ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 20 • The cosmic web of dark matter

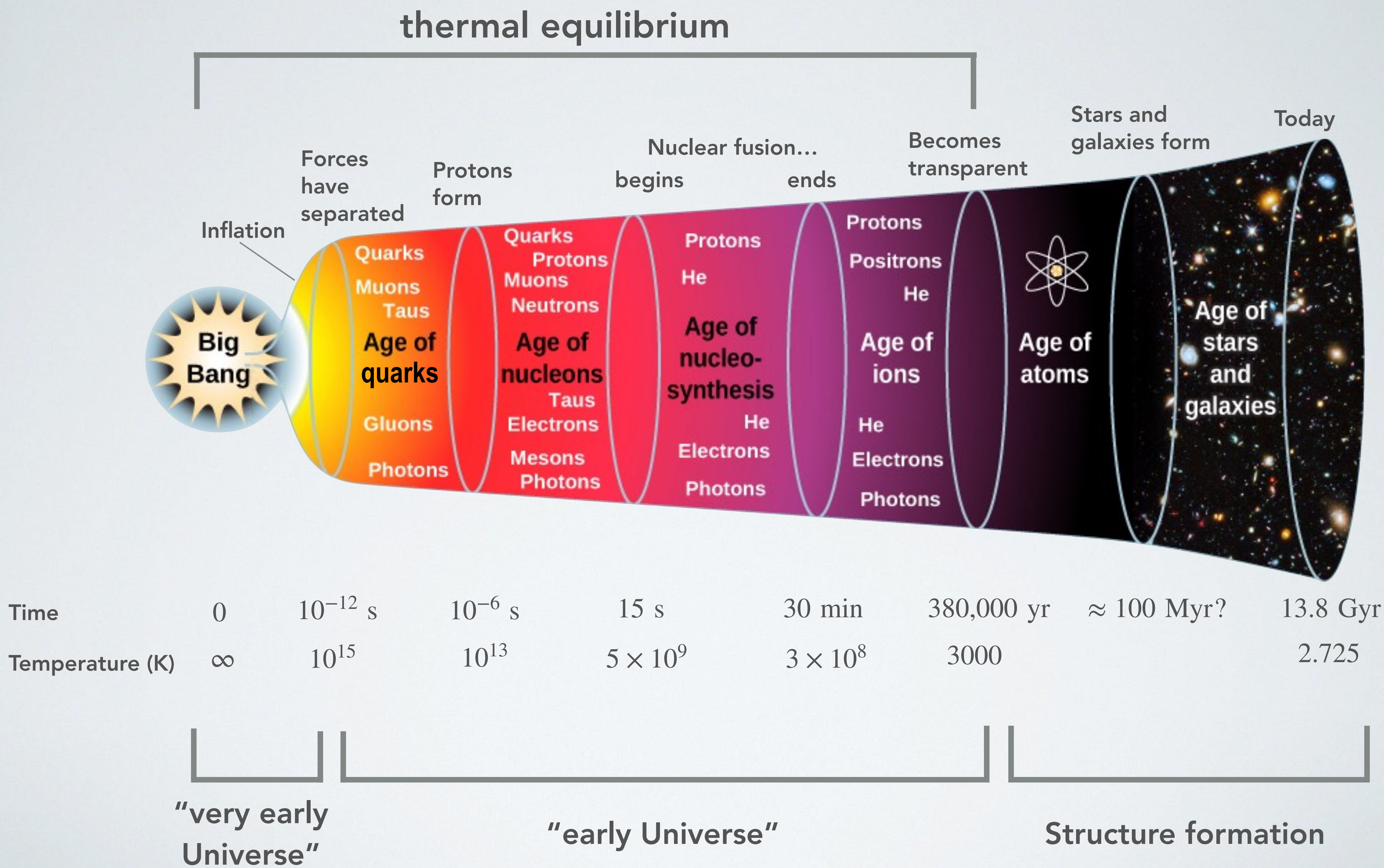
11/11/2020

Today

- What structure?
- From the CMB to dark matter
- Simulating the dark Universe
- The formation of halos
- What is dark matter?
- The cosmic web in 3D

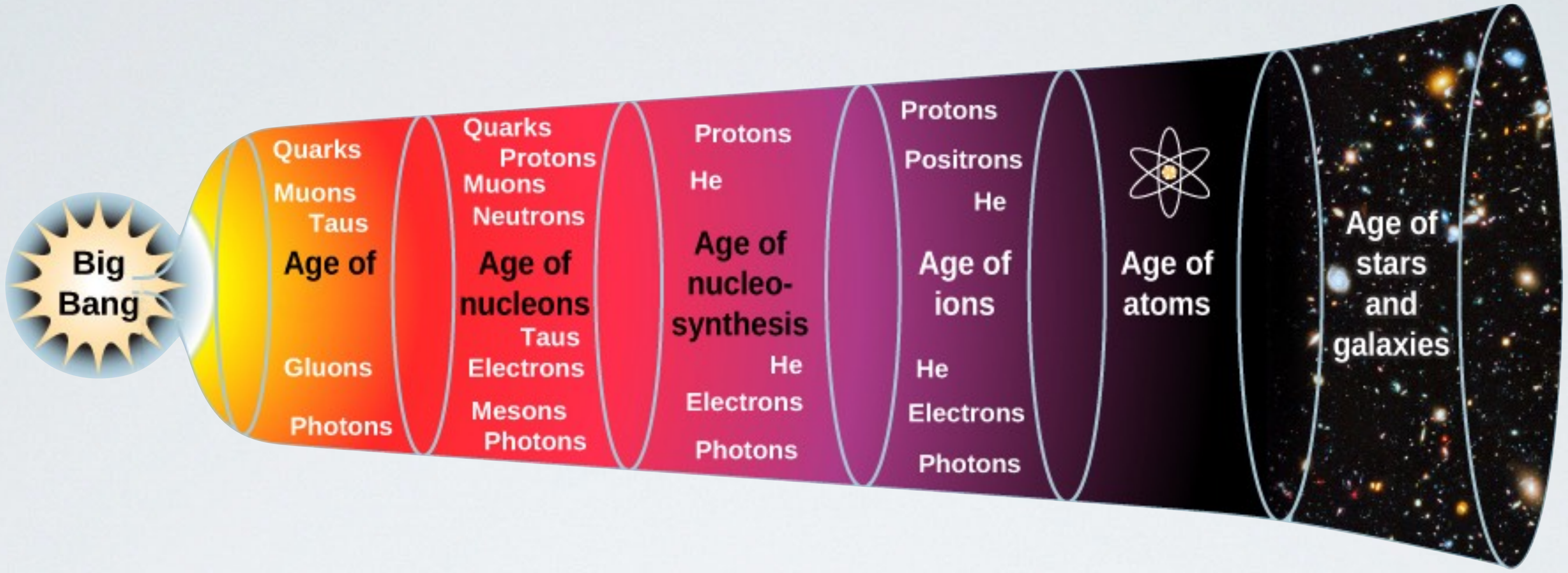
Part 1: What structure?

History of the Universe



SDSS / WMAP collaborations, Dinoj Surendran, Mark SubbaRao

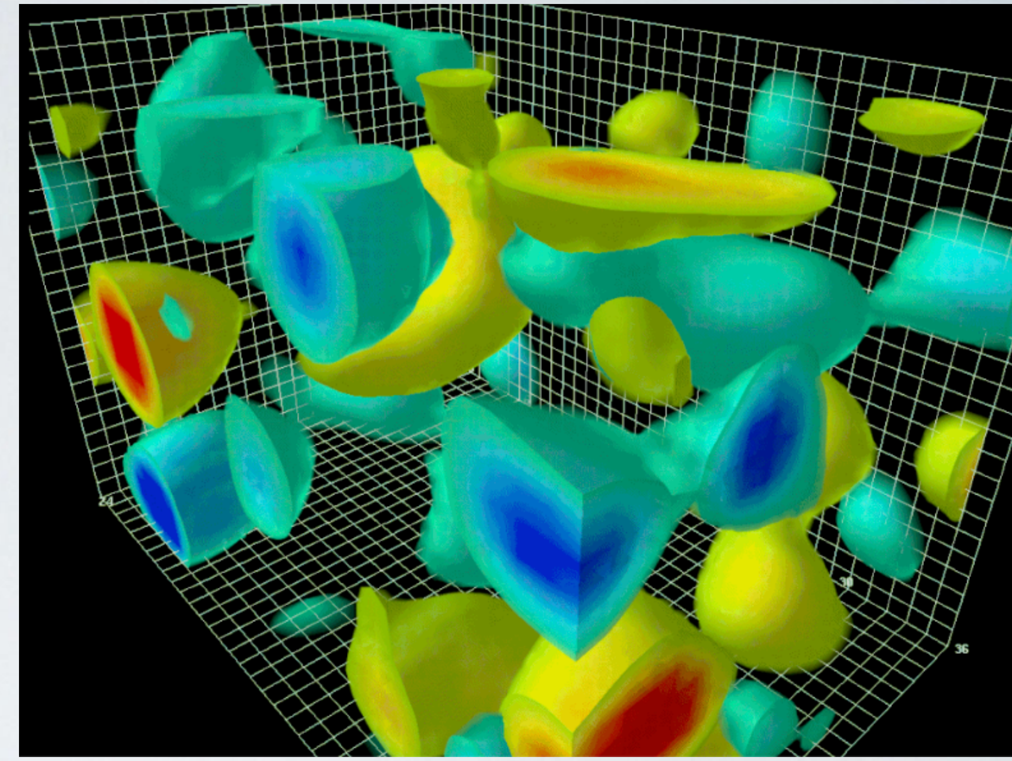
The big question



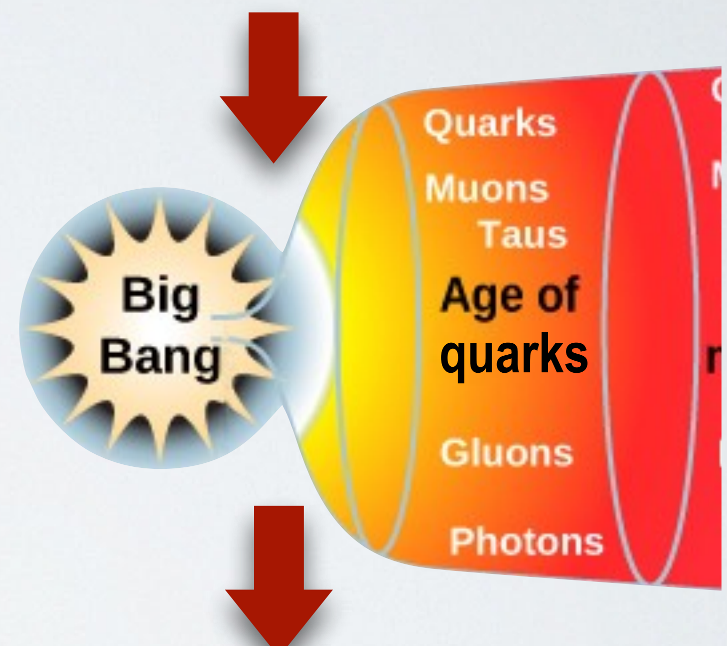
How to we go from an almost smooth early Universe to the structure we see today?

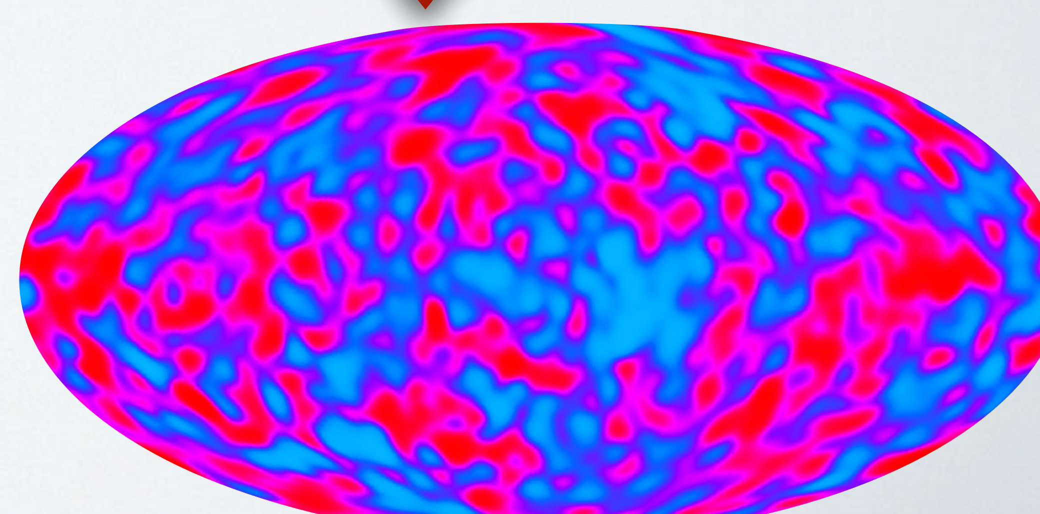
Short answer: gravity!

Evolution of fluctuations

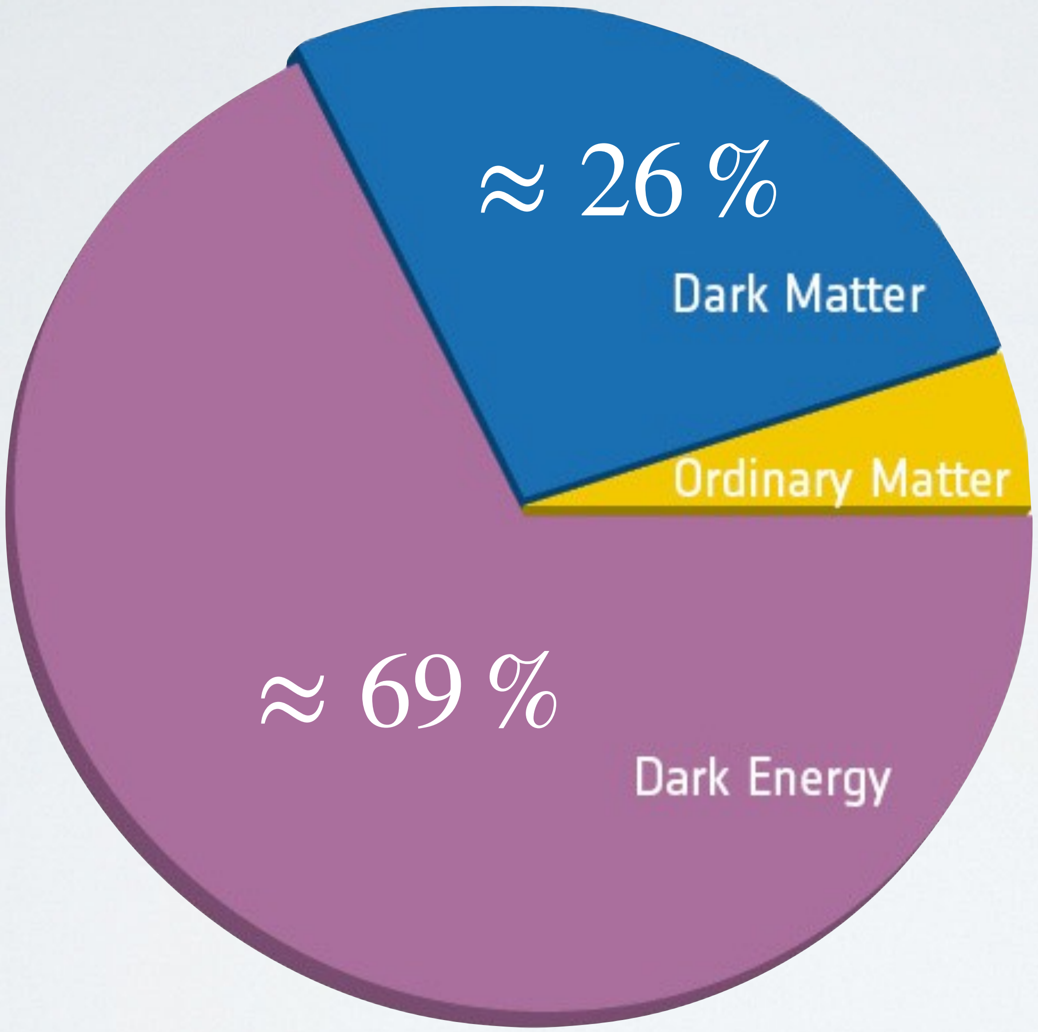


- Quantum fluctuations from Planck epoch are amplified during inflation (described by A_s and n_s parameters in ΛCDM)
- Spot pattern evolves during early Universe in a complicated way, giving rise to the fluctuations in the CMB
- Amplitude of 10^{-5} in CMB (= at epoch of recombination)
- **After recombination**, no more pressure from photons (which are free-streaming)
- **Denser regions exert stronger gravity**, pulling in more matter, leading to higher density
- This positive feedback loop leads to **gravitational collapse**





