ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Particle Physics and Cosmology

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Das Land Steiermark
Wissenschaft und Forschung

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New Trends in Particle Physics, Quantum Gravity & Cosmology

Particle physics

distances $l < 10^{-14}$cm

and

Cosmology

distances $l > 10^{25}$ cm

What is the relation?

Universe expands $\Longrightarrow$

it was very hot and dense in the past $\Longrightarrow$

interactions between elementary particles were essential $\Longrightarrow$

they determined the structure of the Universe we see today

- Structure of the Universe $\Longrightarrow$ structure of particle theory
- Particle theory $\Longrightarrow$ structure of the Universe

Interaction between astronomy and particle physics started long time ago...

1675:

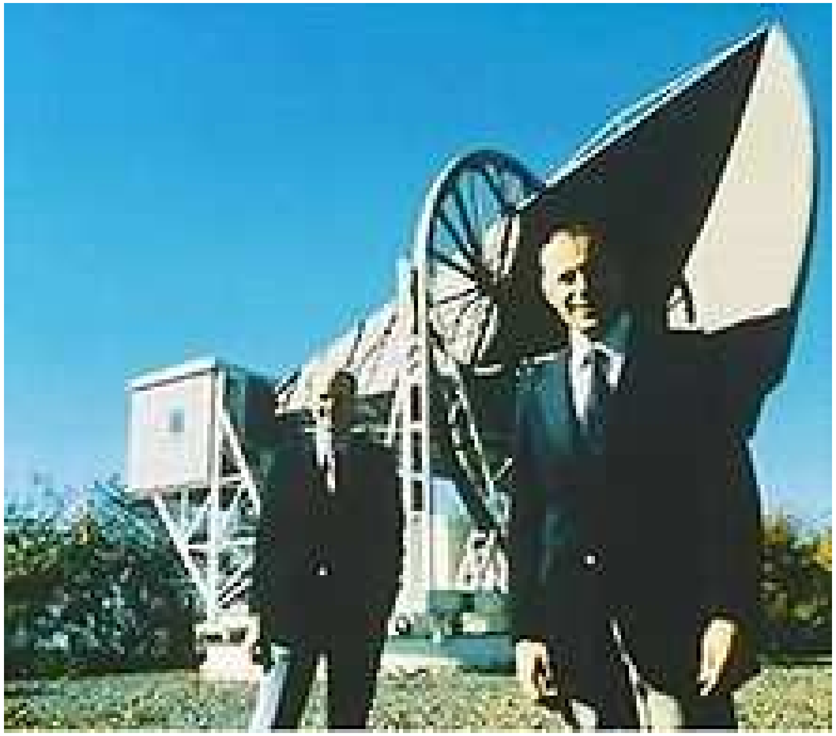
Ole Roemer estimated the speed of light from delay of the Jupiter satellite eclipse

1686:

Newton found the gravity constant (only in 1798 Cavendish measured it in the lab)

G_N and c are important parameters of particle physics!

New era started in 1965 with discovery by Penzias and Wilson of cosmic microwave background radiation, confirming thus the Big Bang theory of Lemaitre and Gamov, following from Fridman expansion



Particle physics, dark matter, and baryon asymmetry of the Universe

What is the nature of dark non-baryonic matter? New stable or long-lived particle?

Why the Universe contains more matter than antimatter? The particle theory theory must violate baryon number and break C and CP symmetries.

Disclaimer: cosmology cannot be used to prove some particular particle physics model. It can be used rather as a tool for rejecting particle physics theories.

Zeldovich: Universe is a poor man accelerator: it can produce very heavy particles, and it can produce very weakly interacting particles, since the temperature and particle number densities were high in the past. Unfortunately, the experiment happened just once!

An overlap between particle physics and cosmology is very rich:

- Inflation
  - Vacuum meta(?) stability
  - UV completion
- Baryogenesis
- Dark matter
- Dark energy
- Nucleosynthesis
- Neutrino properties
- Phase transitions
  - Cosmic strings (?)
  - Stochastic gravitational waves (?)
  - Cosmological magnetic fields?
- . . .

Outline

Lecture 1: What are the problems and ideas for solutions?

- Structure of the Universe at large scales: flatness, horison, etc
  - Inflationary Universe
- Charge asymmetry of the Universe
  - Baryogenesis
- Rotational curves of galaxies, matter content, large scale structure
  - Particle Dark Matter

Outline

Lecture 2

- The current scene: LHC and ΛCDM
- Vacuum meta(?) stability
- Minimal physics for inflation: Higgs as an inflaton

Lecture 3

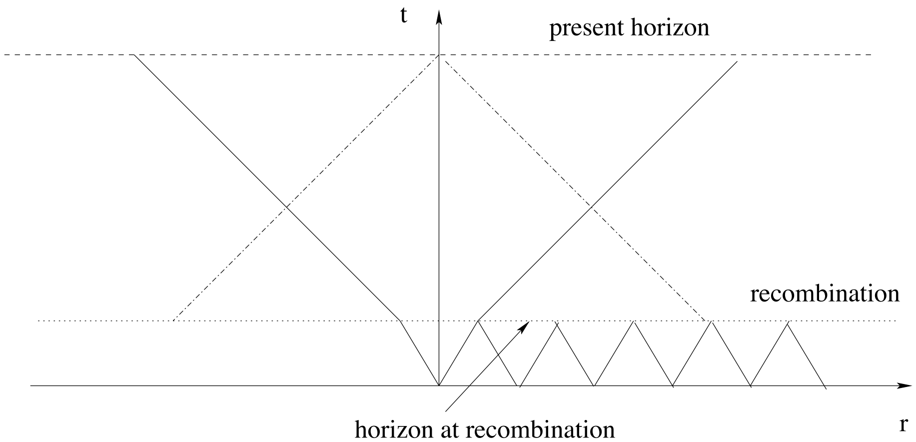
- Minimal physics for neutrino masses
- Baryogenesis
- Dark Matter
- Conclusions

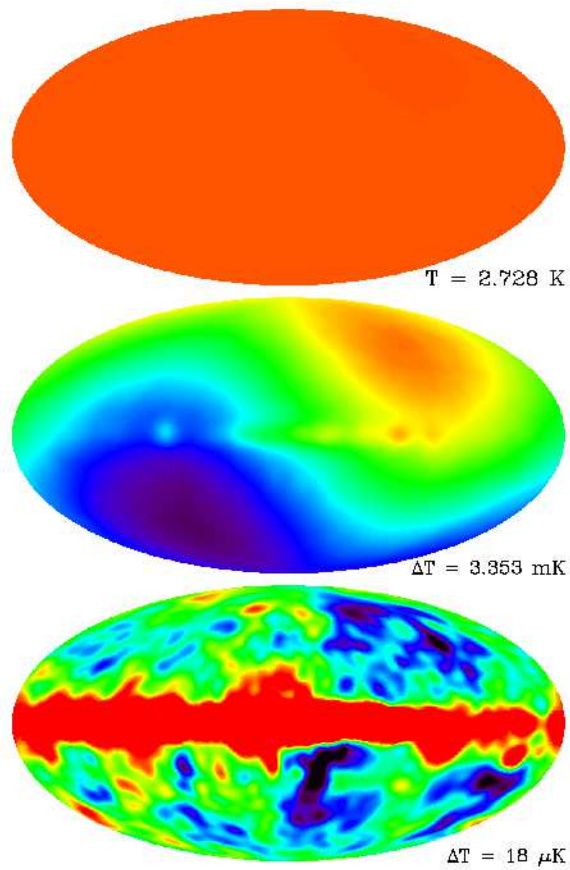
Structure of the Universe at large scales and Inflation

Universe at large scales

Important cosmological problems:

Horizon problem: Why the universe is so uniform and isotropic?





