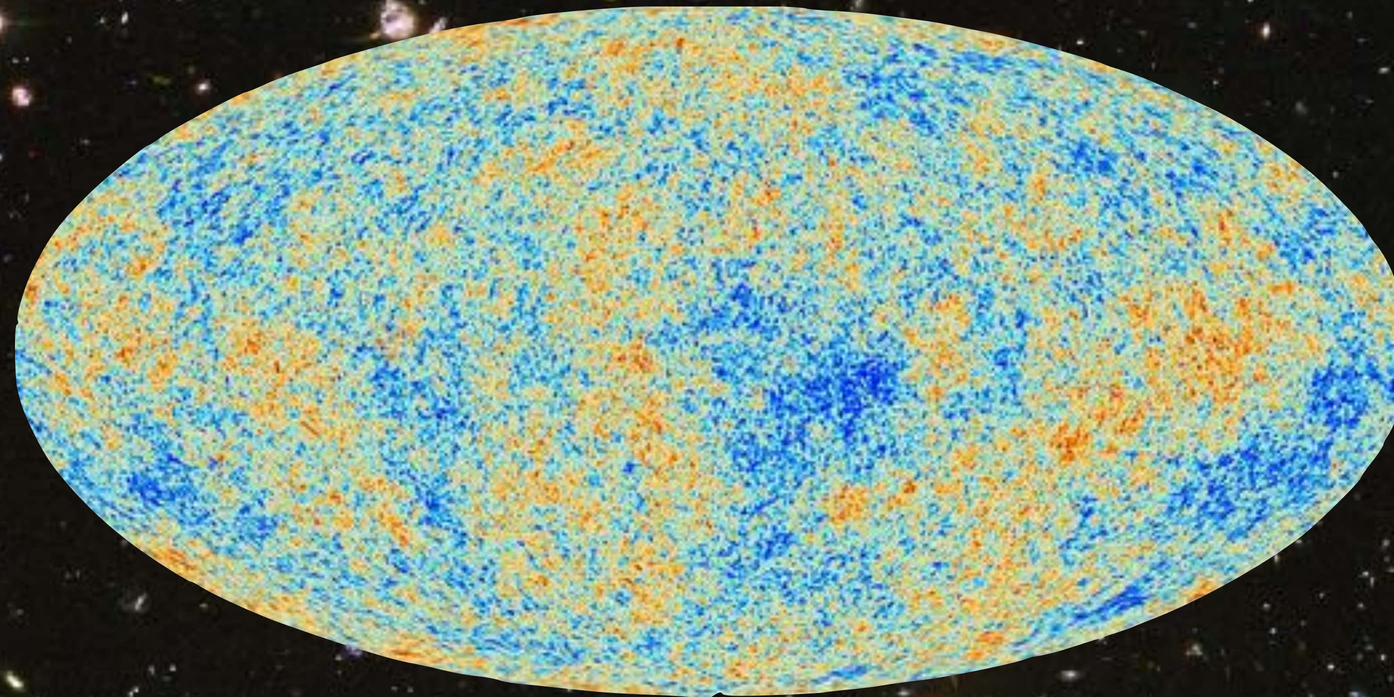
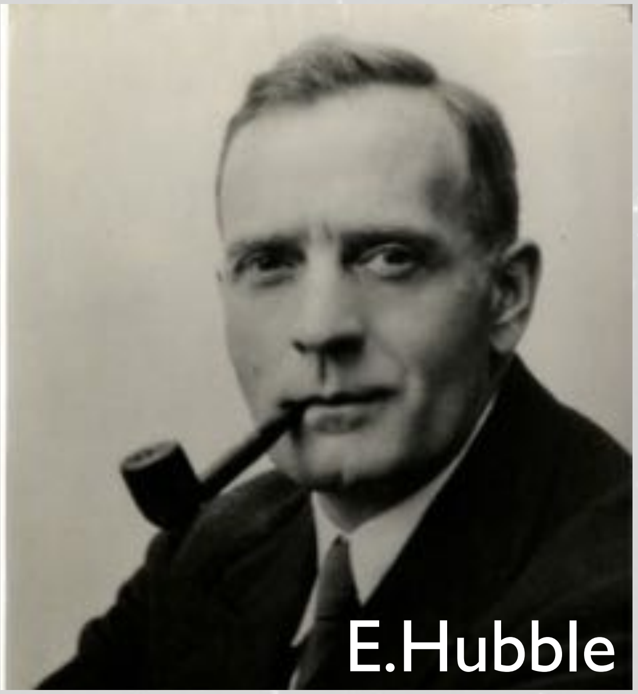


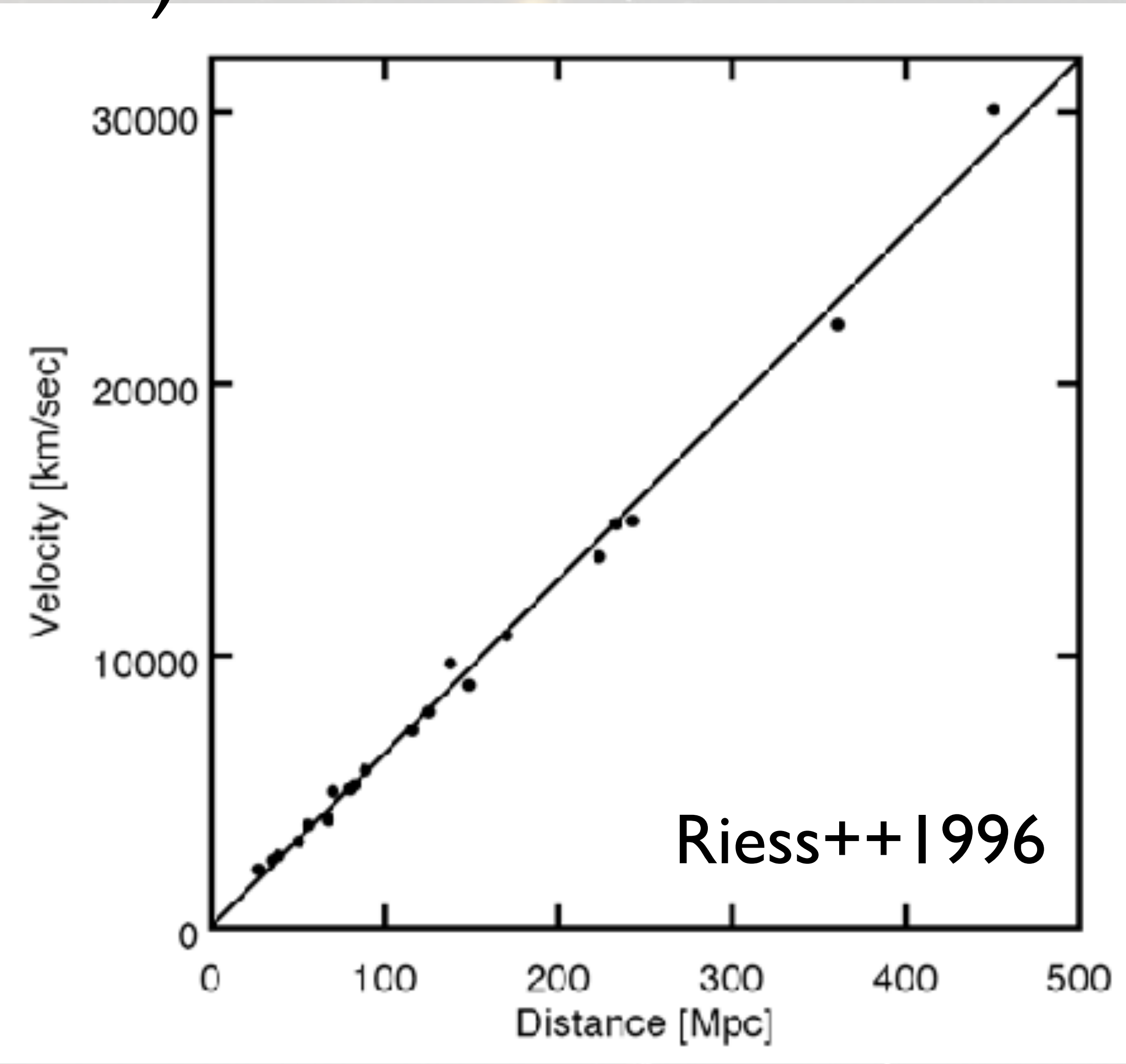
A Universe out of Nothing? Origin and Evolution of the Universe

Koen Kuijken
Sterrewacht Leiden, Universiteit Leiden

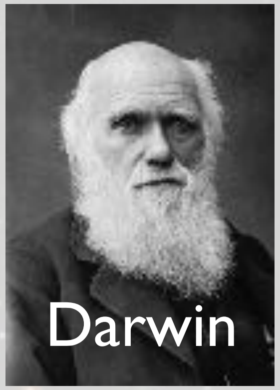
The expanding Universe

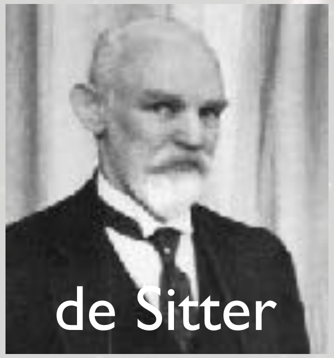


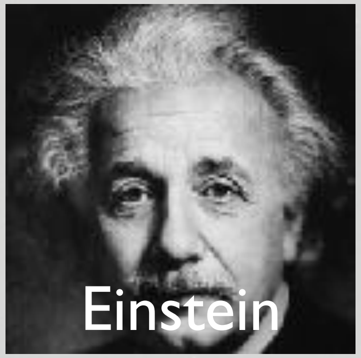
- **Evolution** of the Universe is a fundamental, inevitable consequence of Einstein Gravity (de Sitter, Lemaitre)



- Observed by Hubble, Slipher (1920's)
- The universe expands







The expanding Universe

- One millionth of one percent over human lifetime
- Consequences:
  - radiation gets stretched (redshift)
  - Universe cools (particle physics, phase changes)
  - gravitational attraction weakens

