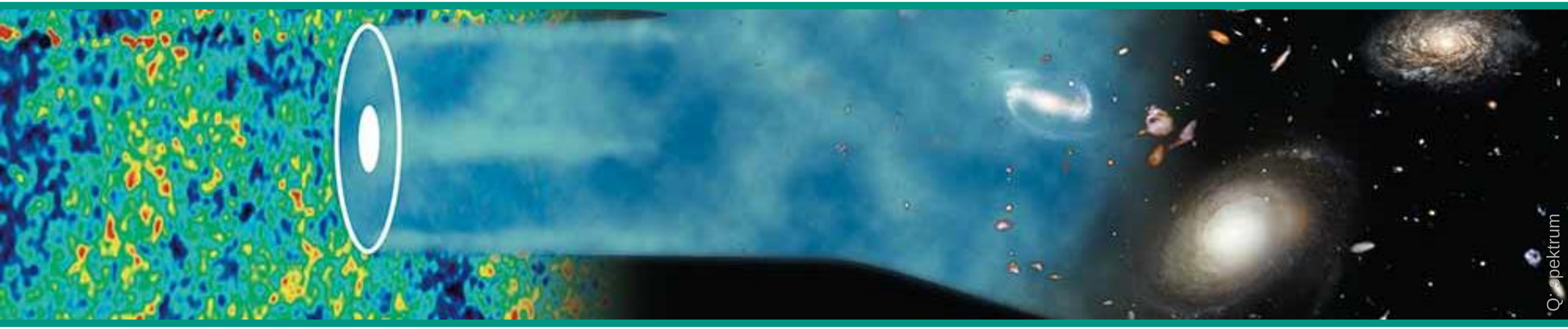
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 23/24 Lecture 12 Jan. 23, 2024



Recap of Lecture 11

- $\boldsymbol{CMB}$: **secondary anisotropies** & **search for circular polarization of** $\boldsymbol{CMB}$

  - $\boldsymbol{ISW}$ effect: $\boldsymbol{I}$ntegrated $\boldsymbol{S}$achs$-\boldsymbol{W}$olfe effect as further, independent evidence for the existence of **dark energy** / cosmological constant with $\boldsymbol{\Lambda \neq 0}$

    $\Rightarrow$ **correlation analysis** for superclusters & voids: $\Delta \boldsymbol{T} \approx \pm (\mathbf{5} \ldots \mathbf{10})\ \boldsymbol{\mu K}$

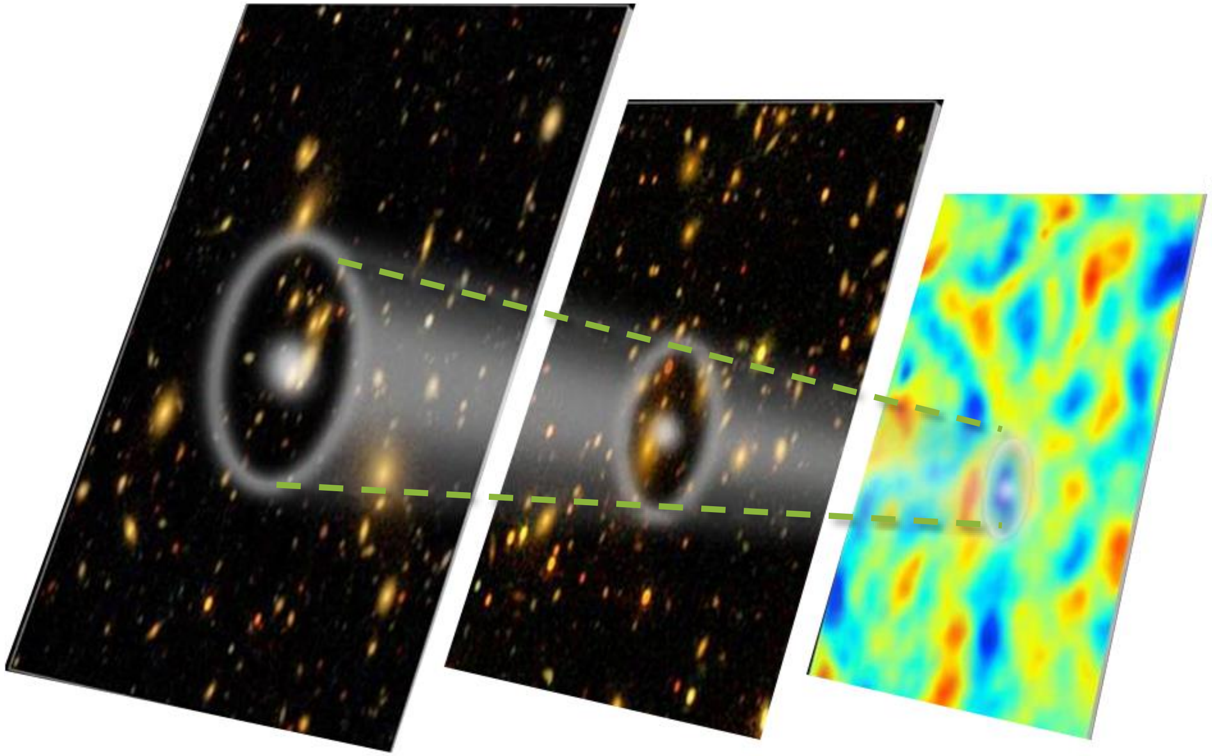
  - $\boldsymbol{SZ}$ ($\boldsymbol{S}$unyaev$-\boldsymbol{Z}$eldovich) **effect**:
    spectral distortion due to **inverse Compton** effect in galaxy clusters due to $\boldsymbol{keV}$ – scale electrons, it requires to cut out clusters from $\boldsymbol{CMB}$ – analyses

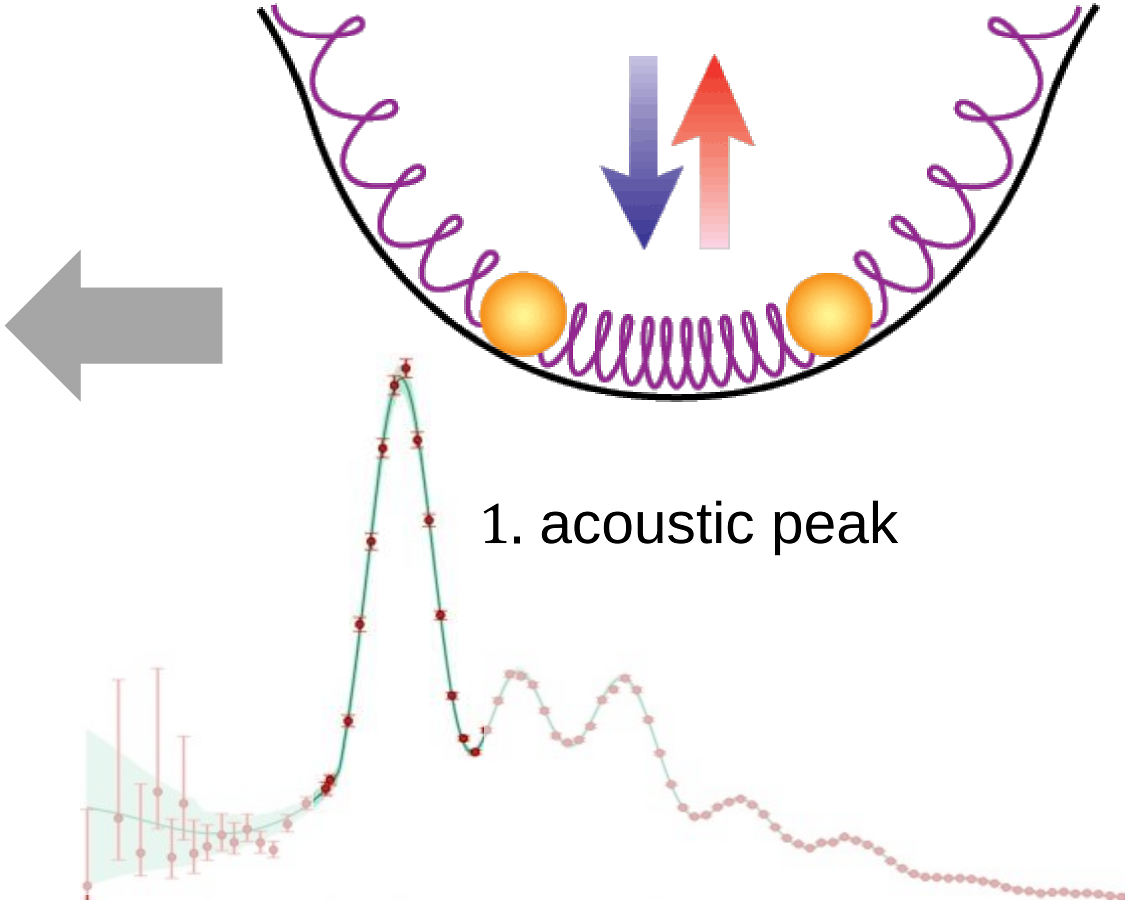
  - **inflationary theory**: rapid expansion of space$-$time can (in principle) be detected via gravitational waves ($\boldsymbol{GW}$)

  - search for **curl$-$like polarisation** patterns in $\boldsymbol{CMB}$ (but: beware of $dust$!)

4.2 BAO – Baryon Acoustic Oscillations

- **Formation in the early universe and relevance today at $t = t_0$**

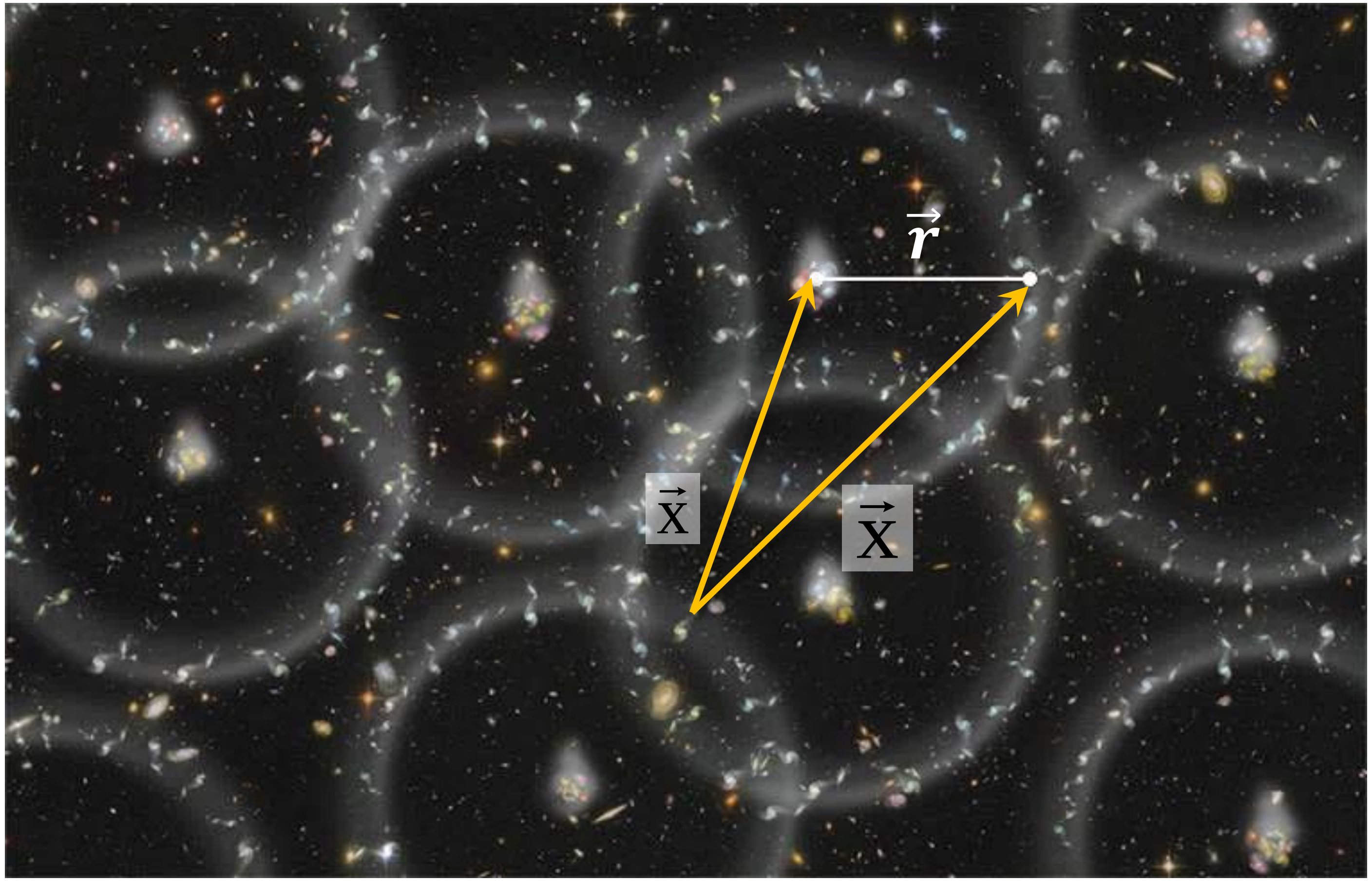




$Gyr = 10^9\ yr$

BAO – today´s signature via correlation analysis

- We can hunt for $BAOs$ by looking for ´circles in the sky´ (galaxy correlation)



- imprint & **characteristic signature of $BAOs$** in an expanding universe:
  ⇨ density contrast of baryons on a **specific length scale λ**

↳ detection of BAO via **statistic correlations within the distribution of galaxies***

*see also Chap: 4.4

BAO – today´s signature via correlation analysis

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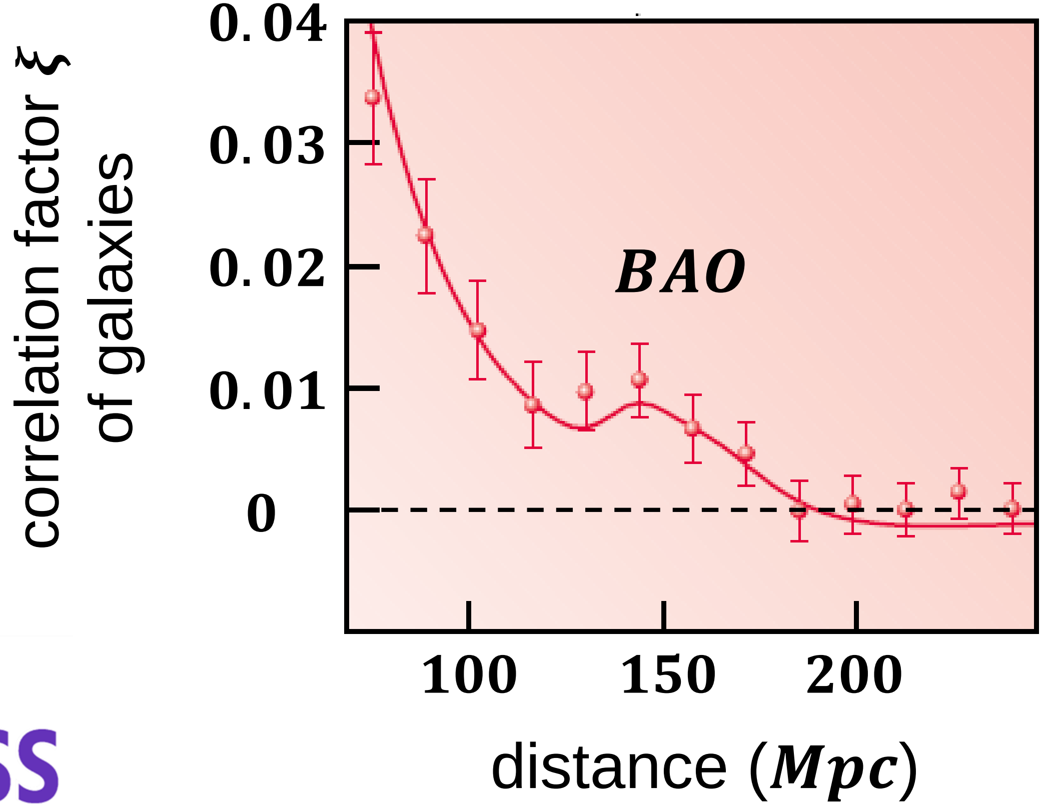
- **Large−scale galaxy surveys have identified the signature of BAOs**

  - physics of the **early universe** ($t < 378.000\ yr$) in the primordial plasma with **fundamental wave** (**rarefaction** → **overdensity**) revealed by galaxies: **bump** due to BAO at $d \approx 150\ Mpc$

SDSS



4.3 Large–Scale galaxy surveys

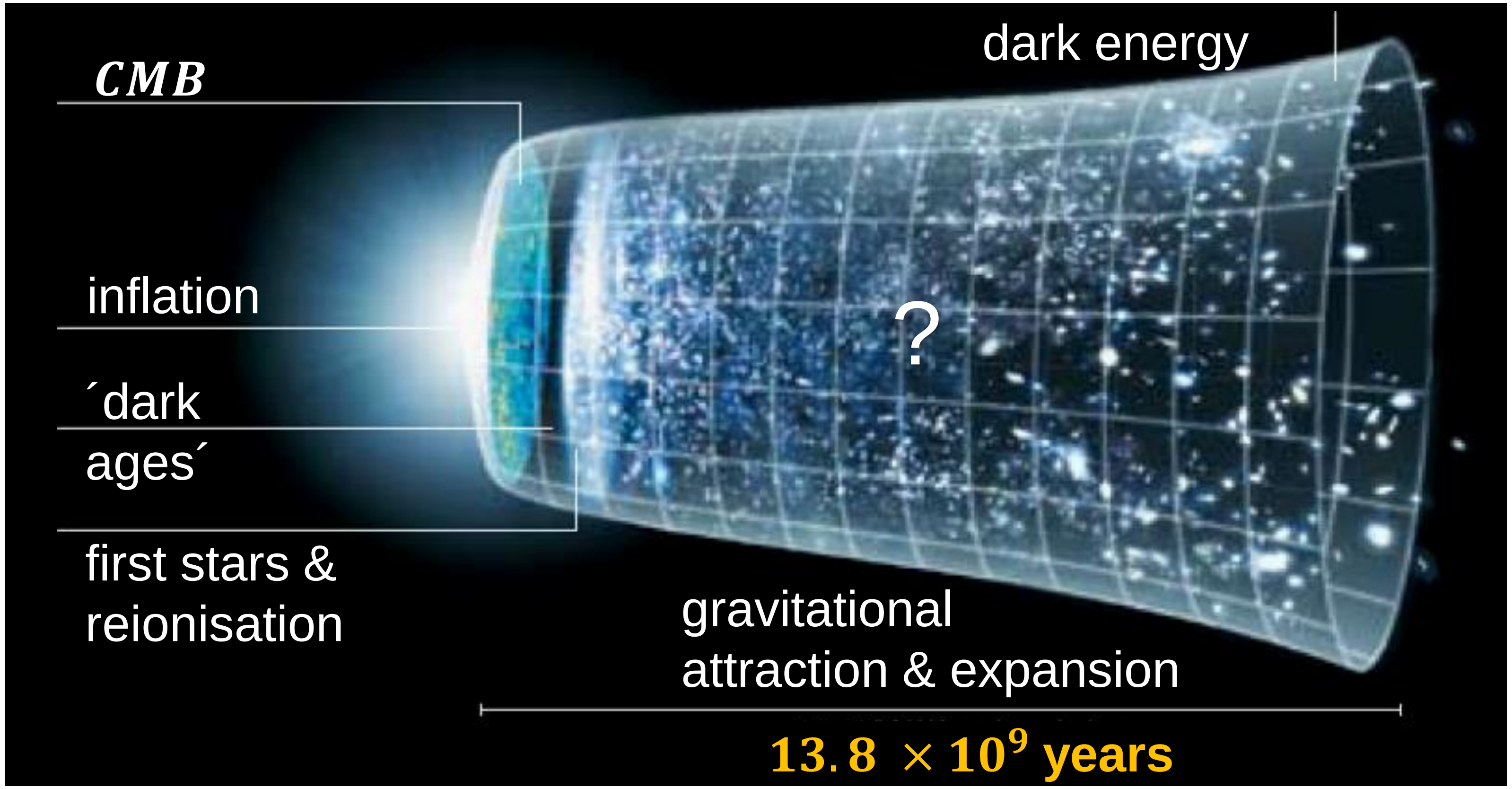
■ The power spectrum of matter as revealed by deep galaxy surveys

- we now investigate the origin & evolution of ***L*****arge** ***S*****cale** ***S*****tructures** (*LSS*) in the universe...