$r \propto t^{1/2}$ (radiation), $r \propto t^{2/3}$ (matter)

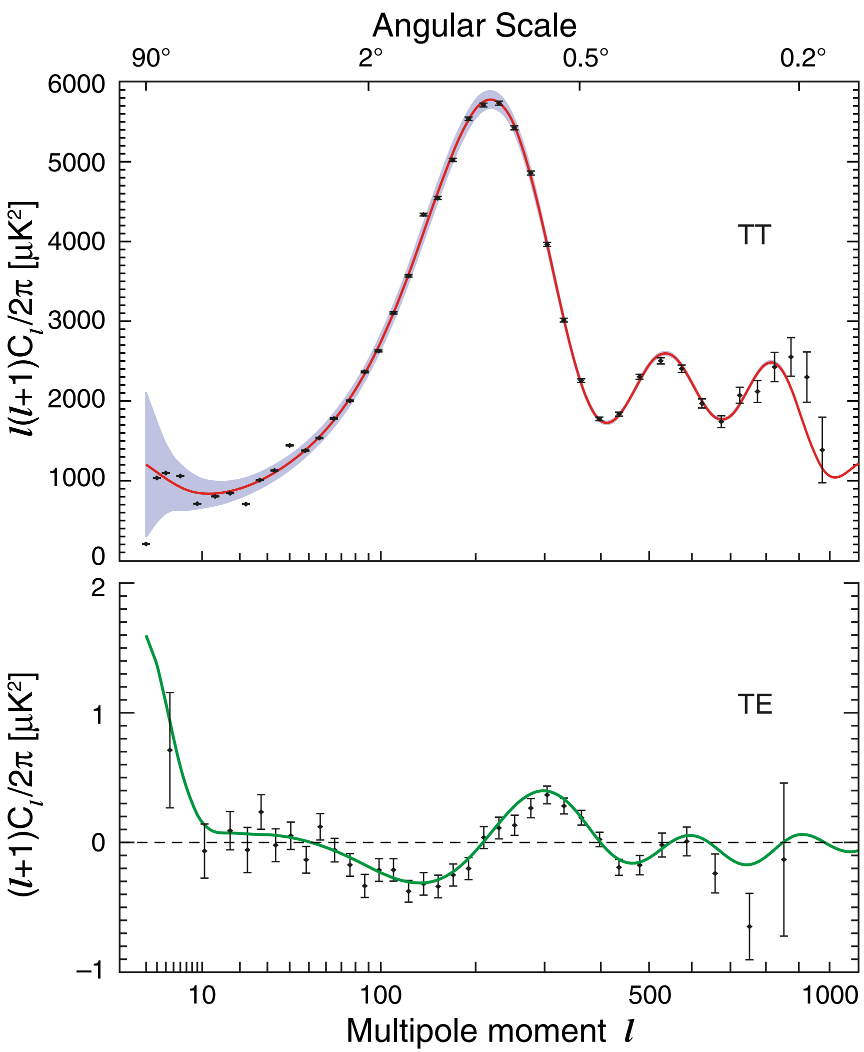
Expected fluctuations at $\theta \sim 1^o$:

$\delta T/T \sim 1$.

Observed fluctuations: $\delta T/T \sim 1O^{-5}$

$t_U \simeq 14$ billion years, $t_r \simeq 2 \times 10^5$ years

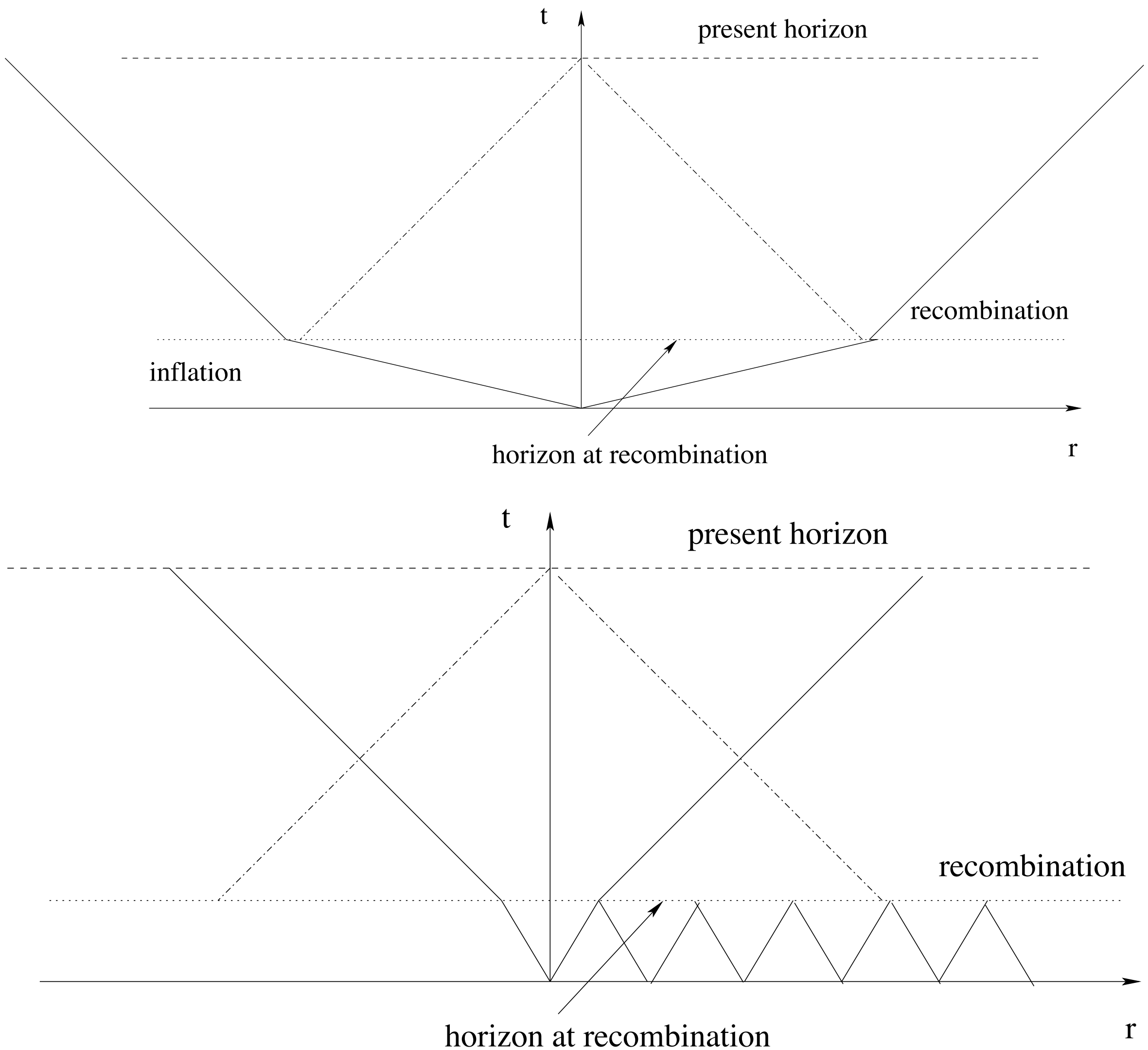
Structure formation problem: What is the origin of cosmological perturbations and why their spectrum is almost scale-invariant?



Flatness problem: Why $\boldsymbol{\Omega_M + \Omega_\Lambda + \Omega_{\mathrm{rad}}}$ is so close to 1 now and was immensely close to 1 in the past?

All this requires enormous fine-tuning of initial conditions (at the Planck scale?) if the Universe was dominated by matter or radiation all the time!

Solution: Inflation = accelerated Universe expansion in the past



Mechanism: scalar field dynamics

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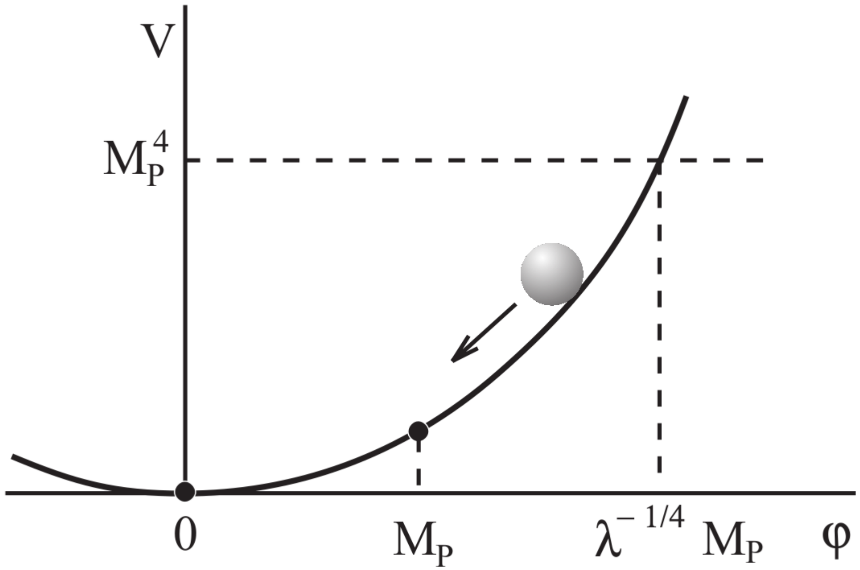
Why scalar?

