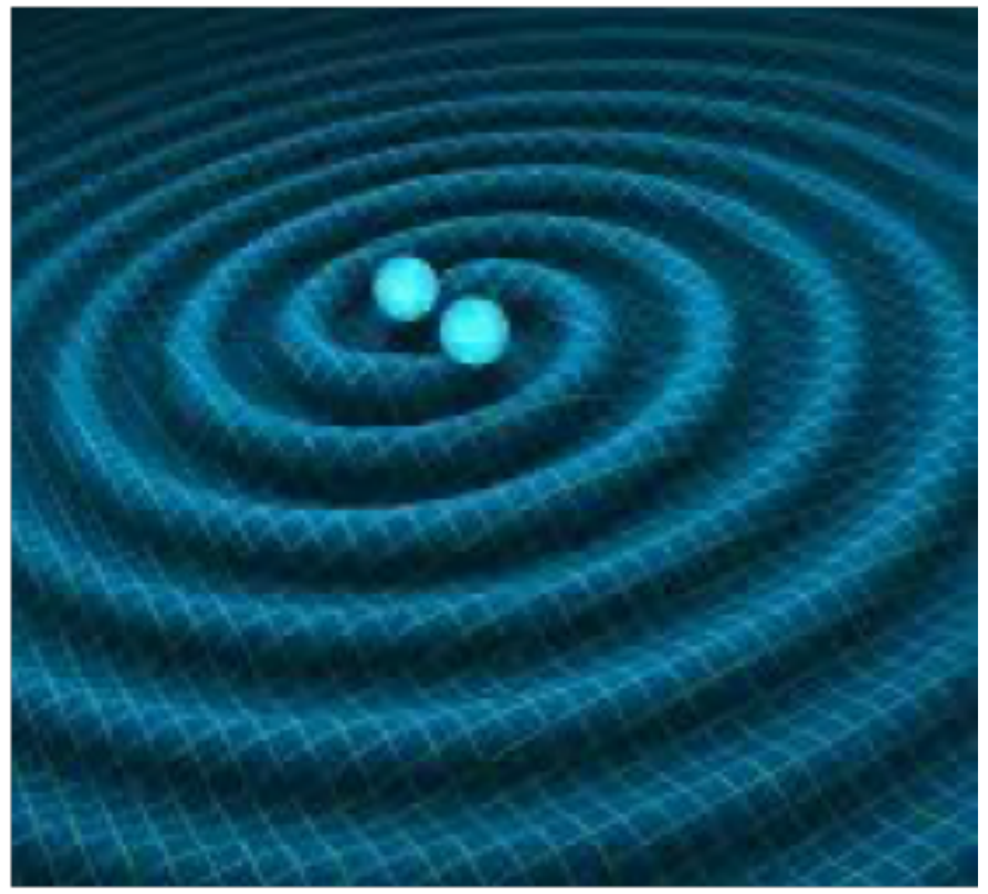
Computational cosmology and dark matter



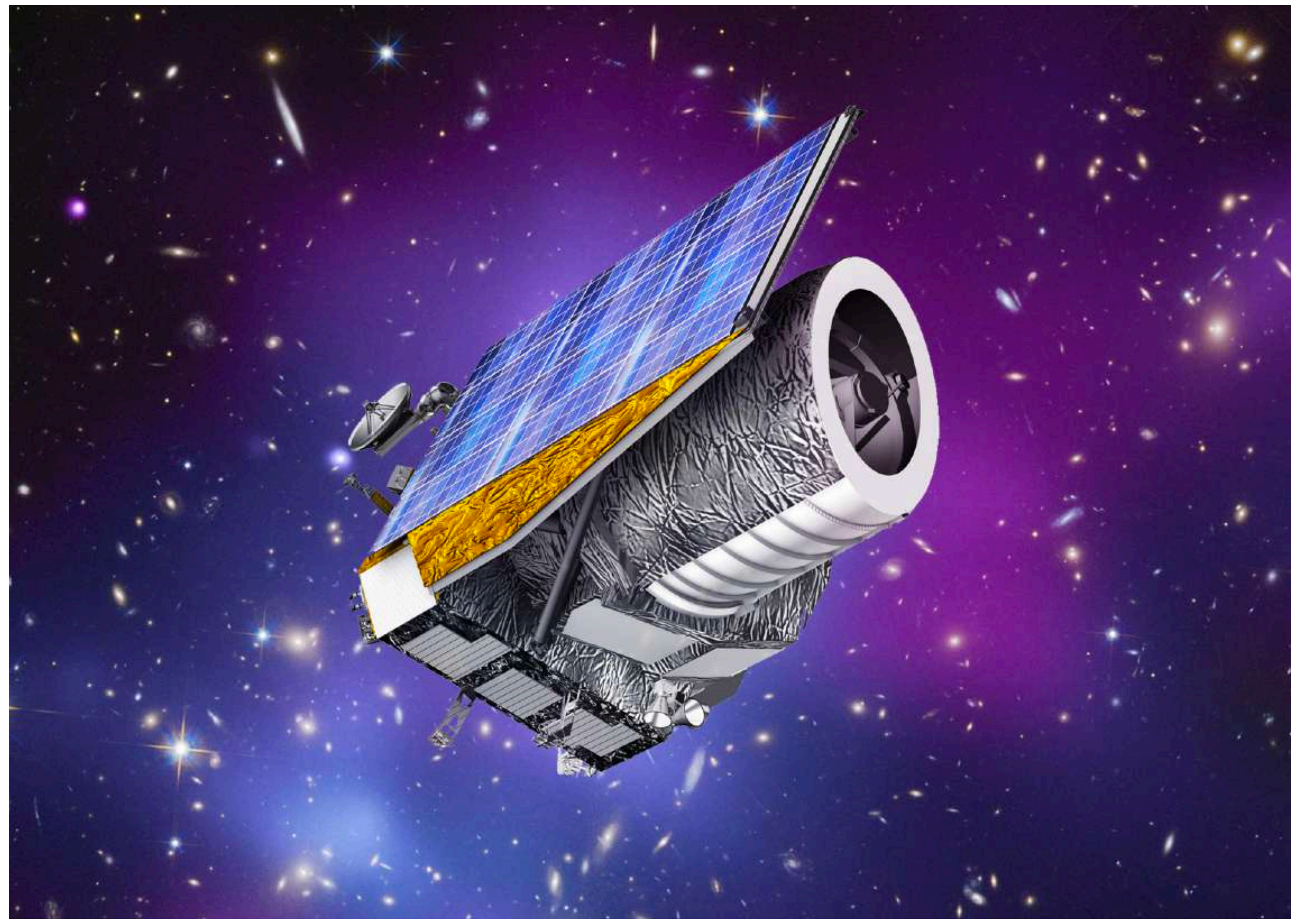
Cosmology with galaxy clusters and voids



Gravitational waves

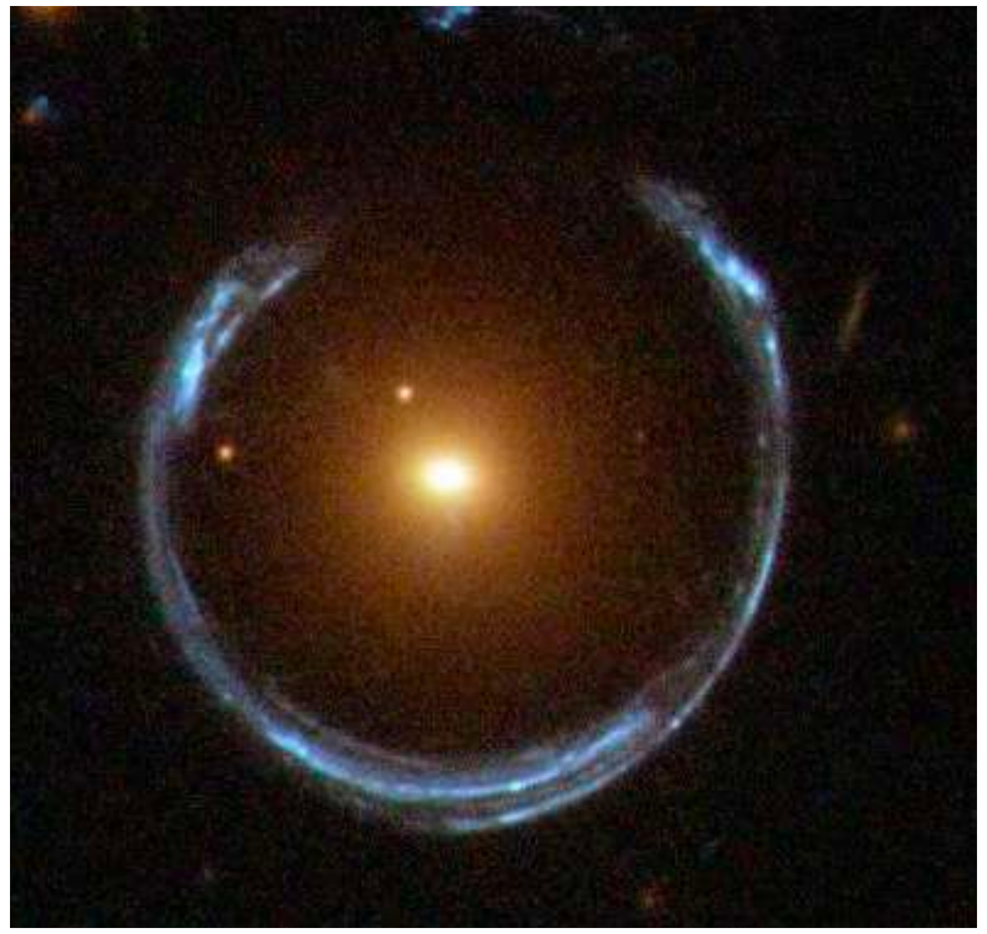


Euclid



Galaxy formation

Gravitational lensing



COMPUTATIONAL COSMOLOGY

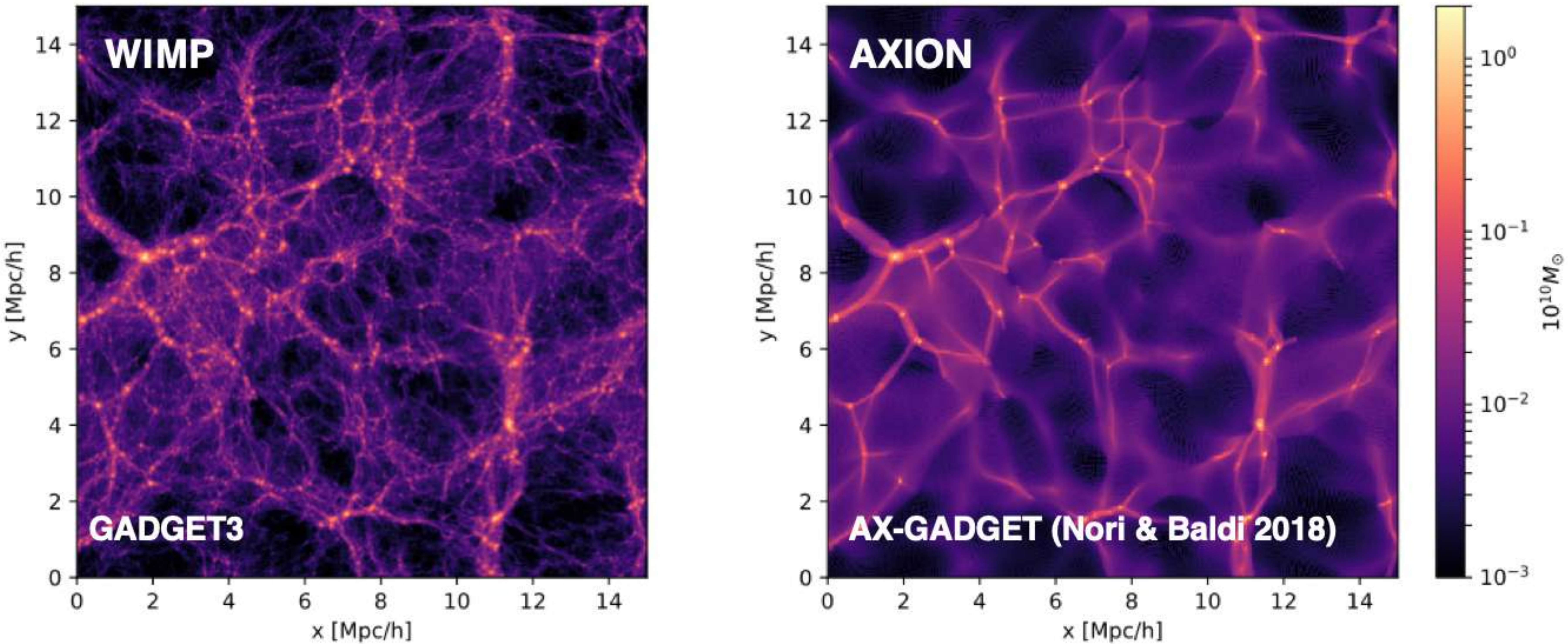
i.e. Simulating the evolution of the Universe with large supercomputers

Ref: Marco Baldi - marco.baldi5@unibo.it - Office 4S5

a couple of EXAMPLES

What is Dark Matter?