... ***what*** is the **origin/seed** of todays´ structures?

... ***when*** did todays´ large structures **develop**?

... ***how*** can we **measure** todays´ large–scale structures?



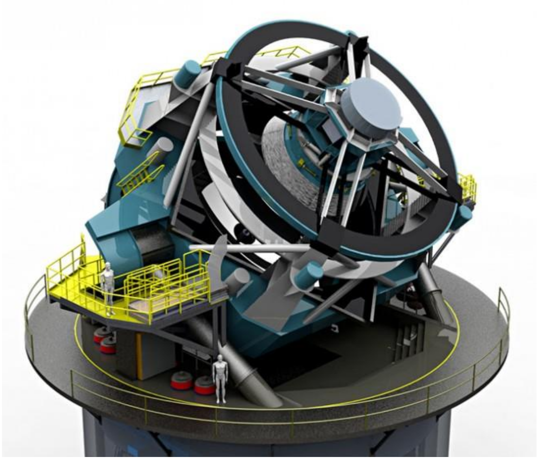
Combining data from the CMB with LSS

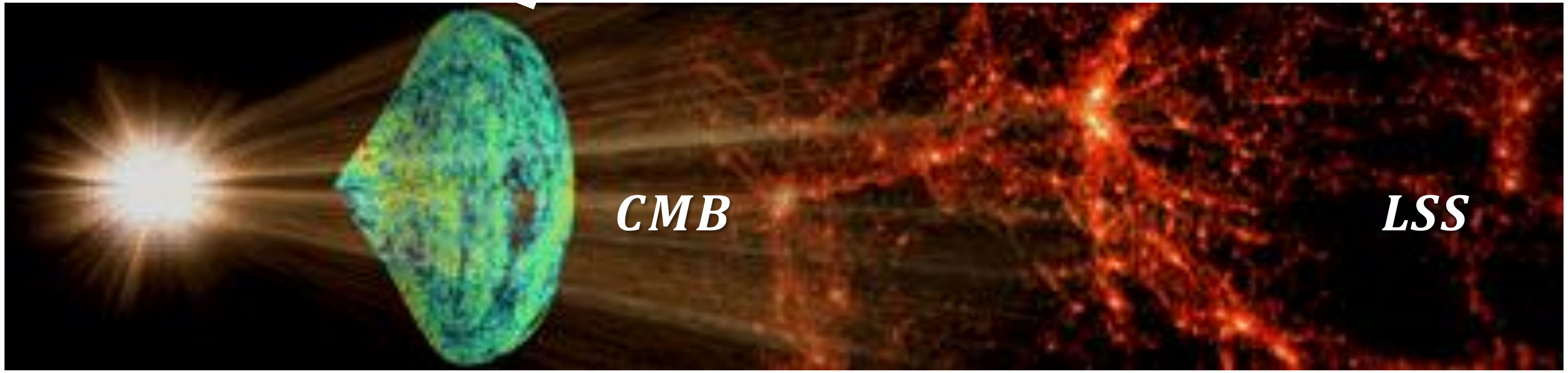
- **We have two observational pillars to anchor our theoretical models**

  - **combination** is of major importance

CMB
($WMAP$, $Planck$)

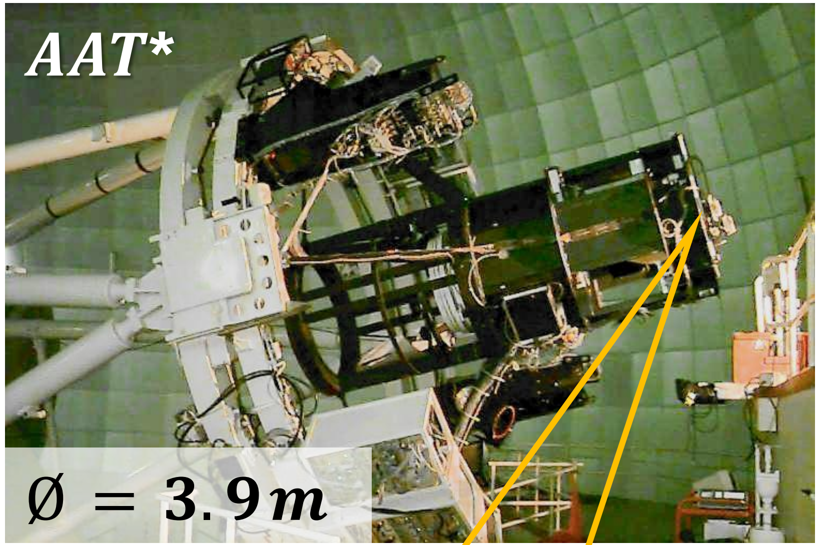
galaxy surveys
($2dFGRS$, $SDSS$, …)

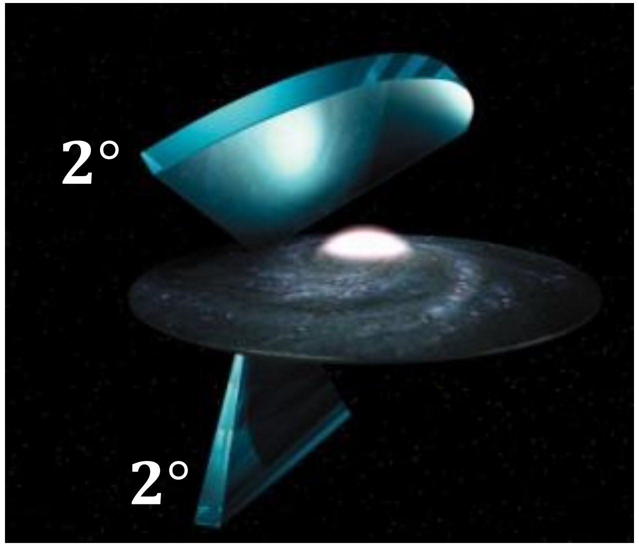




Galaxy surveys: fundamentals & example

- $2dF$ – survey as an important (early) example of todays´ galaxy surveys





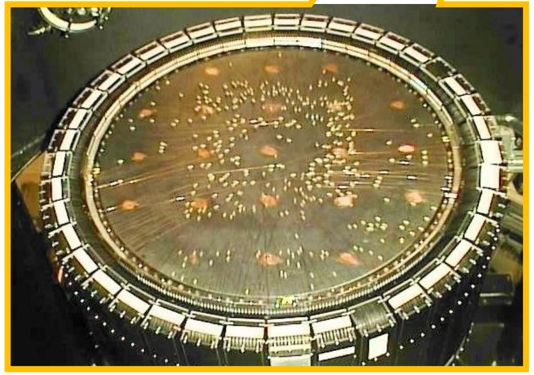
2 degree Field survey (2dF)

area: **1500** square–degrees

objects: up to 19.5^{mag}

field–of–view: **2°**

focal plane

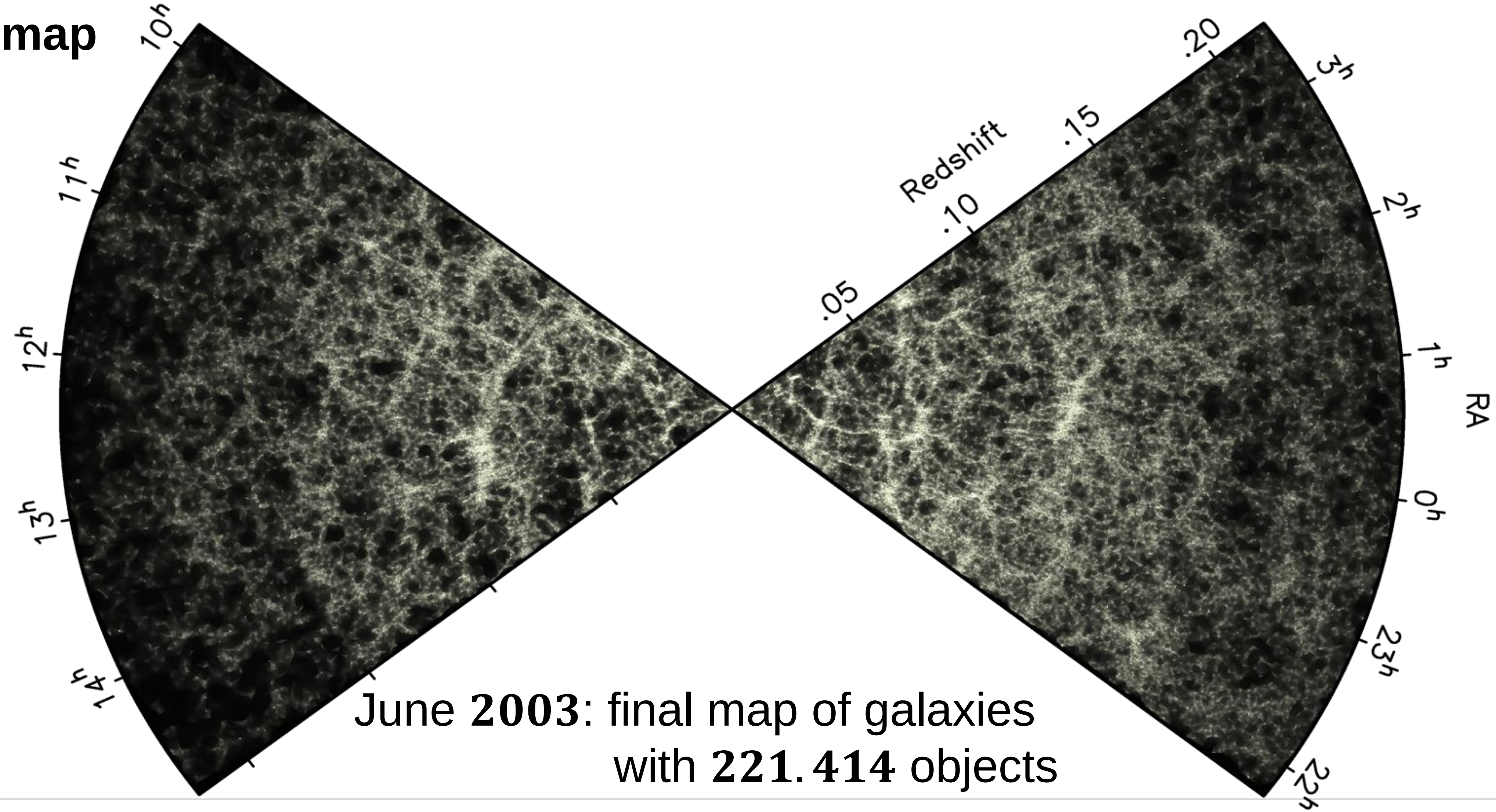


- measurement of **redshift of lines** via **392** optical fibers
- light analysed in spectrograph with $\lambda/\Delta\lambda > 1000$
- optical fiber is automatically positioned at the position of the galaxy to be investigated

*Anglo–Australian Telescope

Galaxy surveys: it all started with $2dF$

- $2dF$ map



June $\mathbf{2003}$: final map of galaxies with $\mathbf{221.414}$ objects

Galaxy surveys: the next big step – $SDSS$

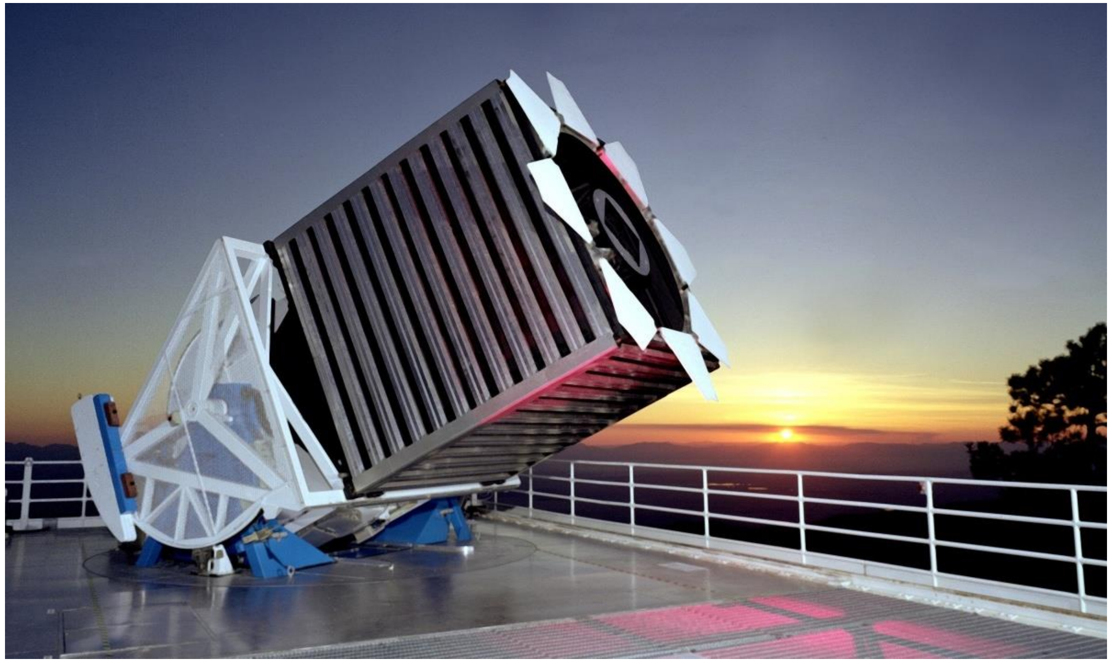
- $\mathbf{20}$ **years to generate a complete galaxy redshift survey of the northern sky**

- observations & data taking since $\mathbf{2000}$

- July $\mathbf{2020}$: most detailed $\mathbf{3-}\boldsymbol{D}$ map of the the universe is released

photometry: $\mathbf{5}$ colour bands with $\mathbf{30}\ \boldsymbol{CCDs}$
$\mathbf{354\,/\,476\,/\,628\,/\,769\,/\,925}\ \boldsymbol{nm}$

spectroscopy: $\mathbf{640}$ optical fibers ($\emptyset = \mathbf{3}°$) for the selected galaxies)



*$\boldsymbol{S}$loan $\boldsymbol{D}$igital $\boldsymbol{S}$ky $\boldsymbol{S}$urvey

