Pacific Northwest NATIONAL LABORATORY

A comparative study of dark matter flow & hydrodynamic turbulence and its applications

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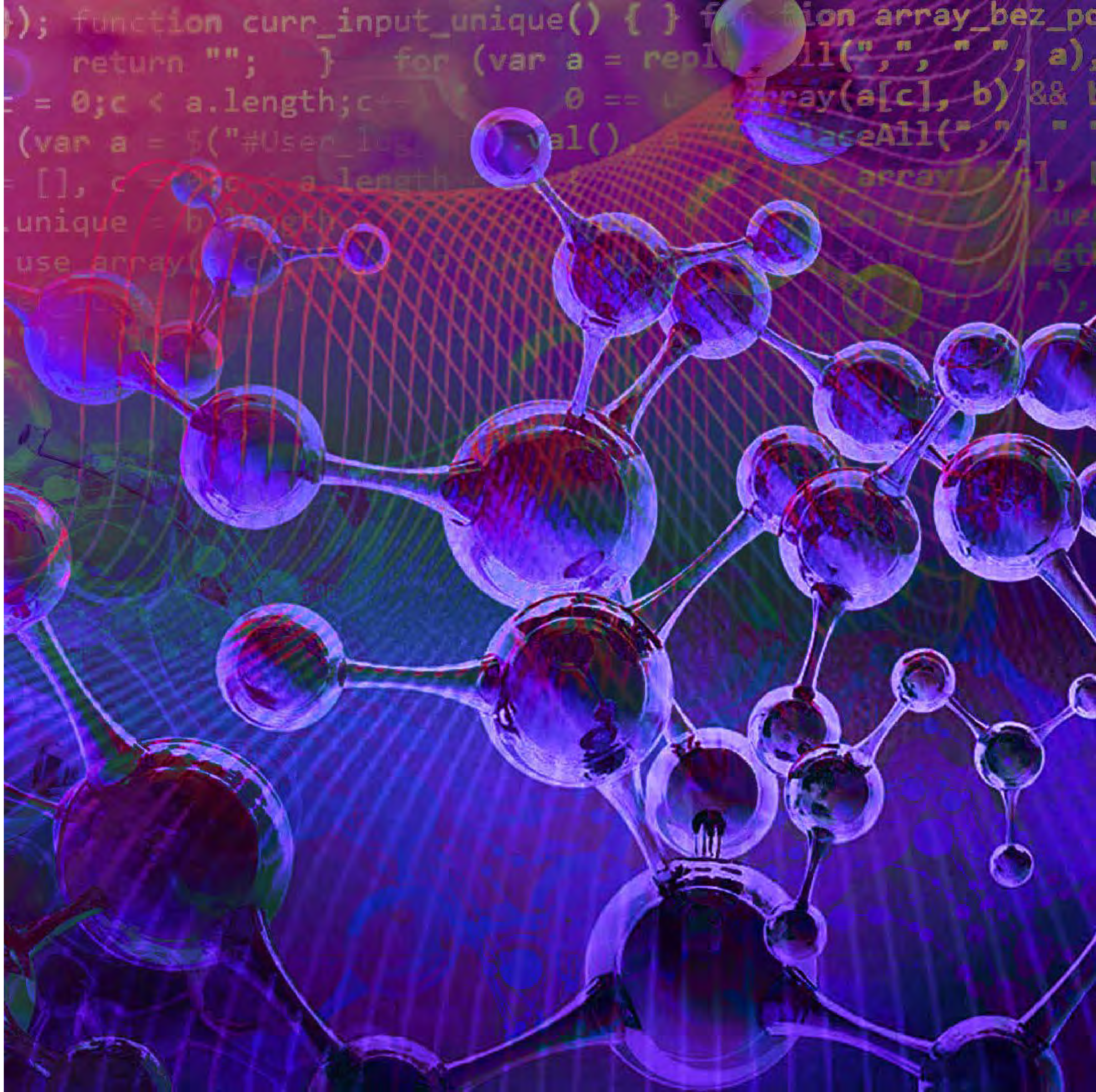


Preface

Dark matter, if exists, accounts for five times as much as ordinary baryonic matter. Therefore, dark matter flow might possess the widest presence in our universe. The other form of flow, hydrodynamic turbulence in air and water, is without doubt the most familiar flow in our daily life. During the pandemic, we have found time to think about and put together a systematic comparison for the connections and differences between two types of flow, both of which are typical non-equilibrium systems.

The goal of this presentation is to leverage this comparison for a better understanding of the nature of dark matter and its flow behavior on all scales. Science should be open. All comments are welcome.

Thank you!

Data repository and relevant publications

Structural (halo-based) approach:

0.	Data https://dx.doi.org/10.5281/zenodo.6541230
1.	Inverse mass cascade in dark matter flow and effects on halo mass functions https://doi.org/10.48550/arXiv.2109.09985
2.	Inverse mass cascade in dark matter flow and effects on halo deformation, energy, size, and density profiles https://doi.org/10.48550/arXiv.2109.12244
3.	Inverse energy cascade in self-gravitating collisionless dark matter flow and effects of halo shape https://doi.org/10.48550/arXiv.2110.13885
4.	The mean flow, velocity dispersion, energy transfer and evolution of rotating and growing dark matter halos https://doi.org/10.48550/arXiv.2201.12665
5.	Two-body collapse model for gravitational collapse of dark matter and generalized stable clustering hypothesis for pairwise velocity https://doi.org/10.48550/arXiv.2110.05784
6.	Evolution of energy, momentum, and spin parameter in dark matter flow and integral constants of motion https://doi.org/10.48550/arXiv.2202.04054
7.	The maximum entropy distributions of velocity, speed, and energy from statistical mechanics of dark matter flow https://doi.org/10.48550/arXiv.2110.03126
8.	Halo mass functions from maximum entropy distributions in collisionless dark matter flow https://doi.org/10.48550/arXiv.2110.09676

Statistics (correlation-based) approach:

0.	Data https://dx.doi.org/10.5281/zenodo.6569898
1.	The statistical theory of dark matter flow for velocity, density, and potential fields https://doi.org/10.48550/arXiv.2202.00910
2.	The statistical theory of dark matter flow and high order kinematic and dynamic relations for velocity and density correlations https://doi.org/10.48550/arXiv.2202.02991
3.	The scale and redshift variation of density and velocity distributions in dark matter flow and two-thirds law for pairwise velocity https://doi.org/10.48550/arXiv.2202.06515
4.	Dark matter particle mass and properties from two-thirds law and energy cascade in dark matter flow https://doi.org/10.48550/arXiv.2202.07240
5.	The origin of MOND acceleration and deep-MOND from acceleration fluctuation and energy cascade in dark matter flow https://doi.org/10.48550/arXiv.2203.05606
6.	The baryonic-to-halo mass relation from mass and energy cascade in dark matter flow https://doi.org/10.48550/arXiv.2203.06899

Some fundamentals of dark matter research

Overview of dark matter research

- Key questions: Does it exist? Where is it? How much is it? and What is it?

- Observational evidences (Does it exist? Where is it? How much is it?)
  - Motion of galaxies in galaxy clusters
  - Rotation curves of spiral galaxies
  - Gravitational lensing
  - Bullet clusters
  - Cosmic microwave background (CMB)
  - ……
- The nature of dark matter (What is it?)
  - Massive astrophysical compact halo object (MACHO)
  - Primordial black holes
  - Axions
  - sterile neutrino
  - WIMPs (Weakly Interacting Massive Particles) ← Most popular
  - Superheavy dark matter
  - ……