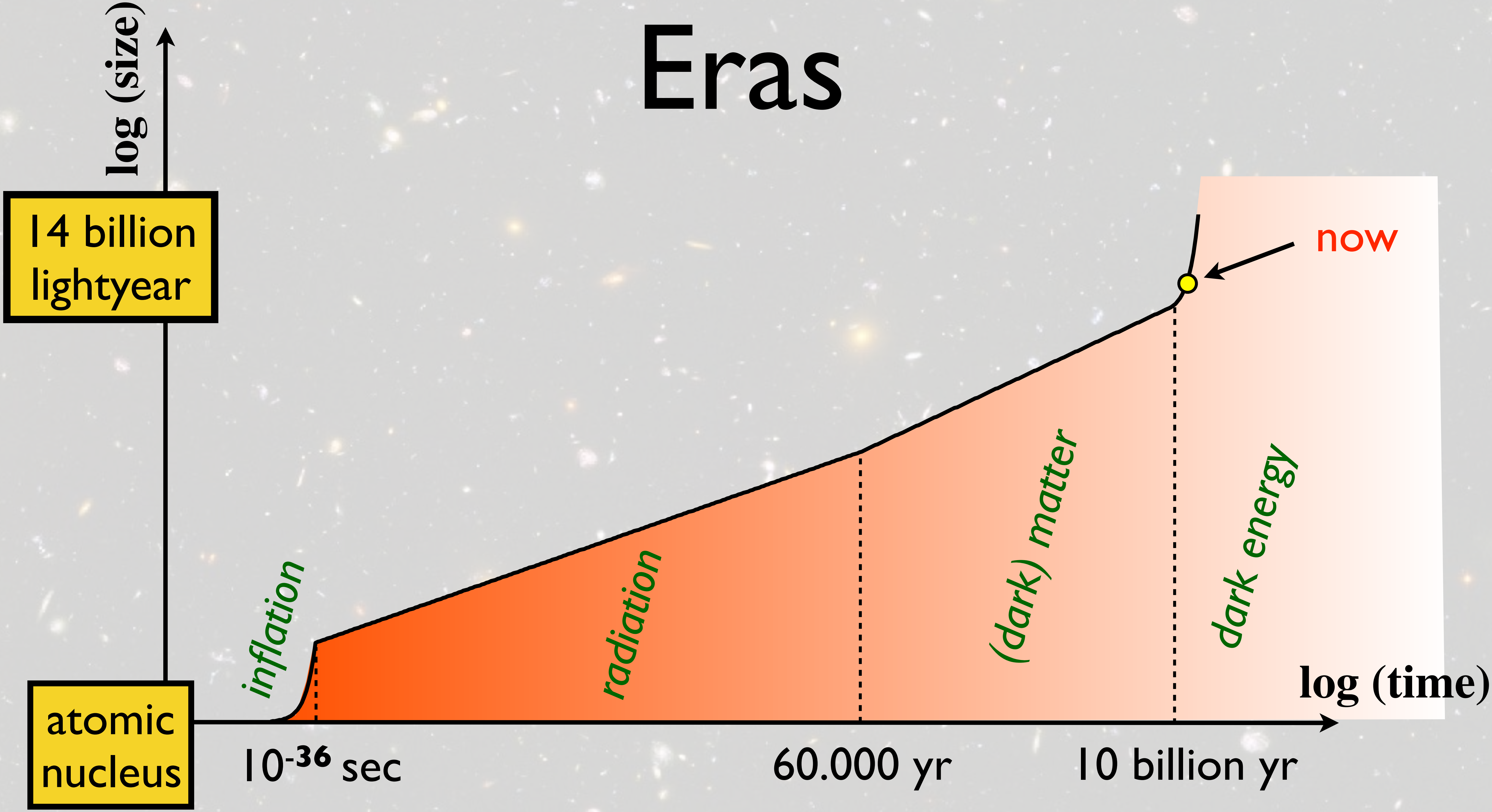
- This can all be observed!

Observations

- Hubble's law: distances, redshifts (cosmography)
- Cosmic background radiation (afterglow of hot beginnings)
- Nucleosynthesis of light elements (nuclear fusion)
- Large-scale matter distribution (clumping by gravity)
- Properties/evolution of galaxies (complex!)

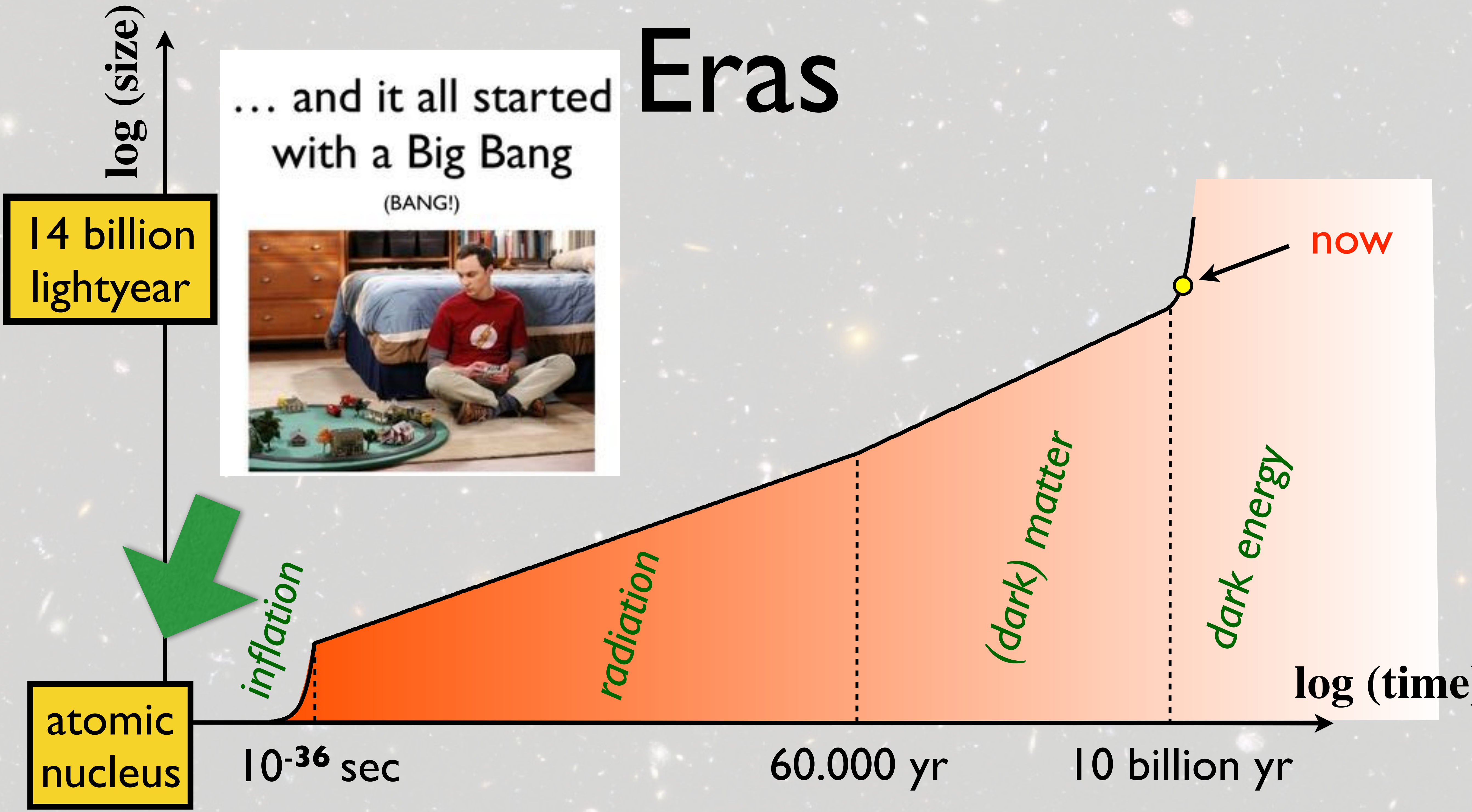
- Very strongly driven by technological advances in telescopes, detectors, computers

Eras



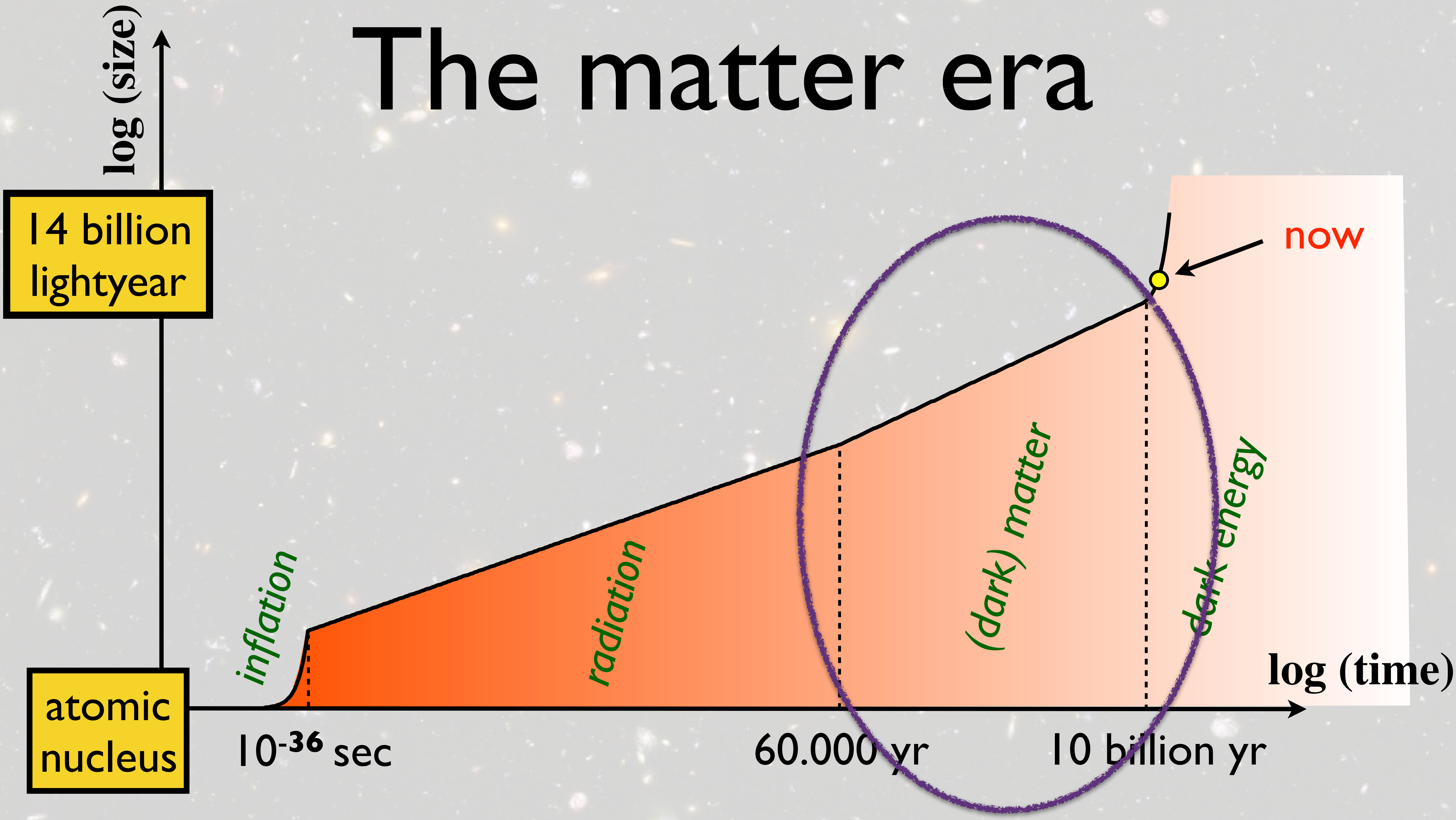
log (size)
14 billion lightyear
now
inflation
radiation
(dark) matter
dark energy
log (time)
atomic nucleus
10^-36 sec
60.000 yr
10 billion yr

