Cosmology : Basics

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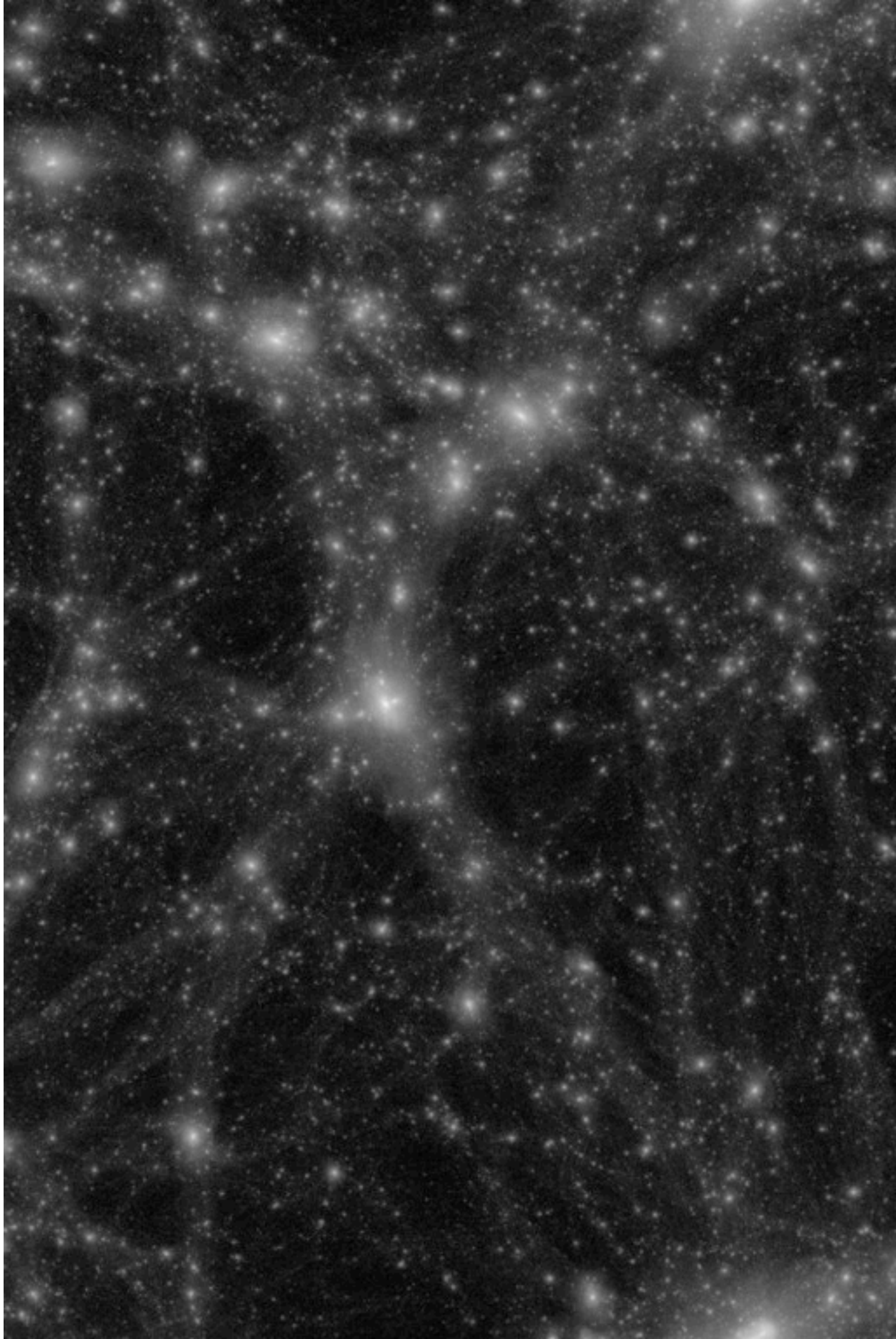
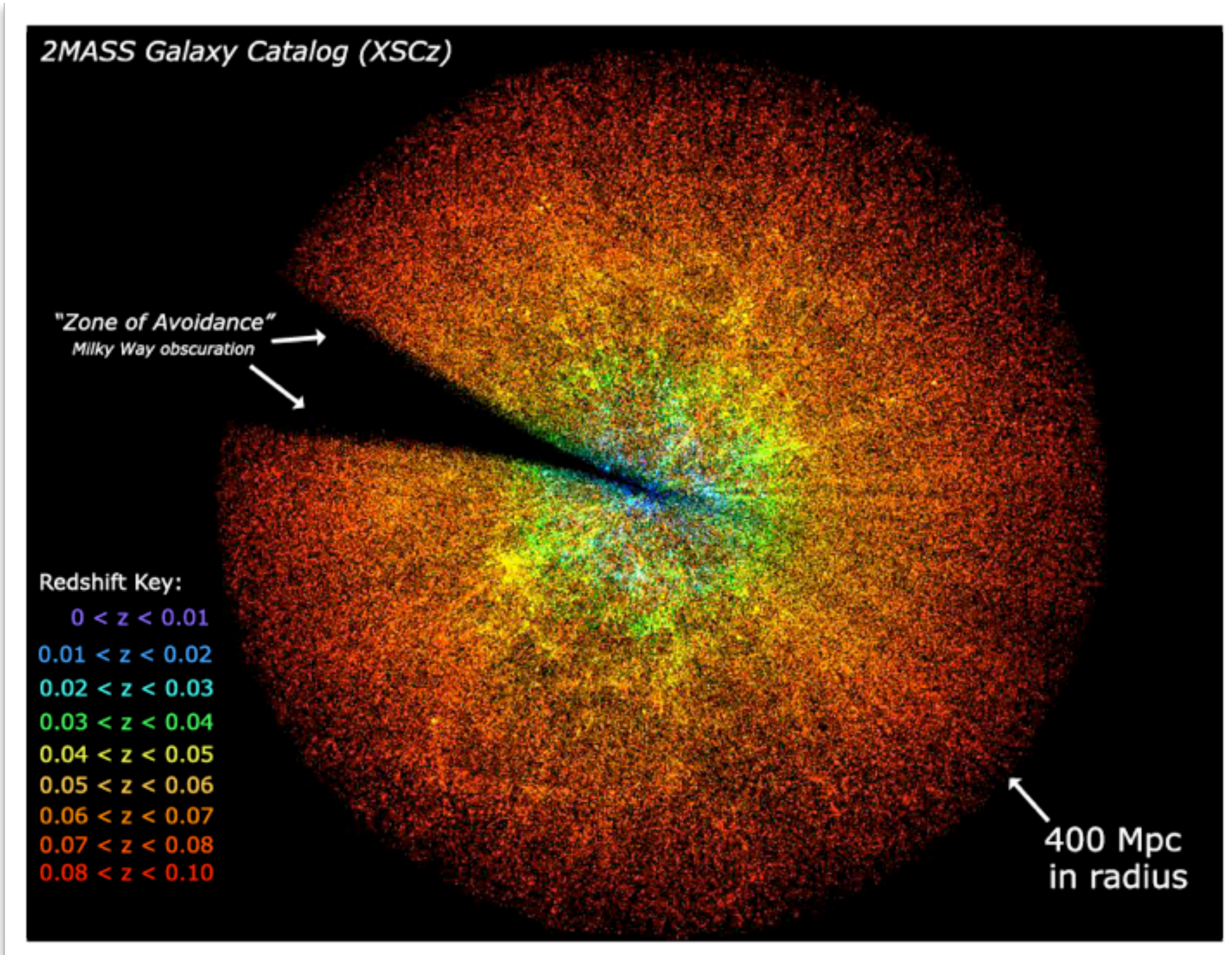


A dynamical Universe

Universe Expansion



the reddening of light or «redshift» is related to the motion of emitters

Cosmological Principle

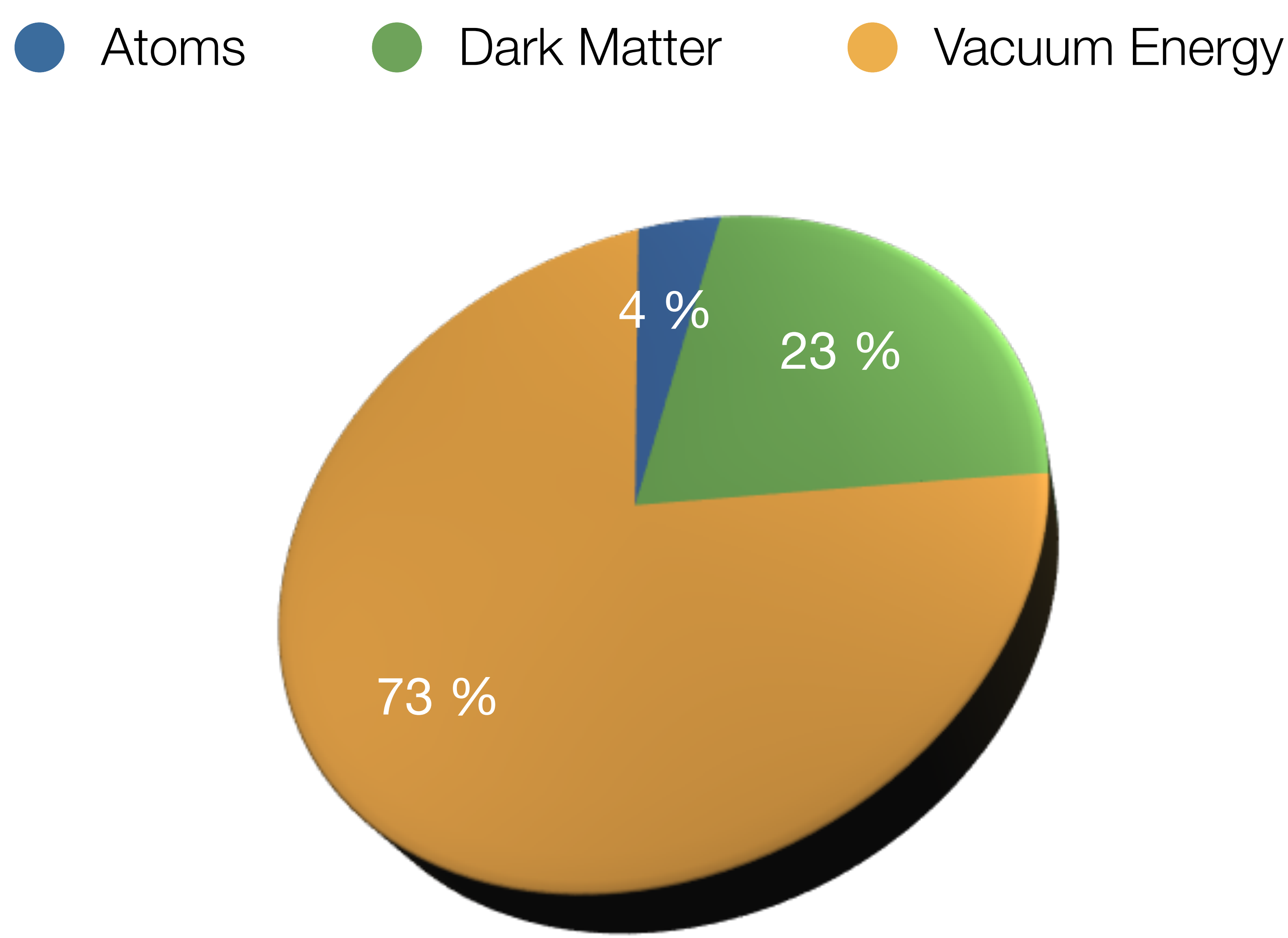
The standard cosmological model assumes :

- the Universe is isotropic and homogeneous (on cosmological scales)
- Gravitation is described by General Relativity (GR)

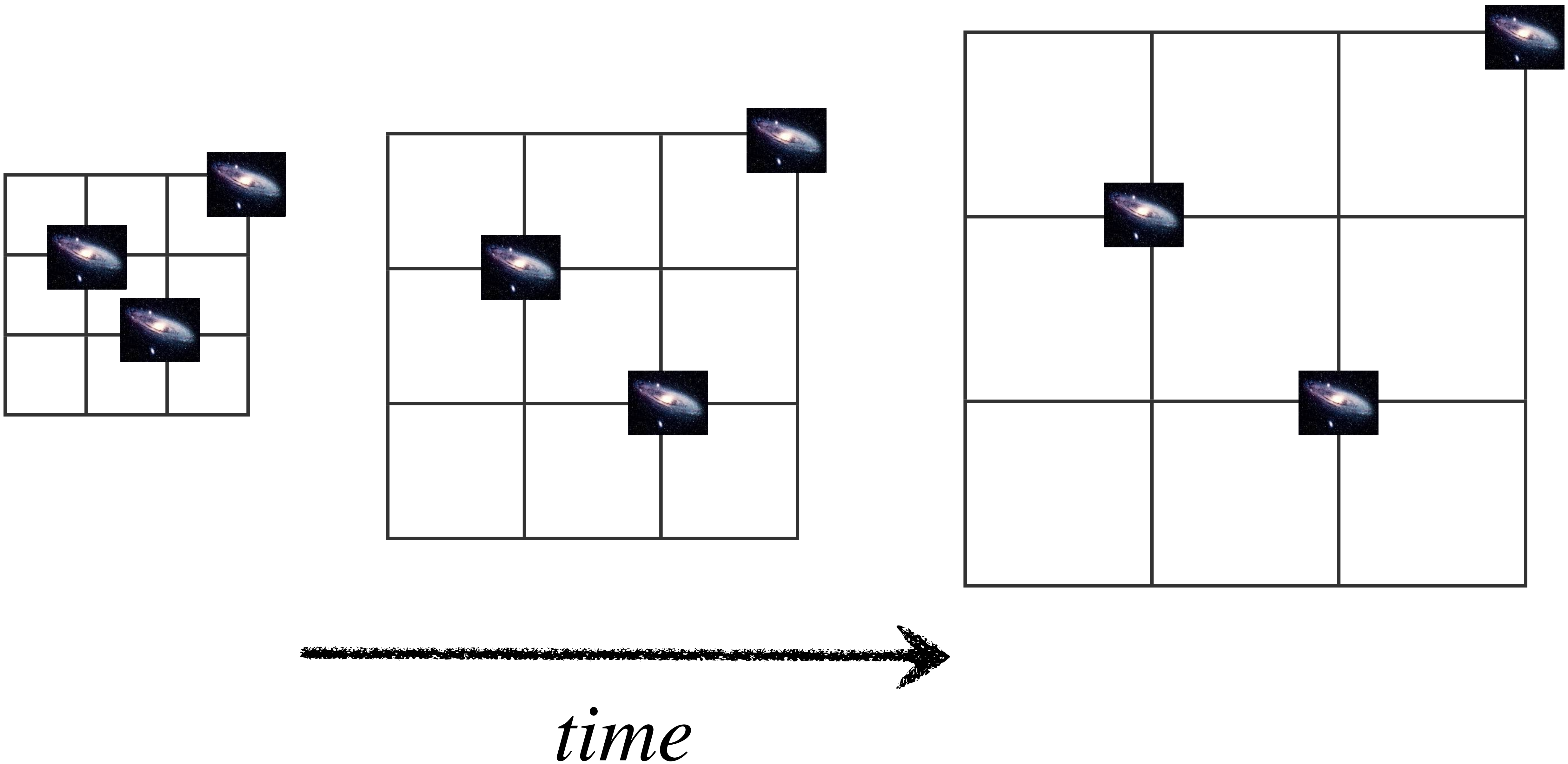
Extension of the Copernician principle. It leads to:

$$\Lambda\text{CDM}$$

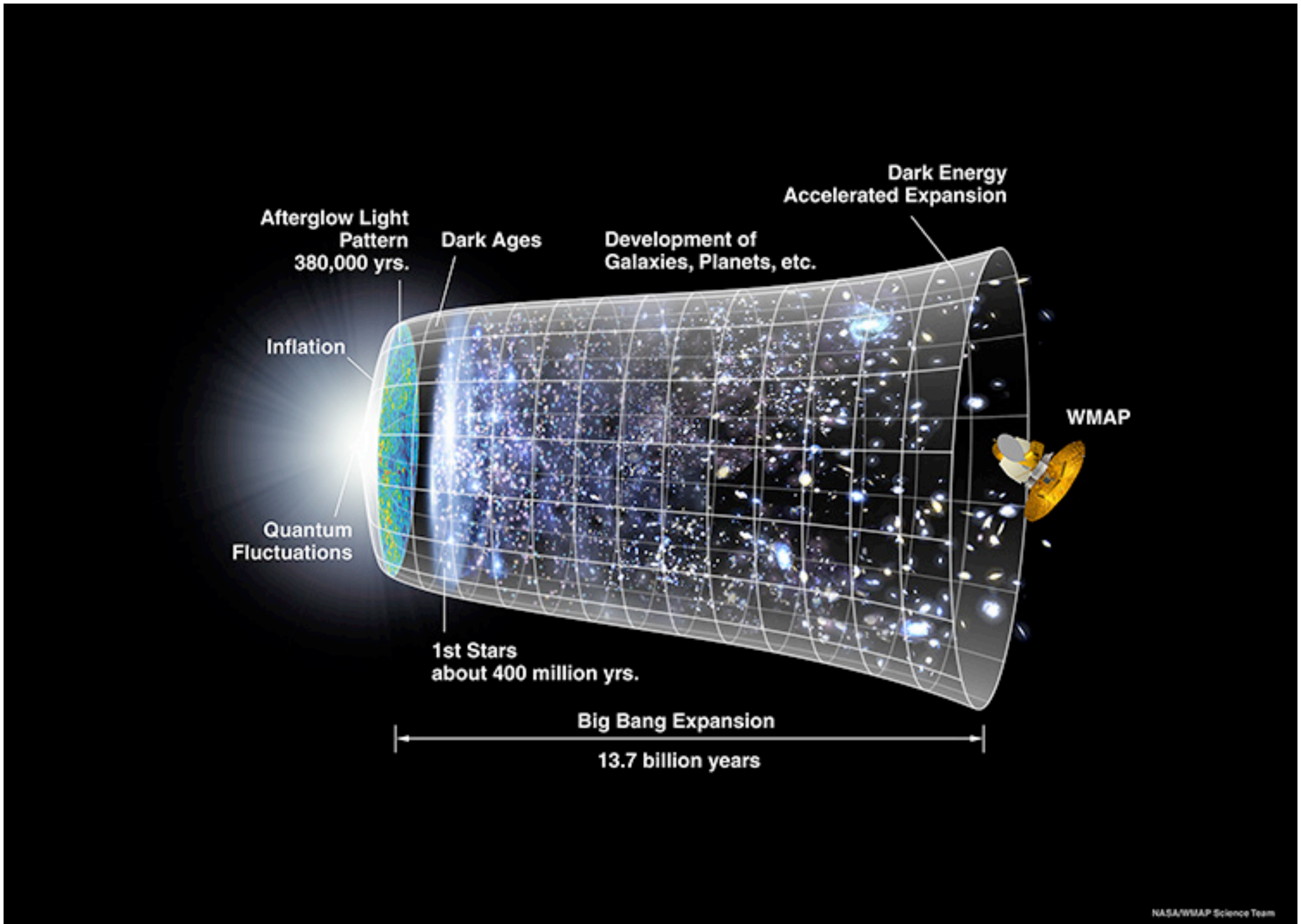
Energetic content of the Universe, today