The standard model assumes a **HEAVY** particle (WIMP) which has **never been detected**. Could it be an **ULTRA-LIGHT** particle (e.g. an AXION) instead? Could it be a **sterile neutrino**? Could it be **Primordial Black Holes**? You will simulate or analyse some of these different models and see how they affect structure formation



COMPUTATIONAL COSMOLOGY

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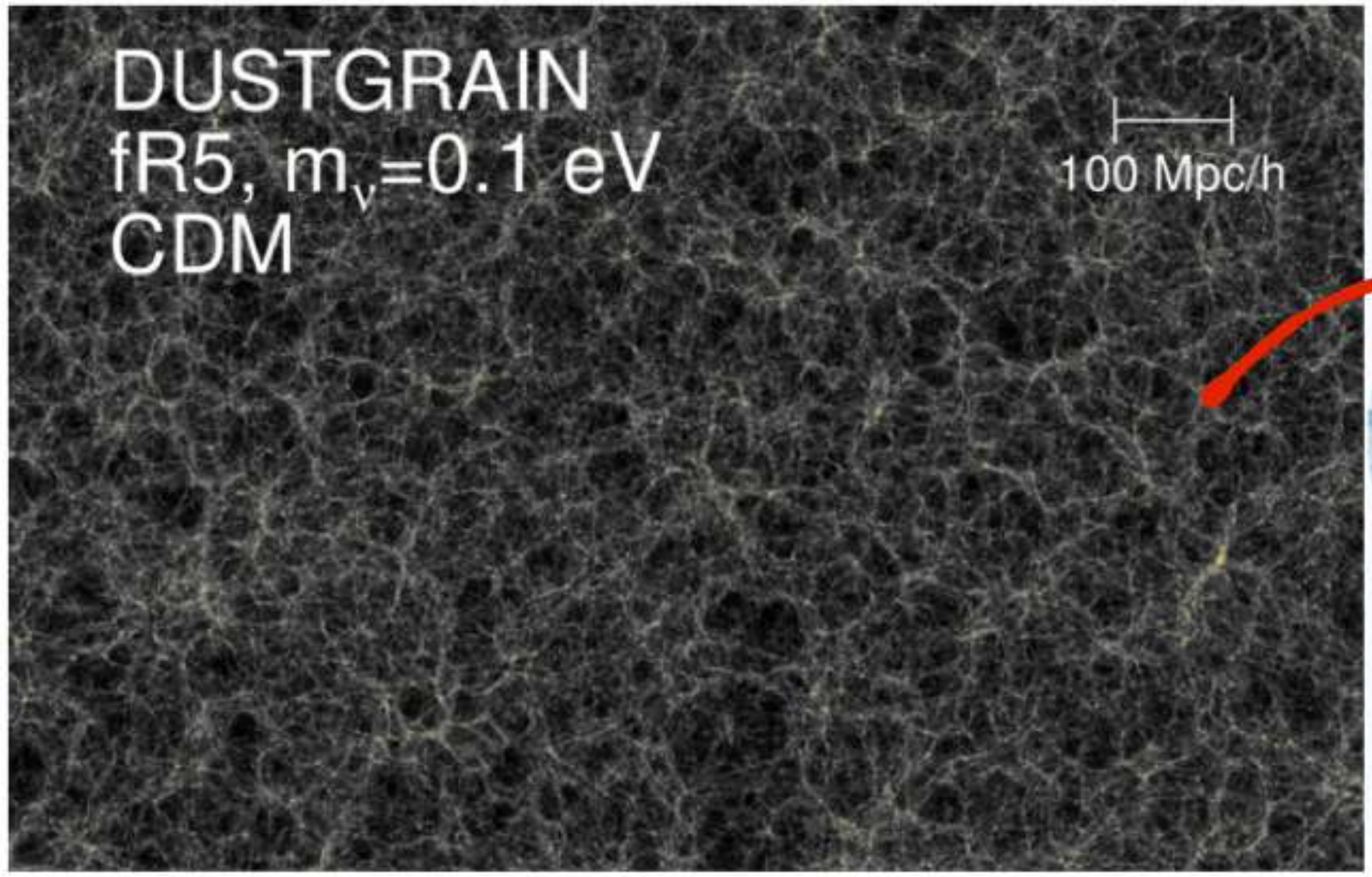
a couple of EXAMPLES

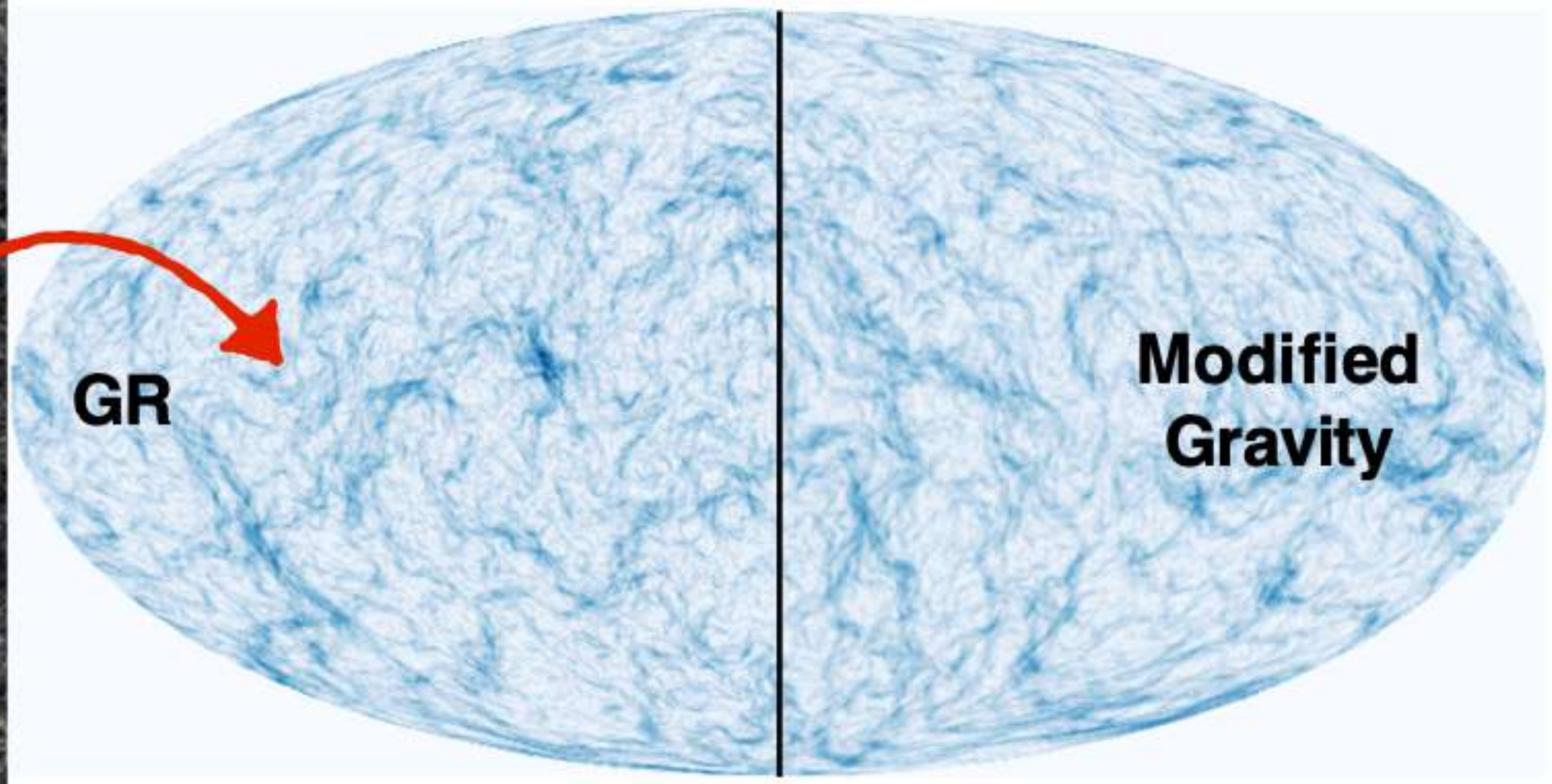
What is driving the acceleration of cosmic expansion?

The standard model assumes a **cosmological constant (Λ)**. Could it be something else? **A new field (Dark Energy)** or an **extension of General Relativity (Modified Gravity)**? You will simulate or analyse some of these different models and see how they affect structure formation

N-body simulation



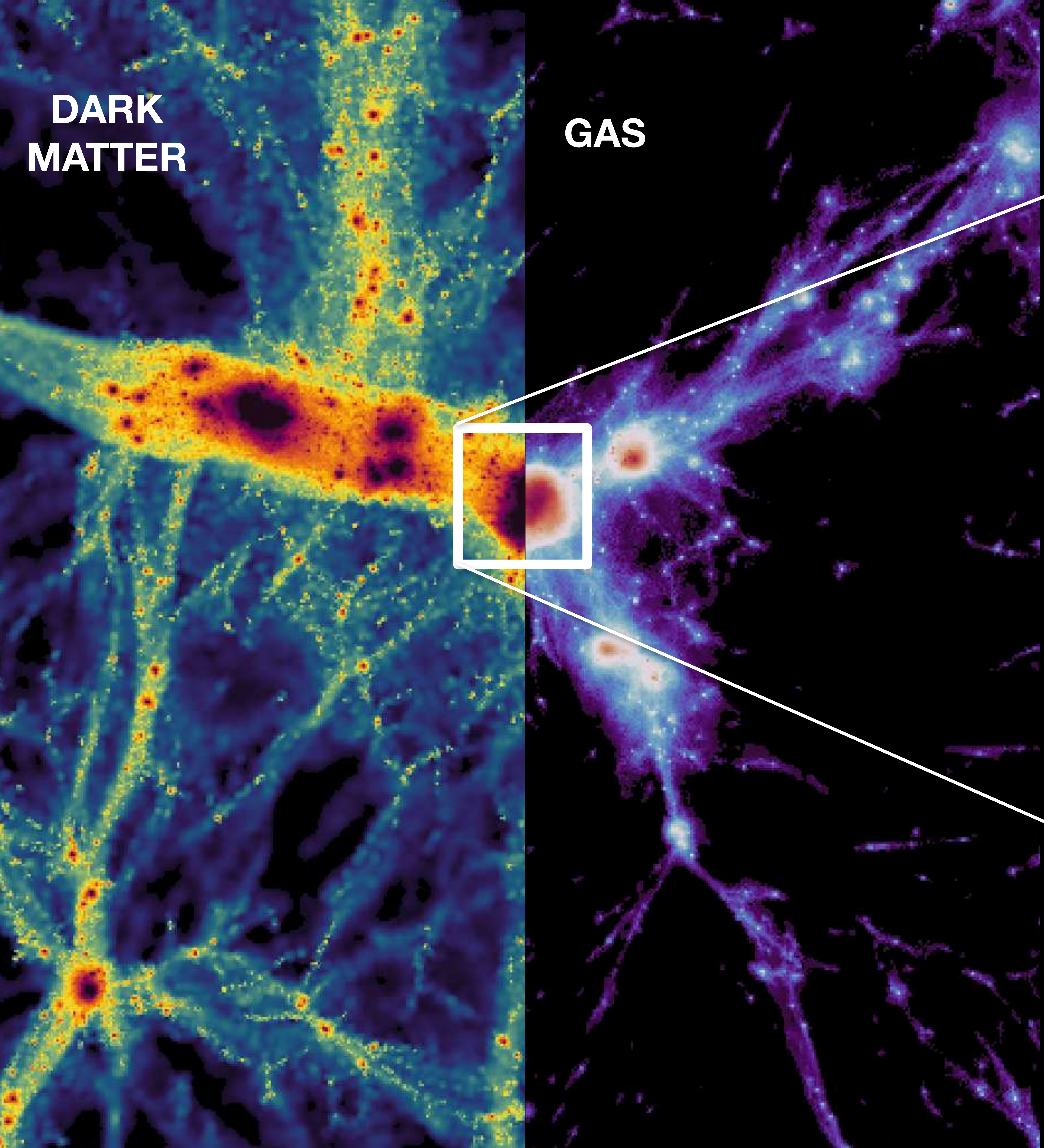
Weak Lensing deflection angle map extracted from simulations