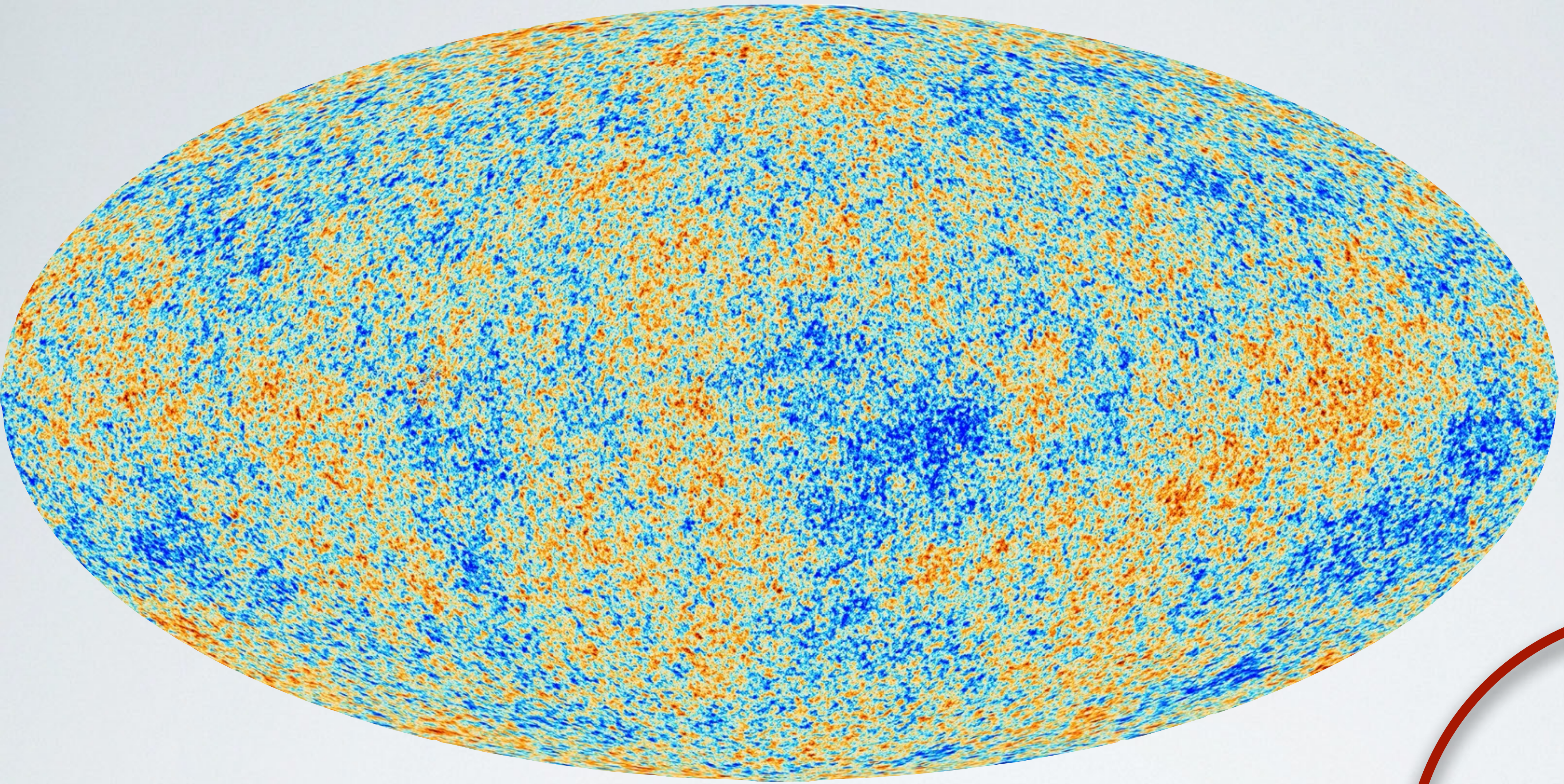
Contents of the Universe

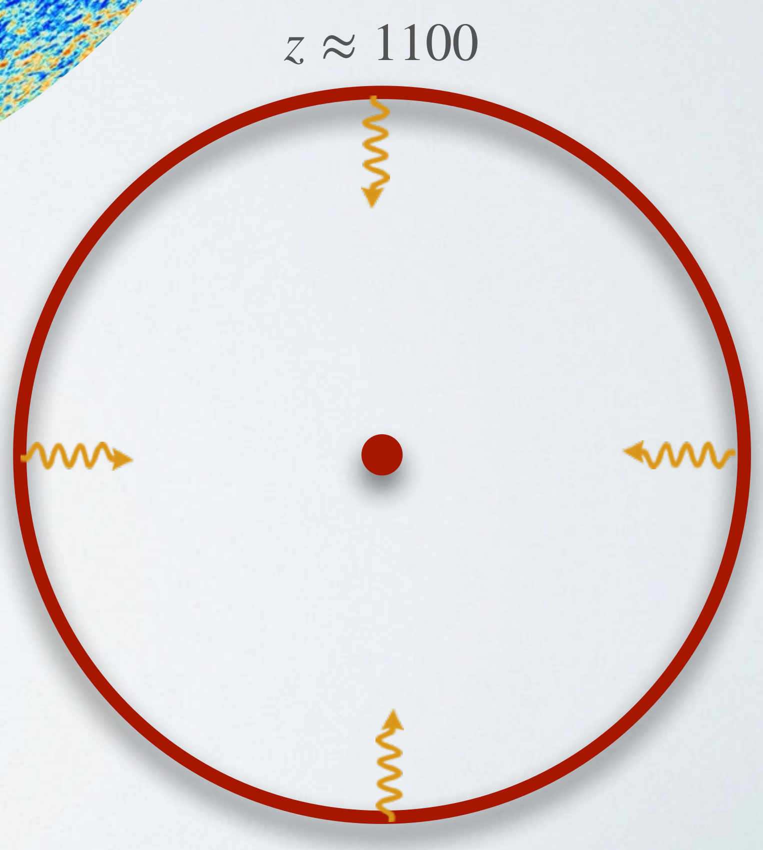


$\approx 4.9\,\%$ baryons

Part 2: From the CMB to dark matter

Start from the CMB





- CMB gives us information on a far-away sphere, **not everywhere in space**
- Cannot simulation the real Universe, only a **random version with statistically similar fluctuations**

Planck Collaboration 2015, 2018

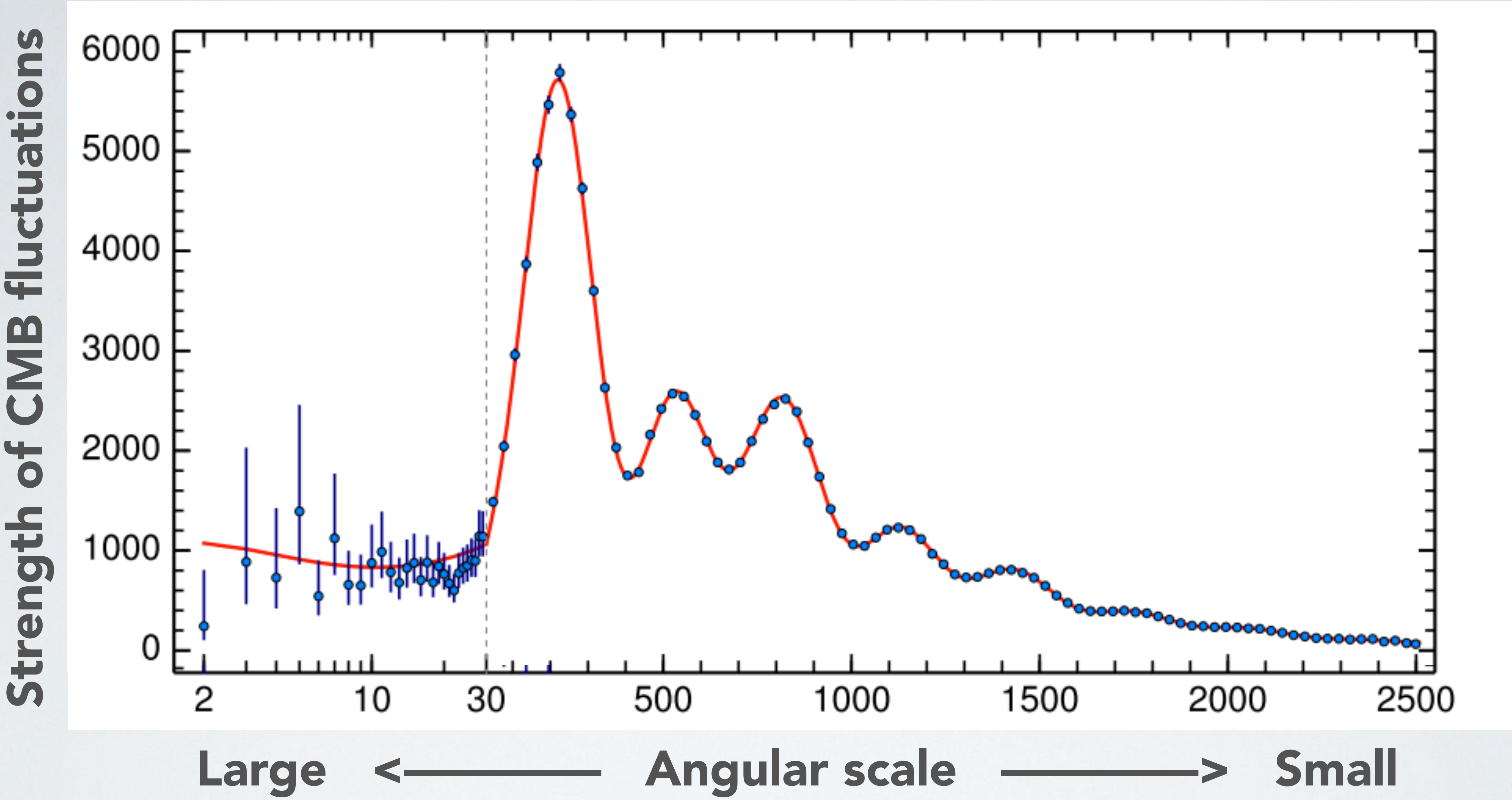
Participation: Recap

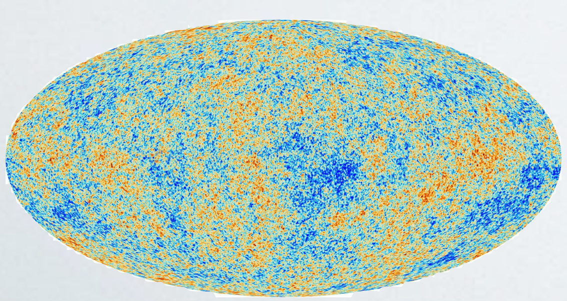
TurningPoint:
What does the CMB power spectrum tell us?