Galaxy surveys: the next big step – $\boldsymbol{SDSS}$

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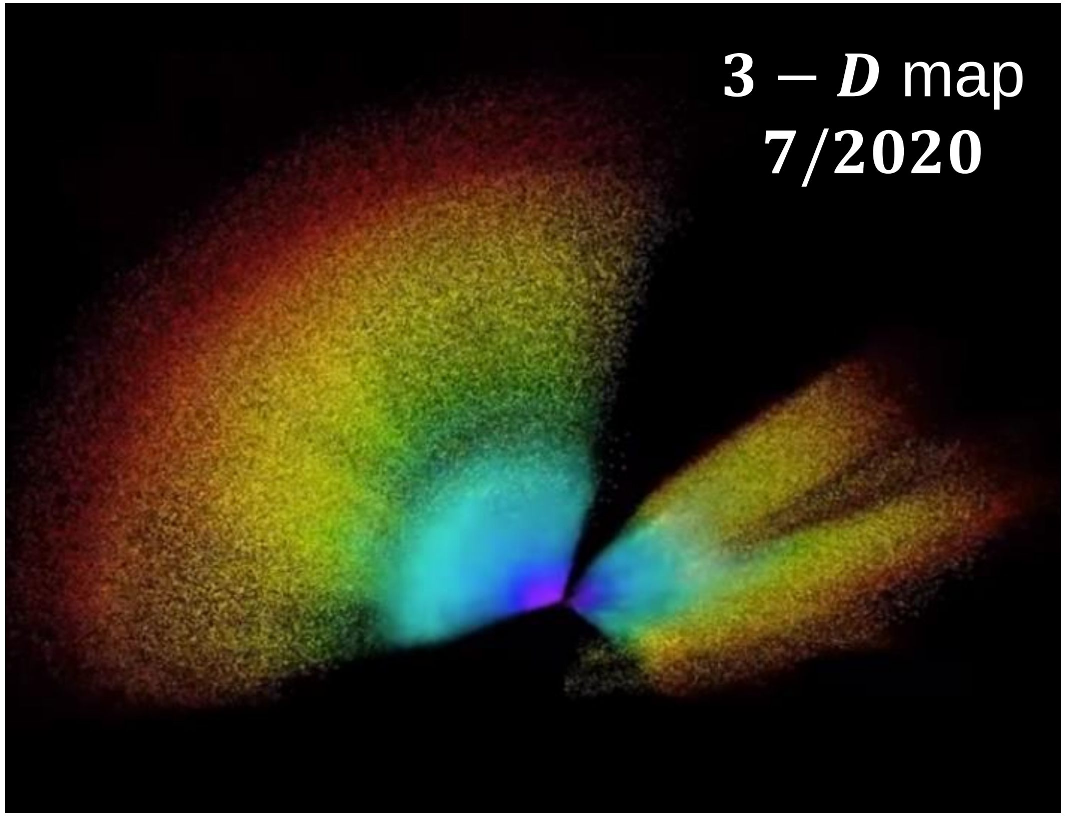
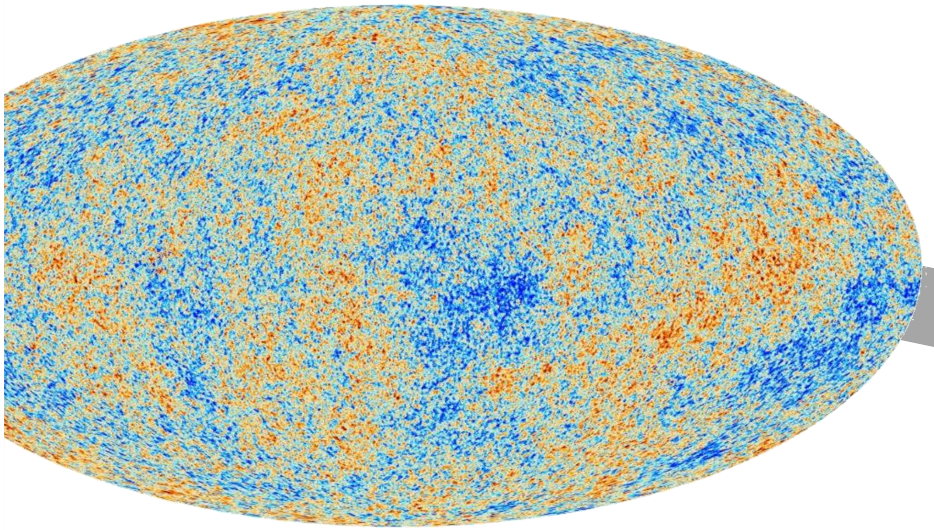
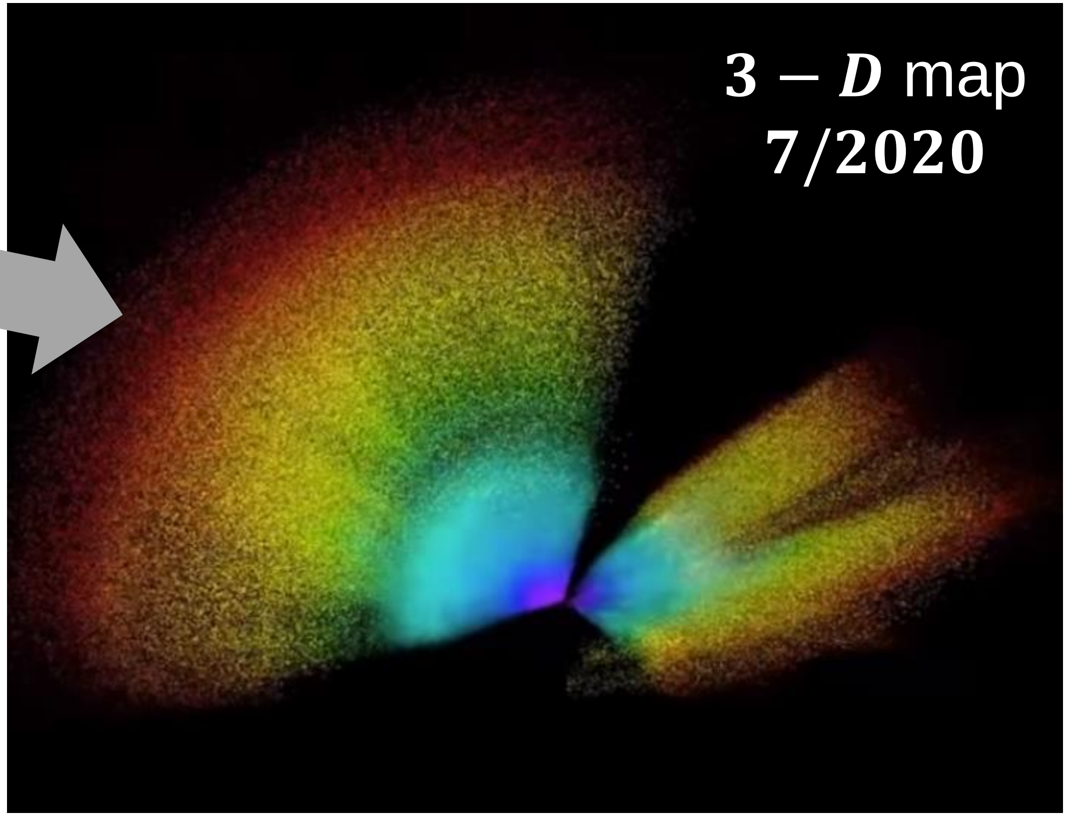


Structure formation: from the CMB to the LSS

- The **density contrast $\delta(\vec{r}, t)$ of matter**: how did it evolve over the Hubble time?





CMB:	LSS:
$\Delta\rho/\rho \sim 10^{-5}$	$\Delta\rho/\rho \sim 2 \ldots 3$

early universe:
$t \sim 378.000\ yr$

todays universe:
$t \sim 13.8 \cdot 10^{9}\ yr$

Structure formation: from the CMB to the LSS

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- **The density contrast $\delta(\vec{r},t)$ of matter: a key parameter in structure formation**

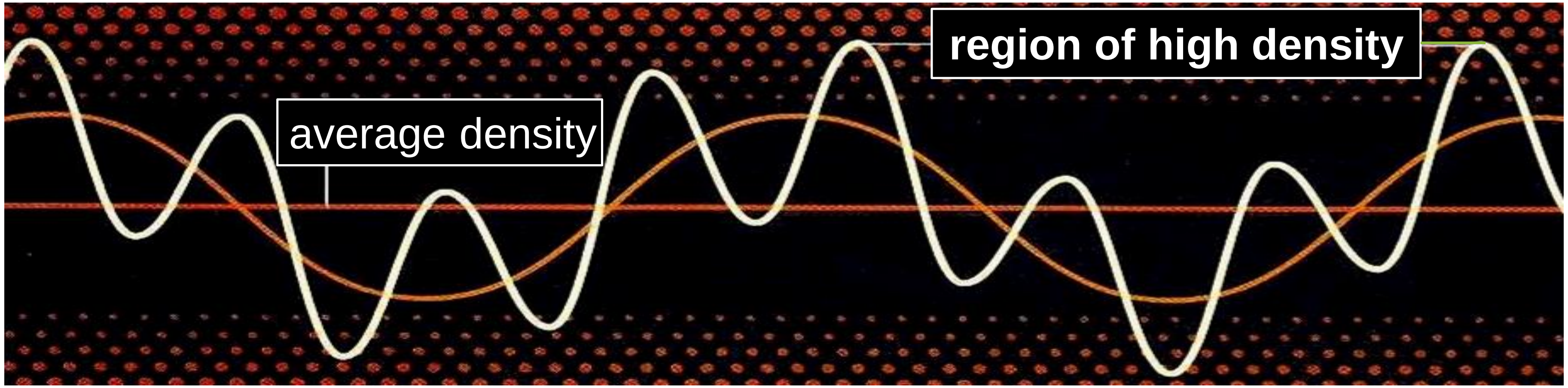
  - RECAP: we (usually) consider co–moving coordinates

$$\delta(\vec{r},t) = \frac{\rho(\vec{r},t) - \bar{\rho}}{\bar{\rho}}$$

dimensionless parameter $\delta(\vec{r},t)$

local density $\rho(\vec{r},t)$ average density $\bar{\rho}$

$\delta(\vec{r},t)$

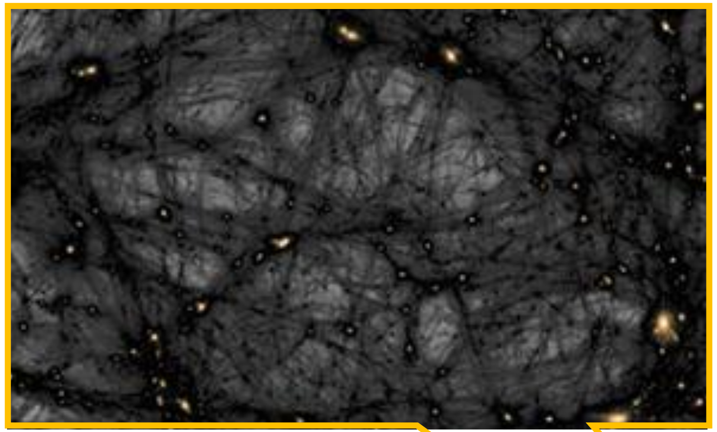


$\bar{\rho}$

Structure formation: from the CMB to the LSS

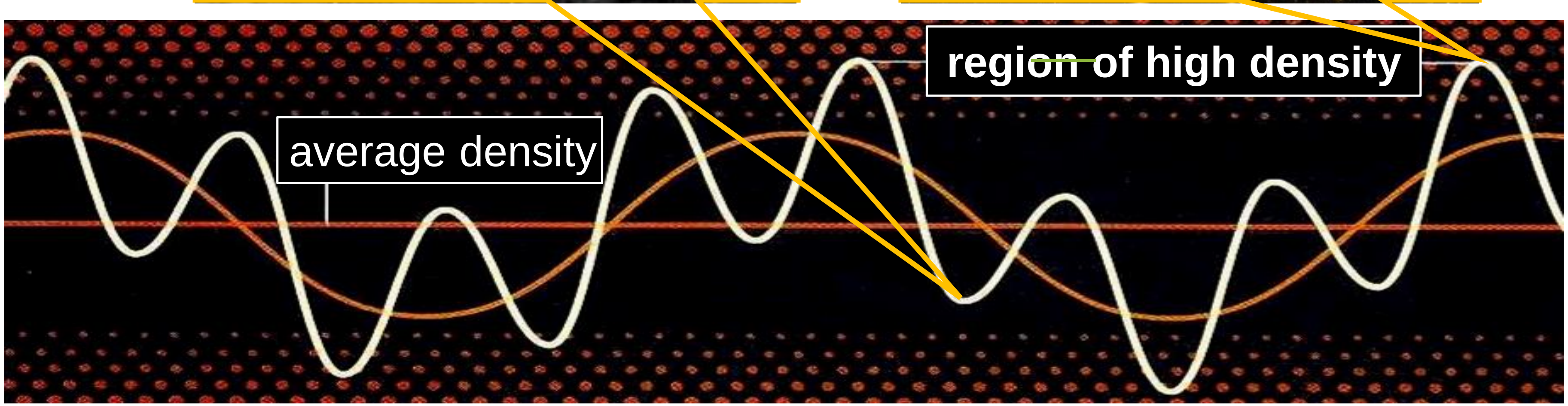
- The **density contrast $\delta(\vec{r}, t)$ of matter**: a key parameter in structure formation

void
$\delta \sim 0.2 \ldots 0.3$



cluster
$\delta \sim 2 \ldots 3$

$\delta(\vec{r}, t)$



$\bar{\rho}$

Structure formation: from the CMB to the LSS

- **What values of density contrast $\delta(\vec{r},t)$ are measured in todays´ universe?**

- **smaller sizes**: very **large** values of density contrast (⇨ **non–linear evolution**)

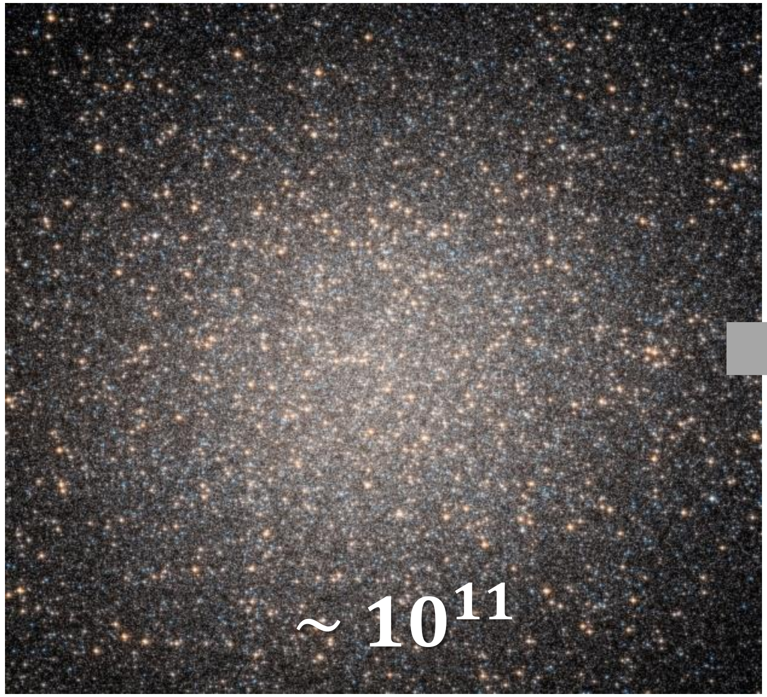
object	$\delta(\vec{r},t)$	dimension λ	mass $[M_\odot]$
globular clusters	10^{11}	$10 - 100\ pc$	$10^5 \dots 10^6$
open star cluster	10^9	$2 - 20\ pc$	$10^2 \dots 10^3$
galaxy	10^6	$30\ kpc$	10^{11}
galaxy cluster	10^3	$1 - 10\ Mpc$	10^{13}
super–clusters	$2 \dots 3$	$30 - 100\ Mpc$	10^{17}
voids	$0.2 \dots 0.3$	$< 100\ Mpc$	

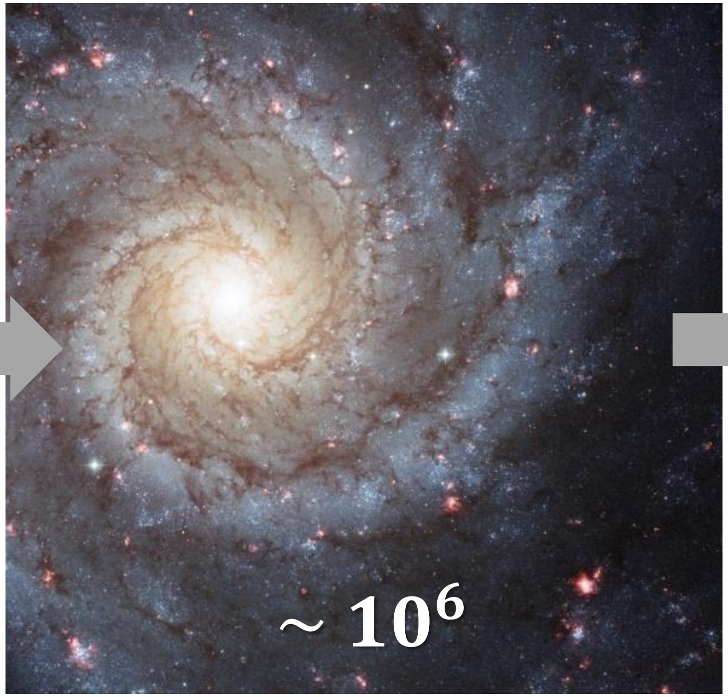
Structure formation: from the CMB to the LSS

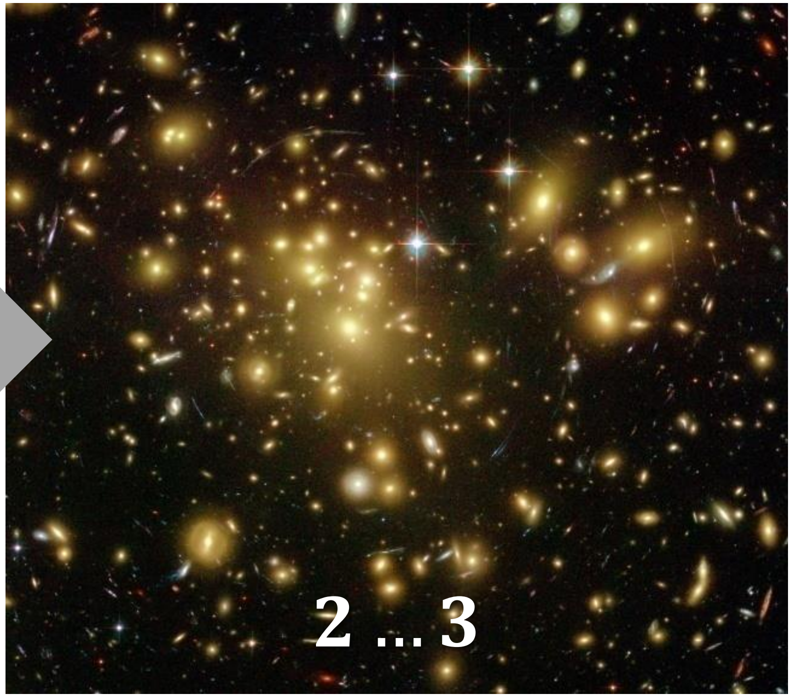
- **What values of density contrast are measured in todays universe?**