Dark matter in galaxy clusters

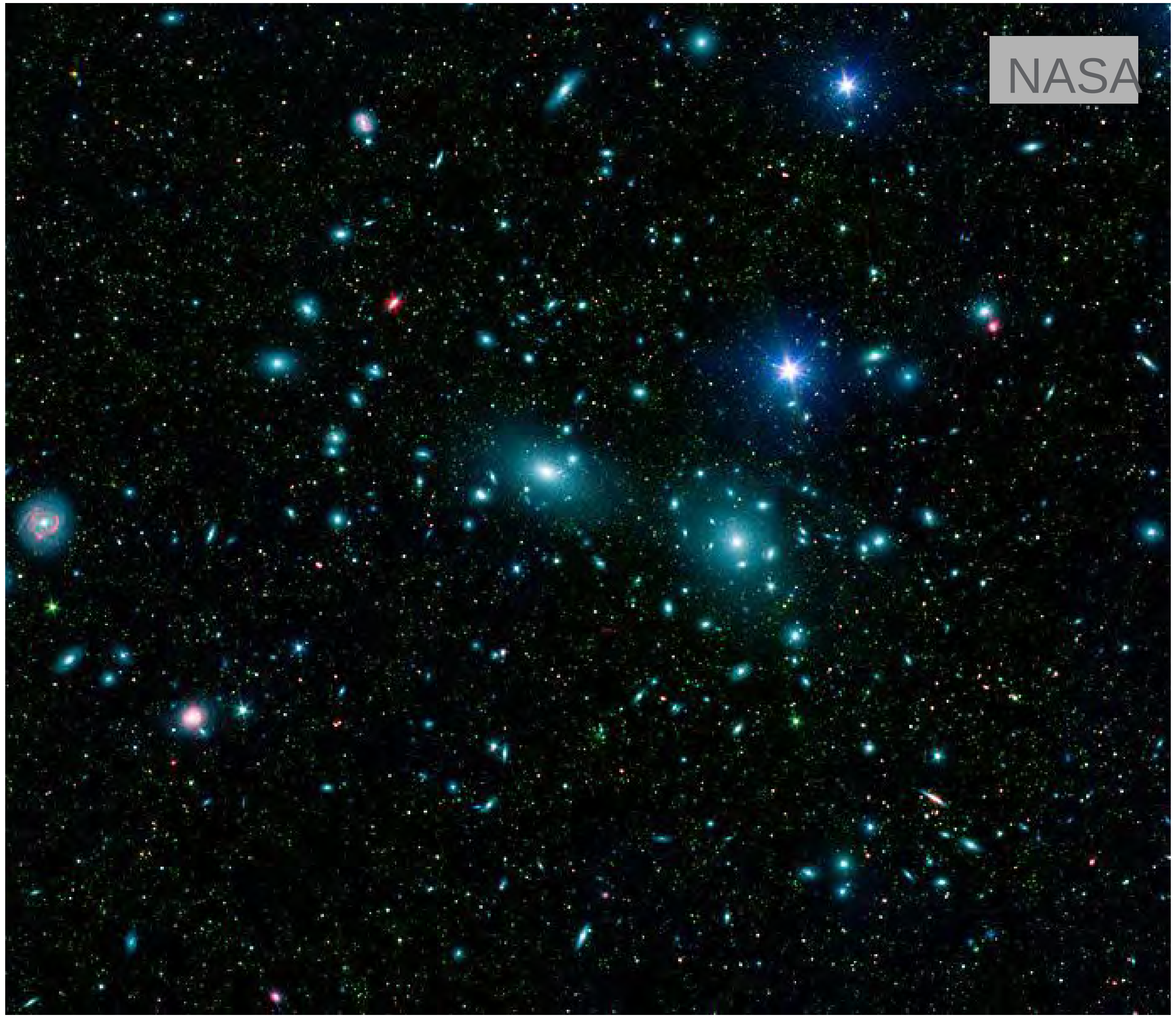
Zwicky (1937):
Coma cluster is much larger than expected!

Coma cluster:
~1000 galaxies
~20Mpc in diameter
~100Mpc from Earth (320Mlys)

1Mpc = 3.086e+19 KM = 3Mlys

Fritz Zwicky

- Measuring speed of galaxies moving in Coma
- Enormous speed found ~1000km/s
- Fast enough to rip the cluster apart
- Unseen matter that holds all galaxies together