Session ID: diemer

30 seconds

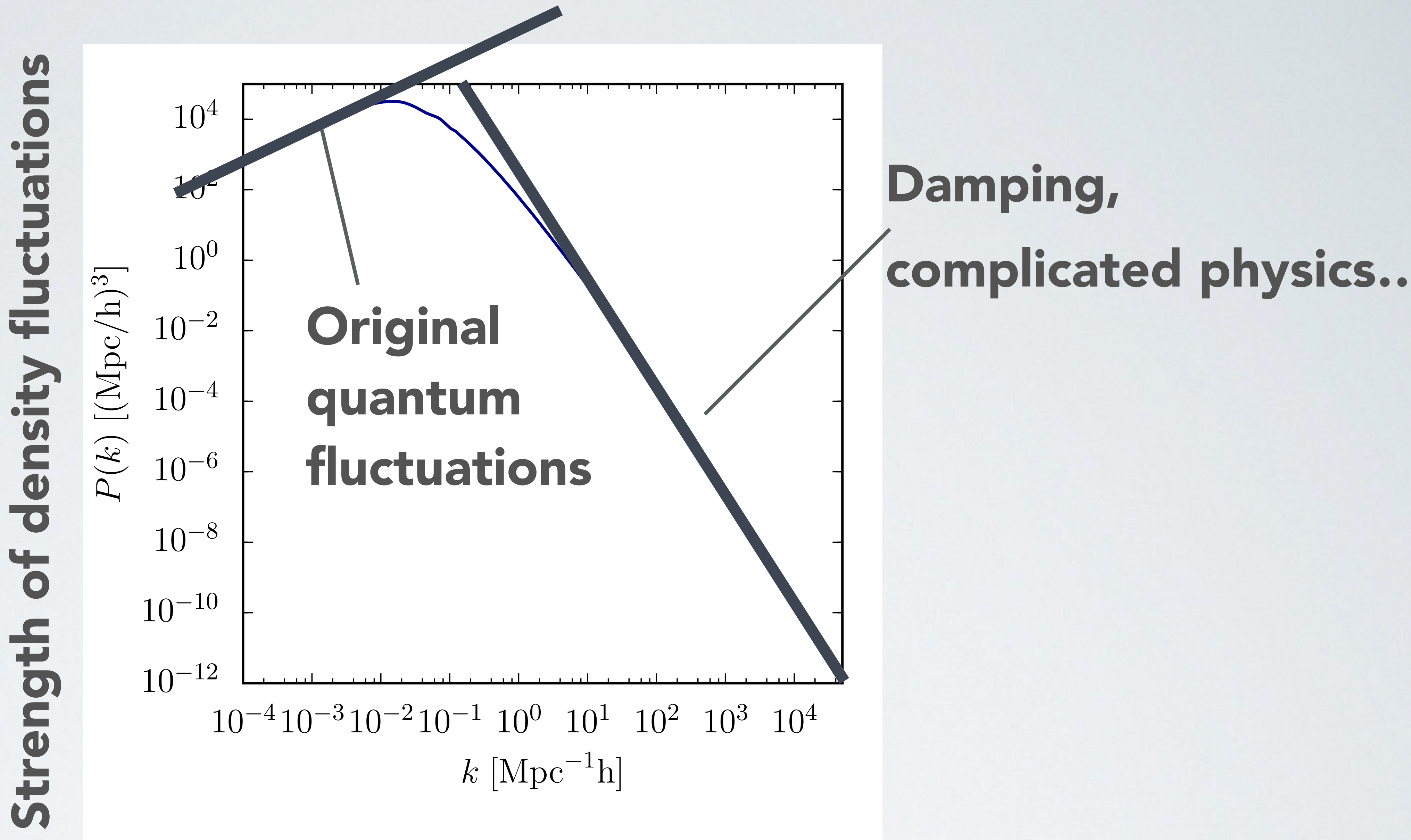
CMB power spectrum



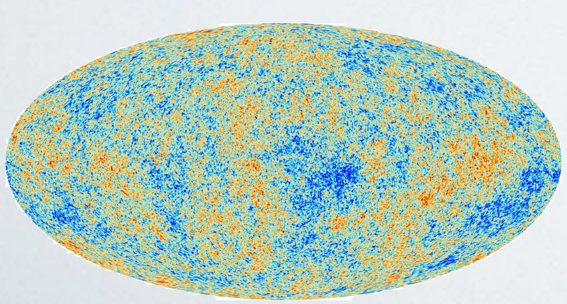


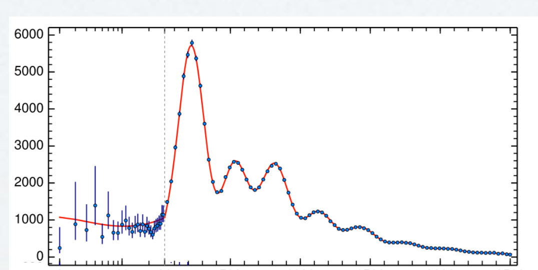
Planck Collaboration 2015

Dark matter power spectrum



Large <— Scale —> Small





CAMB, Lewis et al. 2000

Power spectrum

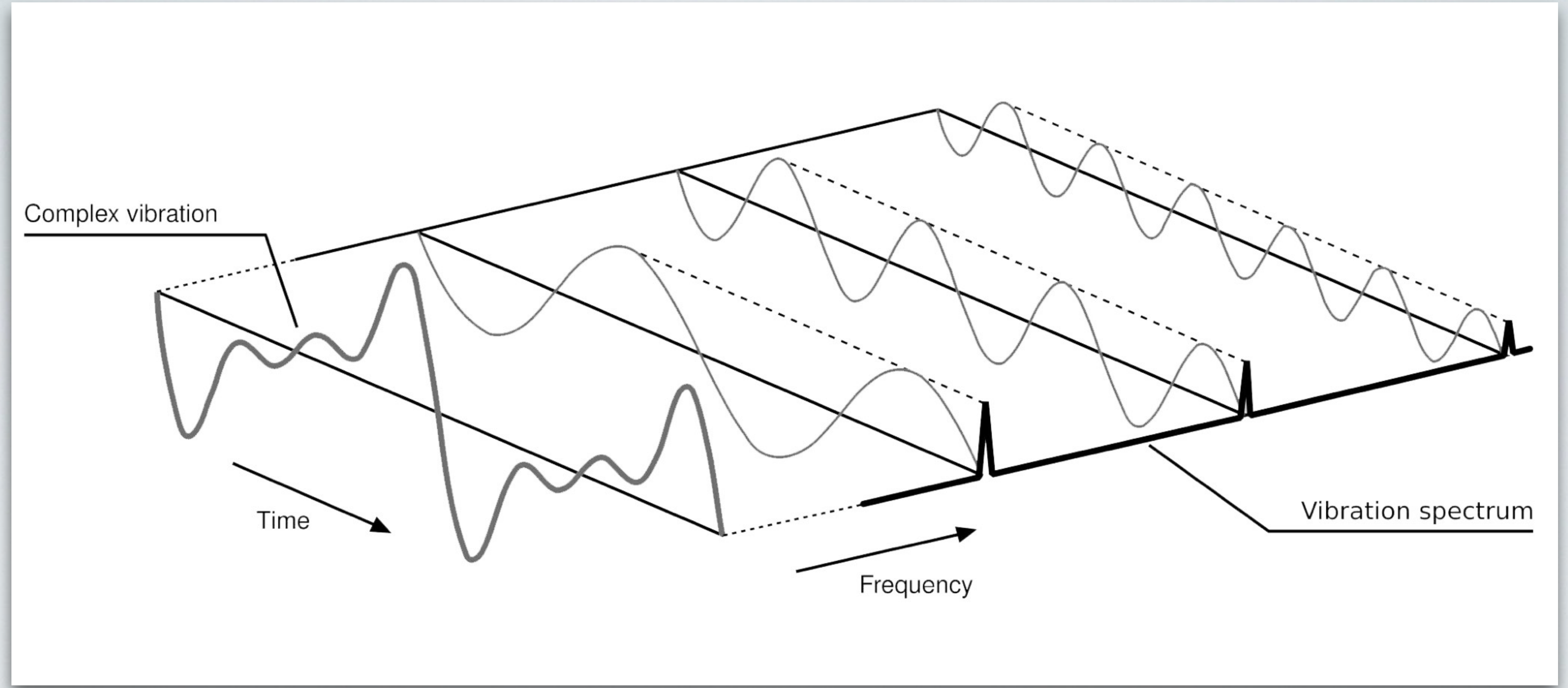
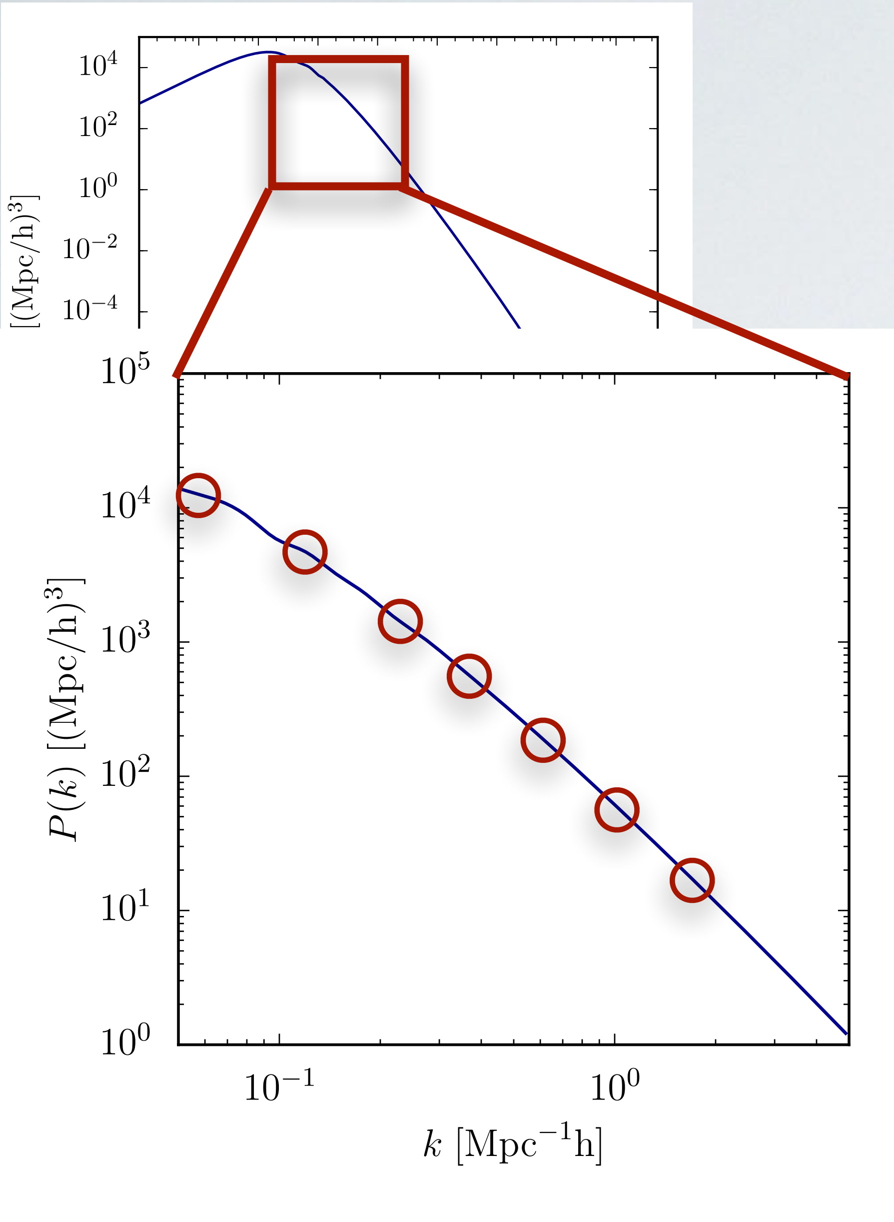
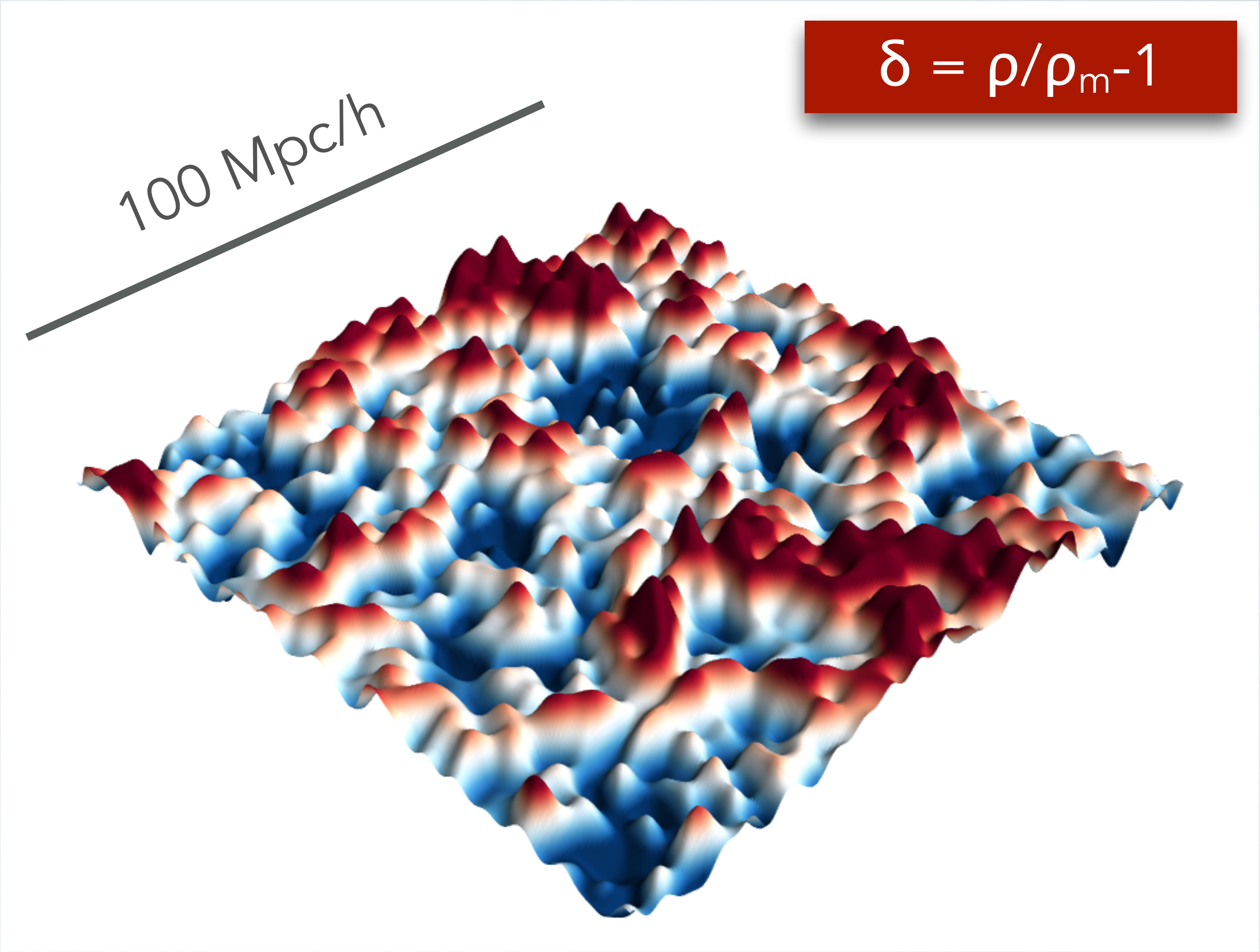
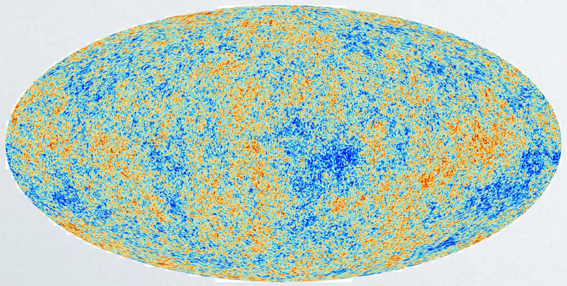