\- **smaller sizes**: very **large** values of density contrast (⇨ **non−linear evolution**)

globular cluster **spiral galaxy** **super−cluster**

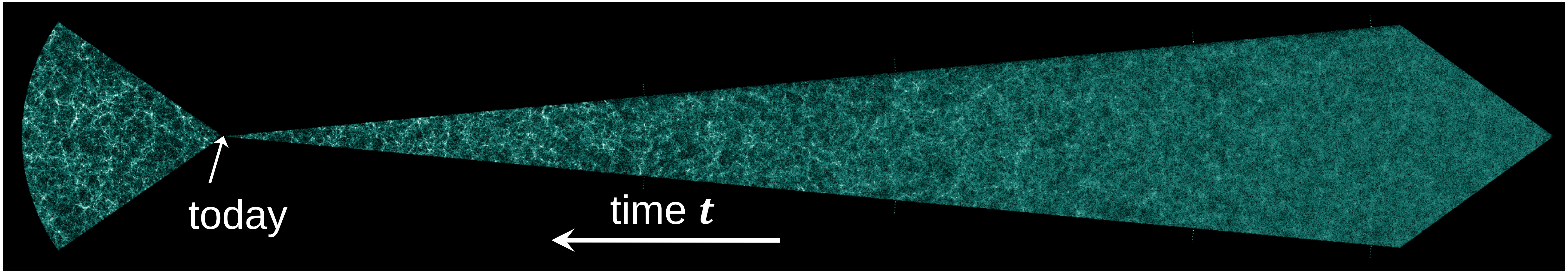


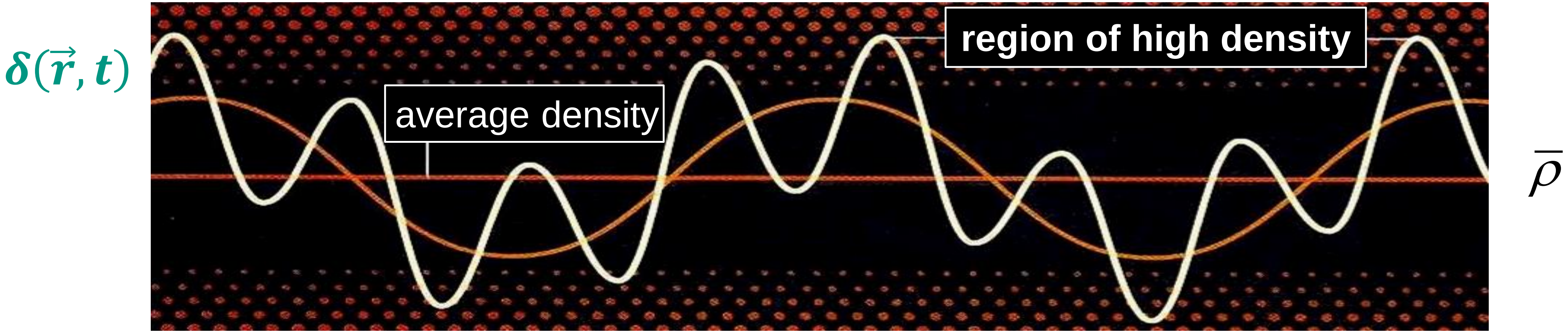




Structure formation: from the CMB to the LSS

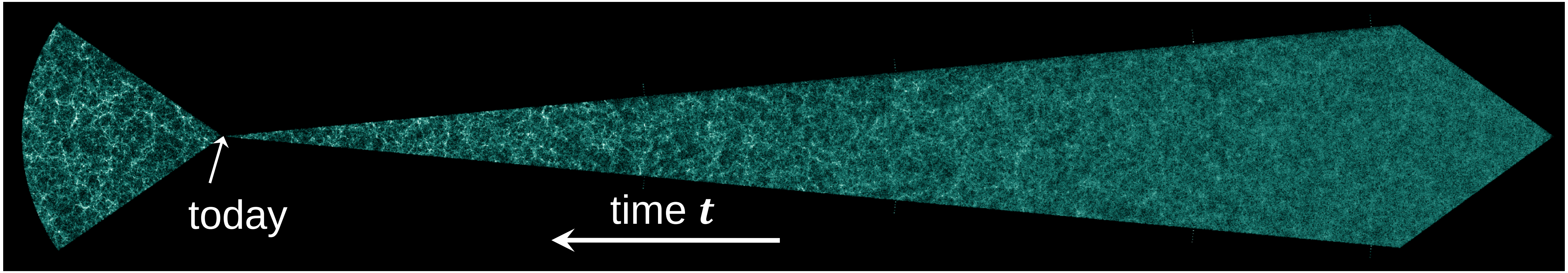
- Visualizing the **evolution of the density contrast δ** over the Hubble time





Structure formation: from the CMB to the LSS

- **Visualizing the evolution of the density contrast δ over the Hubble time**



- weak gravitational fields: Newtonian gravitation ⇨ **apply perturbation theory**

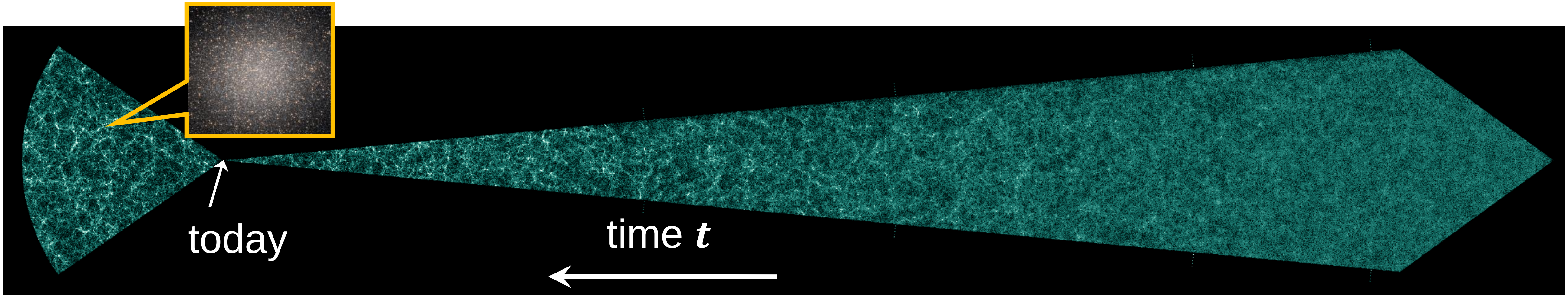
- **increase of local inhomogenity** in comparison to **cosmic mean value $\bar{\rho}$**

under−density $(\delta\rho < 0)$: regions expand **faster** (relative to $\bar{\rho}$)

over−density $(\delta\rho > 0)$: regions expand **slower** (relative to $\bar{\rho}$)

Structure formation: from the CMB to the LSS

- **Visualizing the evolution of the density contrast $\delta(\vec{r}, t)$ over the Hubble time**



- weak gravitational fields: Newtonian gravitation ⇨ **perturbation theory**

- **density contrast $\delta(\vec{r}, t)$ increases linearly with cosmic scale factor $a(t)$**

- as soon as the density contrast reaches $\delta > 1$ the further **evolution is non–linear** ⇨ highly overdense regions (globular clusters) cannot be included in models

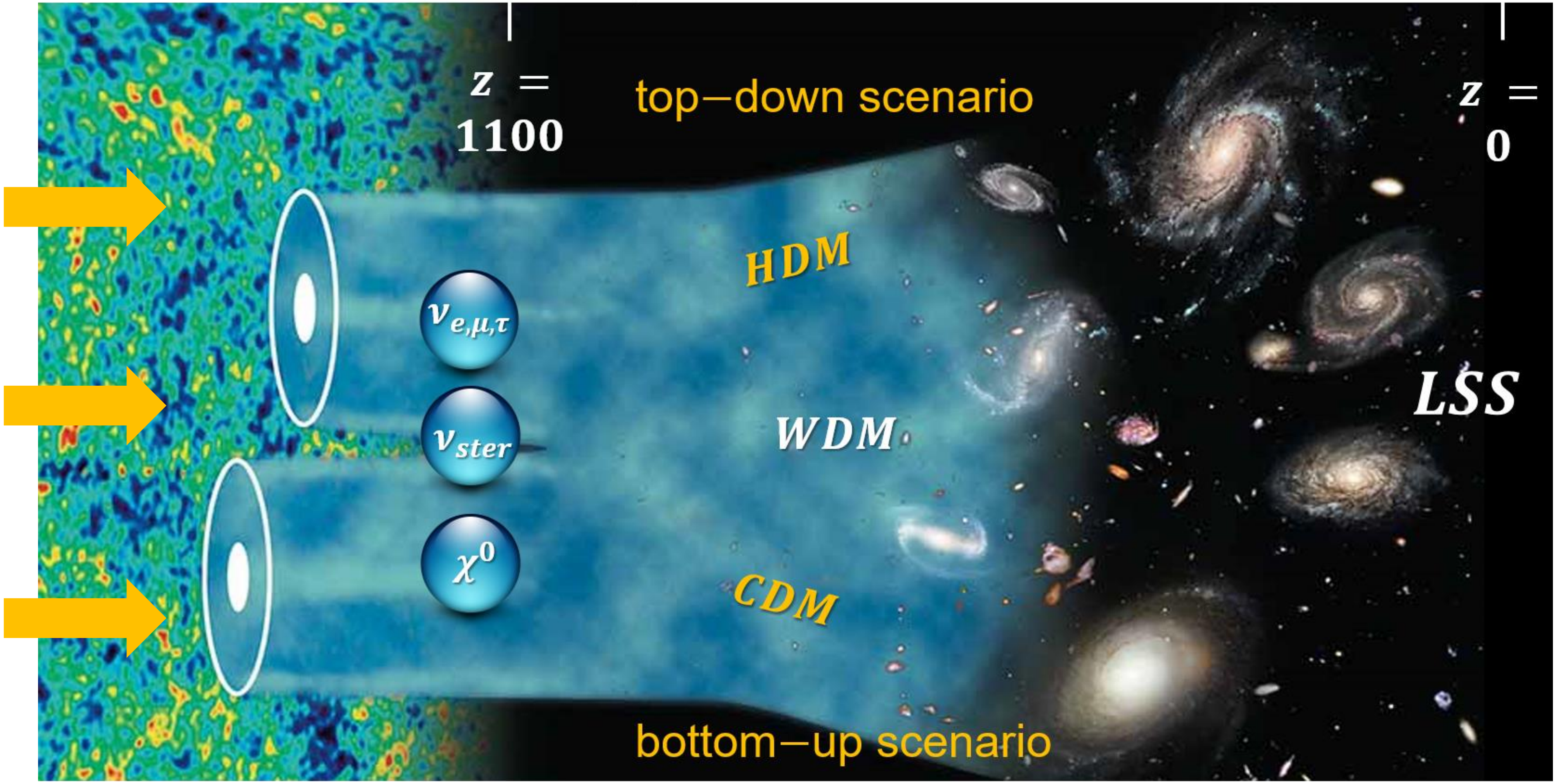
4.4 Evolution of large–scale structures

- Impact of different DM models on the long–term evolution of structures

$HDM =$
Hot Dark Matter

$WDM =$
Warm Dark Matter

$CDM =$
Cold Dark Matter



Structure formation: top−down vs. bottom−up

- ***H*ot *D*ark *M*atter (*HDM*)**

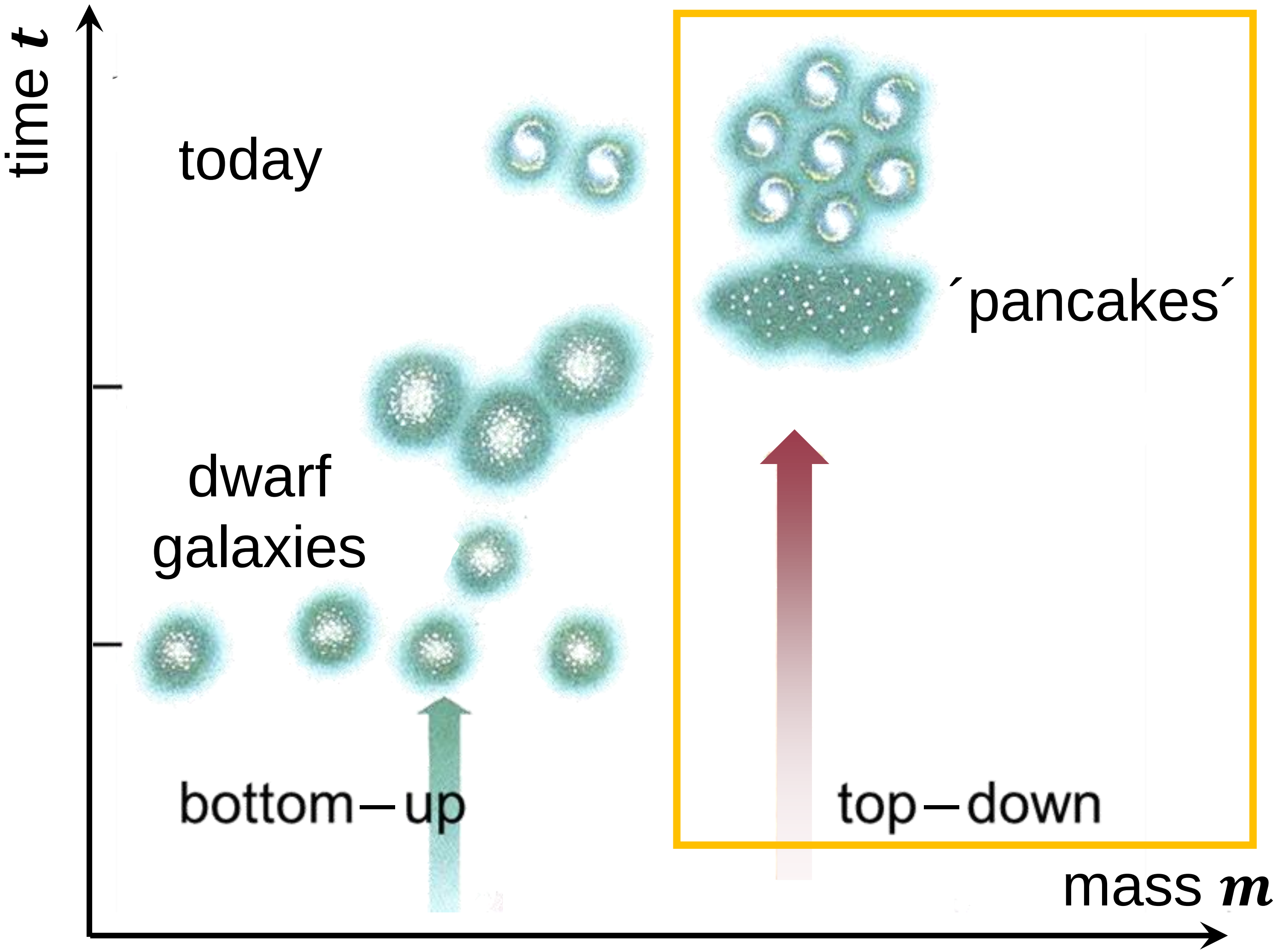
  relativistic particles: free−streaming over Hubble time

  - key example: light $(sub-)eV$ − scale **neutrinos**

  - decoupling of ν´s:
  temperature $T_{dec} \sim 1\ MeV$
  mass: $0.8\ eV$ − scale* or below

  ⇨ Lorentz−factor $\gamma > 10^9$

  ⇨ free−streaming on typical length−scale $\lambda_{fs} \sim 1\ Gpc$



*current $KATRIN$ limit

Structure formation: top−down vs. bottom−up

- $\mathcal{C}$old $\mathcal{D}$ark $\mathcal{M}$atter ($\mathcal{CDM}$)

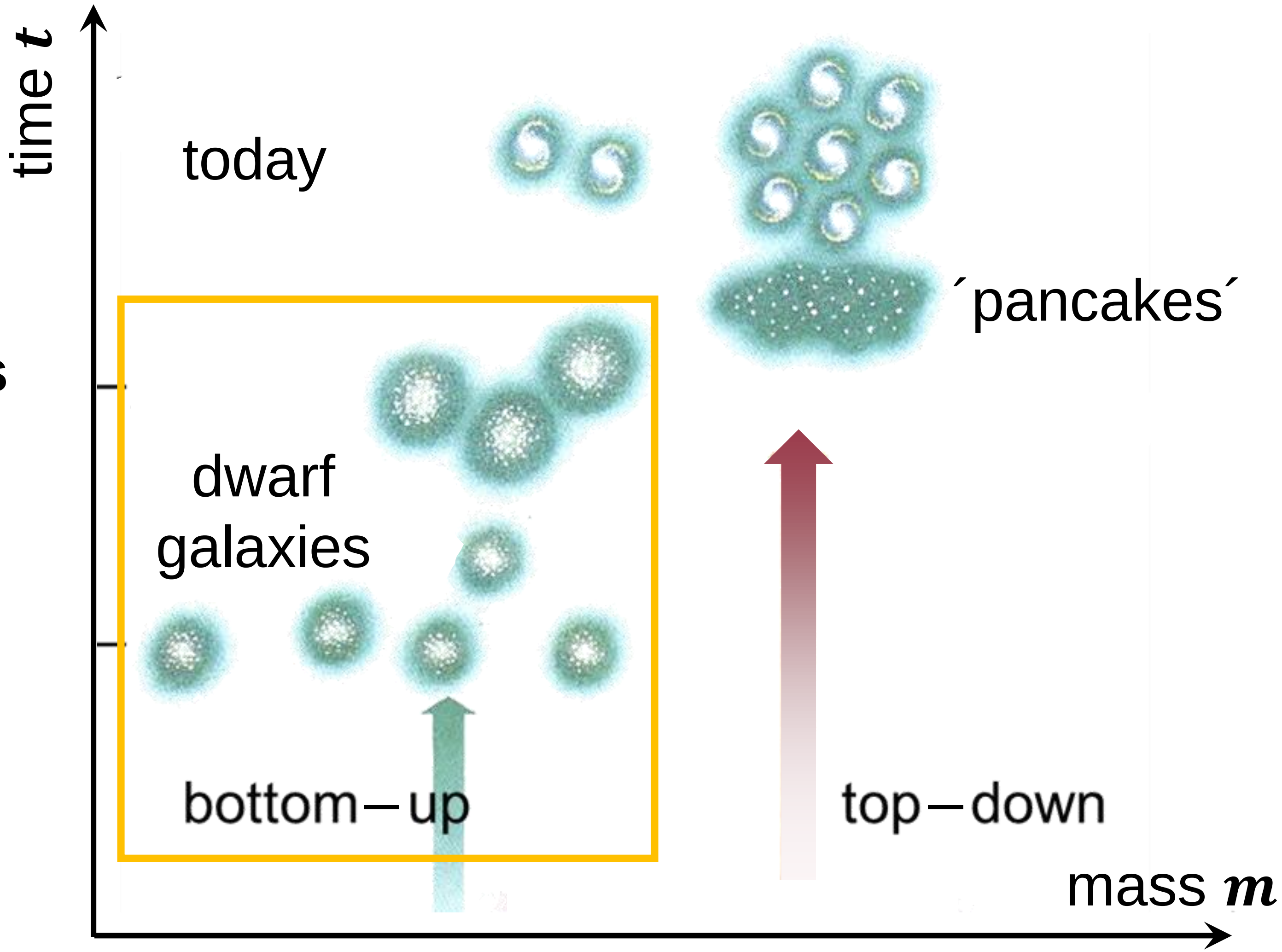
  non−relativistic particles: limited free−streaming range