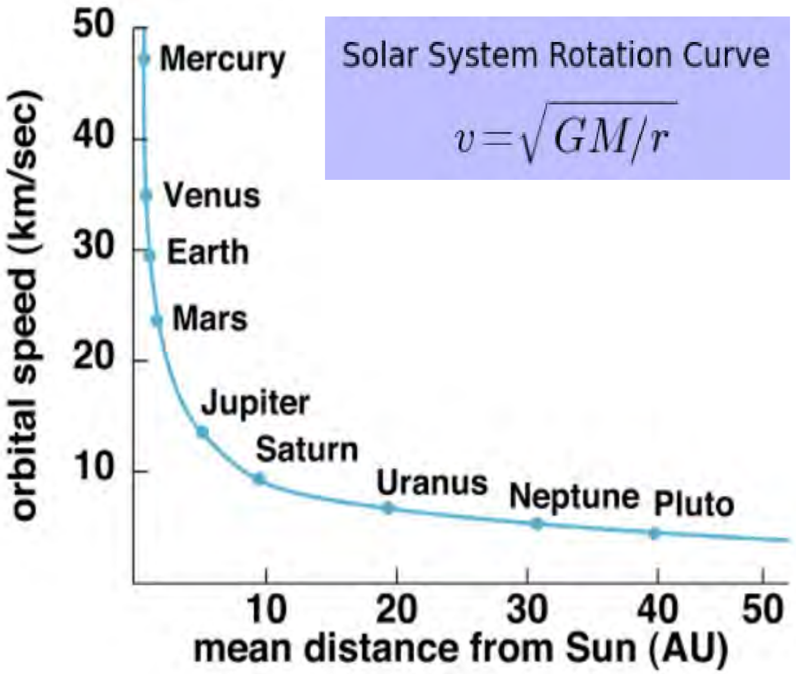
Coma cluster

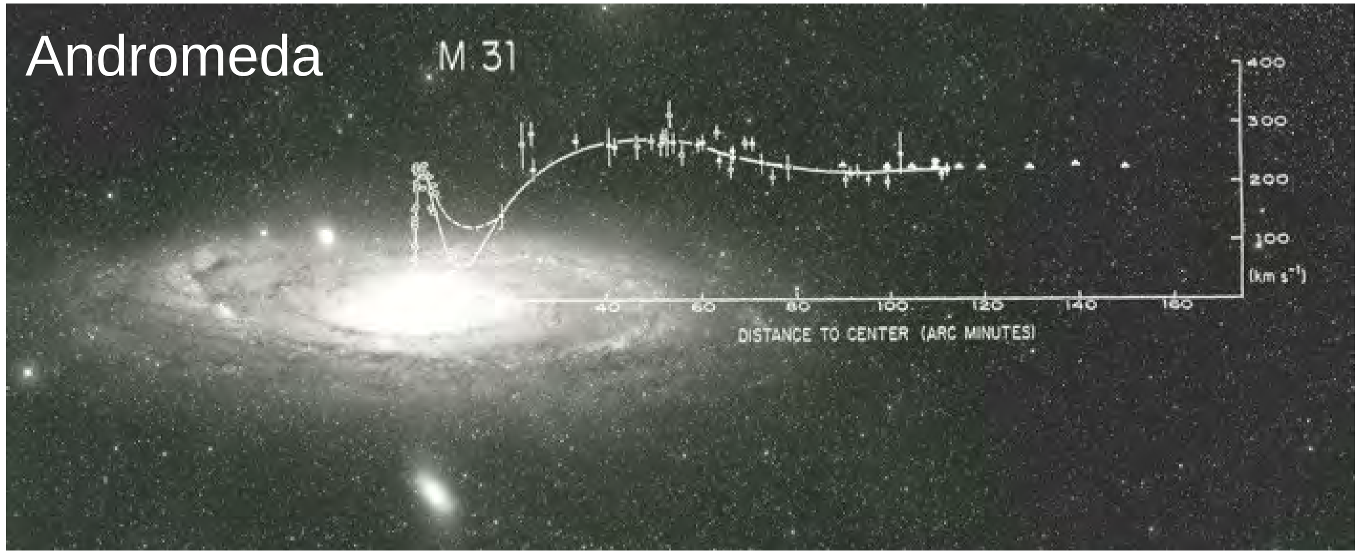
Dark matter in galaxy

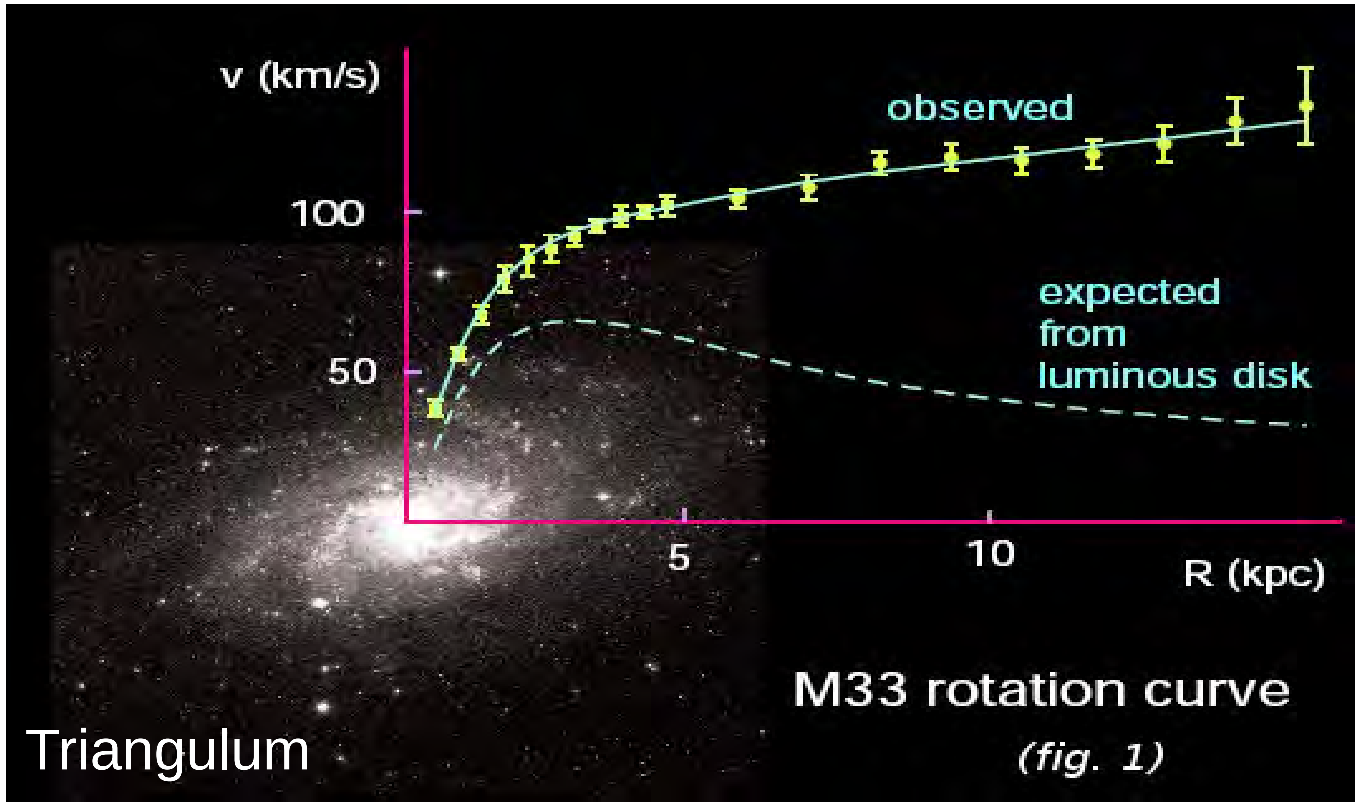
Rubin (1970s):
Rotation of M31
Andromeda Nebula

- Solar system rotation curve
- From Newtonian mechanics
- Galaxy flat rotation curve
- Unseen matter that holds galaxy