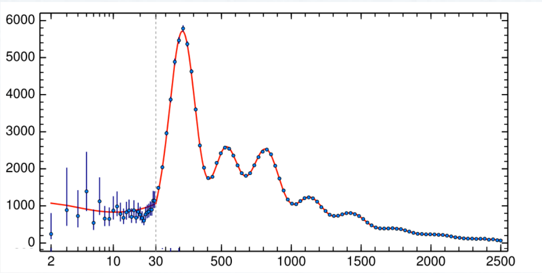
Image: Power-MI

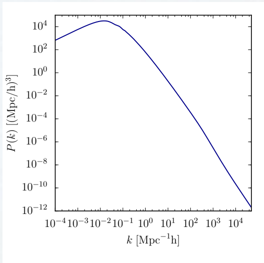
Dark matter power spectrum



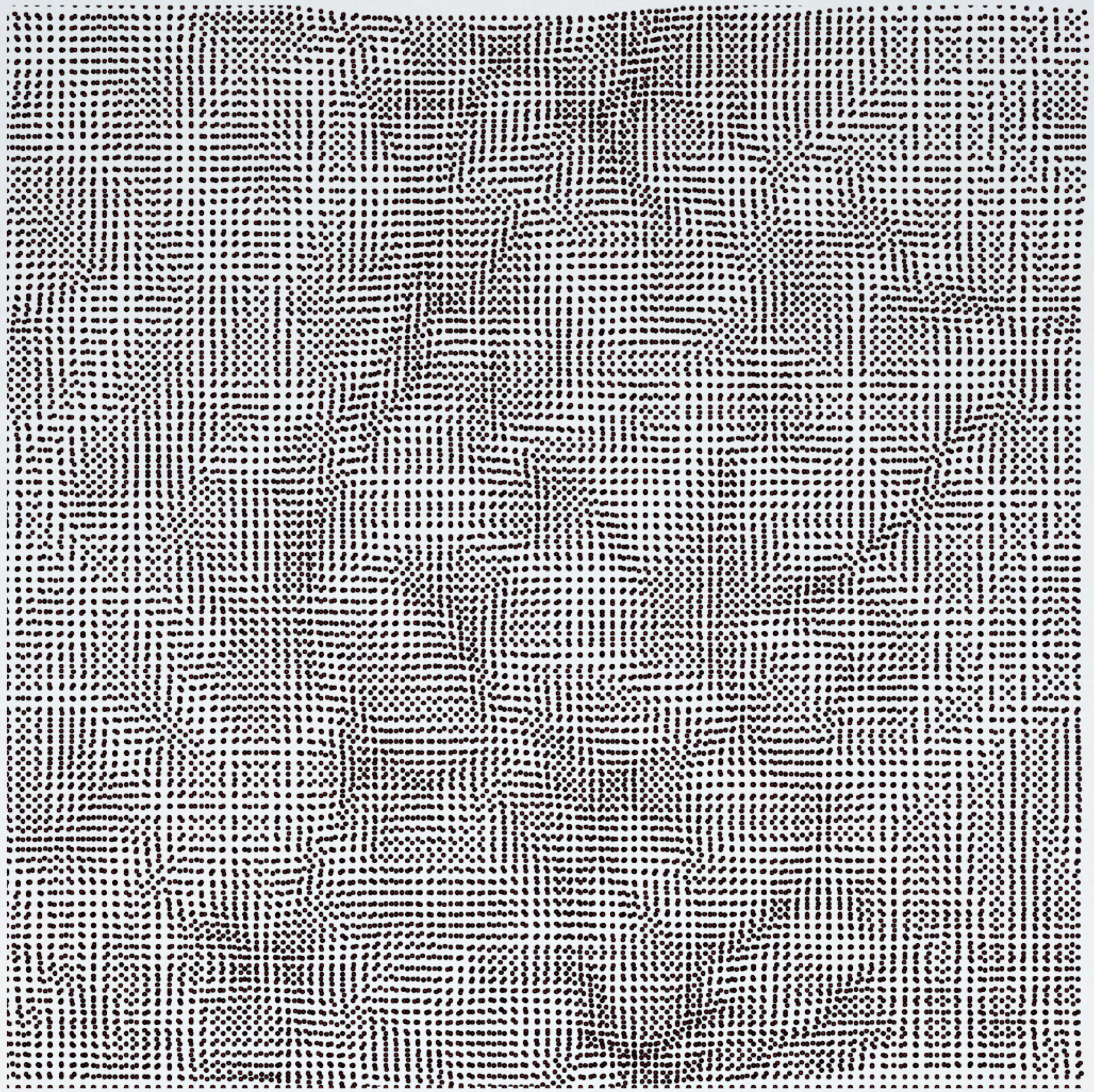


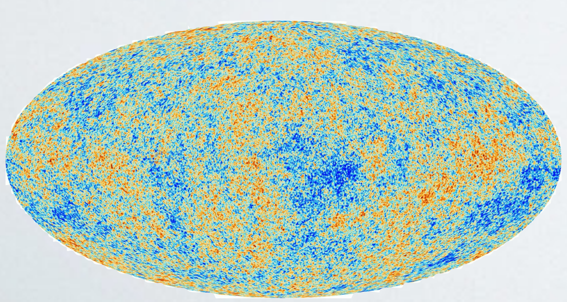


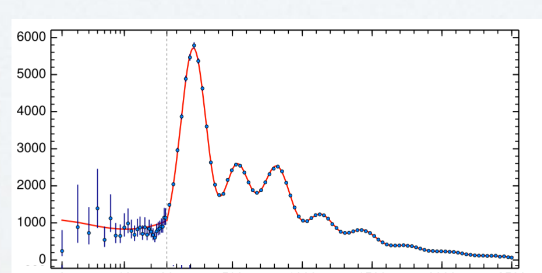


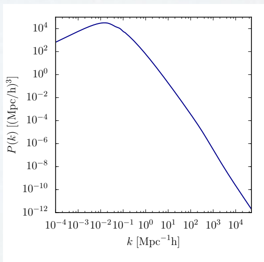


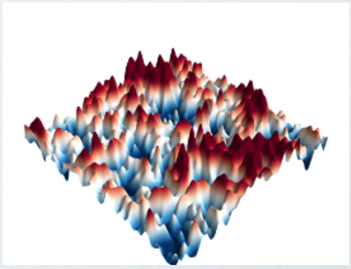
N-body simulations





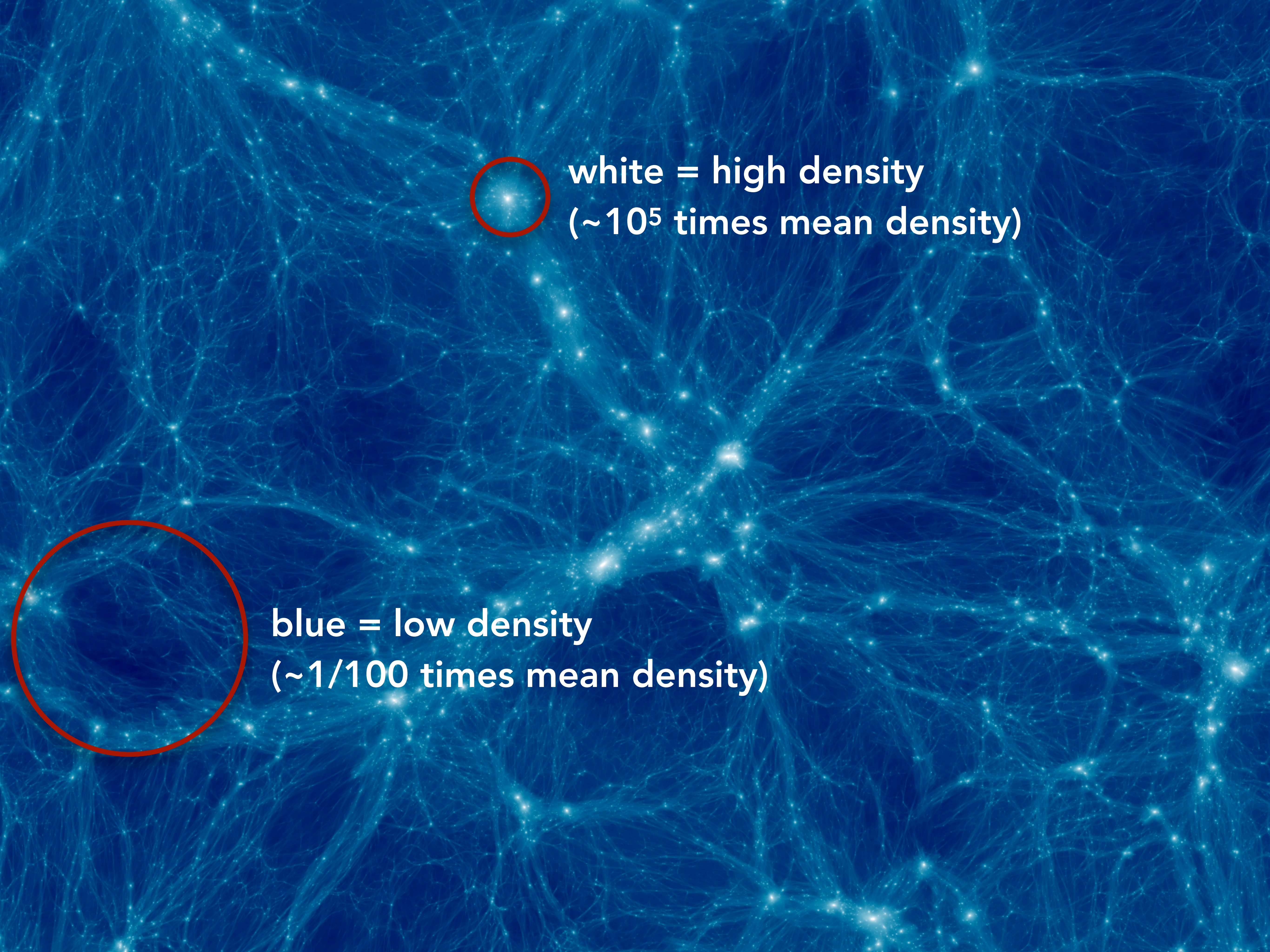




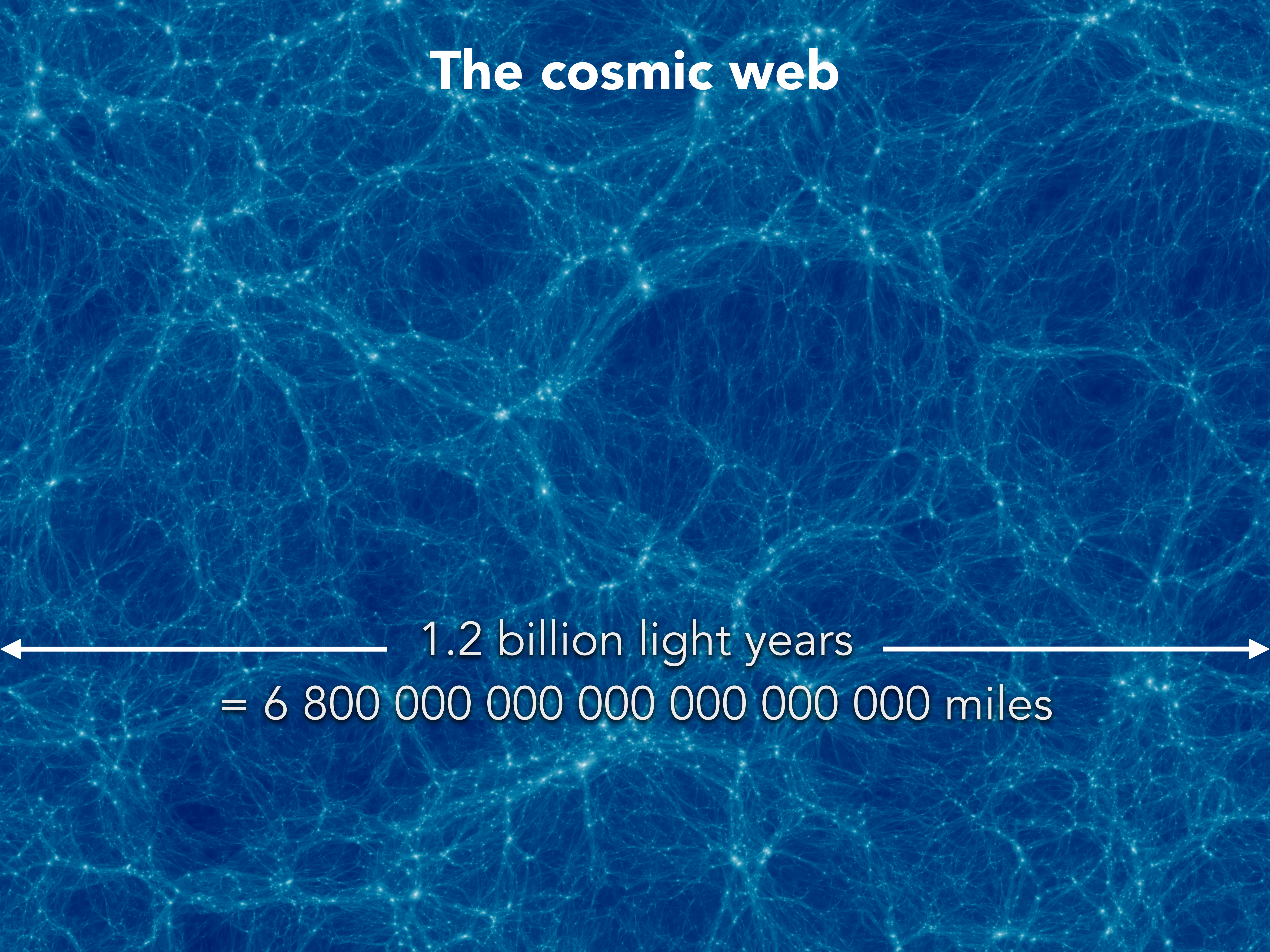


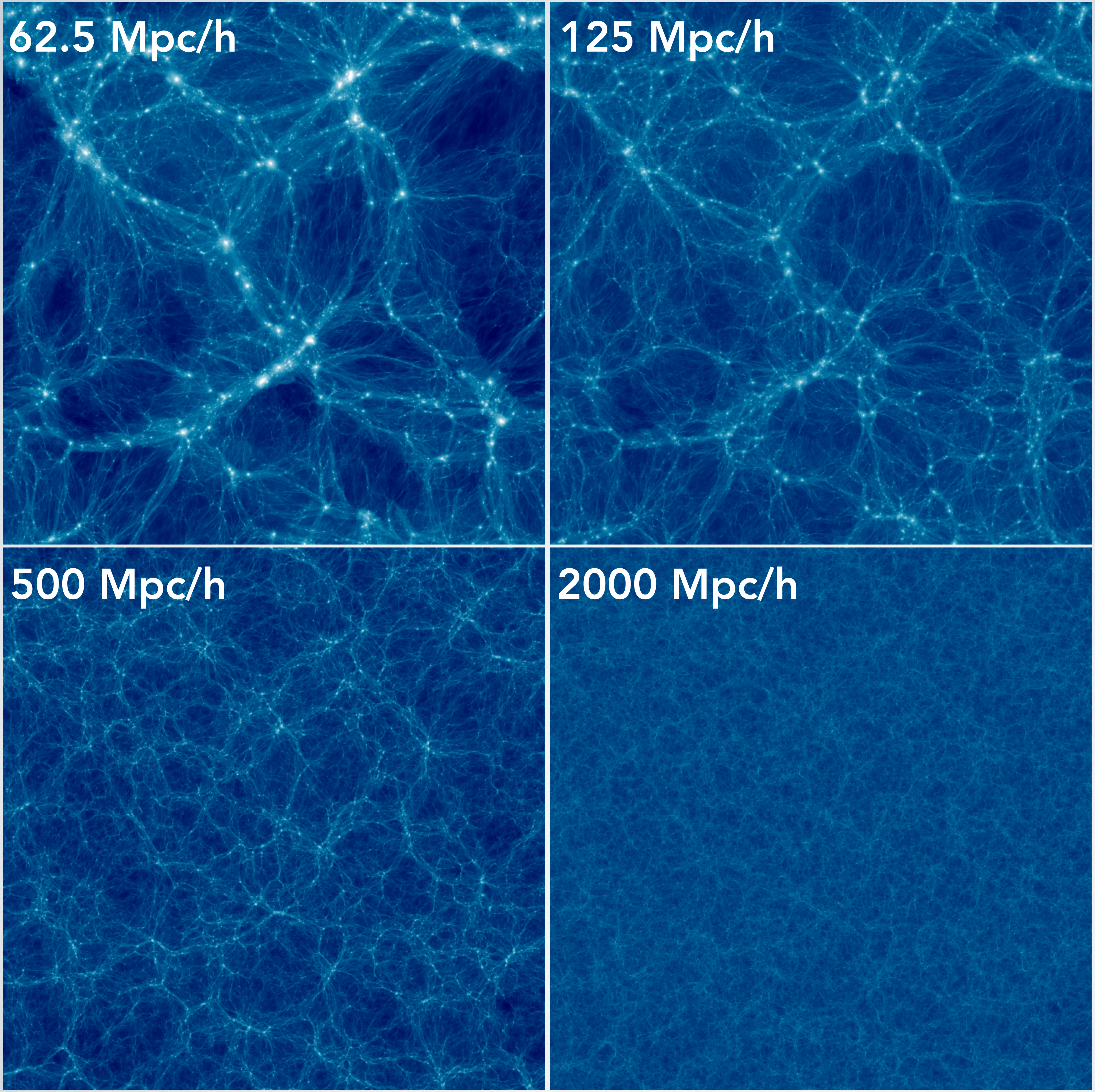
Crocce et al. 2006


$t = 0.1$ Gyr


white = high density
(~10^5 times mean density)
blue = low density
(~1/100 times mean density)

The cosmic web

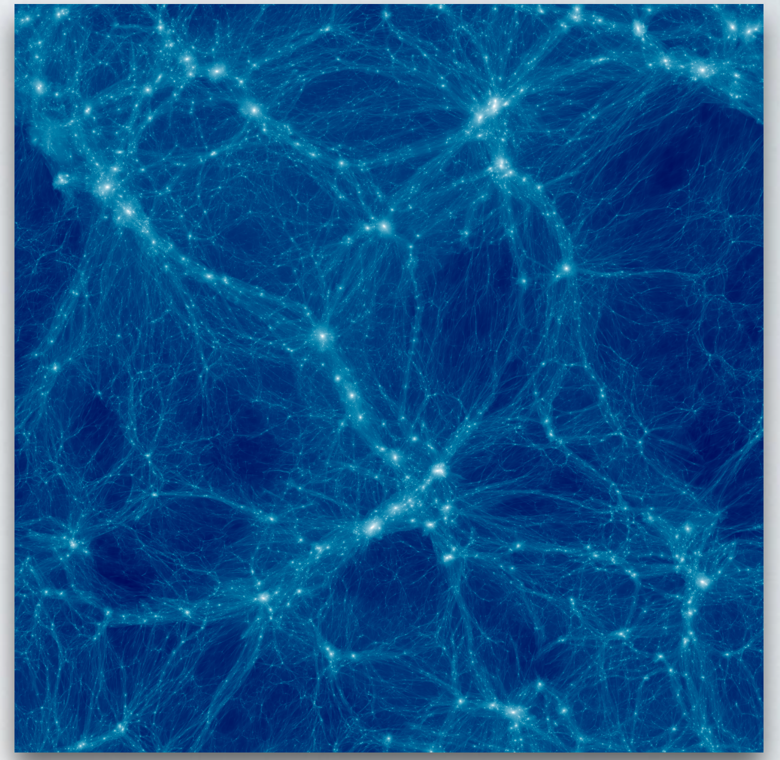




Visualized with **gotetra**
by Phil Mansfield

Formation of the cosmic web

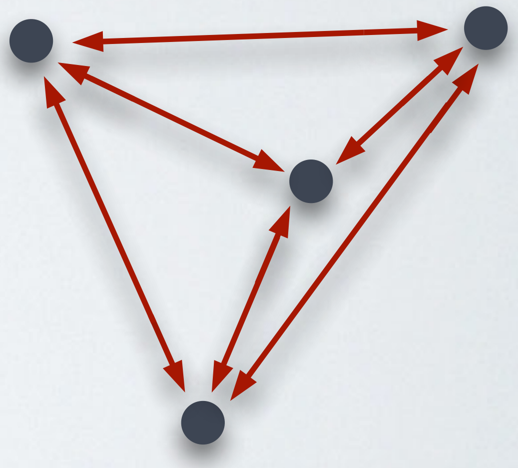
- Starting frominitial conditions of **nearly uniform distribution of matter**, with small inhomogeneities
- Initial conditions follow a power spectrum consistent with that of the CMB
- Gravitational collapse creates **cosmic web**
  - Filaments become more prominent over time
  - Halos form at intersections of filaments
- Structure is **homogeneous on large scales**, more and more **clustered on small scales**



Part 3: Simulating the dark Universe

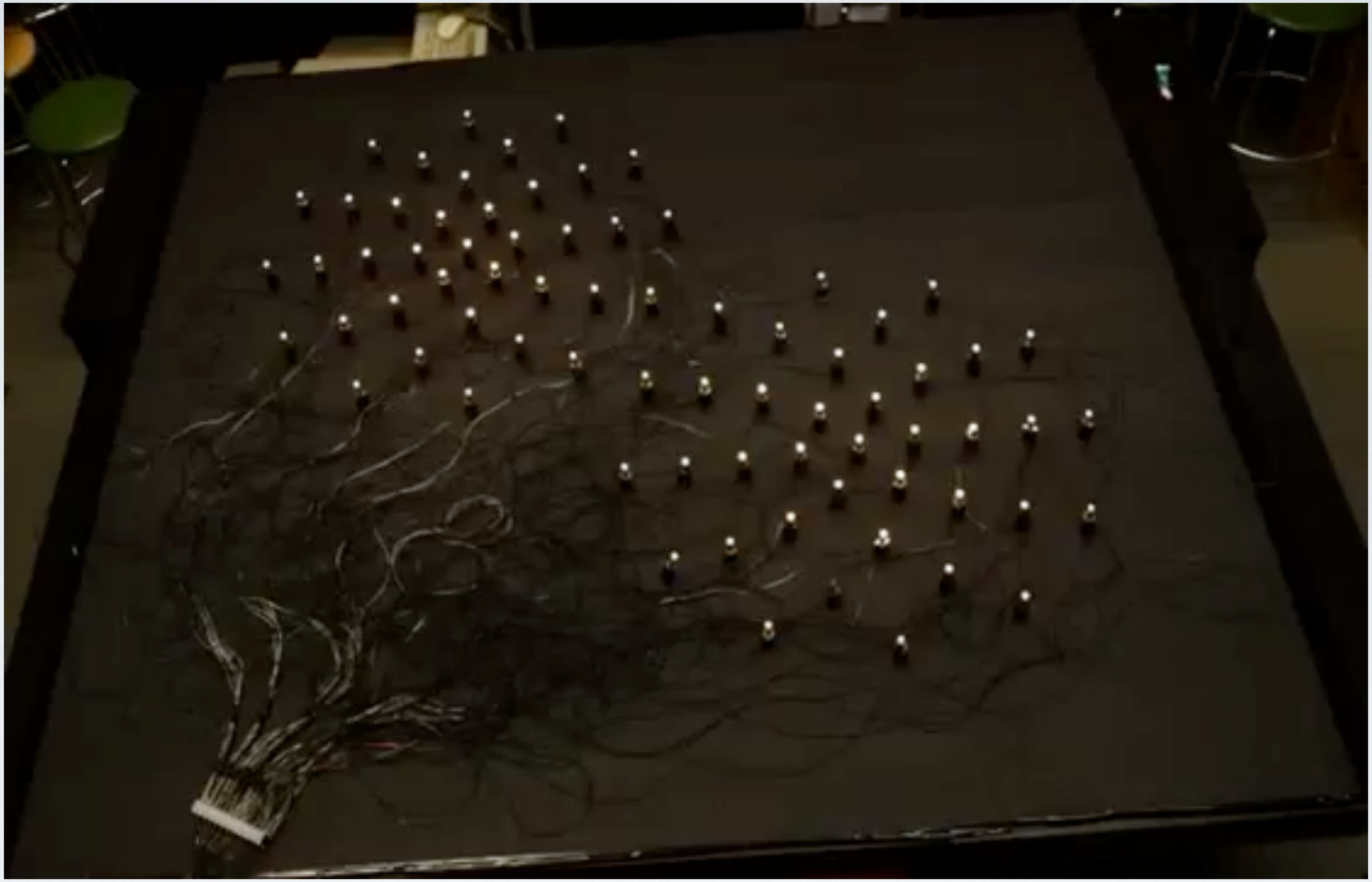
Simulations of dark matter

- Simulate the evolution of dark matter in a large **cube of space**
- Start at a time…
  - Long **after matter/radiation decoupling** (= recombination) at t = 380,000 years after Big Bang
  - Early enough that **initial inhomogeneities are small** (< 1% in density)
- Physics in equations includes:
  - **Expansion** of Universe, including dark energy
  - **Gravity** of dark matter
  - **No collisions** between dark matter particles
- Solve Newton's law between N particles (**N-body simulation**)
- Compute gravitational force, move particles a bit, and so on



$$F = \frac{G m_1 m_2}{r^2}$$

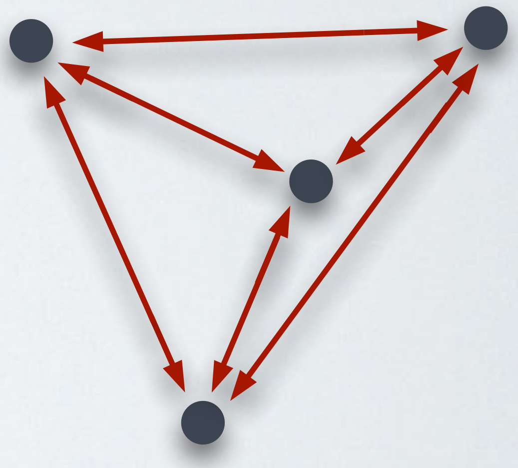
First N-body simulation (1941)



- Erik Holmberg used lightbulbs to mimic $1/r^2$ law of gravity
- Force accelerates particles
- Move bulbs according to their velocity/acceleration

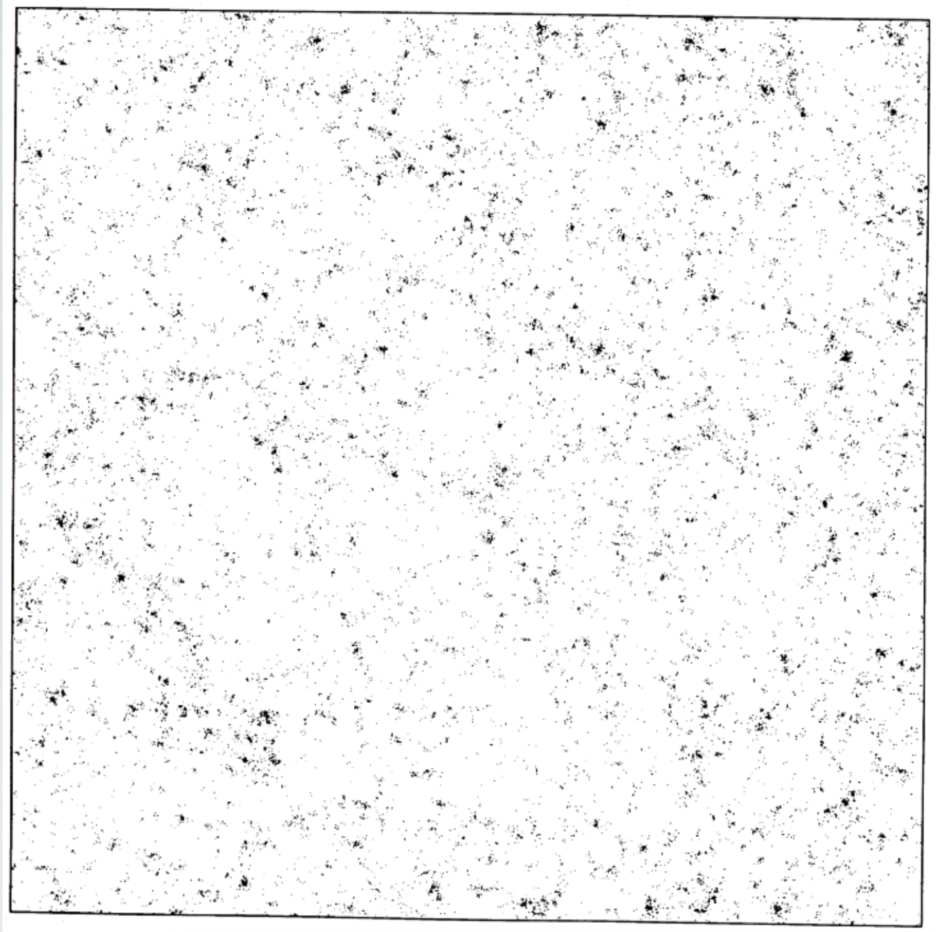
Simulations of dark matter

- Computing the force between each pair of particles takes **N^2 operations** for each timestep!
- For 1 billion particles, that is 10^{18} operations per timestep!
- Need to use clever algorithms (e.g., grouping nearby particles together if they are far away)

