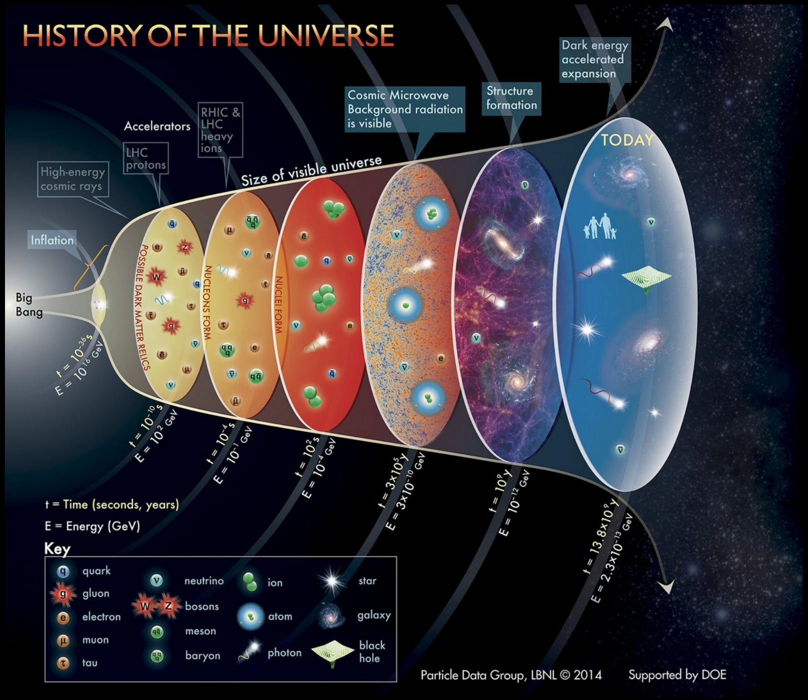
The early universe

as a particle physics laboratory



Valerie Domcke
CERN TH

From the smallest distances...

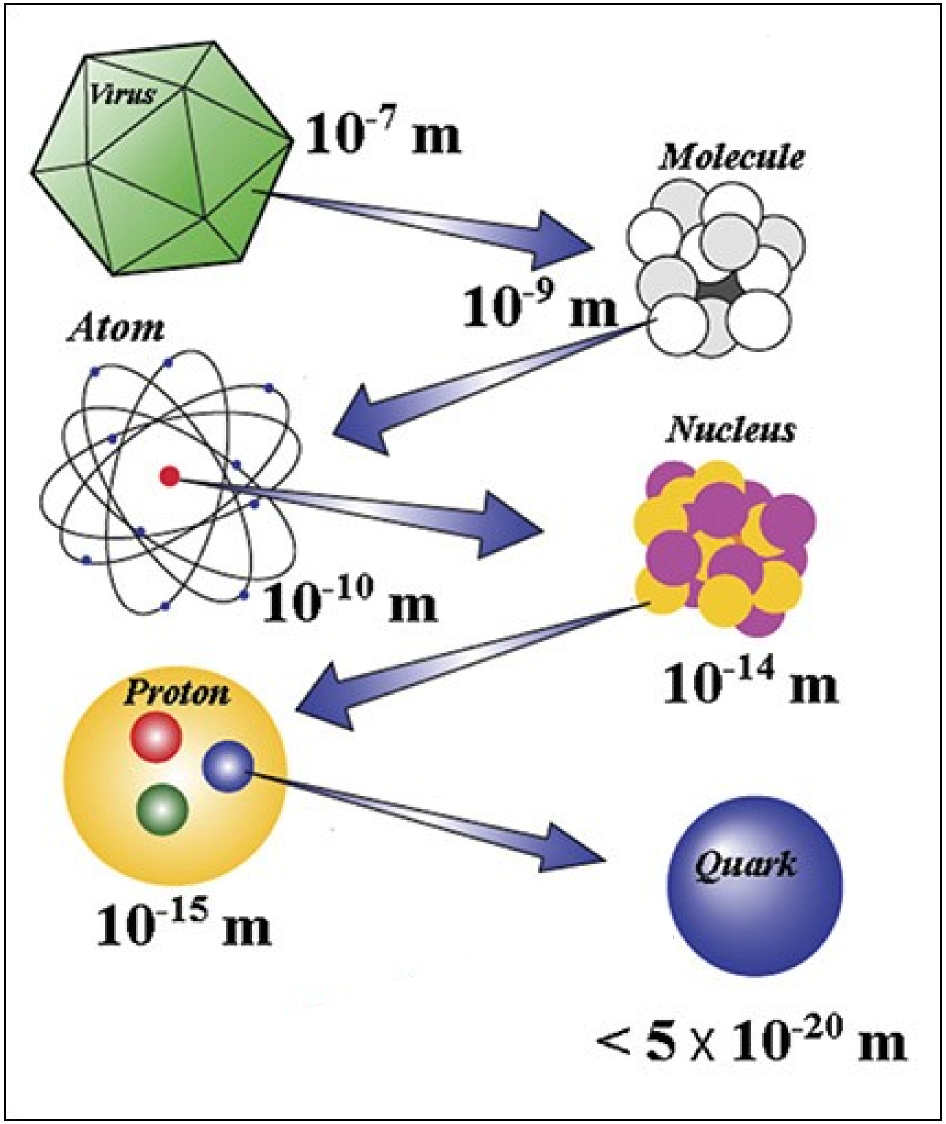


image credit : AAPT

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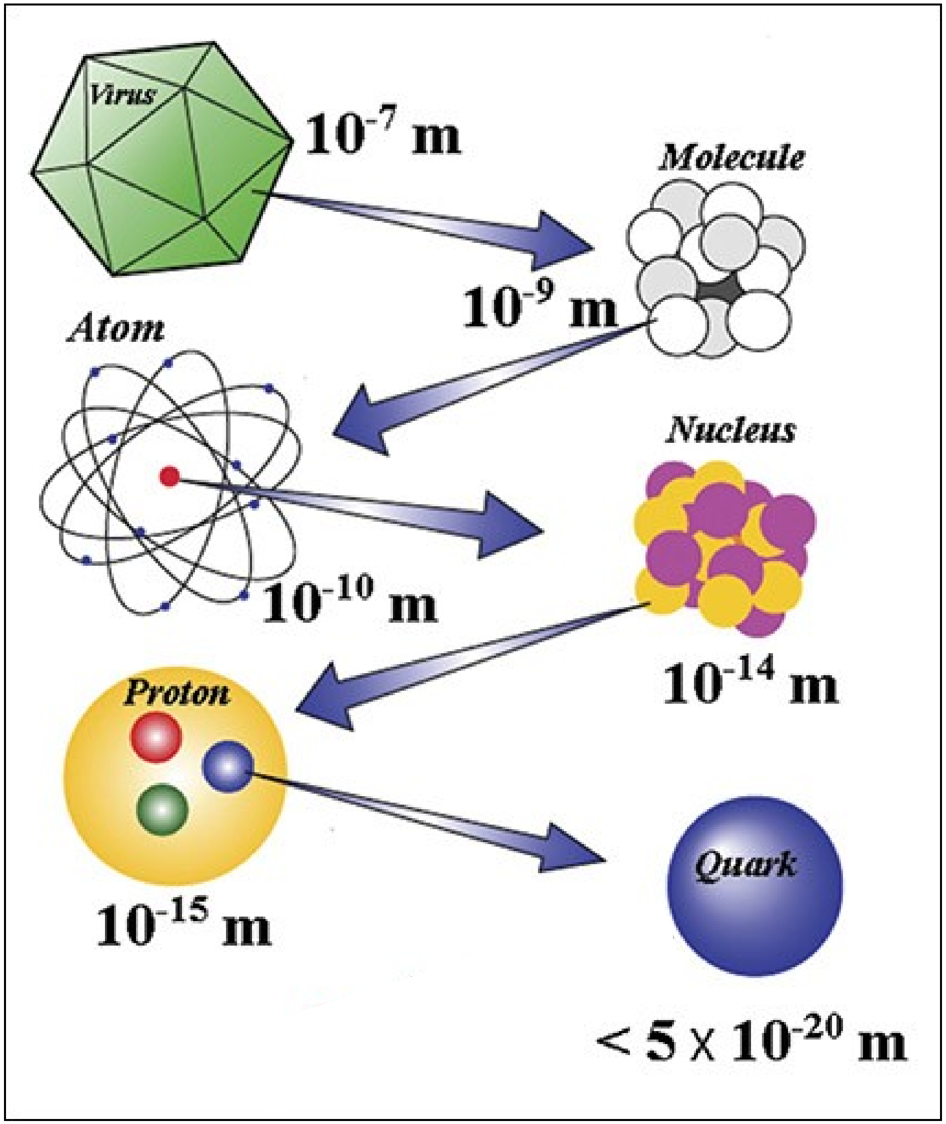

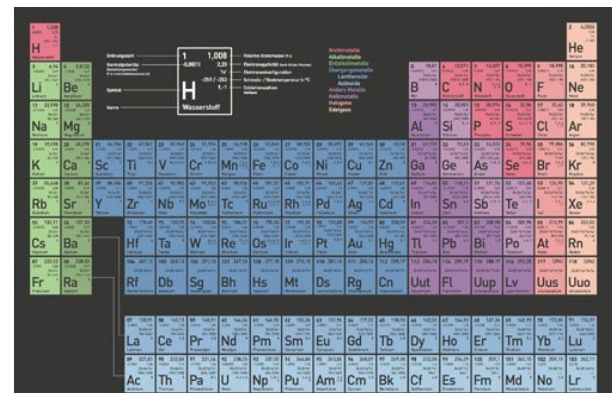

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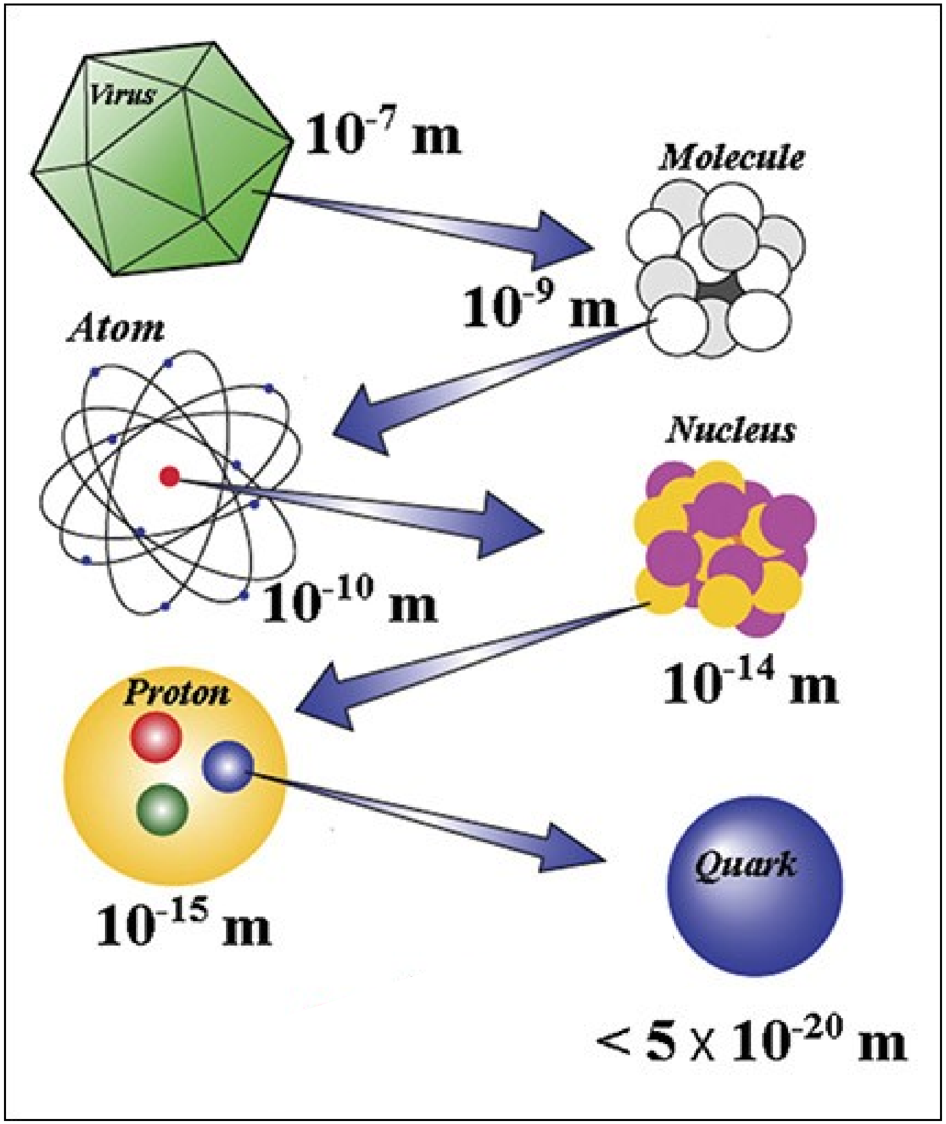