Expansion



History of the Universe



Nasa /WMAP team

Dynamical Distances in the Universe

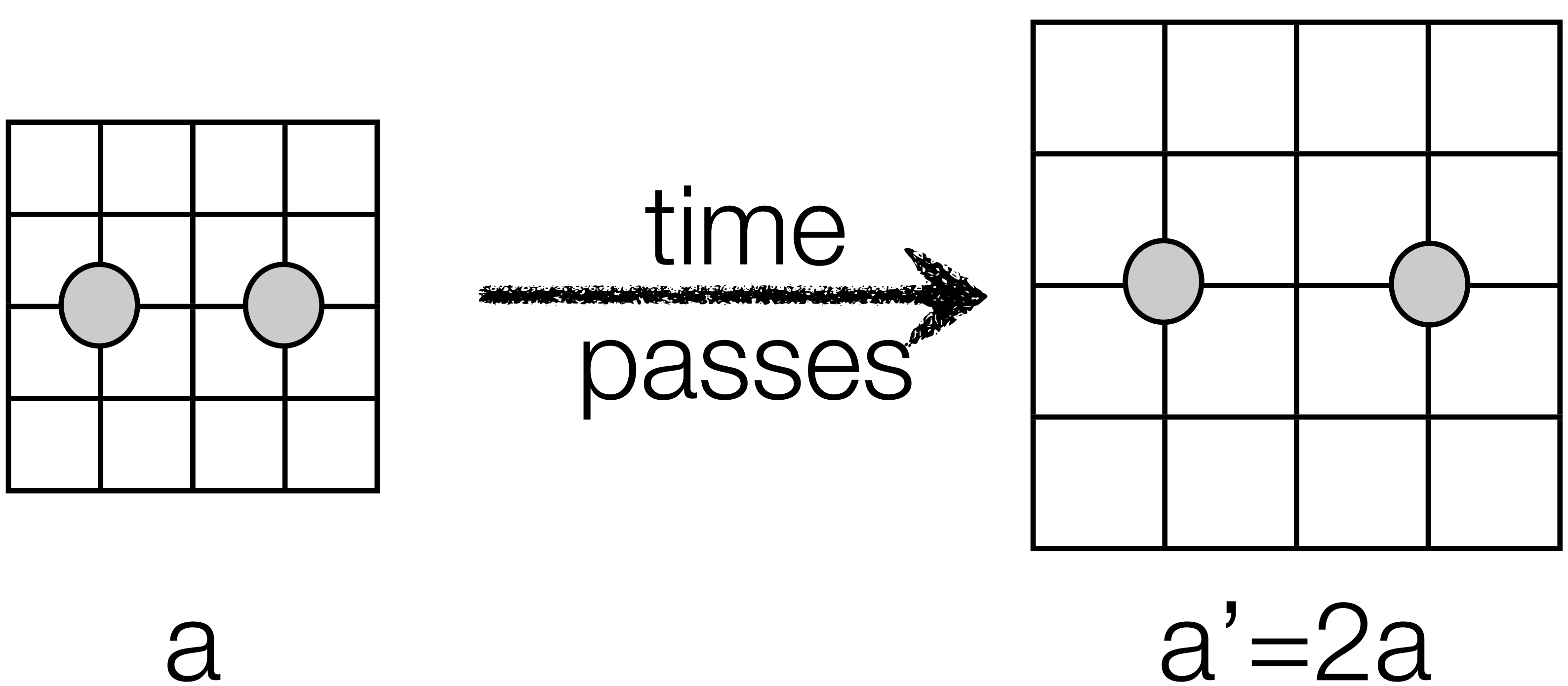
$$r(t) = a(t)r_0$$

a is the *expansion* factor

$a(t_0) = 1$

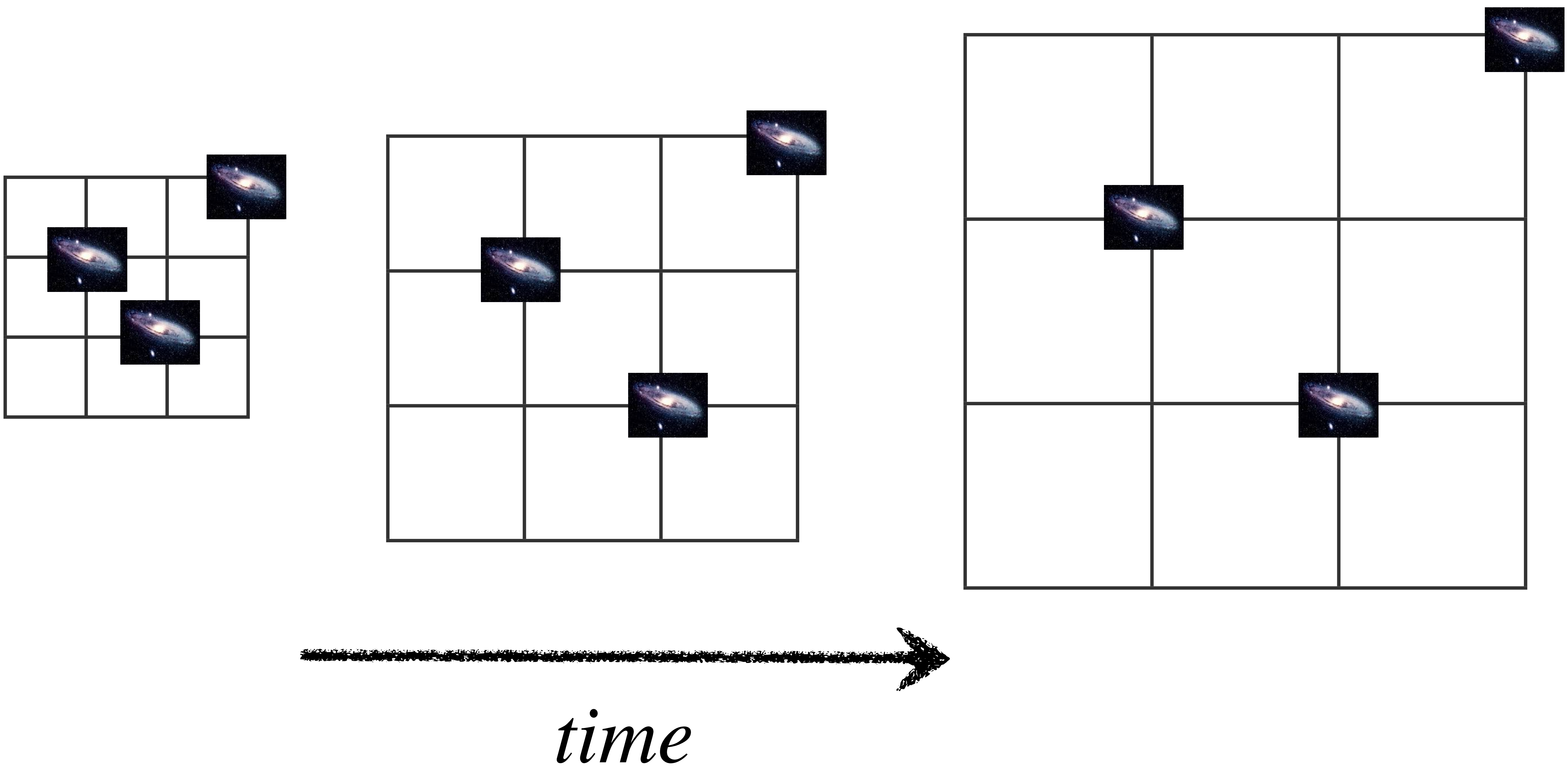
$r(t)$ is the physical distance

r_0 is the comoving distance distance



$$r(a') = 2r(a)$$

Expansion



Standard models imply expansion :
a(t) increases with time

Kinematics in the Universe

$$\frac{dr}{dt} = v(t) = \dot{a}(t)r_0 = \frac{\dot{a}}{a}r(t)$$

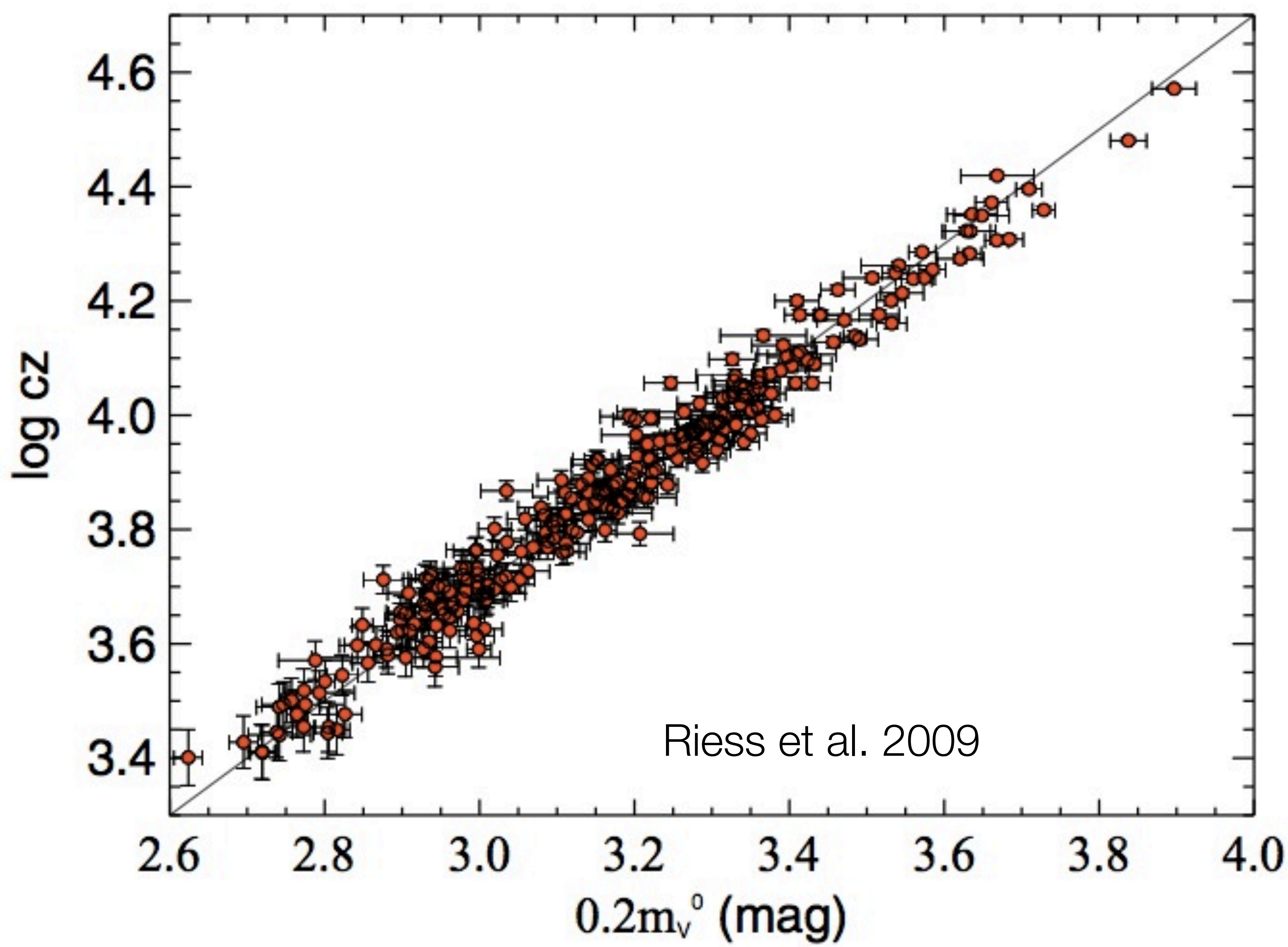
$$v(t) = H(t)r(t)$$

The Hubble Law

$$H(t) = \frac{\dot{a}}{a}$$

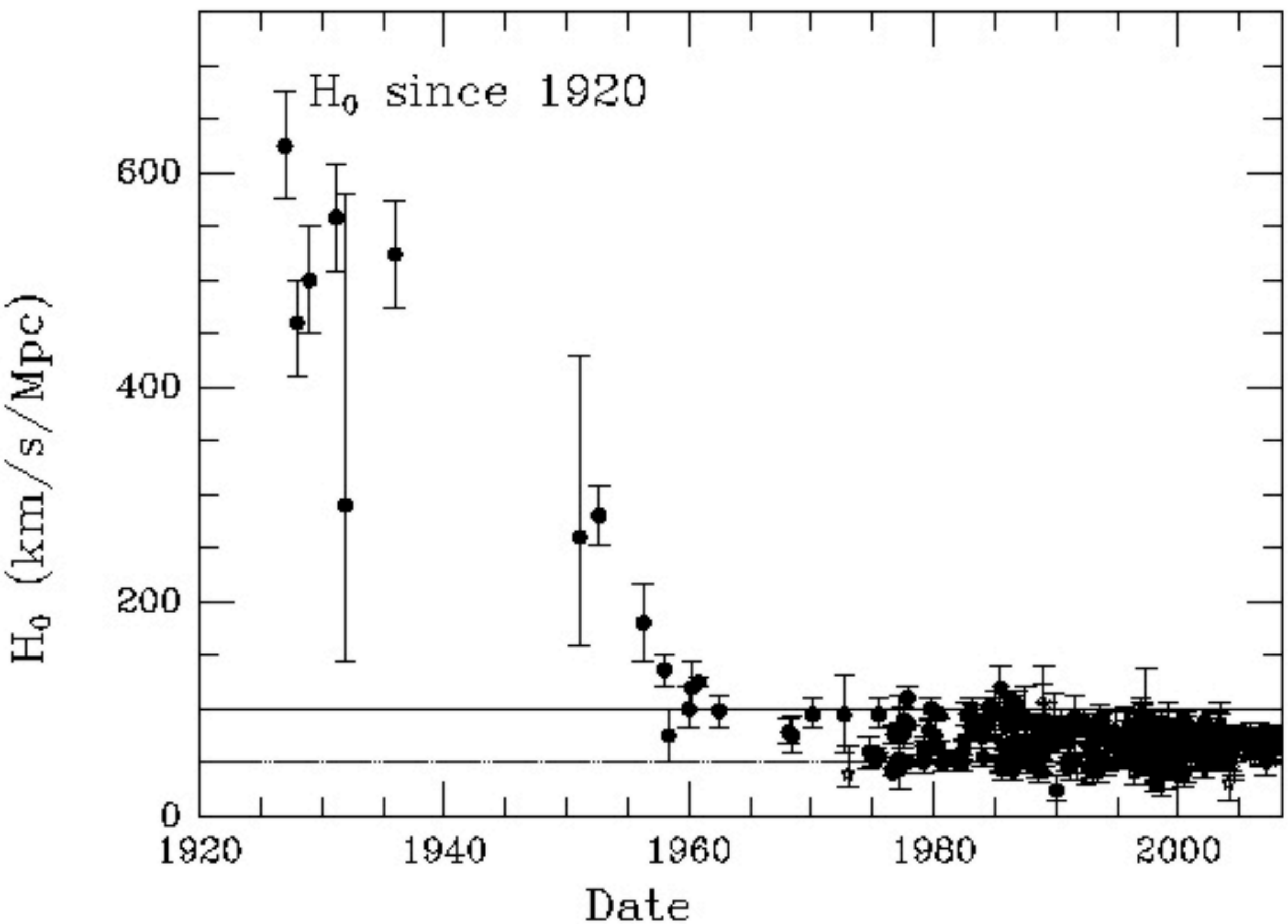
The Hubble parameter is constant in space *but not in time*

The Hubble Parameter H0



$$H_0 = 73.8 \pm 2.5 \text{ km/s/Mpc}$$

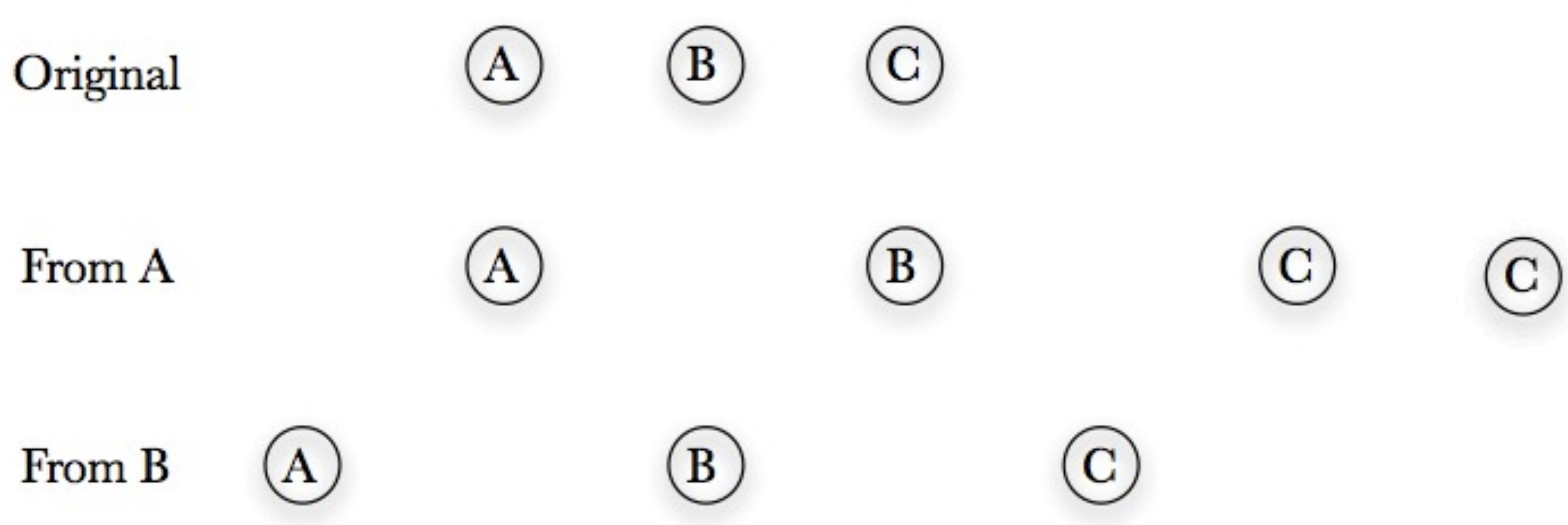
The History of H0



Huchra;https://www.cfa.harvard.edu/~dfabricant/huchra/hubble/

The Hubble Law

$$v(t) = H(t)r(t)$$ Linear with distance



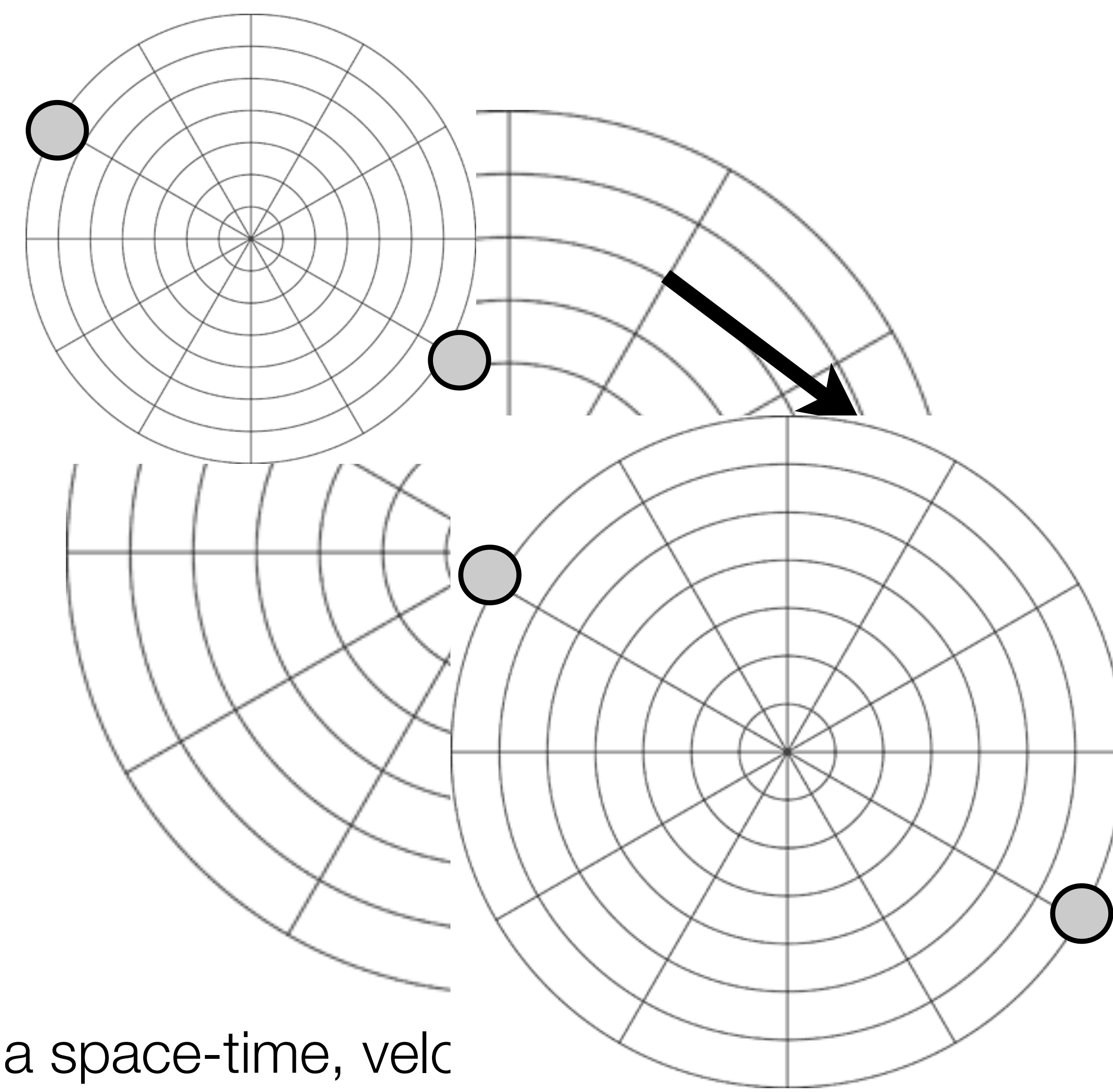
Const

Linear Law

Homogeneity requires a linear Hubble relation

Velocities & Distances in non-Euclidian space time

The structure of space-time is dynamic and potentially curved
velocities and distances are ill-defined !!!



In such a space-time, velc y
Distances may vary only for static objects

Velocities & Distances in non-Euclidian space time

Distances can be modified with ***zero velocities***

$$v(t) = H(t)r(t)$$

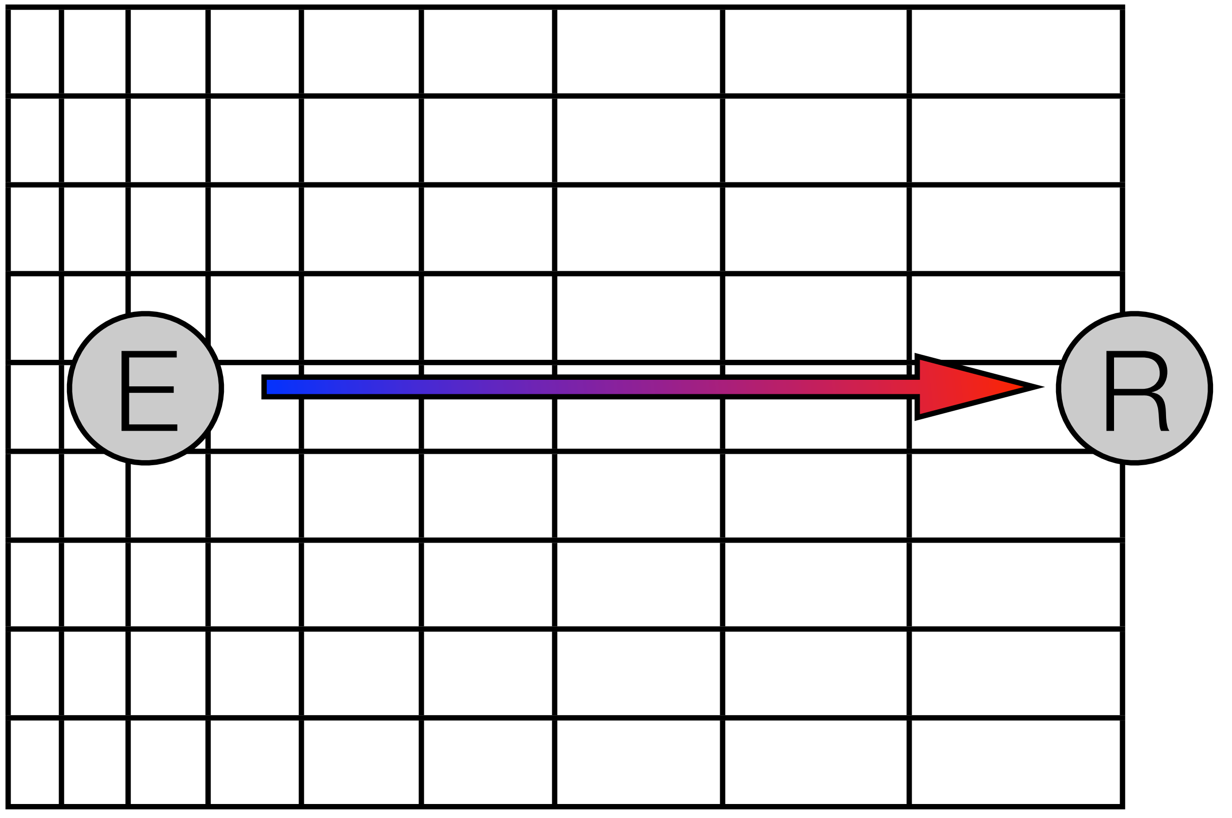
This «variation rate of
distance» can be greater
than c
but it's ok since it is NOT
a velocity

Redshift

Wavelengths are «stretched» by expansion

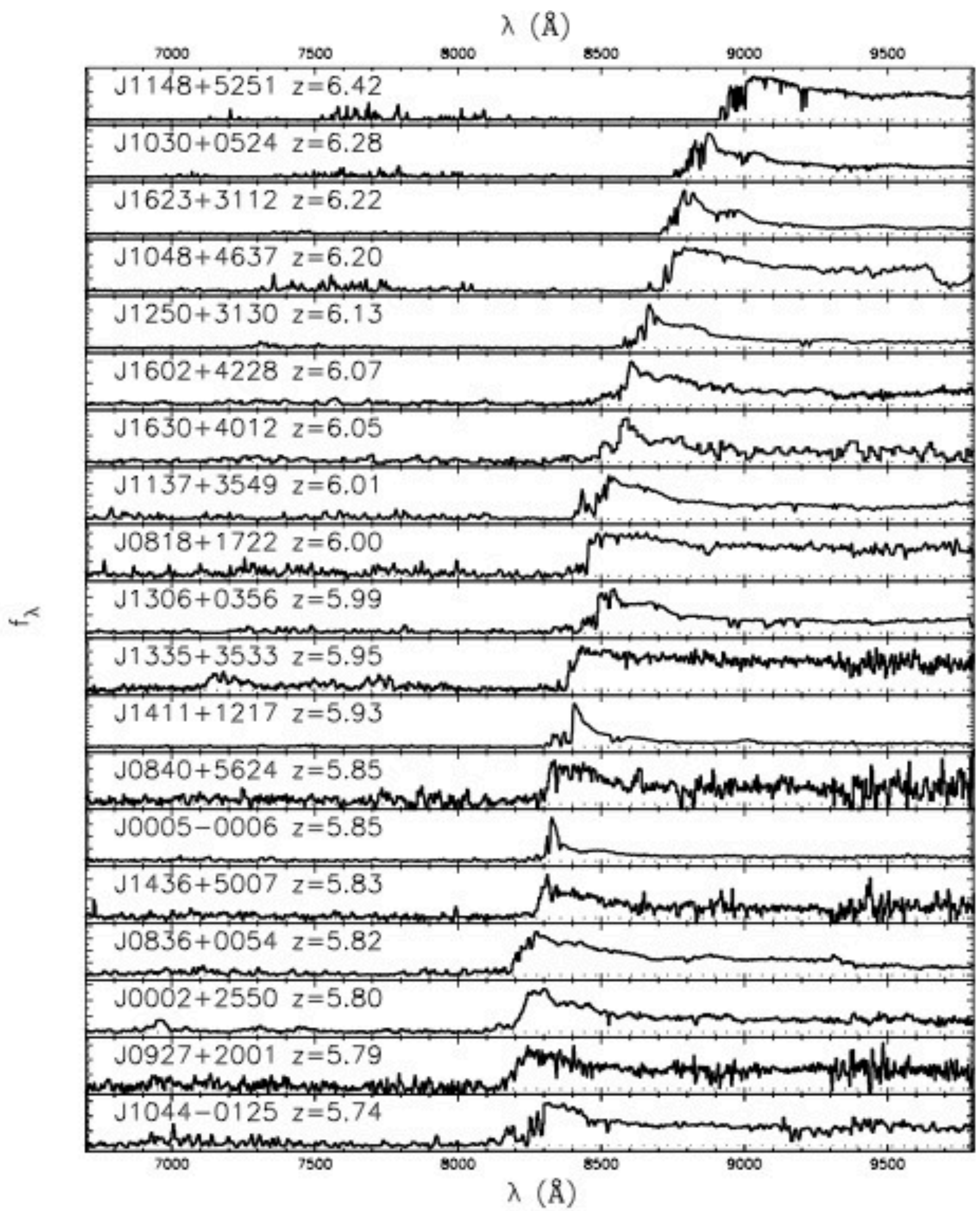
$$z \equiv \frac{\lambda_0 - \lambda_e}{\lambda_e} = \frac{1}{a_e} - 1$$

$$z \sim \frac{v}{c} \text{ for } z \sim 0$$



The redshift measures the expansion factor @ emission time
It can be interpreted as a recession velocity @ small values
z=0 today (a=1)
z decreases with time