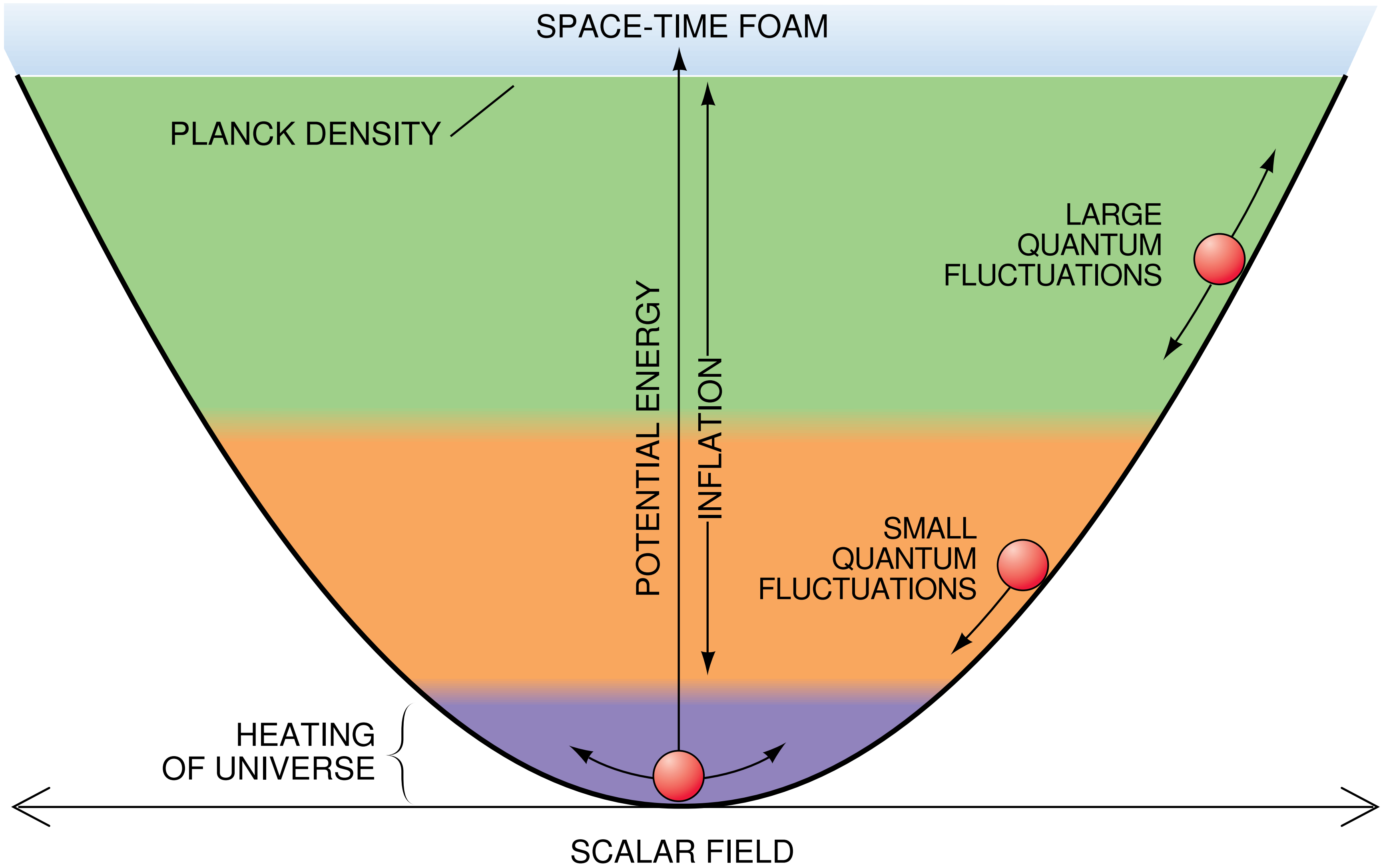
- Vector - breaking of Lorentz symmetry
- Fermion - bilinear combinations are equivalent to scalar fields
- Uniform scalar condensate has an equation of state of cosmological constant and leads to exponential universe expansion

“Standard” chaotic inflation

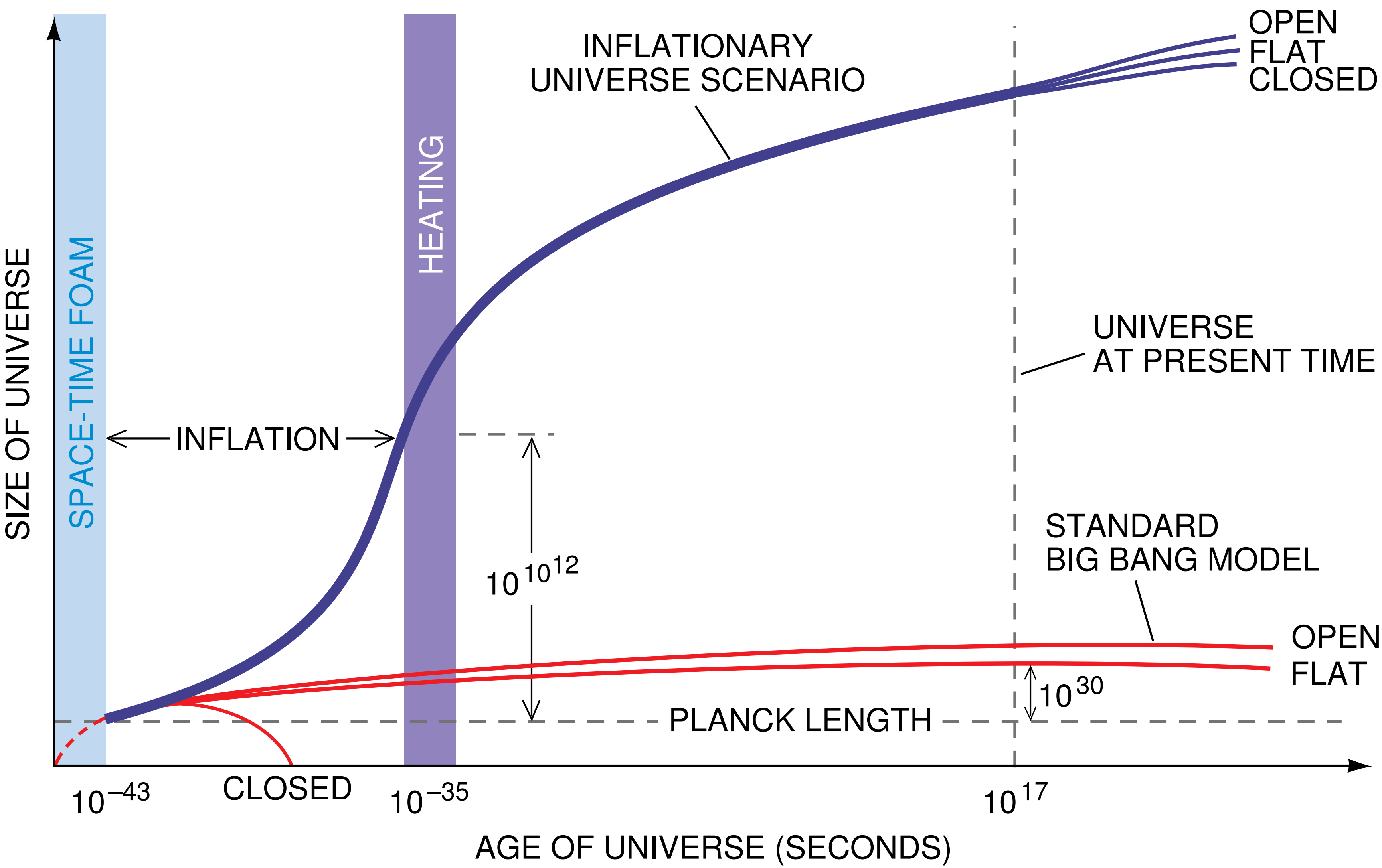
$$V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$$



Chaotic initial conditions: exponential expansion of the Universe at the beginning



Courtesy: Linde



Courtesy: Linde

Challenge for particle physics:

What kind of scalar field drives inflation?