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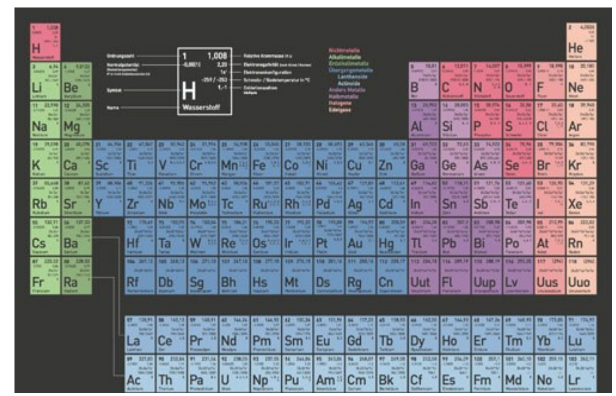
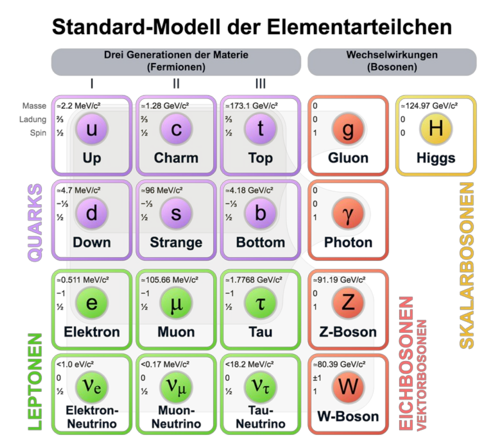
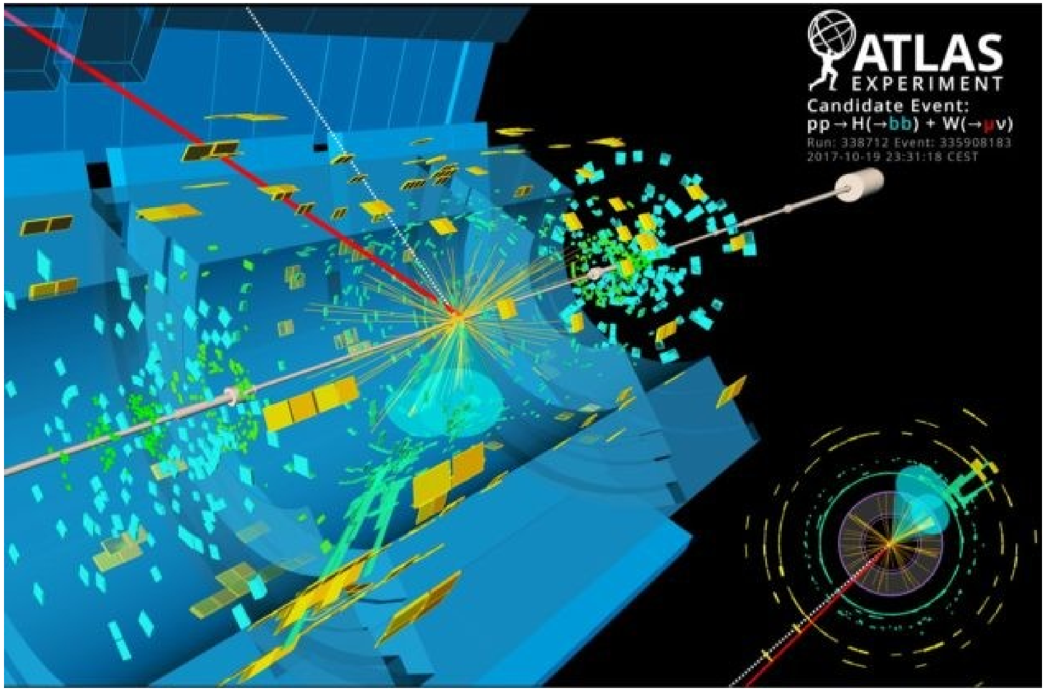




… to the highest energies …



- At „normal“ temperatures, quarks are confined into protons and neutrons, protons are stable
- At high-energy collisions, free quarks become „free“ for a short time period
- More massive virtual (short-lived) elementary particles can be formed

$$10^{-20}\ \mathrm{m} = \hbar c/10\ \mathrm{TeV} \quad \to \quad \frac{L}{10^{-20}\ \mathrm{m}} \mathrel{\widehat{=}} \frac{10\ \mathrm{TeV}}{E}$$

... to the earliest times

universe today

- cold: $-270\ ^\circ\mathrm{C}$ (2.7 K)
- largely empty
- inhomogeneous
- matter consists of atoms, molecules, ...
- expanding

... to the earliest times

Hubble 1929

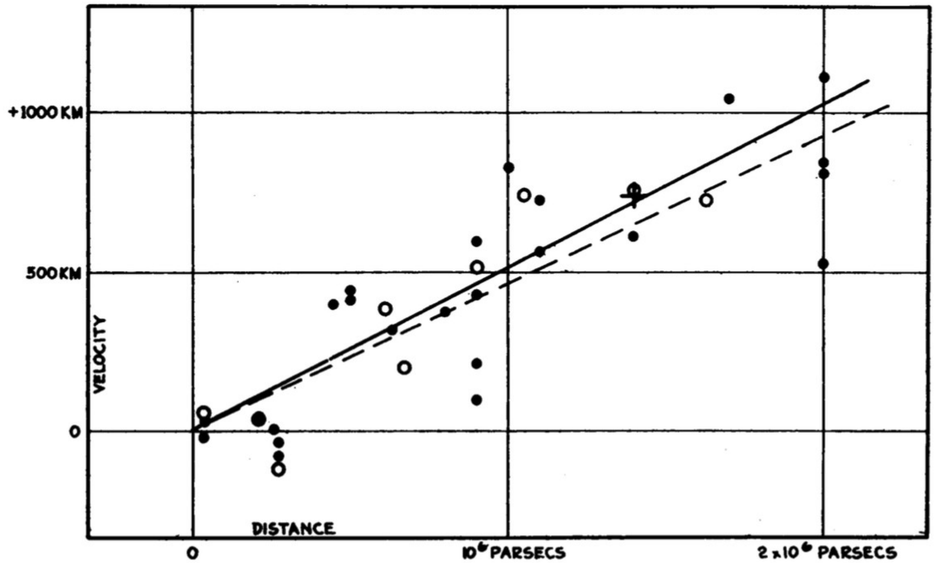


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

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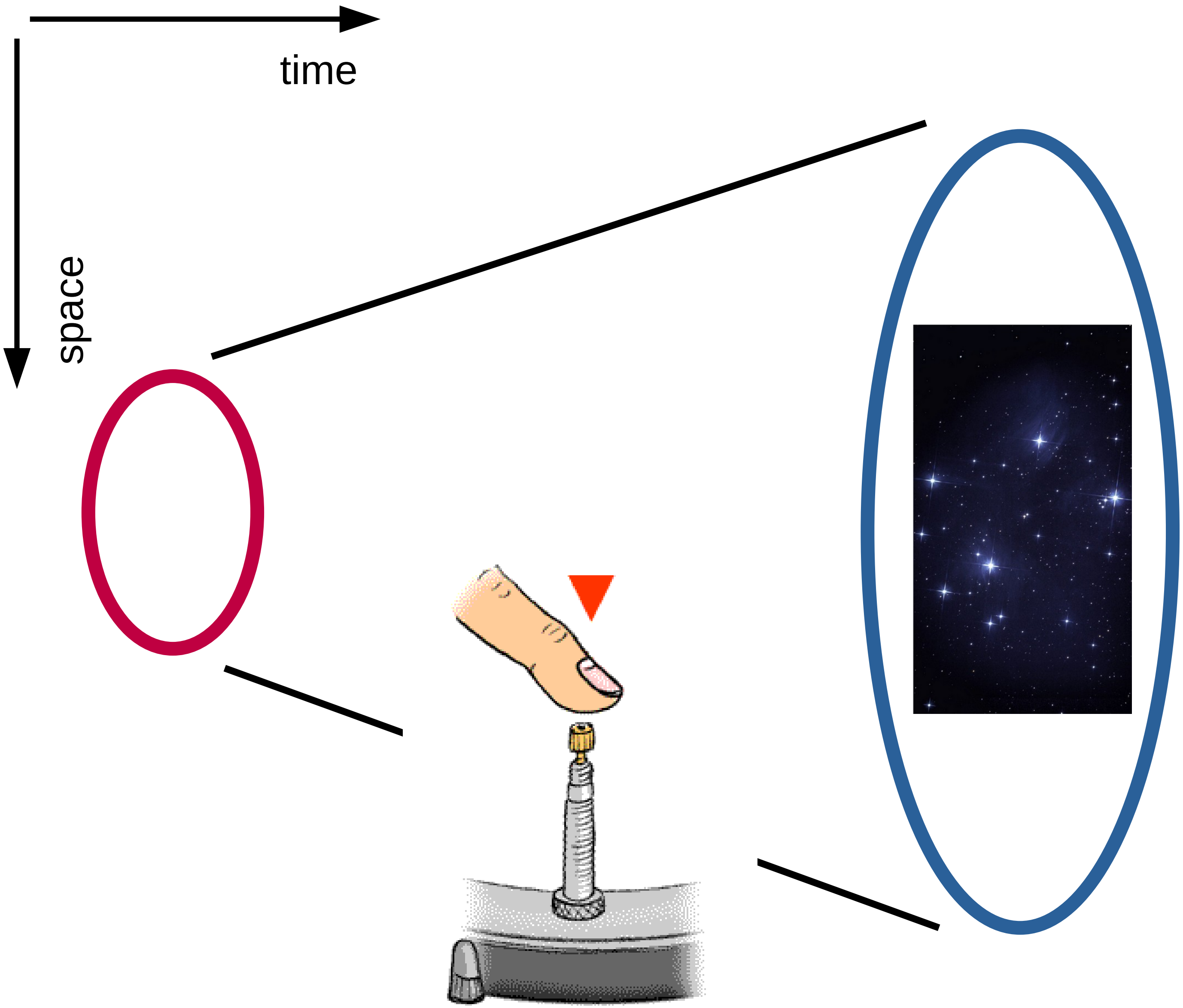

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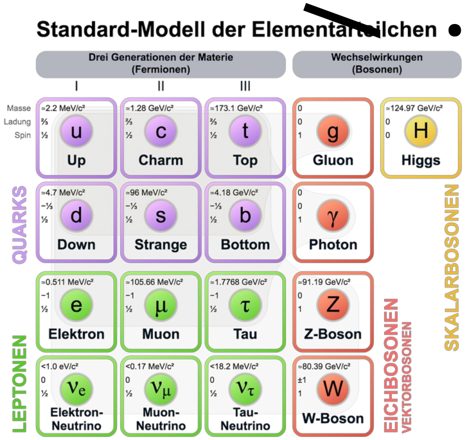
... to the earliest times

time

space

13 billion years ago

- hot: $\sim 10^{20}\ ^\circ\mathrm{C}$
- homogeneous plasma
- elementary building blocks of matter exist as free particles



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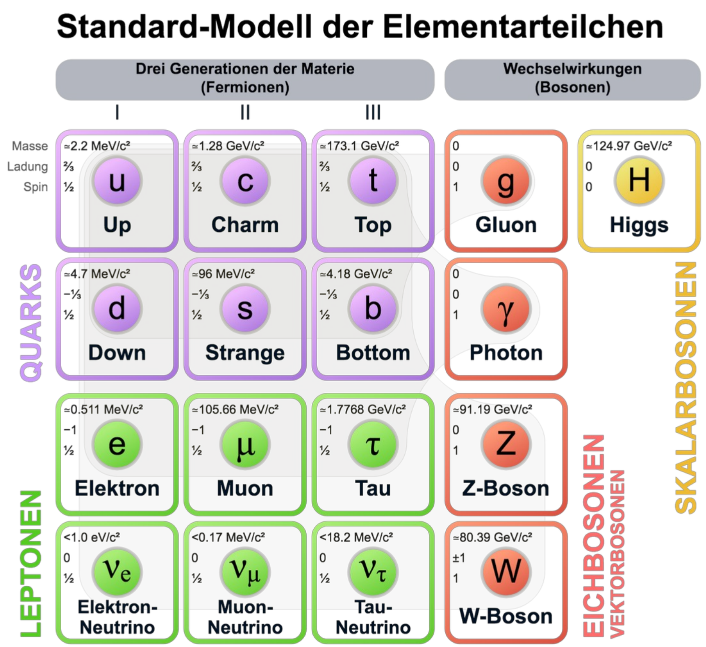
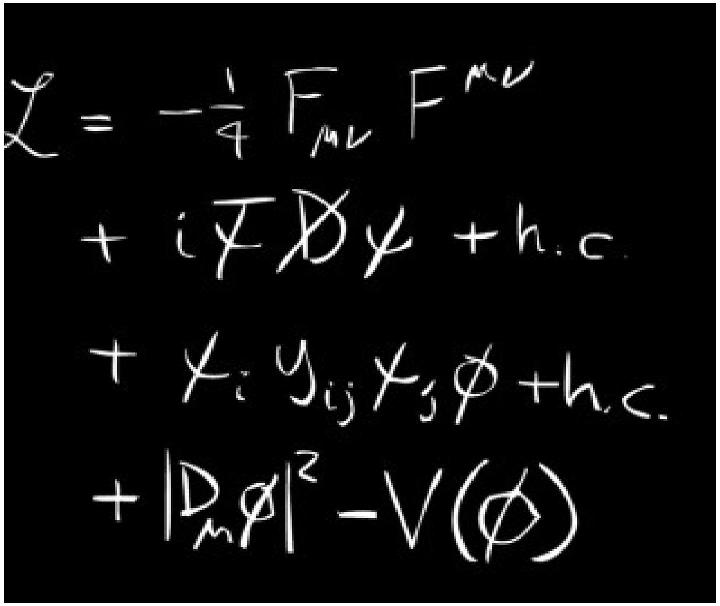
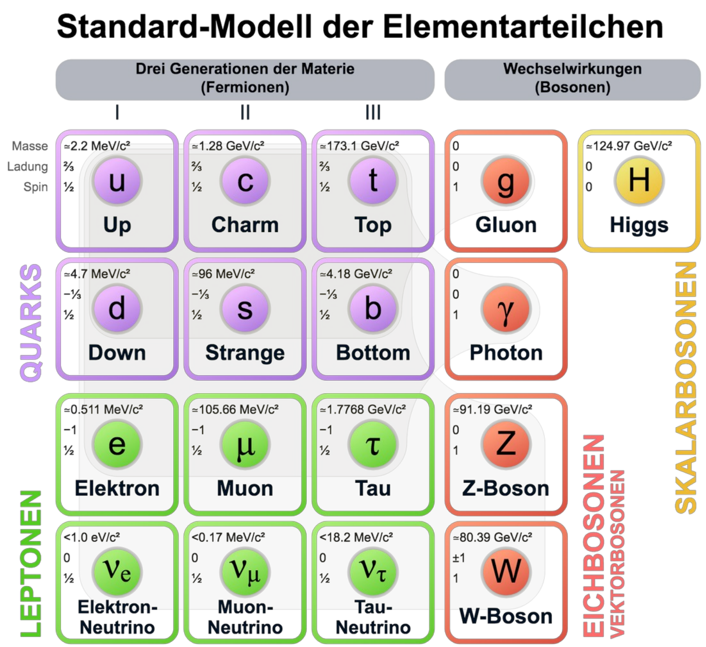
Standard Model (SM) or Particle Physics