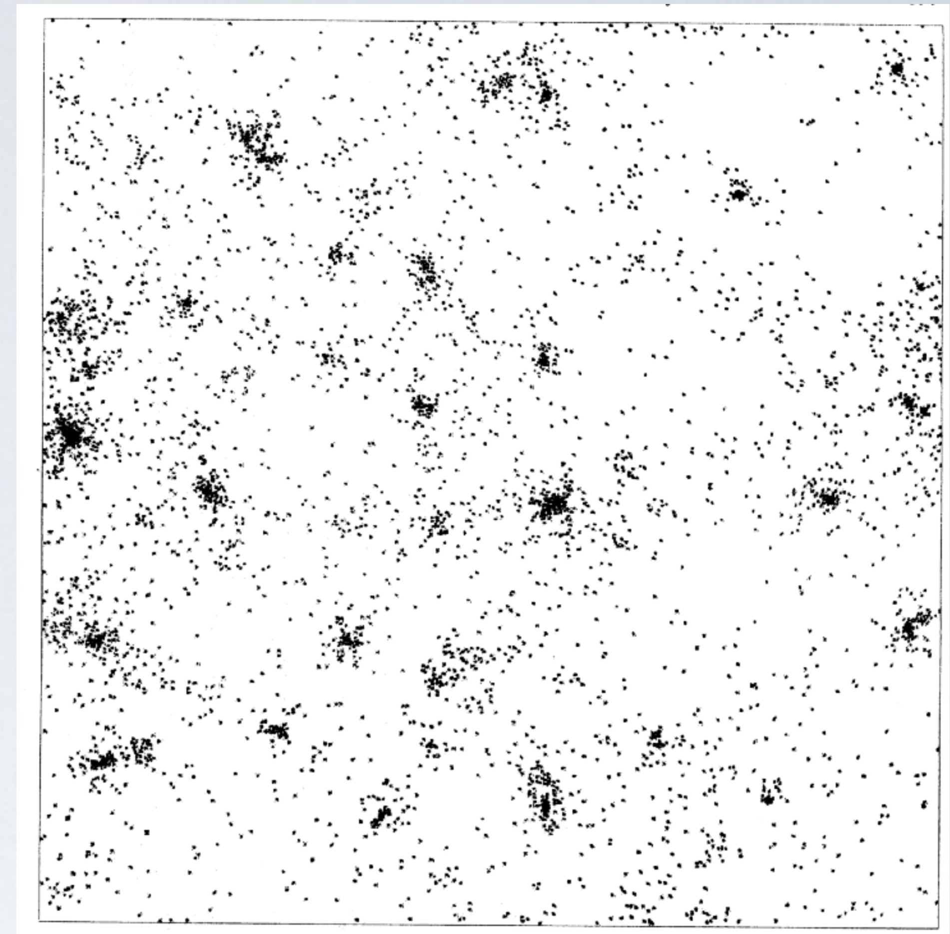


$$F = \frac{Gm_1m_2}{r^2}$$

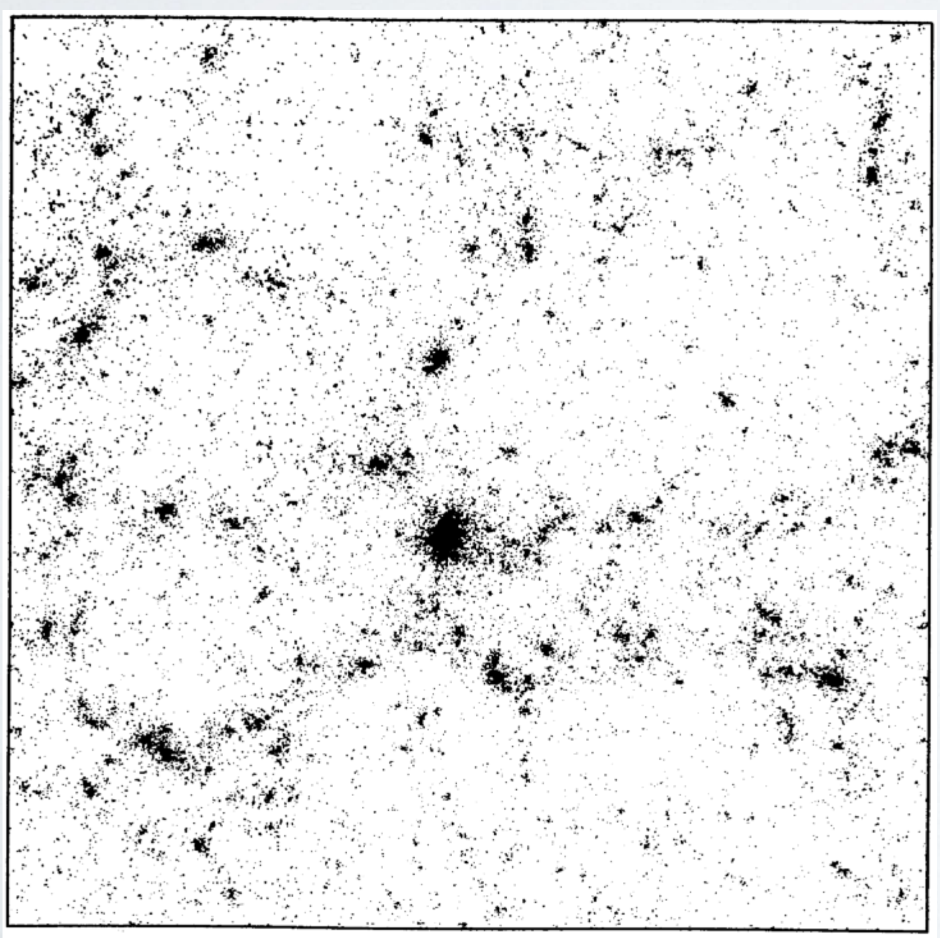
Efstathiou et al. 1981



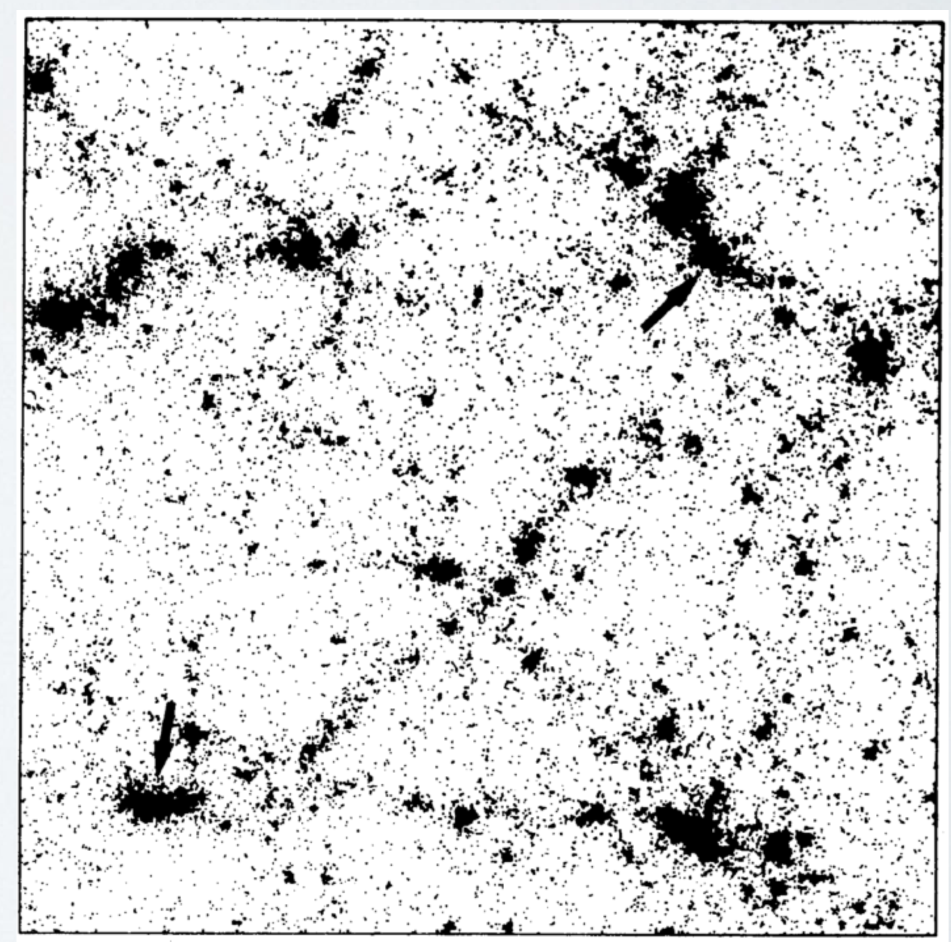
Klypin & Shandarin 1983



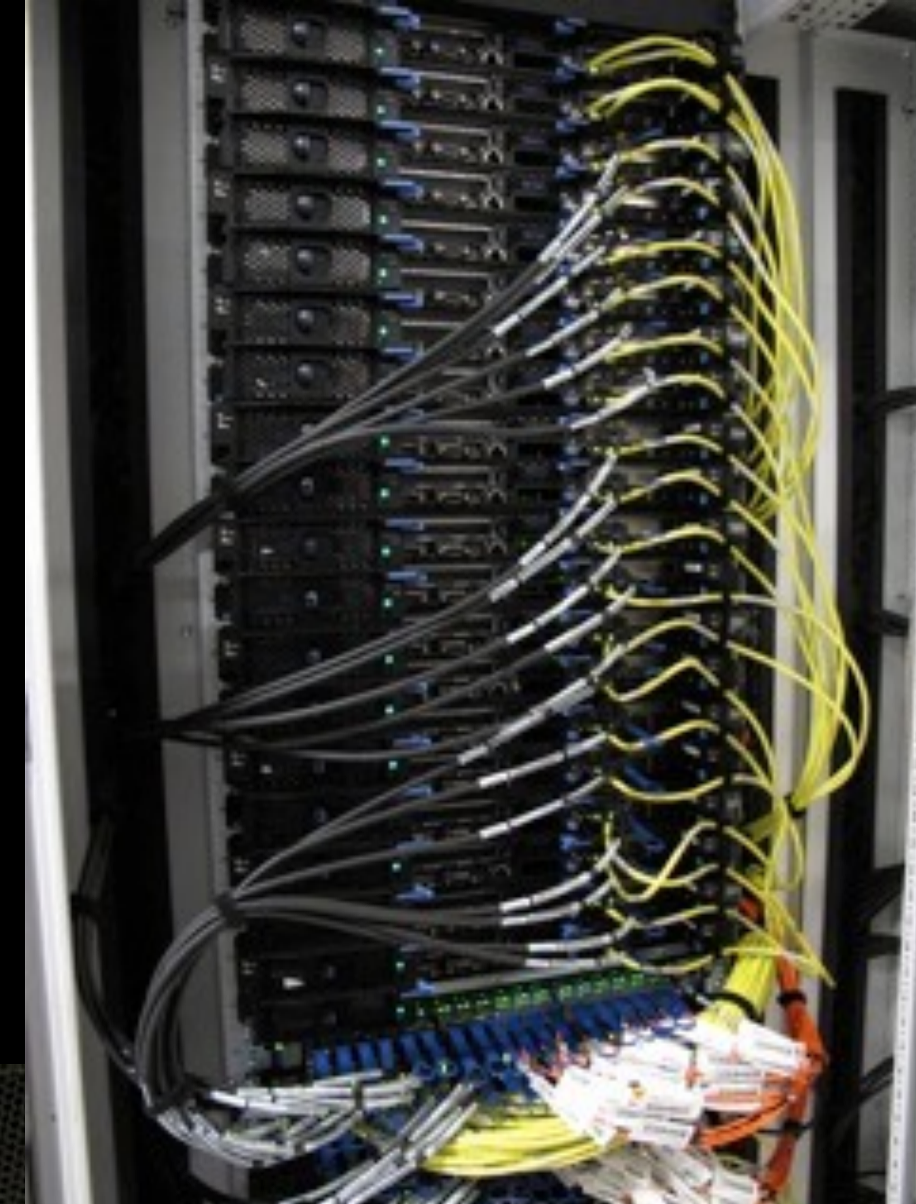
Davis et al. 1985



Frenk et al. 1988

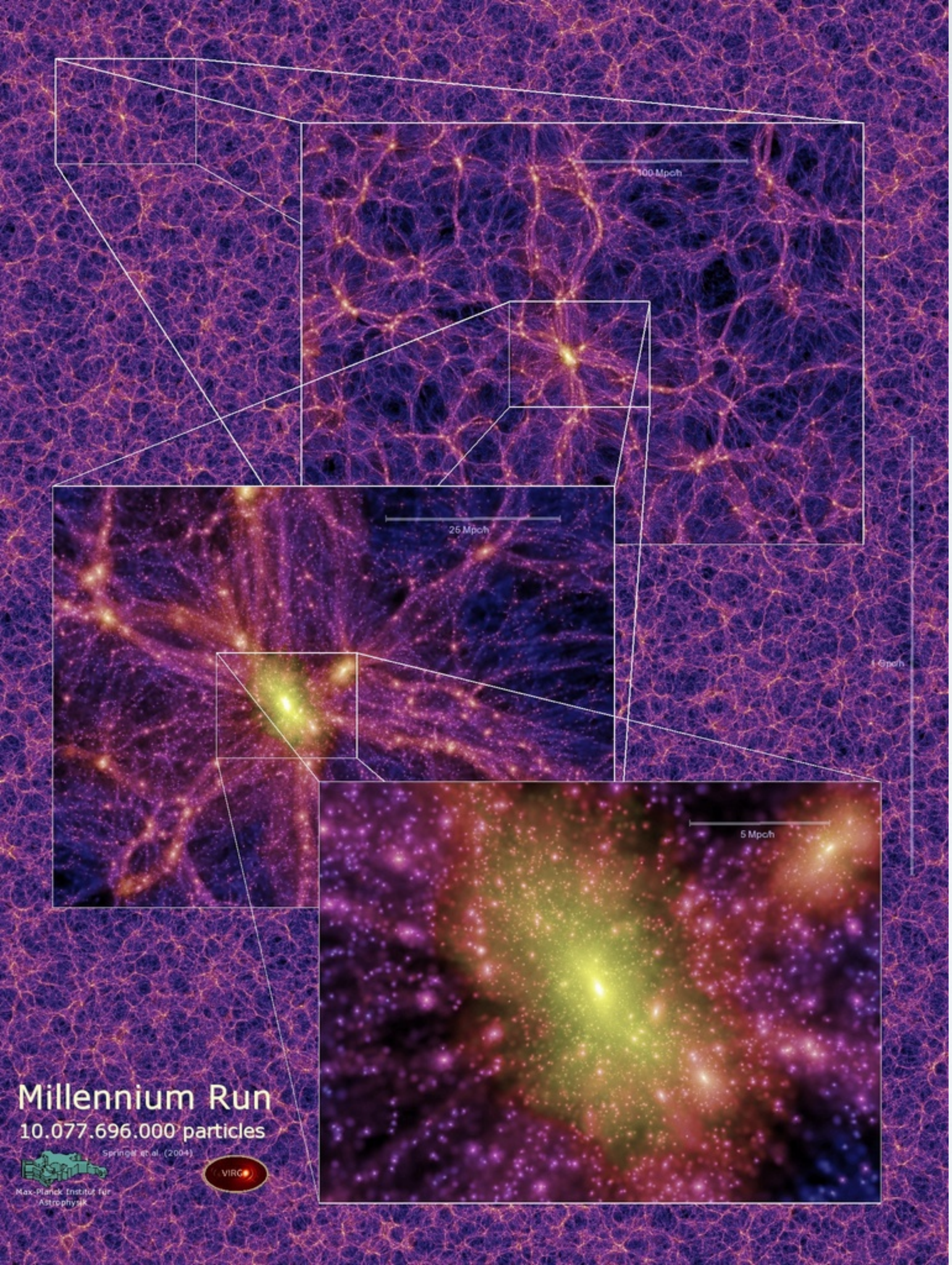


Efstathiou et al. 1981/1985/1988 • Klypin & Shandarin 1983 • Frenk et al. 1983/1985/1988 • Davis et al. 1985