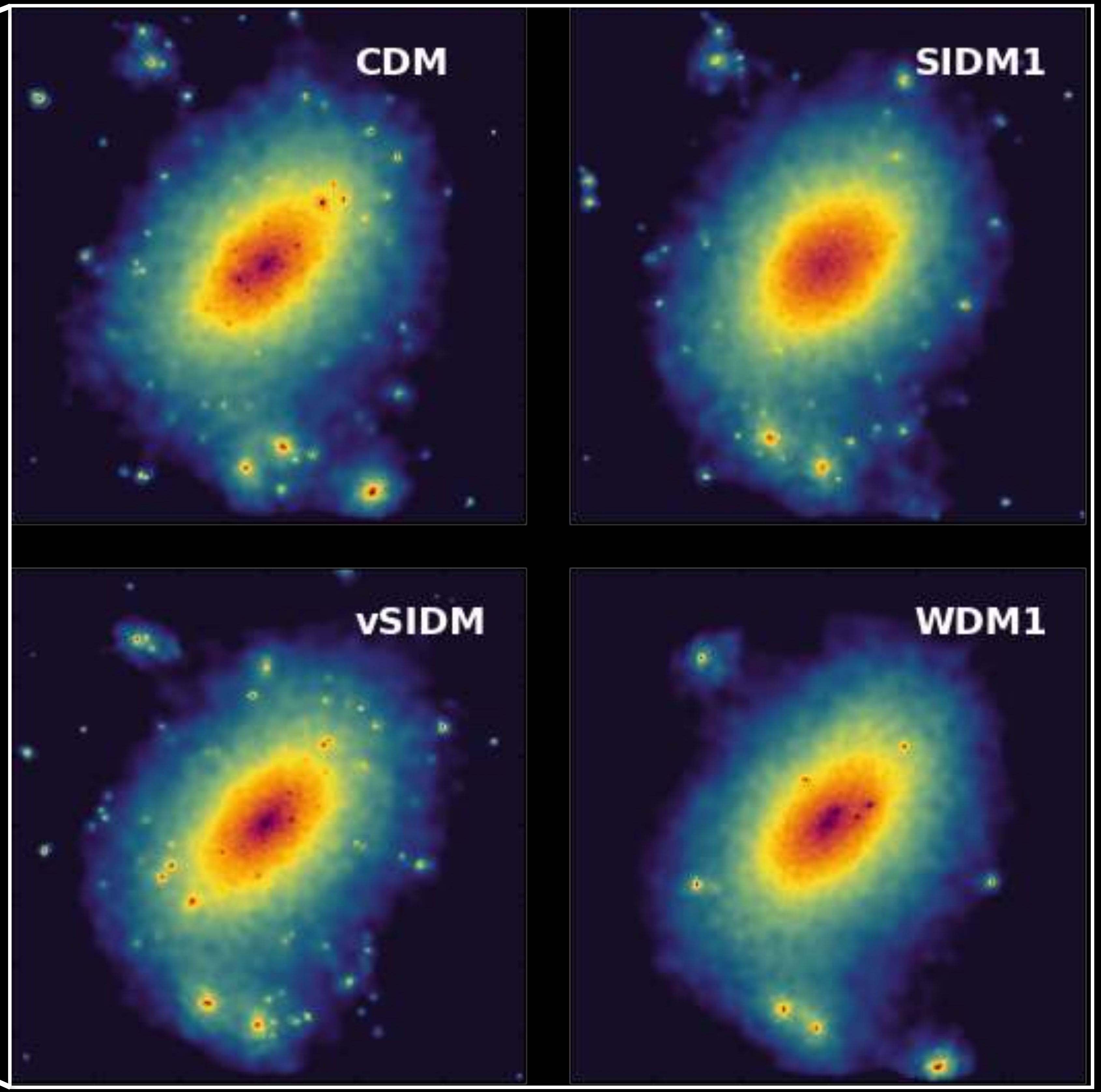


Very small differences, but DETECTABLE with e.g. Euclid

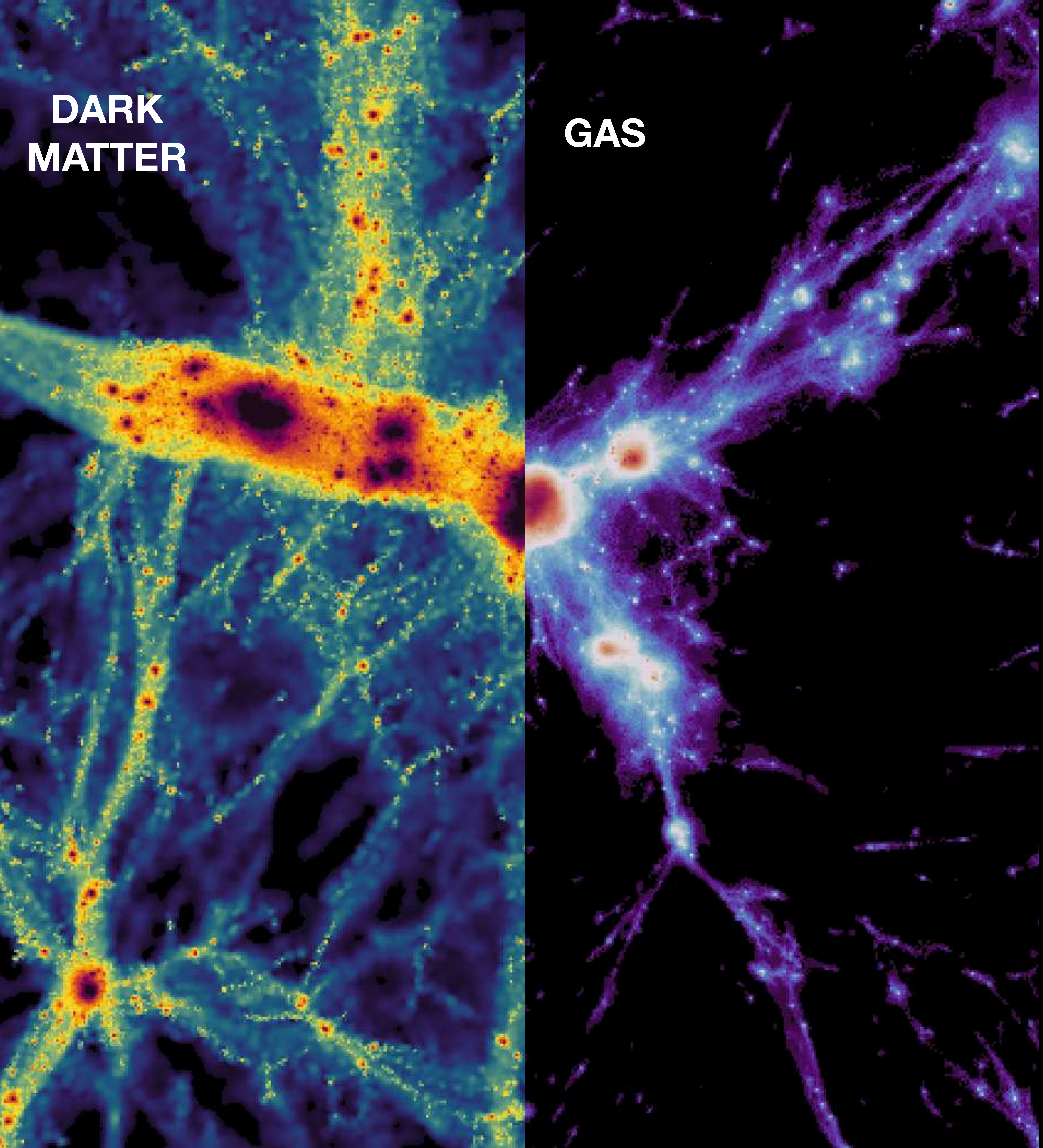
The AIDA simulations

Contact: giulia.despali@unibo.it





The nature of dark matter alters the properties of galaxies and the dark matter haloes they live in



The nature of dark matter

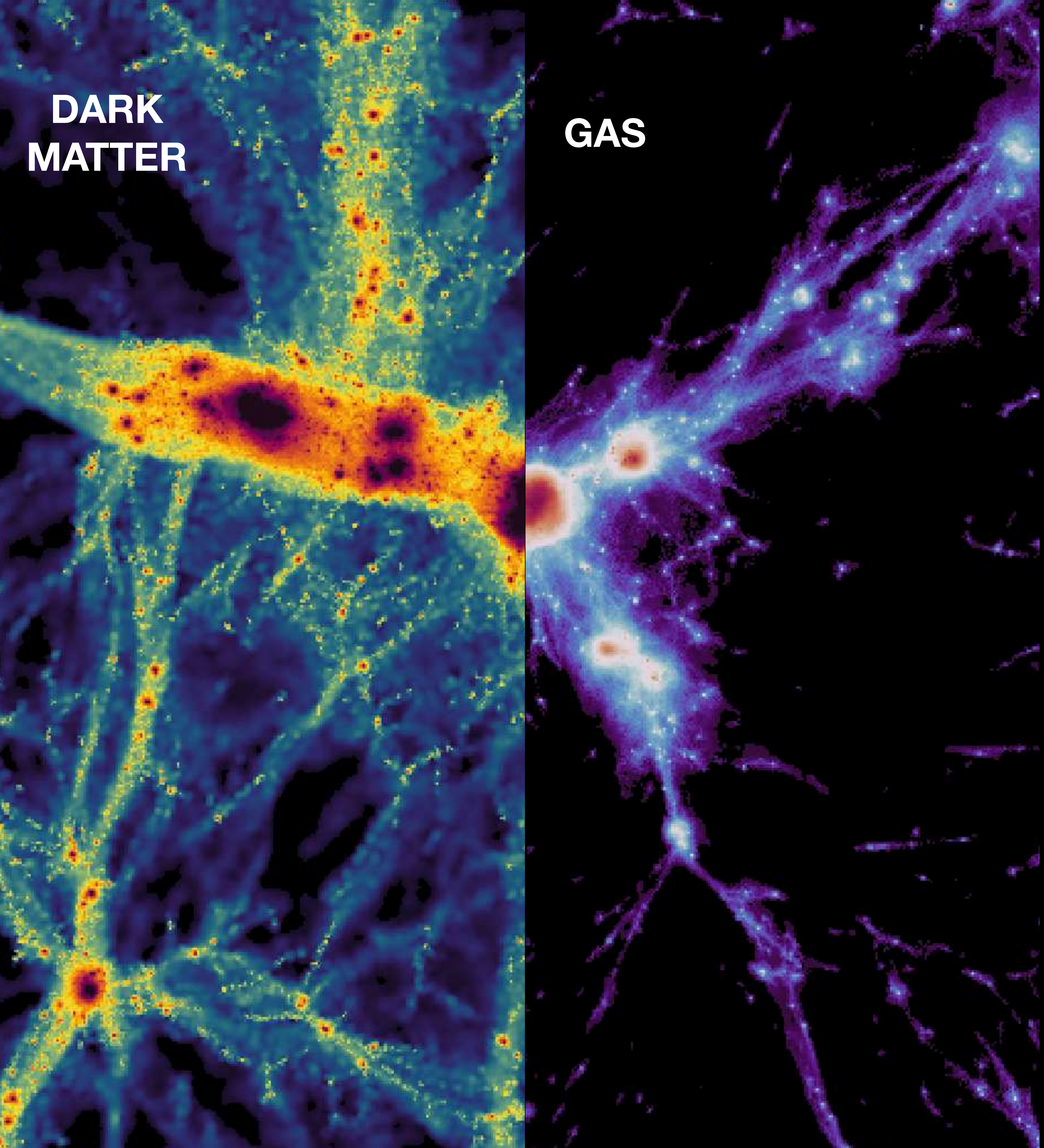
Contact: giulia.despali@unibo.it

Lauro Moscardini
Carlo Giocoli

The AIDA simulations

New hydrodynamical simulations in Cold, Warm and Self-interacting Dark Matter

international collaboration involving the IllustrisTNG team: Volker Springel, Annalisa Pillepich, Dylan Nelson



The AIDA simulations

Contact: giulia.despali@unibo.it

Possible thesis projects:

- analysis and creation of the simulations
- creation of mock observations
- studying the impact of dark matter on observables such as: gravitational lensing, X-ray emission, galaxy scaling relations, dwarf galaxies and MW satellites

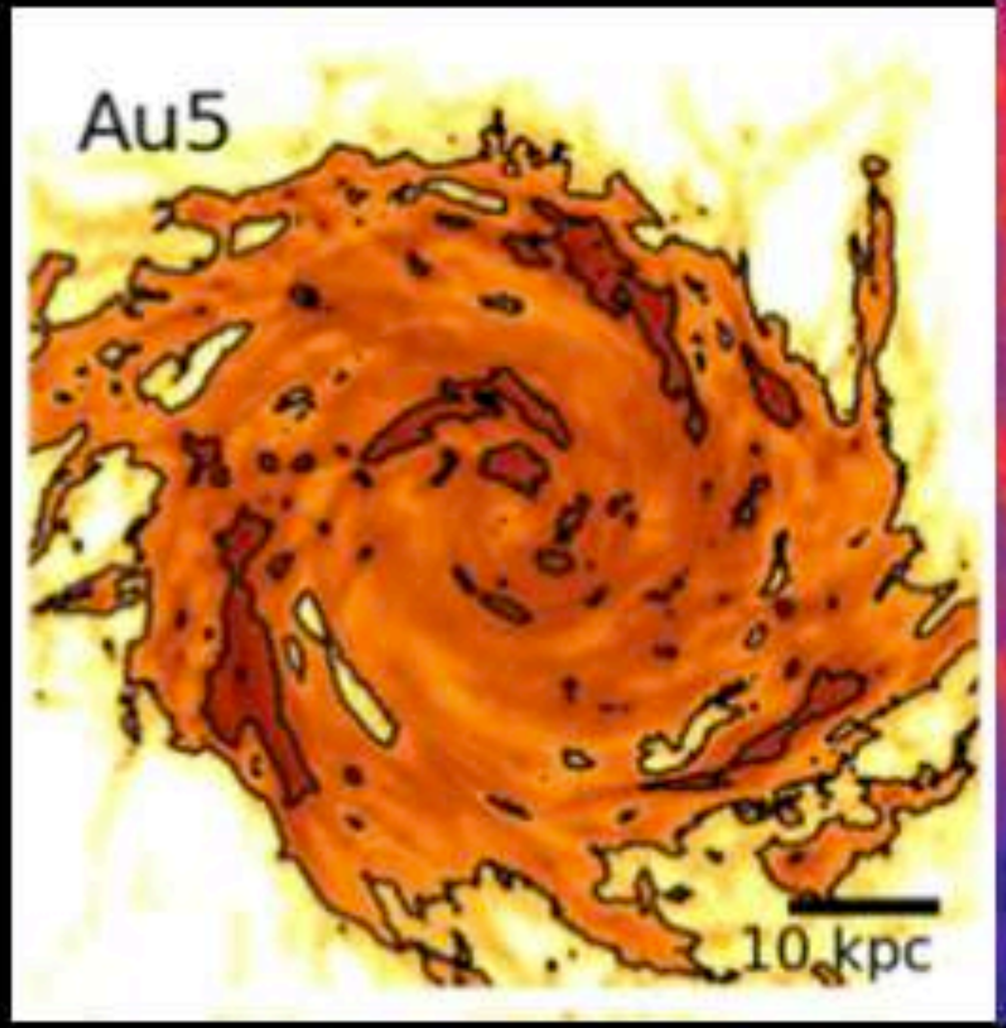
international collaboration involving the IllustrisTNG team: Volker Springel, Annalisa Pillepich, Dylan Nelson