  - **key example:** heavy $\boldsymbol{GeV} \dots \boldsymbol{TeV}$ – scale **neutralinos**

  - **decoupling of χ^0:**
    temperature $\boldsymbol{T_{dec} \sim 50\ TeV}$
    mass: $\boldsymbol{\sim TeV}$ – scale or above

    ⇨ Lorentz−factor $\boldsymbol{\gamma \sim 0.05}$

    ⇨ free−streaming on typical length−scale $\boldsymbol{\lambda_{fs} \sim\ pc}$



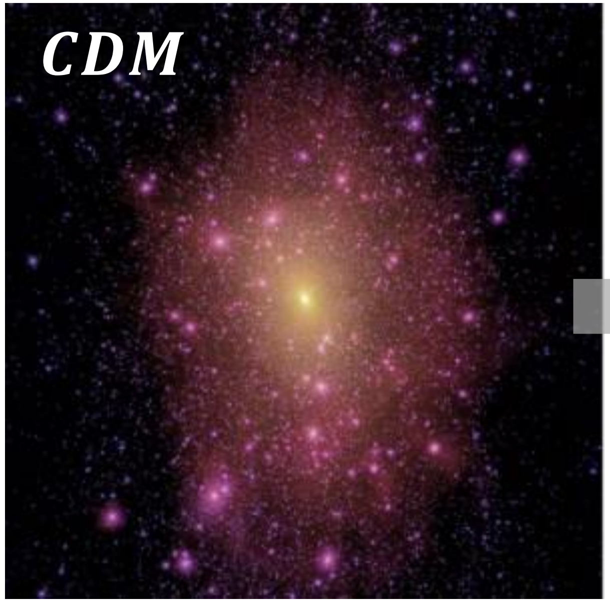
top–down vs. bottom–up

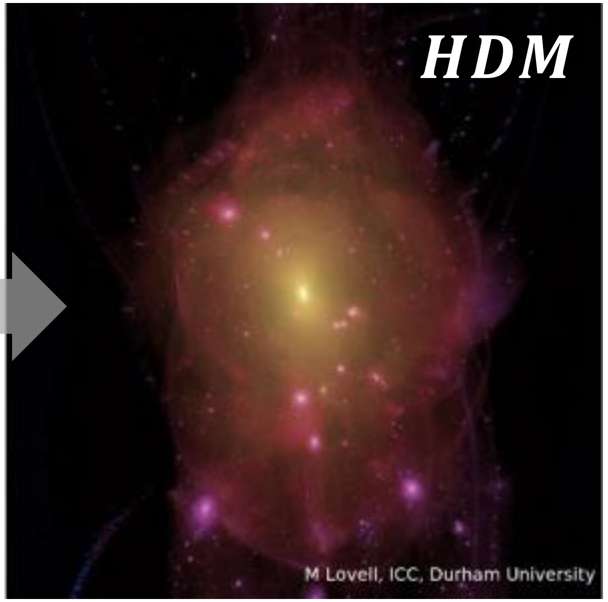
HDM:
wash–out of small structures

- **universe with HDM/CDM**

$T_{dec} \sim 1\,MeV\ t_{dec} \sim 1\,s$
$m(\nu) < 0.8\,eV\ \ \gamma > \ 10^9$

$T_{dec} \sim 50\,TeV\ t_{dec} \sim 10^{-9}\,s$
$m(\chi^0) > 1\,TeV\ \ \gamma \sim 0.05$





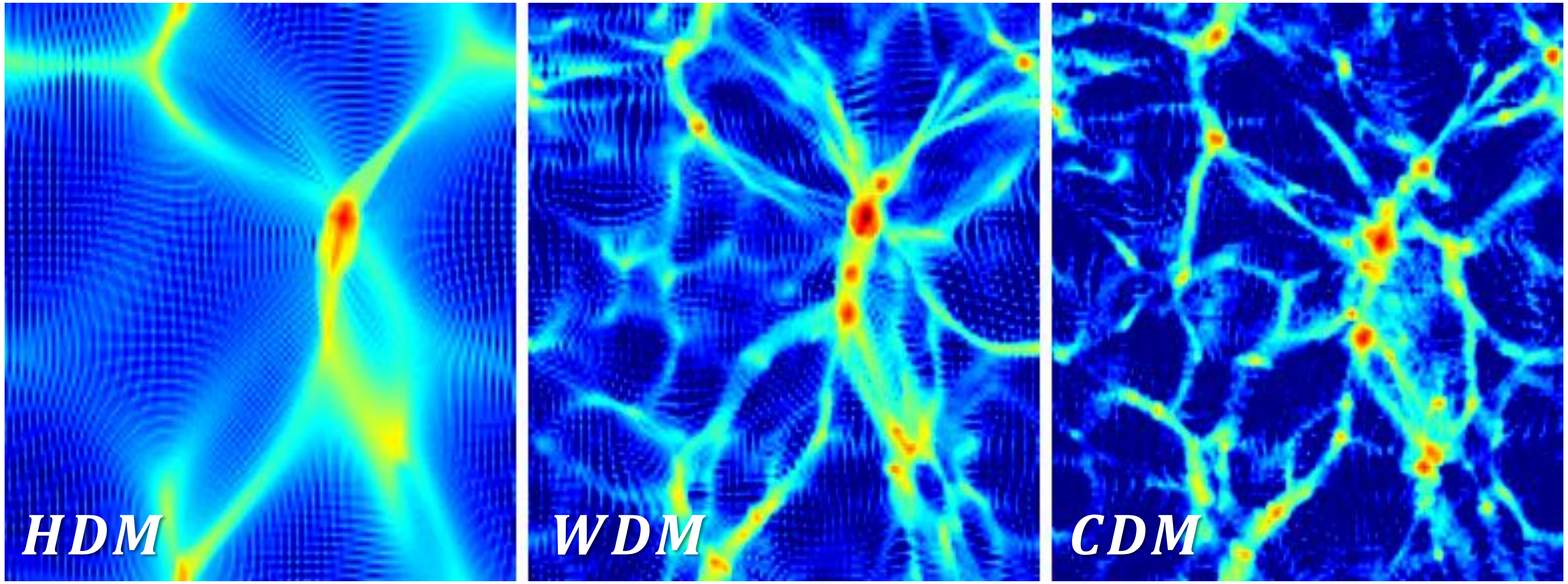
$\boldsymbol{WIMP}$: $\boldsymbol{W}$eakly $\boldsymbol{I}$nteracting $\boldsymbol{M}$assive $\boldsymbol{P}$article

top–down vs. bottom–up

- **Different pathways to forming structures & different impact of wash–out**

neutrinos (relativistic) — $WIMP$s (non–relativistic)

top ↓ down



bottom ↑ up

first: large structures

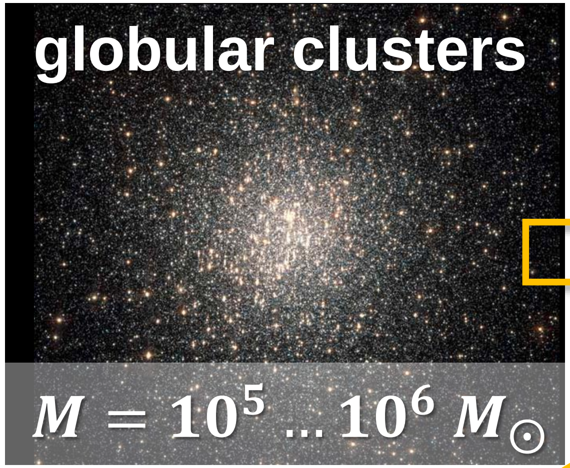
later: small structures

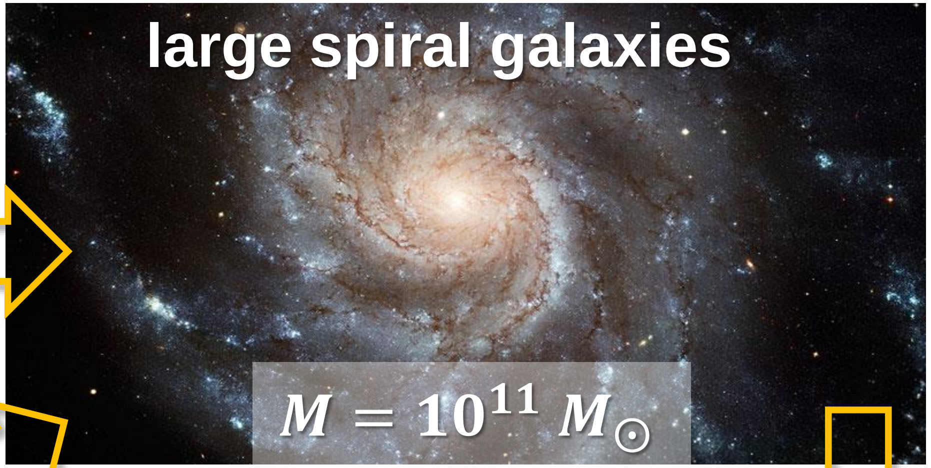
later: **large** structures

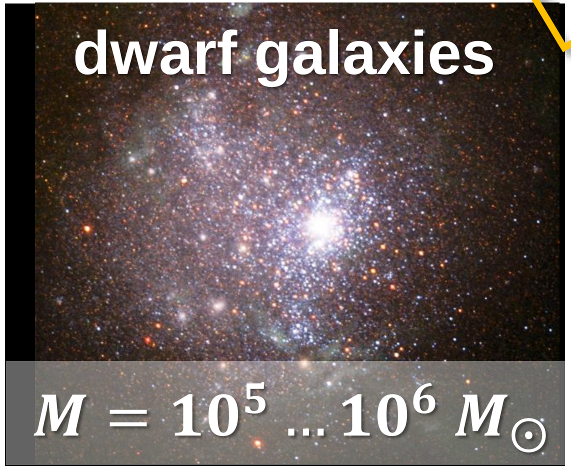
first: **small** structures

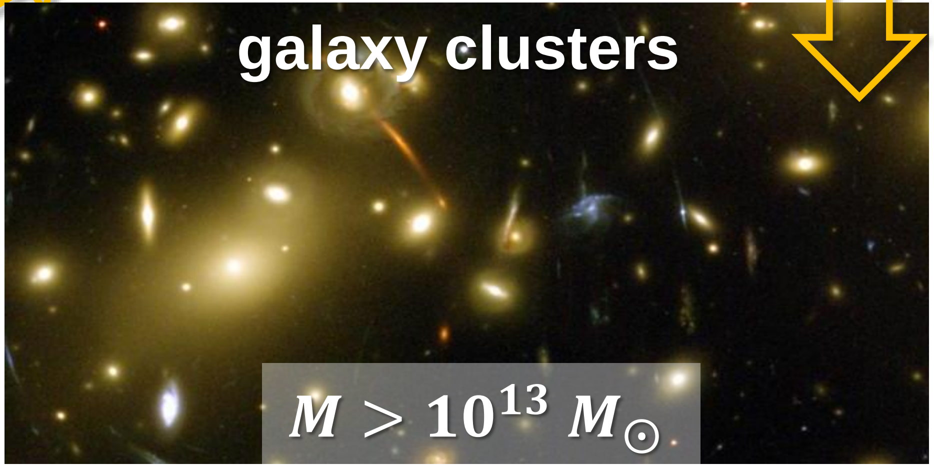
Structure formation: bottom–up scenario

- A universe dominated by **Cold Dark Matter**









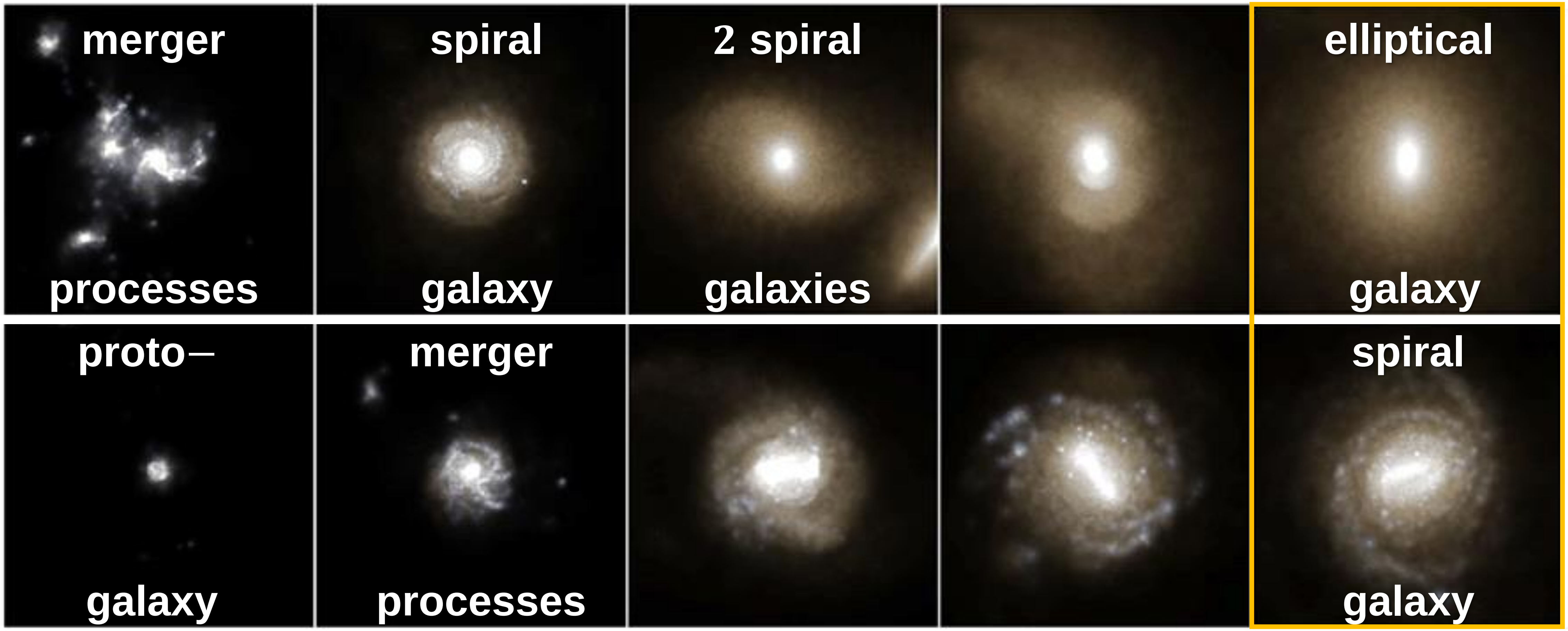
- structures with $\mathbf{10^5 \ldots 10^6\, M_\odot}$ as basic building blocks → **proto–galaxies**

- further evolution: many proto–galaxies are **merging** to **large (spiral) galaxies**

- final steps in evolution: galaxies merge to **clusters** which then are beginning to ´**virialise**´