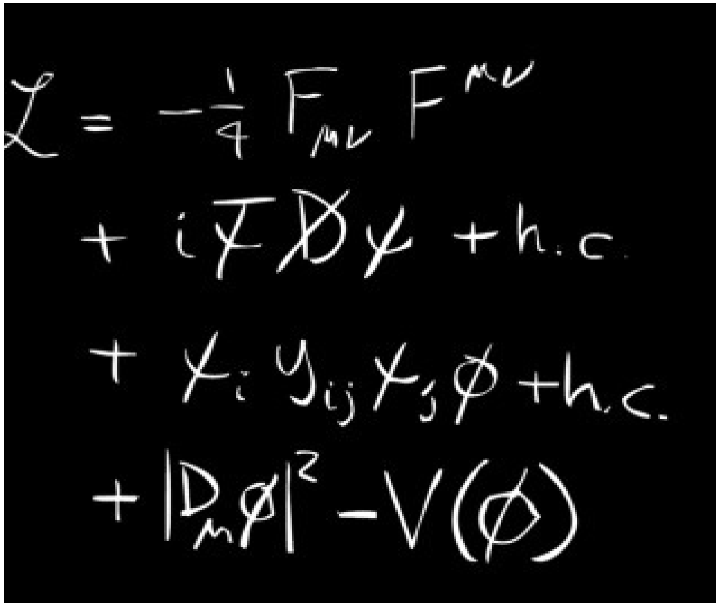




Elementary „building blocks“ in the framework of quantum field theory

Standard Model (SM) or Particle Physics





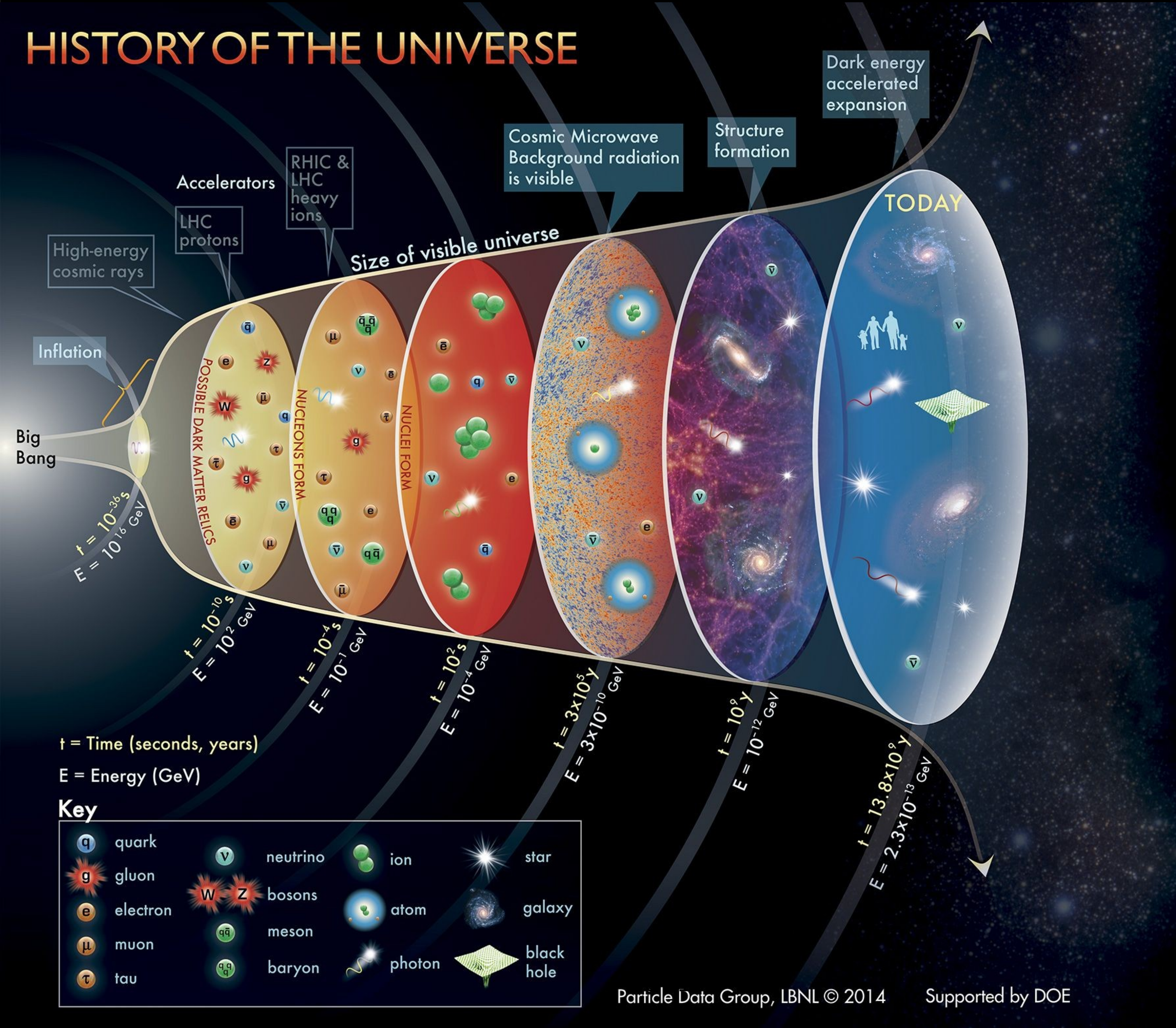
Elementary „building blocks“ in the framework of quantum field theory

High Energy Frontier:

- Other elementary particles?
- Are the SM particles truly elementary?

Early Universe Frontier:

- Can the SM explain all observations to date?
- Possilble relics from earlier times/ higher energies?


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
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$t = 3x10^{5}$ y
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t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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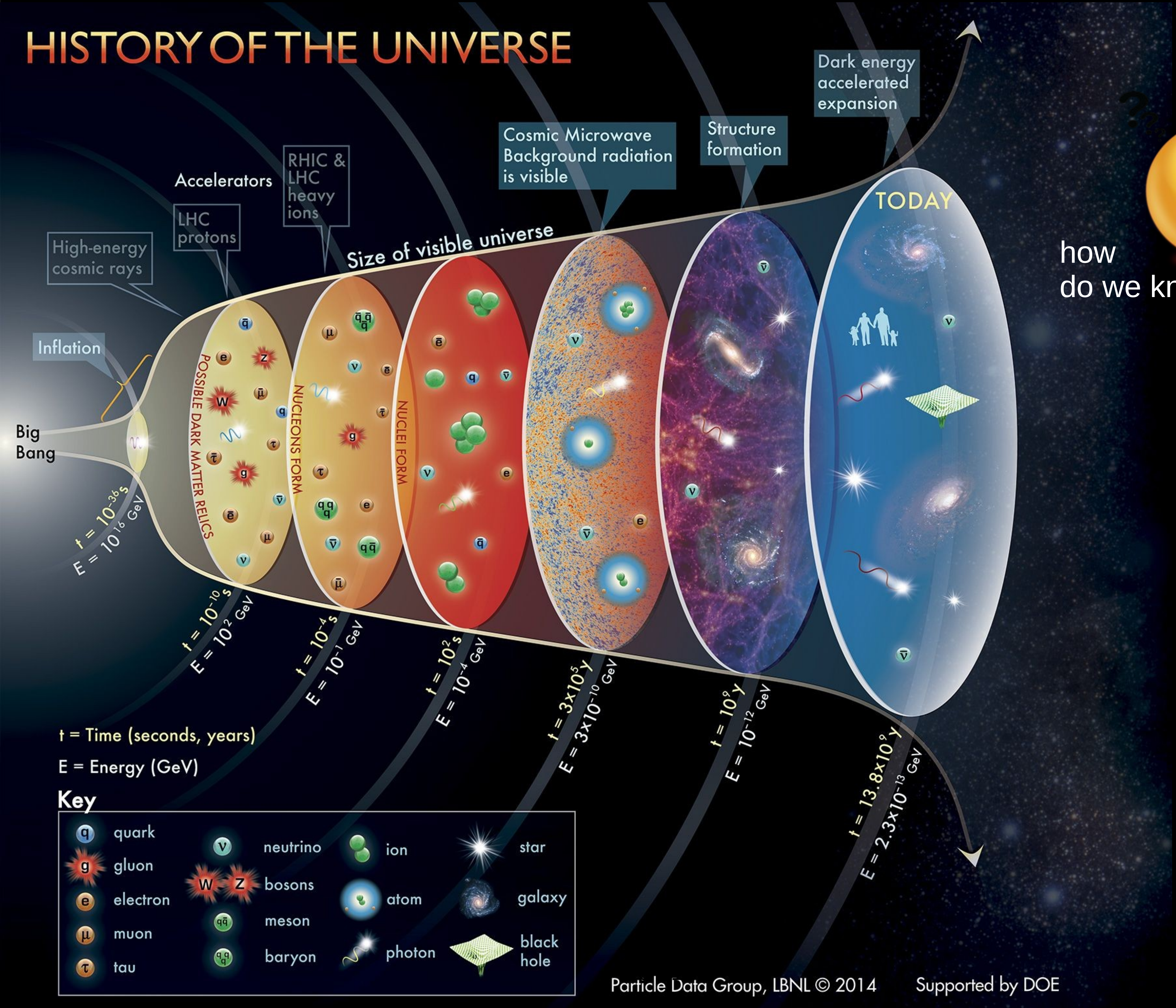
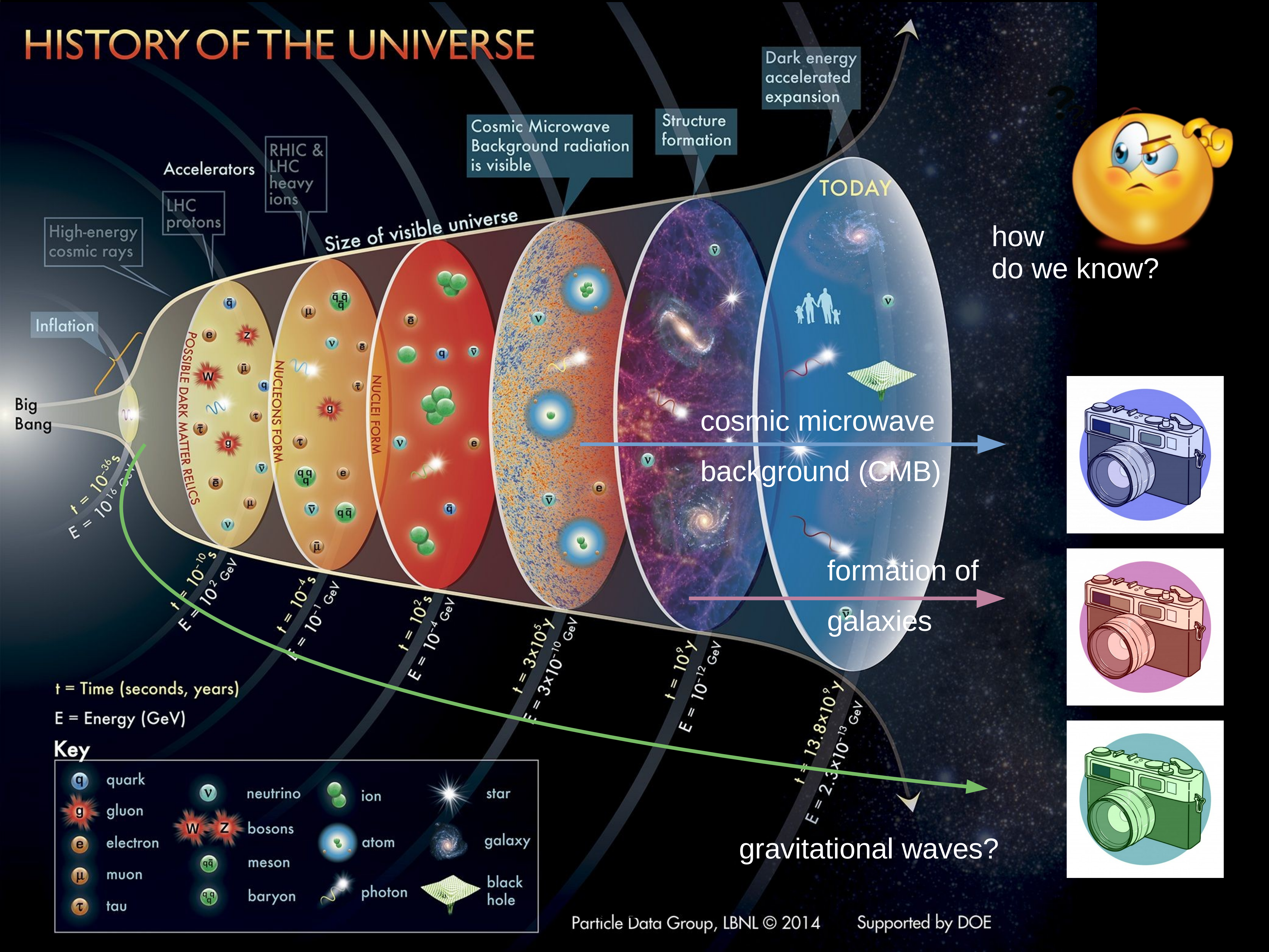


how
do we know?