Eras



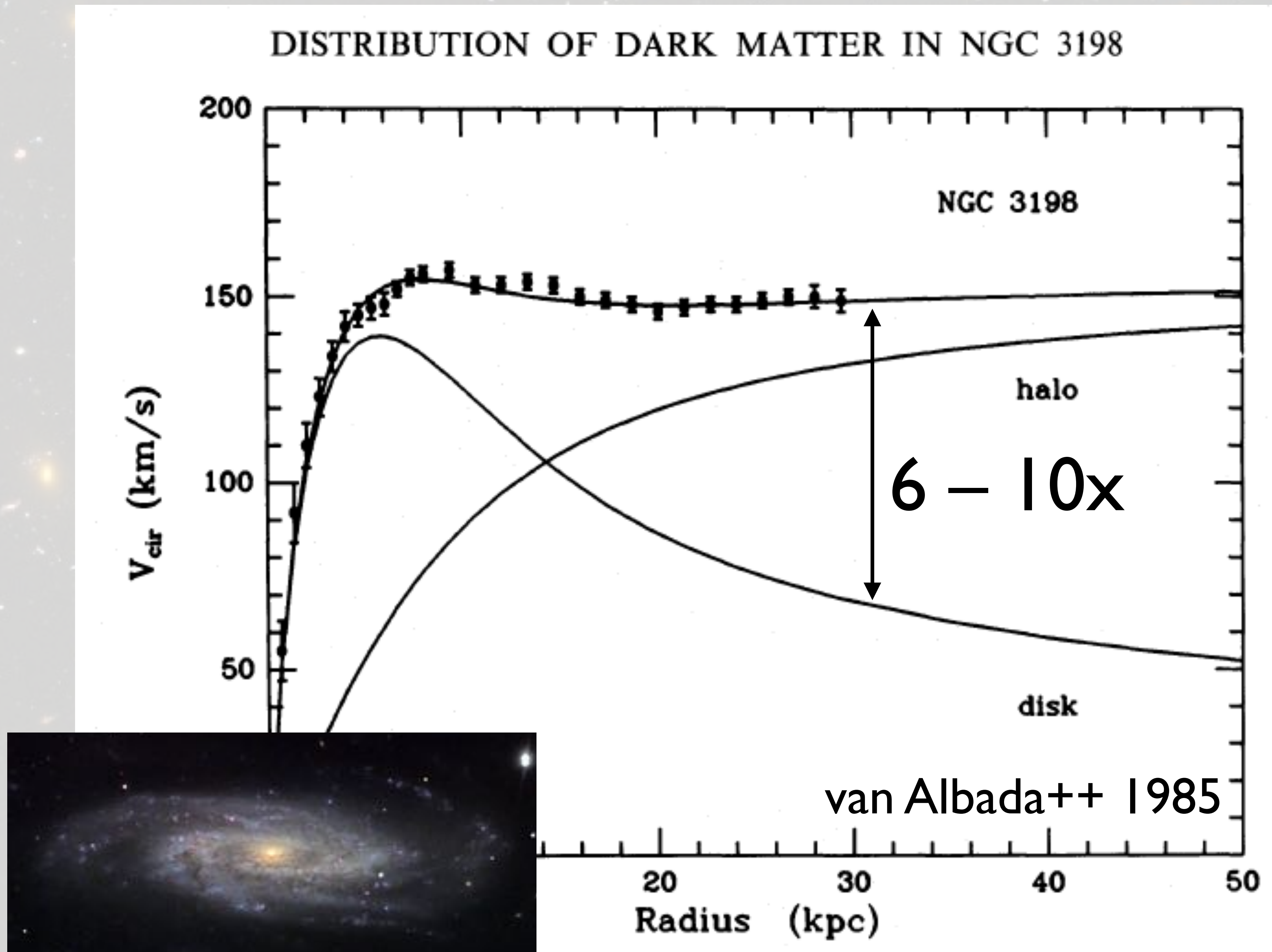
… and it all started with a Big Bang
(BANG!)
log (size)
14 billion lightyear
atomic nucleus
inflation
radiation
(dark) matter
dark energy
now
log (time)
10^{-36} sec
60.000 yr
10 billion yr

The matter era



Dark matter in galaxies

- Fast orbits in outskirts, so extra gravity

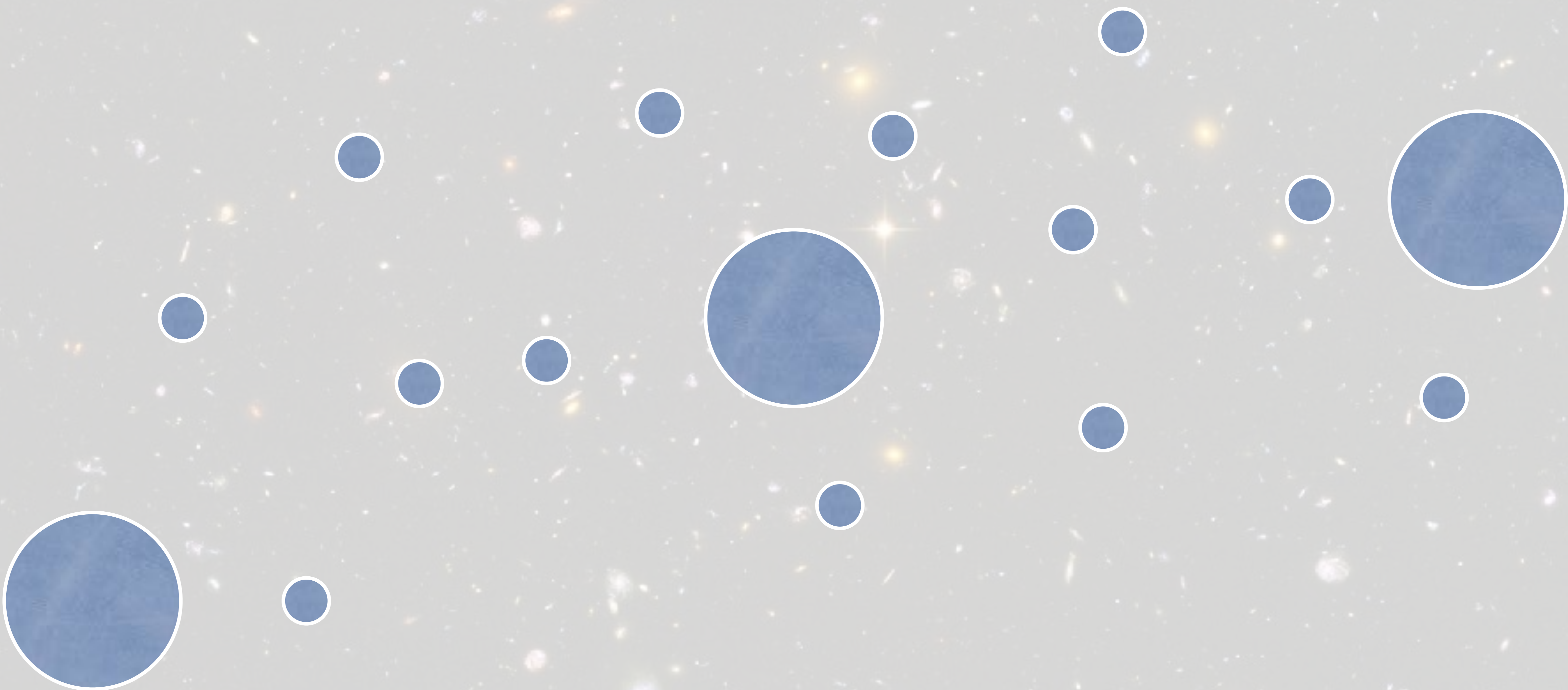


Dark matter and large scale structure

- Matter clumps together under gravity
- Initial conditions were very homogeneous
- The more mass, the more clumping

- Supercomputer simulations

Gravitational instability

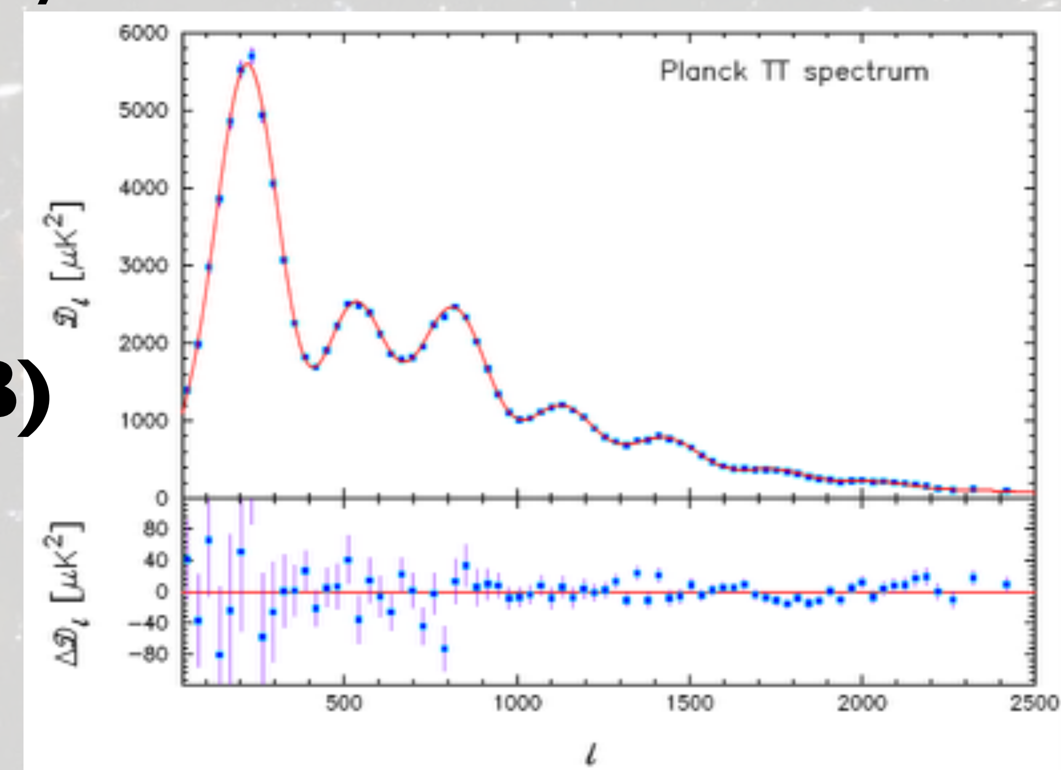


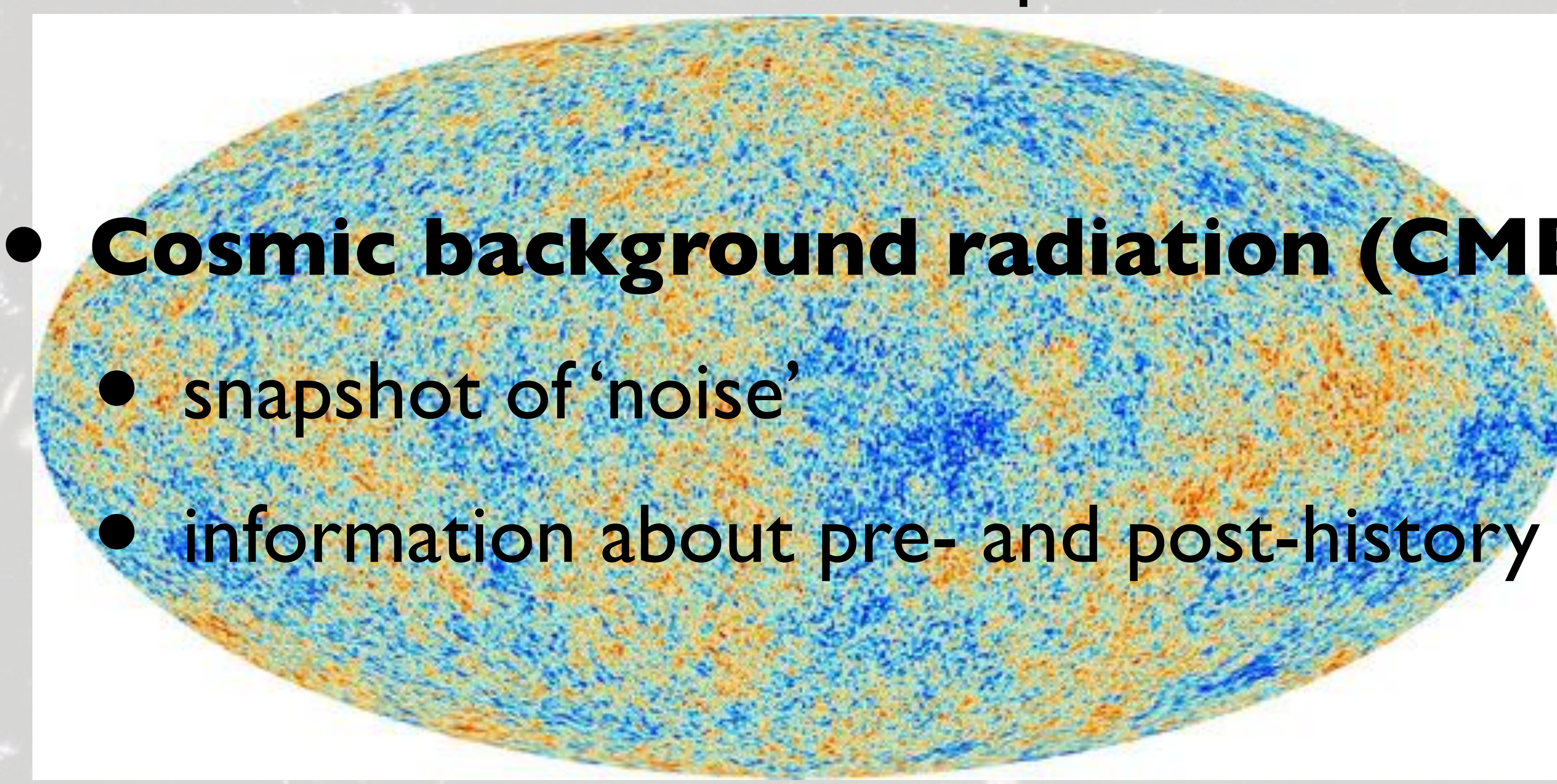
Gravitational instability

- "The rich get richer"