Galaxy formation simulations

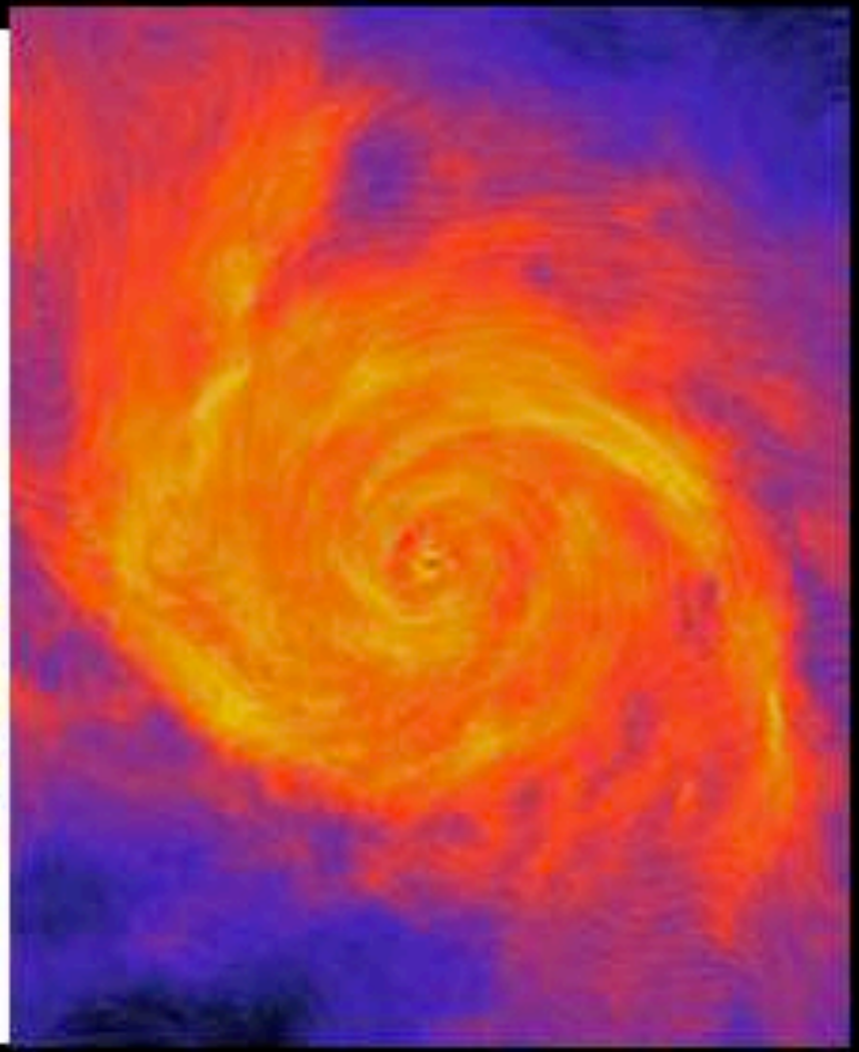
Contact: Federico Marinacci – federico.marinacci2@unibo.it

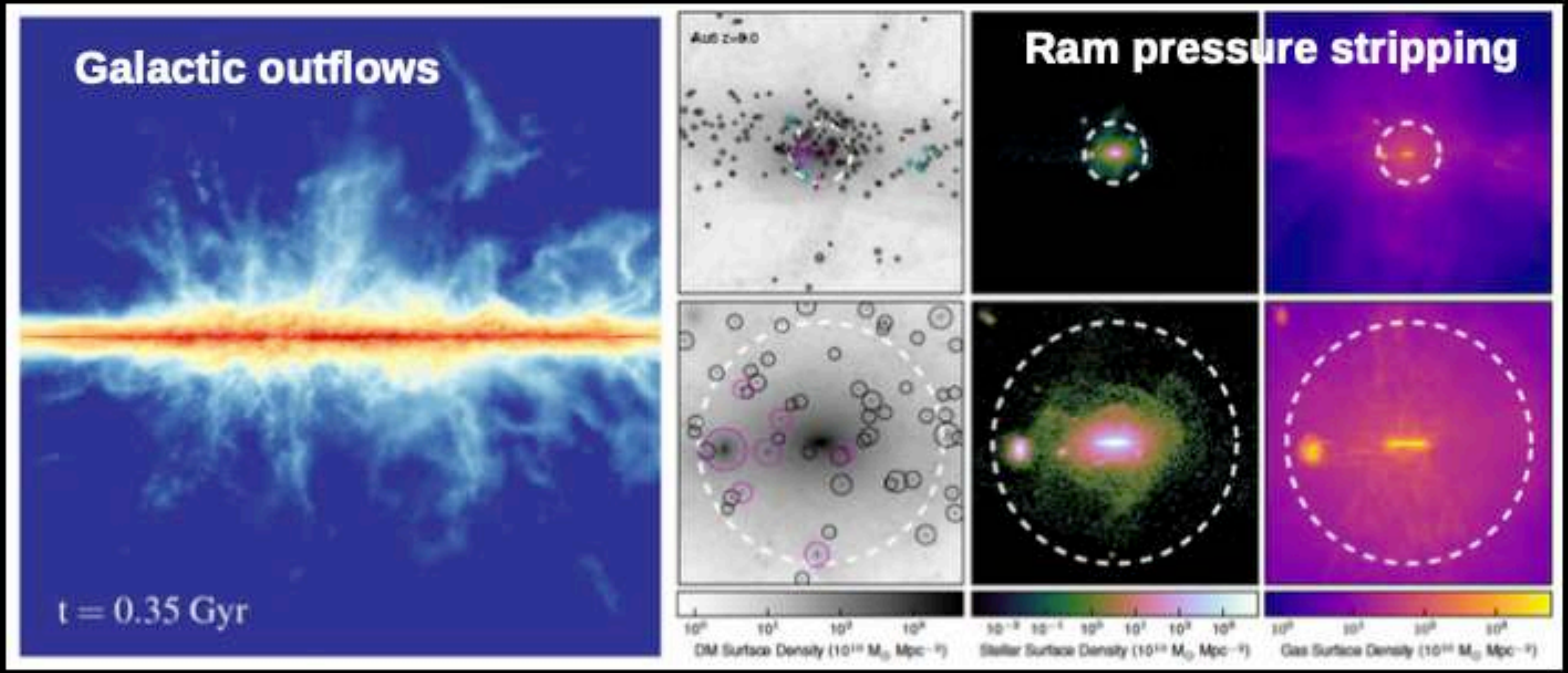
Stellar light

HI distribution



Magnetic fields

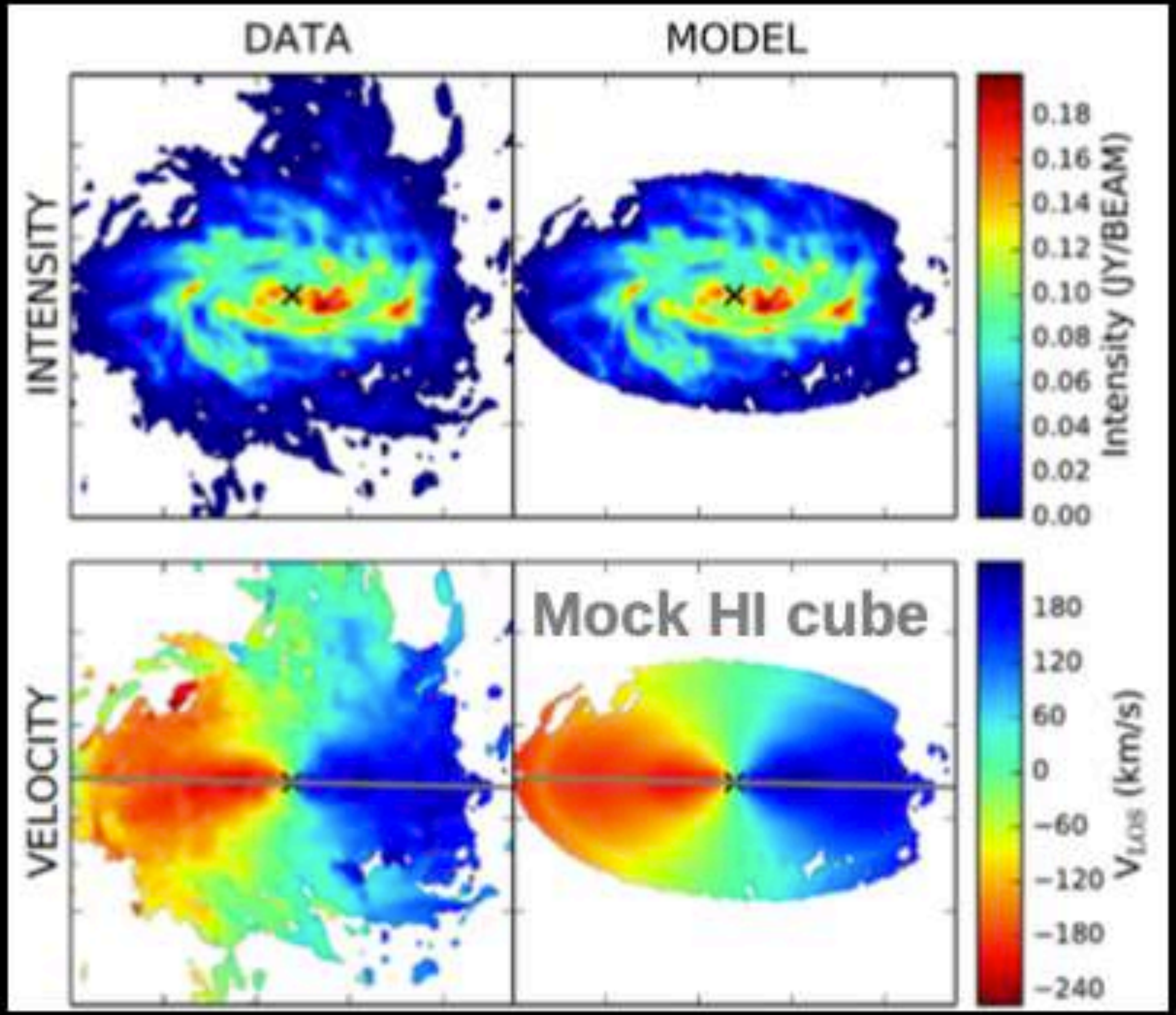


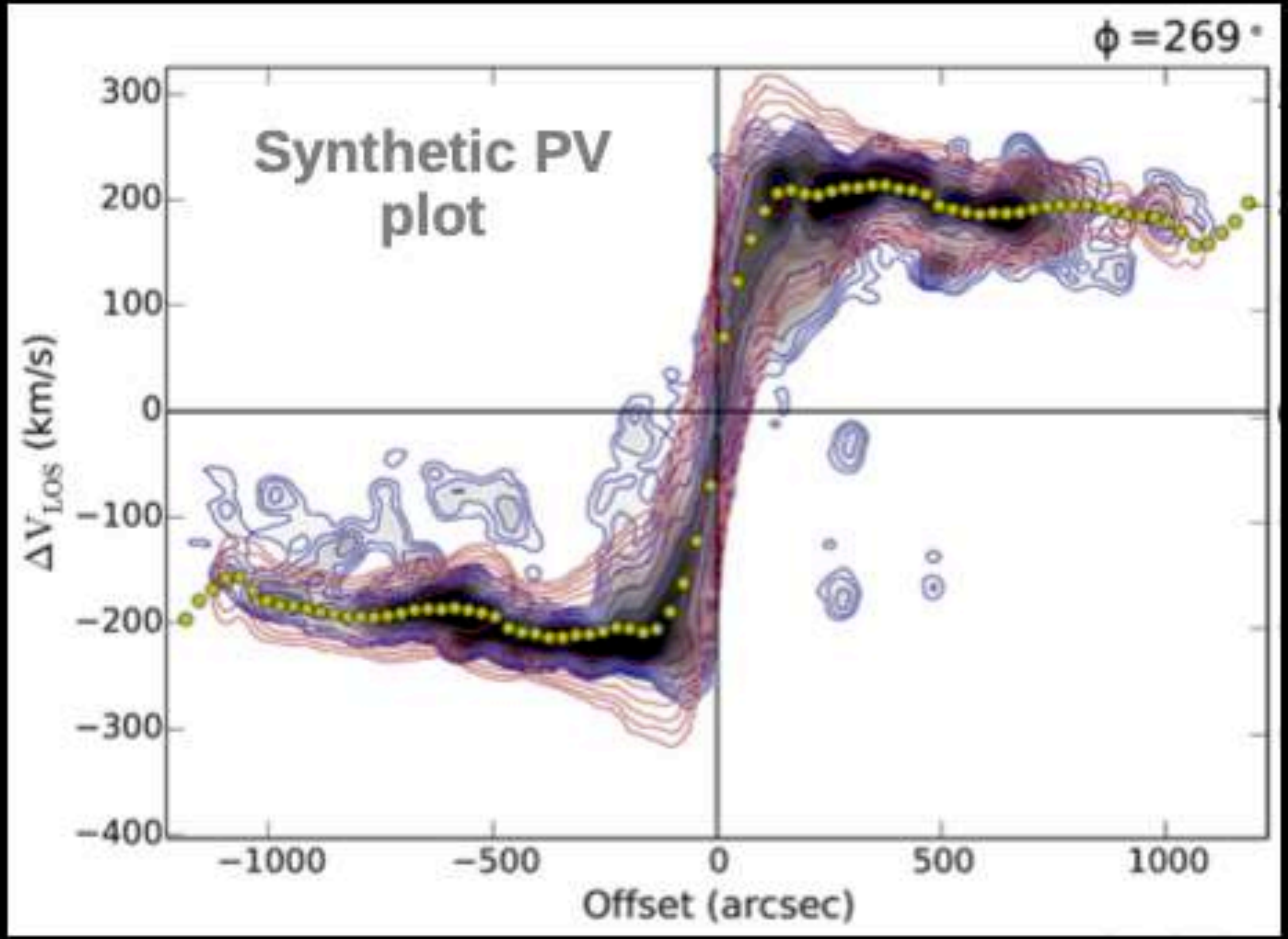


Understanding galaxy formation require the use of sophisticated hydrodynamical simulations capable of modelling many, highly non-linear physical phenomena