Almost flat potential for large scalar fields is needed! Linde

Required for inflation: (to get $\delta T/T \sim 10^{-5}$)

- quartic coupling constant $\lambda \sim 10^{-13}$:
- mass $m \lesssim 10^{13}$ GeV,

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Do we need new particles? New physics is required?

Baryon asymmetry of the Universe and baryogenesis

The birth of antimatter

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Big theoretical issue: how to unify quantum mechanics and special relativity

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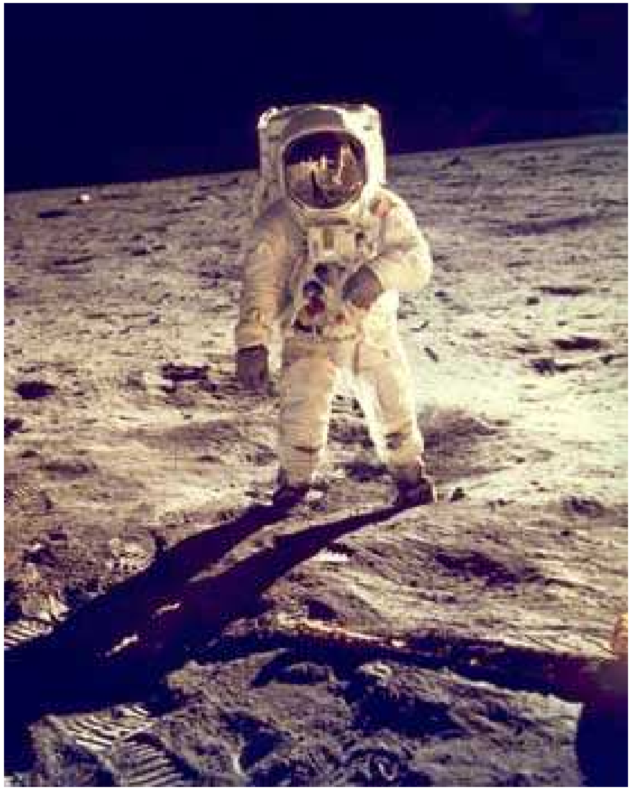
1930, Dirac: construction of relativistic equation describing quantum mechanics of electron (particle with spin $\frac{1}{2}$)

Dirac hypothesis: Nobel Prize Lecture, 1933

“If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regards it rather as an accident that the Earth (and presumably the whole solar system), contains a predominance of electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. In fact, there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

Baryon asymmetry in the present universe

Dirac was perfectly correct that the solar system is constructed from matter!



However, how can we know whether distant stars and galaxies consist of matter or antimatter?

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Baryon asymmetry in the present universe

There are several methods for detection of antimatter:

- The search of antinuclei in cosmic rays: the probability of the process

$$pp \rightarrow antinuclei + etc$$

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is very small!

Result: no antinuclei in cosmic rays have been found!

Detection of antimatter

- Annihilation: particles and antiparticles annihilate:

$$p\bar{p} \quad \rightarrow \quad \pi^+ \quad \pi^- \quad \pi^0 \quad \rightarrow \quad \gamma\gamma$$

$$\nu_\mu \mu^+ \swarrow \qquad\qquad \searrow \mu^- \bar{\nu}_\mu$$

$$e^+ \nu_e \bar{\nu}_\mu \swarrow \qquad\qquad\qquad \searrow e^- \bar{\nu}_e \nu_\mu$$

Detection of γ-rays?

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Detection of γ-rays?

However, this has not been observed!

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Dirac was wrong: cosmological observations do not support the hypothesis that the distant stars and galaxies may consist of antimatter.

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The problem

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Where is antimatter?

Our universe is asymmetric!

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The problem

Where is antimatter?

Its absence looks really strange, as the properties of matter and antimatter are very similar!

On the way to a solution

Breaking of charge symmetry and parity

Till 1956: general belief that the nature is symmetric with respect to change of particle into antiparticle.

C - charge conjugation: $p \leftrightarrow \bar{p}, \quad n \leftrightarrow \bar{n}, \quad e^- \leftrightarrow e^+$

P - parity transformation: $\vec{x} \to -\vec{x}$, $\vec{v} \to -\vec{v}$, but for spin $\vec{m} \to +\vec{m}$

1956: discovery of P and C breaking in weak interactions (Lee, Yang).

Many manifestations, e.g. in $\pi^{\pm}$ decays. In particular, C-transformation change left-handed neutrino into left-handed antineutrino, which does not exist.

Conclusion: properties of particles and antiparticles are in fact (somewhat) different.

However, the combined CP symmetry was believed to be exact:

change particles to antiparticles AND simultaneously their momenta.

Now, CP works for neutrino

$$CP: \quad \nu(\vec{v}) \quad \longrightarrow \quad \bar{\nu}(-\vec{v})$$

So, an antiparticle has the same properties as a particle in the mirror!

Still no solution for the problem of baryon asymmetry of the universe...

Universe is isotropic, according to observations.

Breaking of combined CP symmetry

1964 (Cronin, Fitch, Christenson, Turlay):

decays of K^0 mesons.

In a small fraction of cases ($\sim 10^{-3}$), long-lived K_L (a mixture of K^0 and $\bar{K}^0$ decays into pair of two pions, what is forbidden by CP-conservation. There are other manifestations of CP breaking. For example, if CP were exact symmetry, an equal number of K^0 and $\bar{K}^0$ would produce an equal number of electrons and positrons in the reaction

$$K^0 \to \pi^- e^+ \nu_e, \quad \bar{K}^0 \to \pi^+ e^- \bar{\nu}_e,$$

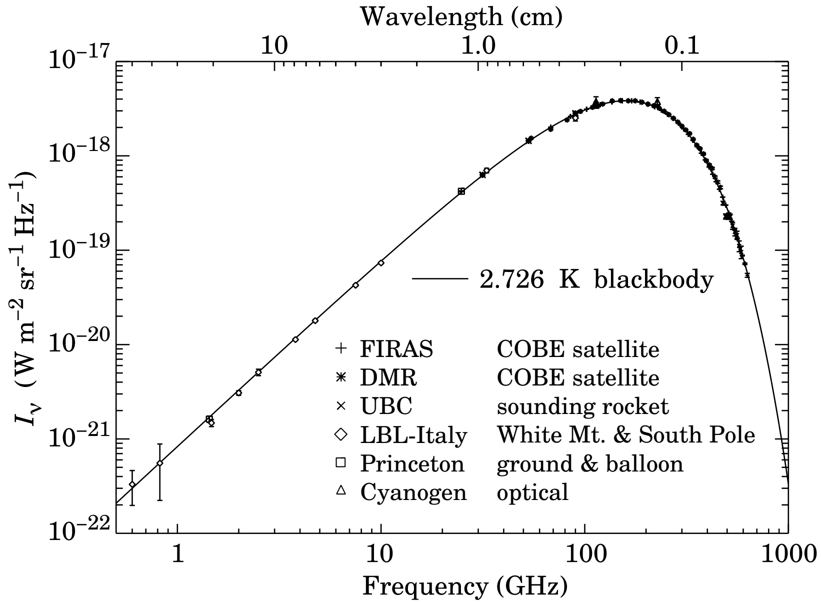
However, this is not the case: the number of positrons is somewhat larger ($\sim \mathbf{10^{-3}}$) than the number of electrons.