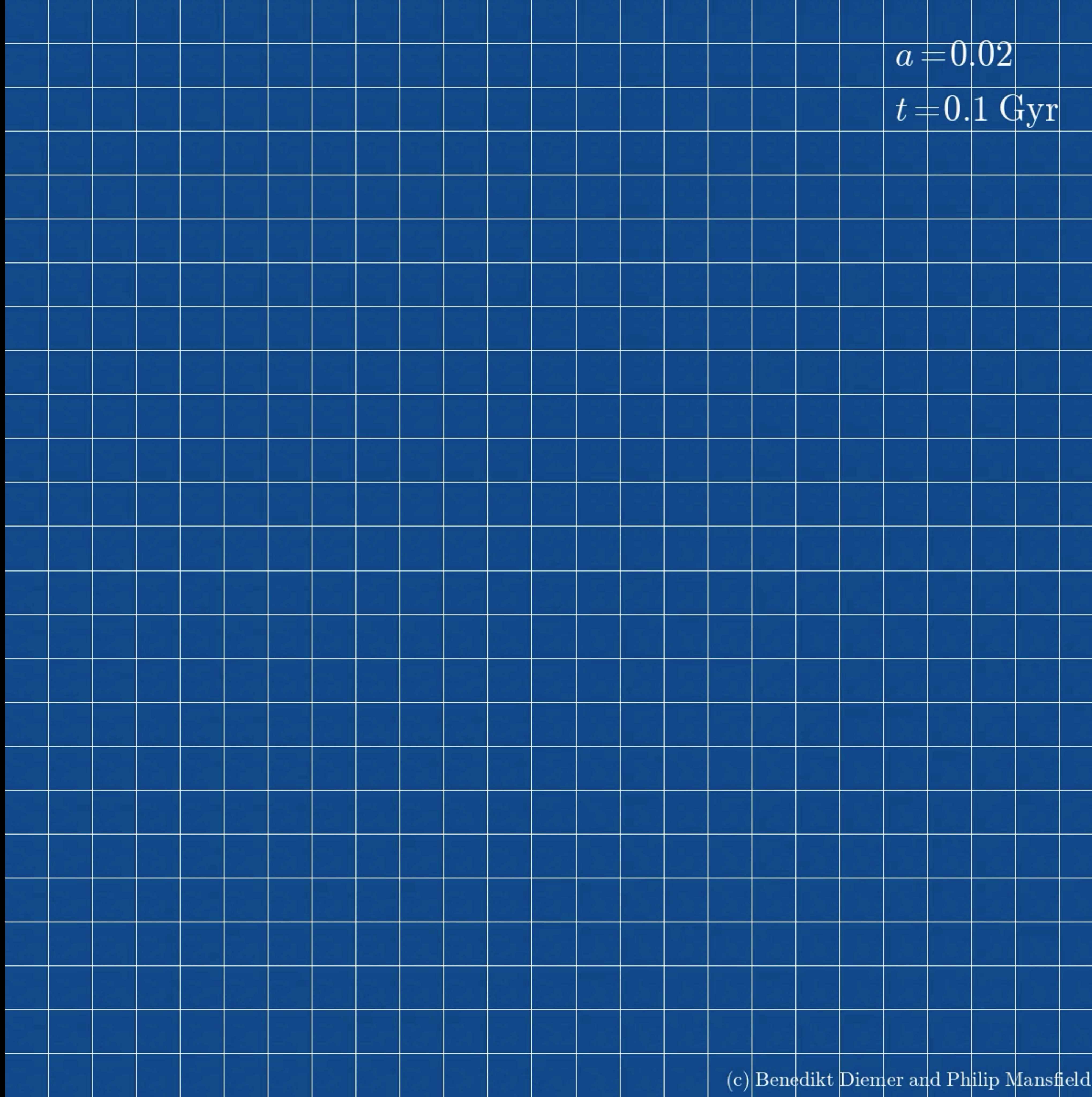
Midway

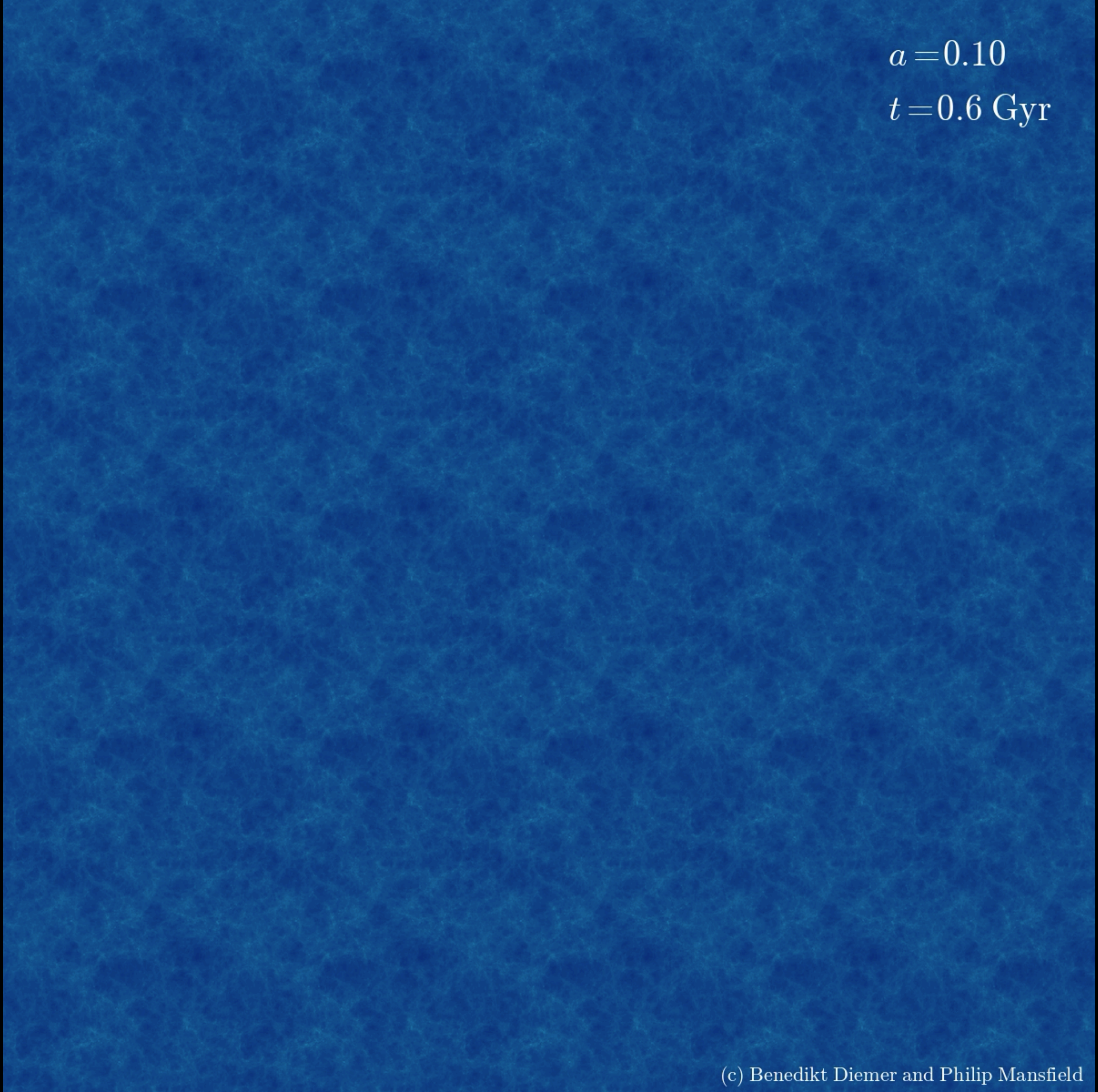
@ UChicago



- Millennium Simulation
  (10 billion particles)
  was largest for a while
- Today reach **1 trillion** particles

Springel et al. 2005/2008


$a = 0.02$
$t = 0.1$ Gyr
(c) Benedikt Diemer and Philip Mansfield



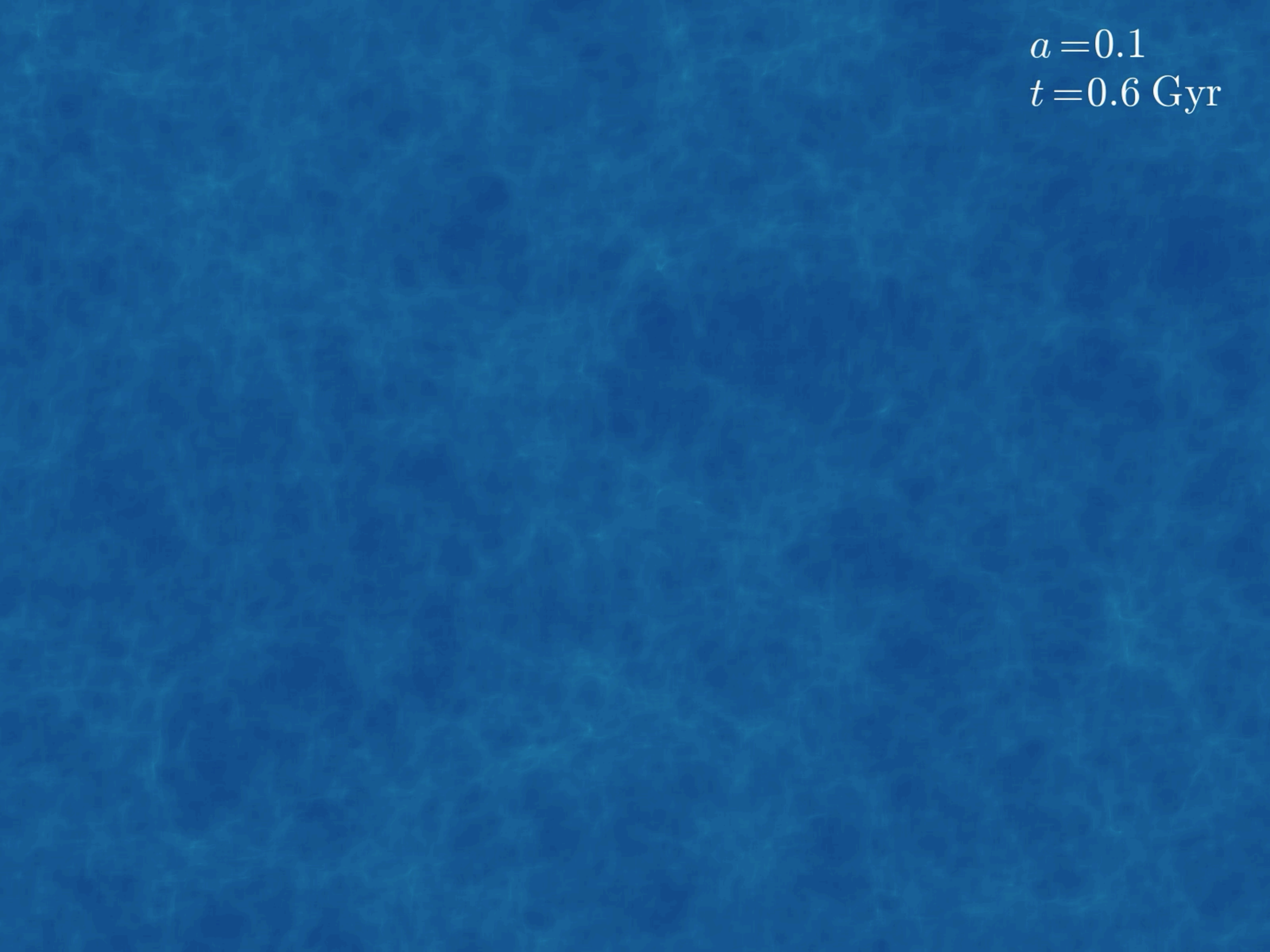
$a = 0.10$
$t = 0.6$ Gyr
(c) Benedikt Diemer and Philip Mansfield

Participation: Future

TurningPoint:
What happens to dark matter structures in the future?

Session ID: diemer

30 seconds

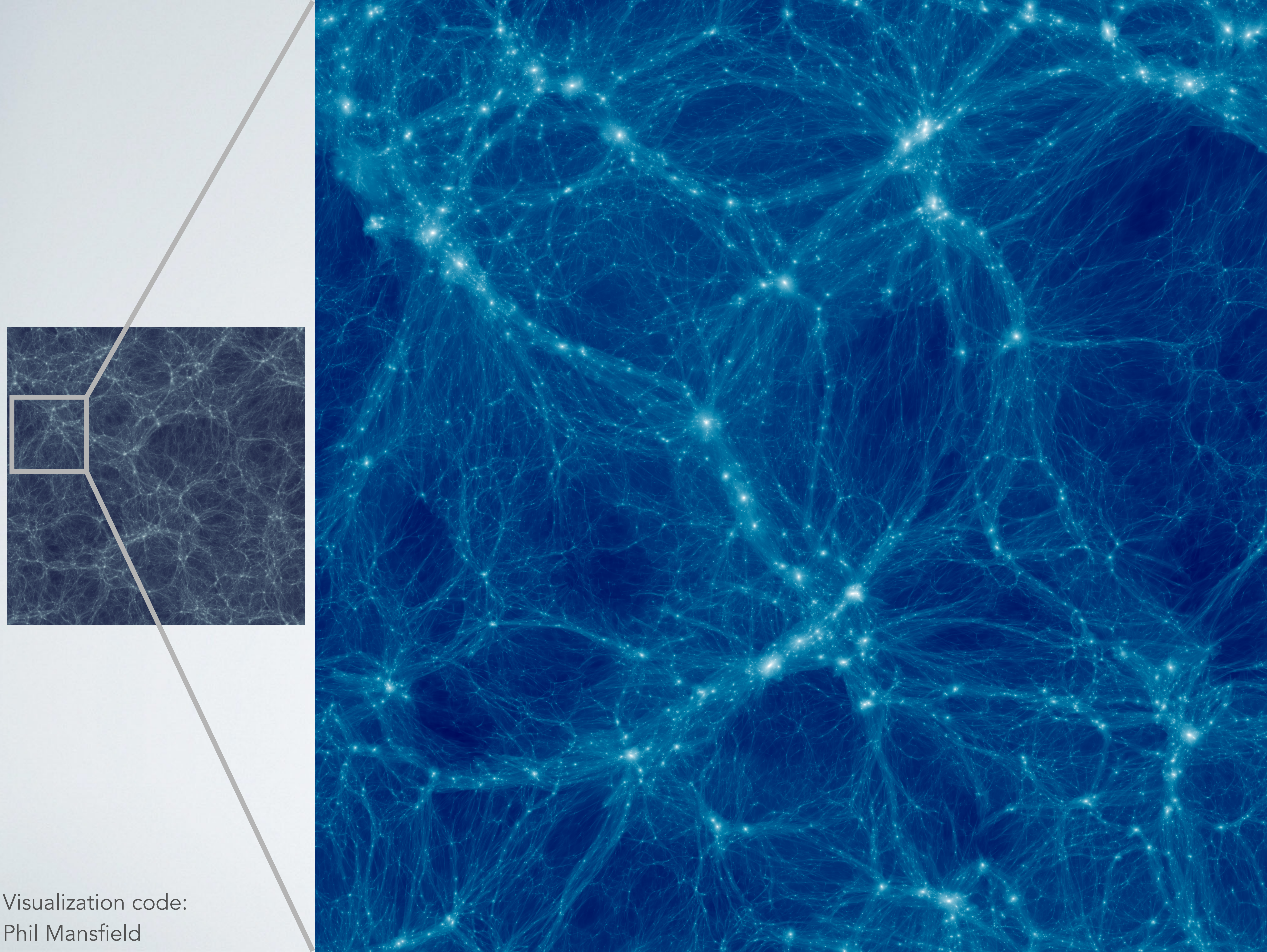

$a = 0.1$
$t = 0.6$ Gyr

The future of the cosmic web

- Growth of structure slows down after z~1 as dark energy accelerates the expansion
- On large scales, gravity cannot keep up with acceleration
- Structure is "frozen in"

Most of the structure that will form in the Universe has already formed!