(Re)combination, Reionisation

- At temperature ~3000K (*380.000 yr*) hydrogen becomes neutral
  - Universe becomes transparant. Astronomy!
  - Matter can start to clump

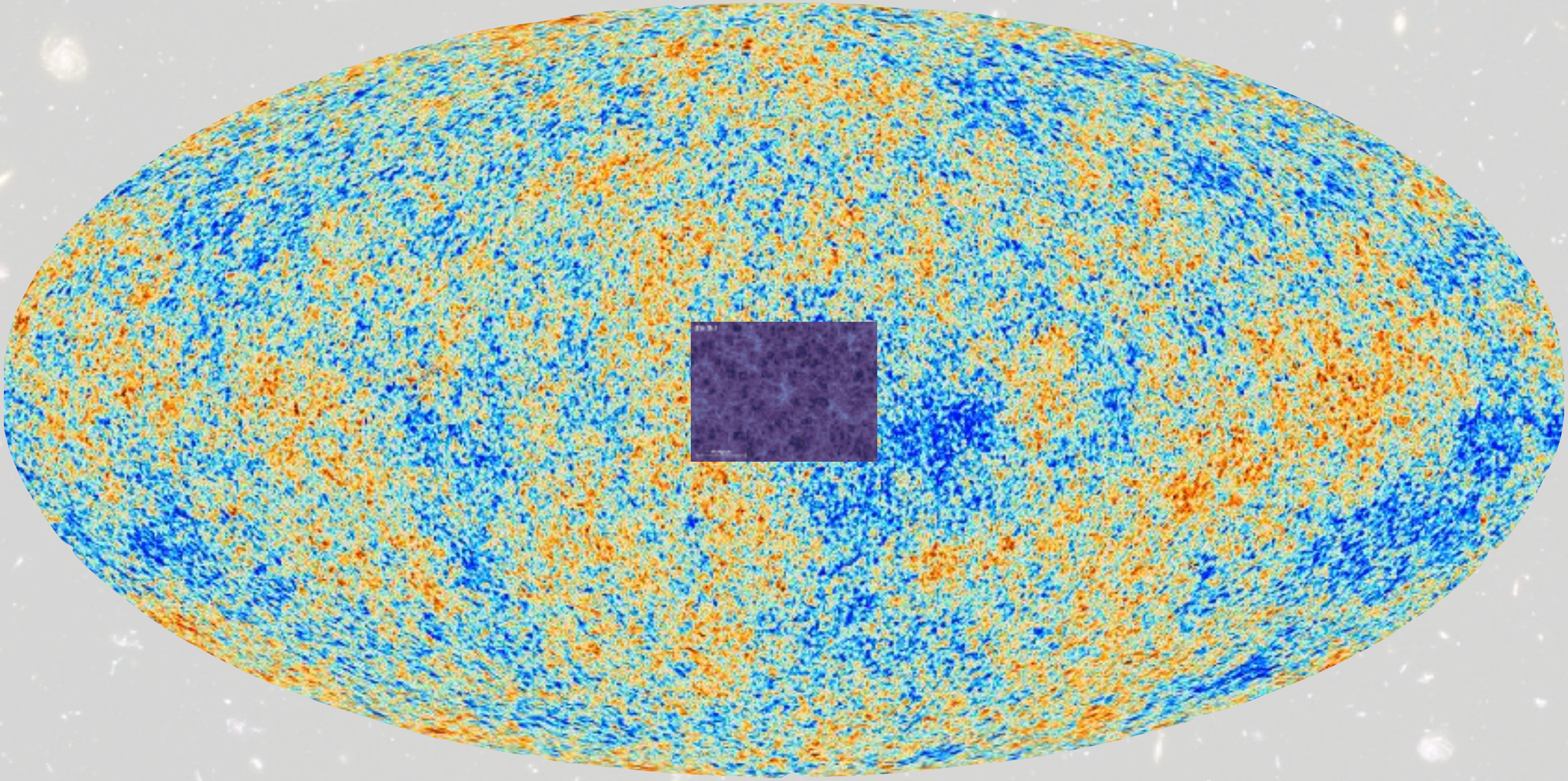


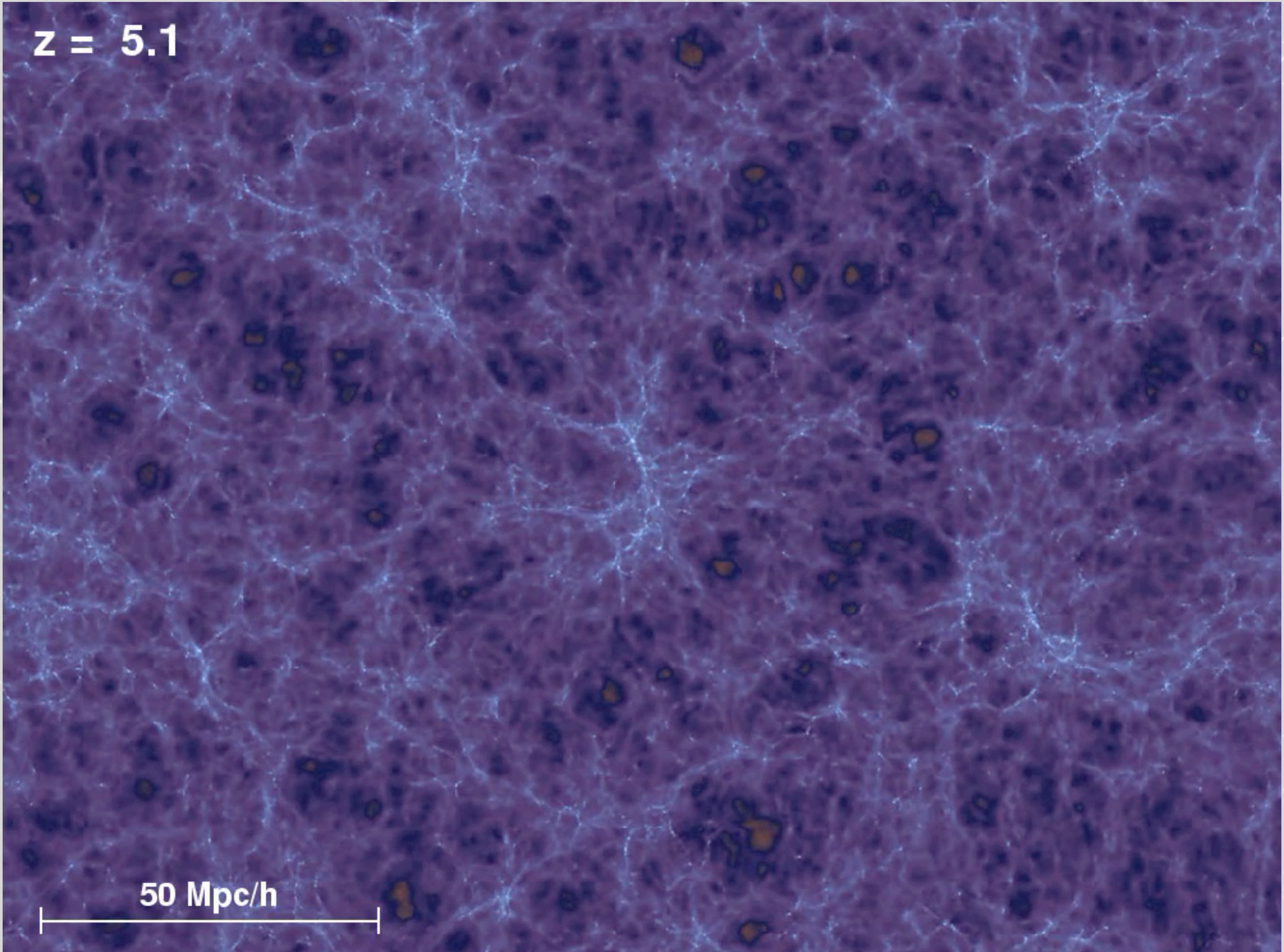


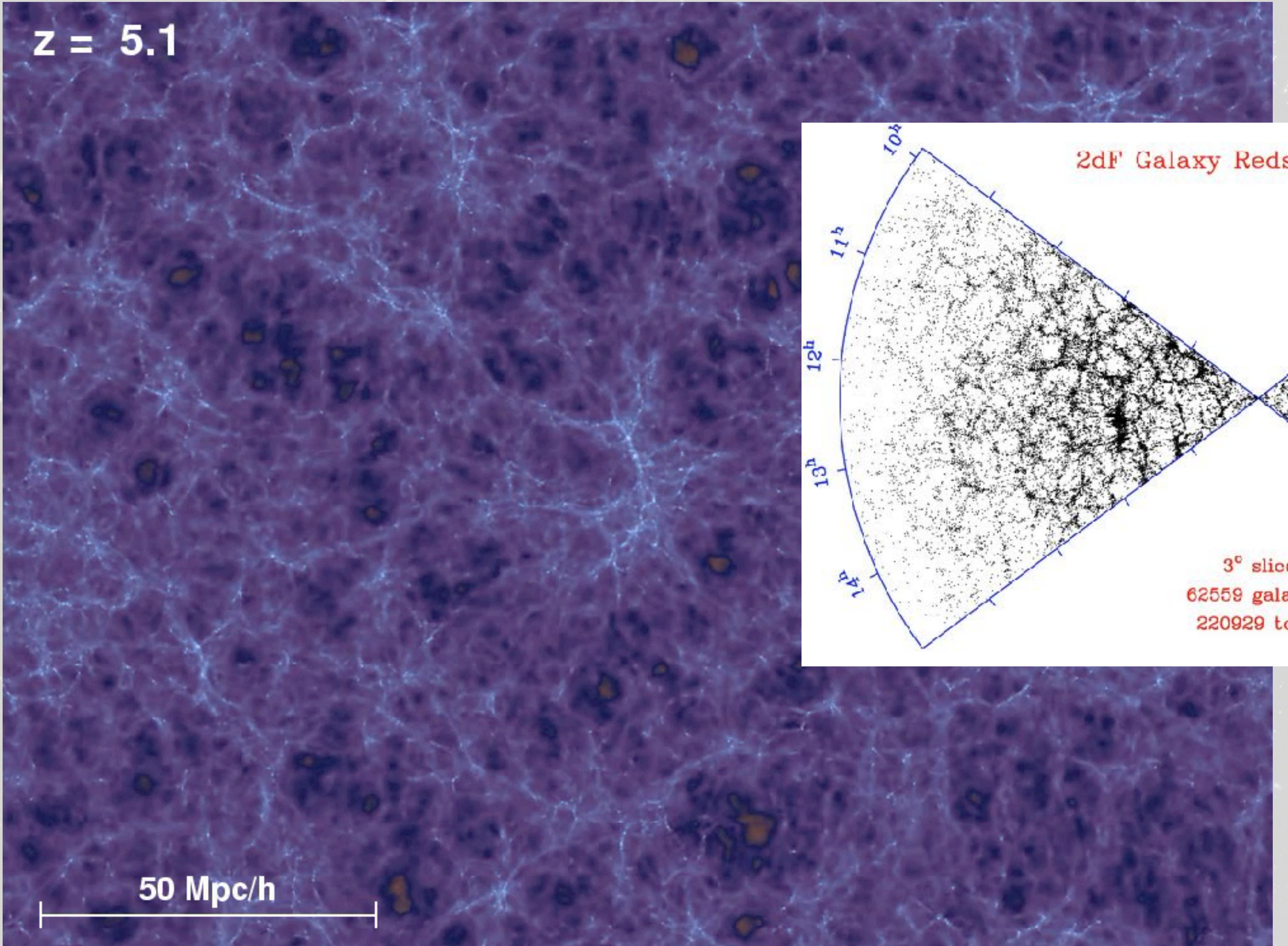
- **Cosmic background radiation (CMB)**
  - snapshot of 'noise'
  - information about pre- and post-history