Quasars



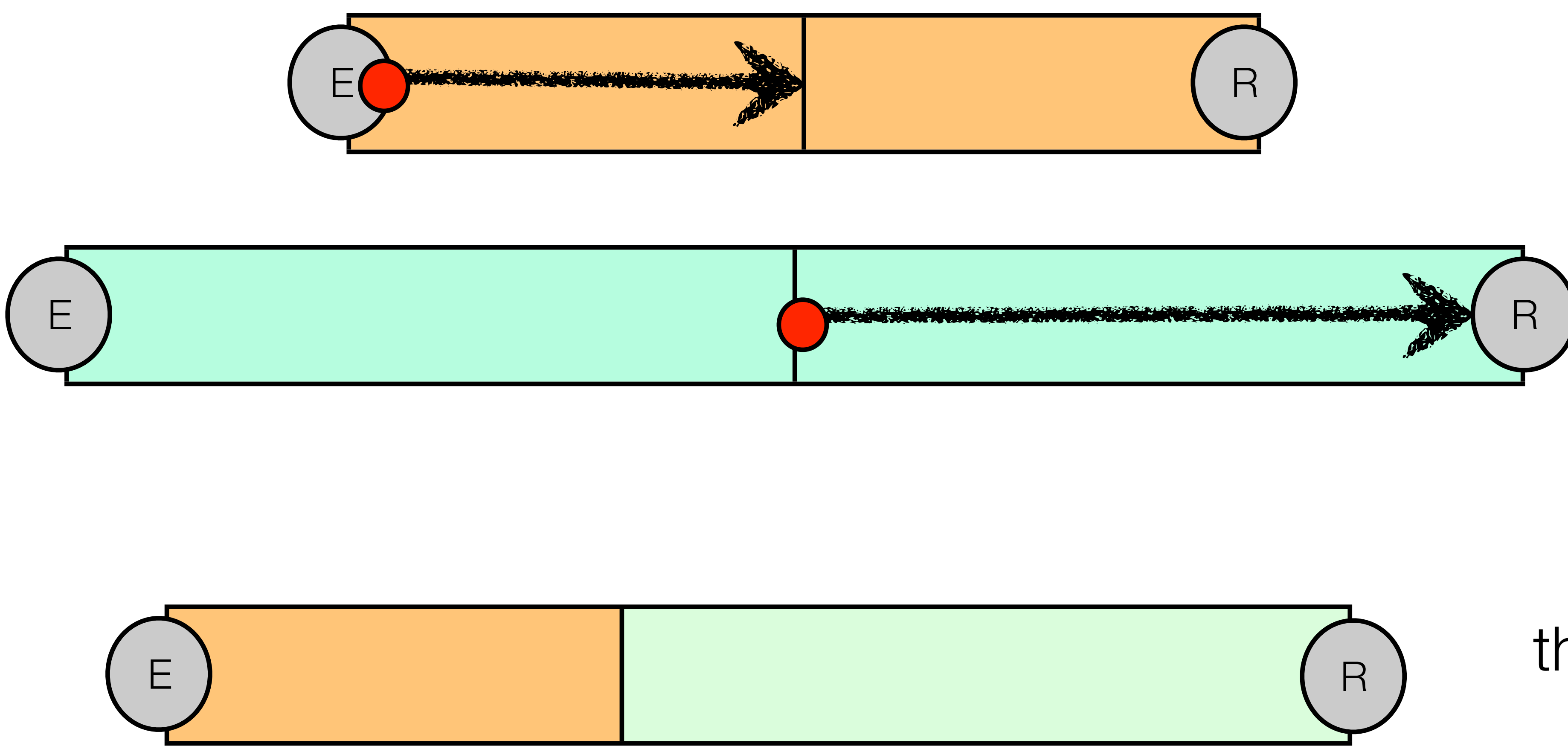
SDSS

z=6 : ~10% of the Age of the Universe

Fan et al. 2006

Velocities & Distances in evolving space time

Let us imagine that expansion proceeds
by intervals of time



situation @ emission

situation @ reception

the actual distance
travelled by light

Light travel distance ≠current distance

An Example of misunderstanding

«New distance record for a quasar 12.9 Billions Light years»

Light Travel Distance : 12.9 Billions light years
Current physical distance : 28 Billions light years

The Cosmological Fluids

Friedman Equation

acceleration of expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3P)$$

energy density of a fluid

pressure of the fluid

Note : at first sight, the expansion should decelerate

Energy : single particle case

$$E^2=p^2c^2+m^2c^4$$

Energy=motion + mass

$$E^2=p^2c^2+{\scriptstyle m^2c^4}$$

$$E\sim pc$$

«ultra-relativistic»

affected by expansion

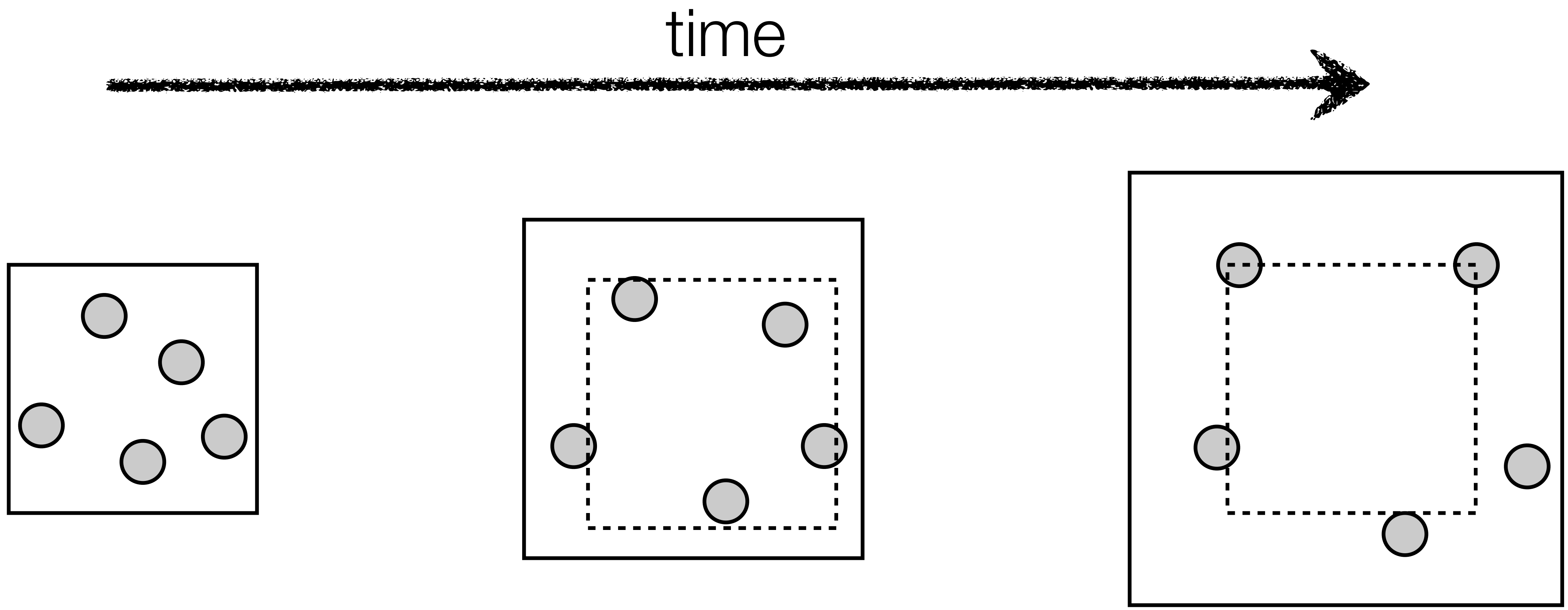
$$E^2={\scriptstyle p^2c^2}+m^2c^4$$

$$E\sim mc^2$$

«non relativistic»

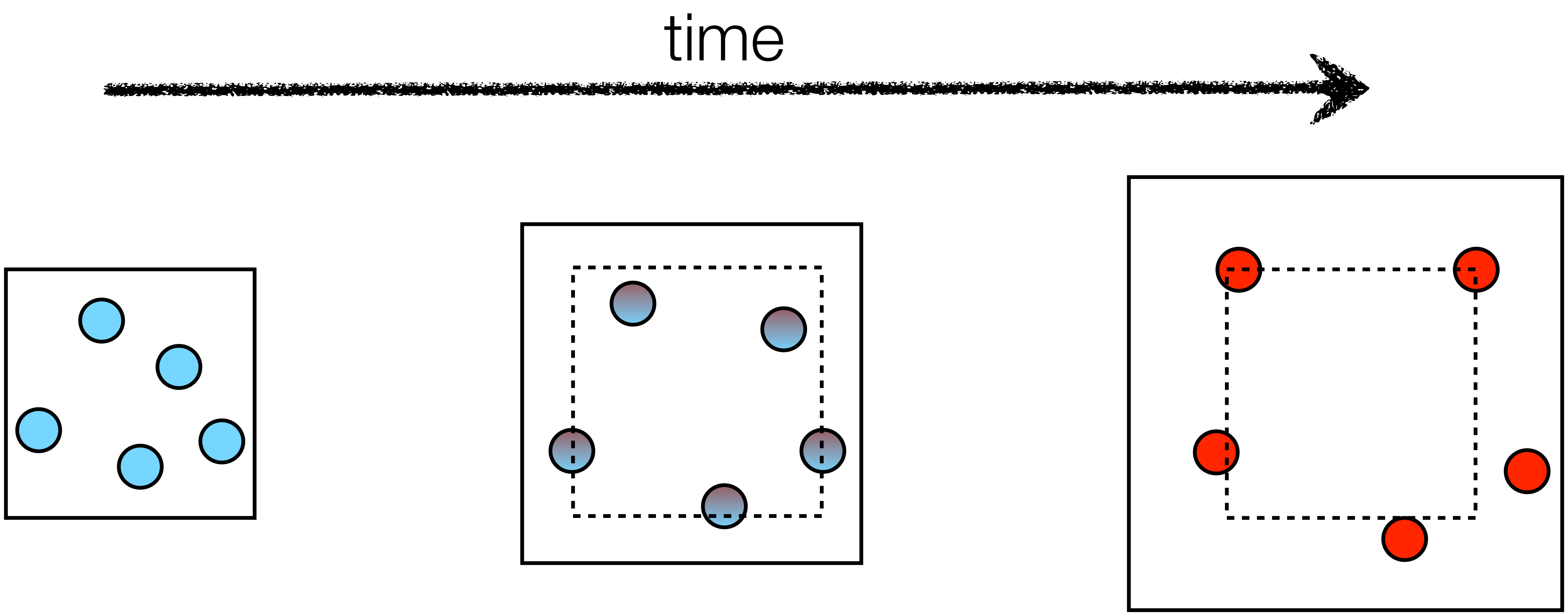
ignore expansion

Matter



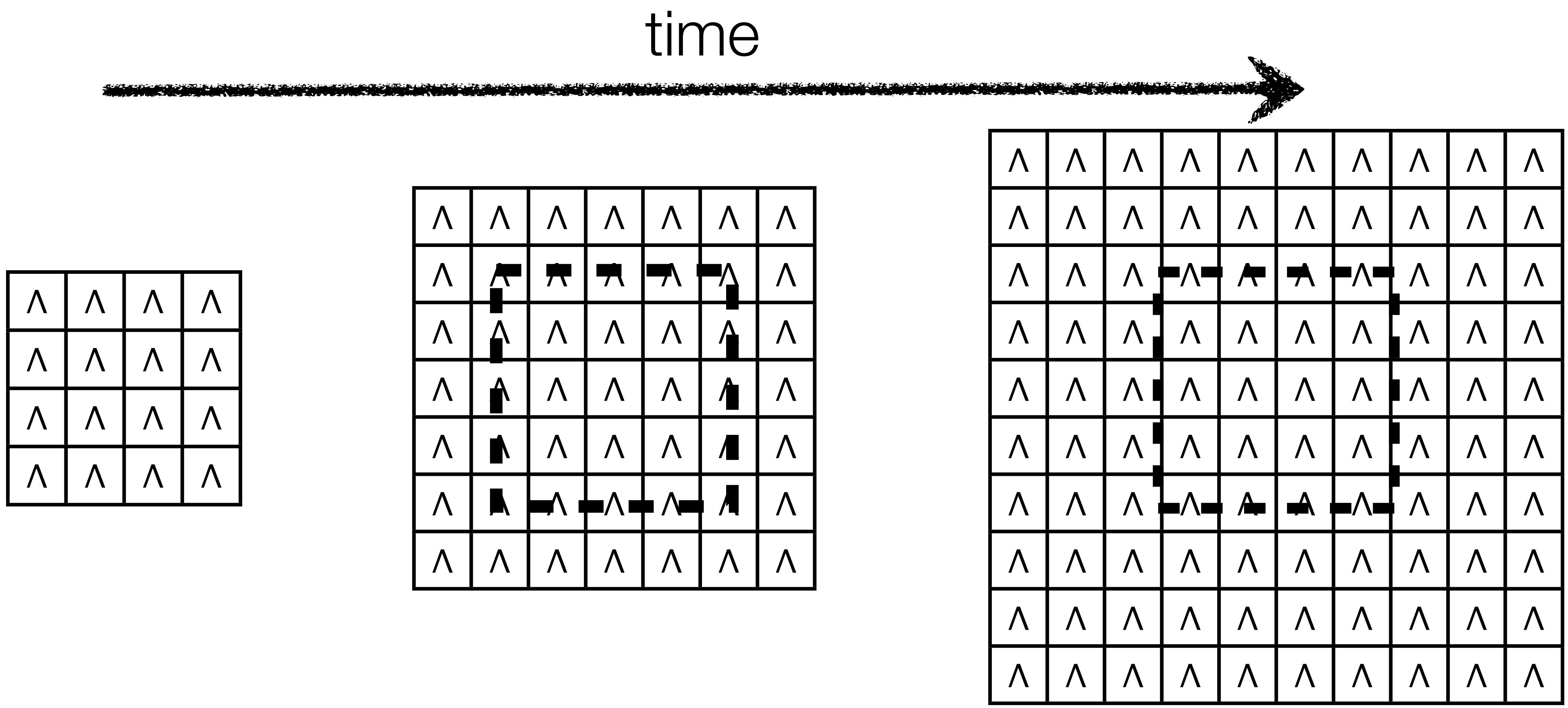
- Mass is constant in an expanding volume
- The physical density of matter decreases

Radiation



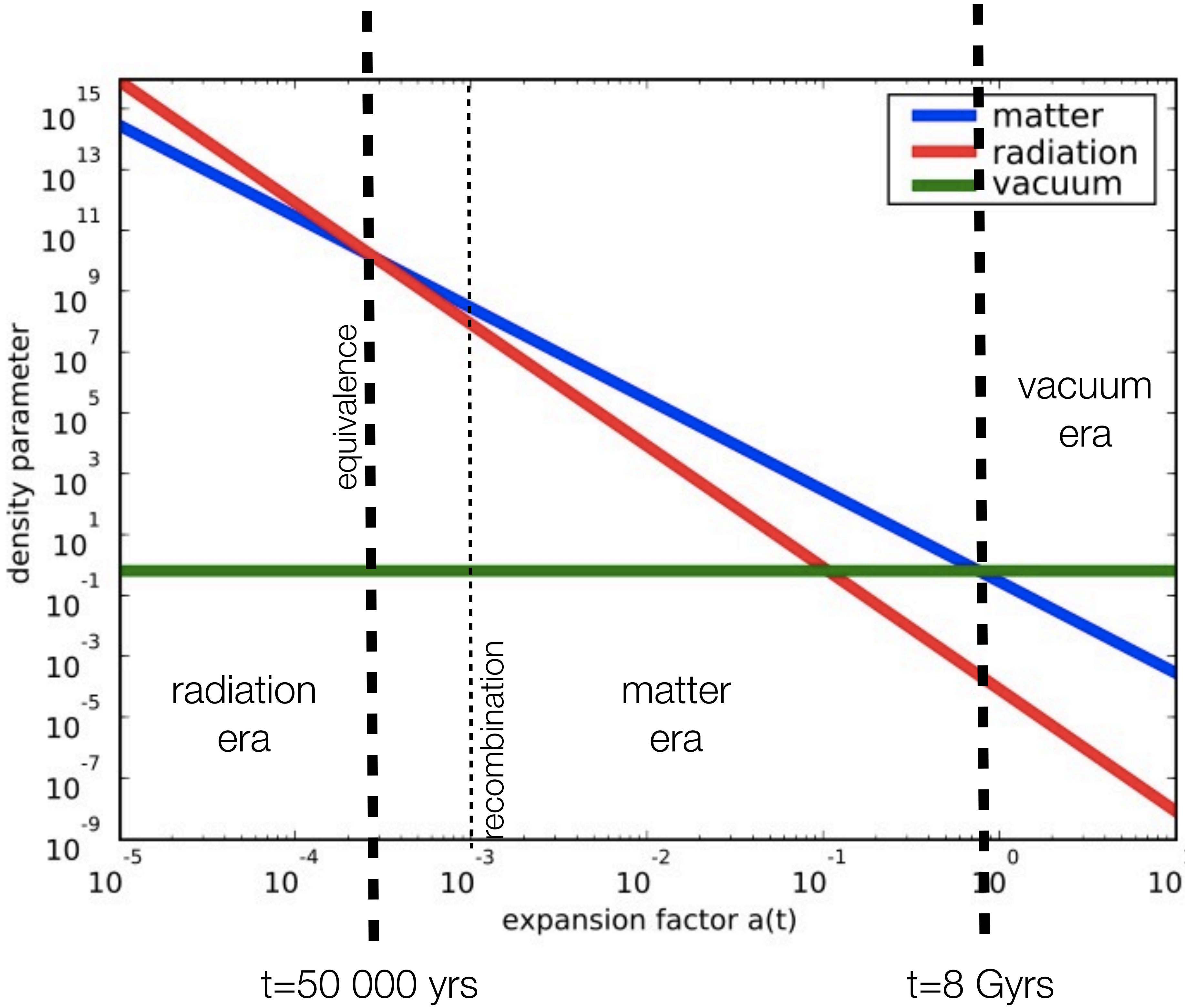
- The individual energy of photons decreases
- The physical density of photons also decreases
- Overall, the energy density of photons decrease faster than for matter

Vacuum



- The vacuum energy density remains constant
- Overall the vacuum energy increases with expansion

Domination eras



Domination eras

The expansion of the Universe is driven by:

- radiation at earliest stages
- matter during the buildup of large scale structures
- vacuum for 5 Gyrs

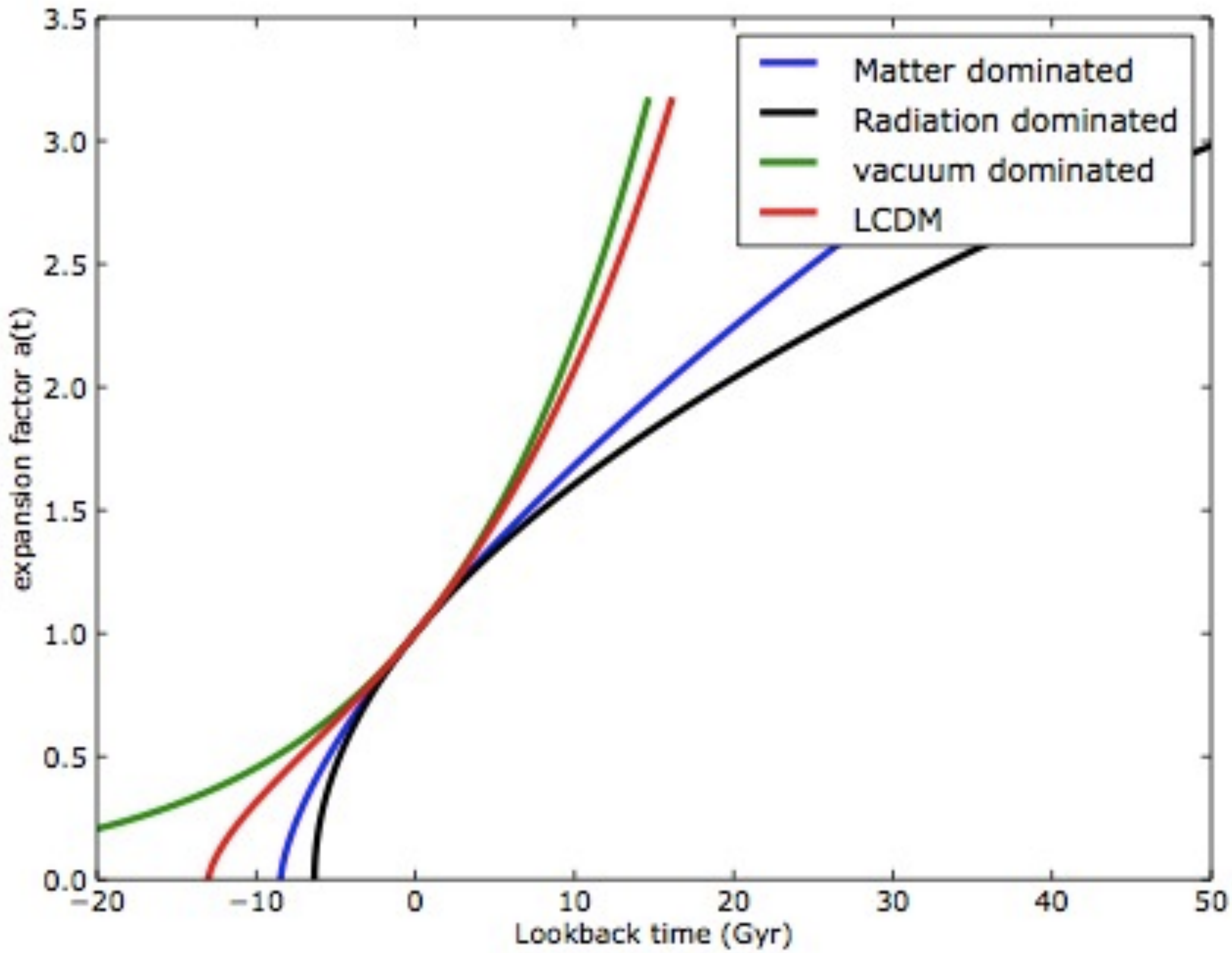
For Vacuum, energy increases with volume:

$$\mathrm{d}U = -P\mathrm{d}V \rightarrow P_v < 0.$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}(\rho c^2 + 3P)$$

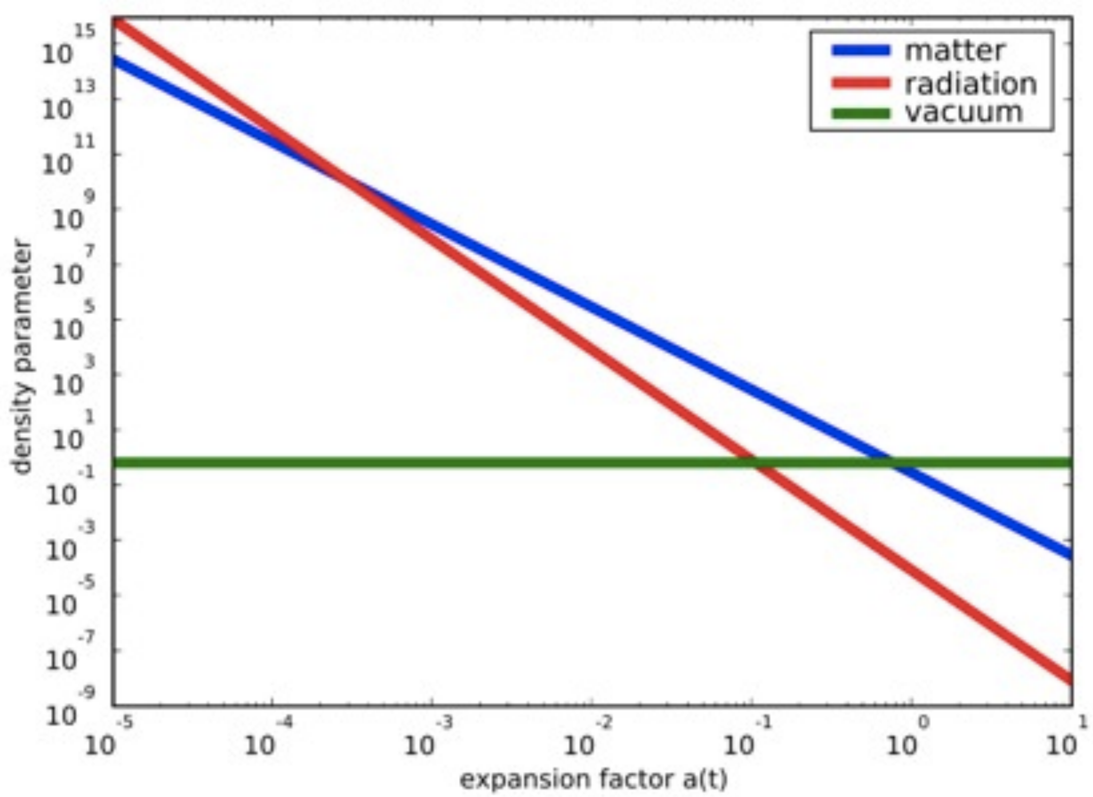
Vacuum accelerates the expansion !