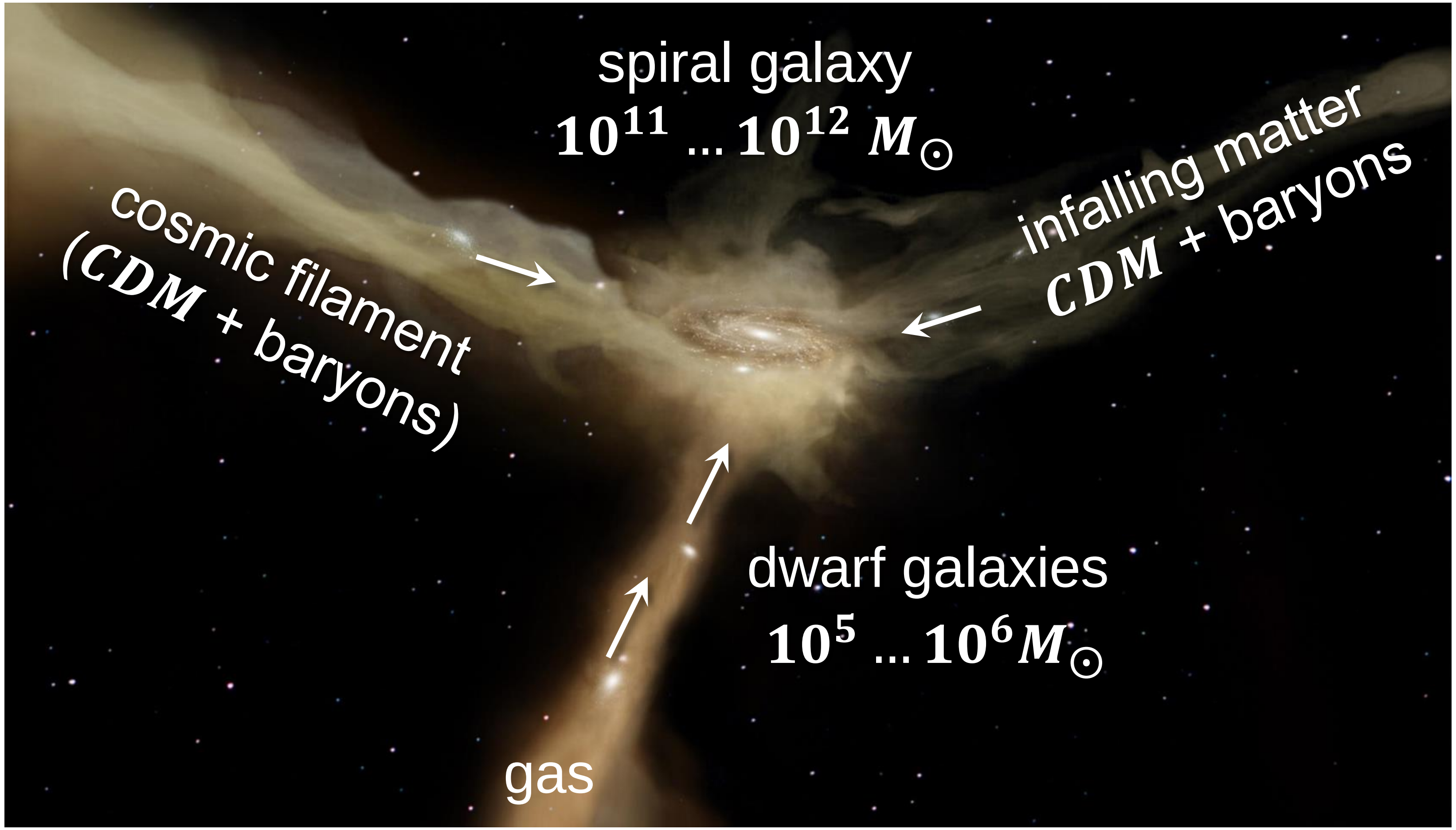
Structure formation: bottom–up scenario

- Elementary building blocks undergo many merger processes to galaxies



Structure formation: formation of filaments

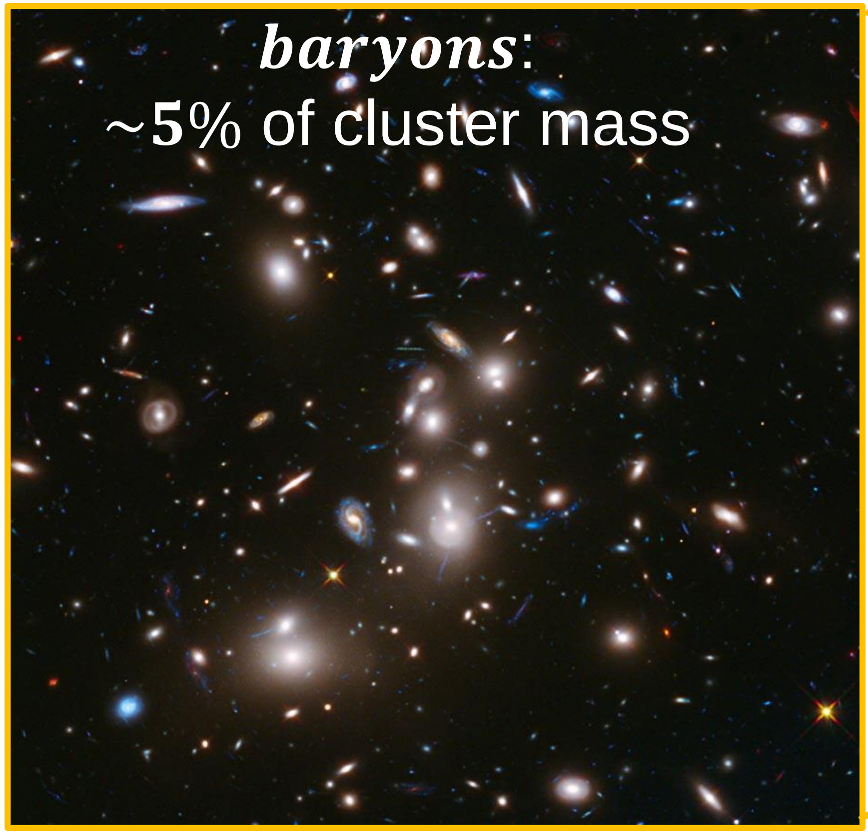
- The growth of galaxies via mergers: infall of matter from nearby filaments



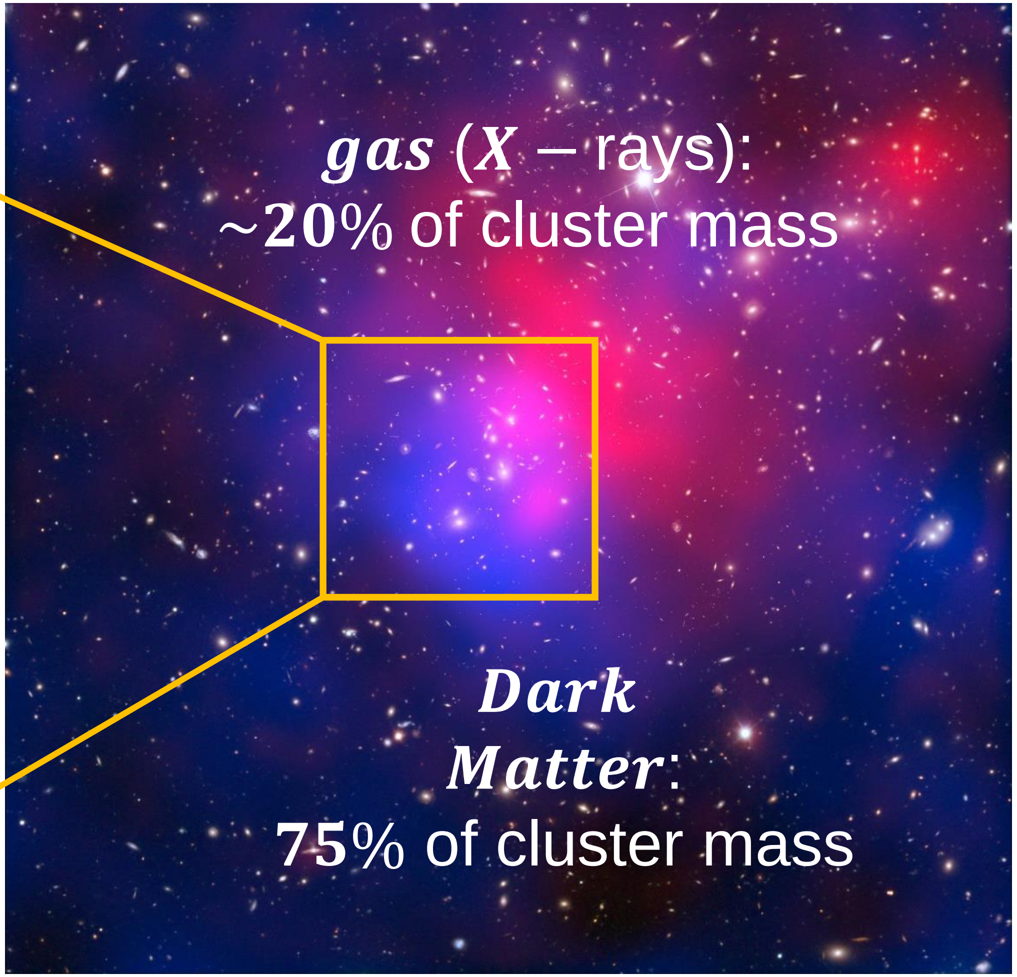
How do galaxy clusters form and evolve?

- **Galaxy clusters: the largest gravitationally bound structures in the universe**

$z = 0.308$
$d = 1.2\ Gpc$



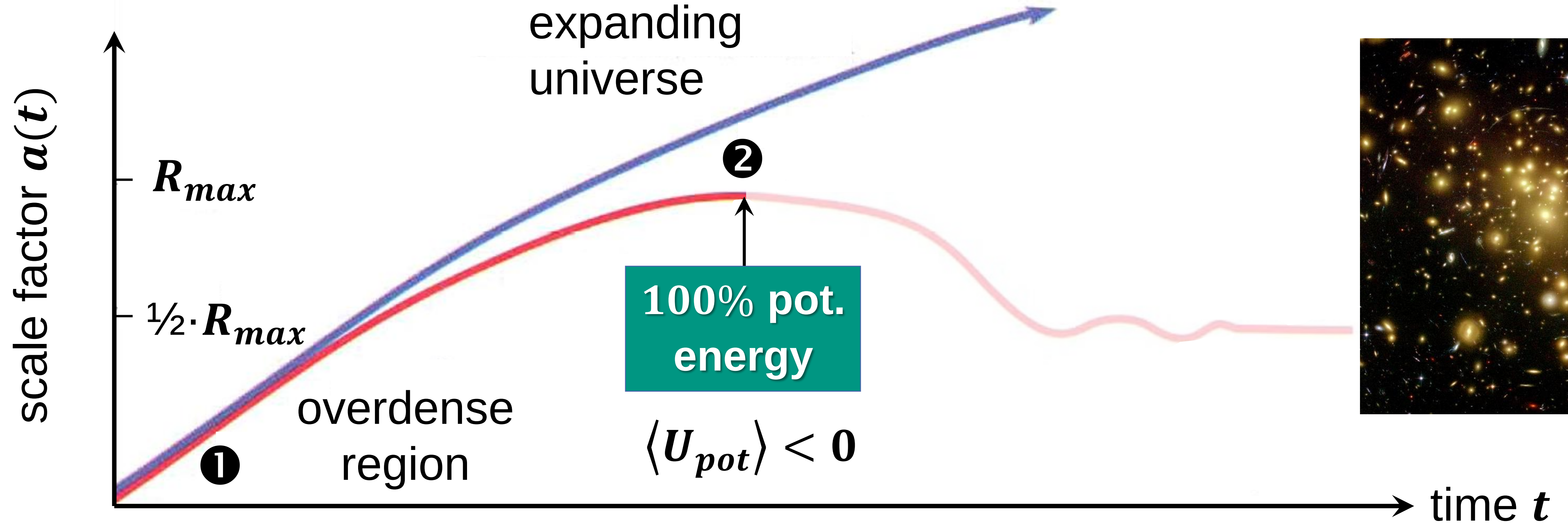
$Abell\ 2744$ – Pandora´ s cluster

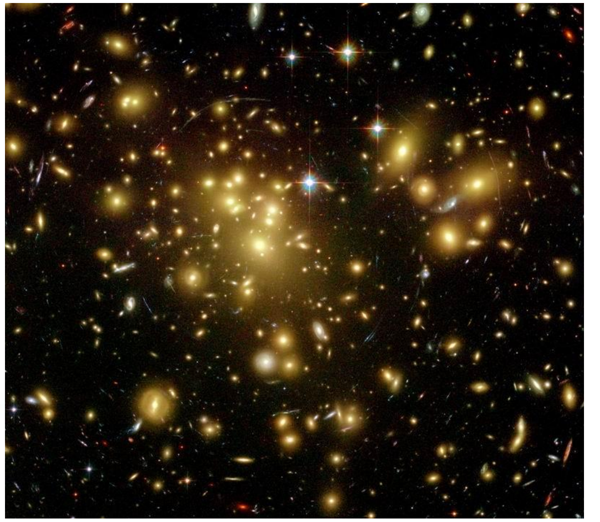


Galaxy clusters: the process of ´virialisation´

- ´Decoupling´ from Hubble expansion: cluster with maximum amount of U_{pot}

❶ participation in **Hubble expansion** ❷ cluster reaches its **maximum size**

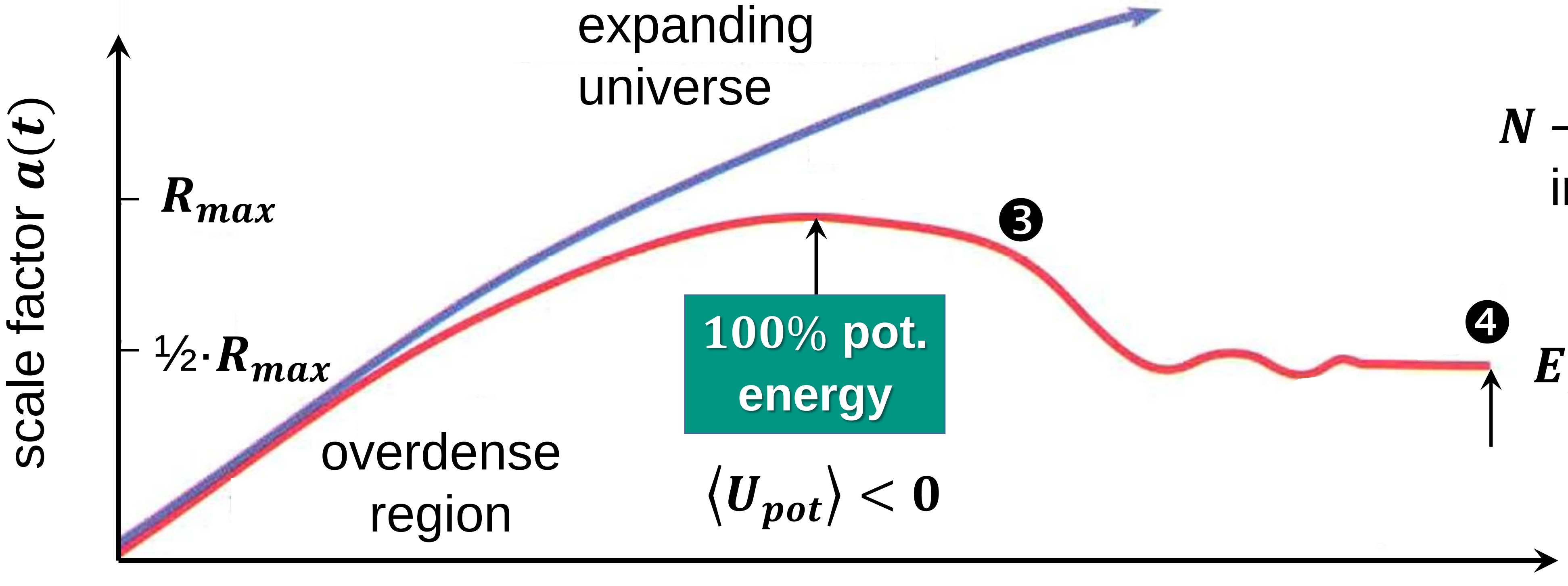




Galaxy clusters: the process of ´virialisation´

- ´Decoupling´ from Hubble expansion: cluster with maximum amount of U_{pot}

❸ **Shrinking** of cluster size ❹ cluster reaches **final size** & is **virialised**



N – body system in equilibrium

$$E_{kin} = -\frac{1}{2}\cdot\langle U_{pot}\rangle$$

Galaxy clusters: the process of ´virialisation´

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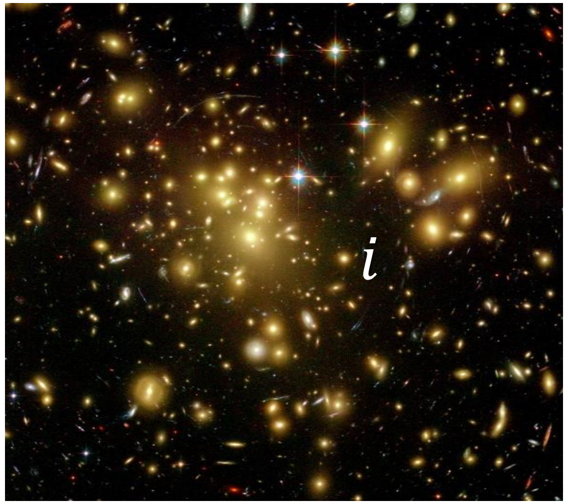
- **Characteristics of a fully virialised N – body system**

  - Virial theorem for gravitationally bound systems:



$$\text{virial } V = \sum_{i=1}^{N} \underbrace{\dot{\vec{p}}_i}_{\text{force}} \cdot \underbrace{\vec{r}_i}_{\text{position}}$$

$i = 1 \ldots N$ galaxies in cluster

$$\boxed{\langle E_{kin} \rangle = -\frac{1}{2} \cdot \langle U_{pot} \rangle}$$

relation between (average) **kinetic energy** & (average) **gravitational potential**

  - allows to estimate* the **total mass** M of a cluster via galaxy velocities v_i