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tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
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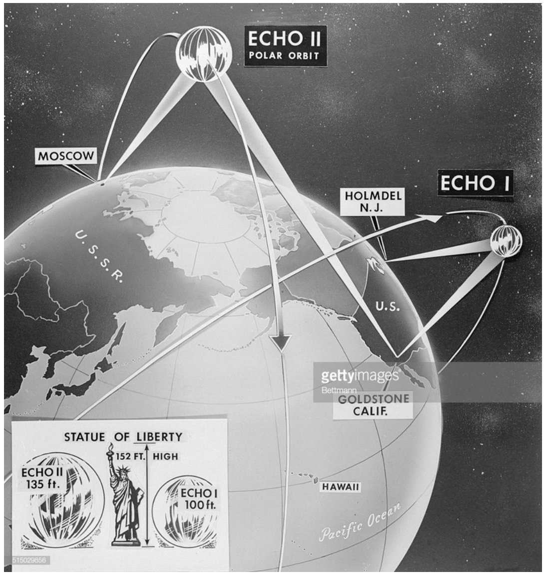
how do we know?
cosmic microwave background (CMB)
formation of galaxies
gravitational waves?

US East Coast, 1960s ...

Arno Penzias, Robert Wilson 1964



Project Echo, 1960

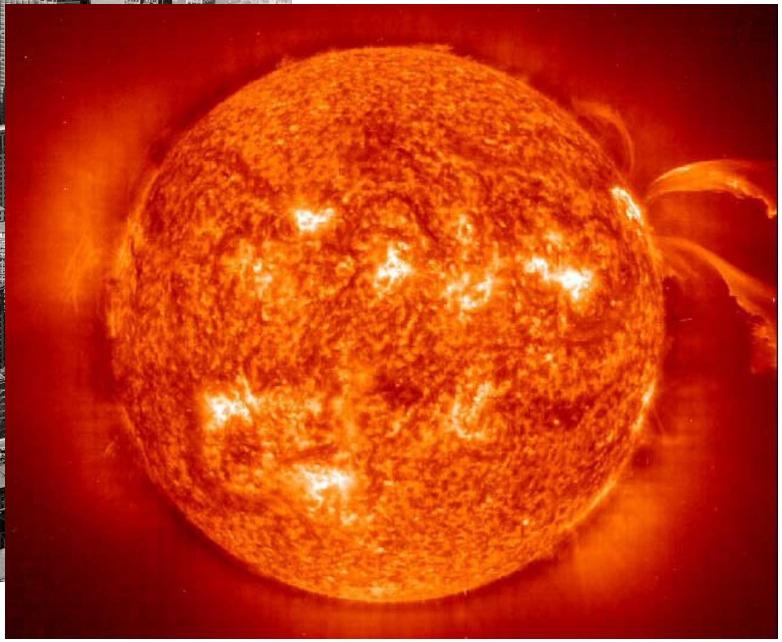
- Bell Lab‘s Horn Antenna: a 6m radio telescope promising unprecedented sensitivity
- But a background noise is disrupting the measurements ...

The search for the culprit begins...

New York?

The search for the culprit begins...

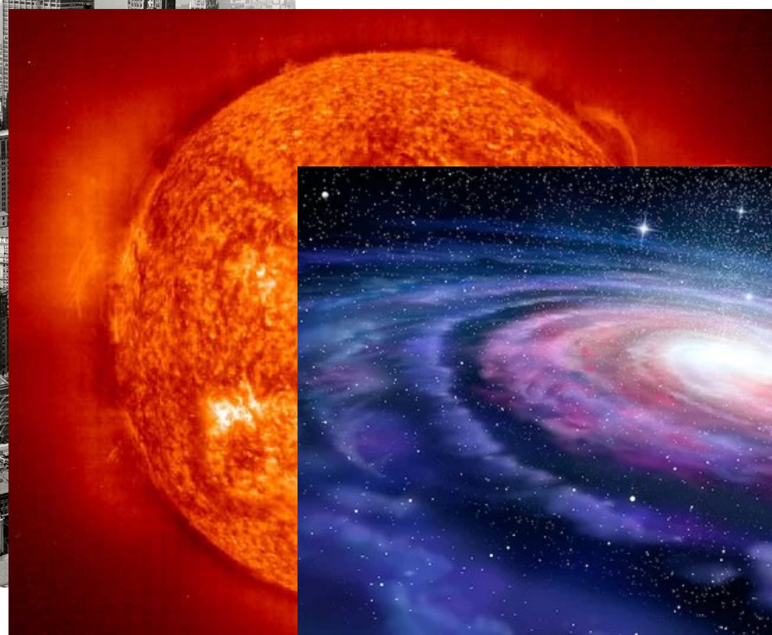
New York?



The sun?

The search for the culprit begins...

New York?



The sun?

The galaxy?

The search for the culprit begins...

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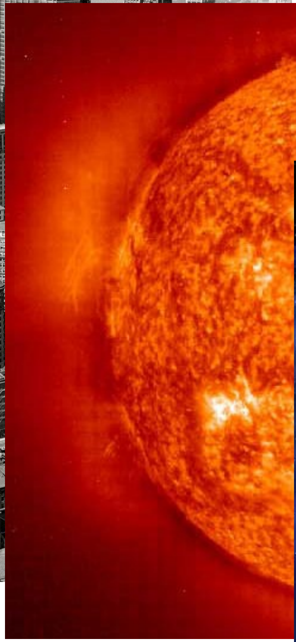


The sun?

The galaxy?

pigeons?

A bold theory

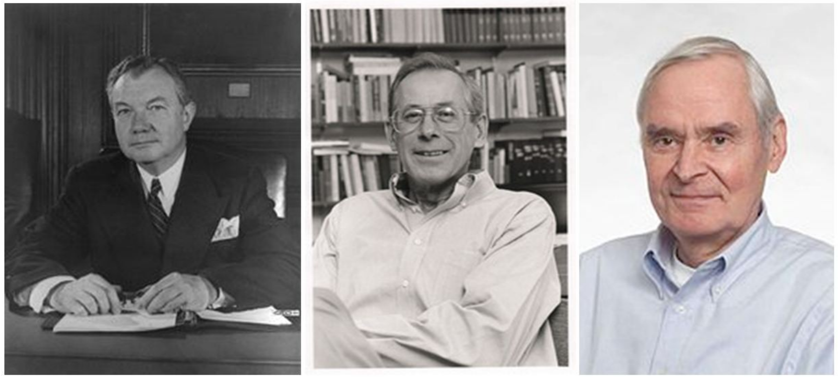
At the same time in Princeton, 60 km away

- Theoretical physicists are discussing the very nature of the universe:

  ''Steady State'' or ''Big Bang'' ?

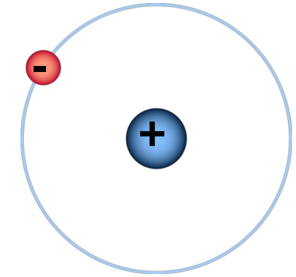
- Robert Dicke, Jim Peebles and David Wilkinson'

  Big Bang Theory → cosmic background radiation as relic of the primordial universe



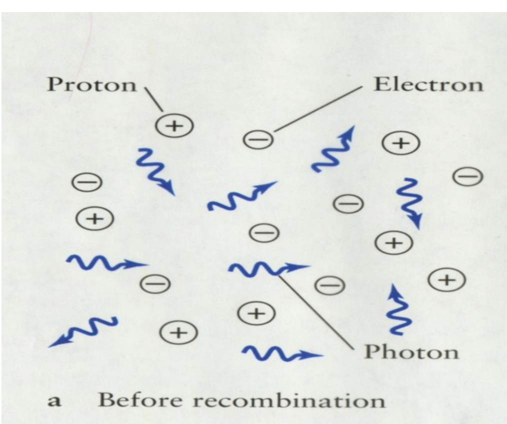
the cosmic microwave background

binding energy of hydrogen atom: $T \sim 3000°C$

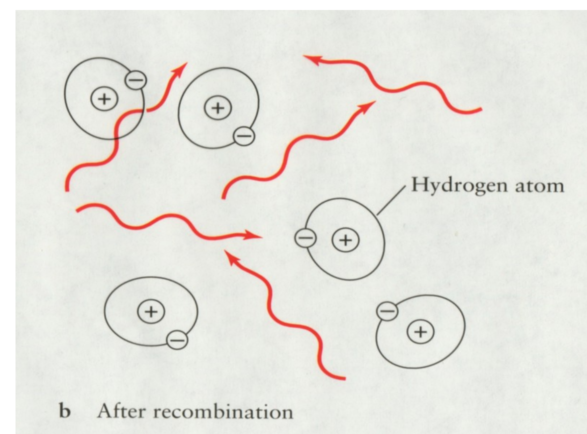


$T > 3000°C$ —— time ——▶ $T < 3000°C$

- many free charged particles (electrons & protons)
- photons scatter multiple times, universe not transparent



- electrons and protons from electrically neutral hydrogen atoms
- universe becomes transparent



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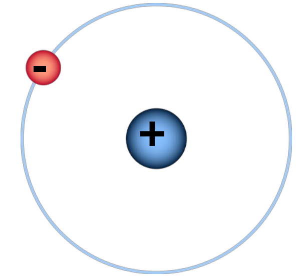

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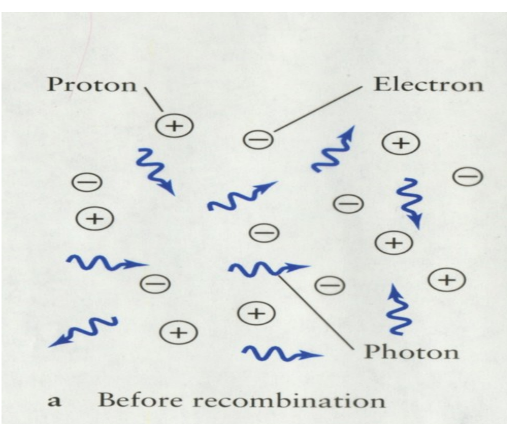
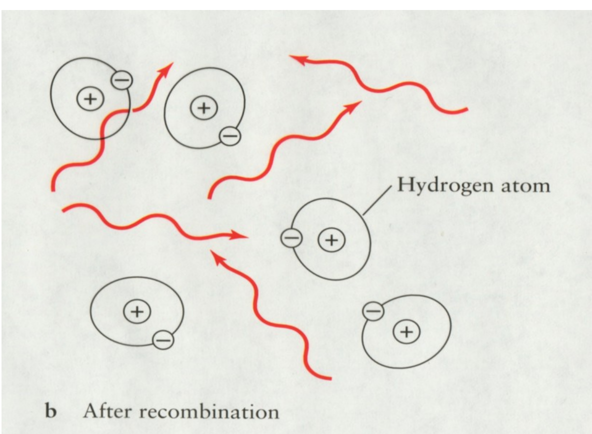


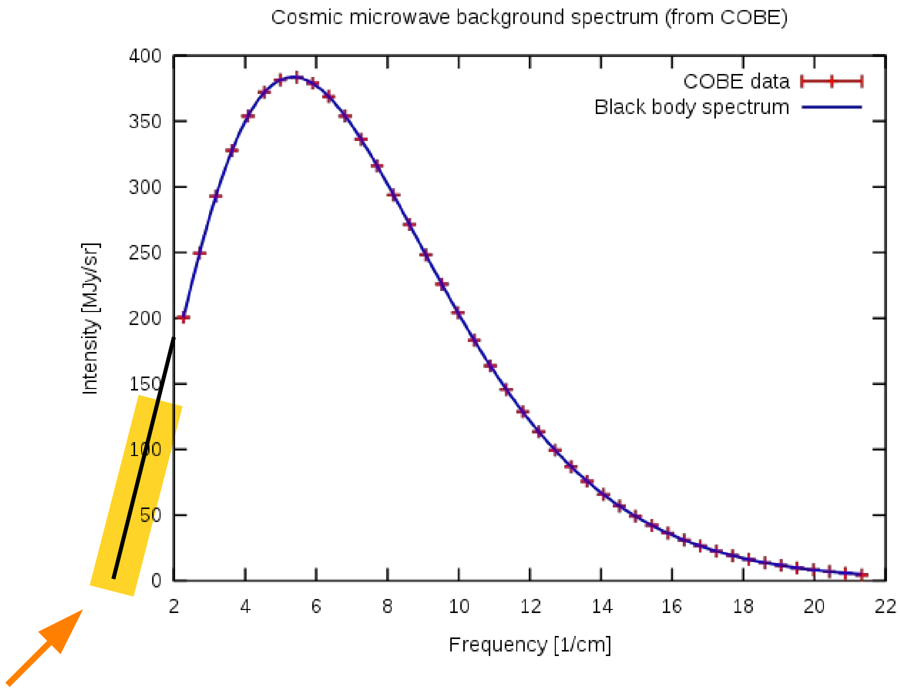
- thermal radiation with T ~ 3000 C as cosmic background radiation
- cools in expanding universe to T << 3000 C