Analysis of mock observations of galaxy formation simulations

Contact: Federico Marinacci – federico.marinacci2@unibo.it





Key objectives:

- use of **sophisticated observational techniques** providing **precise constraints** on the models by using all the information contained in the data
- detailed analysis of **gas kinematics and gaseous flows** in state of the art **galaxy formation simulations**

Creating equilibrium models of multi-component galaxies for hydro N-body simulations

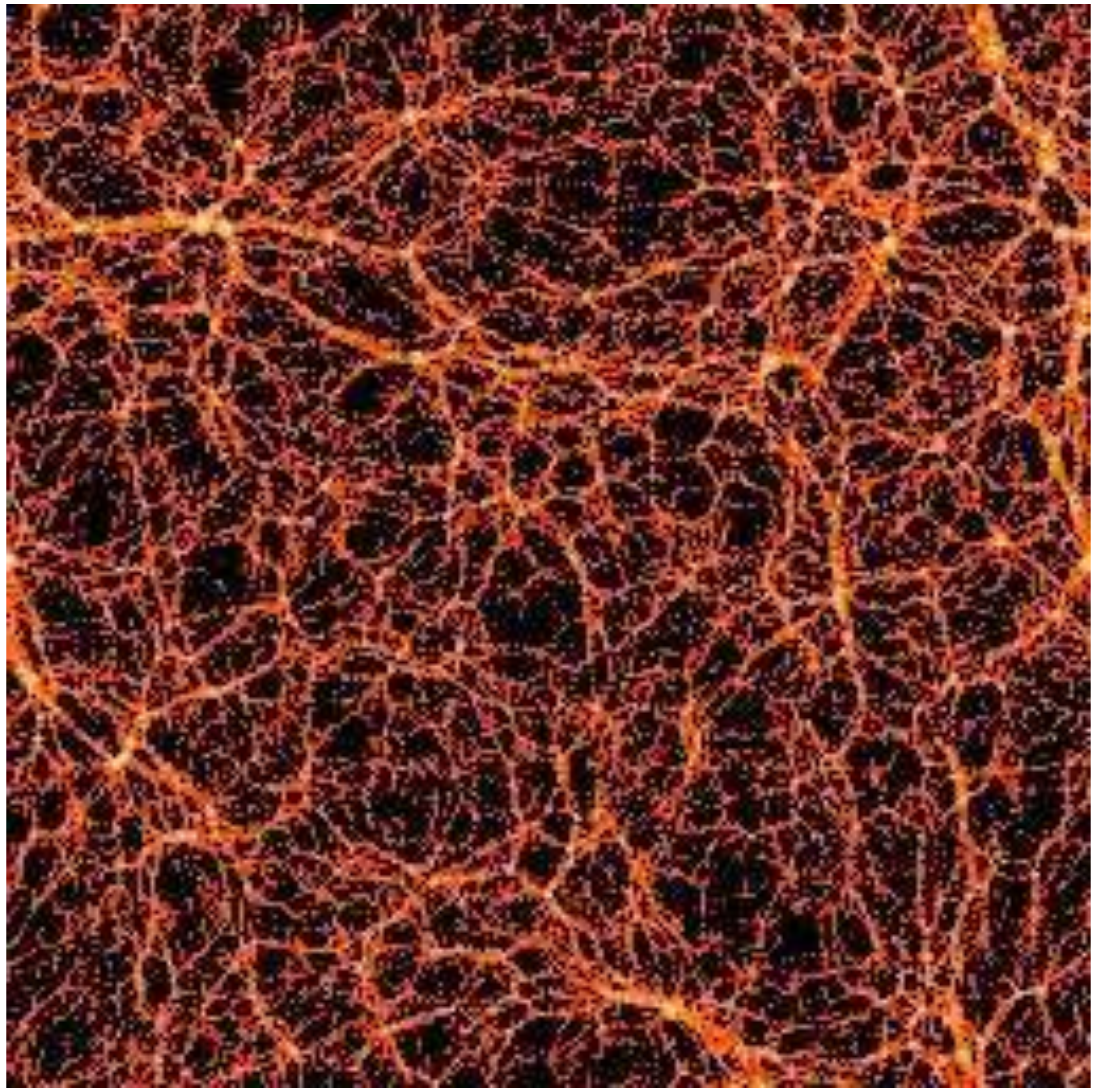
Contact: Federico Marinacci – federico.marinacci2@unibo.it

Key objectives:

- **creating and testing equilibrium models of multi-component galaxies** to be used as ICs by hydro N-body codes
- **arbitrary number** of spherical and axisymmetric **components** (both gaseous and collisionless) with a variety of density profiles
- implementation possible in different programming languages (e.g. **C/C++, Python**)
- **different output modules** so that ICs can be read by major available hydro N-body codes

Galaxy clustering

The geometry and dynamics of the Universe are shaped by gravity. Thus, the understanding of gravity is the key to unveil the nature of the Universe. **The clustering of cosmic structures is one of the most powerful tools to test the gravity theory on the largest scales** (i.e. where dark matter and dark energy arise), in particular exploiting the apparent anisotropies observed in galaxy maps, the so-called redshift-space distortions.



Possible Thesis projects:

- Relativistic effects on the odd multipole moments of the two-point correlation function
- Cosmological constraints from Bayesian Neural Networks
- Emulators for clustering statistics

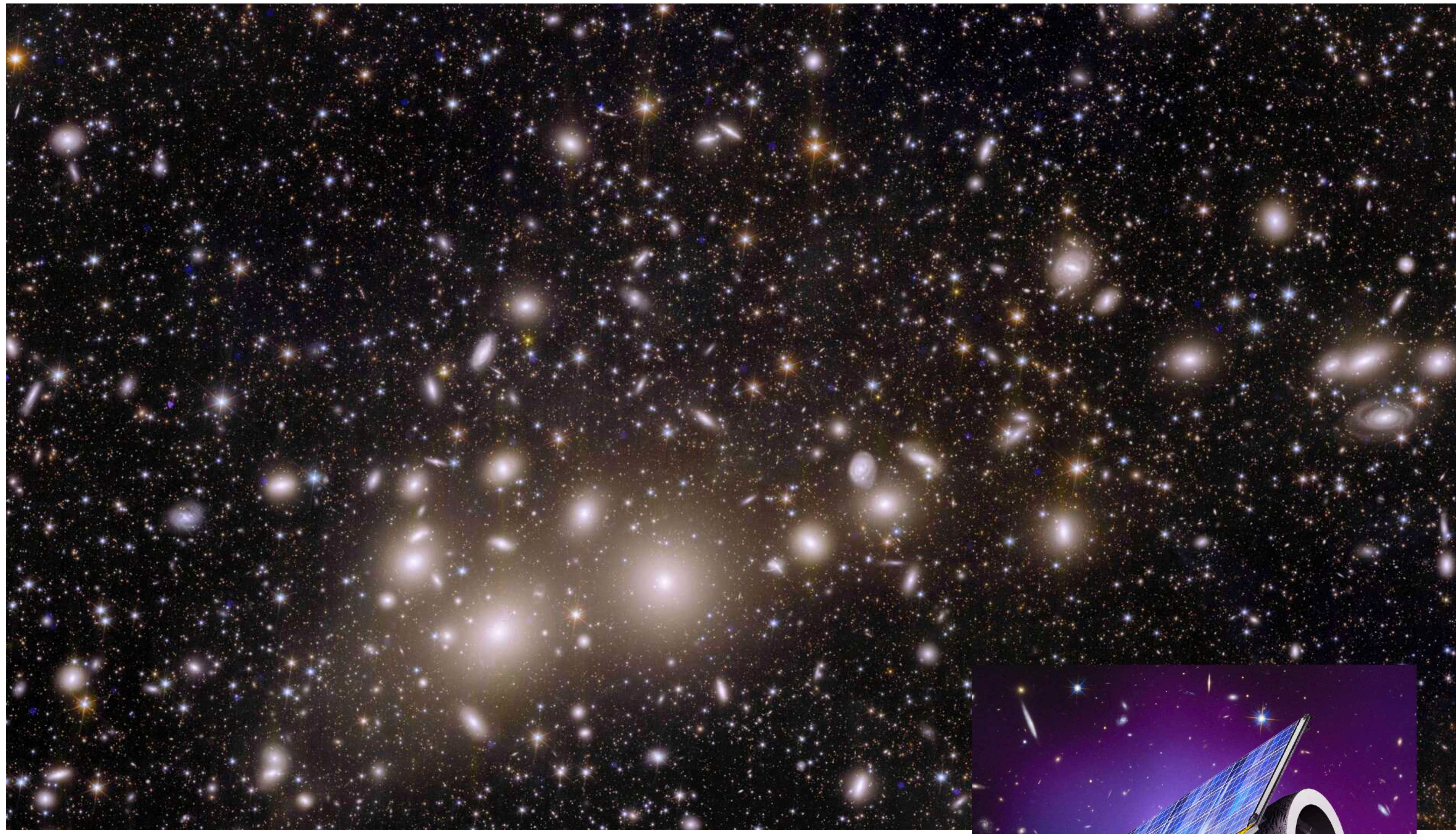
Main contacts:
Federico Marulli
Lauro Moscardini
Carlo Giocoli
Massimiliano Romanello

Galaxy clusters

Galaxy clusters are the biggest collapsed structures in the Universe. Their clustering signal is higher than that of galaxies. Cluster masses can be measured. **Cosmological constraints can be extracted from both number counts and clustering**.

Possible Thesis projects:

- **Testing gravity theories with gravitational redshift measurements in galaxy clusters**
- **Exploiting the splashback radius**
- **Cluster sparsity and abundance**
- **Cosmology from proto-clusters at high redshifts**
- **Cosmology from cluster statistics in the Euclid deep fields**



Euclid view of the Perseus cluster

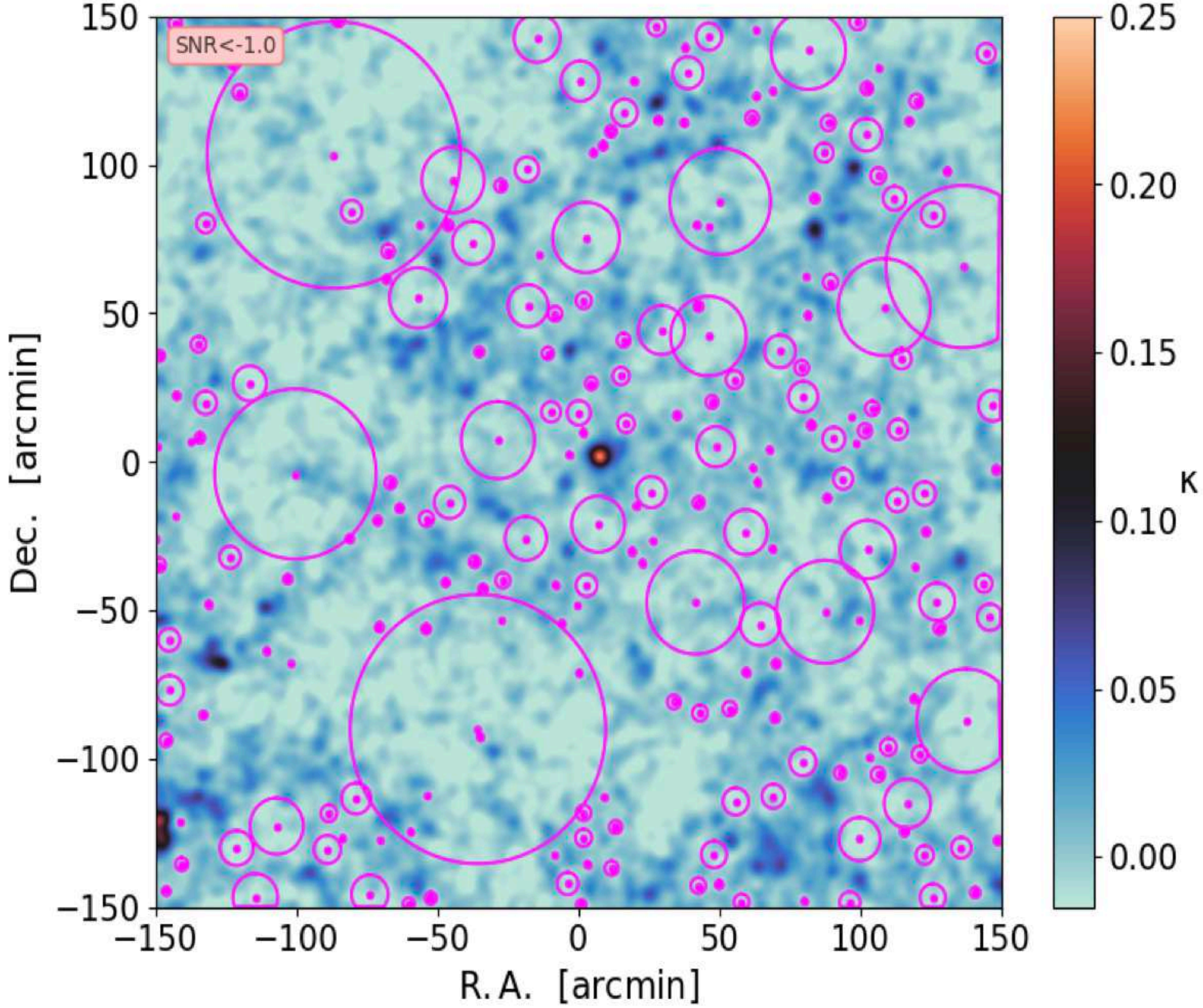
***Main contacts*:**
Federico Marulli
Lauro Moscardini
Giorgio Lesci
Carlo Giocoli
Giulia Despali
Massimiliano Romanello

Cosmic voids

Cosmic voids are large underdense structures that fill a significant volume fraction of the Universe. They are **powerful cosmological probes for constraining dark energy and testing theories of gravity**.