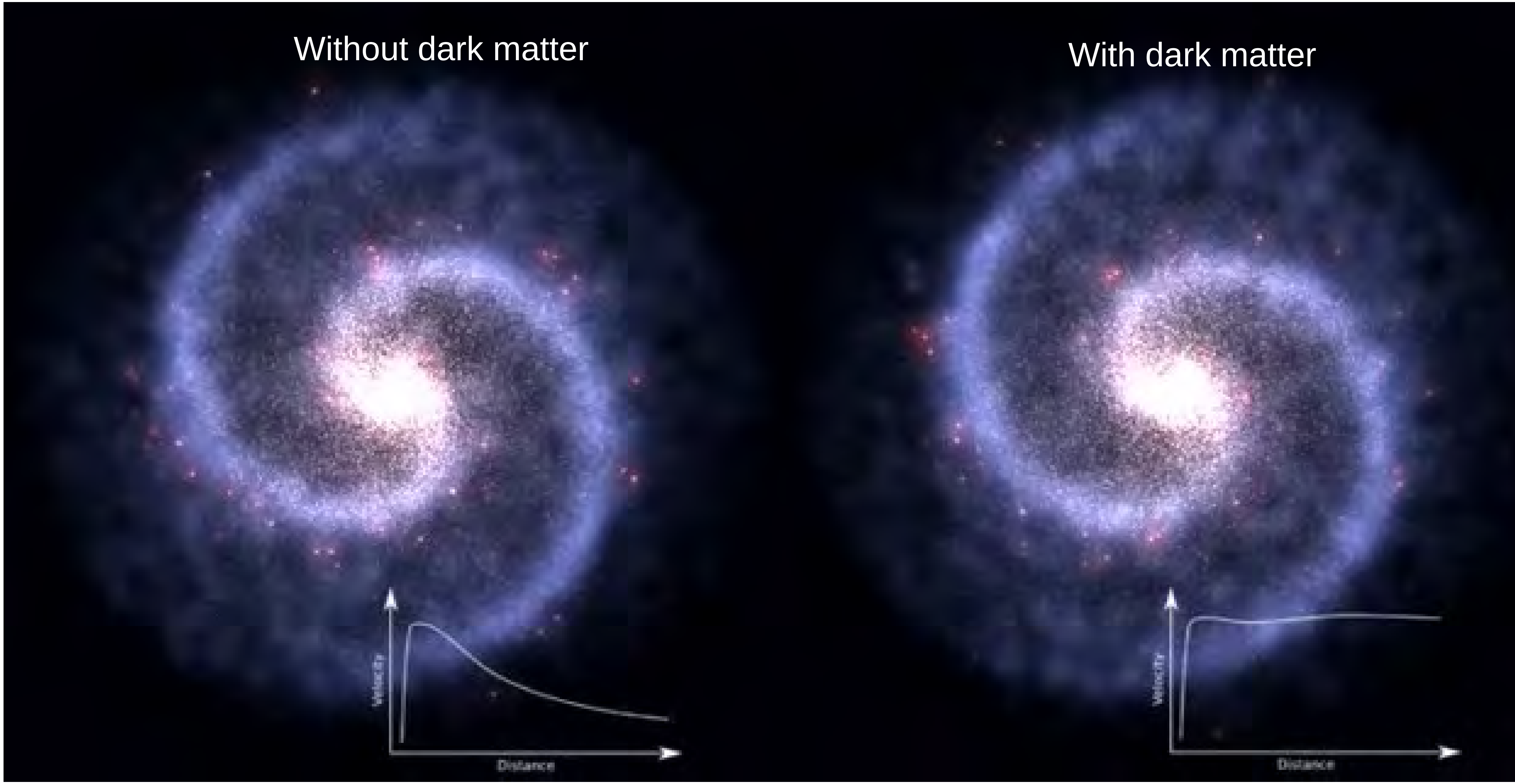
Vera Rubin





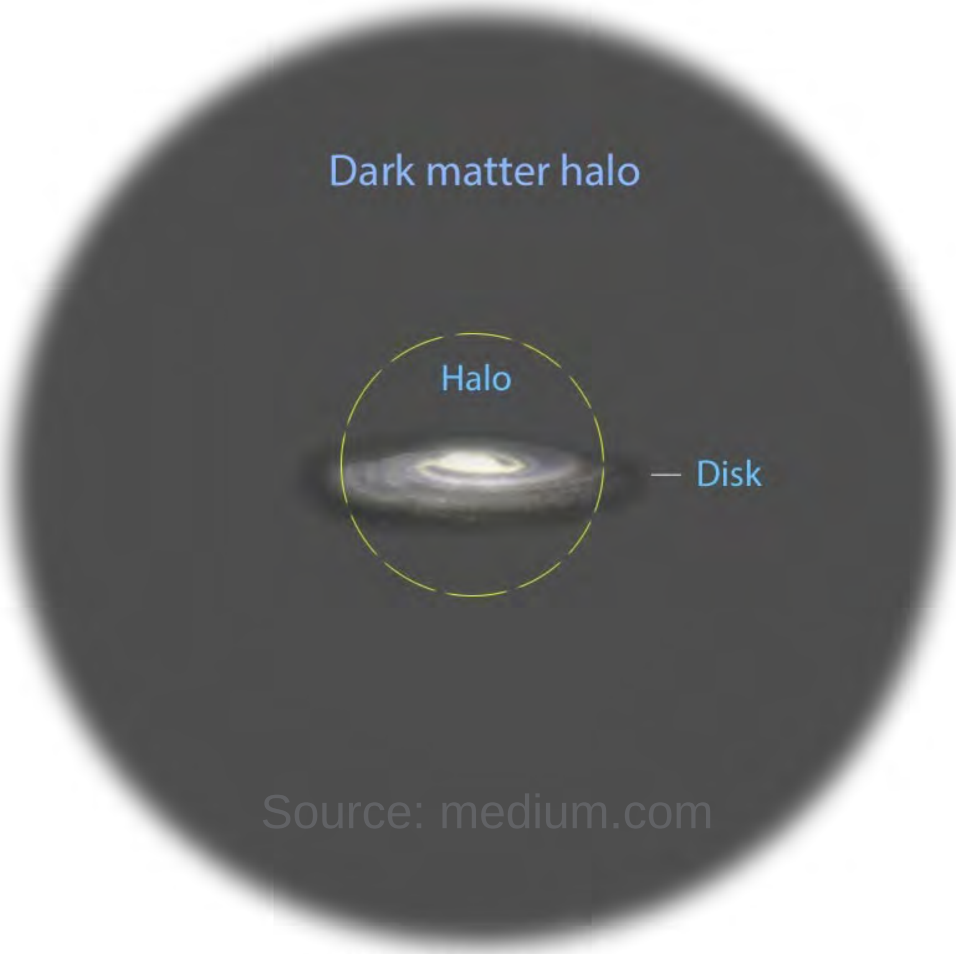


Effect of Dark matter on galaxy rotation curve



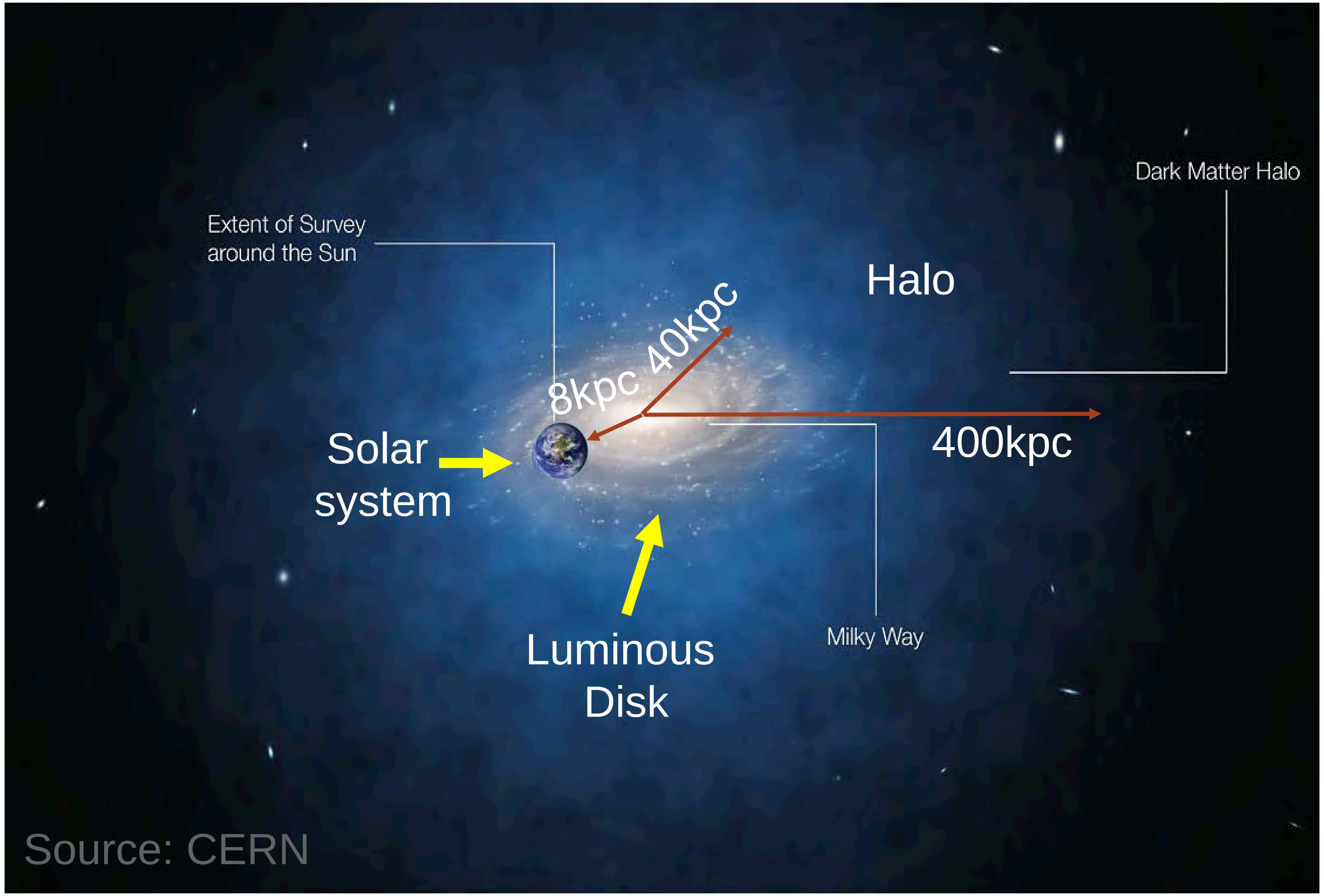
https://en.wikipedia.org/wiki/Galaxy_rotation_curve