*s. Chap. 5.1, Fritz Zwicky

Superclusters of galaxies: the largest structures

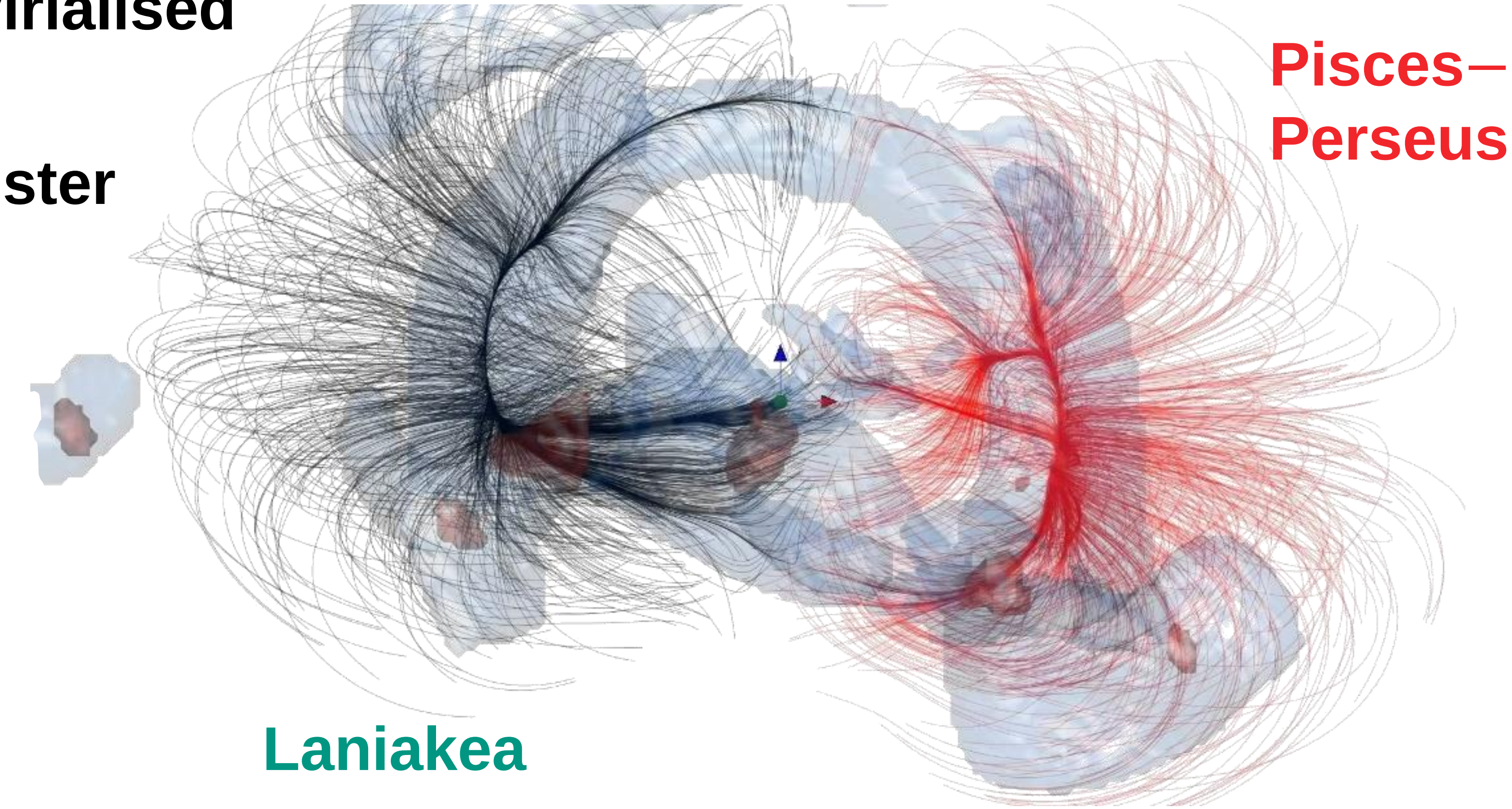
- **Structures that are no longer bound: example Laniakea, our local one**

  - as **superclusters** are gravitationally unbound: they do **NOT** follow the virial theorem, they are **NOT ´virialised´**

  - **example: local supercluster** Laniakea

$N \approx 10^5$ galaxies
in **500 galaxy clusters**

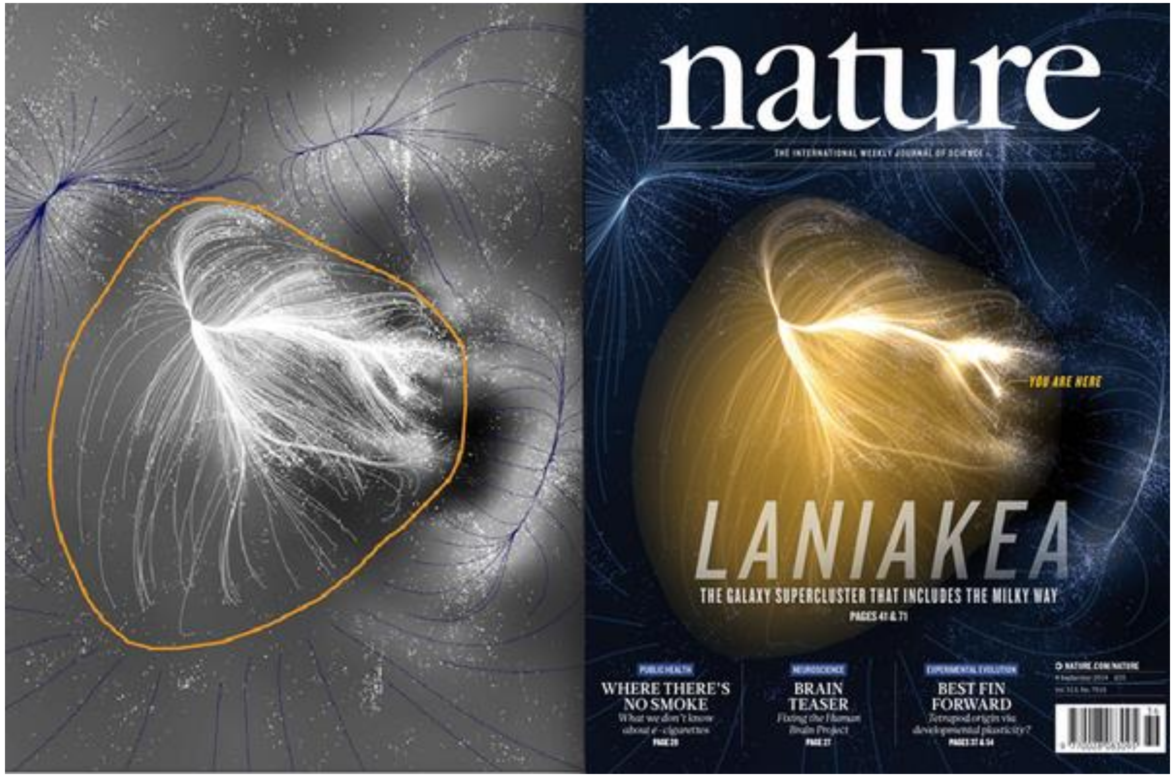
$d = 160\ Mpc$
$M = 10^{17} M_\odot$

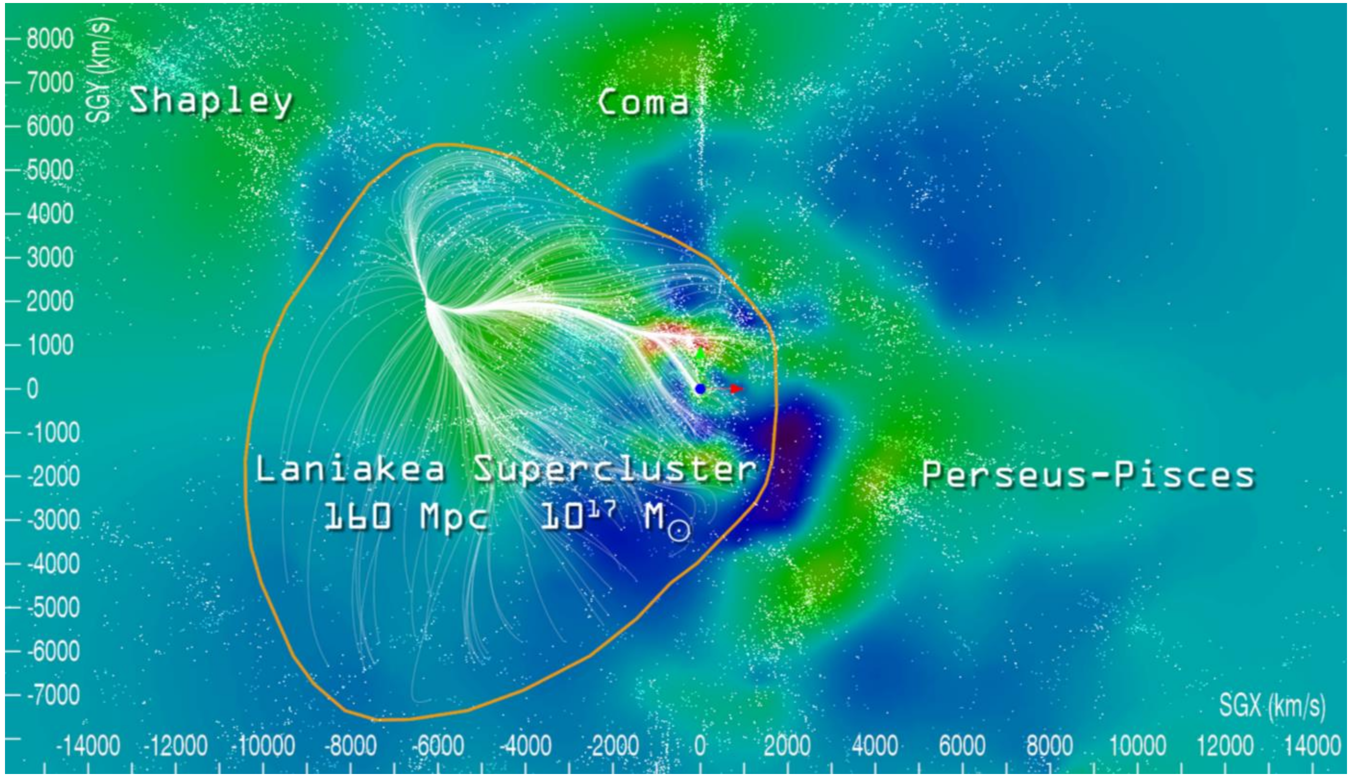


Superclusters of galaxies: the largest structures

- **Your ´postal address´: Laniakea, our local supercluster**

  - as **superclusters** are gravitationally unbound: they do **NOT** follow the virial theorem, they are **NOT ´virialised´**





$N-$ body simulations to study evolution of LSS

Karlsruhe Institute of Technology

- **We now make use of large computing power to model $N-$ body interactions**

  - basis: $\boldsymbol{C}$old $\boldsymbol{D}$ark $\boldsymbol{M}$atter mass ´units´ of $M \sim 10^9\, M_\odot$ which interact purely via **gravitation** (no other interactions are being turned on)

  - second step: baryons fall into potential wells of CDM
    1. **linear** increase of the density contrast δ
    2. once we reach a density contrast $\delta \sim 1$ the **non−linear regime** is reached (*i.e.* baryons start to form interstellar gas clouds, stars,…)

  - we can thus retrace the evolution of $\boldsymbol{L}$arge $\boldsymbol{S}$cale $\boldsymbol{S}$tructures (LSS) via numerically very challenging $N-$ **body simulations**:
    $Millennium$, $Millennium-XXL$, $DEUS$, $Illustris$, …

N – body simulations to study evolution of LSS

- **Basic principles of modern large–scale N – body simulations**

  - basis: **ΛCDM – concordance model** with ´standard´ parameters

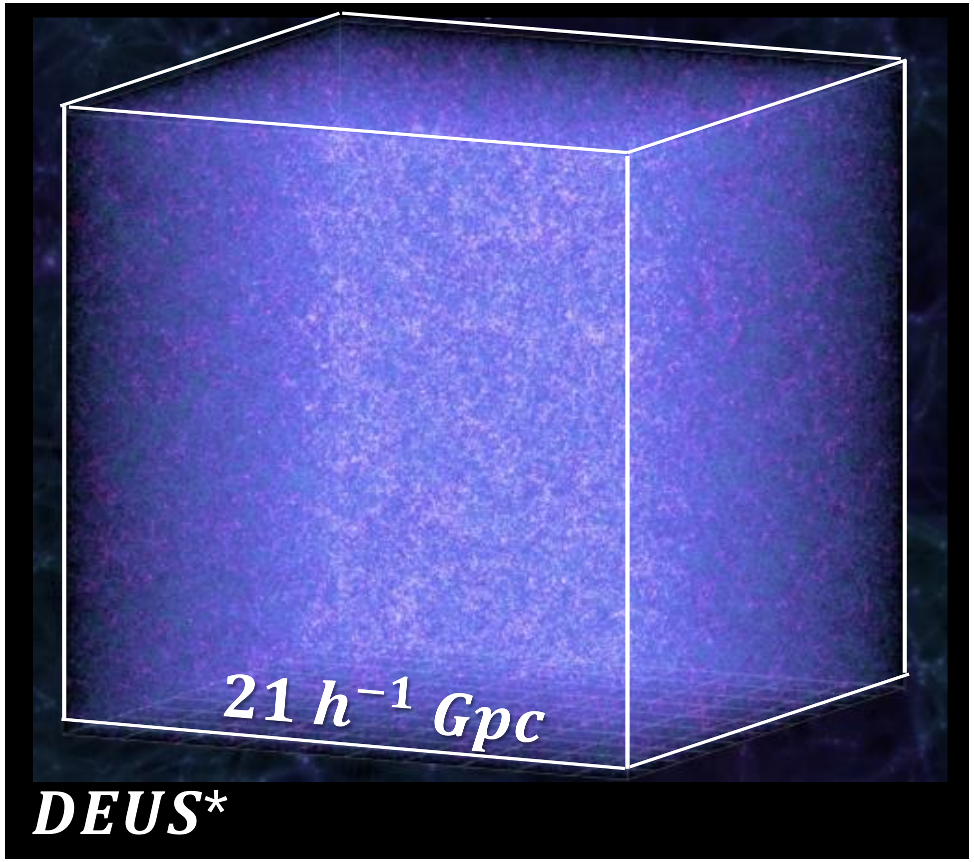
  - purely **gravitational interaction** of the dominant CDM – fraction

  - ´observed´ volume: several Gpc

  - typical ´particle´ mass: $M < 10^{10} M_\odot$

  - $N = (10 \ldots 550) \times 10^9$ particles ($\equiv DM$ clumps)

  - cosmological time scales: $z = 20 \ldots 0$ (today)



*$DEUS$: Dark Energy Universe Simulation

$\boldsymbol{N}$ – body simulations to study evolution of $\boldsymbol{LSS}$

Karlsruhe Institute of Technology

- $\boldsymbol{Millennium}$: **the first large–scale realistic $\boldsymbol{N}$ – body simulation for $\boldsymbol{LSS}$**

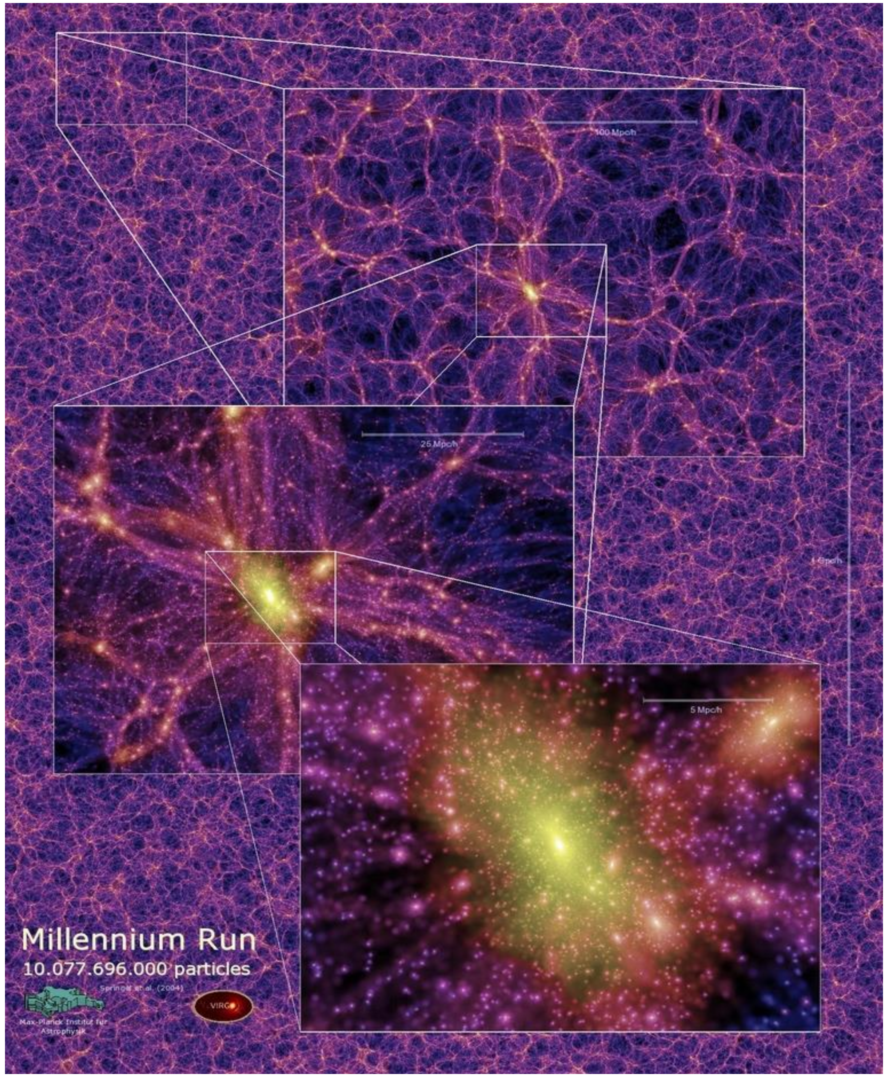
  - performed by the $\boldsymbol{VIRGO}$ consortium

  - size: $\mathbf{10^{10}}$ ´particles´ each with $\mathbf{10^9}\ \boldsymbol{M_\odot}$