Conclusion: so, there is indeed a tiny difference between particles and antiparticles, on the level of $\mathbf{10^{-3}}$

How can this very small distinction be transformed in the 100% asymmetry of the universe we observe today?

Cosmic microwave background

In 1965, Penzias and Wilson observed radio-waves in sub-millimeter range which were coming from all directions of the sky. They have a spectrum of black-body radiation with temperature $\mathbf{2.73^0}$.



The spectrum of the CMB

Big Bang and baryon asymmetry

Why do we care?

The existence of CMB is a proof of the Big Bang theory: universe expands and it was hot and dense in the past:

$$T[^oK] = \frac{10^{10}}{\sqrt{t[sec]}}$$

At temperatures $T > 10^{13}$ ^{0}K $\simeq m_p c^2/k$ reactions like $\gamma + \gamma \to e^+e^-, \quad \bar{p}p$ are effective: amount of antimatter is comparable with that of matter!

Big Bang and baryon asymmetry

Question: what is the baryon asymmetry

$$\Delta(t_0) = \frac{n_B - \bar{n}_B}{n_B + \bar{n}_B}$$

at this moment? ($T \sim 10^{13}\ {}^0K,\ \ t \sim 10^{-6}$s)

Answer:

To find $\Delta(t_0)$ just take n_B/n_γ today!

Why?

Because of reaction $p\bar{p} \rightarrow$ few γ

Big Bang and baryon asymmetry

We have

- $n_\gamma \sim (410.4 \pm 0.5)$ photons/cm^3 (corresponds to temperature 2.73^0K)
- $n_B \sim (0.25 \pm 0.01)$ nucleon/m^3

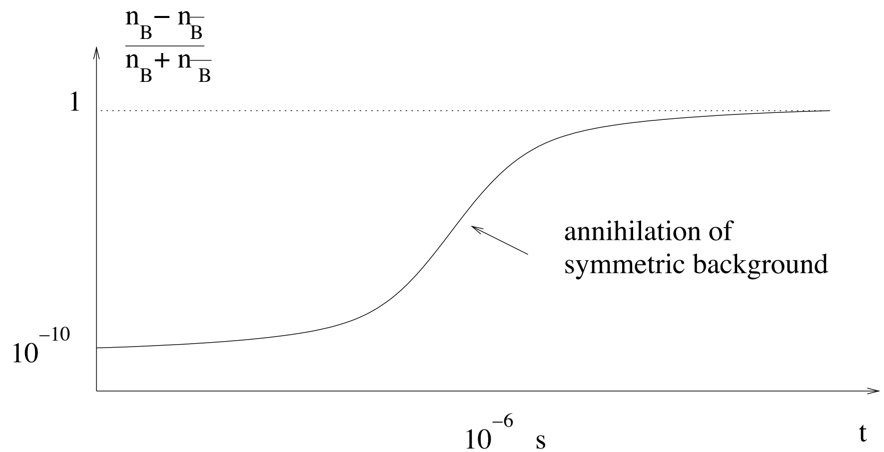
$$\Longrightarrow n_B/n_\gamma \simeq (6.1 \pm 0.2) \times 10^{-10}$$

Conclusion: Big Bang theory tells that the baryon asymmetry of the early universe is a very small number

$$\frac{(n_B - \bar{n}_B)}{(n_B + \bar{n}_B)} = 10^{-10}$$

Big Bang and baryon asymmetry

At $t \sim 10^{-6}$s after the big Bang for every 10^{10} quarks we have $(10^{10} - 1)$ antiquarks. Somewhat later the symmetric background annihilates into photons and neutrinos while the asymmetric part survives and gives rise to galaxies, stars, planets.



Dependence of baryon asymmetry on time

Big Bang and baryon asymmetry

Problems to solve:

- Why in the early universe the number of baryons is (a little bit, $\sim \mathbf{10^{-10}}$) greater than the number of antibaryons?
  Now, the comparison between of the baryon asymmetry in the early universe and the measure of the difference between particles and antiparticles in $\boldsymbol{K^0}$ decays $(\mathbf{10^{-3}})$ is much more comfortable!
- How to compute the primordial baryon asymmetry from fundamental theory?

Andrei Sakharov proposal, 1967:

“According to our hypothesis, the occurrence of C-asymmetry is the consequence of violation of CP-invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

In short: the universe is asymmetric because baryon number is not conserved in C- and CP-violating reactions which produce more baryons than antibaryons in expanding universe.

Consequence: Proton is not stable!

Sakharov model

Superheavy particles with mass $m \sim 10^{-5}$ grams,

and lifetime 10^{-43} s

Decay modes:

$$X \to p\,p, \quad p\,e^{+}, \quad \bar{X} \to \bar{p}\,\bar{p}, \quad \bar{p}\,e^{-}$$

If C and CP are broken, X and $\bar{X}$ will produce different number of protons et antiprotons, as K^0 and $\bar{K}^0$ produce the different numbers of electrons and positrons.

It is sufficient to produce a very small asymmetry 10^{-10} which will then be converted into 100% asymmetry later on.

Sakharov model

Revolutionary solution at that time: there was a believe that the proton is absolutely stable!

Paradox: there is no antimatter in the universe since matter is unstable!

Qualitatively, universe is asymmetric due to

- baryon number non-conservation
- breaking of C and CP
- universe expansion

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- B-violation?

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What kind of physics leads to

- B-violation?
- CP-violation?
- thermal nonequilibrium?

Dark matter in the universe

Problem since 1933, F. Zwicky.

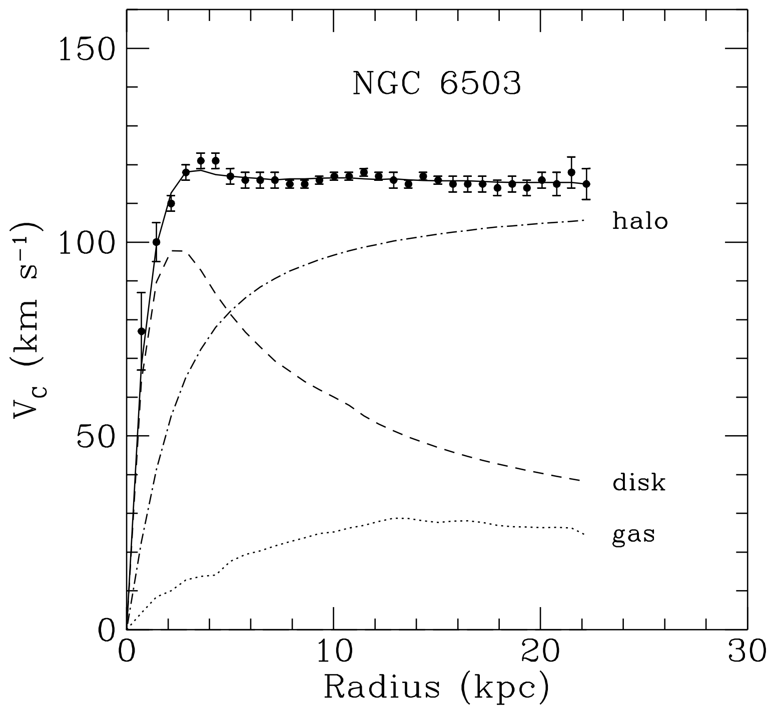
Most of the matter in the universe is dark