Part 4: The formation of halos



Visualization code:
Phil Mansfield

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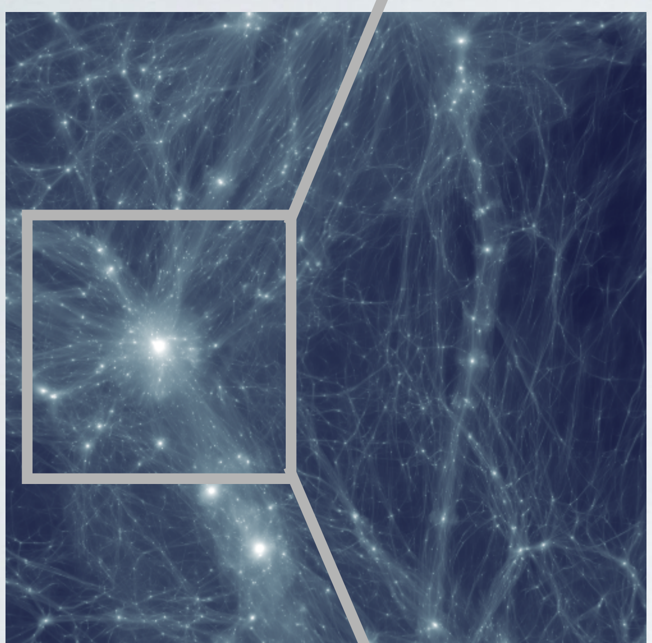
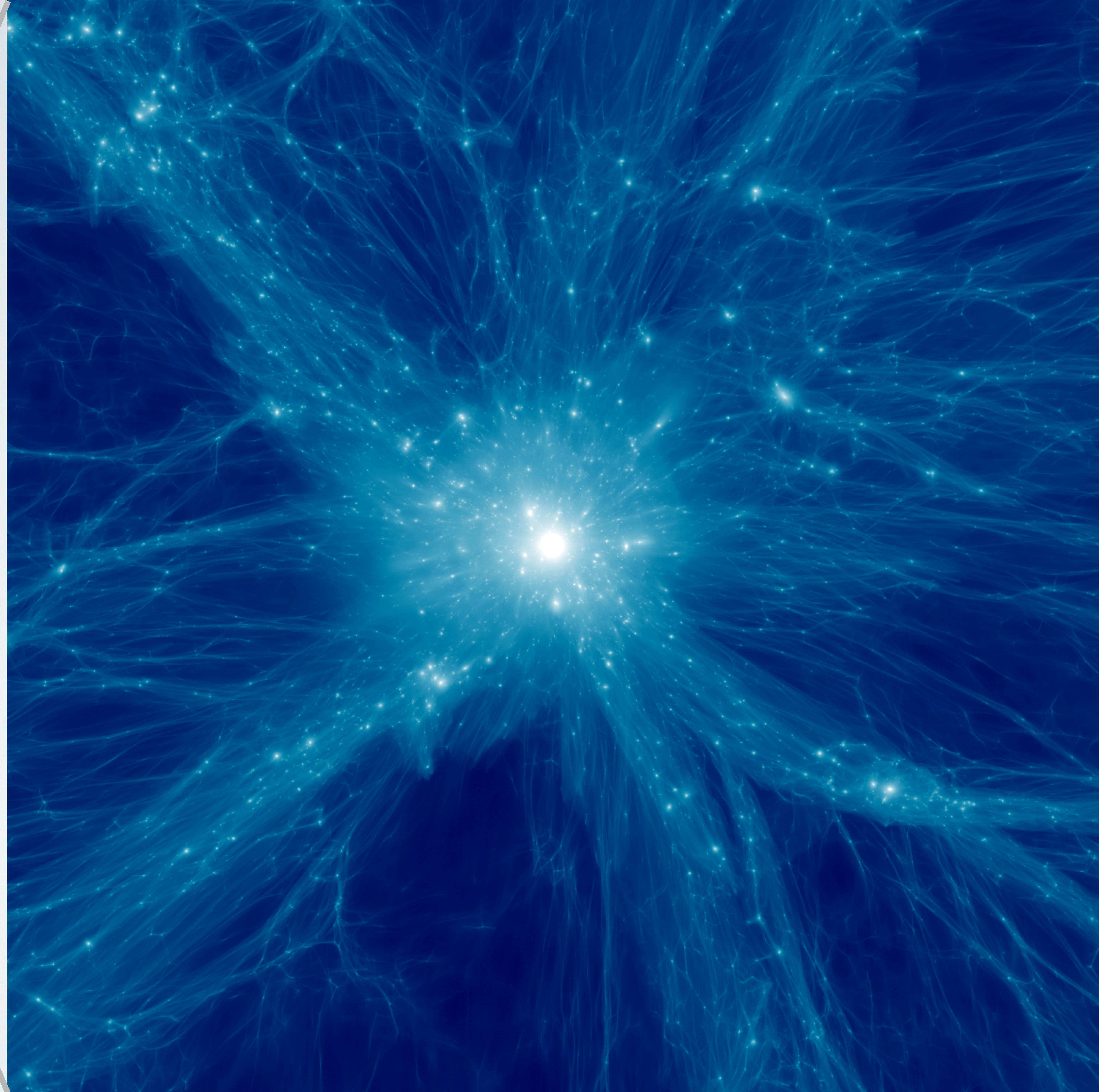
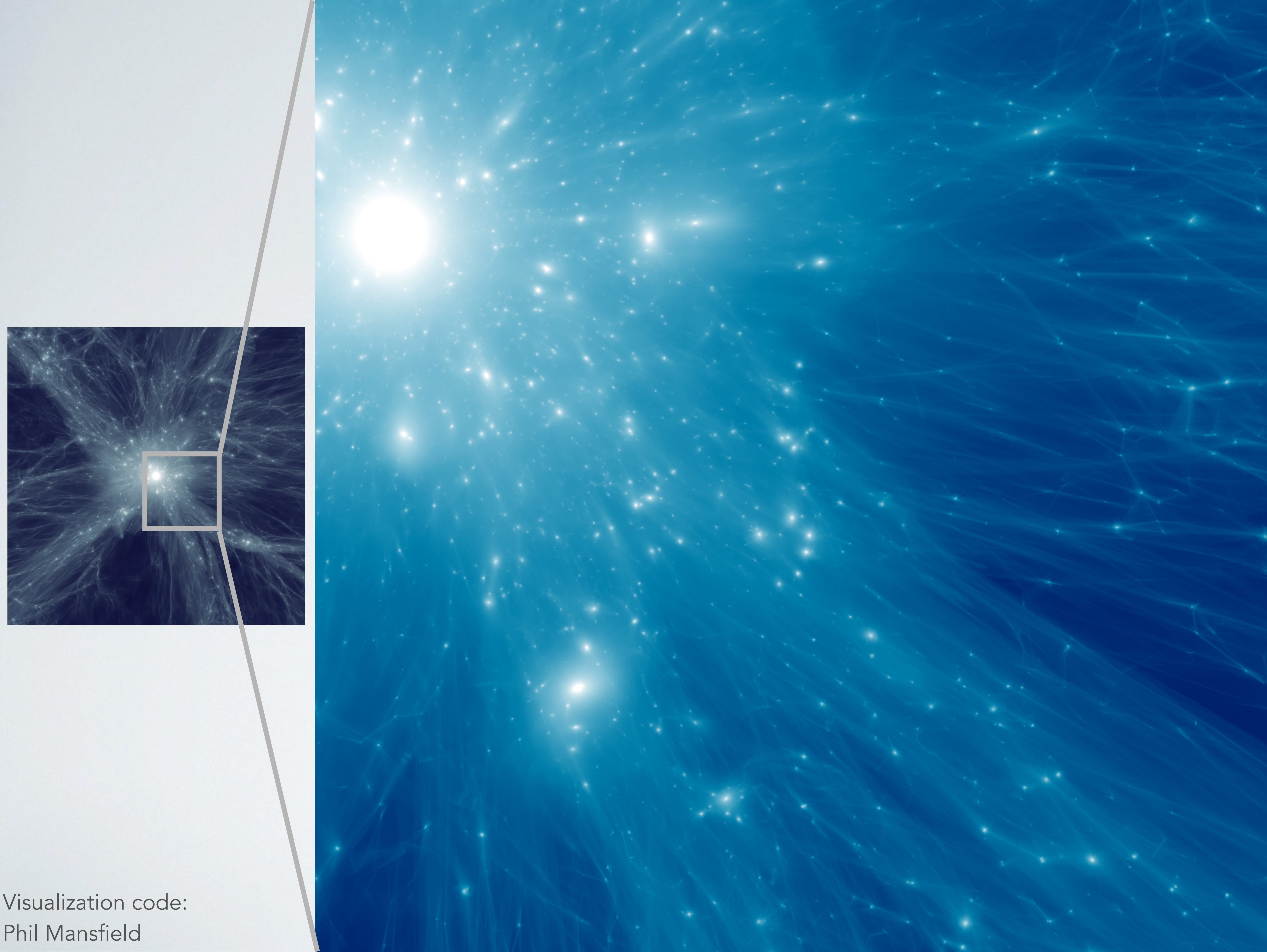
Phil Mansfield





Visualization code:
Phil Mansfield



Visualization code:
Phil Mansfield

Formation of halos

- Could occur…
  - Top-down: Form big structures first, which fragment to make smaller structures
  - Bottom-up: Form small structures first, which merge into big structures


$t = 0.1$ Gyr

Participation: Future

TurningPoint:
How does dark matter structure form?

Session ID: diemer

30 seconds

Formation of halos

Structure forms bottom-up: small structures (halos) form first to make larger structures (halos)

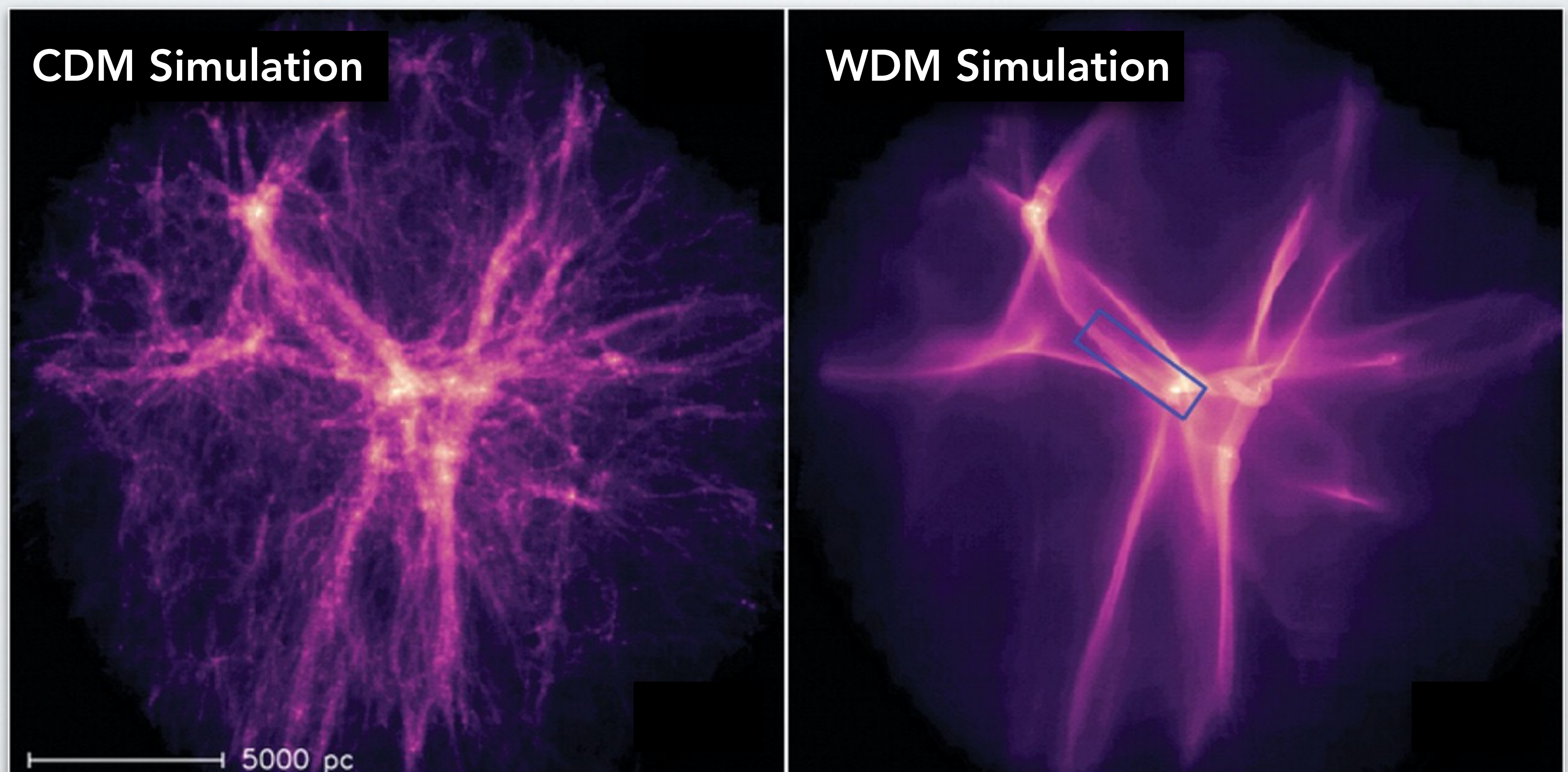
- Halos contain many smaller halos, called “subhalos”
- Merging continues; Milky Way and Andromeda will merge in 5 billion years

Aquarius Simulation, Springel et al. 2008

Part 5: What is dark matter?

Dark matter

- Particles have a temperature:
  - **Cold Dark Matter (CDM)** = no or small initial velocities
  - **Warm Dark Matter (WDM)** = moderate initial velocities
  - **Hot Dark Matter (HDM)** = relativistic initial velocities near c
- Temperature determines the **structures** dark matter can form
- Warm/hot dark matter resists clumping by gravity more than cold DM
- Warm dark matter has **minimum size** of structures that can be made



Gao & Theuns 2007

Dark matter candidates

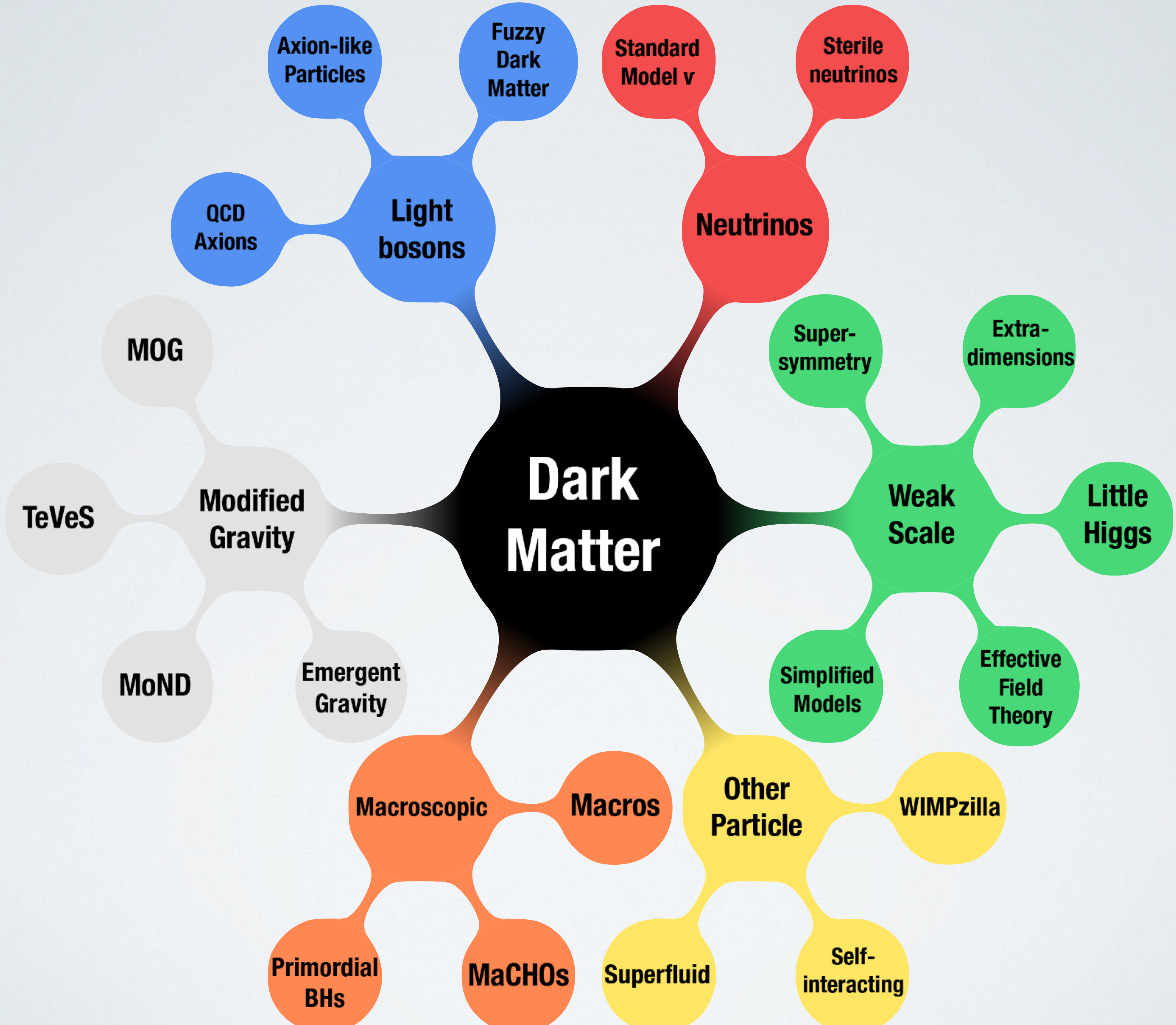
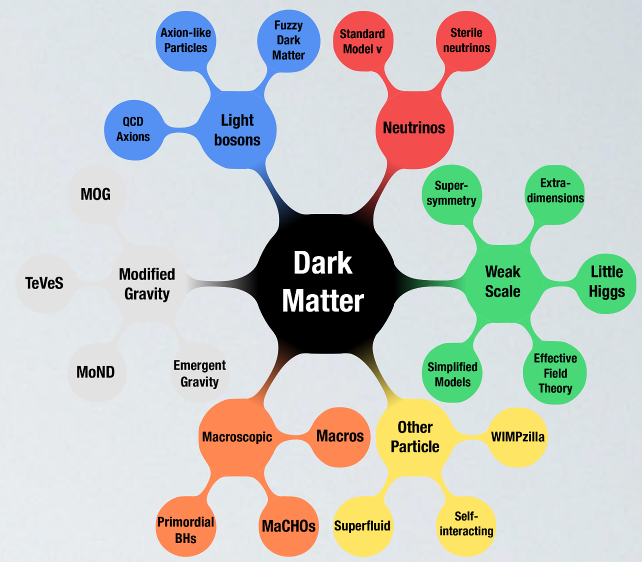
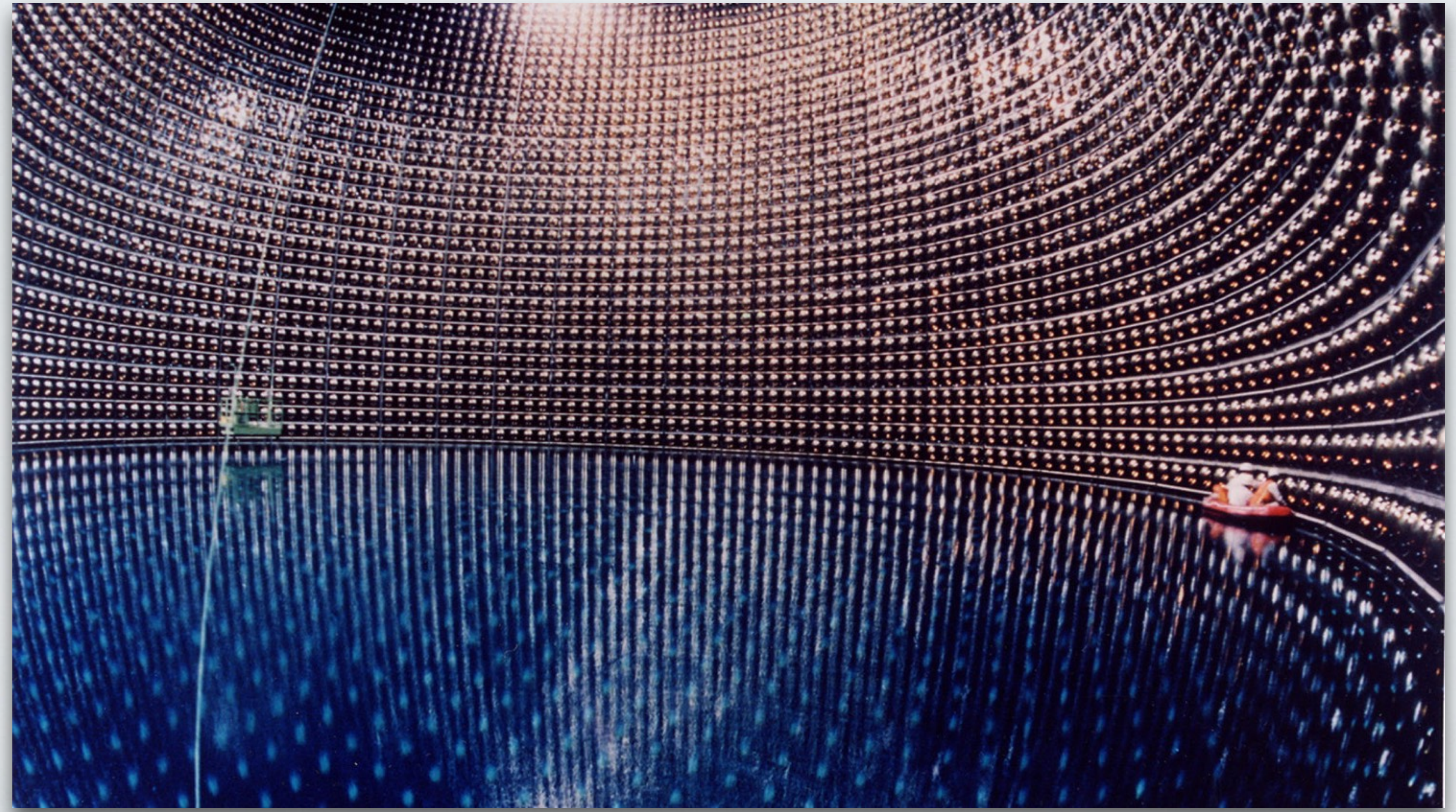