Possible Thesis projects:

- New dynamic void detector algorithms and cleaning methods
- Theoretical models for the void size function and clustering in alternative cosmological models
- Void clustering
- Void lensing
- Machine learning methods to constrain cosmological parameters from void statistics



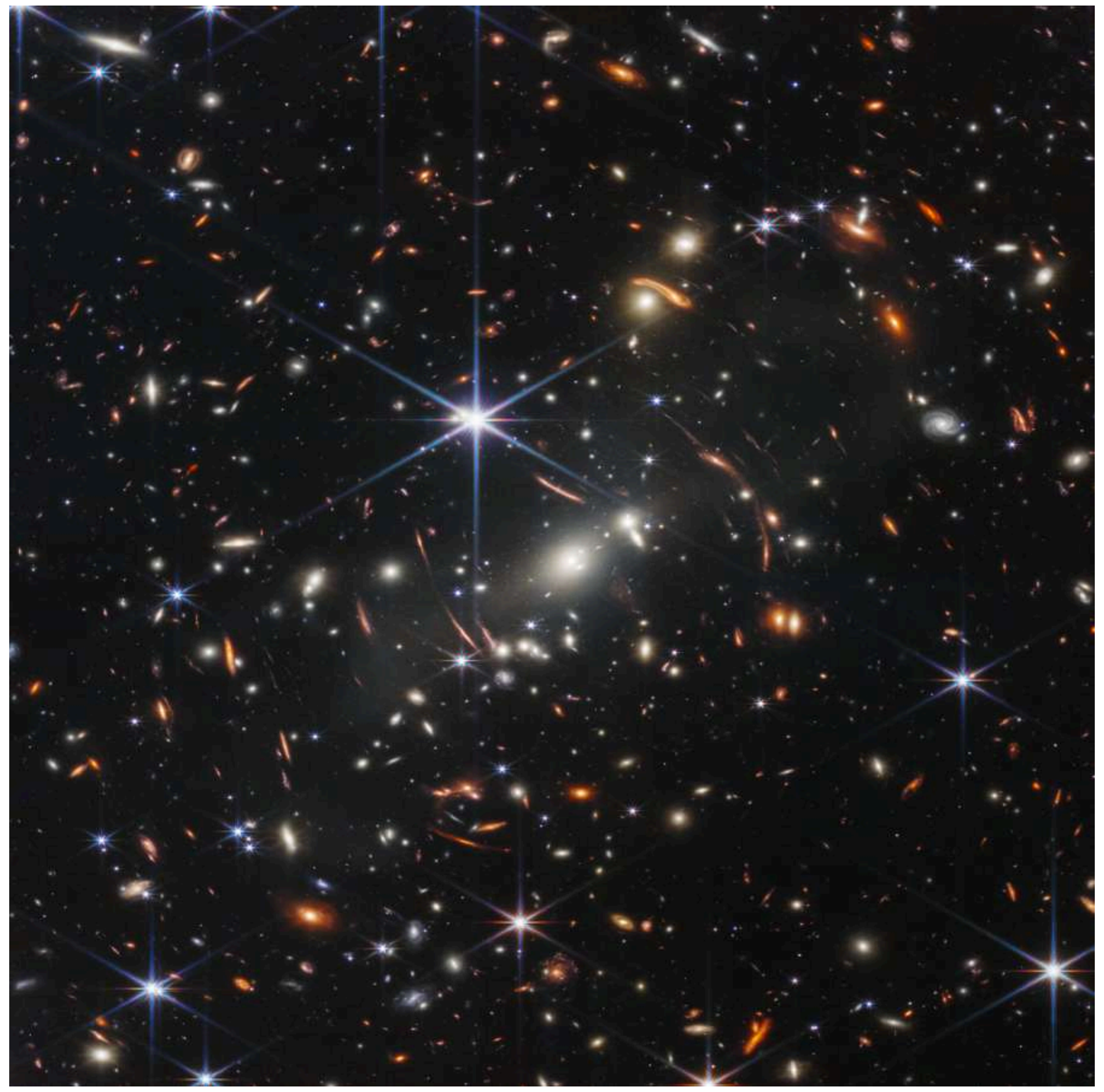
Main contacts:
Sofia Contarini
Federico Marulli
Lauro Moscardini
Carlo Giocoli

Weak lensing

The small distortion caused by the intervening mass density distribution on the light emitted by background sources can be used to **infer the properties of the matter** present along the line-of-sight and to test the General Relativity theory.

Possible thesis projects

- Dependence of the halo concentration-mass relation on the outskirts of the dark matter profiles: assembly bias
- Weak lensing cluster aperture mass calibration and cosmology
- Sparsity, concentration and modelling properties of dark matter haloes hosting clusters



Reinforcing the activities our group is leading within the **KiDS Collaboration**, and paving the way towards future wide field surveys like **Euclid and Rubin**.

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Carlo Giocoli
Giorgio Lesci
Lauro Moscardini
Federico Marulli
Giulia Despali

Weak lensing

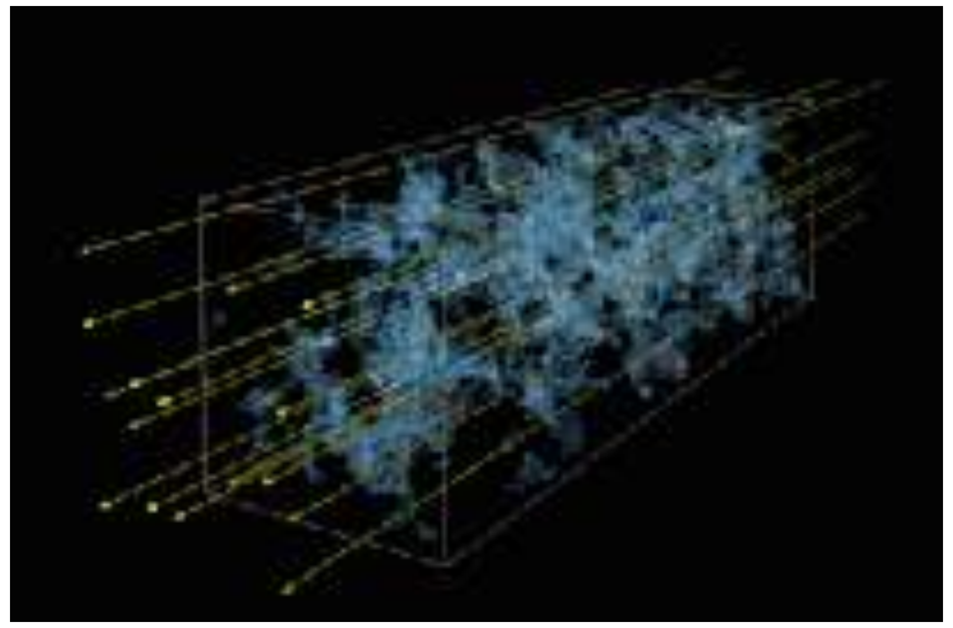
(see Ben Metcalf, robertbenton.metcalf@unibo.it)

Measuring Gravitational Lensing With the Lyman-alpha forest:

We have been developing a new method for measuring weak gravitational lensing using the Lyman-alpha forest (The absorption of light from distant sources by diffuse hydrogen). This would extend the redshift at which weak lensing could be measured, probing new things, and would provide a measurement that is independent of the systematic errors in galaxy weak lensing.

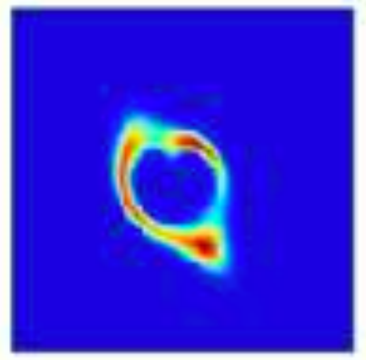
The project would involve some computer programming and some analytic work.

Lyman-alpha forest



Strong Gravitational Lensing

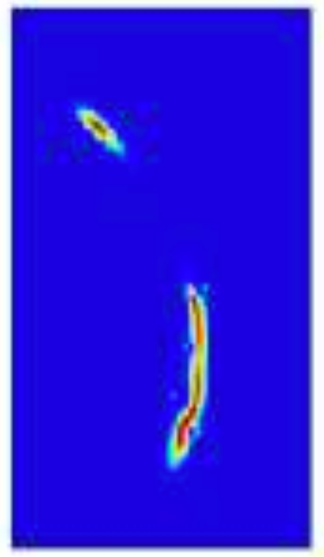
(see Ben Metcalf, robertbenton.metcalf@unibo.it)

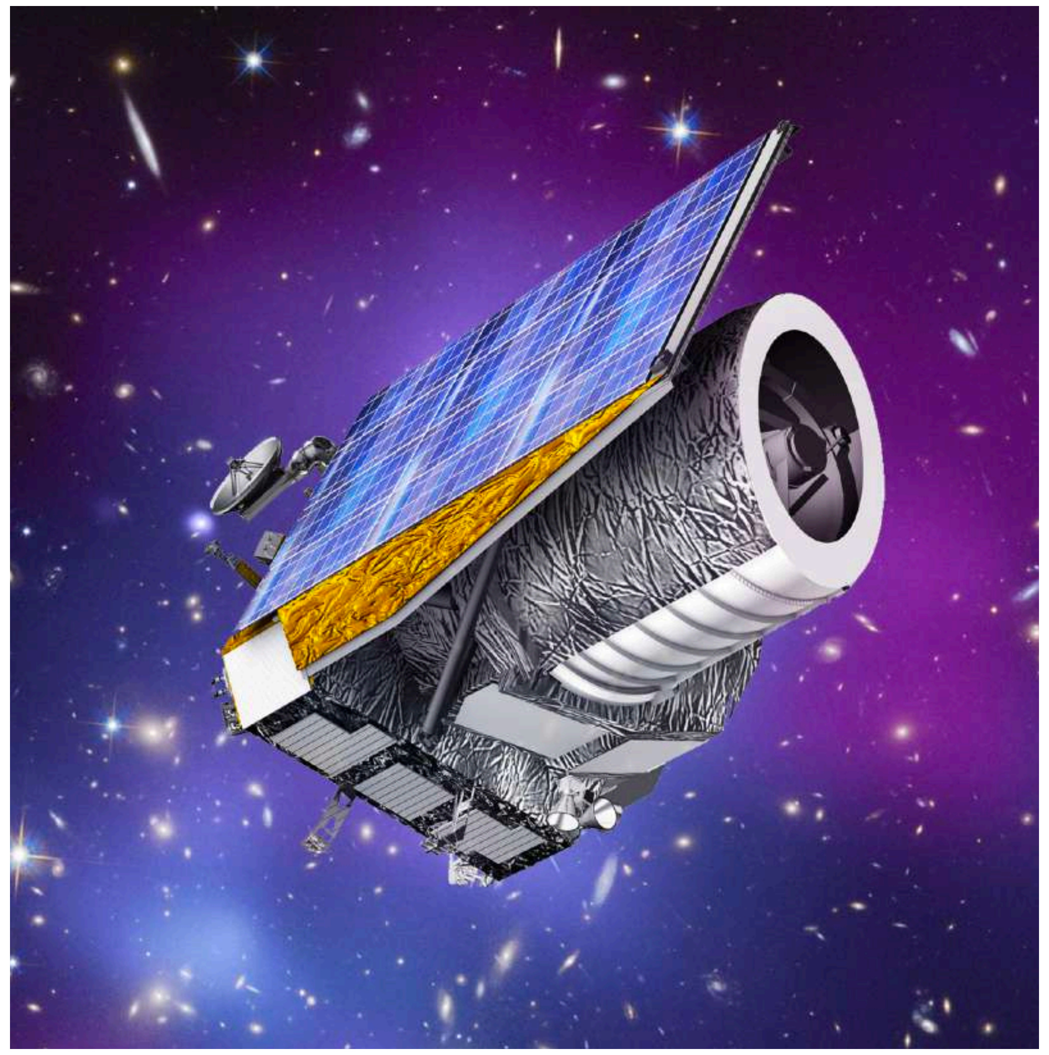


Measuring Substructures in Galaxy Clusters and Dark Matter:

The properties of dark matter (self-interaction, mass, etc.) and galaxy formation affect how dark matter halos survive in galaxy halos. There are many cases where individual objects in clusters act as lenses within the bigger lens. Modelling these objects will provide new constraints on the nature of dark matter and the evolution of clusters.

This project will involve applying already existing modelling software that we have developed to existing data. Some skills with a computer will be required, but extensive programming experience is not necessary.