Dark matter in our galaxy

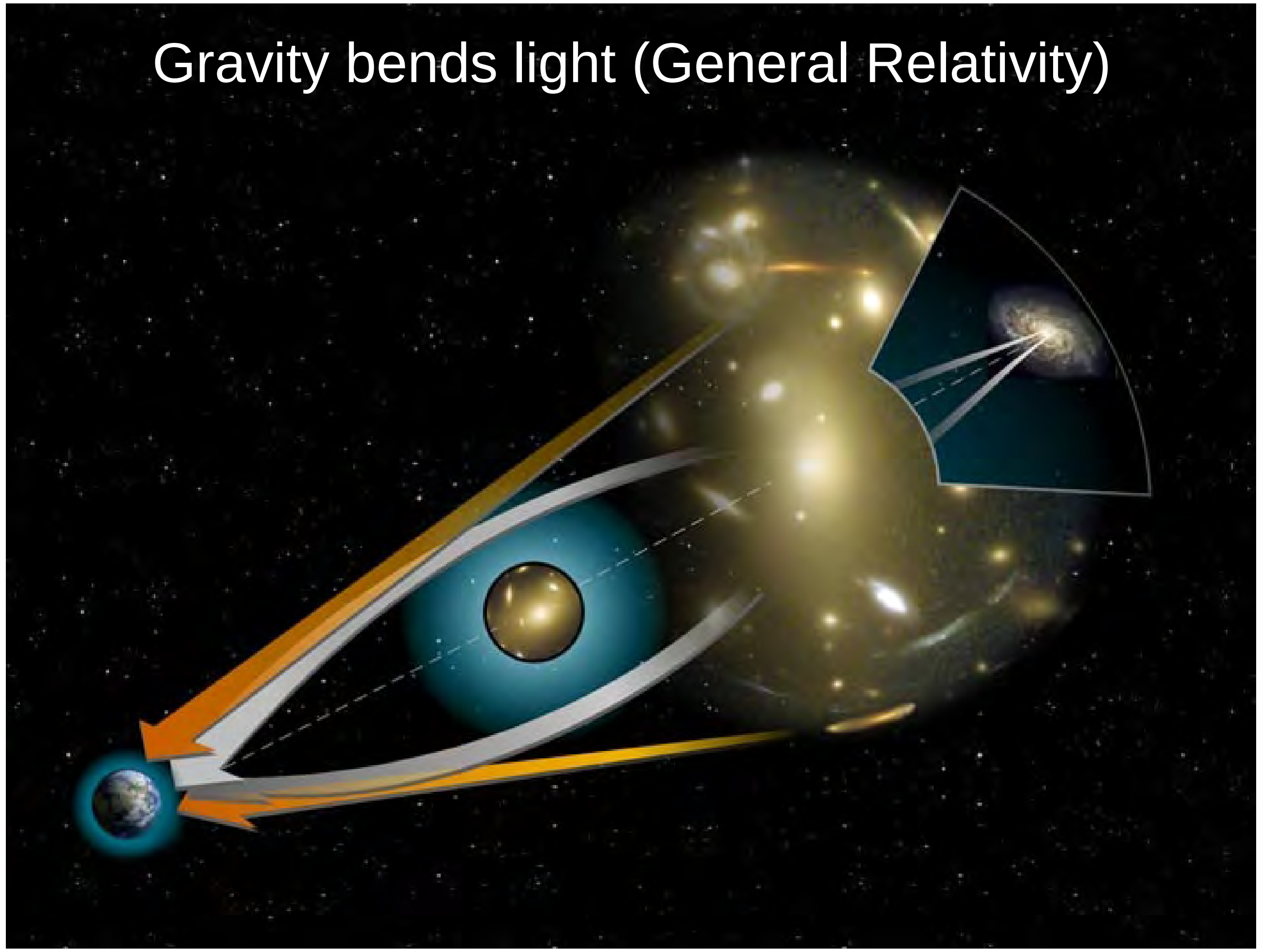


Milky Way model

Dark matter halo harbors our galaxy



Dark matter from gravitational lensing



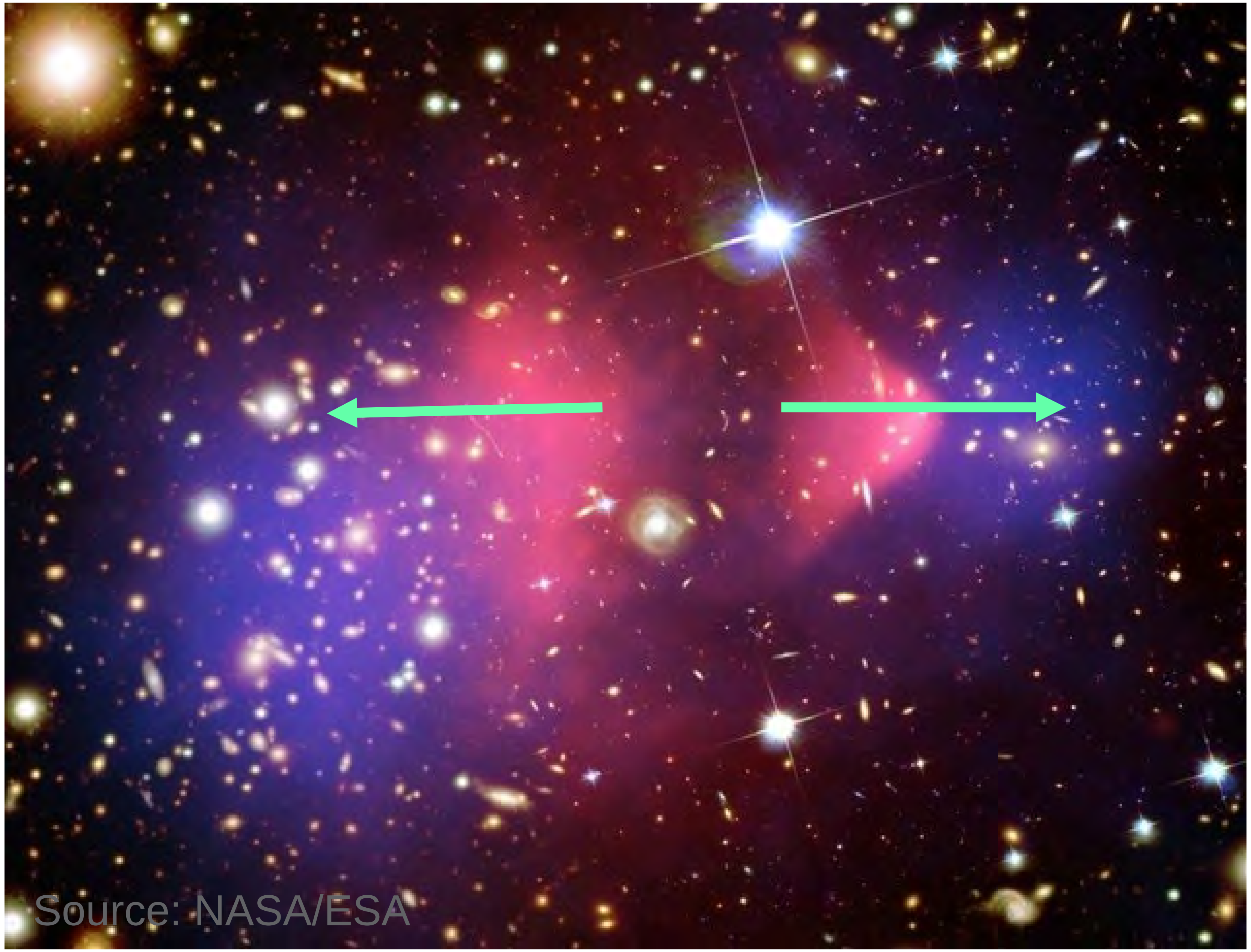
- Gravitational lensing by galaxy cluster
- Gravity from mass of matter bends light
- Effect of bending is stronger than expected from visible matter only

Dark matter from bullet cluster (2000s)

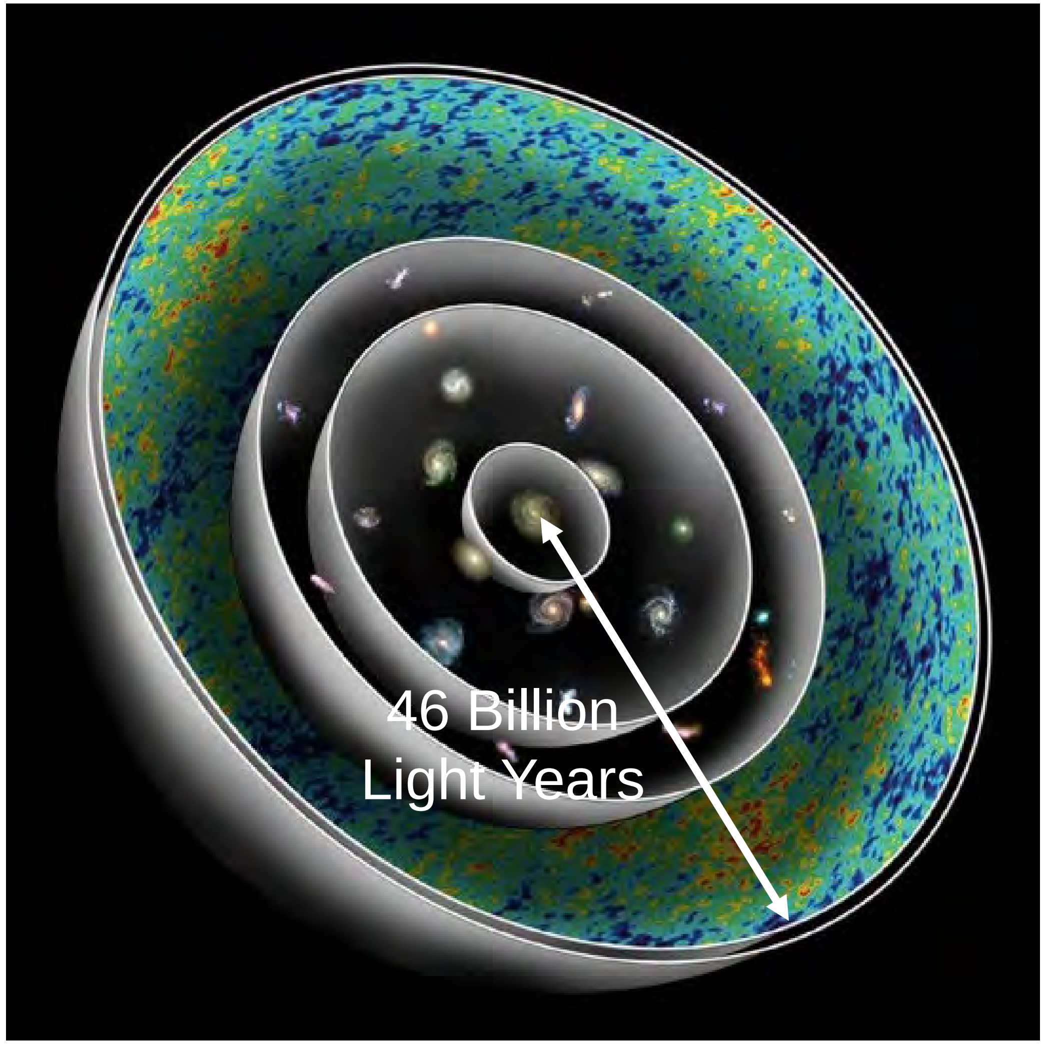
Composite image of X-ray (pink) and weak gravitational lensing (blue) of the famous Bullet Cluster of galaxies (colliding)

Red: gas and dust (baryonic matter)
Moving slower because of viscosity (collisional due to electromagnetic interactions)