CMB black body radiation

COBE satellite,
1989-93

- cosmic microwave background well measured today
- black body radiation with T = 2.7 K (-270 C) (microwaves)



confirms key prediction of `big bang' theory

Penzias, Wilson (nobel prize 1978)

2019 nobel prize Peebles for his contributions to theoretical cosmology

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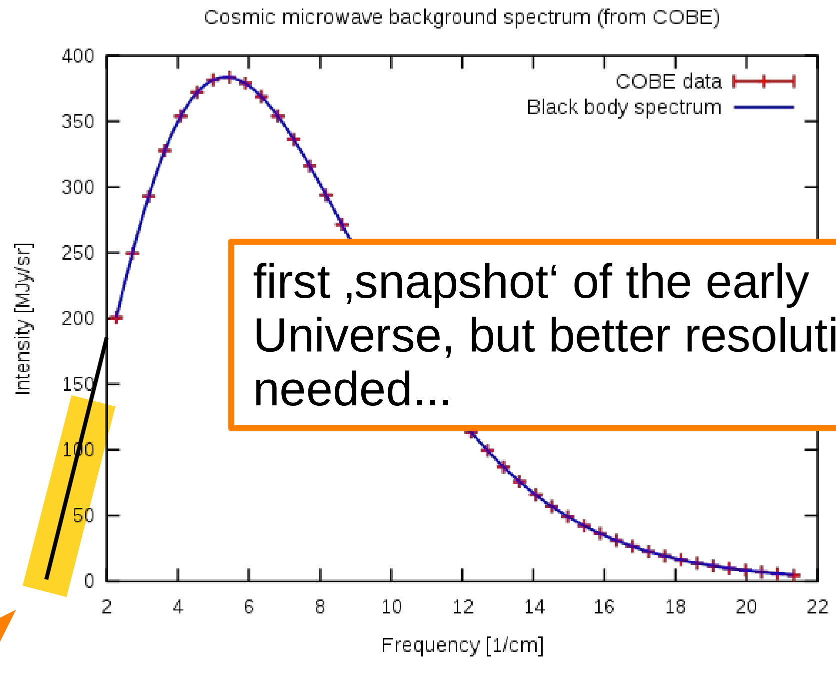

first ‚snapshot‘ of the early Universe, but better resolution needed...

confirms key prediction of `big bang‘ theory

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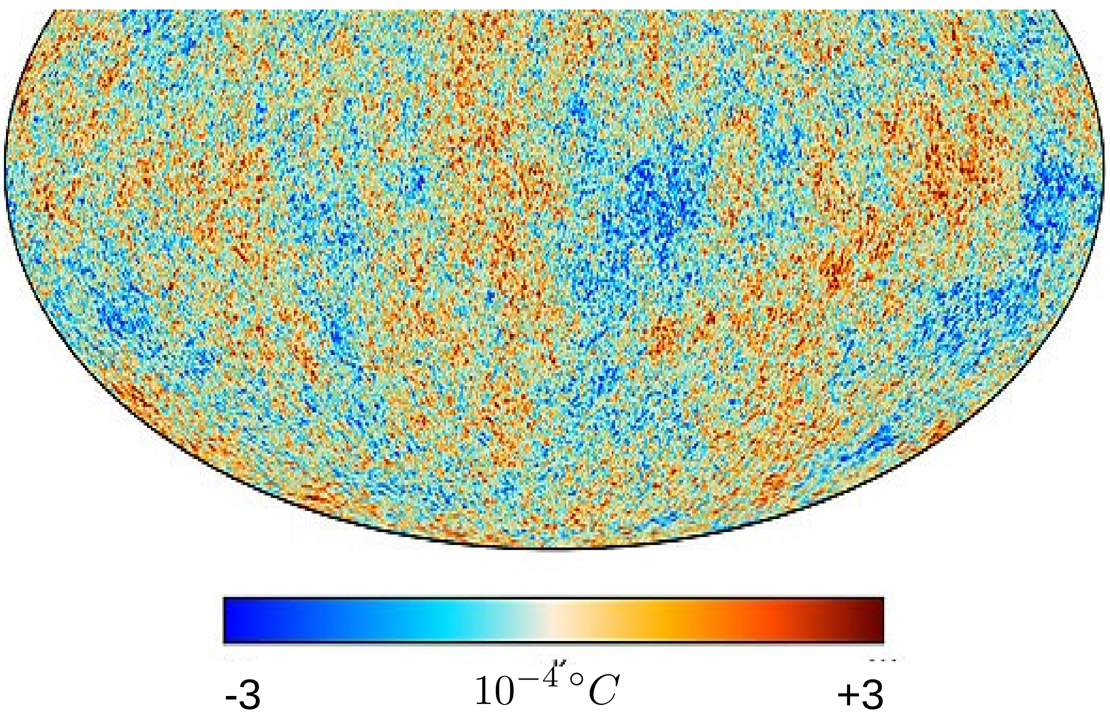
Penzias, Wilson (nobel prize 1978)

anisotropies in the CMB

completely homogeneous plasma → homogeneous universe after cooling

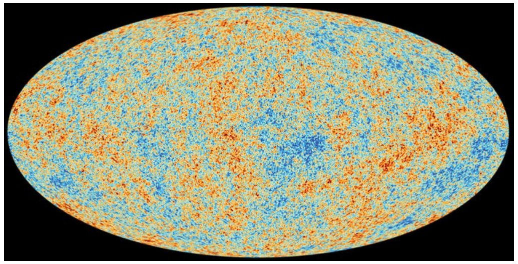
- small pertubations needed as seeds for galaxies to form through gravitational collapse
- anisotropies in the CMB, deviation from black body radiation 1:10^4

PLANCK satellite,
2009 - 2013

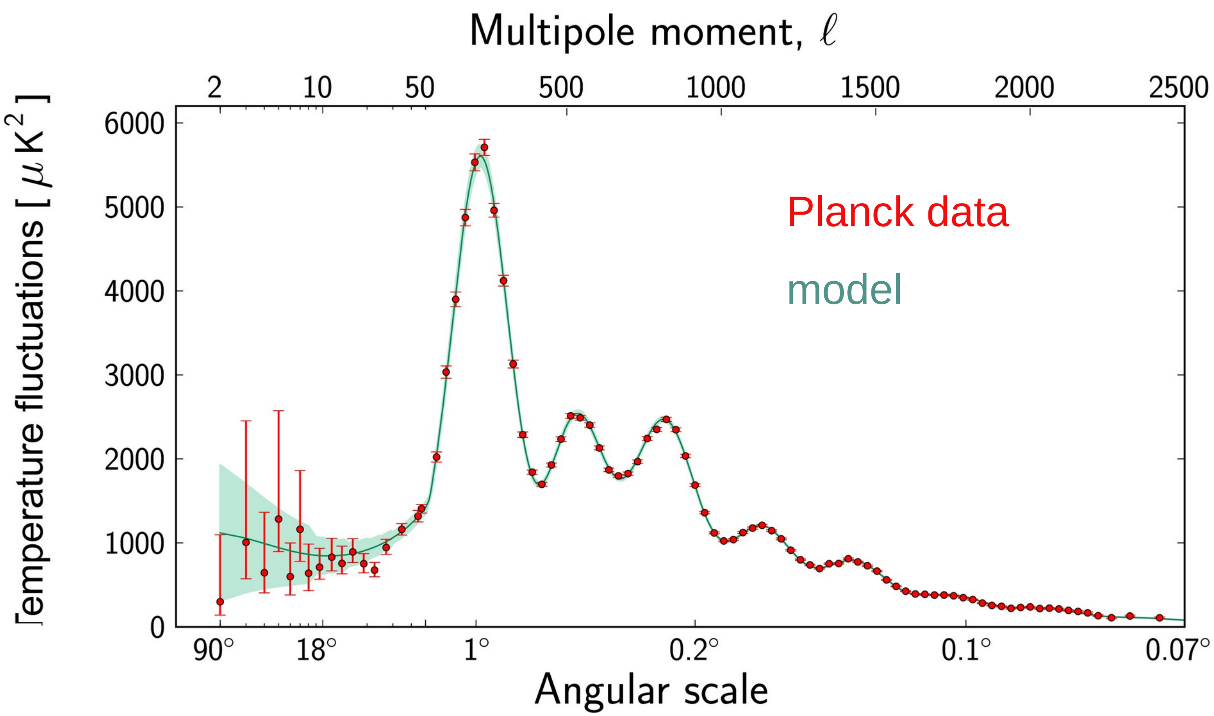


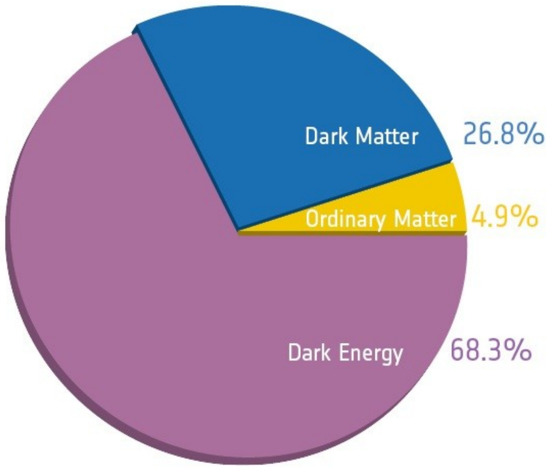
PLANCK 2018 data release

anisotropies in the CMB



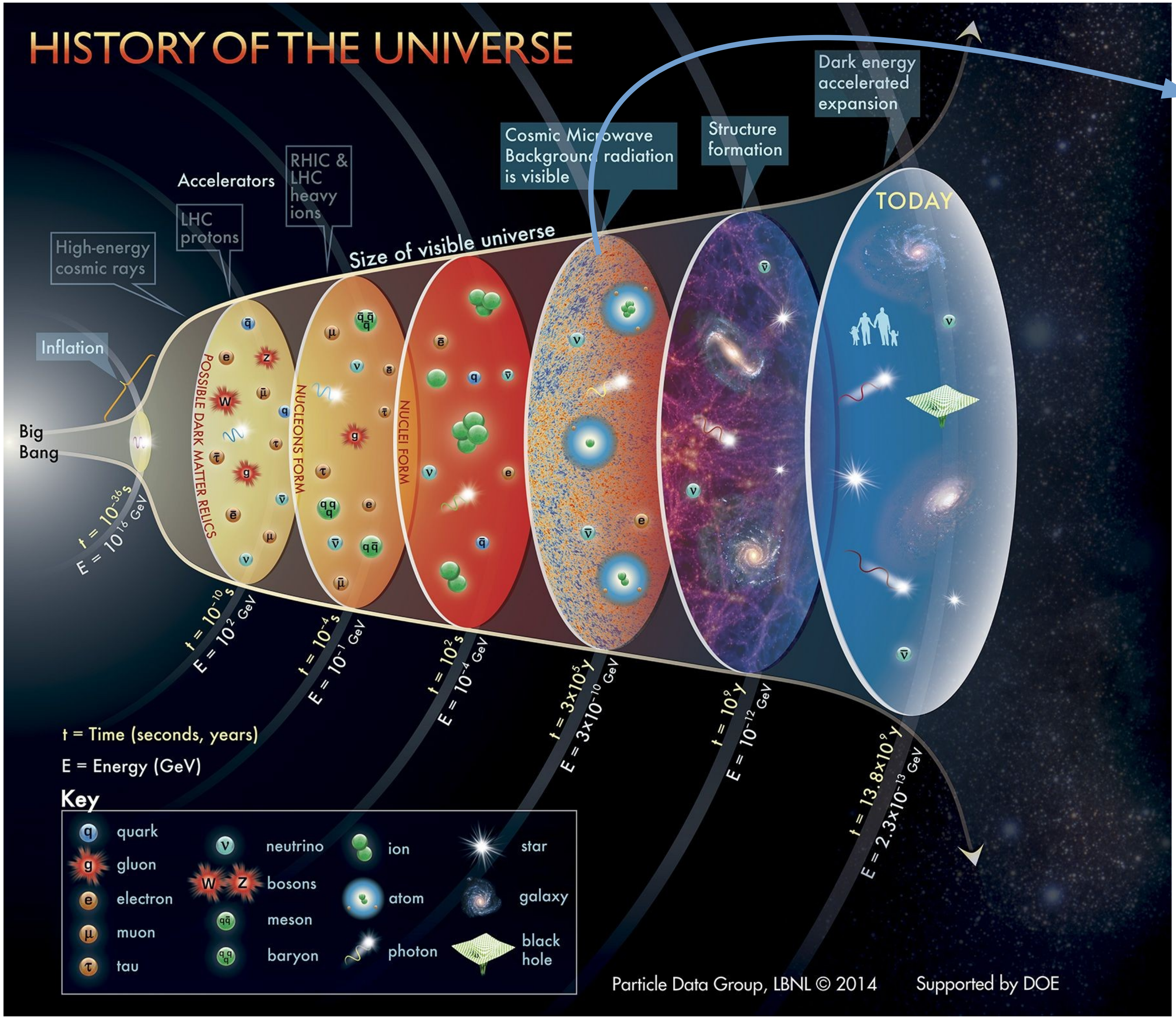
statistical analysis





standard model
of cosmology (ΛCDM)

snapshots of our universe



CMB as relic thermal radiation from the early universe, decoupled in neutral universe