Strong Lensing Statistics from Cosmological Simulations & Simulating Gravitational Lenses :

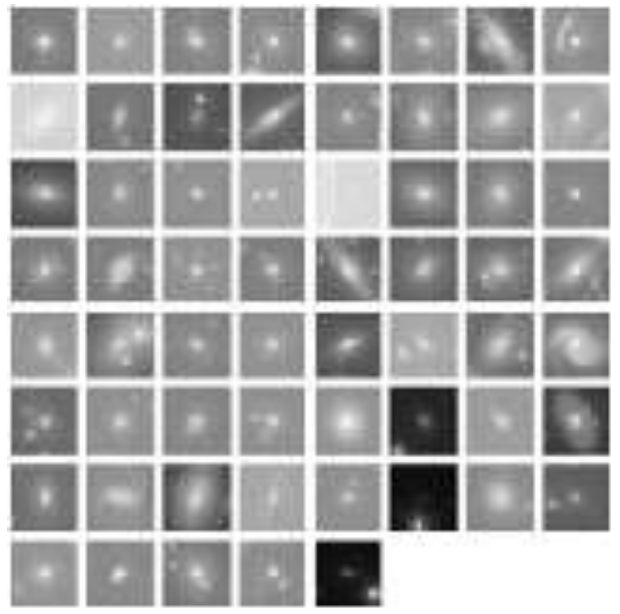
As part of the Euclid mission, we have been making realistic simulated images of strong gravitational lenses. These are used to train machine learning techniques for finding lenses and modelling codes to measure the properties.

The simulations can also be used to predict the properties and statistics of the strong gravitational lenses that will be found and how these depend on models of galaxy formation and structure formation.

Methods for constraining cosmological parameters will be explored.

There is also a project to simulate realistic galaxy images using **machine learning.**

Simulated Lenses



Strong gravitational lensing & dark matter

In strong gravitational galaxy-galaxy lensing, the image of a background source is lensed into an arc by the foreground galaxy. Extra perturbations can appear on the arc due to small substructure in the lens or structure along the line-of-sight, giving us a way to **detect dark matter structures**.

Main contacts:

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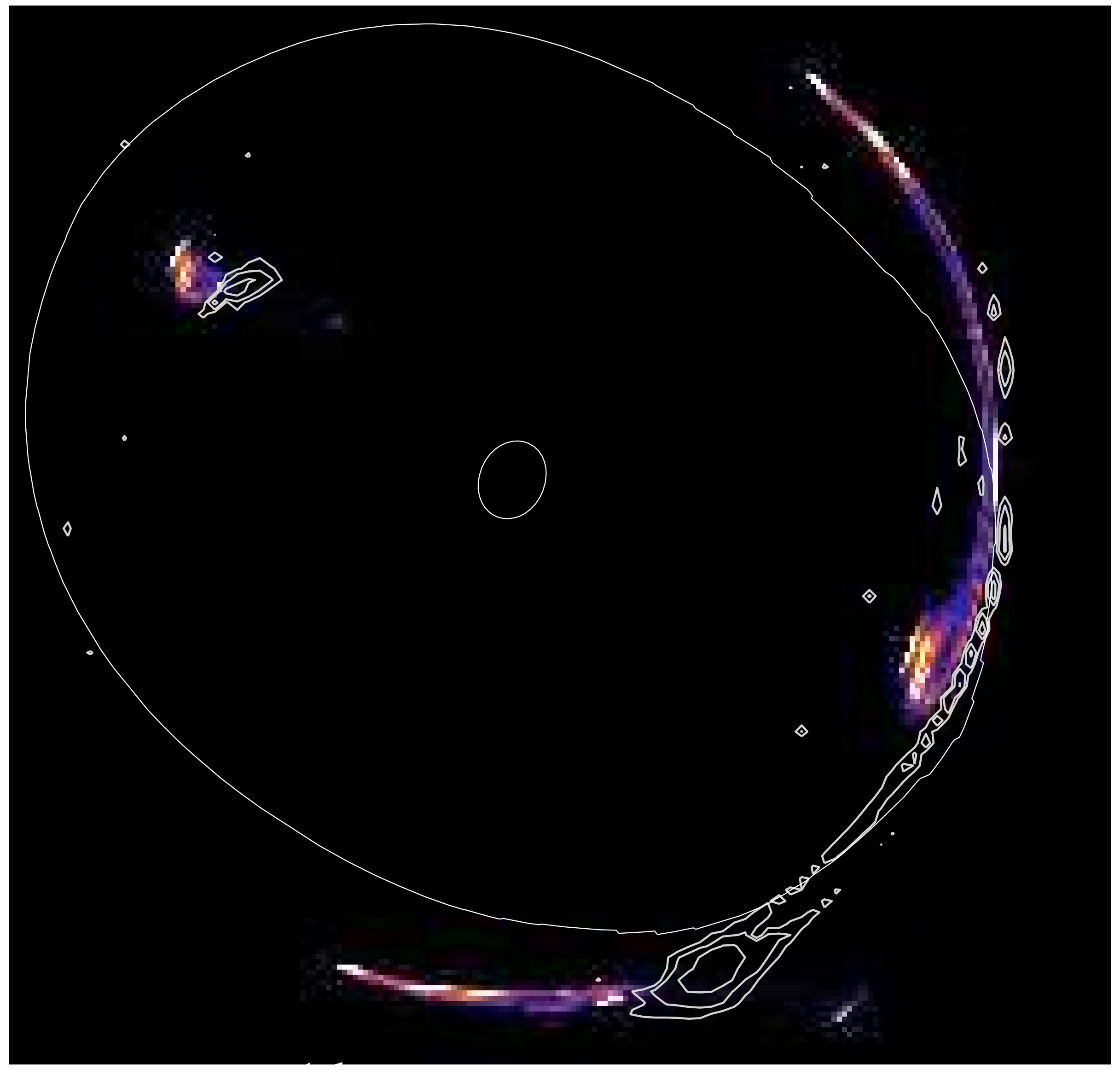

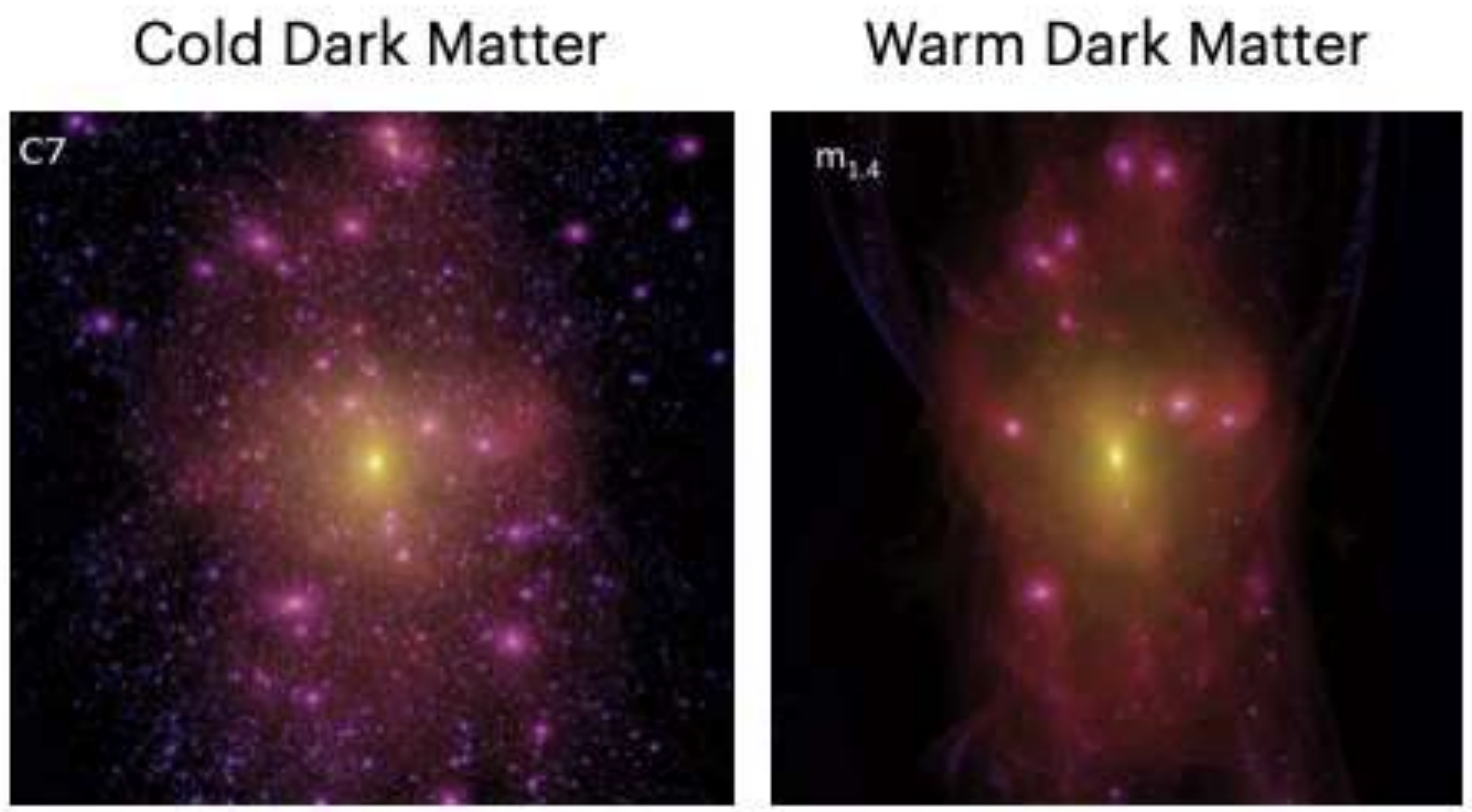

We can use hydro simulations to make predictions for cold, warm or self-interacting dark matter scenarios and derive constraints from the comparison with observational data

Possible thesis projects

- The impact of cuspy core-collapsed SIDM subhaloes on lensed arcs
- Galaxy properties in alternative dark matter models

Strong gravitational lensing & dark matter

Possible thesis projects

- Analysis of observational data from the Keck Telescope (Hawaii) - best sample of optical strong lenses for dark matter studies
- learning lens modelling and applications to galaxy formation & dark matter
- within the international SHARP lensing collaboration