- Around *1 billion yr:* UV radiation from first stars, quasars etc: **reionisation**

Calculating forward




z = 5.1
50 Mpc/h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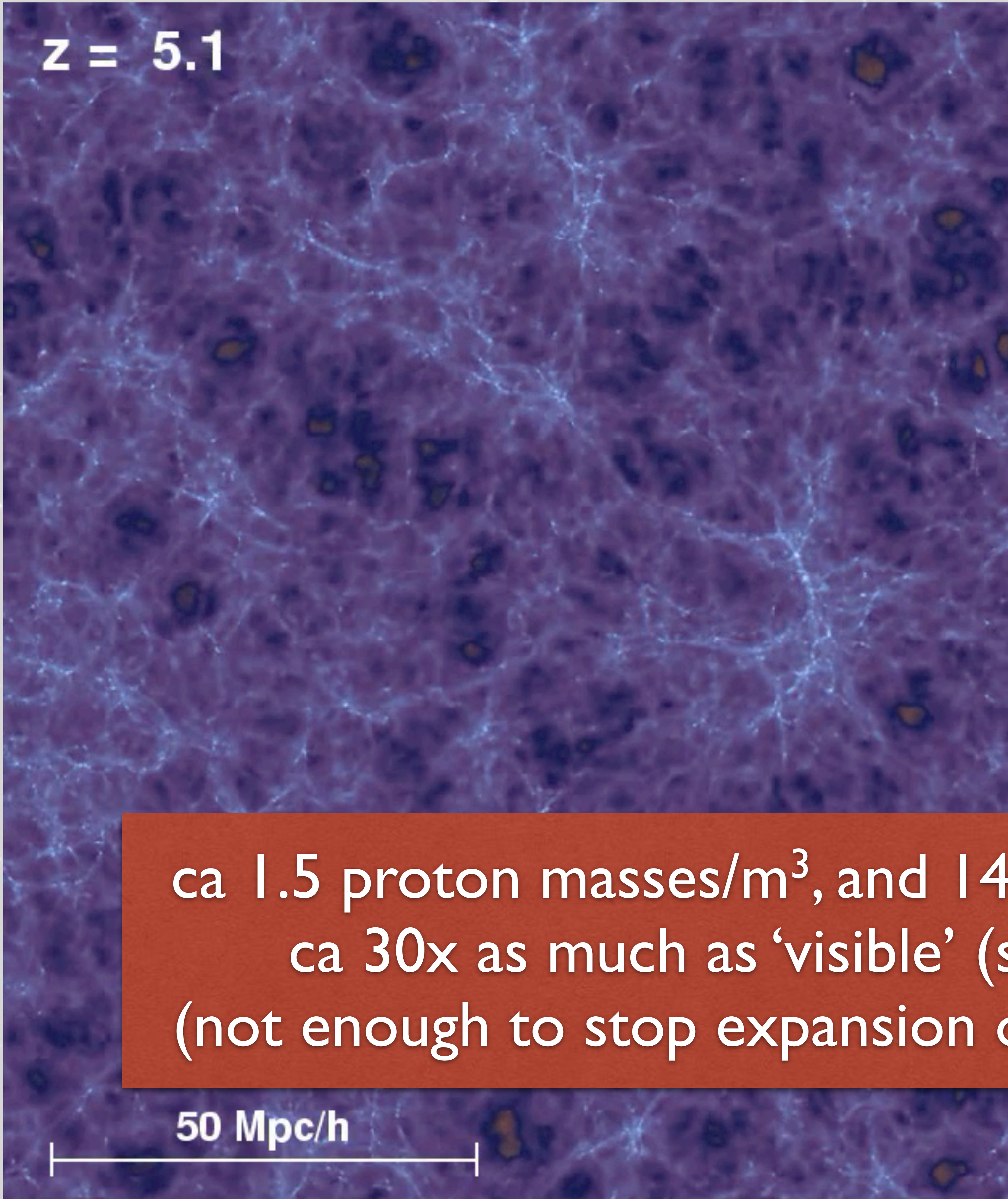
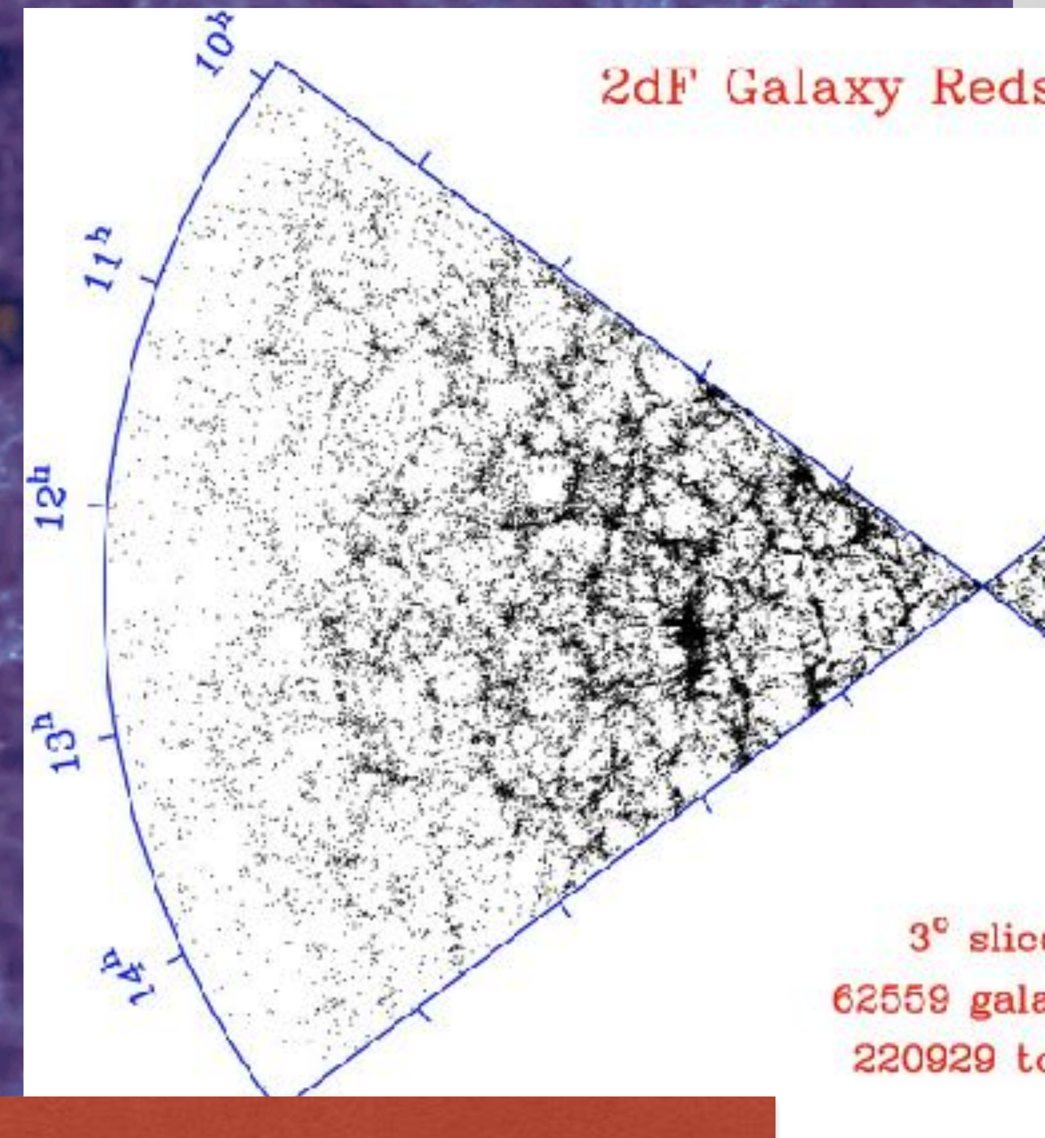
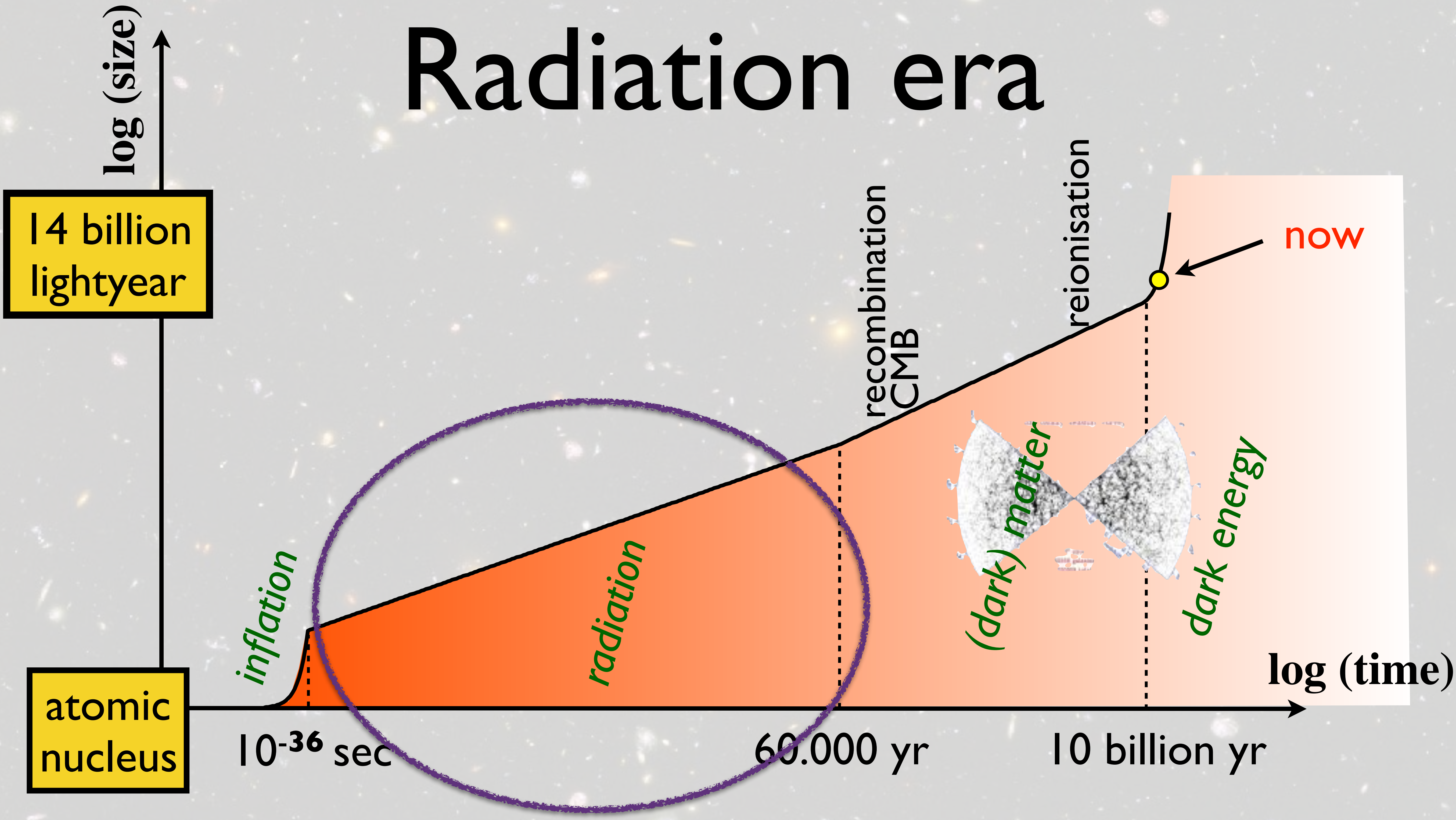
2dF Galaxy Reds
10h
11h
12h
13h
14h
3° slic
62559 gala
220929 to





ca 1.5 proton masses/m^3, and 14 bln yrs, needed
ca 30x as much as 'visible' (stars and gas)
(not enough to stop expansion of the Universe)

Radiation era



Radiation era

- Until *60.000 yr* after Big Bang most of the energy was in radiation
  - Radiation loses energy through redshift
  - Eventually, matter dominates
  - Still millions of photons per atom today!