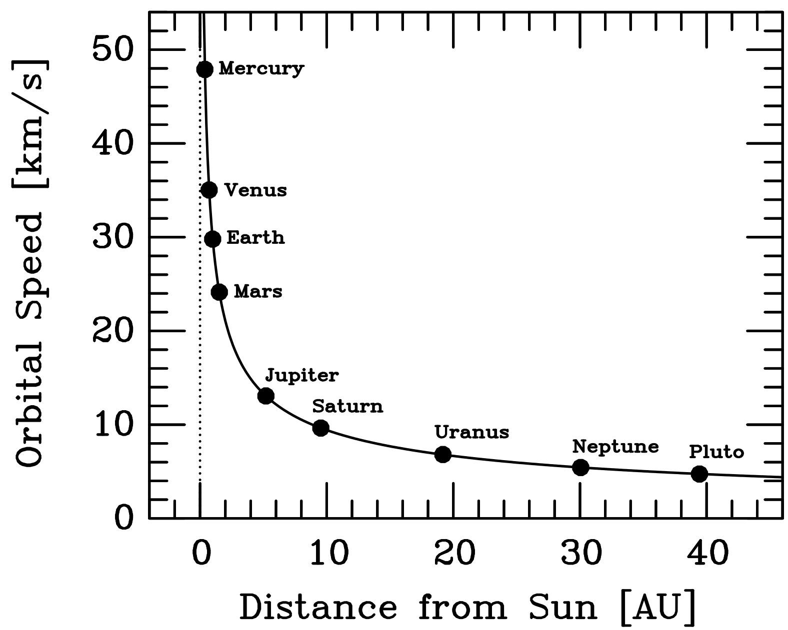
Evidence:

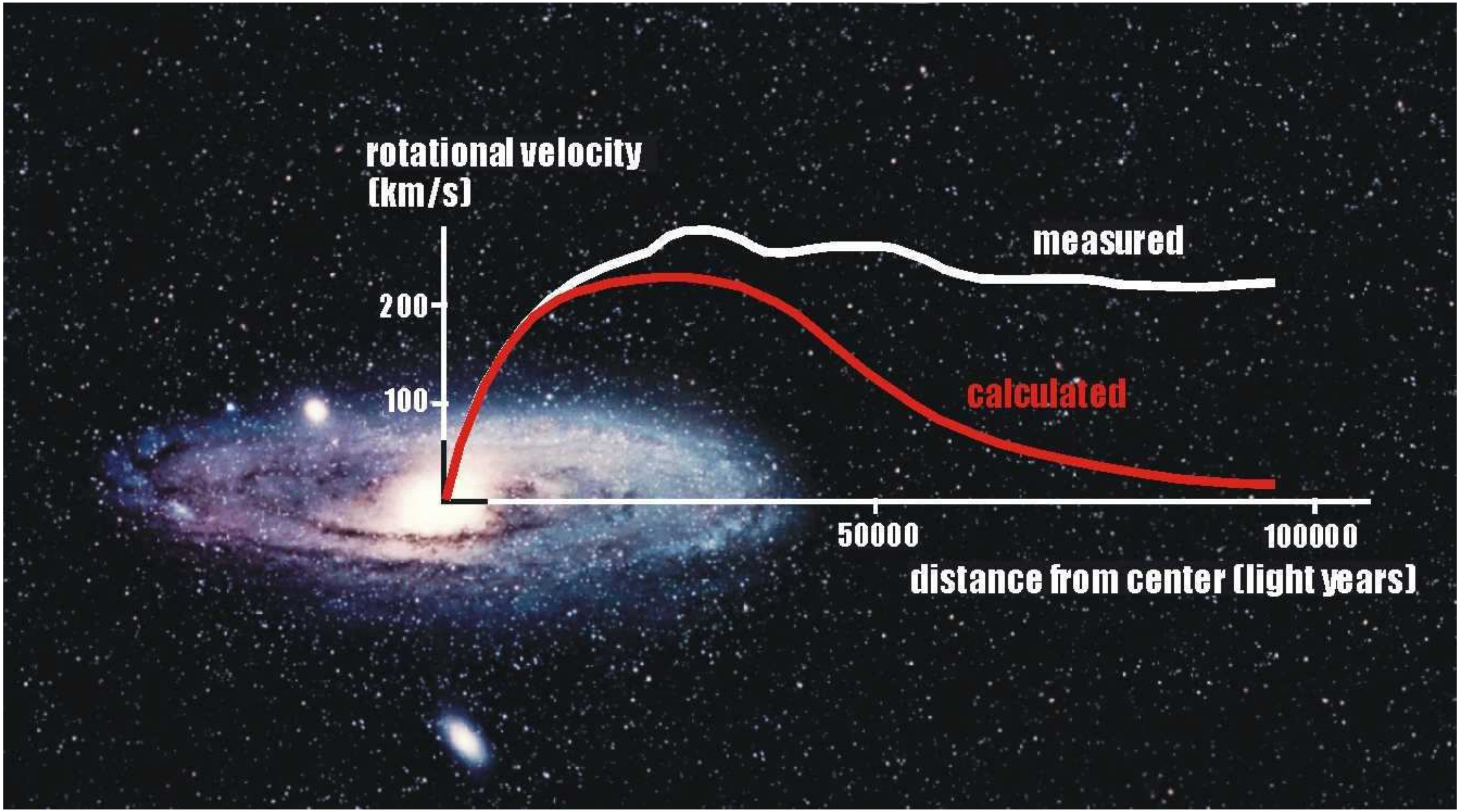
- Rotation curves of galaxies
- Big Bang nucleosynthesis
- Structure formation
- CMB anisotropies
- Supernovae observations

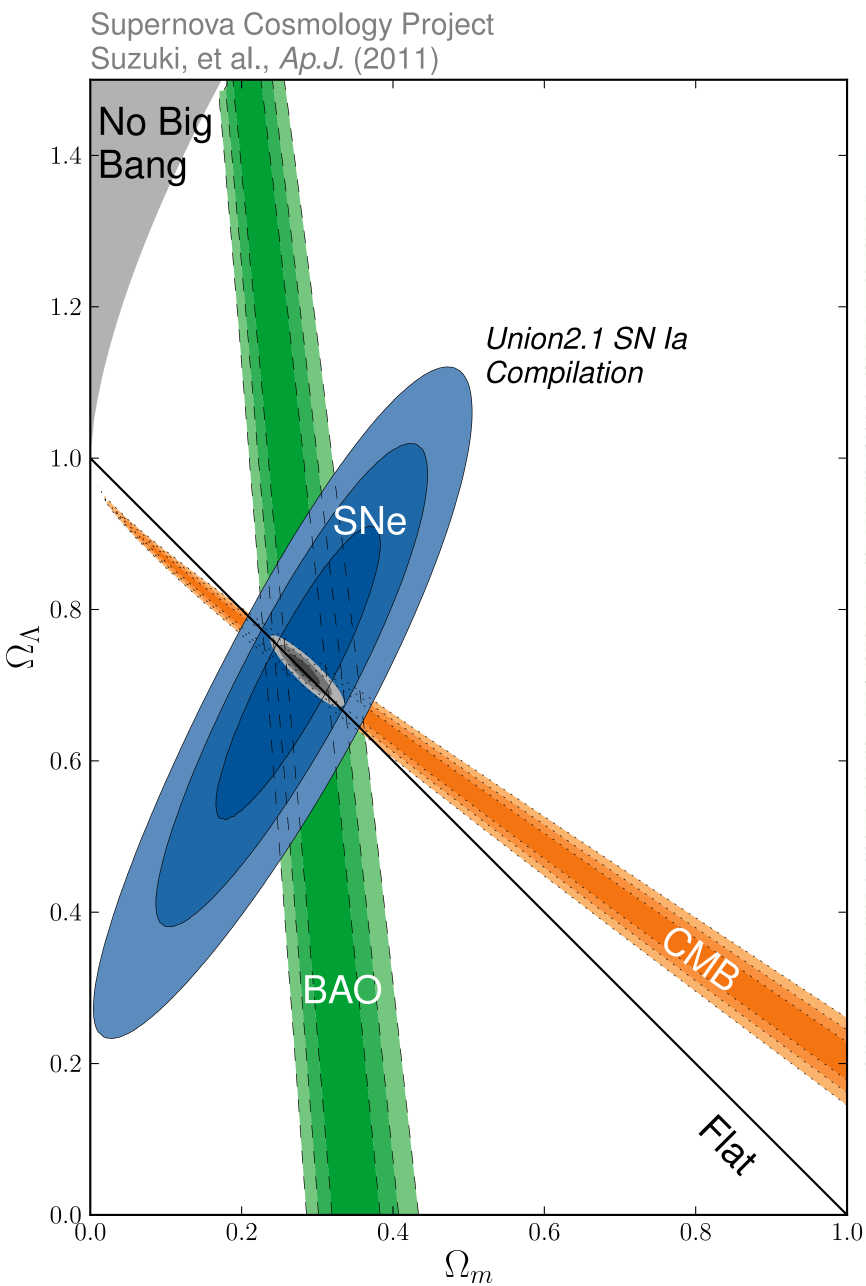
Non-baryonic dark matter:

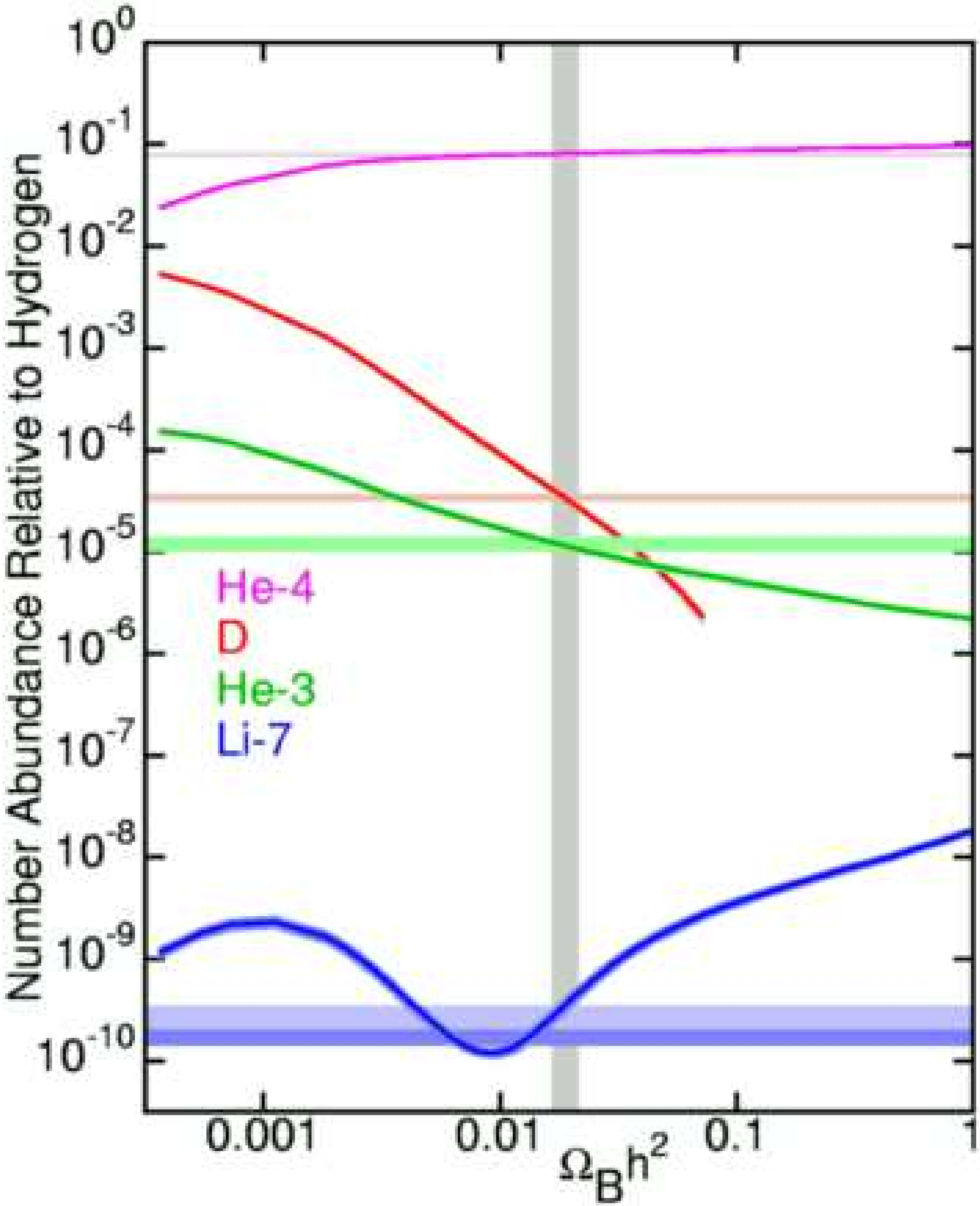
$\Omega_{DM} \simeq 0.22$

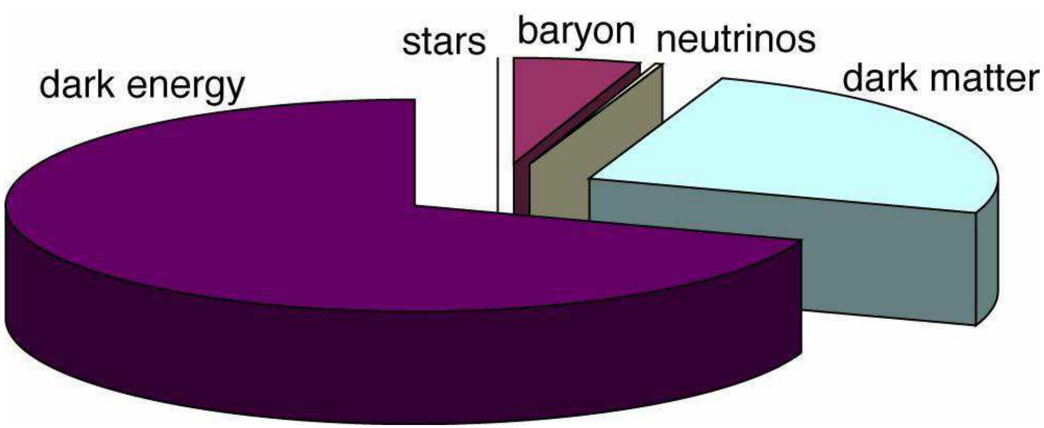





rotational velocity
(km/s)
200
100
measured
calculated
50000
100000
distance from center (light years)


Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)
No Big Bang
Union2.1 SN Ia Compilation
SNe
BAO
CMB
Flat
Ω_Λ
Ω_m