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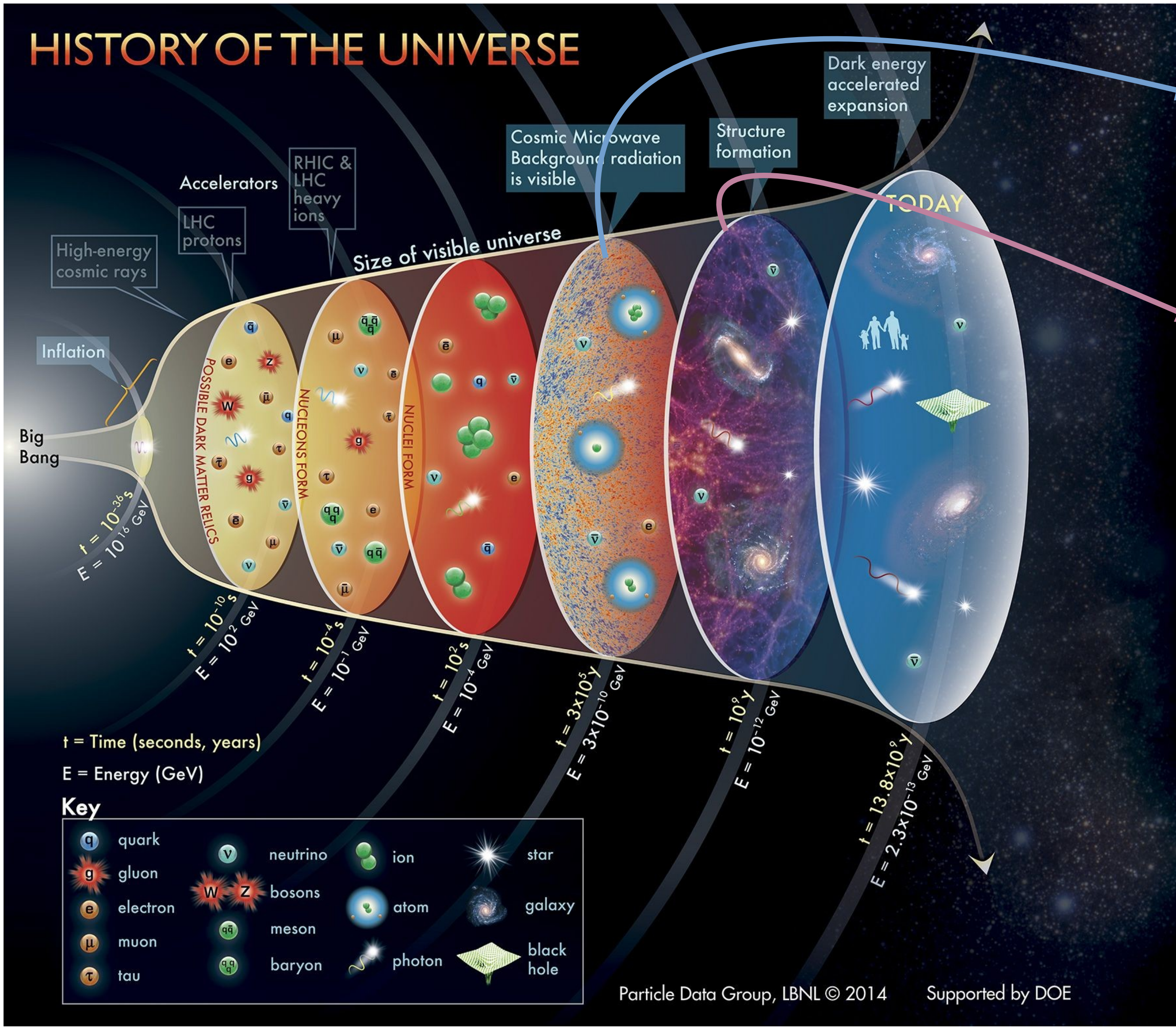

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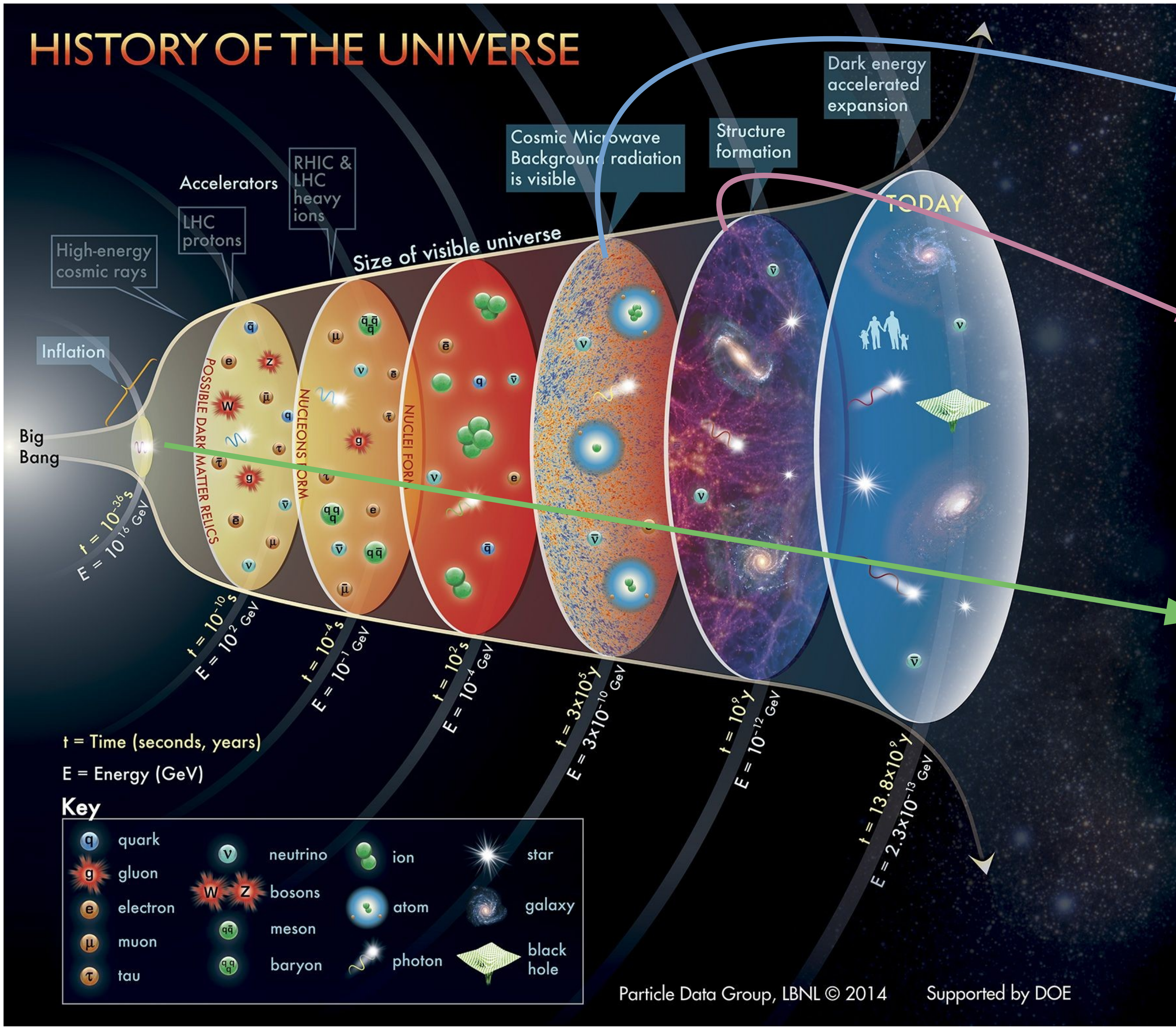

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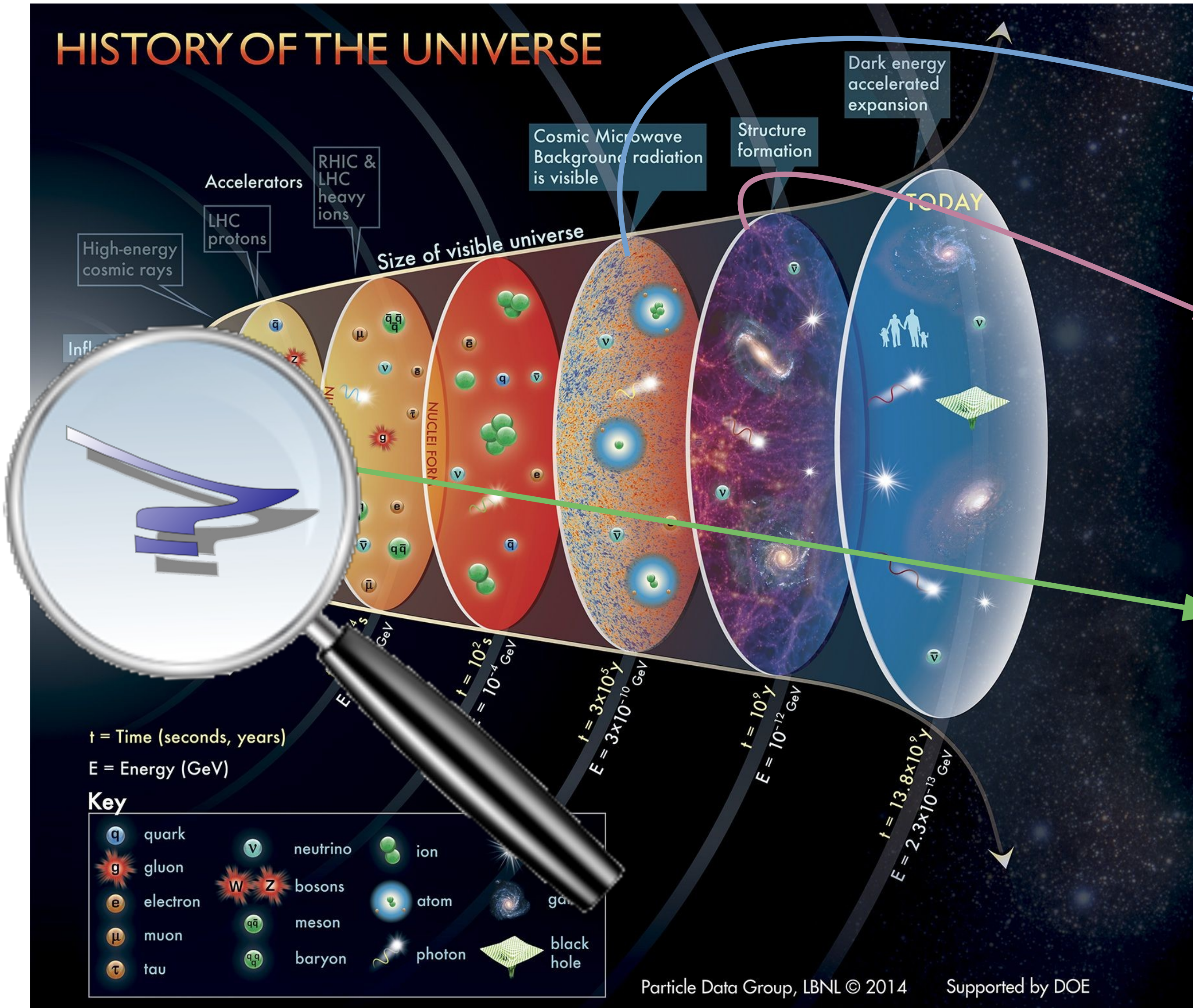

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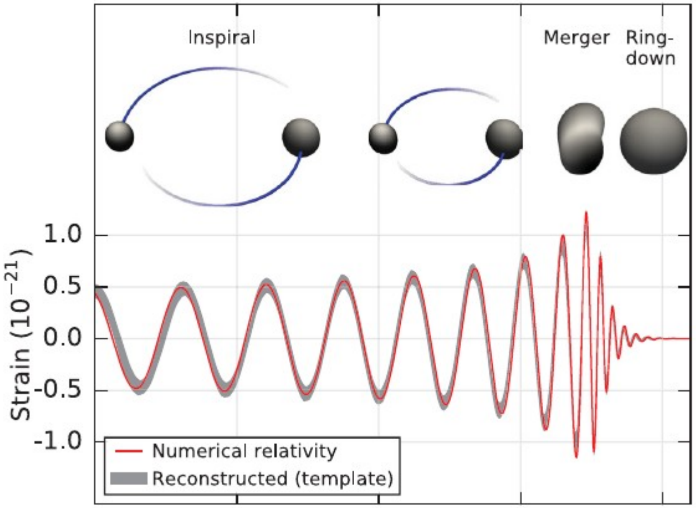
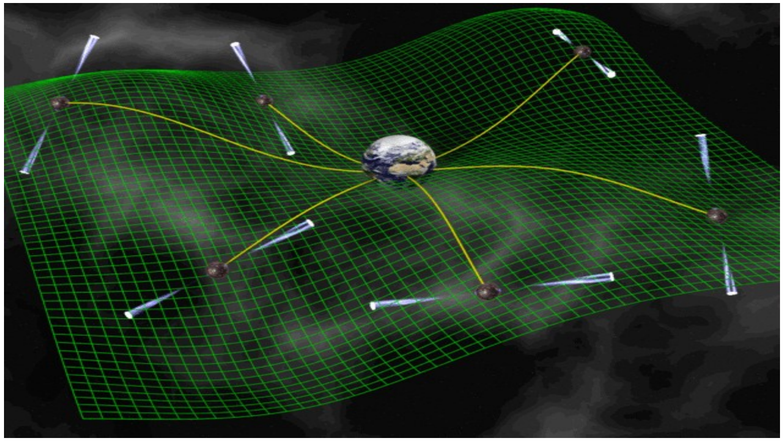