Nucleosynthesis

- Between *10s* en *3min* first atomic nuclei are formed; then this fusion reactor freezes
- Reaction rate depends on density
- Abundances fit for density of ~ 0.3/m³

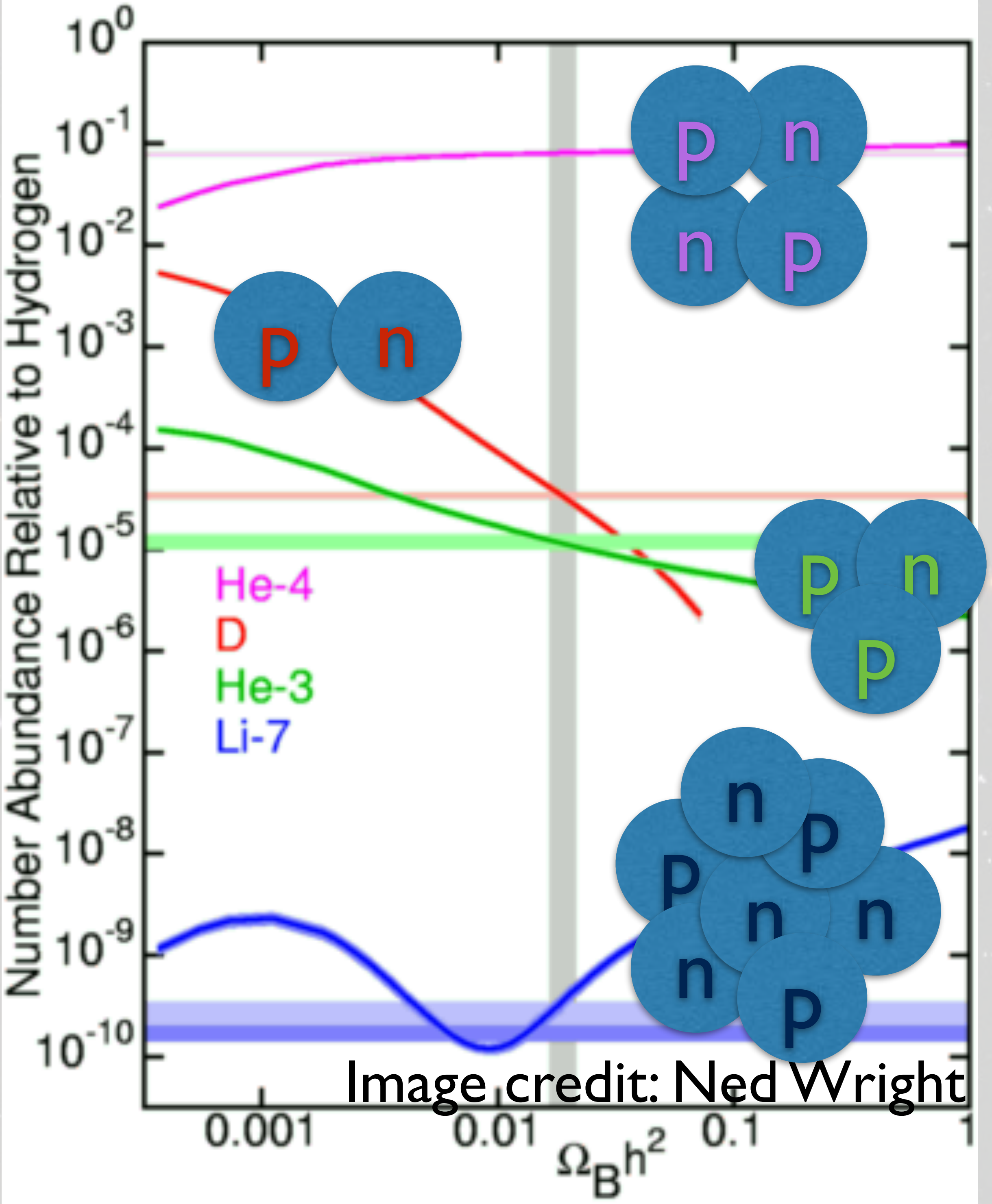


Image credit: Ned Wright

Neutrino's

- Form of 'radiation'
  - Free-stream through Universe after ~ *0.1 sec*
  - Cosmology measures number of neutrino families: 3
  - Neutrino mass influences large-scale structure (mass<0.25meV, cosmology beats experiments!)

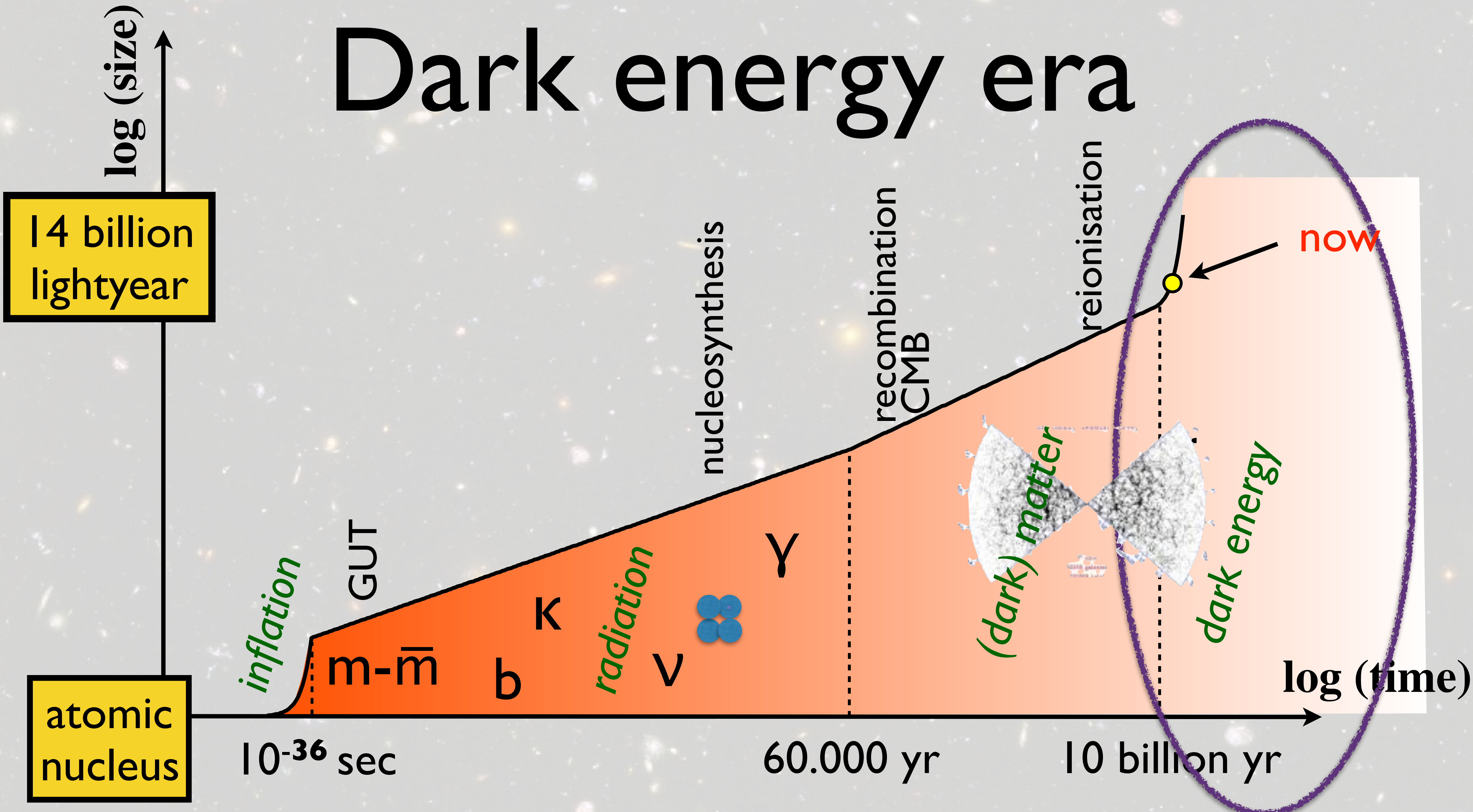
High-energy physics lab

- During radiation era Universe cools tremendously: from 10^{28}K to 10^{4}K. (10^{12}TeV to 1eV).

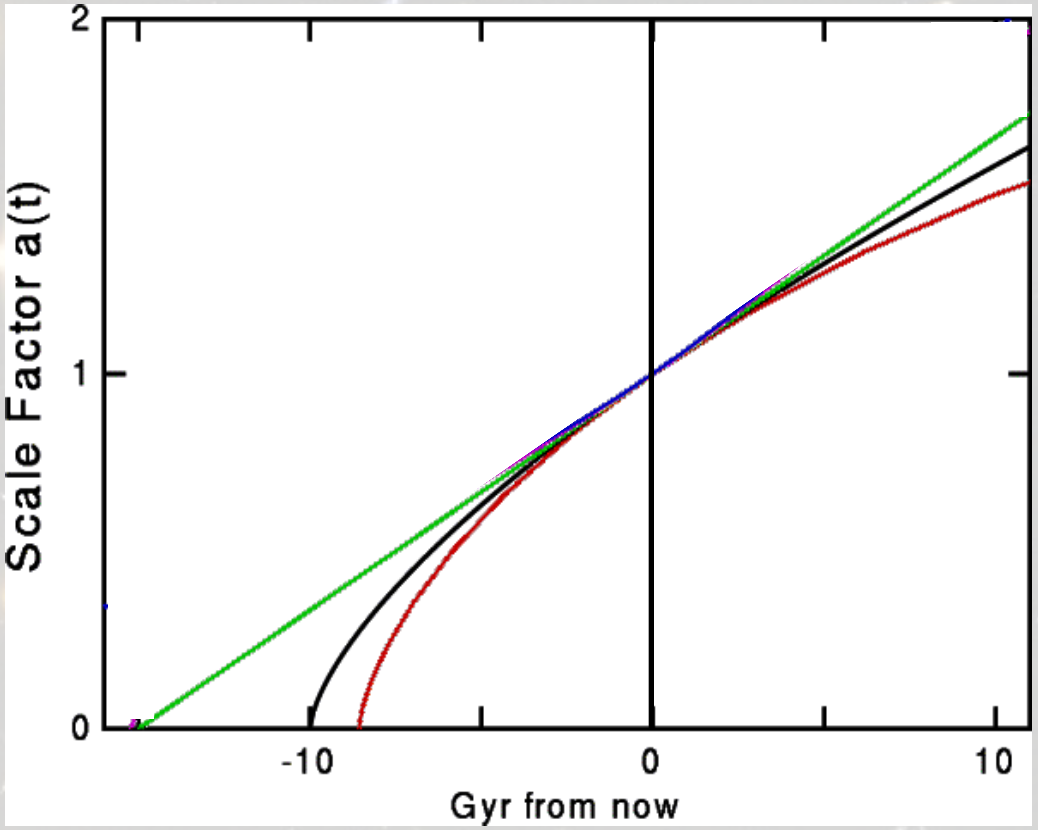
- Couldron of elementary particles! *'Greek alphabet soup'*.

- Origin of matter/antimatter asymmetry?