From energy to expansion



Energy Conservation

Btw: energy is NOT conserved in the Universe



Since the space-time structure evolves, time translation invariance is not guaranteed, hence energy is not conserved

Dont Worry: physical concepts more general than energy are indeed conserved

Energy conservation : photons

Photons dominate the Thermodynamical state of the Universe

$$u \sim T^4$$ for a blackbody

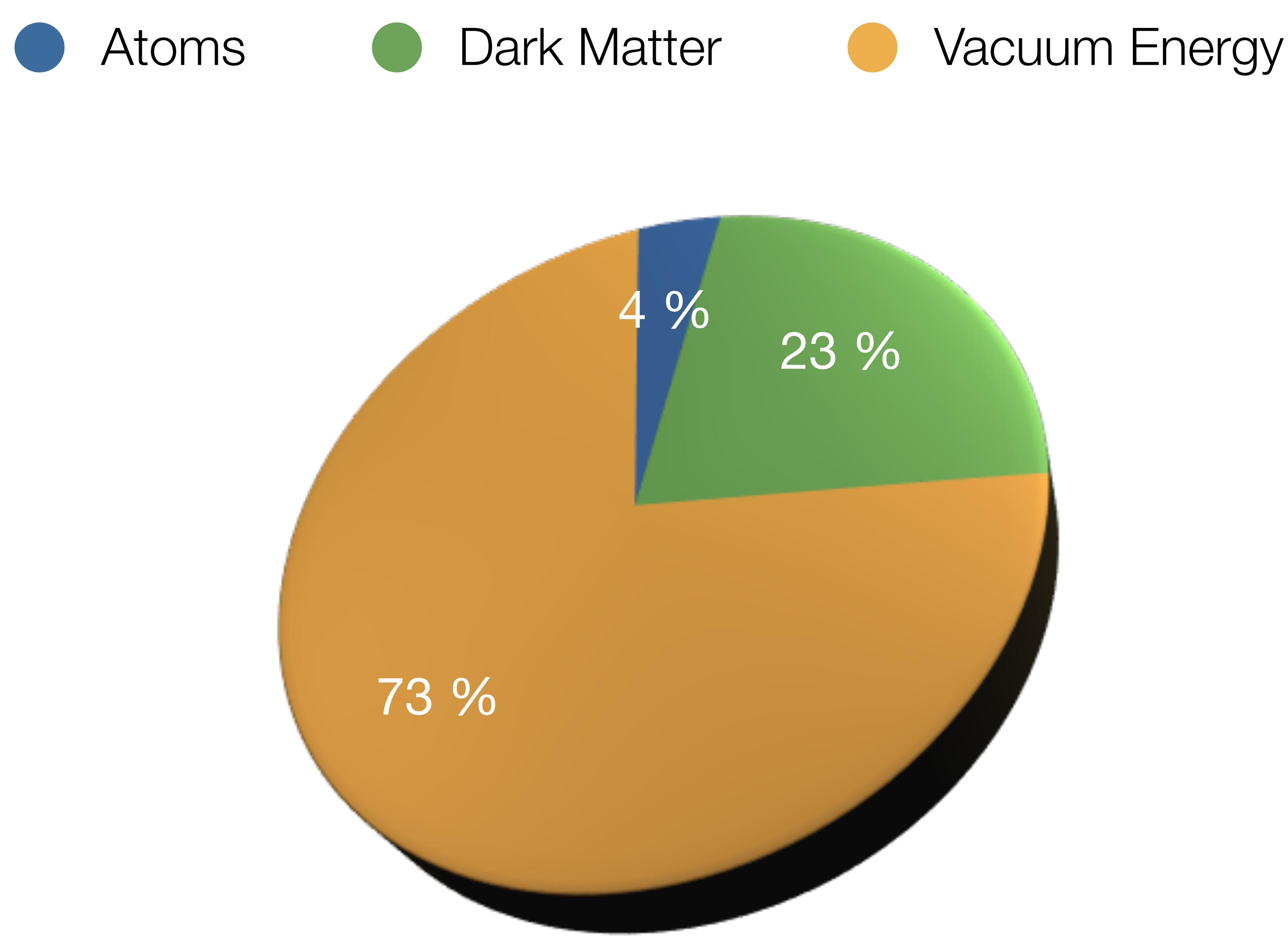
$$u \sim z^4$$ because of expansion

$$T \sim z$$

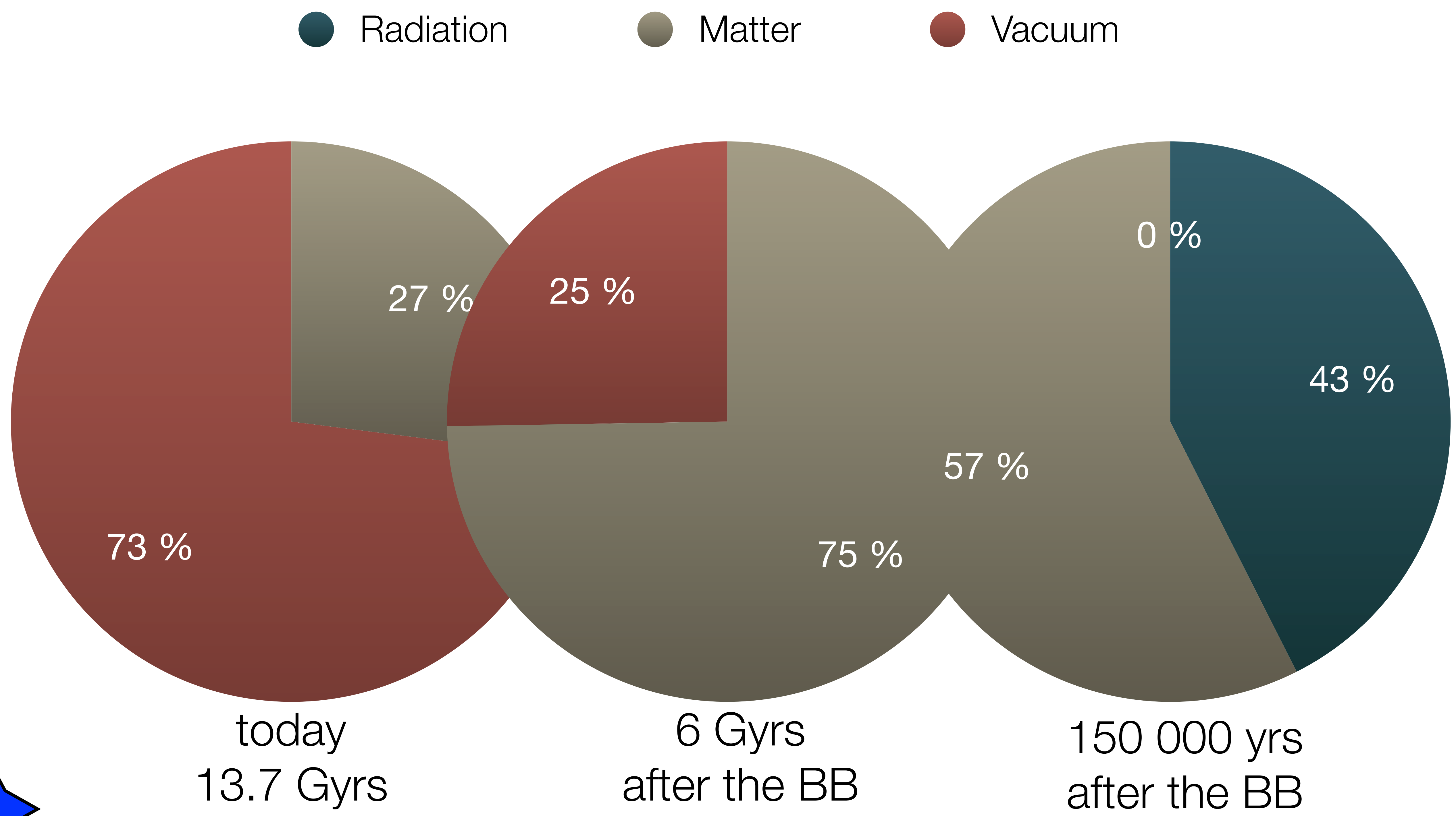
The Universe cools down

The Standard Model

Energetic content of the Universe, today

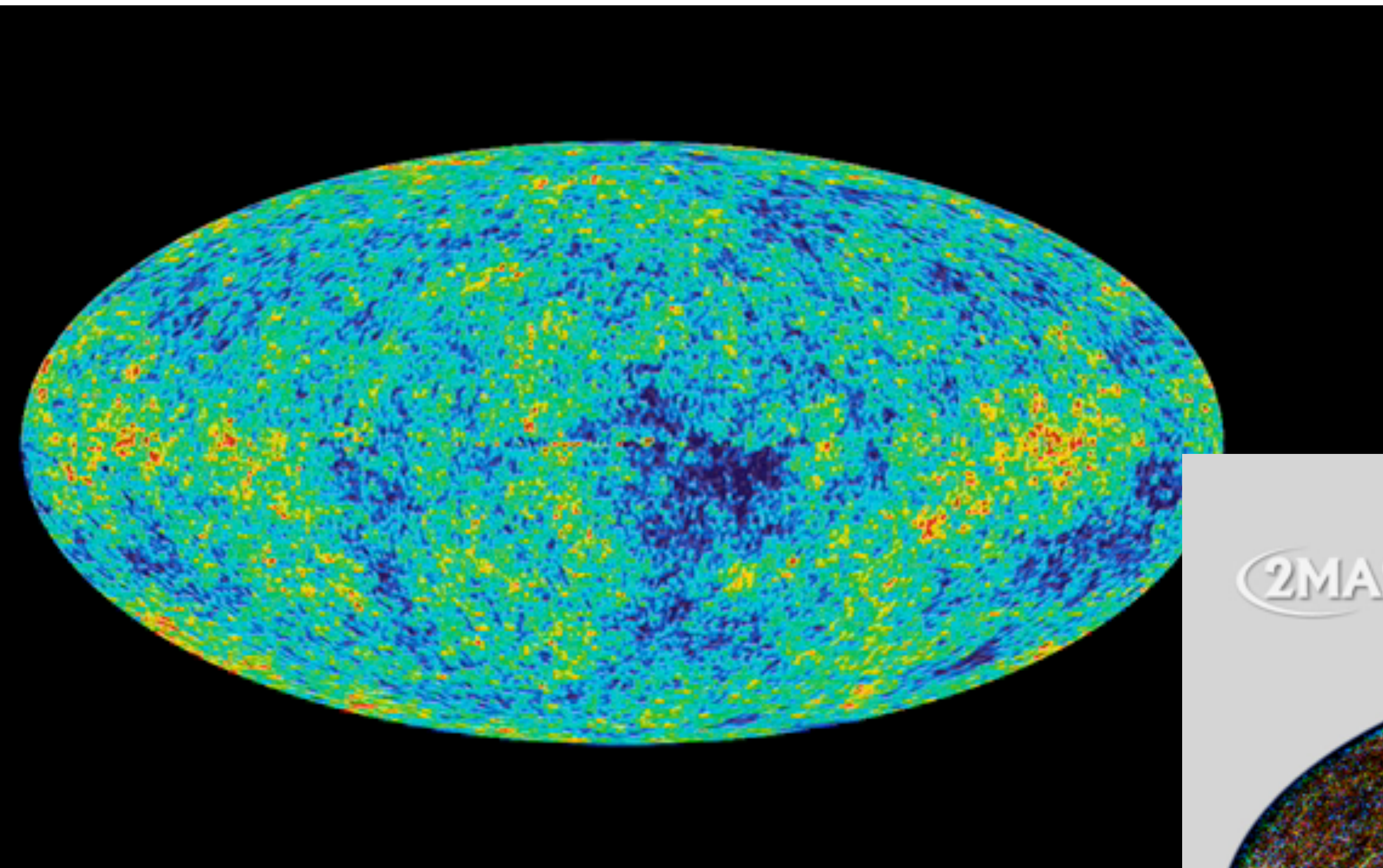


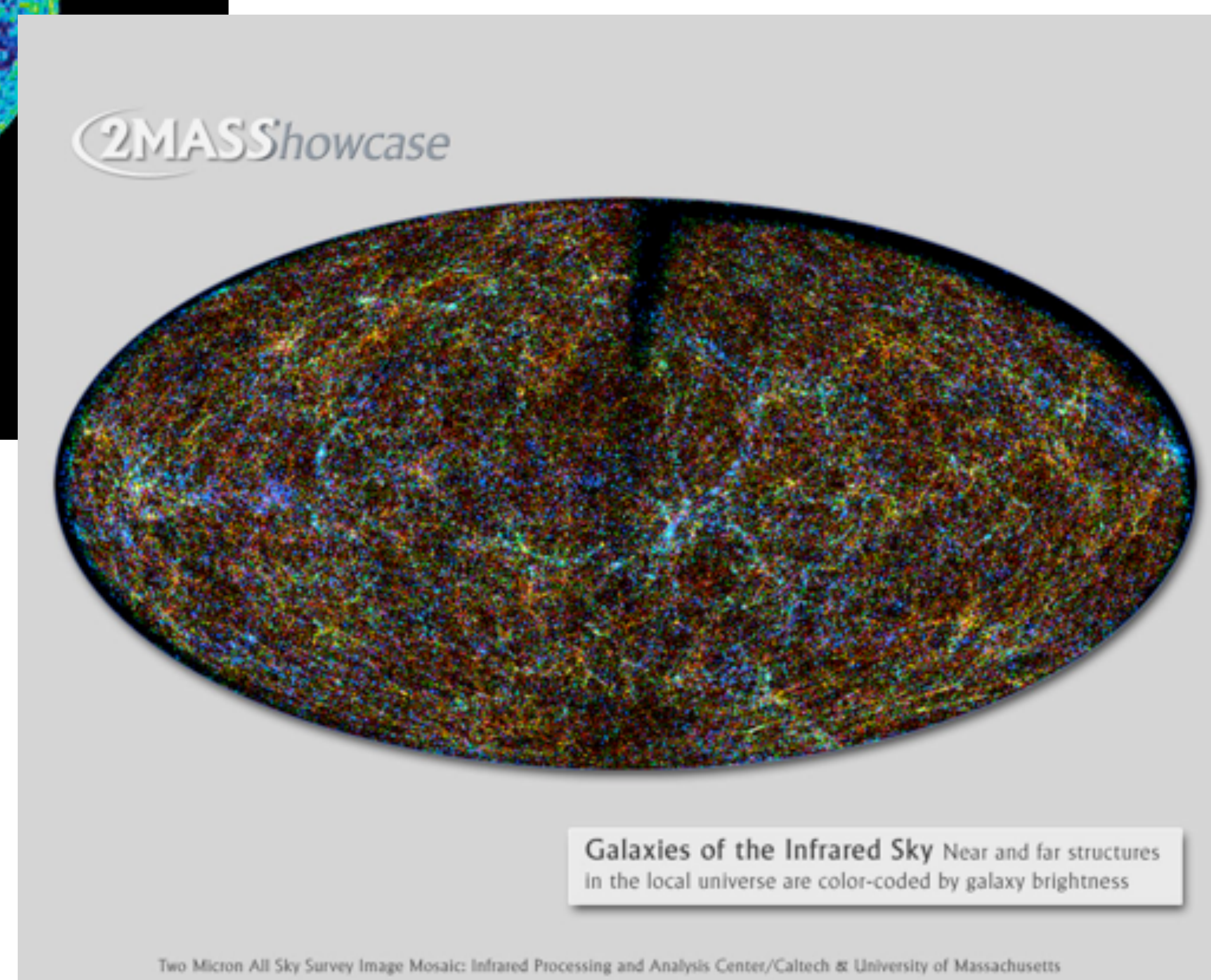
Pies


Radiation
Matter
Vacuum
27 %
73 %
25 %
75 %
0 %
43 %
57 %
today
13.7 Gyrs
6 Gyrs
after the BB
150 000 yrs
after the BB