LIGO Livingston, USA

2015: first direct observation of GWs, collision of two black holes a billion years ago



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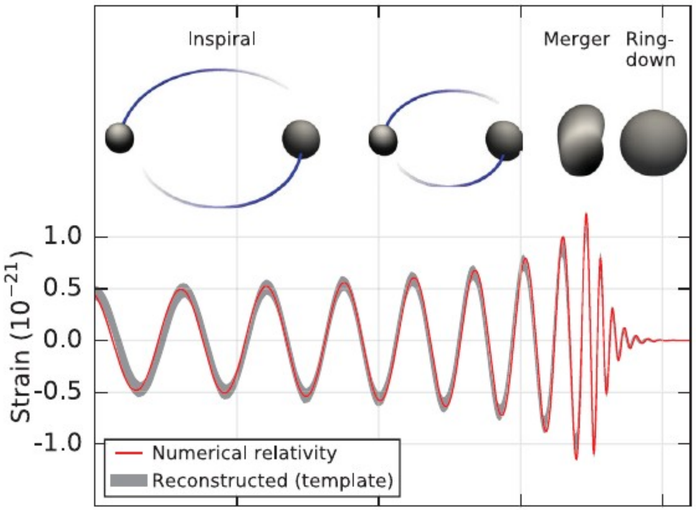

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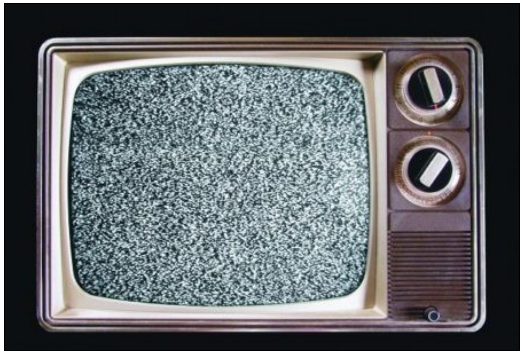
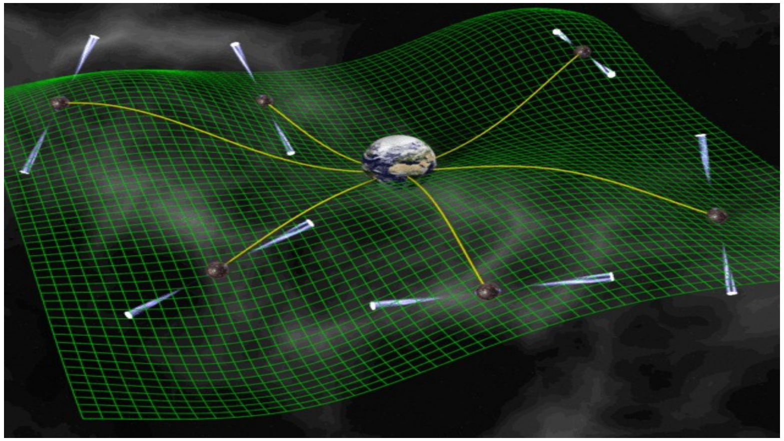


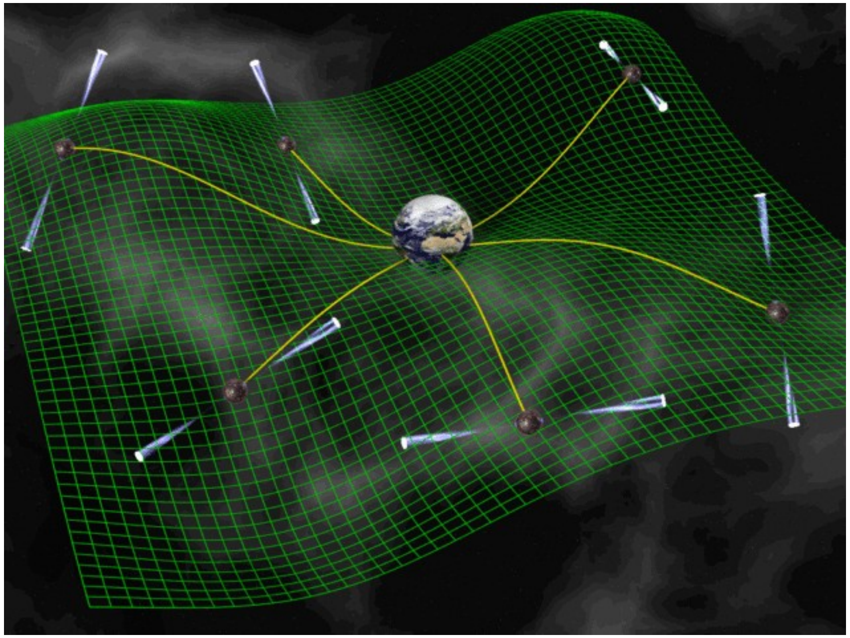
next challenge:
stochastic gravitational wave background

pulsar timing arrays



pulsar timing arrays

- search for delays in pulse arrivals
- 2020: evidence for common stochastic noise component across all pulsars
- 2023: evidence for Hellings-Down correlation (i.e. gravitational waves)



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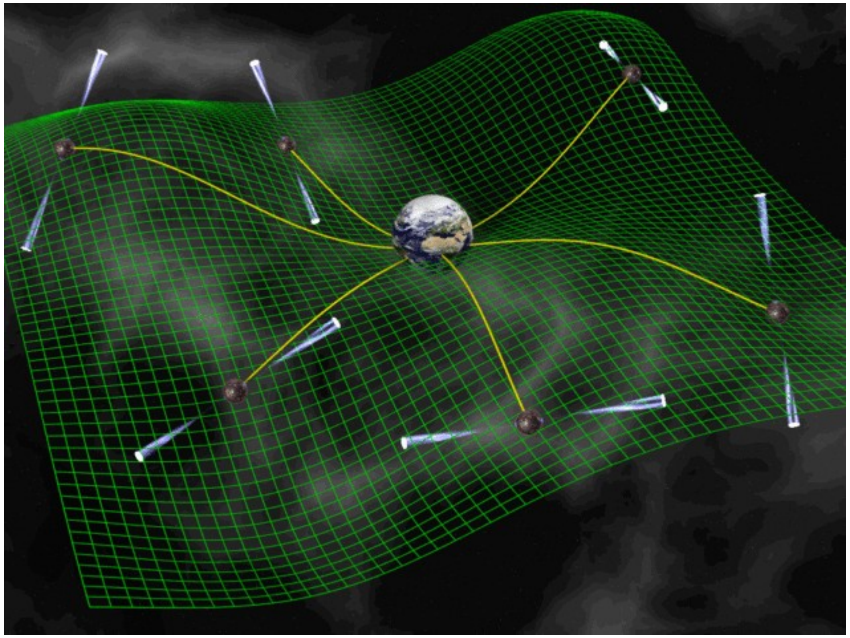

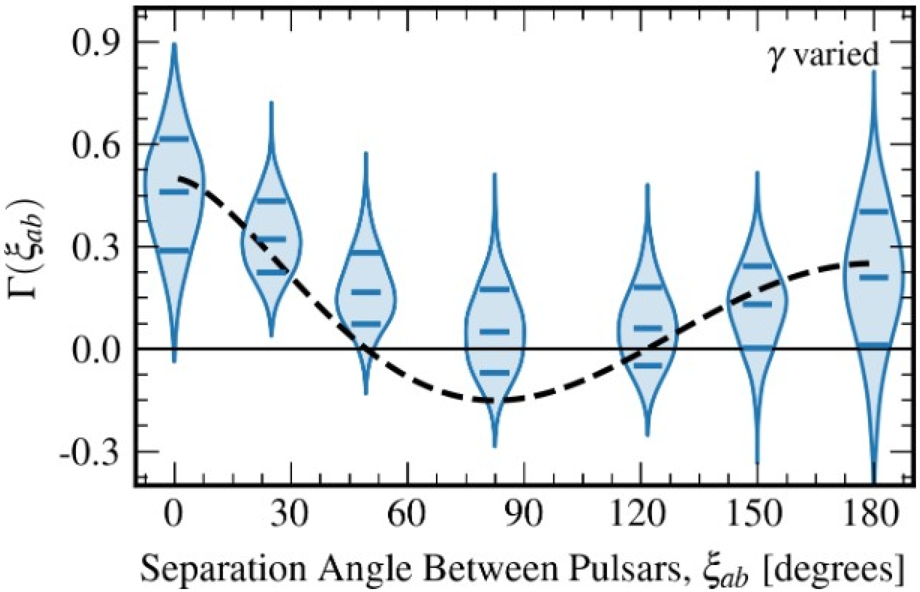

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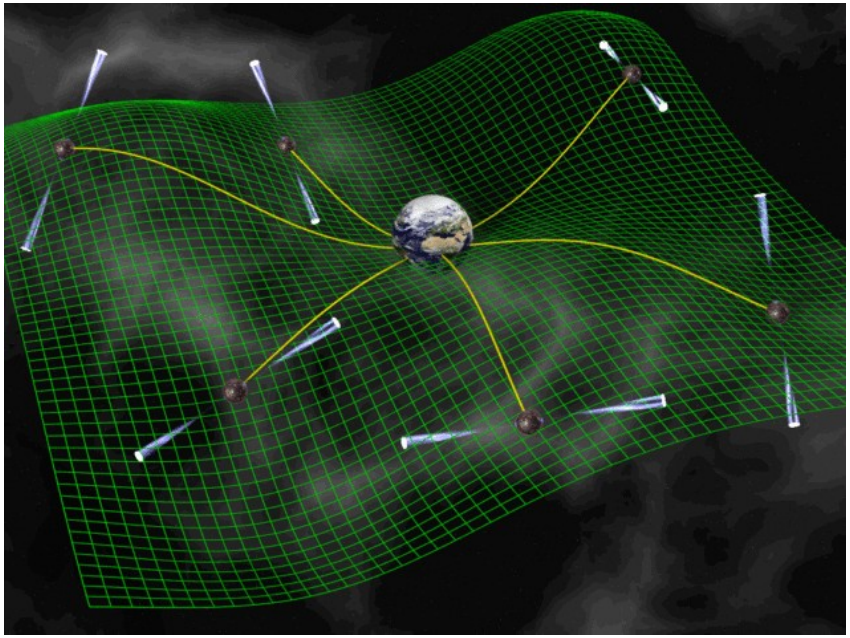
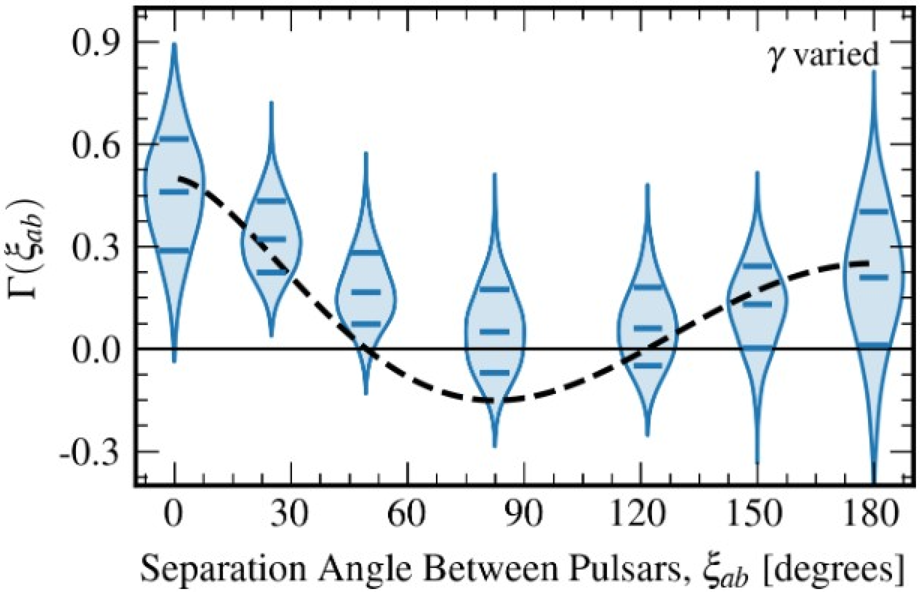




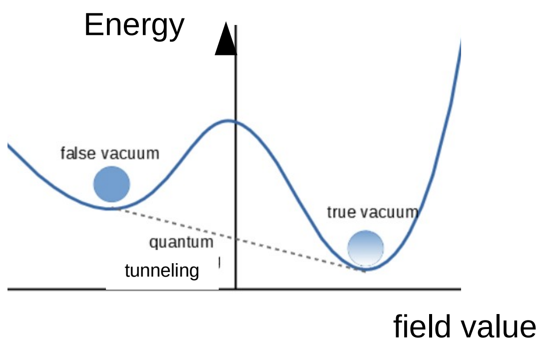
NANOGrav collaboration `23

- likely origin: supermassive BH binaries
- SGWB or individual source?
  → frequency dependence, anisotropy
- cosmological or astrophysical?
  → anisotropy

example : first order phase transition

Electroweak symmetry breaking: Cross-over in the SM, new physics in the Higgs sector can make it 1st order

.. and beyond: extended symmetry groups (eg GUTs) spontaneously broken in cooling Universe