***Main contacts*:**

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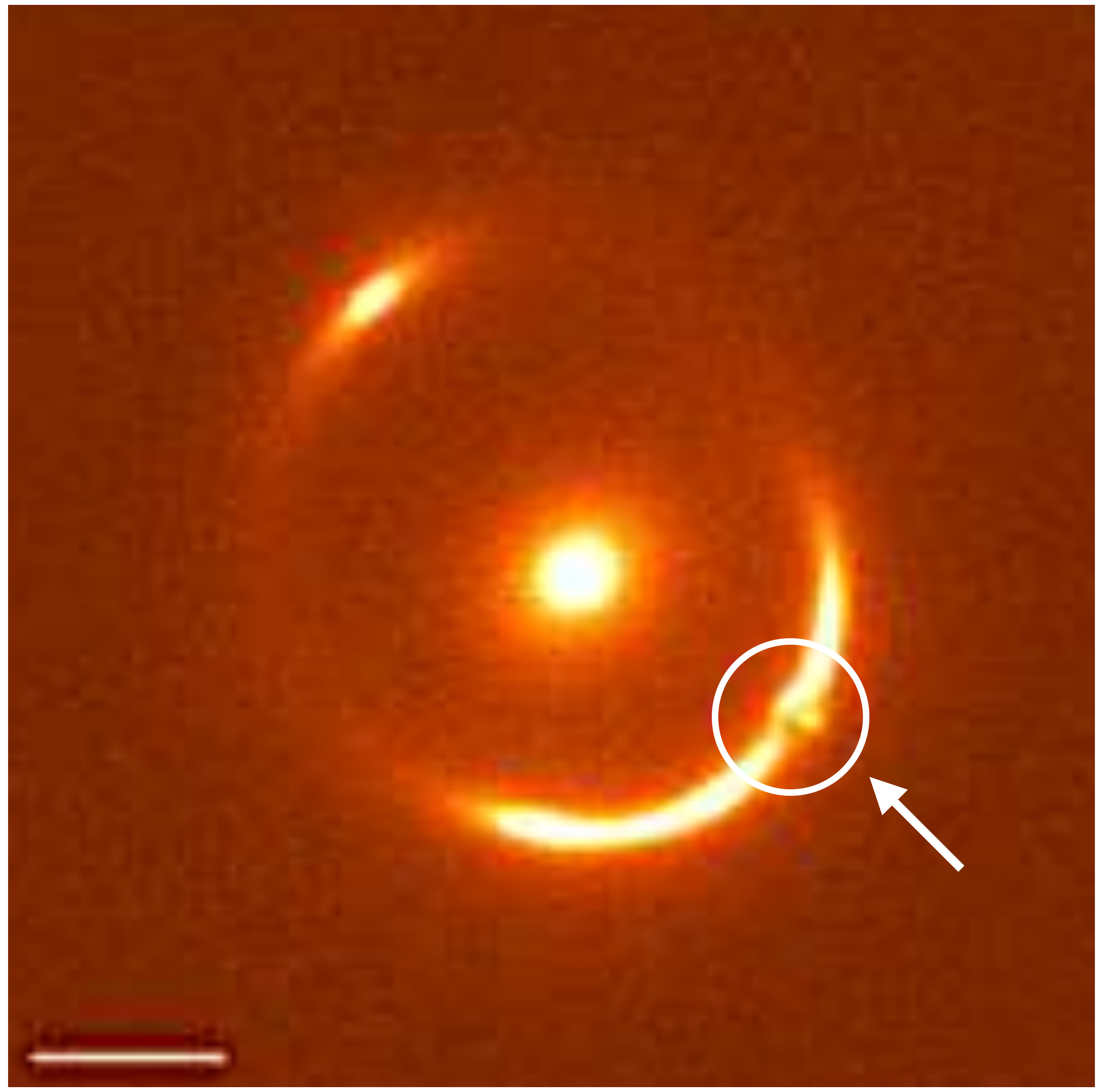
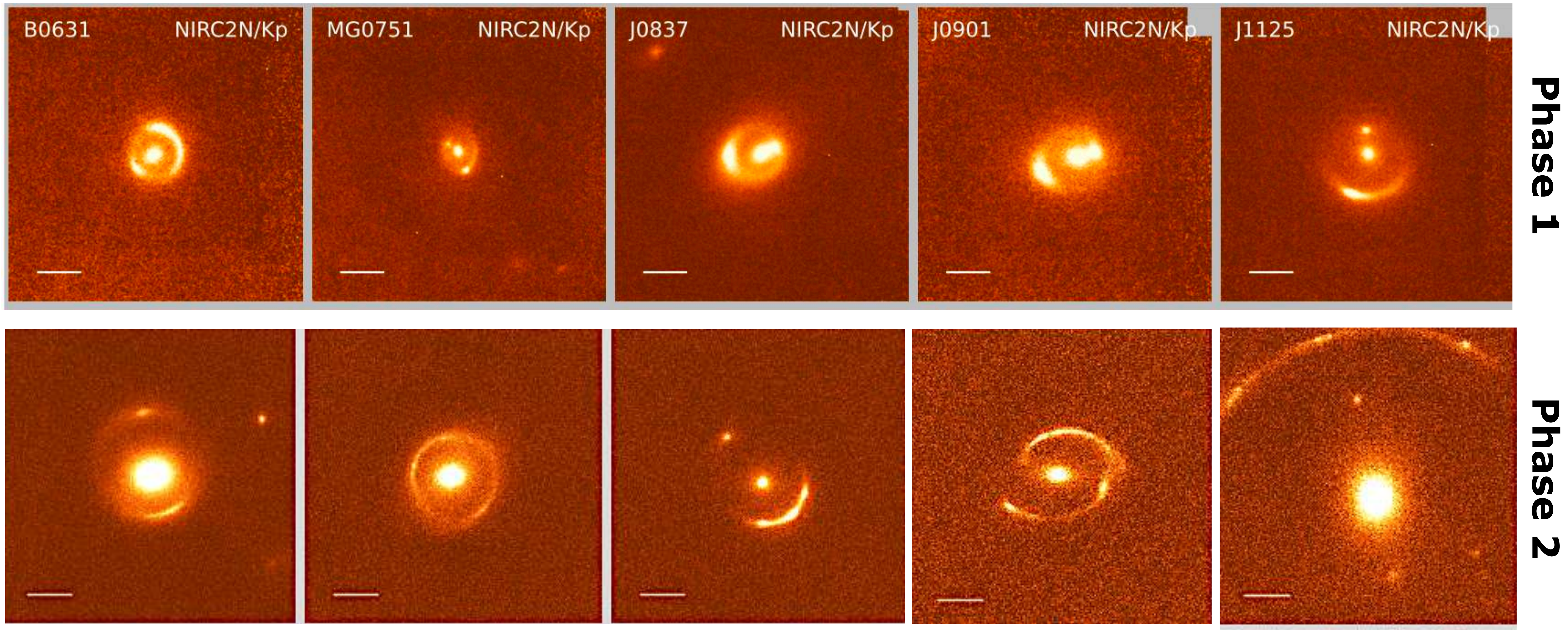
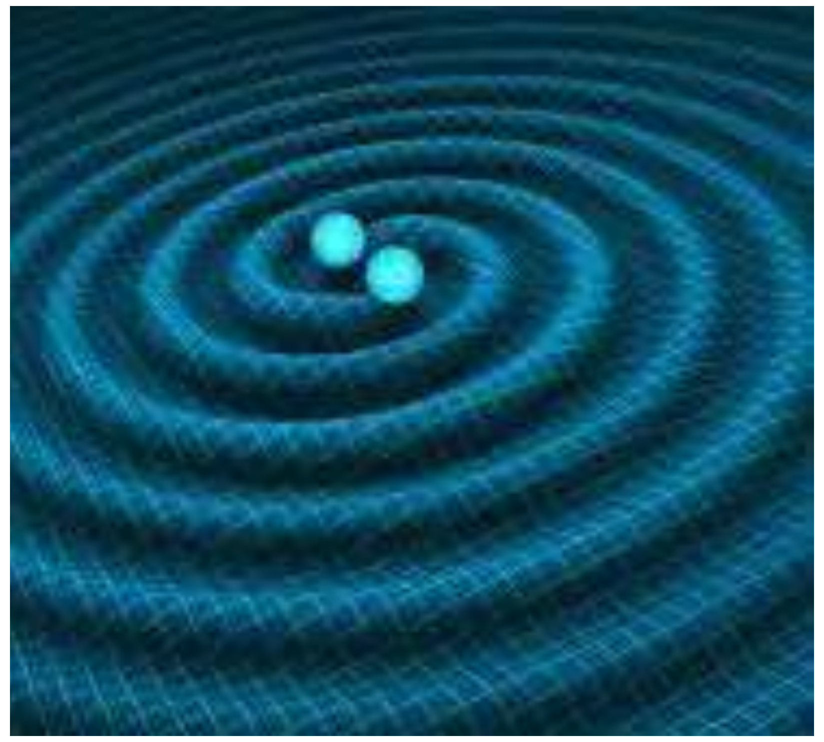
new SHARP lenses





Observational cosmology beyond standard probes

contact: Michele Moresco (UniBo, *michele.moresco@unibo.it*) – office 4S12



Cosmology with gravitational waves as standard candles

Gravitational waves are amongst the most promising new cosmological probes. They can provide a measurement of the distance to the source, and if a EM counterpart is identified, they can be used as standard (dark or bright) sirens.

We recently developed a code (**CHIMERA** https://github.com/CosmoStatGW/CHIMERA/, Borghi et al. 2024) that allows to derive joint constraints on cosmological parameters and on the astrophysical population of binary black holes (BBH).

Several different projects can be explored:

- Study of the impact of a redshift-evolving BBH mass function: from astrophysics to cosmology;

- Forecasts on astrophysics and cosmology with incoming and future GW observations with a non-parametric BBH mass function;

- Impact of peculiar velocities in Ligo-Virgo-Kagra O4 and O5 dark sirens analyses;

- Enhancing GW analysis with galaxy clustering information: a new method to assess and correct for incomplenetess in the cosmological and astrophysical analysis.

contacts: **M. Moresco, N. Borghi, A. Cimatti** (UniBo)

Observational cosmology beyond standard probes

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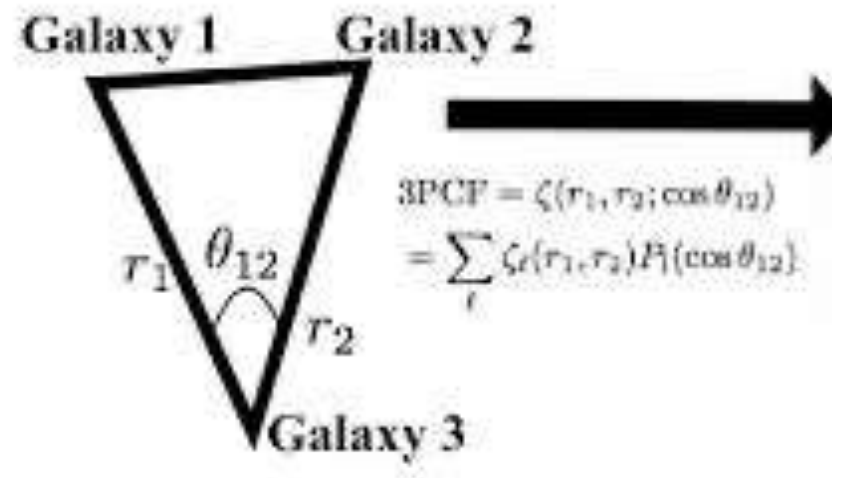

Exploring BAO constraints in the three-point correlation function

Three-point correlation function (3PCF) is a powerful statistical tool to study the statistical distribution of particles (haloes, clusters, galaxies), and it is in particular fundamental to detect non-Gaussian signal and obtain complementary constraints w.r.t lower-order statistics. It will be interesting to explore the constraining power of the 3PCF to get information on the BAO signal, and measuring cosmological parameters in comparison and combination with the 2PCF get set constraints of various cosmological parameters (the age of the Universe, the Hubble constant, Omega_matter).

contacts: M. Moresco, M. Guidi, F. Marulli, L. Moscardini, A. Cimatti (UniBo)

The expansion history of the Universe with cosmic chronometers in the BOSS-DR3 survey

The Cosmic chronometers method (**see Moresco et al. 2022, https://arxiv.org/abs/2201.07241**) is a new cosmological probe that allows to directly measure the expansion history of the Universe (the Hubble parameter) without any cosmological assumption. By measuring the relative ages of passive galaxies in the BOSS-DR3 survey, we will explore which constraints can be obtained on H(z~0.3-0.7), and, in combination with current measurements, how it is possible to improve the determination of various cosmological parameters.

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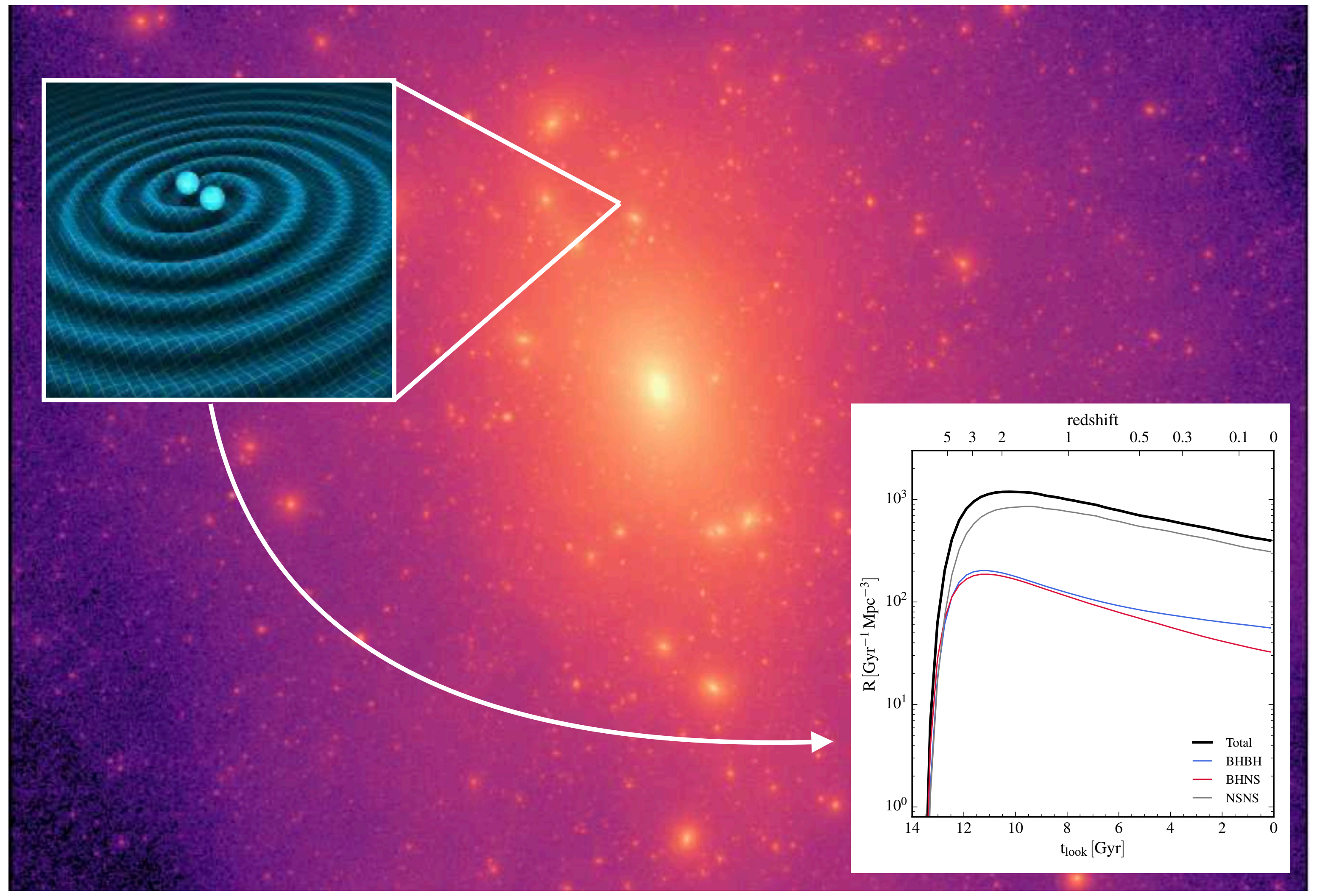
Cosmology with gravitational waves

Main Contacts: Marco Baldi (marco.baldi5@unibo.it) and Federico Marinacci (federico.marinacci2@unibo.it)

The evolution of structures in the Universe leads to the formation of **galaxies where compact objects such as Black Holes and Neutron Stars are produced** as the final stages of stellar evolution processes. These compact objects may form gravitationally bound binary systems that **loose energy by emitting gravitational waves and eventually merge** into a single object. Gravitational waves from **such merger events can now be detected** with large interferometers (such as LIGO/Virgo, and in the next future the Einstein Telescope), and provide **a new observational window on the Universe**.

With **large-volume and high-resolution cosmological simulations of galaxy formation** it is now possible to **predict the spatial and frequency distributions** of these gravitational wave events, and use them as a new probe to test astrophysical and cosmological models



<u>Possible Thesis projects</u>:

- **Analyse large catalogs of gravitational wave events to test their potential constraining power on cosmological parameters**
- **Optimise the pipeline for producing and post-processing GW mocks**

For direct information:

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