Dark energy era

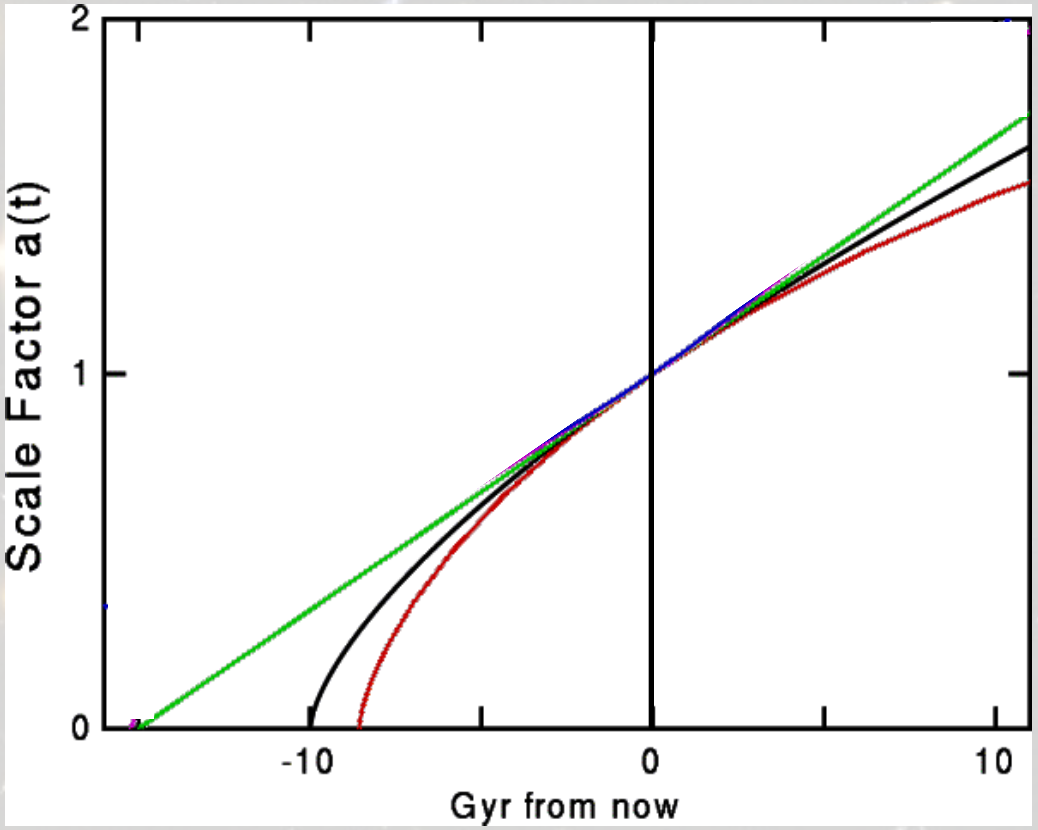


Dark energy



Dark energy

- The expansion of the Universe is slowed down by gravity
- Measure deceleration = measure matter density
- Surprise: Expansion *accelerates!!*



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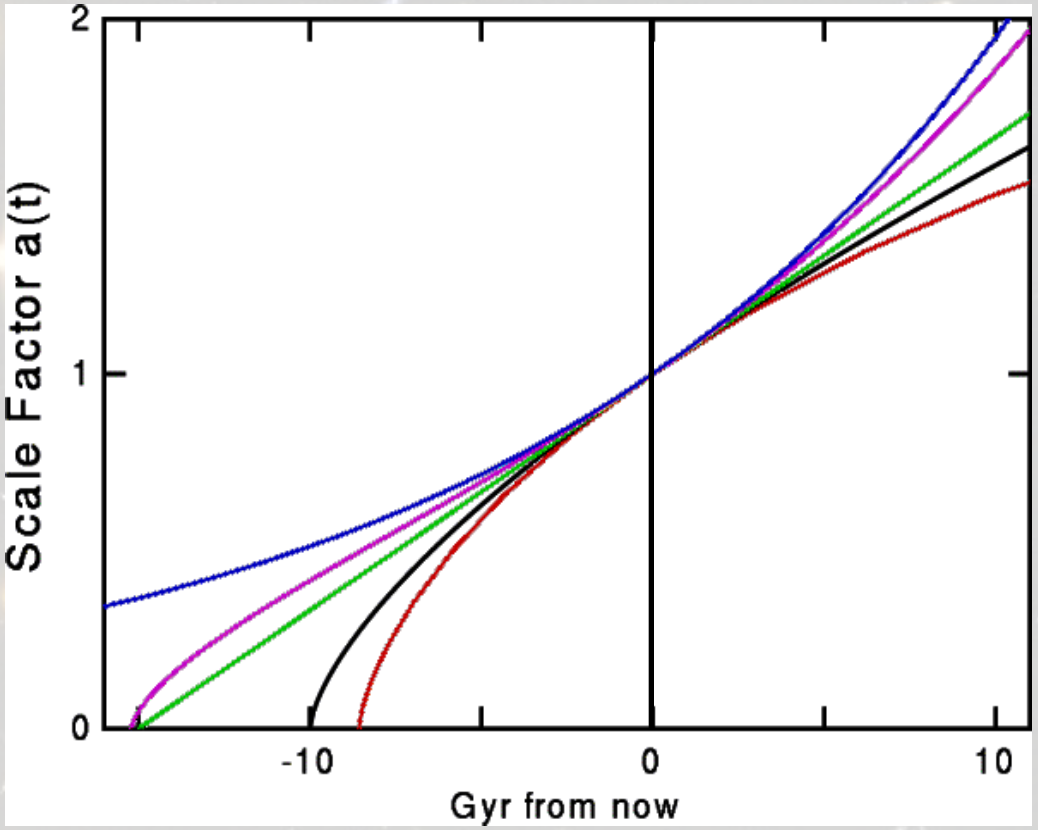
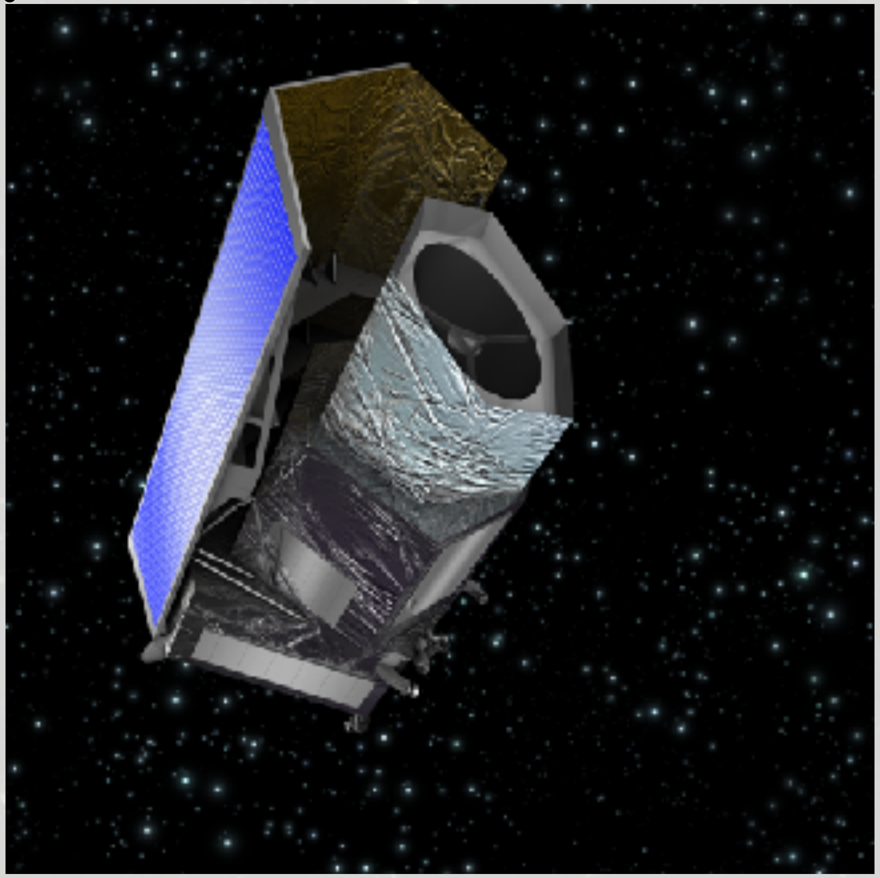


Dark energy??

- Clearly required by the data (also CMB)

- Cosmological constant in Einstein theory?
- Dynamic ingredient of the Universe?
  - Same amount everywhere?
  - Same amount at all times?

- ESA Euclid mission (2020+)



Standard model of cosmology

- **6 parameters** determine the ‘global’ properties of the Universe

density of atoms
density of dark matter
density of dark energy
amplitude of fluctuations
spectrum of fluctuations
scatter due to reionisation