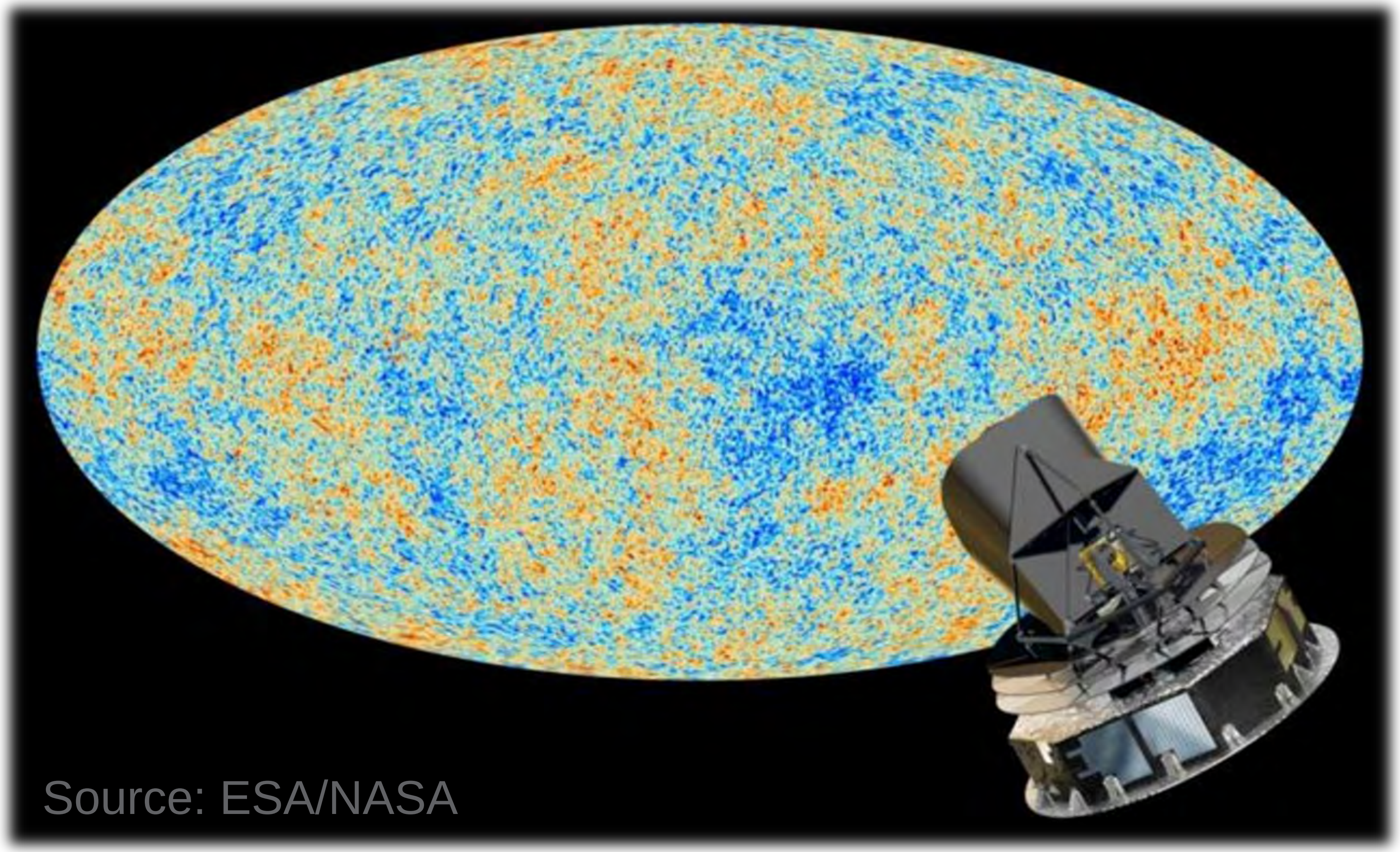
Blue: dark matter
Moving faster than baryonic matter because of collisionless nature