Image: G. Bertone and T. M. P. Tait

Dark matter candidates: Neutrinos

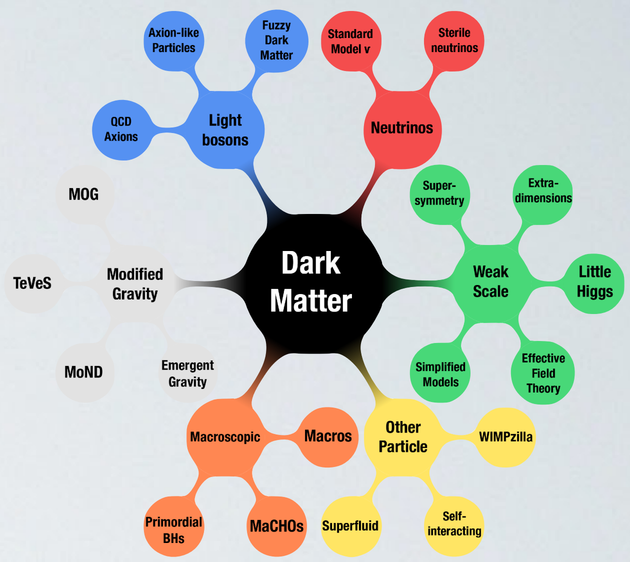


- We can detect most neutrinos, but there could be some types that would be invisible
- Unlikely could not make up for enough mass
- Neutrinos would likely be hot dark matter



SuperKamiokande

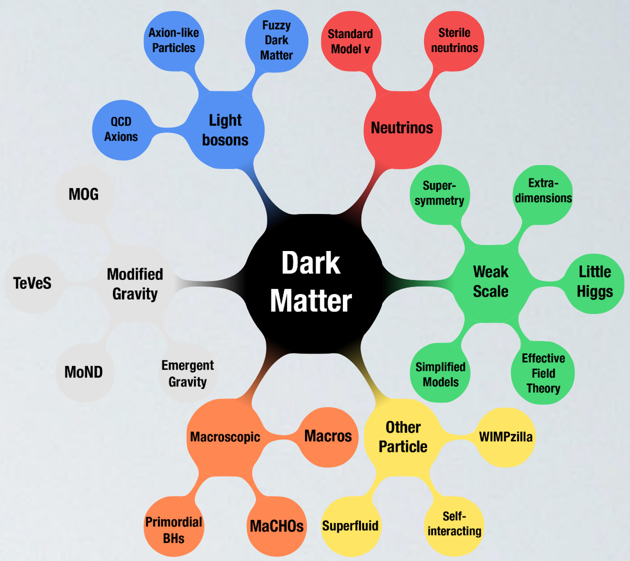
Dark matter candidates: WIMPs



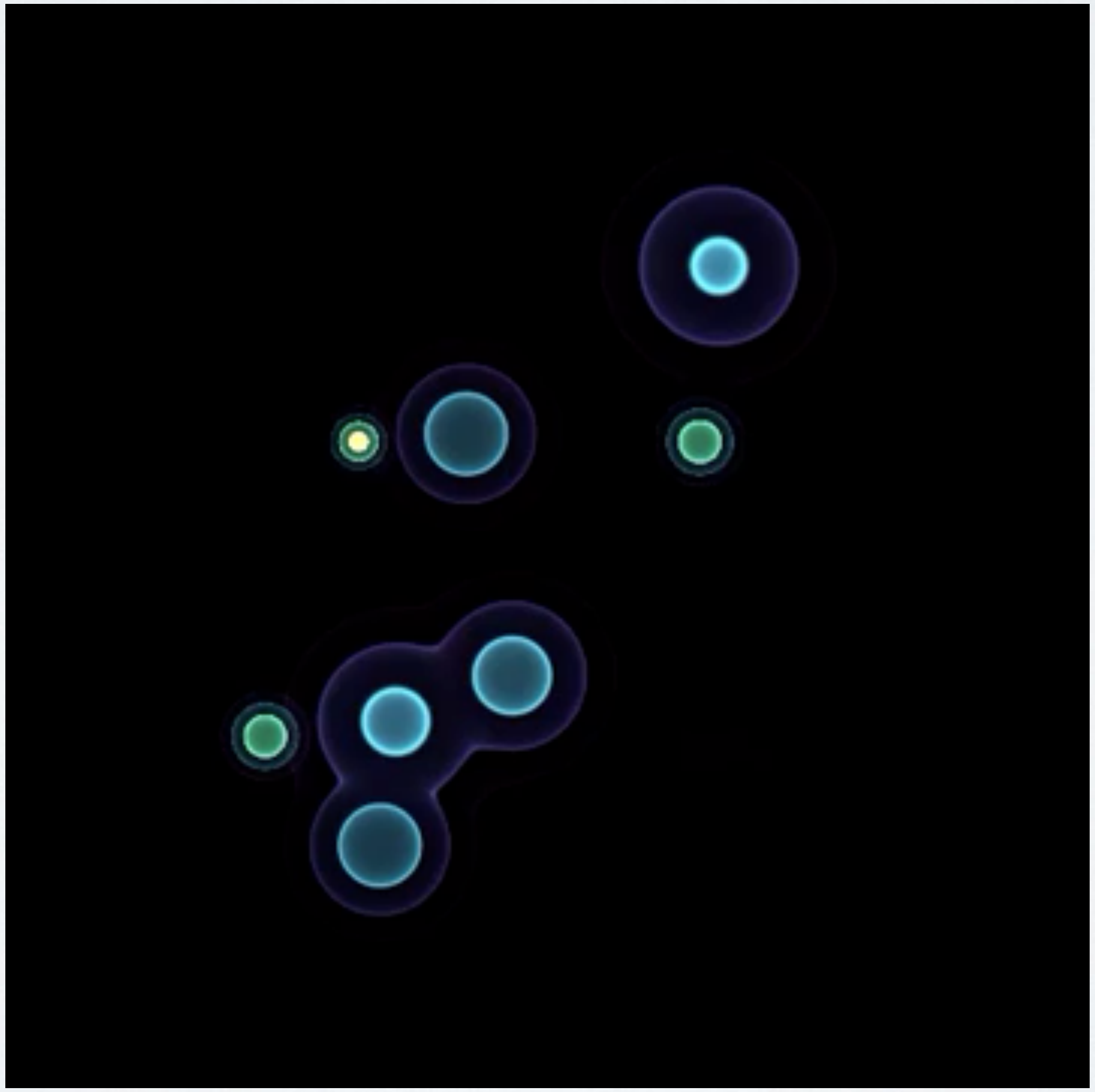
- Weakly Interacting Massive Particles (WIMPs) are/were promising candidate
- As WIMPs are massive, they would be cold
- Many experiments looking for WIMPs, but no success yet

Xenon1T / Gran Sasso Laboratory

Dark matter candidates: Quantum DM



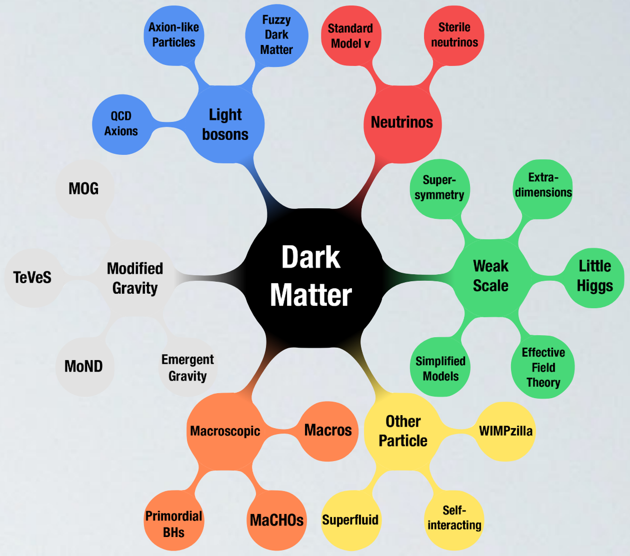
- Extremely light particles
- Experience quantum interference



Movie: Philip Mocz

Dark matter candidates: Overview

- No detection of any type of dark matter
- **Dark matter must be cold or very slightly warm,** otherwise not enough structure / subhalos



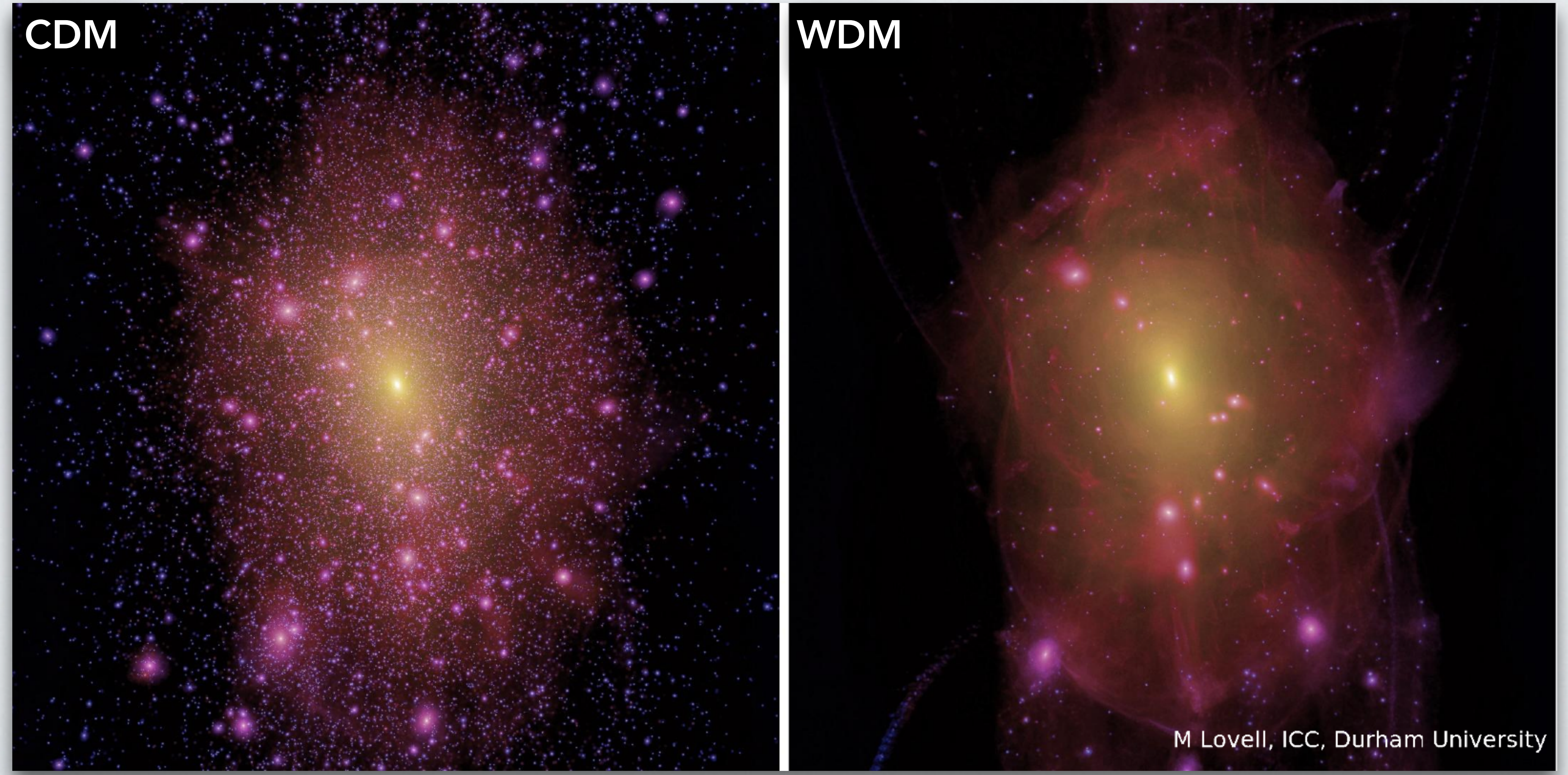
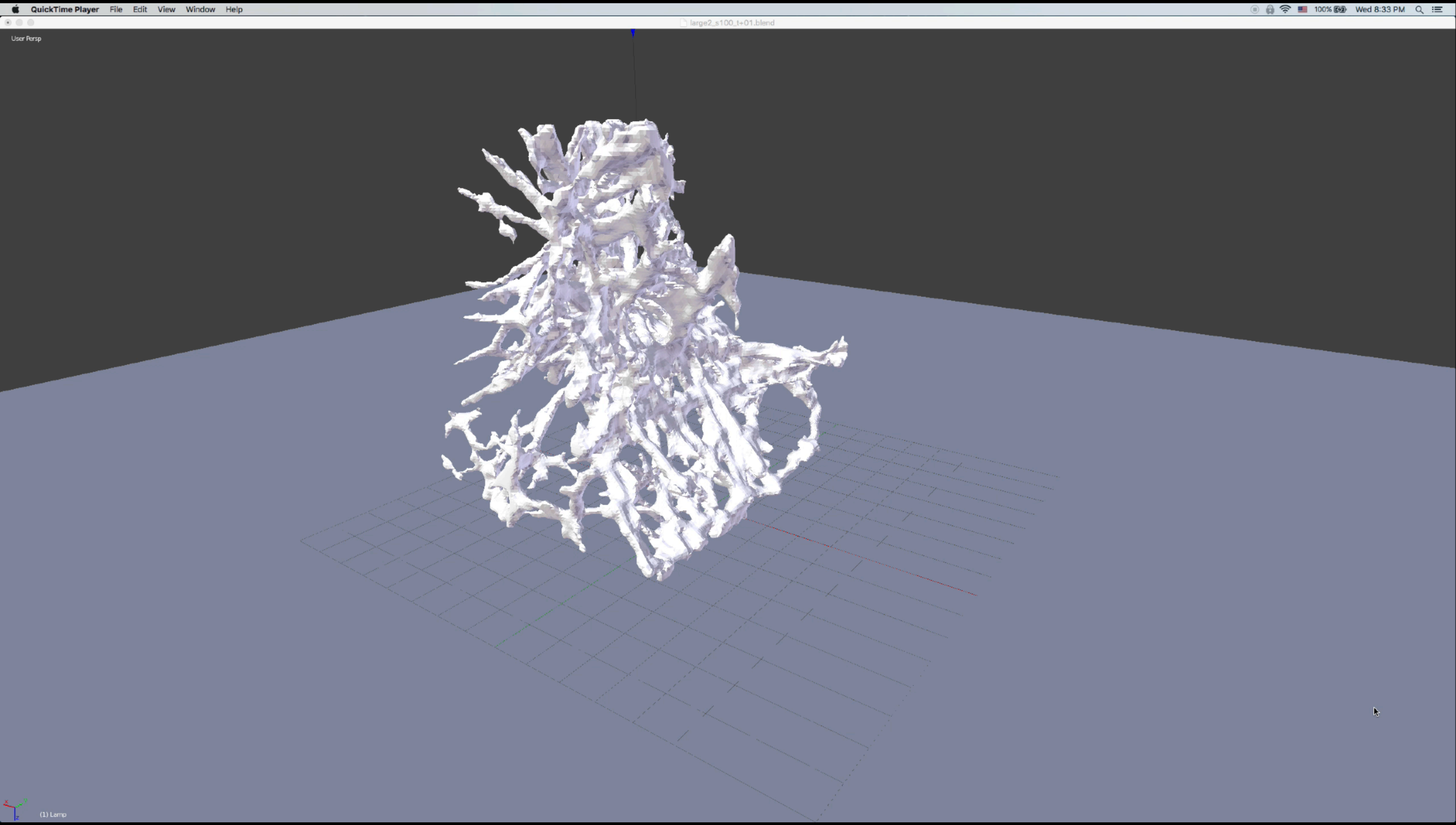


Image: Mark Lovell

Part 6: The cosmic web in 3D



Diemer & Facio 2017 • The Fabric of the Universe

Diemer & Facio 2017 • The Fabric of the Universe

Take-aways

- The **small initial density fluctuations** visible in the CMB **gravitationally collapse** to form the cosmic web

- Structure forms **bottom-up**, with small halos forming first and **merging** into bigger halos

- We do not know what dark matter is, but we think it is more or less **cold** (low initial velocity)

Next time…

We'll talk about:

- Galaxy formation

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #4 (due tonight!)

Reading:

- H&H Chapter 15