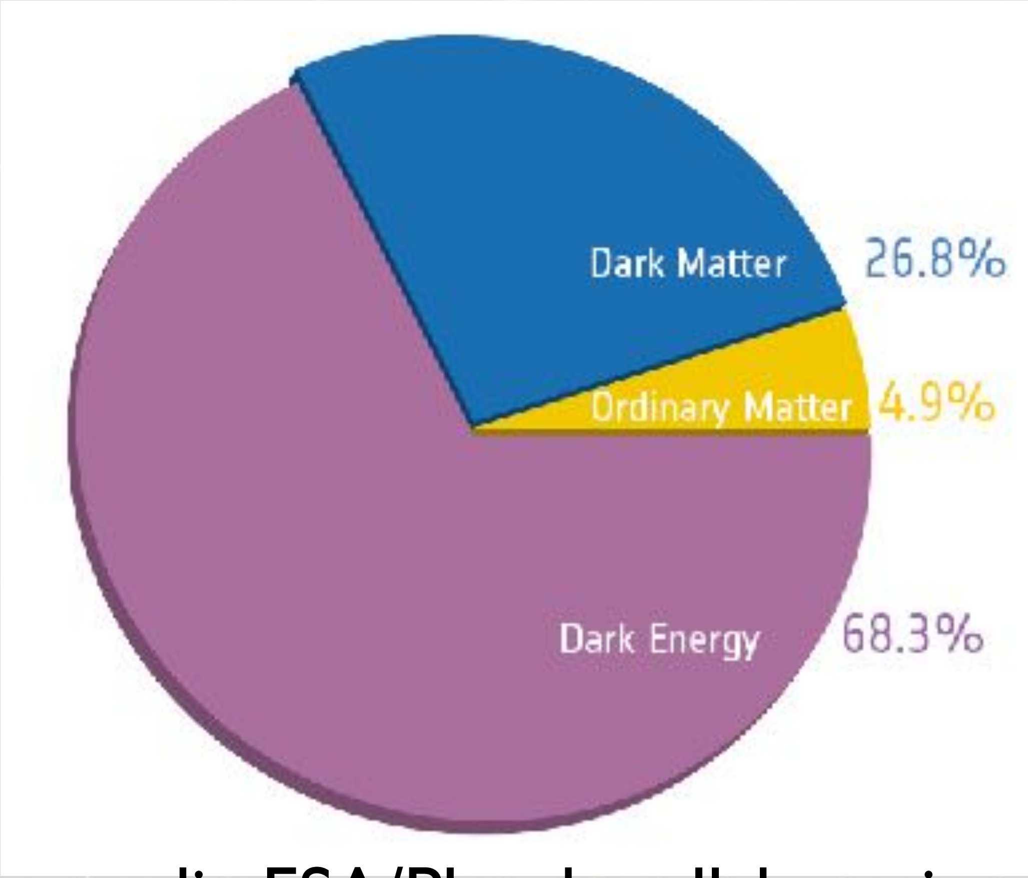


Image credit: ESA/Planck collaboration

Describe
≠
explain

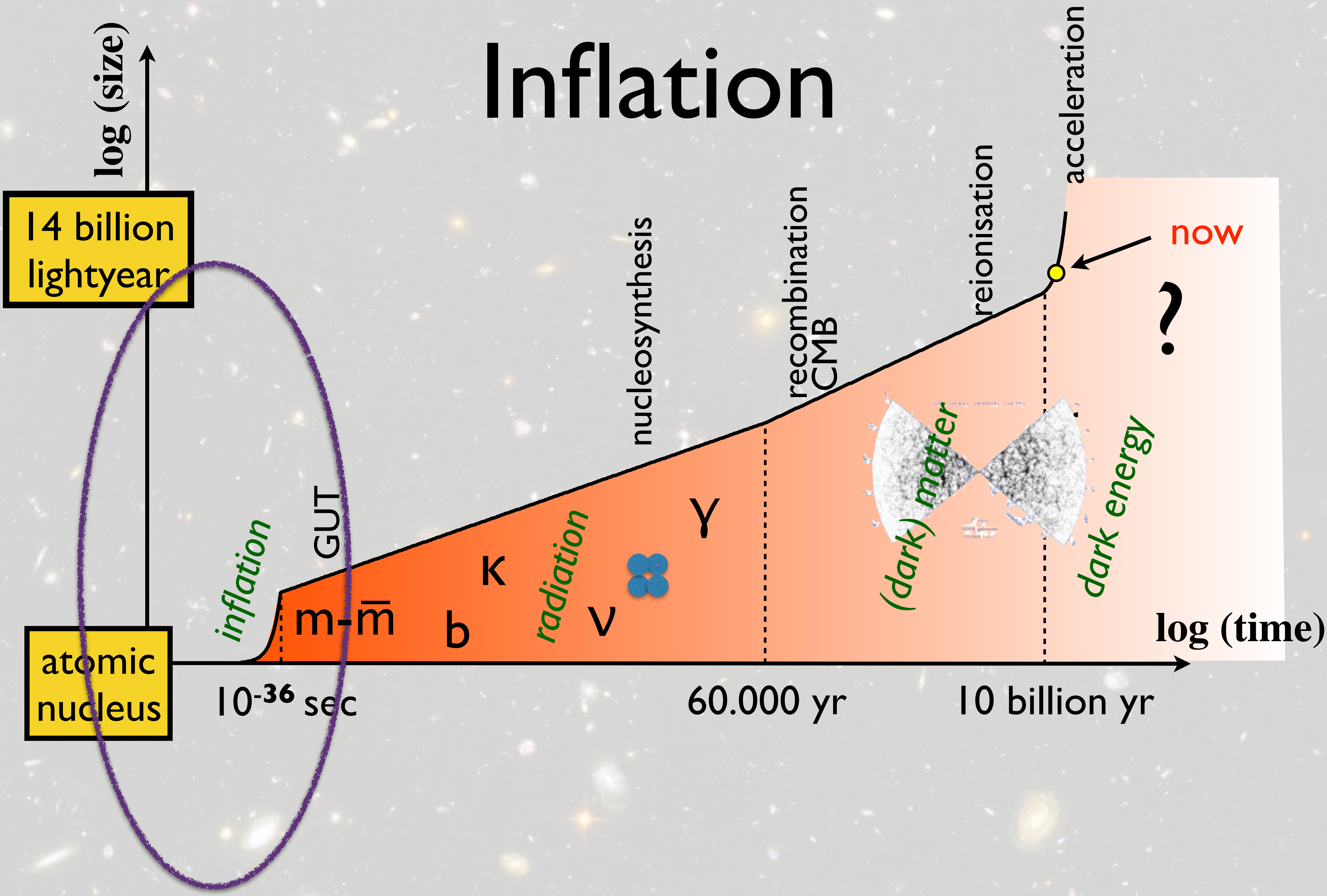
What are dark matter, dark energy?

Initial conditions?

Why is the Universe so homogeneous?

Why is de curvature of space ~ 0?

Inflation

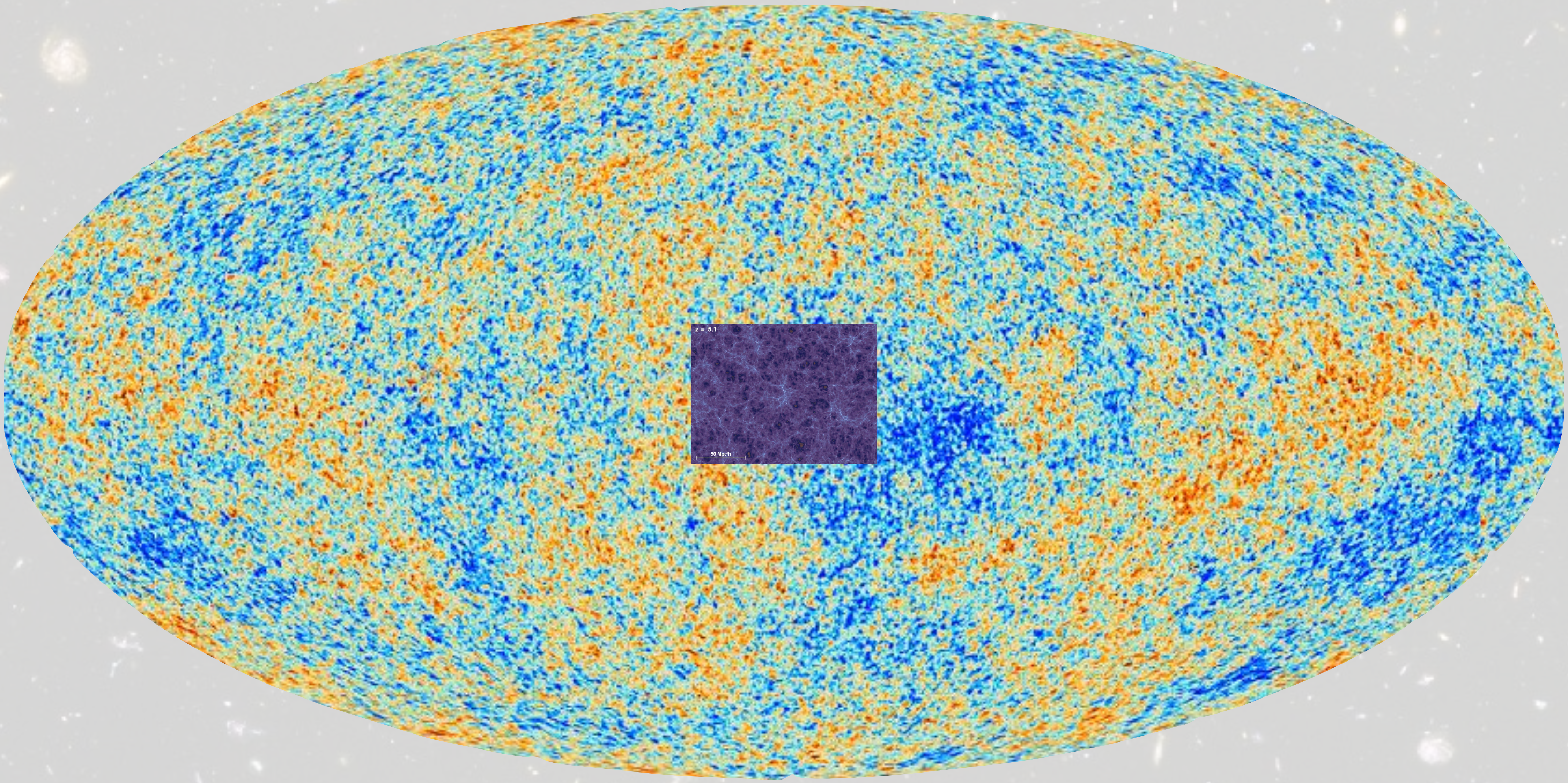


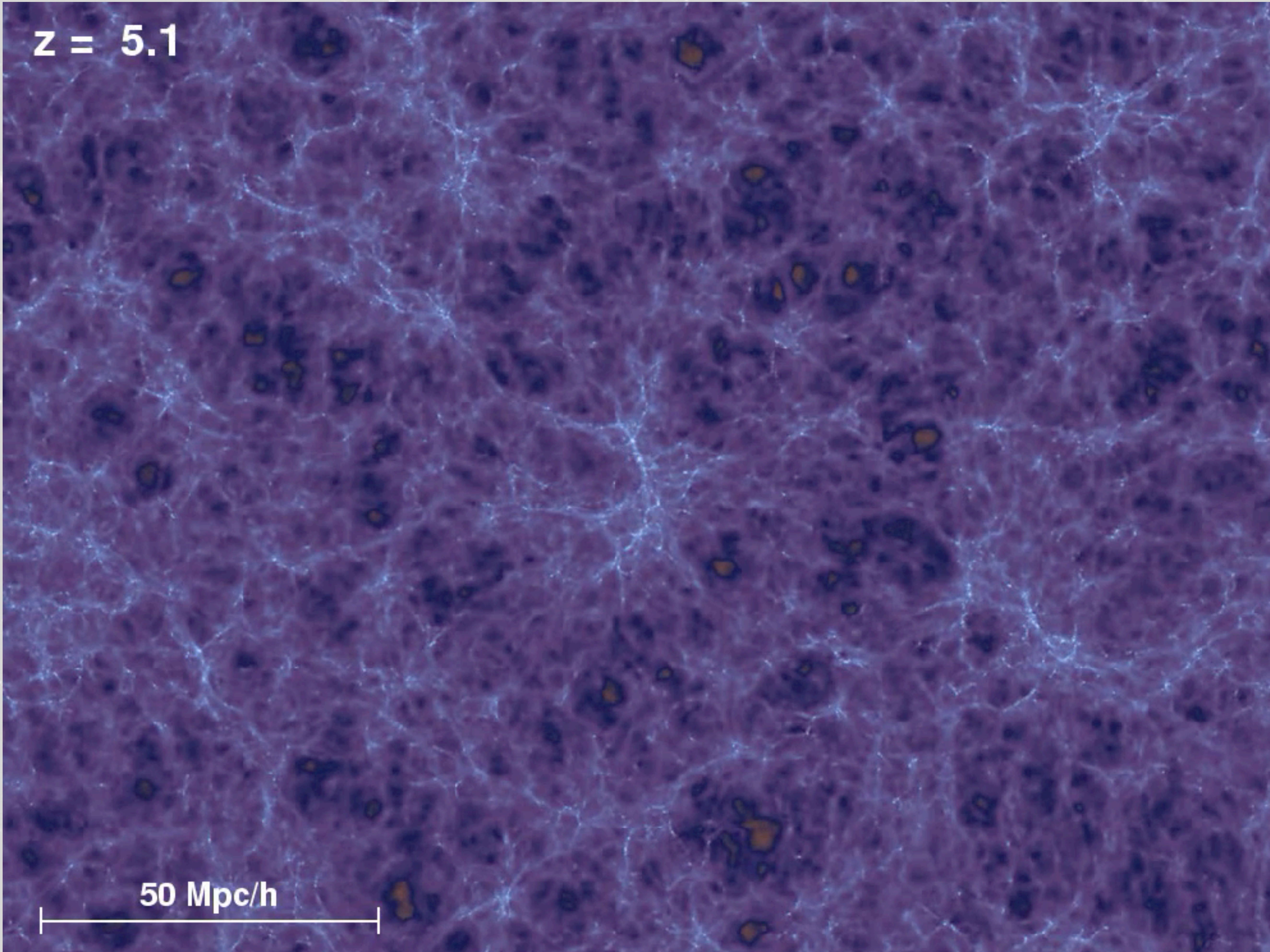
log (size)
14 billion lightyear
atomic nucleus
inflation
GUT
m-m̄
b
κ
radiation
ν
γ
nucleosynthesis
recombination CMB
reionisation
acceleration
now
?
(dark) matter
dark energy
log (time)
10-36 sec
60.000 yr
10 billion yr

Inflation

- Massive expansion in tiny fraction of a second (x billion billion in trillionth of a trillionth of a trillionth of a second)
- Soon after epoch of quantum gravity
- Many theories!
- Could be observed with gravitational waves
- Very neat explanation for flatness, initial conditions, homogeneity
- Initial fluctuations = inflated quantum noise

“A universe out of nothing”

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Dank u!