Number Abundance Relative to Hydrogen
He-4
D
He-3
Li-7
$\Omega_B h^2$



Standard Model: no particle physics candidate for Dark Matter

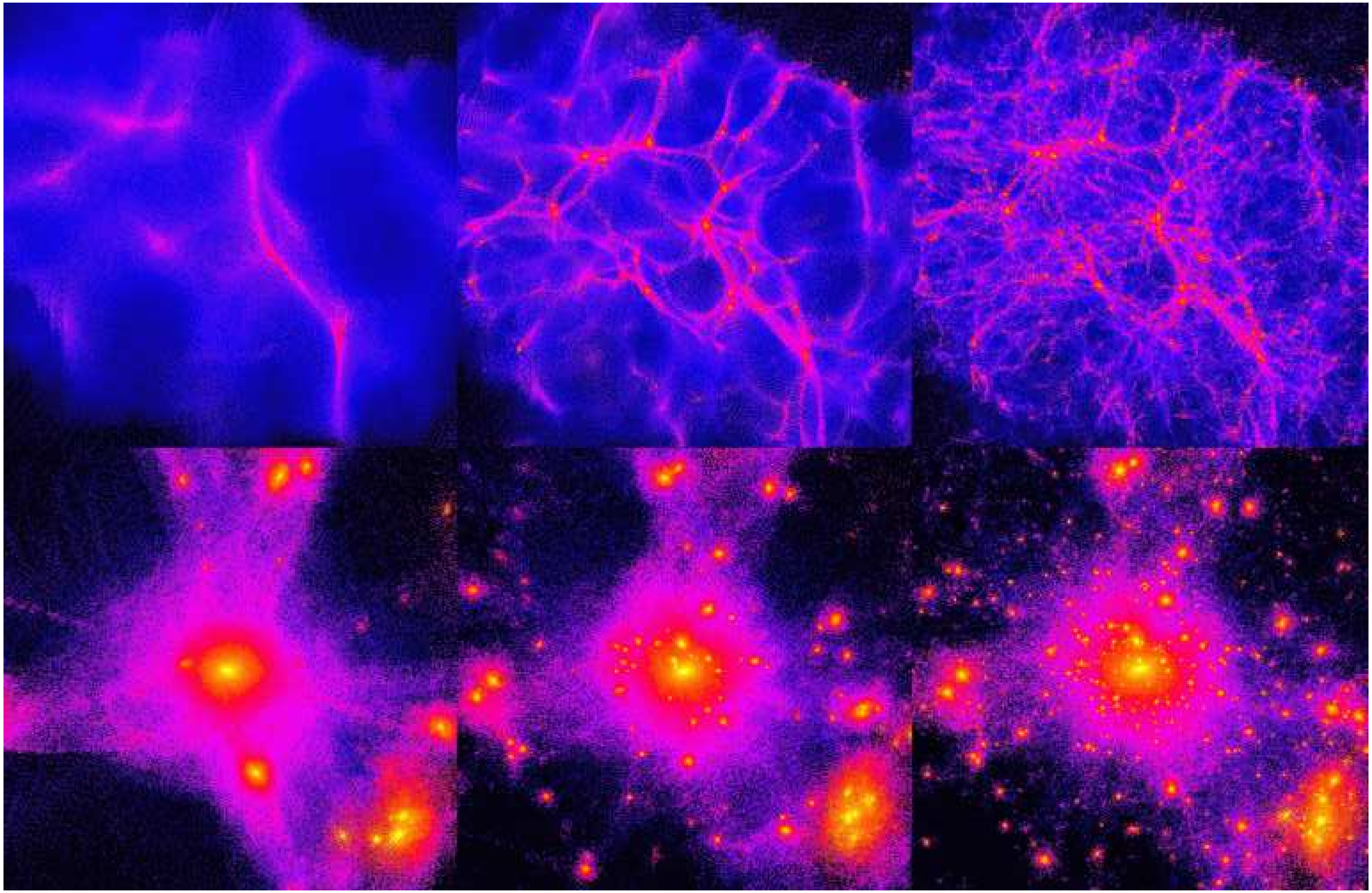
- The only neutral stable objects - atoms and neutrinos
- if atoms: contradiction with BBN - so many baryons are not admitted
- if neutrinos - hot DM: contradiction with structure formation - small scale inhomogeneities are erased

Dark Matter : new particle (?)

What do we know for sure about DM particles

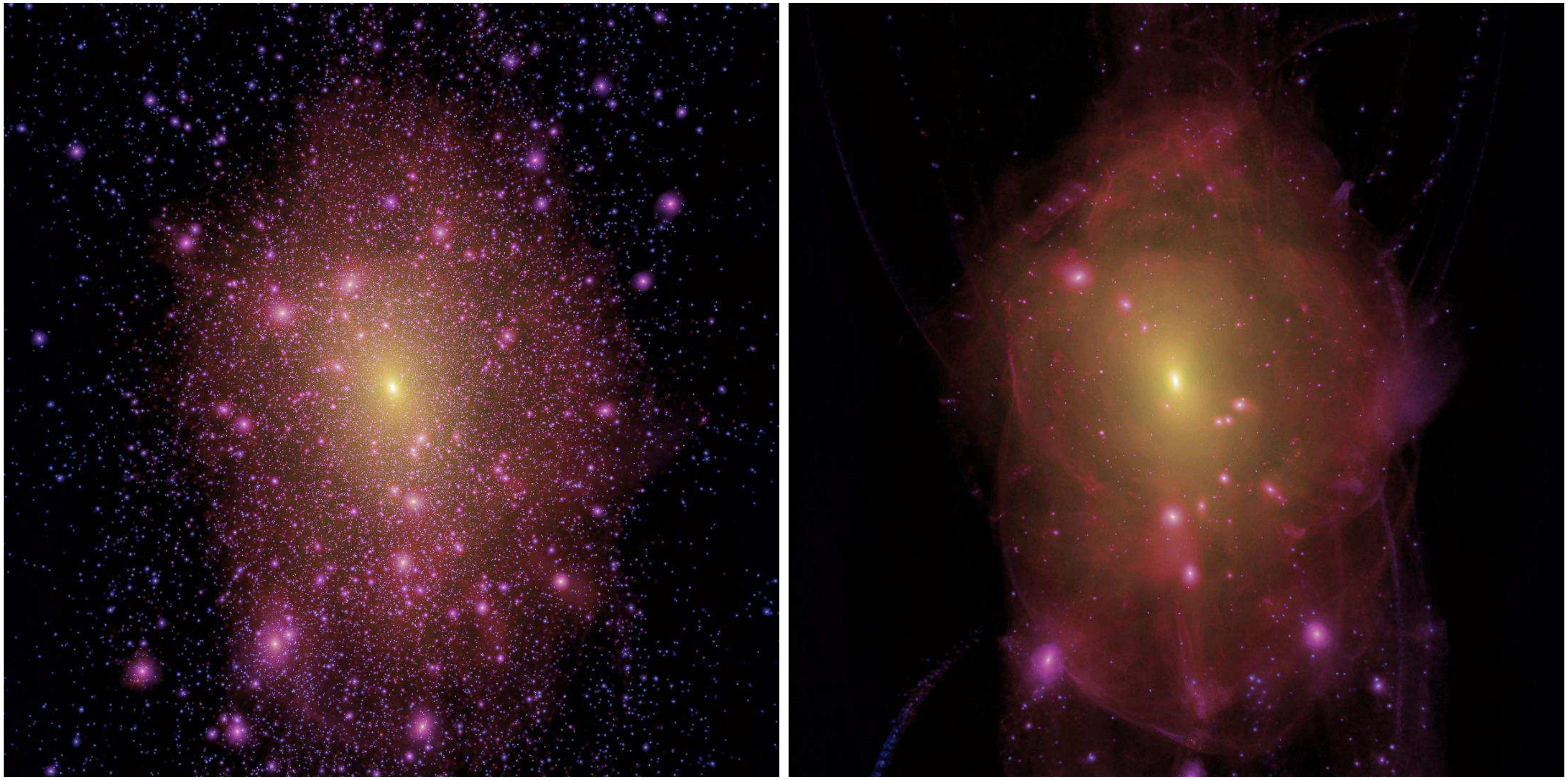
- They must have a lifetime exceeding the age of the Universe - otherwise they would have decayed.
- Relatively light particles ($M <$ few TeV) must be neutral and very weakly interacting - otherwise we would easily detect their cosmic flux.
- The DM particles should form the cold or warm DM – they must not be relativistic at the onset of structure formation, Lyman-α data puts $\lambda_{FS} < 150$ kpc.
- If they are fermions, their mass should not be below 400 eV – Tremaine-Gunn bound.

Hot DM Warm DM Cold DM



Ben Moore simulations

Number of satellites of the Milky way



CDM versus WDM, Carlos Frenk et al.

Lower mass bound on fermionic DM

- The smaller is the DM mass the bigger is the number of particles in an object with the mass M_{vir}
- Average phase-space density of **fermion** DM particles should be **smaller** than density of **degenerate Fermi gas**

$$\frac{M_{\text{vir}}}{\frac{4\pi}{3}R_{\text{vir}}^3}\frac{1}{\frac{4\pi}{3}v_\infty^2} \leq \frac{2{m_{\mathbf{DM}}}^4}{(2\pi\hbar)^3}$$

- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass $m_{\text{DM}} \gtrsim 400$ **eV**
  "Tremaine-Gunn bound"

What we do not know about DM particles

- Mass : the range from $\mathbf{10^{-33}}$ eV (stringy axions) to $\mathbf{10^{24}}$ GeV (supersymmetric Q-balls) was considered
- Spin : both fermions and bosons are OK
- Interaction strength and interaction type
- Production mechanism
- How they are embedded into Big Picture of particle physics

Conclusions, Lecture 1

Particle physics offers solutions to outstanding cosmological problems:

- Large scale structure of the Universe
  - Cosmological inflation driven by scalar field - inflaton
- Baryon asymmetry of the Universe
  - Baryogenesis, requiring CP-violation and baryon number non-conservation
- Rotational curves of galaxies, matter content of the Universe
  - Particle dark matter

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Big questions for particle physics: What is the inflaton? What is the physics of B-violation leading to BAU? What is the dark matter particle?