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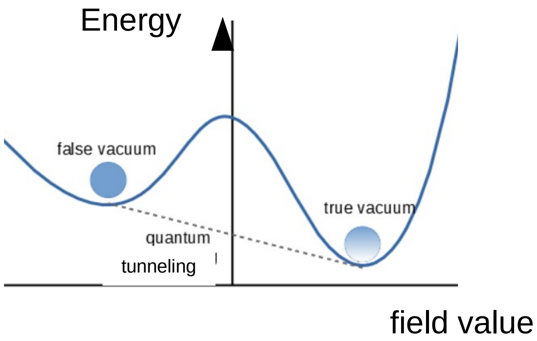
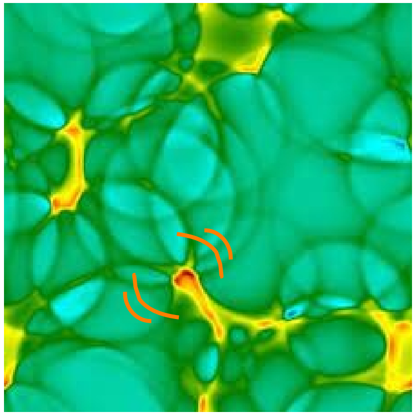
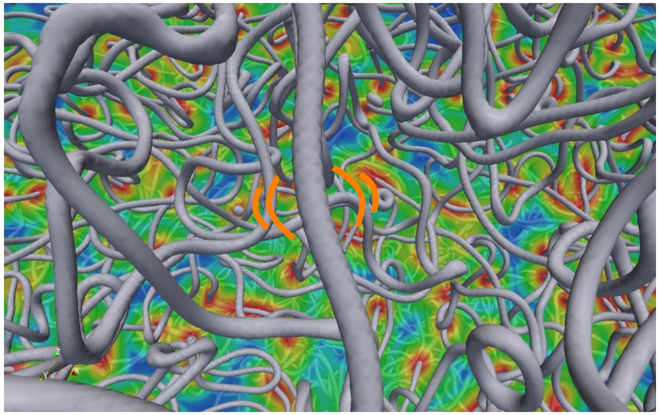
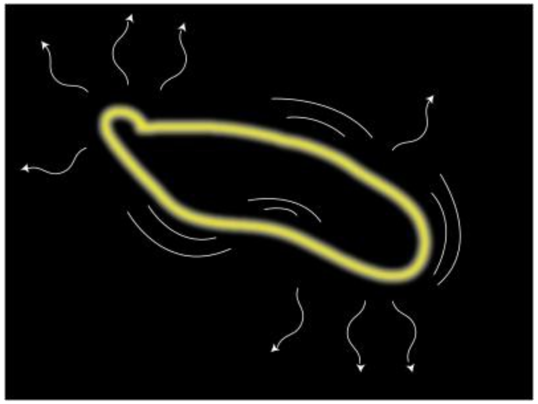








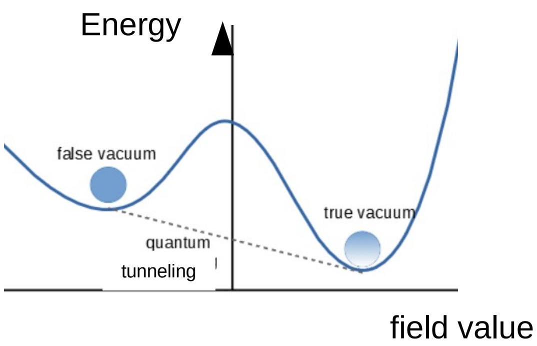
1st order PT sources GWs

topological defects formed during PT radiate GWs

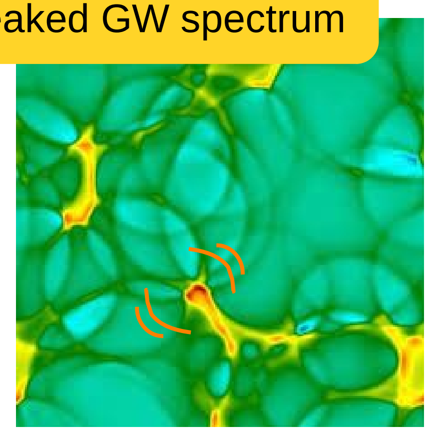
example : first order phase transition

Electroweak symmetry breaking: Cross-over in the SM,
new physics in the Higgs sector can make it 1st order

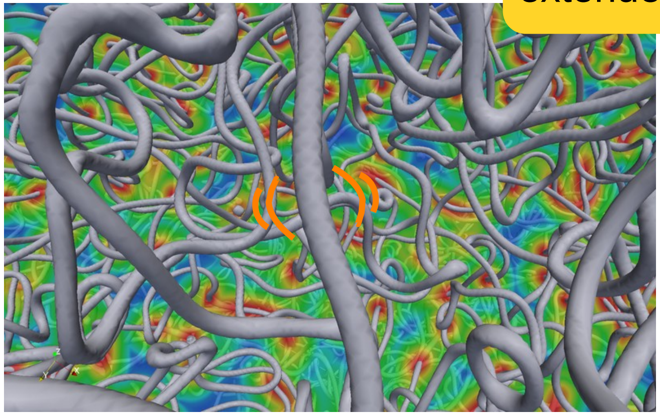
.. and beyond: extended symmetry groups (eg GUTs)
spontaneously broken in cooling Universe

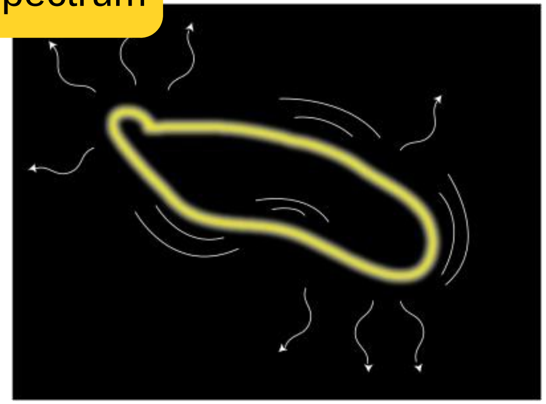


transient event → peaked GW spectrum



persistent source → extended GW spectrum

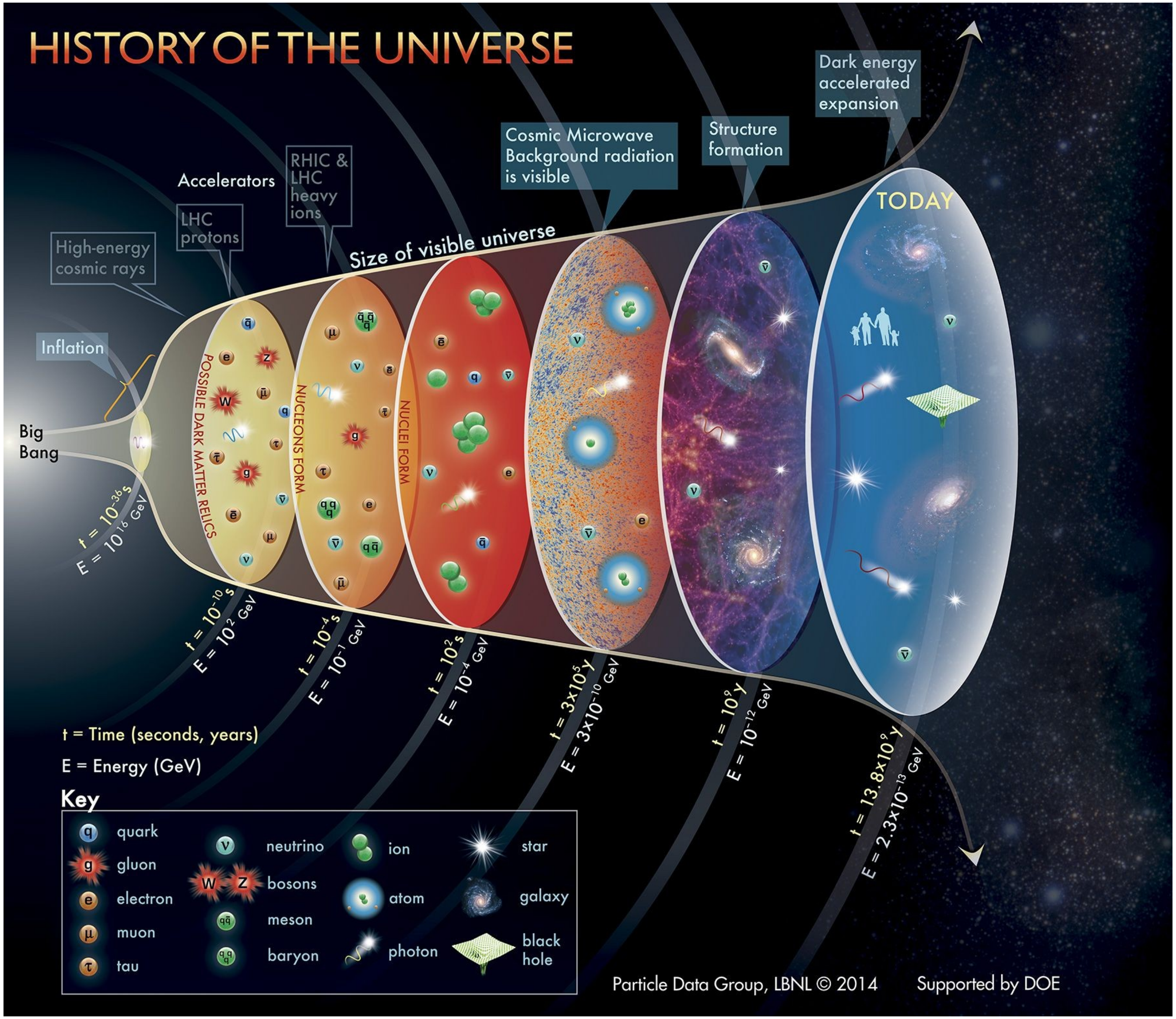




1st order PT sources GWs

topological defects formed during PT radiate GWs

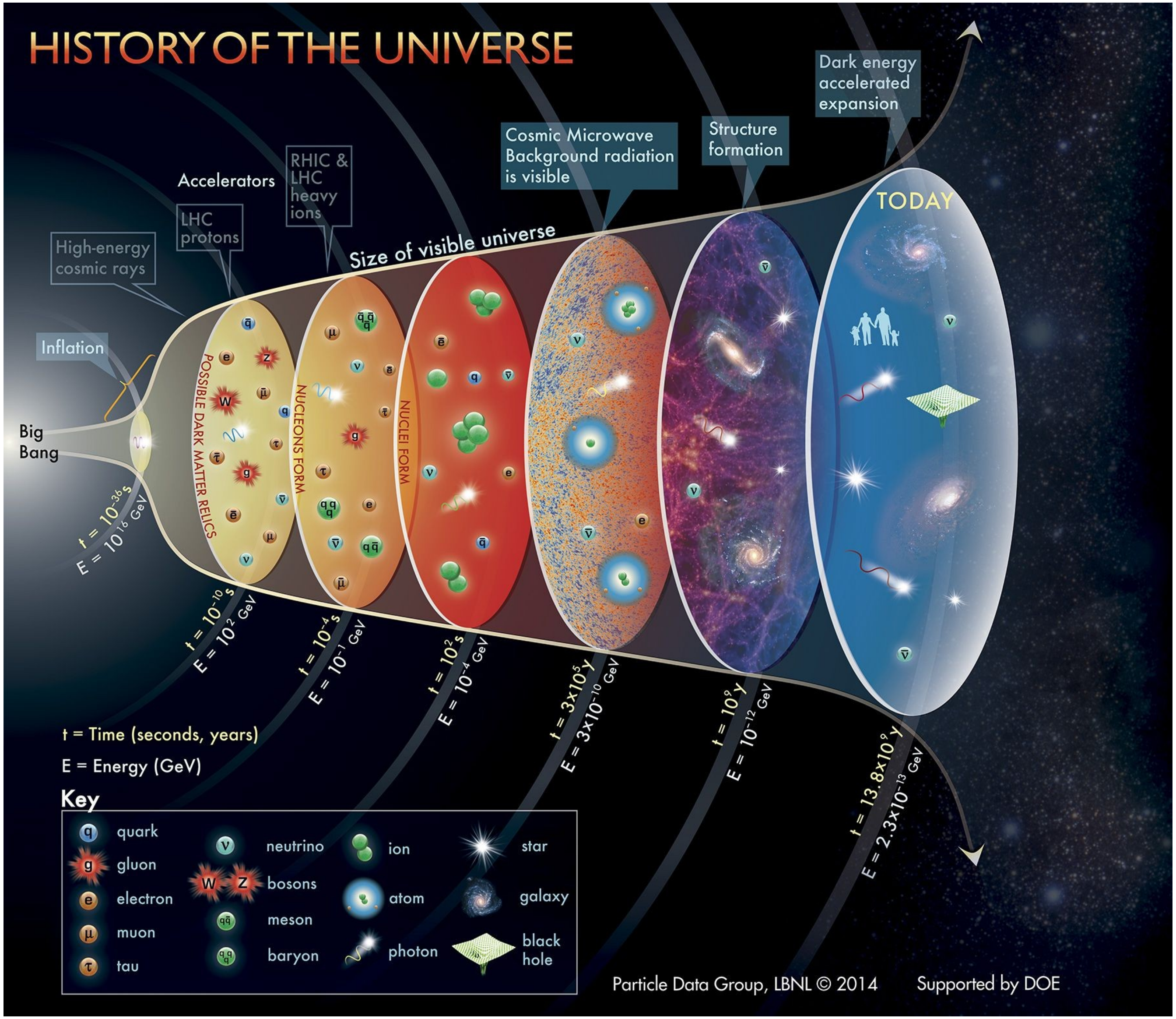
conclusions and outlook



the discovery of the CMB revolutionarized our under-standing of the universe

what surprises do gravitational waves reserve for us?

conclusions and outlook



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Thank you for your attention !