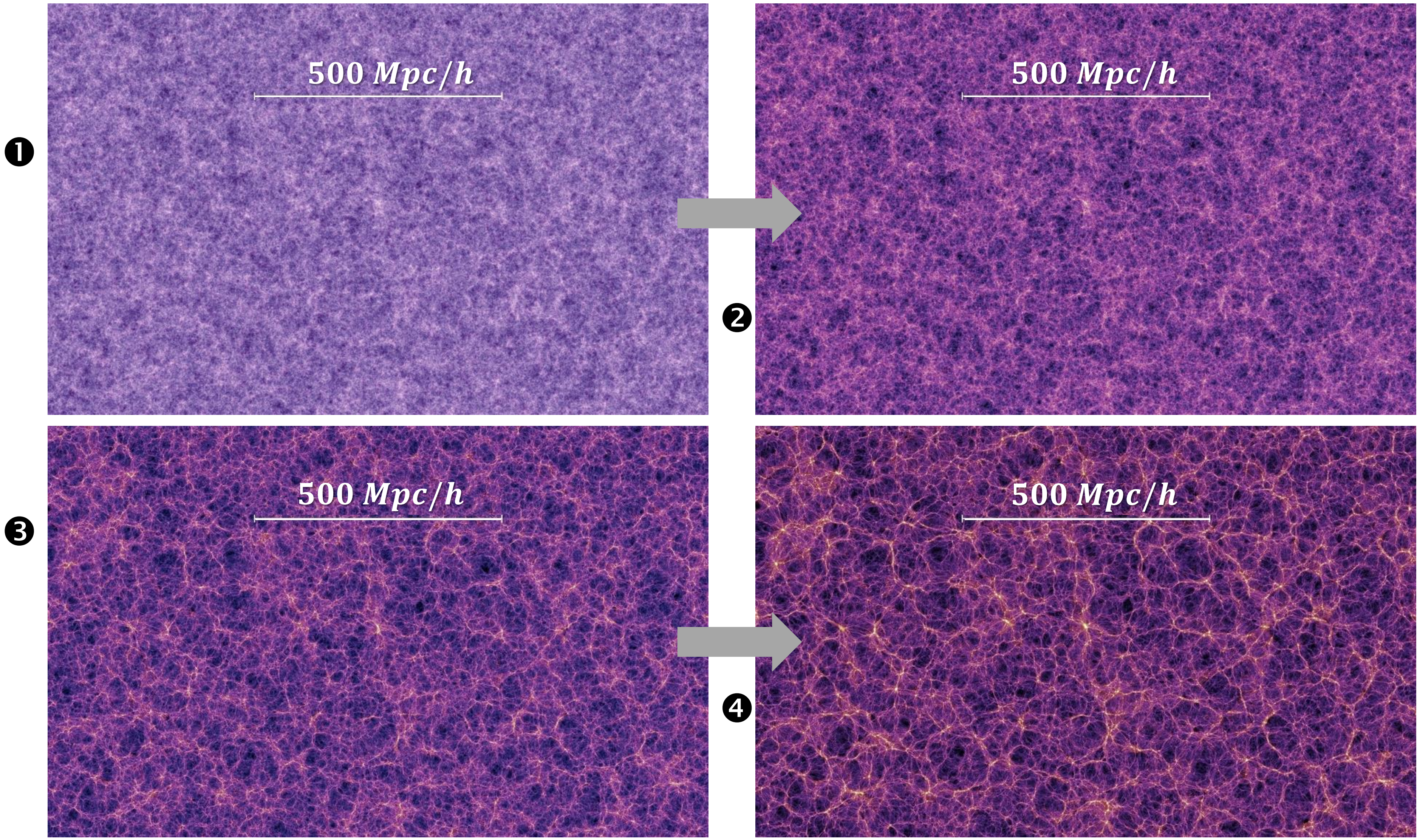
  - volume: cube with edge length $\boldsymbol{a} = \mathbf{700}\ \boldsymbol{Mpc}$

  - only gravitational interaction of **dark matter**

  - then modelling of baryons starts: → baryonic matter falls into $\boldsymbol{DM}$ – gravitational wells



$N-$ body simulations: results of $Millennium$ run



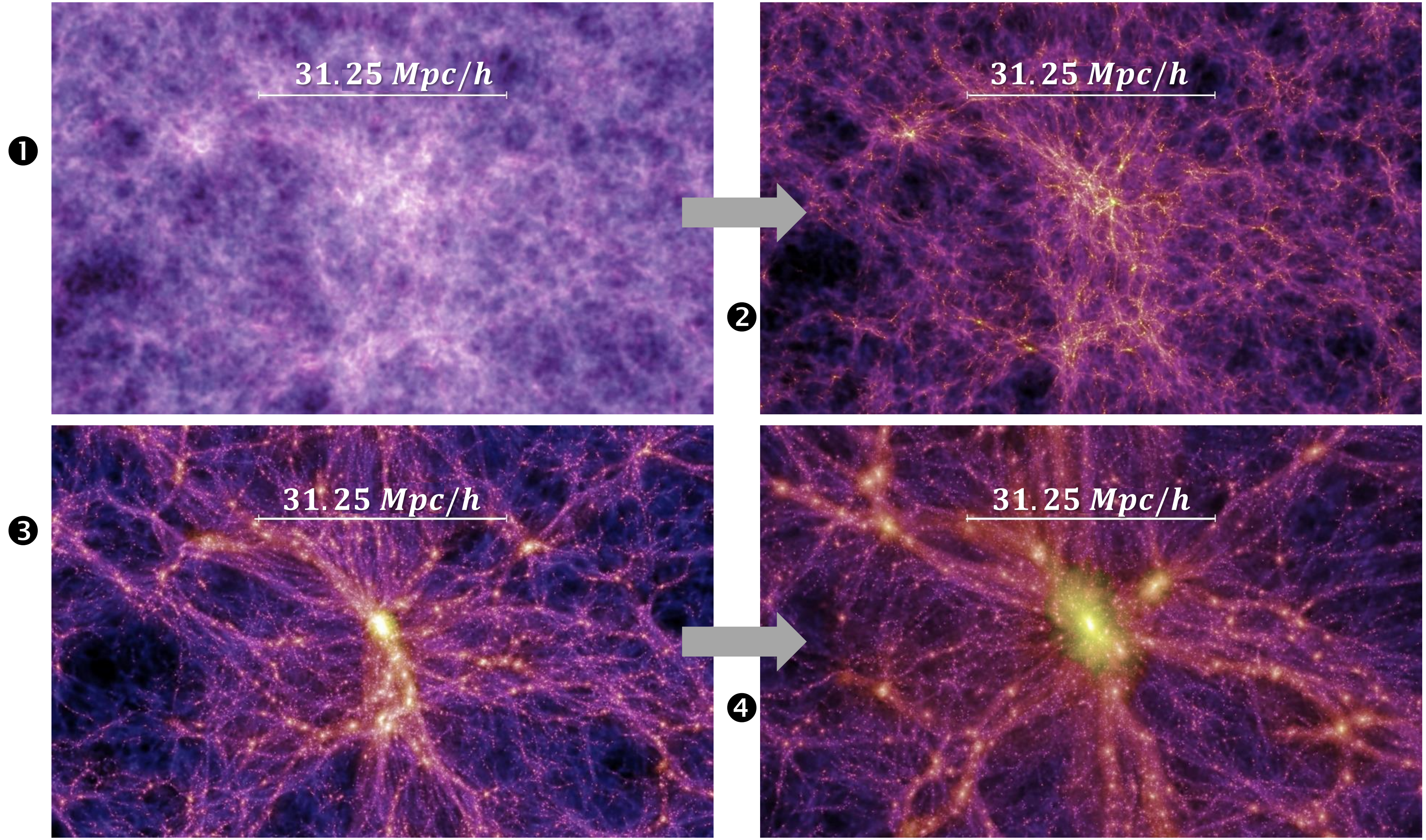
❶ $z = 18.3$ $t = 0.2\ Gyr$

❷ $z = 5.7$ $t = 1.0\ Gyr$

❸ $z = 1.4$ $t = 4.7\ Gyr$

❹ $z = 0.0$ $t = 13.8\ Gyr$

$N-$ body simulations: results of $Millennium$ run



❶ $z = 18.3$ $t = 0.2\ Gyr$

❷ $z = 5.7$ $t = 1.0\ Gyr$

❸ $z = 1.4$ $t = 4.7\ Gyr$

❹ $z = 0.0$ $t = 13.8\ Gyr$

$N-$ body simulations: $\boldsymbol{Millennium\ XXL}$

- **$\mathbf{2011}$: an improved run with more particles & over a larger volume**

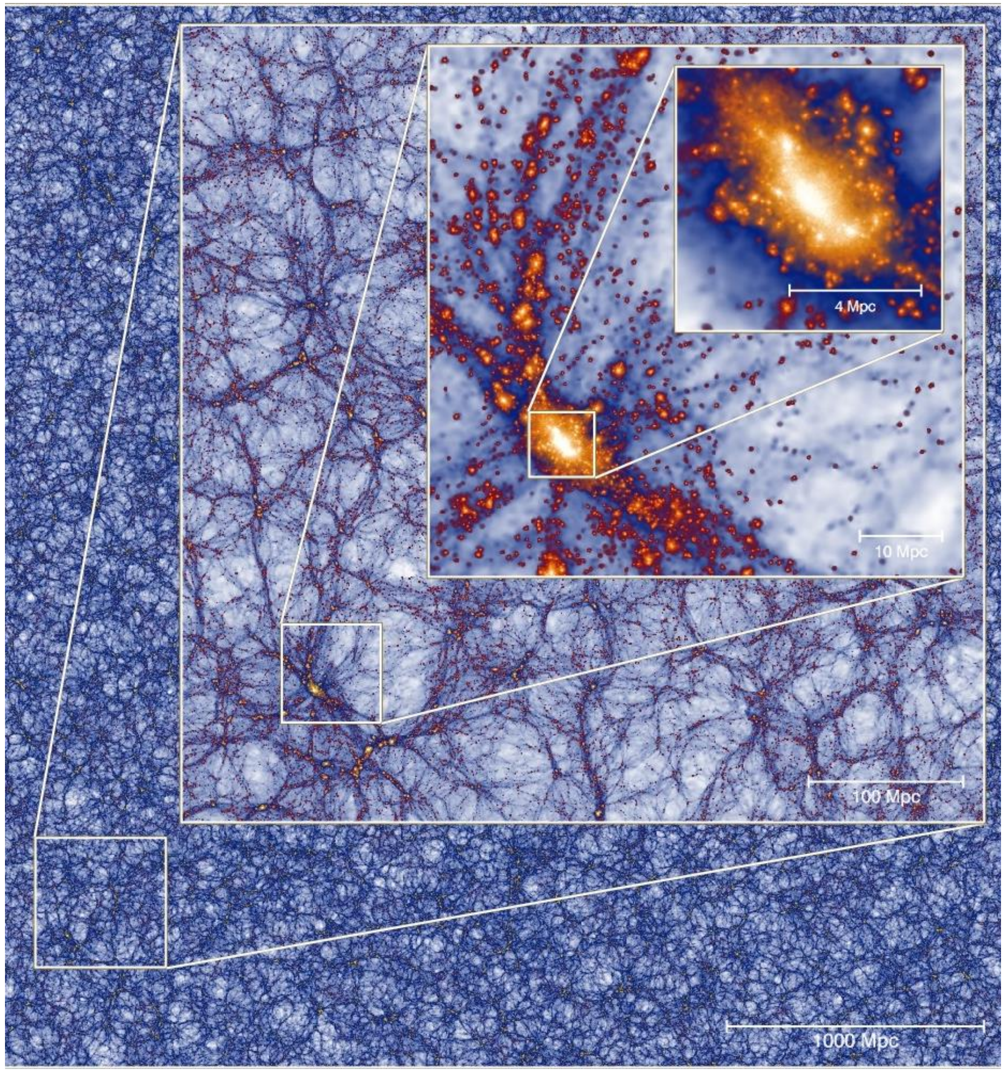
- performed by the $\boldsymbol{VIRGO}$ consortium

- size: $\mathbf{3 \cdot 10^{10}}$ ´particles´ each with $\mathbf{5 \cdot 10^{9}}\ \boldsymbol{M_\odot}$

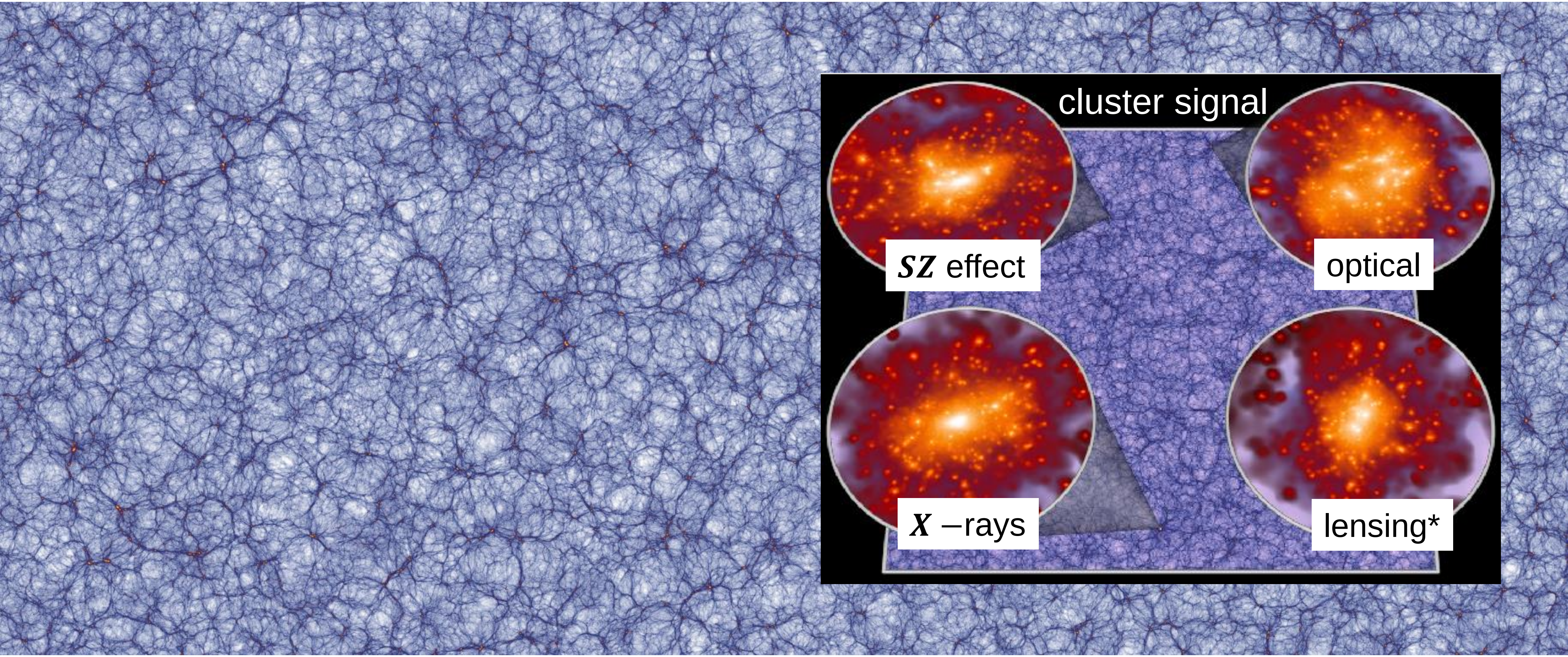
- volume: cube with edge length $\boldsymbol{a = 4.3\ Gpc}$

- only gravitational interaction of **dark matter**

- $\boldsymbol{300\ CPU - years}$: $\mathbf{10}$ days with $\mathbf{12228}$ cores
$\Longrightarrow$ confirmation of earlier simulation runs)



$N-$ body simulations: $Millennium\ XXL$ results



*gravitational lensing

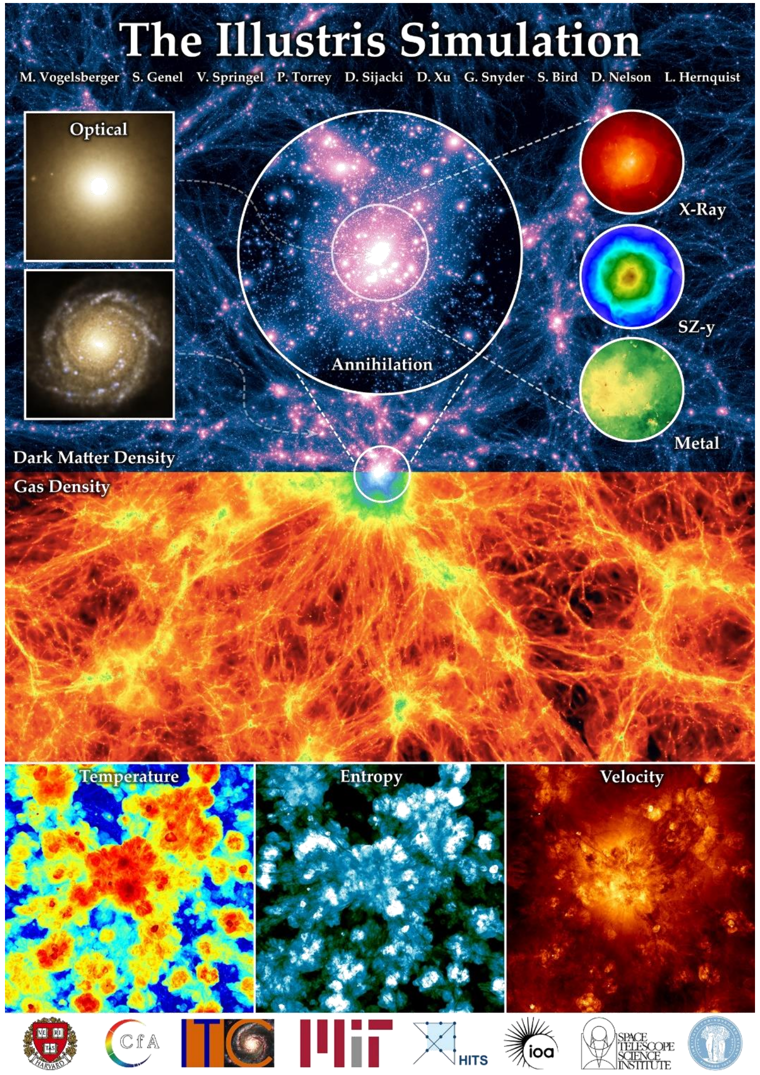
$N-$ body simulations: next step $Illustris-TNG$

- **2018: further improvements with the aim to study the formation of galaxies**

  - performed by the TNG* consortium

  - extensive modelling of all relevant physics processes: gravitational interaction, cosmological expansion using $H(t)$, **gas hydrodynamics**, star formation & formation of black holes

  - **interaction of DM, gas & stars**: important for precise investigations of underlying cosmological parameters



*The Next Generation