The Growth of structures

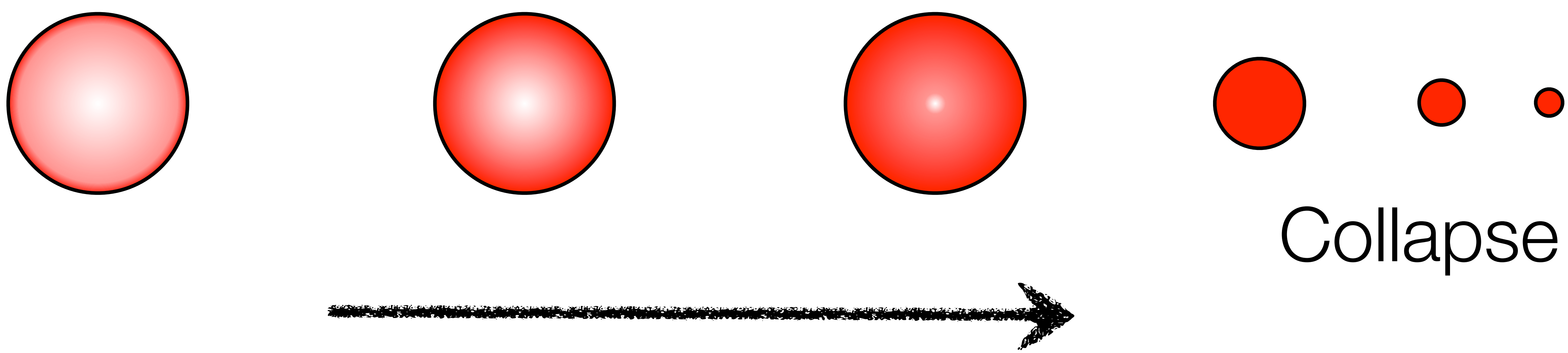
From CMB to LSS





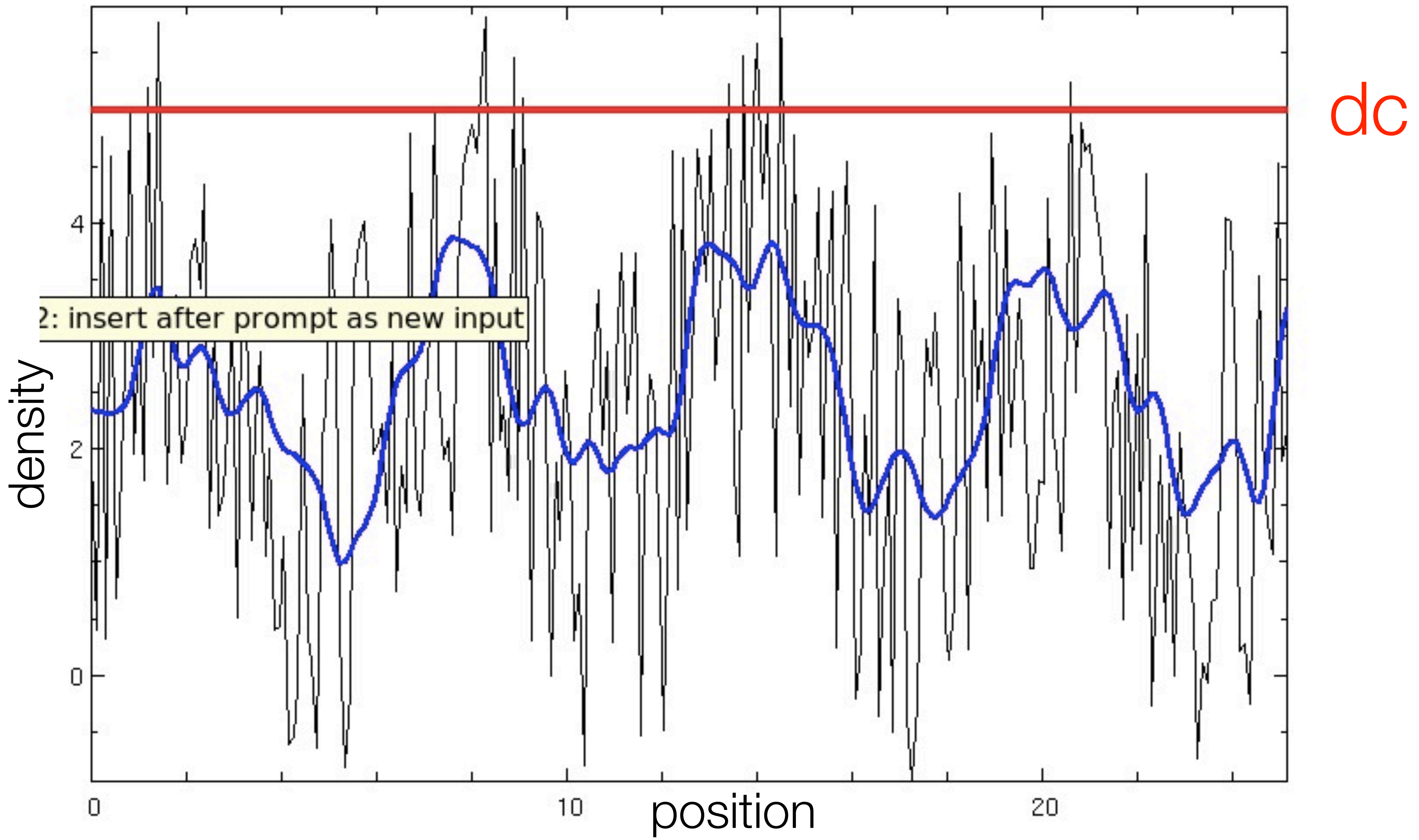
Dynamics of matter

on cosmological scales,
Gravity rule them all



Above a given threshold, clump of matter collapses

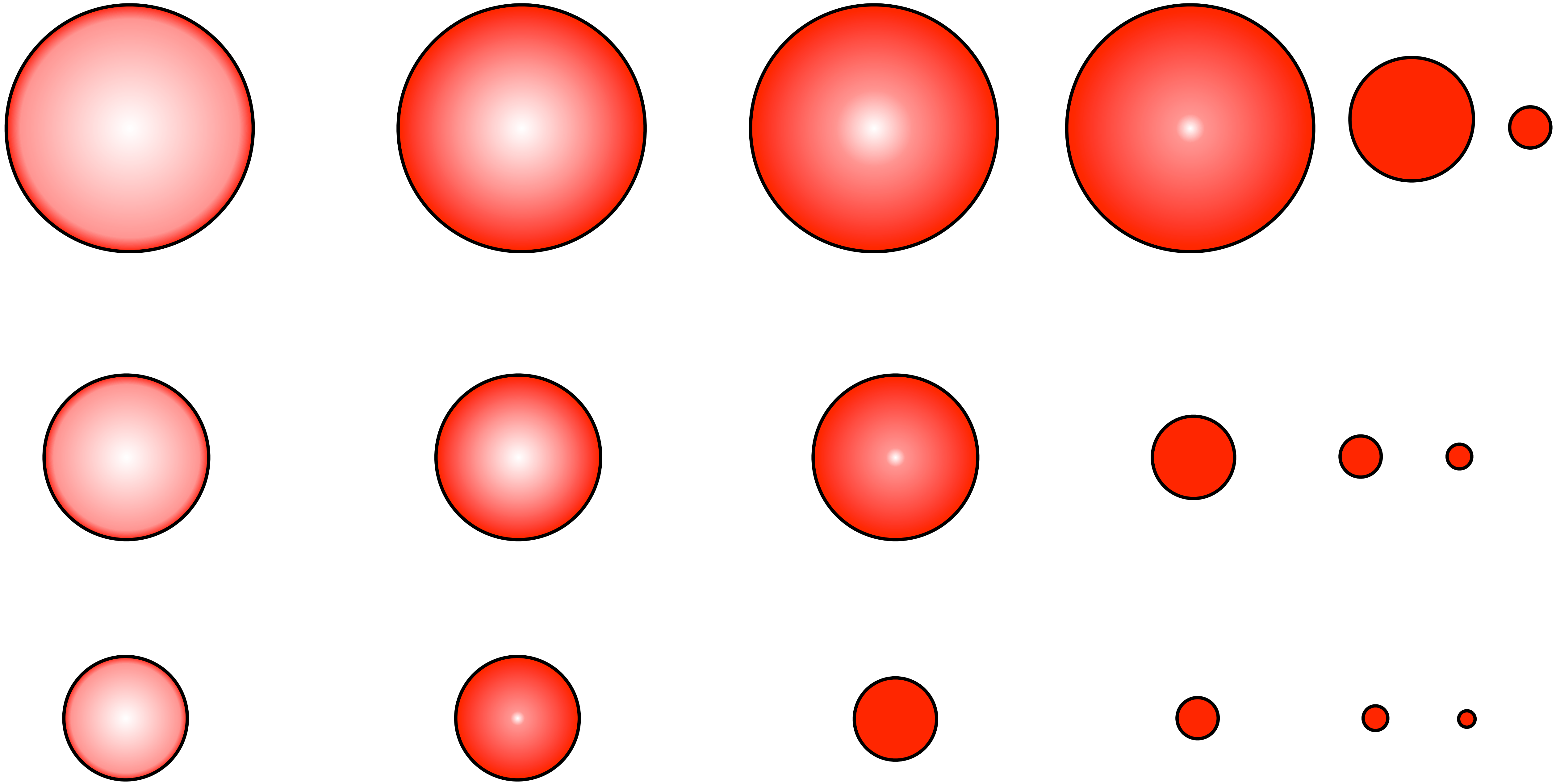
Multiscale density fluctuations



small scales fluctuations exhibit events with d >dc

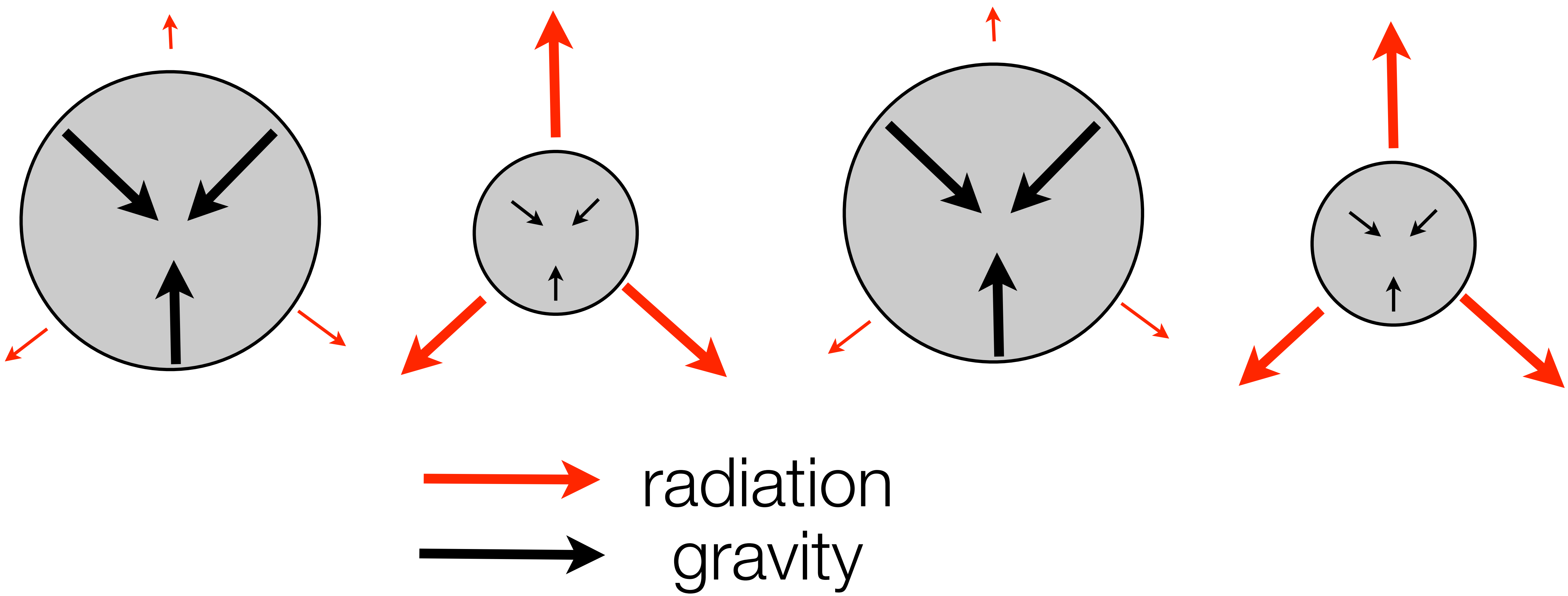
large scales should grow further to collapse

Hierarchical Model



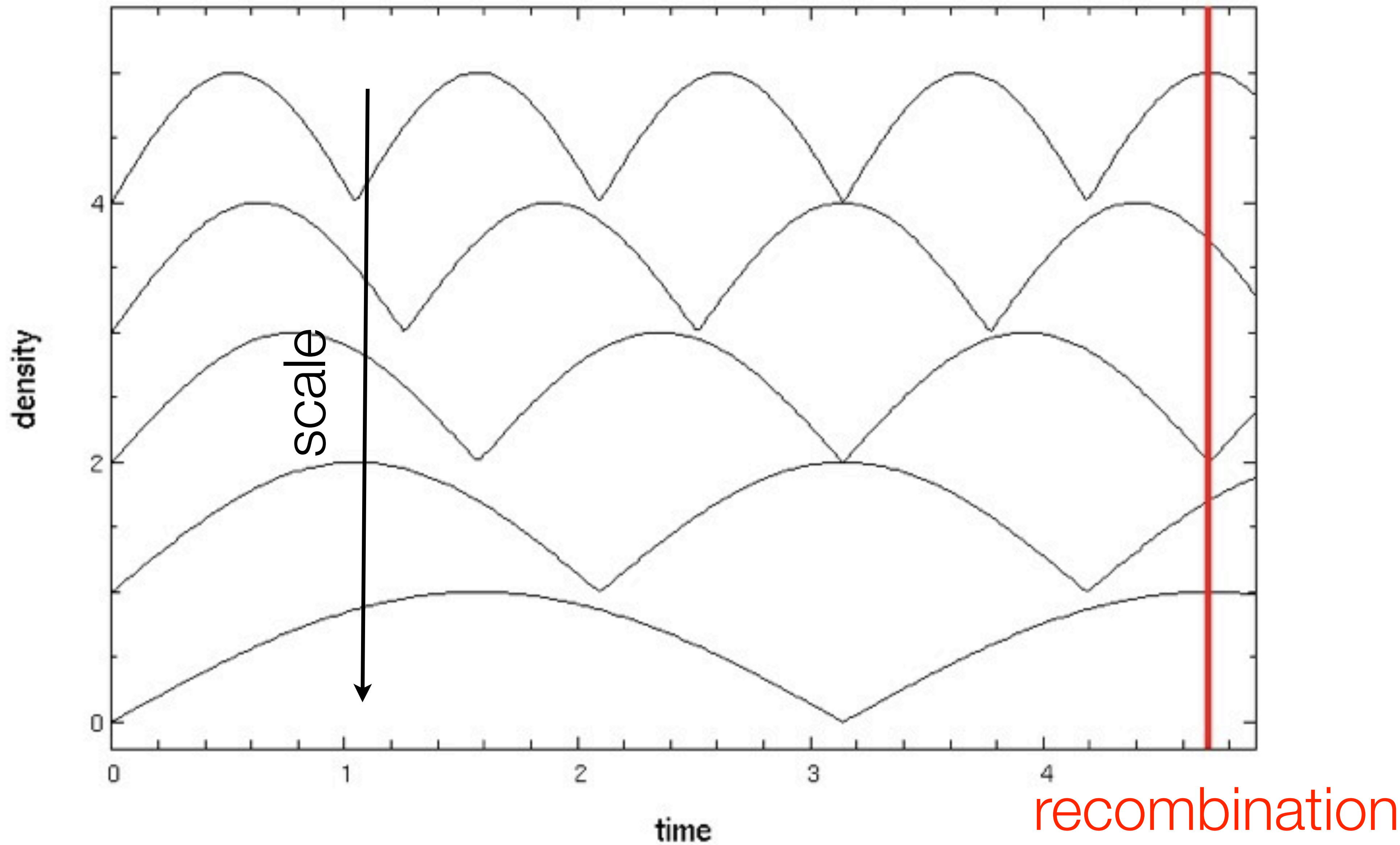
Baryonic Oscillations

Baryons (aka «normal matter») is coupled to radiation before recombination



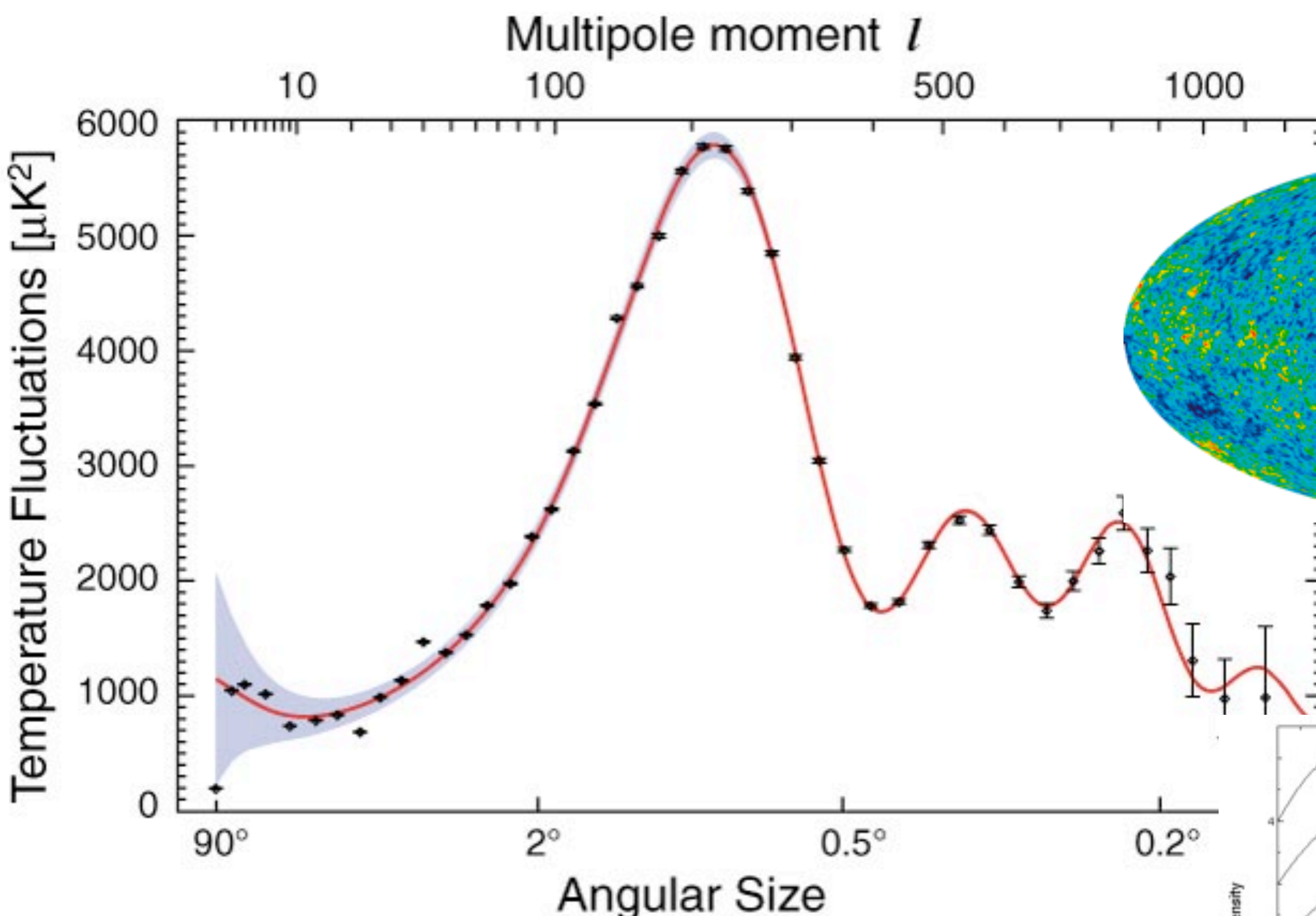
Baryons oscillate

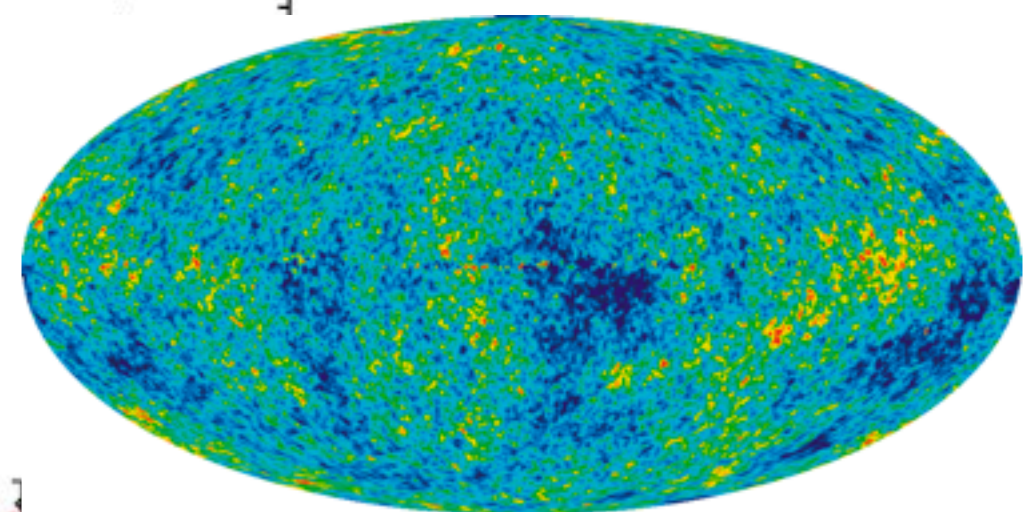
Spatio-temporal resonance cavity

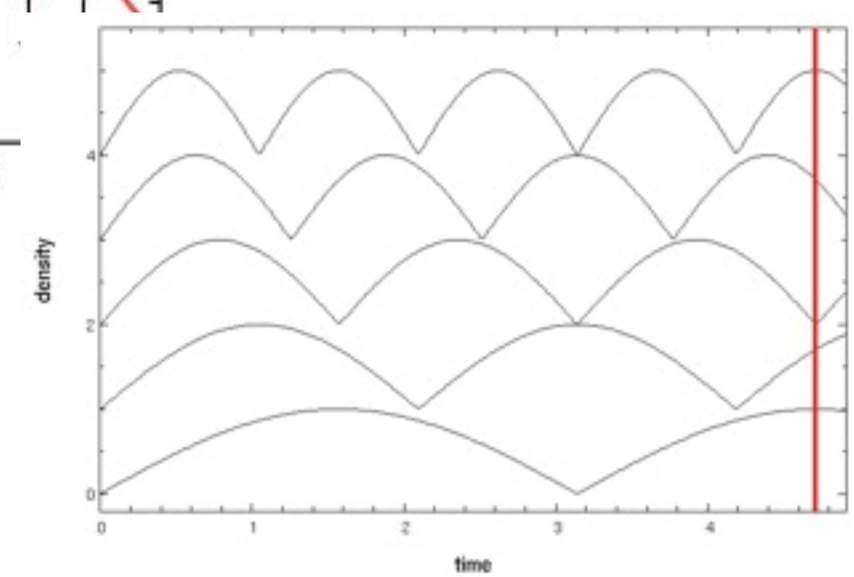


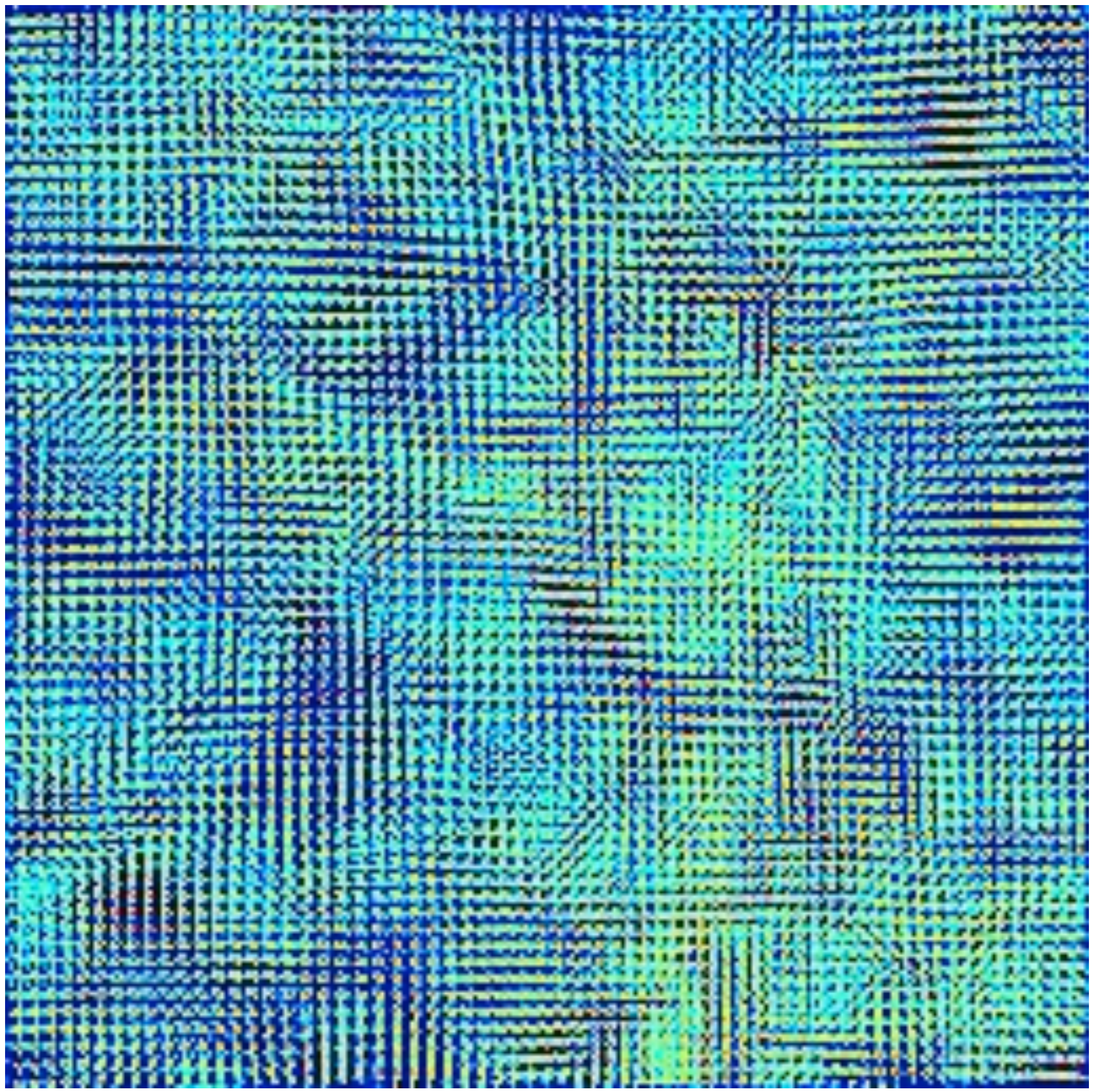
some scales are at maximal amplitude at recombination