Dark matter from cosmic microwave background

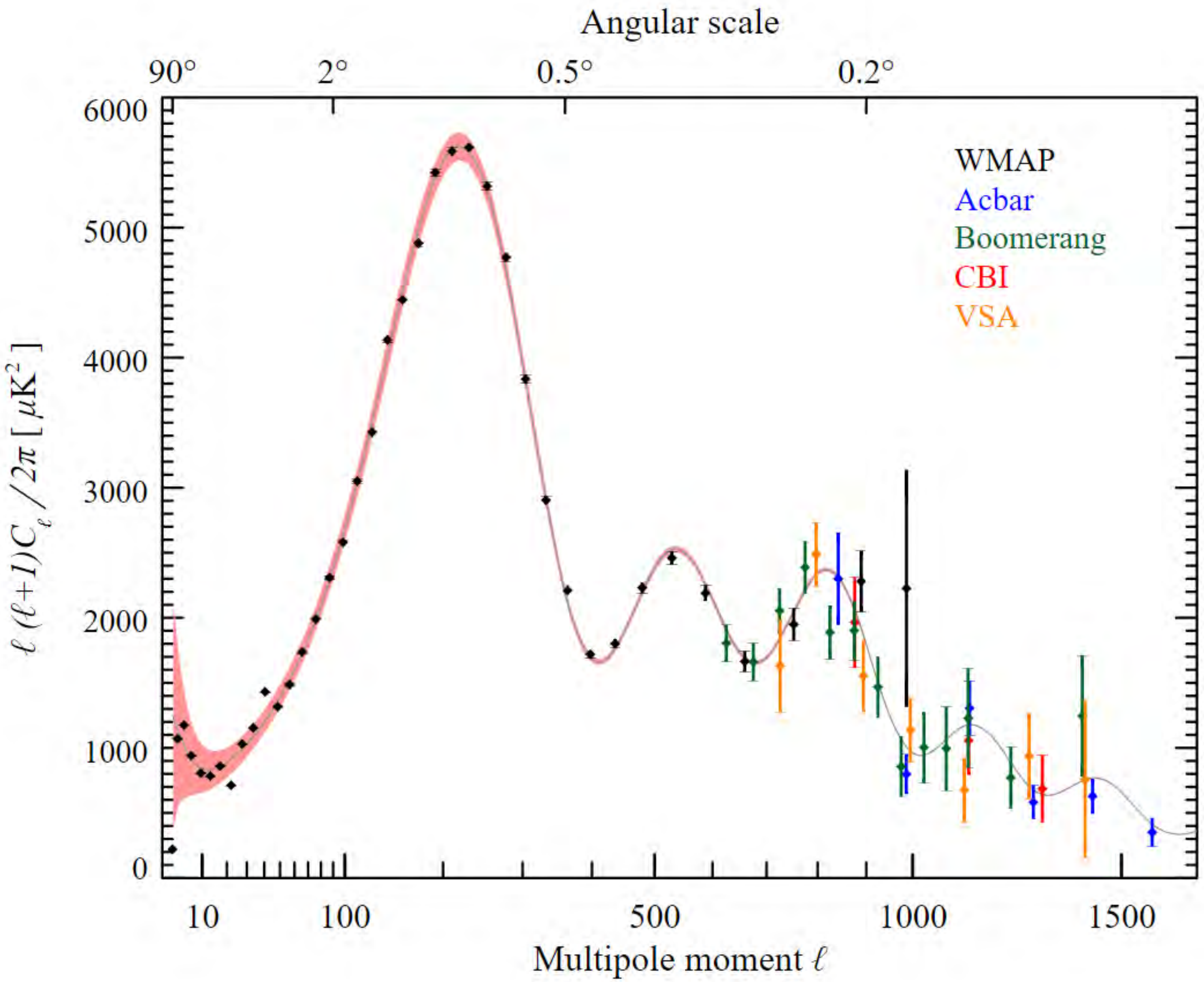


Cosmic Spheres of Time
http://new-universe.org/



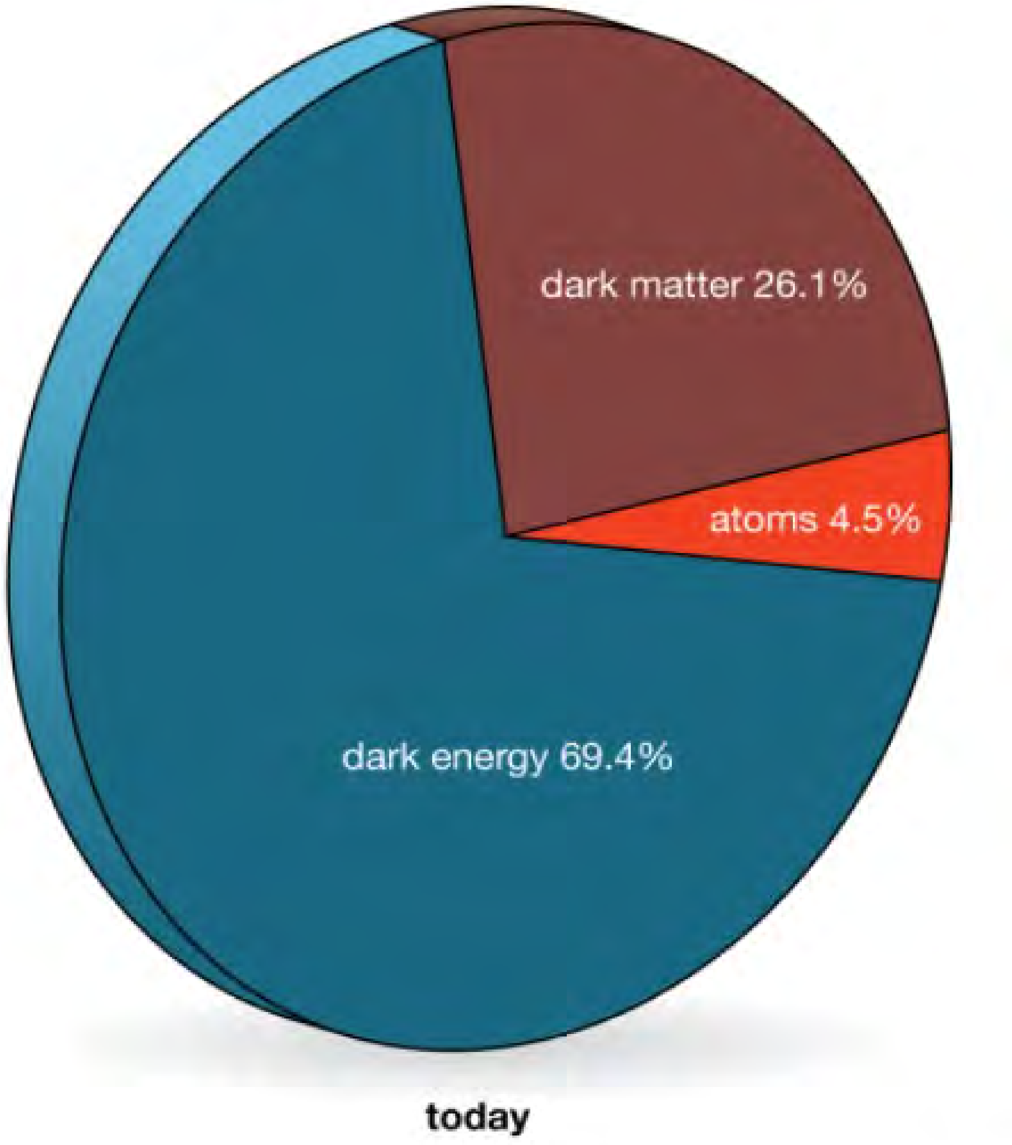
Planck results of CMB temperature anisotropy
(4-year survey from 2009-2013)
Baby universe: 400,000 years after Big Bang
cold (blue) and hot (red)

Quantifying amount of dark matter from CMB



Power spectrum of the CMB temperature anisotropy in terms of the angular scale. Also shown is a theoretical (double-dark ΛCDM) model (solid line)

Today's universe matter-energy content



Brief timeline for dark matter research (~100 years)

1930s: Discovery of galaxy cluster velocity ~1000km/s

1960s: Discovery of the CMB

1970s: Discovery of flat galaxy rotation curves

1980s: Cold Dark Matter (CDM) model proposed; MOND theory;

1992: CMB fluctuations from COBE Confirms CDM prediction

1998: Evidence for Dark Energy and accelerating expansion: Type Ia supernova

2000: ΛCDM as the standard cosmological model

2003-2008: WMAP and LSS data Confirm ΛCDM predictions

2013-2018: Planck data of CMB anisotropies Confirm ΛCDM predictions

2022: James Webb Space Telescope

2030s: Discovery of dark matter particles??

COBE: COsmic Background Explorer (NASA)
WMAP: Wilkinson Microwave Anisotropy Probe (NASA)
LSS: Large Scale Structure (LSS) of the universe
CMB: Cosmic Microwave Background
ΛCDM: dark energy + cold dark matter (double dark)
Planck: European Space Agency (ESA)

What is dark matter?

No definite answer.

What it should not be?

- No electric charge
- No color charge (strong interactions)
- No strong self-interaction
- No fast decay: stable and long-lived
- Not any particles in standard model of particle physics

What it should be?

- Non-baryonic
- Cold (non-relativistic)
- Collisionless
- Dissipationless (optically dark)
- Sufficiently smooth with a fluid-like behavior (justifies a fluid dynamics approach)

What is the nature of dark matter flow (DMF)?
Dark matter flow can be described by a non-relativistic, self-gravitating, collisionless fluid dynamics (SG-CFD).

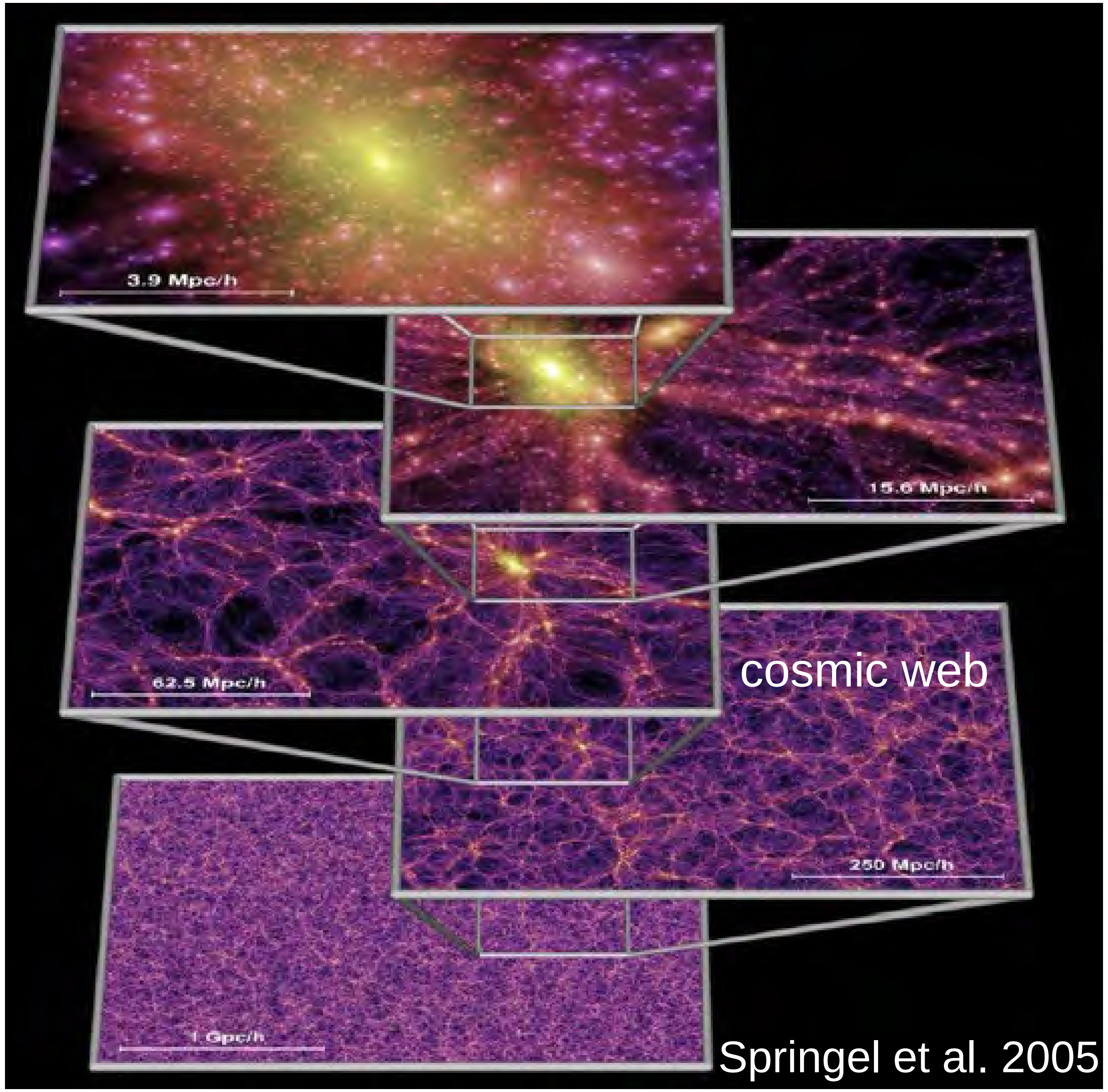
Then why dark matter flow? understanding dark matter flow behavior on entire spectrum.