The Baryon wiggles

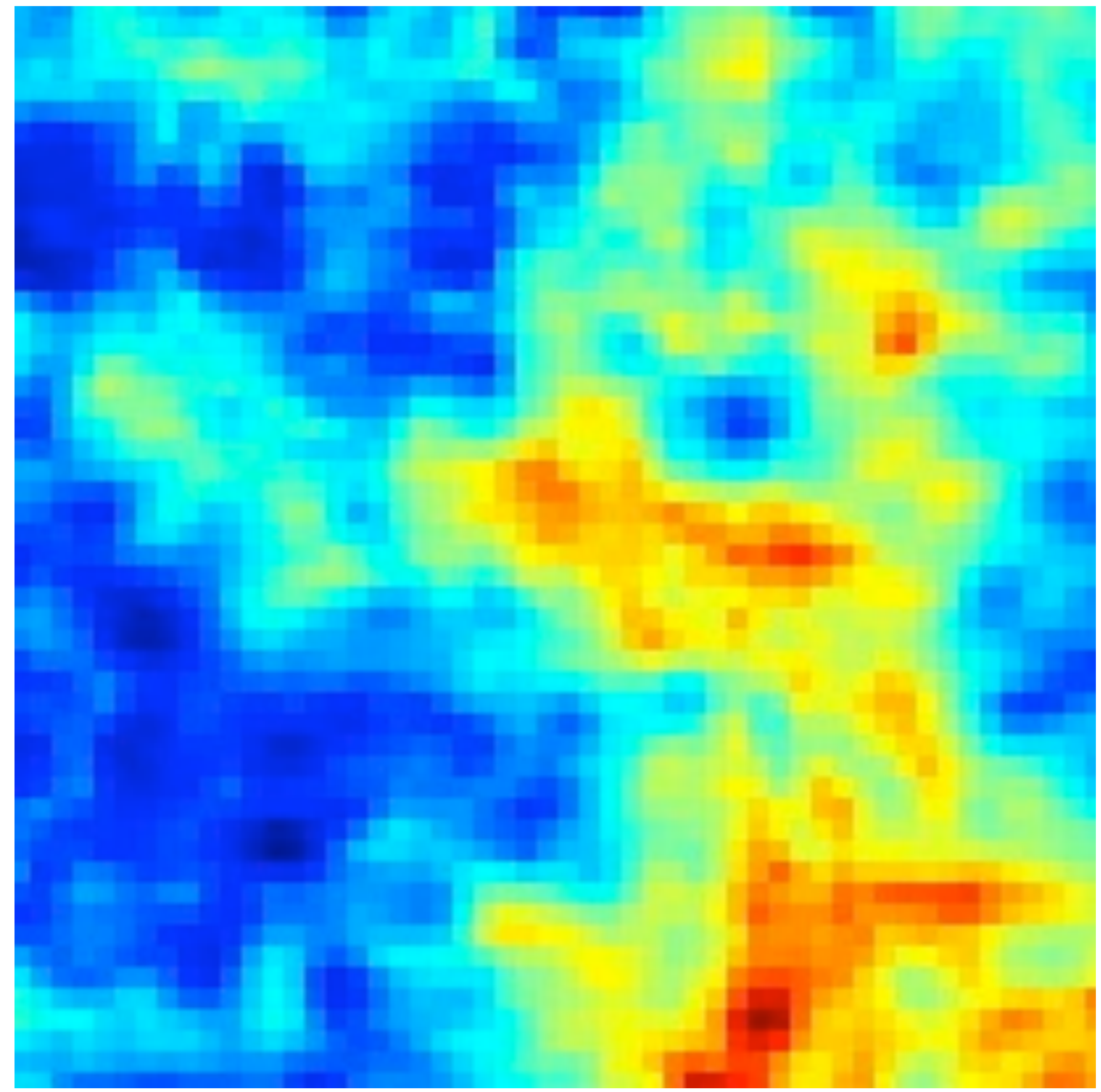






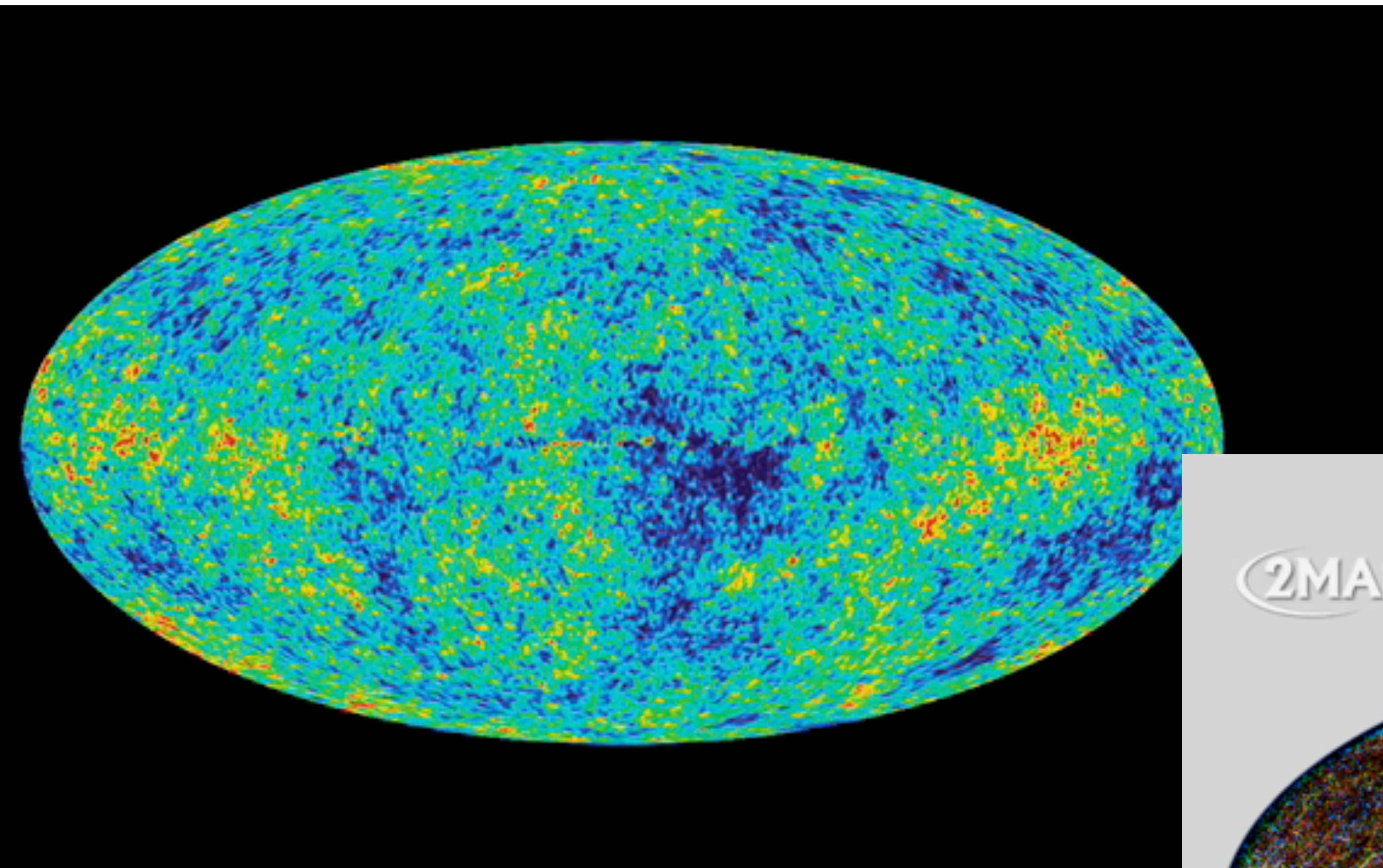


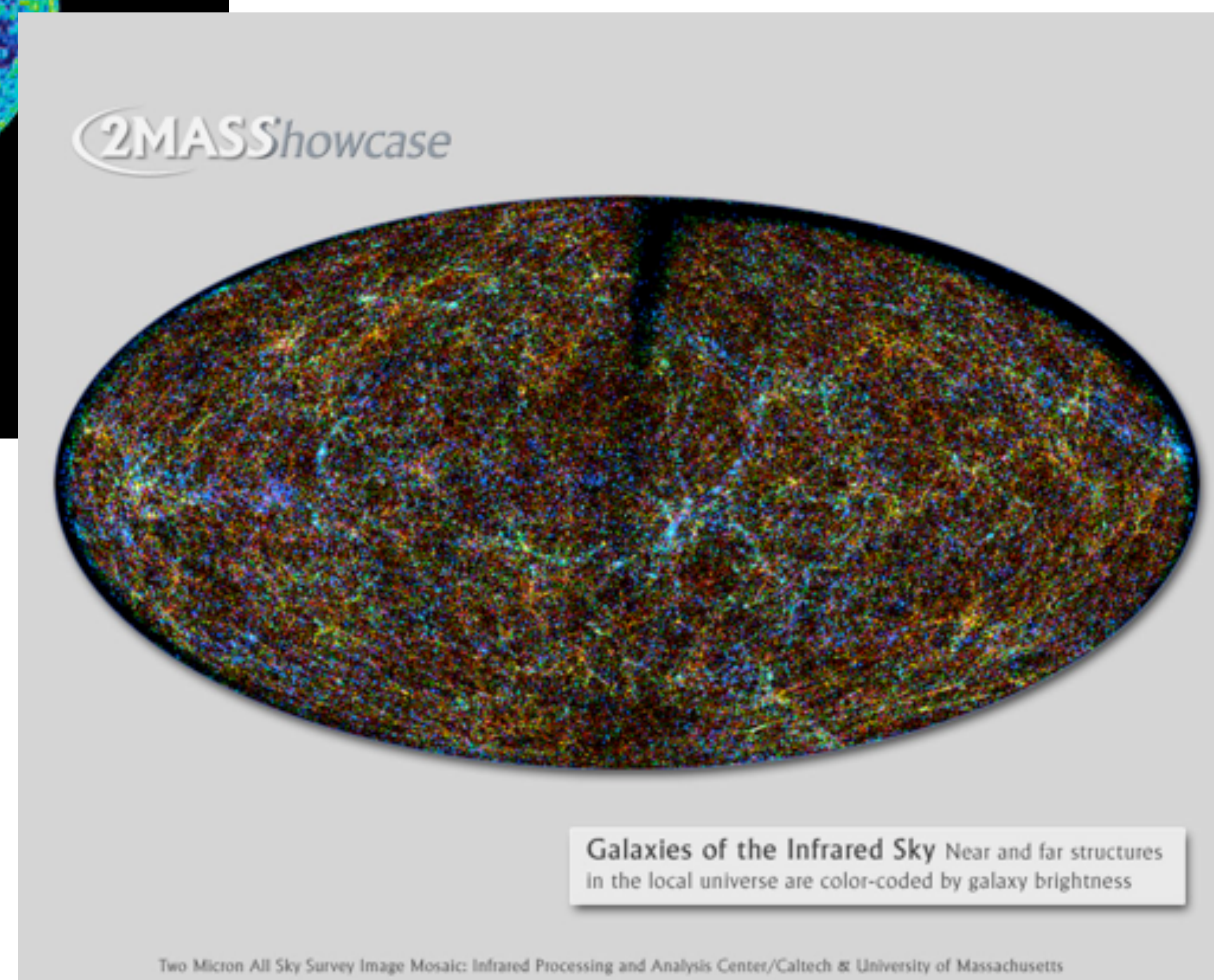
Dark Matter



Gas

From CMB to LSS





BAOs in the galaxy distribution !

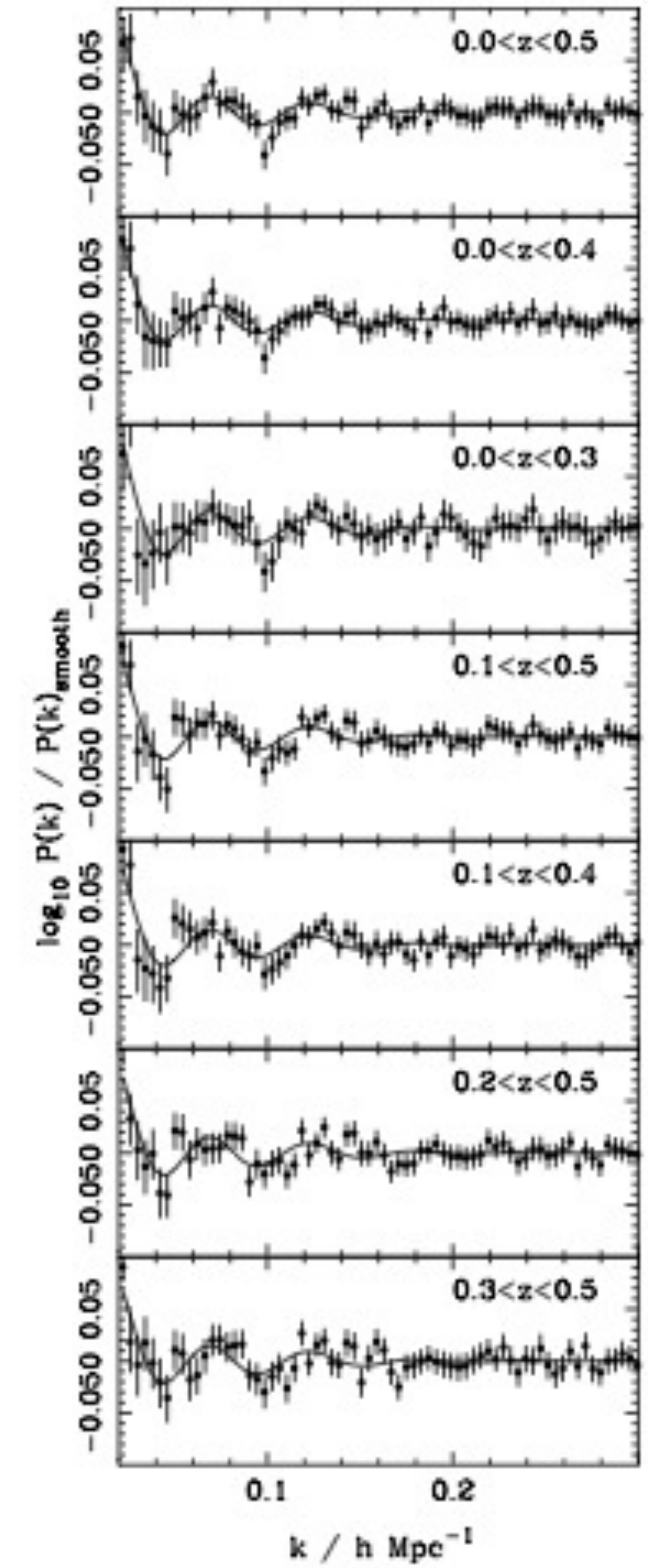
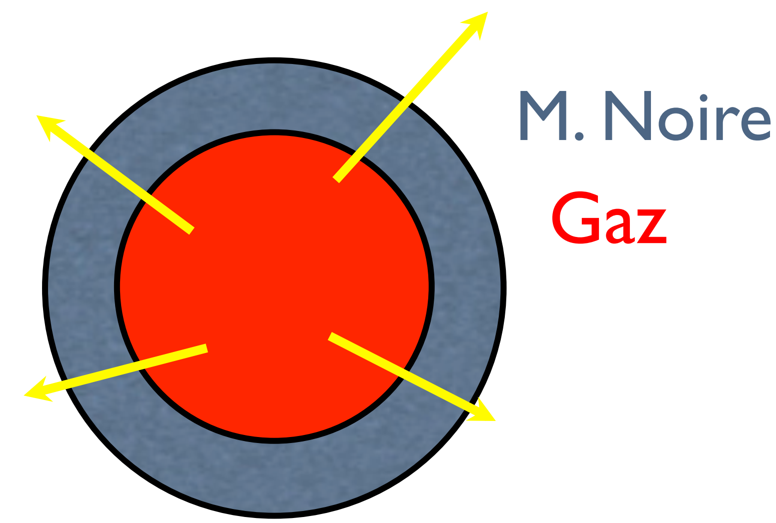


Figure 3. BAO recovered from the data for each of the redshift slices (solid circles with 1σ errors). These are compared with BAO in our default ΛCDM model (solid lines).

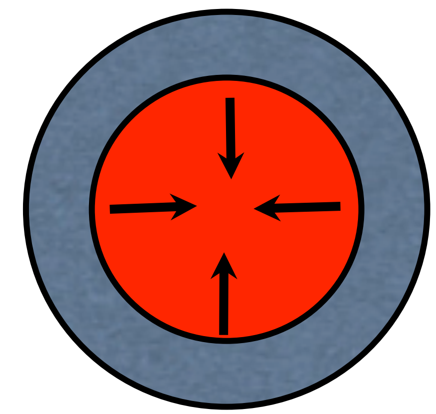
Percival et al. 2010

Galaxy formation

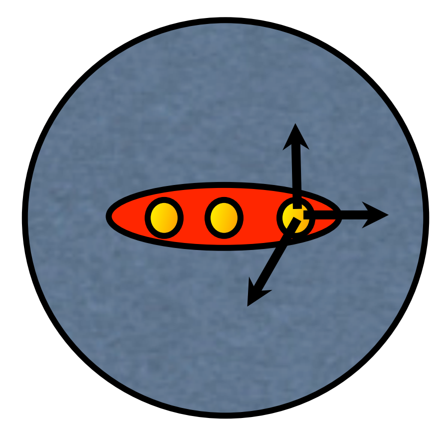
- Gaz radiates energy and cools down in the potential well of dark haloes



- Because of rotation, gaz spins to form discs

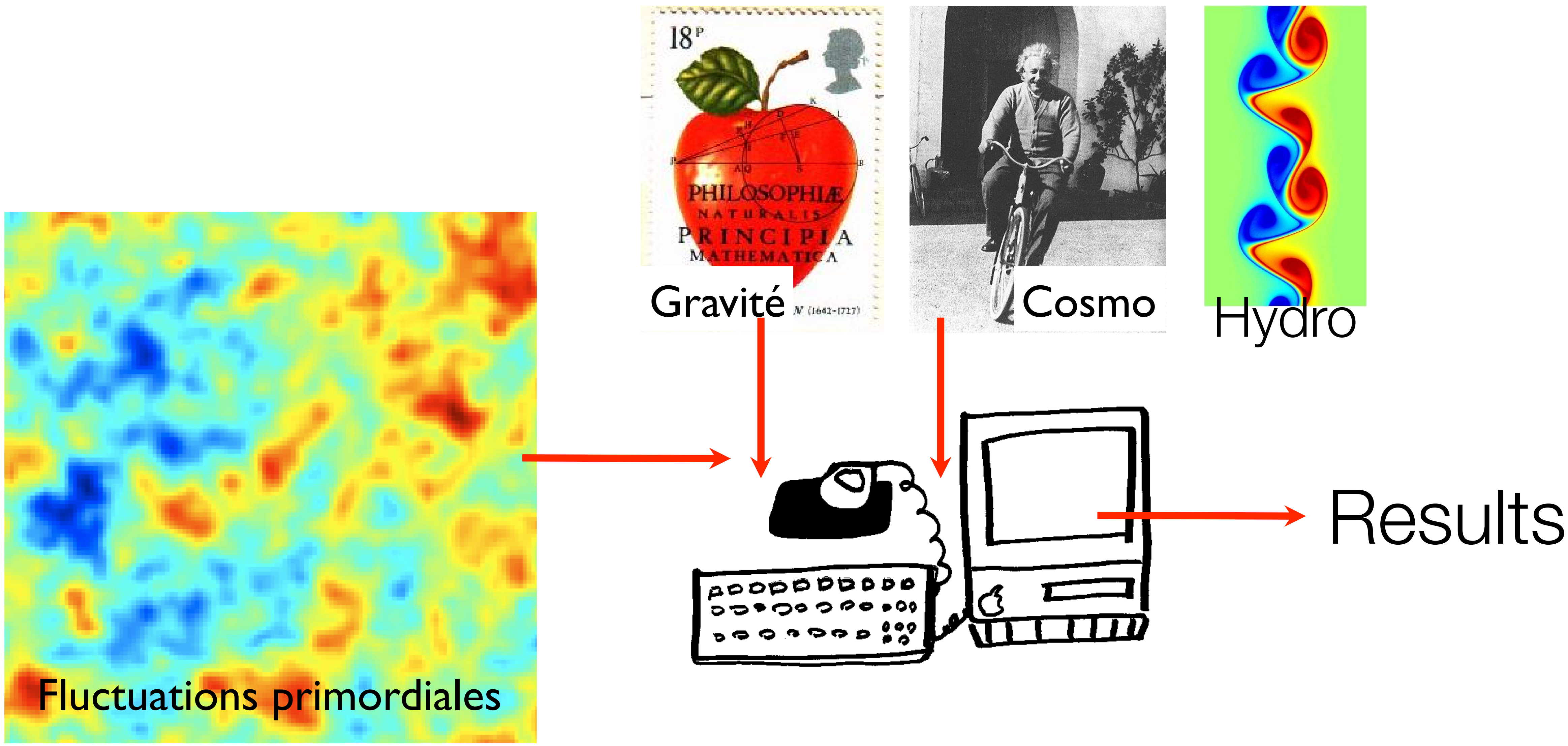


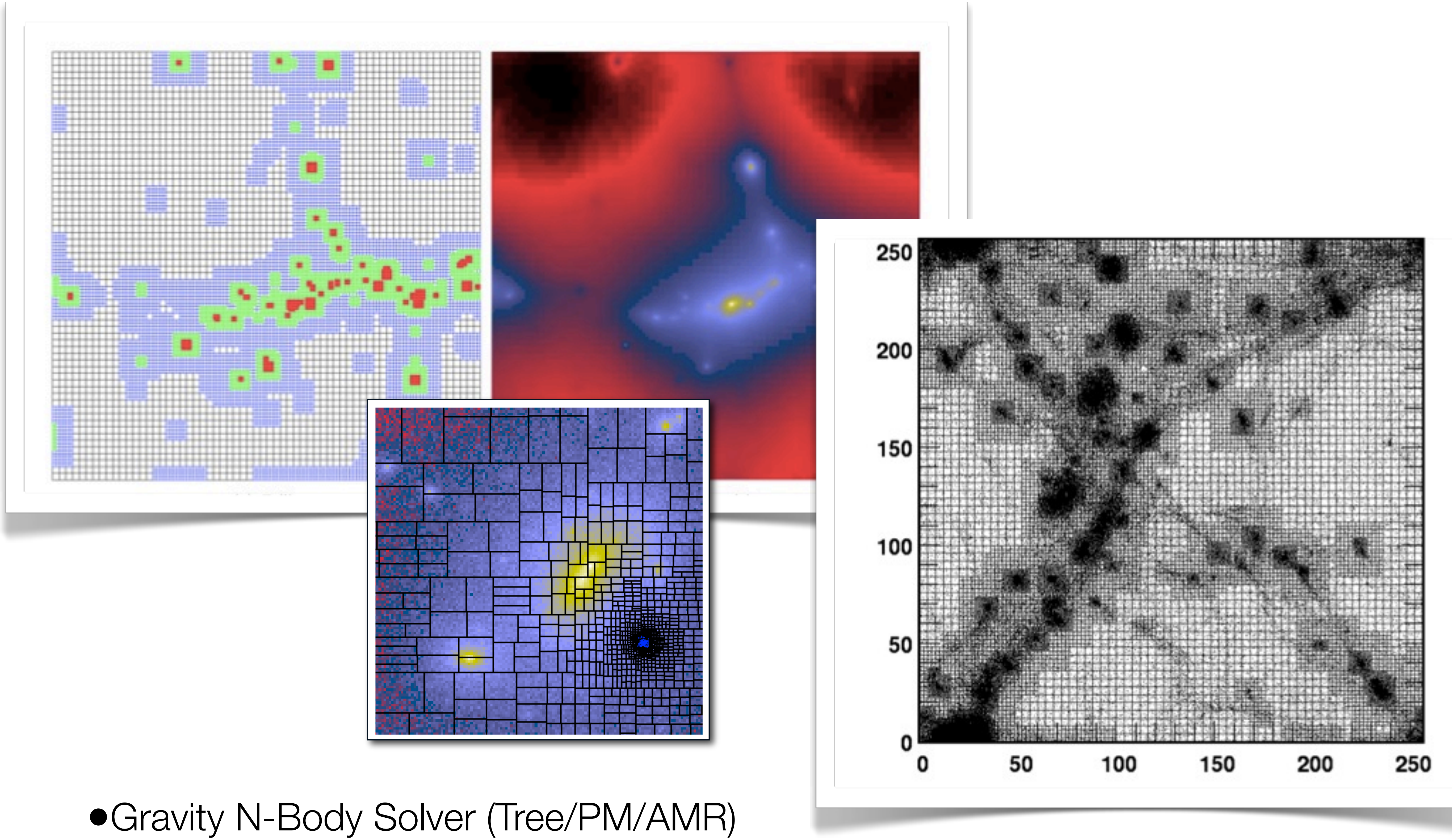
- stars may form and explodes later (SN feedback)



Numerical Simulations of Structure formation

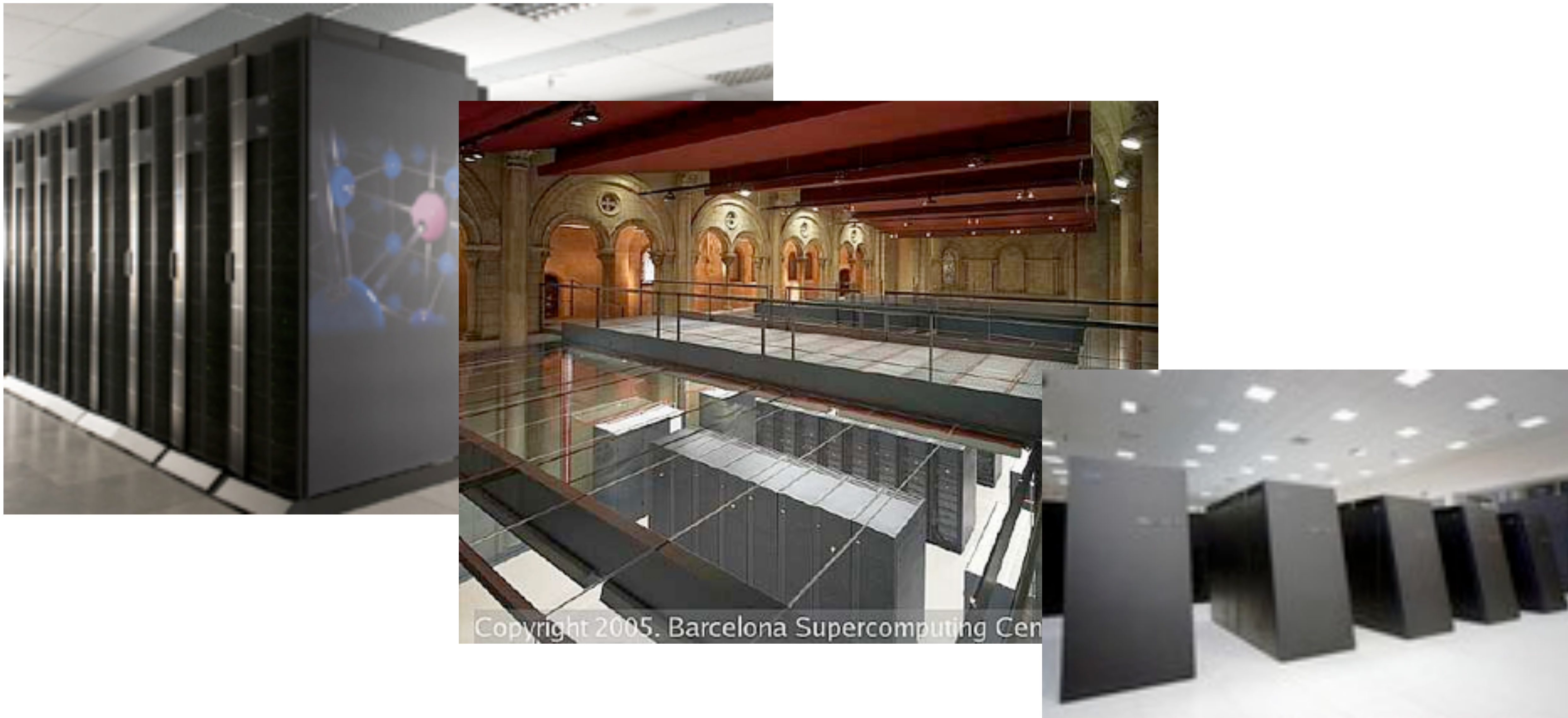
Principle of numerical simulations



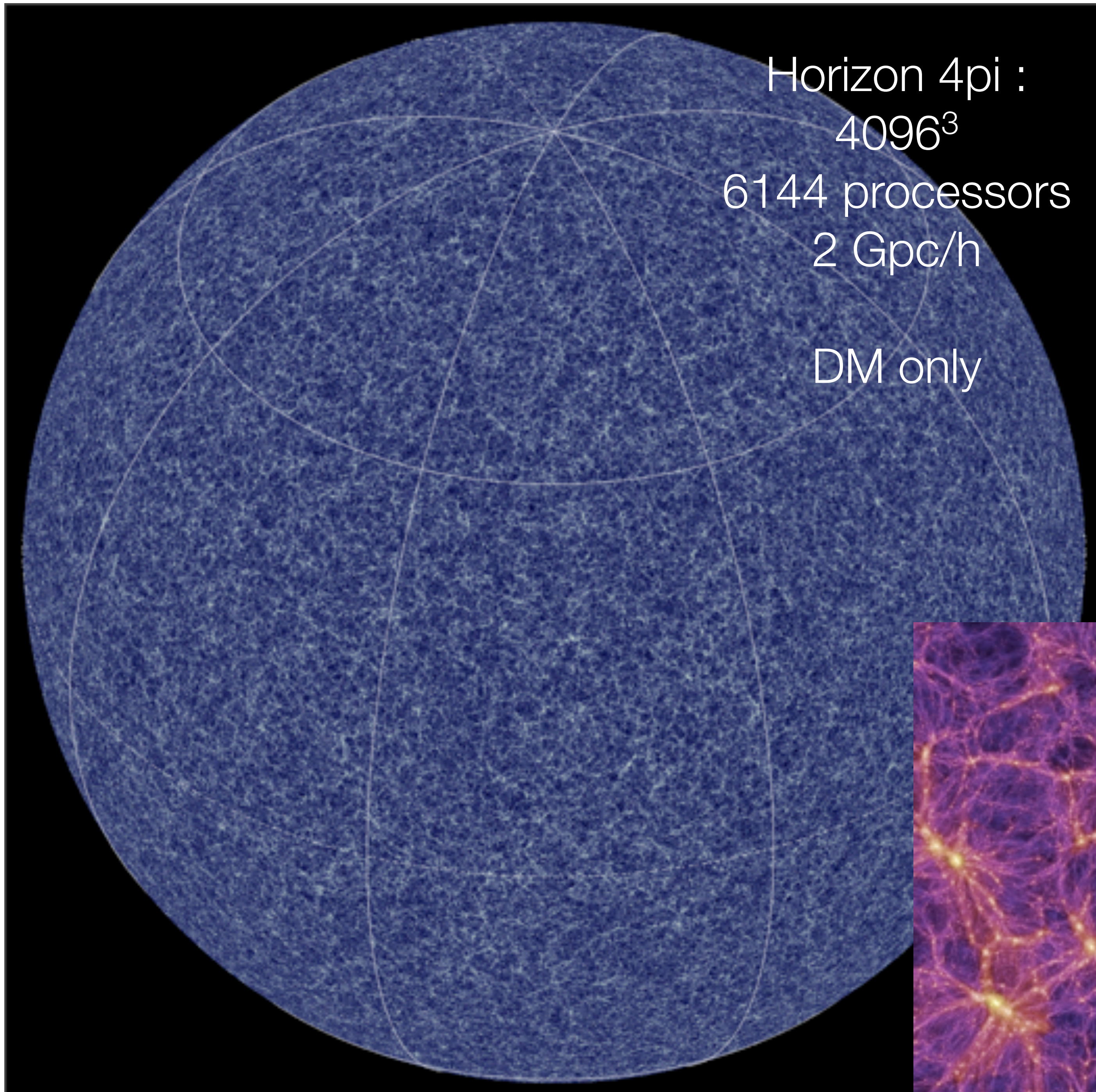


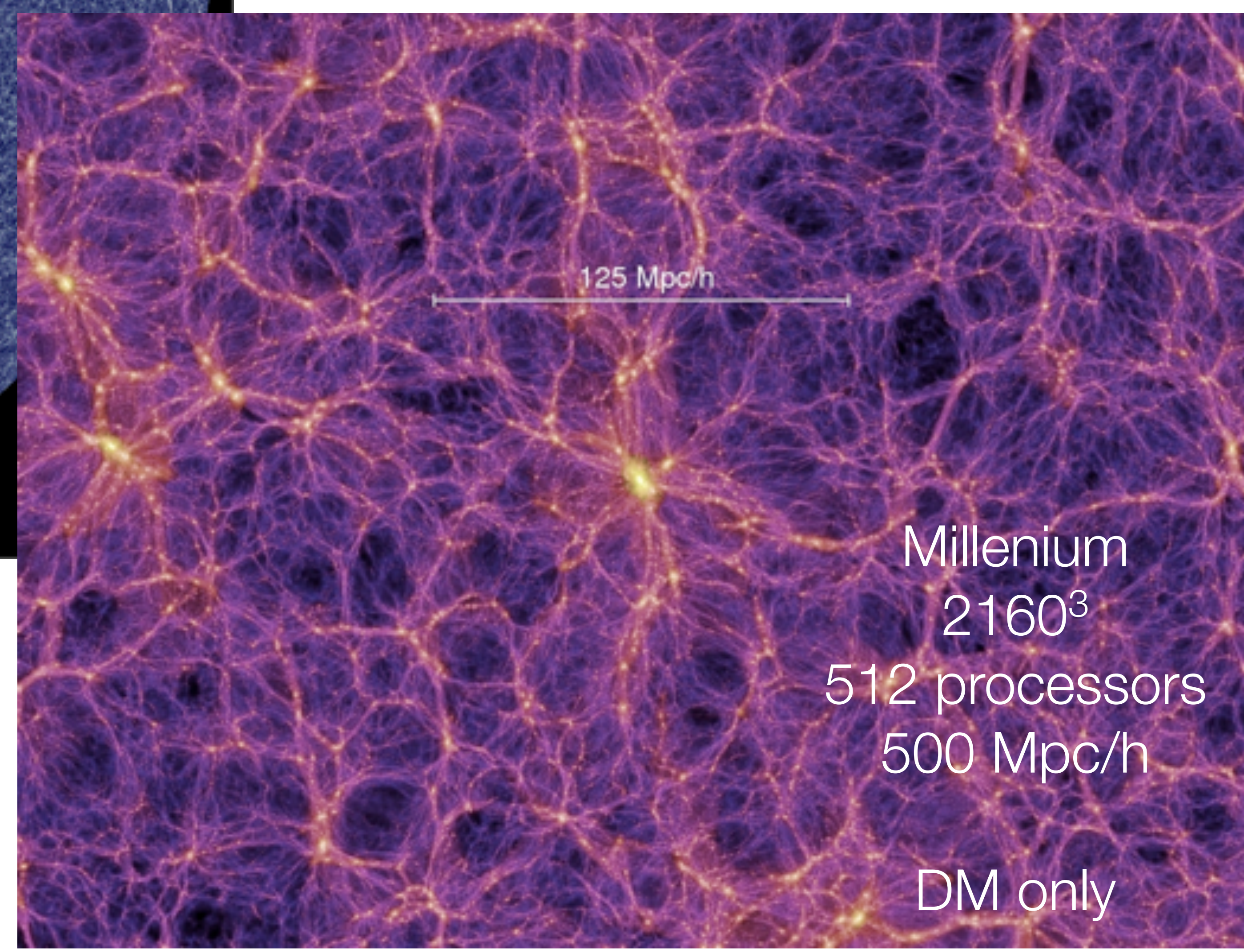
- Gravity N-Body Solver (Tree/PM/AMR)
- Computational Fluid Dynamics (AMR/SPH)
- Radiative transfer (MC,Moment,Ray casting)
- Chemistry - Atomic Physics
- Massive Parallelisation for Supercomputers

The Universe in Supercomputers

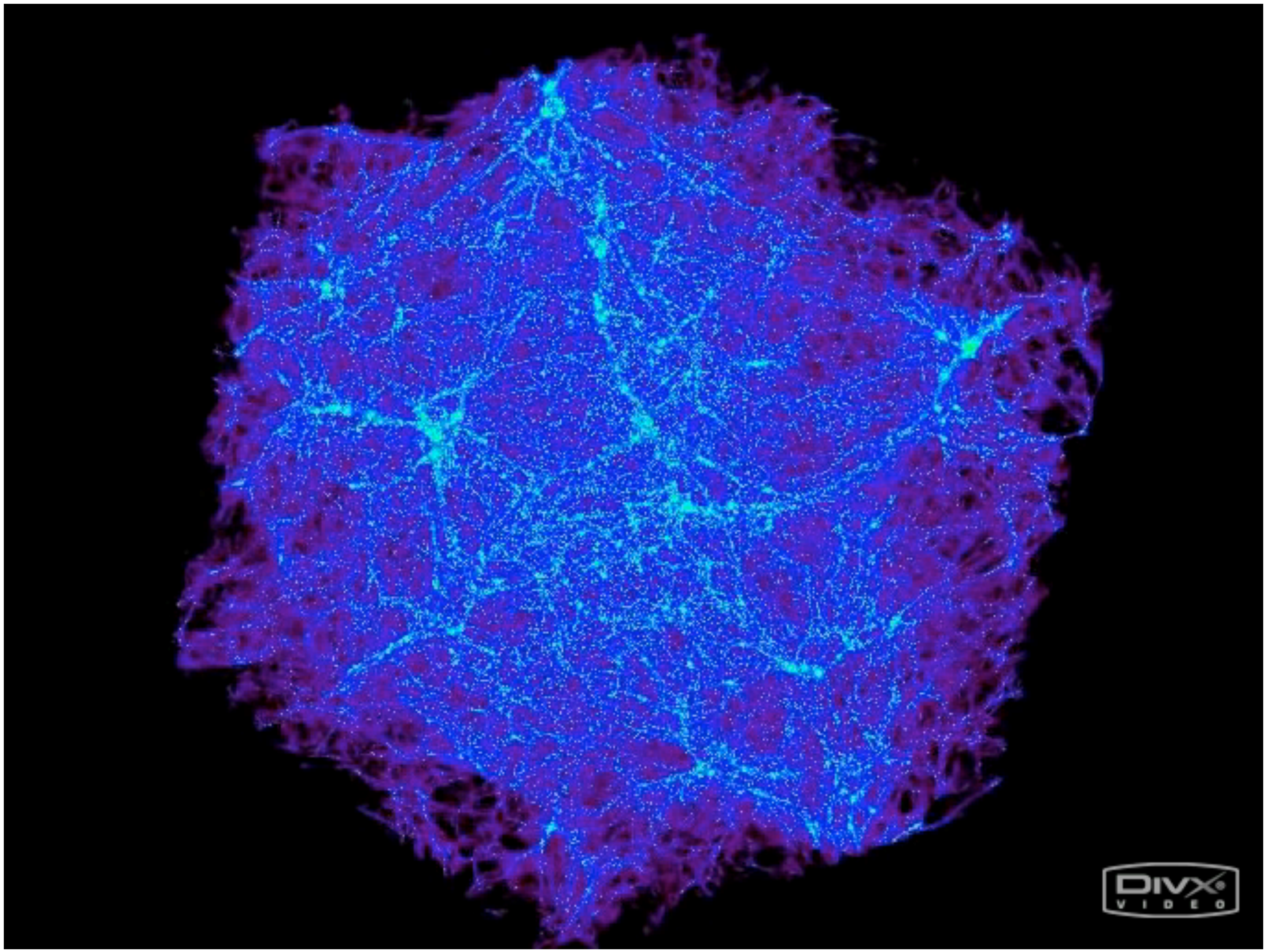


Among the largest calculations ever performed


Horizon 4pi :
4096³
6144 processors
2 Gpc/h
DM only

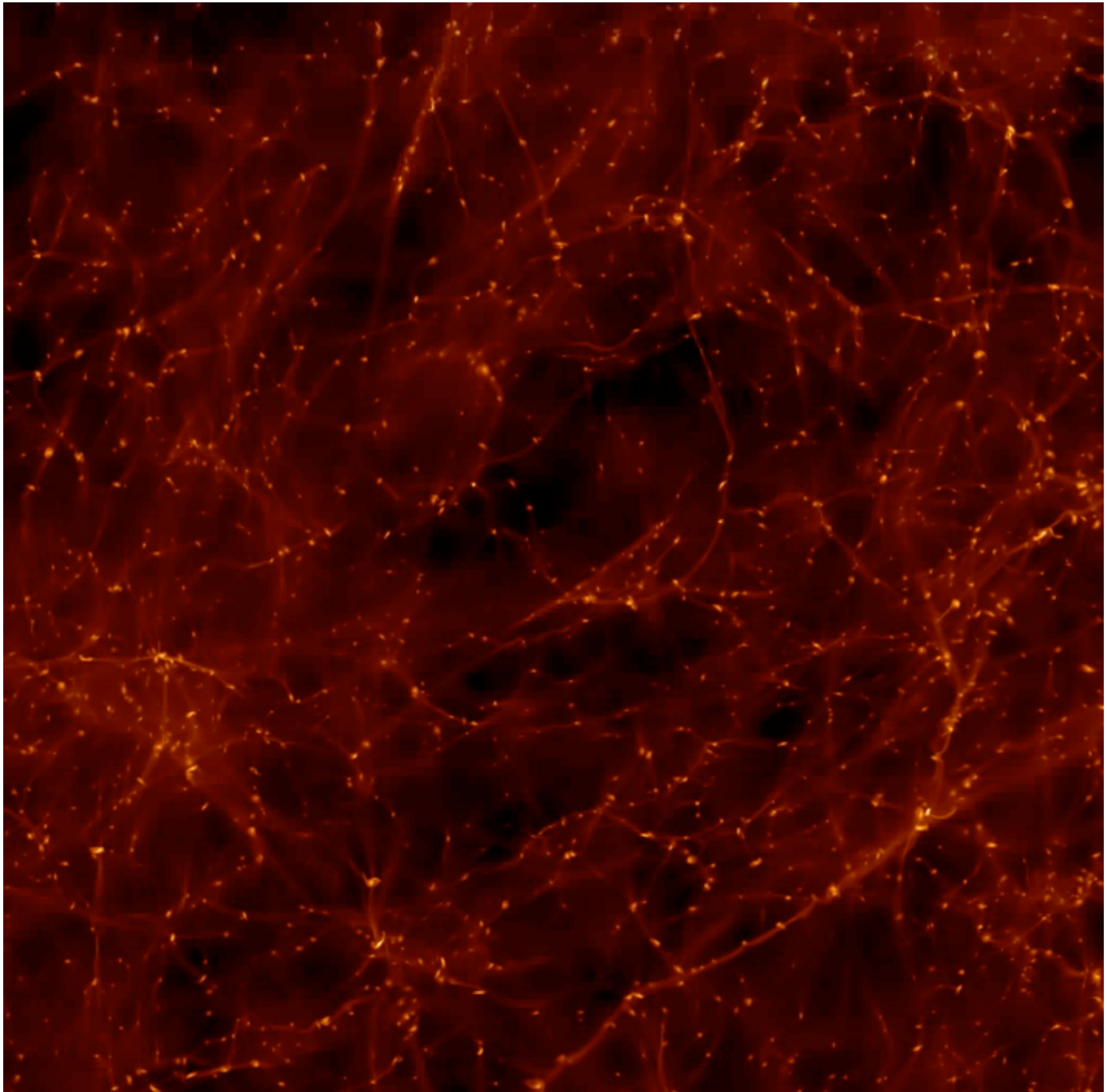

125 Mpc/h
Millenium
2160³
512 processors
500 Mpc/h
DM only

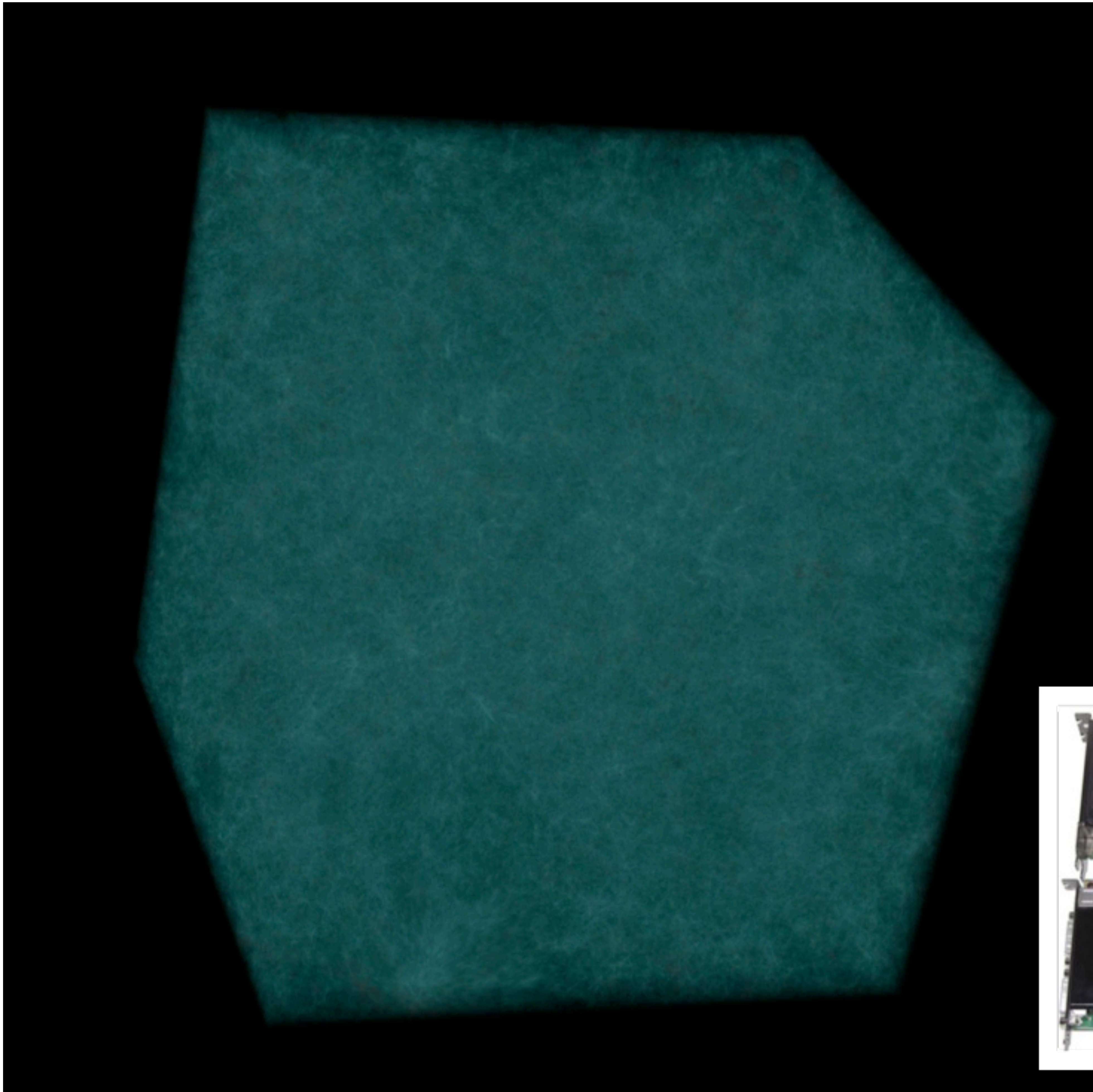
Mare Nostrum Simulation (Horizon Project)