Dark matter particle mass & properties? — 10^{-10}m

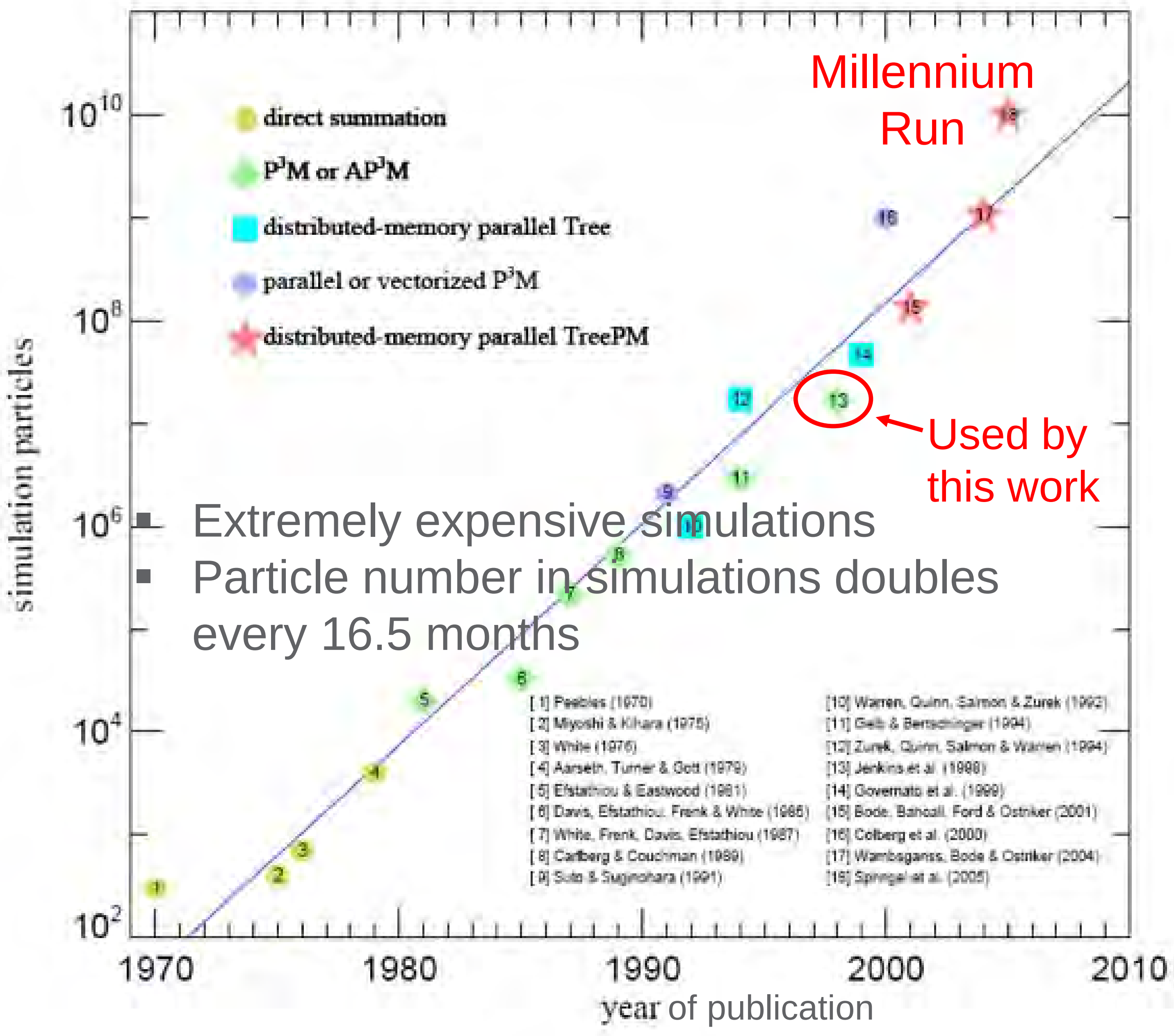
Halo scale structure property & evolution — Kpc~Mpc ~10^{20}m

Large scale structure formation & evolution — 100Mpc~10^{24}m

Cosmological N-body simulations



Springel et al. 2005



- Extremely expensive simulations
- Particle number in simulations doubles every 16.5 months

Dehnen and J. I. ReadThe European Physical Journal Plus, 126, 55

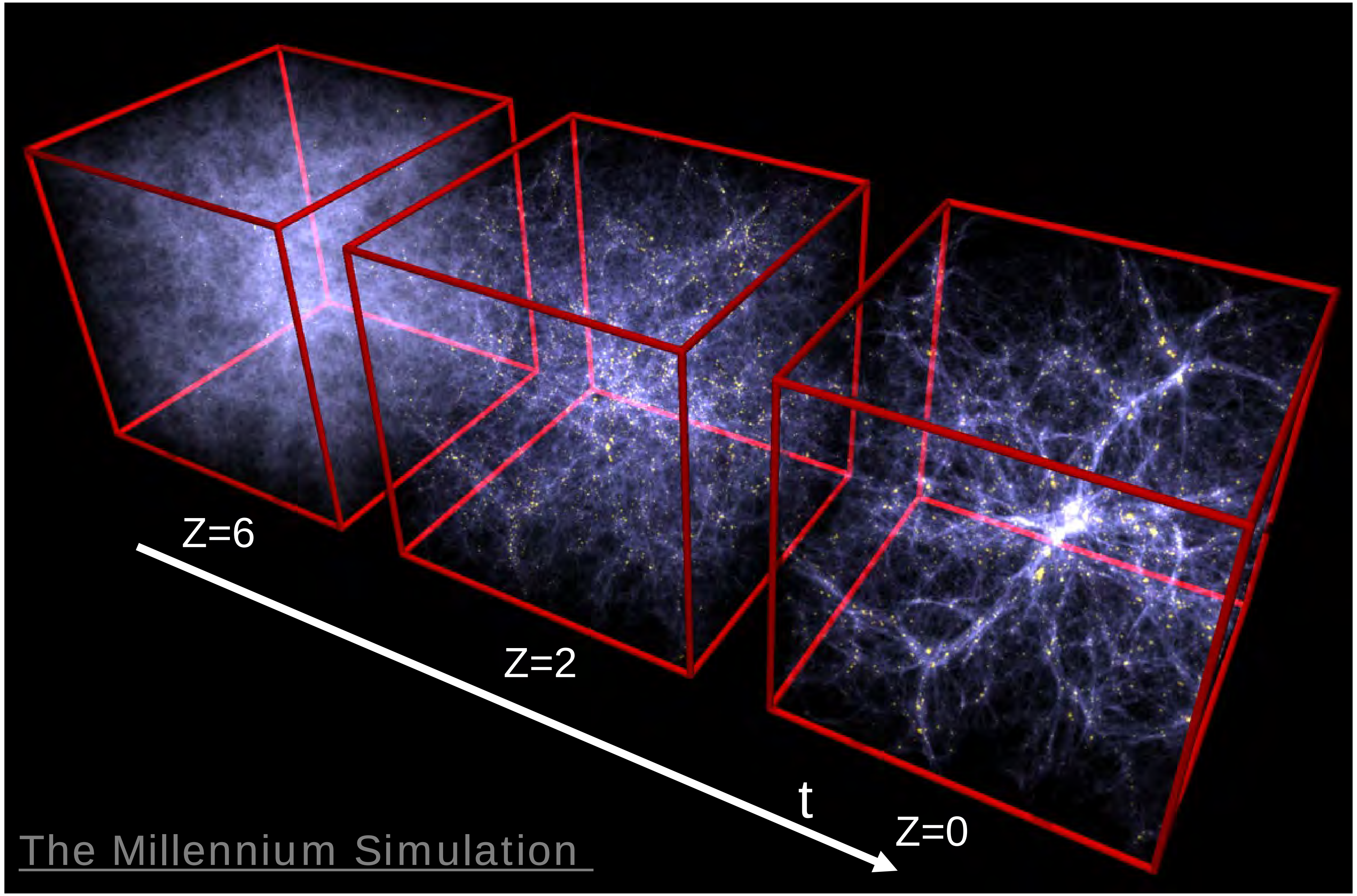
N-body simulations and dark matter flow

The Millennium Simulation:

- More than 10 billion "particles“
- Each with a billion Solar mass
- The large-scale structure of the universe ("the cosmic web")
- The largest simulation of dark matter structure at the time

Use N-body simulation:

- Self-gravitating collisionless fluid-like behavior
- Dark matter flow forms and evolves structures on both large and small scales



N-body simulations in this comparative study

Run	Ω_0	Λ	h	Γ	σ_8	$L(Mpc/h)$	N_p	$m_p(M_\odot/h)$	$l_{soft}(Kpc/h)$
SCDM1	1.0	0.0	0.5	0.5	0.51	239.5	256^3	2.27×10^{11}	36

- The numerical data are public available and generated from N-body simulations carried out by the Virgo consortium. https://wwwmpa.mpa-garching.mpg.de/Virgo/data_download.html
- As the first step, current study focus on the standard CDM power spectrum (SCDM) with matter-dominant gravitational flow.
- Similar analysis can be extended to other models with different assumptions and parameters.
- The same set of data has been widely used in many studies from clustering statistics to formation of halos in large scale environment, and test of models for halo abundances and mass functions.