1024^3
50 Mpc/h
2048 processors

Gravity
+
hydro
+
stars
+
SN
+
metals

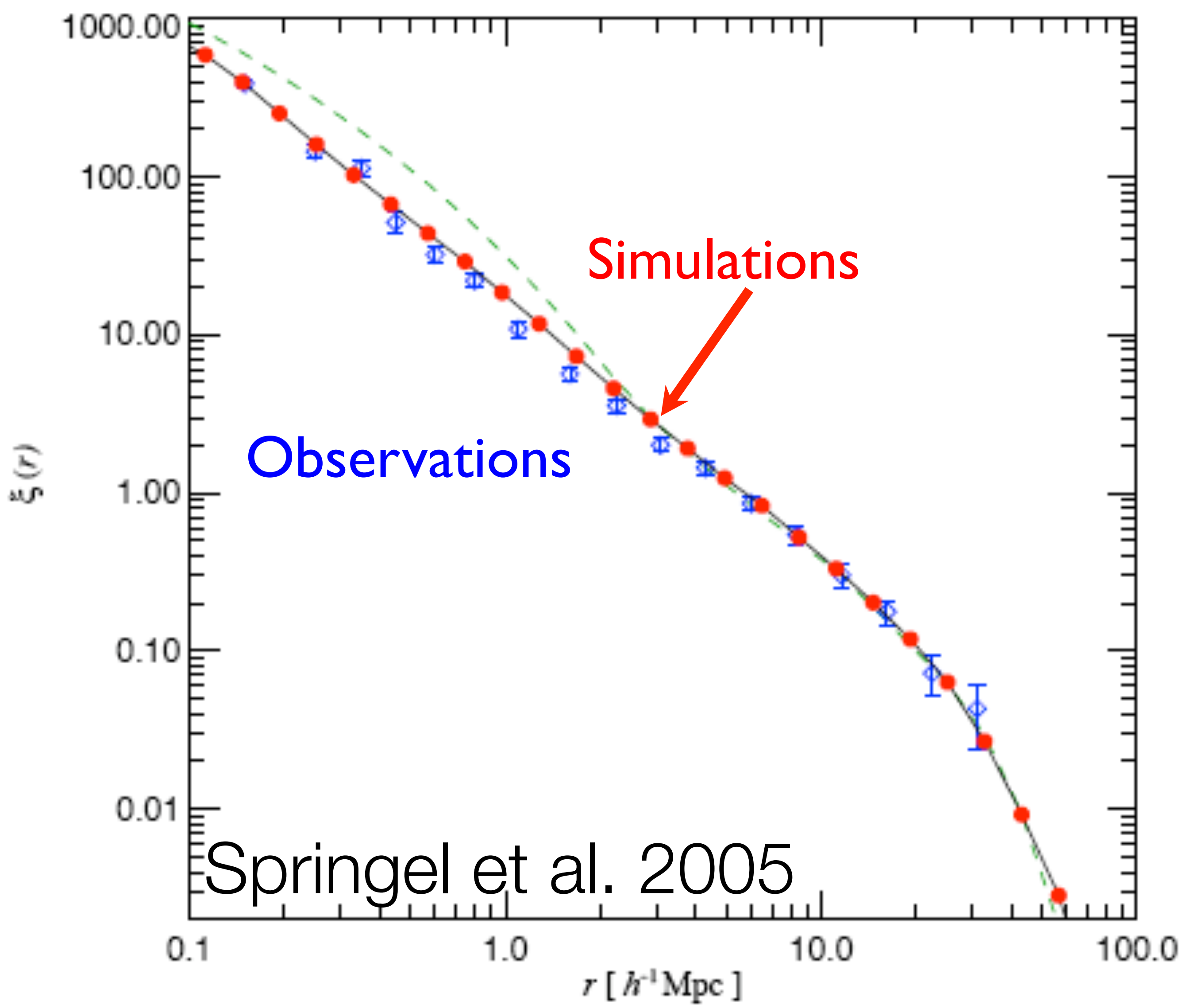




TRASH project

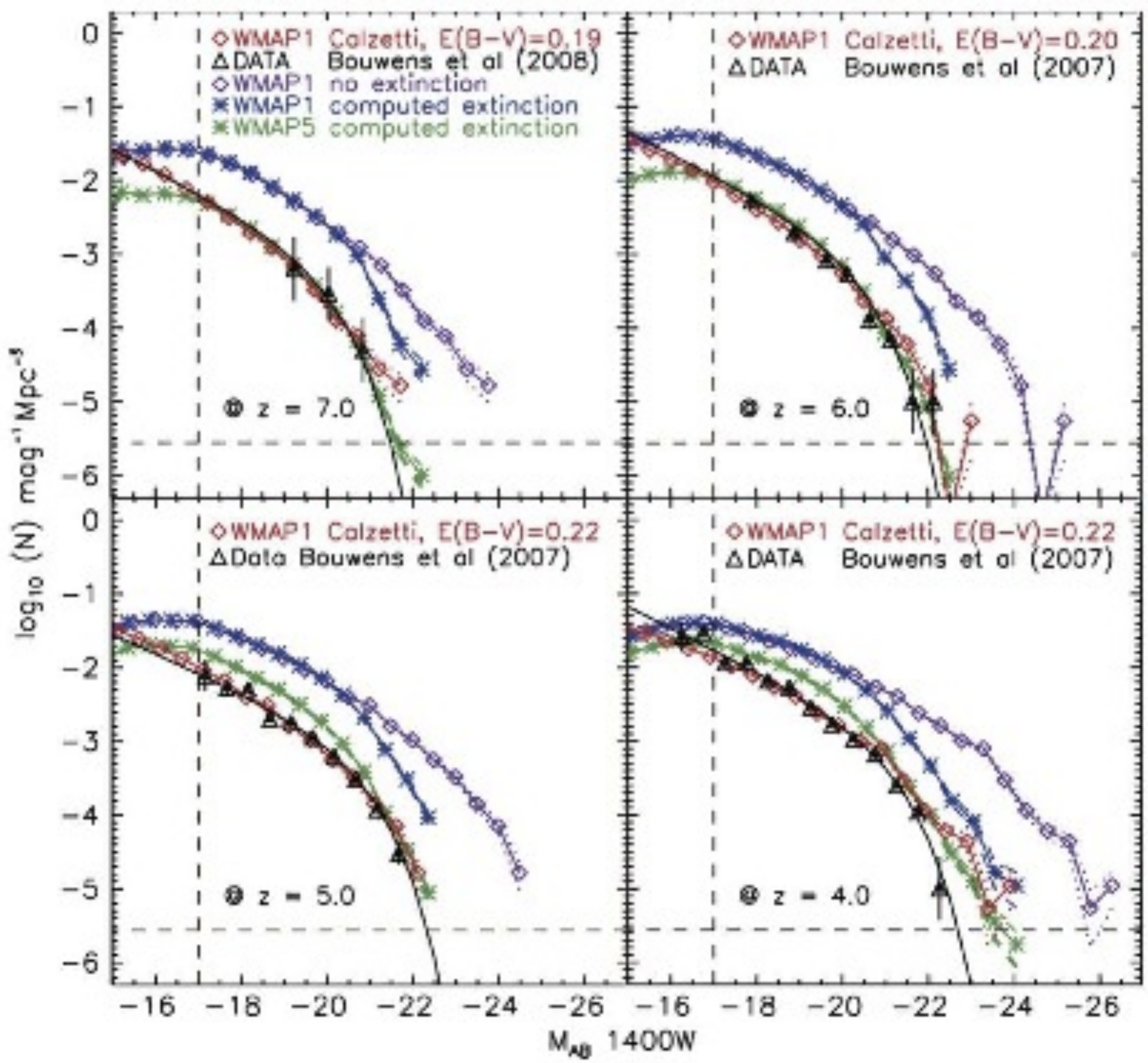
1024^3
128 GPUs
+
1024^3
CPUs

Large Scales success



Two - points correlation function

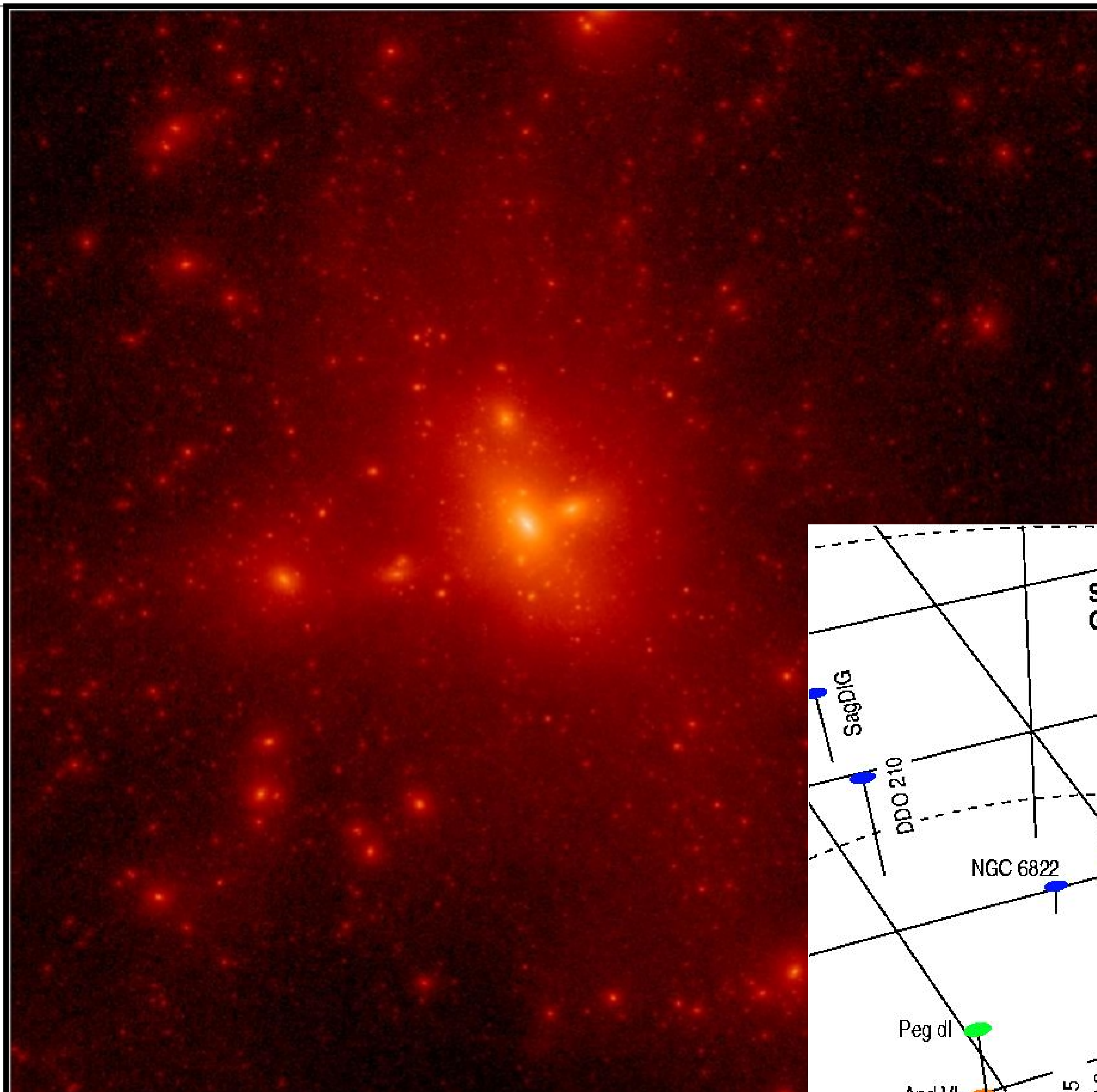
Large scales success



Devriendt et al. 2010

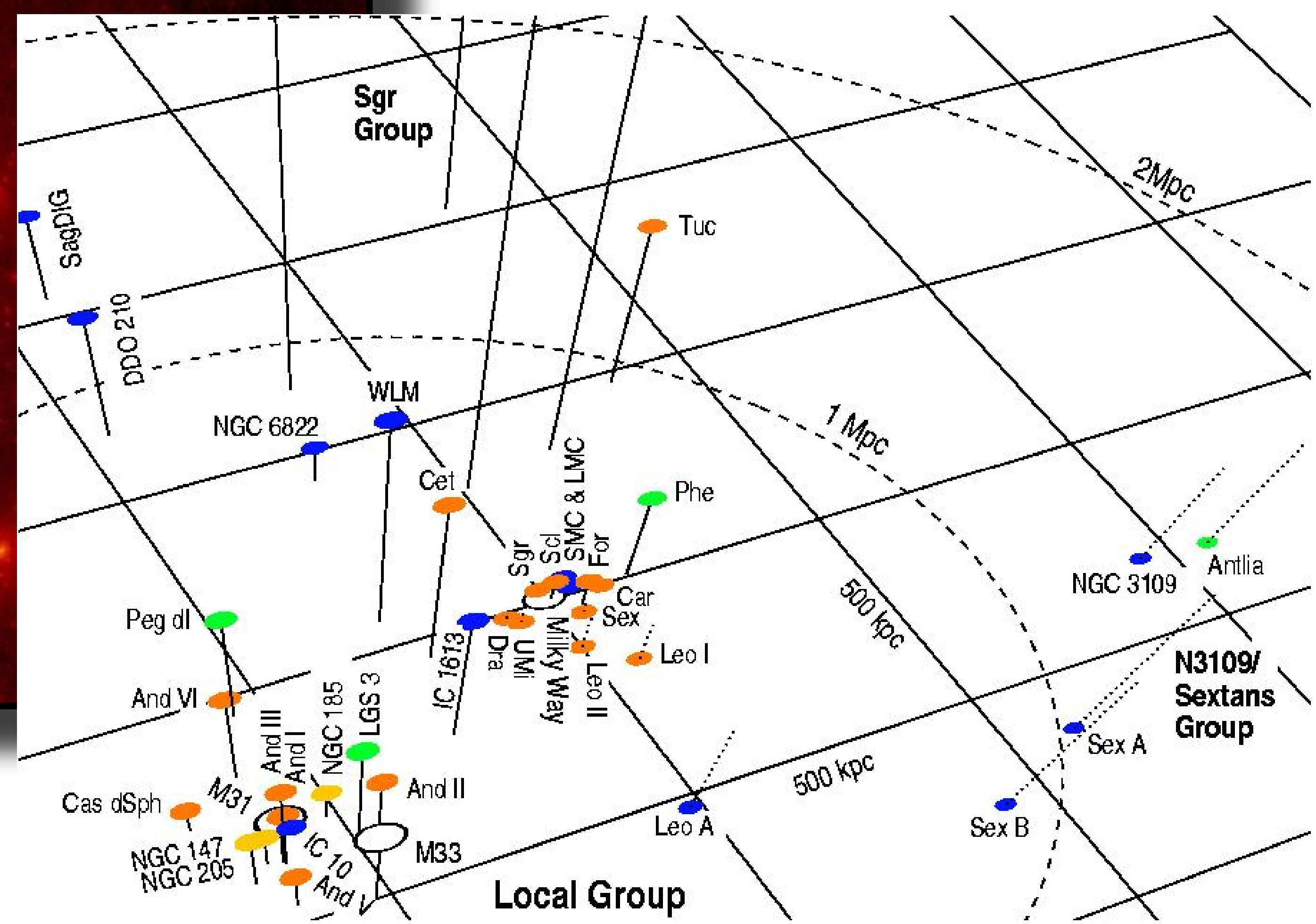
High Z
Luminosity
function

Small Scales Issues



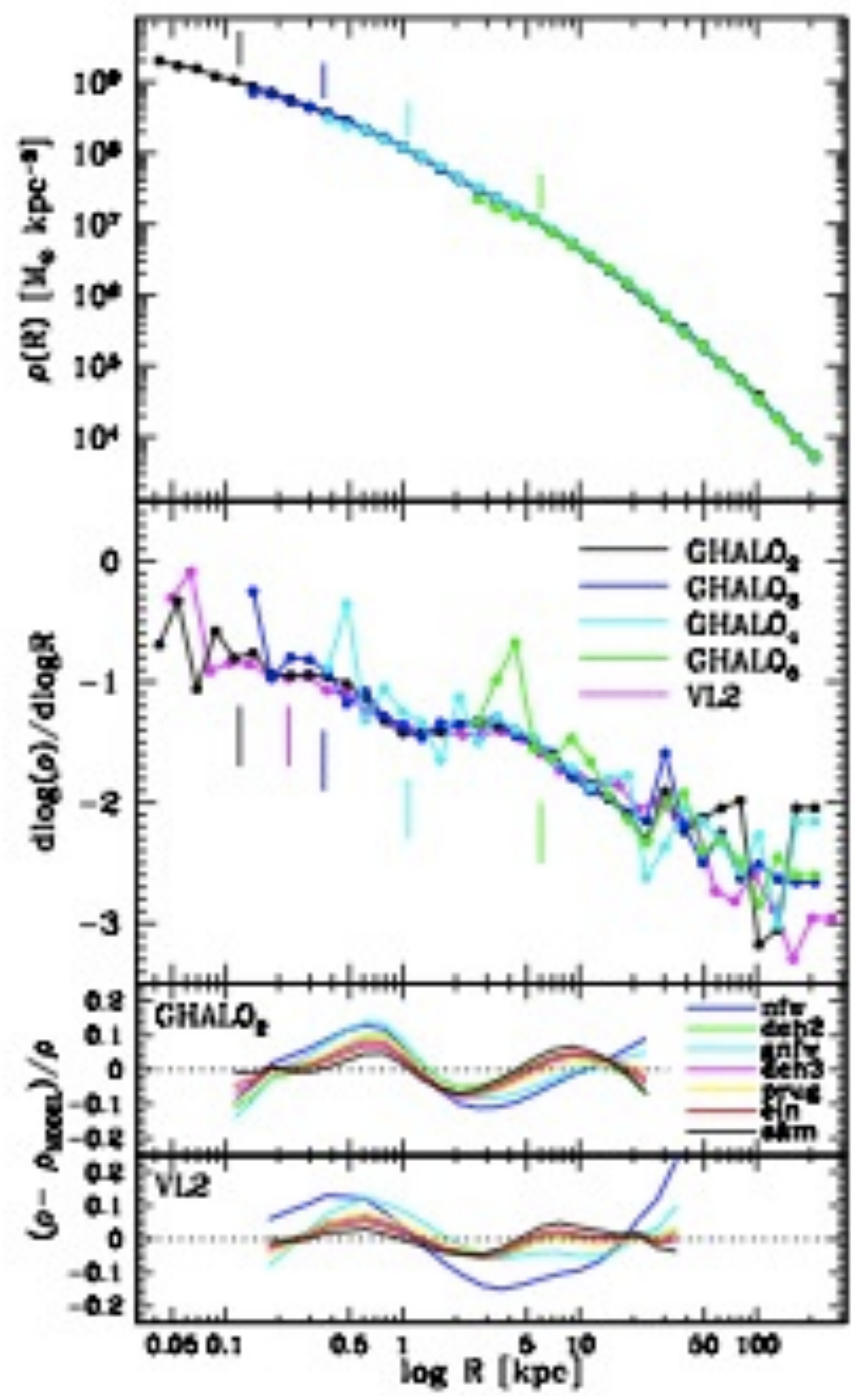
~10000s DM satellites expected
~20 observed

Reionisation may solve this



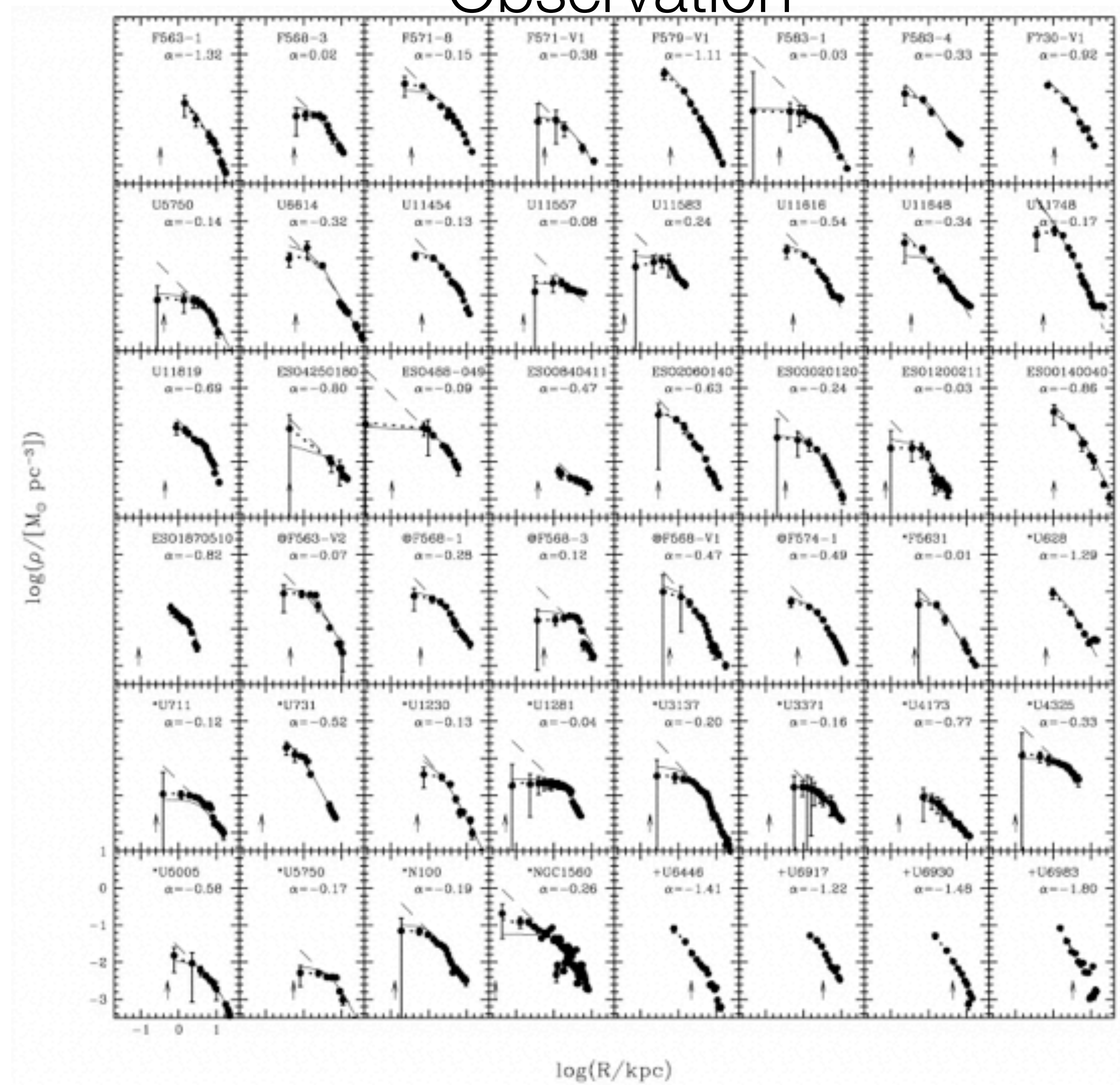
Small Scales Issues : Cusp-Core

Simulation



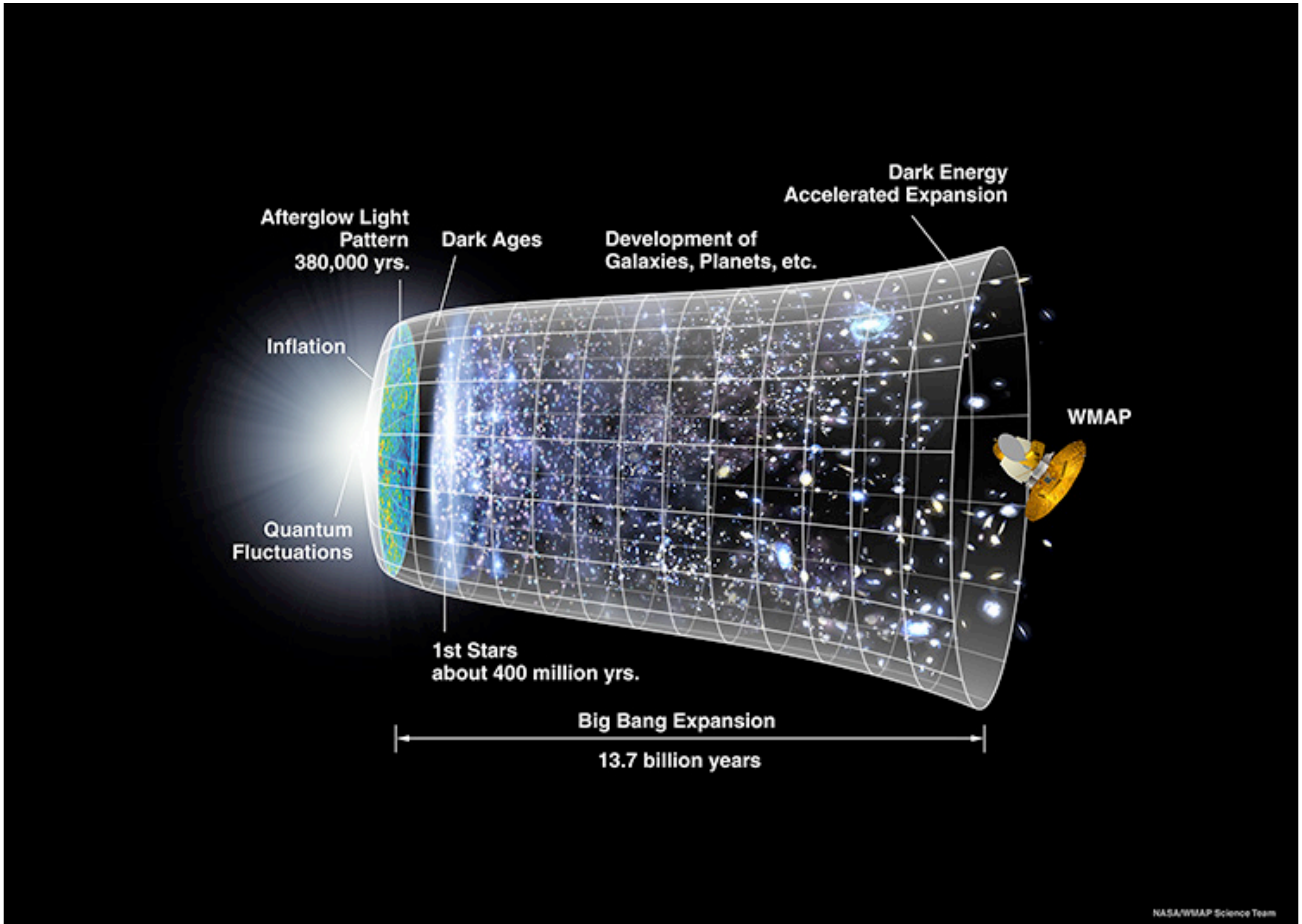
Stadel et al. 2008

Observation



De Blok et al. 2001

History of the Universe



Nasa /WMAP team